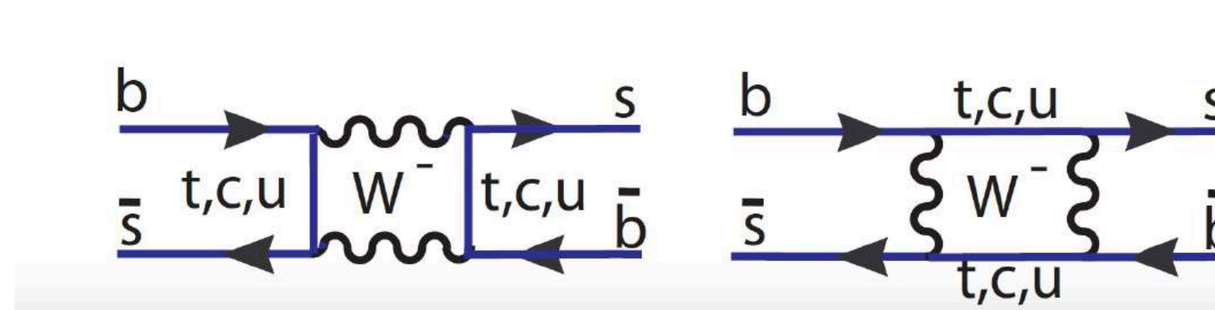
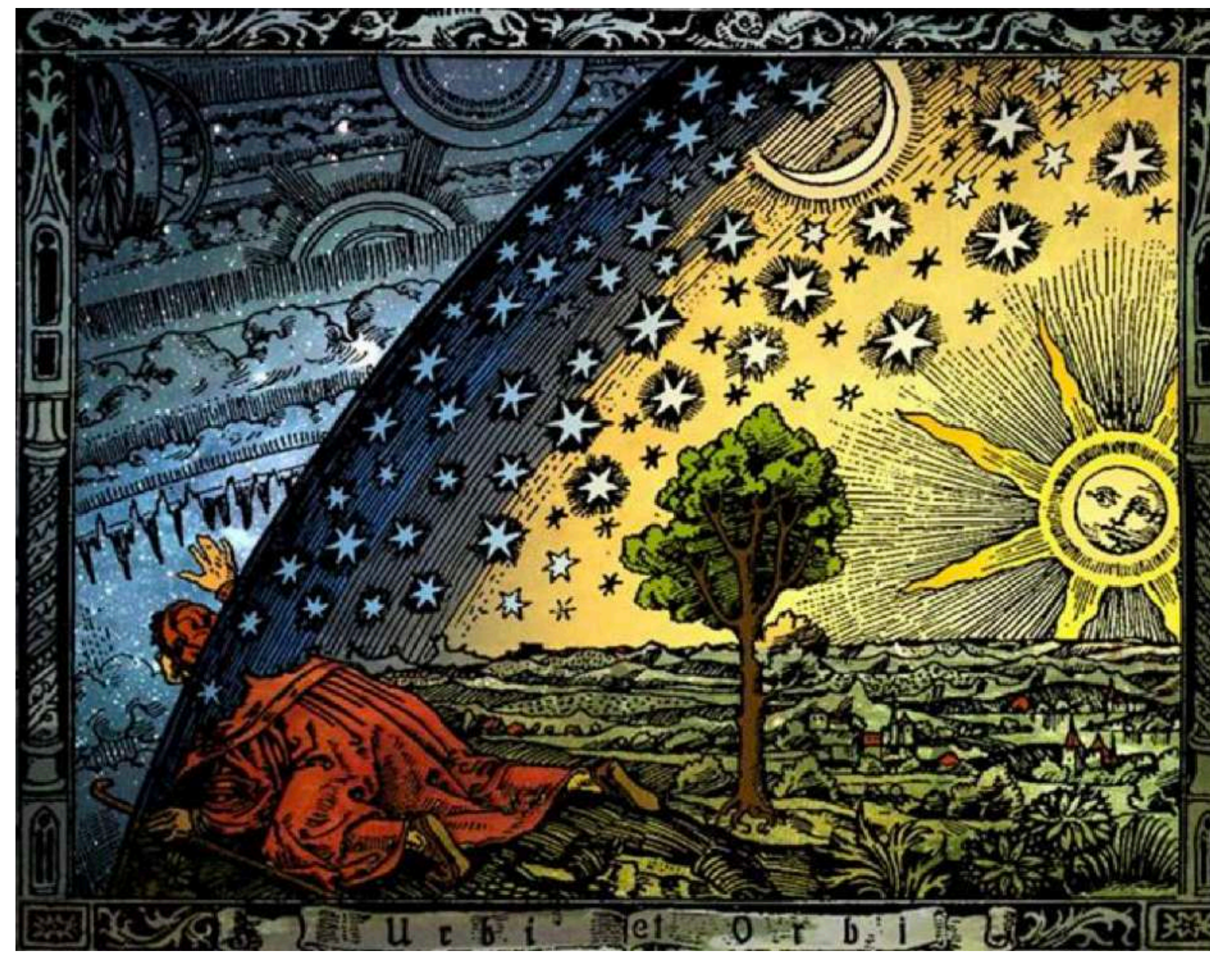
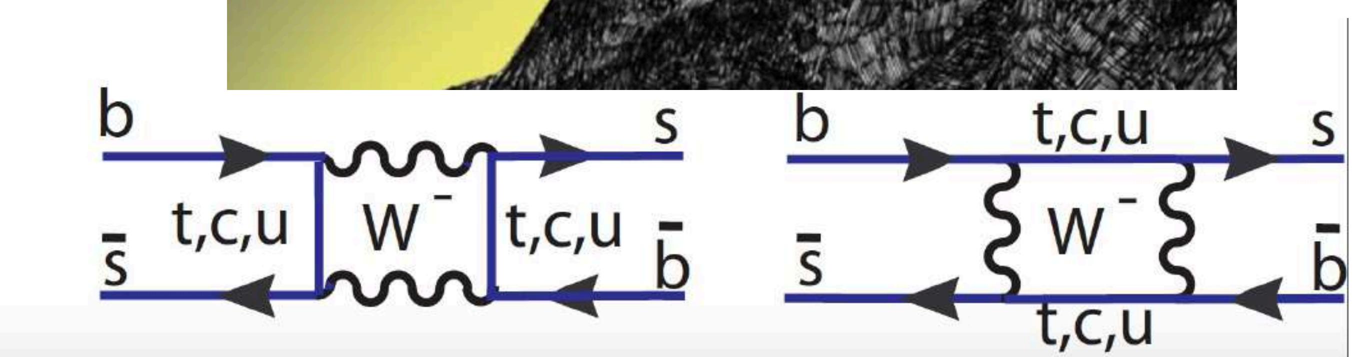
Flavour Physics - Quo vadis?

Precision Calculations in Flavour Physics







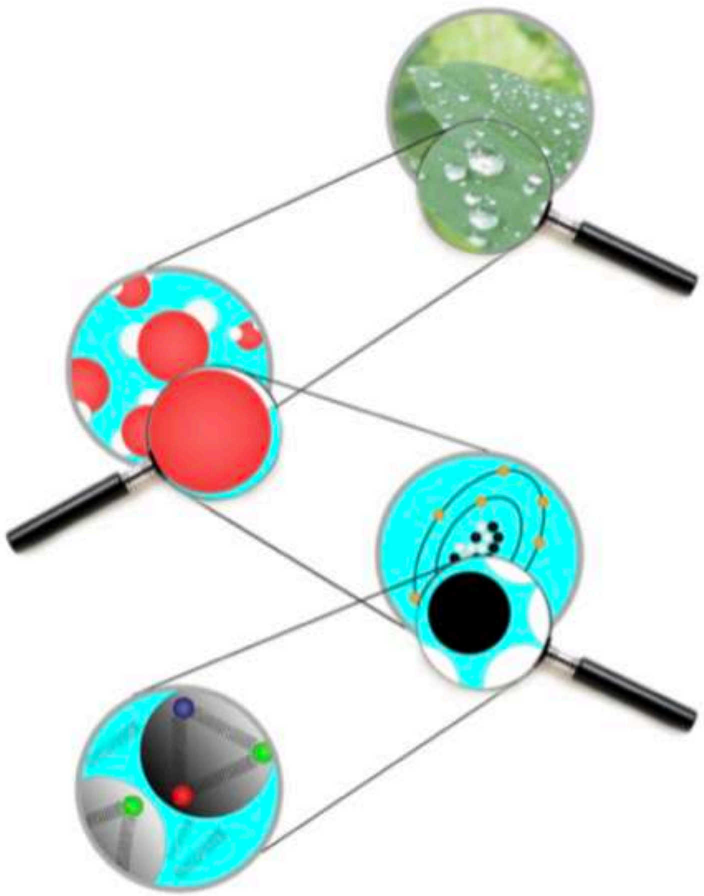
Alexander Lenz, Siegen

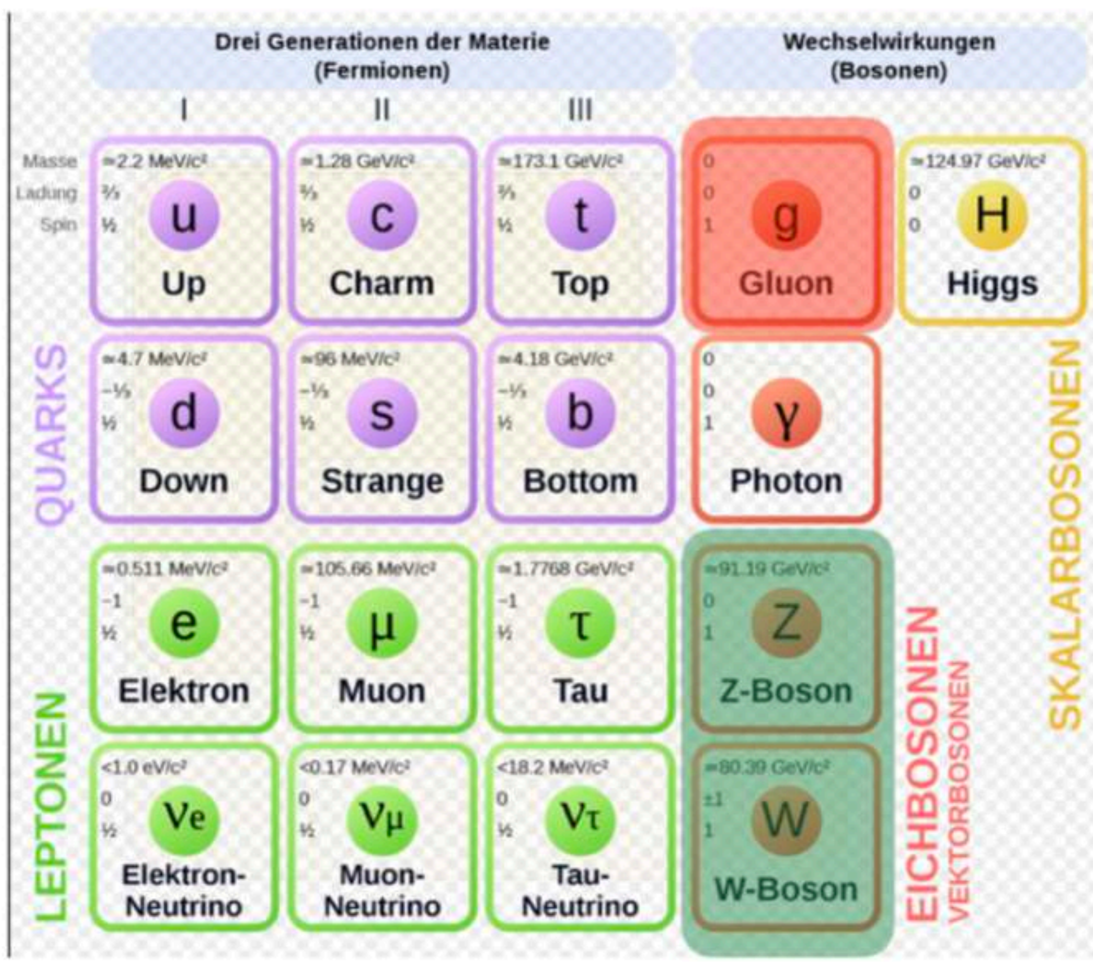
Lake Louise Winter Institute 2024

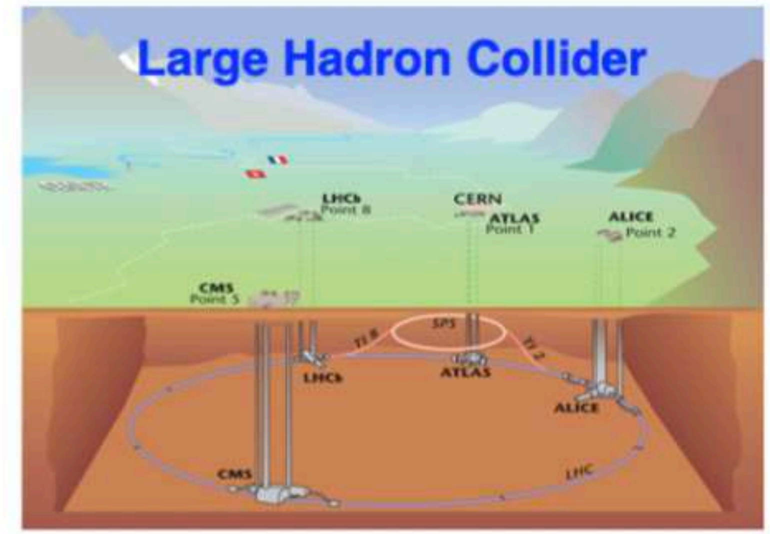
Chateau Lake Louise 21.2.2024

Content

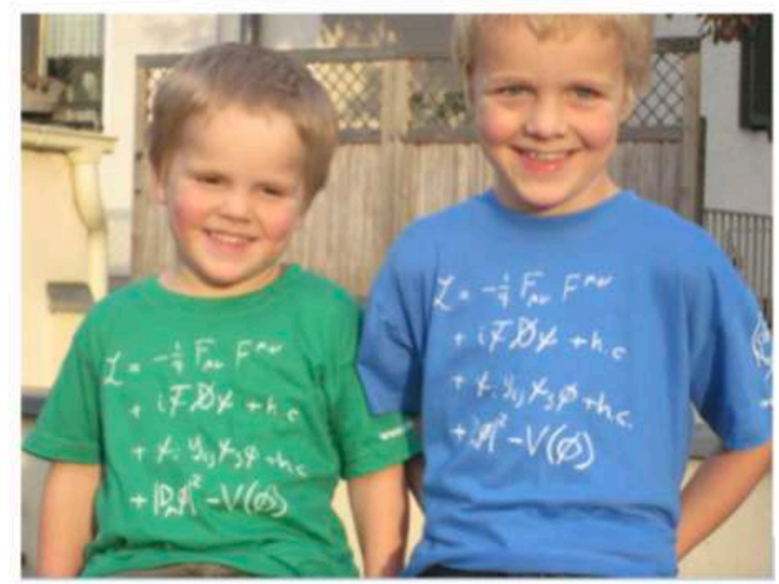
Introduction to Particle Physics







Standardmodel(s)



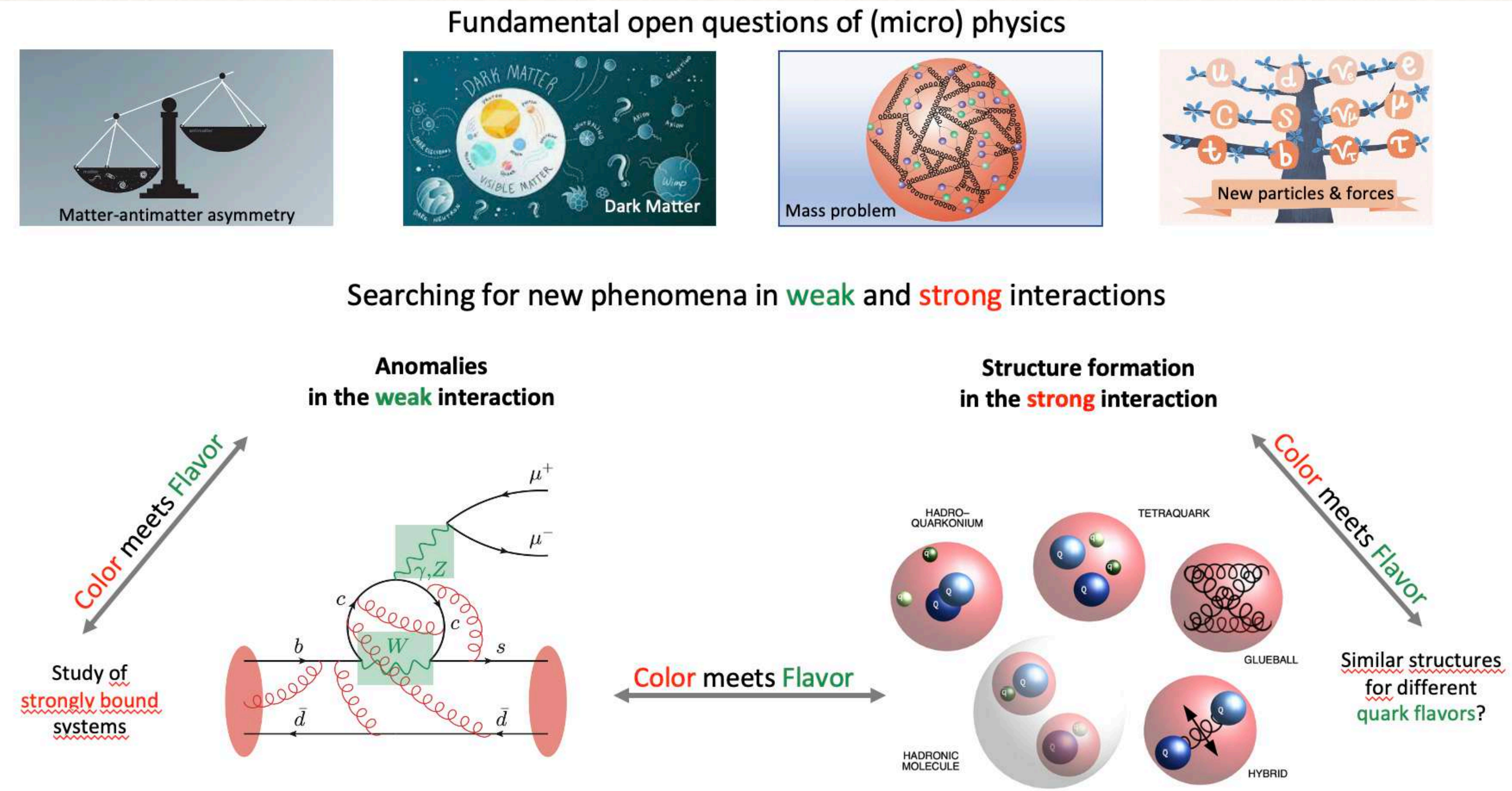
Elektromagnetic interaction (IA), strong IA, weak IA, (Gravitation)

Color: binds quarks into proton

Flavor: radioactive decay of a neutron to a proton

SM describes thousands of measurement with a very high precision!

Introduction to Particle Physics



talk by Lorenzo Capriotti

Introduction to Particle Physics

Time for high precision experiments and high precision SM predictions

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

$$f^{\mathrm{Exp}} \pm \delta^{\mathrm{Exp}} = f^{\mathrm{SM}} \pm \delta^{\mathrm{SM}} + f^{\mathrm{BSM}} \pm \delta^{\mathrm{BSM}}$$

Hard experimental Work (→ δ^{Exp})

Hard theoretical Work (→ δ^{SM})

Fun (→ f^{BSM})

Content

Ia Introduction to Particle Physics
Ib Decays of heavy Hadrons
Ic Flavour Physics

IIa First Hints for New Physics?
IIb Physics Beyond the Standard Model (**SM**)?

IIIa The Necessity of Precision SM Predictions
IIIb Test of Theory Tools
IIIc Models beyond the SM
Mathematical Elegance vs. *"Leave no Stone unturned"*

IV Final Remarks

Decays of heavy Hadrons

There are (at least) 6 kinds (= flavours) of quarks

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

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- **Proton = |uud> + …**
- **(Heavy) flavour physics = b,c quark**

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BESSIII, LHCb,..

NA62, KOTO…

ATLAS, BELLE II,

CMS, LHCb,..

- Proton = |uud> + …
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Talks by B. Echenard, R. van Tonder, G. de Marino, J. Skorupa, F. Wilson, S. Wallner, C. Miller, J. Davies

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- Proton = |uud> + …
- (Heavy) flavour physics = b,c quark

	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$
Mass (GeV)	5.27965(12)	5.27934(12)	5.36688(14)	6.27447(32)
Lifetime (ps)	1.519(4)	1.638(4)	1.516(6)	0.510(9)
$\tau(X)/\tau(B_d)$	1	1.076(4)	0.998(5)	0.336(6)*

Talks by B. Echenard, R. van Tonder, G. de Marino, J. Skorupa, F. Wilson, S. Wallner, C. Miller, J. Davies

Roughly the same lifetime

Sizable spread in lifetimes

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$
Mass (GeV)	1.86484(5)	1.86966(5)	1.96835(7)
Lifetime (ps)	0.4101(15)	1.040(7)	0.504(4)
$\tau(X)/\tau(D^0)$	1	2.536(17)	1.229(10)

Decays of heavy Hadrons

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

BESSIII, LHCb,..

NA62, KOTO...

ATLAS, BELLE II, CMS, LHCb,..

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Similar lifetime since

$$m_b^5 V_{cb}^2 \approx m_c^5 V_{cs}^2$$

Roughly the same lifetime

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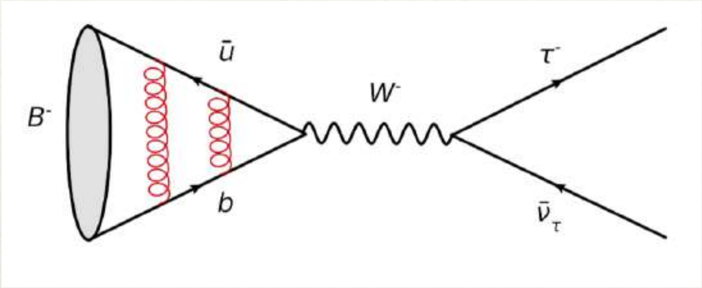
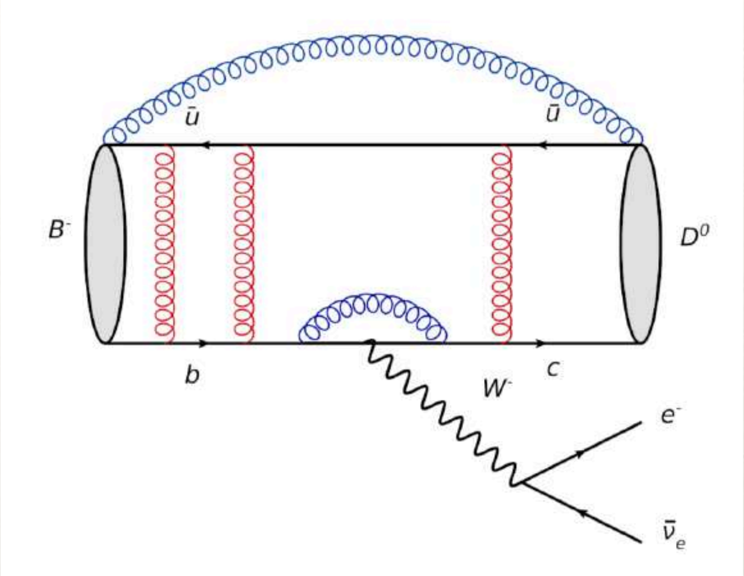
Decays of heavy Hadrons

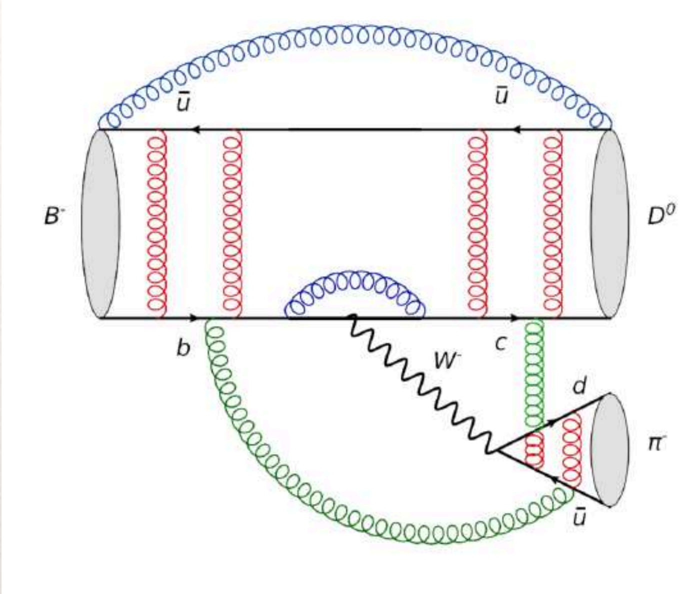
- **Leptonic Decays**



- **Semi-leptonic Decays**

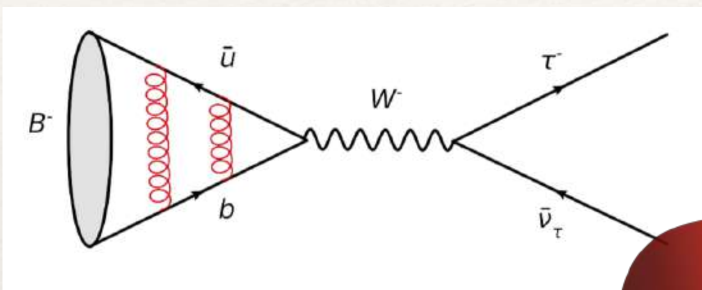


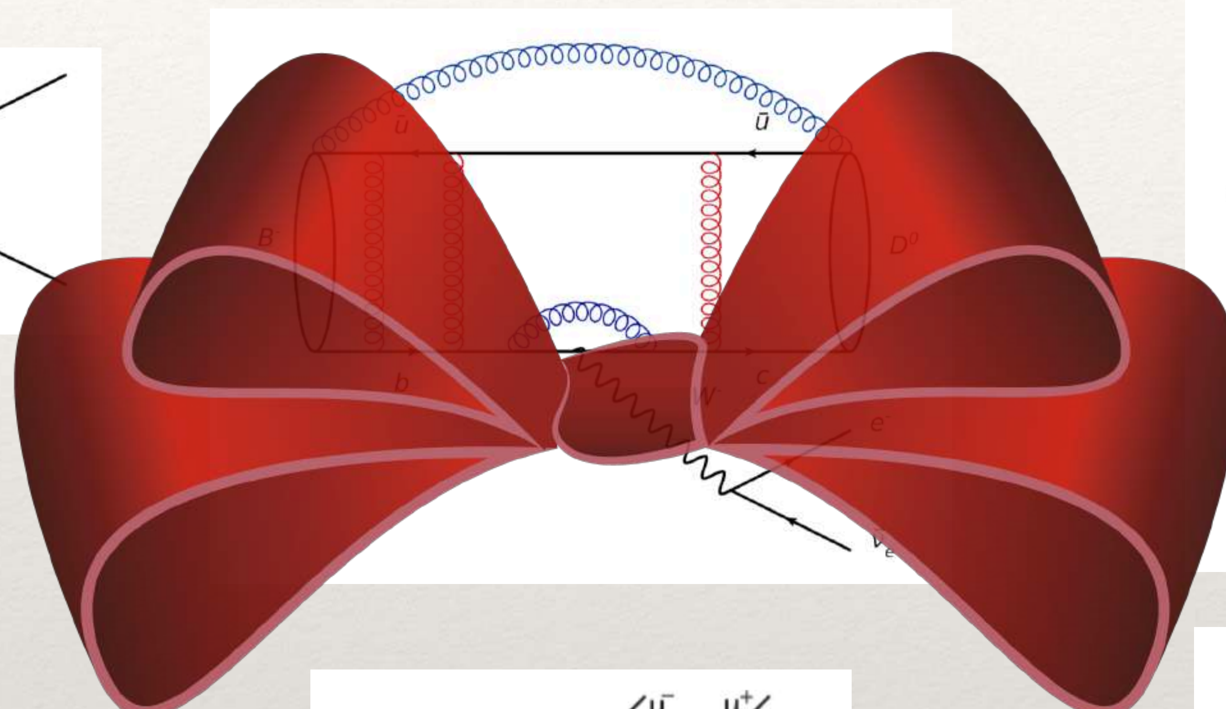
- **Non-leptonic Decays**

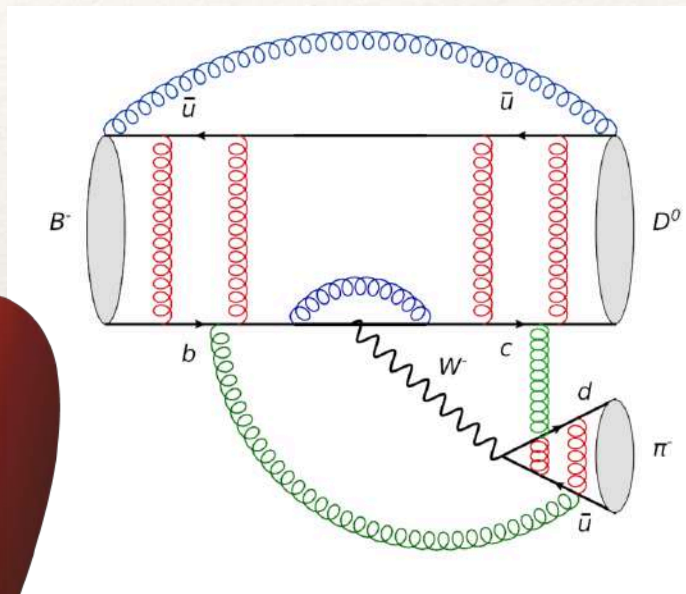


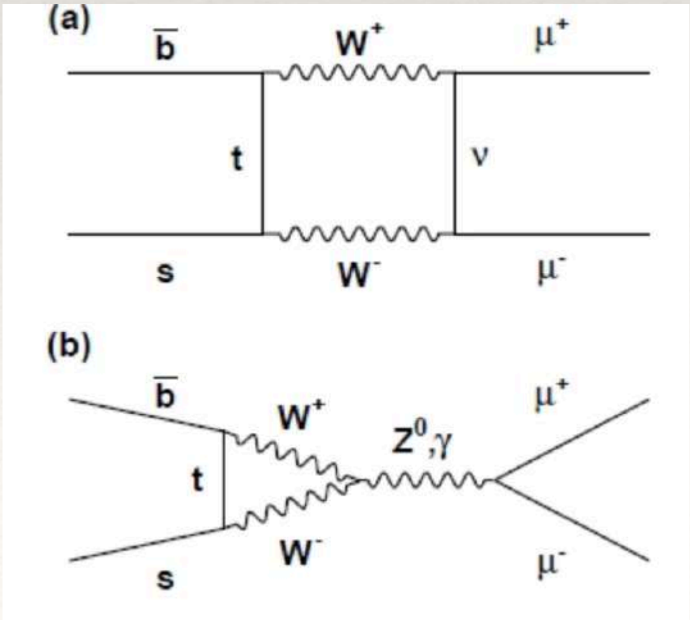
Decays of heavy Hadrons

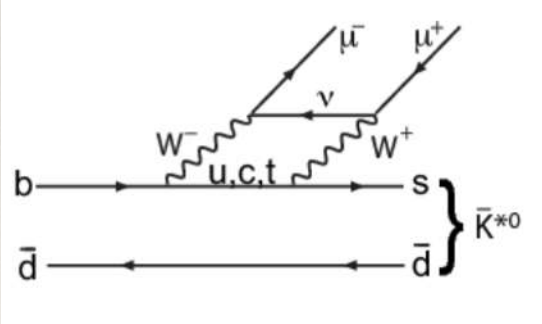
- Leptonic Decays
- Semi-leptonic Decays
- Non-leptonic Decays

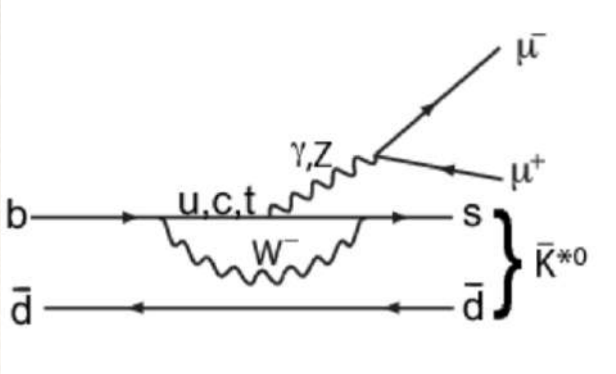


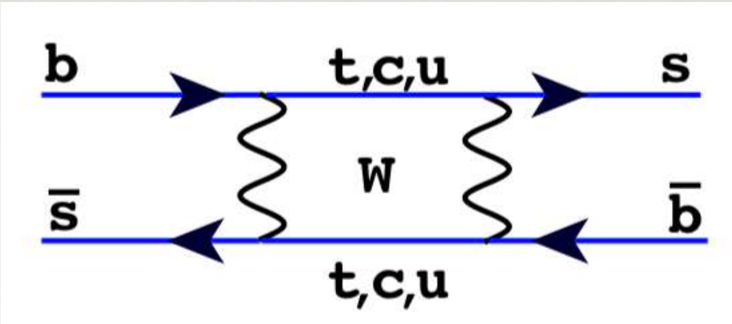


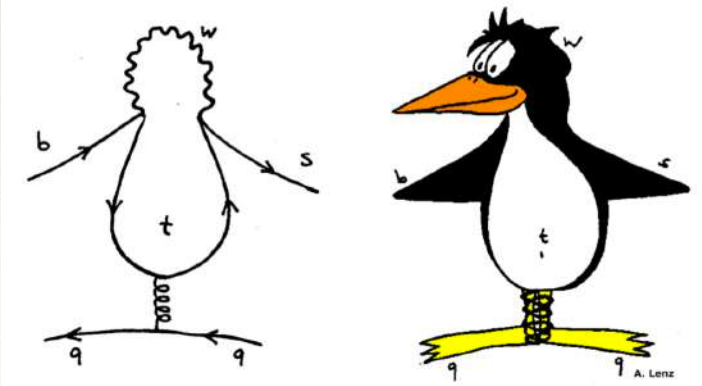








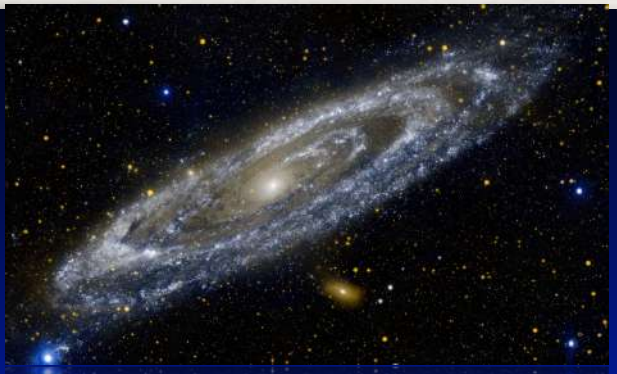




Content

Flavour Physics

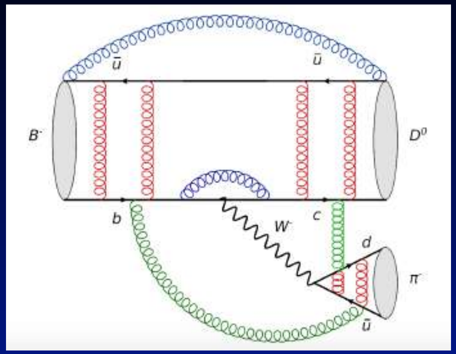
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated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

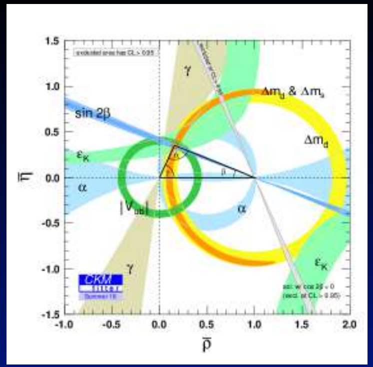


Indirect Search for BSM Physics:
To find hints for Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements. New contributions to an observable f are identified via:

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

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

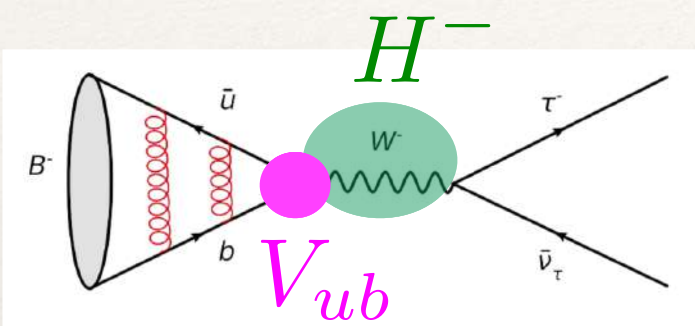




Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

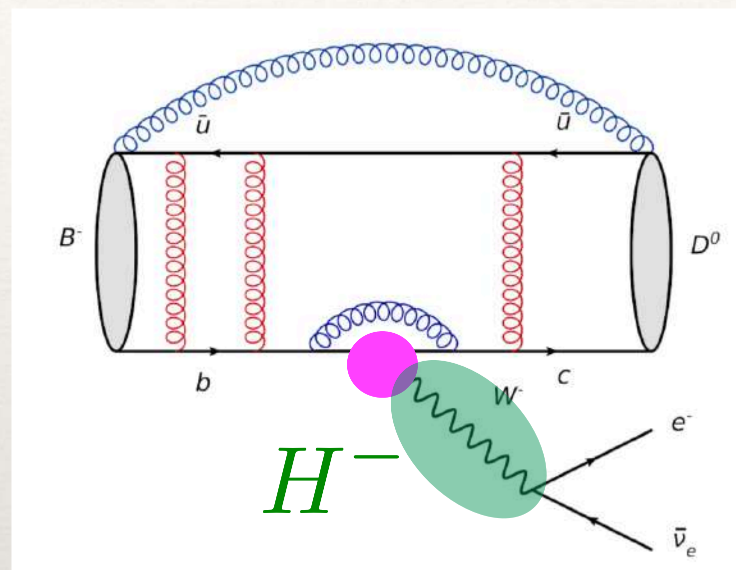
Flavour Physics

- Leptonic Decays

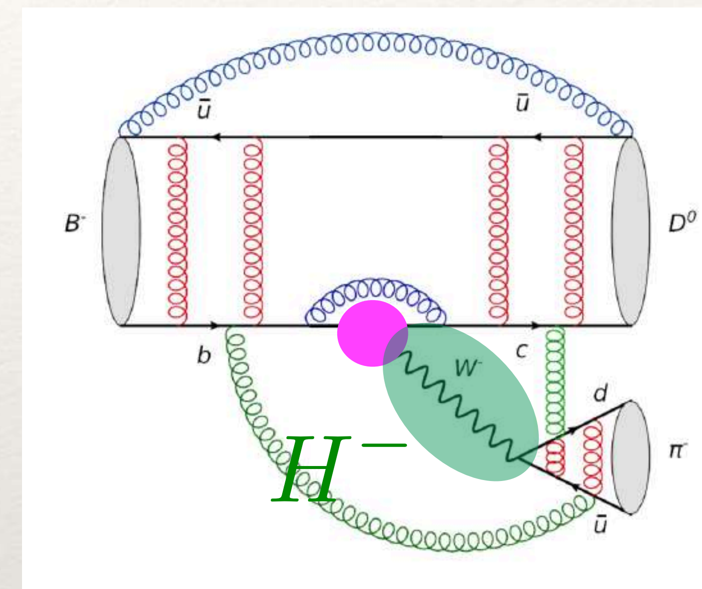


$$\langle 0|\bar b\gamma^\mu\gamma_5 u|B_q(p)\rangle = i f_{B_q} p^\mu$$

- Semi-leptonic Decays



- Non-leptonic Decays



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

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

I) Imaginary part of CKM-elements = CP Violation

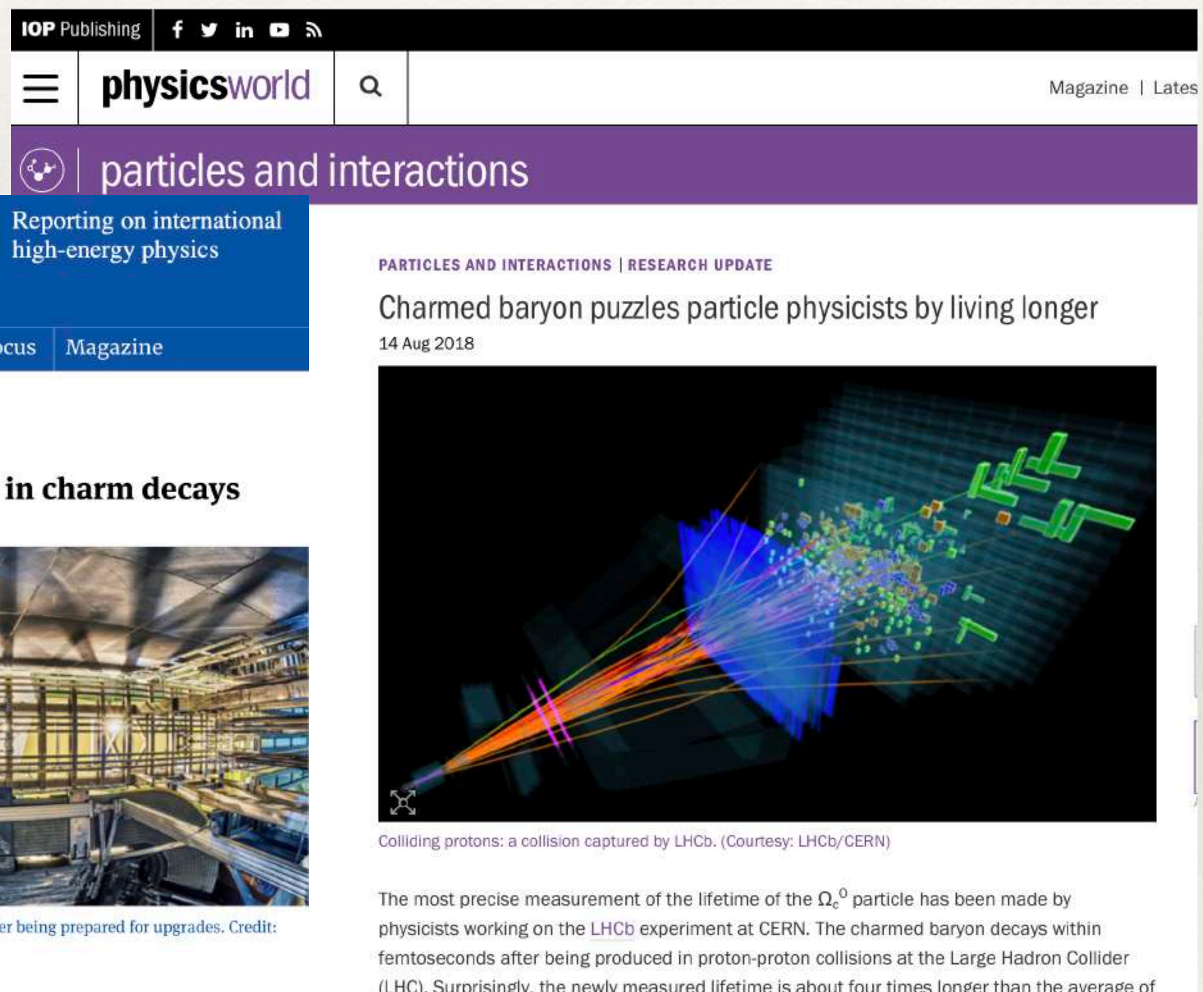
II) Instead of a W-Boson a charged Higgs particle could be exchanged

III) QCD Effects are crucial! Perturbative QCD corrections
Non-perturbative: Decay constants, Form Factors, Factorisation

IV) Determination of SM-Parameter

Flavour Physics

- Huge amount of precise data: **B-Factories, Tevatron, BESS III** and **LHC** (**ATLAS, CMS, LHCb**), **NA62** as well as **Belle II**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particles and interactions

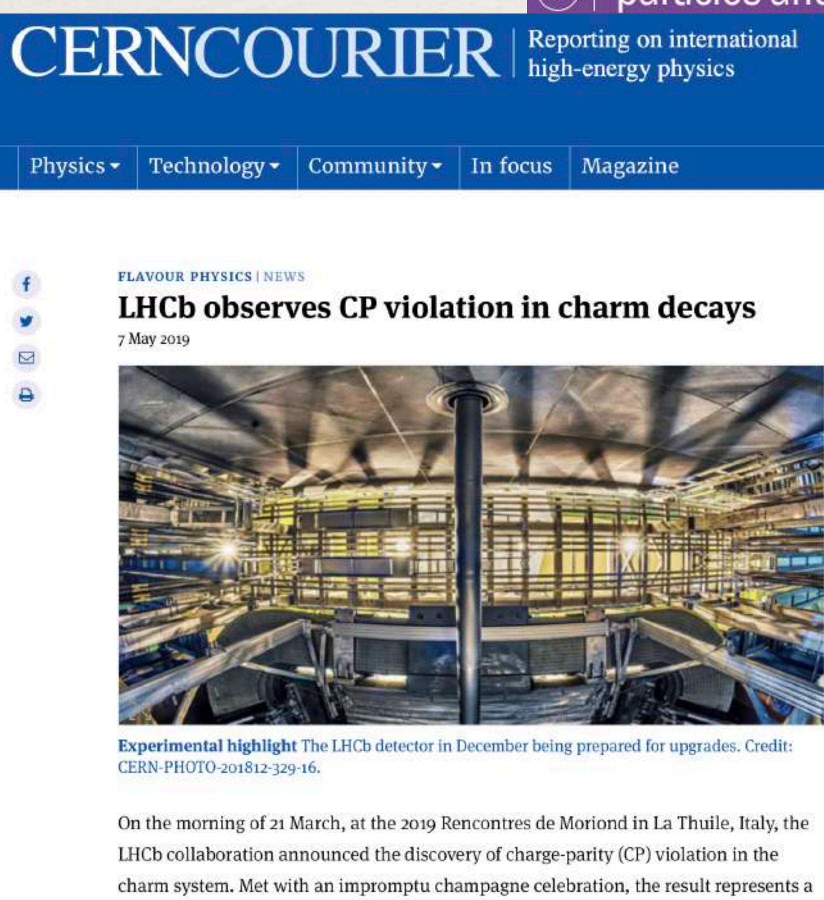
PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Charmed baryon puzzles particle physicists by living longer

14 Aug 2018

Colliding protons: a collision captured by LHCb. (Courtesy: LHCb/CERN)

The most precise measurement of the lifetime of the Ω_c^0 particle has been made by physicists working on the LHCb experiment at CERN. The charmed baryon decays within femtoseconds after being produced in proton-proton collisions at the Large Hadron Collider (LHC). Surprisingly, the newly measured lifetime is about four times longer than the average of


CERNCOURIER Reporting on international high-energy physics

Physics ▾ Technology ▾ Community ▾ In focus Magazine

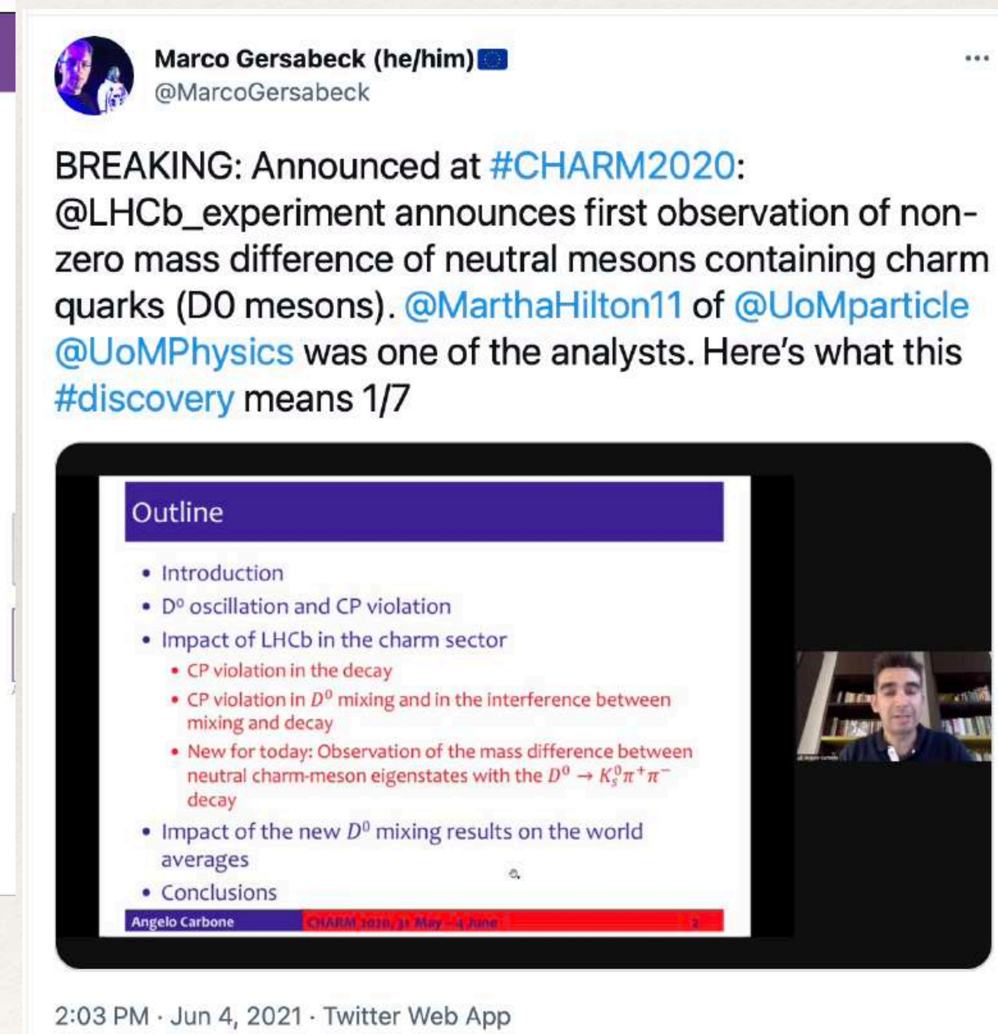
FLAVOUR PHYSICS | NEWS

LHCb observes CP violation in charm decays

7 May 2019

Experimental highlight The LHCb detector in December being prepared for upgrades. Credit: CERN-PHOTO-201812-329-16.

On the morning of 21 March, at the 2019 Rencontres de Moriond in La Thuile, Italy, the LHCb collaboration announced the discovery of charge-parity (CP) violation in the charm system. Met with an impromptu champagne celebration, the result represents a


Marco Gersabeck (he/him)

@MarcoGersabeck

BREAKING: Announced at #CHARM2020: @LHCb_experiment announces first observation of non-zero mass difference of neutral mesons containing charm quarks (D0 mesons). @MarthaHilton11 of @UoMparticle @UoMPhysics was one of the analysts. Here's what this #discovery means 1/7

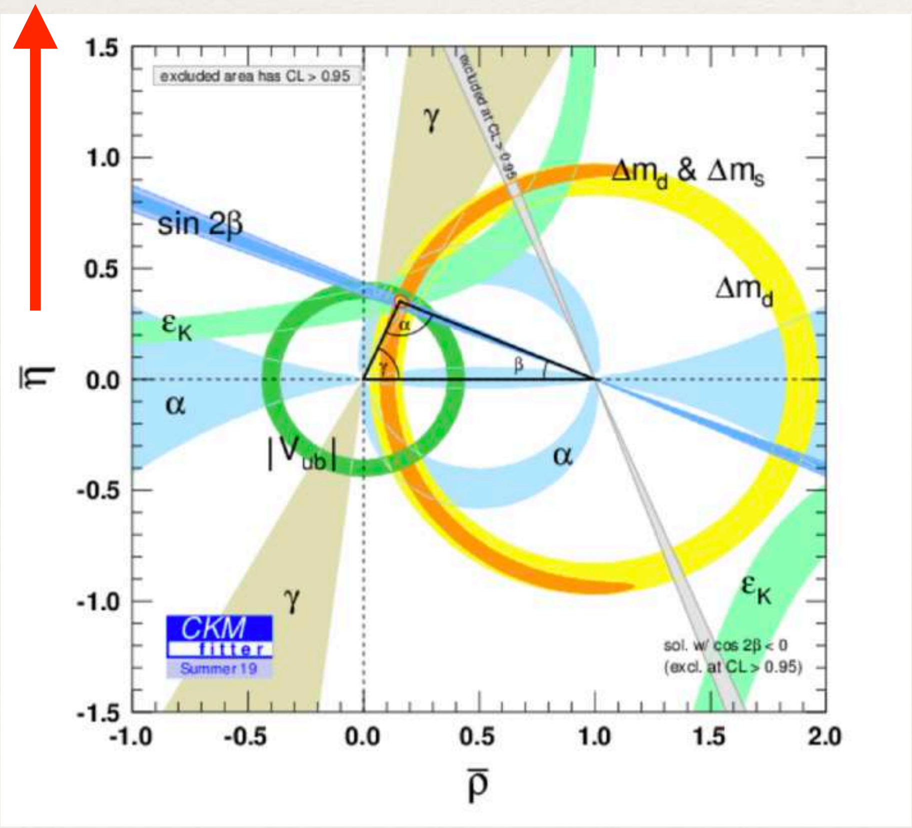
2:03 PM · Jun 4, 2021 · Twitter Web App

Theory has to match that precision

Flavour Physics

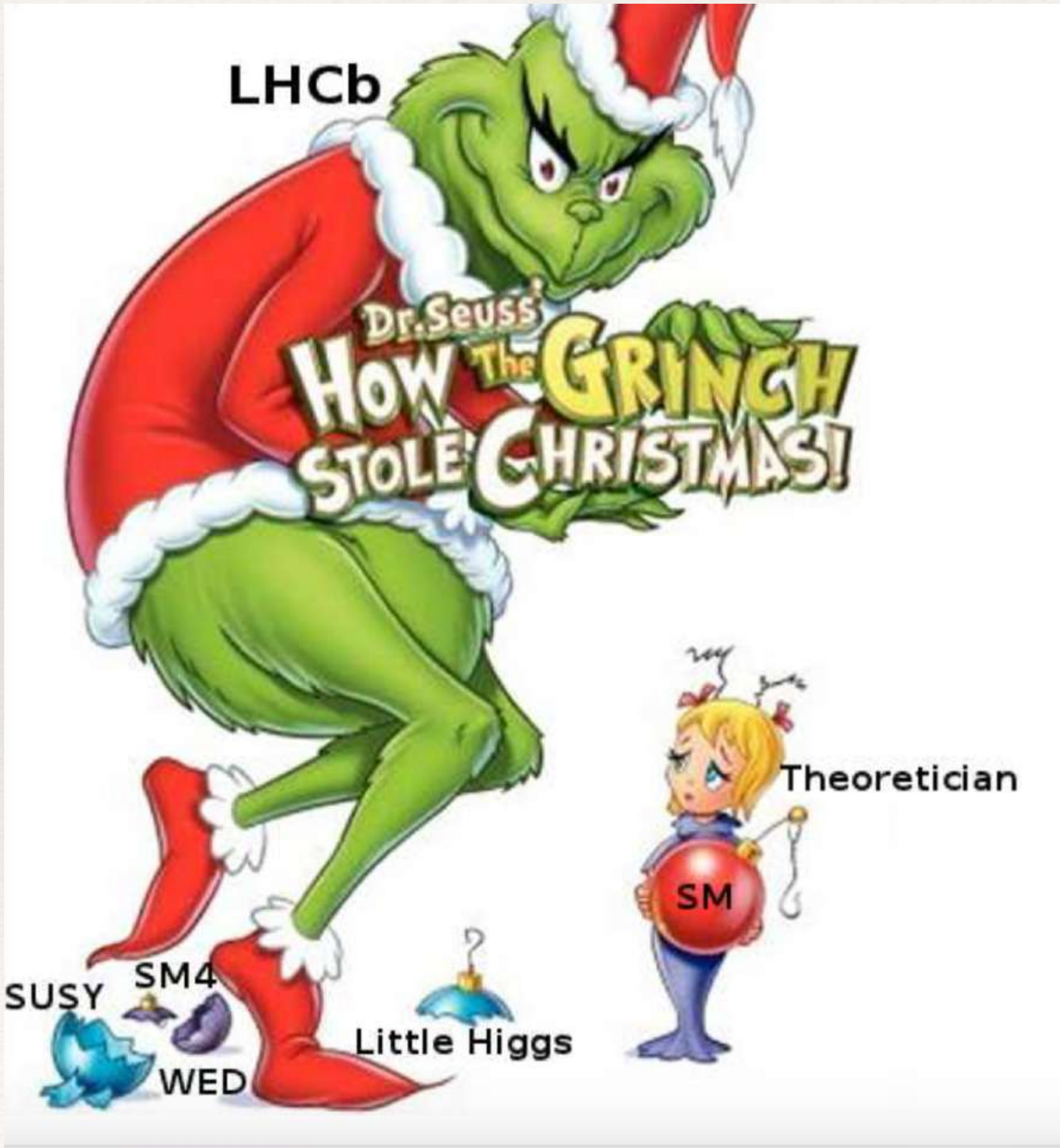
- **Insight #1:** SM and CKM have passed numerous tests
- dominant contribution to the flavour structure of nature

CP Violation



Nobel prize 2008
Kobayashi, Maskawa

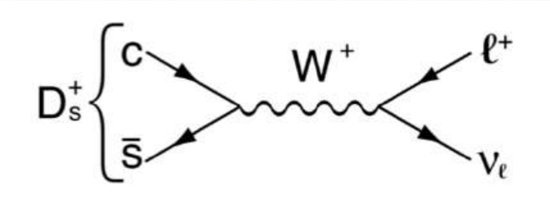
Similar results by UTfit; Eigen et al.; Laiho et al



Direct experiment vs. CKM fit

$$\beta^{\text{HFLAV}} = 22.2^\circ \pm 0.7^\circ \;\; \text{vs.} \;\; \beta^{\text{CKMFitter}} = 22.56^{\circ}{}^{+0.47^\circ}_{+0.40^\circ}$$

$$\gamma^{\text{HFLAV}} = 66.2^\circ \pm 3.5^\circ \;\; \text{vs.} \;\; \gamma^{\text{CKMFitter}} = 65.80^{\circ}{}^{+0.94^\circ}_{-1.29^\circ}$$



Flavour Physics

- **Insight #2:** QCD-effects are often under good control
- both non-perturbative (lattice, sum rules) and perturbative

$$\Gamma\left(D_s^+ \to \ell^+\nu_\ell\right) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_\ell^2 m_{D_s^+} \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2 |V_{cs}|^2,$$

$$f_{D_s^+} = (241.0 \pm 16.3 \pm 6.6)\ \text{MeV},$$

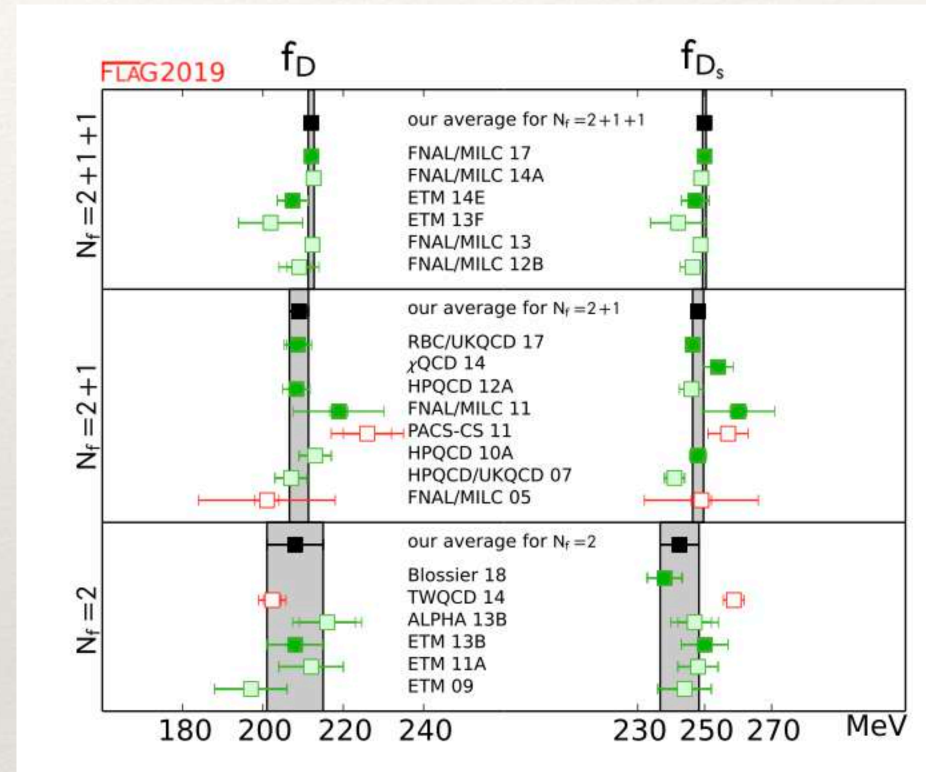
1608.06732 BESSIII

$$|V_{cs}| f_{D_s^+} = 248.8 \pm 5.8\ \text{MeV}$$

PDG

$$f_{D_s} = (238^{+13}_{-23})\ [266]\ \text{MeV}$$

1305.5432 Gelhausen, Khodjamirian, Pivovarov, Rosenthal



Anomaly friends take care!

Accumulating evidence for nonstandard leptonic decays of D_s mesons

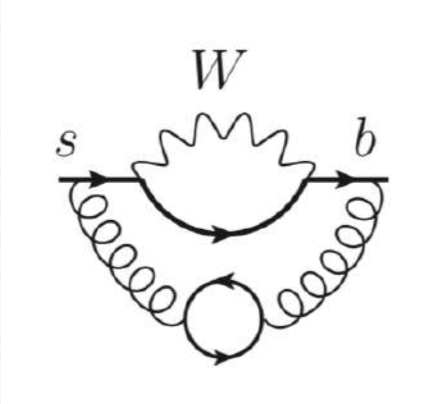
Bogdan A. Dobrescu and Andreas S. Kronfeld
Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois, USA
(Dated: March 4, 2008; revised April 28, 2008)

The measured rate for $D_s^+ \to \ell^+\nu$ decays, where ℓ is a muon or tau, is larger than the standard model prediction, which relies on lattice QCD, at the 3.8σ level. We discuss how robust the theoretical prediction is, and we show that the discrepancy with experiment may be explained by a charged Higgs boson or a leptoquark.

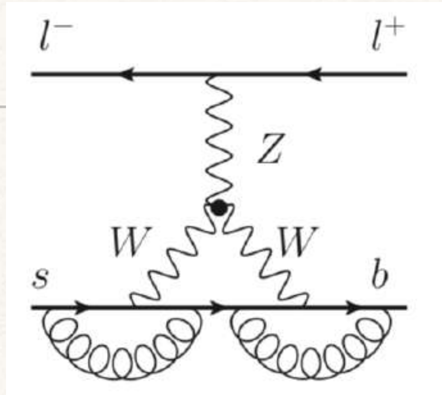
$$(f_{D_s})_{\text{expt}} = 277 \pm 9\ \text{MeV}.$$

urate calculation from lattice

$$(f_{D_s})_{\text{QCD}} = 241 \pm 3\ \text{MeV},$$

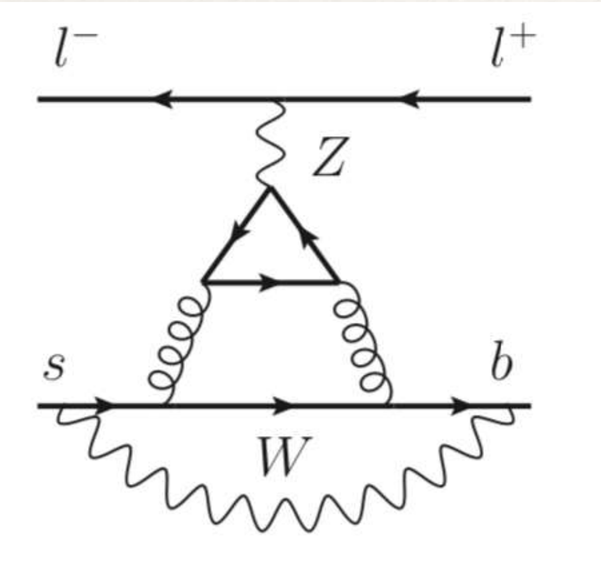


Flavour Physics



- **Insight #2:** QCD-effects are often under good control
- both non-perturbative (lattice, sum rules) and perturbative

HFLAV : $(3.45 \pm 0.29) \cdot 10^{-9}$

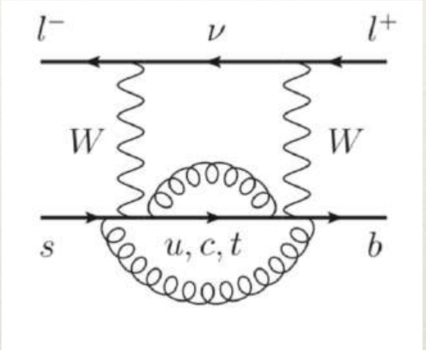


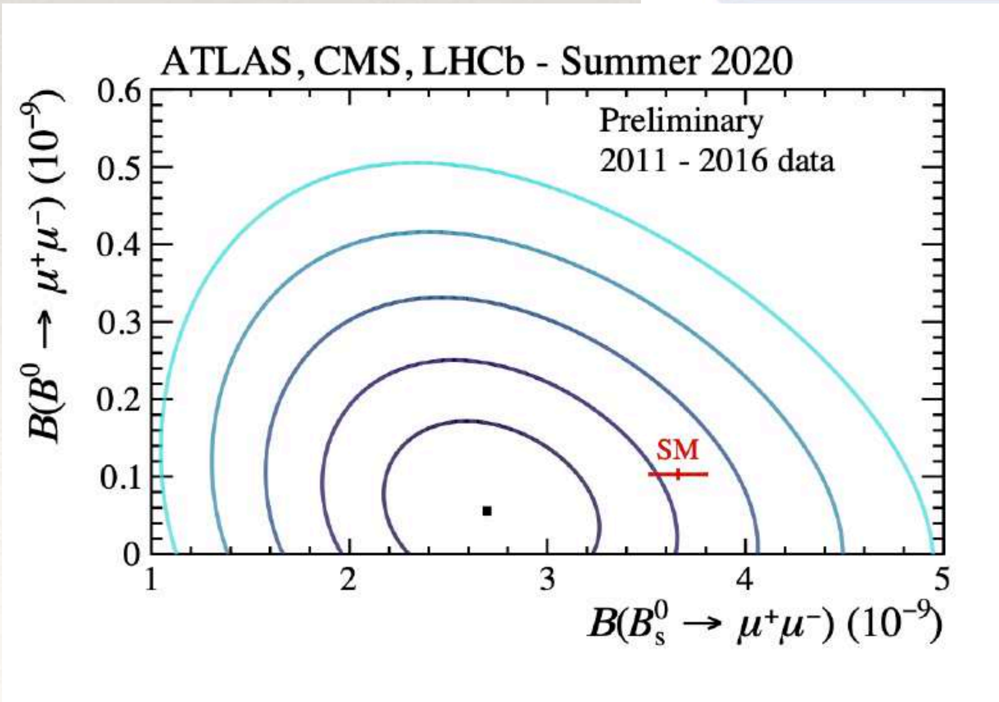
- **perturbative corrections under control**
  - at μ_W: NLO EW + NNLO QCD [CB/Gorbahn/Stamou 1311.1348, Hermann/Misiak/Steinhauser 1311.1347]
  - $\mu_W \to \mu_b$: RGE NLO QED + NNLO QCD [CB/Gambino/Gorbahn/Haisch hep-ph/0312090]
  - $\mu_b \to \Lambda_{\rm QCD}$: **power-enhanced QED correction** $\delta Br \sim \mathcal{O}(-1\%)$ [Beneke/CB/Szafron 1708.09152]
- **hadronic uncertainty** only decay constant f_{B_q} (at LO in QED)

  $\Rightarrow$ lattice $\delta f_{B_q} \lesssim 0.5\%$: $f_{B_d} = (189.4 \pm 1.4)$ MeV & $f_{B_s} = (230.7 \pm 1.2)$ MeV [FNAL/MILC 1712.09262]

  !!! only other compareable precision in flavor: $Br(K^+ \to \pi^+ \nu\bar{\nu})$ (NA62), $Br(K_L \to \pi^0 \nu\bar{\nu})$ (KOTO), $\Delta M_{d,s}$ (lattice)
- **Error budget** [2017: f_{B_s} from FLAG, CKM from CKMfitter/UTfit, τ_H^s HFLAV]

$$10^9 \times \overline{Br}(B_s \to \mu\bar{\mu})_{\rm SM} = 3.57 \pm 0.022|_{\tau_H^s} \pm 0.116|_{f_{B_s}} \pm 0.053|_{\rm non-pmr} \pm 0.030|_{\rm pmr-PE-QED} \pm 0.039|_{m_t} \pm 0.111|_{V_{cb}} \pm 0.003|_{\alpha_s}$$





$$B(B_s \to \mu\bar{\mu}) = 2.4 \times 10^{-9} \frac{\tau(B_s)}{1.28 \text{ ps}} \left[\frac{F_B}{200 \text{ MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.041}\right]^2 \left[Y_0^2(x_t) + \frac{\alpha_s}{2\pi} Y_0(x_t) Y_1(x_t)\right]. \qquad (4.12)$$

$$2.49 \frac{1.516}{1.28} \left(\frac{230}{200}\right)^2 \approx 3.9$$

Nuclear Physics B400 (1993) 225–239
North-Holland

NUCLEAR PHYSICS B

QCD corrections to rare K- and B-decays for arbitrary top quark mass *

Gerhard Buchalla and Andrzej J. Buras

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Ic Flavour Physics

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Mathematical Elegance vs. *"Leave no Stone unturned"*

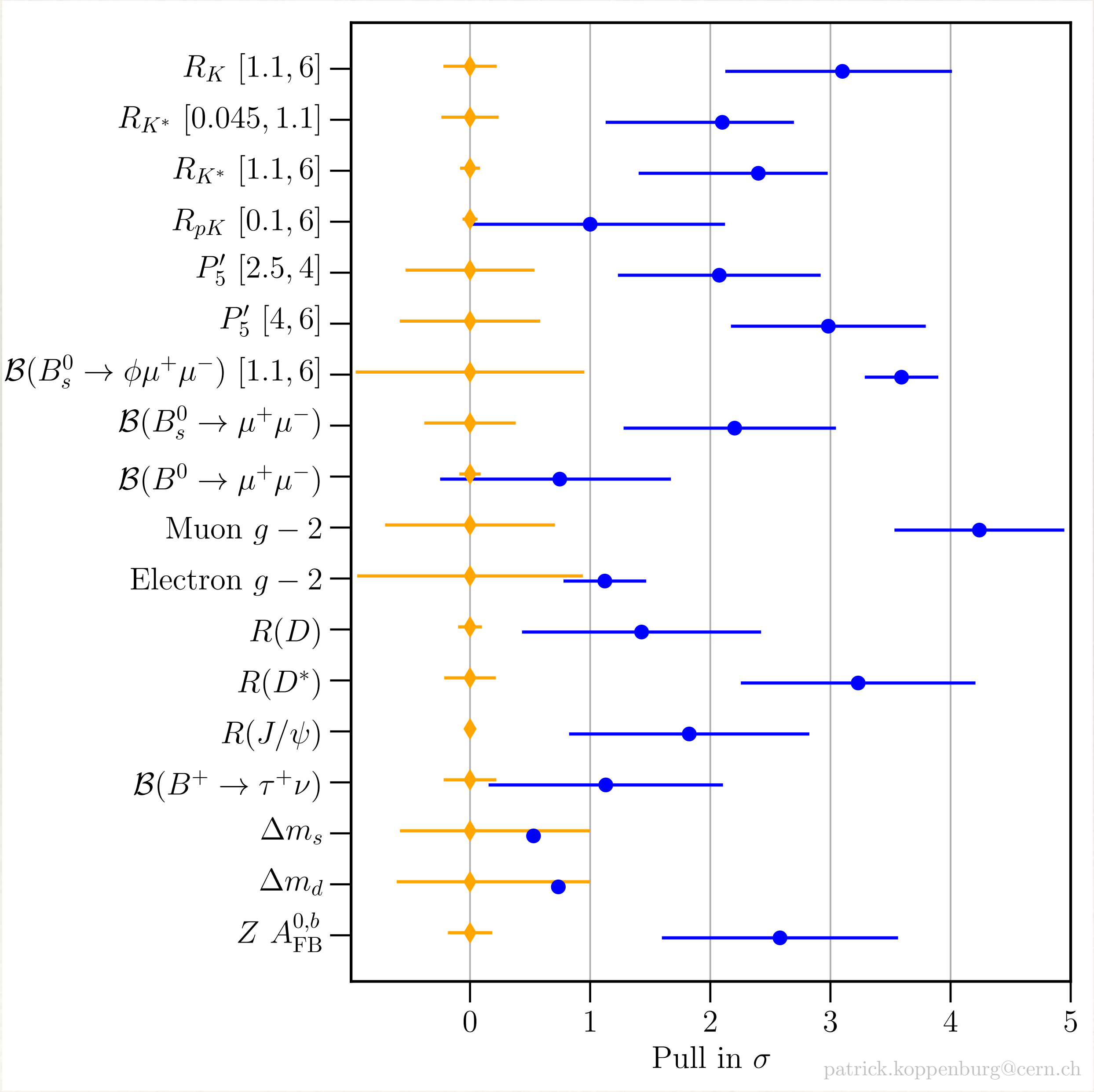
IV Final Remarks

First Hints for New Physics?

➤ **Insight #3:** First discrepancies appear (and seem to stay)

Standard deviations: 3 sigma = 0.27%, 6 sigma = 2×10^{-7}%, Lotto 7×10^{-7} %

- 3-7: Semileptonic loop-level decays (small BSM effects $b \to sll$)
- 5-7: Non-leptonic tree-level decays (large BSM effects $b \to c\bar{u}d, c\bar{c}s$,...)
- 3.9: Semileptonic tree-level decays. (large BSM effects $b \to cl\nu$)
- 3.6: B-mixing phase (Di-muonasymmetry)
- 2.x: V_{cb}, V_{ub} inclusive vs exclusive
- 2.x: $K - \pi$ Puzzle
- 2.x: $\tau \to \mu\nu\nu / \tau \to e\nu\nu$
- 2.x: V_{us}: K vs. τ, CKM Unitarity



Slow but steady evidence building for new physics
or
systematic underestimation of uncertainties

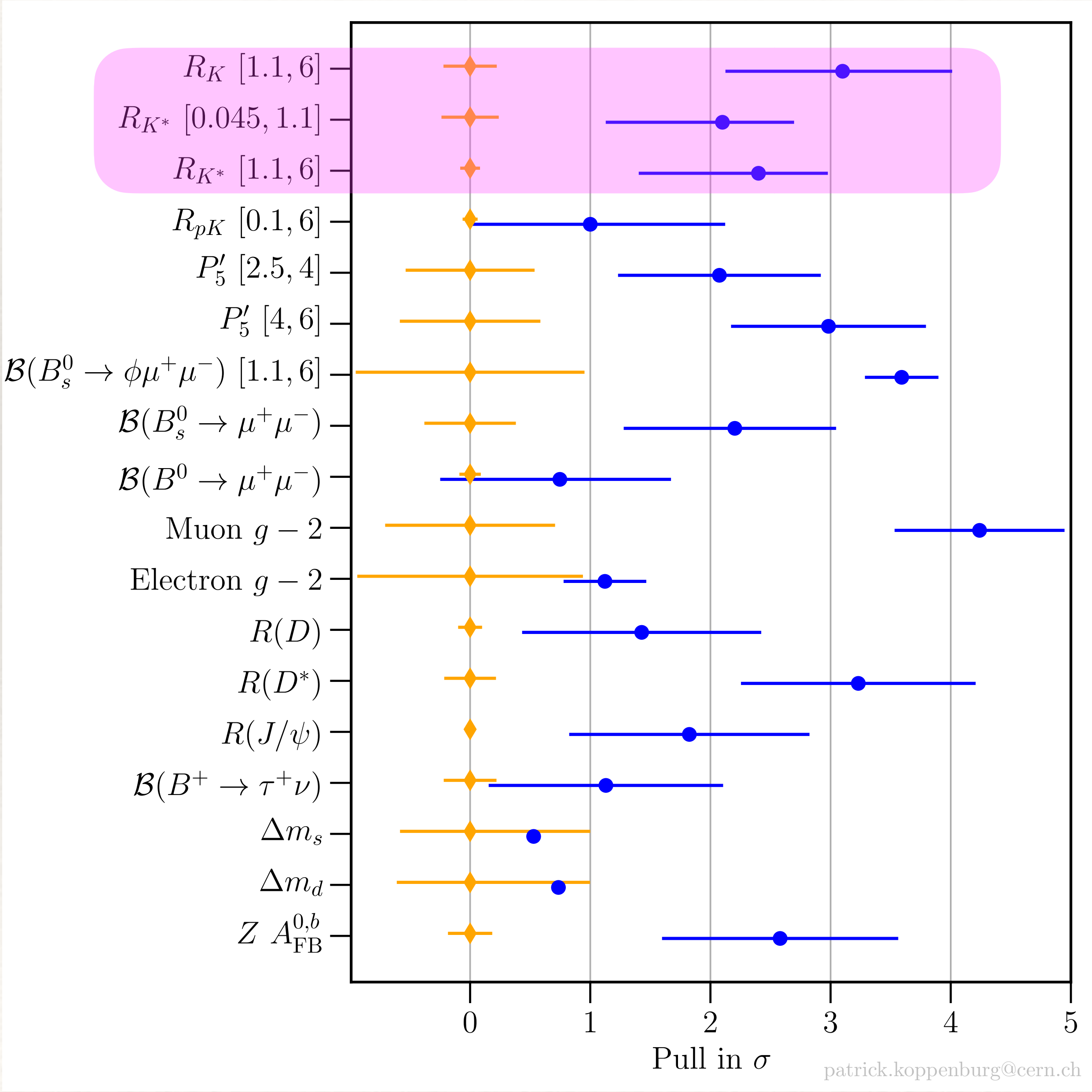
First Hints for New Physics?

➤ **Insight #3:** First discrepancies appear (and seem to stay)

Standard deviations: 3 sigma = 0.27%, 6 sigma = 2×10^{-7}**%, Lotto** 7×10^{-7} **%**

Slow but steady evidence building for new physics
or
systematic underestimation of uncertainties

- Experimental uncertainties
- Hadronic Uncertainties
- Combination of many small effects
- New physics



First Hints for New Physics?

➤ **Insight #3:** First discrepancies appear (and seem to stay)

Standard deviations: 3 sigma = 0.27%, 6 sigma = $2 \times 10^{-7}\%$**, Lotto** $7 \times 10^{-7}\ \%$

Slow but steady evidence building for new physics
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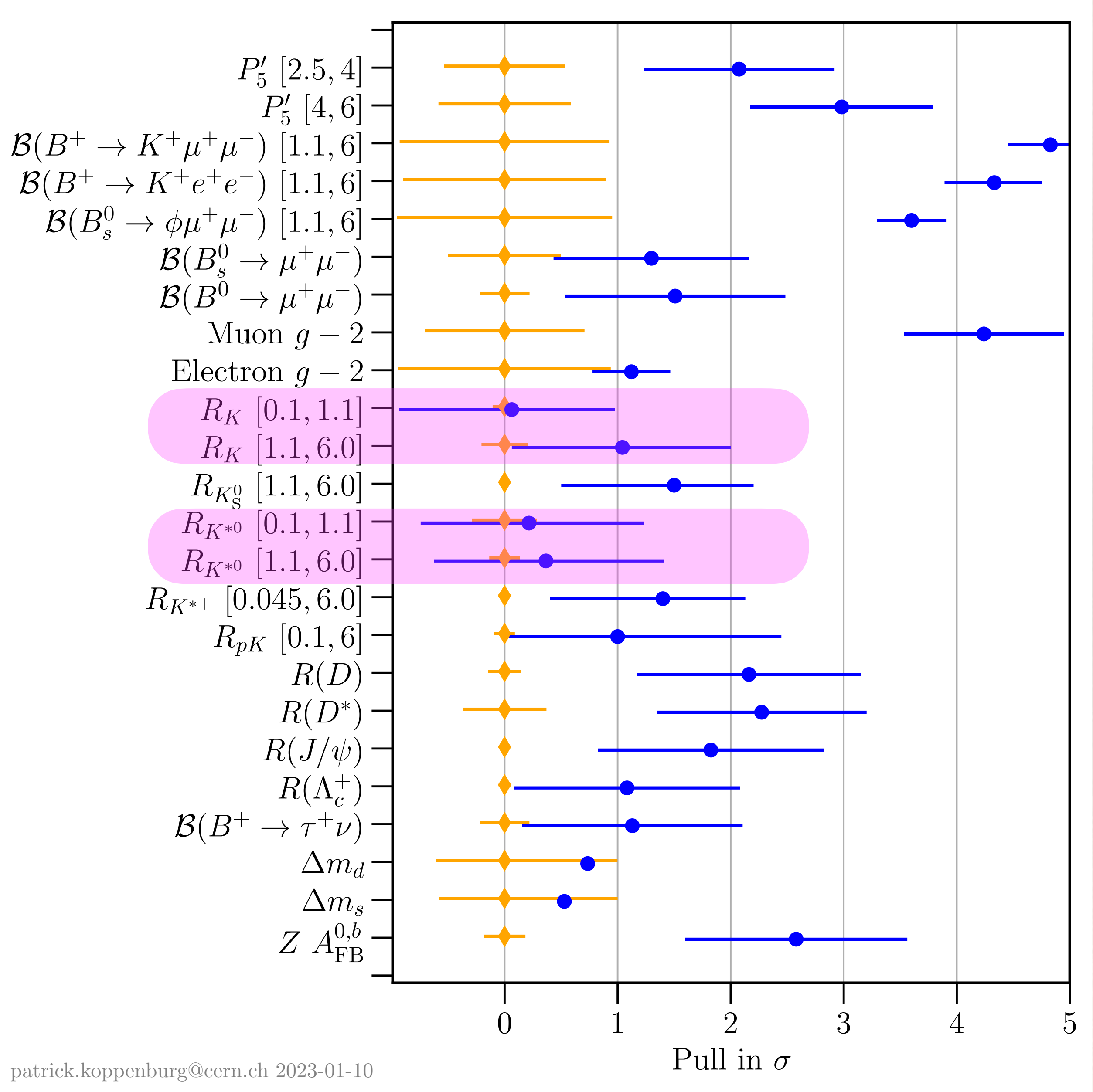
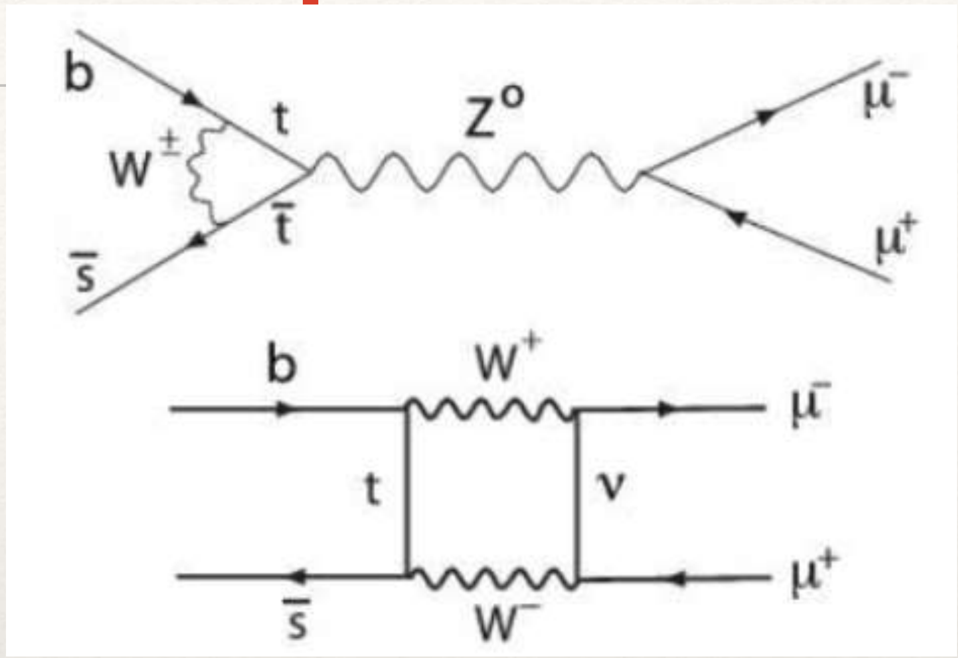


Flavour Anomalies at Loop Level



"Relative" simple hadronic structure

$B_{d,s} \to \mu\mu$: decay constant f_{B_q}

$H_b \to H_q \mu\mu$: form factor $F_{H_b \to H_q}(q^2)$

can be determined by LCSR or with lattice QCD

Reliable theoretical determination of perturbative corrections, decay constants, form factors, non-local contributions is crucial!!!!!

Many observables differ by about 2-4 standard deviations:

O: Branching ratios like $Br(B_s \to \phi\mu\mu)$, $Br(B \to K^*\mu\mu)$,

+: Angular observables like P_5' hadronic uncertainties cancel partially

++: Ratios like $R_K = \frac{Br(B^+ \to K^+\mu^-\mu^+)}{Br(B^+ \to K^+e^-e^+)}$ hadronic uncertainties cancel almost completely

Flavour Anomalies at Loop Level

Consistent picture of > 200 observables:

all deviations can be fitted in a very simple scenario **BSM = -1/4 SM**

e.g. modify only the Wilson coefficient C9 or C9 = -C10!

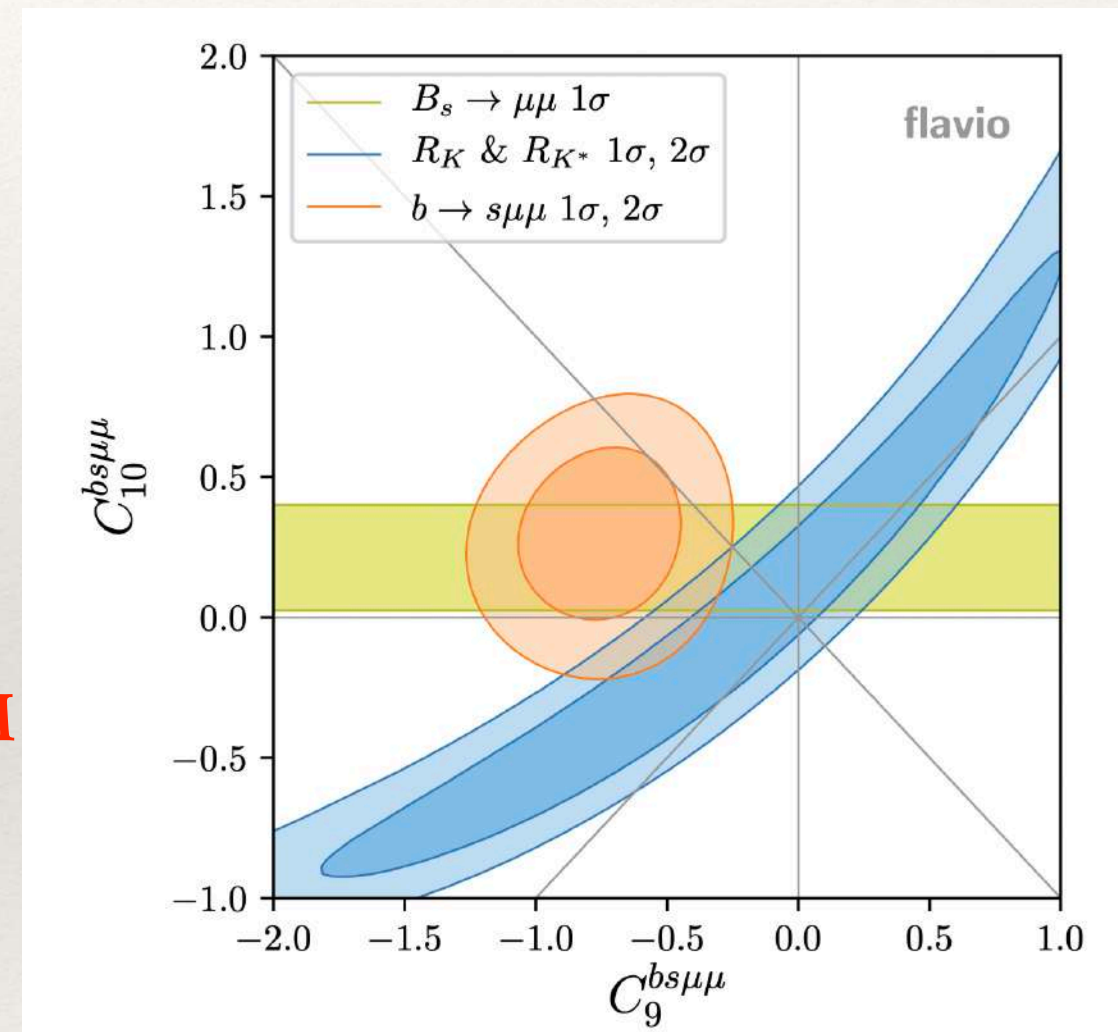
$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \left[\left(C_9^{\text{SM}} + C_9^{\text{BSM}} \right) Q_9 + \left(C_{10}^{\text{SM}} + C_{10}^{\text{BSM}} \right) Q_{10} \right]$$

e.g.. 2104.08921: Exp. was 7 sigma away from SM

Alguero, Capdevilla, Descotes-Genon, Matias, Novoa-Brunet

b to sll global fits after Moriond 2021 results

as well as many other fitting groups



Reliable theoretical determination of perturbative corrections, decay constant, form factors, non-local contributions crucial!
Experimental cross-check by ATLAS, CMS, BELLE II,…

Rare b decays meet high-mass Drell-Yan

Admir Greljo (Bern U. and Basel U.), Jakub Salko (Bern U. and Basel U.), Aleks Smolkovič (Bern U.), Peter Stangl (Bern U. and CERN) (Dec 20, 2022)

e-Print: 2212.10497 [hep-ph]

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Physics Beyond the Standard Model

Hundreds of publications…

List of models:

- **Z' - new U(1) or SU(2) W'**
- **Leptoquarks**
- 2HDM
- SUSY
- Vectorlike quarks
- Composite models
- WED
- ….
- ….

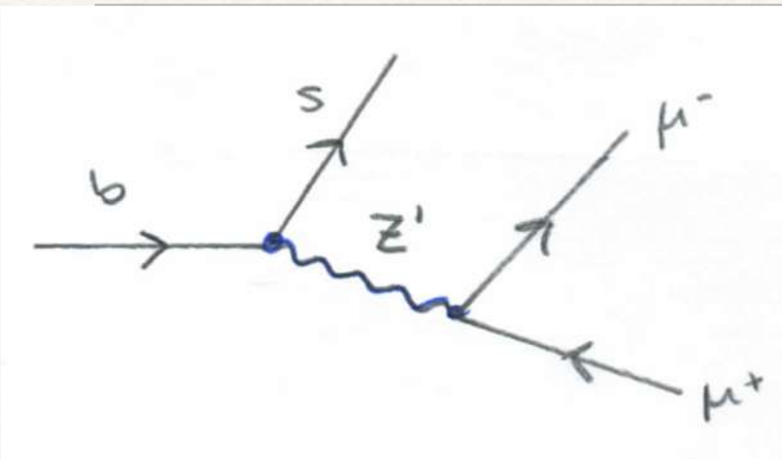
The agony of choice

or

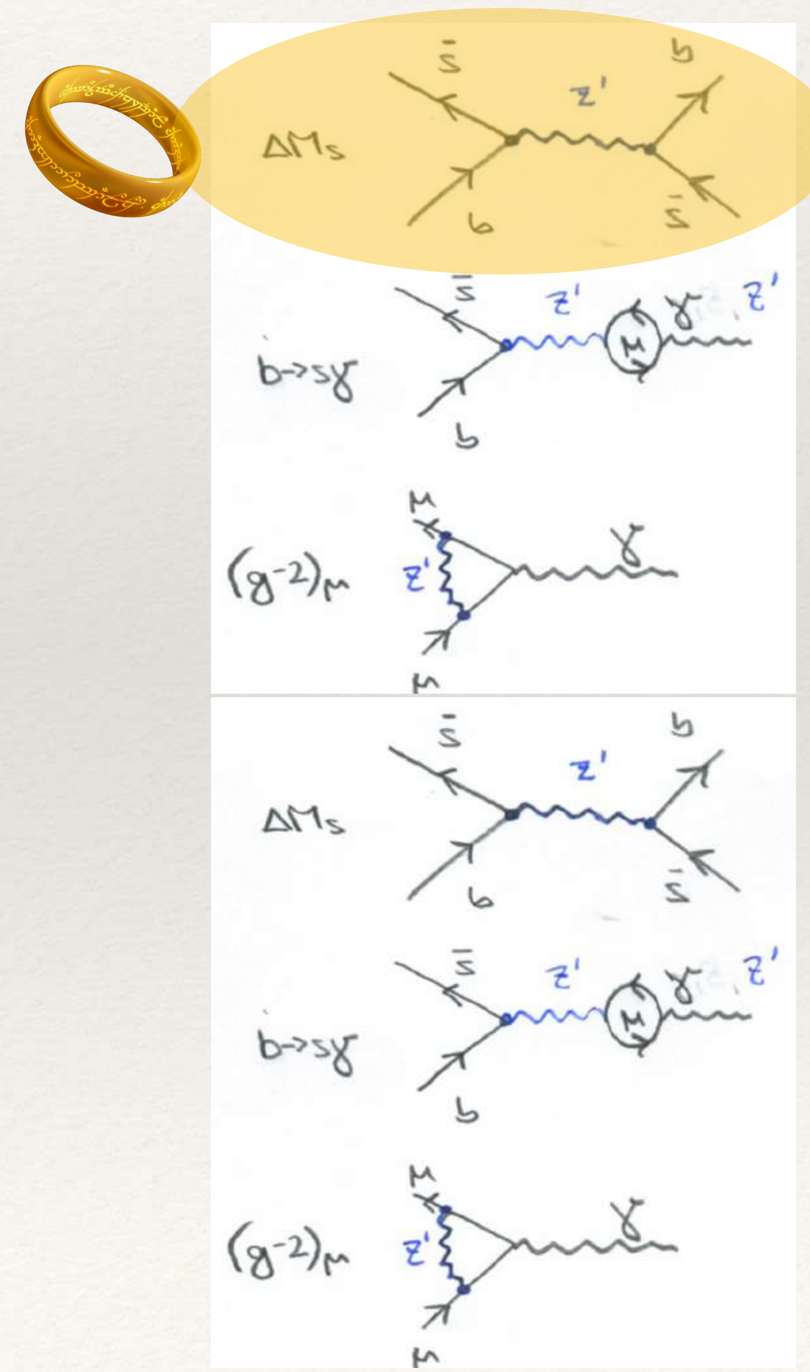
the choice of agony ?

Peter Paul Rubens (born in Siegen), Die Wahl des Paris ca 1638

Physics Beyond the Standard Model



Z' models are popular attempts in explaining the anomalies

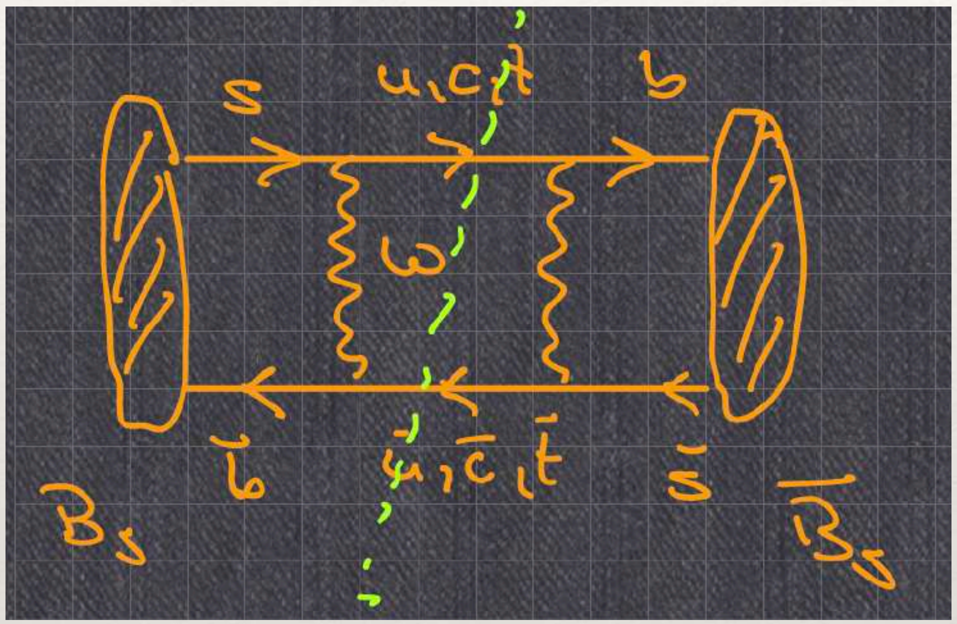


Such new "Tree-level"-transitions will also modifiy many other observables - in particular **B-Mixing**

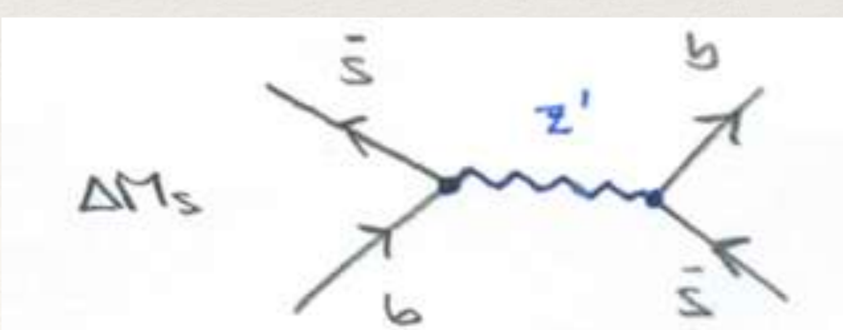
= indirect bound on BSM models

Physics Beyond the Standard Model

SM: $B_s \leftrightarrow \bar{B}_s$ only at loop-level



BSM: $B_s \leftrightarrow \bar{B}_s$ already at tree-level

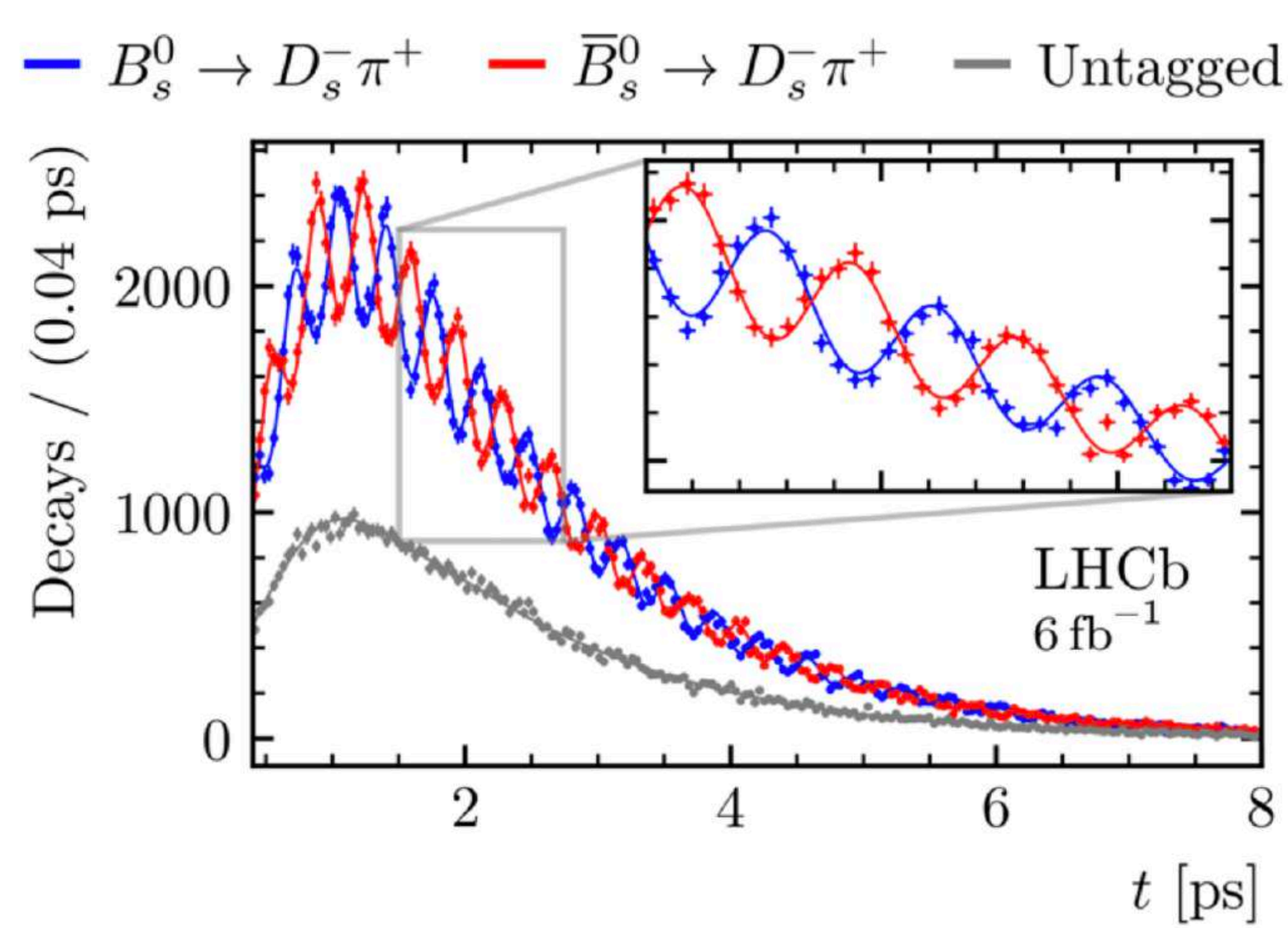


12 April 2021: Fascinating quantum mechanics.

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.



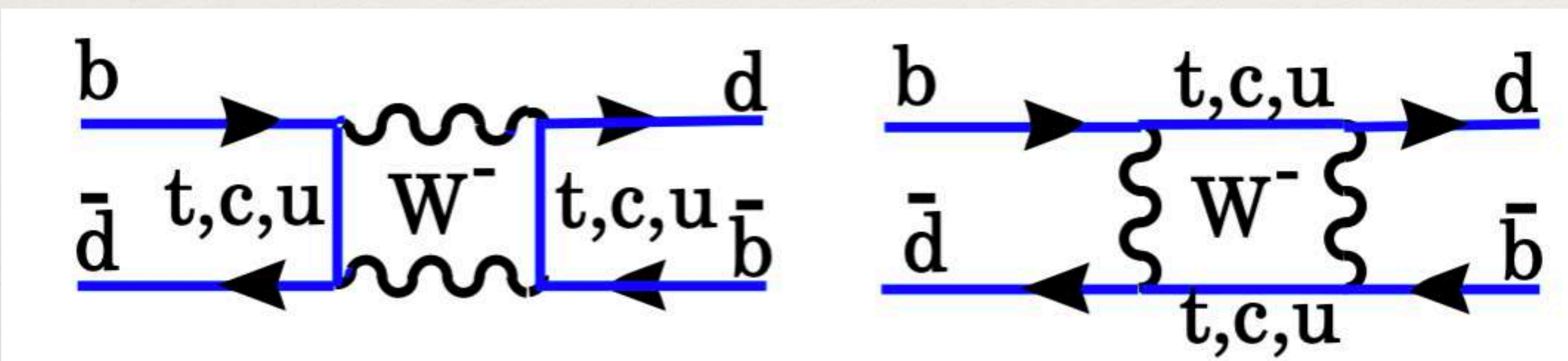
Content

The Necessity of Precision SM Predictions

Reliable theoretical determination of perturbative corrections, decay constants, form factors and non-local contributions obviously crucial!

But even more: precise SM predictions are also crucial for any indirect bounds

Example: B-Mixing



HFLAV

$$\Delta M_s^{\text{Exp.}} = (17.765 \pm 0.006)\,\text{ps}^{-1}$$

2016: Latest theory prediction -
based on lattice-QCD
Larger values than previous predictions
=> further anomaly?
Di Luzio, Kirk, AL 1712.06572

$$\Delta M_s^{\text{SM, 2017}} = (20.01 \pm 1.25)\ \text{ps}^{-1}\ .$$

The Necessity of Precision SM Predictions

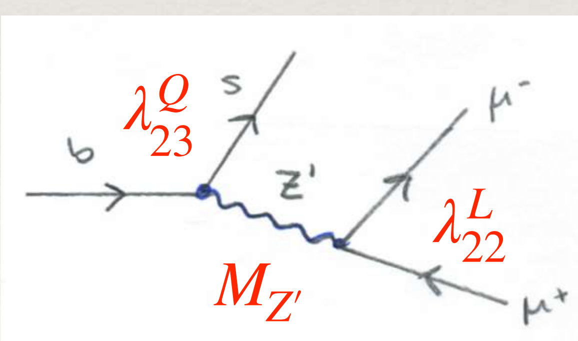
The 2016 theory value for B-mixing has dramatic consequences

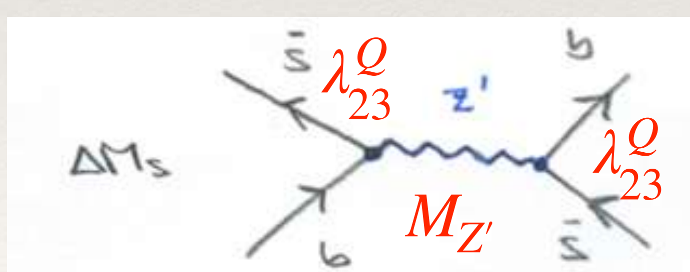
1712.06572, 1811.12884

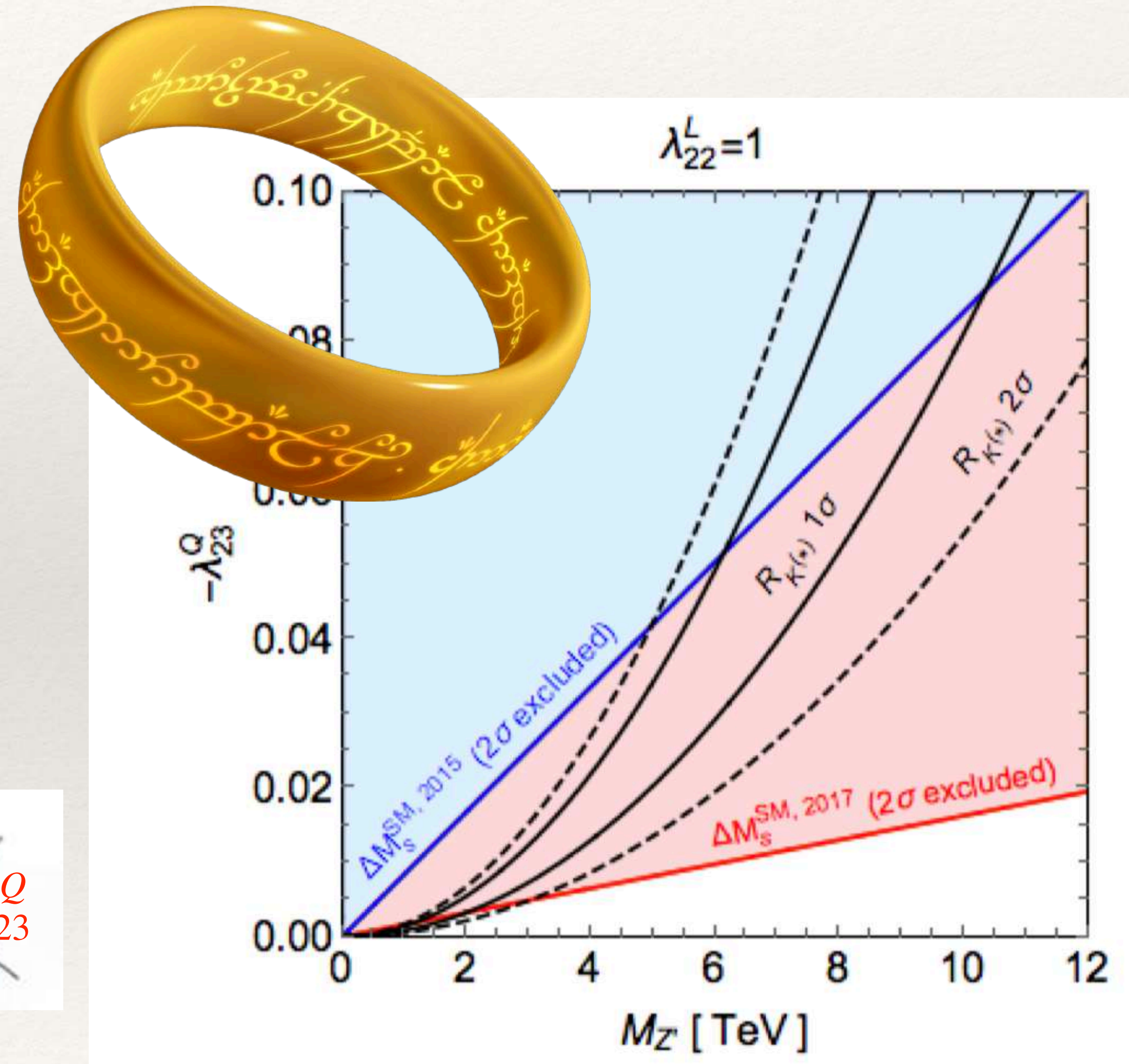
One constraint to kill them all?

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

The 2016 value from FNAL/MILC dominated the FLAG average







$$\Delta M_s^{\text{SM}} > \Delta M_s^{\text{Exp}}, \Delta M_s^{\text{BSM}} > 0$$

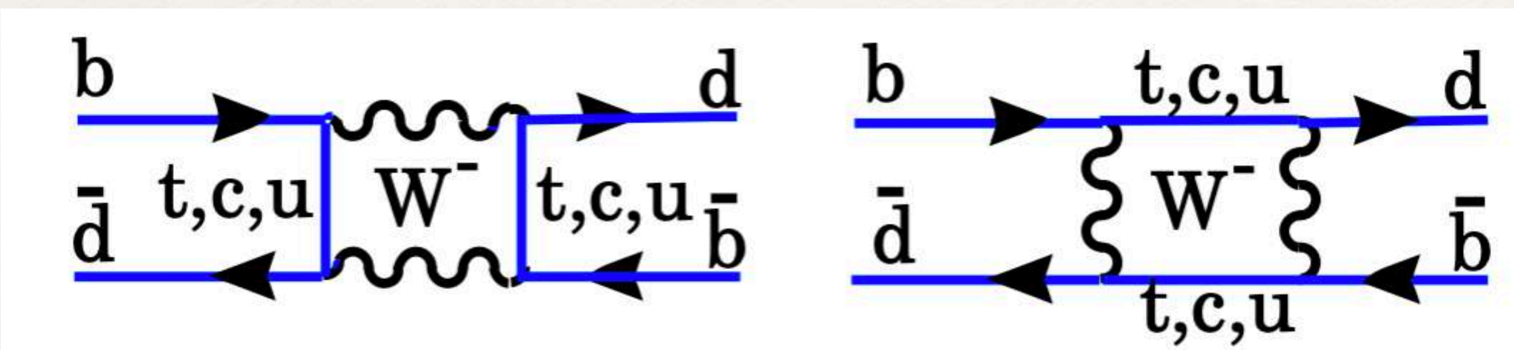
The Necessity of Precision SM Predictions

HFLAV 2018

Mass difference of neutral B Mesons

$$\Delta M_s = 2|M_{12}^s|$$

$$\Delta M_s^{\mathrm{Exp.}} = (17.765 \pm 0.006)\,\mathrm{ps}^{-1}$$



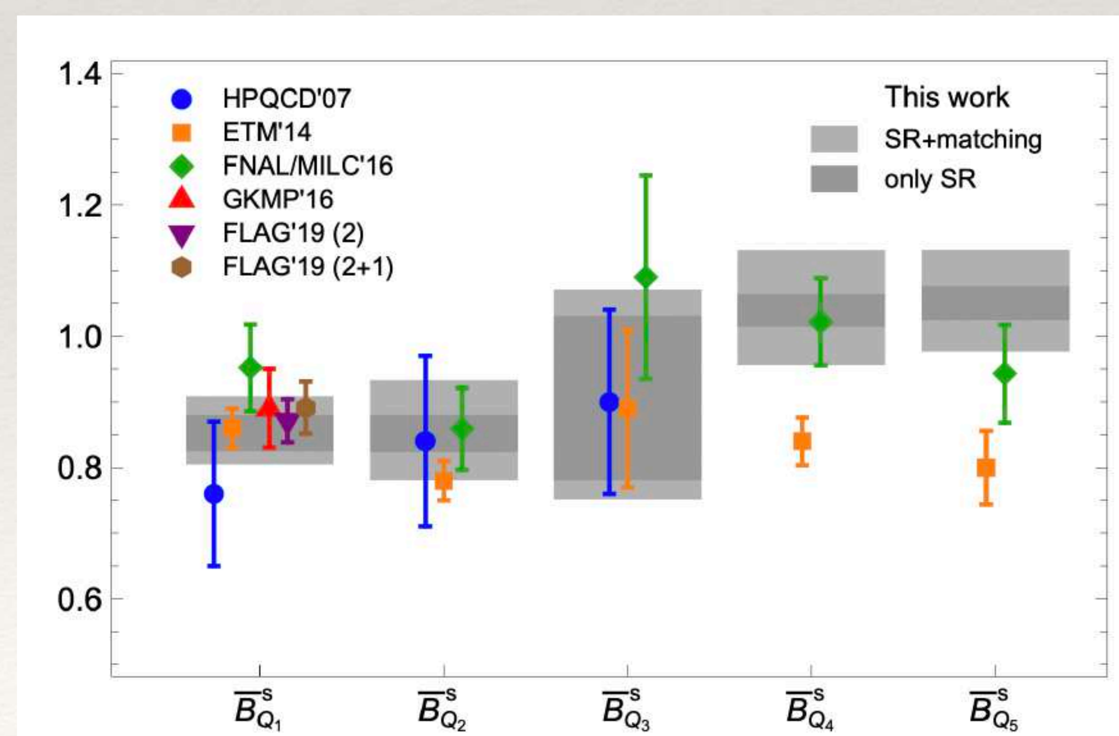
$$Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$$

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

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

Significant CKM dependence

By far dominant uncertainty

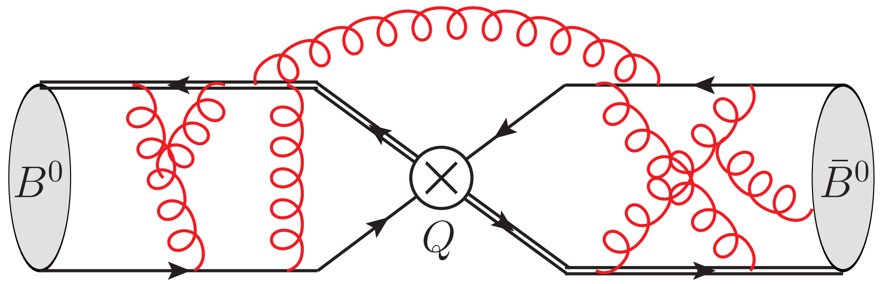


Test of non-perturbative results

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:
*FNAL/MILC:
 1602.03560
*HPQCD:
 1907.01025
*RBC-UKQCD:
 1812.08791

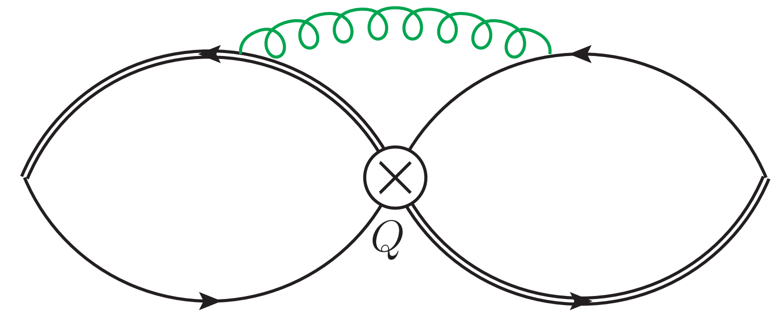
The Necessity of Precision SM Predictions



Sum rule

Quark-hadron duality

Analyticity



Hadronic matrix element

Characteristic scale: Λ_{QCD}

$\alpha_s\left(\Lambda_{\text{QCD}}\right) \sim \mathcal{O}(1)$

$\Rightarrow$ non-perturbative

Correlation function

Characteristic scale: 'virtuality' ω

Choose ω s.t. $\alpha_s(\omega) \ll 1$

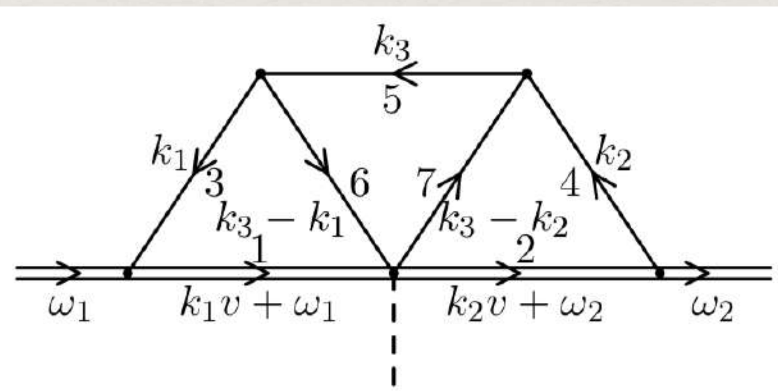
$\Rightarrow$ perturbatively calculable

1. **HQET Sum rule at hadronic scale**
2. **HQET running to scale mb**
3. **HQET-QCD matching**

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

arXiv:0812.4522v2

Andrey G. Grozin and Roman N. Lee

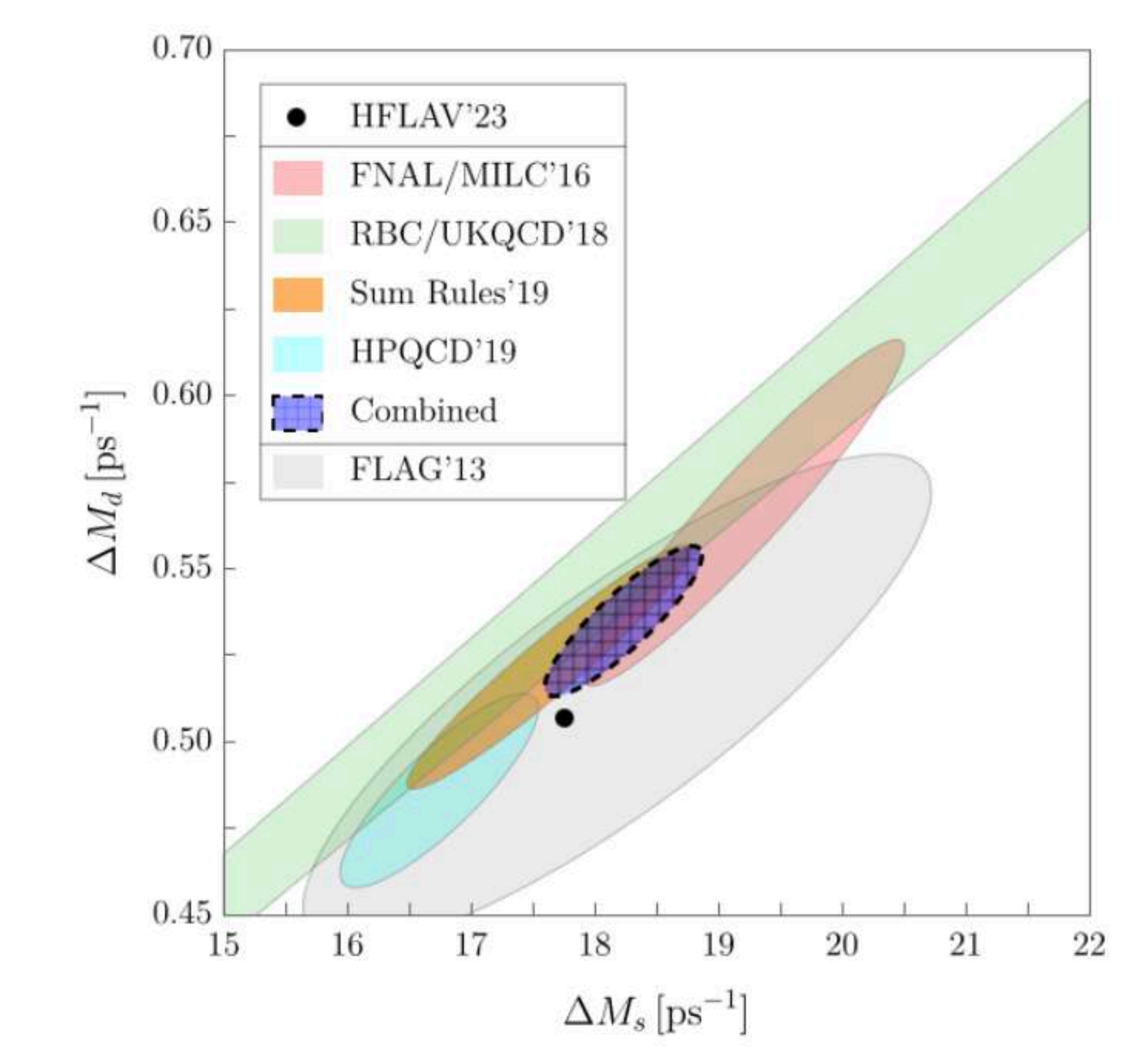



```
(* ------------------------------------ Light the Fire --------------------------------------------------*)
Get["FIRE5.m"]

External = {v}
Internal = {k1, k2, k3}
Propagators = {-2 (v*k1 + w1), -2 (v*k2 +  w2), -k1^2, -k2^2, -k3^2, -(k3 - k1)^2, -(k3 - k2)^2, -2 v*k3, -(k1 - k2
(* replace v^2 -> 1`*)

PrepareIBP[]
Prepare[AutoDetectRestrictions -> True]

SaveStart["IBPlightlight"]


(* ---- second set *)

Get["FIRE5.m"]

External = {v}
Internal = {k1, k2, k3}
Propagators = {-2 (v*k1 + w1), -2 (v*k2 +  w2), -2(v (k1 + k3) + w1), -k1^2, -k2^2, -k3^2, -(k3 - k2)^2, -(k3 - k1)
 (* replace v^2 -> 1`*)
```

Recursive reduction of integrals: FIRE

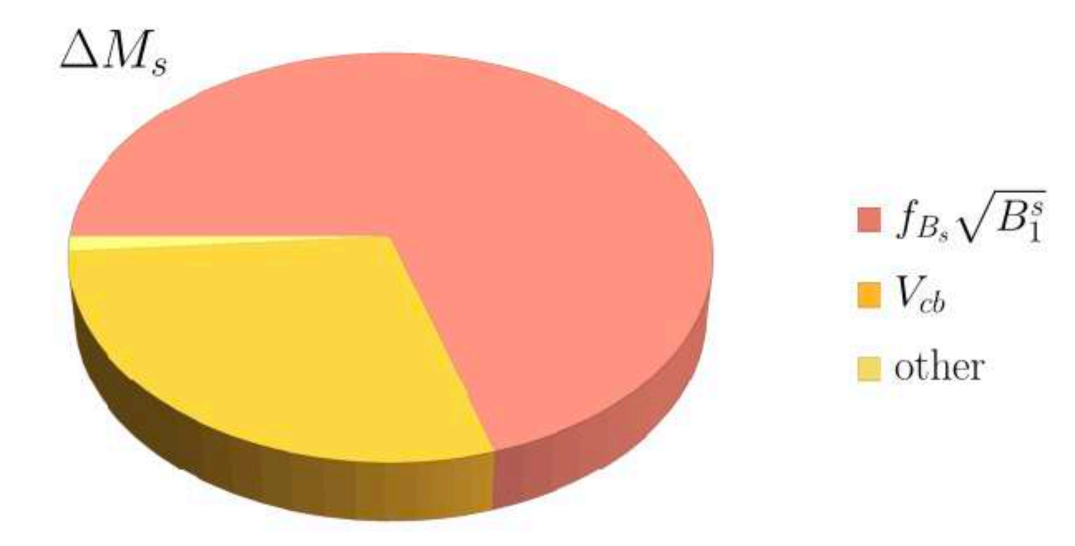
The Necessity of Precision SM Predictions

First sum rule results for Bs Mixing



$$\Delta M_s^{\mathrm{Exp.}} = (17.765 \pm 0.006)\,\mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{SM,2024}} = (18.34 \pm 0.64)\,\mathrm{ps}^{-1}$$

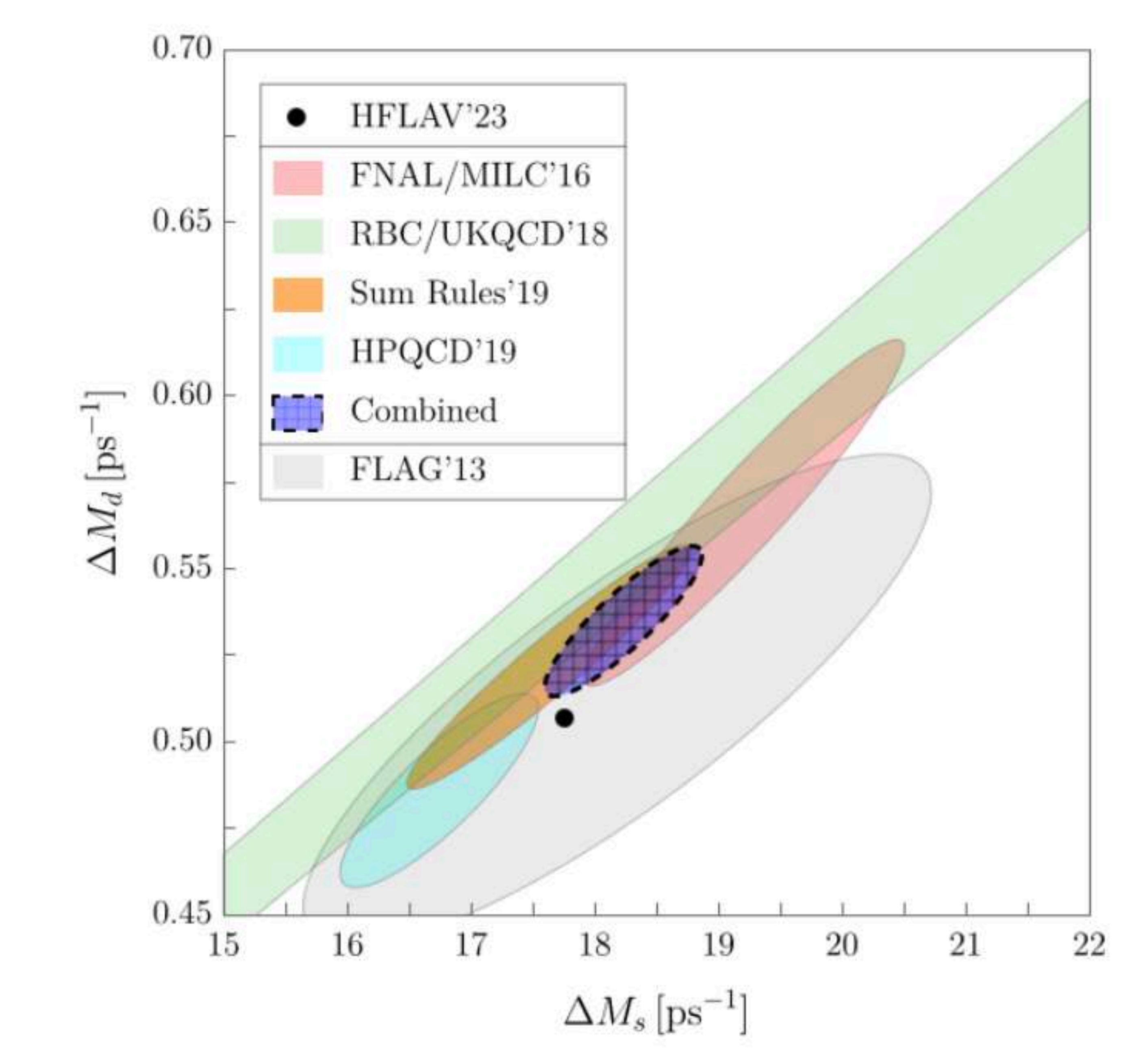


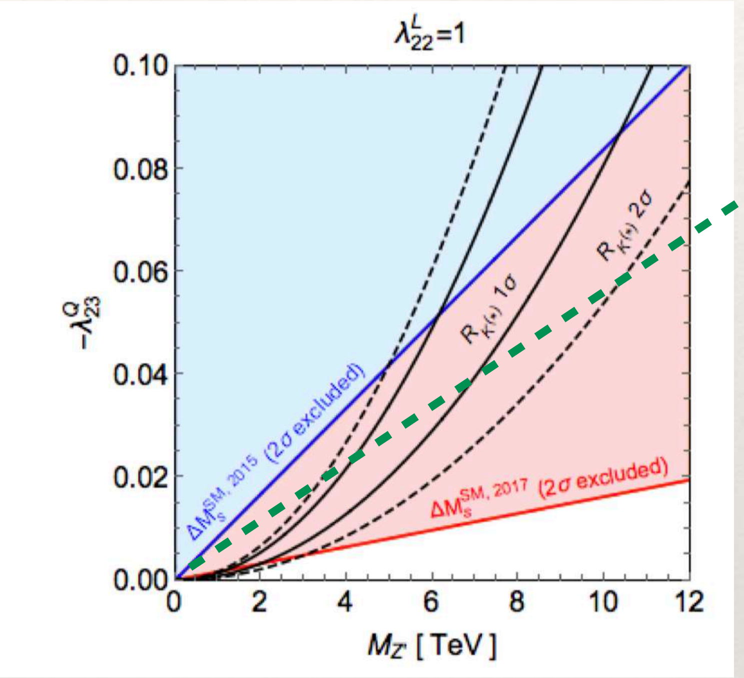
Need more precise lattice values and more precise CKM elements

Lifetimes of b-hadrons and mixing of neutral B-mesons: theoretical and experimental status
Johannes Albrecht, Florian Bernlochner, Alexander Lenz, Aleksey Rusov (Feb 6, 2024)
e-Print: 2402.04224 [hep-ph]

The Necessity of Precision SM Predictions

First sum rule results for Bs Mixing





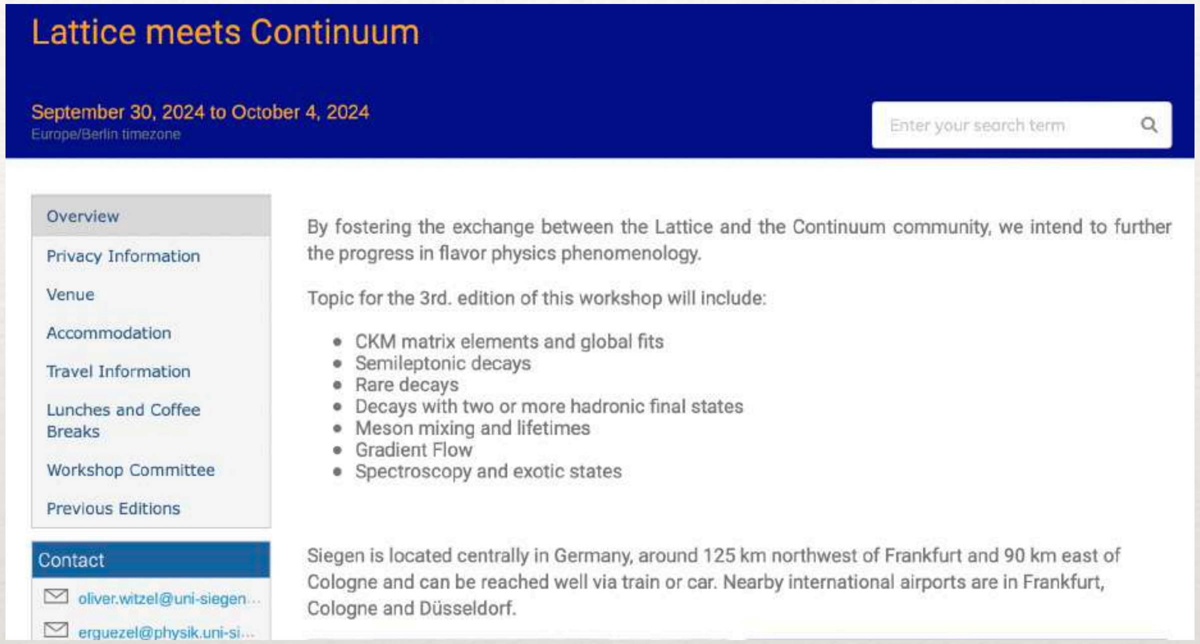
- **Sum rules still relevant**
- **Results on a shorter time scale**
- **Dramatic consequences for BSM**
- **Can be systematically improved**

The Necessity of Precision SM Predictions

Cooperation Lattice/Sum rules will be advantageous

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

*** New physics contributions to lifetimes**
Siegen: Matthew Black, AL, Zac Wüthrich in progress


Lattice meets Continuum

September 30, 2024 to October 4, 2024
Europe/Berlin timezone

Enter your search term

Overview
Privacy Information
Venue
Accommodation
Travel Information
Lunches and Coffee Breaks
Workshop Committee
Previous Editions

Contact
oliver.witzel@uni-siegen...
erguezel@physik.uni-si...

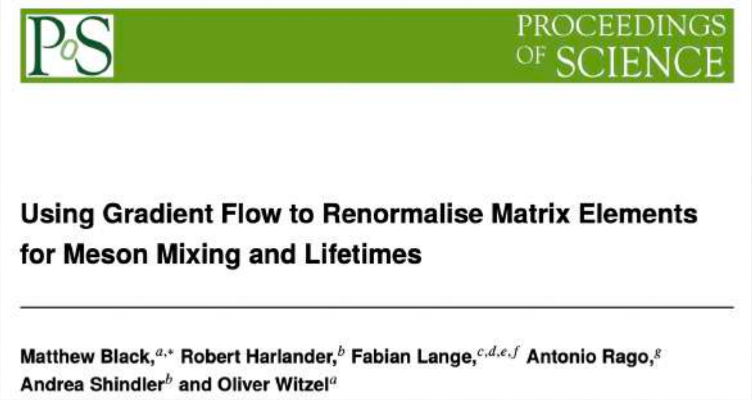
By fostering the exchange between the Lattice and the Continuum community, we intend to further the progress in flavor physics phenomenology.

Topic for the 3rd. edition of this workshop will include:

- CKM matrix elements and global fits
- Semileptonic decays
- Rare decays
- Decays with two or more hadronic final states
- Meson mixing and lifetimes
- Gradient Flow
- Spectroscopy and exotic states

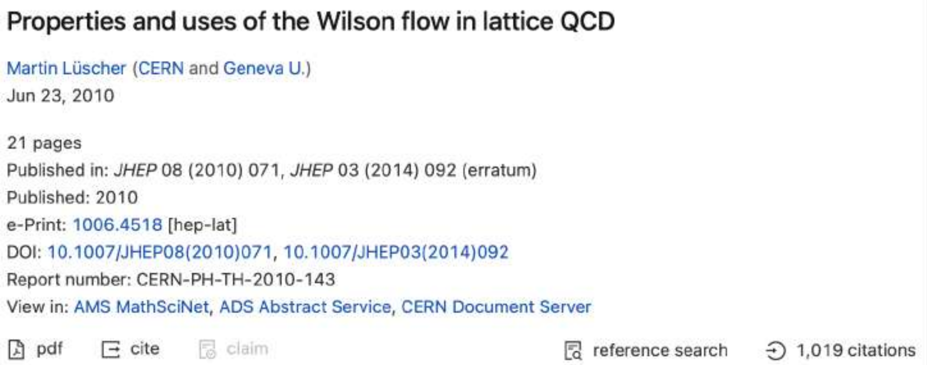
Siegen is located centrally in Germany, around 125 km northwest of Frankfurt and 90 km east of Cologne and can be reached well via train or car. Nearby international airports are in Frankfurt, Cologne and Düsseldorf.

- First ever lattice determination of matrix elements of D=6 operator for lifetime
- Determination of matrix elements of D=7 operators for lifetimes and mixing with lattice and sum rules


PoS PROCEEDINGS OF SCIENCE

Using Gradient Flow to Renormalise Matrix Elements for Meson Mixing and Lifetimes

Matthew Black,[a,*] Robert Harlander,[b] Fabian Lange,[c,d,e,f] Antonio Rago,[g] Andrea Shindler[b] and Oliver Witzel[a]


Properties and uses of the Wilson flow in lattice QCD

Martin Lüscher (CERN and Geneva U.)
Jun 23, 2010

21 pages
Published in: *JHEP* 08 (2010) 071, *JHEP* 03 (2014) 092 (erratum)
Published: 2010
e-Print: 1006.4518 [hep-lat]
DOI: 10.1007/JHEP08(2010)071, 10.1007/JHEP03(2014)092
Report number: CERN-PH-TH-2010-143
View in: AMS MathSciNet, ADS Abstract Service, CERN Document Server

pdf cite claim reference search 1,019 citations

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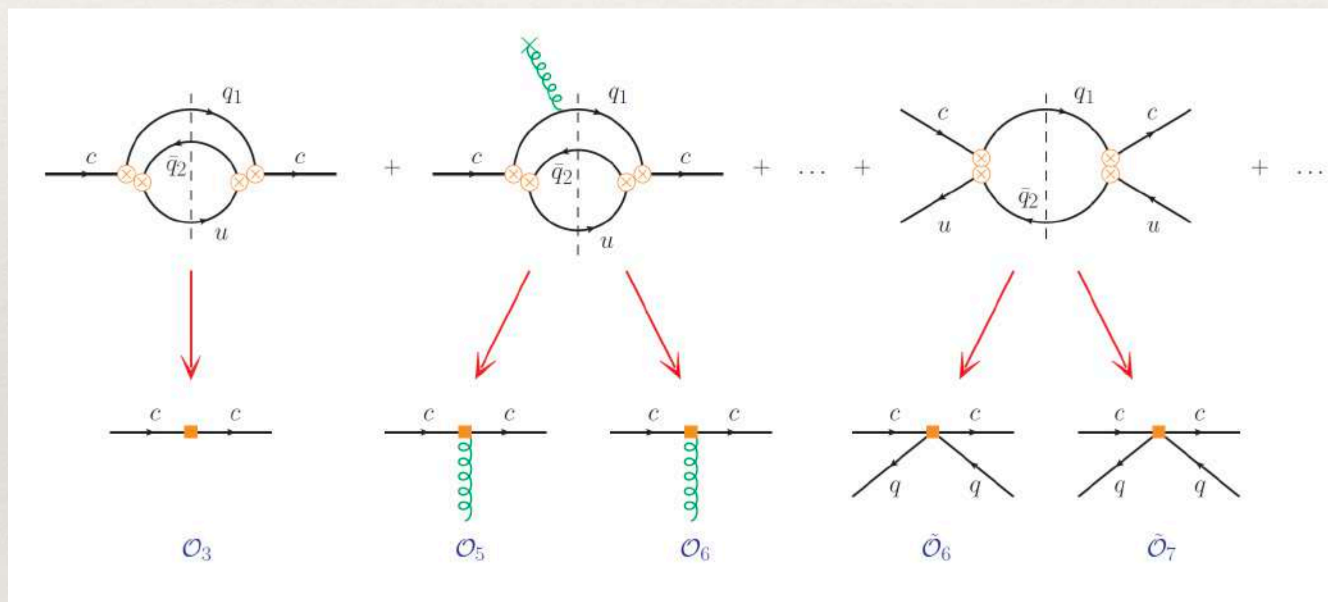
Test of Theory Tools

Lifetime ($\tau = 1/\Gamma_{tot}$) and mass among the most fundamental properties of particles

HQE:

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



Each term: perturbative Wilson coefficient times non-perturbative matrix element

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

- **No huge BSM contributions expected => Test of theory tools**

Test of Theory Tools

Semi-leptonic

$\Gamma_3^{(1)}$	1983	Ho-Kim, Pham [180]
$\Gamma_3^{(2)}$	1997/98	Czarnecki, Melnikov [181, 182]
	1999	van Ritbergen [183]
	2008	Melnikov [184]
	2008	Pak, Czarnecki [185, 186]
	2008	Dowling, Pak, Czarnecki [187]
	2008	Bonciani, Ferroglia [188]
	2009	Biswas, Melnikov [189]
	2013	Brucherseifer, Caola, Melnikov [190]
	2023	Egner, Fael, Schönwald Steinhauser [191]
$\Gamma_3^{(3)}$	2020	Fael, Schönwald, Steinhauser [192]
	2021	Czakon, Czarnecki, Dowling [193]
	2023	Fael, Usovitsch [194]
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein [195]
	1992	Bigi, Blok, Shifman, Uraltsev, Vainshtein [196]
	1992	Blok, Shifman [197, 198]
$\Gamma_5^{(1)}$	2013	Alberti, Gambino, Nandi [199]
	2014/15	Mannel, Pivovarov, Rosenthal [200, 201]
$\Gamma_6^{(0)}$	1996	Gremm, Kapustin [202]
	2017	Mannel, Rusov, Shahriaran [203]
	2022	Rahimi, Vos [204]
$\Gamma_6^{(1)}$	2019	Mannel, Pivovarov [205]
	2021	Mannel, Moreno, Pivovarov [206]
	2022	Moreno [207]
$\Gamma_7^{(0)}$	2006	Dassinger, Mannel, Turczyk [208]
$\Gamma_8^{(0)}$	2010	Mannel, Turczyk, Uraltsev [209]
	2023	Mannel, Milutin, Vos [210]

Non-leptonic

$\Gamma_3^{(1)}$	1983	Ho-Kim, Pham [180]
	1991	Altarelli, Petrarca [211]
	1994	Voloshin [212]
	1994/95	Bagan, Ball, Braun/Fiol, Goszinsky [213, 214]
	1997/98	Lenz, Nierste, Ostermaier [215, 216]
	2008	Greub, Liniger [217, 218]
	2013	Lenz, Krinner, Rauh [219]
$\Gamma_3^{(2)}$	2005	Czarnecki, Slusarczyk, Tkachov [220] (*partly*)
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein [195]
	1992	Bigi, Blok, Shifman, Uraltsev, Vainshtein [196]
	1992	Blok, Shifman [197, 198]
$\Gamma_5^{(1)}$	2023	Mannel, Moreno, Pivovarov [221]
$\Gamma_6^{(0)}$	2020	Lenz, Piscopo, Rusov [179]
	2020	Mannel, Moreno, Pivovarov [222, 223]
$\tilde{\Gamma}_6^{(0)}$	1979	Guberina, Nussinov, Peccei, Ruckl [225]
	1986	Shifman, Voloshin [22]
	1996	Uraltsev [226]
	1996	Neubert, Sachrajda [227]
$\tilde{\Gamma}_6^{(1)}$	2002	Beneke, Buchalla, Greub, Lenz, Nierste [228]
	2002	Franco, Lubicz, Mescia, Tarantino [229]
	2013	Lenz, Rauh [230]
$\tilde{\Gamma}_7^{(0)}$	2003/04	Gabbiani, Onishchenko, Petrov [231, 232]

Non-perturbative

$\langle Q_5 \rangle_{B_d}$	1993/96	QCD sum rule [234, 235]
	2013-2023	Fit of inclusive data [236–241]
	2017/18	Lattice QCD [242, 243]
$\langle Q_5 \rangle_{B_s}$	2011	Spectroscopy relations [244]
$\langle Q_5 \rangle_{\mathcal{B}}$	2023	Spectroscopy relations [34]
$\langle Q_6 \rangle_{B_d}$	1994/2022	EOM relation [31, 245]
	2013-2023	Fit of inclusive data [236–241]
$\langle Q_6 \rangle_{B_s}$	1994/2022	EOM relation [31, 245]
	2011	Sum rule [244]
$\langle Q_6 \rangle_{\mathcal{B}}$	2023	EOM relation [34]
$\langle \tilde{Q}_6 \rangle_{B_d}$	2017	HQET sum rule [246]
$\langle \tilde{Q}_6 \rangle_{B_s}$	2022	HQET sum rule [247]
$\langle \tilde{Q}_6 \rangle_{\Lambda_b}$	1996	QCD sum rule [248]
$\langle \tilde{Q}_6 \rangle_{\mathcal{B}}$	2023	NRCQM [34]
$\langle \tilde{Q}_7 \rangle$		VIA

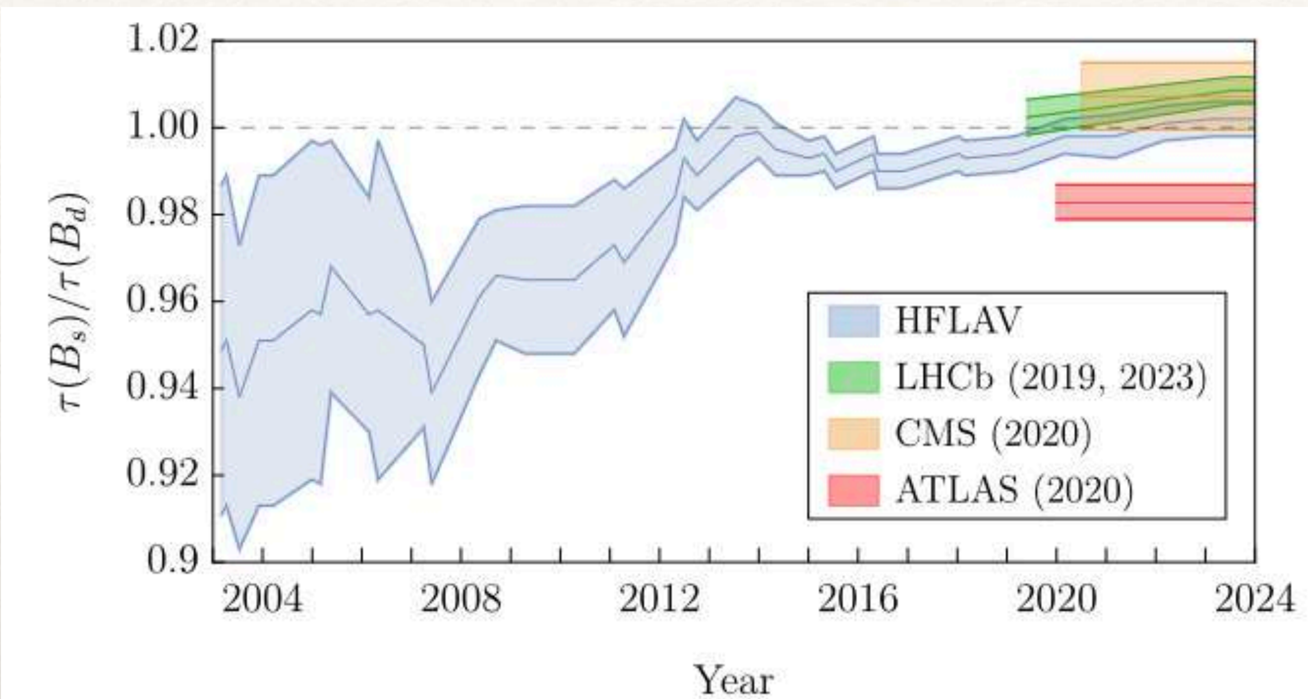
Lifetimes of b-hadrons and mixing of neutral B-mesons: theoretical and experimental status
Johannes Albrecht, Florian Bernlochner, Alexander Lenz, Aleksey Rusov (Feb 6, 2024)
e-Print: 2402.04224 [hep-ph]

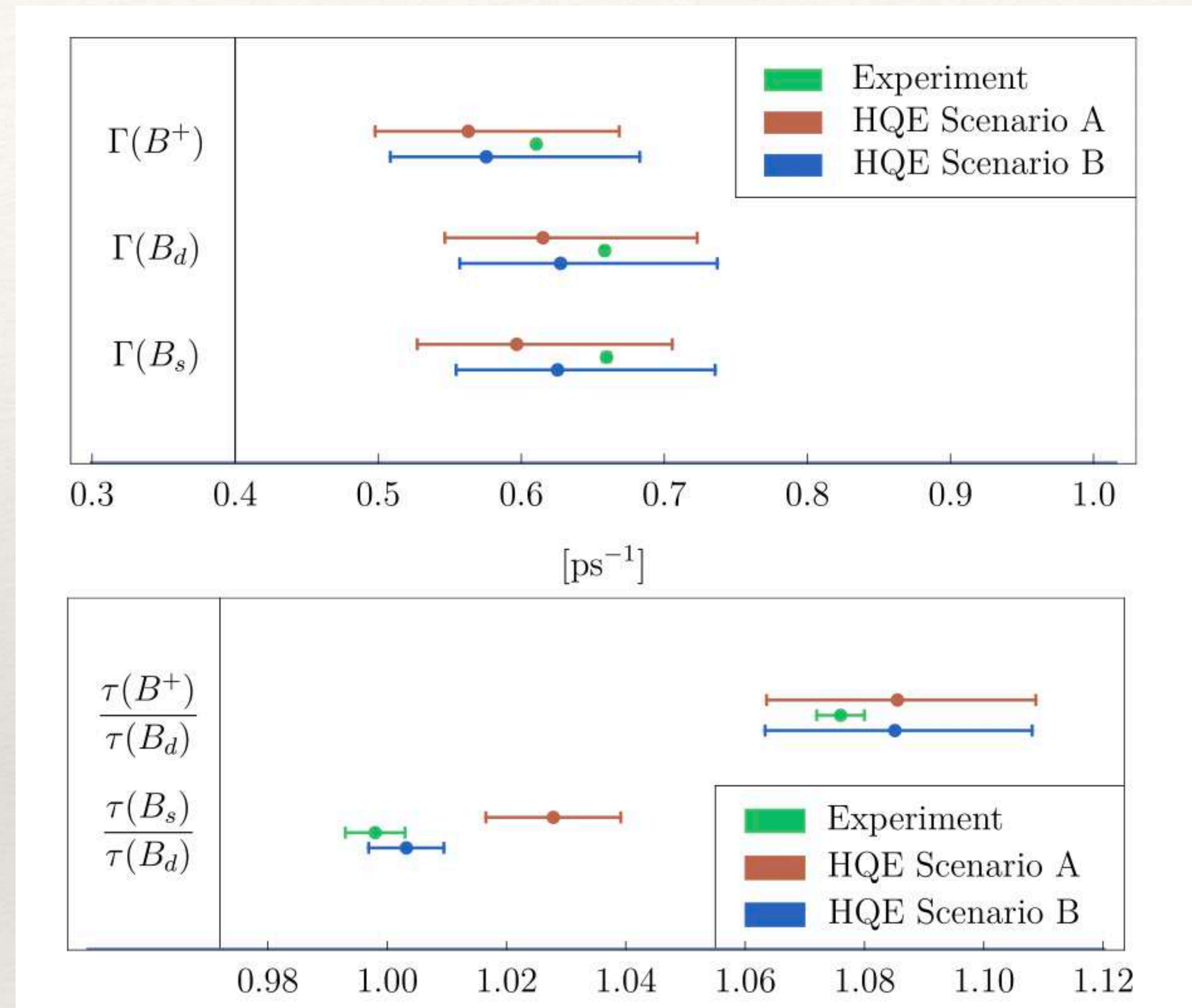
Darwin operator has an unexpected large contribution

$$\frac{\tau(B_s)}{\tau(B_d)} = 1 + \ldots + \frac{C_D}{m_b^3}\left[\rho_D^3(B_d) - \rho_D^3(B_s)\right]\tau(B_s)^{\text{Exp}} + \ldots .$$

Work in progress: higher orders in α_s and $1/m_b$

Test of Theory Tools





HQE + HQET sum rules for B lifetimes:

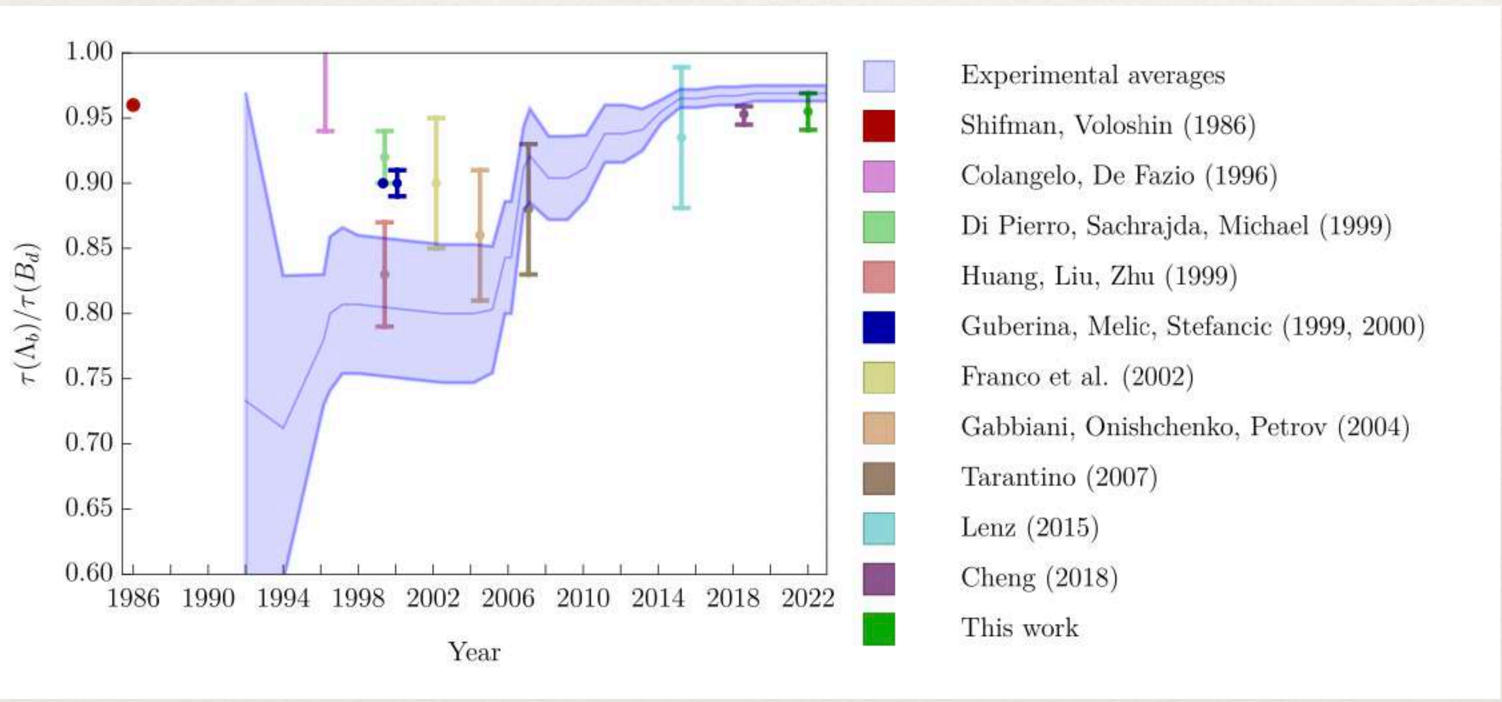
- Very good agreement with experiment
- Precise value of the Darwin term needed
- Precision of HQET sum rules can be further improved
- Independent lattice evaluation highly desirable **Oliver Witzel and Matthew Black within RBC/UKQCD**

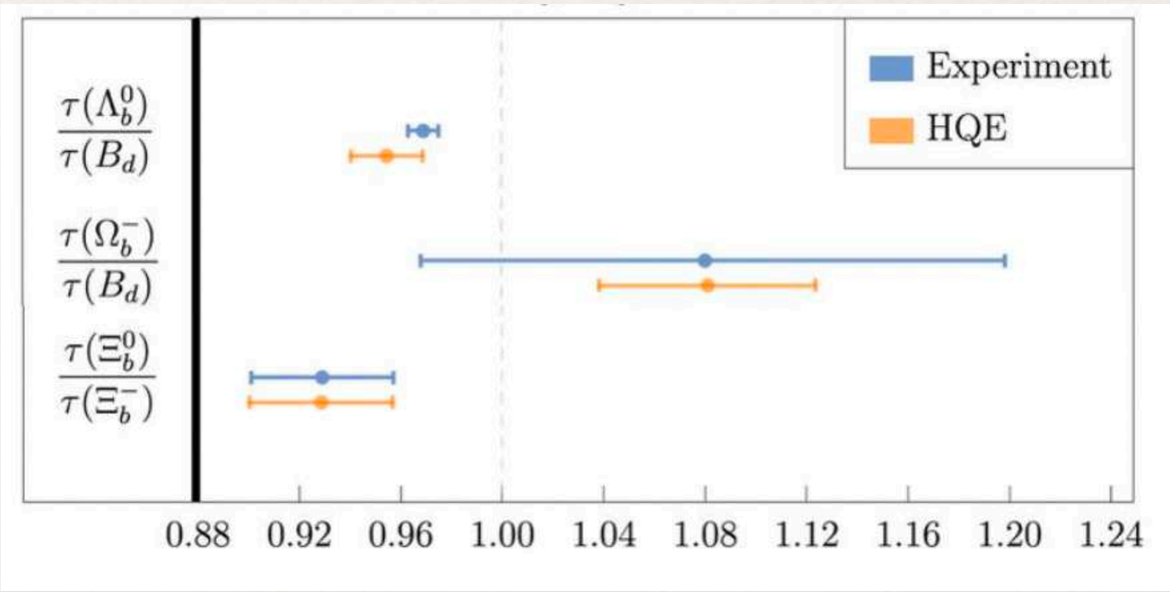
AL, Rusov, Piscopo 2208.02643

Darwin term is extracted from the V_{cb} fit
Inclusive vs. Exclusive puzzle

Test of Theory Tools

Quark-hadron duality at work:





HQE + NRCQM (spectroscopy) for b baryon lifetimes:

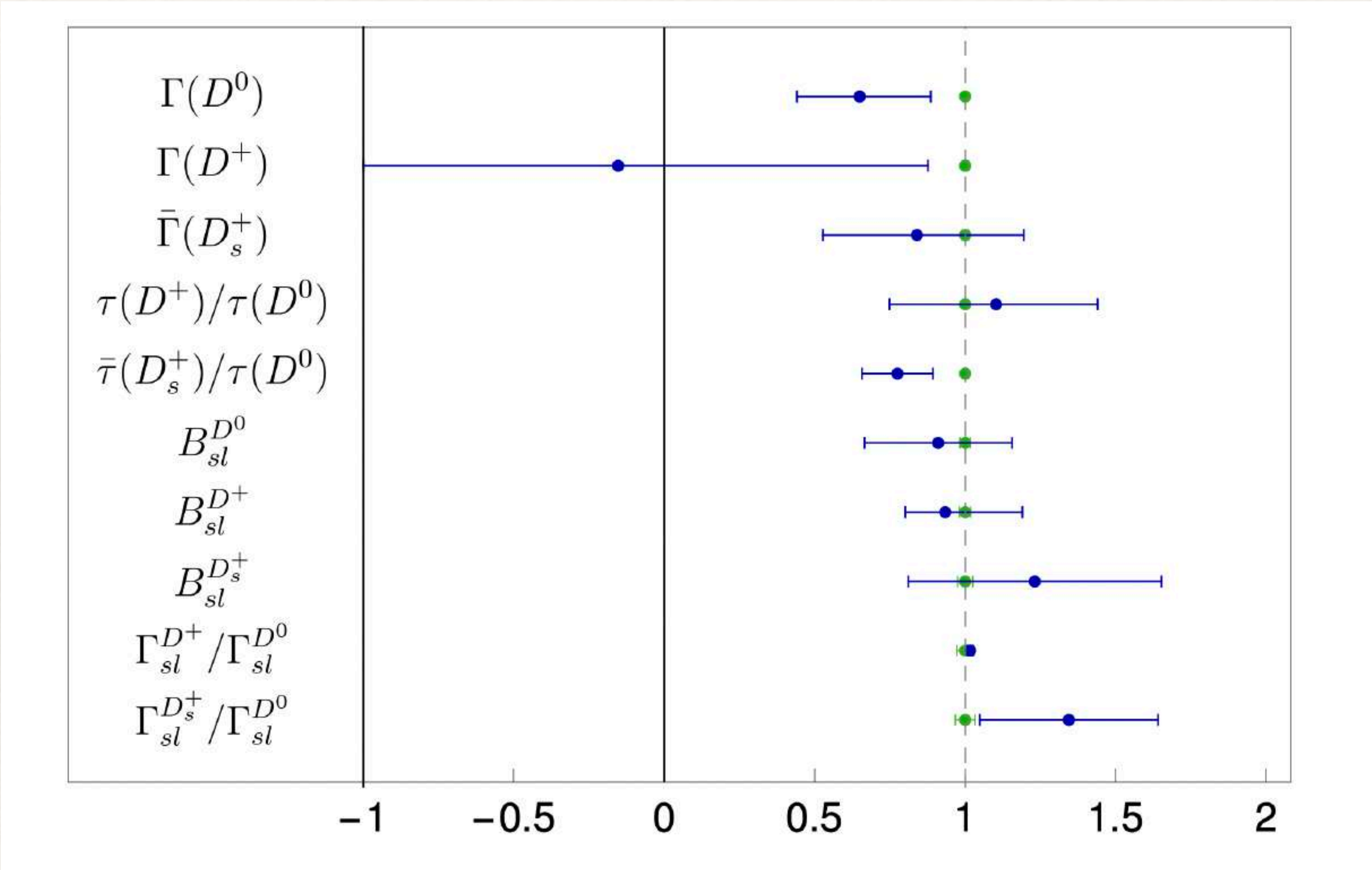
- Very good agreement with experiment
- Precise value of the Darwin term needed
- Independent lattice evaluation highly desirable

Gratrex, AL, Melic, Nisandzic, Rusov, Piscopo 2301.07698

Test of Theory Tools

HQE at the extreme limit

	D^0	D^+	D_s^+
τ [ps]	0.4101(15)	1.040(7)	0.504(4)
Γ [ps^{-1}]	2.44(1)	0.96(1)	1.98(2)
$\tau(D_q)/\tau(D^0)$	1	2.54(2)	1.20(1)
$\mathrm{Br}(D_q \to X e^+ \nu_e)[\%]$	6.49(11)	16.07(30)	6.30(16)
$\frac{\Gamma(D_q \to X e^+ \nu_e)}{\Gamma(D^0 \to X e^+ \nu_e)}$	1	0.977(26)	0.790(26)



HQE + HQET sum rules for D lifetimes:

- No evidence for a breakdown of the 1/mc expansion
- Higher orders in QCD needed
- Independent lattice evaluation highly desirable

King, AL, Rauh ,Rusov, Piscopo 2109.13219

Content

Ia Introduction to Particle Physics
Ib Decays of heavy Hadrons
Ic Flavour Physics

IIa First Hints for New Physics?
IIb Physics Beyond the Standard Model (**SM**)?

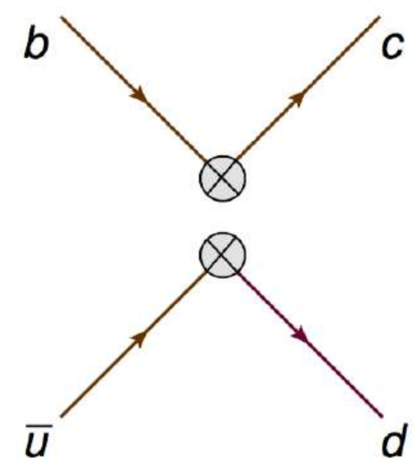
IIIa The Necessity of Precision SM Predictions
IIIb Test of Theory Tools
IIIc Models beyond the SM
Mathematical Elegance vs. *"Leave no Stone unturned"*

IV Final Remarks

Beyond the SM

Can there be new physics in non-leptonic tree-level decays?

$$\hat{\mathcal{H}}_{eff} = \frac{V_{cb}V_{ud}^*}{\sqrt{2}}\left(C_1\hat{Q}_1 + C_2\hat{Q}_2\right)$$



Systematic study of non-leptonic tree-level decays

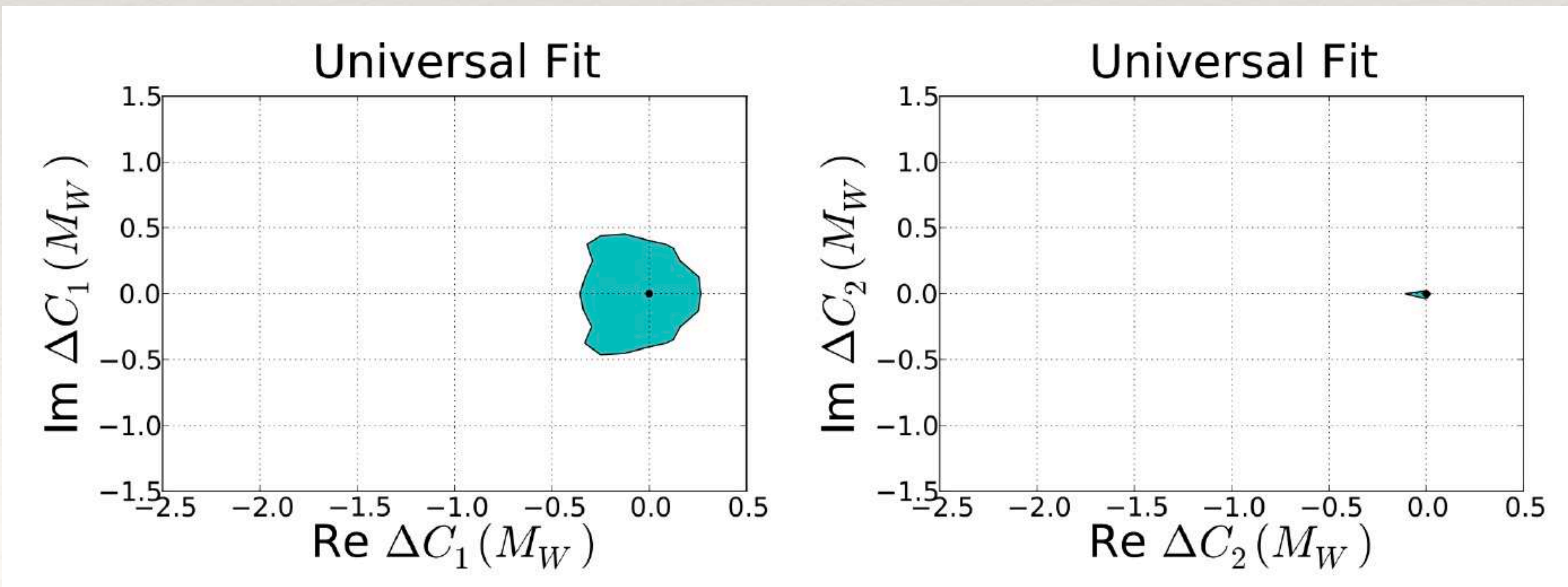
$$C_{1,2}^{SM} \to C_{1,2}^{SM} + \Delta C_{1,2}$$

AL, Tetlalmatzi-Xolocotzi
1912.07621

What does this imply?

Is such a shift relevant

or irrelevant?



Beyond the SM

- Decay rate difference of B_d Mesons $\Delta\Gamma_d$, can be enhanced by more than 100%
  inspired by D0 Dimuon asymmetry - **Borissov**
  inspired the ATLAS measurement of $\Delta\Gamma_d$ - **Borissov**

On new physics in $\Delta\Gamma_d$
Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi
JHEP 1406 (2014) 040

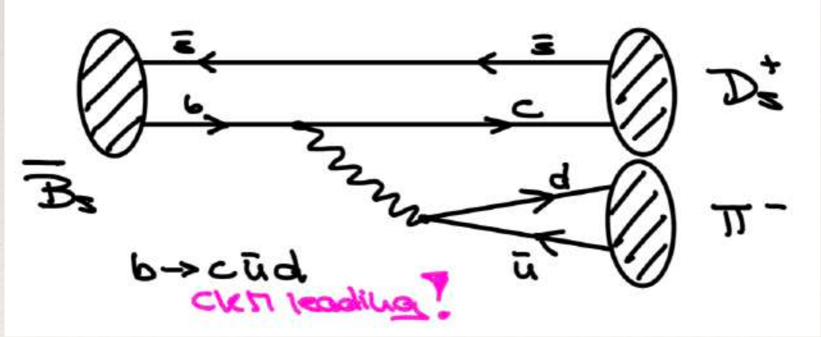
- Determination of the CKM angle γ can be modified by several degrees
  SM precision 1 ppm
  Exp. precision: now 3.5°, in future < 1°

NP effects in tree-level decay and the precision of γ
Brod, AL, Tetlamatzi-Xolocotzi
Phys. Rev. D92(2015) no.3,033002

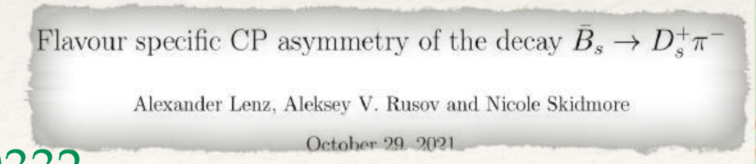
Model independent bounds on NP effects in non-leptonic tree-level decay and the
AL, Tetlamatzi-Xolocotzi
JHEP 2007 (2020) 177

- Systematic fit so far **only SM Dirac structures**

- New Anomalies

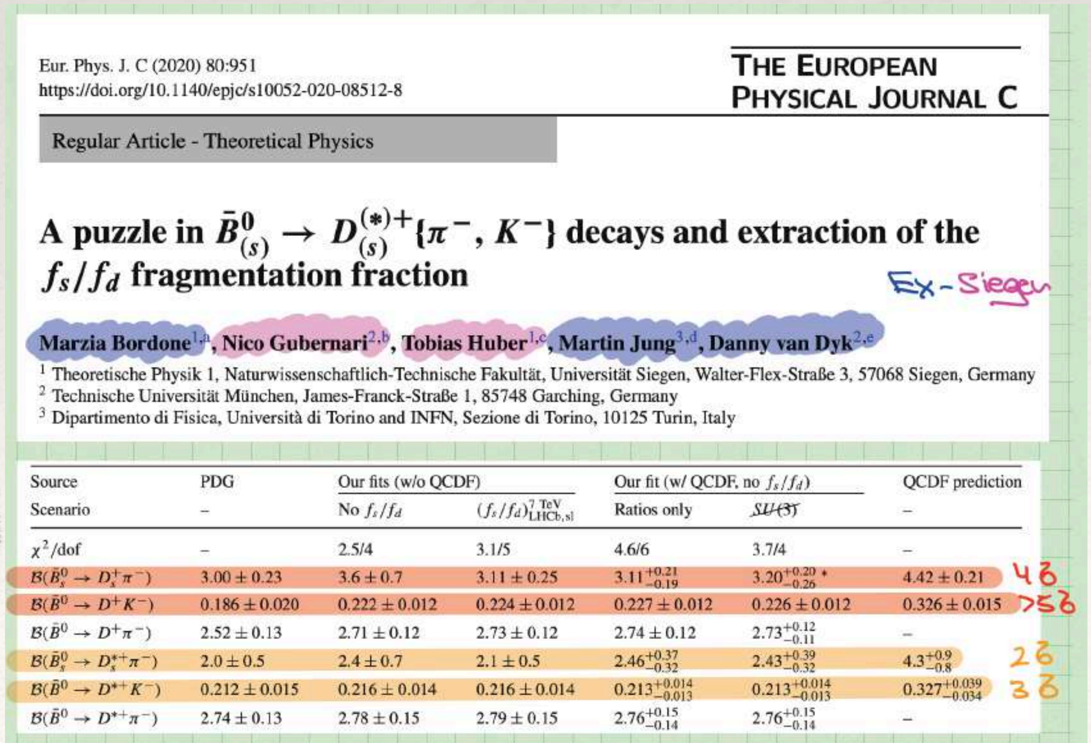


- **Huber, Kränkl** 1606.02888
- **Bordone, Gubernari, Huber, Jung, vanDyk** 2007.10338
- **Iguro, Kitahara** 2008.01086
- **Cai, Deng, Li, Yang** 2103.04138
- **Bordone, Greljo,Maryocca** 2103.10332
- **Beneke, Böer, Finauro, Vos** 2107.03819


Flavour specific CP asymmetry of the decay $\bar{B}_s \to D_s^+\pi^-$

Alexander Lenz, Aleksey V. Rusov and Nicole Skidmore

October 29, 2021


Eur. Phys. J. C (2020) 80:951
https://doi.org/10.1140/epjc/s10052-020-08512-8

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

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

Ex-Siegen

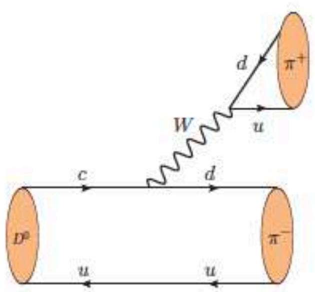
Marzia Bordone[1,a], Nico Gubernari[2,b], Tobias Huber[1,c], Martin Jung[3,d], Danny van Dyk[2,e]

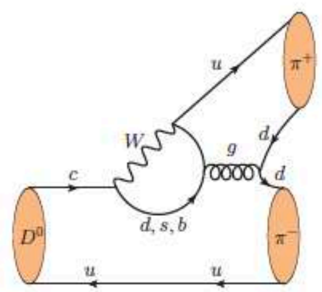
[1] Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany
[2] Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany
[3] Dipartimento di Fisica, Università di Torino and INFN, Sezione di Torino, 10125 Turin, Italy

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

Beyond the SM

Understand QCD better!





- Study of hadronic effects in exclusive decays using LCSR*
  - Tree-level non-leptonic B-meson decays like $B^0 \to D^+K^-$

    Currently, tensions between data and QCD factorisation

  - Two-body non-leptonic D-meson decays like $D^0 \to \pi^+\pi^-$

    Crucial step to understand recent discovery of CPV in charm

* Light-Cone Sum Rules

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

JHEP10(2023)180

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.

Problem are power-corrections

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

Indication for lager QCD uncertainties than previously expected

=> deviation becomes smaller

Beyond the SM

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

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

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

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FLAVOUR PHYSICS | NEWS

LHCb observes CP violation in charm decays

7 May 2019

Experimental highlight The LHCb detector in December being prepared for upgrades. Credit: CERN-PHOTO-201812-329-16.

On the morning of 21 March, at the 2019 Rencontres de Moriond in La Thuile, Italy, the LHCb collaboration announced the discovery of charge-parity (CP) violation in the charm system. Met with an impromptu champagne celebration, the result represents a

arXiv:2312.13245v1 [hep-ph] 20 Dec 2023

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

Alexander Lenz,[a] Maria Laura Piscopo,[a] Aleksey V. Rusov[a]

[a] *Physik Department, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany*

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

Abstract: Motivated by the recent measurements of CP violating effects in singly Cabibbo suppressed D^0 decays, we revisit the theoretical predictions of these channels. Using up-to-date values for the decay constants and form factors, we find already within naive QCD factorisation surprisingly good agreement between the central values of the branching ratios and the corresponding experimental data. We further extend the study of these modes by employing the method of light-cone sum rules (LCSR) with light-meson light-cone distribution amplitudes. Using for the first time this framework to compute the leading contribution to the decay amplitude, we can again describe well the experimental branching ratios for the modes $D^0\to\pi^+K^-$, $D^0\to K^+K^-$, $D^0\to\pi^+\pi^-$ and $D^0\to K^+\pi^-$. The combination of our results with known predictions for the penguin contributions, obtained with LCSR, leads to an upper bound for the value of direct CP violation expected in the Standard Model of $|\Delta a_{\rm CP}^{\rm dir}| \le 2.4\times10^{-4}$, which is approximately a factor six smaller than the current measurement.

Big fights in the community whether this can be QCD or not

$$\mathcal{B}(D^0\to K^+K^-)\big|_{\rm exp} = (4.08\pm0.06)\times10^{-3}\,,$$
$$\mathcal{B}(D^0\to \pi^+\pi^-)\big|_{\rm exp} = (1.454\pm0.024)\times10^{-3}\,.$$
$$\mathcal{B}(D^0\to \pi^+K^-)\big|_{\rm exp} = (3.947\pm0.030)\times10^{-2}\,,$$
$$\mathcal{B}(D^0\to K^+\pi^-)\big|_{\rm exp} = (1.50\pm0.07)\times10^{-4}\,.$$

$$\mathcal{B}(D^0\to K^+K^-)\big|_{\rm LCSR} = \left(3.67^{+3.90}_{-2.69}\right)\times10^{-3}\,,$$
$$\mathcal{B}(D^0\to \pi^+\pi^-)\big|_{\rm LCSR} = \left(1.40^{+1.53}_{-1.06}\right)\times10^{-3}\,,$$
$$\mathcal{B}(D^0\to \pi^+K^-)\big|_{\rm LCSR} = \left(2.99^{+3.26}_{-2.26}\right)\times10^{-2}\,,$$
$$\mathcal{B}(D^0\to K^+\pi^-)\big|_{\rm LCSR} = \left(1.80^{+1.93}_{-1.33}\right)\times10^{-4}\,,$$

$$|\Delta a_{\rm CP}^{\rm dir}|_{\rm LCSR} \le 2.4\times10^{-4}$$

Beyond the SM

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 -> ccs transitions with general Dirac structures

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

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

This affects both rare decays and lifetimes:

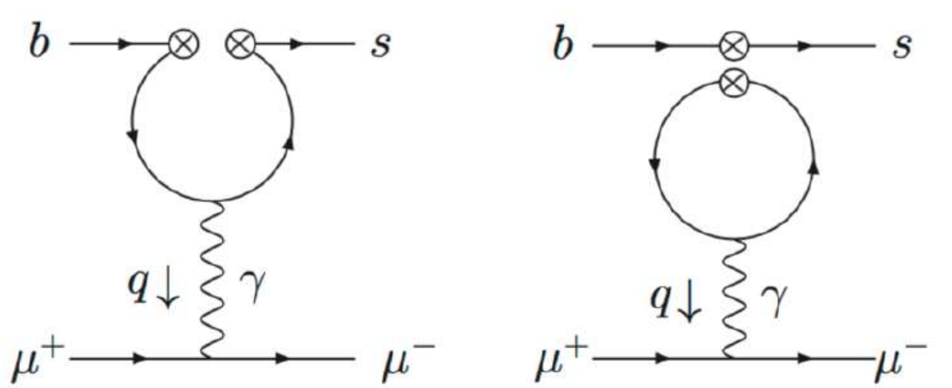


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

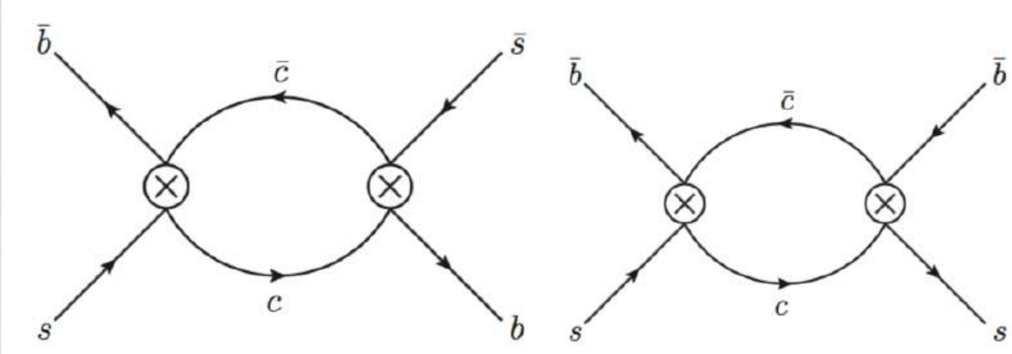


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

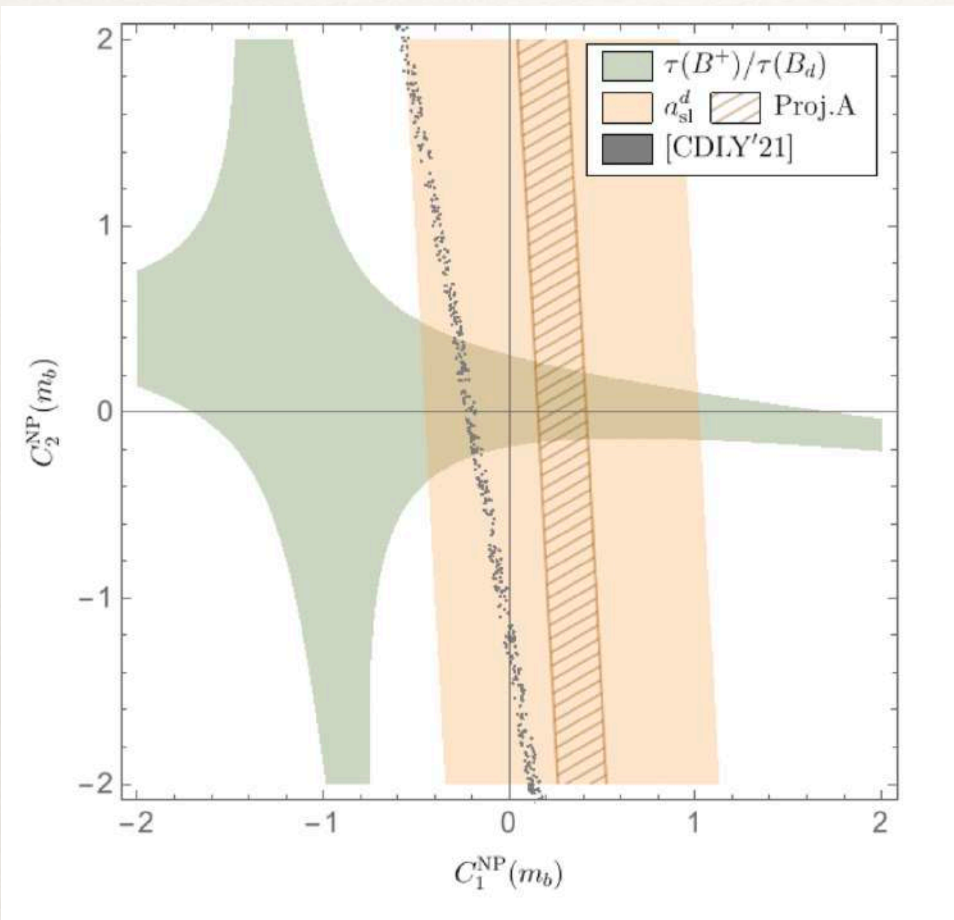
q^2 dependent BSM contributions are possible

This was considered to be a smoking gun for a hadronic origin of the anomalies

Precise SM values crucial

Beyond the SM

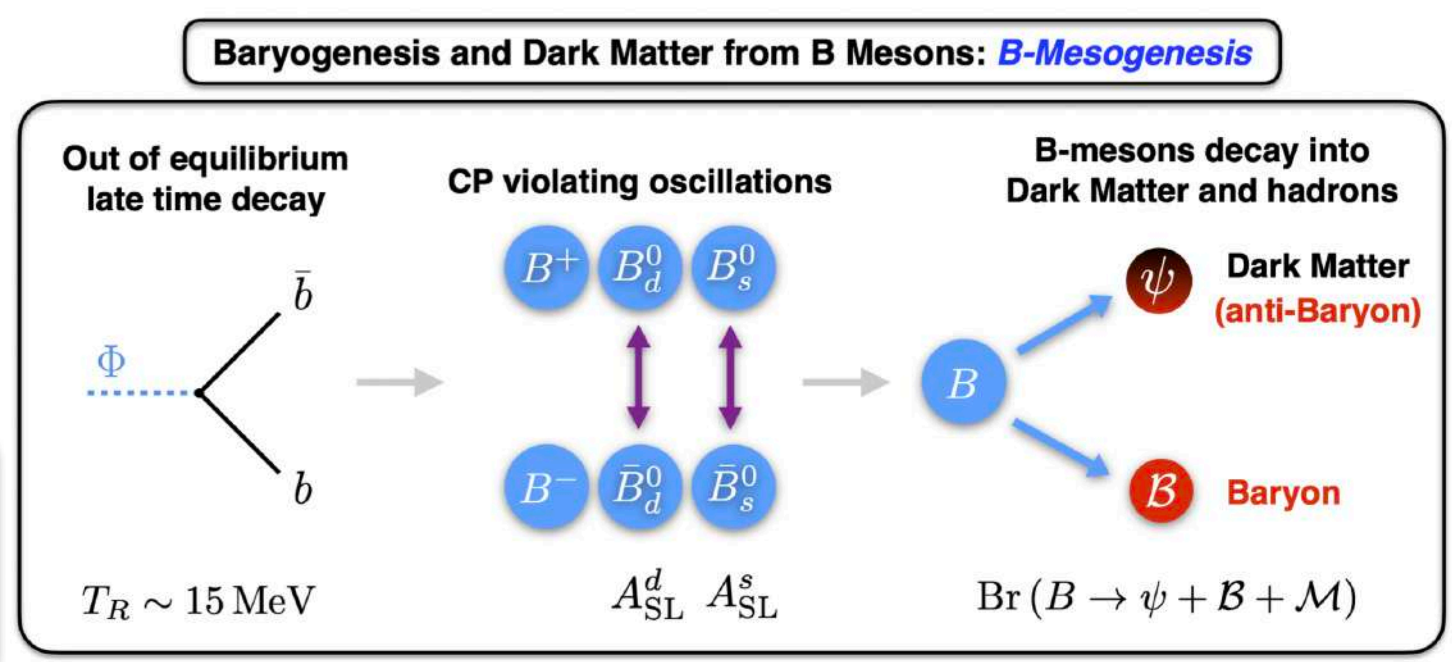
Search for BSM effects in lifetimes:



$$\underbrace{\frac{\tau(B_s)}{\tau(B_d)}}_{\text{exp.}} \approx 1 - \underbrace{\Gamma_b^{-1}\left(\delta\Gamma_{B_s}^{\text{SM}} - \delta\Gamma_{B_d}^{\text{SM}}\right)}_{\text{theory}} - \underbrace{\left[\text{BR}(B_s \to X)^{\text{BSM}} - \text{BR}(B_d \to X)^{\text{BSM}}\right]}_{\text{indirectly constrained}}$$

AL, Müller, Rusov, Piscopo 2211.02724

Effects of new decay channels on lifetimes and mixing
AL, Mohamed, Piscopo, Rusov, Wüthrich, in progress



Baryogenesis and Dark Matter from B Mesons

Gilly Elor (Washington U., Seattle), Miguel Escudero (King's Coll. London and Valencia U., IFIC), Ann Nelson (Washington U., Seattle) (Oct 1, 2018)

Published in: Phys.Rev.D 99 (2019) 3, 035031 • e-Print: 1810.00880 [hep-ph]

Content

Final Remarks

- **SM very successful, some problems still unsettled**
- **Indirect search for new physics**

$$O^{\mathrm{Exp}} \pm \delta O^{\mathrm{Exp}} = O^{\mathrm{SM}} \pm \delta O^{\mathrm{SM}} + O^{\mathrm{BSM}} \pm \delta O^{\mathrm{BSM}}$$

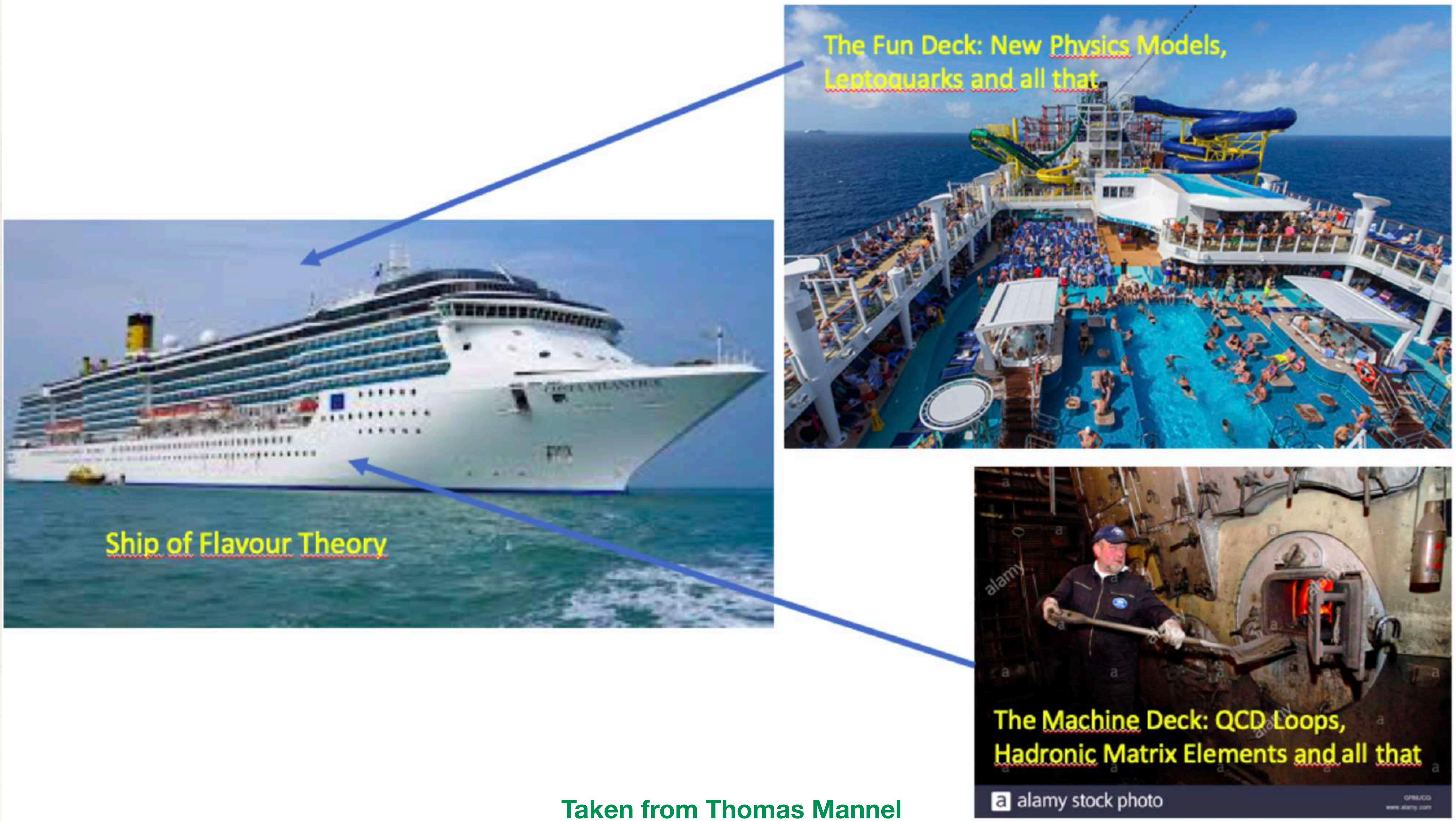
Control over (hadronic) uncertainties crucial!!!!

- **Huge amount of data, theory often under control and we (still) have a bunch of anomalies!**
- **Model dependent studies, e.g. Z', 2HDM, 4th gen. vs. model independent approaches**
- **Some text book assumptions should be reconsidered**
- **Combine different theory tools, lattice & sum rules**

Future Measurements

- Direct determination of V_{cb}: ultimate precision at FCC-ee on Z
- Inclusive semi-leptonic B_s and D decays -> HQE parameter
- More precise data on $b \to s, dl^+l^-$ transitions
- Semi-leptonic CP asymmetries
- Flavour-specific CP asymmetries in e.g. $\bar{B}_s \to D_s^+\pi^-$
- More precise values of some lifetimes: Ω_b, Ξ_b
- More precise values of branching fractions of e.g. $\bar{B}_s \to D_s^+\pi^-$
- CPV in charm - check ΔA_{CP}
- ….

Final Remarks



Taken from Thomas Mannel

Why you should work in heavy flavour physics?

United Kingdom (GBP)

Another heavy one

We welcomed another cluster (the official collective noun) of physicists back to the Distillery for the 2023 Heavy Flavours event. Thirty leading experts from the worldwide 'heavy flavour physics' community were warmly received for a day of tours, food, and whisky-fuelled debate.

Heavy flavour physics isn't just a phrase coined by Ardbeg-loving boffins, it's a real term originating from the heaviness of an elemental particle, which is studied at the Large Hadron Collider in Switzerland. Well, if you're choosing a mascot for a scientific pursuit such as this, you can't go wrong with Ardbeg.

The group initially visited us in 2016 because one of its members, Professor Alex Lenz, was a huge Ardbeg fan. His particular interest lay in our Supernova bottlings, as their intense, heavy flavour suited his scientific experiments.

He said, "The hospitality of Jackie and the Ardbeg Team was outstanding, and the remoteness of Islay sparked many deep discussions and ideas among the scientists. Thank you for everything!"

We hope to see them all again soon and we assure everybody in the community that our work in the field of heavy flavour continues.