Heavy quark decays: Gate to new physics?

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Fundamental questions of physics

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1. What are the smallest building blocks of matter?
2. Which forces act between them?
3. How did the universe begin?

Elementary Particle Physics

=

High Energy Physics

Cosmology, astrophysics

Contents

Standard Model

Standard Model of Elementary Particles

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Fermions (= matter particles): quarks and leptons with spin 1/2:

$$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} \quad \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} \quad \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$$

$$\begin{matrix} u_R, u_R, u_R & \quad c_R, c_R, c_R & \quad t_R, t_R, t_R \\ d_R, d_R, d_R & \quad s_R, s_R, s_R & \quad b_R, b_R, b_R \end{matrix}$$

$$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$$

$$e_R \quad \mu_R \quad \tau_R$$

fermion fields

Enrico Fermi

Gauge bosons

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spin 1

Gauge group

- hypercharge: one boson field B^μ (related to photon field A^μ) — *U(1)*
- weak interaction: three bosons $W^{+\mu}, W^{-\mu}$ and $W^{3\mu}$ (related to Z^μ) — *SU(2)*

$\left.\begin{array}{l} U(1) \\ SU(2) \end{array}\right\}$ electroweak interaction (Glashow, Salam, Weinberg)

- strong interaction: eight gluons $g_1^\mu, \ldots g_8^\mu$ — *SU(3)*

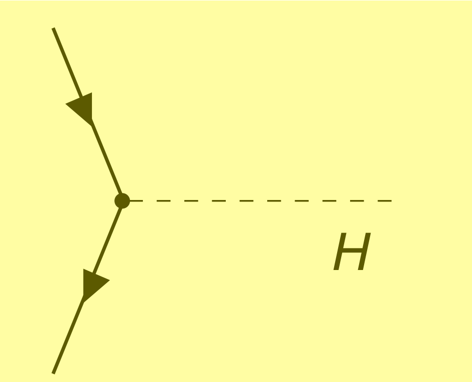
Quantum Chromodynamics (QCD)

(Gross,Wilczek,Politzer)

Higgs boson

The Higgs boson h has spin 0. It has been discovered in 2012 by the LHC experiments ATLAS and CMS. It gives rise to two new types of interaction:

- the Yukawa interaction of the Higgs field with quarks and leptons
  $\rightarrow$ relevant for this talk,
- the Higgs self-interaction
  $\rightarrow$ hard to study experimentally.



Natural units (Planck units)

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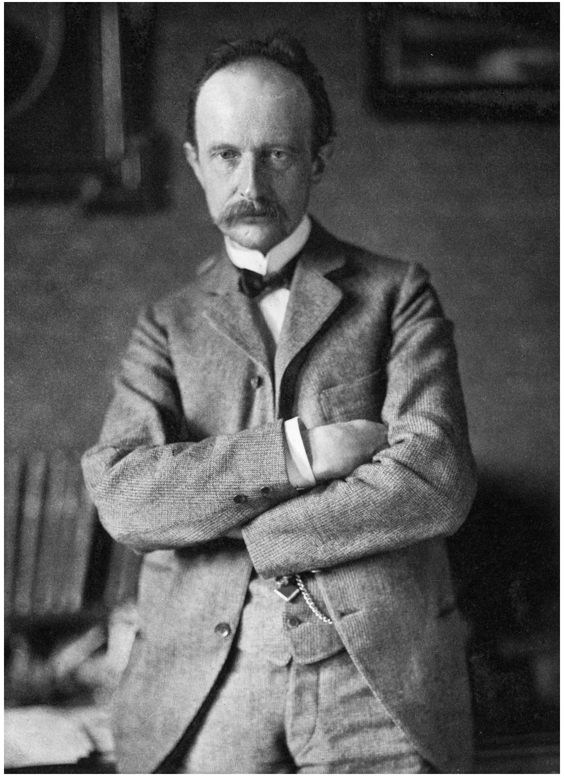
$$\hbar = c = 1$$



Max Planck

Natural units

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Max Planck stated that his natural units...

„...necessarily keep their relevance for all times and all, also extraterrestrial and non-human cultures and therefore can be denoted as natural “units of measure”.

translated from:

„...ihre Bedeutung für alle Zeiten und für alle, auch außerirdische und außermenschliche Culturen nothwendig behalten und ...daher als natürliche „Maaßeinheiten” bezeichnet werden können...”

Quark Yukawa interaction

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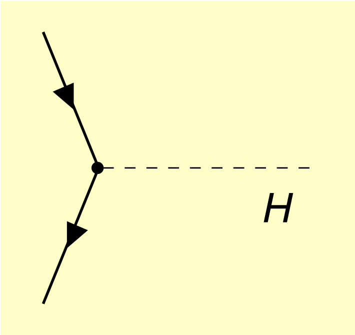
Three generations:

$(d_1, d_2, d_3) \equiv (d', s', b')$ for down, strange, and bottom quark

$(u_1, u_2, u_3) \equiv (u', c', t')$ for up, charm, and top quark

Yukawa lagrangian:

$$-L_Y = Y^d_{jk}\, \bar{d}^j_L\, d^k_R \frac{h}{\sqrt{2}} + Y^u_{jk}\, \bar{u}^j_L\, u^k_R \frac{h}{\sqrt{2}} + \text{h.c.}$$

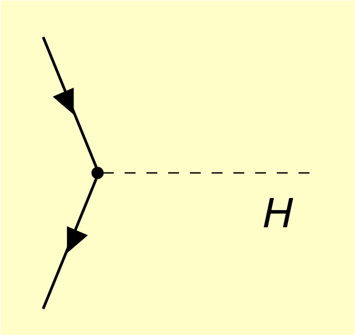


with two complex 3×3 matrices Y^d and Y^u.

→ uglier than the gauge interactions, many couplings!

Quark Yukawa interaction

Yukawa lagrangian:



$$-L_Y = Y^d_{jk}\, \bar{d}^j_L\, d^k_R\, \frac{h}{\sqrt{2}} + Y^u_{jk}\, \bar{u}^j_L\, u^k_R\, \frac{h}{\sqrt{2}} + \text{h.c.}$$

Write $h = \sqrt{2}\,v + h'$, where h' represents the physical Higgs boson and v is the vacuum expectation value.

→ Two mass matrices $M^d = Y^d v$ and $M^u = Y^u v$!

To find the physical quark fields *(d,s,b)* and *(u,c,t)* we must diagonalise the mass matrices by unitary rotations of $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$ and $\begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}$ (for both *L* and *R*).

Quark Yukawa interaction

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The unitary rotations diagonalising $M^d = Y^d v$ and $M^u = Y^u v$ drop out everywhere except in the coupling of the *W* boson:

$$L_W = \frac{g_2}{\sqrt{2}} \left[\bar{u}_L V \gamma^\mu \, d_L \, W_\mu^+ \; + \; \bar{d}_L V^\dagger \gamma^\mu \, u_L \, W_\mu^- \right]$$

weak gauge coupling

$$\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}$$

unitary 3×3 matrix

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

V is the Cabibbo-Kobayashi-Maskawa matrix or quark mixing matrix

It is the only source of transitions between quarks of different fermion generations!

Cabibbo-Kobayashi-Maskawa matrix

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$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.23 & 0.0037 \cdot e^{-i\gamma} \\ -0.23 & 0.97 & 0.041 \\ 0.0085 \cdot e^{-i\beta} & -0.041 \cdot e^{i\beta_s} & 0.999 \end{pmatrix}$$

with $\gamma = 66^\circ, \beta = 22^\circ, \beta_s = 1.1^\circ$.

Cabibbo-Kobayashi-Maskawa matrix

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$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.23 & 0.0037 \cdot e^{-i\gamma} \\ -0.23 & 0.97 & 0.041 \\ 0.0085 \cdot e^{-i\beta} & -0.041 \cdot e^{i\beta_s} & 0.999 \end{pmatrix}$$

with $\gamma = 66^\circ, \beta = 22^\circ, \beta_s = 1.1^\circ$.

To summarise:

- The Yukawa interaction is the only source of transitions between quarks of different generations (flavour violation) in the Standard Model.
- Flavour violation only appears in the W couplings; its strength is encoded in V, e.g. the $W - \bar{u} - b$ coupling reads

$$L_{W\bar{u}b} = \frac{g_2}{\sqrt{2}} \left[\bar{u}_L V_{ub} \gamma^\mu b_L W_\mu^+ + \bar{b}_L V_{ub}^* \gamma^\mu u_L W_\mu^- \right]$$

Flavour physics

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…studies transitions between fermions of different generations.

flavour = fermion species

In the Standard Model flavour physics is the physics of the Yukawa sector.
This sector involves 10 parameters (for quarks):

- 6 quark masses $\Rightarrow$ Yukawa couplings $y_q = \dfrac{m_q}{v}$
- 4 parameters in the unitary CKM matrix V:
  - 3 angles
  - 1 phase

$\Rightarrow$ We “knew” Higgs couplings well before the Higgs was discovered.

Search for new physics

Energy vs. precision

Cornerstones of quantum field theory:

- Forces are mediated by the exchange of particles, which are described by fields.
  A particle of mass M mediates a force ranging over the distance $1/M$.
  $\Rightarrow$ build colliders with higher energy to produce new heavy particles
- A particle with mass M contributes through quantum effects to physical processes at energies well below M (and is called a virtual particle in this context).
  $\Rightarrow$ build high-precision experiments

Decoupling theorem

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We can organise particle physics in terms of hierarchical energy scales, thanks to the Appelquist-Carazzone decoupling theorem:

> If a gauge theory valid at energy scale M_1 is embedded into a larger theory with new particles of mass $M_2 \gg M_1$, the effects on observables probed at the scale M_1 are suppressed by powers of M_1/M_2.

Decoupling theorem

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Blessing:

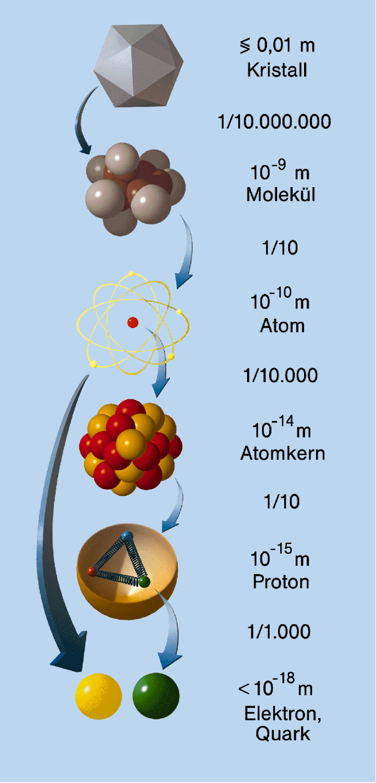
One could formulate e.g. atomic physics $(E_1 \sim 10\,\mathrm{eV})$ without understanding nuclear physics $(E_2 \sim 100\,\mathrm{MeV})$ and the SM $(E_2 \sim \sqrt{1/G_F} \sim 200\,\mathrm{GeV})$ without understanding quantum gravity $(E_2 = M_{\mathrm{Planck}} \sim \sqrt{1/G_N} \sim 10^{19}\,\mathrm{GeV})$.

Curse:

To find laws of physics beyond the SM ("new physics") we must build colliders with $E_2 > E_{\mathrm{SM}} \sim \sqrt{1/G_F}$ or with high statistics to reach the precision E_{SM}^2/E_2^2.

G_F: Fermi constant

G_N: Newton constant



Physics beyond the Standard Model

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The Standard Model correctly describes the physics probed at terrestrial experiments between ~4μeV (Lamb shift) and ~4TeV (LHC).

The most successful theory of science?

Physics beyond the Standard Model

The Standard Model correctly describes the physics probed at terrestrial experiments between ~4μeV (Lamb shift) and ~4TeV (LHC).

The most successful theory of science?

The Standard Model

...fails in cosmology:

- no dark-matter particle
- violates Sakharov criteria, no explantion of surplus of matter over antimatter
- no explanation of dark energy

...has severe shortcomings:

- no explanation of charge quantisation, why is $Q(e) = 3Q(d)$?
- unclear nature of neutrino fields
- 26 or 28 free parameters, unpredicted masses
- no gravity

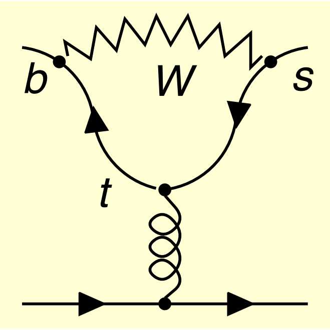
Precision flavour physics

Precision physics

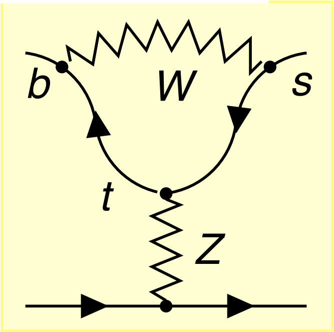
Prime strategy for precision physics: Identify observables for which the SM contribution is parametrically suppressed, while permitting unsuppressed new-physics contributions.

$\Rightarrow$ flavour-changing neutral current (FCNC) processes

In the Standard Model FCNC transitions are loop-suppressed quantum effects.



gluon penguin



Z penguin

FCNC in the Standard Model

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In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,
- Suppression of loops with charm or down-type quarks, $\propto (m_c^2 - m_u^2)/M_W^2$, $(m_s^2 - m_d^2)/M_W^2$ (Glashow-Iliopoulos-Maiani effect).
- helicity suppression in radiative and leptonic decays, because FCNCs involve only left-handed fields, so helicity flips bring a factor of m_b/M_W or m_s/M_W.

FCNC beyond the Standard Model

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Generic models of new physics typically have new sources of unsuppressed FCNC transitions.

Examples:

extra Higgses	$\Rightarrow$	Higgs-mediated FCNC's at tree-level , helicity suppression possibly absent,
squarks/gluinos	$\Rightarrow$	FCNC quark-squark-gluino coupling, no CKM/GIM suppression,
vector-like quarks	$\Rightarrow$	FCNC couplings of an extra Z',
$SU(2)_R$ gauge bosons	$\Rightarrow$	helicity suppression absent

Flavoured mesons

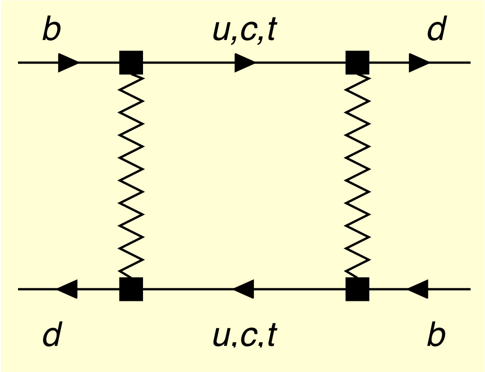
charged:

$$K^+ \sim \bar{s}u, \quad D^+ \sim c\bar{d}, \quad D_s^+ \sim c\bar{s}, \quad B^+ \sim \bar{b}u, \quad B_c^+ \sim \bar{b}c,$$
$$K^- \sim s\bar{u}, \quad D^- \sim \bar{c}d, \quad D_s^- \sim \bar{c}s, \quad B^- \sim b\bar{u}, \quad B_c^- \sim b\bar{c},$$

neutral:

$$K \sim \bar{s}d, \qquad D \sim c\bar{u}, \qquad B_d \sim \bar{b}d, \qquad B_s \sim \bar{b}s,$$
$$\bar{K} \sim s\bar{d}, \qquad \bar{D} \sim \bar{c}u, \qquad \bar{B}_d \sim b\bar{d}, \qquad \bar{B}_s \sim b\bar{s},$$

The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\bar{K}$, $\bar{D}$, $\bar{B}_d$ and $\bar{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).



New-physics discoveries of the past

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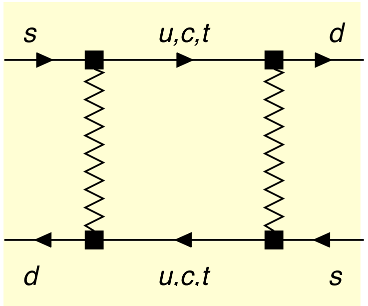
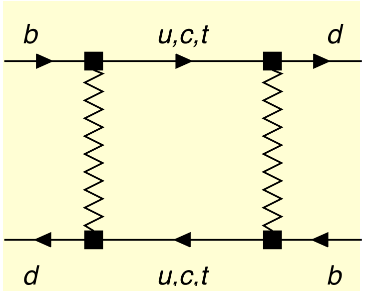
…with FCNC processes:

- Charge-parity (CP) symmetry violation in $K \to \pi^+\pi^-$: Effect of top quark in $K-\bar{K}$ mixing: $\frac{m_t}{m_K} \approx 350$! Christenson,Cronin,Fitch,Turlay; 1964
- Charm quark from $K \to \mu^+\mu^-$ and $K-\bar{K}$ mixing
  Glashow,Iliopoulos,Maiani;Gaillard
- Heaviness of top quark: $B_d-\bar{B}_d$ mixing
  Schröder,Zaitsev (ARGUS at DESY) 1987
- Direct CP violation in $K \to \pi\pi$ Kleinknecht et al. (NA31,NA64 at CERN)
- …





B physics

Recall:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.23 & 0.0037 \cdot e^{-i\gamma} \\ -0.23 & 0.97 & 0.041 \\ 0.0085 \cdot e^{-i\beta} & -0.041 \cdot e^{i\beta_s} & 0.999 \end{pmatrix}$$

$|V_{cb}|$ is small

$\Rightarrow$ The total b decay rate Γ_{tot} is suppressed by a factor of at least $|V_{cb}|^2 = 1.8 \cdot 10^{-3}$!

$\Rightarrow$ Large B meson lifetimes!

$\Rightarrow$ Interesting branching ratios $\dfrac{\Gamma(B \to f)}{\Gamma_{\text{tot}}}$ enhanced!

→ Motivation for dedicated B physics experiments!

Experiments

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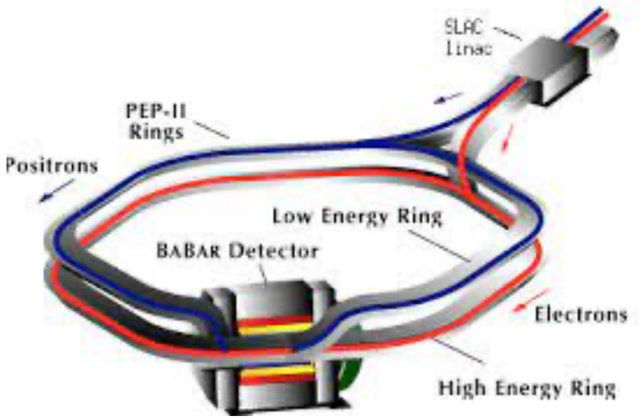
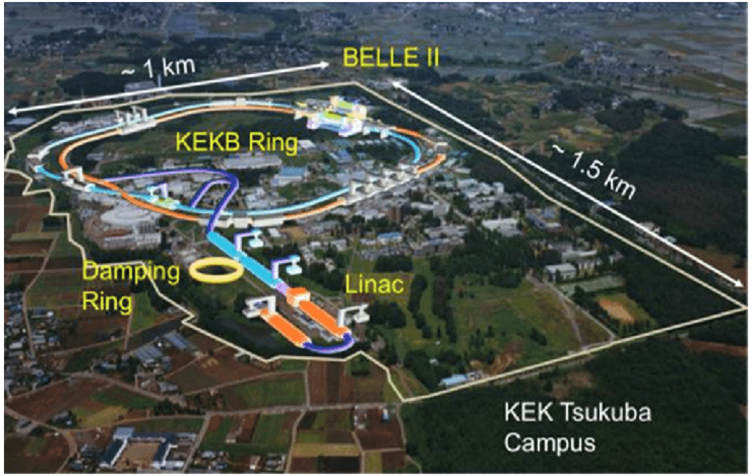
Asymmetric B factories: e^+e^- colliders with different energies of the e^+ and e^- beams (3.1 GeV vs. 9 GeV).

Center-of-mass energy: $\sqrt{s} = M_{\Upsilon(4S)} = 10.58\,\mathrm{GeV}$.

Only $B_d\bar{B}_d$ and B^+B^- pairs produced!



PEP-II collider with BaBar experiment
SLAC,USA, 1999-2008



Super-KEKB collider with Belle experiment
KEK, Tsukuba, Japan, 1999-2010,
Belle II since 2018

Experiments

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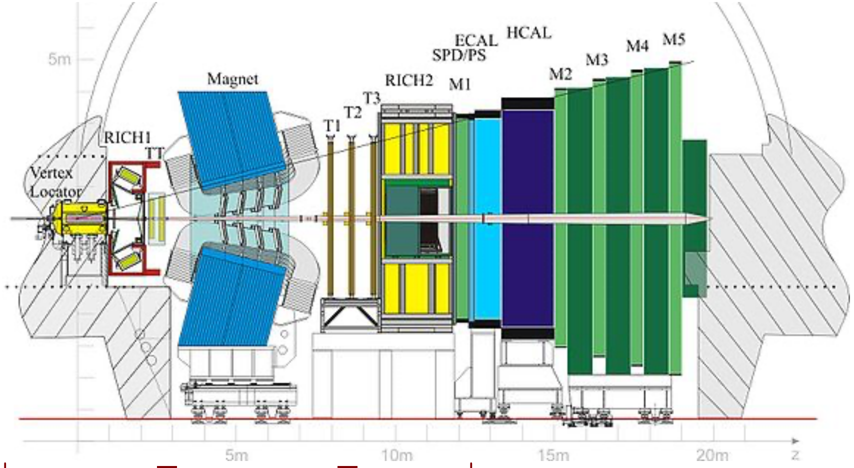
LHCb at CERN, Geneva, Switzerland, since 2010: *pp* collisions



All b-flavoured hadrons are produced: $B^{\pm}, B_d, \bar{B}_d, B_s, \bar{B}_s, B_c^{\pm}, \Lambda_b$ and other baryons. $\Lambda_b \sim bud$

Flavour anomalies

Flavour anomalies

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In recent years several discrepancies between measurements (of branching ratios and/or angular decay distributions) and SM predictions have emerged, denoted as *flavour anomalies*.

Flavour anomalies

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- $b \to s\mu^+\mu^-$: Deficit for $q^2 < 6\,\mathrm{GeV}$, where q^2 is the invariant mass of the muon pair, statistical significance σ grows since 2013 to σ between 4.4 and 7.3 in a combination of data on $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$ with $\ell = e, \mu$ and $B_s \to \phi\mu^+\mu^-$. $\phi \sim s\bar{s}$

  (Alguero et al. 2022, Geng et al 2021, Hurth et al. 2022, Cornella et al. 2021)

- Anomalous magnetic moment of the muon, $(g-2)_\mu \propto y_\mu$ Yukawa coupling deviation from SM prediction is 4.2 σ.

  (Muon g-2 Coll, Fermilab, USA, 2021; BNL AGS-E821 Brookhaven, USA)

- $b \to c\tau\nu$: Enhancement of the ratios of branching ratios $B(B \to D\tau\nu)/B(B \to D\ell\nu)$ and $B(B \to D^*\tau\nu)/B(B \to D^*\ell\nu)$. Discrepancy at 3.2 σ with some inconsistency between experiments.

  (BaBar, Belle, LHCb)

$b \to s\mu^+\mu^-$

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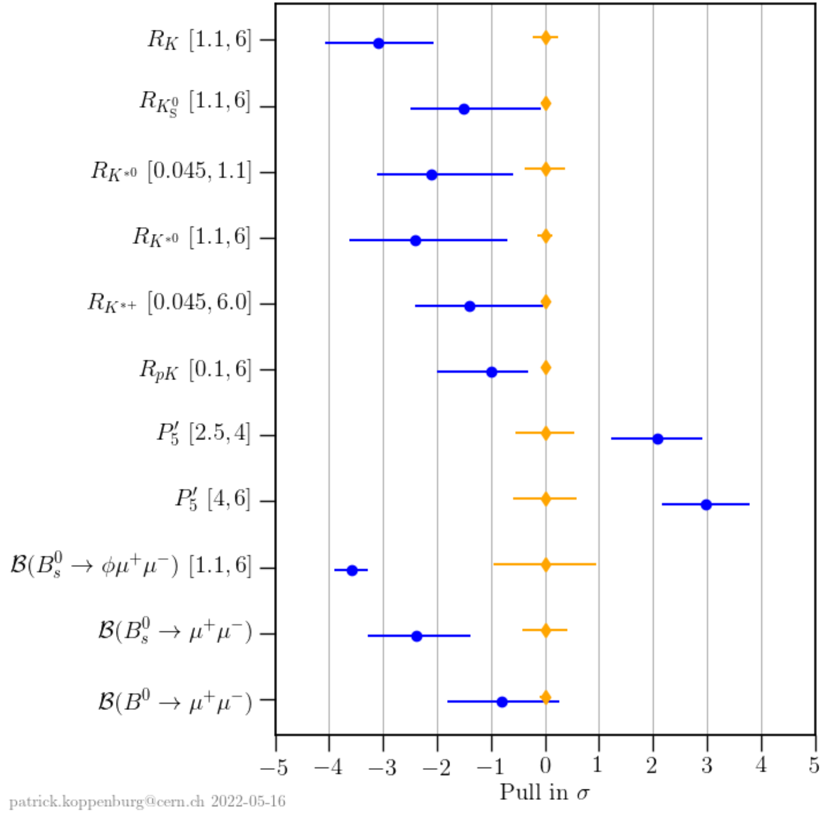
Measured quantities:

$$R_{K^*} = \frac{B(B \to K^*\mu^+\mu^-)}{B(B \to K^*e^+e^-)}\,, \quad R_K = \frac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)}, \quad B(B_s \to \phi\mu^+\mu^-)$$

for several bins of q^2, the invariant mass of the lepton pair.
The error of the SM preditions of R_K, R_{K^*} is essentially zero.
R_K, R_{K^*} are equal to 1 in the SM (except for very low q^2).

In $B \to K^*\mu^+\mu^-$ also angular distributions of the decay products are measured, here theory predictions and estimate of their uncertainties are more difficult. Quantity with deviation: P_5'

$b \to s\mu^+\mu^-$



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No pull of an individual quantity is above 4σ.
In B physics measurements are highly redundant, different observables depend on the same theoretical quantities.

→ Need combined analyses and likelihoos ratio tests between best-fit point and SM point for the theoretical parameters.

Patrick Koppenburg, LHCb,
https://www.nikhef.nl/~pkoppenb/anomalies.html

Effective hamiltonian

At the energy scale of a B decay, $m_b \sim 5\,\text{GeV}$, interactions mediated by much heavier particles appear point-like.

Concept: Derive an effective hamiltonian with four-fermion operators:

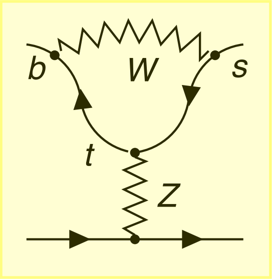
$$H = -\frac{4 G_F V_{tb} V_{ts}^*}{\sqrt{2}} \sum_{\ell,\ell'=e,\mu,\tau} \left[C_9^{\ell\ell'} O_9^{\ell\ell'} + C_{10}^{\ell\ell'} O_{10}^{\ell\ell'} \right] + \ldots$$

The couplings of the effective operators are called Wilson coefficients and are calculated from the Feynman diagrams.

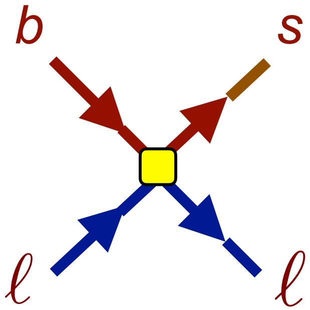
We are interested in

$$O_9^{\ell\ell'} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L]\, [\bar{\ell} \gamma_\mu \ell'], \qquad O_{10}^{\ell\ell'} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L]\, [\bar{\ell} \gamma_\mu \gamma^5 \ell']$$

α is the QED coupling (Sommerfeld constant).



Four-fermion interaction as in Fermi theory of beta decay:



Semileptonic FCNC operators

Operators:

$$O_9^{\ell\ell'} = \frac{\alpha}{4\pi}[\bar{s}_L\gamma^\mu b_L]\,[\bar{\ell}\gamma_\mu \ell'], \qquad O_{10}^{\ell\ell'} = \frac{\alpha}{4\pi}[\bar{s}_L\gamma^\mu b_L]\,[\bar{\ell}\gamma_\mu\gamma^5 \ell']$$

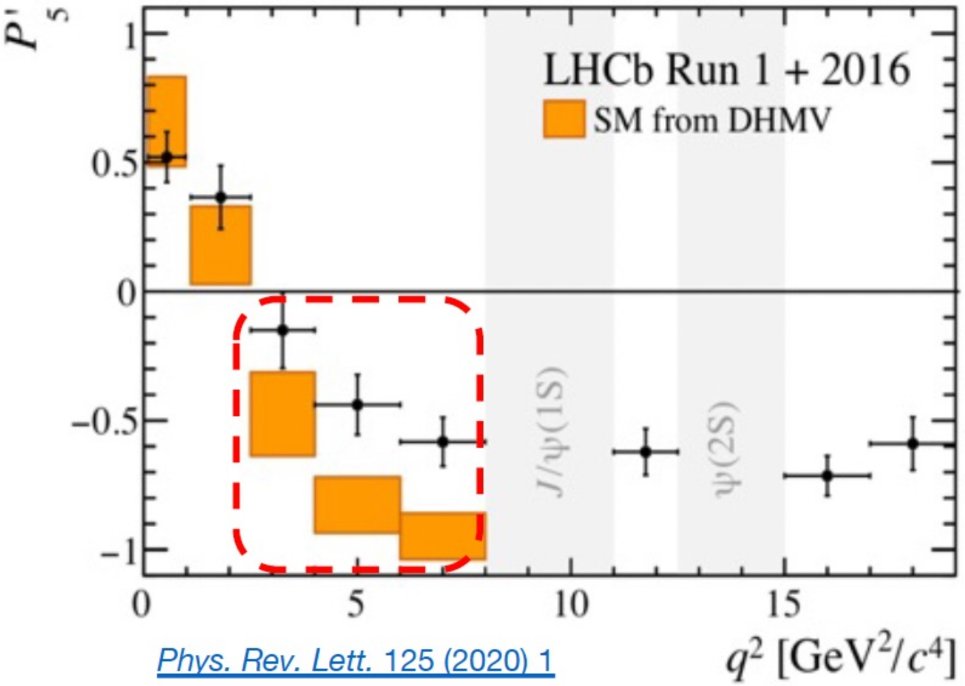
Coefficients: In the Standard Model

$$C_{9,10} \equiv C_{9,10}^{ee} = C_{9,10}^{\mu\mu} = C_{9,10}^{\tau\tau}$$

and

$$C_{9,10}^{\ell\ell'} = 0 \qquad \text{for } \ell \neq \ell'$$

Angular distribution



Phys. Rev. Lett. 125 (2020) 1

The decay $B \to K^* \ell^+ \ell^-$ can be described by three angles and q^2.

P_5' is calculated from the number of decays counted in a certain direction characterised by these angles.

LHCb, 2020

Lepton flavour universality

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$$R_{K^*} = \frac{B(B \to K^* \mu^+ \mu^-)}{B(B \to K^* e^+ e^-)} \quad \text{and} \quad R_K = \frac{B(B \to K \mu^+ \mu^-)}{B(B \to K e^+ e^-)}$$

are predicted to 1 in the SM, because *W*, *Z*, and photon couple to all charged leptons with the same coupling:

lepton universality of the electroweak interaction

Experimental results

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$\underline{B^0 \to K^{*0}\ell^+\ell^-}$ (3 fb^{-1})

$$R_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \qquad [0.045 < q^2/\text{GeV}^2 < 1.1]$$
$$R_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \qquad [1.1 < q^2/\text{GeV}^2 < 6.0]$$

2.2–2.5σ deviation from SM in each bin. *[JHEP 08 (2017) 55]*

$\underline{B^+ \to K^+\ell^+\ell^-}$ (9 fb^{-1})

$$R_{K^+} = 0.846^{+0.042}_{-0.039}(\text{stat})\ ^{+0.013}_{-0.012}(\text{syst})$$

3.1σ deviation from SM.

[Nature Physics 18, (2022) 277-282]

with same trend in other $b \to s\mu^+\mu^-$ modes

courtesy of Johannes Albrecht, LHCb

Global fit

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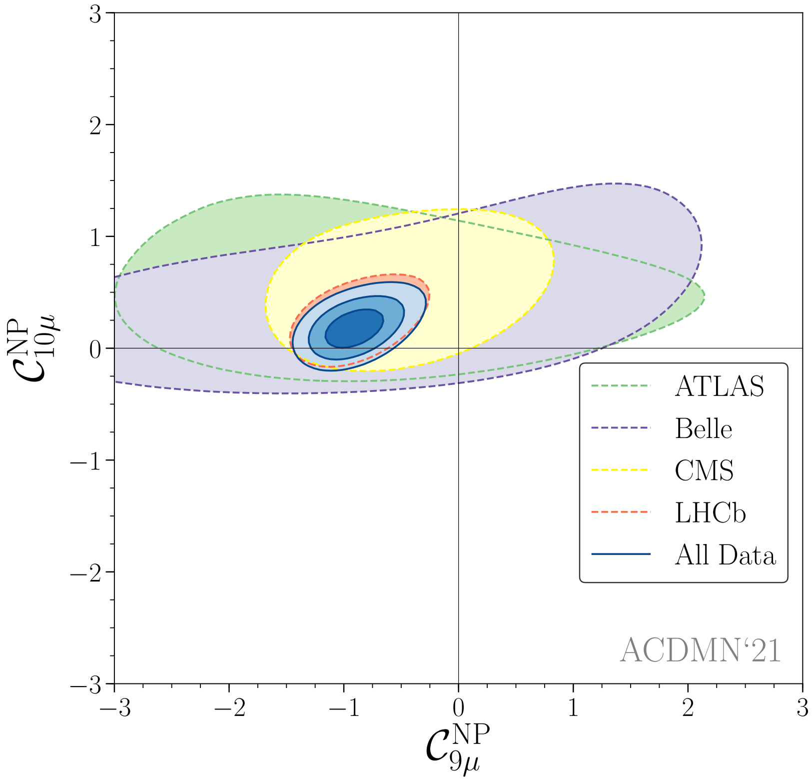

Operators:

$$O_9^{\ell\ell'} = \frac{\alpha}{4\pi}[\bar{s}_L\gamma^\mu b_L]\,[\bar{\ell}\gamma_\mu\ell'], \qquad O_{10}^{\ell\ell'} = \frac{\alpha}{4\pi}[\bar{s}_L\gamma^\mu b_L]\,[\bar{\ell}\gamma_\mu\gamma^5\ell']$$

Fit to new-physics (NP) contribution to $C_{9,10}^{\mu\mu}$ using all data (also those complying with the SM).

(Alguero et al, *Eur.Phys.J.C* 82 (2022) 4, 326)

Explanations

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Experimental issues:

The combined significance of the anomaly is too large for a statistical fluctuation.

Could the efficiencies for *e* or *μ* detection be incorrectly estimated?

LHCb measures double ratios:

$$\underbrace{\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)}}_{R_{K^{(*)}}} \cdot \underbrace{\frac{B(B \to K^{(*)}J/\psi[\to e^+e^-])}{B(B \to K^{(*)}J/\psi[\to \mu^+\mu^-])}}_{\frac{B(J/\psi \to e^+e^-)}{B(J/\psi \to \mu^+\mu^-)}}$$

= 1 (measured)

J/ψ is a narrow $(c, \bar{c})$ resonance with mass 3.1 GeV contributing to $B \to K^{(*)}\ell^+\ell^-$ for $q^2 = (3.1\,\mathrm{GeV})^2 = 9.6\,\mathrm{GeV}^2$.

Explanations

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Experimental issues:

To first approximation the *e* and *μ* efficiencies cancel from the ratio

$$\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)} \cdot \frac{B(B \to K^{(*)}J/\psi[\to e^+e^-])}{B(B \to K^{(*)}J/\psi[\to \mu^+\mu^-])},$$

but in the interesting bins $q^2 \in [0.045, 1.1]$ and $q^2 \in [1.1, 6]$ the angle between the two leptons is smaller than for $q^2 = (3.1\,\mathrm{GeV})^2 = 9.6\,\mathrm{GeV}^2$.

Currently all LHCb data on $R_{K^{(*)}}$ are re-analysed by a new team.

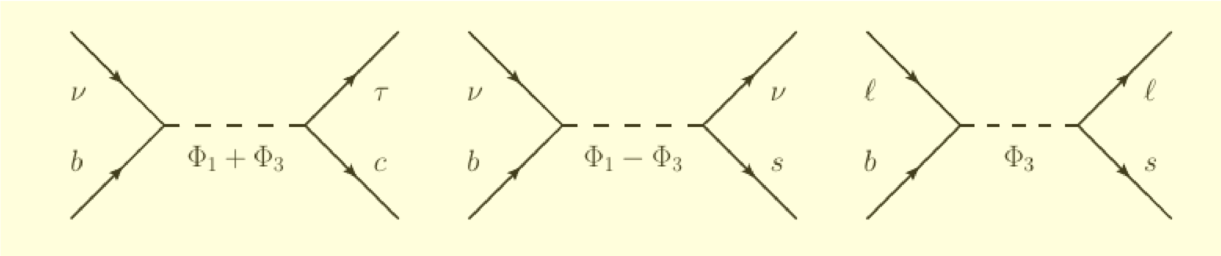
"Extraordinary claims require extraordinary evidence."

(Sherlock Homes in The Sign of Four)

Explanations

New physics:

- Leptoquarks:
  - bosons with quark-lepton coupling
  - can also explain $(g-2)_\mu$ and $b \to c\tau\nu$ anomalies



  - appear in SU(4) gauge theories, where lepton number is the fourth colour
- Z' boson related to a new gauged U(1) symmetry, maybe $L_\mu - L_\tau$ (difference of muon and tau lepton number)
  - may help with $(g-2)_\mu$ but not with $b \to c\tau\nu$

$b \to c\tau\bar{\nu}$

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studied through

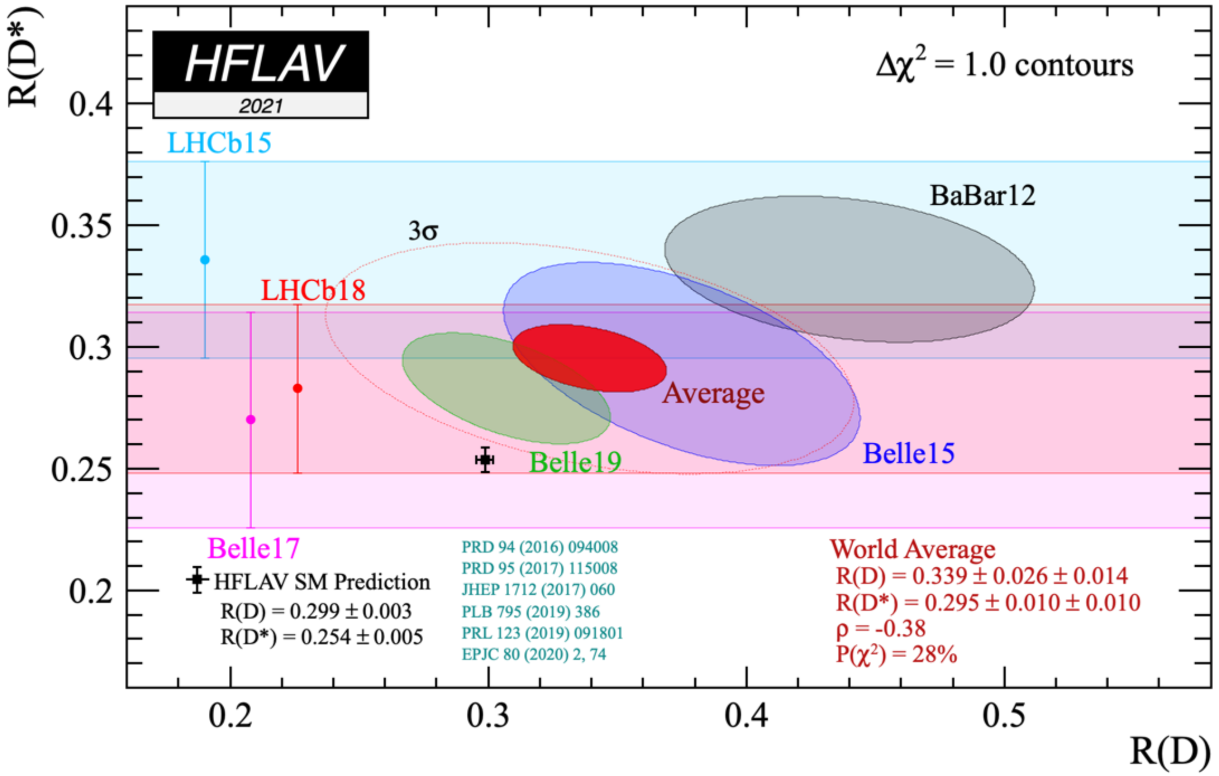
$$R(D) = \frac{B(B \to D\tau\bar{\nu})}{B(B \to D\ell\bar{\nu})}$$

and

$$R(D^*) = \frac{B(B \to D^*\tau\bar{\nu})}{B(B \to D^*\ell\bar{\nu})}$$

at
BaBar, Belle, LHCb and in the future also Belle II.

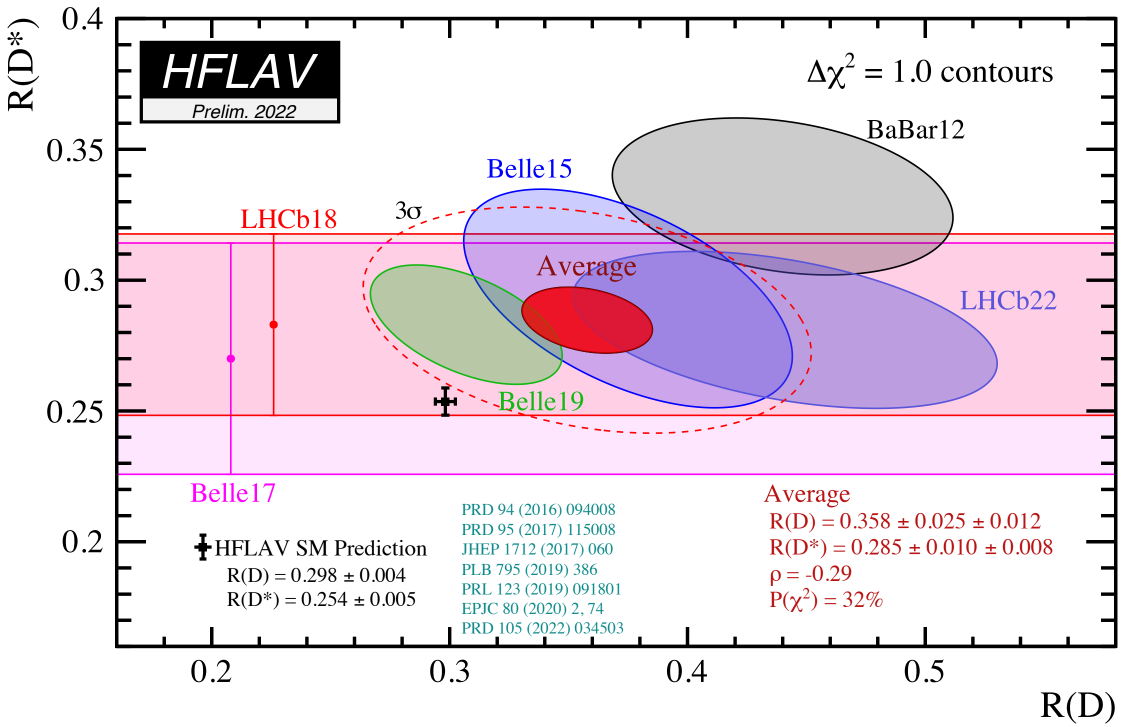
Here $\ell = e, \mu$.



$b \to c\tau\bar{\nu}$

New development: first combined measurements of $R(D)$ and $R(D^*)$ by LHCb,

- supporting large $R(D)$ of BaBar,
- increasing consistency between all measure-ments .



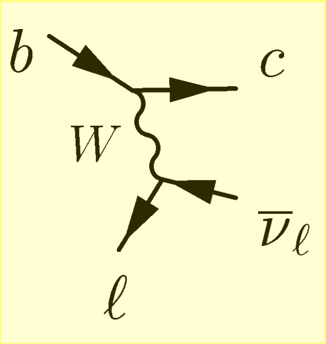
$b \to c\tau\bar{\nu}$

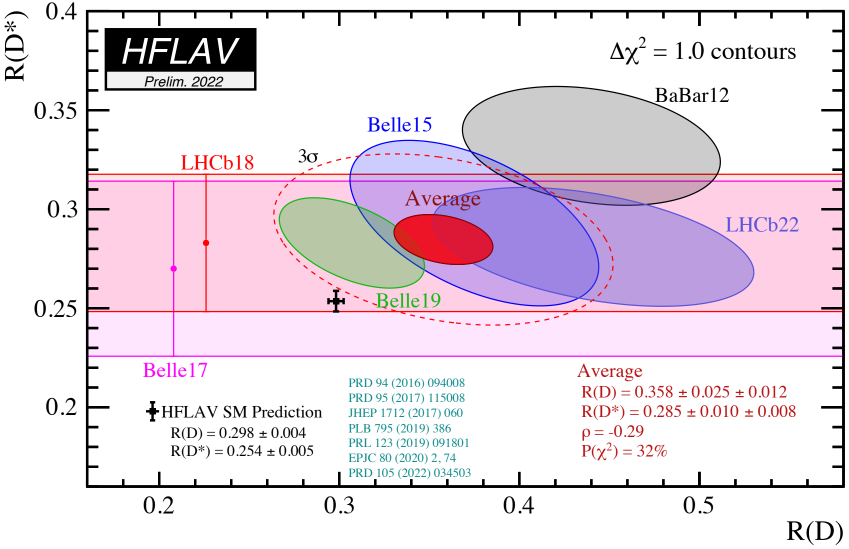
Lepton-flavour universality violation in a tree-level decay (all HFLAV):

	$R(D)$	$R(D^*)$
exp :	$0.358 \pm 0.025 \pm 0.012$	$0.285 \pm 0.010 \pm 0.008$
SM :	0.298 ± 0.004	0.254 ± 0.005

significance: *3.2σ*

- tensions among different experimental analyses
- effect is (too?) large





Heavy Flavour Averaging Group, https://hflav.web.cern.ch/content/semileptonic-b-decays

$b \to c\tau\bar{\nu}$

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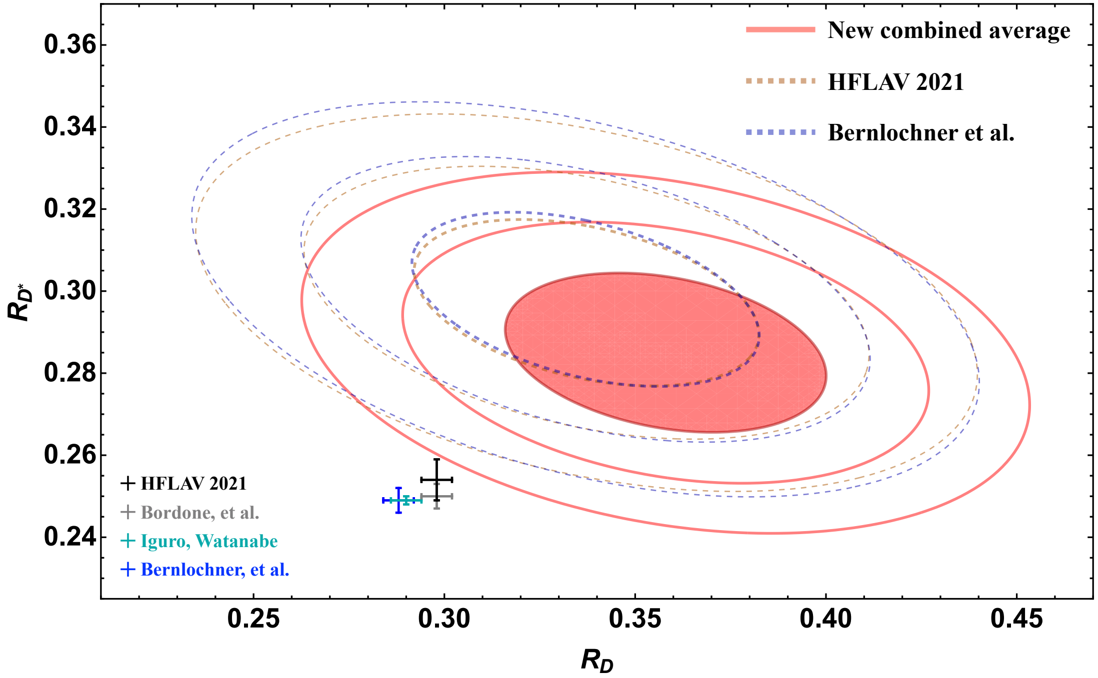
S. Iguro, T. Kitahara, R. Watanabe, arXiv:2210.10751



New-physics explanations

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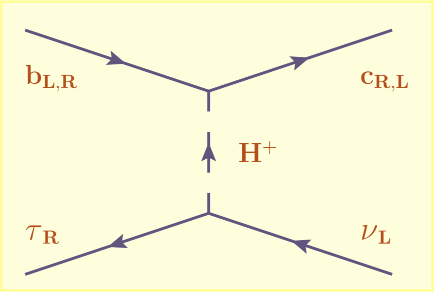
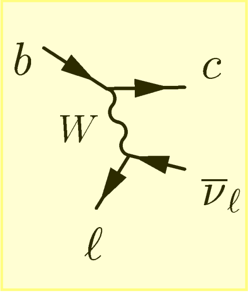
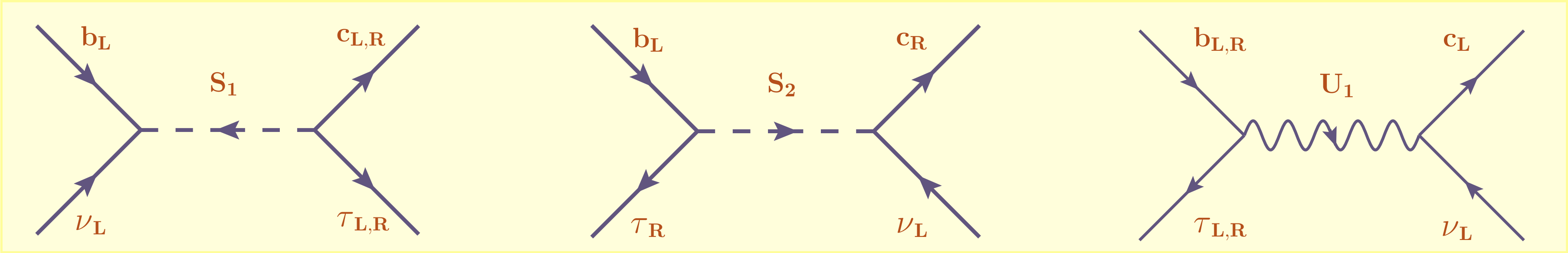
$b \to c\tau\bar{\nu}$ was known to be sensitive to effects of a hypothetical charged Higgs boson since 1992. (Grzadkowski,Hou, Phys. Lett. B **283** (1992) 427)





Leptoquarks:



spin 0, SU(2) singlet, Q=1/3 spin 0, SU(2) doublet, Q=2/3 spin 1, SU(2) singlet, Q=2/3

New-physics explanations

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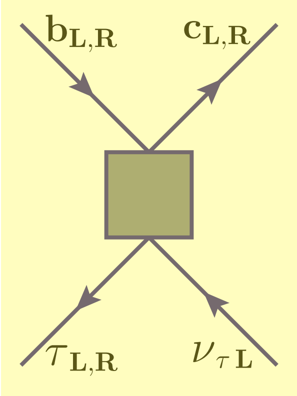
As in the case of $b \to s\mu^+\mu^-$ we can accomodate all types of new physics in terms of effective four-quark operators.



$$
\begin{aligned}
O_V^L &= \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_{\tau L} \,, \\
O_S^R &= \bar{c}_L b_R \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_S^L &= \bar{c}_R b_L \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_T &= \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \,.
\end{aligned}
$$

(Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara,*Phys.Rev.D* 100(2019) 3, 035035)

New-physics explanations

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Fit the corresponding coefficients $C_V^L, C_S^{R,L}, C_T$ to $R(D)$, $R(D^*)$, and the tau polarisation asymmetry

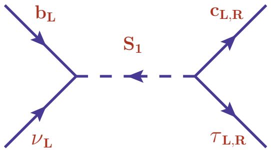
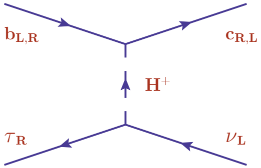
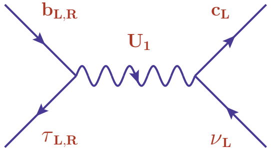
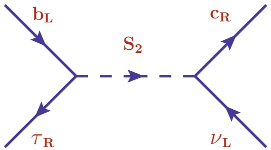
$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16} \quad \text{(Belle 2017)}$$

and the fraction of longitudinally polarised D^* mesons

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035 \quad \text{(Belle 2018)}$$

Blanke,Crivellin,de Boer,Kitahara,Moscati,UN,Nisandzic, *Phys.Rev.D* 99 (2019) 7, 075006;
Blanke,Crivellin,de Boer,Kitahara,UN,Nisandzic, *Phys.Rev.D* 100(2019) 3, 035035

New-physics explanations

coefficients	motivated by
real C_V^L, $C_S^L = -4C_T$	
real C_S^R, C_S^L	
real C_V^L, C_S^R	
$\mathrm{Re}[C_S^L = 4C_T]$, $\mathrm{Im}[C_S^L = 4C_T]$	

All scenarios fit the $B \to D^{(*)}\tau\bar{\nu}$ data, with different predictions for *$F_L(D^*)$* and $B(B_c^+ \to \tau^+\nu)$.

- H^+: either $B(B_c^+ \to \tau^+\nu)$>0.3 or $R(D^*)$ will come down, larger *$F_L(D^*)$*.
- S_1 and U_1: smaller (SM-like) *$F_L(D^*)$*; U_1 can also explain $b \to s\mu^+\mu^-$ and $(g-2)_\mu$.
- S_2: similar to H^+, but small *$F_L(D^*)$* testable at ATLAS and CMS.

Sum rule for $b \to c\tau\bar{\nu}$

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$R(D^*)$ and $R(D)$ are correlated with

$$R(\Lambda_c) = \frac{B(\Lambda_b \to \Lambda_c \tau \bar{\nu})}{B(\Lambda_b \to \Lambda_c \ell \bar{\nu})}\,,$$

where $\Lambda_b \sim bud, \quad \Lambda_c \sim cud$:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.262\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + x\,.$$

with $|x| < 0.05$ in any scenario of new physics.

(Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara,*Phys.Rev.D* 100(2019) 3, 035035)

Sum rule for $b \to c\tau\bar{\nu}$

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$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\mathrm{SM}}(\Lambda_c)} = 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\mathrm{SM}}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\mathrm{SM}}(D^*)} + x.$$

Our 2019 prediction:

$$R(\Lambda_c) = R_{\mathrm{SM}}(\Lambda_c)\,(1.15 \pm 0.04) = 0.38 \pm 0.01 \pm 0.01$$

Tension with 2022 LHCb measurement:

$$R(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

(LHCb, *Phys.Rev.Lett.* 128 (2022) 19, 191803)

→ with future data either $R(D^{(*)})$ will come down or $R(\Lambda_c)$ will go up.

New-physics explanations

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2022 updates include

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18 \quad \text{(Belle 2018)}$$

vs. $R(J/\psi)_{\mathrm{SM}} = 0.258 \pm 0.004$ (HPQCD)

and

$$R(\Lambda_b) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059 \quad \text{(LHCb 2022)}$$

vs. $R(\Lambda_b)_{\mathrm{SM}} = 0.324 \pm 0.004$ (Detmold et al. 2015)

2022 updates:

Iguro, Kitahara, Watanabe,

Global fit tot $b \to c\tau\nu$ anomalies 2022 mid-autumn, arXiv:2210.10751

Fedele, Blanke, Crivellin, Iguro, Kitahara, UN, Watanabe,

Impact of $\Lambda_b \to \Lambda_c \tau \nu$ measurement on New Physics in $b \to c\, l \nu$ transitions, arXiv:2211.14172.

2022 update

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\mathrm{SM}}} = 0.280\frac{R(D)}{R(D)_{\mathrm{SM}}} + 0.720\frac{R(D^*)}{R(D^*)_{\mathrm{SM}}} + x$$

Fedele, Blanke, Crivellin, Iguro, Kitahara, UN, Watanabe, arXiv:2211.14172.

Prediction unchanged:

$$R(\Lambda_c) = 0.380 \pm 0.012 \pm 0.005$$

compared to 2019:

$$R(\Lambda_c) = 0.38 \pm 0.01 \pm 0.01$$

The sum rule assumes that new physics only affects the τ mode. Can one relax the constraint by permitting new physics also in $b \to c\ell\nu$ with a light lepton $\ell = e, \mu$?

$\Rightarrow$ Even in a fit permitting arbitrary new physics in both τ and light lepton modes does not relieve the tension between $R(D^{(*)})$ and $R(\Lambda_c)$.

Fedele, Blanke, Crivellin, Iguro, Kitahara, UN, Watanabe, arXiv:2211.14172.

Summary

Summary

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- Flavour physics probes virtual effects of heavy particles with masses far above the reach of high-p_T experiments.
- Predictions of BSM theories for B physics observables are highly correlated, because many quantities depend on few (calculable) coefficients encoding the BSM effects. $\longrightarrow$ intrinsic redundancy of B physics
- Combining all data on $b \to s\mu^+\mu^-$ data reveals a tension on the Standard Model with a significance between 4.4σ and 7.3σ in likelihood ratio tests.
- $b \to s\mu^+\mu^-$ can be explained with a leptoquark with mass below 40 TeV.
  $\longrightarrow$ Precision physics can give guidance for the design of future collider.
- Leptoquarks can also explain anomalous data in $(g-2)_\mu$ and $b \to c\tau\bar{\nu}$.
- The new LHCb measurement of $R(\Lambda_c)$ points to inconsistent measurements of at least one of $R(D)$, $R(D^*)$, or $R(\Lambda_c)$ irrespective of the presence of BSM physics.
  $\longrightarrow$ Redundancy of B physics helps to disentangle BSM physics from mistakes.

$b \to s\mu^+\mu^-$ penguin diagrams

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wake-up call for new physics?