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Probing beyond the Standard Model with Flavor Physics

Matthias Neubert

PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

mitp Mainz Institute for Theoretical Physics

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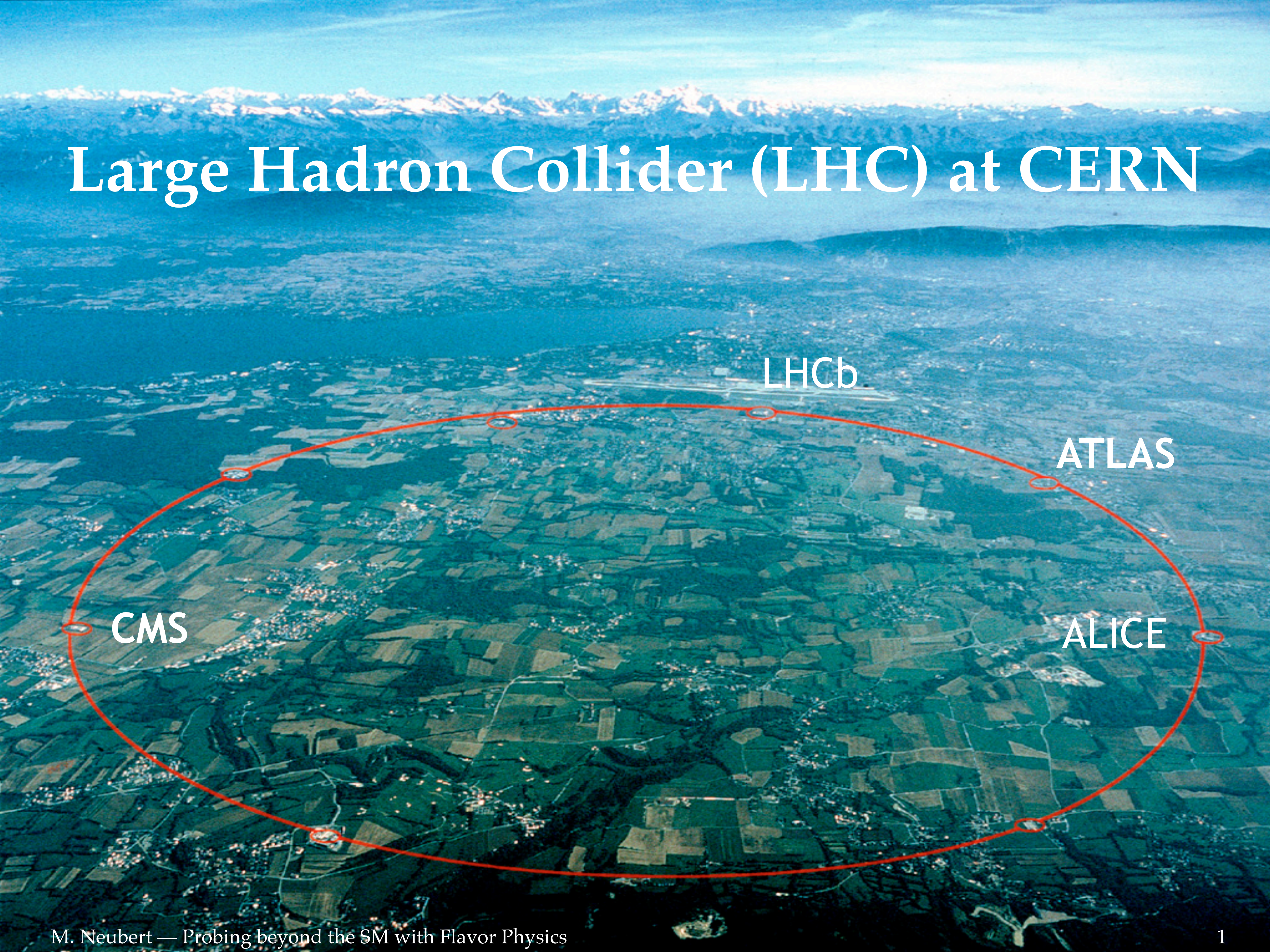
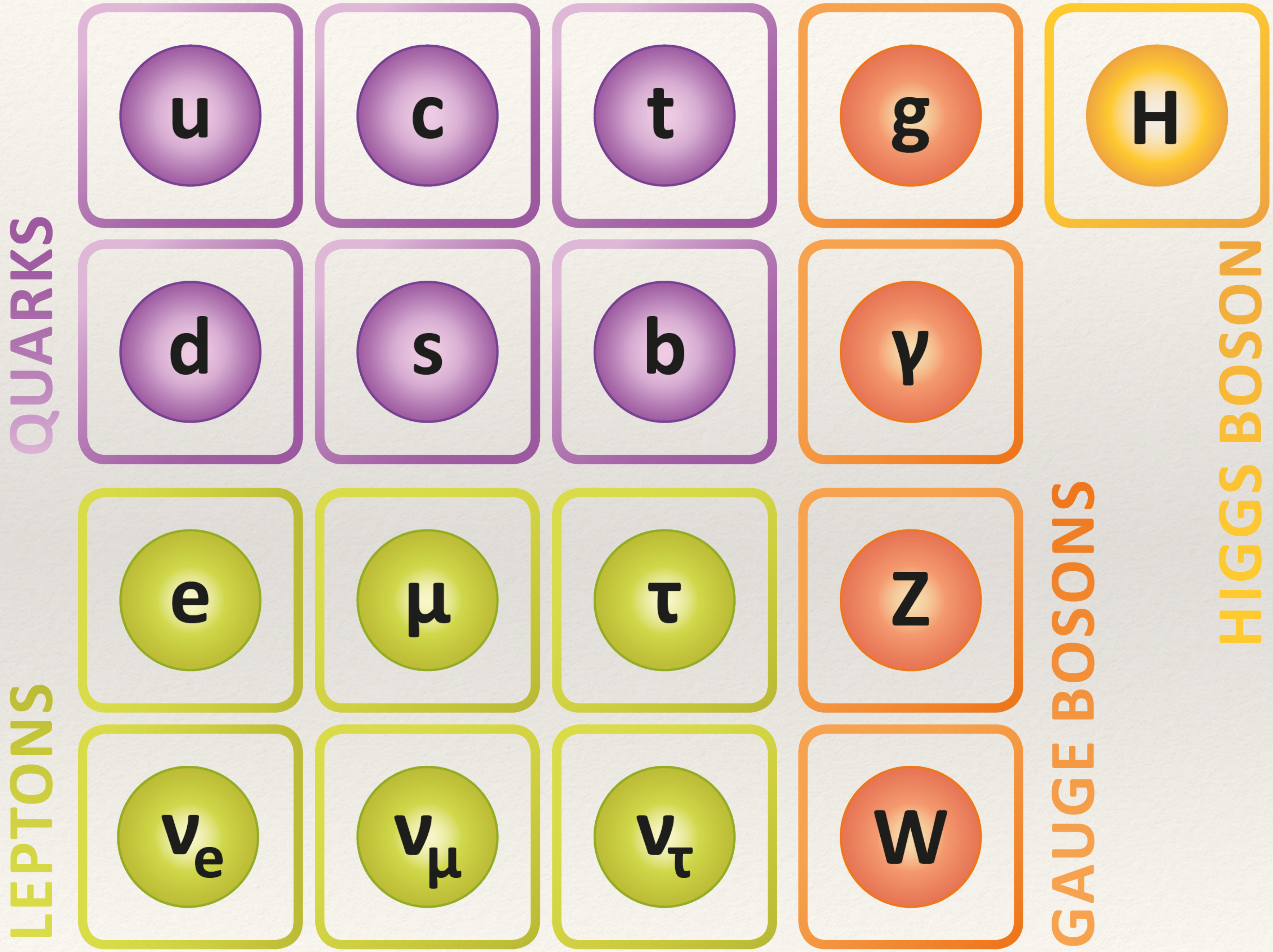
Large Hadron Collider (LHC) at CERN



The Standard Model



The Standard Model

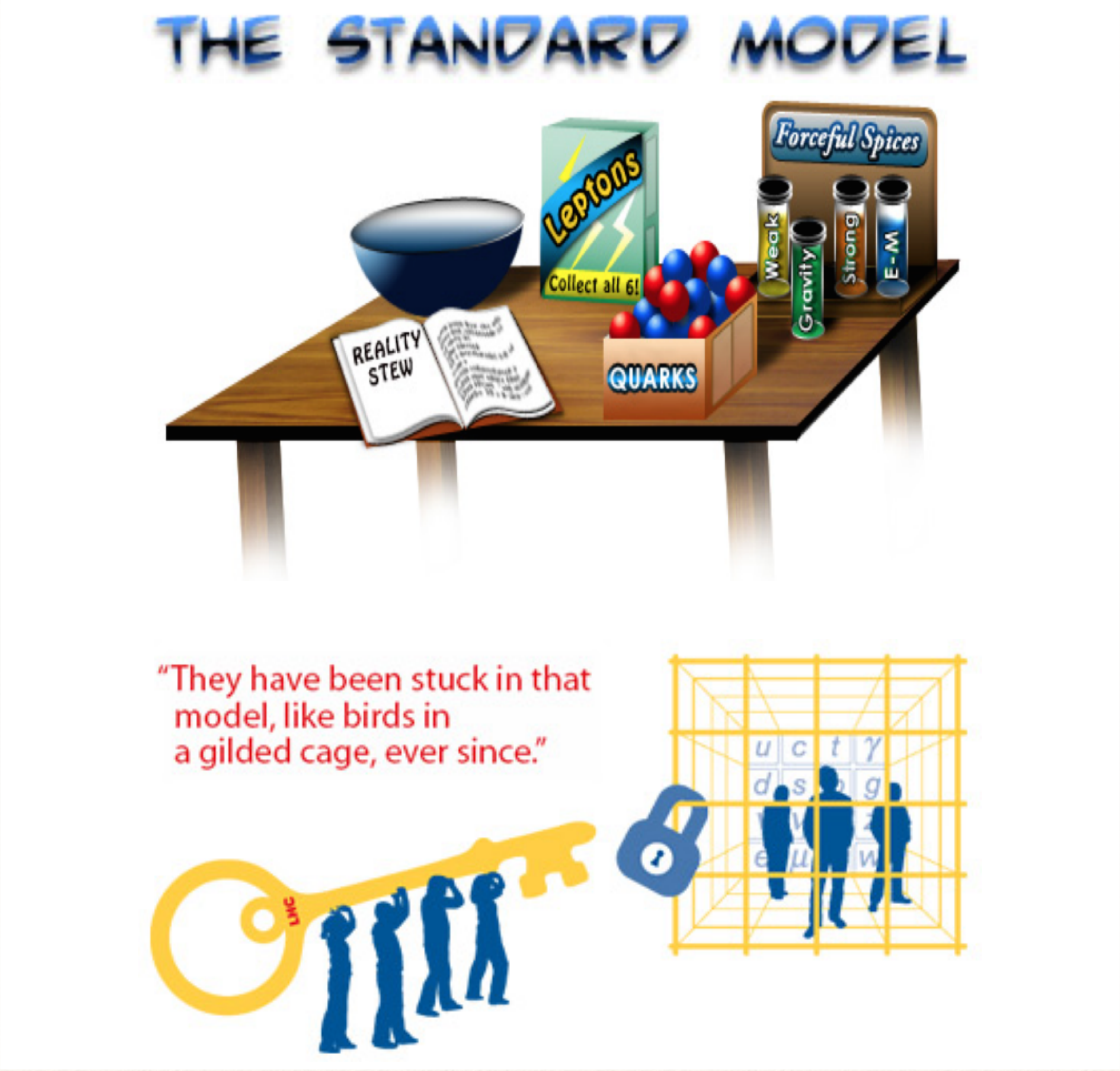
Leaves several questions unanswered:

Why is there more matter than antimatter?

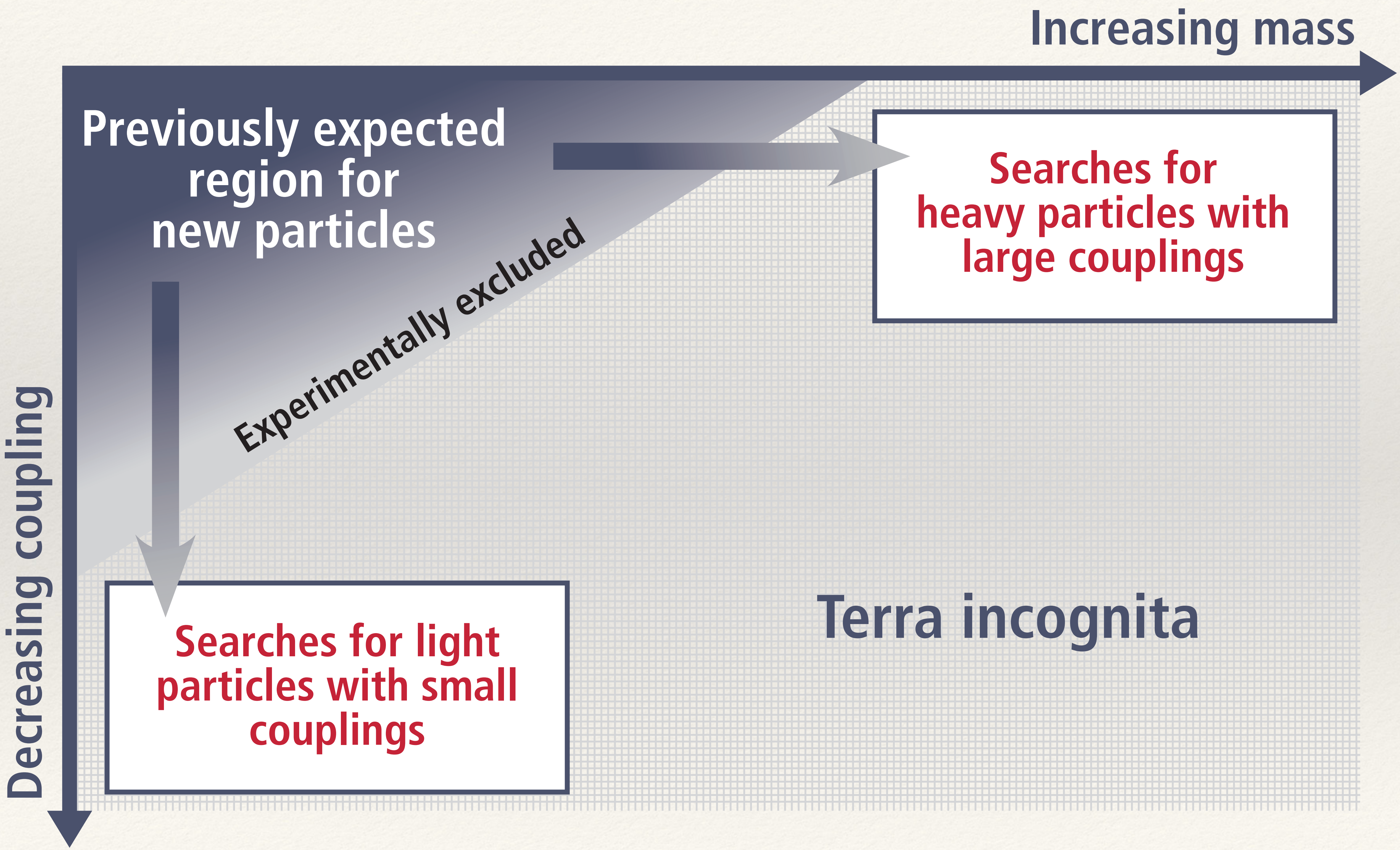
What is the dark matter made of?

How is the electroweak scale stabilized?

The Standard Model



Beyond the SM?



SMEFT

- Direct searches for new heavy particles at LHC have so far not led to a discovery
- Indirect searches for heavy new physics should be analyzed in context of a systematic extension of the SM as an effective field theory:

[Buchmüller, Wyler 1986;
Grzadkowski, Iskrzynski, Misiak, Rosiek 2010]

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_W}\,\mathcal{O}_W^{(D=5)} + \sum_{i=1}^{\rm many} \frac{1}{\Lambda_i^2}\,\mathcal{O}_i^{(D=6)} + \dots$$

SM without neutrino masses

Neutrino masses and oscillations

Generic new-physics phenomena

SMEFT

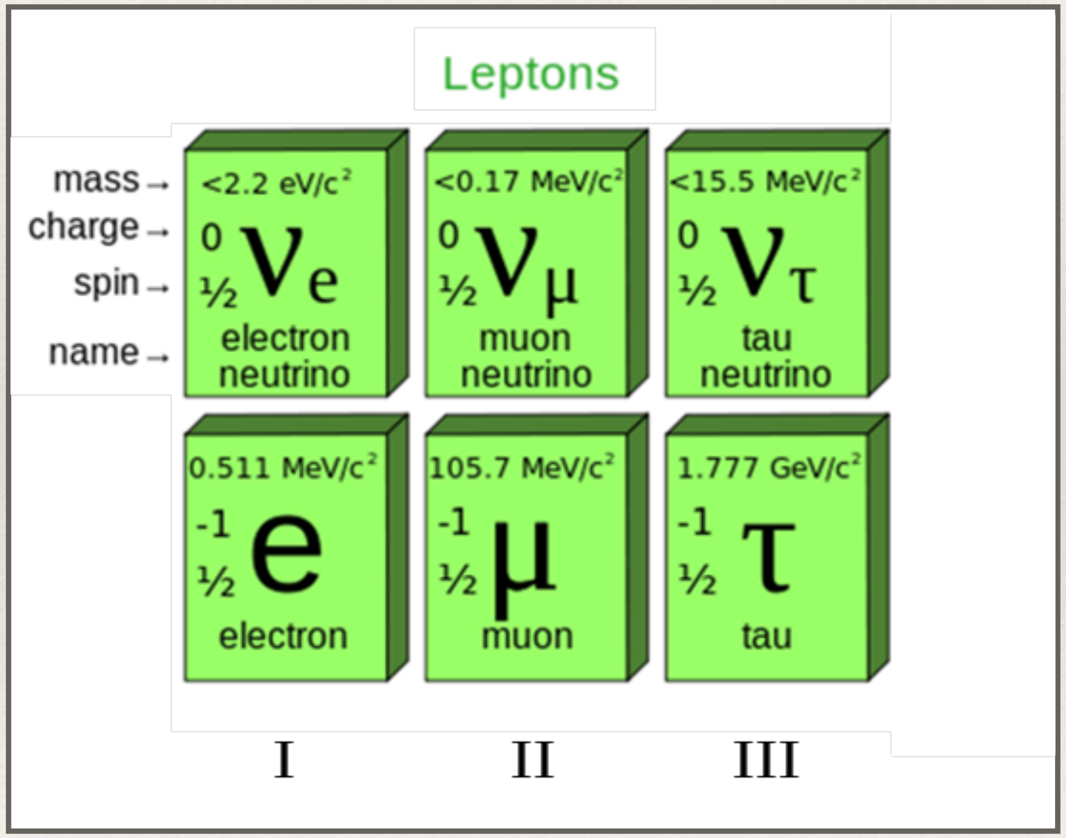
- All new-physics scales probed so far are rather large:

Order	Observable	New-physics scale for g=O(1)
D=5	Neutrino oscillations	$\Lambda \sim 10^9$ TeV
D=6	Proton decay	$\Lambda \sim 10^{12}$ TeV
D=6	Flavor physics	$\Lambda > 1\text{–}10^5$ TeV
D=6	EWPT	$\Lambda > 1$ TeV
D=6	Higgs couplings	$\Lambda > 0.5\text{–}1$ TeV

Beyond the SM

- No solution yet to hierarchy problem (SUSY ???)
- No answers yet to other big questions:
  - Nature of Dark Matter?
  - Origin of matter-antimatter asymmetry?
  - Explanation of flavor puzzle?
  - Dark energy / cosmological constant and strong CP problems
- While the field waits for clues, remarkable things are happening in the flavor sector!

B-meson flavor anomalies:
Violations of lepton universality ?



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Tensions in the Standard Model

B-meson flavor anomalies

- Intriguing hints of anomalies in B decays entered stage starting in 2012 (R_D, R_{D^*}; R_K, R_{K^*}; P_5', …)

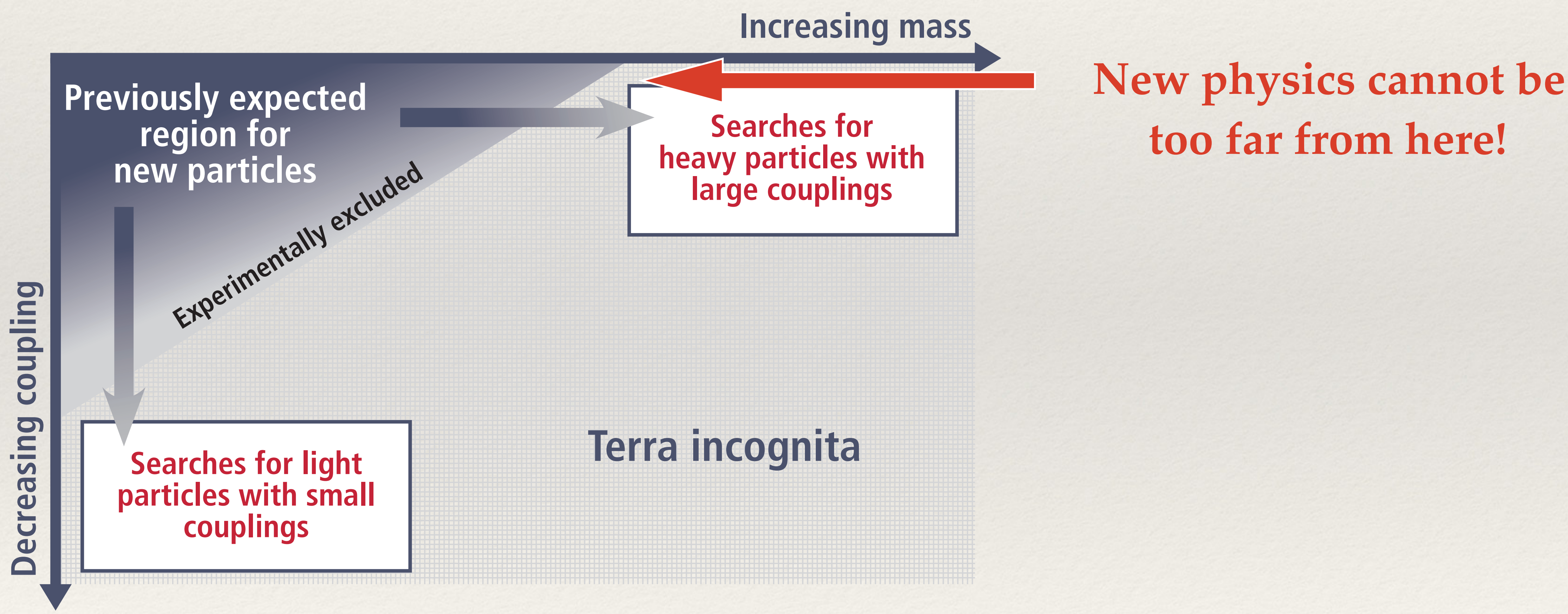
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)} \tau \bar{\nu})}{\Gamma(\bar{B} \to D^{(*)} \ell \bar{\nu})}\,; \quad \ell = e, \mu$$

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)} e^+ e^-)}$$

- If true, they would be hugely important for the future development of high-energy particle physics at large!
- In fact, their importance cannot be overstated …

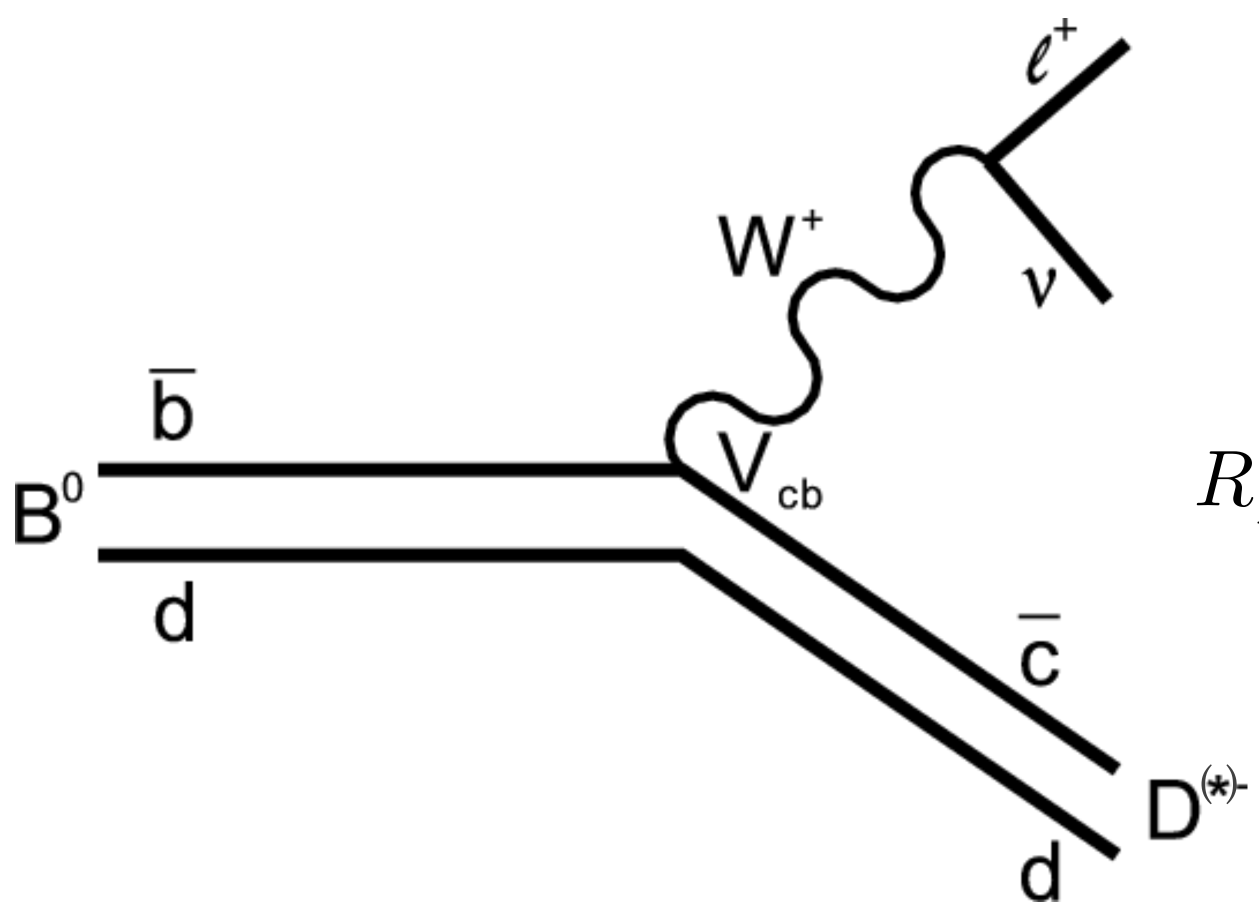
B-meson flavor anomalies

- … because they would give a clear target for future searches at energy frontier!



Flavor anomalies: R_D & R_{D^*}

- A totally unexpected signal of new physics in tree-level, CKM-favored, semileptonic decays of B mesons:



$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)} \tau \bar{\nu})}{\Gamma(\bar{B} \to D^{(*)} \ell \bar{\nu})} \; ; \qquad \ell = e, \mu$$

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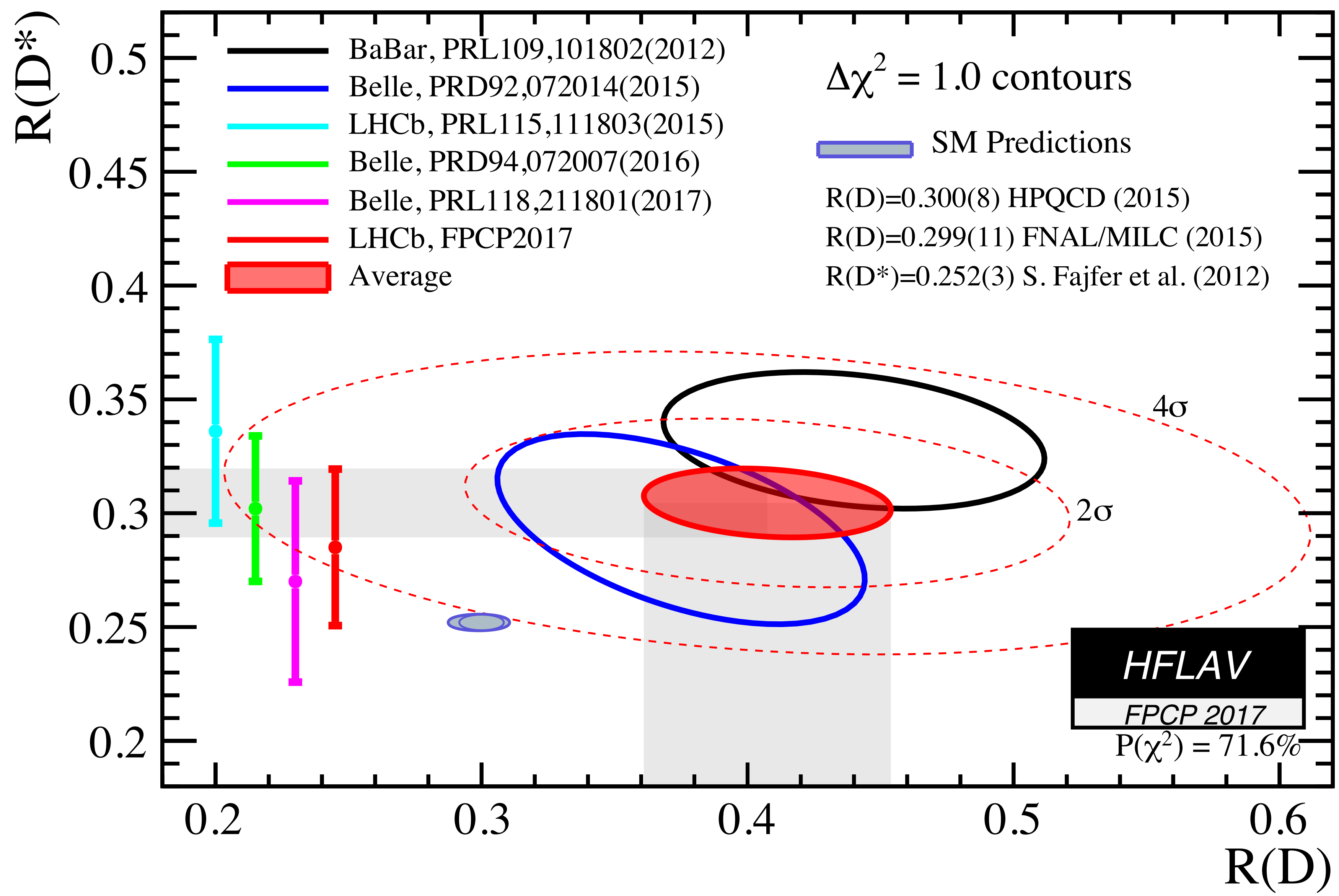
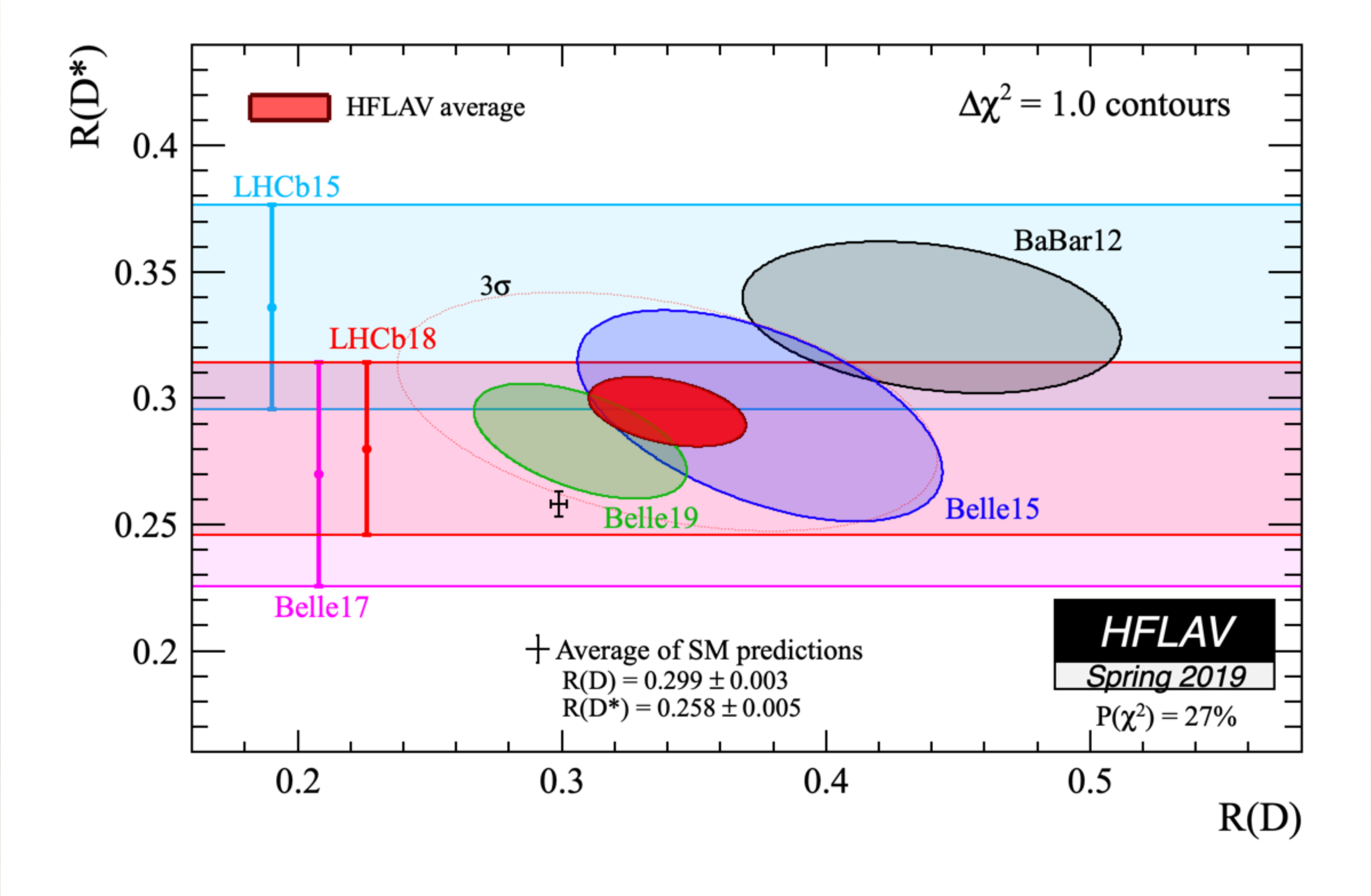


$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})} \;; \quad \ell = e, \mu$$

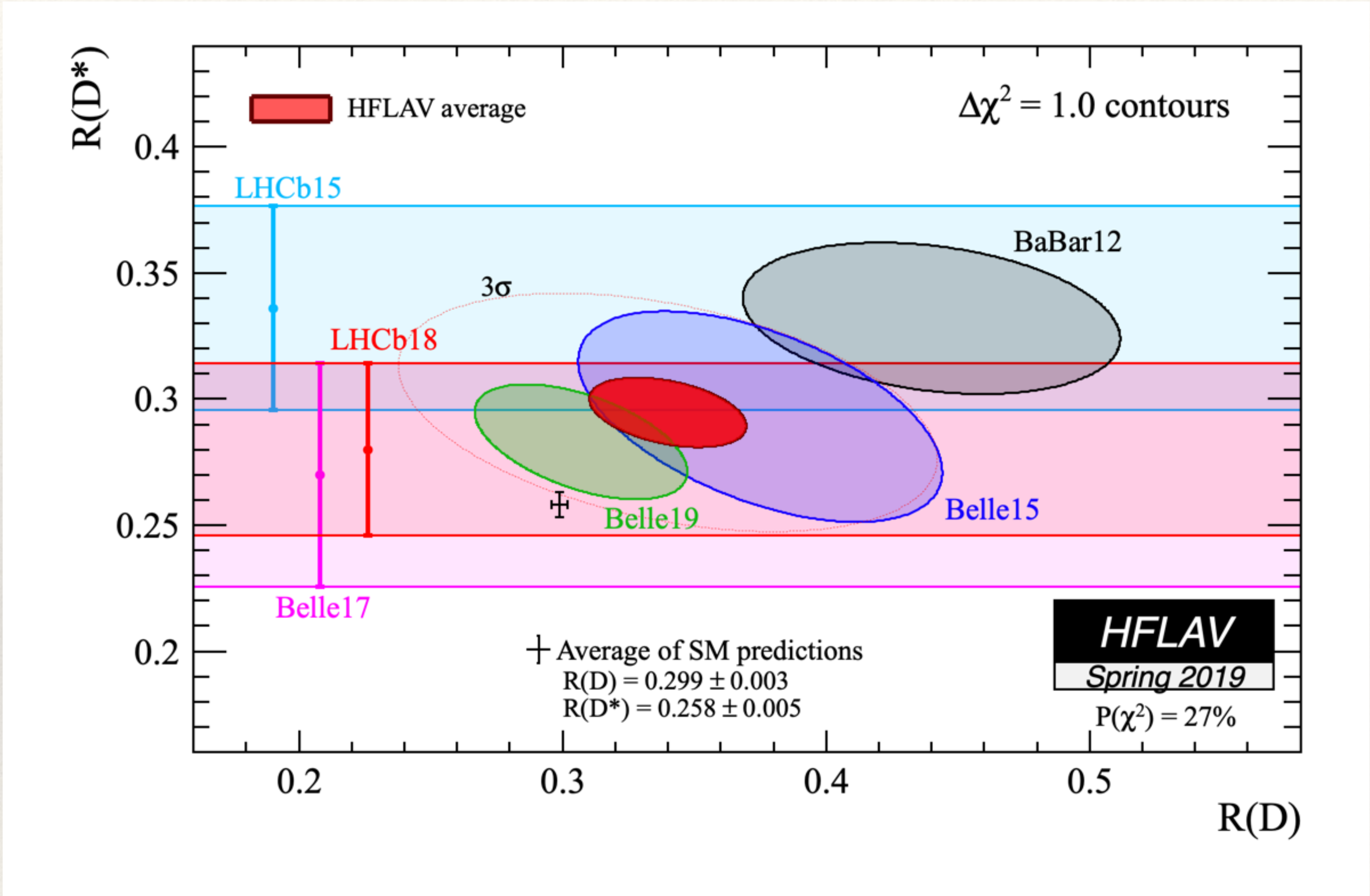
Recent update from Belle (03/19)



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

(1.2σ)

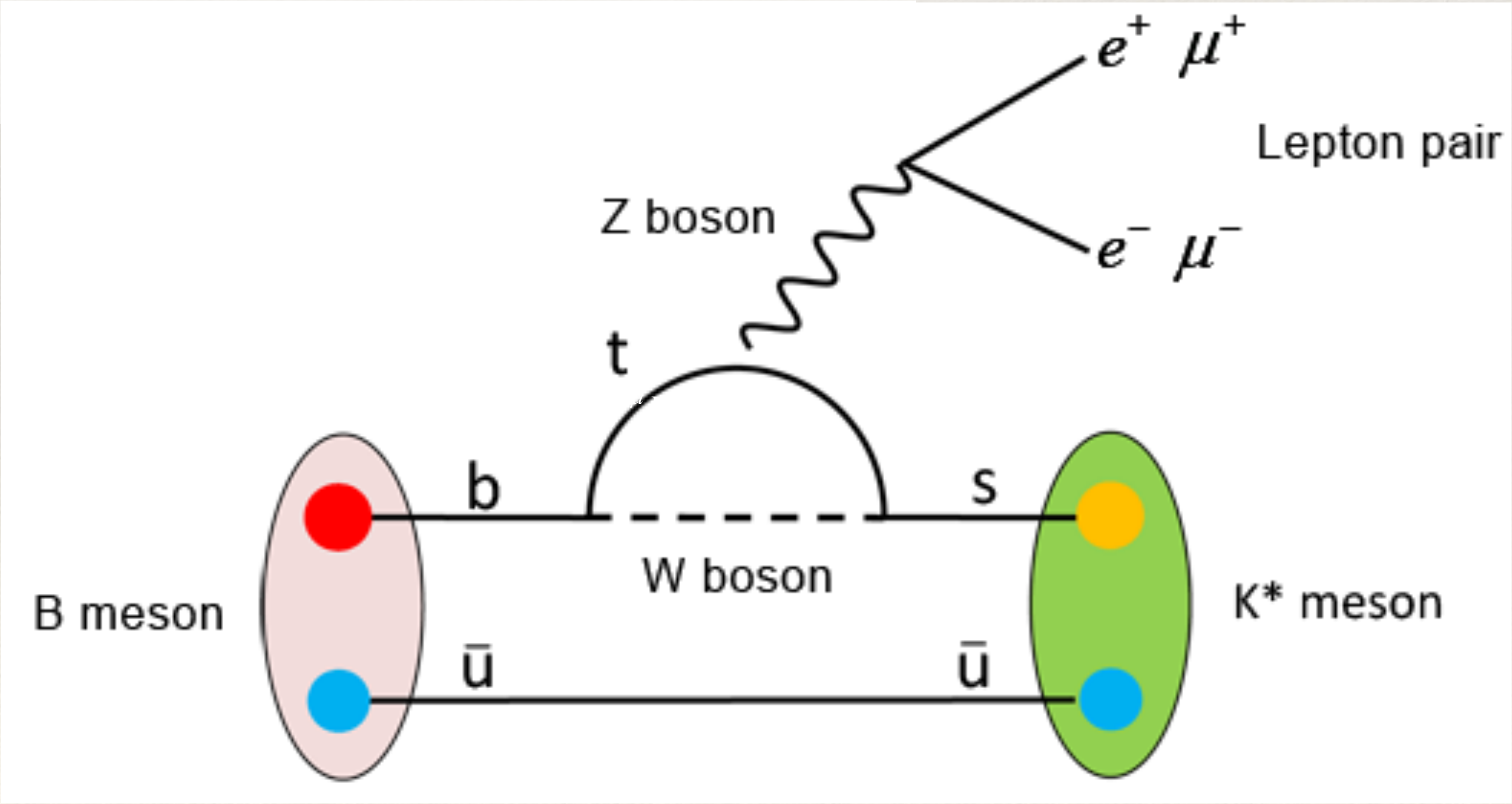
Recent update from Belle (03/19)



Significance reduced from 3.8 to 3.1σ 🙁

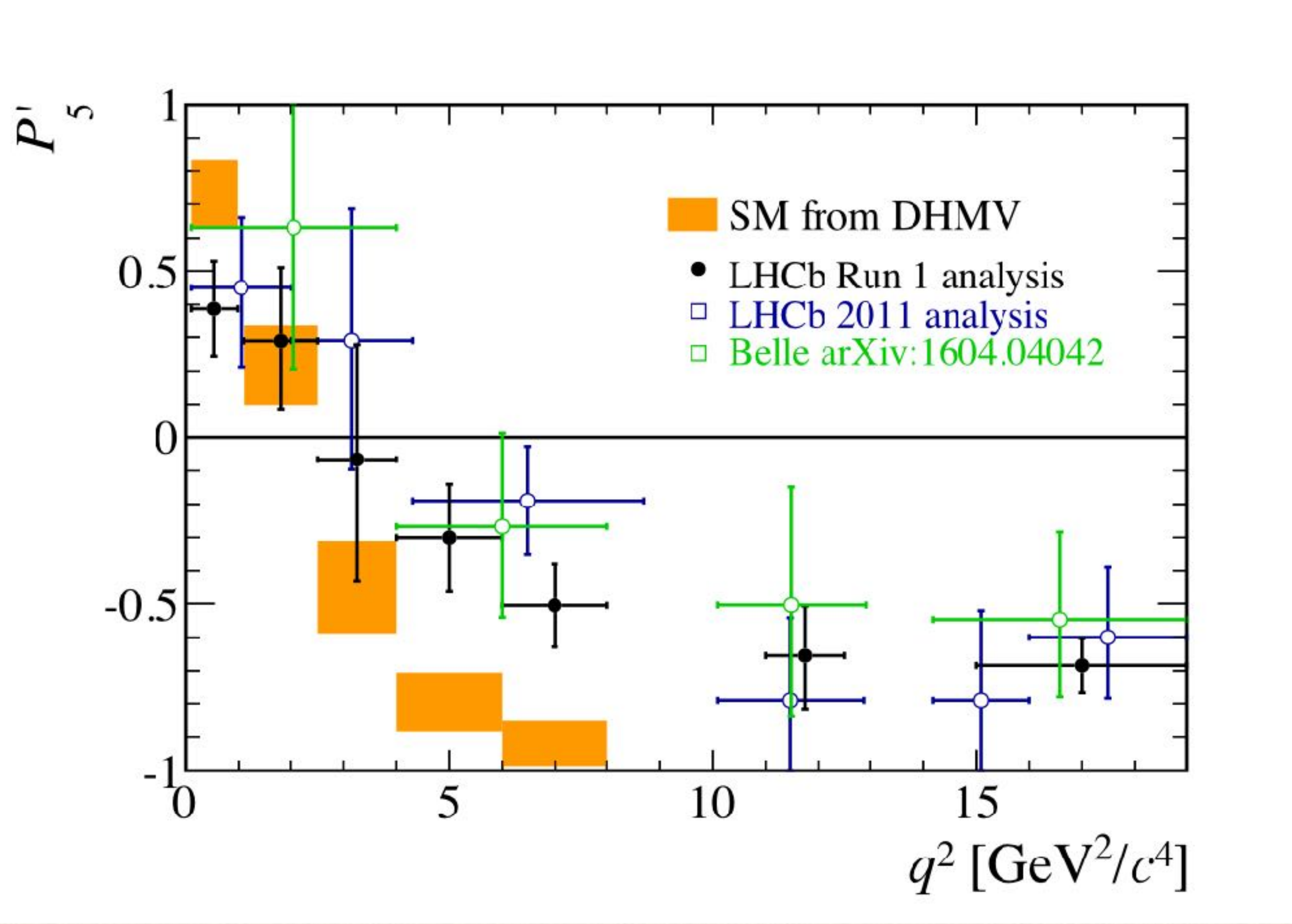
Flavor anomalies: P_5' etc.

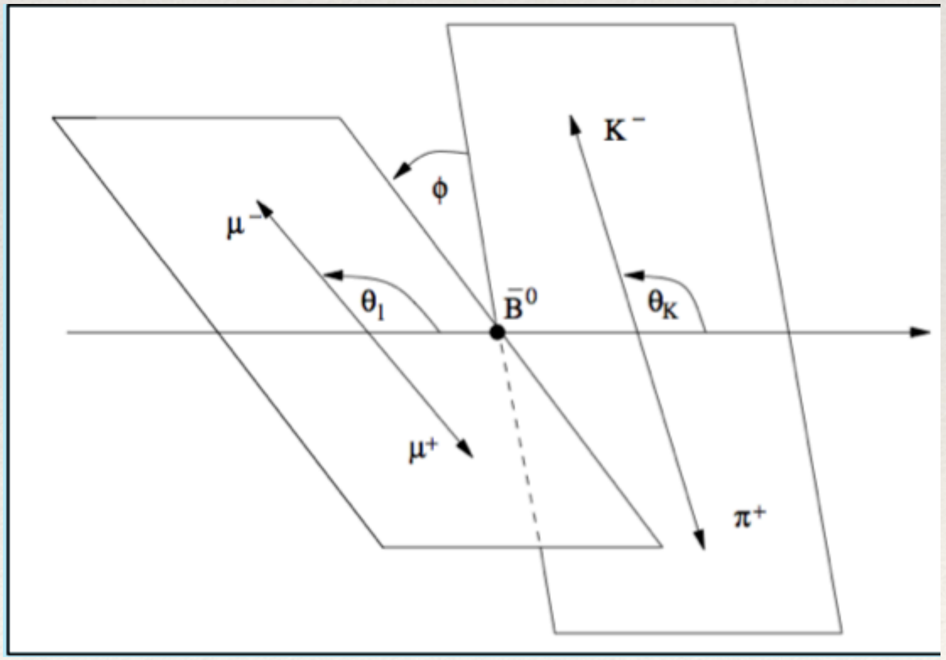
- Various hints of new physics in decays $\bar{B} \to K^* \ell^+ \ell^-$
- Being rare, loop-mediated FCNC processes, these are prime observables to probe BSM effects



Flavor anomalies: P_5' etc.

- Several angular observables measured as functions of q^2
- Some, like P_5', are optimized to be insensitive to hadronic uncertainties: [Descotes-Genon, Matias, Ramon, Virto 2012]





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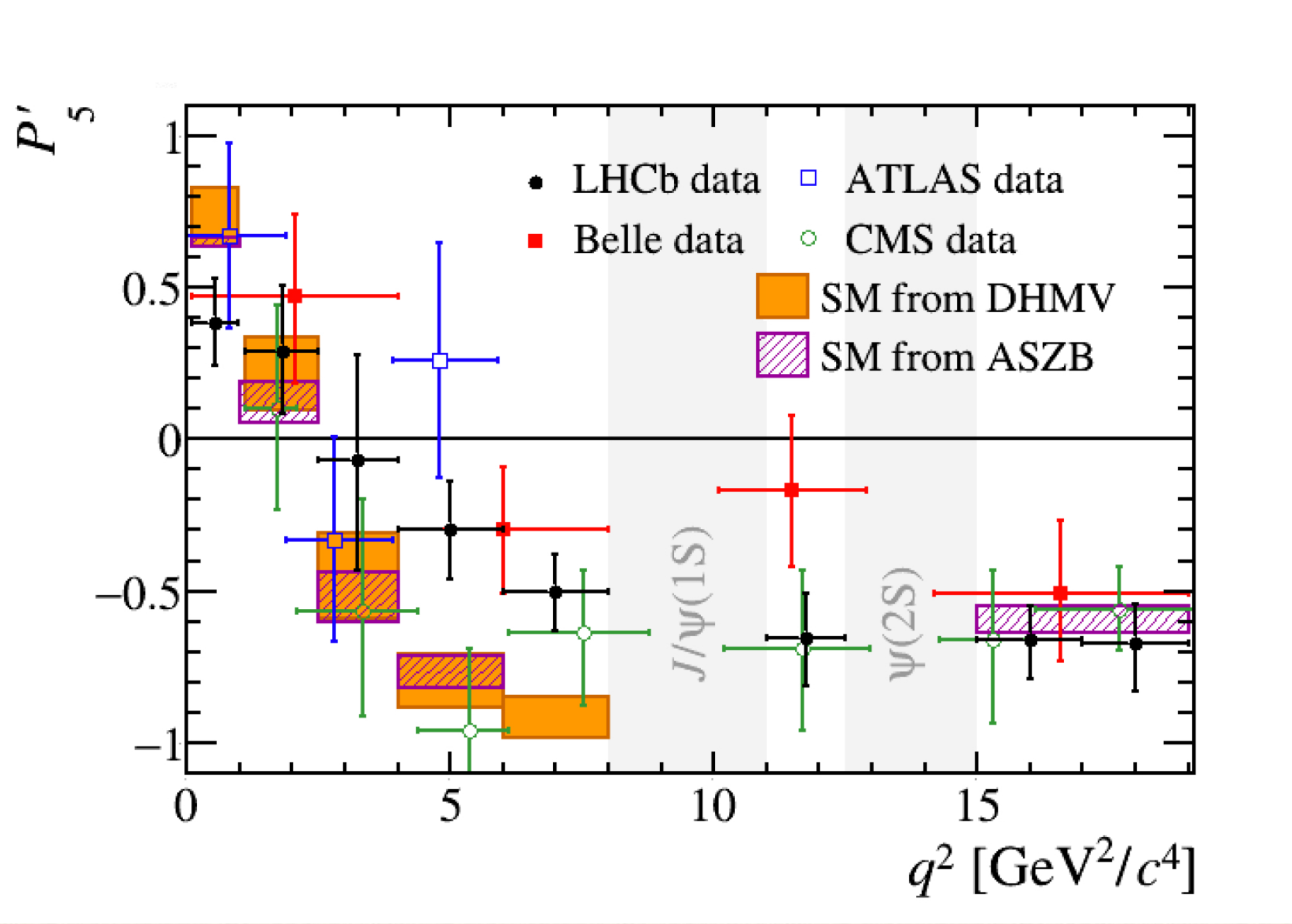
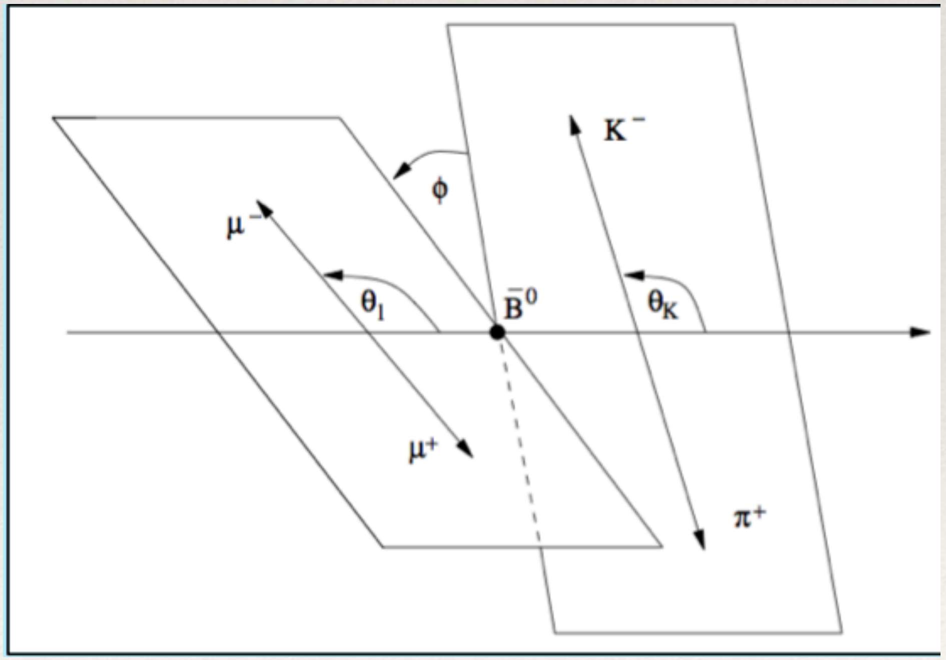




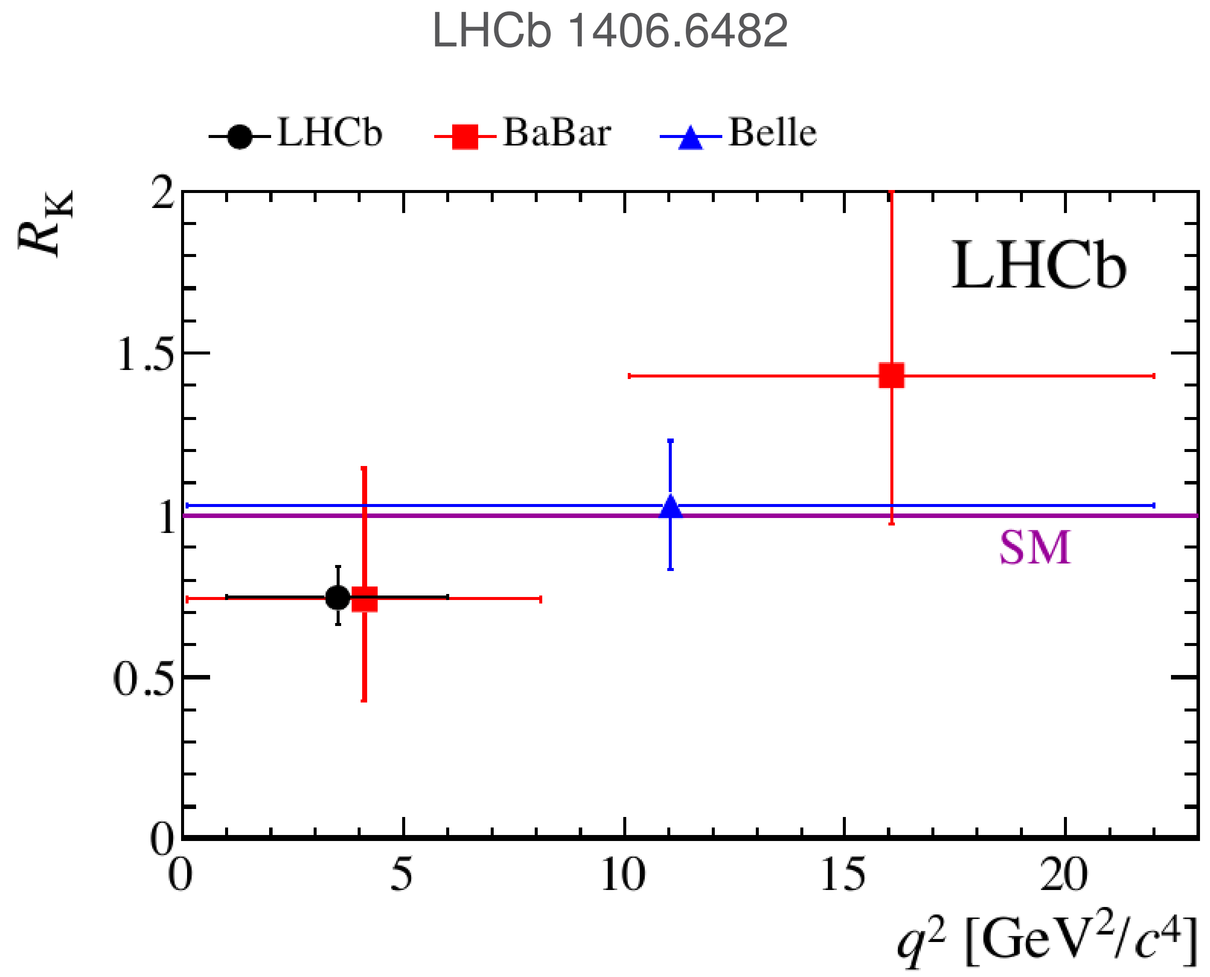
Flavor anomalies: R_K & R_{K^*}

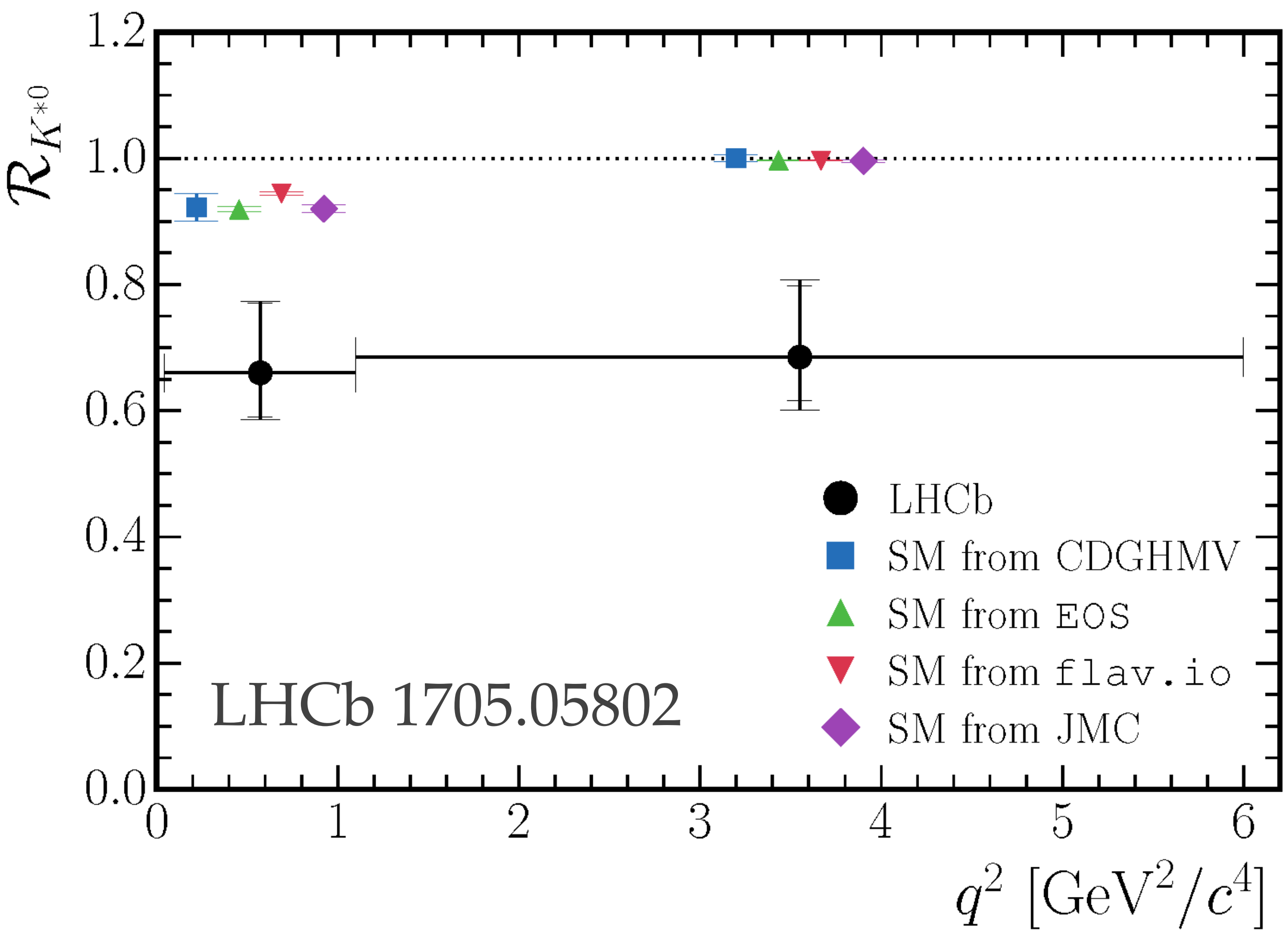
- Some scenarios explaining the anomalies in angular observables predicted a departure from unity in the ratios: [Altmannshofer, Gori, Pospelov, Yavin 2014]

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)} e^+ e^-)}$$

- Quite spectacularly, such deviations were later observed at LHCb!

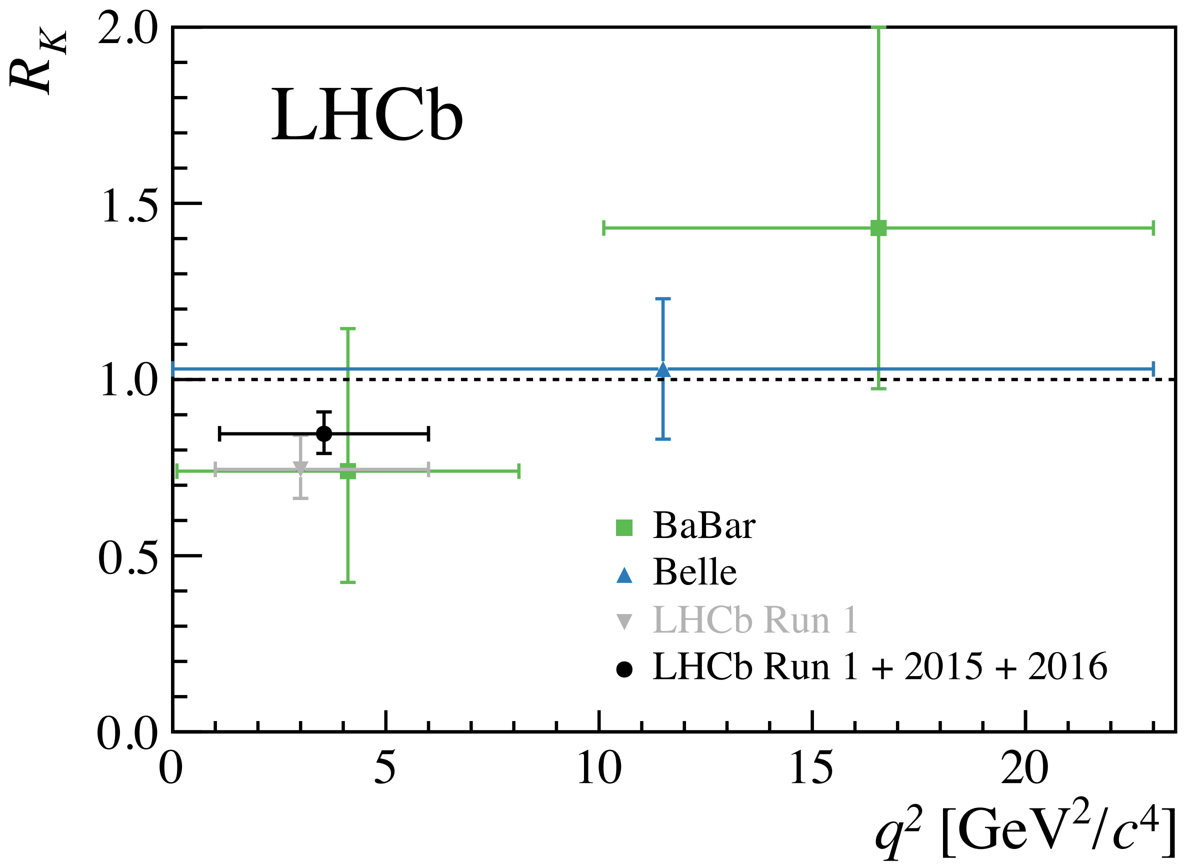
Flavor anomalies: R_K & R_{K^*}





$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)} e^+ e^-)}$$

Recent update on R_K (03/19)



R_K result with 2011 to 2016 data

Using 2011 and 2012 LHCb data, R_K was:

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

Adding 2015 and 2016 data, R_K becomes:

$$\boldsymbol{R_K = 0.846\,^{+0.060}_{-0.054}(\text{stat.})\,^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **2.5 σ** from SM.

If instead the Run 1 and Run 2 were fitted separately:

$$R^{\text{new}}_{K\ \text{Run 1}} = 0.717^{+0.083\,+0.017}_{-0.071\,-0.016}, \qquad R_{K\ \text{Run 2}} = 0.928^{+0.089\,+0.020}_{-0.076\,-0.017},$$

$$R^{\text{old}}_{K\ \text{Run 1}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{(PRL113(2014)151601)},$$

Compatibility taking correlations into account:

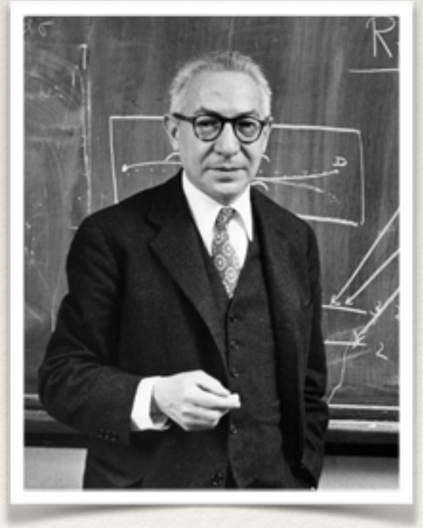
- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\,\sigma$;
- Run 1 result vs. Run 2 result: $1.9\,\sigma$.

B-flavor anomalies: Analysis

- Lots of reasons to be excited!
  - Two different sets of anomalies of very different taste
  - Several seen by more than one experiment
  - In case of $b \to s\ell^+\ell^-$ several observables deviate from SM predictions, and deviations appear to fit a simple pattern
- All combined, the most compelling hints for physics beyond the SM we have seen so far

Who ordered that?

- Unexpectedly large new-physics effect!
- No apparent connection to big questions of our field!
- Is it good for something else?



(I.I. Rabi)

Model-independent analyses

- Effective weak Hamiltonian for $b \to s\ell^+\ell^-$ transitions, including both SM and NP effects:

$$\mathcal{H}_{\rm eff}^{\rm NP} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} (C_i^\ell O_i^\ell + C_i'^{\,\ell} O_i'^{\,\ell}) + \text{h.c.}$$

with:

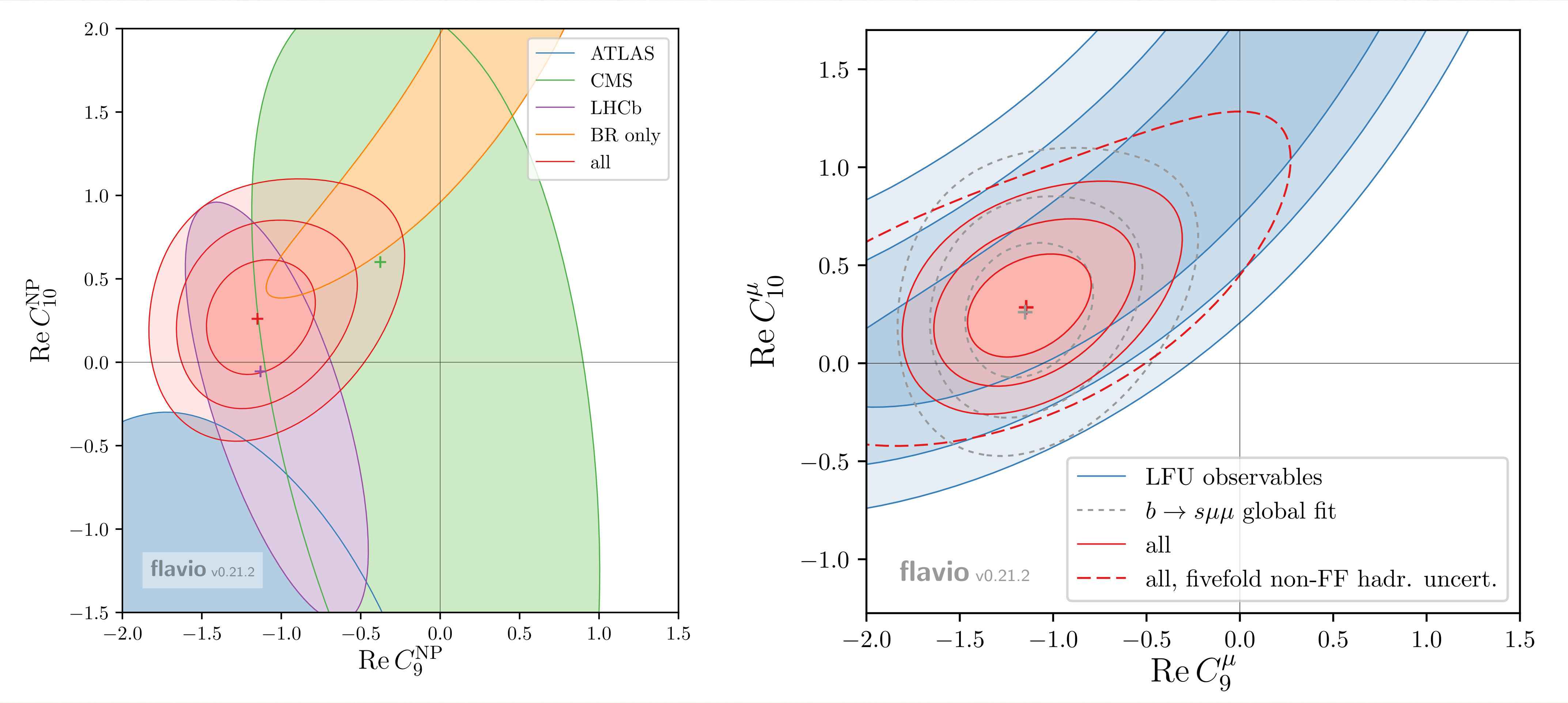
$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{\,\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{\,\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Excellent fits obtained with only two NP contributions!

- Analogous Hamiltonian can be written for $b \to c\,\ell^-\bar{\nu}$

Model-independent analyses

- Global fits to data assuming NP for muons only, e.g.:

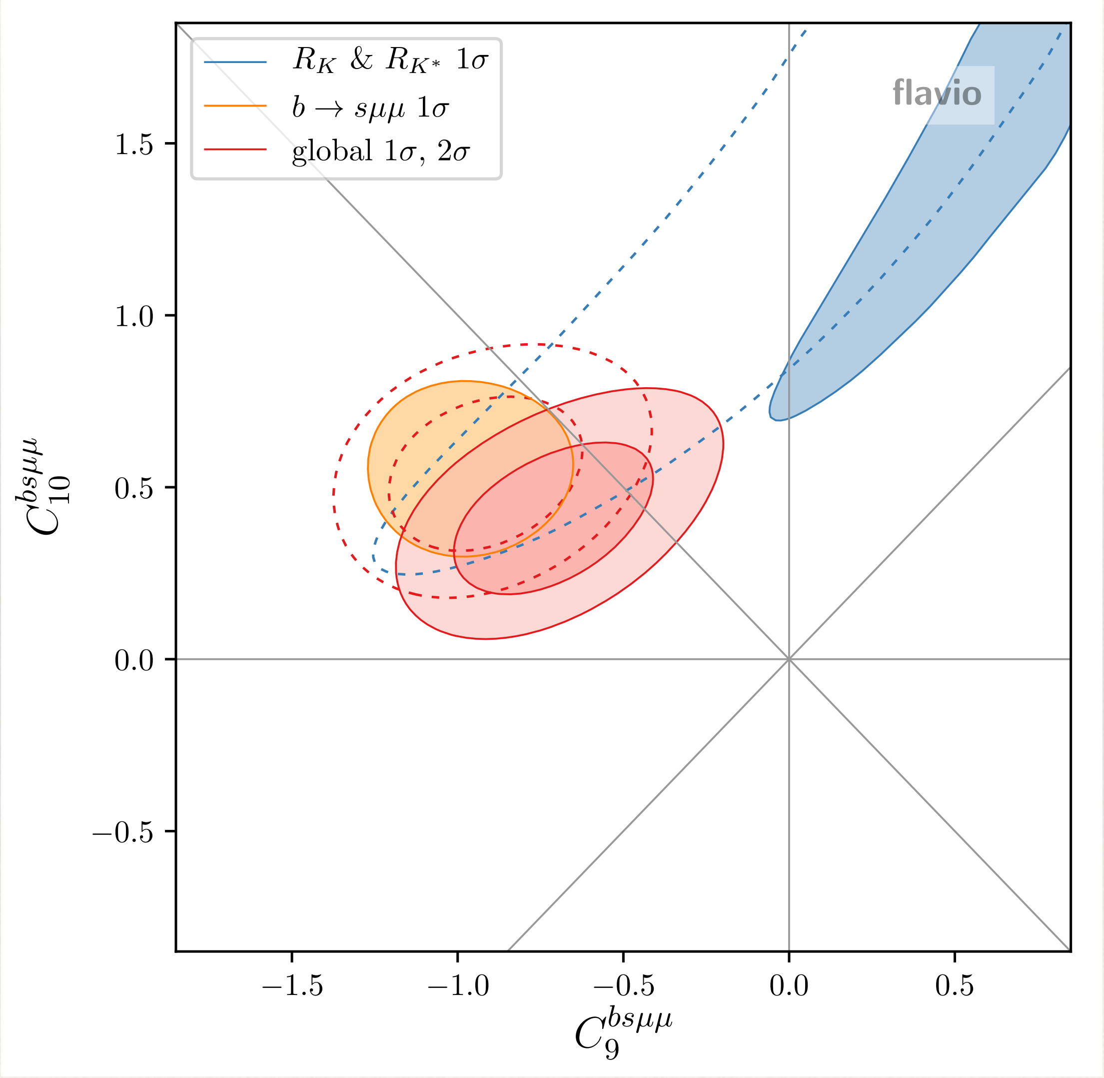


[Altmannshofer, Nies, Stangl, Straub 2017]

[see also: Capdevila, Crivelin, Descotes-Genon, Matias, Virto 2017; Hurth, Mahmoudi, Neshatpour 2016; Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli 2017; …]

Model-independent analyses

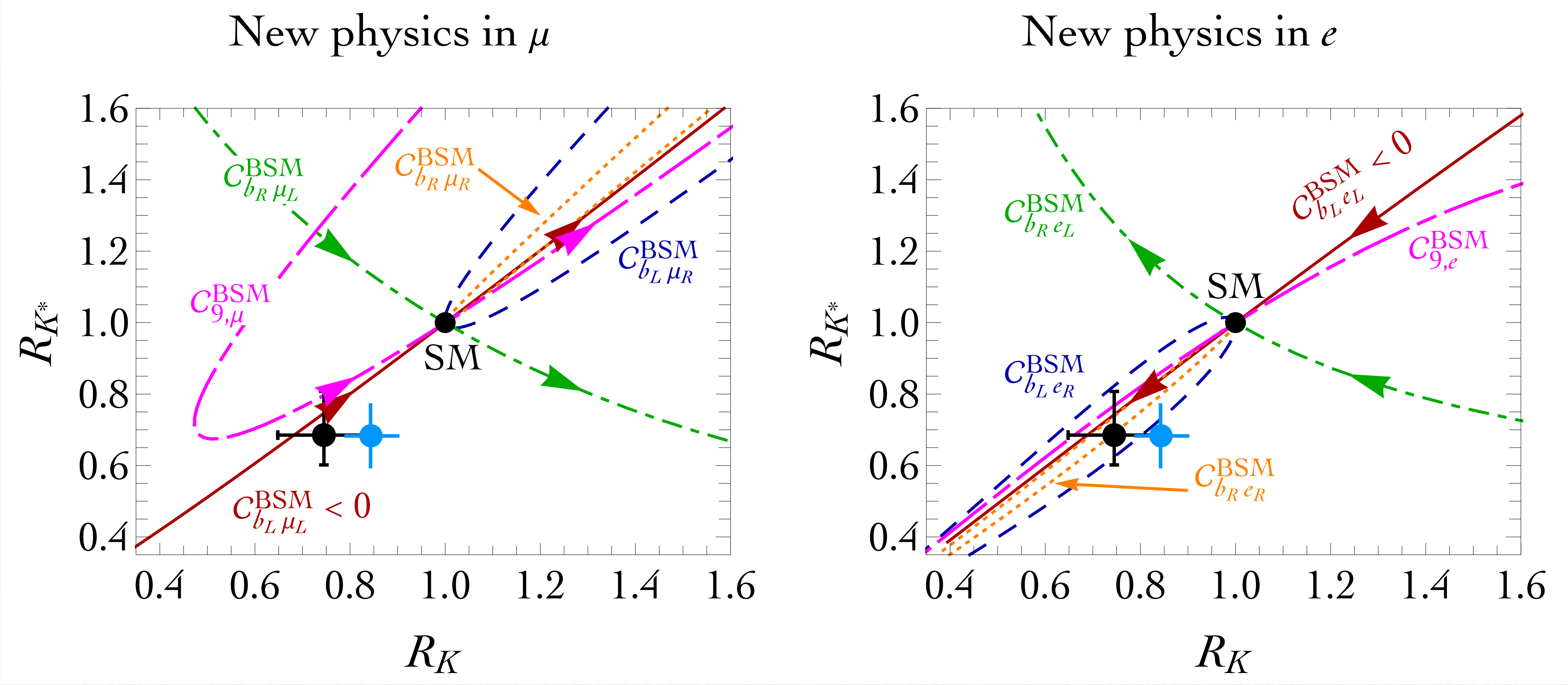
- Changes due to new R_K result are moderate:



Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub 1903.10434

Model-independent analyses

- Discriminating power of R_K and R_{K^*}:



[D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 2017; Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi 2017]

Model building

- Several (but not all) models aim at explaining all anomalies, sometimes along with $(g\text{-}2)_\mu$ (optimistic 😊)

  [Bhattacharya, Datta, London, Shivashankara 2014; Alonso, Grinstein, Martin Camalich 2015; Greljo, Isidori, Marzocca 2015; Calibbi, Crivellin, Ota 2015; Bauer, MN 2015; Fajfer, Kosnik 2915; Barbieri, Isidori 2015; Das, Hati, Kumar, Mahajan 2016; Boucenna, Celis, Fuentes-Martin, Vicente, Virto 2016; Becirevic, Kosnik, Sumensari, Zukanovich Funchal 2016; Becirevic, Fajfer, Kosnic, Sumensari 2016; Hiller, Loose, Schoenwald 2016; Bhattacharya, Datta, Guevin, London, Watanabe 2016; Buttazzo, Greljo, Isidori, Marzocca 2016; Barbieri, Murphy, Senia 2016; Bordone, Isidori, Trifinopoulos 2017; Crivellin, Müller, Ota 2017; Megias, Quiros, Salas 2017; Cai, Gargalionis, Schmidt, Volkas 2017; …]

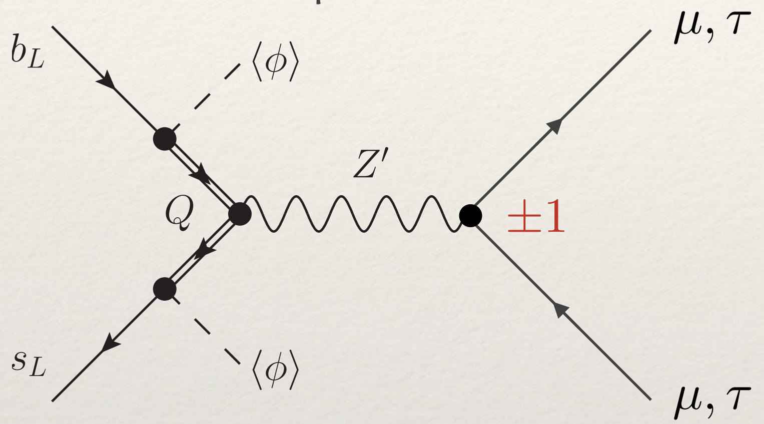
- R_D and R_{D^*} require tree-level NP near TeV scale

- Rare decays $b \to s\ell^+\ell^-$ (R_K, R_{K^*}, P_5', …) require suppressed NP contributions

- If common origin: suppression either dynamically or by means of a symmetry

Model building

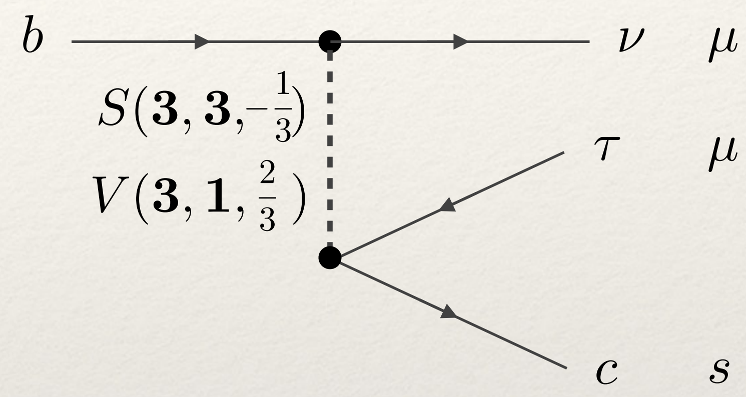
- New colorless bosons, e.g. Z′ coupled to (L_μ-L_τ):



[Altmannshofer, Gori, Pospelov, Yavin 2014]

  - Z′ mass in low TeV range, heavy vector-like quarks ~ tens of TeV
  - Can explain P_5' and predicted LFU violation in R_K and R_{K^*}
  - But tree-level contribution to B-meson mixing is problematic

- Scalar / vector leptoquarks, e.g.:

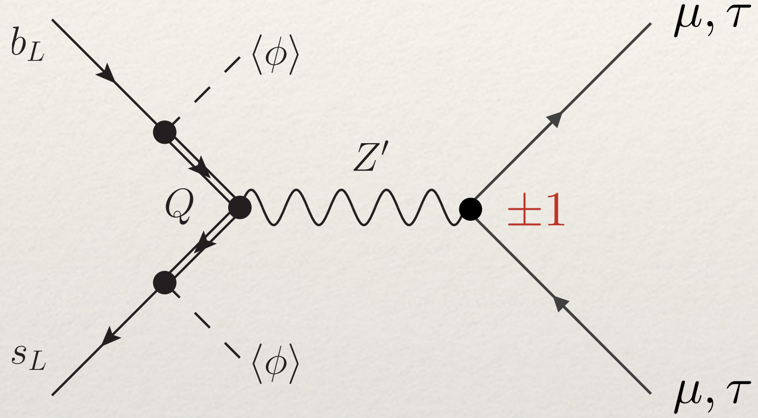


[Hiller, Schmaltz 2014; Alonso, Grinstein, Martin Camalich 2015; Freytsis, Ligeti, Ruderman 2015]

  - Can explain both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ at tree-level
  - Requires huge hierarchy in flavor couplings (flavor symmetry?)
  - Constraints from B mixing and $B \to K^{(*)} \nu\nu$, $B \to K^{(*)} \tau^+\tau^-$

Model building

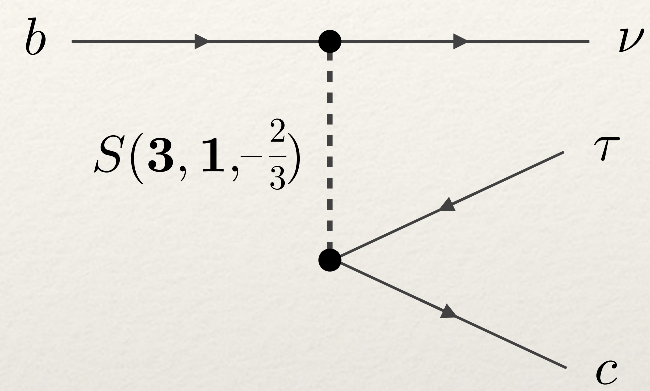
- New colorless bosons, e.g. Z′ coupled to (L_μ-L_τ):

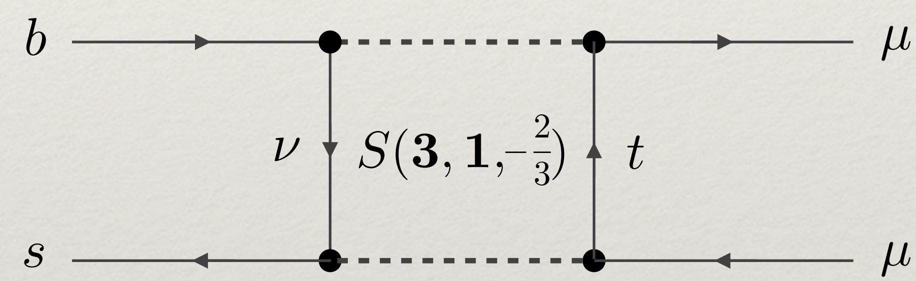


[Altmannshofer, Gori, Pospelov, Yavin 2014]

  - Z′ mass in low TeV range, heavy vector-like quarks ~ tens of TeV
  - Can explain P_5' and predicted LFU violation in R_K and R_{K^*}
  - But tree-level contribution to B-meson mixing is problematic

- Scalar SU(2)$_L$ singlet LQ ($\hat{=}\,\tilde{b}_R$):





[Bauer, MN 2015; Cai, Gargalionis, Schmidt, Volkas 2017]

  - Explains $R_{D^{(*)}}$ at tree-level but $R_{K^{(*)}}$ at one-loop level, like SM
  - CKM-like hierarchy in coupling parameters

Model building

- Interesting framework for addressing all anomalies: [Buttazzo, Greljo, Isidori, Marzocca 2017]
  - Assume that NP only couples to LHD quarks and leptons:

$$\mathcal{H}_{\rm NP} = \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

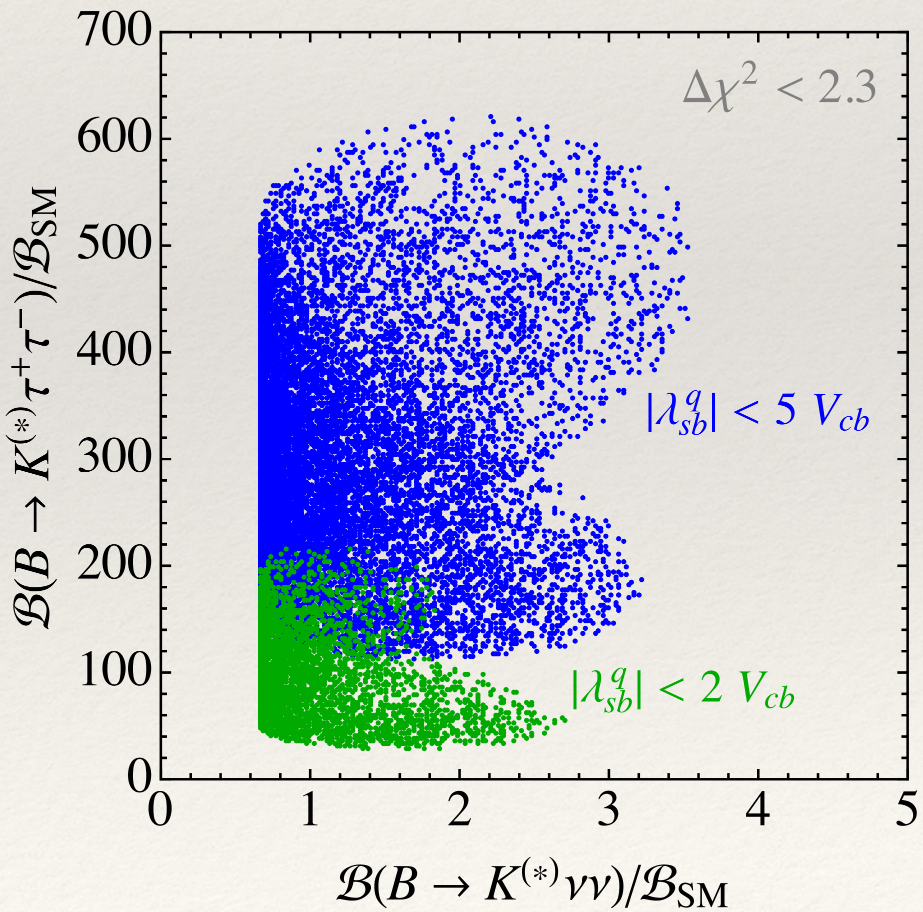
  - Hypothesis that NP couples primarily to 3rd generation fermions explains enhancement of $b\to c\tau\bar{\nu}$ over $b\to s\mu^+\mu^-$ and absence of anomalies in K, π, τ decays [Glashow, Guadagnoli, Lane 2014]
  - Impose flavor structure governed by minimally broken $U(2)_q$ x $U(2)_l$ flavor symmetry: [Barbieri, Isidori, Jones-Perez, Lodone, Straub 2011]

$$\lambda^q_{sb}\sim V_{cb}\,, \qquad \lambda^\ell_{\tau\mu}\sim V_{\tau\mu}\,, \qquad \lambda^\ell_{\mu\mu}\sim V^2_{\tau\mu}$$

Model building

- Besides flavor physics, additional constraints from precision measurements of τ decays and Z couplings, as well as $pp \to \tau^+\tau^- X$ [Faroughy, Greljo, Kamenik 2016] [Feruglio, Paradisi, Pattori 2017]
- Smoking-gun signature: enhancement of $B \to K^{(*)}\tau^+\tau^-$ branching ratio by factor > 100

[Buttazzo, Greljo, Isidori, Marzocca 2017]



Emergence of a bigger picture?

- Required new particles in low TeV range, precisely where we (now) expect a solution to the hierarchy problem!
- Leptoquarks can arise from GUTs, neutrino mass models, SUSY models, or as pNGBs [Popov, White 2016]
- E.g.: Composite Higgs models with partial fermion compositeness: [Buttazzo, Greljo, Isidori, Marzocca 2016; Barbieri, Murphy, Senia 2016; …]
  - Address hierarchy and flavor problems at ~10 TeV, light scalar leptoquarks (~ TeV) as pNGBs
  - Interesting challenges for model building!

Emergence of a bigger picture?

- Data may teach us an important lesson:
  - Complementarity of different fields (flavor was sometimes considered irrelevant in the LHC era …)
  - Intimate connection between flavor and high-p_T physics!
- Imagine the LHC legacy:
  - Discovery of the Higgs boson (2012)
  - Discovery of lepton-flavor non-universality (2020)
  - Discovery of predicted leptoquarks / colorless bosons (202?)
  - Embedding in a consistent theory of flavor and EWSB (20??)

Conclusions

- If confirmed, the B-meson flavor anomalies are the most important discovery in particle physics since discovery of the weak gauge bosons and the Higgs
  - Point to existence of new heavy particles in few-TeV range
  - Possibly, these might be connected to a fundamental theory of electroweak symmetry breaking and flavor
  - Strong physics case for future high-energy colliders
- Independent confirmation of the flavor anomalies by Belle II is as crucial as refining current LHCb analyses