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Status of the B-Meson Flavor Anomalies

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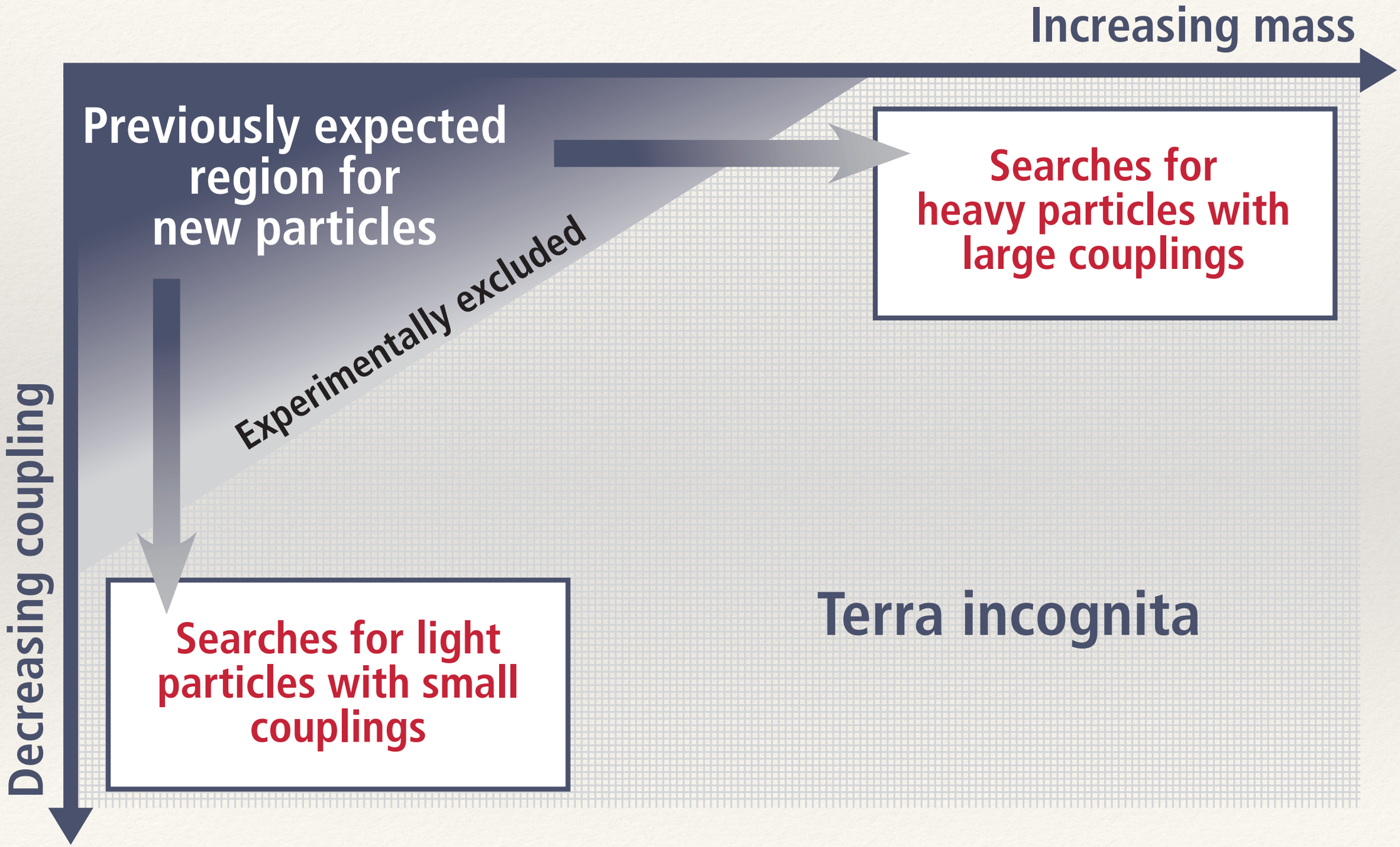
Tensions in the Standard Model?

- B-meson flavor anomalies:
  - Among the most interesting tensions we have in particle physics
  - Potential to revolutionize our field and help us to unravel the next layer of fundamental physics
  - … if present hints are confirmed by future data!

Beyond the SM



Beyond the SM

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

B-meson flavor anomalies

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

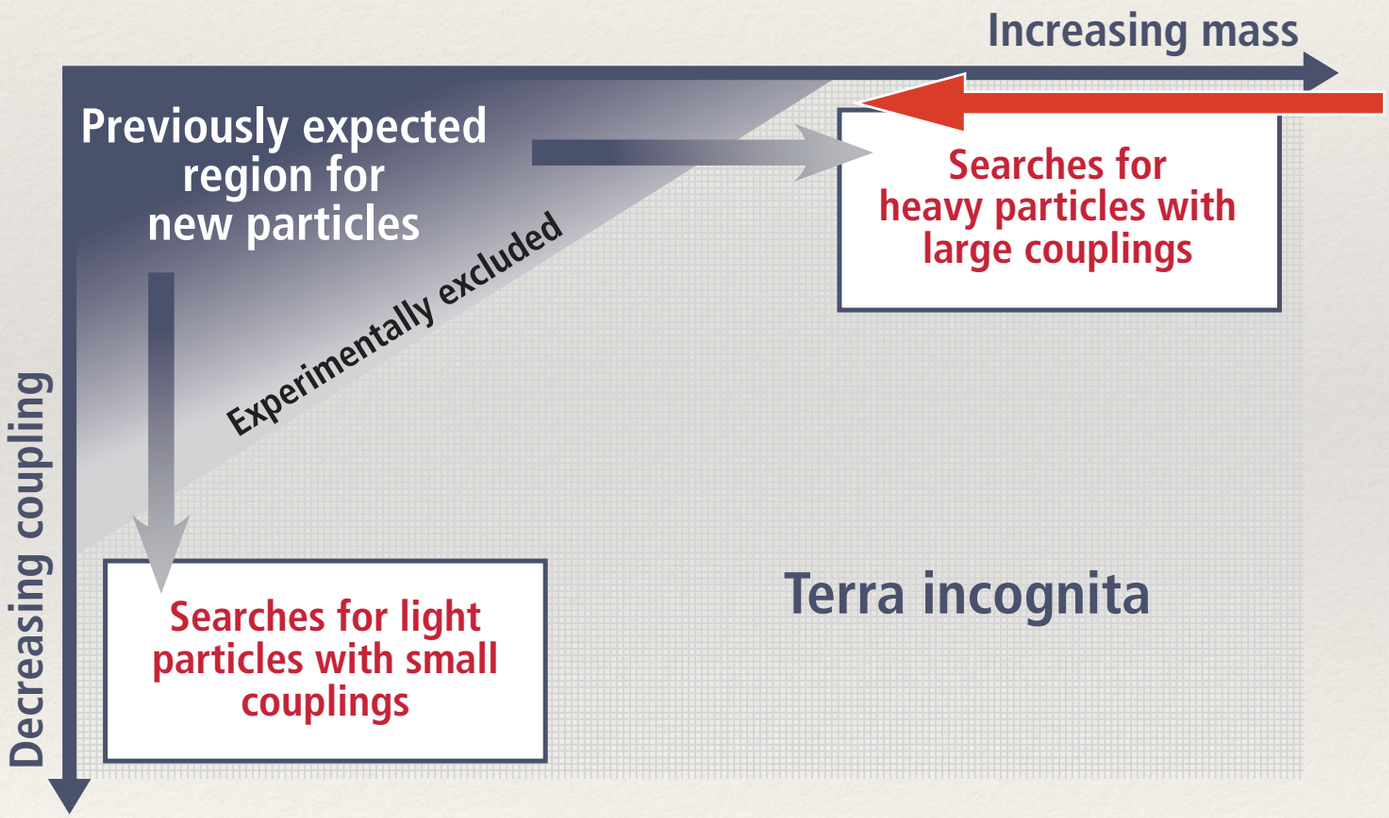
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$

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

- 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

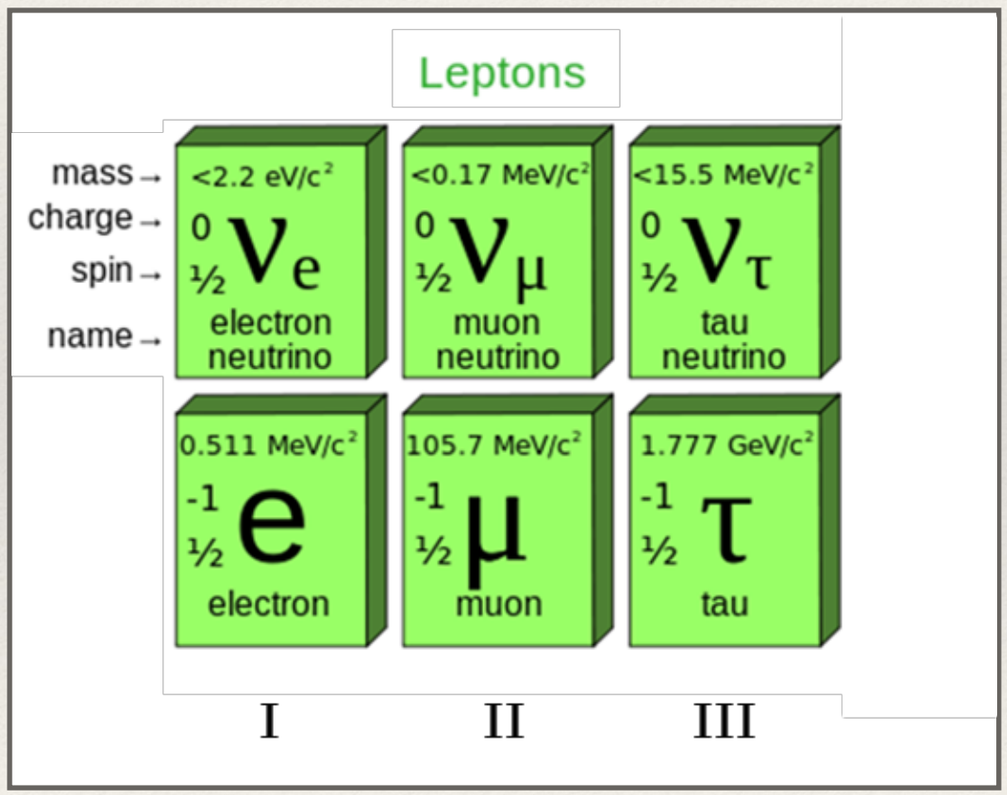
- … because they would give a clear target for future searches at energy frontier!



New physics cannot be too far from here!

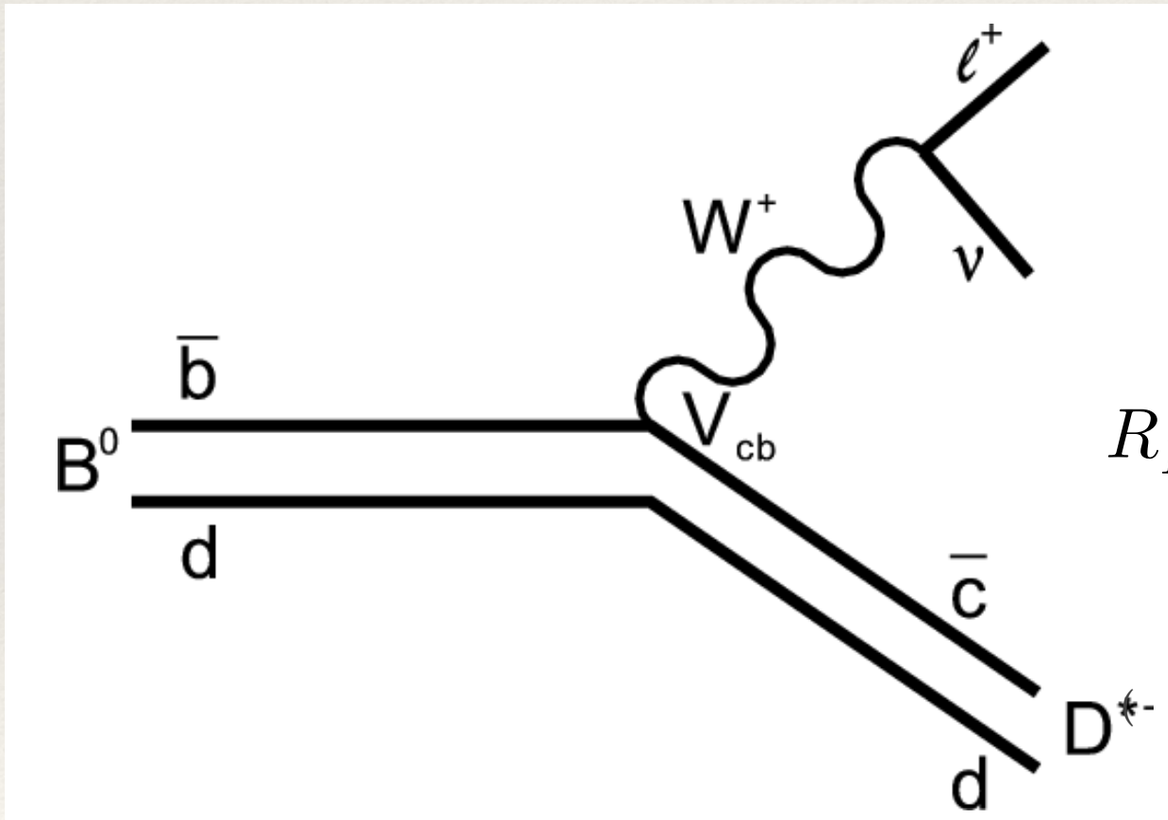
B-meson flavor anomalies:

Violations of lepton universality?



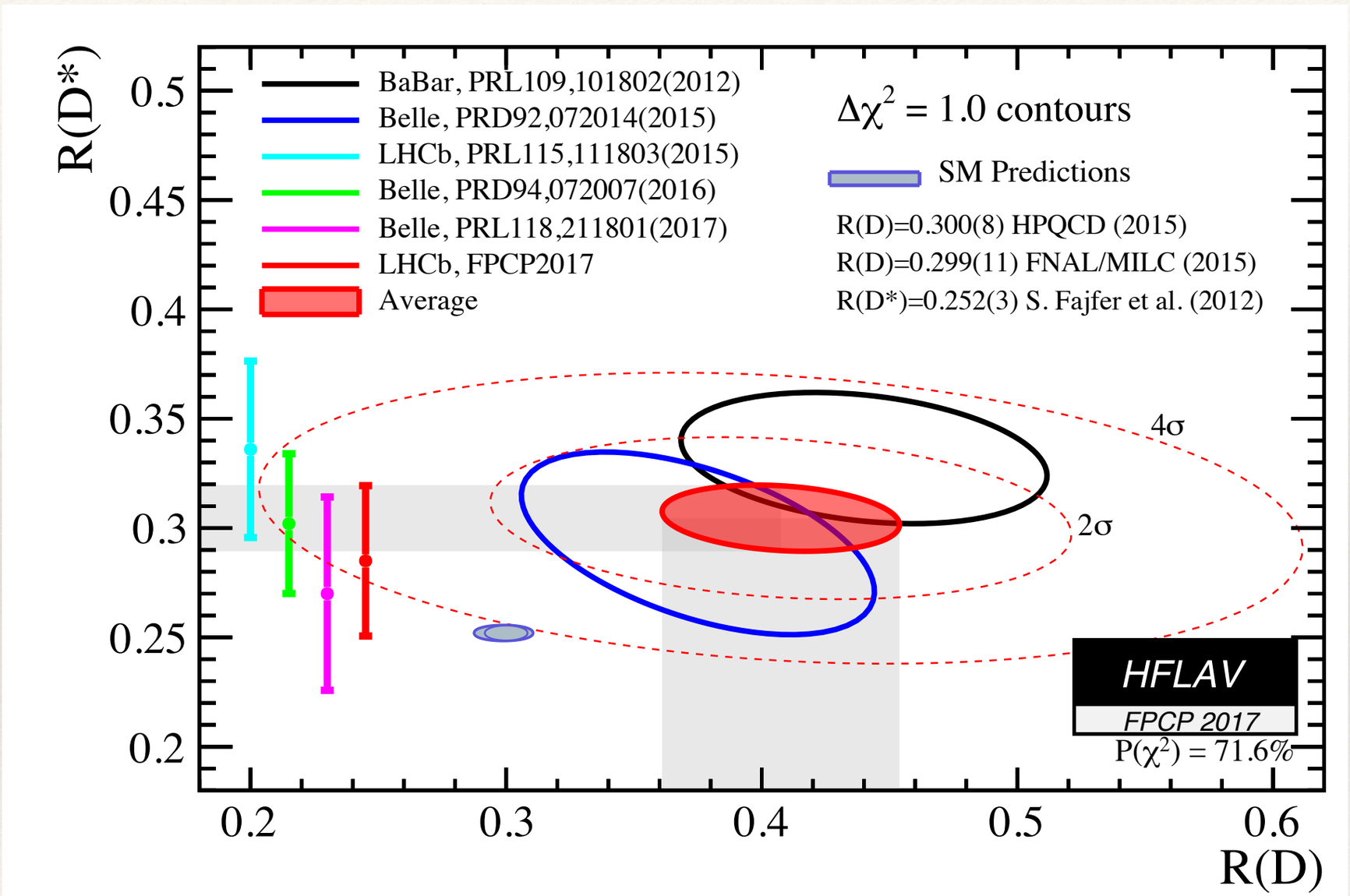
Flavor anomalies: R_D & R_{D^*}

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



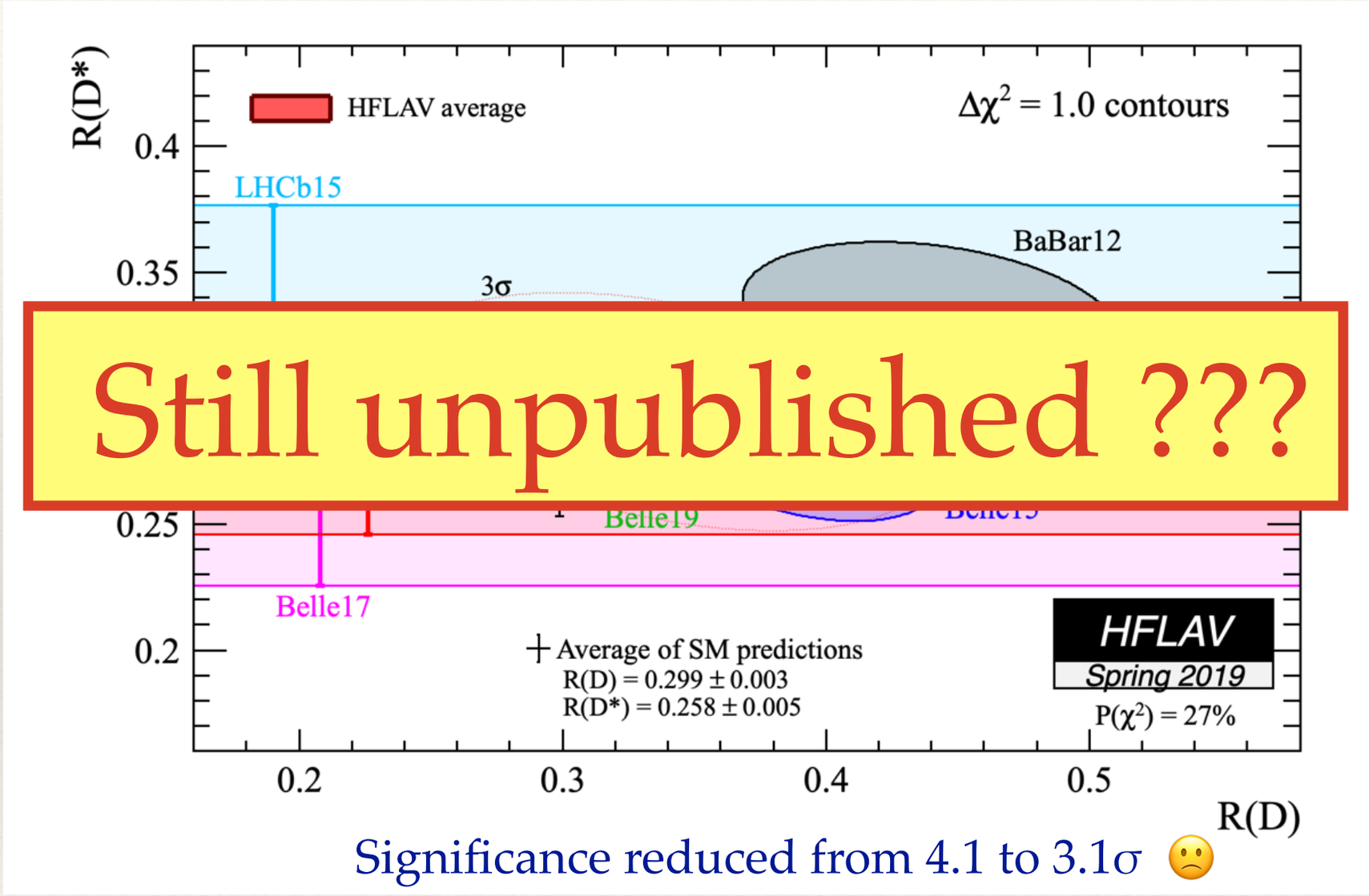
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$

Flavor anomalies: R_D & R_{D^*}



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

Recent update from Belle (03/19)



Still unpublished ???

Significance reduced from 4.1 to 3.1σ 😕

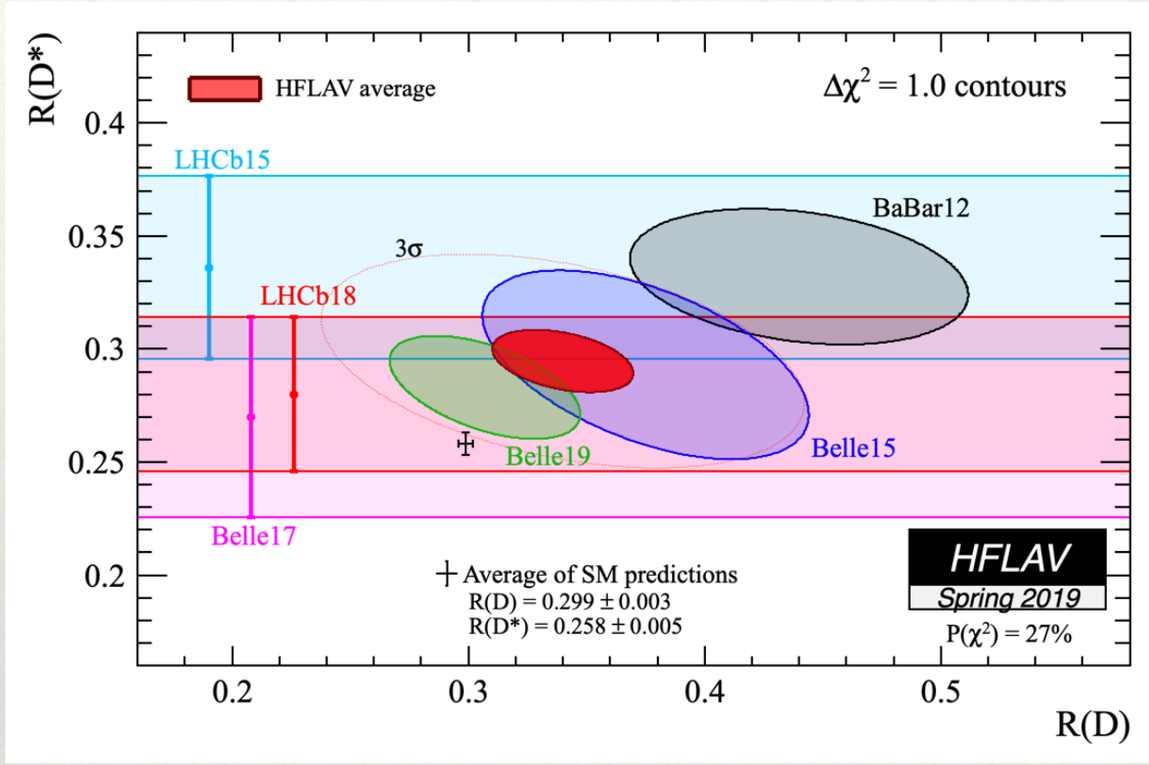
$$\begin{aligned}\mathcal{R}(D) &= 0.307 \pm 0.037 \pm 0.016 \\ \mathcal{R}(D^*) &= 0.283 \pm 0.018 \pm 0.014\end{aligned}$$

(Belle 2019: 1.2σ)

Flavor anomalies: R_D & R_{D^*}

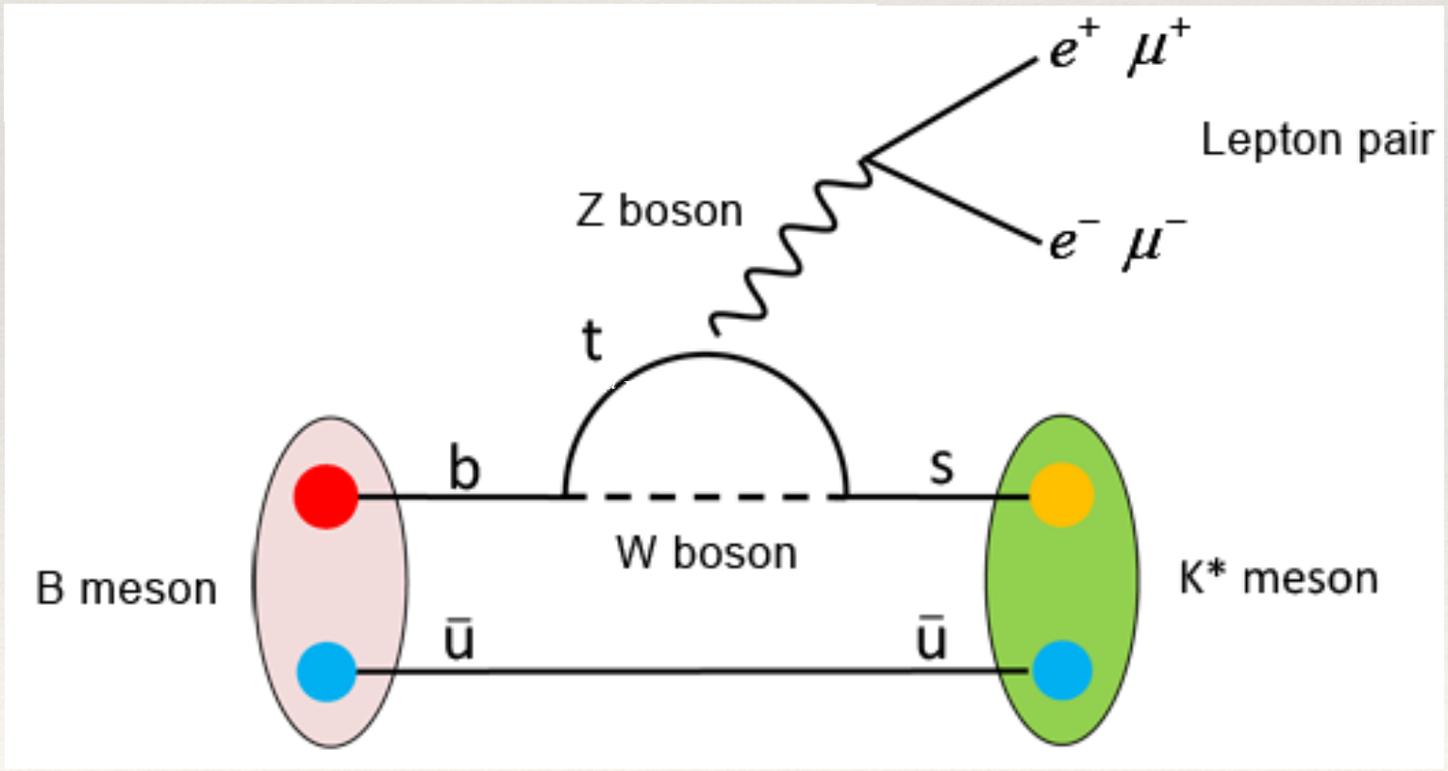
- New world average still shows a tension; hints at smaller new-physics effects
- May be good news, since effect was (and still is) in a way much too large
- Expect in case of tree-level new physics:

$$\frac{v^2}{\Lambda^2} \sim \text{at most few } \%$$



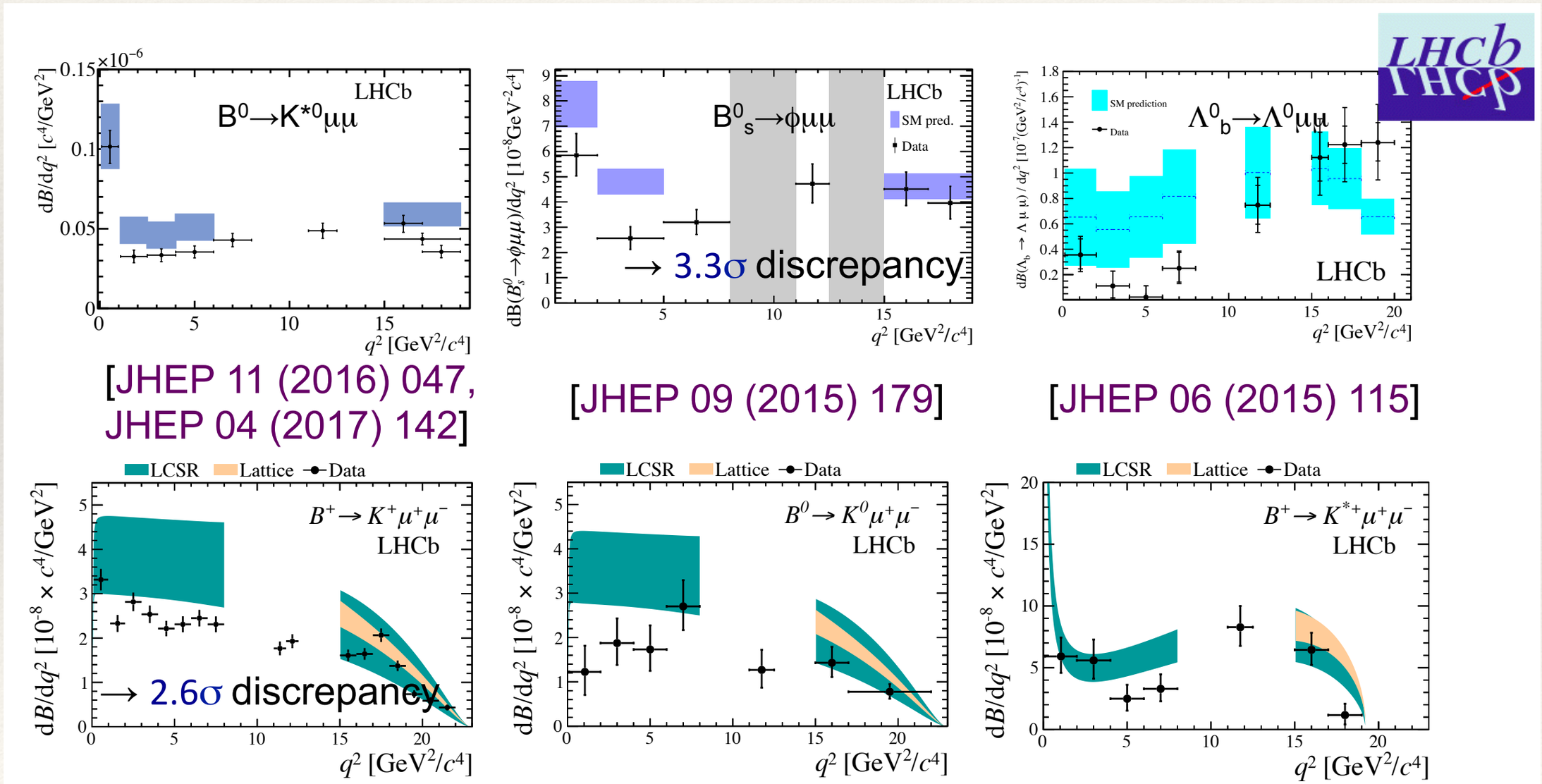
Flavor anomalies: P_5' & BRs

- 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



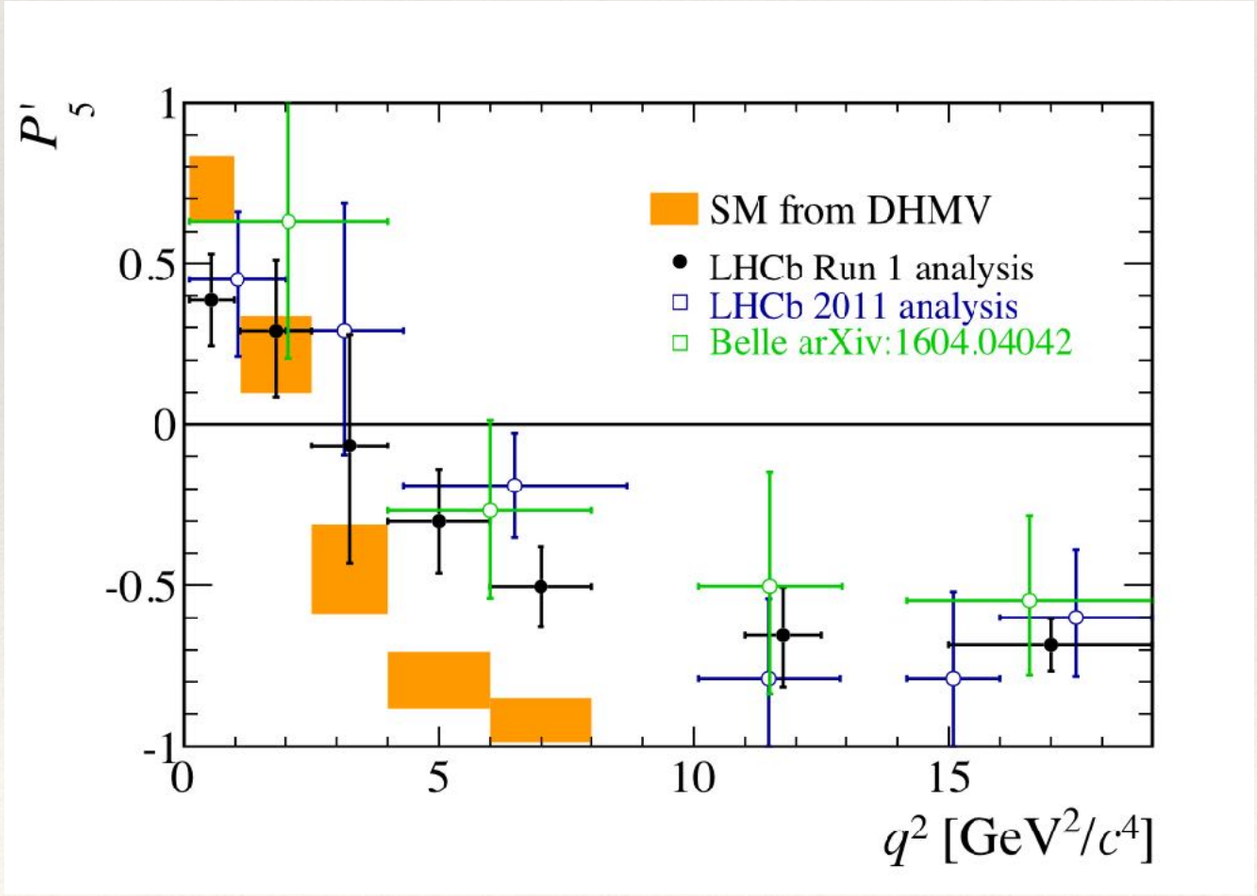
Flavor anomalies: P_5' & BRs

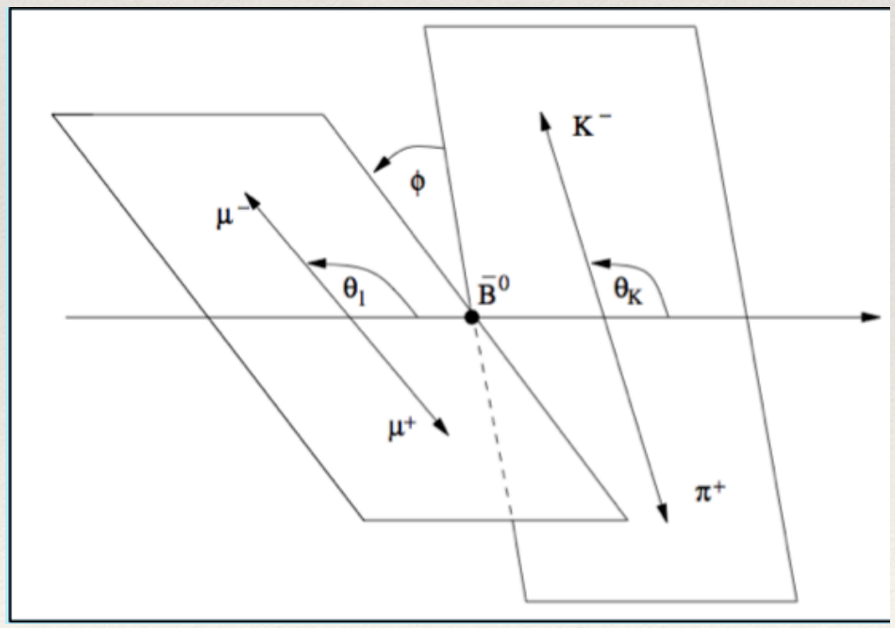
- Deficit in various branching ratios, e.g.:



Flavor anomalies: P_5' & BRs

- 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]





Flavor anomalies: R_K & R_{K^*}

- Some scenarios explaining these anomalies in angular observables predicted a departure from SM in ratios:

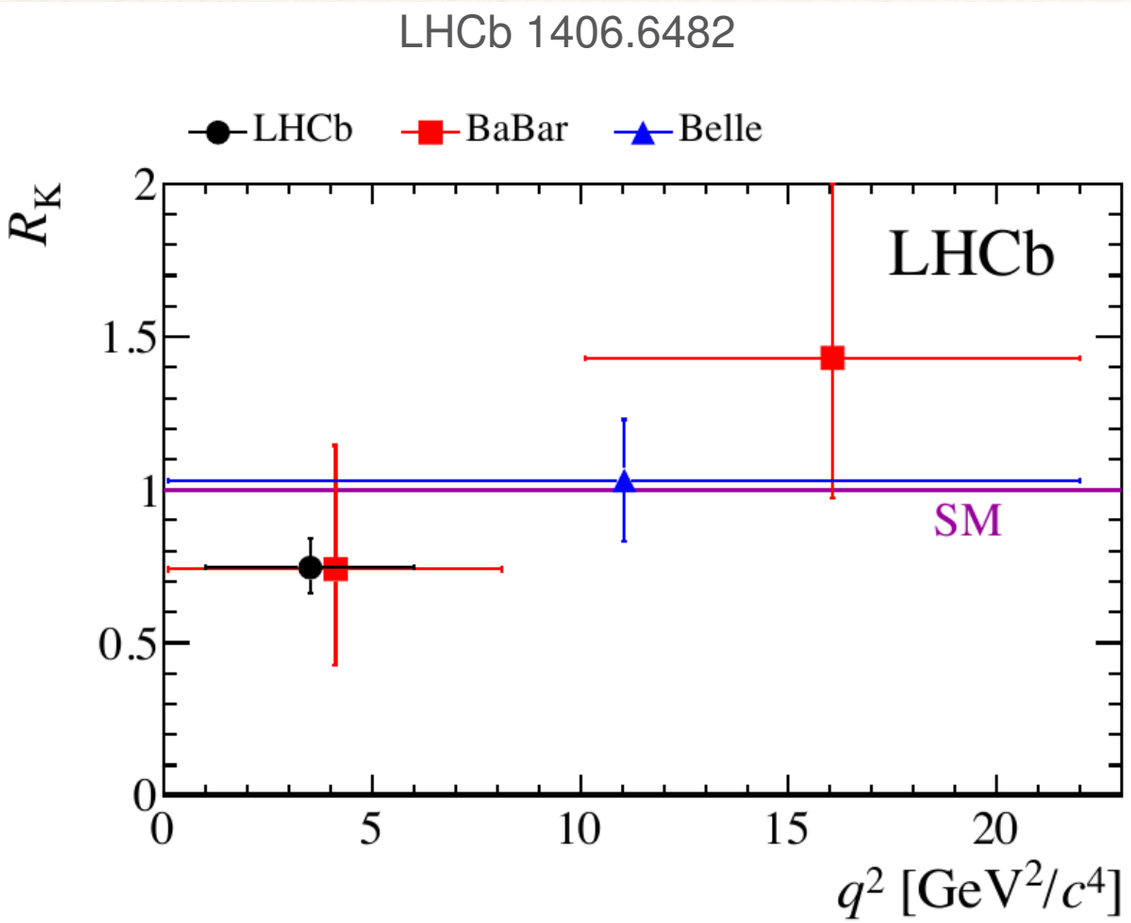
[Altmannshofer, Gori, Pospelov, Yavin 2014]

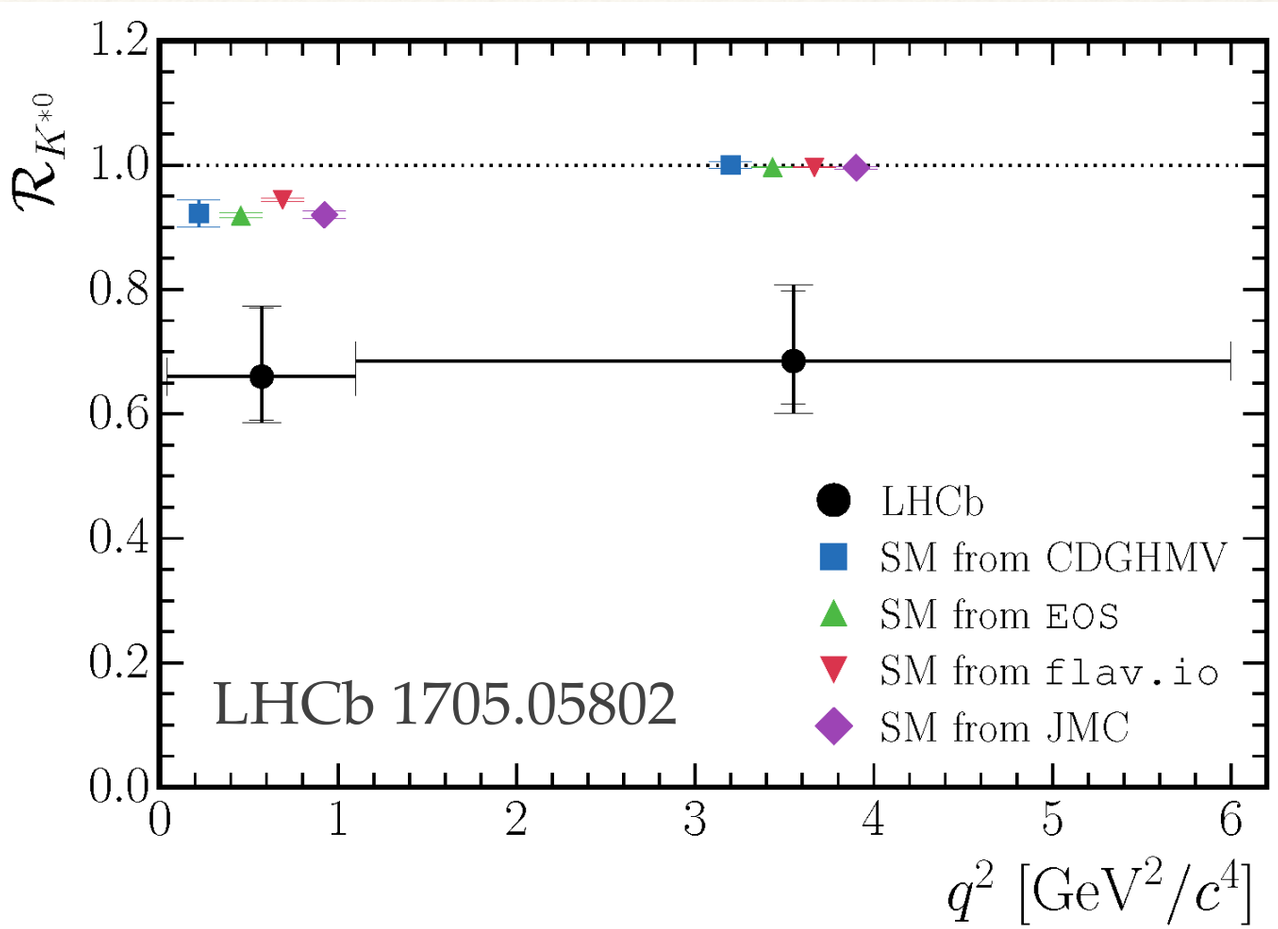
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)} e^+ e^-)}$$

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

- "Smoking gun" observables, but present hints below 3σ!

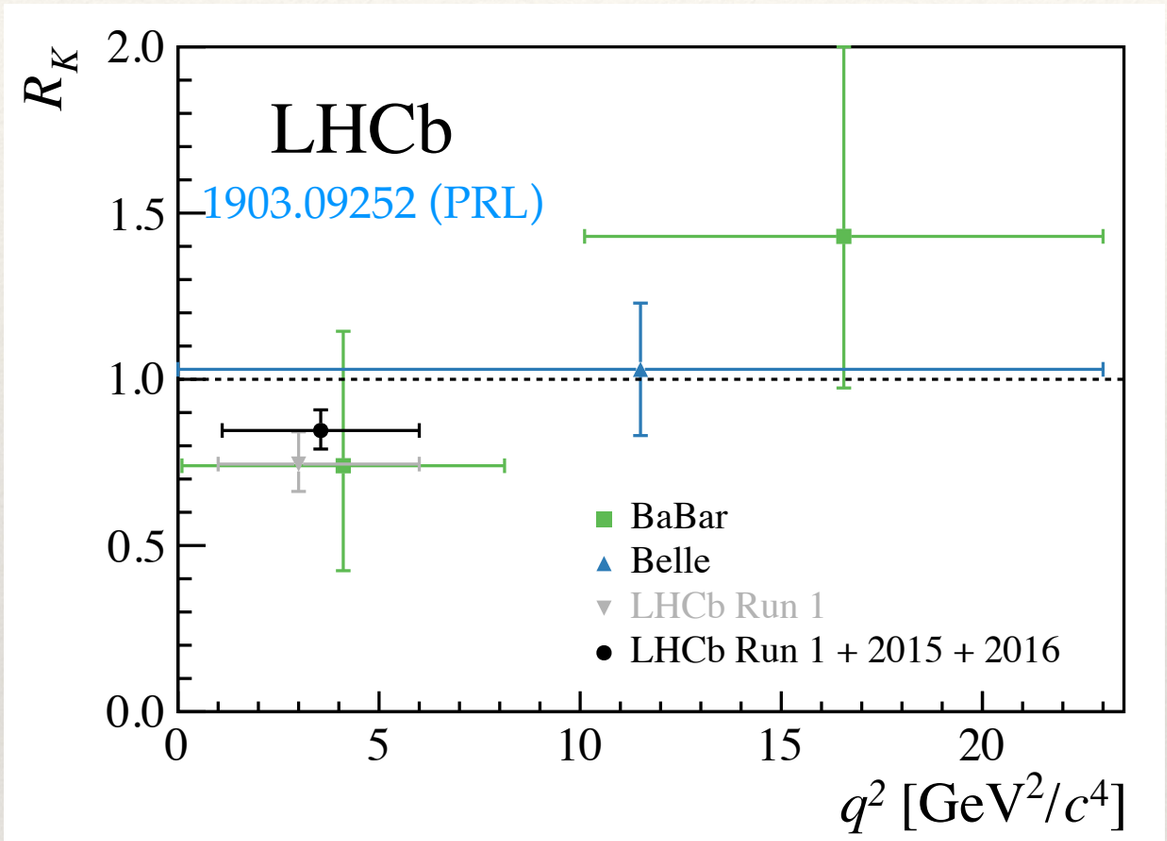
Flavor anomalies: R_K & R_{K^*}





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

Recent LHCb update on R_K



- Original LHC*b* result (2.6σ):

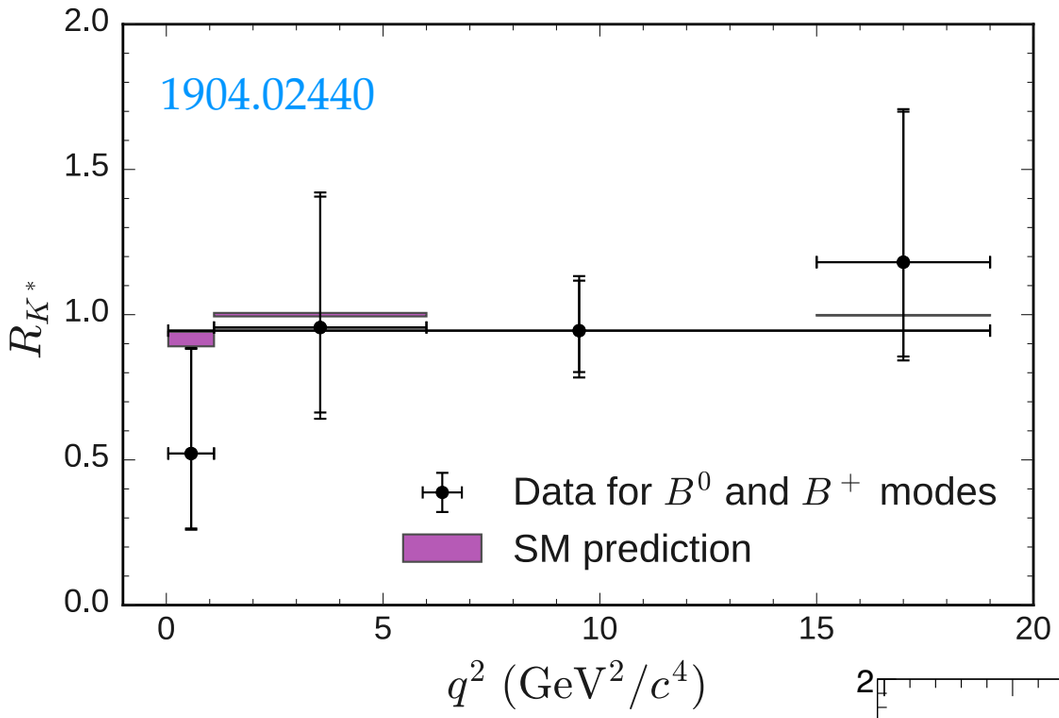
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

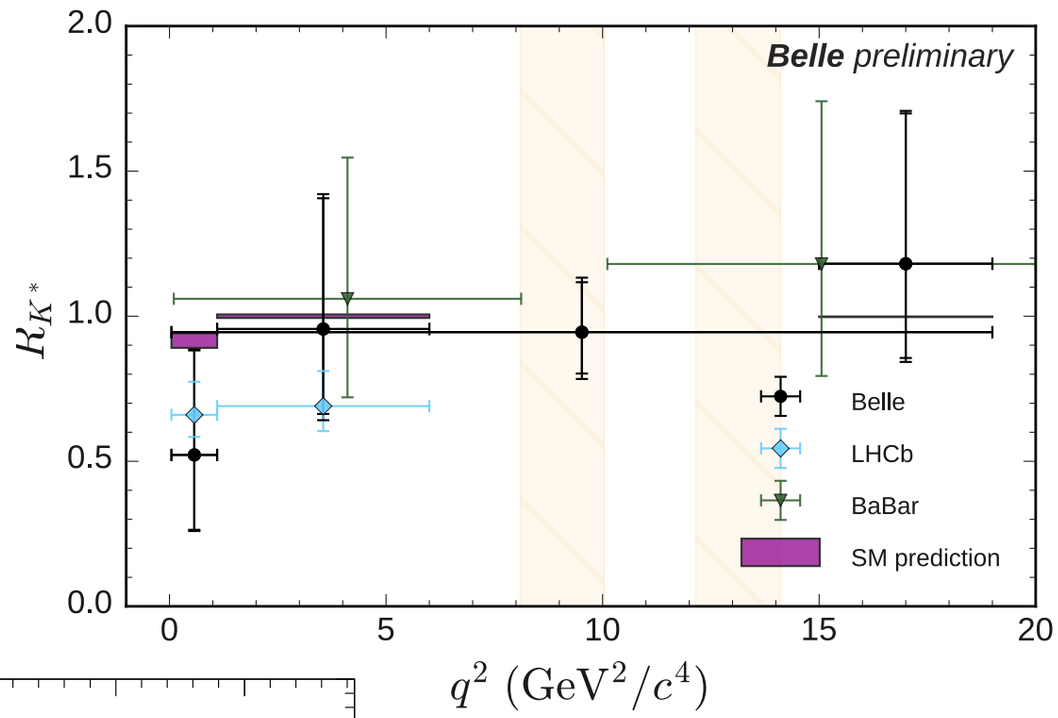
- New result including data until 2016 (2.5σ):

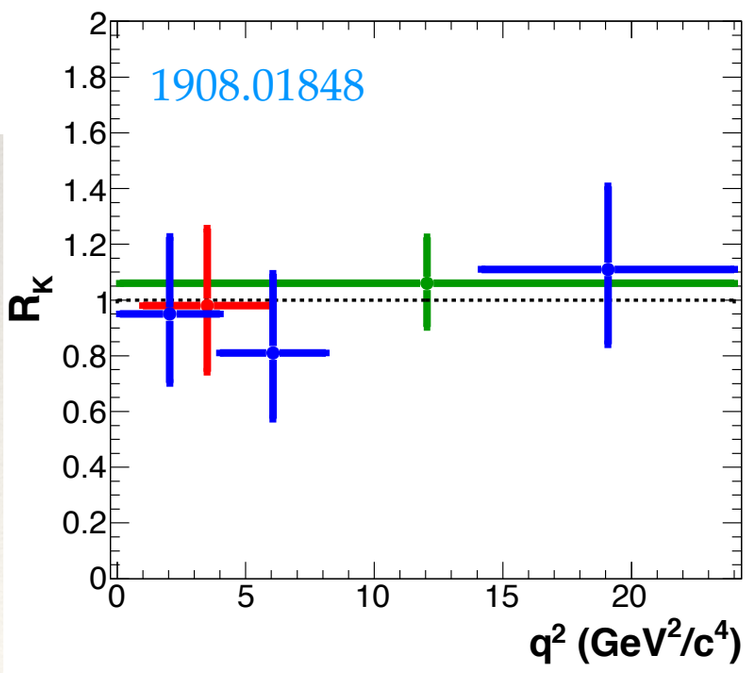
$$R_K = 0.846\,^{+0.060\,+0.016}_{-0.054\,-0.014}$$

- And there is more: promising news from Belle …

Belle enters the game of R_K & R_{K^*}





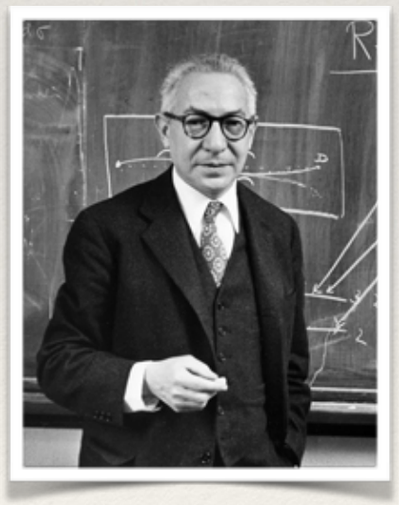


B-flavor anomalies: Status

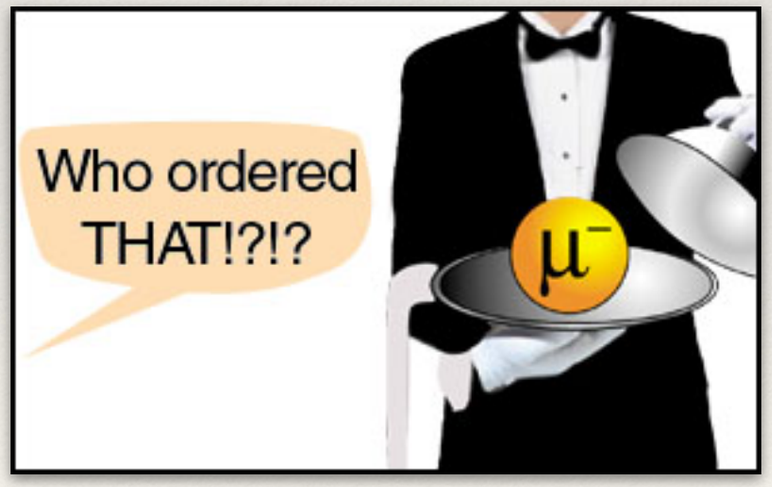
- Lots of reasons to be excited!
  - Two different sets of anomalies of very different taste
  - Several seen by more than one experiment
  - In case of $b \to s\ell^+\ell^-$ several observables deviate from SM predictions, and deviations appear to fit a simple pattern
- All combined, perhaps the most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

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:

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \left(C_7^{bs} O_7^{bs} + C_7^{\prime bs} O_7^{\prime bs} + \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell} O_i^{\prime bs\ell\ell} \right) \right) + \text{h.c.}$$

with:

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

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

- Excellent fits obtained with only 1-2 NP contributions!
- Analogous Hamiltonian can be written for $b \to c\,\ell^-\bar{\nu}$

Model-independent analyses

- From global fit to $b \to s\ell^+\ell^-$ observables:

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.97	$[-1.12, -0.81]$	$[-1.27, -0.65]$	5.9σ
$C_9^{\prime bs\mu\mu}$	$+0.14$	$[-0.03, +0.32]$	$[-0.20, +0.51]$	0.8σ
$C_{10}^{bs\mu\mu}$	$+0.75$	$[+0.62, +0.89]$	$[+0.48, +1.03]$	5.7σ
$C_{10}^{\prime bs\mu\mu}$	-0.24	$[-0.36, -0.12]$	$[-0.49, +0.00]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.06, +0.36]$	$[-0.09, +0.52]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.61, -0.45]$	$[-0.69, -0.37]$	6.6σ

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

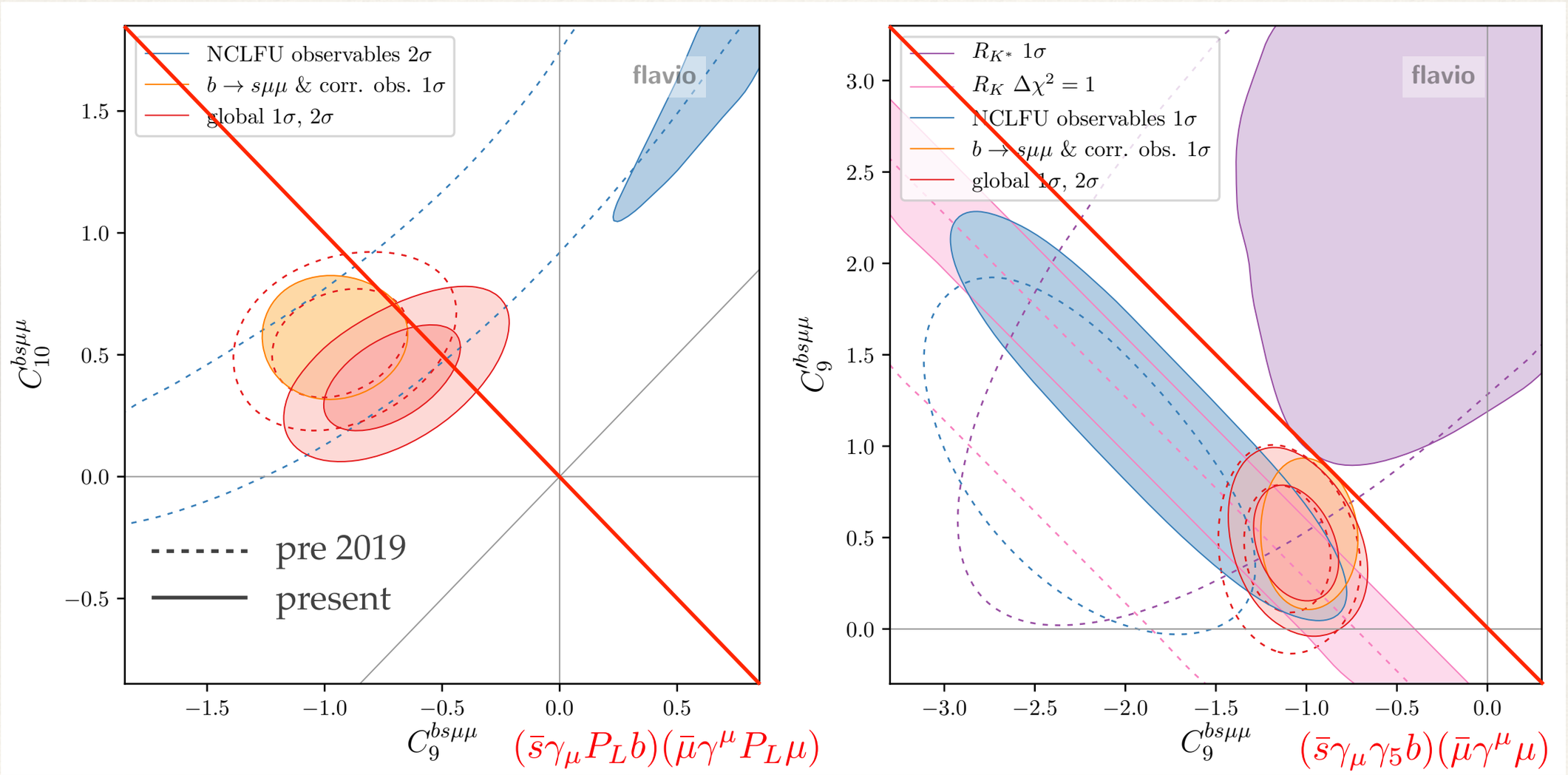
	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.01	-1.10	+0.15	+0.02	+0.36	-0.16
$1\ \sigma$	$[-0.01, +0.05]$	$[-1.28, -0.90]$	$[-0.00, +0.36]$	$[-0.00, +0.05]$	$[-0.14, +0.87]$	$[-0.39, +0.13]$
$2\ \sigma$	$[-0.03, +0.06]$	$[-1.44, -0.68]$	$[-0.12, +0.56]$	$[-0.02, +0.06]$	$[-0.49, +1.23]$	$[-0.58, +0.33]$

6D fit
pull: 5.1σ

Algueró, Capdevila, Crivellin, Descotes-Genon, Masjuan, Matias, Virto 1903.09578

Model-independent analyses

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



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

Model building: Mediators

- 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; …]

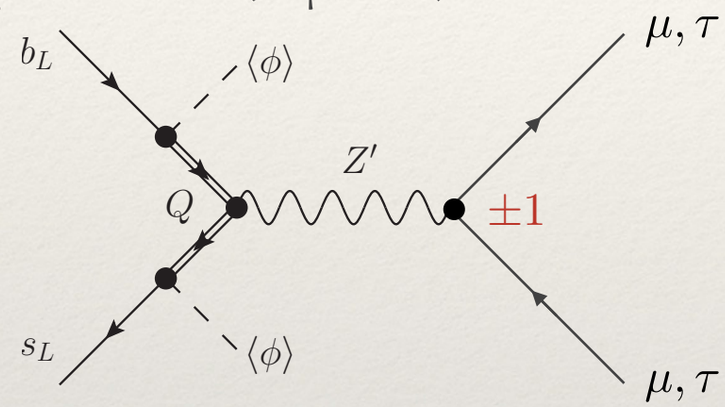
- R_D and R_{D^*} require tree-level NP near TeV scale

- 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: Mediators

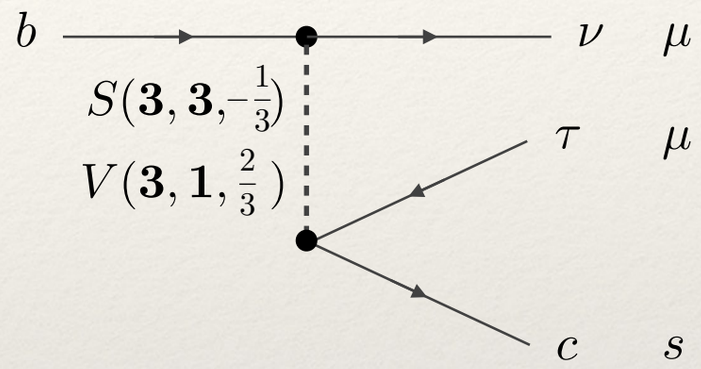
- New colorless bosons, e.g. Z' coupled to (L_μ-L_τ):



[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.:

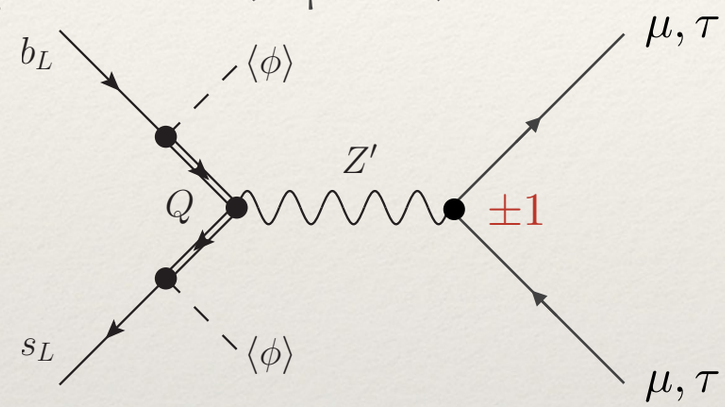


[Hiller, Schmaltz 2014; Alonso, Grinstein, Martin Camalich 2015; Freytsis, Ligeti, Ruderman 2015]

- 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: Mediators

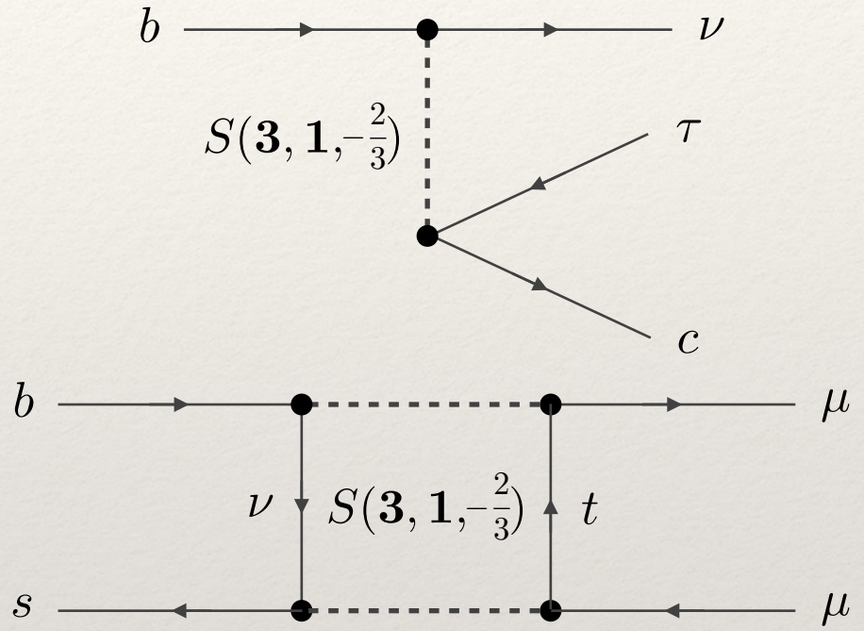
- New colorless bosons, e.g. Z' coupled to (L_μ-L_τ):



[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

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!

Outlook

- Future looks bright:
  - Many more data from LHC*b* and ATLAS/CMS; Belle 2 soon a strong competitor; rare kaon experiments
- Expect lots of new and surprising results and many high-precision measurements
- How exciting this is will depend on what we will find!

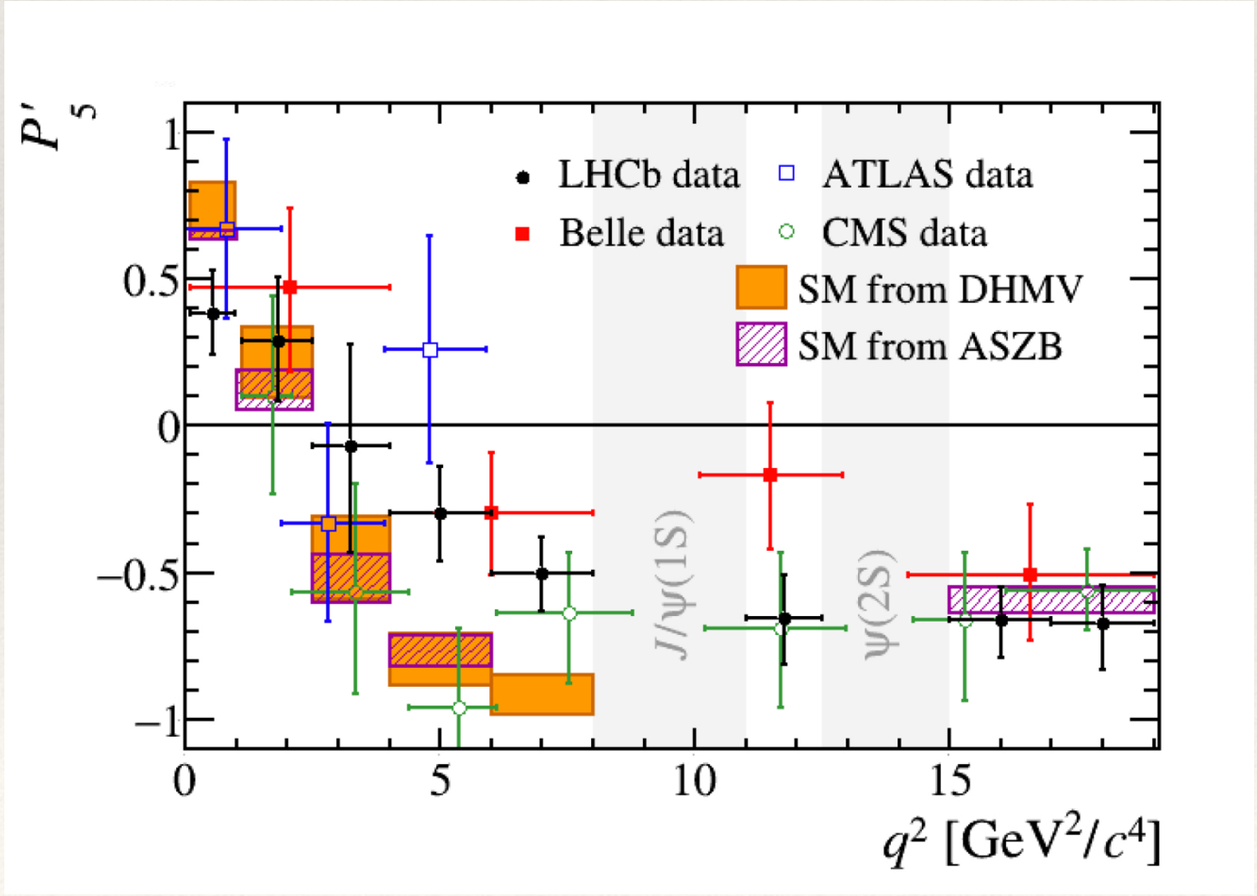
Conclusions

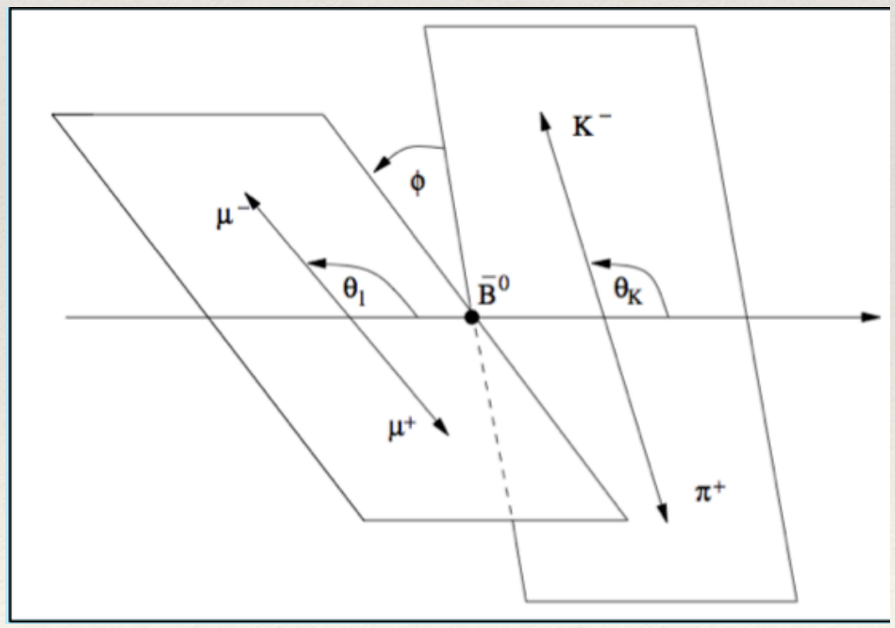
- If confirmed, the B-meson flavor anomalies would be the most important discovery in particle physics since discovery of the weak gauge bosons and the Higgs
  - Point to existence of new heavy particles in few-TeV range
  - Possibly, these might be connected to a fundamental theory of electroweak symmetry breaking and flavor
  - Strong physics case for future high-energy colliders
- Independent confirmation of the flavor anomalies by Belle 2 is as crucial as refining current LHC*b* analyses

Backup Slides

Flavor anomalies: P_5' & BRs

- 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]





Model building

- Interesting framework for addressing all anomalies:

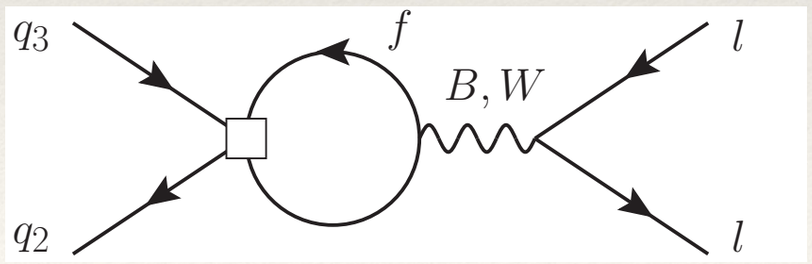
  [Buttazzo, Greljo, Isidori, Marzocca 2017]

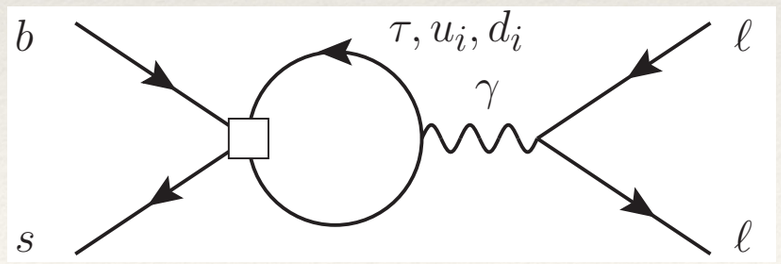
  - Assume that NP only couples to LHD quarks and leptons:

$$\mathcal{H}_{\rm NP} = [C_{\ell q}^{(1)}]_{ii23}\,(\bar{L}_L^i \gamma_\mu L_L^i)(\bar{Q}_L^2 \gamma^\mu Q_L^3) + [C_{\ell q}^{(3)}]_{ii23}\,(\bar{L}_L^i \gamma_\mu \tau^I L_L^i)(\bar{Q}_L^2 \gamma^\mu \tau^I Q_L^3)$$

  - 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]

  - Universal contribution to C_9 can be generated at loop level:

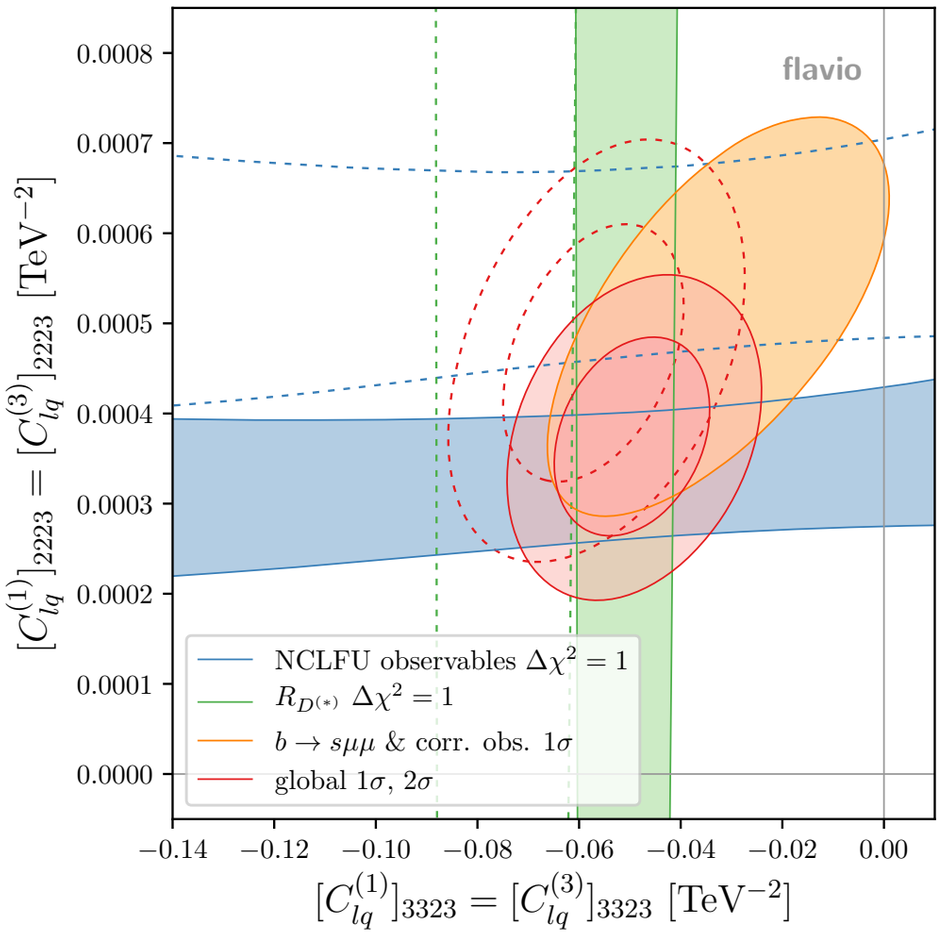




[Crivellin, Greub, Saturnino, Müller 2018]

Model building

- Provides a consistent description of all data:



Observable	1σ	2σ	SM
$R_{K^*}^{[0.045,1.1]}$	$0.88\,^{+0.01}_{-0.01}$	$[0.86, 0.90]$	0.926 ± 0.004
$R_{K^*}^{[1.1,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	$[0.73, 0.89]$	0.9964 ± 0.0006
$R_{K^*}^{[0.1,8.0]}$	$0.83\,^{+0.04}_{-0.03}$	$[0.77, 0.90]$	0.995 ± 0.002
$R_{K^*}^{[15,19]}$	$0.79\,^{+0.04}_{-0.04}$	$[0.71, 0.88]$	0.99807 ± 0.00004
$R_{K}^{[1.0,6.0]}$	$0.80\,^{+0.04}_{-0.04}$	$[0.71, 0.88]$	1.0008 ± 0.0003
$R_{\phi}^{[1.0,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	$[0.73, 0.89]$	0.9970 ± 0.0003
$\langle P_5' \rangle^{[4.0,6.0]}$	$-0.58\,^{+0.13}_{-0.12}$	$[-0.82, -0.33]$	-0.763 ± 0.072
R_D	$0.34\,^{+0.01}_{-0.01}$	$[0.32, 0.37]$	0.303 ± 0.006
R_{D^*}	$0.29\,^{+0.01}_{-0.01}$	$[0.27, 0.31]$	0.255 ± 0.004
$\overline{\text{BR}}(B_s \to \mu^+\mu^-)$	$2.98\,^{+0.20}_{-0.19} \times 10^{-9}$	$[2.60, 3.38] \times 10^{-9}$	$(3.67 \pm 0.16) \times 10^{-9}$
$\text{BR}(B^\pm \to K^\pm\tau^+\tau^-)$	$3.05\,^{+1.78}_{-1.06} \times 10^{-5}$	$[1.01, 6.47] \times 10^{-5}$	$(1.66 \pm 0.19) \times 10^{-7}$
$\overline{\text{BR}}(B_s \to \tau^+\tau^-)$	$1.41\,^{+0.80}_{-0.47} \times 10^{-4}$	$[0.52, 2.94] \times 10^{-4}$	$(7.78 \pm 0.33) \times 10^{-7}$

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