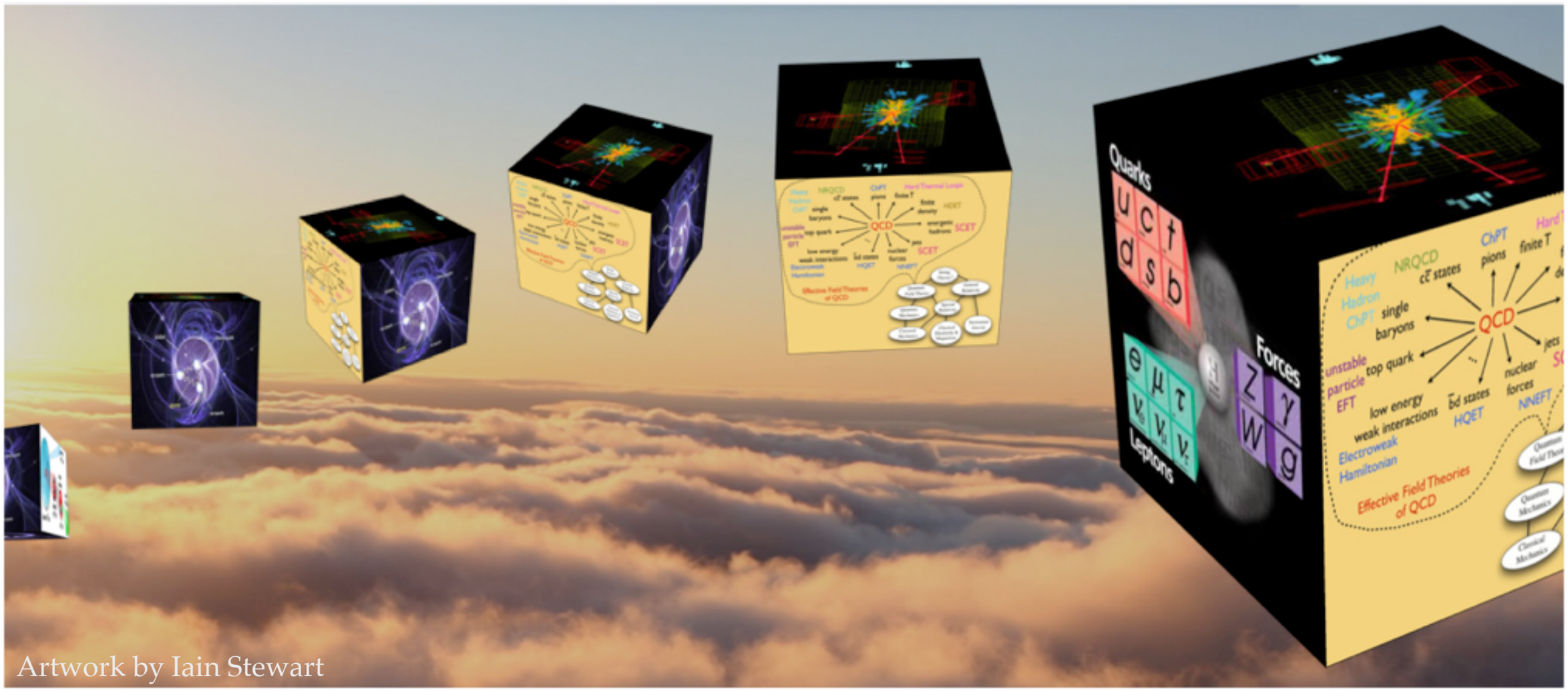


Artwork by Iain Stewart

Exotic Hadrons & Flavor Physics — Simons Center for Geometry and Physics, 28 May—1 June 2018

Theory Summary
Flavor anomalies

Matthias Neubert

PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

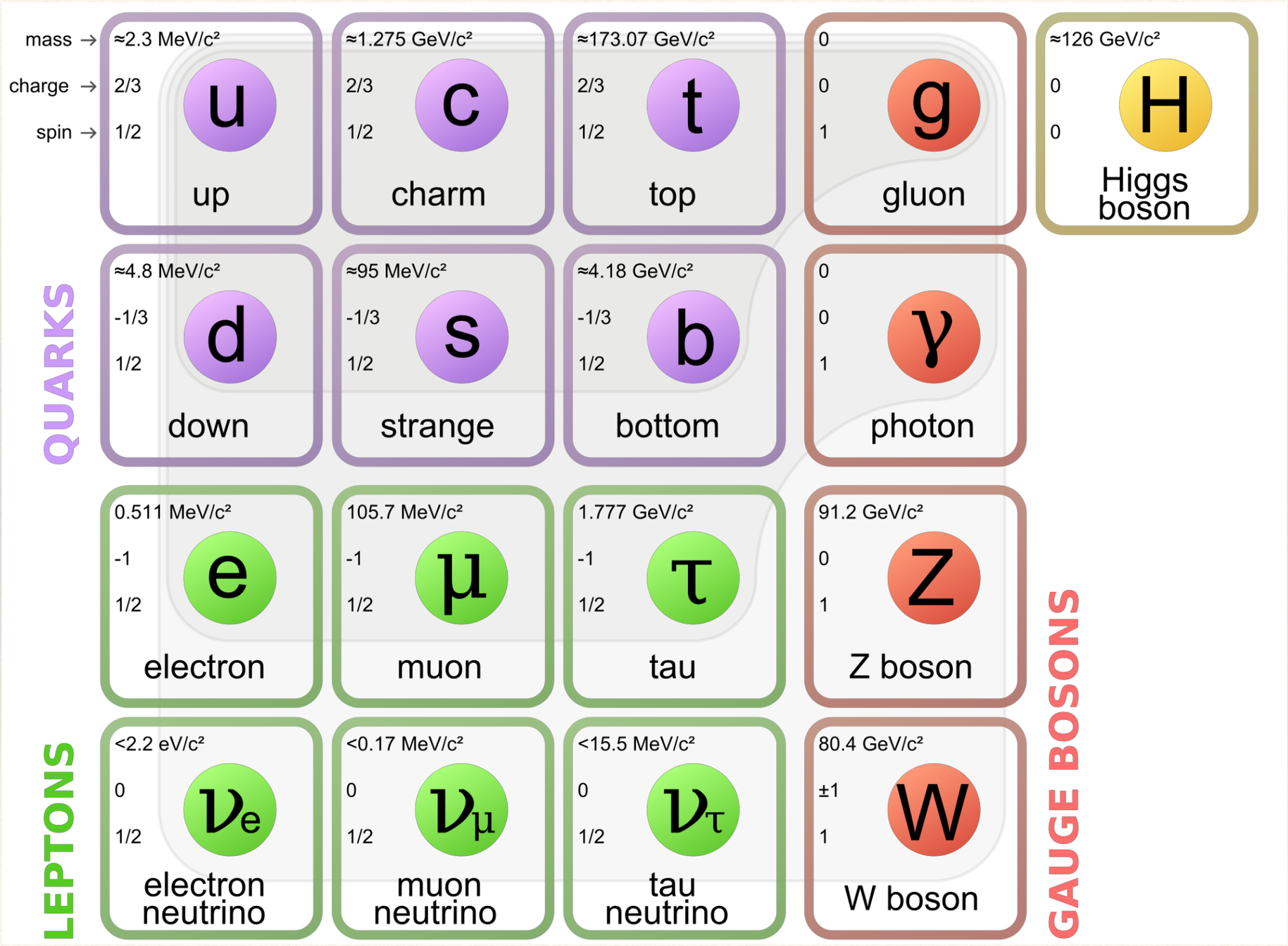
Mainz Institute for Theoretical Physics

PRISMA

JG|U

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

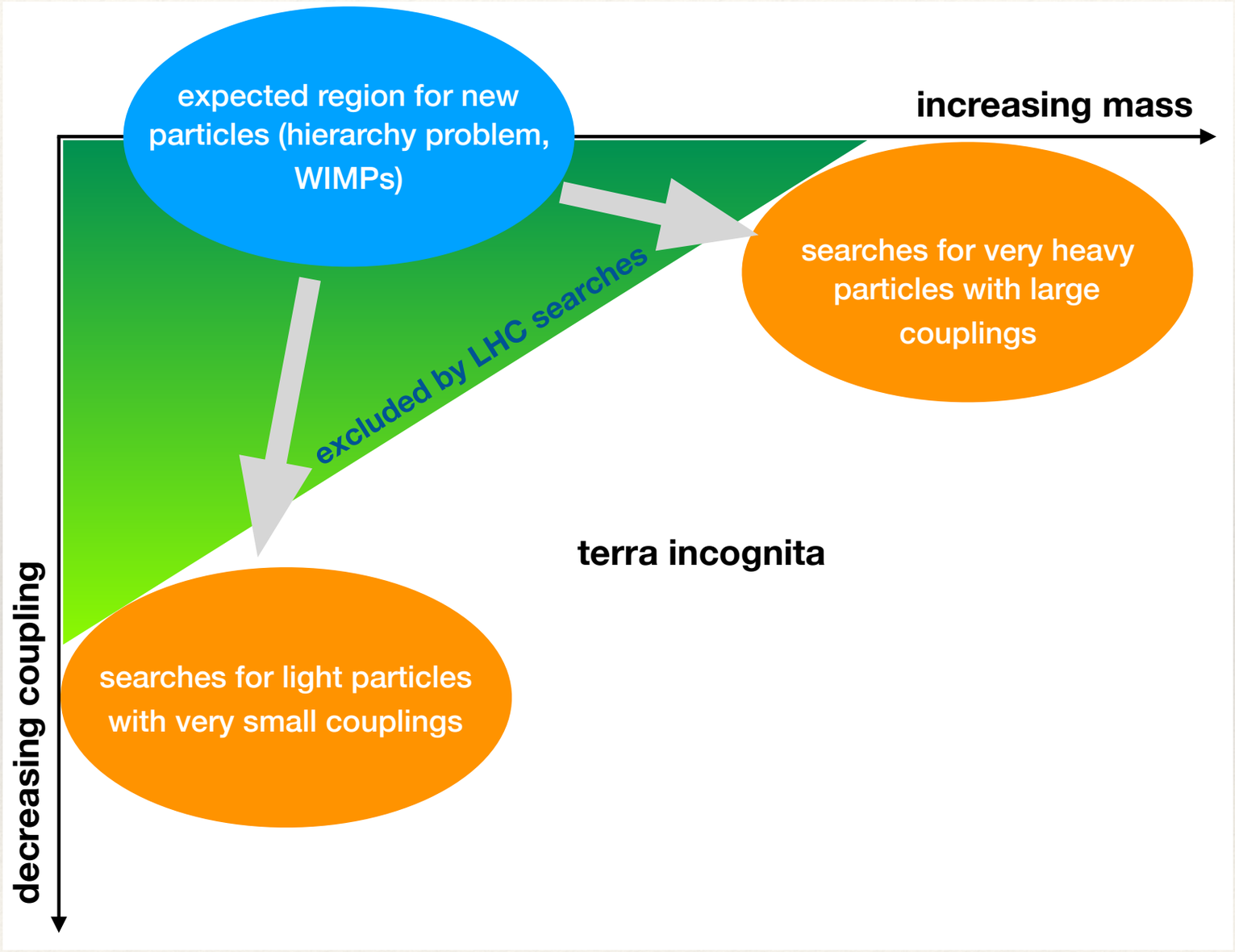
The Standard Model



Beyond the SM

→ let's hope that the same can be said about flavor physicists!

Beyond the SM



SMEFT

- 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

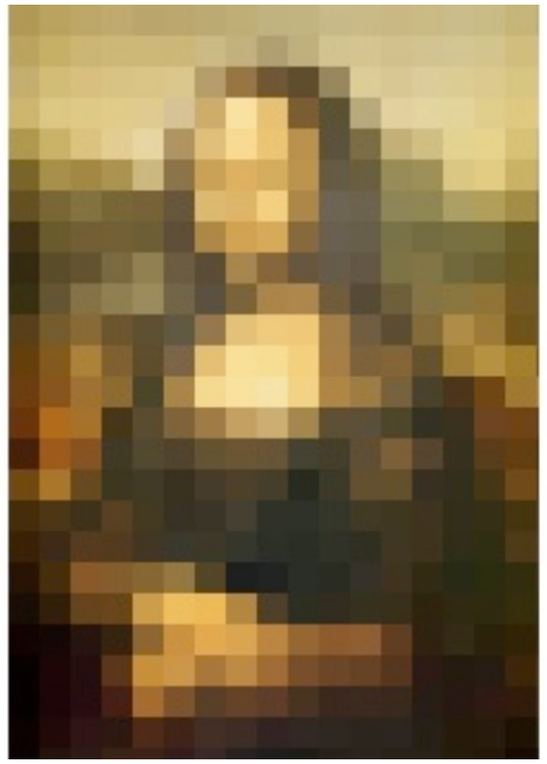
Generic new-physics phenomena

SMEFT

- All scales Λ_i probed so far appear to be rather large:

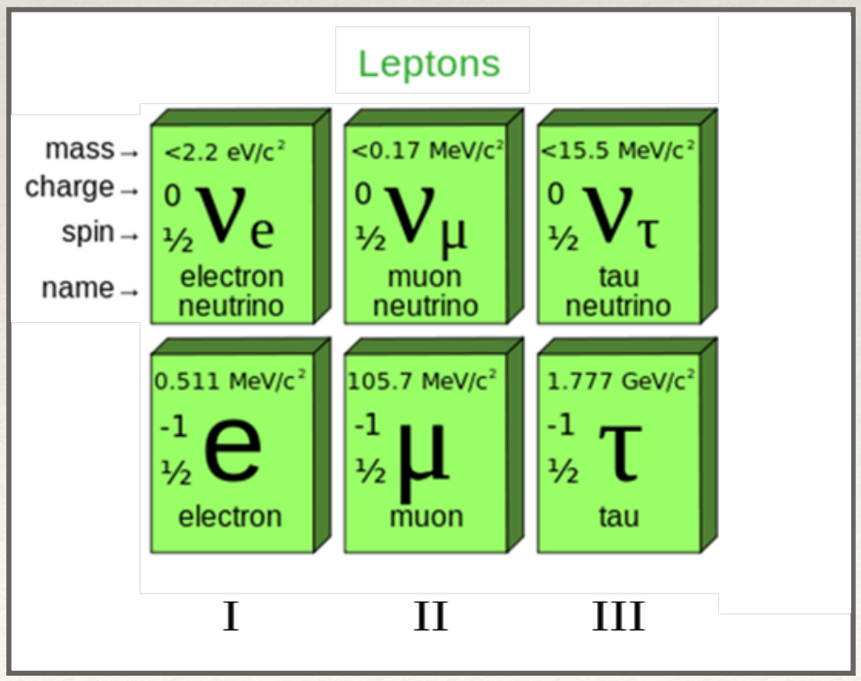
Order	Observable	New-physics scale for g=O(1)
D=5	Neutrino oscillations	$\Lambda \sim 10^9$ TeV
D=6	Proton decay	$\Lambda > 10^{12}$ TeV
D=6	Flavor physics	$\Lambda > 1–10^5$ TeV
D=6	EWPT	$\Lambda > 1$ TeV
D=6	Higgs couplings	$\Lambda > 0.5–1$ TeV

Searching on all Fronts



Violations of lepton universality?

Heavy flavor anomalies



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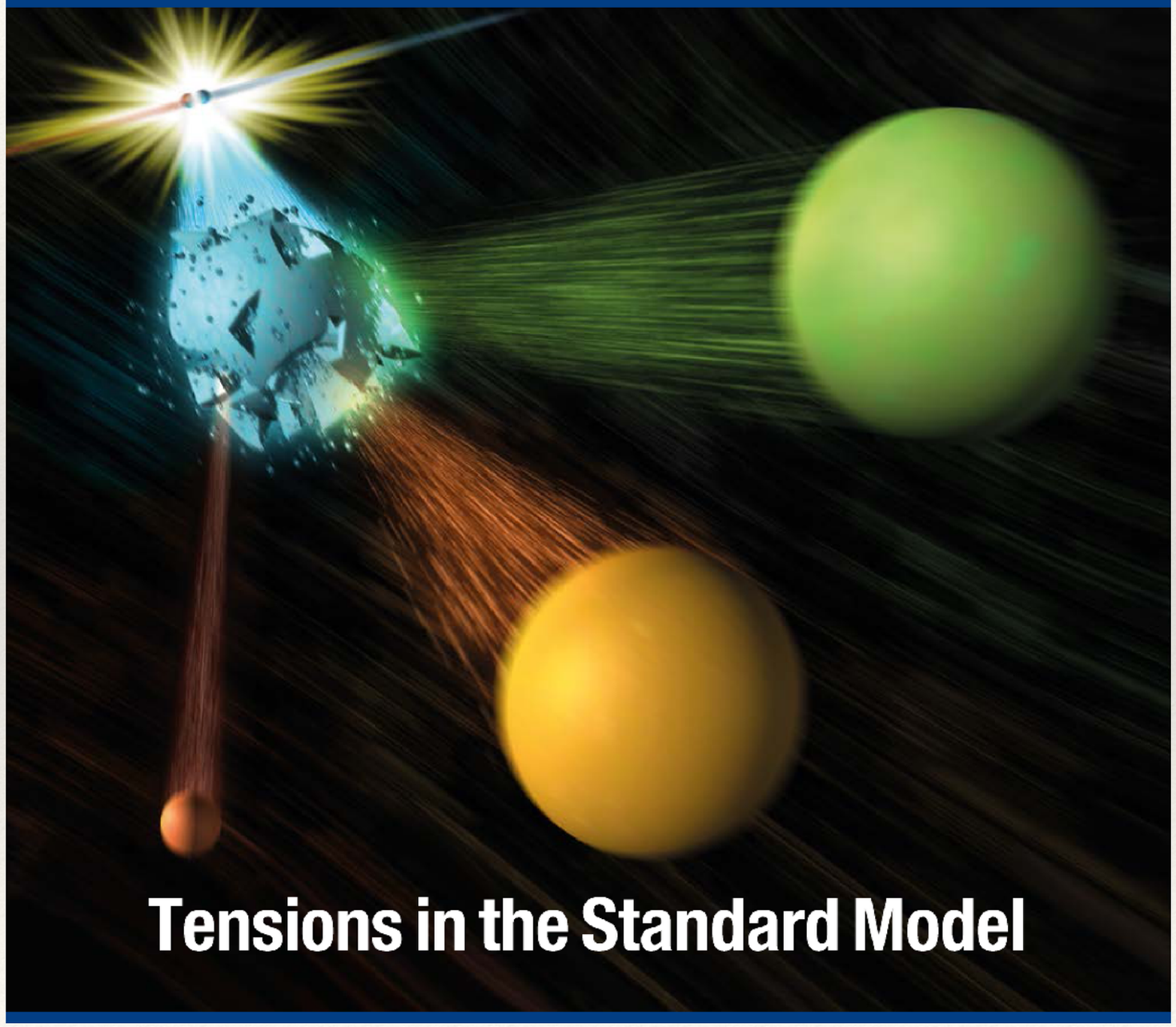


Tensions in the Standard Model

B-flavor anomalies

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

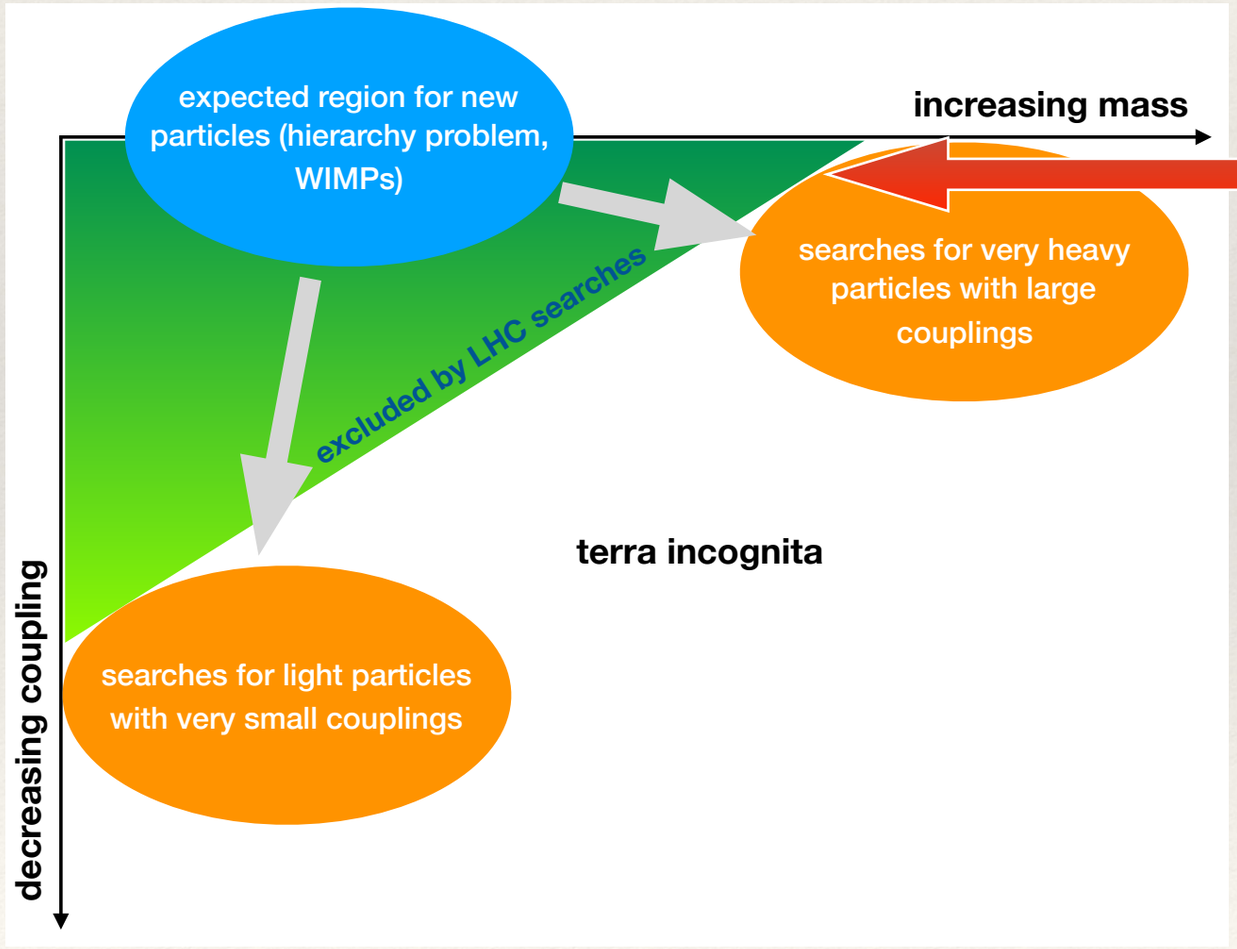
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$

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

- 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-flavor anomalies

- … as they would give a clear target for future searches at energy frontier — exactly what's missing right now!



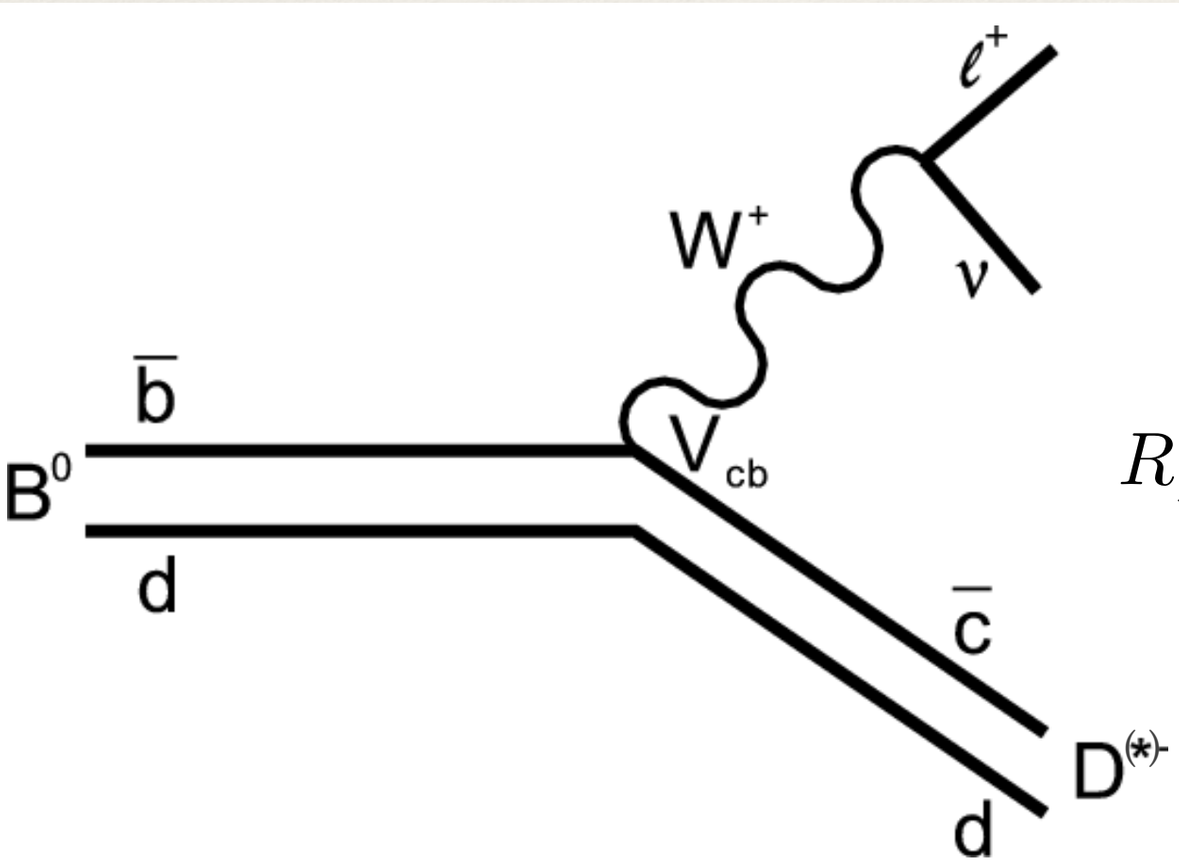
New physics cannot be too far from here!

(primarily driven by $R_{D^{(*)}}$)

→ talk by Jernej Kamenik

B-flavor anomalies: R_D & R_{D^*}

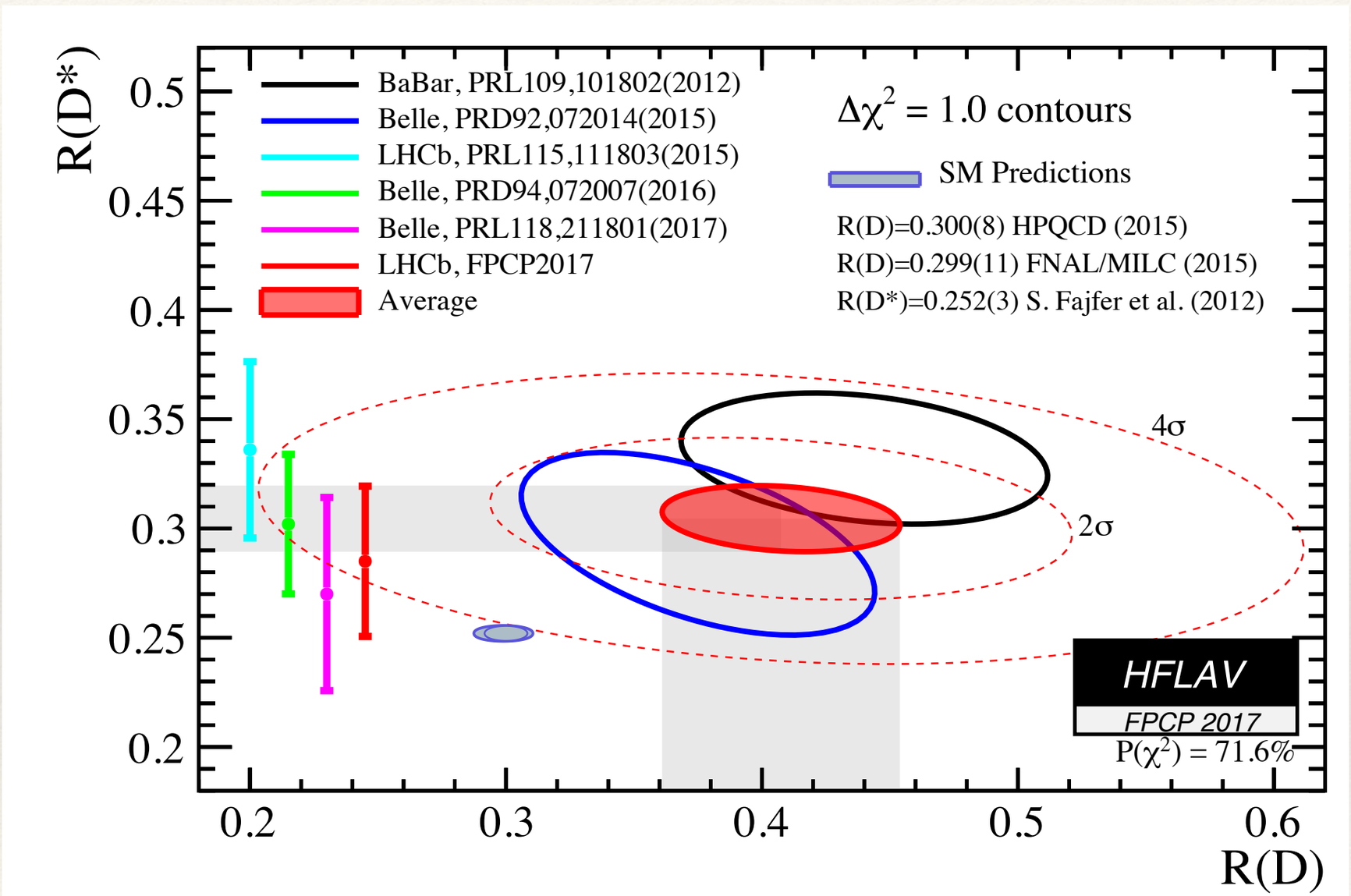
- A totally unexpected signal of new physics in tree-level, CKM-favored, semileptonic decays of B mesons:



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

→ talks by Michele Papucci, Elvira Gamiz

B-flavor anomalies: R_D & R_{D^*}



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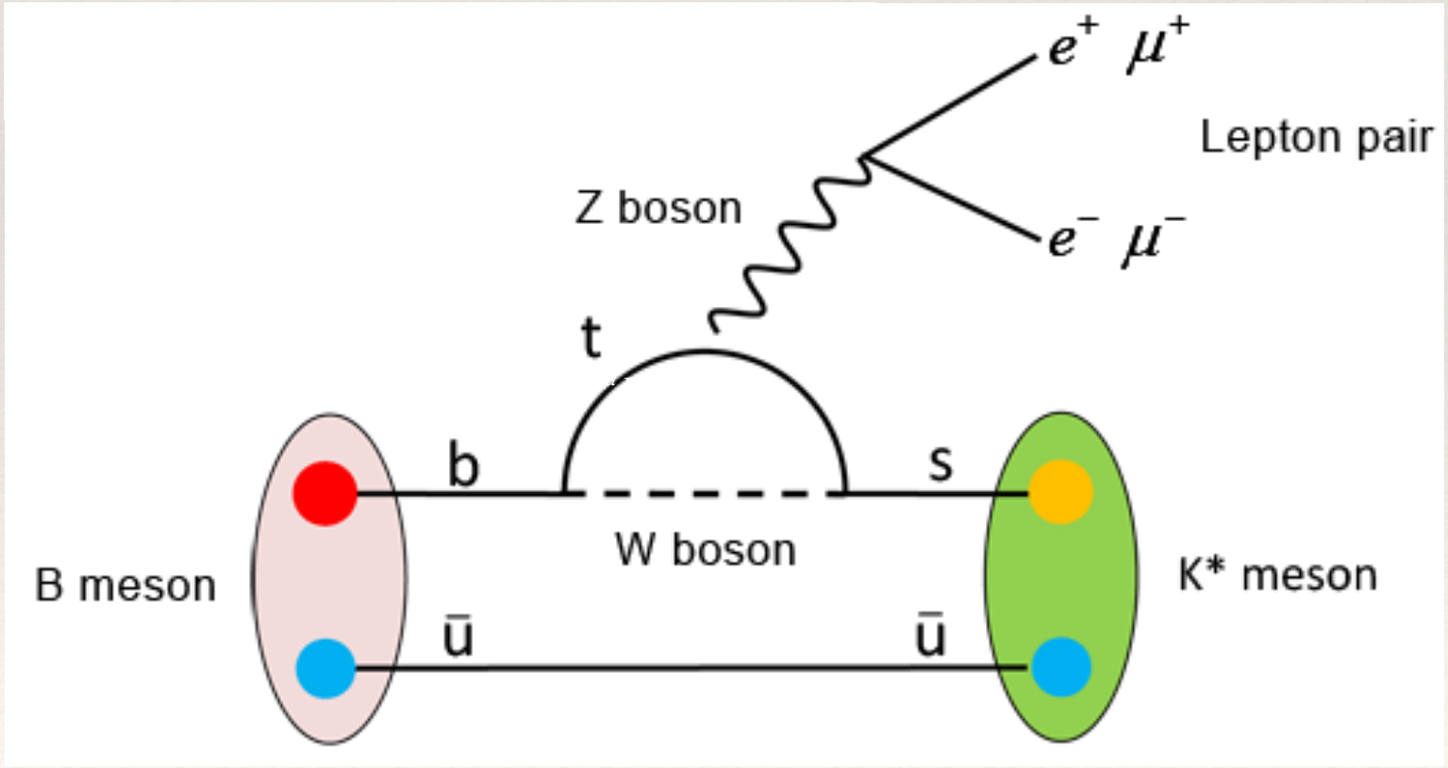
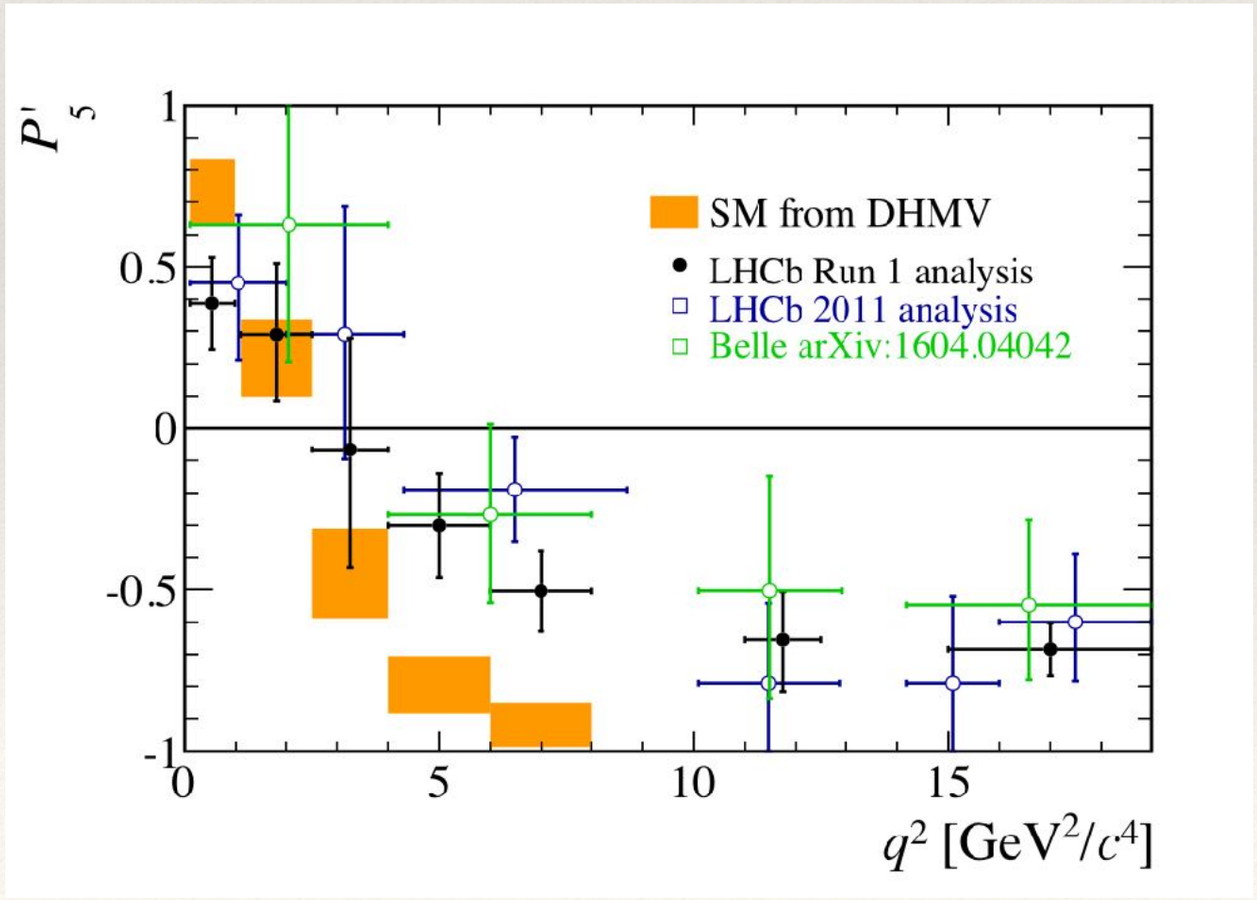
B-flavor anomalies: P_5'

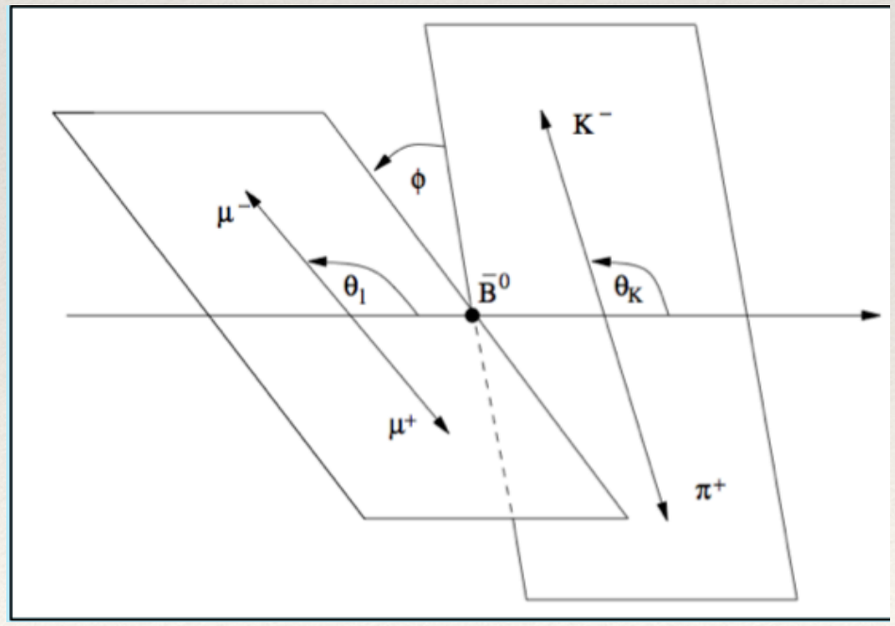
- Various hints of new physics in decays $\bar{B} \to K^* \ell^+ \ell^-$
- As rare, loop-mediated FCNC processes, these were prime observables to probe for BSM effects



B-flavor anomalies: P_5'

- 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: 1207.2753]





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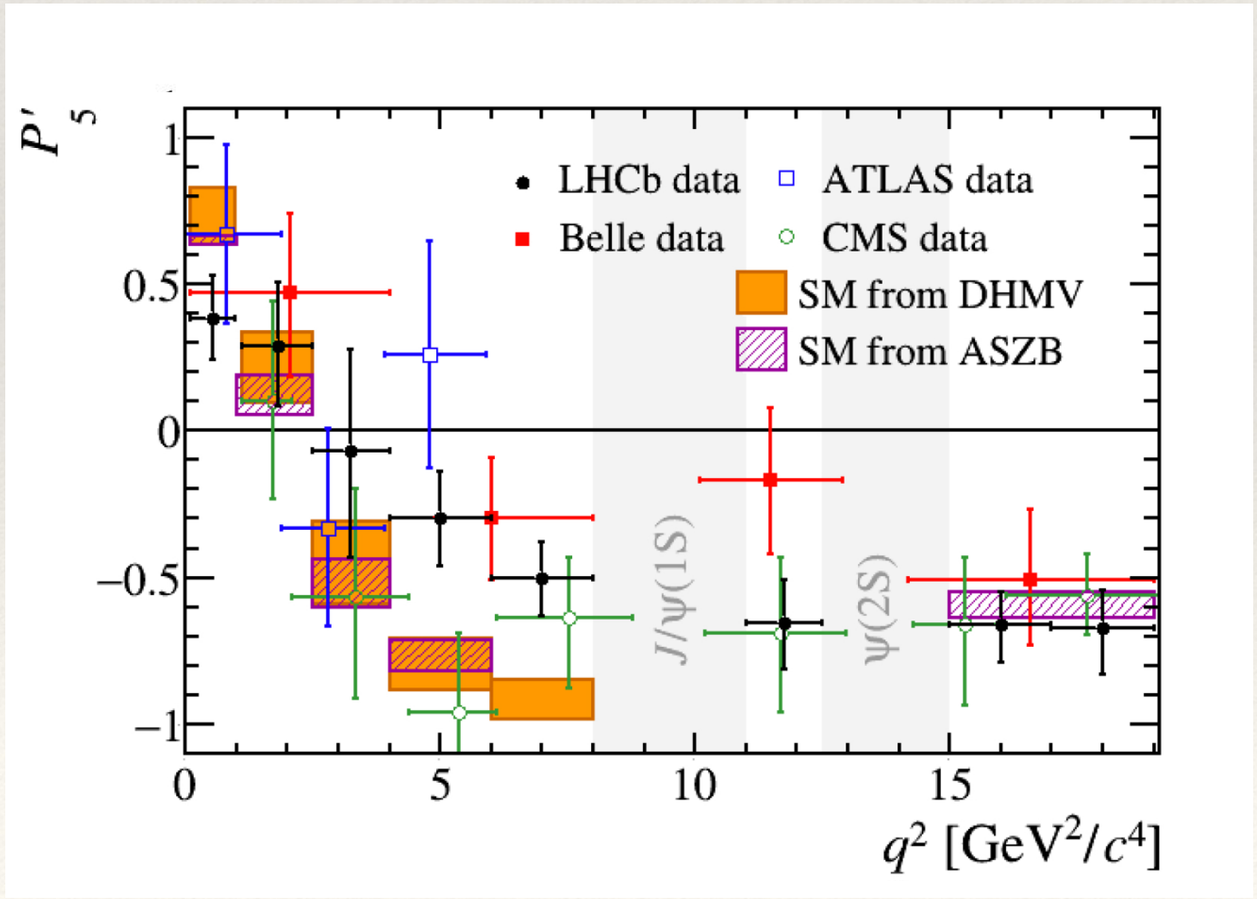
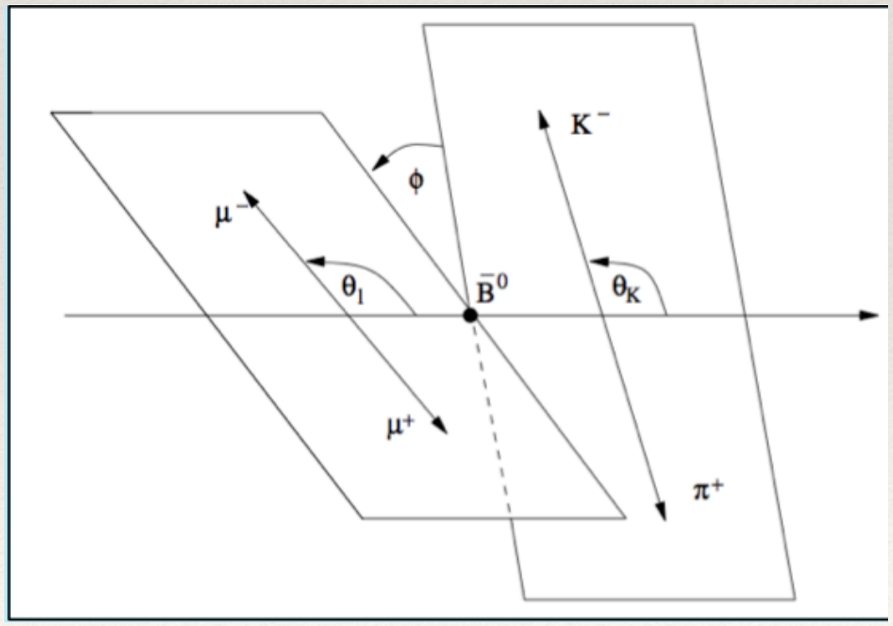




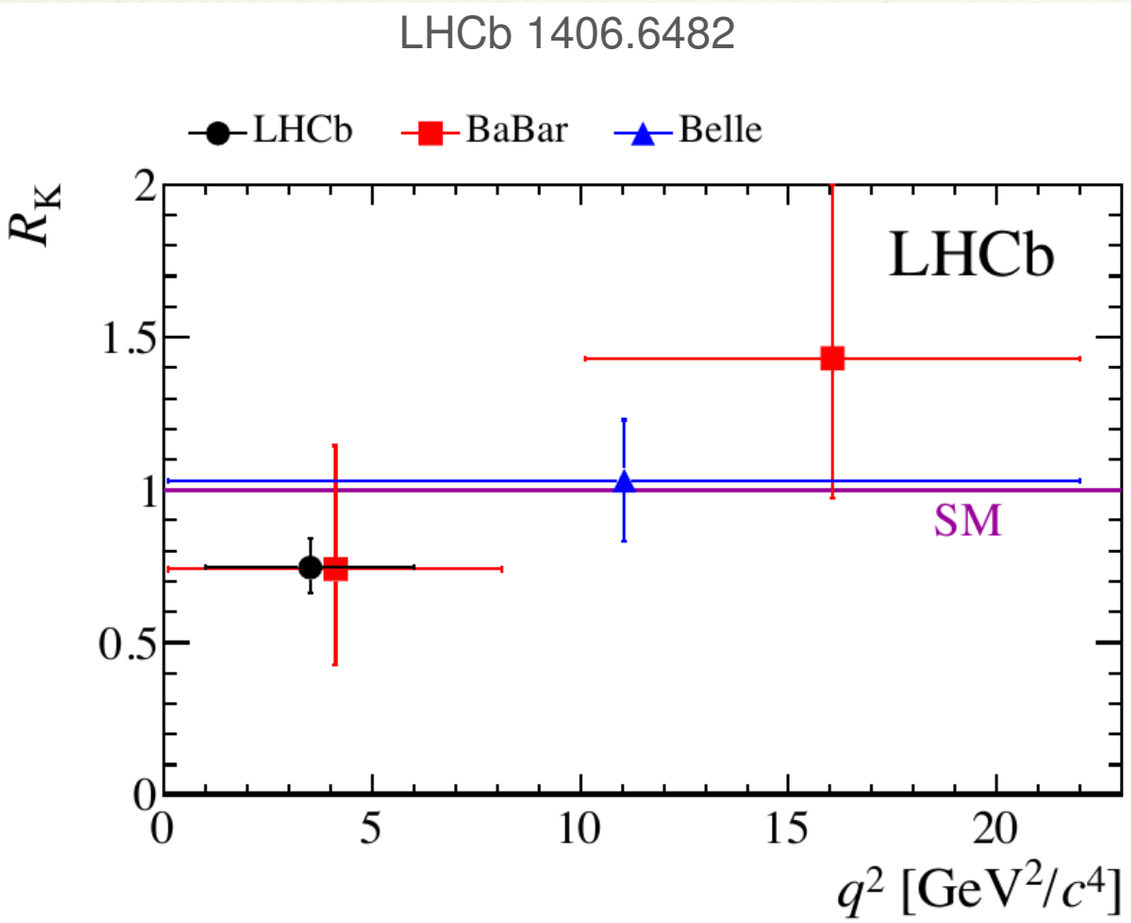
B-flavor anomalies: R_K & R_{K^*}

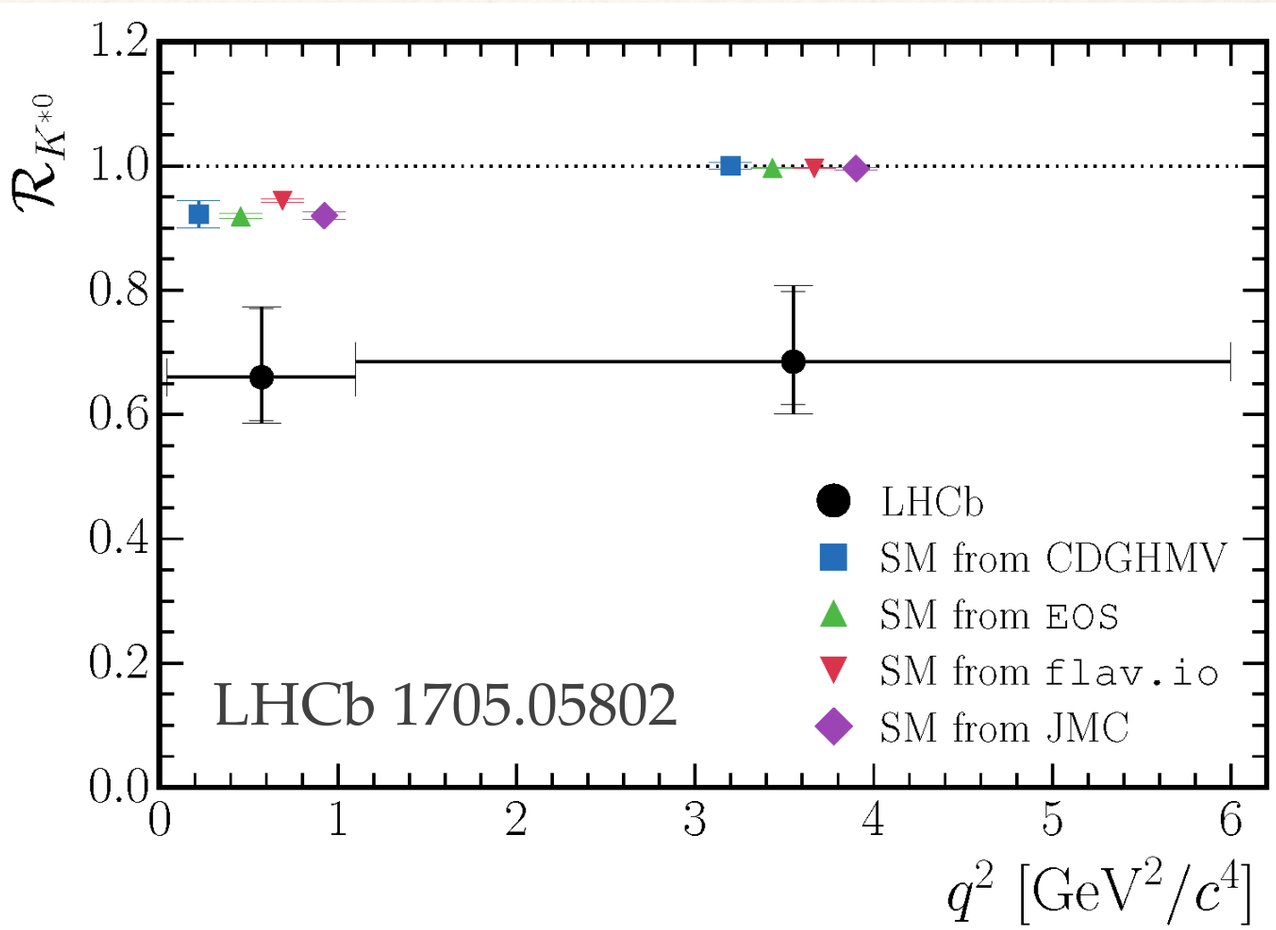
- Some scenarios explaining the anomalies in angular observables predicted a departure from unity in the ratios: [Altmannshofer, Gori, Pospelov, Yavin 2014]

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

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

B-flavor anomalies: R_K & R_{K^*}





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

[Hiller, Krüger 2003]

B-flavor anomalies

- These data teach an important lesson about the complementarity of different fields (as flavor physics was sometimes considered irrelevant in the LHC era)
- Cherish the connection between flavor and high-p_T !

→ talk by Jernej Kamenik

- Imagine the LHC legacy:
  - discovery of the Higgs boson (2012)
  - discovery of lepton-flavor non-universality (2019)

B-flavor anomalies

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- Cherish the connection between flavor and high-p_T !

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- Imagine the LHC legacy:
  - discovery of the Higgs boson (2012)
  - discovery of lepton-flavor non-universality (2019)
  - discovery of the predicted Z' bosons/leptoquarks (2022?)

B-flavor anomalies: Analysis

- **Lots of reasons to be excited!**
  - two different sets of anomalies of very different taste
  - many are seen by more than one experiment
  - in case of b→sll several observables appear to deviate from SM predictions, and the deviations appear to fit a simple pattern

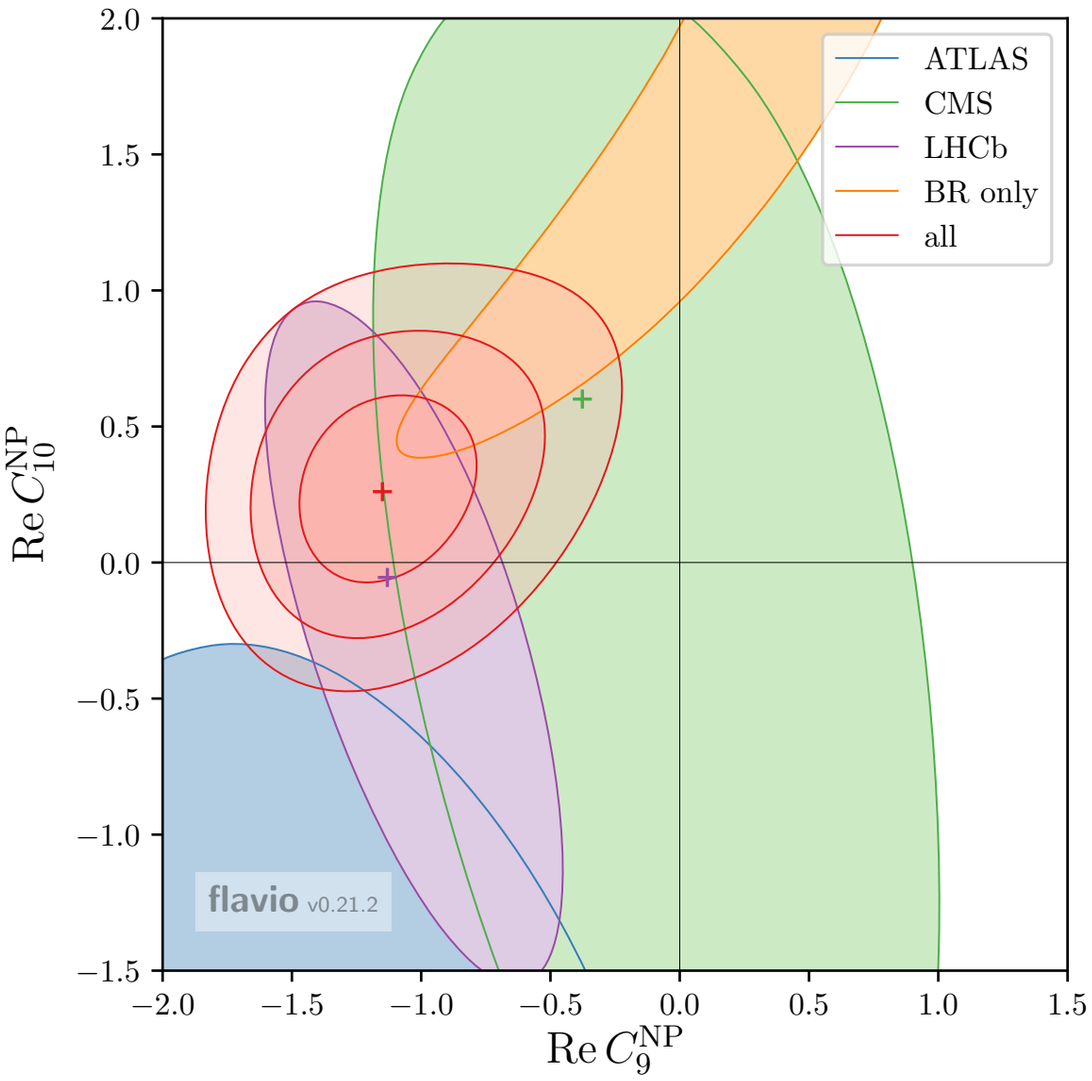
→ talks by Jorge Martin Camalich, Gudrun Hiller

B-flavor anomalies: Analysis

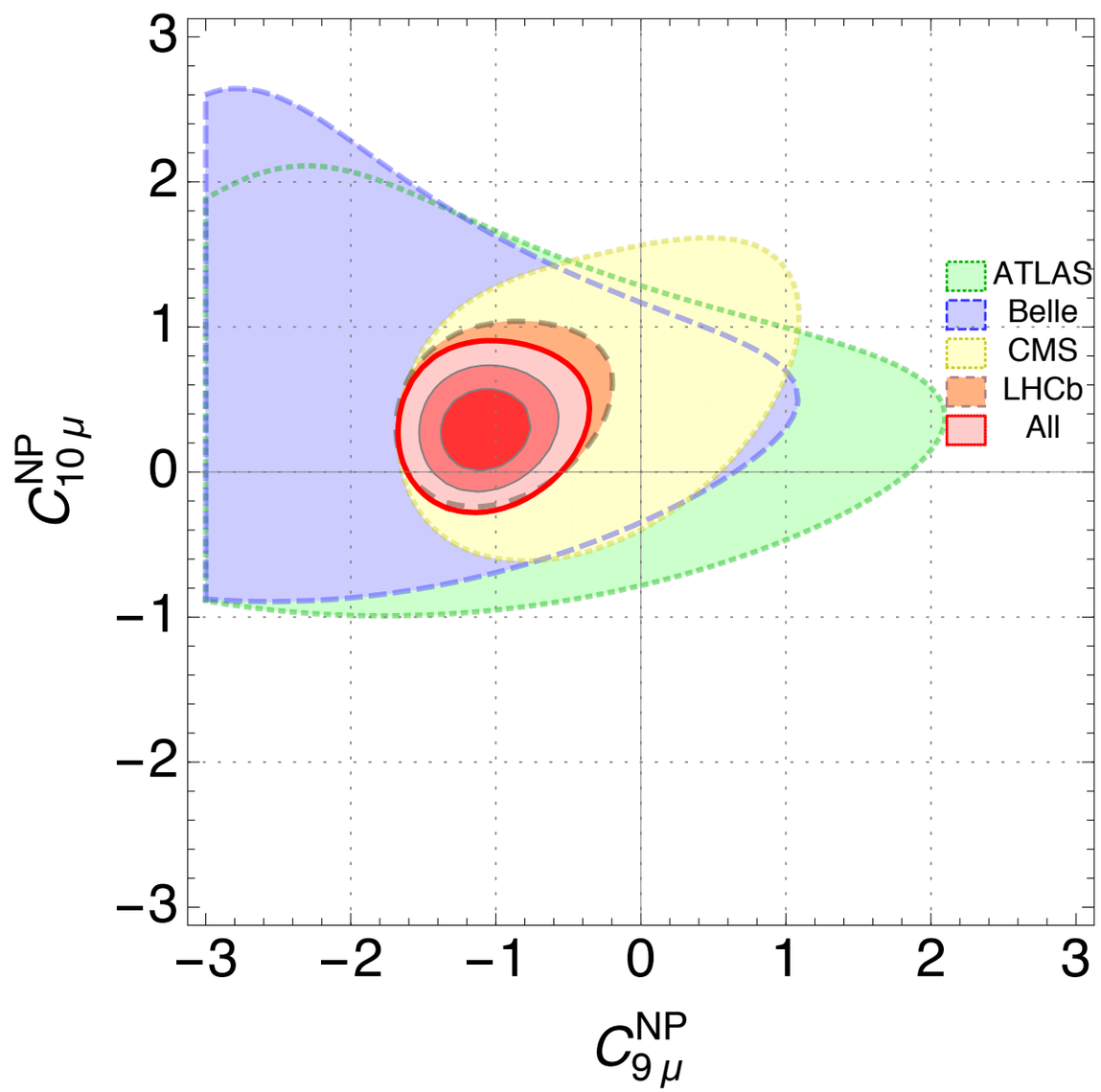
	$b \to c l \nu$	$b \to s l l$
Observables	R_D, R_{D^*}	R_K, R_{K^*}, angular distributions
SM	tree level, CKM favored	one-loop FCNC, GIM suppressed
LFU violation	τ vs. e/μ	μ vs. e
Caveats	τ reconstruction difficult, oldest experiment (BaBar) shows largest effect	electron reconstruction difficult at LHC*b*, so far no confirmation by another experiment
Benefits	Solid theory	Solid theory for $R_{K(*)}$, some caveats for P_5'

→ talks by Michele Papucci, Jernej Kamenik, Elvira Gamiz, Sheldon Stone

B-flavor anomalies: Analysis

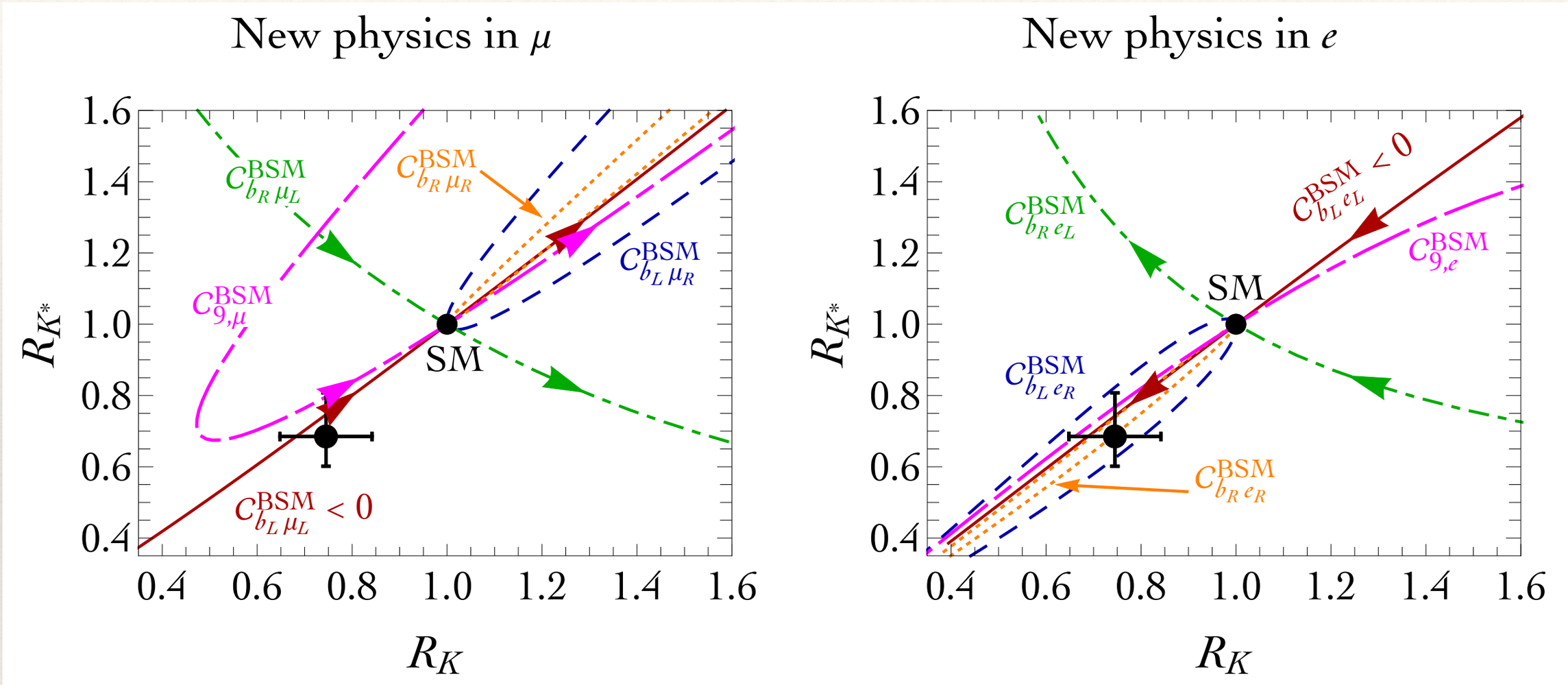


[Altmannshofer, Nies, Stangl, Straub 2017]



[Capdevila, Crivelin, Descotes-Genon, Matias, Virto 2017]

B-flavor anomalies: Analysis



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

B-flavor anomalies: Models

- Challenge to model building, yet several interesting models have been proposed (Z', leptoquarks, …)

→ talks by Jorge Martin Camalich, Gudrun Hiller, Ulrich Nierste

B-flavor anomalies: Models

- Challenge to model building, yet several interesting models have been proposed (Z', leptoquarks, ...)

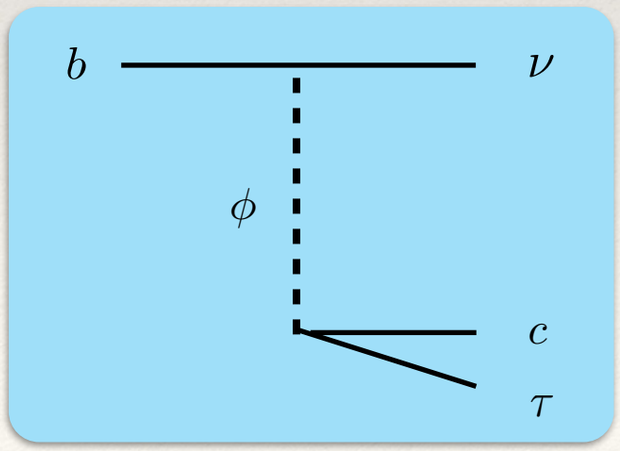
→ talks by Jorge Martin Camalich, Gudrun Hiller, Ulrich Nierste

- E.g.: Adding a single leptoquark $\phi \sim (\mathbf{3}, \mathbf{1})_{-1/3}$ to the SM can address the flavor anomalies along with $(g\text{-}2)_\mu$

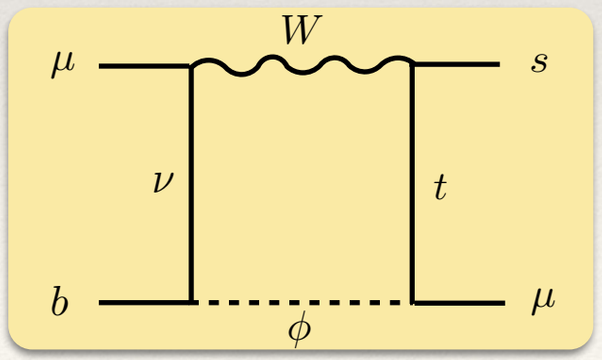
[Bauer, MN 2016]

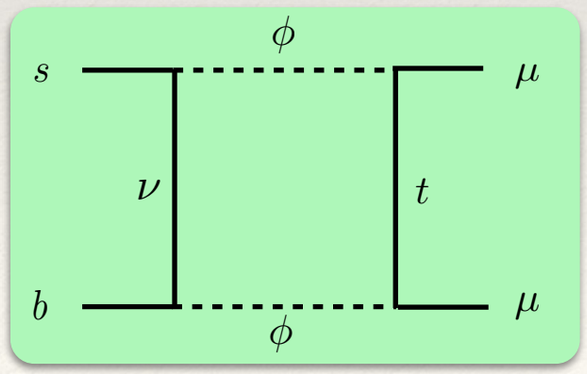
- Relevant diagrams for R_D and R_K:

R_D & R_{D^*}



R_K & R_{K^*}






Don't get too excited
before you really know
what's what
Behappy.me

Should we believe LFU violation?

Yes

- R measurements are double ratio's to J/ψ, LHCb's check with $K^*J/\psi \to e^+e^-/\mu^+\mu^-$ $=1.043\pm0.006\pm0.045$
- $\mathcal{B}(B^- \to K^-e^+e^-)$ agrees with SM prediction puts onus on muon mode which is well measured and low
- Both R_K & R_{K^*} are different than ~1
- Supporting evidence of effects in angular distributions

No, not yet

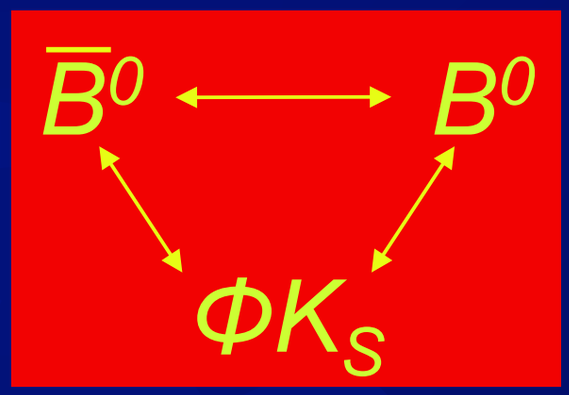
- Statistics are marginal in each measurement
- Need confirming evidence in other experiments for R_K & R_{K^*}
- Disturbing that R_{K^*} is not ~1 in lowest q^2 bin, which it should be, because of the photon pole
- Angular distribution evidence can be effected by hadronic uncertainties

Past (elusive) B-flavor anomalies

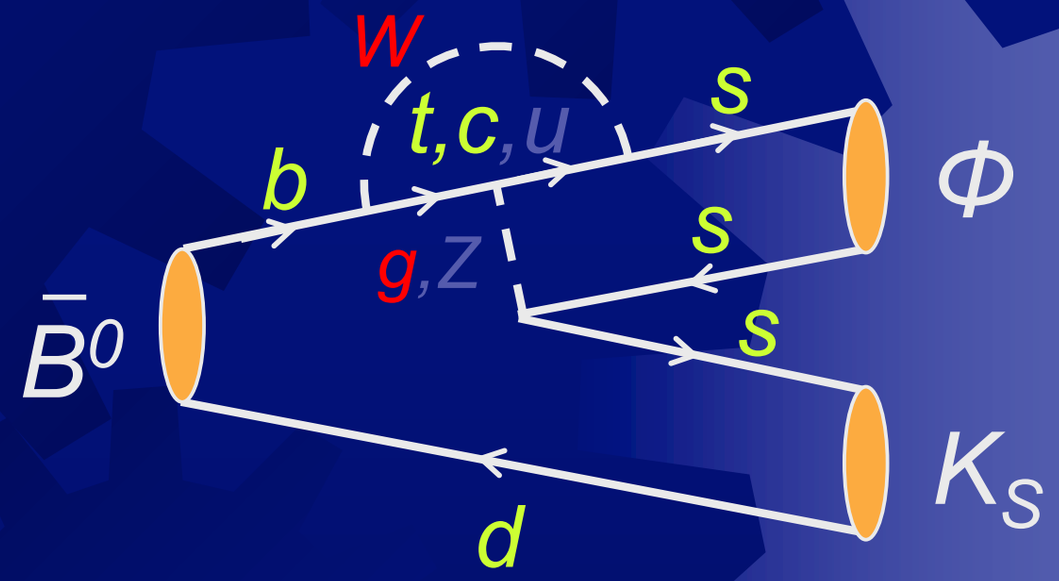
- Several anomalies in B physics (many rather persistent, some at the 3-4σ level) have created quite some excitement at their times:
  - puzzle of the too short Λ_b lifetime
  - **evidence for a low sin2$\beta_{\phi Ks}$ from loop processes**
  - puzzle of the too large $B \to \tau\nu$ branching ratio
  - $\Delta A_{CP}(B \to \pi K)$ puzzle of direct CP asymmetries
  - …

CP Asymmetry in $B \to \Phi K_S$

- Interference of mixing and decay:



- Penguin graph is real to very good approximation!



- Phase structure identical to the decay $B \to J/\psi\, K_S$
- Model-independent result:

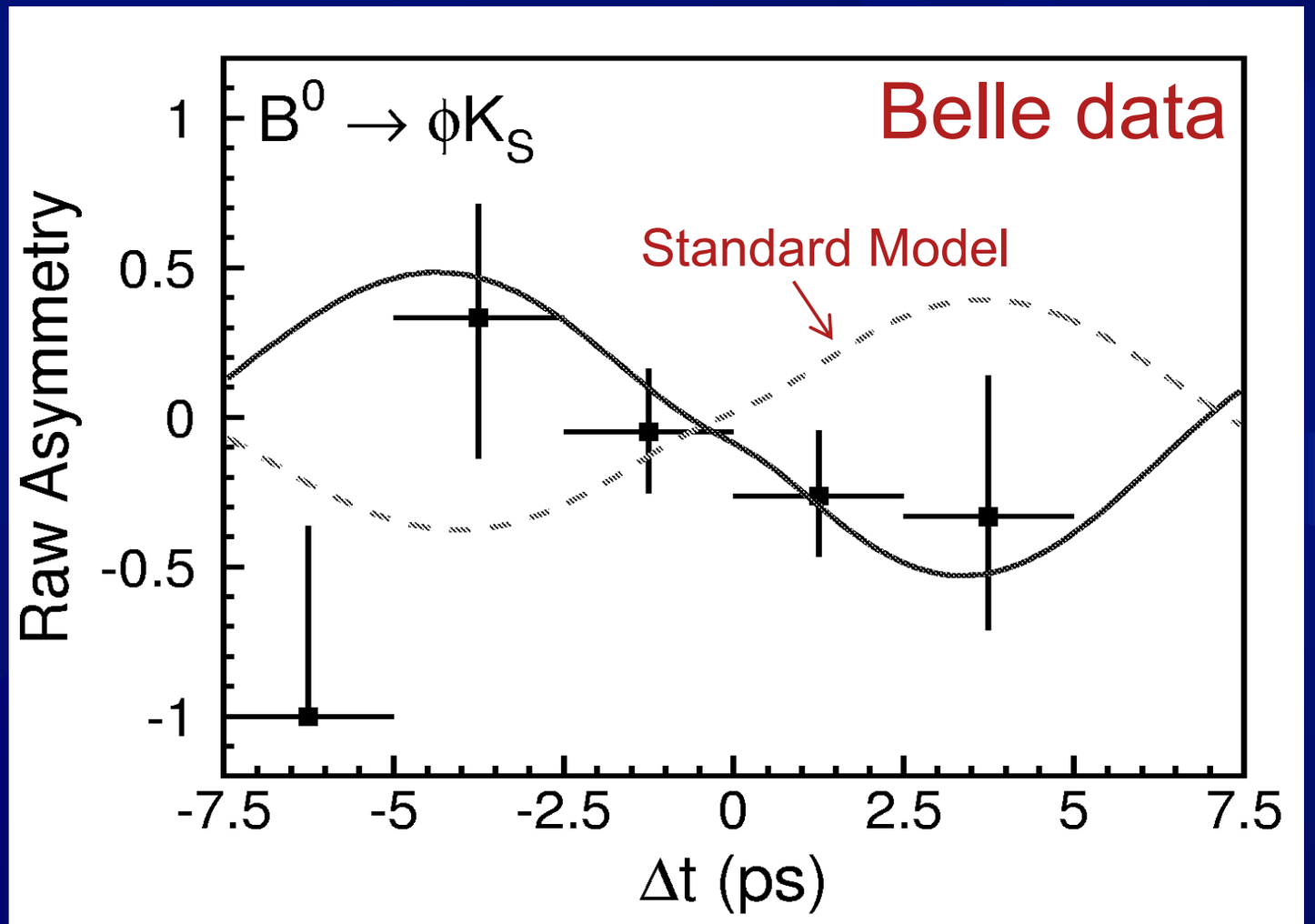
$$S(\Phi K_S) - S(J/\psi\, K_S) = 0.02 \pm 0.01$$

[Beneke, Neubert 2003]

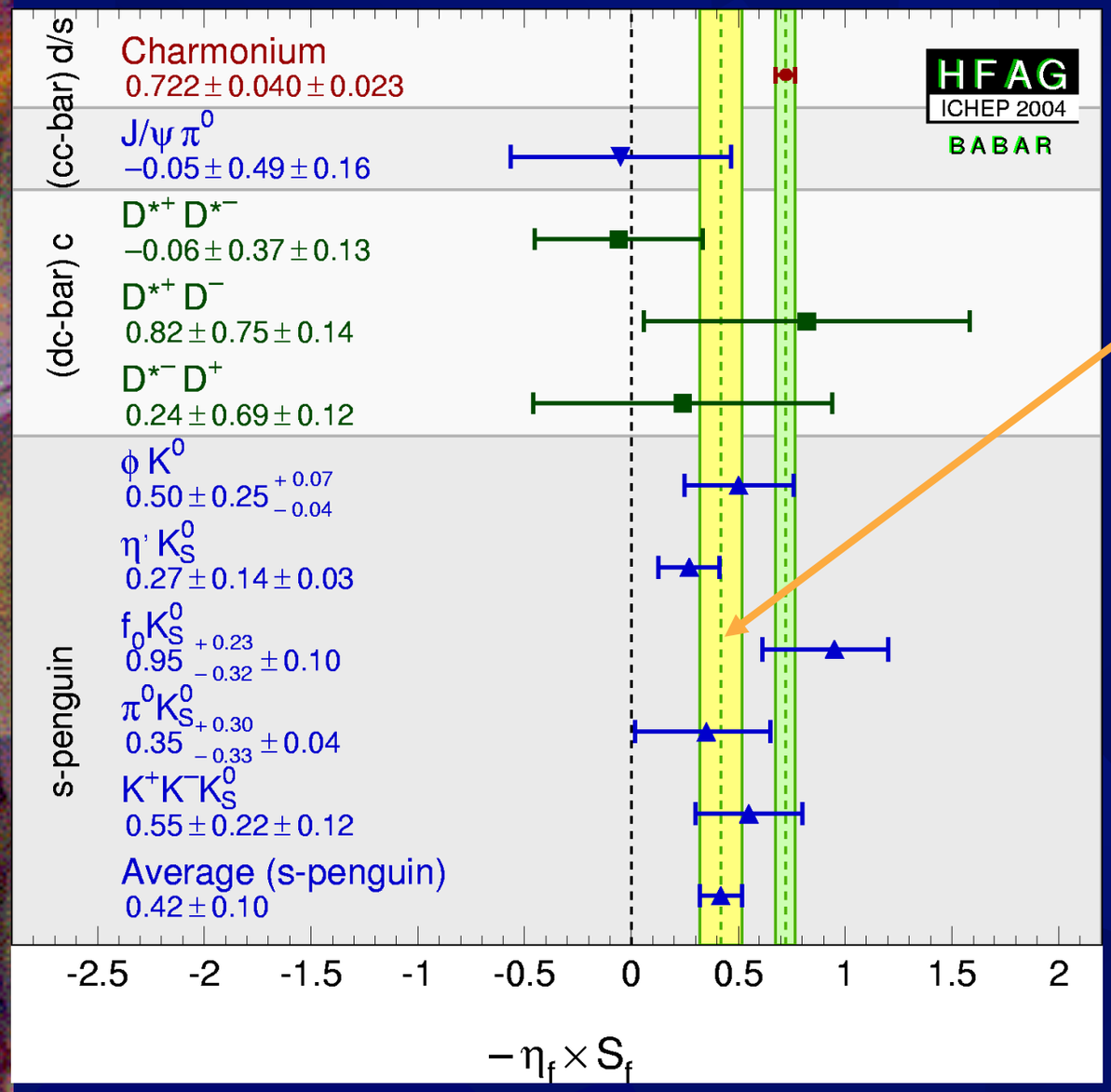
- Experimental situation: (after LP 03)
  - $S(\Phi K_S)$ =+0.45±0.43±0.07 BaBar
  - $S(\Phi K_S)$ = -0.96±0.50±0.10 Belle

  } -0.15±0.33

$S(\Phi K_S) - S(J/\psi\, K_S) = -0.88 \pm 0.33\ (2.7\sigma)$



New Physics in penguins?



s-penguin average at 2.7σ different from sin2β[cc] (BABAR)

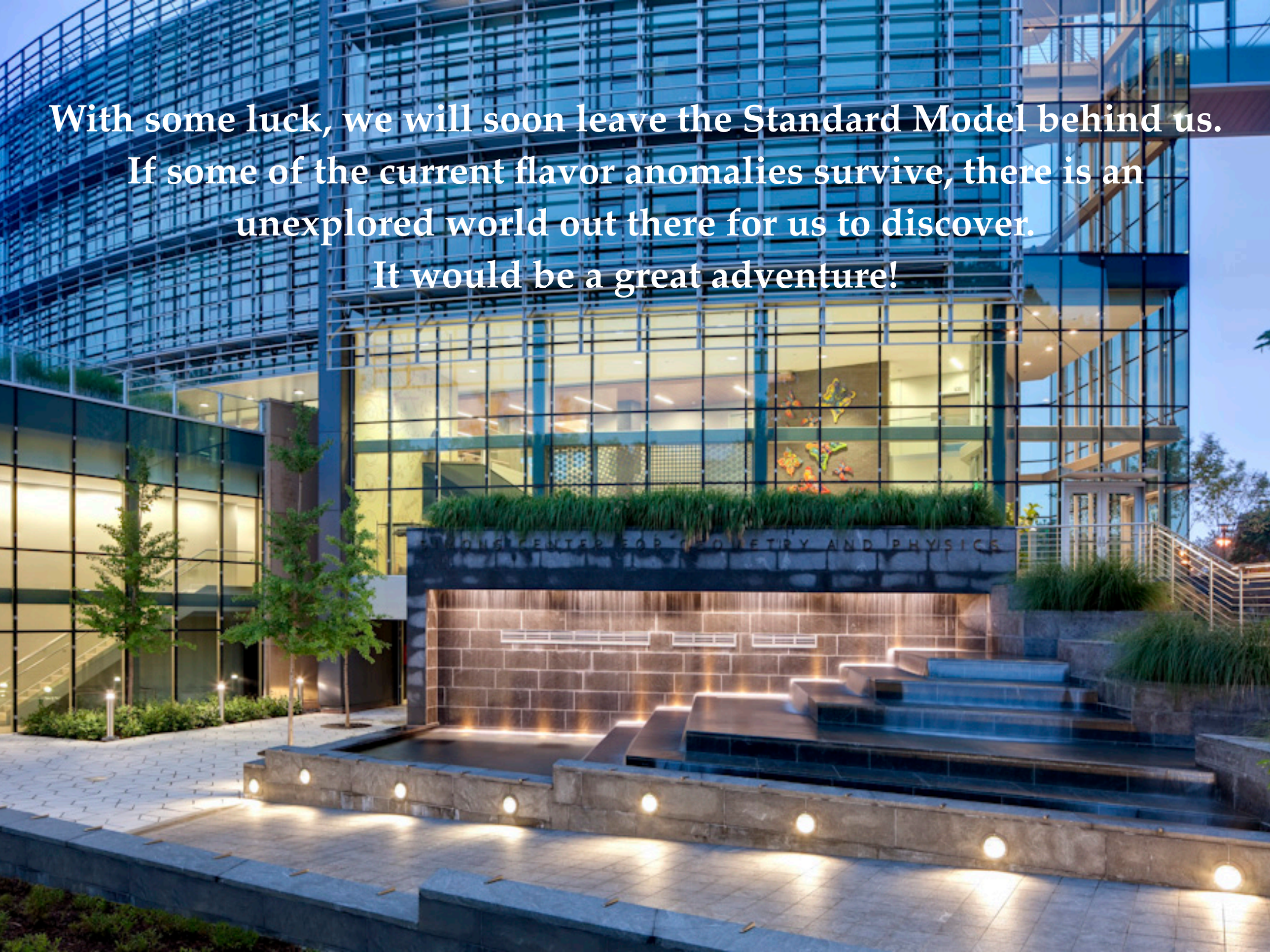
Similar difference at 2.4 σ seen by Belle

[A. Hoecker, ICHEP 2004]

$B^0 \to \phi K^0$ $B^0 \to K^+K^-K^0$ $B^0 \to \eta' K^0$ $B^0 \to f_0 K^0$ $B^0 \to \pi^0 K^0$

B-flavor anomalies - quo vadis?

- Today we are in a much better situation, and the flavor anomalies are **much more compelling**!
- But also now, we should not necessarily assume that all anomalies are correct ….
- An independent confirmation of the flavor anomalies by Belle II is as crucial as refining the current LHCb analyses


With some luck, we will soon leave the Standard Model behind us.
If some of the current flavor anomalies survive, there is an
unexplored world out there for us to discover.
It would be a great adventure!