PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Flavor Physics & Flavor Anomalies

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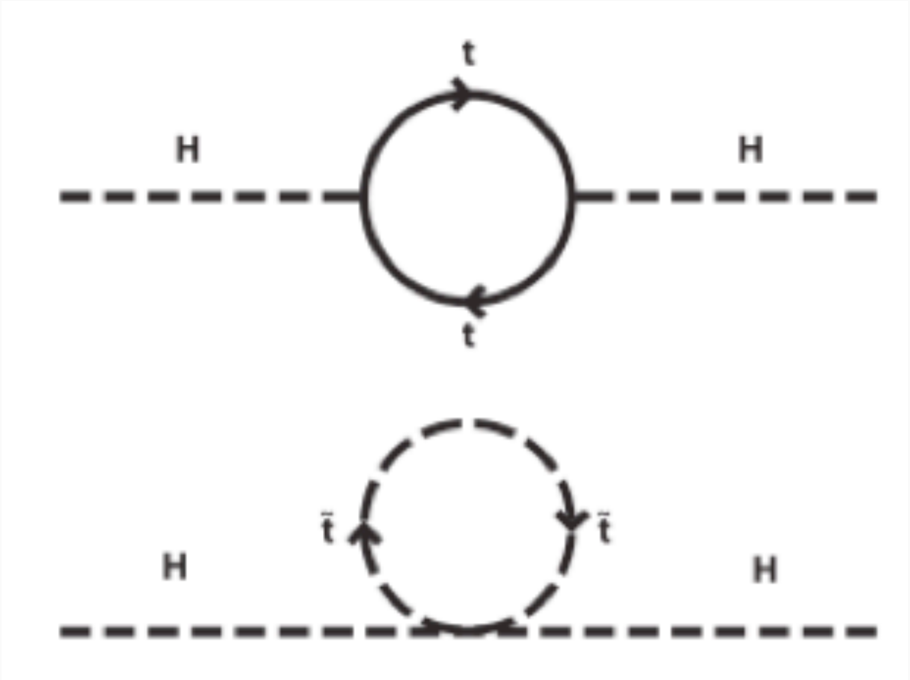
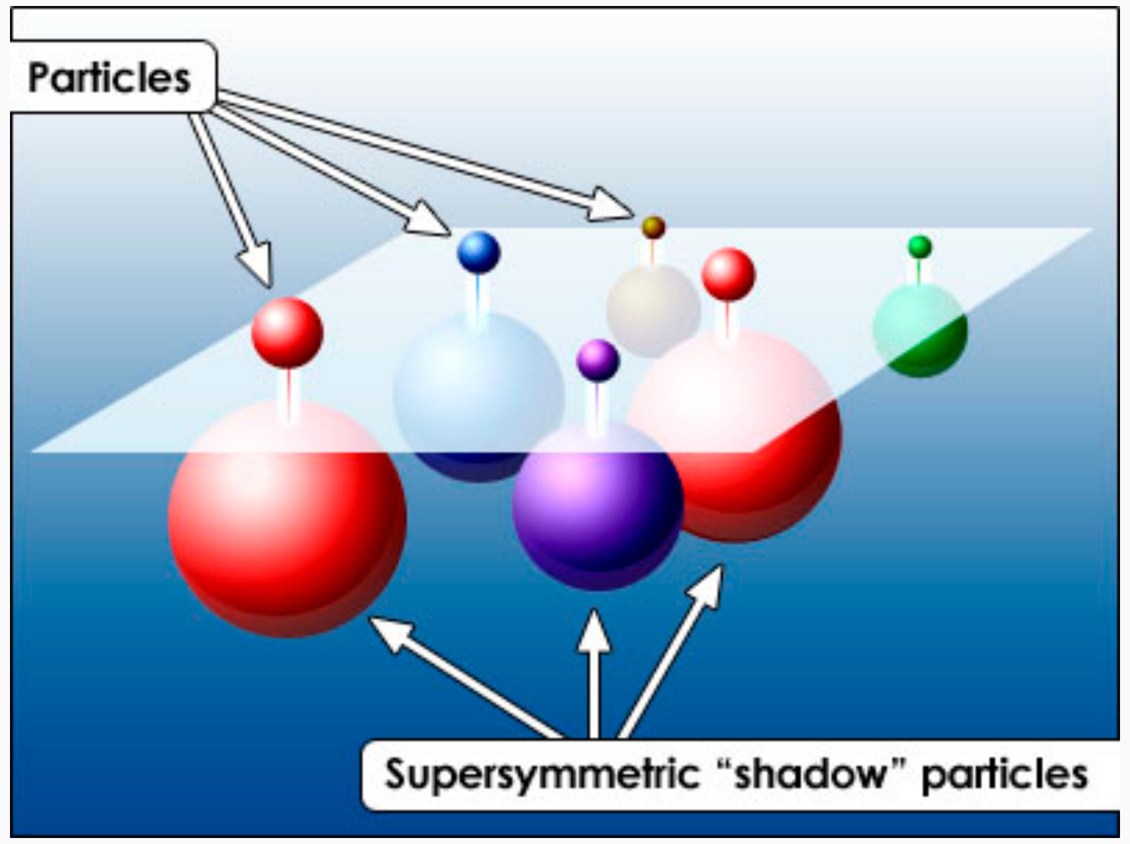
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

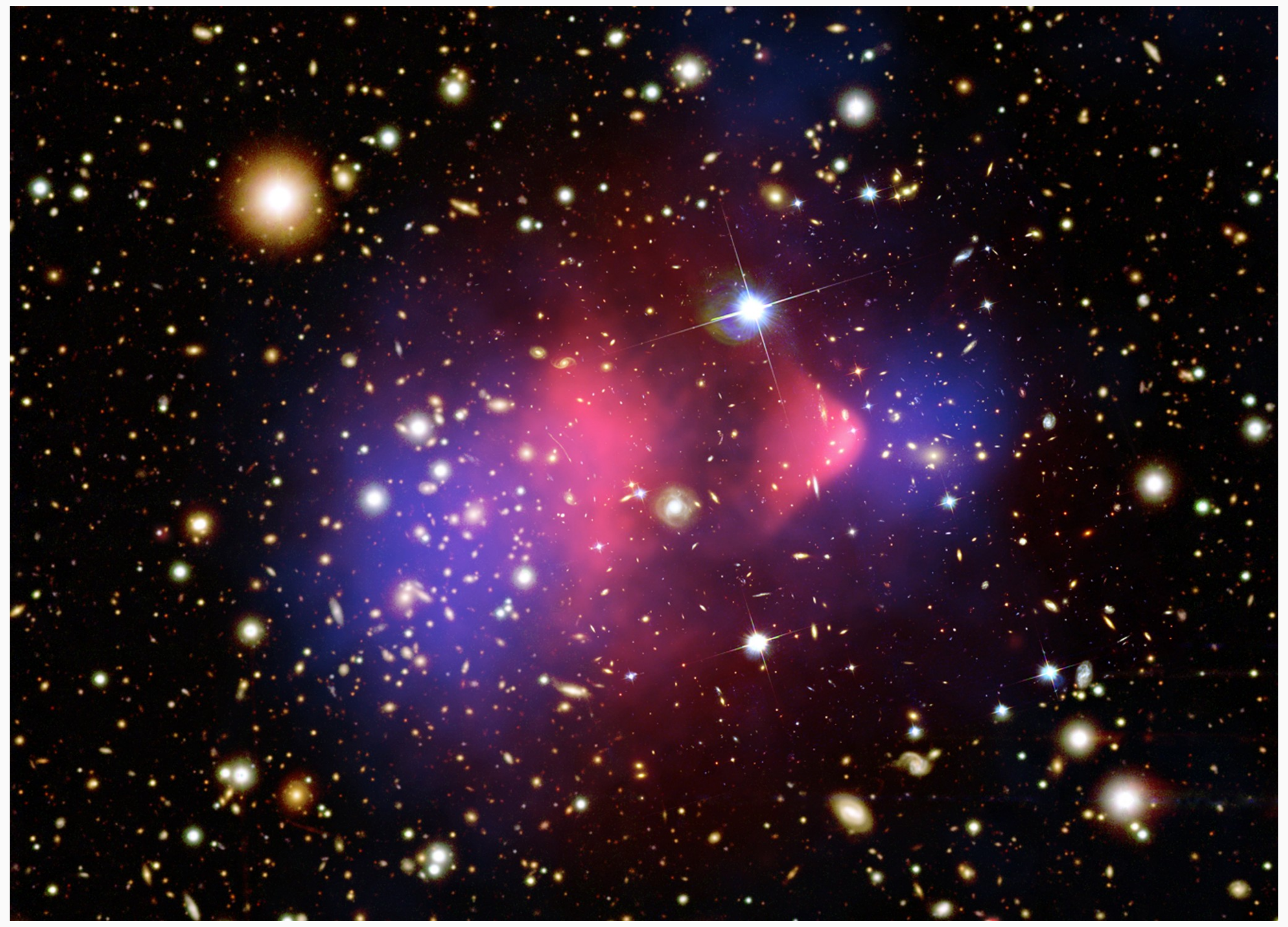
Mainz Institute for Theoretical Physics

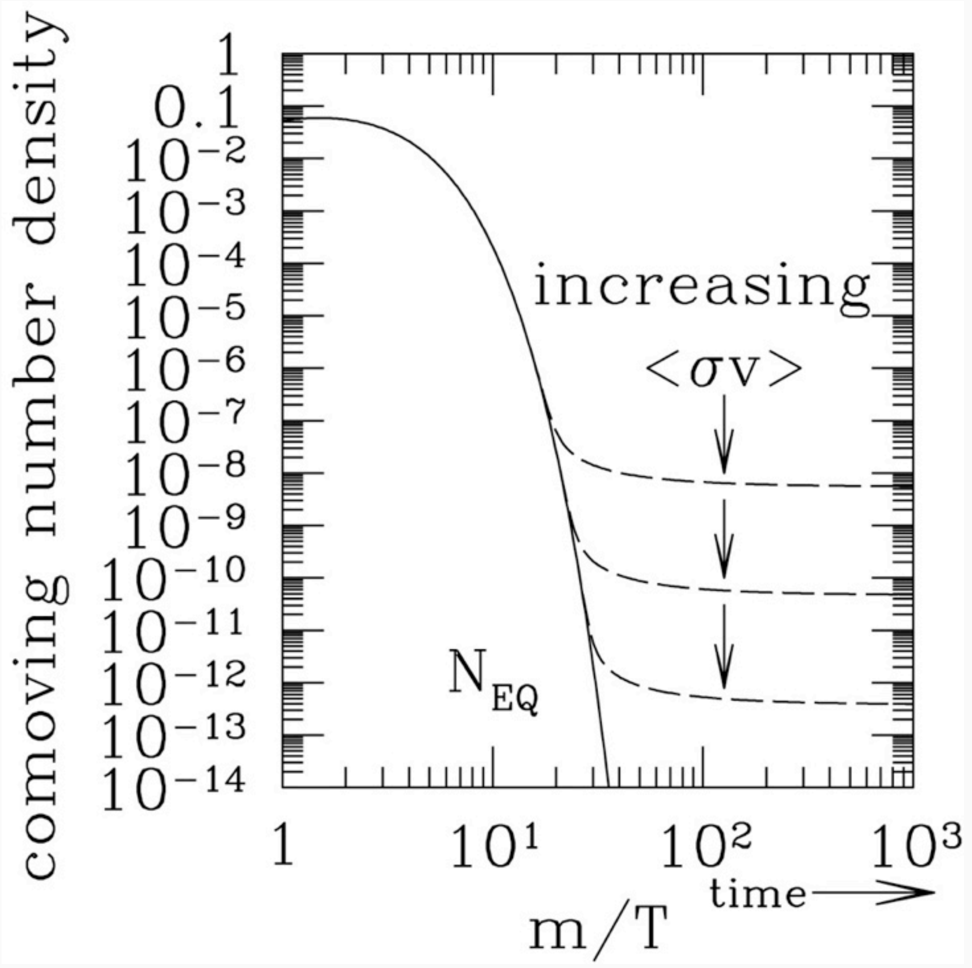
Is Nature natural?

Hierarchie problem suggested that a “natural” theory of electroweak symmetry breaking should contain new colored particle near the weak scale









Existence of dark matter suggested that there should be new weakly interacting particles near the weak scale (WIMP miracle)

Where are they?

Overview

1. Hints for New Physics
2. The Flavor of h(125) and S(750)
3. Flavor Anomalies in the B Sector
4. One Leptoquark to Rule Them All
5. Outlook

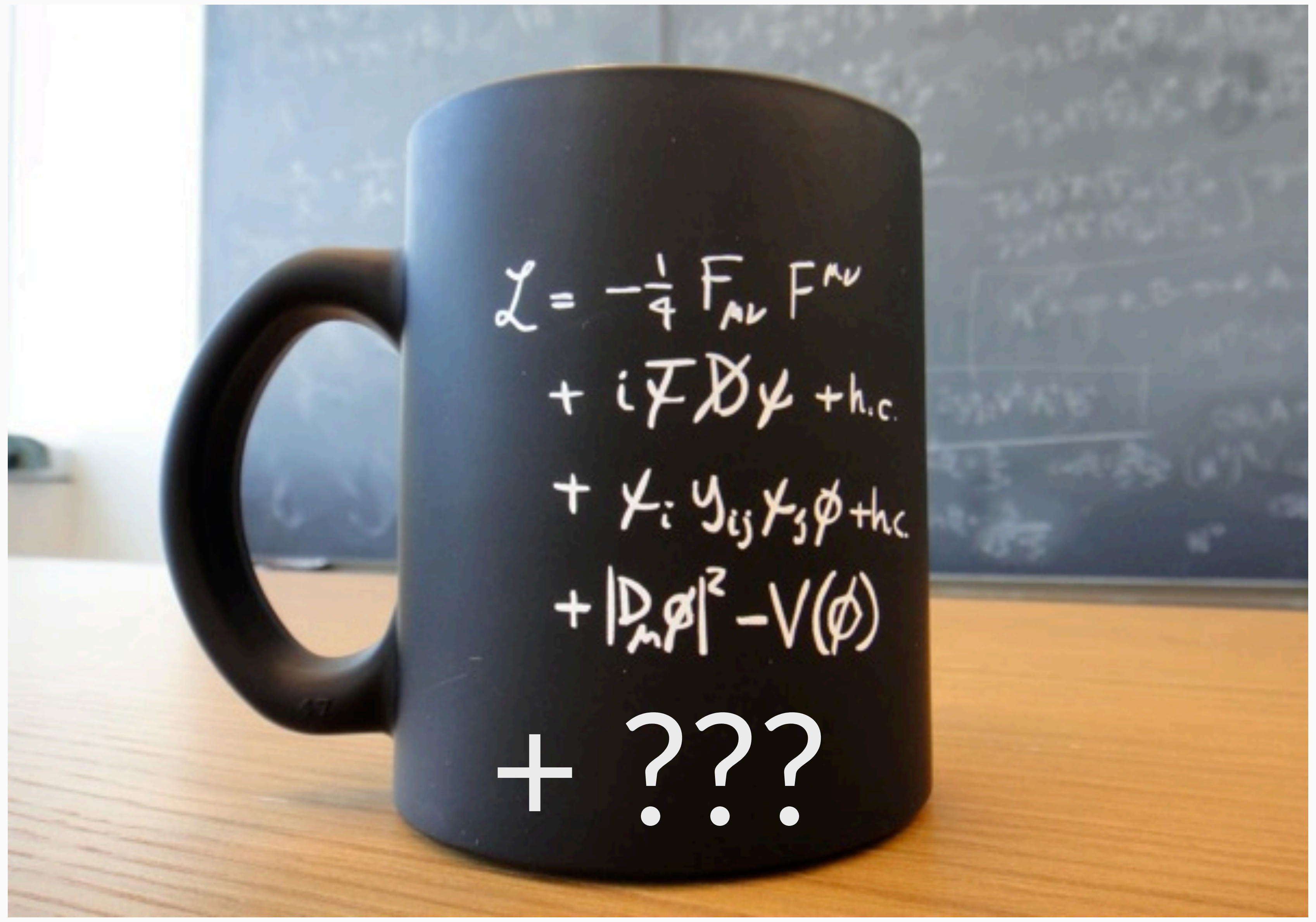
Hints for New Physics

Dark matter, flavor anomalies and a diphoton resonance

On the verge of another discovery?

While we have not observed any of the expected faces of new physics, there exist several tantalizing hints of effects which cannot be explained by the Standard Model

- Dark matter
- Neutrino masses and mixings
- Anomalous magnetic moment of the muon
- **Various anomalies in the flavor sector**
- Hints for new heavy resonance S(750) from Run 2



Anomalies in the flavor sector

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\|V_{ub}\|$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\|V_{cb}\|$
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$

(Wolfgang Altmannshofer, Aspen Winter Conference on Particle Physics 2016)

The Flavor of h(125) and S(750)

Deciphering the flavor of the scalar bosons

Flavor-changing Higgs couplings ?

In the Standard Model, the Higgs couplings are automatically flavor-diagonal in the mass basis

$$\mathcal{L}_{SM} = \bar{f}_L^j i\not{D} f_L^j + \bar{f}_R^j i\not{D} f_R^j - \left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$

Presence of new-physics interactions can change this; at low energies effects can be parameterized through higher-dimensional operators:

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c.$$

Transformation to the mass basis no longer diagonalizes the Higgs couplings:

$$\sqrt{2}m = V_L\left[\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right]V_R^\dagger v\,, \qquad \sqrt{2}Y = V_L\left[\lambda + 3\frac{v^2}{2\Lambda^2}\lambda'\right]V_R^\dagger$$

Net result:

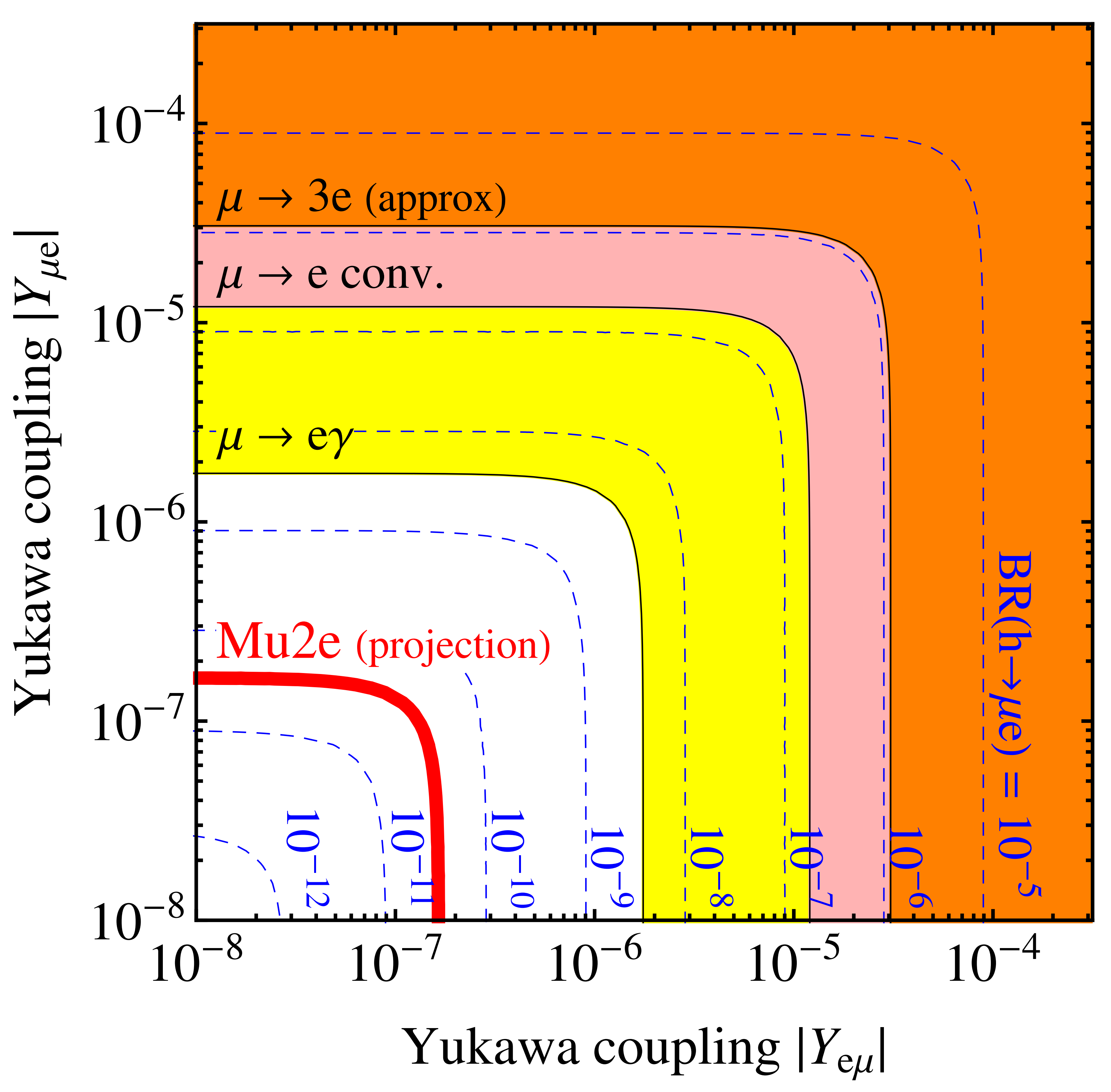
$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

Entries of these matrices (for up, down and lepton sectors) are constrained by **direct and indirect measurements** of various kinds, e.g.:

- dipole transitions
- EDMs
- neutral meson mixing
- …

Flavor-changing Higgs couplings to leptons ?

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \dots 1.0$
$\mu \to e\gamma$	$(\lvert Y_{\tau\mu} Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau} Y_{\tau e}\rvert^2)^{1/4}$	$< 3.4 \times 10^{-4}$



Harnik, Kopp, Zupan (arXiv:1209:1397)

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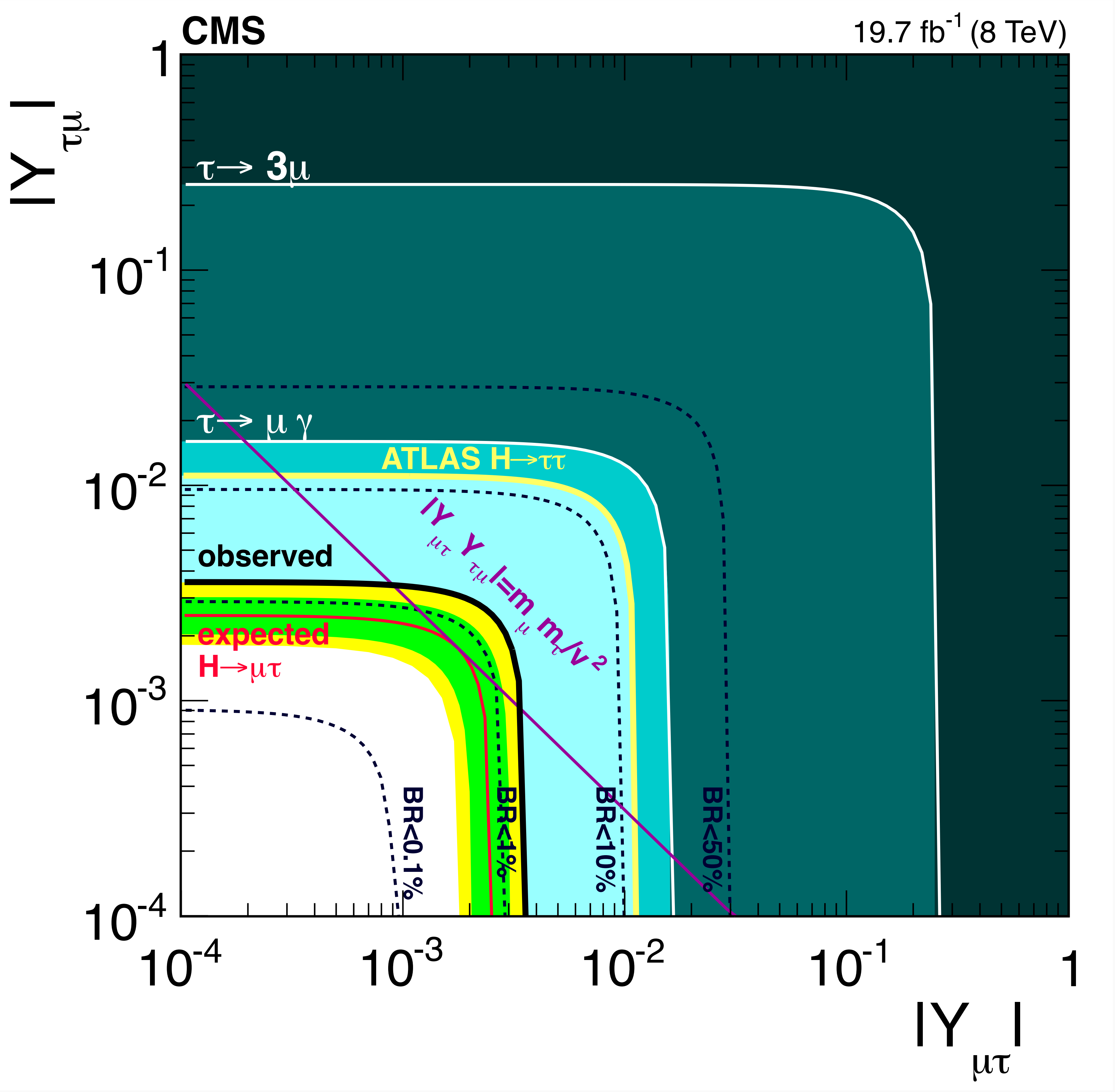


$$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2} = (2.6 \pm 0.6) \cdot 10^{-3}$$

Harnik, Kopp, Zupan (arXiv:1209:1397)

Flavor-changing Higgs couplings to quarks ?

Technique	Coupling	Constraint
D^0 oscillations [49]	$\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$	$< 5.0\times10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5\times10^{-10}$
B_d^0 oscillations [49]	$\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$	$< 2.3\times10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3\times10^{-9}$
B_s^0 oscillations [49]	$\lvert Y_{sb}\rvert^2,\ \lvert Y_{bs}\rvert^2$	$< 1.8\times10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5\times10^{-7}$
K^0 oscillations [49]	$\mathrm{Re}(Y_{ds}^2),\ \mathrm{Re}(Y_{sd}^2)$	$[-5.9\ldots5.6]\times10^{-10}$
	$\mathrm{Im}(Y_{ds}^2),\ \mathrm{Im}(Y_{sd}^2)$	$[-2.9\ldots1.6]\times10^{-12}$
	$\mathrm{Re}(Y_{ds}^*Y_{sd})$	$[-5.6\ldots5.6]\times10^{-11}$
	$\mathrm{Im}(Y_{ds}^*Y_{sd})$	$[-1.4\ldots2.8]\times10^{-13}$

Technique	Coupling	Constraint
single-top production [50]	$\sqrt{\lvert Y_{tc}^2\rvert+\lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert+\lvert Y_{ut}\rvert^2}$	< 1.6
$t\to hj$ [51]	$\sqrt{\lvert Y_{tc}^2\rvert+\lvert Y_{ct}\rvert^2}$	< 0.34 < 0.13
	$\sqrt{\lvert Y_{tu}^2\rvert+\lvert Y_{ut}\rvert^2}$	< 0.34 < 0.12
D^0 oscillations [49]	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6\times10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2\times10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9\times10^{-3}$
neutron EDM [37, 52]	$\lvert\mathrm{Im}(Y_{ut}Y_{tu})\rvert$	$< 4.3\times10^{-7}$
	$\lvert\mathrm{Im}(Y_{ct}Y_{tc})\rvert$	$< 5.0\times10^{-4}$

Recent ATLAS measurements:

$$\mathrm{BR}(t\to ch) < 0.0046$$
$$\mathrm{BR}(t\to uh) < 0.0045$$

Harnik, Kopp, Zupan (arXiv:1209:1397)
Buschmann, Kopp, Liu, Wang (arXiv:1601.02616)

Flavor-changing couplings of S(750) ?

A hypothetical new heavy scalar resonance S, which is a singlet under the Standard Model, can couple to SM particle via dimension-5 effective interactions:

$$\mathcal{L}_{\rm eff} = -\lambda_1\, S\,\phi^\dagger\phi - \frac{\lambda_2}{2}\, S^2\,\phi^\dagger\phi - \frac{\lambda_3}{6\Lambda}\, S^3\,\phi^\dagger\phi - \frac{\lambda_4}{\Lambda}\, S\,(\phi^\dagger\phi)^2$$
$$+ \frac{c_{gg}}{\Lambda}\frac{\alpha_s}{4\pi}\, S\, G_{\mu\nu}^a G^{\mu\nu,a} + \frac{c_{WW}}{\Lambda}\frac{\alpha}{4\pi s_w^2}\, S\, W_{\mu\nu}^a W^{\mu\nu,a} + \frac{c_{BB}}{\Lambda}\frac{\alpha}{4\pi c_w^2}\, S B_{\mu\nu} B^{\mu\nu}$$
$$+ \frac{\tilde c_{gg}}{\Lambda}\frac{\alpha_s}{4\pi}\, S\, G_{\mu\nu}^a \widetilde{G}^{\mu\nu,a} + \frac{\tilde c_{WW}}{\Lambda}\frac{\alpha}{4\pi s_w^2}\, S\, W_{\mu\nu}^a \widetilde{W}^{\mu\nu,a} + \frac{\tilde c_{BB}}{\Lambda}\frac{\alpha}{4\pi c_w^2}\, S B_{\mu\nu} \widetilde{B}^{\mu\nu}$$
$$- \frac{1}{\Lambda}\Big(S\,\bar Q_L\, \hat{\boldsymbol{Y}}_u\, \tilde\phi\, u_R + S\,\bar Q_L\, \hat{\boldsymbol{Y}}_d\, \phi\, d_R + S\,\bar L_L\, \hat{\boldsymbol{Y}}_e\, \phi\, e_R + \text{h.c.}\Big)$$

After transformation to the mass basis, define:

$$\boldsymbol{\lambda}_f \equiv \frac{\boldsymbol{U}_f^\dagger \hat{\boldsymbol{Y}}_f \boldsymbol{W}_f + \boldsymbol{W}_f^\dagger \hat{\boldsymbol{Y}}_f^\dagger \boldsymbol{U}_f}{2}\,, \qquad \widetilde{\boldsymbol{\lambda}}_f \equiv \frac{\boldsymbol{U}_f^\dagger \hat{\boldsymbol{Y}}_f \boldsymbol{W}_f - \boldsymbol{W}_f^\dagger \hat{\boldsymbol{Y}}_f^\dagger \boldsymbol{U}_f}{2i}$$

This leads to the following couplings:

$$\mathcal{L}_{\rm eff} \ni -\frac{v}{\sqrt{2}\,\Lambda}\left(1 + \frac{h}{v}\right) \sum_{f=u,d,e} \left(S\,\bar f\, \boldsymbol{\lambda}_f\, f + S\,\bar f\, \widetilde{\boldsymbol{\lambda}}_f\, i\gamma_5\, f \right)$$

Entries of these matrices (for up, down and lepton sectors) are constrained by same **direct and indirect measurements** which constrain the Higgs couplings

Flavor-changing couplings of S(750) ?

Summary of constraints:

Bound on $Y_{f,f'}$	Observable	$\Gamma(S \to f f')/M$
$\lvert\text{Im}(Y_{ee})\rvert \lesssim 6 \times 10^{-8}$	d_e	$\lesssim 1 \times 10^{-16}$
$\lvert\text{Im}(Y_{dd})\rvert \lesssim 2 \times 10^{-4}$	d_N, d_{Hg}	$\lesssim 5 \times 10^{-9}$
$\lvert\text{Im}(Y_{uu})\rvert \lesssim 3 \times 10^{-4}$	d_N, d_{Hg}	$\lesssim 1 \times 10^{-8}$
$\lvert\text{Im}(Y_{cc})\rvert \lesssim 0.3$	d_N, d_{Hg}	$\lesssim 0.01$
$\lvert Y_{e\mu}\rvert, \lvert Y_{\mu e}\rvert \lesssim 1 \times 10^{-5}$	$\mathcal{B}(\mu \to e\gamma)$	$\lesssim 4 \times 10^{-12}$
$\lvert Y_{e\tau}\rvert, \lvert Y_{\tau e}\rvert \lesssim 0.05$	$\mathcal{B}(\tau \to e\gamma)$	$\lesssim 1 \times 10^{-4}$
$\lvert Y_{\mu\tau}\rvert, \lvert Y_{\tau\mu}\rvert \lesssim 0.06$	$\mathcal{B}(\tau \to \mu\gamma)$	$\lesssim 1 \times 10^{-4}$
$\sqrt{\text{Re}[(Y_{sd})^2]}, \sqrt{\text{Re}[(Y_{ds})^2]} < 1.0 \times 10^{-4}$	Δm_K	$< 1.2 \times 10^{-9}$
$\sqrt{\text{Im}[(Y_{sd})^2]}, \sqrt{\text{Im}[(Y_{ds})^2]} < 7.2 \times 10^{-6}$	ϵ_K	$< 6.2 \times 10^{-12}$
$\lvert(Y_{cu})\rvert, \lvert(Y_{uc})\rvert < 3.0 \times 10^{-4}$	x_D	$< 1.1 \times 10^{-8}$
$\lvert(Y_{bd})\rvert, \lvert(Y_{db})\rvert < 6.4 \times 10^{-4}$	Δm_d	$< 4.9 \times 10^{-8}$
$\lvert(Y_{bs})\rvert, \lvert(Y_{sb})\rvert < 5.7 \times 10^{-3}$	Δm_s	$< 3.9 \times 10^{-6}$

$$Y_{f_i f_j} \equiv \frac{v}{\sqrt{2}\Lambda}\left(\lambda_f + i\tilde{\lambda}_f\right)_{ij}$$

Goertz, Kamenik, Katz, Nardecchia (arXiv:1512.08500)

After transformation to the mass basis, define:

$$\boldsymbol{\lambda}_f \equiv \frac{\boldsymbol{U}_f^\dagger \hat{\boldsymbol{Y}}_f \boldsymbol{W}_f + \boldsymbol{W}_f^\dagger \hat{\boldsymbol{Y}}_f^\dagger \boldsymbol{U}_f}{2}\,, \qquad \widetilde{\boldsymbol{\lambda}}_f \equiv \frac{\boldsymbol{U}_f^\dagger \hat{\boldsymbol{Y}}_f \boldsymbol{W}_f - \boldsymbol{W}_f^\dagger \hat{\boldsymbol{Y}}_f^\dagger \boldsymbol{U}_f}{2i}$$

For $\boldsymbol{\lambda}_f$ and $\widetilde{\boldsymbol{\lambda}}_f$ to be nearly diagonal, they should be related to the SM Yukawa matrices in some way!

Example:

S can be the 5-dimensional **bulk scalar field** in **Randall-Sundrum** models, whose VEV determines the 5D mass terms for the fermions

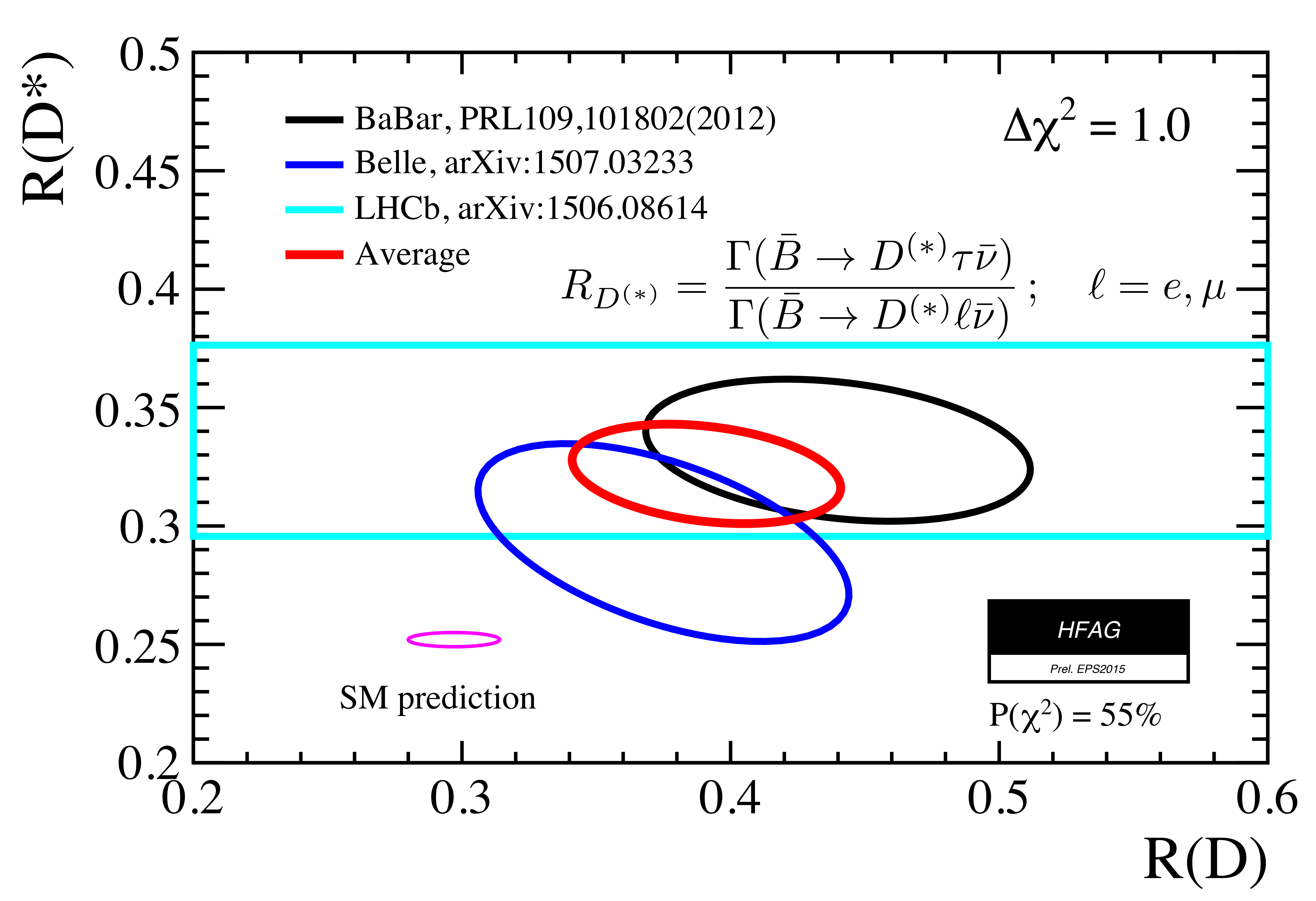
⇒ its flavor-changing couplings are protected by the RS-GIM mechanism and automatically hierarchical

Bauer, Hörner, MN (arXiv:1603.05978)

Flavor Anomalies in the B Sector

A brief tour through flavorland

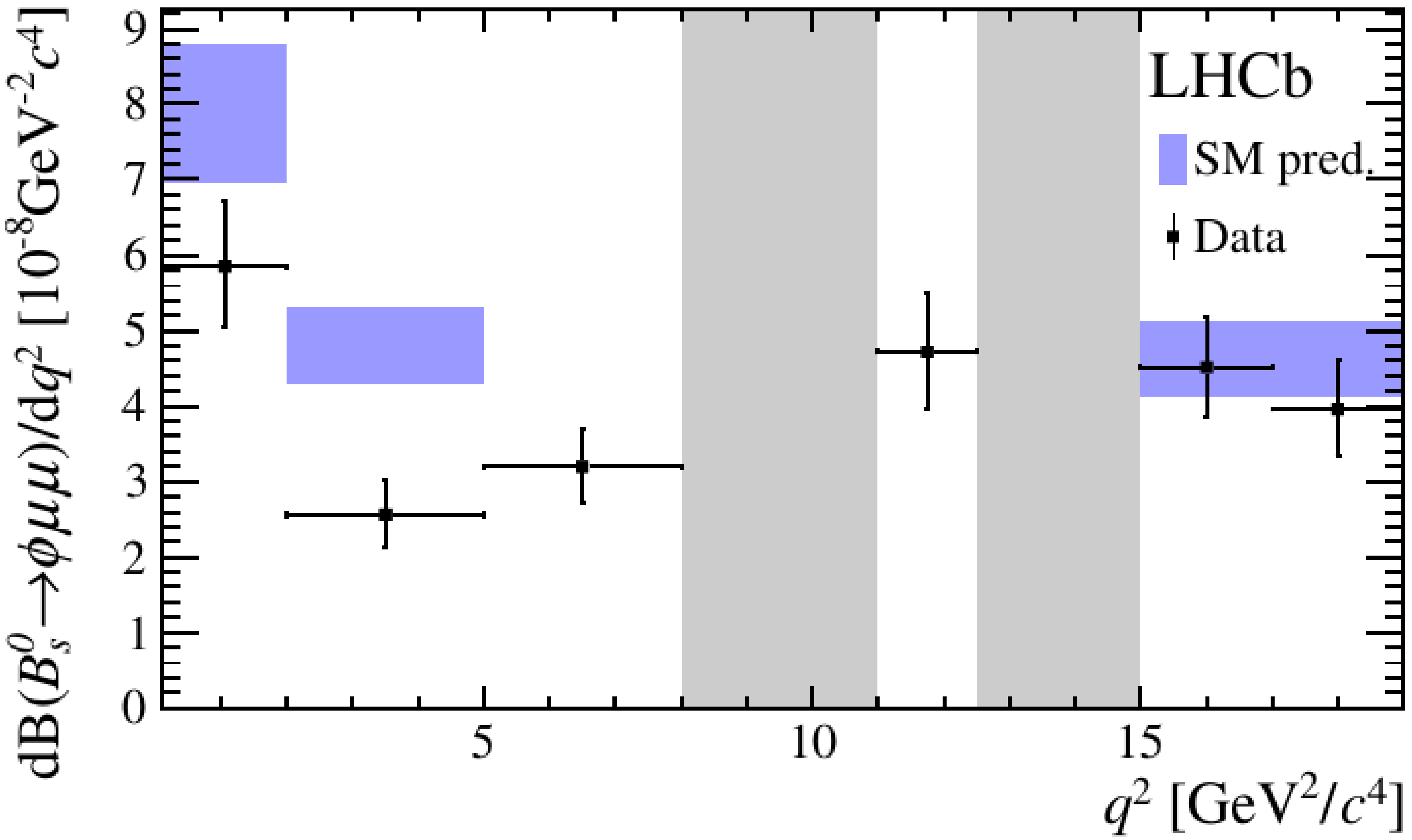
Flavor anomalies: Enhanced $B \to D^{(*)}\tau\nu$ rates



Semileptonic decays with tau leptons are 3.5σ higher than SM prediction!

Flavor anomalies: Suppressed $B_s \to \Phi\, \mu^+\mu^-$ branching ratio

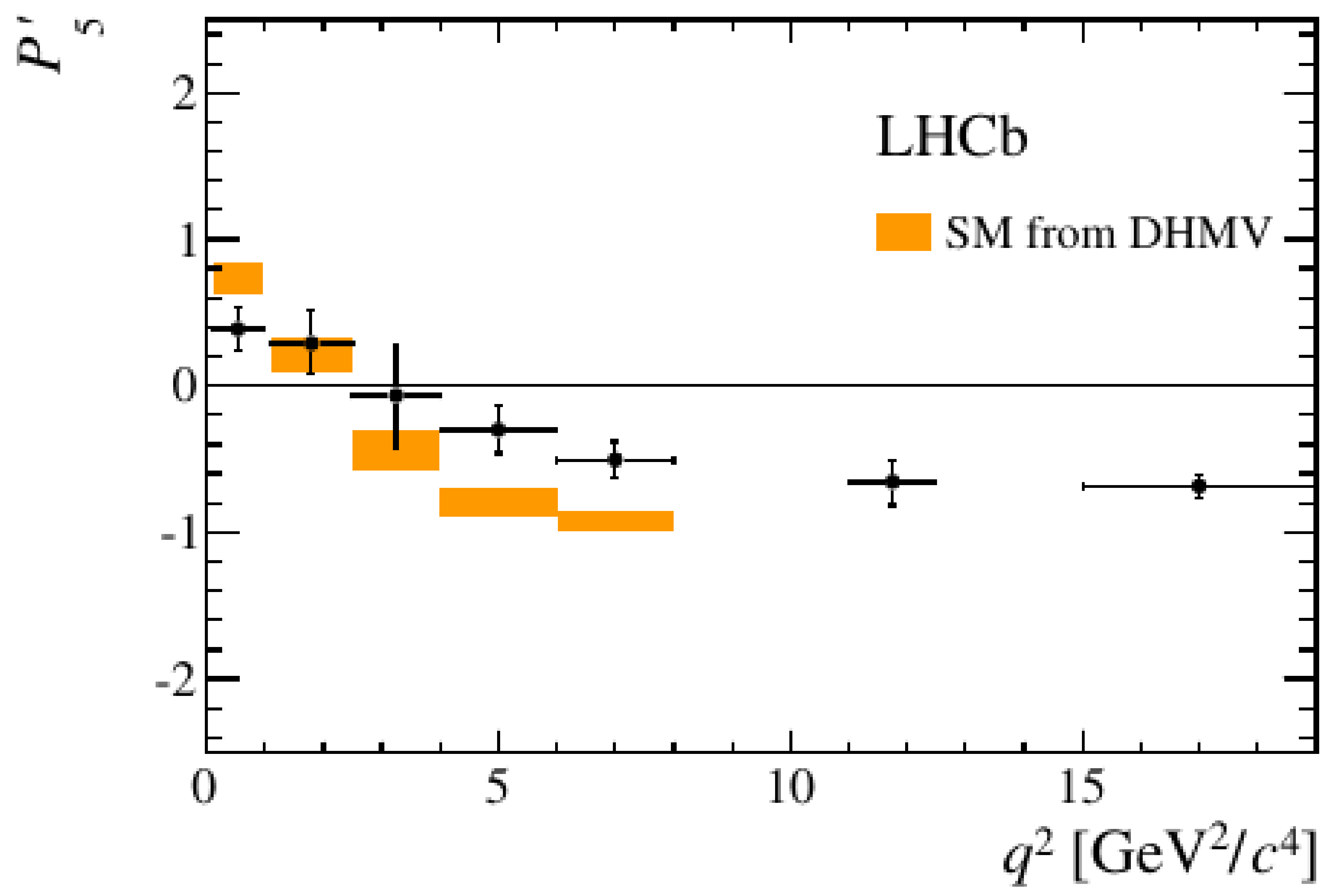
LHCb 1506.08777



Branching ratio in region 1 GeV^2 < q^2 < 6 GeV^2 is 3.5σ lower than SM prediction!

Flavor anomalies: $B \to K^* \mu^+ \mu^-$ angular distributions

LHCb 1512.04442



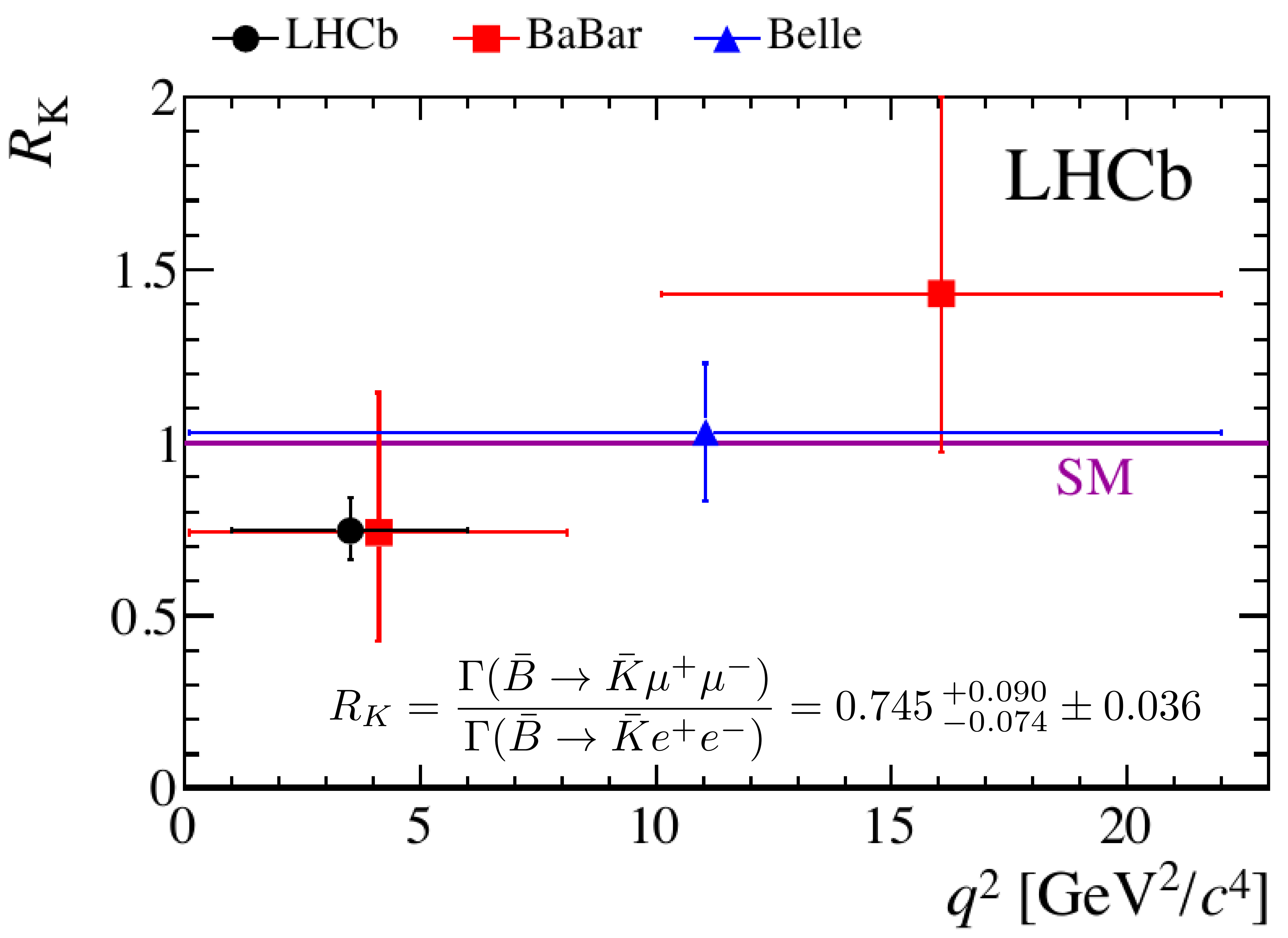
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$

Altmannshofer, Straub (arXiv:1503:06199)

2.8σ deviation in q^2 bin between [4, 6] GeV^2 (3.0σ in bin [6, 8] GeV^2) !

Flavor anomalies: $B \to K \mu^+\mu^-$ vs. $B \to K e^+e^-$

LHCb 1406.6482



2.6σ hint for a violation of lepton flavor universality!

Flavor anomalies — reason for excitement

The flavor anomalies in rare *B*-meson decays are:

- in many cases statistically significant
- seen by more than one experiment
- provide a **coherent picture** when interpreted in terms of new physics contributions to one or two operators in the effective weak Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i O_i$$

Coefficient	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\mathcal{C}_9^{\text{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	4.5
$\mathcal{C}_{10}^{\text{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7
$\mathcal{C}_{9'}^{\text{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8
$\mathcal{C}_{10'}^{\text{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	4.1
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	4.8

Descotes-Genon, Hofer, Matias, Virto (arXiv:1510:04239)

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{9'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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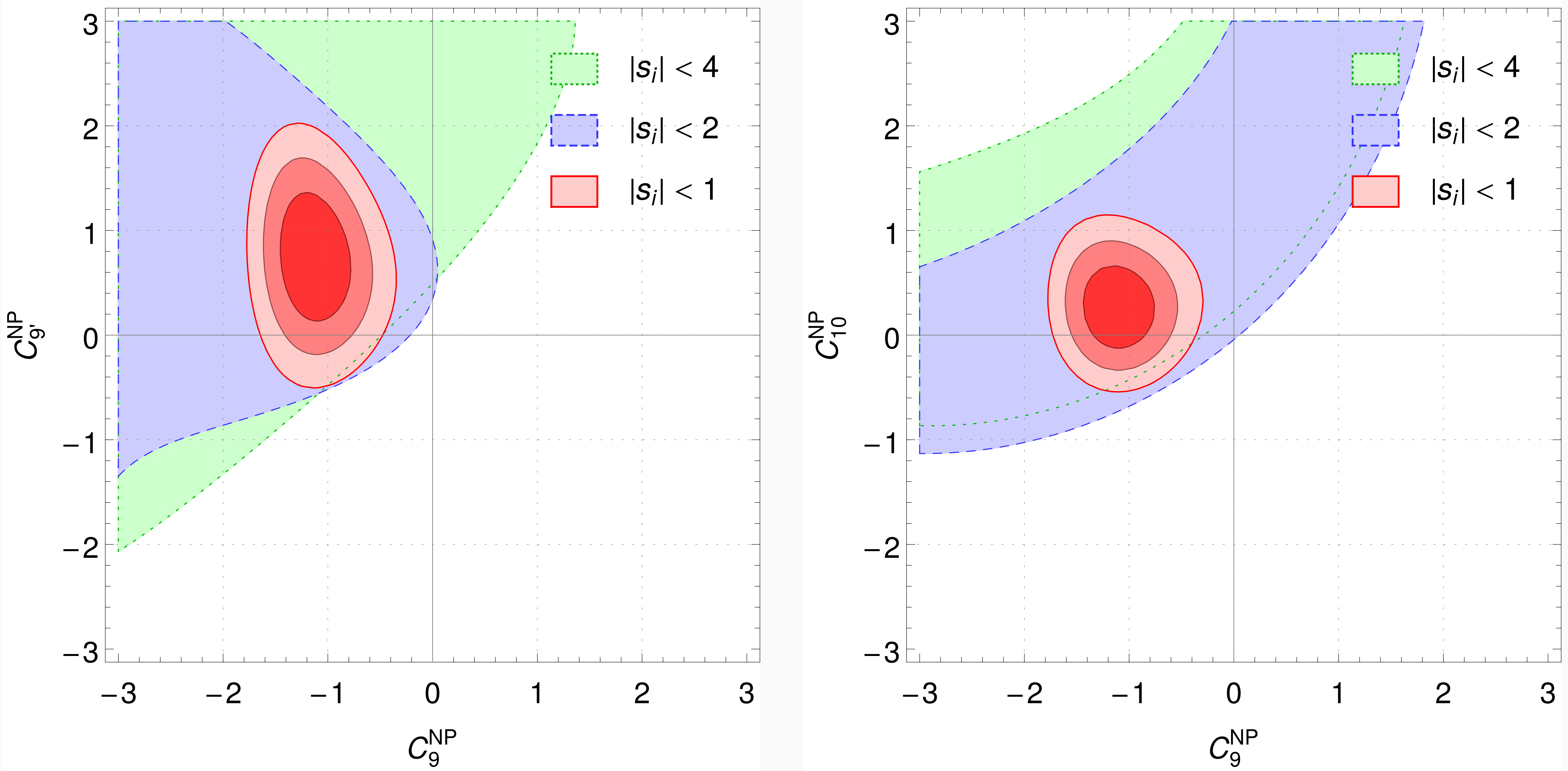

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$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

One Leptoquark to Rule them All

Explaining the flavor anomalies

Based on a collaboration with Martin Bauer (arXiv:1511:01900, Phys. Rev. Lett. 2016)

A minimal leptoquark model

We add a single leptoquark $\phi \sim (\mathbf{3},\mathbf{1})_{-1/3}$ to the Standard Model, with couplings:

$$\mathcal{L}_\phi = (D_\mu\phi)^\dagger D_\mu\phi - M_\phi^2\,|\phi|^2 - g_{h\phi}\,|\Phi|^2|\phi|^2 \\ + \bar{Q}^c\boldsymbol{\lambda}^L i\tau_2 L\,\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}^R e_R\,\phi^* + \text{h.c.}$$

After rotation to the mass basis, we have:

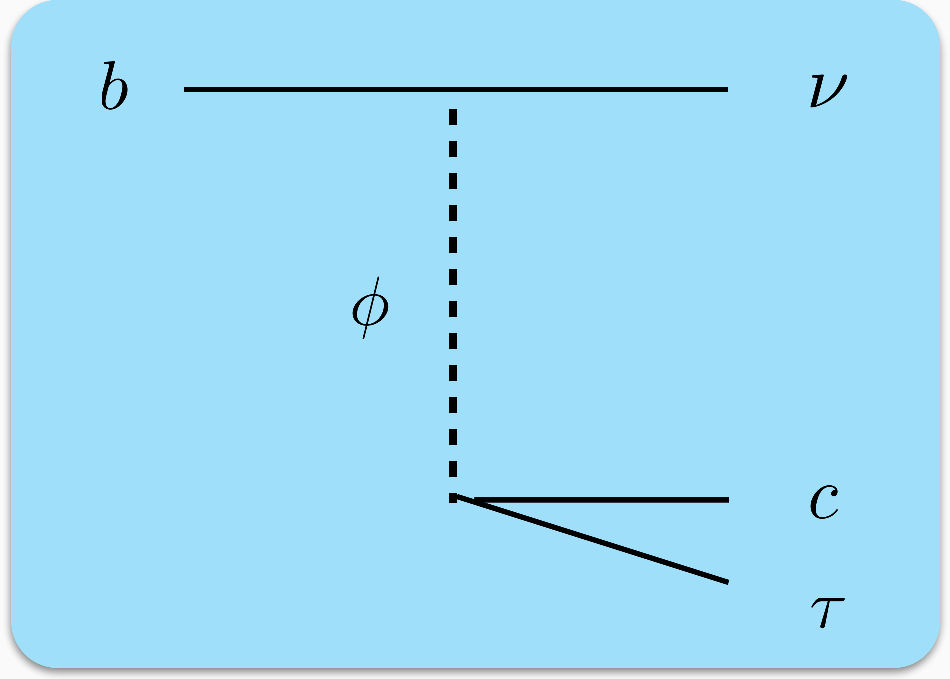
$$\mathcal{L}_\phi \ni \bar{u}_L^c\boldsymbol{\lambda}_{ue}^L e_L\,\phi^* - \bar{d}_L^c\boldsymbol{\lambda}_{d\nu}^L\nu_L\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}_{ue}^R e_R\,\phi^* + \text{h.c.}$$

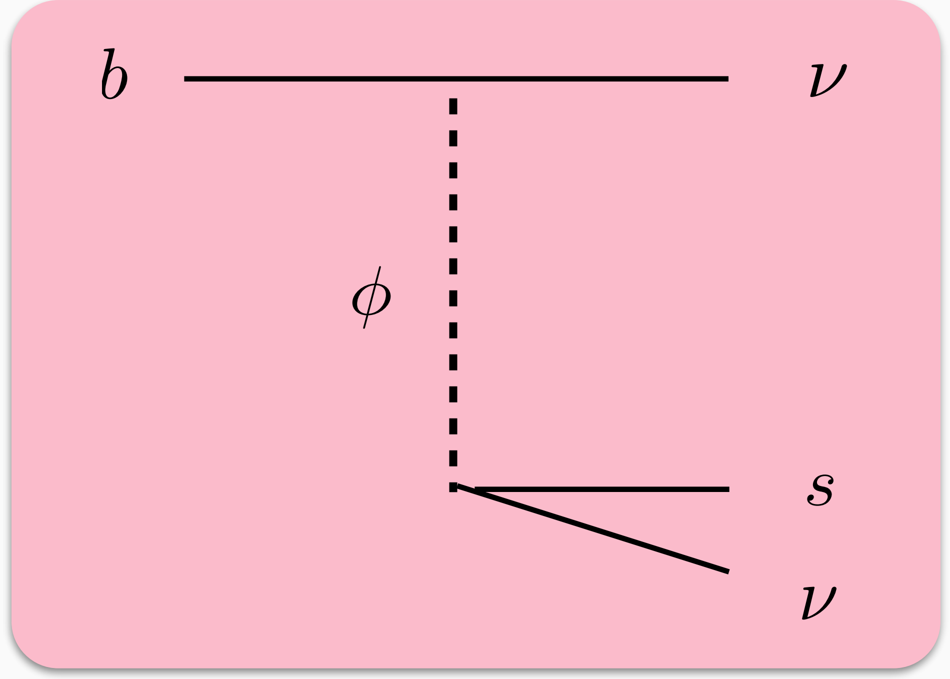
with:

$$\boldsymbol{V}_{\text{CKM}}^T\,\boldsymbol{\lambda}_{ue}^L = \boldsymbol{\lambda}_{d\nu}^L\boldsymbol{U}_e$$

UV completion: ϕ could be the right-handed sbottom of a split SUSY model, with left-handed couplings derived from the R-parity violating terms in the superpotential (expect $|\lambda^R| \ll |\lambda^L|$)

At tree level, this gives rise to e.g.:



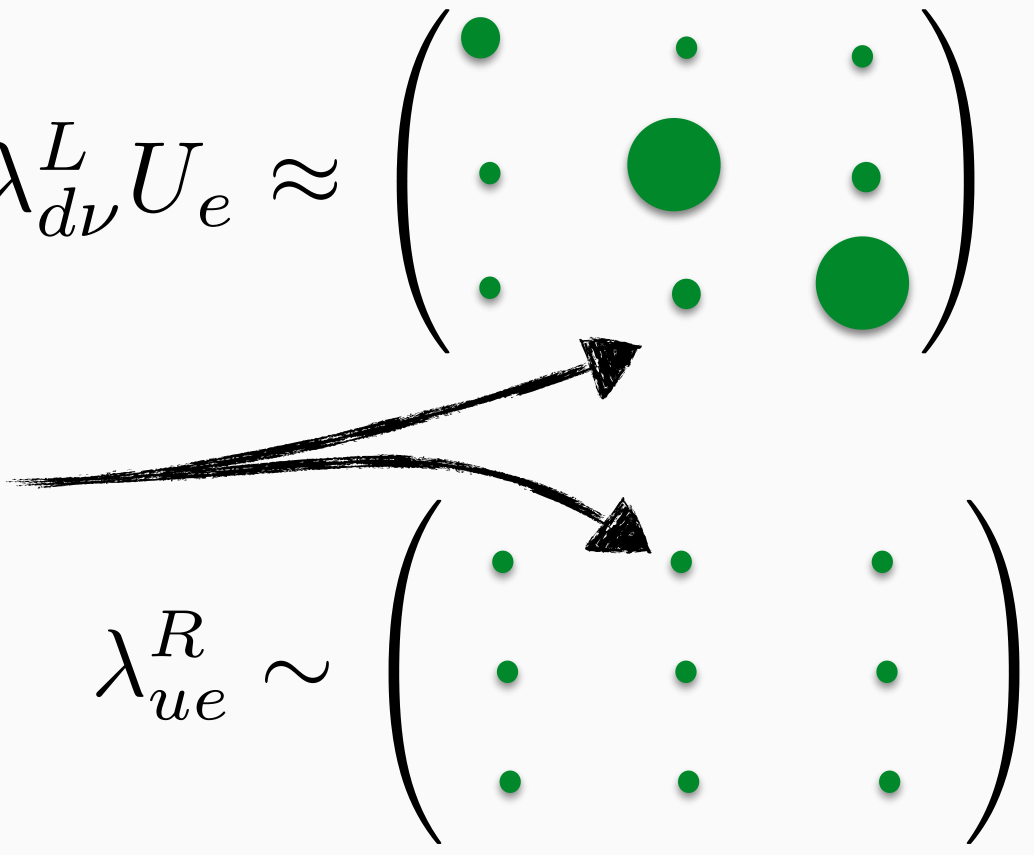


Will need:

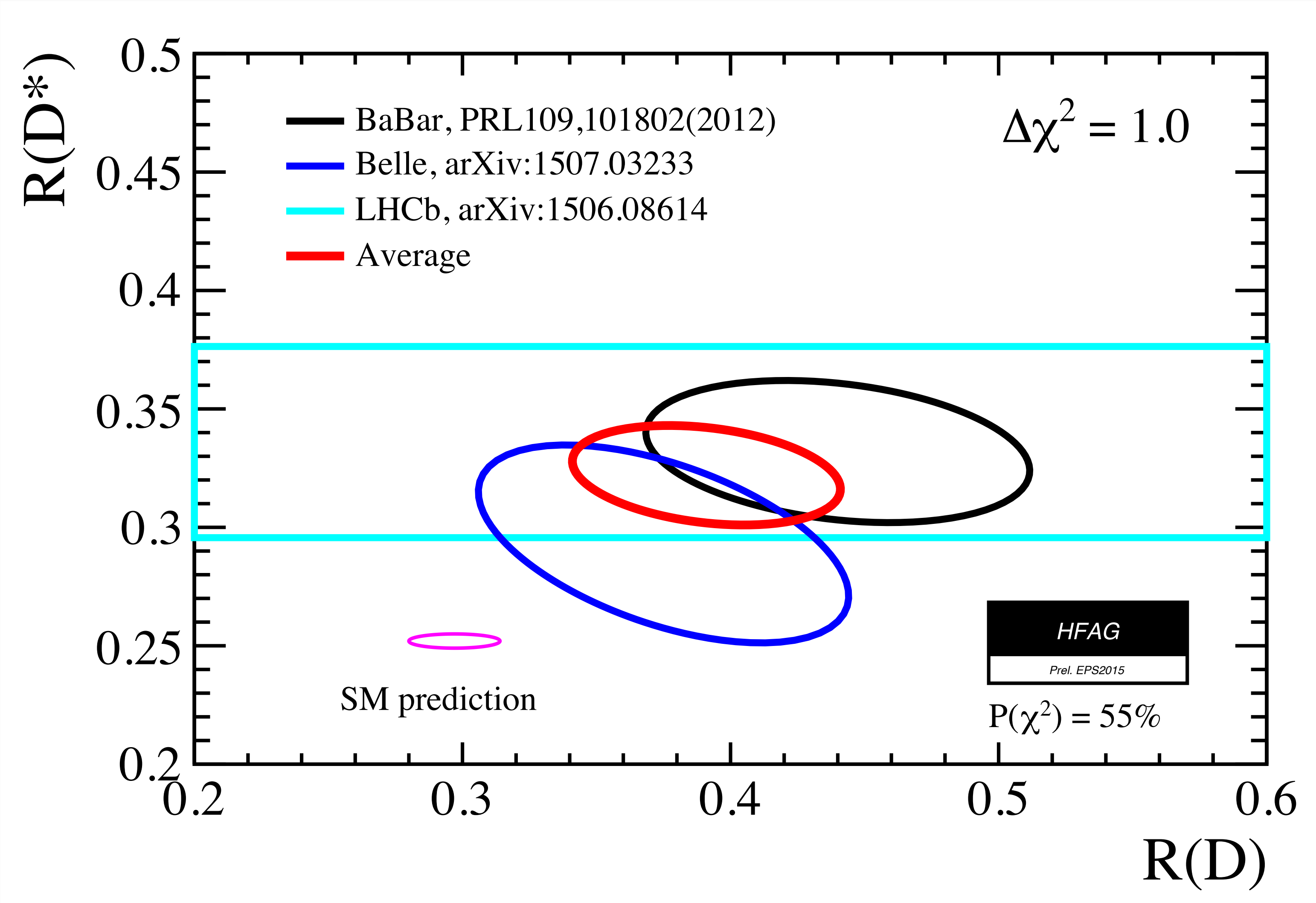
$$\lambda_{ue}^L = V_{\text{CKM}}^*\lambda_{d\nu}^L U_e \approx$$

$$10^{-1} - 10^{-3}$$

$$\lambda_{ue}^R \sim$$



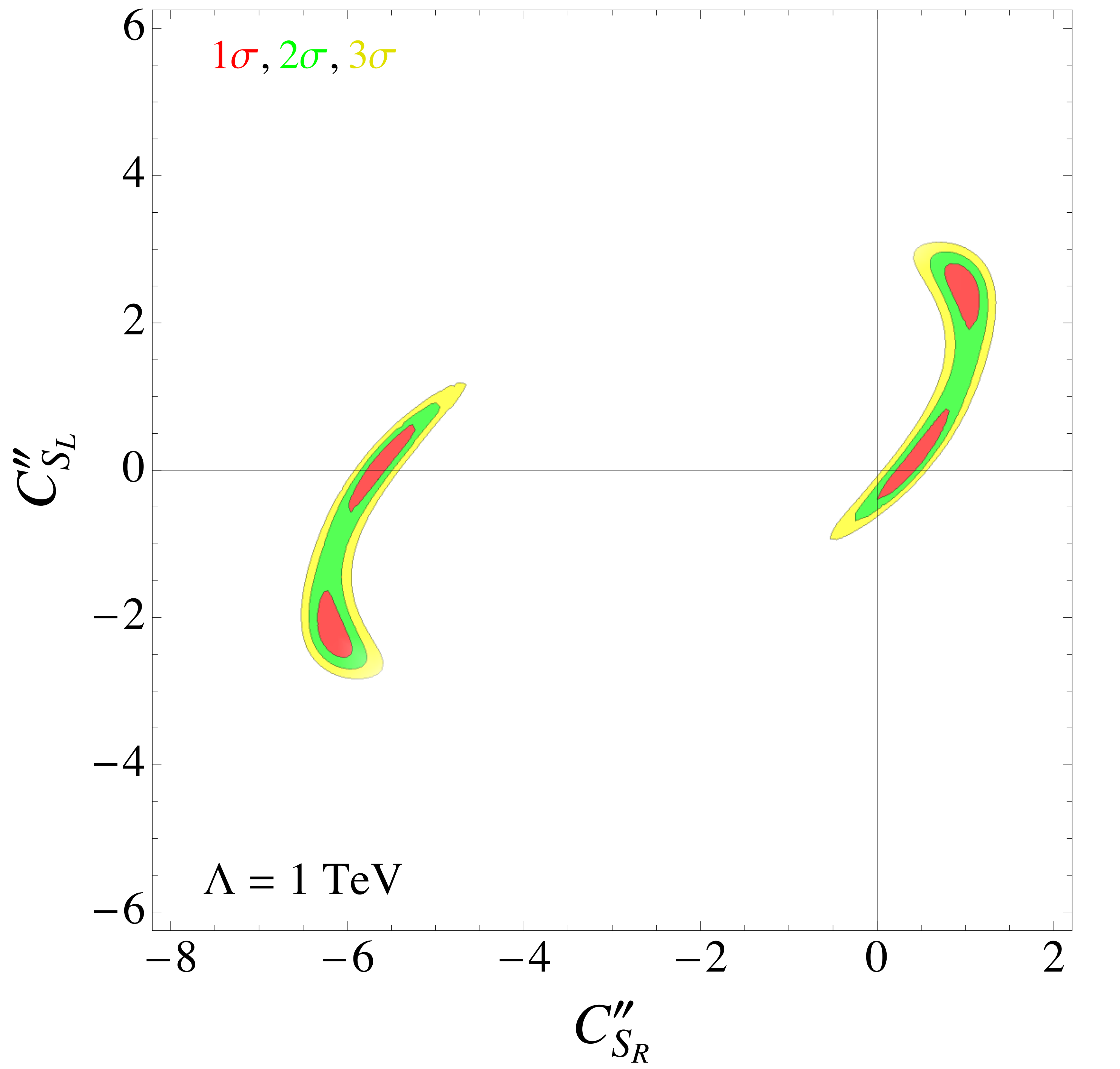
Explanation of the enhanced $B \to D^{(*)} \tau \nu$ rates



Semileptonic decays with tau leptons are 3.5σ higher than SM prediction!

Model-independent operator analysis:

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$$

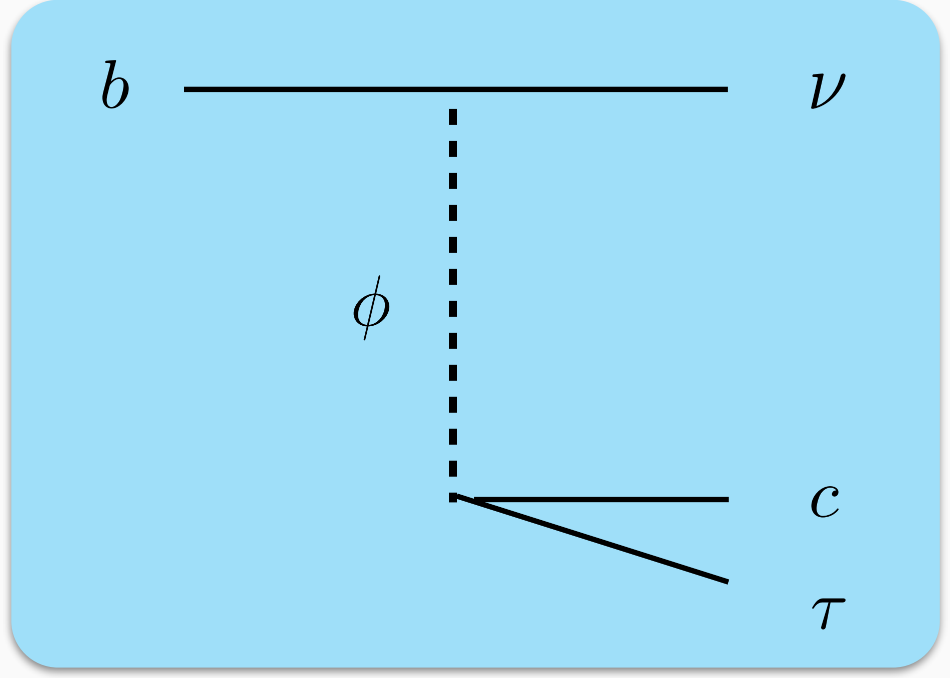


$$\mathcal{O}''_{S_L} = (\bar\tau P_L c^c)(\bar b^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar\tau P_R c^c)(\bar b^c P_L \nu)$$

Freytsis, Ligeti, Rudermann (arXiv:1506:08896)

Explanation of the enhanced $B \to D^{(*)} \tau \nu$ rates

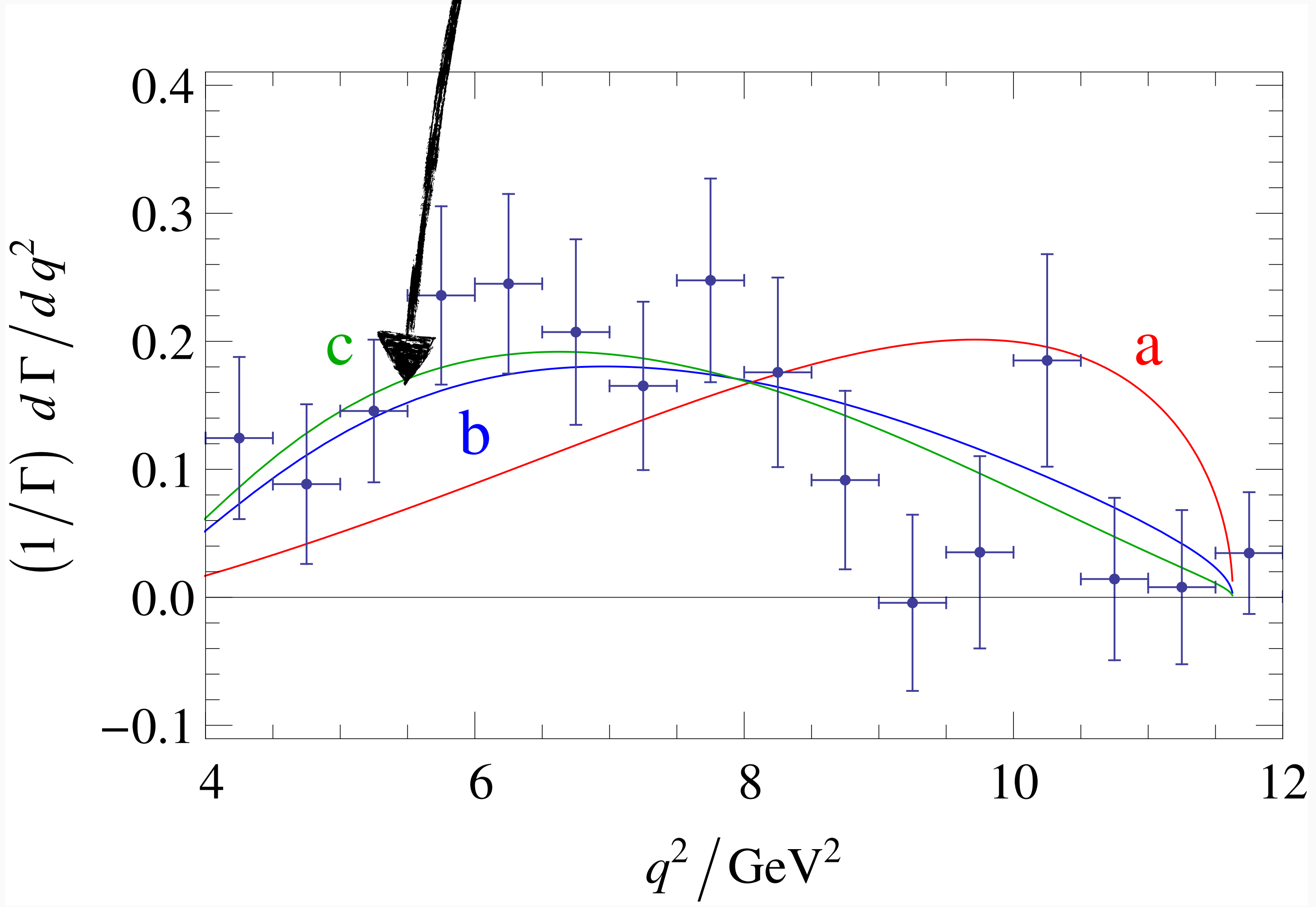
Leptoquark contribution:



$$\frac{\lambda_{c\tau}^{L*}\,\lambda_{b\nu_\tau}^{L}}{M_\phi^2} \approx \frac{0.35}{\text{TeV}^2} = C''_{S_R}$$

$$\frac{\lambda_{c\tau}^{R*}\,\lambda_{b\nu_\tau}^{L}}{M_\phi^2} \approx -\frac{0.03}{\text{TeV}^2} = C''_{S_L}$$

q^2 distribution:



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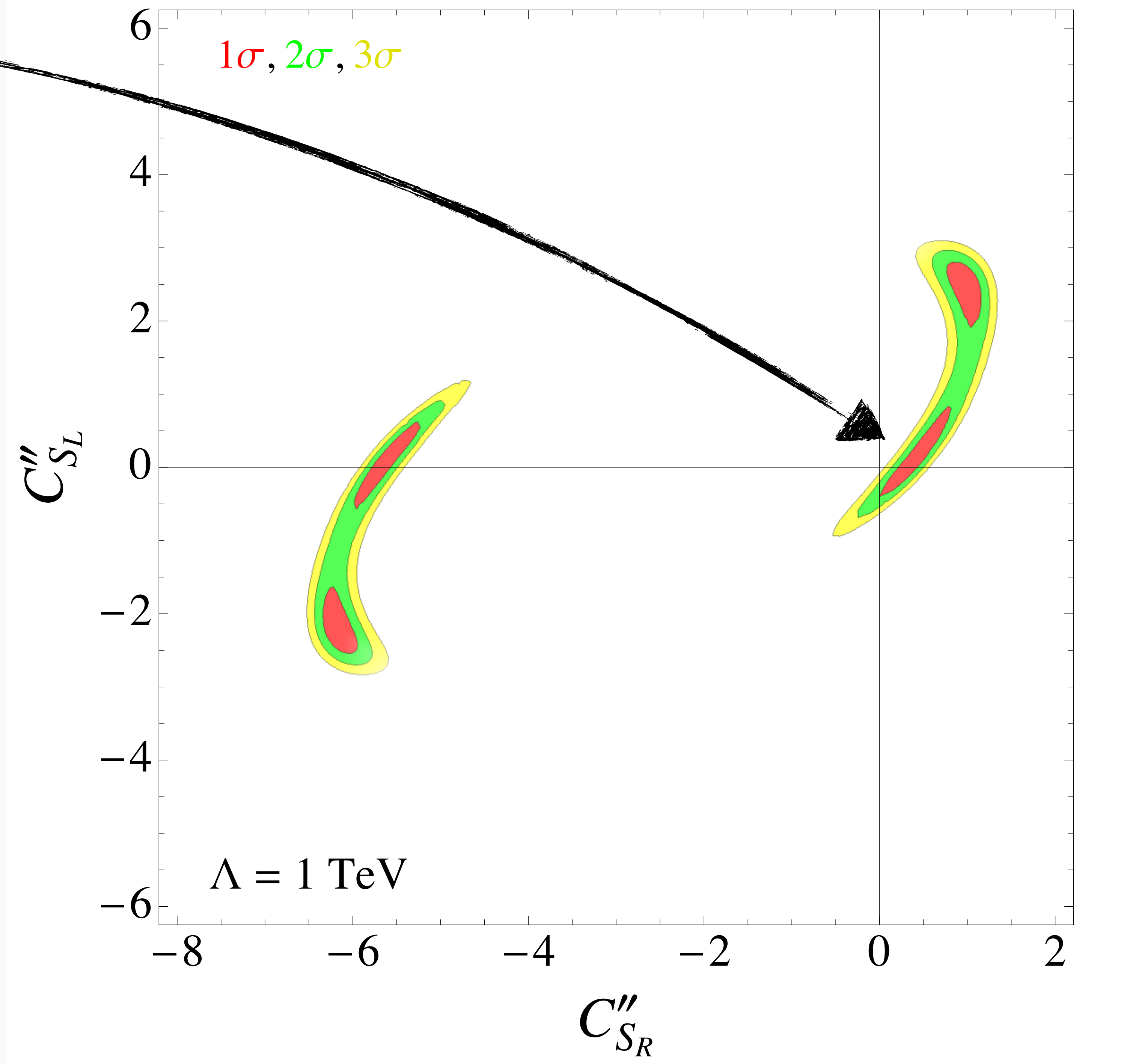

$$\mathcal{O}''_{S_L} = (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu)$$

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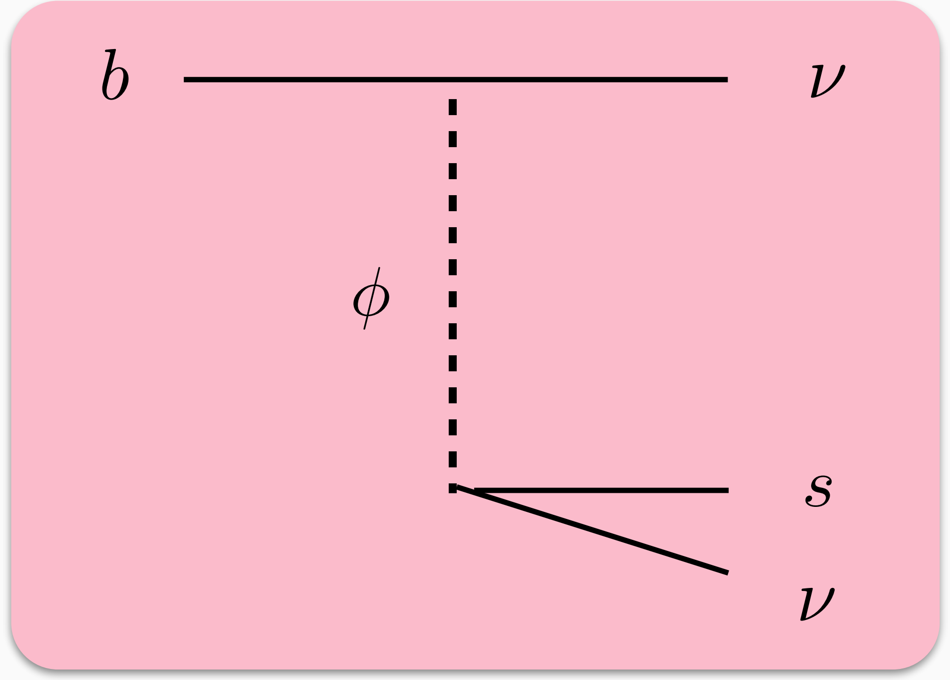
Bound from $B \to K^{(*)}\nu\nu$ rates

Leptoquark contribution:



$$\mathcal{L}_{\text{eff}}^{(\phi)} = \frac{1}{2M_\phi^2}\,\lambda_{s\nu_i}^{L*}\lambda_{b\nu_j}^{L}\,\bar{s}_L\gamma_\mu b_L\,\bar{\nu}_L^i\gamma^\mu\nu_L^j$$

Interference with SM yields for $R_{\nu\bar{\nu}} = \Gamma/\Gamma_{\text{SM}}$:

$$R_{\nu\bar{\nu}}^{(\phi)} = 1 - \frac{2r}{3}\,\text{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*} + \frac{r^2}{3}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bb}\left(\lambda^L\lambda^{L\dagger}\right)_{ss}}{\left|V_{tb}V_{ts}^*\right|^2}$$

with:

$$r = \frac{s_W^4}{2\alpha^2}\,\frac{1}{X_0(x_t)}\,\frac{m_W^2}{M_\phi^2} \approx 1.91\,\frac{\text{TeV}^2}{M_\phi^2}$$

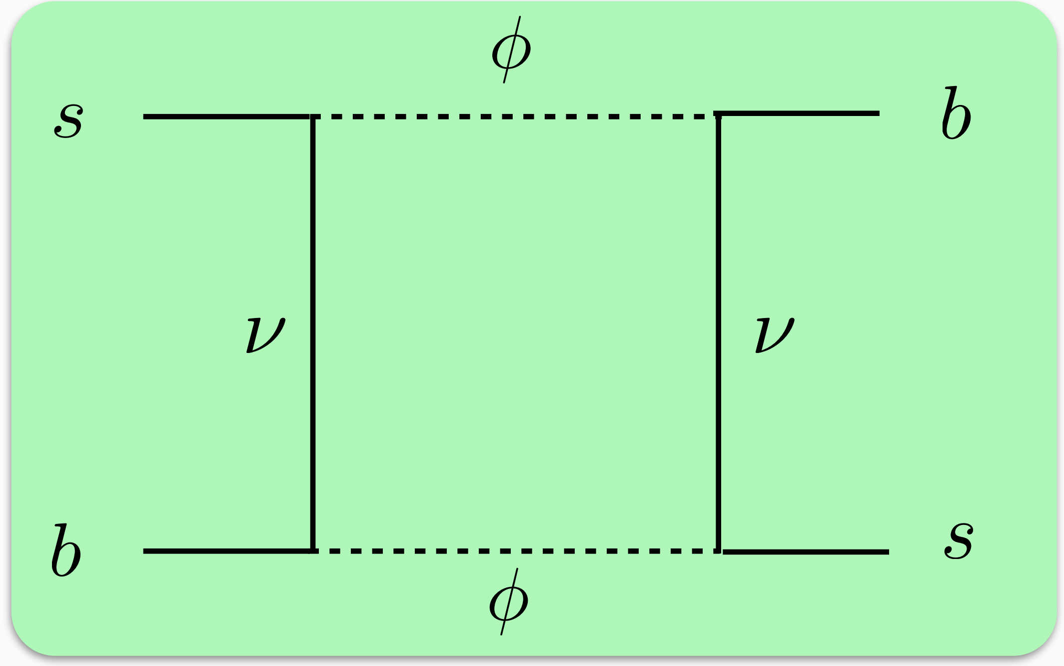
$$\left(\lambda^L\lambda^{L\dagger}\right)_{bs} = \sum_i \lambda_{b\nu_i}^L\,\lambda_{s\nu_i}^{L*}$$

Current BaBar bound $R_{\nu\bar{\nu}} < 4.3$ @ 90% CL implies:

$$-\frac{1.2}{\text{TeV}^2} < \frac{1}{M_\phi^2}\,\text{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*} < \frac{2.3}{\text{TeV}^2}$$

Constraints from B_s mixing and $B \to X_s \gamma$

Leptoquark contribution:



Correction to SM mixing amplitude:

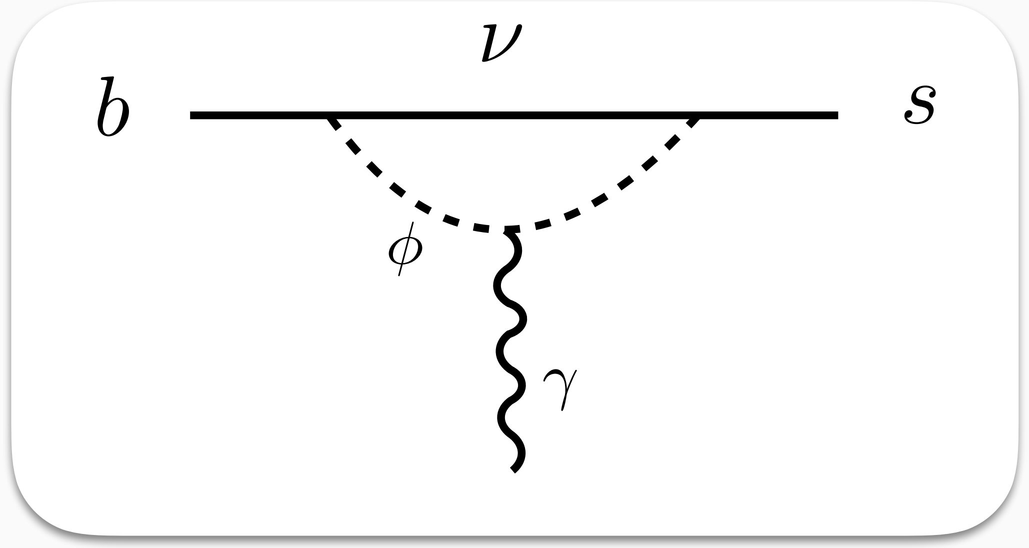
$$C_{B_s}^{(\phi)}\, e^{2i\phi_{B_s}^{(\phi)}} = 1 + \frac{1}{g^4 S_0(x_t)}\, \frac{m_W^2}{M_\phi^2} \left[\frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*} \right]^2$$

Best fit value:

$$\frac{1}{M_\phi}\, \frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*} \approx \frac{1.87 + 0.45i}{\text{TeV}}$$

Bona *et al.*, UT*fit* collaboration (arXiv:0707.0636)

Leptoquark contribution:

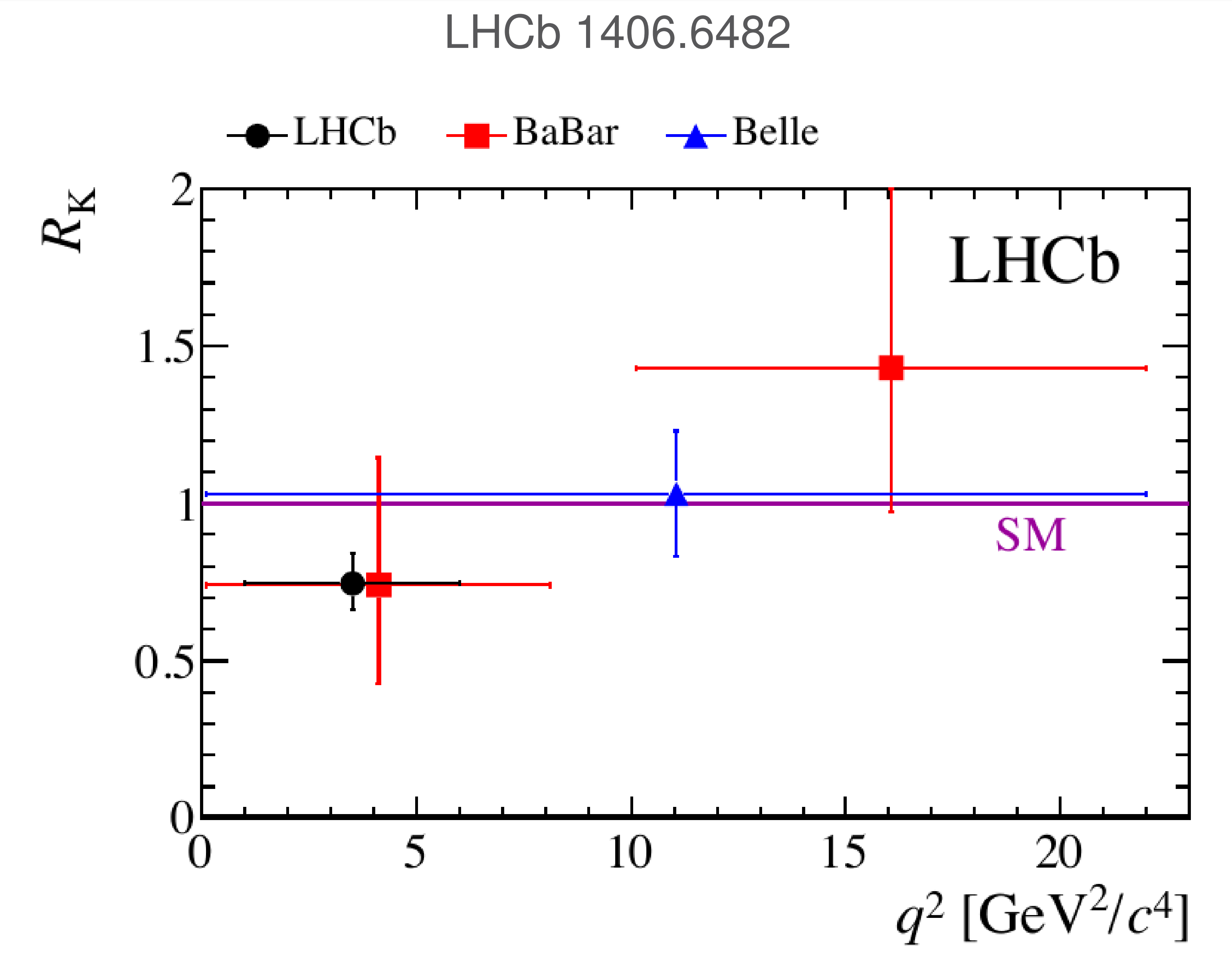


Correction to SM amplitude:

$$C_{7\gamma} = C_{7\gamma}^{\text{SM}} + \left(\frac{v}{12 M_\phi} \right)^2 \frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*}$$

Correction to branching ratio of order 1% or less, below current level of sensitivity

Explanation of the R_K and $B \to K^* \mu^+ \mu^-$ anomalies



2.6σ hint for a violation of lepton flavor universality!

Model-independent operator analysis:

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

with:

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

Take new linear combinations:

$$\mathcal{O}_{LL}^\ell \equiv (\mathcal{O}_9^\ell - \mathcal{O}_{10}^\ell)/2\,, \quad \mathcal{O}_{LR}^\ell \equiv (\mathcal{O}_9^\ell + \mathcal{O}_{10}^\ell)/2$$
$$\mathcal{O}_{RL}^\ell \equiv (\mathcal{O}_9'^\ell - \mathcal{O}_{10}'^\ell)/2\,, \quad \mathcal{O}_{RR}^\ell \equiv (\mathcal{O}_9'^\ell + \mathcal{O}_{10}'^\ell)/2$$

A good fit is obtained for:

$$C_{LL}^\mu \approx -1\,, \qquad C_{ij}^\mu \approx 0 \text{ otherwise}$$

Hiller, Schmaltz (arXiv:1408.1627)

Explanation of the R_K and $B \to K^{*}\mu^{+}\mu^{-}$ anomalies

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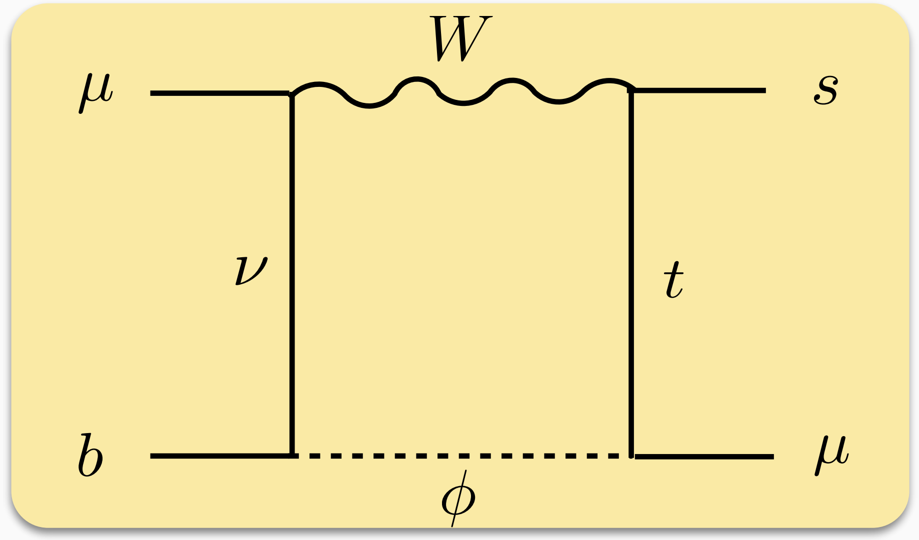

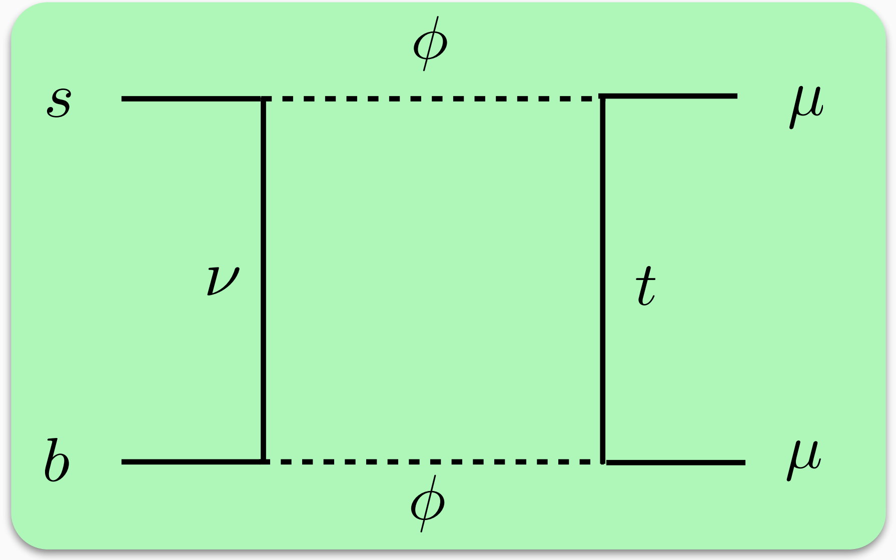

Contributions to Wilson coefficients:

$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^L\right|^2 - \frac{1}{64\pi\alpha}\,\frac{\sqrt{2}}{G_F M_\phi^2}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V_{ts}^*}\,(\lambda^{L\dagger}\lambda^L)_{\mu\mu}$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^R\right|^2\left[\ln\frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha}\,\frac{\sqrt{2}}{G_F M_\phi^2}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V_{ts}^*}\,(\lambda^{R\dagger}\lambda^R)_{\mu\mu}$$

Best fit values can be obtained for:

$$\sqrt{\left|\lambda_{u\mu}^L\right|^2 + \left|\lambda_{c\mu}^L\right|^2 + \left(1 - \frac{0.77}{\hat{M}_\phi^2}\right)\left|\lambda_{t\mu}^L\right|^2} > 2.36$$

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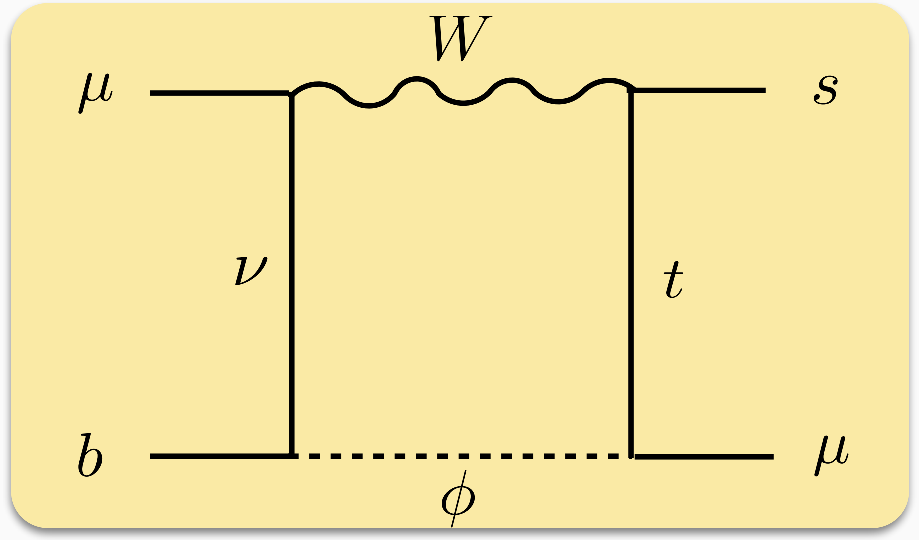

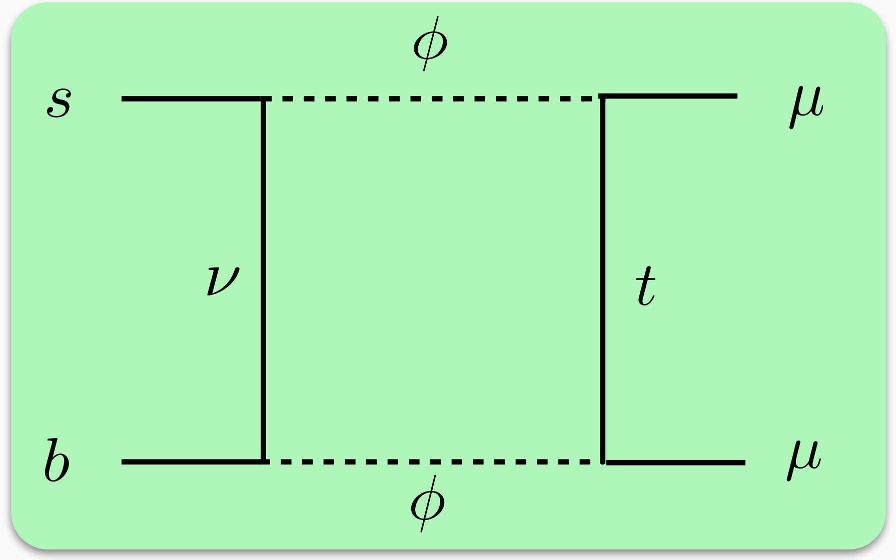

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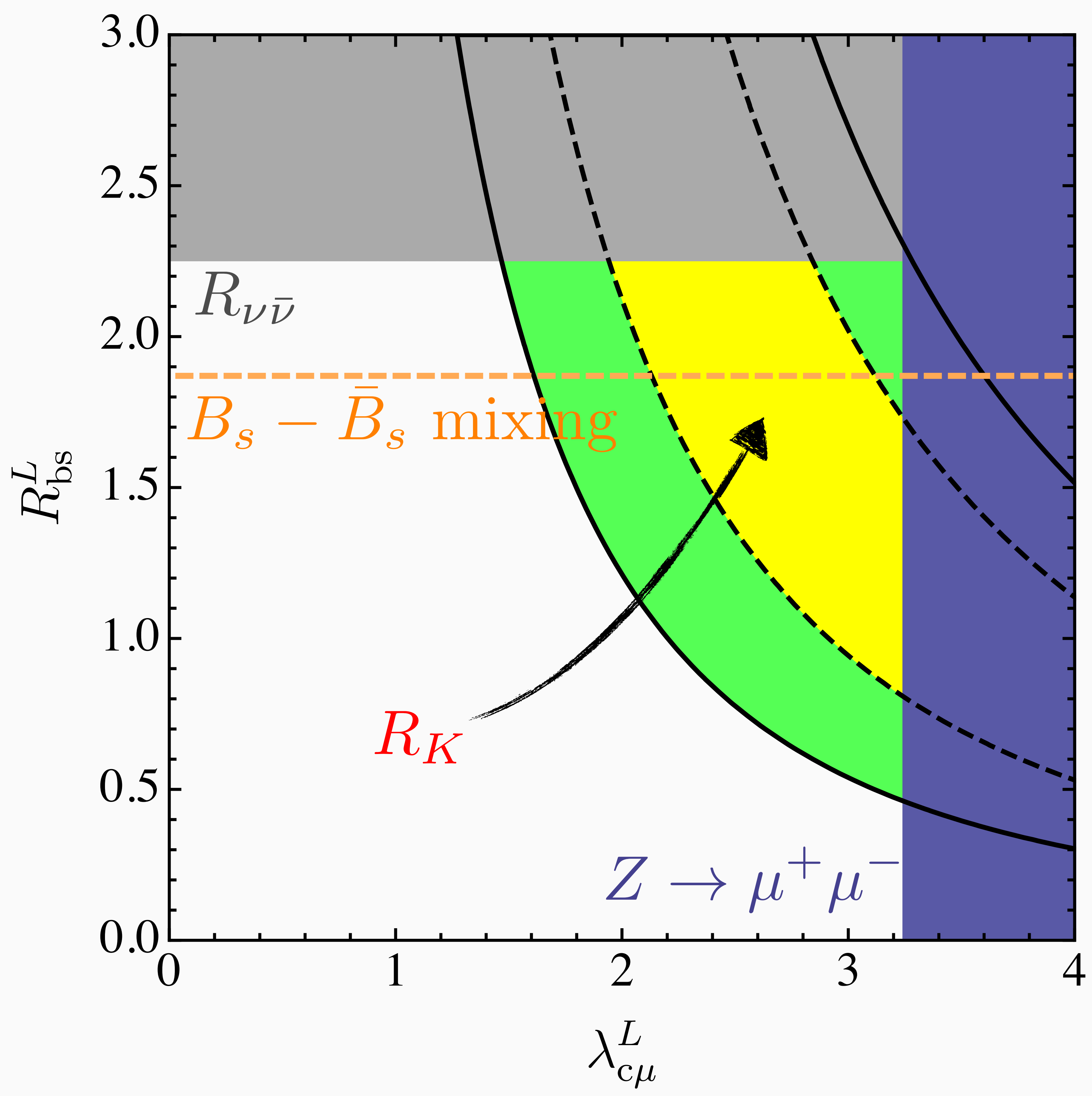
Allowed parameter space for $M_\phi = 1$ TeV:

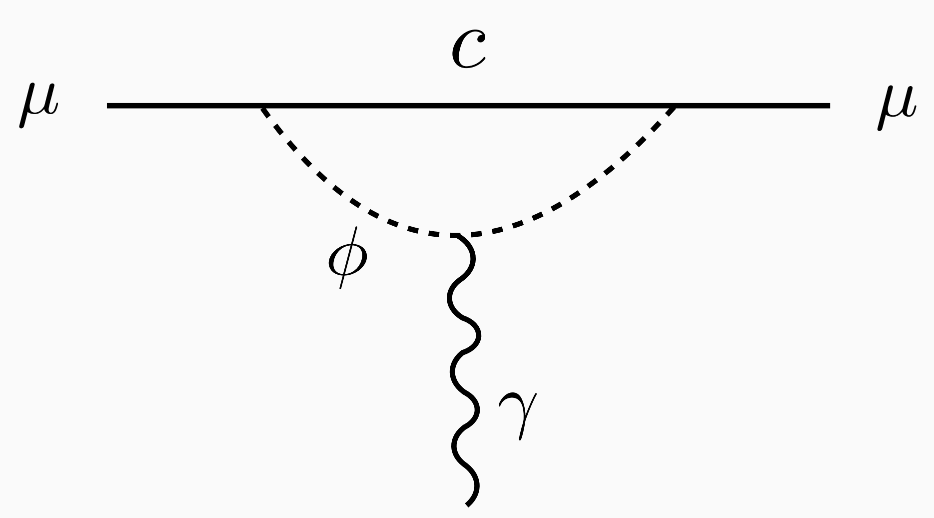


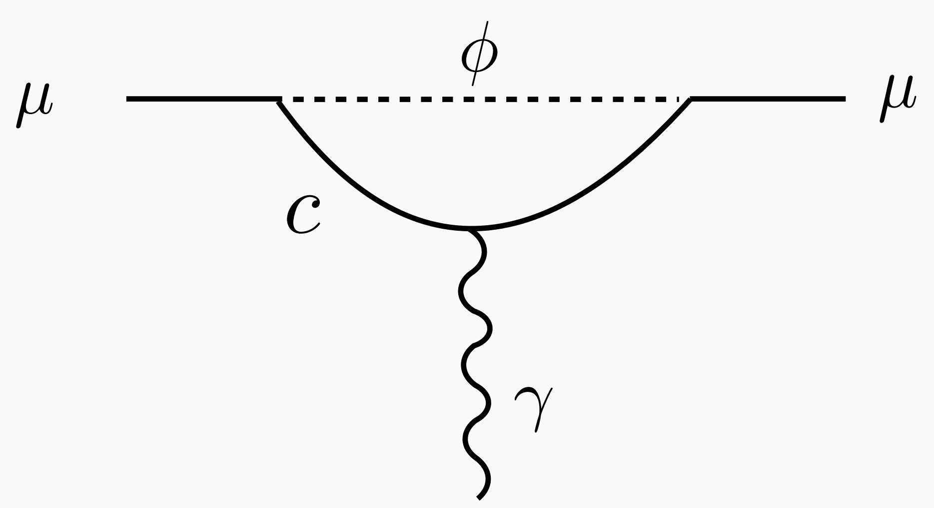
Other observables

With a modest right-handed coupling

$$|\lambda_{c\mu}^R| \sim 0.03$$

our model can explain the **anomalous magnetic moment** of the muon!





Without much fine-tuning, our model survives the bounds from:

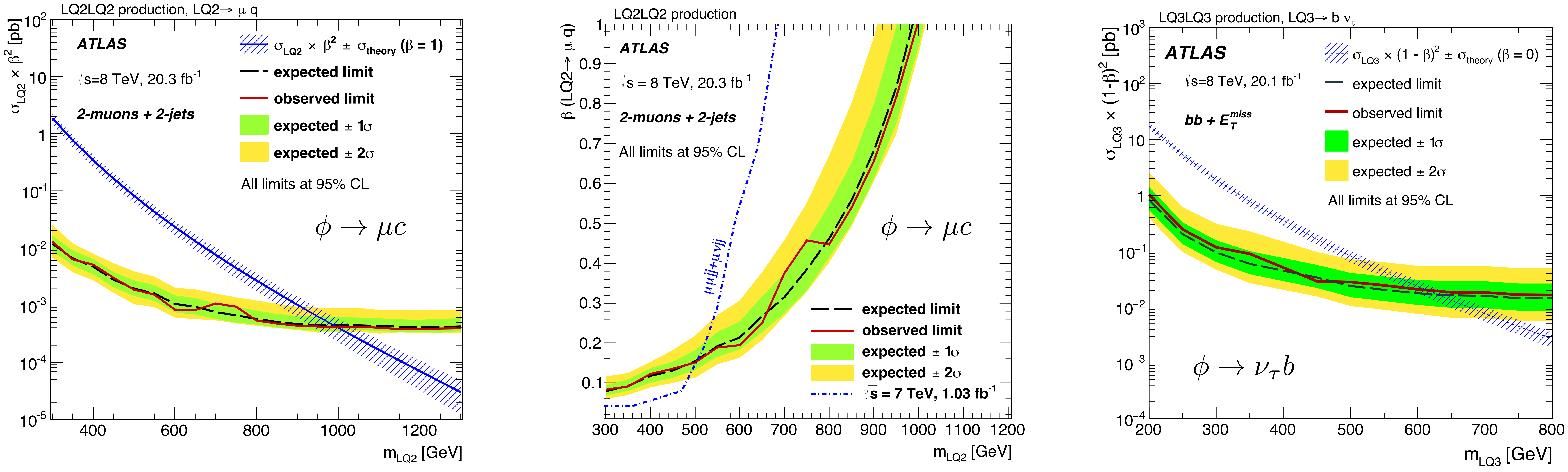
- rare *D*-meson decays such as $D \to \mu\mu$
- precision data on *Z*-boson couplings to muons
- rare decays of the tau lepton, such as $\tau \to \mu\gamma$
- …

However, our model **cannot** explain the h→μτ signal reported by CMS!

This signal can only be explained (along woth the tight constraint from $\tau \to \mu\gamma$) in models with two sources of electroweak symmetry breaking!

Altmannshofer, Gori, Kagan, Silvestrini, Zupan (arXiv:1507.07927)

Collider bounds



Outlook

One the verge of more discoveries?

- Discovery of the Higgs boson has opened a new era in exploration of fundamental structures of Nature
- Growing number of anomalies – both at the precision frontier and the energy frontier – give us confidence that the Standard Model may soon be cracked

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Mainz Institute for Theoretical Physics

Events 2017

- Scientific Programs

Date	Scientific Program
February 6 - 17, 2017	Amplitudes - practical and theoretical developments
March 13 - 24, 2017	Quantum Vacuum and Gravitation
May 2 - 24, 2017	Low-energy Probes of New Physics
June 12 - July 7, 2017	The TeV scale: a threshold to new physics?
September 18 - 29, 2017	Monte Carlo for QFTs in Particle,- Nuclear-, and Condensed Matter Physics

- Topical Workshops

Date	Topical Workshop
February 6 - 10, 2017	Quantum methods for lattice gauge theories calculations
March 6 - 10, 2017	Women at the Intersection of Mathematics and High Energy Physics
April 24 - 28, 2017	Geometry, Gravity and Supersymmetry
May 29 - June 2, 2017	Foundational and Structural Aspects of Gauge Theories
October 9 - 13, 2017	Supernova Neutrino Observations

Thank you!

ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Mainz Institute for Theoretical Physics