Flavorful New Physics & Wrinkles in the Froggatt–Nielsen Mechanism

[arXiv:2308.01340]

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In collaboration with
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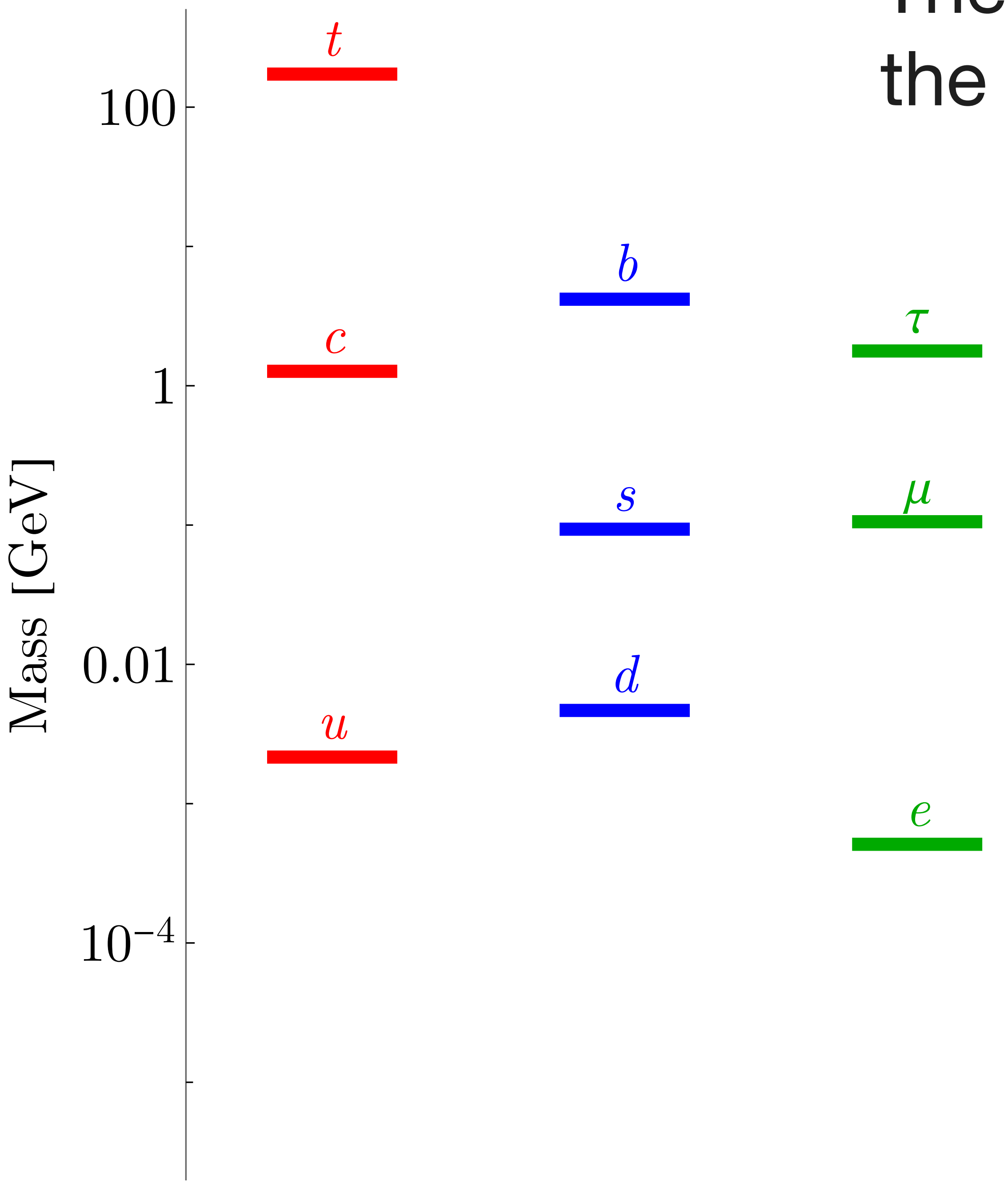
The Flavor Puzzle

The fermion masses and mixing angles in the SM are *highly* non-generic



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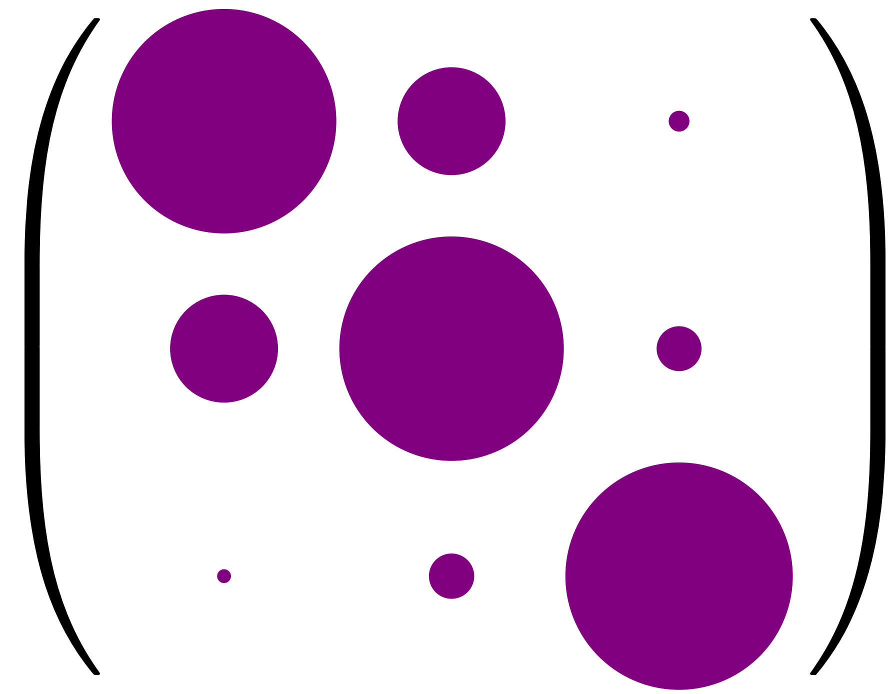

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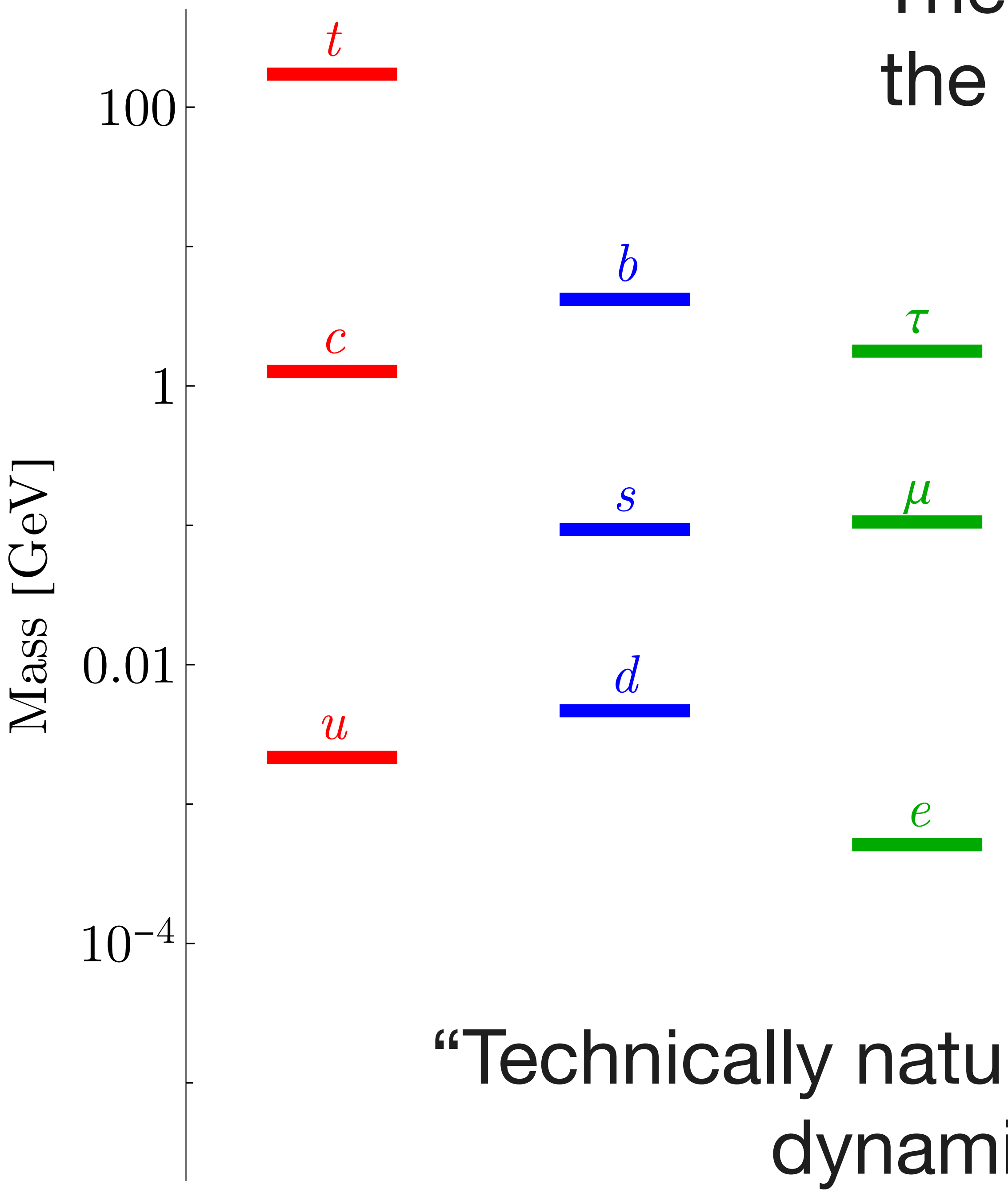
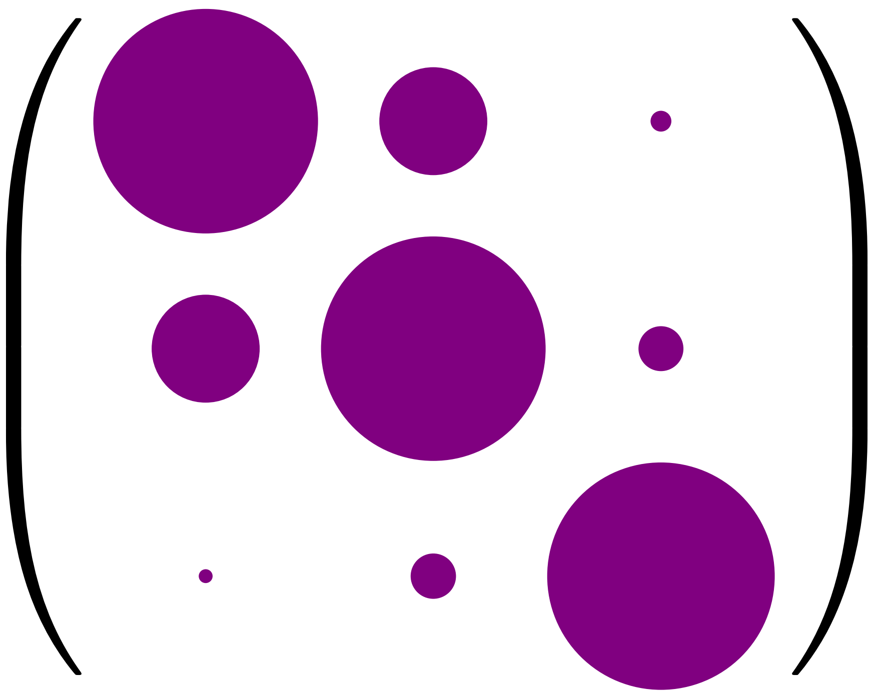


$V_{\mathrm{CKM}} =$ 

"Technically natural", but begging for some dynamical explanation!

Solutions to the Flavor Puzzle:

Alongside hundreds of particular attempts at explaining the flavor puzzle, there are three well-studied “paradigms”:

- The Froggatt–Nielsen Mechanism
  (Horizontal Symmetries)
- Extra-Dimensions / RS
  (Wave-function overlap)
- Nelson–Strassler
  (RG Flow from Strongly Coupled Sector)

The Froggatt–Nielsen Mechanism

$$V_{\text{CKM}} \sim \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$$m_u/m_c \sim \lambda^4, \quad m_c/m_t \sim \lambda^3,$$
$$m_d/m_s \sim \lambda^2, \quad m_s/m_b \sim \lambda^2,$$
$$m_e/m_\mu \sim \lambda^3, \quad m_\mu/m_\tau \sim \lambda^2$$

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$\Longrightarrow$ Replace hierarchies in SM Yukawas by powers of $\lambda \sim 0.2$

$$(Y_{Q\bar{u}})^i{}_j \;\sim\; \lambda^{m_{ij}} \qquad (Y_{Q\bar{d}})^i{}_j \;\sim\; \lambda^{n_{ij}}$$

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$$(Y_{Q\bar{u}})^i{}_j \sim \lambda^{m_{ij}} \equiv \left(\frac{\langle\varphi\rangle}{M}\right)^{m_{ij}}, \quad (Y_{Q\bar{d}})^i{}_j \sim \lambda^{n_{ij}} \equiv \left(\frac{\langle\varphi\rangle}{M}\right)^{n_{ij}}$$

The small parameter is given by the vev of a scalar field (the *flavon*) over a heavy cutoff scale, M.

The Froggatt–Nielsen Mechanism

So at scales below M, have an effective theory:

$$\mathcal{L} \supset \left(\frac{\varphi}{M}\right)^{m_{ij}} Q_i H \bar{u}^j + \left(\frac{\varphi}{M}\right)^{n_{ij}} Q_i H^c \bar{d}^j + \left(\frac{\varphi}{M}\right)^{l_{ij}} L_i H^c \bar{e}_j + \text{h.c.}$$

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Now, the powers can be fixed by introducing a $\mathrm{U}(1)_H$ "horizontal" symmetry, which distinguishes the fermion generations.

Conventionally take $[\varphi]_H = -1$

Then, e.g., $m_{ij} = \left|[Q_i]_H + [\bar{u}^j]_H\right|$

$\Longrightarrow$ Hierarchies are replaced with a definite *power counting*

Horizontal Charge Assignments

Now we can choose the horizontal charges for the fermions using the IR relations:

$$m_i^u \sim \lambda^{\left|[Q_i] + [\bar{u}_i]\right|}, \quad m_i^d \sim \lambda^{\left|[Q_i] + [\bar{d}_i]\right|}, \quad m_i^\ell \sim \lambda^{\left|[L_i] + [\bar{e}_i]\right|},$$

$$V_{ij} \sim \lambda^{\left|[Q_i] - [Q_j]\right|}, \quad U_{ij} \sim \lambda^{\left|[L_i] - [L_j]\right|}$$

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The general solution (with the ratios given earlier) is:

	Gen. 1	Gen. 2	Gen. 3
Q	$-q_0 - 3X$	$-q_0 - 2X$	$-q_0$
$\bar{u}$	$q_0 + 3X \pm 7$	$q_0 - X$	q_0
$\bar{d}$	$q_0 + 3X \pm 6$	$q_0 - 3X$	$q_0 - 2X$
L	$l_0 + Y$	l_0	l_0
$\bar{e}$	$-l_0 - Y \pm 8$	$-l_0 + 5Y$	$-l_0 + 3Y$

(See also: Cornell, Curtin, Neil, Thompson [2306.08026])

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Here, $q_0, l_0 \in \mathbb{Z}$, and $X, Y = \pm 1$.

In supersymmetric theories, holomorphy of the superpotential requires $X = -Y = -1$, and picks the positive signs for 1st generation fermions.

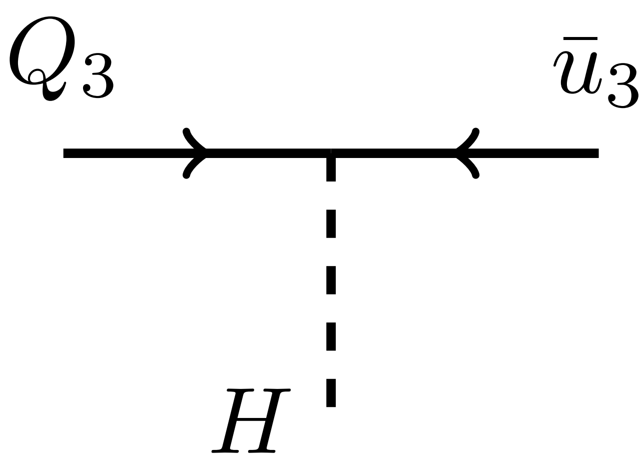
We'll choose $q_0 = 0$, $l_0 = -1$ and demand holomorphy, so:

$$([Q_1], [Q_2], [Q_3]) = (3, 2, 0), \qquad ([\bar{u}_1], [\bar{u}_2], [\bar{u}_3]) = (4, 1, 0), \qquad ([\bar{d}_1], [\bar{d}_2], [\bar{d}_3]) = (3, 3, 2),$$

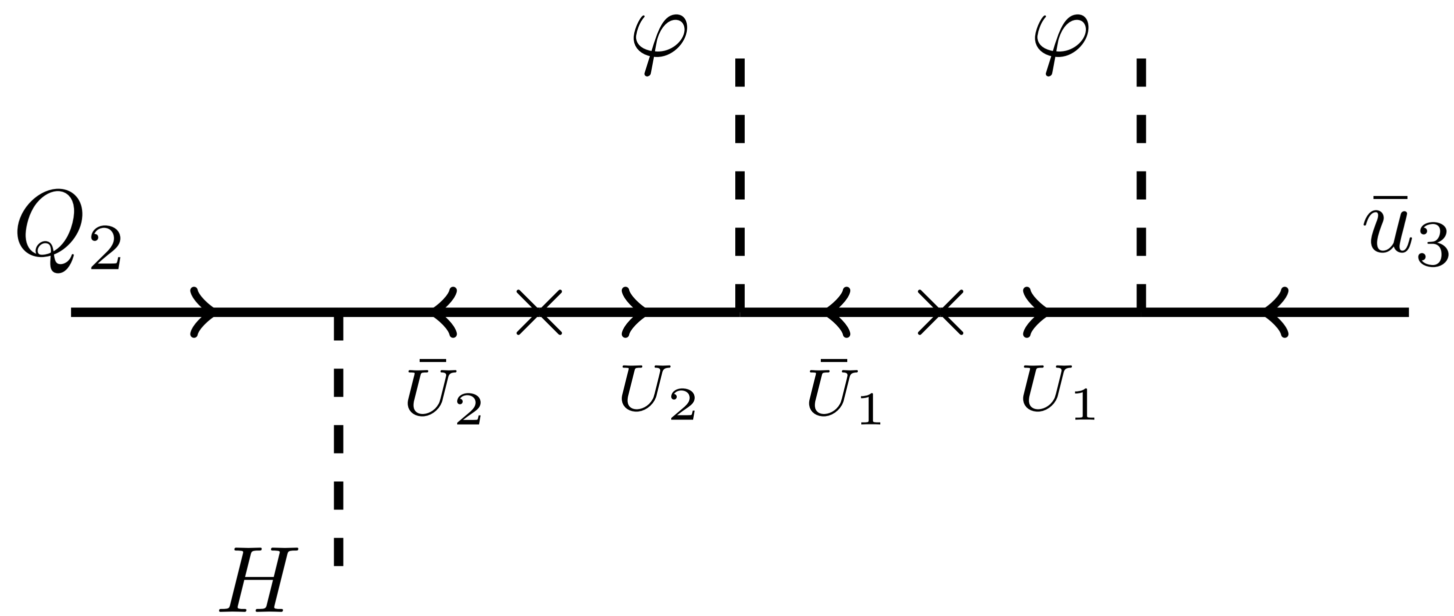
$$([L_1], [L_2], [L_3]) = (0, -1, -1), \qquad ([\bar{e}_1], [\bar{e}_2], [\bar{e}_3]) = (8, 6, 4).$$

Froggatt-Nielsen "Chains"

To complete the story, we have to generate these non-renormalizable operators at the scale M. Can do so with heavy vector-like fermions with SM-like charges, e.g.,



$\sim 1 \times Q_3 H \bar{u}_3$



$\sim \lambda^2 \times Q_2 H \bar{u}_3$

Typically assume heavy matter exists with all $\mathrm{U}(1)_H$ charges necessary to generate the full spectrum — from EFT perspective, details don't matter.

What about Flavorful *New Physics*?

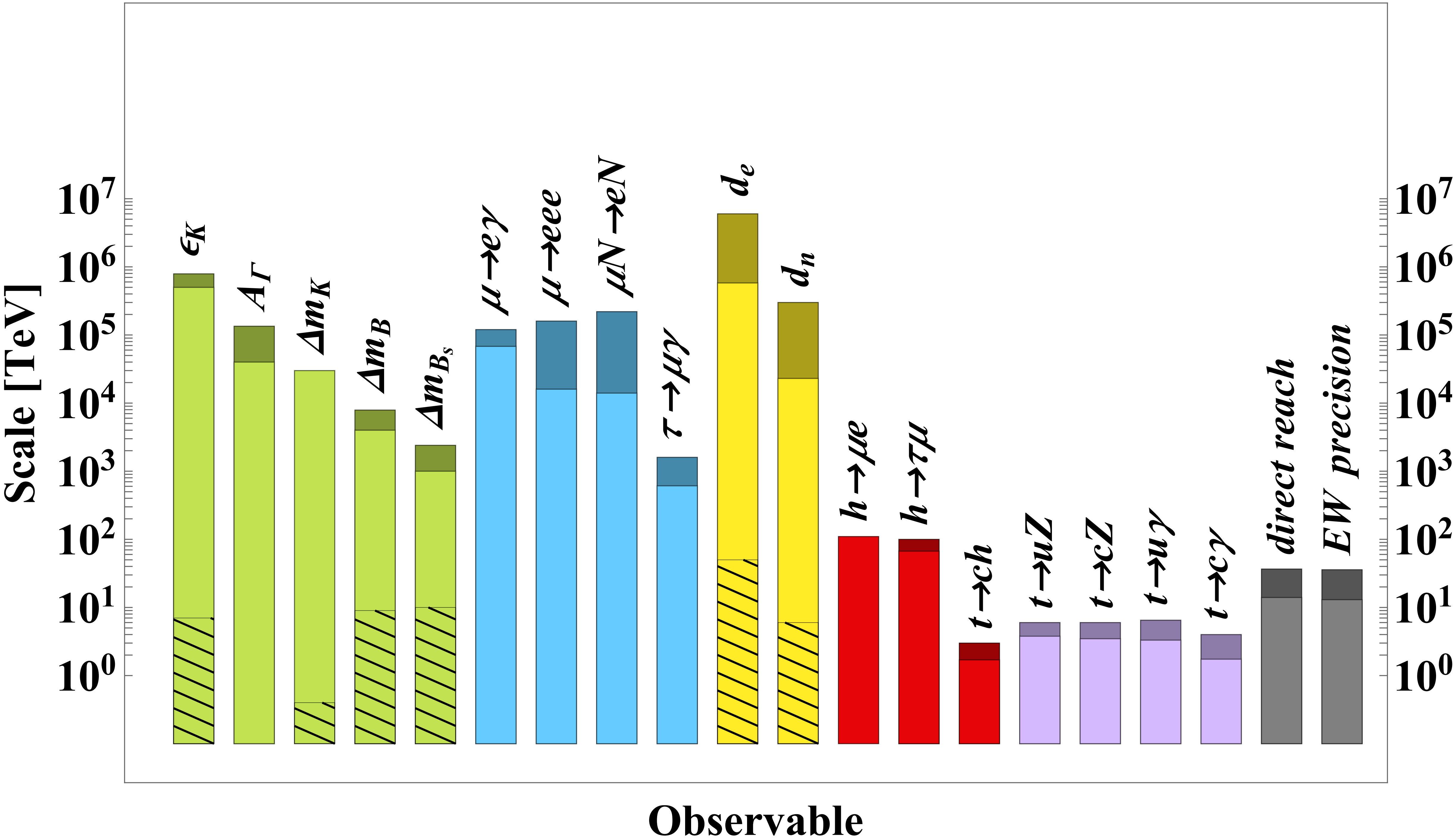
We've illustrated a solution to the flavor problem in the context of the SM, but what if there is *flavorful* new physics near the TeV scale?

- We often focus on "simpler" flavor-universal models, but new physics with couplings to the quarks and leptons is a generic, interesting possibility

- We often think about flavorful new physics models in the context of *anomalies*, but we should think about what these models/anomalies actually *teach us* about the flavor puzzle!

Flavorful New Physics Requires Structure

Generically, introducing new states with arbitrary couplings to fermions leads to large *flavor-changing* processes, which are tightly constrained:



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$\Longrightarrow$ New physics couplings must be either *universal* or *aligned*

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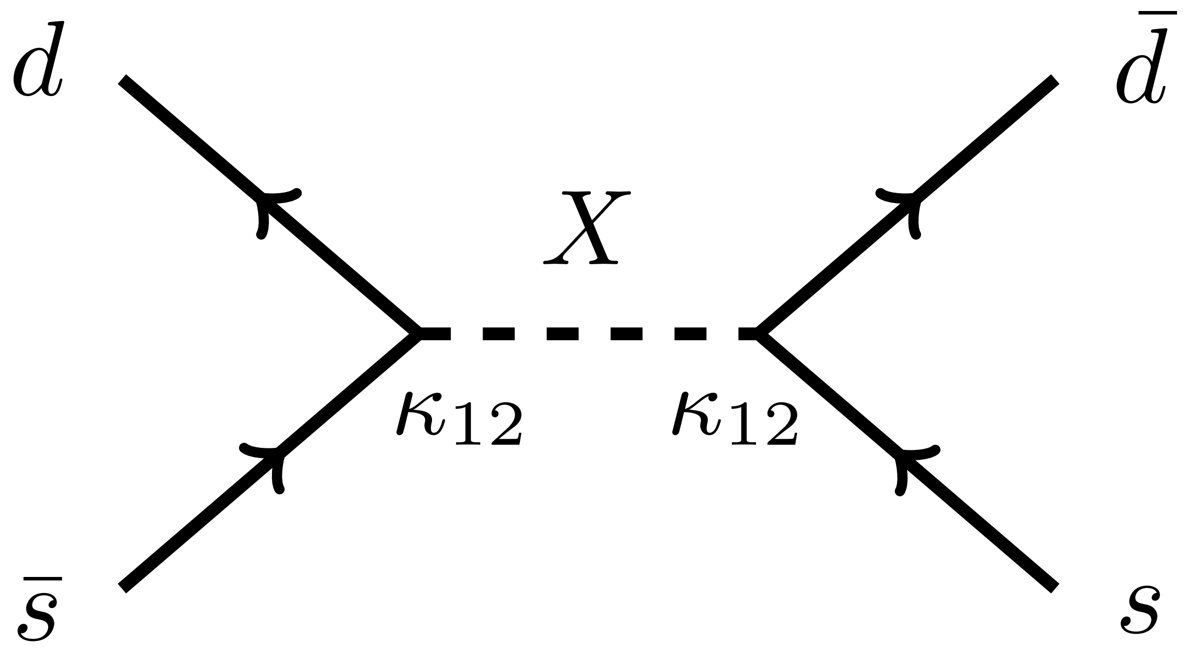

$$\propto \kappa_{12}^2 = 0$$

Note: *alignment* can be enforced with symmetries *without* proportionality

$\Longrightarrow$ large couplings to first, second generation, w/ no FCNCs is possible!

(D. Egaña, SH, P. Meade [1811.00017], [1908.11376])

The SM Flavor Symmetry

$$\mathcal{L}_{\text{kin.}} = iQ^{\dagger\,i}\bar{\sigma}^\mu D_\mu Q_i + iL^{\dagger\,i}\bar{\sigma}^\mu D_\mu L_i$$
$$+ i\bar{u}_i^\dagger\bar{\sigma}^\mu D_\mu \bar{u}^{\,i} + i\bar{d}_i^\dagger\bar{\sigma}^\mu D_\mu \bar{d}^{\,i} + i\bar{e}_i^\dagger\bar{\sigma}^\mu D_\mu \bar{e}^{\,i}$$

Neglecting their masses, the fermion sector of the Standard Model has a *huge* global symmetry:

$$G_{\text{flavor}} = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_L \times \mathrm{SU}(3)_u$$
$$\times\, \mathrm{SU}(3)_d \times \mathrm{SU}(3)_e \times \underline{\mathrm{U}(1)^5}$$

Includes Y, B, L

Very useful for organizing both the SM and flavorful BSM!

Flavor Violation in the SM

$$\mathcal{L}_{\text{Yuk.}} = (Y_{Q\bar{u}})^i{}_j \, Q_i H \bar{u}^j + (Y_{Q\bar{d}})^i{}_j \, Q_i H^c \bar{d}^j + (Y_{L\bar{e}})^i{}_j \, L_i H^c \bar{e}^j + \text{h.c.}$$

The source of *all* non-trivial flavor in the SM is the Higgs Yukawa matrices — these *explicitly* break G_{flavor} down to a few $\text{U}(1)$ subgroups.

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We can formally restore the symmetry by considering the Yukawas as *spurions* of G_{flavor}, e.g.:

$$Y_{Q\bar{u}} \sim (\bar{\mathbf{3}}_Q, \mathbf{3}_u), \qquad Y_{Q\bar{d}} \sim (\bar{\mathbf{3}}_Q, \mathbf{3}_d),$$

The Froggatt-Nielsen mechanism provides an explicit UV completion for these spurions.

Minimal Flavor Violation (MFV)

As an example of the utility of the $\mathrm{U}(3)^5$ flavor group, consider the MFV Ansatz:

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$$\frac{1}{\Lambda^2}(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2 \longrightarrow \frac{(V^T Y_{Q\bar{u}}^2 V^*)^2}{\Lambda^2}(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$$

Constraints from $K - \bar{K}$ mixing:

$$\Lambda > 1.5 \times 10^4\,\mathrm{TeV} \longrightarrow \Lambda > 5.1\,\mathrm{TeV}$$

The FN Ansatz for Flavorful New Physics

Example: the S_1 Leptoquark

Consider the scalar leptoquark $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

$$\mathcal{L} \supset -\Delta^{ij}_{QL} \epsilon^{ab} S_1 Q_{bi} L_{aj} - \Delta^{ij}_{\bar{u}\bar{e}} S_1^\dagger \bar{u}_i \bar{e}_j + \text{h.c.}$$

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We can promote these couplings to spurions of G_{flavor}:

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But there's no way to build these as tensor products of $Y_{Q\bar{u}}$, $Y_{Q\bar{d}}$, $Y_{L\bar{e}}$

$\Longrightarrow$ If we want to include (flavorful) new fields in our EFT, we need a more general Ansatz than MFV!

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(See e.g., Feldmann et al., [hep-ph/0611095], [1910.02641], [2010.03297])

The Froggatt-Nielsen mechanism provides this Ansatz:

$$\Delta_{QL}^{ij} \sim \lambda^{\left|[Q_i] + [L_j]\right|}, \quad \Delta_{\bar{u}\bar{e}}^{ij} \sim \lambda^{\left|[\bar{e}_j] + [\bar{u}_i]\right|}$$

$$\Delta_{QL} \sim \begin{pmatrix} \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^2 & \lambda & \lambda \\ 1 & \lambda & \lambda \end{pmatrix}, \qquad \Delta_{\bar{u}\bar{e}} \sim \begin{pmatrix} \lambda^{12} & \lambda^{10} & \lambda^8 \\ \lambda^9 & \lambda^7 & \lambda^5 \\ \lambda^8 & \lambda^6 & \lambda^4 \end{pmatrix}$$

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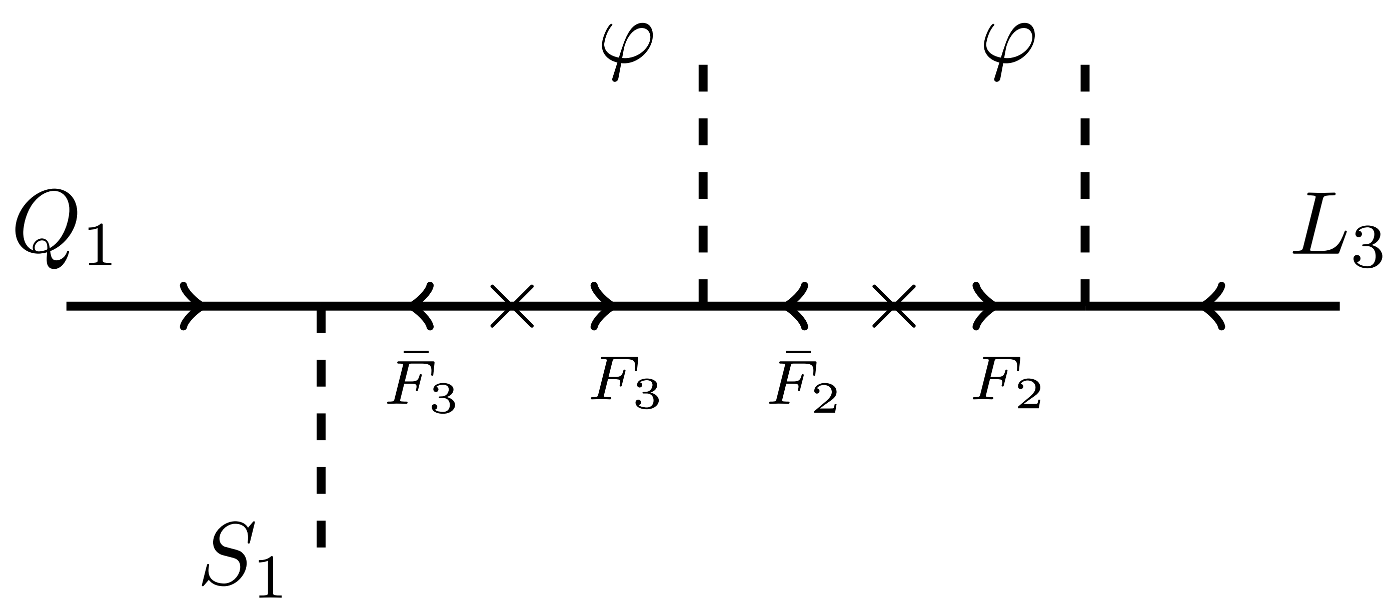
In the UV, picture these as coming from similar chain diagrams, again with heavy fermions with SM quantum numbers:



Correlated Constraints on the LQ

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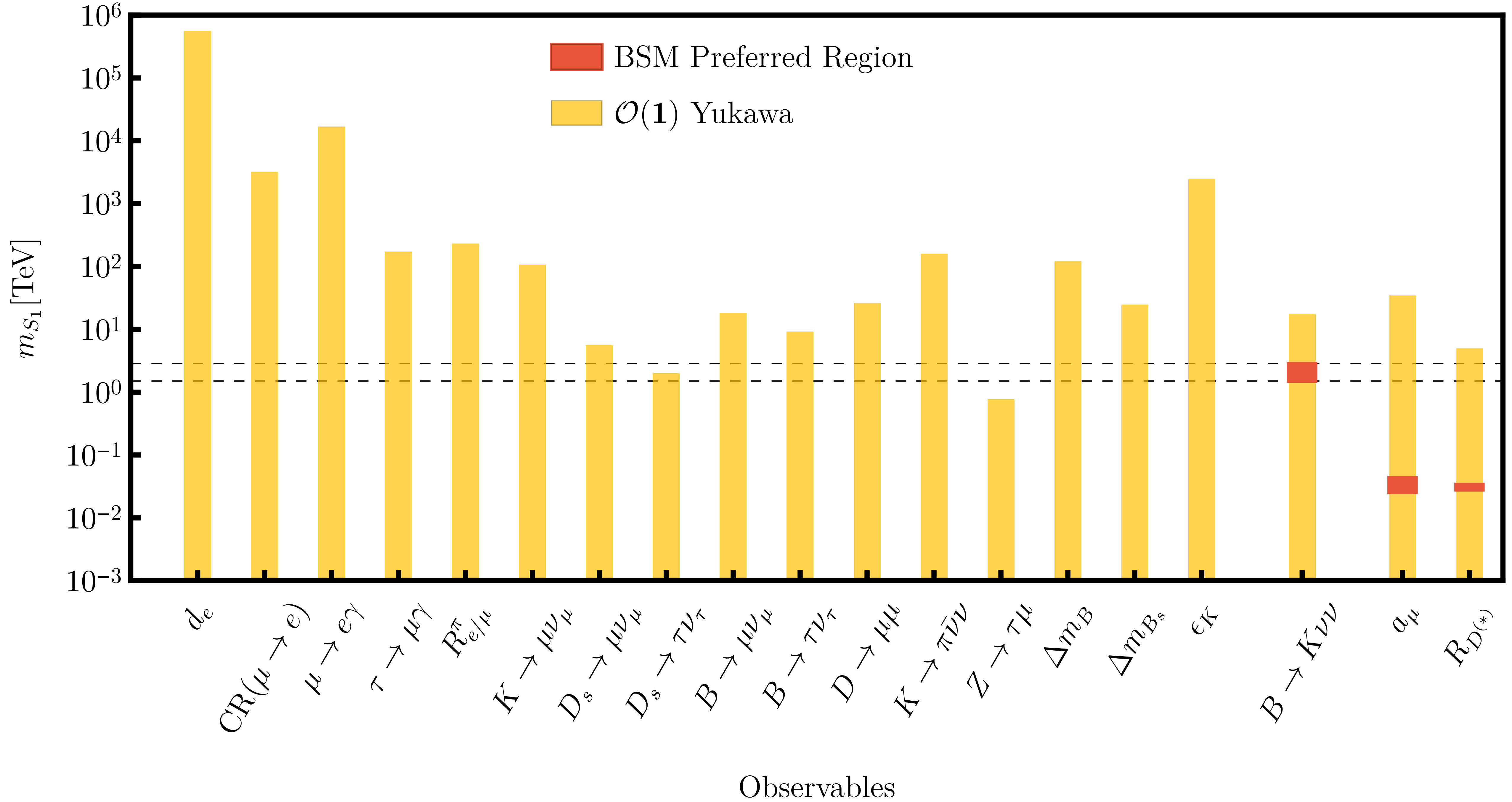

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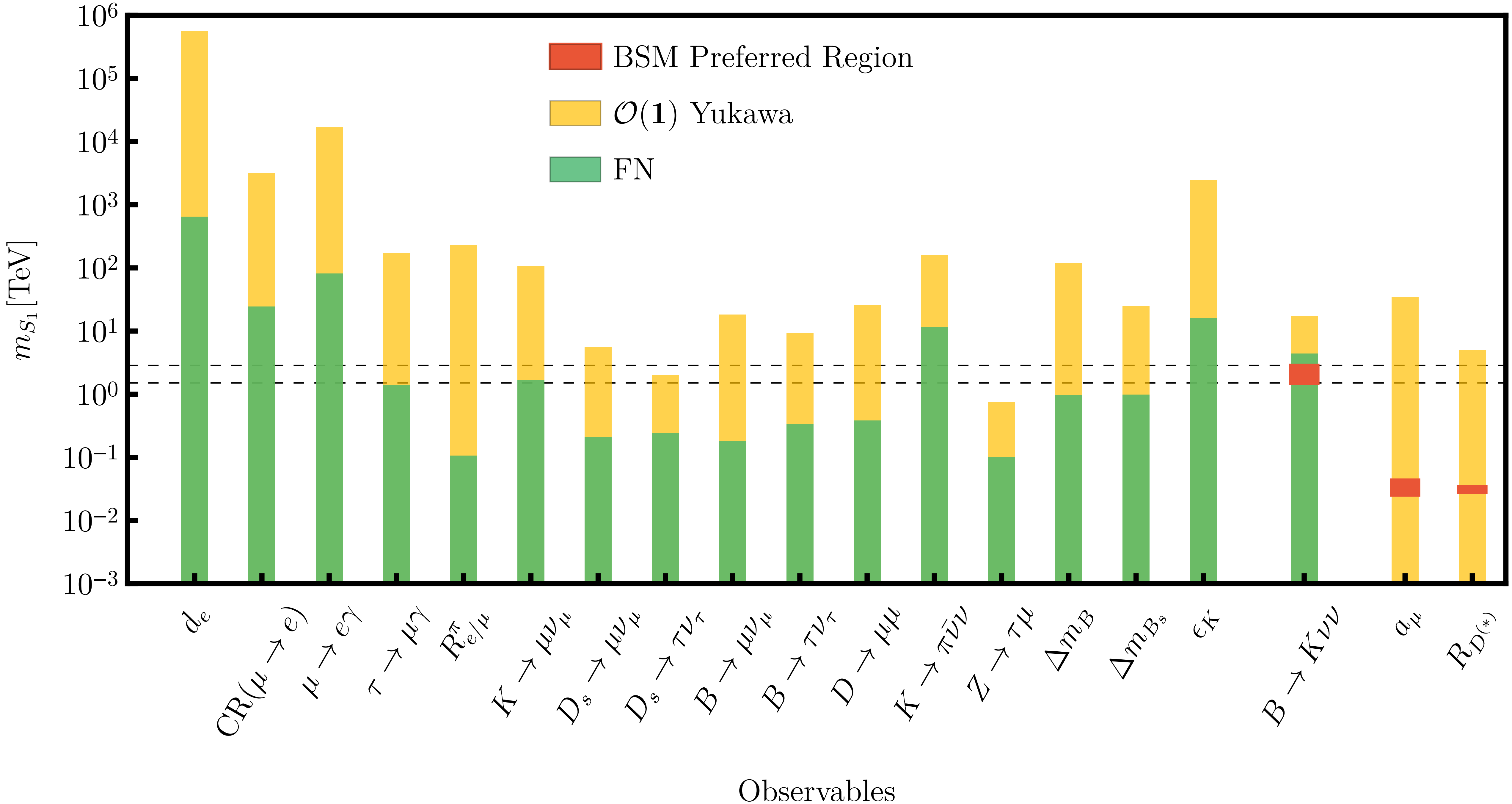

“Wrinkles” in Froggatt-Nielsen

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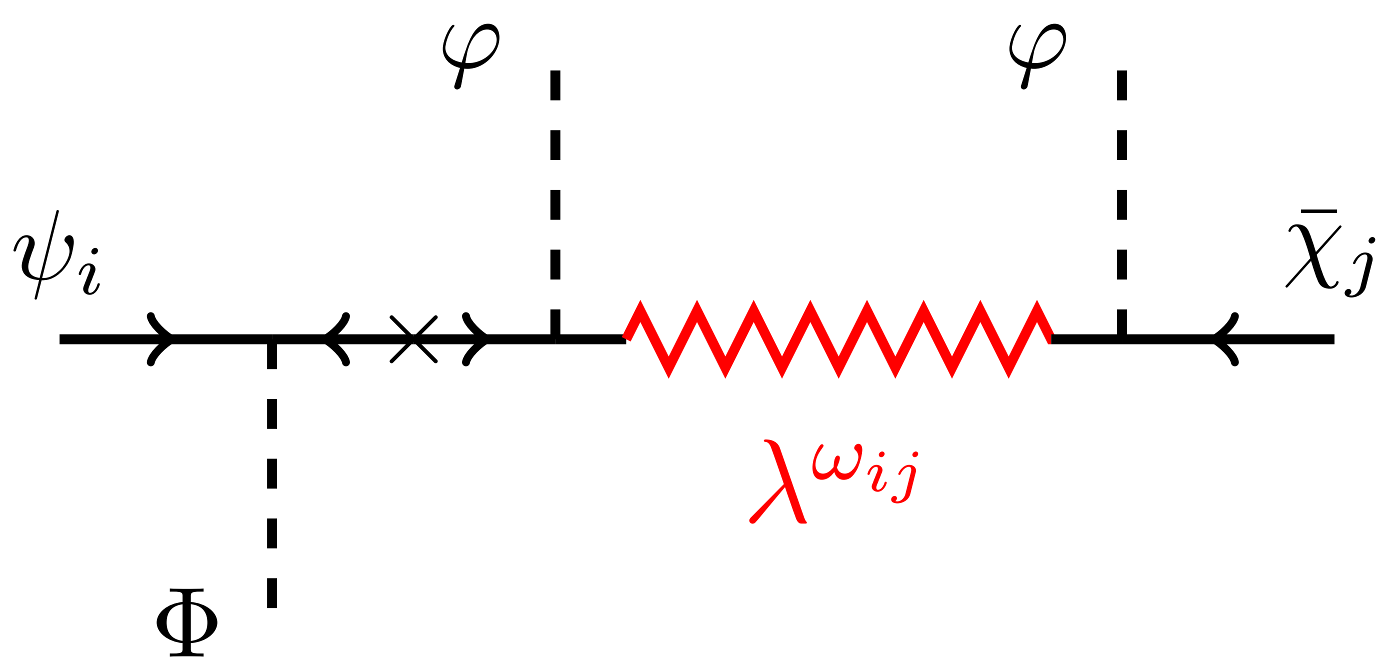
Idea: what if some extra symmetries or dynamics exist in the UV, that modify the spectrum of vector-like matter?



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Precisely, given a coupling to fermions ψ_i, $\bar{\chi}_j$ we allow for a *Wrinkle factor*, W^{ij} which changes the power of λ in the coupling:

$$(Y_{\psi\bar{\chi}})^i{}_j \sim W^{ij}_{\psi\bar{\chi}} \, \lambda^{\left|[\psi_i] + [\bar{\chi}_j]\right|} \equiv \lambda^{\omega^{ij}_{\psi\bar{\chi}} + \left|[\psi_i] + [\bar{\chi}_j]\right|}$$

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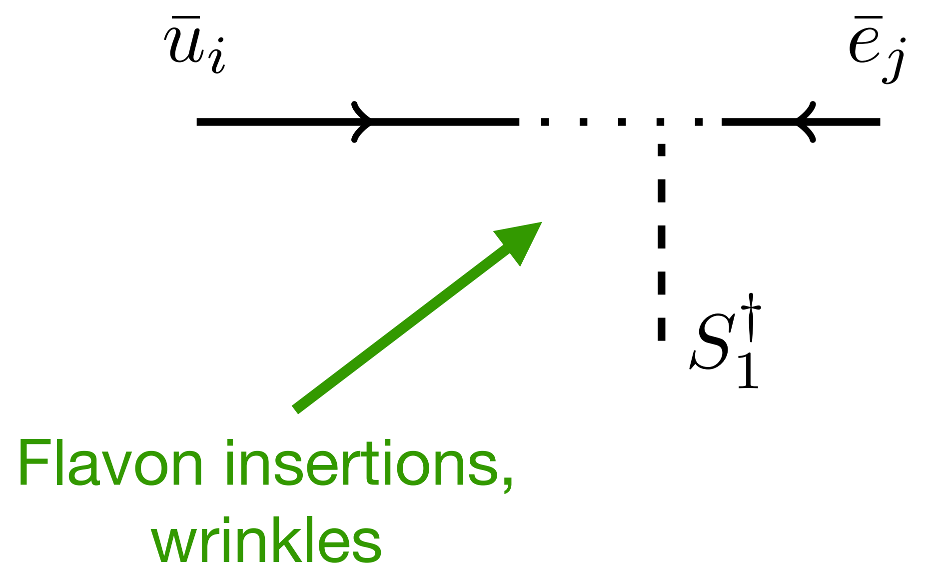
Two possibilities:

Focus on this possibility today

- Wrinkles in BSM chains: new physics couplings to fermions have extra factors of λ which change correlations between different constraints.
- Wrinkles in *Standard Model* chains: the observed masses & mixings are due to a *combination* of wrinkles and $\mathrm{U}(1)_H$ charges, so the charge assignments for the SM are different (this in turn affects the vanilla Ansatz for BSM couplings)

Consistency Condition on Wrinkles

There is a bound on how many wrinkles can be introduced without "spoiling" the FN mechanism.



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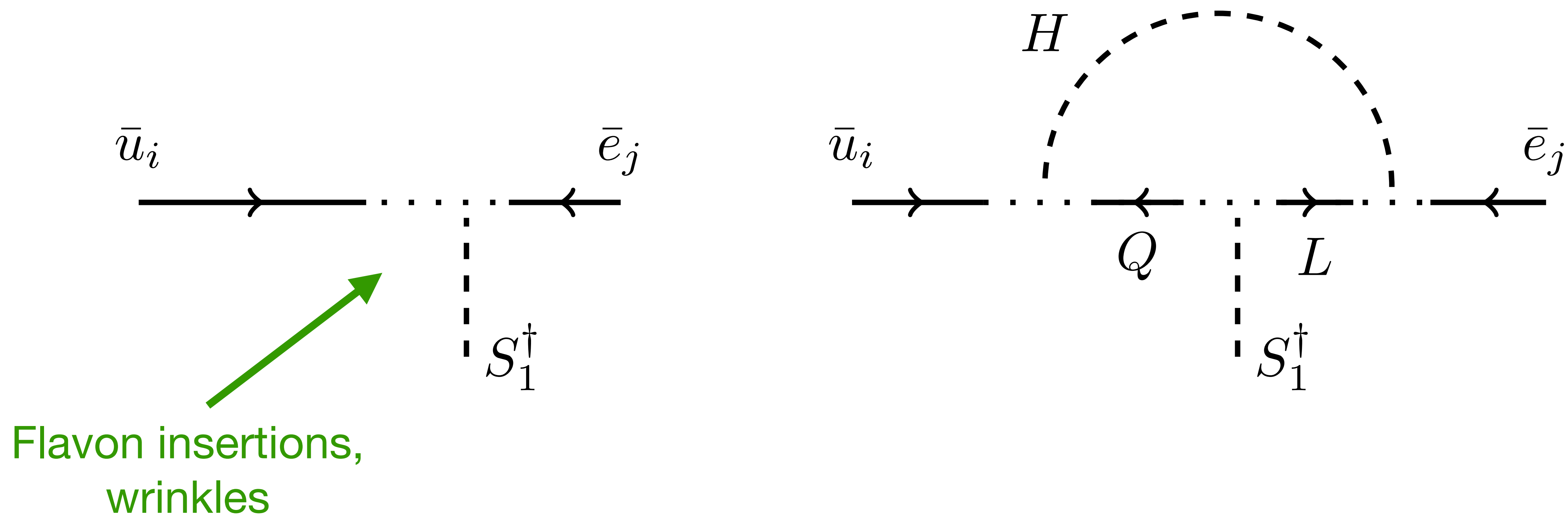

For a “faithful” FN description, we want the tree-level contribution to the IR Yukawa to be larger than the loop contribution:

(can also think of this as a constraint on “tuning”, e.g. Arnold, Fornal, Wise [1304.6119])

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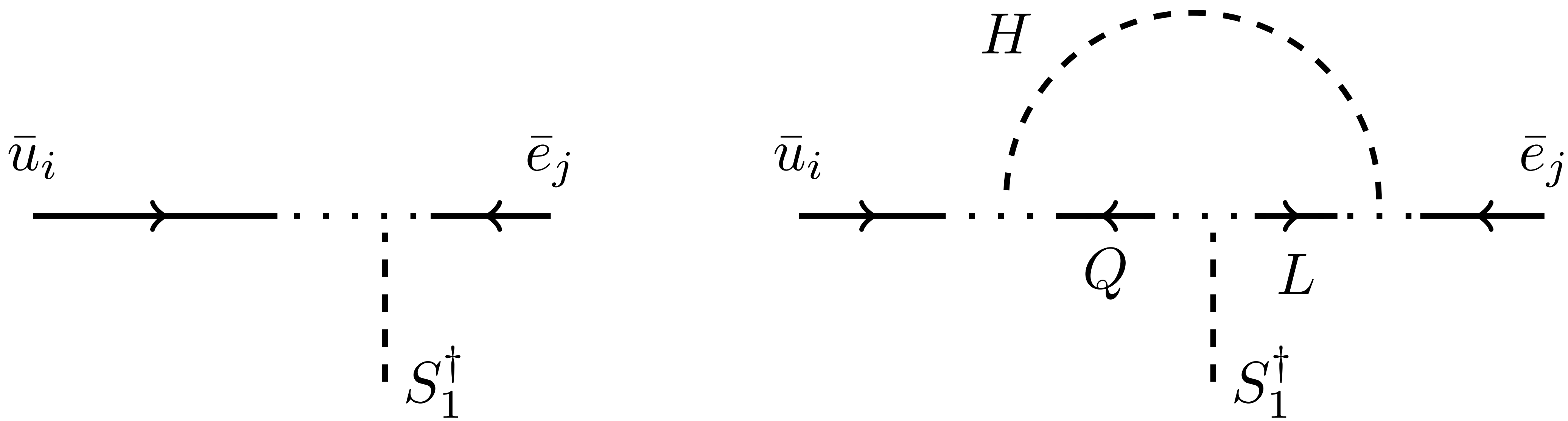

$$\Delta^{ij}_{\bar{u}\bar{e}}\Big|_{\text{tree}} > \Delta^{ij}_{\bar{u}\bar{e}}\Big|_{\text{loop}} \sim \frac{1}{16\pi^2}\left(Y^T_{Q\bar{u}} \cdot \Delta^*_{QL} \cdot Y_{L\bar{e}}\right)^{ij}$$

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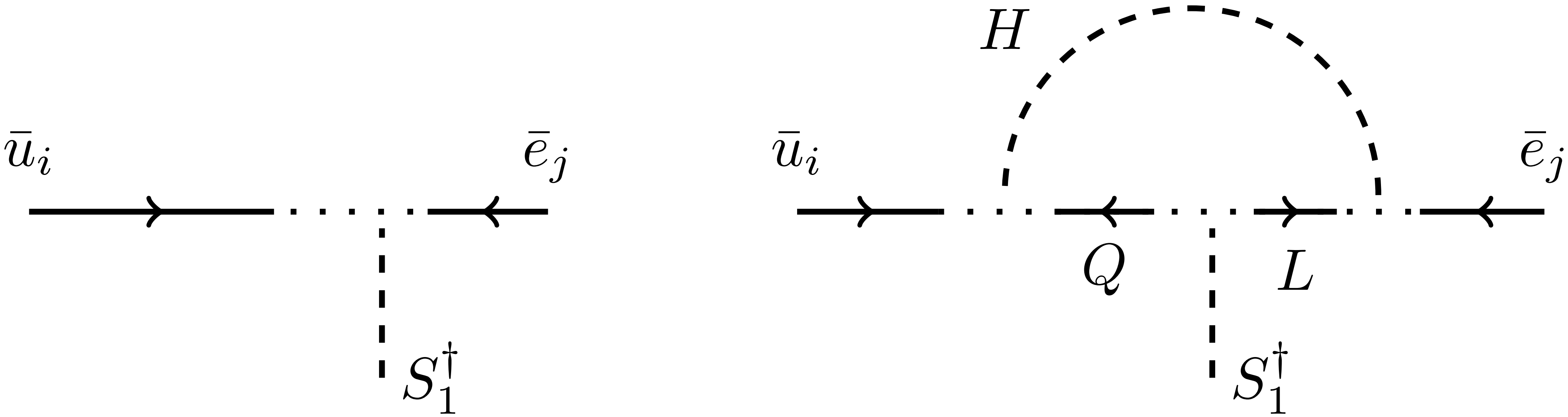

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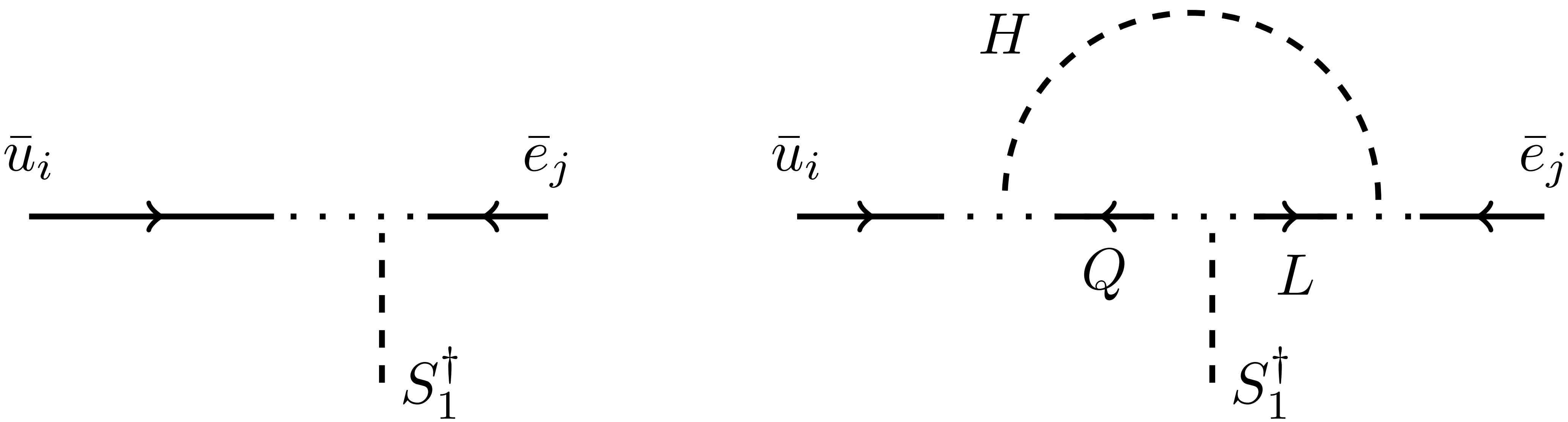
All of these couplings can include wrinkles!

Consistency Condition on Wrinkles



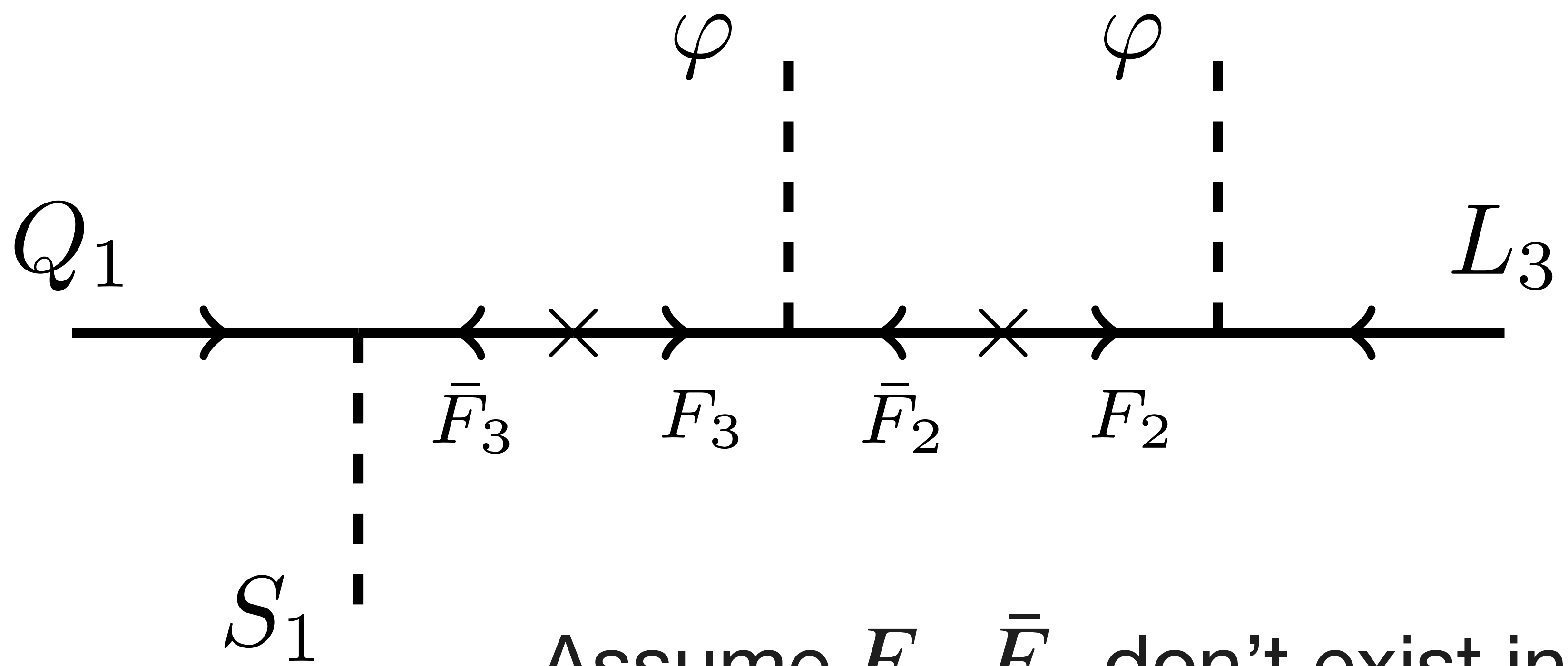
$$\Delta^{ij}_{\bar{u}\bar{e}}\Big|_{\text{tree}} > \Delta^{ij}_{\bar{u}\bar{e}}\Big|_{\text{loop}} \sim \frac{1}{16\pi^2}\left(Y^T_{Q\bar{u}} \cdot \Delta^*_{QL} \cdot Y_{L\bar{e}}\right)^{ij}$$

All of these couplings can include wrinkles!

There are 20 other "consistency conditions" like this for the S_1 LQ that must be checked.

Fortunately, since $1/(16\pi^2) \sim \lambda^3$, there is a simple *sufficient* condition, which is just that all $\omega^{ij} < 3$.

UV Completions I: Missing Heavy Fermions



Assume $F_2, \bar{F}_2$ don’t exist in the UV spectrum…

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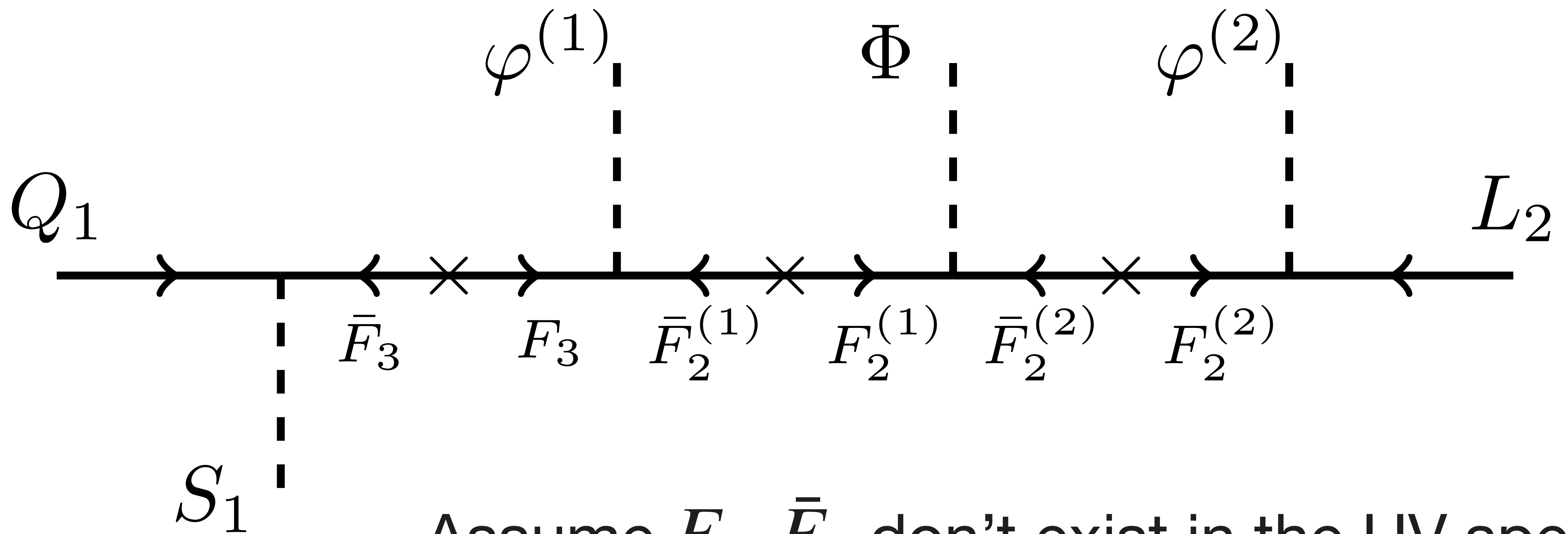


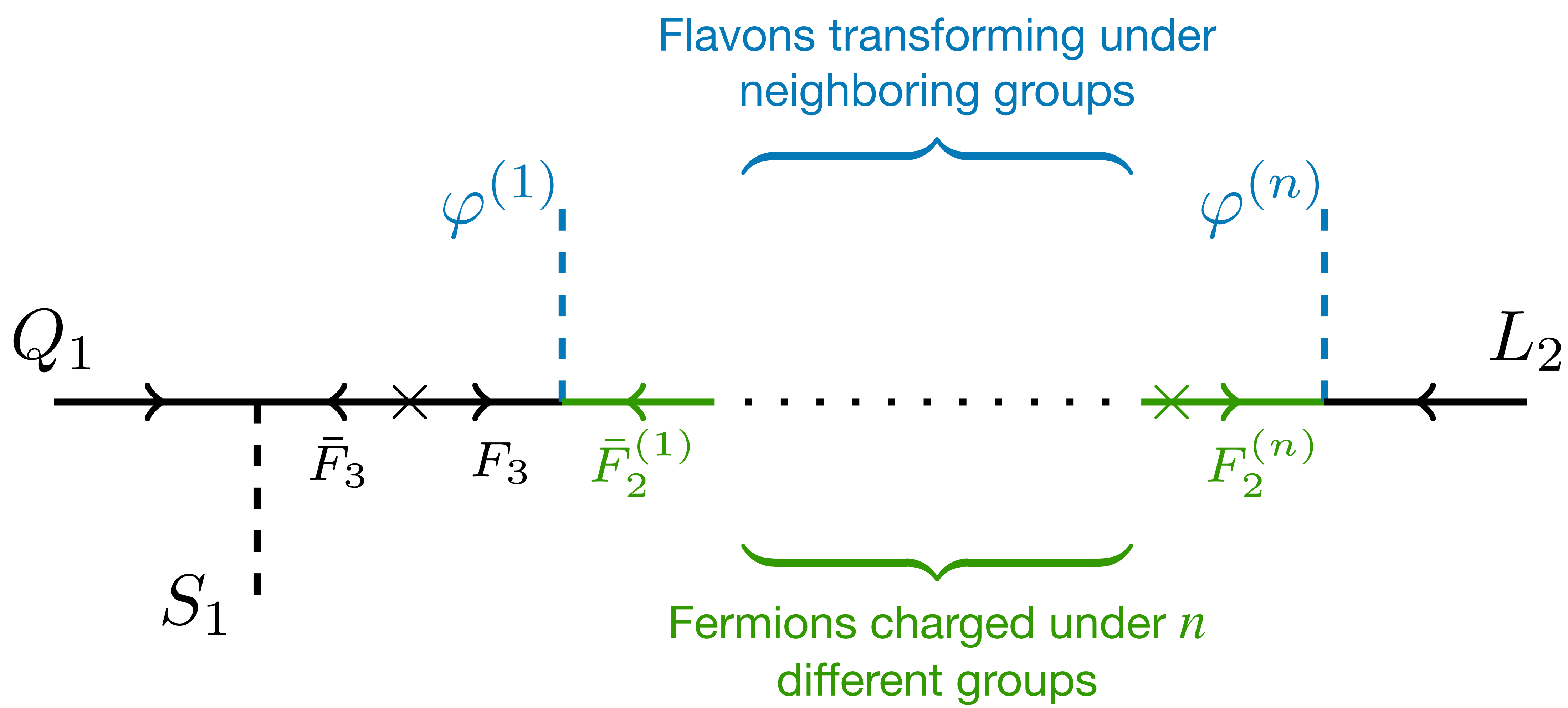
Assume $F_2, \bar{F}_2$ don't exist in the UV spectrum…

…but other heavy matter with same SM charges does, but with additional symmetries.

For concreteness, assume $F_2^{(1)}, \bar{F}_2^{(1)}$ (anti-)fundamentals under $\mathrm{SU}(N_1)$, and $F_2^{(2)}, \bar{F}_2^{(2)}$ (anti-)fundamentals under $\mathrm{SU}(N_2)$

UV Completions I: Missing Heavy Fermions

Can extend this to add as many wrinkles as we want (within consistency conditions)



Note that this "missing fermion" will lead to wrinkles in every coupling it's involved in — wrinkles are generally correlated!

UV Completions II: Gauged Flavor Symmetries

Alternatively, assume there exist additional UV (Abelian) symmetries that act on the *Standard Model* fermions (e.g., B, L, $L_\mu - L_\tau$, $\ldots$)

If new fields (e.g., S_1) are neutral under this symmetry, then the couplings must be a spurion of both $\mathrm{U}(1)_H$ *and* the new $\mathrm{U}(1)$.

E.g., $\mathrm{U}(1)_{B-L}$:

$$\Delta^{ij}_{QL}\, S_1\, Q_i\, L_j$$

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E.g., $\mathrm{U}(1)_{B-L}$:

$$\Delta_{QL}^{ij}\, S_1\, Q_i\, L_j$$

$$\supset \langle\tilde{\varphi}\rangle^2, \quad [\tilde{\varphi}]_{B-L} = 1/3 \qquad\qquad [Q_i L_j]_{B-L} = -2/3$$

In contrast, the SM Yukawas are unchanged since they respect $B - L$

UV Completions II: Gauged Flavor Symmetries

Flavor non-universal examples are more ~~complicated~~ interesting.

Consider $B-3L_e$, extend the flavon sector: (All with $\mathrm{U}(1)_H = -1$)

$$[\varphi]_{B-3L_e} = 0, \quad [\varphi_2]_{B-3L_e} = 3, \quad [\varphi_3]_{B-3L_e} = -1/3$$

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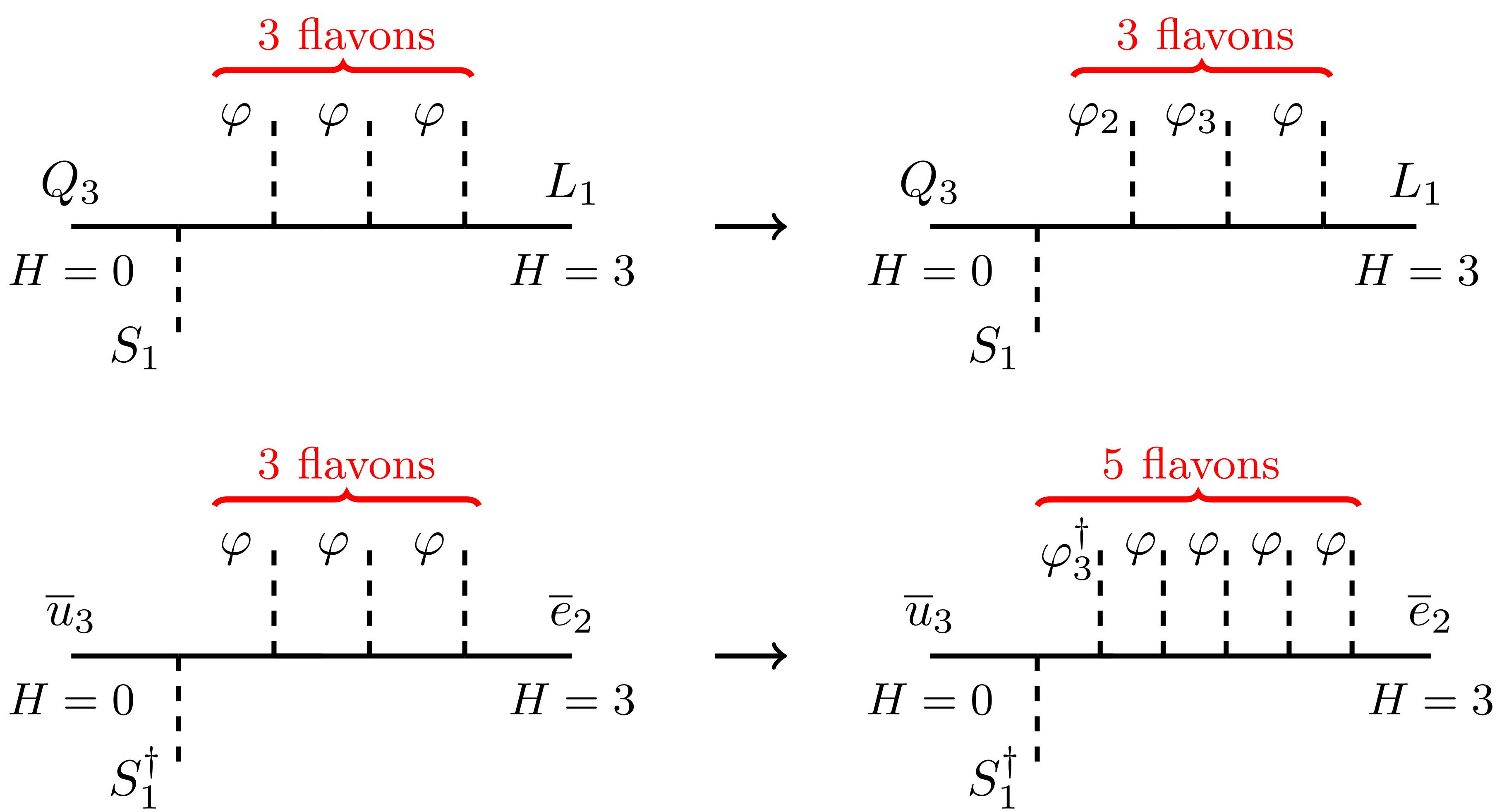

Wrinkles give extra (but not unlimited) flexibility in modifying the correlations dictated by FN Ansatz.

This flexibility is best understood in an example:

We'll study the $B \to K\nu\bar{\nu}$ decay, which was fortuitously just updated by Belle II!

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First a detour on why B decays still attract a lot of attention…

New Physics in $B \to K$ Transitions?

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

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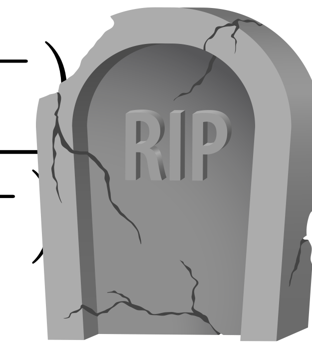

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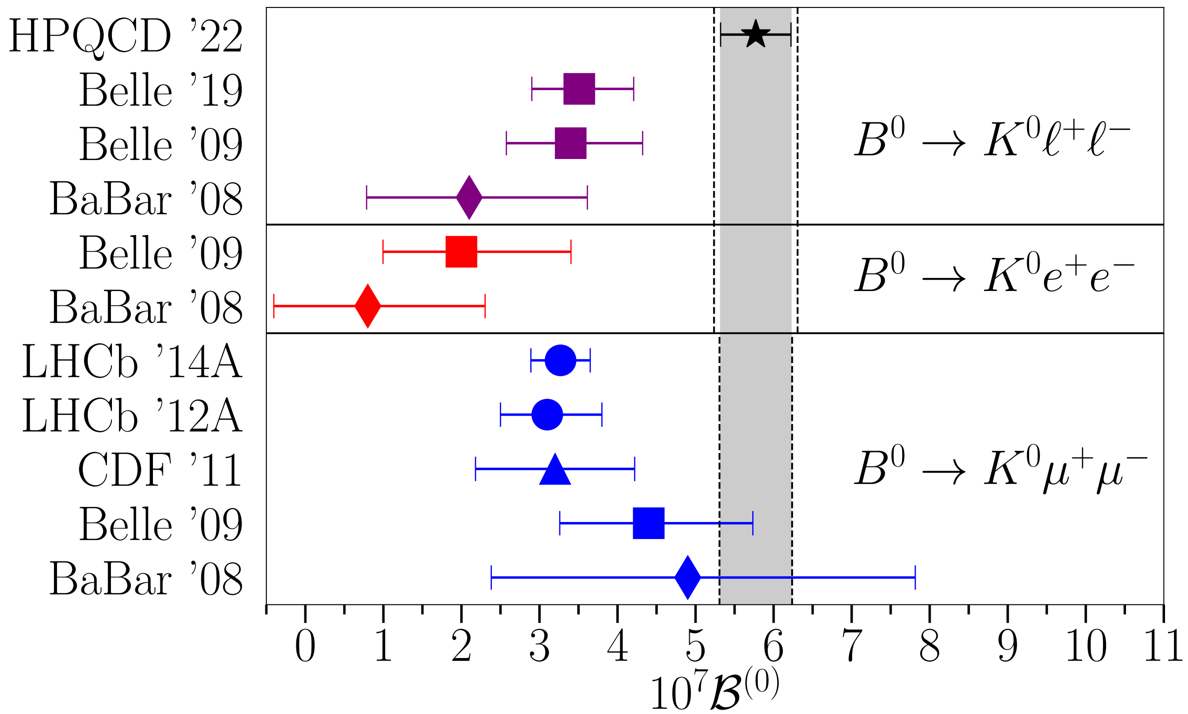
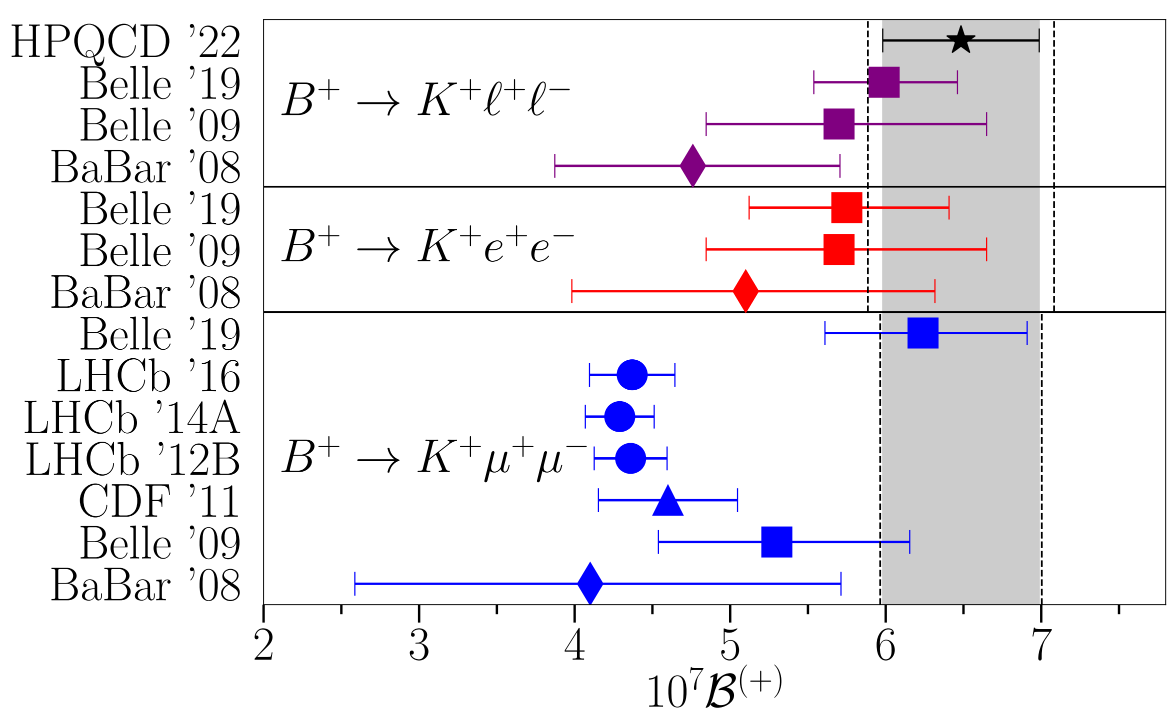
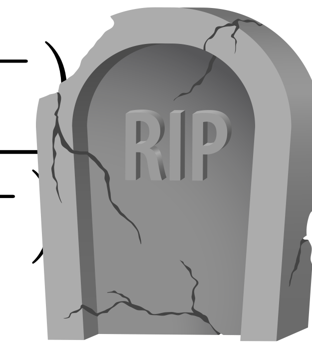




$$R_{K^{(*)}} \sim \frac{\Gamma(B \to K \mu^+ \mu^-)}{\Gamma(B \to K e^+ e^-)}$$



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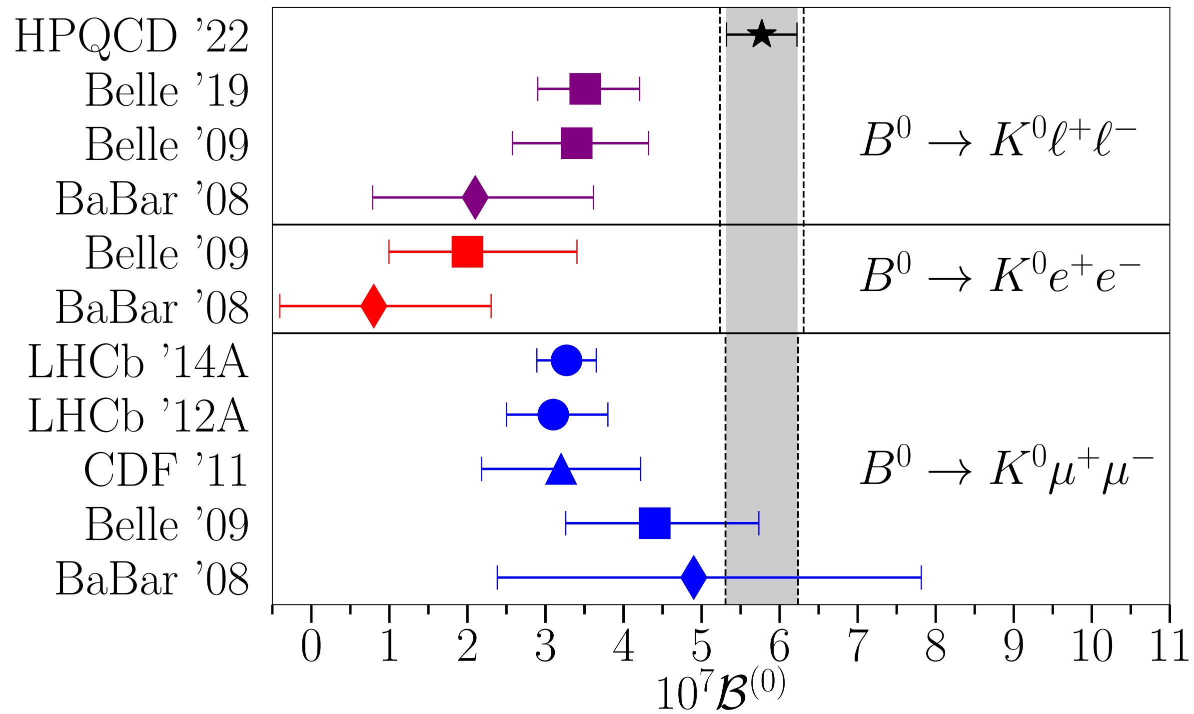

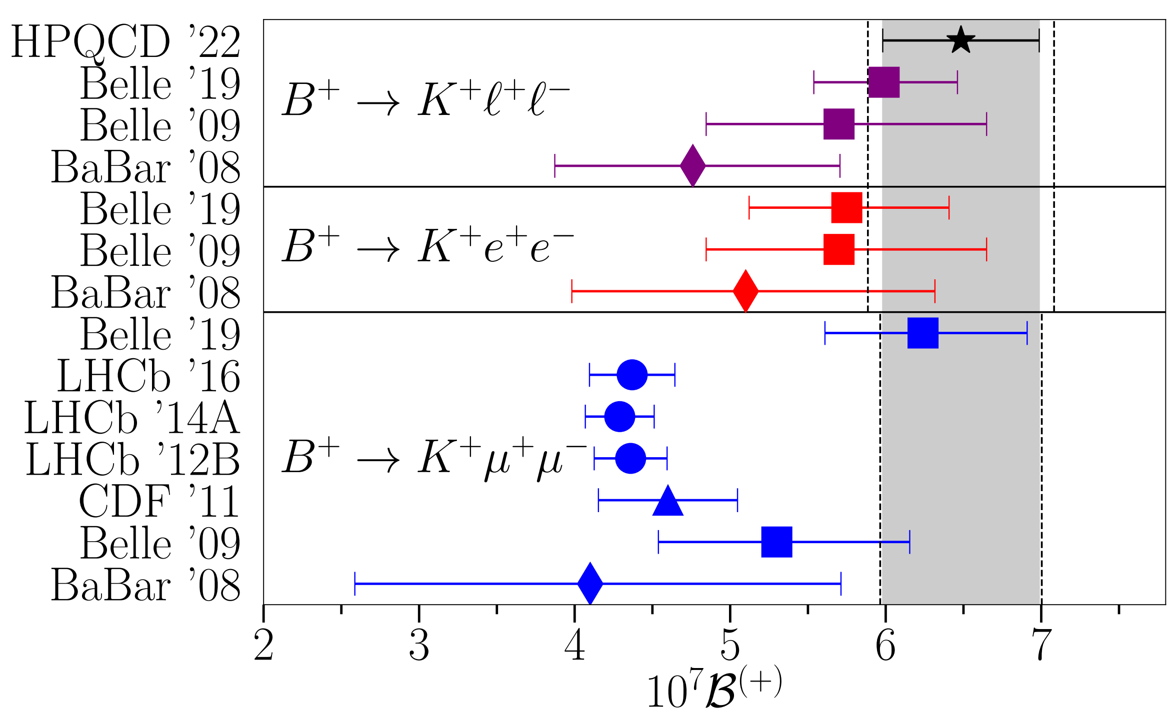

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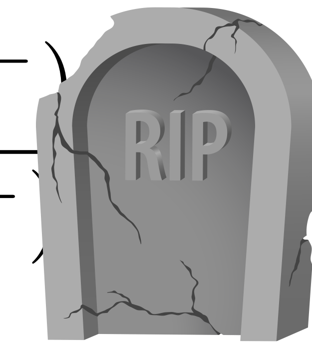

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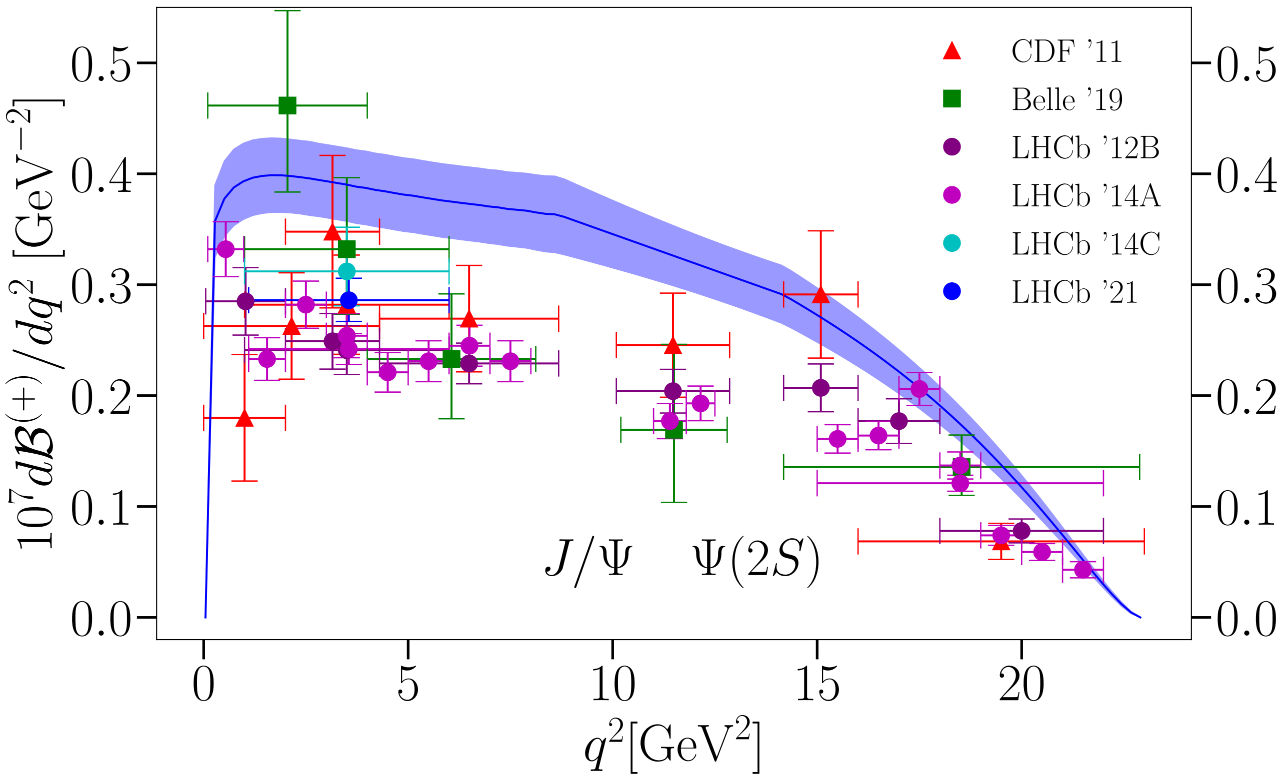

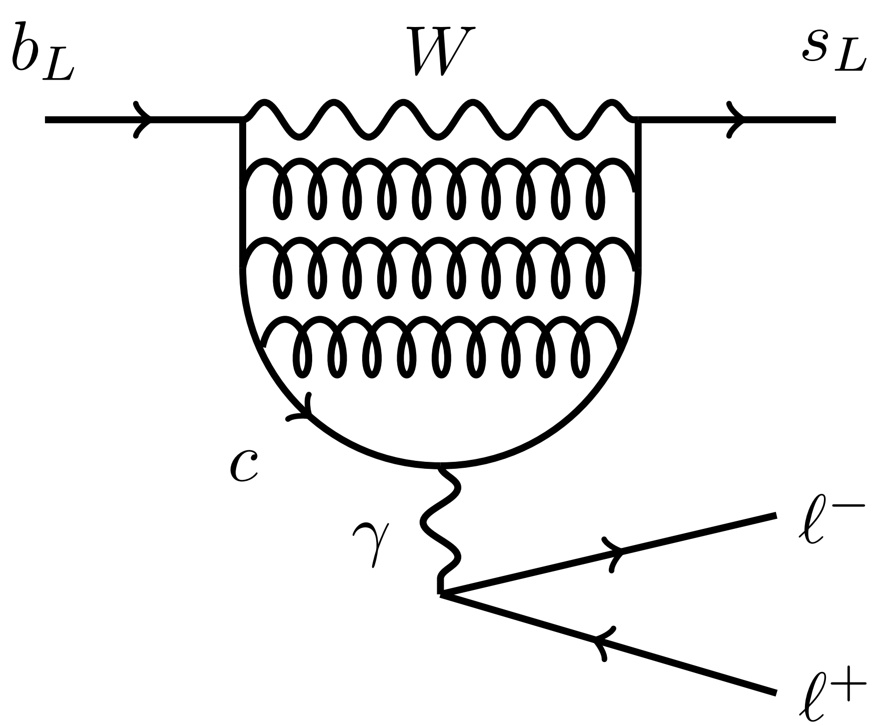

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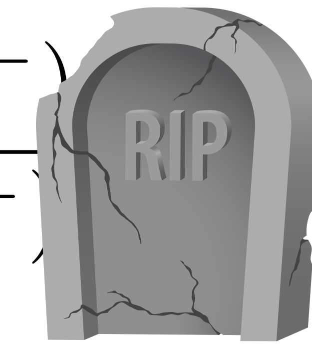
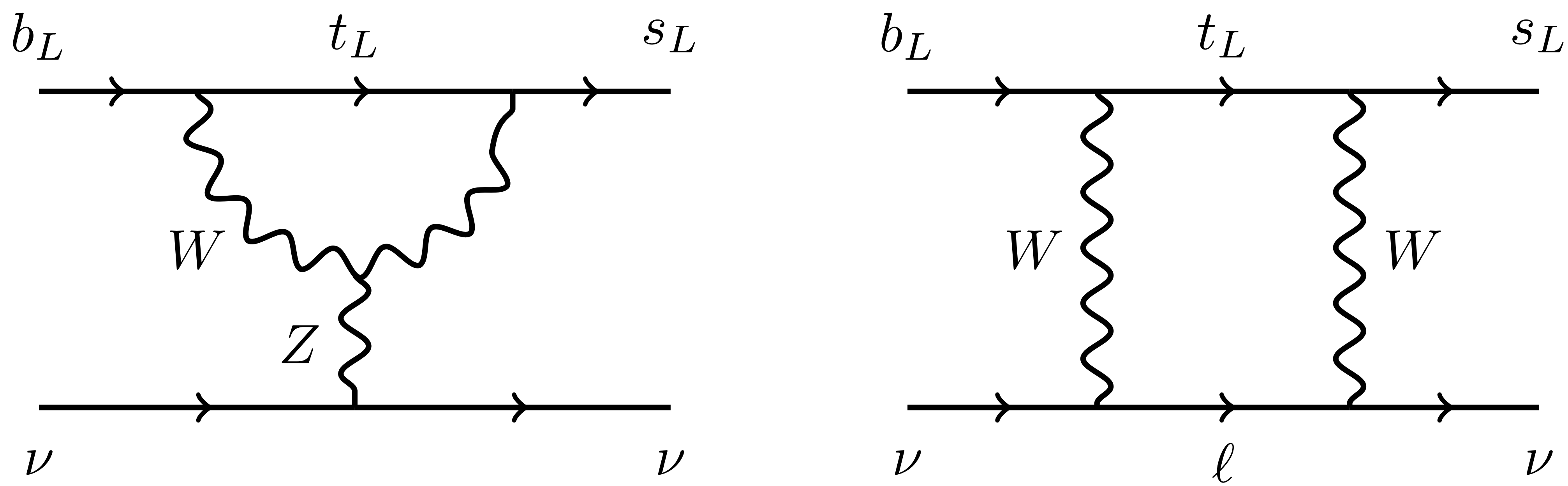


Absolute rates are extremely challenging, both experimentally and theoretically.

On the theory side:

- Uncertainty in form factors from the lattice
- Long-distance QCD contributions are challenging to estimate (resonance regions have to be masked)

$B \to K\nu\bar{\nu}$ in the Standard Model



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^{ij} \frac{\alpha_{\text{em}}}{2\pi} (s_L^\dagger \bar{\sigma}^\mu b_L)(\nu_j^\dagger \bar{\sigma}_\mu \nu_i) + (L \leftrightarrow R) \right) + \text{h.c.}$$

SM contribution, ~ 6

$$\text{BR}(B^+ \to K^+ \nu\bar{\nu})\Big|_{\text{SM}} = (0.46 \pm 0.05) \times 10^{-5}$$

$\Longrightarrow$ Theoretically *clean*! Long-distance contributions suppressed due to lack of photon penguins.

(See e.g., Altmannshofer et al., [0902.0160])

Measurements of $B \to K\nu\bar{\nu}$

(As of ~April 2021)

$$e^+e^- \to \Upsilon(4S) \to B^+\, B^-$$

Decays to final state involving neutrinos

"Tagging" meson, with decays to visible states (either hadronic or semi-leptonic)

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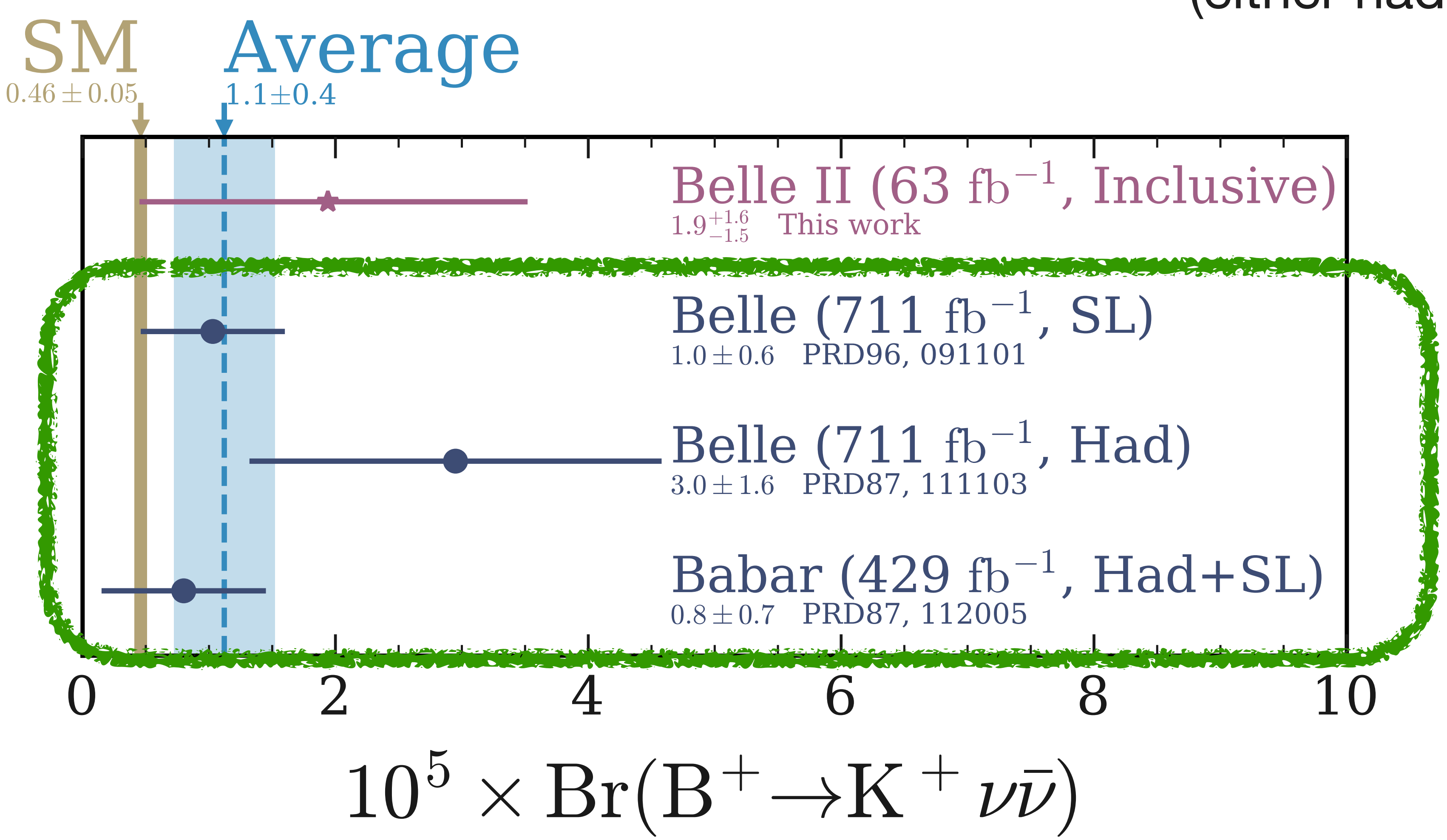

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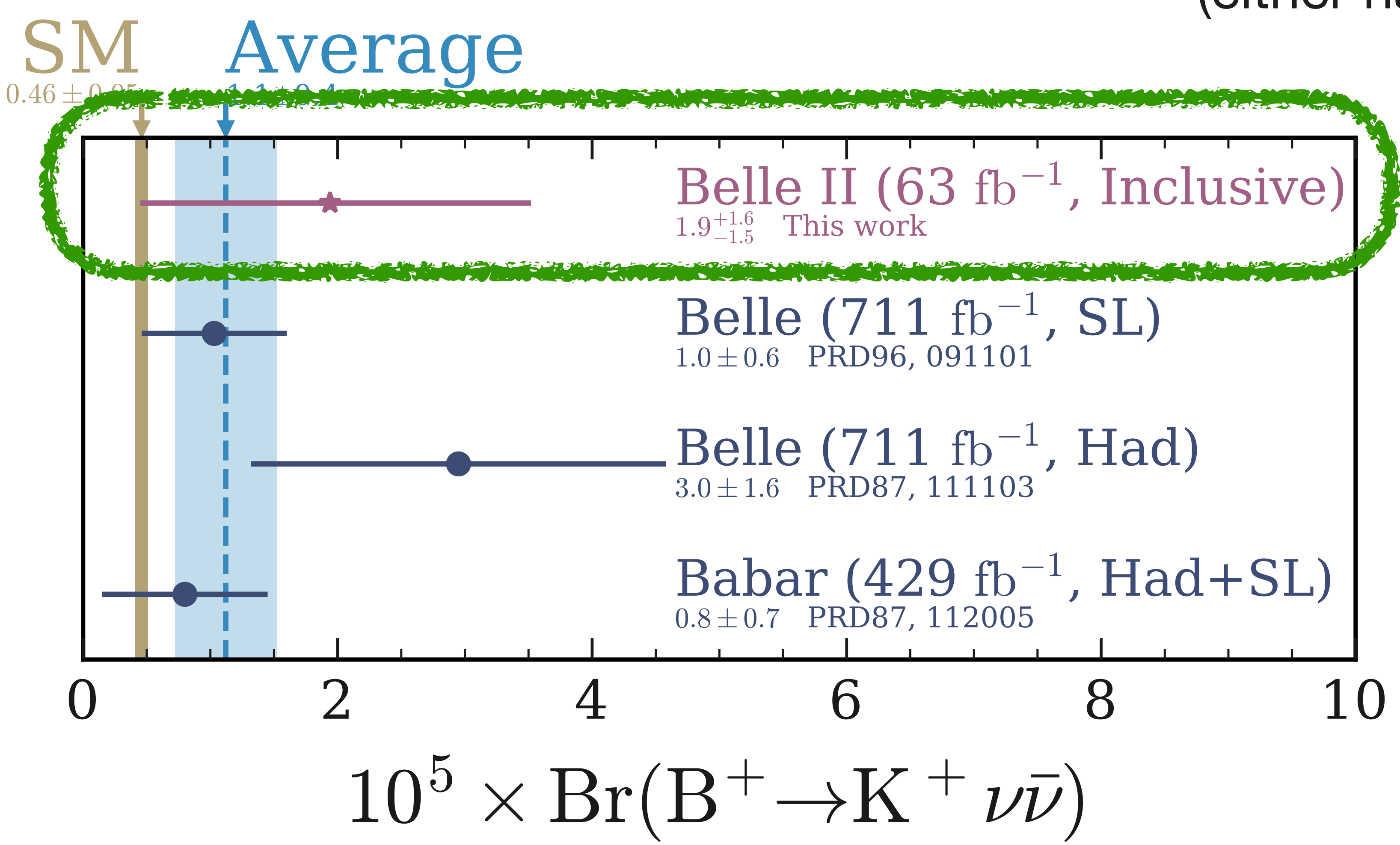
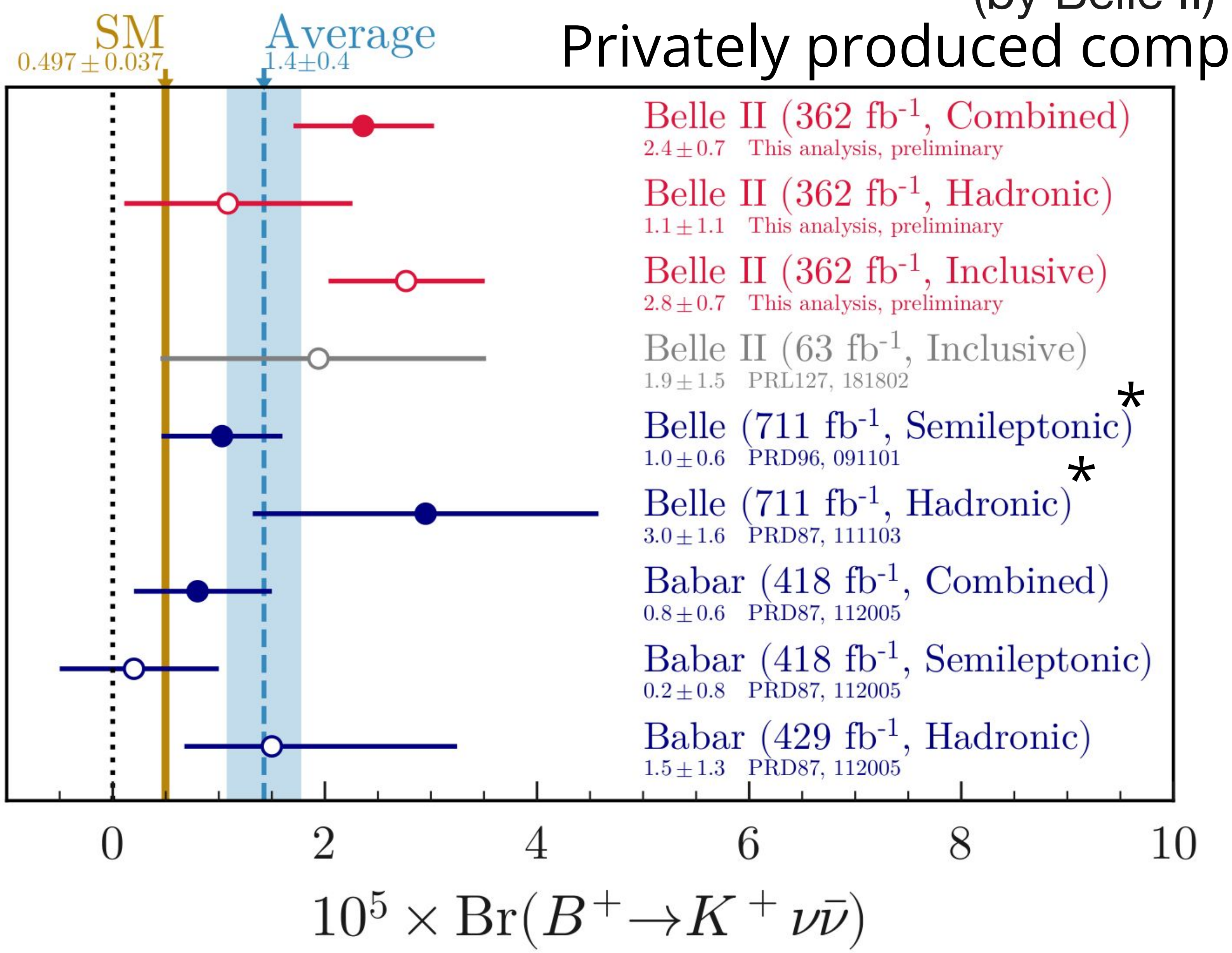


New "inclusive" tagging measurements train classifiers to pick out the Kaon and (large) missing energy, along with the other *B* remnants, with a much higher signal efficiency (at the cost of a larger background)

Measurements of $B \to K\nu\bar{\nu}$

(As of August 2023!)

(by Belle II)
Privately produced comparison



Recent update at EPS HEP 2023 (see two Belle II talks: here and here)

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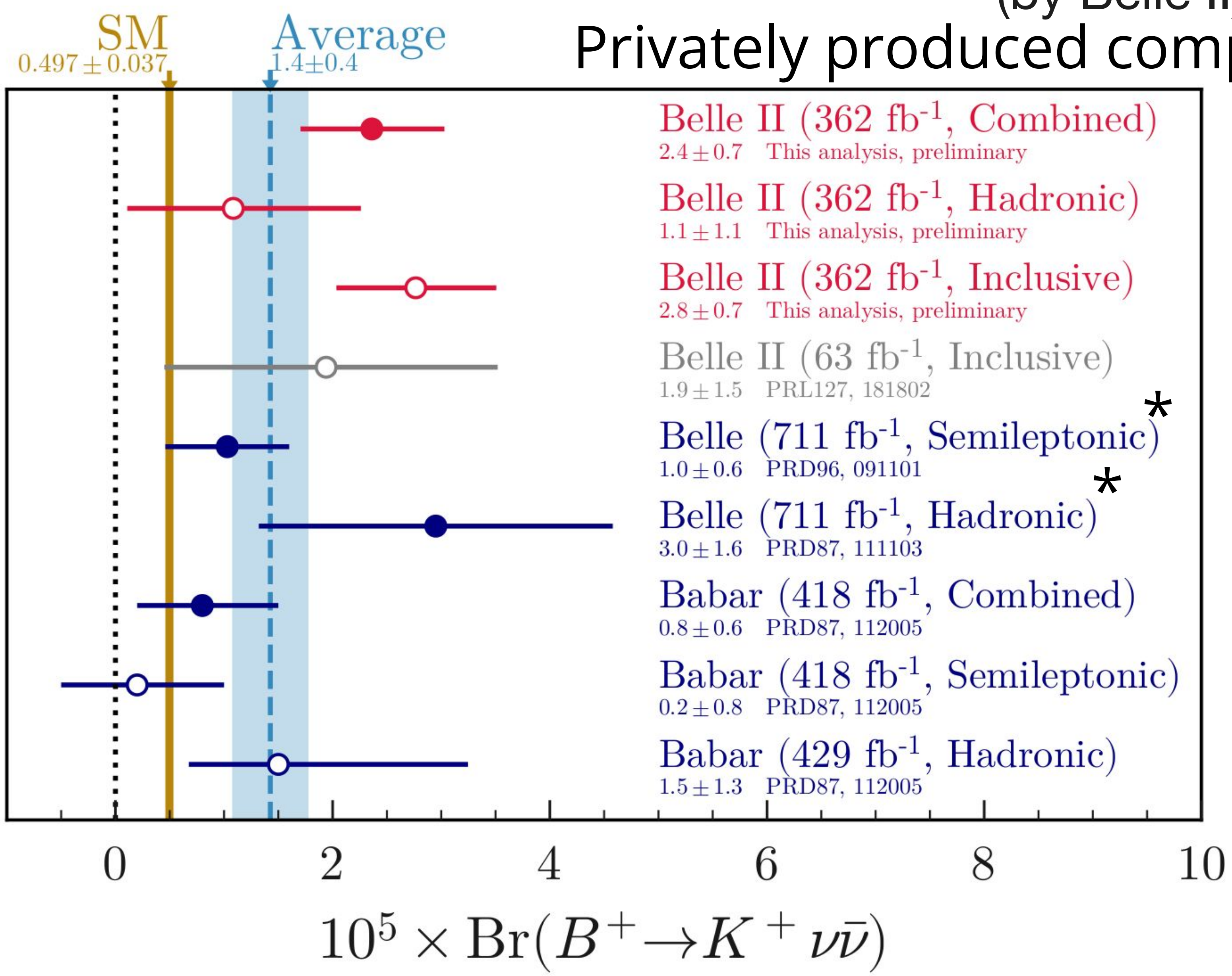


Recent update at EPS HEP 2023 (see two Belle II talks: here and here)

Belle II average:
$(2.4 \pm 0.7) \times 10^{-5}$
~ 2.8σ above SM

World average:
$(1.4 \pm 0.4) \times 10^{-5}$
~ 2.2σ above SM

What to make of this excess?

(Beyond the fact that it's only $\sim 2.5\sigma$)

Absolute rate measurements are extremely difficult

(experiments have to carefully calibrate their efficiencies, and theory relies on non-perturbative QCD)

SM Calculation of $B \to K\ell^+\ell^-$ and $B \to K\nu\bar{\nu}$ relies on the same form factor: this can't explain the deficit in $\ell^+\ell^-$ *and* the excess in $\nu\bar{\nu}$

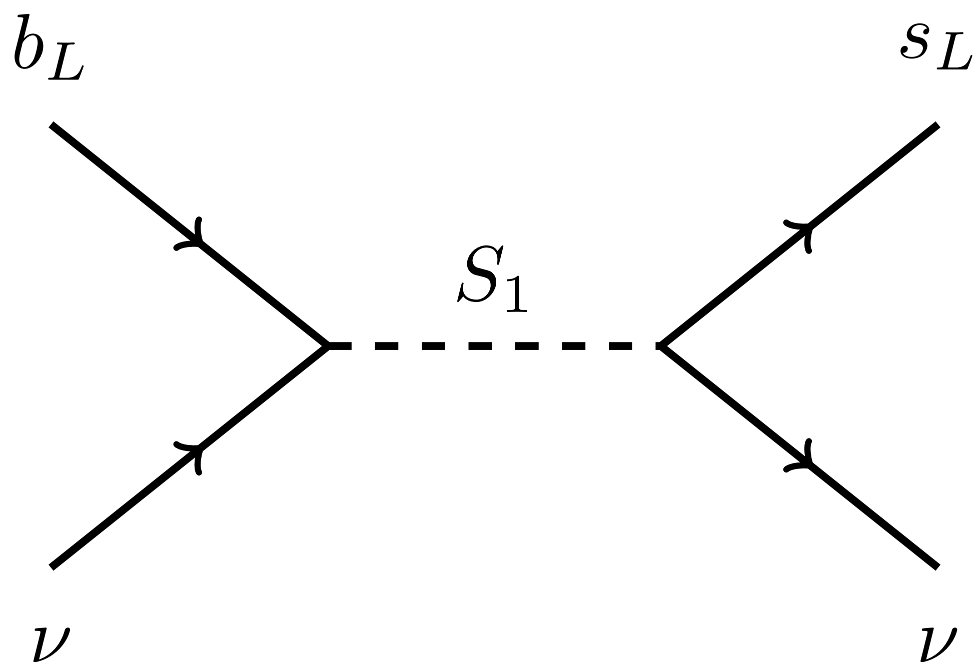
(the long distance contributions can be very different, however)

A number of BSM interpretations already exist (naturally)

EFT interpretations, [2308.13426, 2309.00075, 2309.02246], Leptoquarks [2308.13329], or light new physics [2309.02940, 2309.03706, 2309.03727] (and more…)

Leptoquark Contributions to $B \to K\nu\bar{\nu}$

The S_1 leptoquark contributes to $B \to K\nu\bar{\nu}$ at tree-level:



$$C_L^{ij} \propto \frac{v^2}{m_{S_1}^2} \Delta_{QL}^{3i} \Delta_{QL}^{2j\,*}$$

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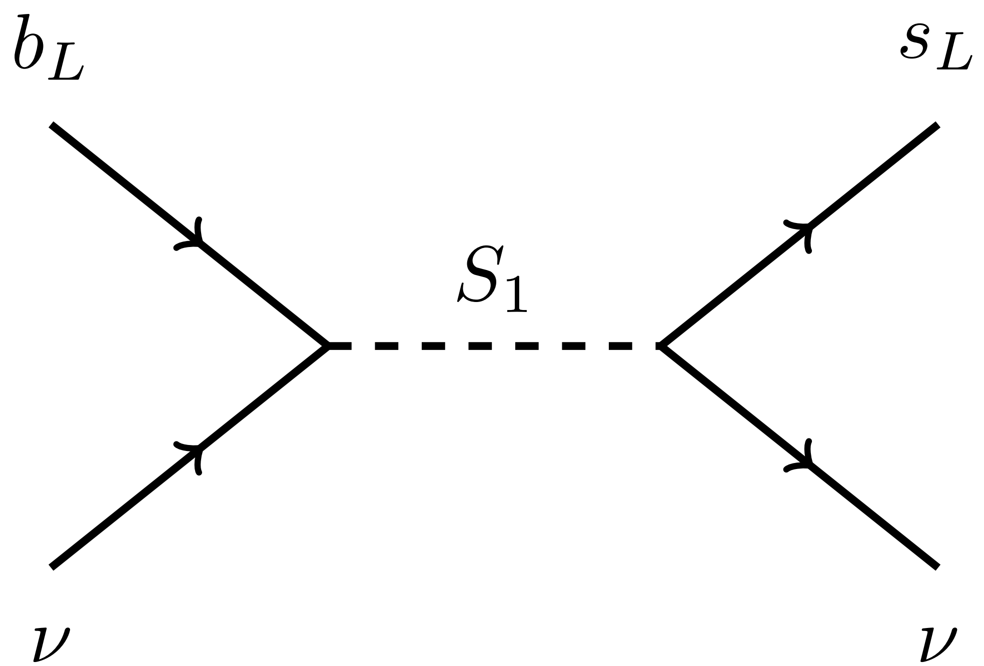


$$C_L^{ij} \propto \frac{v^2}{m_{S_1}^2} \Delta_{QL}^{3i} \Delta_{QL}^{2j\,*}$$

- Only contributes to C_L (the same operator as the SM), not C_R.
- No dependence on $\Delta_{\bar{u}\bar{e}}$!

$$R_K^{\nu\nu} \simeq 1 - \left(\frac{1.2\,\mathrm{TeV}}{m_{S_1}}\right)^2 \mathrm{Re}\left[\frac{(\Delta_{QL}^{3i}\Delta_{QL}^{2i\,*})}{V_{tb}V_{ts}^*}\right] + \frac{3}{4}\left(\frac{1.2\,\mathrm{TeV}}{m_{S_1}}\right)^4 \frac{(\Delta_{QL}^{3i}\Delta_{QL}^{3i\,*})(\Delta_{QL}^{2j}\Delta_{QL}^{2j\,*})}{\left|V_{tb}V_{ts}^*\right|^2}$$

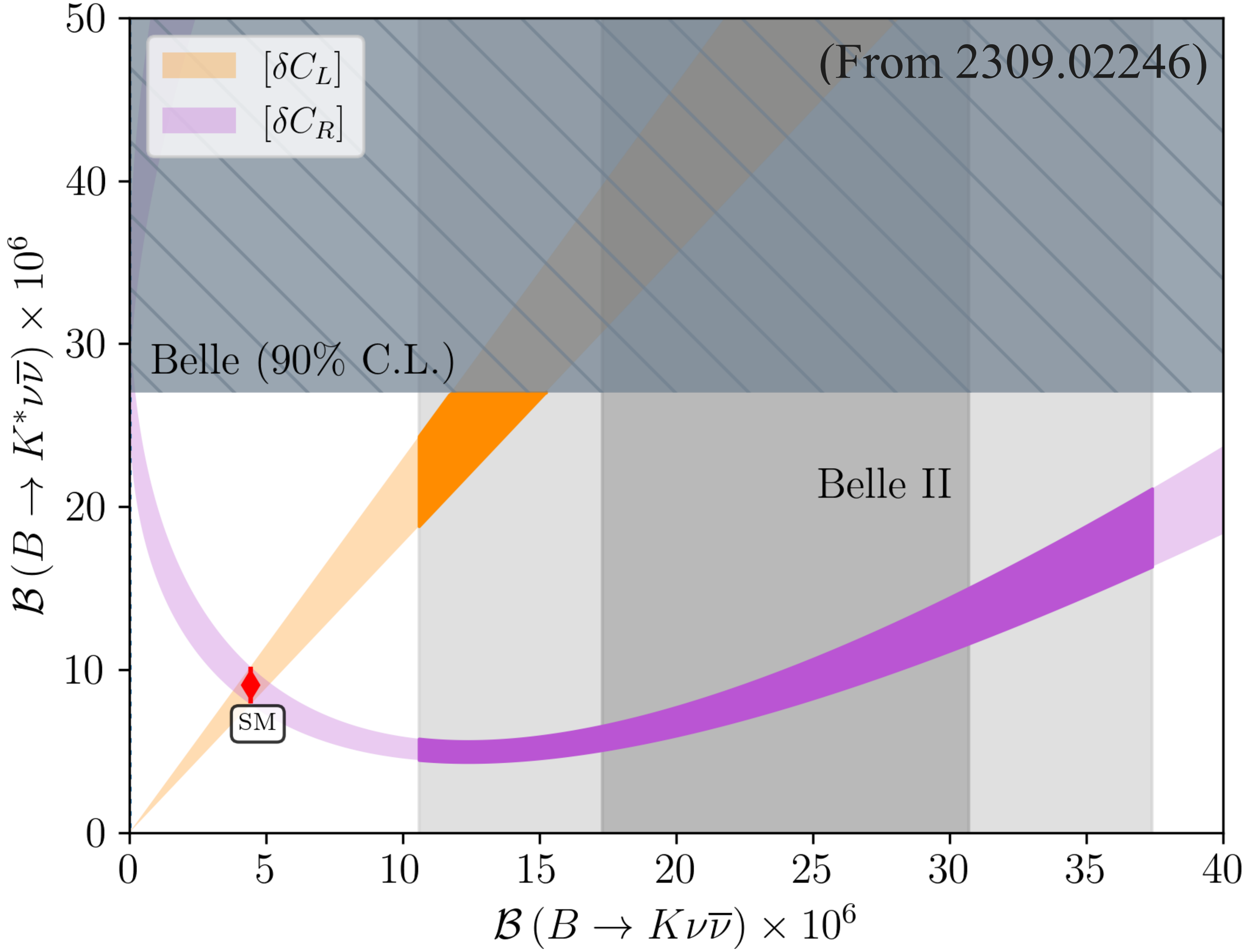
Is One Leptoquark Enough?

Bause, Gisbert, Hiller [2309.00075], Allwicher et al., [2309.02246]

NP Contributions to C_L are constrained by the similar $B \to K^* \nu\bar{\nu}$ decay, for which there is no excess.

Contributions to both C_L and C_R are also constrained by lepton flavor universality measurements, depending on the flavor structure.

$\Longrightarrow$ Challenging to fully explain the anomaly with a single leptoquark (esp. S_1)



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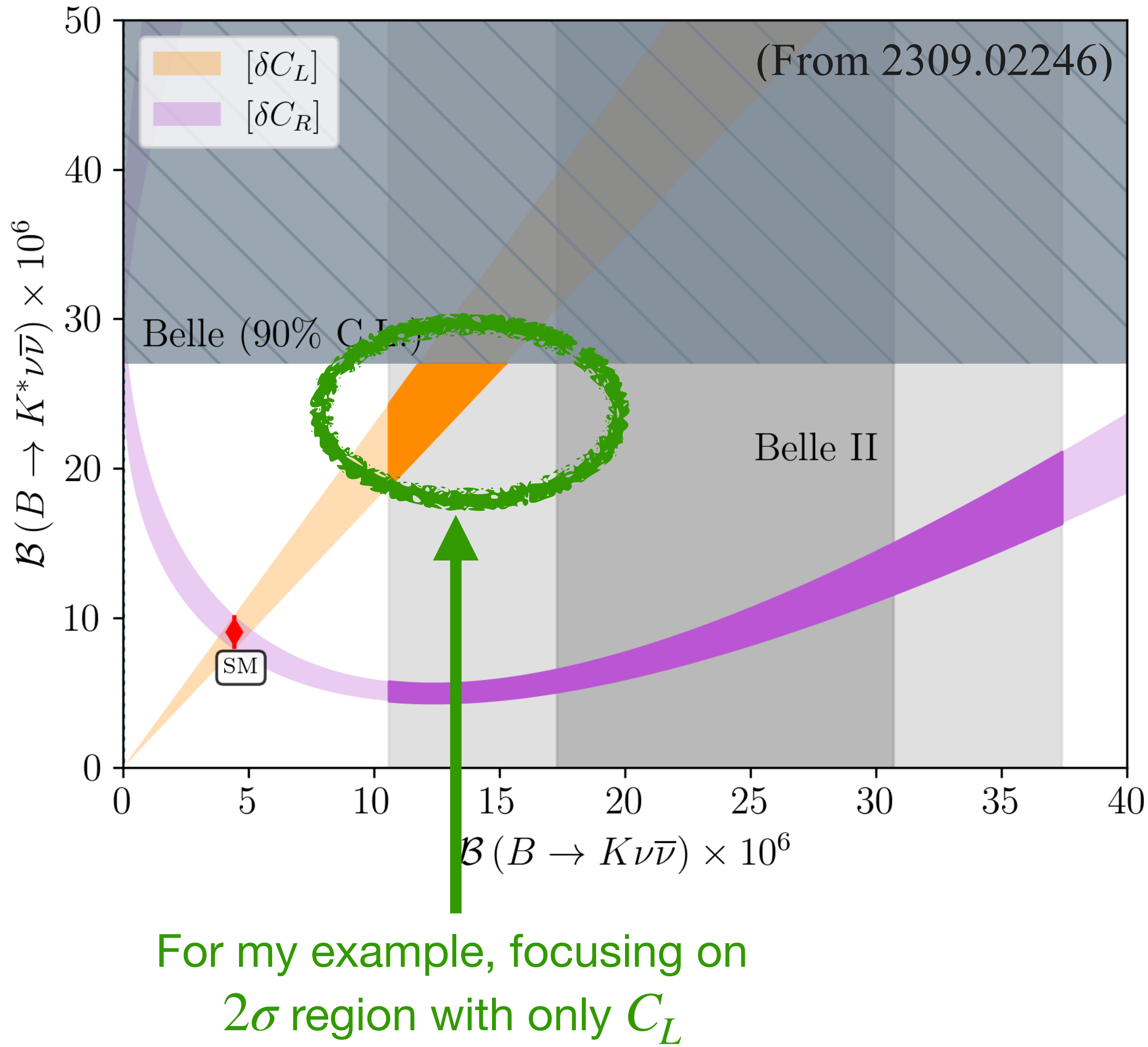


A “Maximally” Wrinkled Ansatz

To understand the limitations of wrinkles, we add the “maximal” number of wrinkle factors ($\sim \lambda^3$) to every entry that doesn’t significantly suppress the $B \to K\nu\bar{\nu}$ branching ratio:

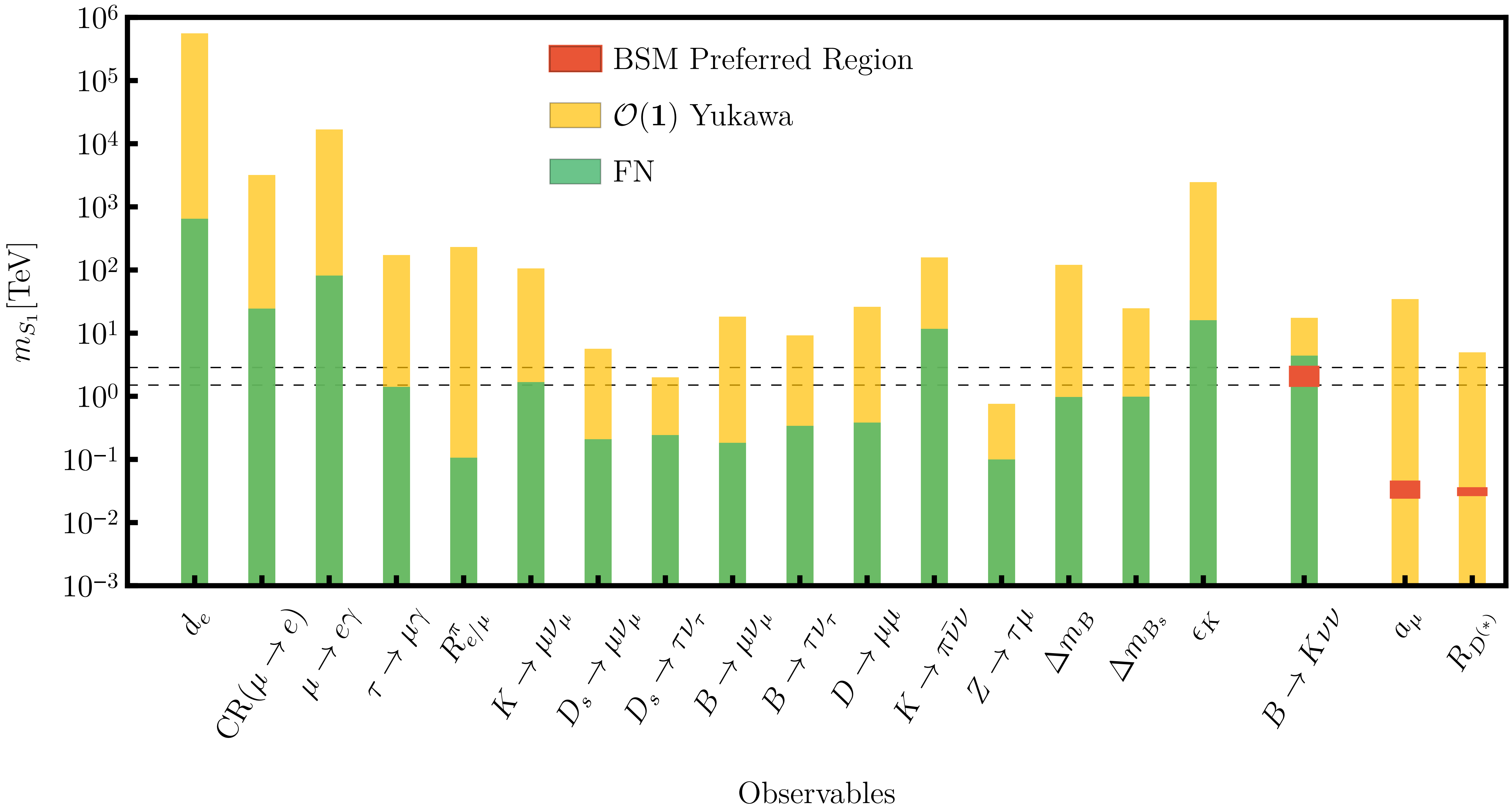
$$W_{QL} = \begin{pmatrix} \lambda^3 & \lambda^3 & \lambda^3 \\ \lambda^3 & 1 & 1 \\ \lambda^3 & 1 & 1 \end{pmatrix}, \qquad W^{ij}_{\bar{u}\bar{e}} = \lambda^3$$

With these, the LQ couplings are:

$$\Delta_{QL} \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda & \lambda \\ \lambda^3 & \lambda & \lambda \end{pmatrix}, \qquad \Delta_{\bar{u}\bar{e}} \sim \begin{pmatrix} \lambda^{15} & \lambda^{13} & \lambda^{11} \\ \lambda^{12} & \lambda^{10} & \lambda^8 \\ \lambda^{11} & \lambda^9 & \lambda^7 \end{pmatrix}$$

Correlated Constraints on the LQ

$$[Q_i] = (3,2,0), \quad [\bar{u}_i] = (4,1,0), \quad [\bar{d}_i] = (3,3,2), \quad [L_i] = (0,-1,-1), \quad [\bar{e}_i] = (8,6,4)$$



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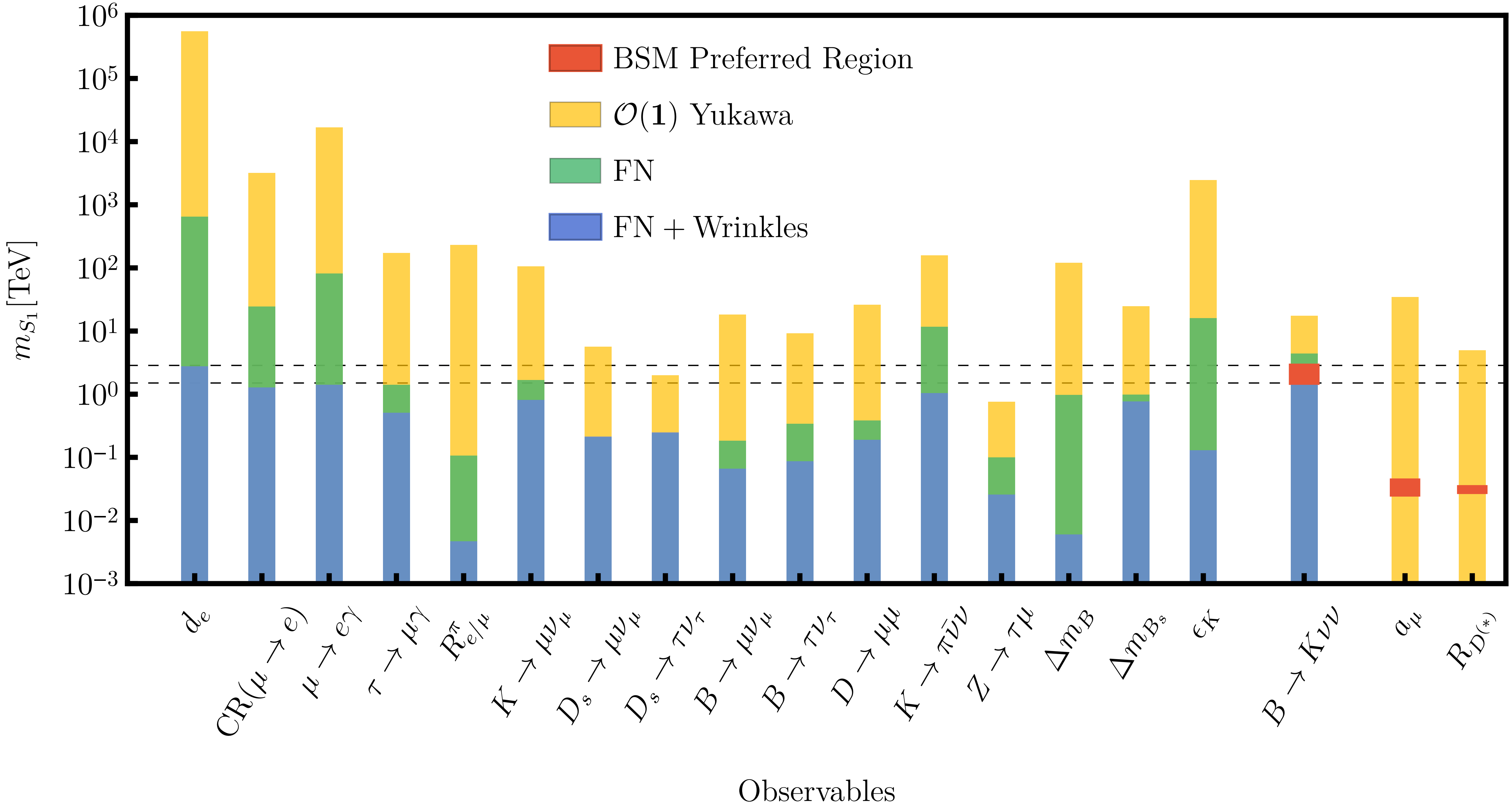
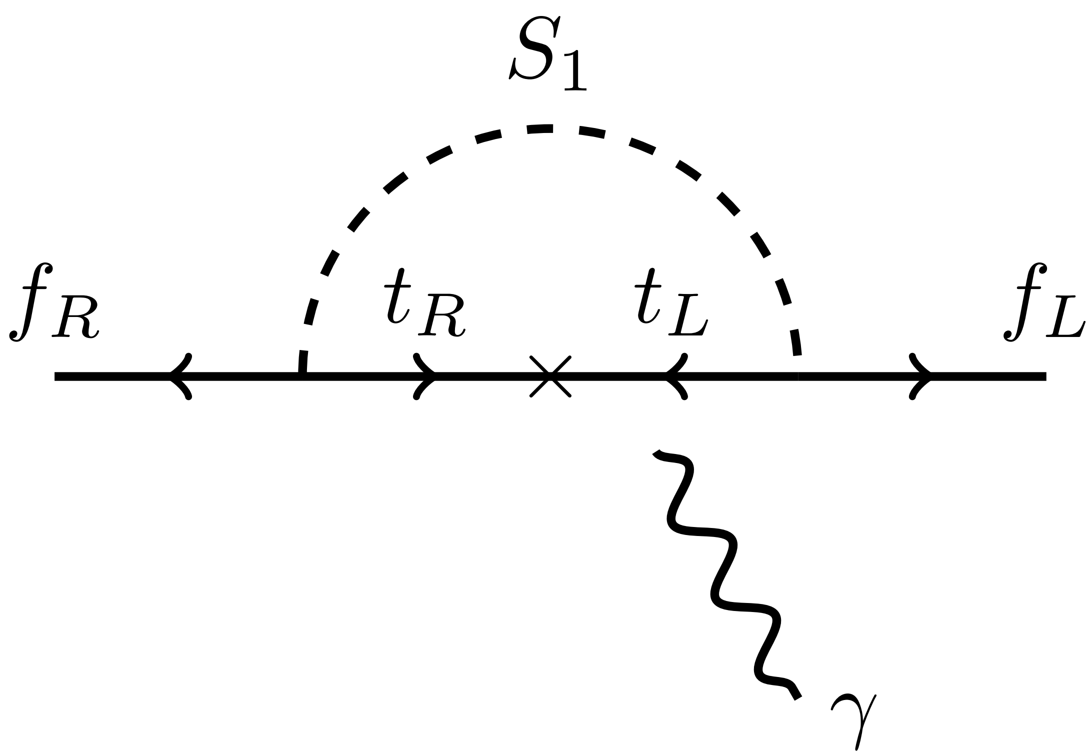
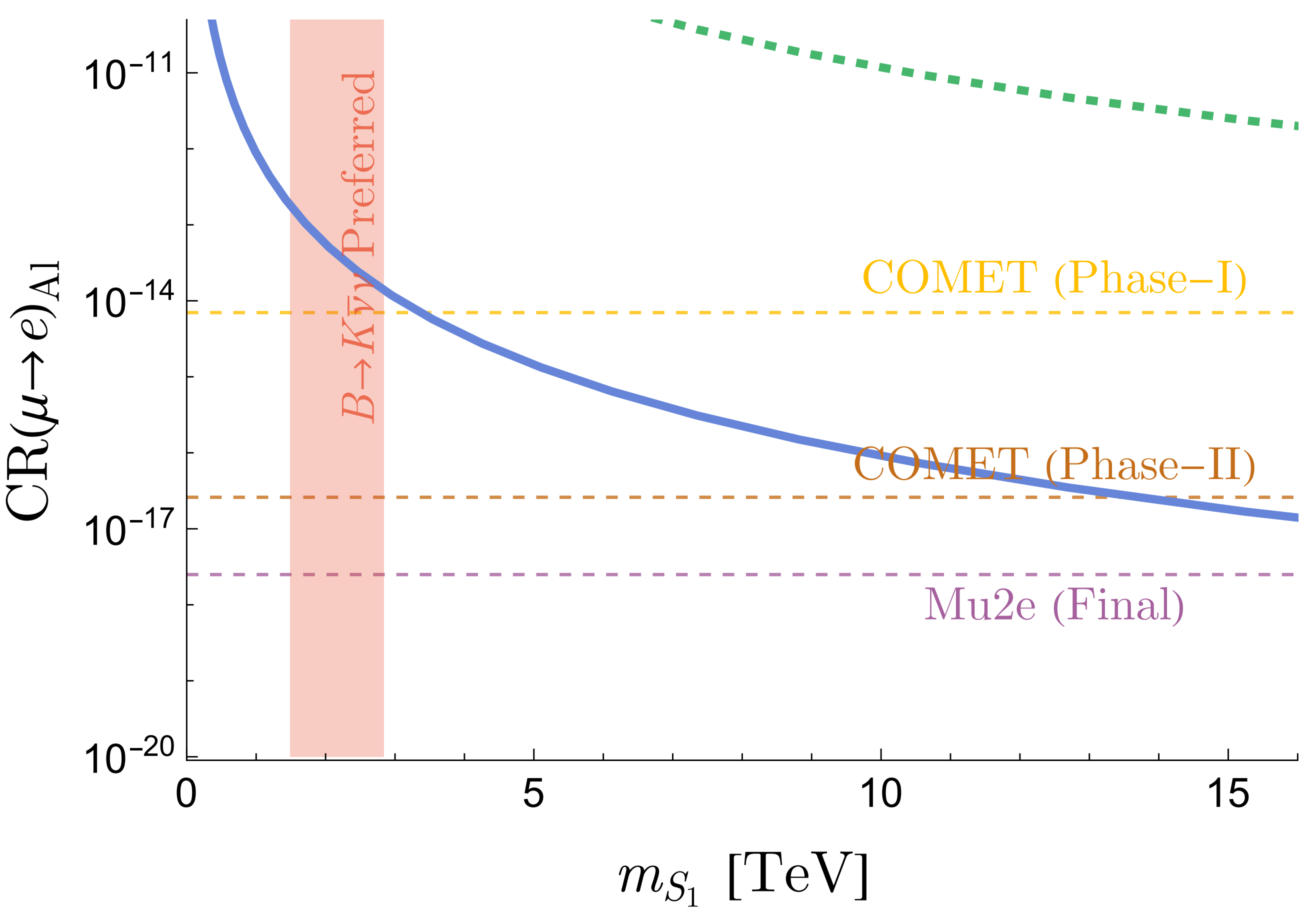


Predictions for Future Measurements

With the "maximal" number of wrinkles added, we can ask what "irreducible" *predictions* this flavor Ansatz makes.

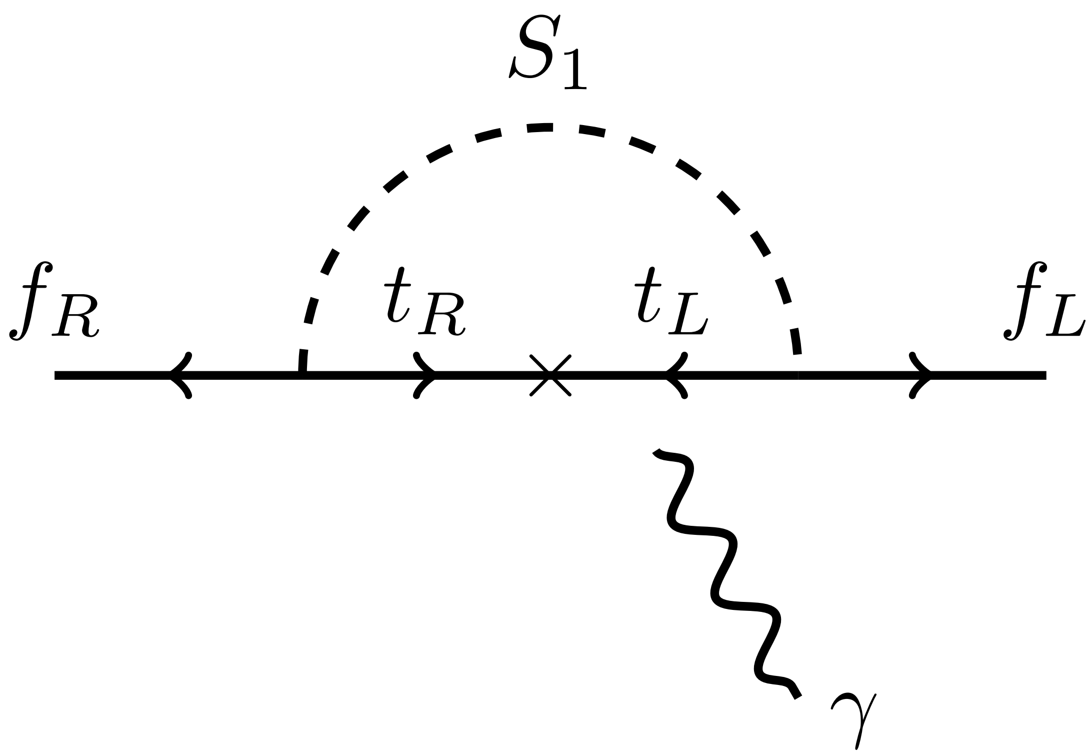
For instance, the LQ contributes to $\mu \to e$ conversion processes:

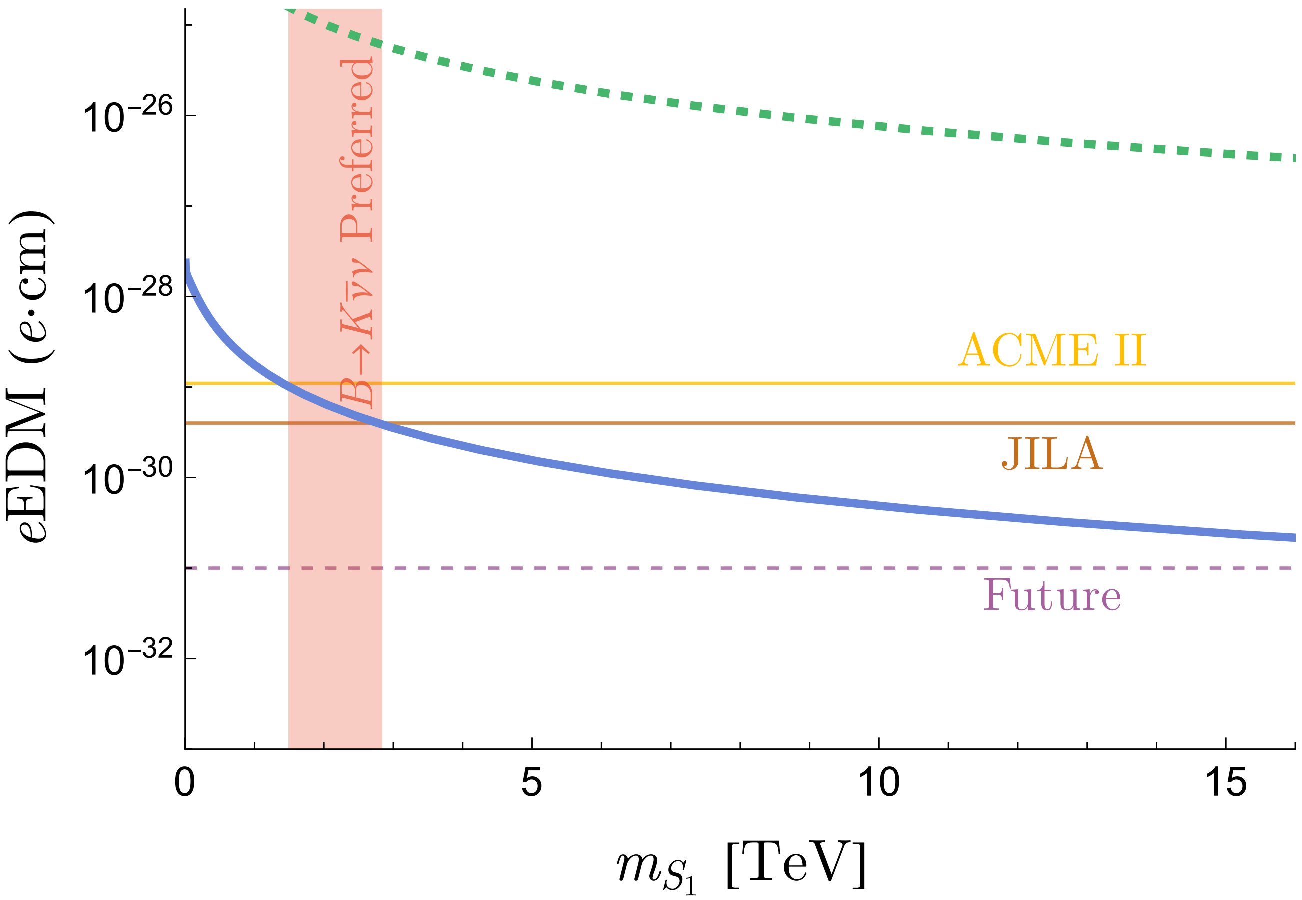




Predictions for Future Measurements

A similar diagram also gives rise to an electron EDM:





This LQ solution will be well-tested by complementary probes in the coming decade.

$\Longrightarrow$ These flavor Ansätze inherently predict *complementary* probes of flavor in different channels.

Conclusions

- The Froggatt-Nielsen mechanism provides a powerful Ansatz for effective theories *including* flavorful new physics, with a built-in connection to a solution of the SM flavor puzzle.

- Wrinkles are a useful way of parameterizing potential extra symmetries or dynamics in the UV, while maintaining predictivity.

- A real anomaly in flavor observables would be *unexpected* and *exciting* — we should take these seriously, and think about our priors!

Thanks for your attention!