Proton Decay and Flavor Symmetry

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References: 2412.19484 and 2510.13617

Take-home message

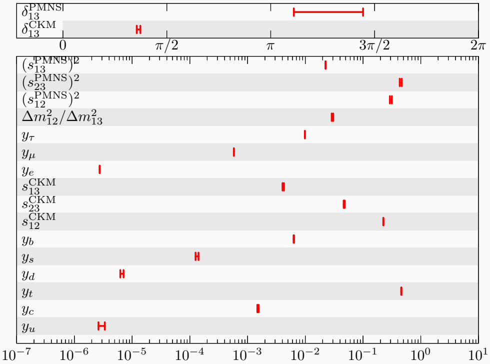
- Fermion masses and mixings suggest non-trivial flavor structure at high scales.
- That same structure shapes baryon-violating operators $\Rightarrow$ proton-decay **modes/lifetimes** can carry flavor fingerprints.

Outline

1. The flavor puzzle and a Bayesian notion of “typicality”
2. Froggatt–Nielsen (FN) flavor symmetry as a benchmark
3. Proton decay in EFT: why it is flavor-sensitive
4. SUSY, dimension-5 operators, and Planck-suppressed threats

The flavor puzzle

- Fermion masses span many orders of magnitude: $y_t \sim 1$ vs $y_u \sim 10^{-5}$.
- Quark mixing is small (CKM), while lepton mixing is large (PMNS).
- The pattern looks *unnatural/atypical* under naive expectations.
- There are several suggestive relations, e.g.,
  $\sin\theta_{12}^{\mathrm{CKM}} = 0.2245 \simeq \sqrt{m_d/m_s} = 0.2248$.



Yukawa hierarchies and mixing angles of SM fermions

What does "typical" / "natural" mean here?

Naive expectation

- Yukawas are 3×3 complex matrices with "generic" $\mathcal{O}(1)$ entries.
- Random matrices typically give:
  - $\mathcal{O}(1)$ **mass eigenvalues** (no large hierarchies),
  - $\mathcal{O}(1)$ **mixing angles**.

Reality

- strong hierarchies in **masses/Yukawas**,
- structured (often small) **CKM** mixing angles.

Key point: not a contradiction, but a "typicality" issue.

From intuition to a quantitative question with Bayesian approach

- We often say the SM flavor pattern looks "unnatural", but **how do we quantify that?**
- A useful criterion: **typicality**
  - Is the observed pattern *typical* among "generic" parameters of a model?
  - If not, how much of parameter space reproduces it?
- This also enables **model comparison**:
  - Does a flavor symmetry make the data more typical than the SM with random Yukawas?
- Bayesian language provides a natural dictionary:

$$\text{“}\mathcal{O}(1)\text{ parameters”} \quad \longleftrightarrow \quad \text{a prior distribution.}$$

Bayesian crash course

- **Prior** $\pi(\lambda|M)$: what we call "generic" parameters in model M.
- **Likelihood** $\mathcal{L}(\lambda) \equiv P(D|\lambda, M)$: how well parameters match the data D.
- **Evidence** $\mathcal{Z}_M \equiv P(D|M)$:

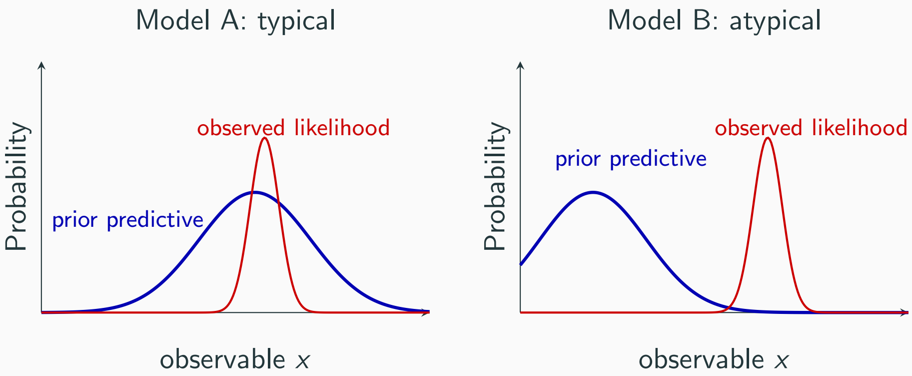
$$\mathcal{Z}_M = \int d\lambda\, \mathcal{L}(\lambda)\, \pi(\lambda|M).$$

- **Bayes factor**:

$$B_{12} = \frac{\mathcal{Z}_1}{\mathcal{Z}_2}.$$

We will use this as a quantitative language for "typical vs atypical."

Evidence as an overlap



$$\mathcal{Z}_M = \int dx \underbrace{P(D|x)}_{\text{likelihood}} \underbrace{p(x|M)}_{\text{prior predictive}} \quad \propto \quad \text{overlap area.}$$

A prior for "$\mathcal{O}(1)$" parameters

- For dimensionless $\mathcal{O}(1)$ parameters, a simple choice: Gaussian,

$$\lambda \sim \mathcal{N}(0, 1),$$

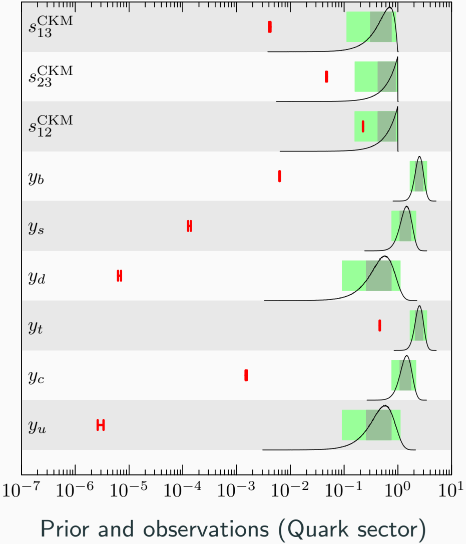
  i.e. centered, unit-variance, maximum-entropy given mean/variance.
- Generate **prior-predictive** distributions for observables x (masses/mixings):

$$Z(x|M) = \int d\lambda \, L(x|\lambda, M) \, \pi(\lambda|M).$$

- Compare where the real-world values sit within these distributions.

SM “random Yukawa” prior-predictive vs data

- Treat SM Yukawas as generic $\mathcal{O}(1)$ matrices (with the chosen prior).
- Observed hierarchies/mixings appear in the *tails* of the distribution.



Why model comparison (Bayes factor) is the right question

- Evidence penalizes fine-tuned parameter regions automatically.
- Absolute evidence values depend on conventions (priors), so the number itself is not very informative.
- **Ratios** (Bayes factors) provide a meaningful comparison between hypotheses/models.

Example (our conventions): $\log_{10} \mathcal{Z}_{\mathrm{SM,\,quark}} \simeq -76.5, \quad \log_{10} \mathcal{Z}_{\mathrm{SM,\,lepton}} \simeq -42.$

Goal: define “good” flavor models by improved typicality.

Froggatt–Nielsen flavor symmetry

FN flavor symmetry

- Add a $U(1)_F$ with charges assigned to SM fields.
- Introduce a flavon with $\varepsilon = \langle\phi\rangle/\Lambda_{\mathrm{FN}} \ll 1$.
- Yukawa operators arise with FN insertions (use ϕ or $\phi^\dagger$ to make them $U(1)_F$ neutral):

$$\left(\frac{\phi^{(\dagger)}}{\Lambda_{\mathrm{FN}}}\right)^{|n_{ij}|} \psi_i \bar{\psi}_j H.$$

- The power is fixed by charges:

$$n_{ij} = f_{\psi_i} + f_{\bar{\psi}_j}.$$

- Therefore,

$$(Y_f)_{ij} \sim \varepsilon^{|n_{ij}|} \times \mathcal{O}(1),$$

leading to textures, hierarchies, and mixings.

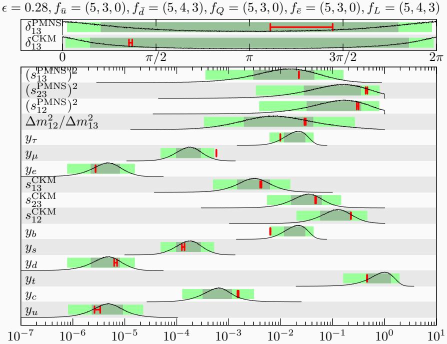
A benchmark FN charge assignment: better typicality

- Example FN charges:

$$(\bar{d}, L) = (5, 4, 3), \quad (\bar{u}, Q, \bar{e}) = (5, 3, 0).$$

- Prior-predictive distributions move much closer to the observed data.
- Evidence improves dramatically:

$$\log_{10} B \equiv \log_{10}\left(\frac{\mathcal{Z}}{\mathcal{Z}_{\rm SM}}\right) \simeq 146.$$



Prior and observed values.

Many viable FN charges

- Scanning over charges often yields many similarly good fits.
- SM flavor data alone leaves degeneracies among flavor models.
- Need additional probes: BSM/EFT observables sensitive to flavor structure.

Quark sector (examples)

f_Q	$f_{\bar{u}}$	$f_{\bar{d}}$
$(5,3,0)$	$(7,3,1)$	$(6,5,5)$
$(3,2,0)$	$(4,2,0)$	$(3,3,3)$
$(4,4,0)$	$(4,2,-1)$	$(3,-10,4)$

Lepton sector (examples)

f_L	$f_{\bar{e}}$
$(9,-8,-8)$	$(1,2,4)$
$(5,4,4)$	$(5,2,0)$
$(8,0,0)$	$(10,6,-4)$

Representative examples; even exotic-looking charges can fit.

Data products (charge lists, simulator): `https://member.ipmu.jp/satoshi.shirai/flavor/`

Proton decay as a flavor probe

Proton decay: an ultra-high-scale probe

- Baryon number is an **accidental** symmetry of the renormalizable SM.
- Generic UV physics can generate baryon-violating effective operators $\Rightarrow$ nucleon decay.
- The enormous proton lifetime translates into sensitivity to very high scales:
  - dimension-6: $\Lambda \sim 10^{15}$–$10^{16}\,\mathrm{GeV}$ (GUT scale),
  - in favorable cases, indirect reach can approach **near-Planckian** physics.
- Since proton decay involves only SM fermions, its **rates and modes** are naturally linked to flavor structure.

Key point: proton decay is not only "how long", but also "which channel": a flavor fingerprint.

EFT view: dimension-6 baryon-violating operators

- At low energies, baryon violation can be encoded by four-fermion operators:

$$\mathcal{L}_{\Delta B\neq 0} \supset \frac{C^{(6)}_{ijkl}}{\Lambda^2}(q_i q_j q_k \ell_l) + \cdots$$

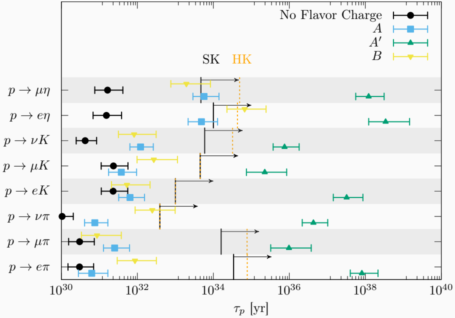
- Crucially, coefficients carry **flavor indices** i, j, k, l.
- Flavor symmetries predict patterns in $C^{(6)}_{ijkl} \Rightarrow$ distinctive **branching ratios**.

Dim-6 proton decay: branching ratios as flavor fingerprints

- Dim-6 operators involve only SM fermions $\Rightarrow$ branching ratios inherit **flavor-charge** suppressions.
- Different $U(1)_F$ charges can lead to **very different dominant modes**.

Models compared (No-charge, A, A′, B):

- **A:** $\bar{u}(4,2,0),\ \bar{d}(4,4,3),\ Q(4,2,0),\ L(4,4,3),\ \bar{e}(4,2,0)$
- **A′:** same quarks, but $L(-4,-4,-3),\ \bar{e}(-4,-2,0)$
- **B:** $\bar{u}(7,3,0),\ \bar{d}(6,5,5),\ Q(5,3,0),\ L(10,-9,-9),\ \bar{e}(5,3,1)$



Predicted decay modes and lifetimes for $\Lambda = 10^{15}$.

Takeaway: the decay channels can probe of the flavor structure.

PeV-scale SUSY, flavor violation, and proton decay

Why consider PeV-scale SUSY today?

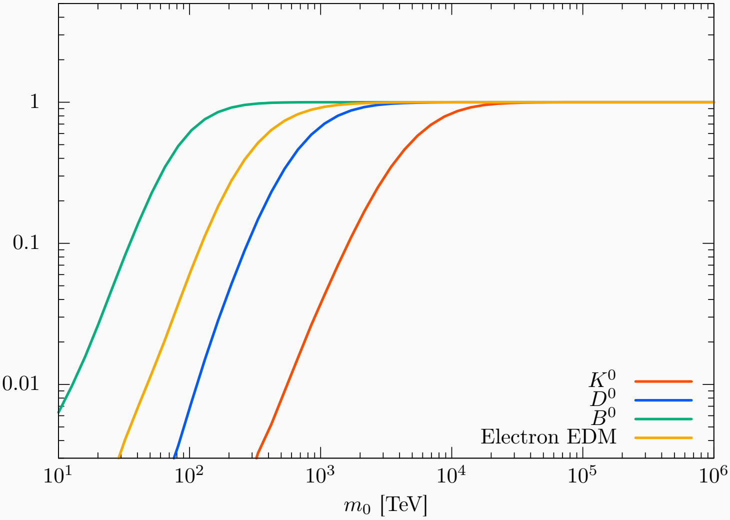
- LHC pushes colored superpartners to multi-TeV; "high-scale" SUSY remains viable.
- A PeV-ish superpartner scale appears in several modern contexts:
  - **AMSB / mini-split SUSY**: scalars heavy, gauginos lighter; simple and predictive.
  - **Higgs mass**: $m_h \simeq 125$ GeV can be compatible with heavy stops.
- Even if SUSY is heavy, **flavor** and **proton decay** can remain decisive constraints.

Message: PeV-scale SUSY is not "safe by default" if flavor is generic.

PeV SUSY is not automatically flavor-safe

- If sfermion masses have $\mathcal{O}(1)$ flavor/CP violation, FCNC and EDM bounds are powerful.
- Even at $m_0 \sim \mathrm{PeV}$, **Kaon mixing typically still forces non-generic structure**.
- This also motivates **flavor symmetry** (and links directly to proton decay).

How much parameter space survives flavor/CP constraints?



What is shown:

- Constraints from K, D, B mixing and the electron EDM.
- Vertical axis: Bayes factor vs the SM.

Rule of thumb:
Bayes factor $\sim$ surviving fraction of "generic" parameters.

Takeaway:
At $m_0 \sim 1\,\mathrm{PeV}$, Kaons give $B \sim 10^{-2}$
$\Rightarrow \sim$ percent-level tuning.

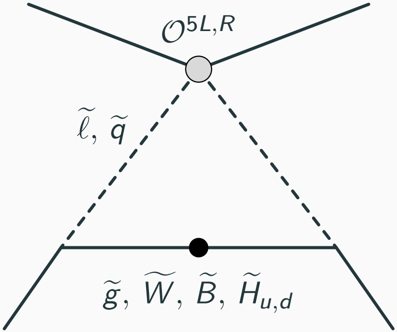
Why SUSY dimension-5 proton decay is dangerous

- In SUSY (even with R-parity), dim-5 operators can appear:

$$\mathcal{O}^{5L} \supset \frac{1}{\Lambda_B} QQQL, \qquad \mathcal{O}^{5R} \supset \frac{1}{\Lambda_B} u^c u^c d^c e^c.$$

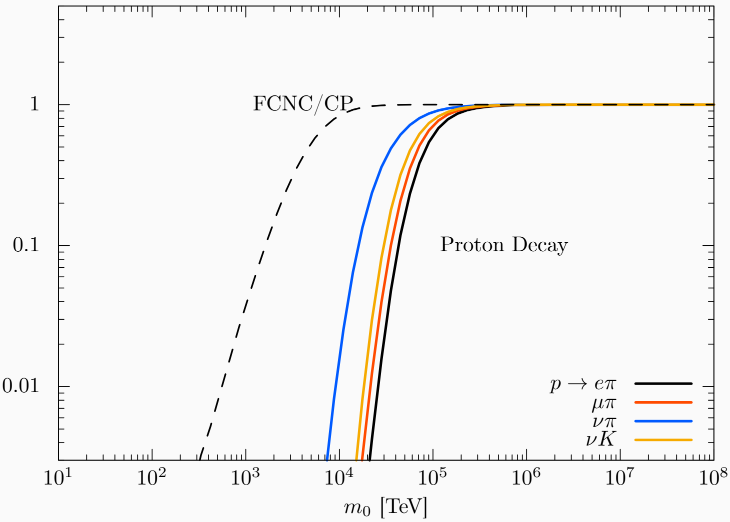
- **Wino/Higgsino dressing** converts them into dim-6 4-fermion operators.
- Heavier sfermions suppress the rate (schematic):

$$\Gamma_p \propto \frac{1}{\Lambda_B^2 m_{\tilde{f}}^4}.$$



dim-5 → dim-6 (4-fermion)

Planck-suppressed dim-5 ($\Lambda_B = M_{\rm Pl}$): even $10\,\mathrm{PeV}$ can be non-generic



What is shown:

- Planck-suppressed dim-5 proton decay.
- Vertical axis: Bayes factor vs SM.

Rule of thumb:

Bayes factor $\sim$ surviving fraction of generic parameters.

Takeaway:

At $m_0 \sim 10\,\mathrm{PeV}$, $B \ll 10^{-2}$ $\Rightarrow$ stronger tuning than flavor/CP constraints.

Why do we need a flavor symmetry in SUSY?

- In the SM, flavor models mainly address Yukawa hierarchies and mixings.
- In SUSY, **generic** soft terms induce large **FCNC/CPV** (e.g. K mixing, EDMs).
- SUSY also introduces **new sources of proton decay** (dim-5 operators).

A flavor symmetry can simultaneously control

Yukawas + soft terms (FCNC/EDM) + dim-5 proton decay.

Four charge assignments to compare

- Flavon chiral field ϕ and $\bar{\phi}$ have same VEV.
- Higgs charges: $Q_F(H_u) = Q_F(H_d) = 0$; RH neutrino: $Q_F(N^c) = 0$.
- Prime ($'$) means flipping the **lepton** charges: $(\bar{e}, L) \to -(\bar{e}, L)$.

Model	$\bar{u}$	$\bar{d}$	Q	$\bar{e}$	L
A	$(5, 2, 0)$	$(4, 3, 3)$	$(4, 3, 0)$	$(5, 2, 0)$	$(4, 3, 3)$
A$'$	$(5, 2, 0)$	$(4, 3, 3)$	$(4, 3, 0)$	$(-5, -2, 0)$	$(-4, -3, -3)$
B	$(-8, 2, 0)$	$(-9, 3, 3)$	$(-10, 3, 0)$	$(5, 2, 0)$	$(4, 3, 3)$
B$'$	$(-8, 2, 0)$	$(-9, 3, 3)$	$(-10, 3, 0)$	$(-5, -2, 0)$	$(-4, -3, -3)$

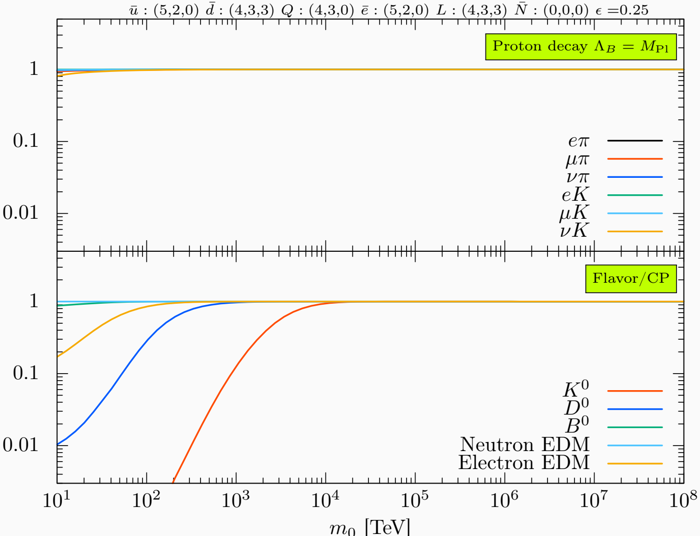
Motivation: A vs A$'$ (and B vs B$'$) isolate proton-decay sensitivity while keeping Yukawas/FCNC largely similar in our setup.

Strategy: let data discriminate charges

- For each charge assignment, we evaluate:
  - Bayes factor from **FCNC/CP** data (mixing + EDM),
  - Bayes factor from **dim-5 proton decay** (Planck-suppressed operators + dressing).
- Vertical axis (rule of thumb): Bayes factor $\sim$ surviving fraction of generic $\mathcal{O}(1)$ coefficients.

Next: four plots (A, A′, B, B′) — same layout, different outcomes.

Model A



Top: Bayes factor from dim-5 proton decay

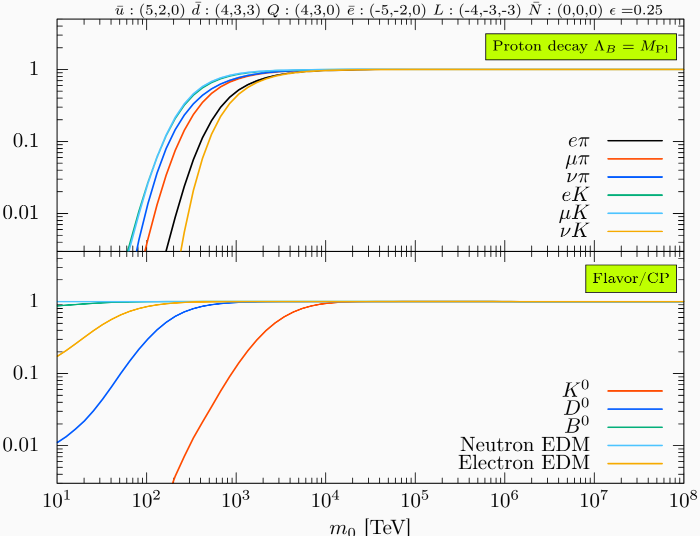
Bottom: Bayes factor from FCNC/CP (mixing + EDM)

Rule of thumb: $B \sim$ surviving fraction of generic parameters

Comment:

Suppresses dim-5 proton decay efficiently.

Model A' (opposite lepton charge)



Top: Bayes factor from dim-5 proton decay

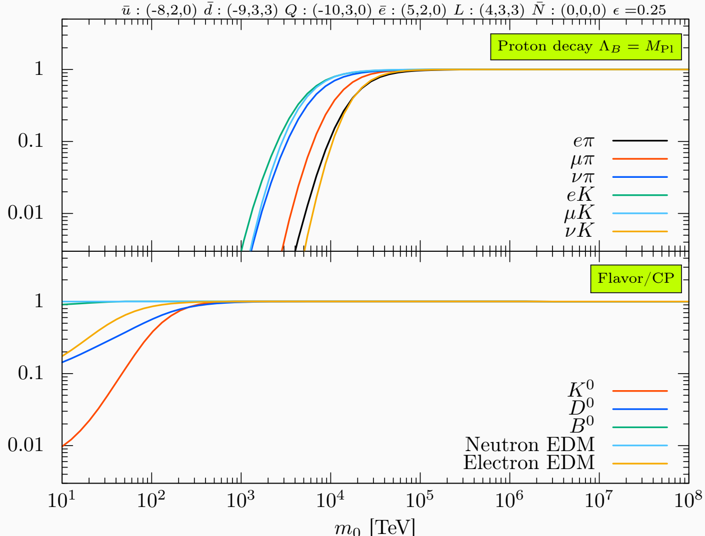
Bottom: Bayes factor from FCNC/CP (mixing + EDM)

Rule of thumb: $B \sim$ surviving fraction of generic parameters

Comment:

Same as A but for dim-5 proton decay. HK can probe PeV-scale SUSY.

Model B



Top: Bayes factor from dim-5 proton decay

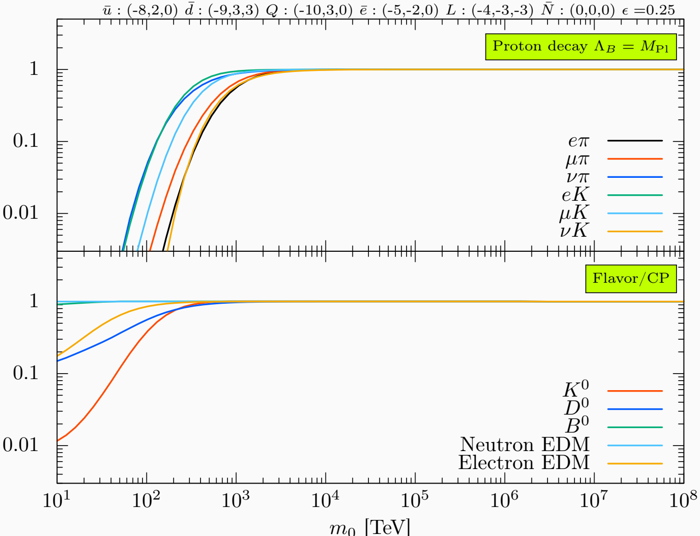
Bottom: Bayes factor from FCNC/CP (mixing + EDM)

Rule of thumb: $B \sim$ surviving fraction of generic parameters

Comment:

Suppresses FCNC/CP efficiently, but not proton decay.

Model B’ (opposite lepton charge)



Top: Bayes factor from dim-5 proton decay

Bottom: Bayes factor from FCNC/CP (mixing + EDM)

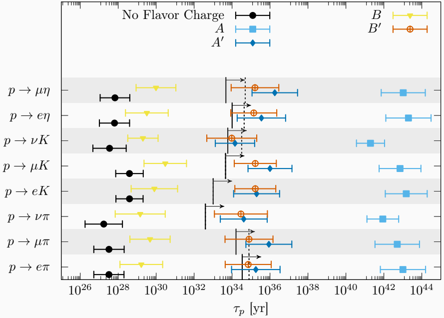
Rule of thumb: $B \sim$ surviving fraction of generic parameters

Comment:

Suppresses both FCNC/CP and dim-5 proton decay efficiently.

SUSY dim-5 proton decay: even stronger flavor dependence

- SUSY allows baryon-violating **dimension-5** operators (even with R-parity).
- Benchmark spectrum:
  - $m_0 \sim 1\,\mathrm{PeV}$ (sfermions/Higgsino)
  - $M_{1,2,3} \sim \mathrm{TeV}$ (gauginos).
- Models compared: **A, A′, B, B′**.



Predicted branching ratios (dim-5, SUSY).

Takeaway: SUSY dim-5 modes provide a sharp discriminator among flavor charges.

SUSY summary: FCNC & proton decay as probes of flavor models

- In SUSY, a flavor symmetry controls
  - **soft terms** $\Rightarrow$ FCNC/CPV (mixing, EDMs),
  - **dim-5 operators** $\Rightarrow$ proton decay.
- In a scan of $U(1)_F$ (FN-type) charge assignments, **FCNC/CP and proton decay provide strong, complementary discriminants**.
- Within this FN class, **GUT-like patterns tend to suppress** Planck-induced dim-5 proton decay, but then **GUT-induced channels** may become the leading targets:
  - heavy gauge bosons (X, Y), colored Higgs exchange.

Summary

- The SM flavor pattern is consistent but looks atypical under "generic $\mathcal{O}(1)$ Yukawas".
- Bayesian evidence/Bayes factors provide a quantitative language for typicality.
- FN-like flavor symmetries can improve typicality, but many charge assignments remain viable.
- Proton decay (dim-6 and, in SUSY, dim-5) is highly flavor-sensitive: branching ratios can discriminate among models.
- Depending on the charges, some models preferentially populate **higher-generation final states** (e.g. enhanced μ modes or strange final states such as K).
- Open direction: embedding flavor symmetries in gauge/discrete frameworks under quantum gravity.

Open issues: quantum gravity and quality of flavor symmetry

- Global symmetries may be violated by quantum gravity.
- Can a global $U(1)_F$ truly suppress Planck-induced operators?
- Gauged flavor symmetries (or discrete gauge symmetries) may:
  - protect the structure,
  - impose anomaly constraints,
  - increase predictivity.

Proton decay can then become a test of the *origin* of flavor symmetry itself.