Nucleon decay fingerprints from SUSY GUT models (using `SusyTCProton`)

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Introduction

Motivation:

- Is there a process generically predicted by SUSY GUTs?
  Can it be used to distinguish between models?

  Nucleon (proton and neutron) decay!

- Need software for completely general computation (including all flavor dependence, etc.).

Based on `arXiv:2011.15026`.

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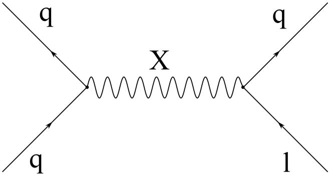
Contents of the talk:

1. A quick recap of $D = 5$ proton decay in SUSY
2. Example models and results
3. Software for proton decay calculation: `SusyTCProton`

Based on `arXiv:2011.15026`.

Notes on $D = 5$ proton decay — part 1

$D = 6$ decay (example):



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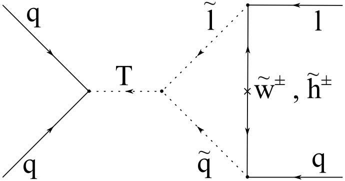

$$\mathcal{A}_{D=5} \approx \frac{\alpha}{4\pi}\, y_u y_d\, \frac{m_{\tilde{w}}}{m_T\, m_{\tilde{f}}^2}$$

- Generic form for proton decay operators: *qqql* $(B - L = 0)$
- $D = 5$: requires SUSY and triplets... SM superpartners in loops

  $\tilde{w}$ dominates, complicated flavor structure

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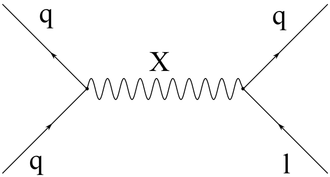

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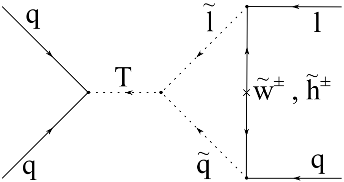

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$$\Gamma \approx |\mathcal{A}|^2\, m_p^5 \quad \Rightarrow \quad \Gamma_5 \sim \frac{y^2}{(4\pi)^2}\,\frac{m_p^5}{M_{\mathrm{GUT}}^2 M_{\mathrm{SUSY}}^2} \quad > \quad \Gamma_6 \sim \frac{m_p^5}{M_{\mathrm{GUT}}^4}$$

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Notes on $D = 5$ proton decay — part 2

- Yukawa operators in $\mathrm{SU}(5)$: also contain triplets $T \sim (3, 1, -1/3)$

$$\begin{aligned} \mathbf{Y}_{\bar{\mathbf{5}}}\, \mathbf{10}_F\, \bar{\mathbf{5}}_F \bar{\mathbf{X}} &\sim \mathbf{Y}_d\, Q d^c H_d + \mathbf{Y}_e\, L e^c H_d + \tilde{\mathbf{Y}}_{ql}\, Q L \bar{T} + \tilde{\mathbf{Y}}_{ud}\, u^c d^c \bar{T} \\ \mathbf{Y}_{\mathbf{10}}\, \mathbf{10}_F \mathbf{10}_F \mathbf{X} &\sim \mathbf{Y}_u\, Q u^c H_u \qquad\qquad\qquad + \tilde{\mathbf{Y}}_{qq}\, Q Q T + \tilde{\mathbf{Y}}_{eu} e^c u^c T \end{aligned}$$

Above: $\mathbf{X} \in \{\mathbf{5}, \mathbf{45}\}$. Can also use non-renormalizable operators.

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  Above: $\mathbf{X} \in \{\mathbf{5}, \mathbf{45}\}$. Can also use non-renormalizable operators.

- Effective Lagrangian for $D = 5$ nucleon decay:

$$\begin{aligned} W_5 = \quad & \mathbf{C}^{5L}\; QLQQ & \qquad \mathbf{C}^{5L}_{ijkl} &= (\mathbf{M}_T^{-1})_{IJ}\, (\tilde{\mathbf{Y}}_{ql})_{Iij}\, (\tilde{\mathbf{Y}}_{qq})_{Jkl} \\ + & \mathbf{C}^{5R}\; u^c d^c e^c u^c & \mathbf{C}^{5R}_{ijkl} &= (\mathbf{M}_T^{-1})_{IJ}\, (\tilde{\mathbf{Y}}_{ud})_{Iij}\, (\tilde{\mathbf{Y}}_{eu})_{Jkl} \end{aligned}$$

- To describe nucleon decay: add $\mathbf{C}^{5L}$ and $\mathbf{C}^{5R}$ to MSSM
- In each operator: some GUT relation between $\mathbf{Y}$ and $\tilde{\mathbf{Y}}$

Nucleon decay channels — experimental bounds

Proton decay:

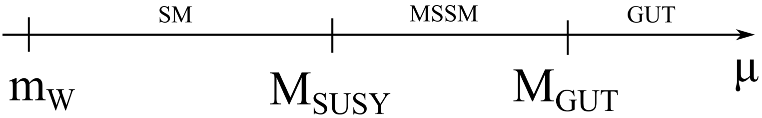
decay channel	$\tau/\mathcal{B}$ [year]
$p \to K^+ \bar{\nu}$	$> 6.6 \cdot 10^{33}$
$p \to K^0 e^+$	$> 1.1 \cdot 10^{33}$
$p \to K^0 \mu^+$	$> 1.6 \cdot 10^{34}$
$p \to \pi^+ \bar{\nu}$	$> 2.8 \cdot 10^{32}$
$p \to \pi^0 e^+$	$> 2.4 \cdot 10^{34}$
$p \to \pi^0 \mu^+$	$> 1.6 \cdot 10^{34}$
$p \to \eta^0 e^+$	$> 4.1 \cdot 10^{33}$
$p \to \eta^0 \mu^+$	$> 1.2 \cdot 10^{33}$

Neutron decay:

decay channel	$\tau/\mathcal{B}$ [year]
$n \to K^0 \bar{\nu}$	$> 1.2 \cdot 10^{32}$
$n \to \pi^0 \bar{\nu}$	$> 9.9 \cdot 10^{32}$
$n \to \pi^- e^+$	$> 2.1 \cdot 10^{33}$
$n \to \pi^- \mu^+$	$> 9.9 \cdot 10^{32}$
$n \to \eta^0 \bar{\nu}$	$> 5.6 \cdot 10^{32}$

- Table is from `arXiv:2011.15026`, bounds mostly from Super-K
- Generic form: nucleon $\to$ meson $+$ lepton
- $D = 5$ decay favors K over π (2nd family quarks involved)

Model setup: flavor SUSY GUT



- We are in $\mathrm{SU}(5)$, we model Yukawa sector but not breaking sector
- Assume single operator dominance:
  each Yukawa-matrix entry dominated by one non-renormalizable operator (generated by integrating out mediators, cf. 0902.4644)

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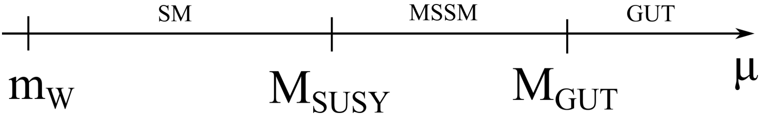

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- M_{GUT}:
  - GUT relations between $\mathbf{Y}$ (and $\tilde{\mathbf{Y}}$ relevant for $\mathbf{C}^{5L,R}$)
  - mSUGRA boundary conditions
  - GUT-breaking sector: we assume all Higgs fields lie at M_{GUT}
- M_{SUSY}: scale of SM superpartners
- m_W: fit to low energy data
- We compare two example models (from 1405.6962)...

Example models — Yukawa textures

Model 1:

$$\mathbf{Y_{10}} = \begin{pmatrix} * & * & 0 \\ * & * & * \\ 0 & * & * \end{pmatrix}, \mathbf{Y_{\bar{5}}} = \begin{pmatrix} 0 & * & 0 \\ * & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

Y and $\tilde{\mathbf{Y}}$ relations:

$$\mathbf{Y}_e = \mathbf{Y}_d^T \cdot \begin{pmatrix} 0 & 6 & 0 \\ -1/2 & 6 & 0 \\ 0 & 0 & -3/2 \end{pmatrix}$$

$$\tilde{\mathbf{Y}}_{ql} = \mathbf{Y}_d \cdot \begin{pmatrix} 0 & -1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & 3/2 \end{pmatrix}$$

$$\tilde{\mathbf{Y}}_{ud} = \mathbf{Y}_d \cdot \begin{pmatrix} 0 & 2/3 & 0 \\ -4 & -4 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Model 2:

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Also: $\tilde{\mathbf{Y}}_{qq} = -\mathbf{Y}_u$ and $\tilde{\mathbf{Y}}_{eu} = +\mathbf{Y}_u$ (both models). No neutrino sector.

- Factors come from choice of GUT operator in each entry.
- Construction for $\mathbf{M}_T$: multiple T, one only couples to fermions

  $\Rightarrow M_T^{\text{eff}} = ((\mathbf{M}_T^{-1})_{11})^{-1}$ effective T-mass (unrelated to a physical scale)

Numerical analysis of the models

- At $M_{\text{GUT}} = 2 \cdot 10^{16}\,\mathrm{GeV}$ we impose boundary conditions:
  - Yukawa inputs: we only need to specify $\mathbf{Y}_d$ and $\mathbf{Y}_u$
  - Fix CMSSM/mSUGRA parameters with $\mathrm{sgn}(\mu) = +1$:

$$\tan\beta = 28.4, \quad m_0 = 4\,\mathrm{TeV}, \quad M_{1/2} = 1.7\,\mathrm{TeV}, \quad A_0 = -10\,\mathrm{TeV}.$$

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  ⇒ compute χ^2

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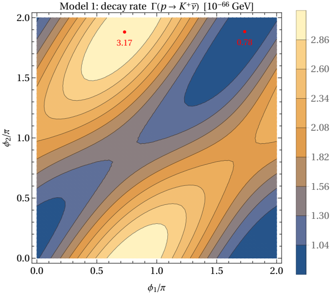
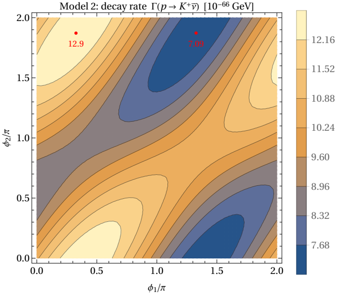
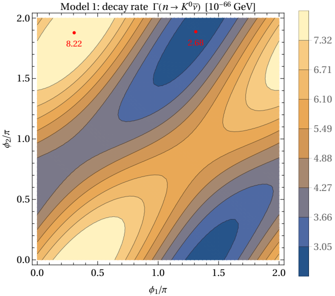
- Use `SusyTCProton` $\Rightarrow$ obtain mass and mixing predictions at m_W
  $\Rightarrow$ compute χ^2
- Careful analysis of parameters shows:
  - 14(+3) inputs vs 14 outputs for χ^2
  - inputs: 10(+3) in Yukawa sector (varied), 4 soft parameters (fixed)
  - outputs: fermion masses and CKM mixings, SM Higgs mass
  - The +3 inputs: the "GUT phases" ϕ_1, ϕ_2, M_T^{eff}
    Influence nucleon decay, no effect on SM observables!
- Best fit: $\chi^2 \approx 5$ for both models

Results — GUT-phase dependence of $p \to K^+\bar{\nu}$ and $n \to K^0\bar{\nu}$


Model 1: decay rate $\Gamma(p \to K^+\overline{\nu})$ $[10^{-66}\text{ GeV}]$


Model 2: decay rate $\Gamma(p \to K^+\overline{\nu})$ $[10^{-66}\text{ GeV}]$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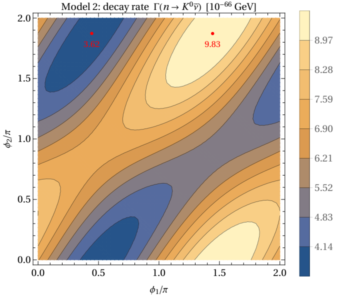
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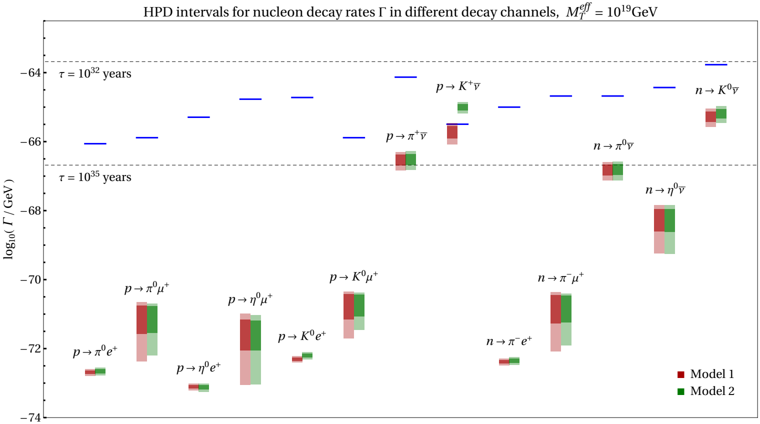
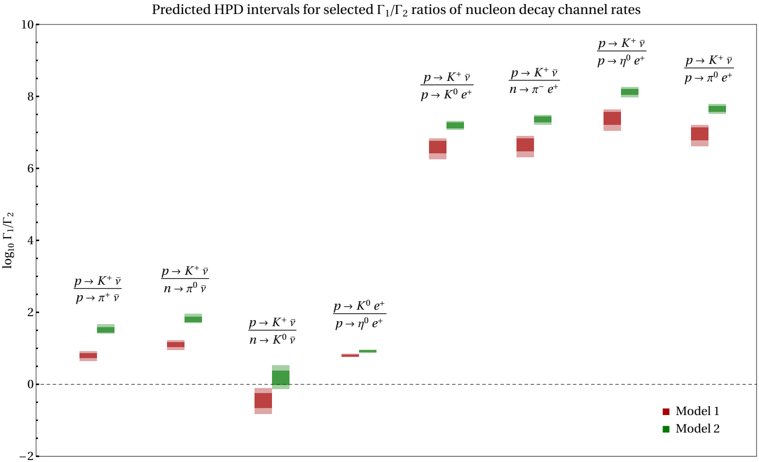
Results — decay rates ($D = 5$ only)



- Perform MCMC around best fit point: vary Yukawa parameters.
- M_T^{eff} is an input: experimental bounds avoided if raised. Benchmark value: $M_T^{\text{eff}} = 10^{19}\ GeV$.

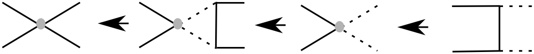
Results — decay rate ratios ($D = 5$ only)



- Perform MCMC around best fit point: vary Yukawa parameters.
- Decay ratios fingerprints: models can be distinguished!

Software for proton decay computation

Procedure: follow Goto-Nihei (also: review by Nath-Perez):



Our software: 2 Mathematica packages.

`SusyTCProton`:

- Improved version of `SusyTC`. Based on `REAP`.
- Inputs: values at GUT scale (including $\mathbf{C}^{5L}$ and $\mathbf{C}^{5R}$)
- Performs RGE (including $\mathbf{C}^{5L,R}$), computes SUSY spectrum.

`ProtonDecay`:

- Input: from `SusyTCProton` or extended SLHA (add $\mathbf{C}^{5L,R}$).
- Computes decay rates: 8 proton channels, 5 neutron channels.
- Extra feature: $\mathbf{C}^{6}$ inputs. Can be used as a standalone.

Conclusions

1. Nucleon decay: an important process to consider in SUSY GUT
   - Limitation on models
   - Can be used to distinguish models

2. Decay ratios (aka decay fingerprint) can give important insight

3. Example shown how to distinguish: 2 flavor SUSY GUT models

   (flavor structure can indeed have an important effect)

4. Public software for ($D = 5$) decay: `SusyTCProton`

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Thank you for your attention!