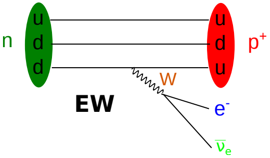
# Planck-scale induced uncertainties in proton lifetime estimates and flavour structure of GUTs

Helena Kolešová

University of Stavanger

Joint work with Michal Malinský (Charles University in Prague)

# Introduction: flavour structure of gauge interactions





**Interaction basis:** Non-diagonal Yukawa interactions, diagonal gauge interactions

$$\mathcal{L} \ni \frac{g_2}{\sqrt{2}} \bar{u}_a \gamma^\mu d_a W_\mu^+$$

**Mass basis:** Diagonalize Yukawa interactions ⇒ non-diagonal gauge interactions

$$Y_u^{\text{diag}} = U_C^T Y_u U, \quad Y_d^{\text{diag}} = D_C^T Y_d D$$

$$\Rightarrow \mathcal{L} \ni \frac{g_2}{\sqrt{2}} \bar{u}_i U_{ia}^\dagger \gamma^\mu D_{aj} d_j W_\mu^+$$

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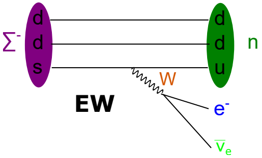
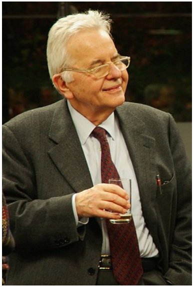
# Introduction: flavour structure of gauge interactions



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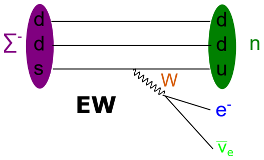


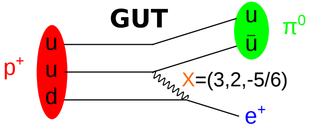


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**Interaction basis:**

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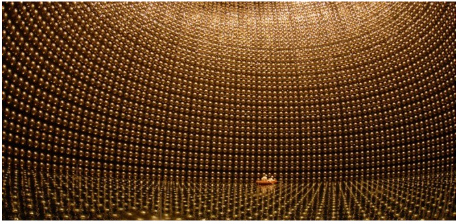
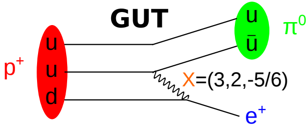
$$\Rightarrow \left( U_C^\dagger U \right)_{11} \text{ factor}$$

# Introduction: flavour structure of gauge interactions

**Proton lifetime predictions?**



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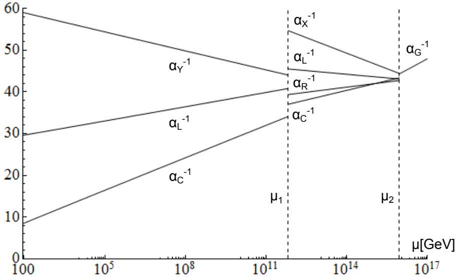
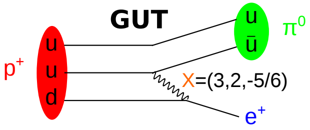
# Introduction: flavour structure of gauge interactions

**Proton lifetime predictions?**

- $g_G, M_X$ calculable from gauge unification constraints
- No low-energy constraint on $U_C$ !

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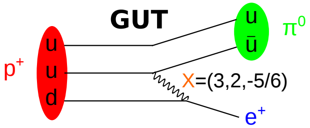


**Outline:**

1. Can $U_C$ be constrained in specific unified models and can one then obtain predictions on all partial proton decay widths?
2. If so, what uncertainty is brought in by the effective Planck-scale-suppressed operators?

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# Partial proton decay rates in case of VB mediation

[Nath, Pérez:Phys.Rept.(2007)], [Dorsner, Pérez: Phys.Lett.B625(2005)]

(dominant in non-SUSY GUTs, present in SUSY GUTs)

$$\Gamma(p \to \pi^0 e_\alpha^+) \propto \left\{ \left| c(e_\alpha, d^C) \right|^2 + \left| c(e_\alpha^C, d) \right|^2 \right\} ,$$

$$\Gamma(p \to K^0 e_\alpha^+) \propto \left\{ \left| c(e_\alpha, s^C) \right|^2 + \left| c(e_\alpha^C, s) \right|^2 \right\} ,$$

$$\Gamma(p \to \pi^+ \overline{\nu}) \propto \sum_{l=1}^{3} \left| c(\nu_l, d, d^C) \right|^2 ,$$

$$\Gamma(p \to K^+ \overline{\nu}) \propto \sum_{l=1}^{3} \left| B_1 c(\nu_l, d, s^C) + B_2 c(\nu_l, s, d^C) \right|^2$$


$$c(e_\alpha, d_\beta^C) = k_1{}^2 \left( U_C^\dagger U \right)_{11} \left( D_C^\dagger E \right)_{\beta\alpha} + k_2{}^2 \left( D_C^\dagger U \right)_{\beta 1} \left( U_C^\dagger E \right)_{1\alpha},$$

$$c(e_\alpha^C, d_\beta) = k_1{}^2 \left[ \left( U_C^\dagger U \right)_{11} \left( E_C^\dagger D \right)_{\alpha\beta} + \left( U_C^\dagger D \right)_{1\beta} \left( E_C^\dagger U \right)_{\alpha 1} \right],$$

$$c(\nu_l, d_\alpha, d_\beta^C) = k_1{}^2 (U_C^\dagger D)_{1\alpha} (D_C^\dagger N)_{\beta l} + k_2{}^2 (D_C^\dagger D)_{\beta\alpha} (U_C^\dagger N)_{1l}$$

$$Y_f^{\text{diag}} = F_C^T Y_f F, \quad k_{1/2} = \frac{g_G}{\sqrt{2} M_{X/X'}}, \quad X = \left(3, 2, -\frac{5}{6}\right), \; X' = \left(3, 2, \frac{1}{6}\right) \quad \alpha, \beta \in \{1, 2\}$$

# Yukawa sector in unified models

[Steve King talk]

- SM fermions grouped into multiplets of the unified gauge group - e.g. for $SU(5)$

$$1_F = \nu_L^c \quad \bar{5}_F = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}_L \qquad 10_F = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}_L$$

- for $SO(10)$ *all* SM fermions in 16-dimensional spinor representation: $16 = 1 + \bar{5} + 10$
- Yukawa interactions in terms of these multiplets $\Rightarrow$ relations among mass matrices for different fermion species [Georgi,Glashow(1974)]

$$\mathcal{L}_{SU(5)} \ni Y_5 \bar{5}_{Fi} 10_F^{ij} 5_{Hj}^\dagger + h.c. \quad \Rightarrow \quad M_d = M_e^T$$

# Yukawa sector in unified models

Example: SO(10) with $10_H$, $126_H$ and type I seesaw [Babu,Mohapatra(1993)]...

$$\mathcal{L}_Y = Y_{10} 16\,16\,10_H + Y_{126} 16\,16\,\overline{126}_H, \qquad Y_{10} = Y_{10}^T,\ Y_{126} = Y_{126}^T$$

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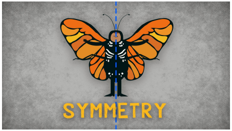
$$\begin{aligned} M_u &= v_{10}^u Y_{10} + v_{126}^u Y_{126}, \\ M_d &= v_{10}^d Y_{10} + v_{126}^d Y_{126}, \\ M_{\nu_D} &= v_{10}^u Y_{10} - 3 v_{126}^u Y_{126}, \\ M_l &= v_{10}^d Y_{10} - 3 v_{126}^d Y_{126}, \\ M_{\nu_R} &= v_{126}^R Y_{126} \end{aligned}$$

$$(16 \times 16 = 10_s + 120_a + \overline{126}_s)$$




- $\Rightarrow$ all mass matrices symmetric
- $\Rightarrow$ diagonalized as $Y_u^{\text{diag}} = U^T Y_u U$, i.e., $U_C = U$!
- $\Rightarrow$ flavour structure of $\Gamma(p \to \pi^+ \overline{\nu})$, $\Gamma(p \to K^+ \overline{\nu})$ fully determined by $V^{CKM}$! [Perez(2004)]

**But the decay channels with charged leptons in the final state unconstrained (no grip on combinations like $E^\dagger D$)!**

# Yukawa sector in unified models

Example: SO(10) with $10_H$, $126_H$ and type I seesaw

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$$\begin{aligned}
M_u &= v_{10}^u Y_{10} + v_{126}^u Y_{126},\\
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\end{aligned}$$

$\Rightarrow$ fits for mass matrices [Dueck, Rodejohann: JHEP(2013)][Joshipura,Patel: Phys.Rev.D(2011)]
$\Rightarrow$ $U, D, E$ calculable!

# Yukawa sector in unified models

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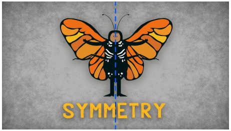
**But what if one adds higher dimensional operators?**

# Yukawa sector in unified models

SO(10)+$10_H$+$126_H$+$54_H$ [Harvey,Reiss,Ramond(1982)][Abud,Buccella,Rosa,Sciarrino(1989)][Babu,Khan(2015)]

$$\mathcal{L}_Y = Y_{10} 16\,16\,10_H + Y_{126} 16\,16\,\overline{126}_H + \frac{\tilde{Y}_{10}}{M_{pl}} 16\,16\,10_H\,54_H + \frac{\tilde{Y}_{126}}{M_{pl}} 16\,16\,\overline{126}_H\,54_H \ldots$$

$$\tilde{Y}_{10} = \tilde{Y}_{10}^T, \quad \tilde{Y}_{126} = \tilde{Y}_{126}^T \qquad (10\times 54 = 10+210+320,\; 126\times 54 = \overline{126}+1728+4950)$$




$$M_u = v_{10}^u Y_{10} + v_{126}^u Y_{126} + \frac{M_G}{M_{Pl}} v \left( c_{10}^u \tilde{Y}_{10} + c_{126}^u \tilde{Y}_{126} \right),$$

$$M_d = v_{10}^d Y_{10} + v_{126}^d Y_{126} + \frac{M_G}{M_{Pl}} v \left( c_{10}^d \tilde{Y}_{10} + c_{126}^d \tilde{Y}_{126} \right),$$

$$M_{\nu_D} = v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} + \frac{M_G}{M_{Pl}} v \left( c_{10}^D \tilde{Y}_{10} + c_{126}^D \tilde{Y}_{126} \right),$$

$$M_l = v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} + \frac{M_G}{M_{Pl}} v \left( c_{10}^l \tilde{Y}_{10} + c_{126}^l \tilde{Y}_{126} \right),$$

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# Yukawa sector in unified models

SO(10)+$10_H$+$126_H$+$45_H$ [Yasue(1981)][Anastaze et.al.(1983)][Babu,Ma(1985)][Bertolini,Di Luzio,Malinsky(2010)]

$$\mathcal{L}_Y = Y_{10} 16\, 16\, 10_H + Y_{126} 16\, 16\, \overline{126}_H + \frac{\tilde{Y}_{10}}{M_{pl}} 16\, 16\, 10_H\, 45_H + \frac{\tilde{Y}_{126}}{M_{pl}} 16\, 16\, \overline{126}_H\, 45_H \ldots$$

$$\tilde{Y}_{10} \neq \tilde{Y}_{10}^T, \quad \tilde{Y}_{126} \neq \tilde{Y}_{126}^T \qquad (10\times 45 = 10+120+320,\ 126\times 45 = 120+126+1728+3696)$$

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# Yukawa sector in unified models

## Effect of Planck-scale-suppressed operators

**Fitting the Yukawa sector including also the higher-dimension operators?**

# Yukawa sector in unified models

## Effect of Planck-scale-suppressed operators

**Couldn't one say something about the effect of higher-dimensional operators without performing such fits?**

- Assumption: "Continuity" of the fits [the fit of the Yukawa matrices including the non-renormalizable operators won't differ from the fit of the renormalizable theory by more than $\mathcal{O}(M_G/M_{Pl})$]
- Simplification: No correlations among shifts in Yukawa matrices for different fermion sectors

⇒ We take an existing fit and try to modify the individual Yukawa matrices by a random $\mathcal{O}(M_G/M_{Pl})$ term:

$$\boxed{Y_f \to Y_f + \Delta Y_f \qquad |\Delta Y_f| \lesssim \mathcal{O}(M_G/M_{Pl}) \qquad f = u, d, l}$$

# Yukawa sector in unified models

## Effect of Planck-scale-suppressed operators

$$Y_f \to Y_f + \Delta Y_f \qquad |\Delta Y_f| \lesssim \mathcal{O}(M_G/M_{Pl}) \qquad f = u, d, l$$

- both $Y_f$ and $Y_f + \Delta Y_f$ have to reproduce the correct fermion masses

$$Y_f^{\text{diag}} = F_C^T Y_f F = \tilde{F}_C^T (Y_f + \Delta Y_f) \tilde{F}$$

**How much can $\tilde{F}$,$\tilde{F}_C$ differ from $F$,$F_C$ if $|\Delta Y_f| \lesssim \mathcal{O}(M_G/M_{Pl}) \sim 10^{-2}$ required???**

# Yukawa sector in unified models

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**How much can $\tilde{F}$,$\tilde{F}_C$ differ from $F$,$F_C$ if $|\Delta Y_f| \lesssim \mathcal{O}(M_G/M_{Pl}) \sim 10^{-2}$ required???**

- Yukawa matrices typically hierarchical:

$$Y_u \sim \begin{pmatrix} < \mathcal{O}(10^{-2}) & < \mathcal{O}(10^{-2}) & \\ < \mathcal{O}(10^{-2}) & < \mathcal{O}(10^{-2}) & \\ & & \mathcal{O}(1) \end{pmatrix}$$

$\Delta Y_u \sim \mathcal{O}(10^{-2}) \Rightarrow \tilde{U}$,$\tilde{U}_C$ **may differ from** $U$,$U_C$ **by arbitrary 1-2 rotation!**

# Numerical results

## "Golden channel" $p \to \pi^0 e^+$ in SO(10)

$$\Gamma(p \to \pi^0 e^+) \propto \left\{ \left| \left(U_C^\dagger U\right)_{11} \left(D_C^\dagger E\right)_{11} + \left(D_C^\dagger U\right)_{11} \left(U_C^\dagger E\right)_{11} \right|^2 + \left| \left(U_C^\dagger U\right)_{11} \left(E_C^\dagger D\right)_{11} + \left(U_C^\dagger D\right)_{11} \left(E_C^\dagger U\right)_{11} \right|^2 \right\}$$

# Numerical results

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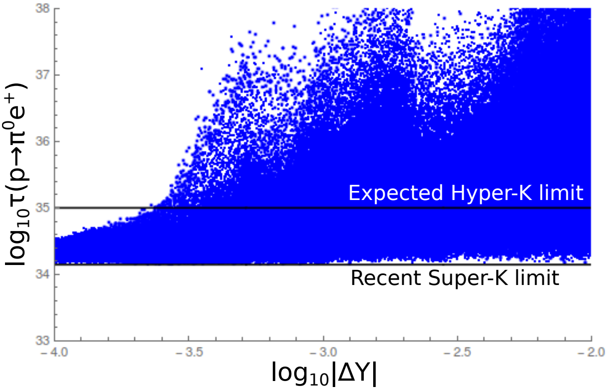


$$(M_X = M'_X = 3 \times 10^{15}\,\text{GeV fixed}, \; \Delta Y \equiv \max_{f=u,d,l} Y_f \text{ varied})$$

# Numerical results

## Channels $p \to$ charged meson $+ \bar{\nu}$ summed, SO(10)

$$\Gamma(p \to \pi^+\overline{\nu}) \propto \sum_{l=1}^{3} \left|(U_C^\dagger D)_{11}(D_C^\dagger N)_{1l} + (D_C^\dagger D)_{11}(U_C^\dagger N)_{1l}\right|^2 ,$$

$$\Gamma(p \to K^+\overline{\nu}) \propto \sum_{l=1}^{3} \left|B_1 \left[(U_C^\dagger D)_{11}(D_C^\dagger N)_{2l} + (D_C^\dagger D)_{21}(U_C^\dagger N)_{1l}\right] + B_2 \left[(U_C^\dagger D)_{12}(D_C^\dagger N)_{1l} + (D_C^\dagger D)_{12}(U_C^\dagger N)_{1l}\right]\right|^2$$

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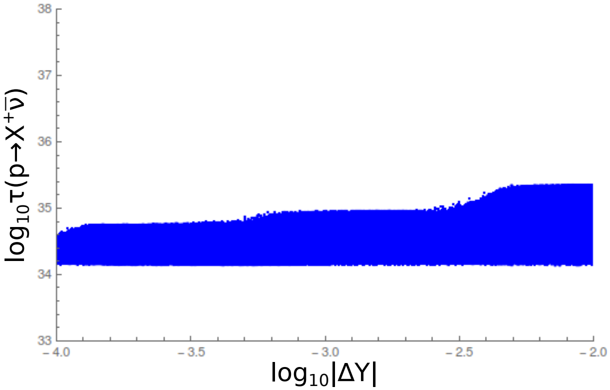
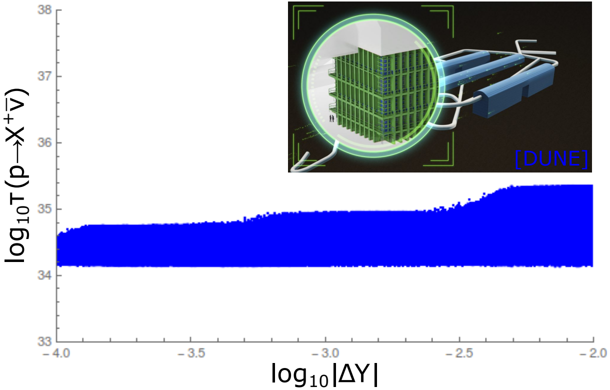
$$\Gamma(p \to K^+ \overline{\nu}) \propto \sum_{l=1}^{3} \left| B_1 \left[ (U_C^\dagger D)_{11} (D_C^\dagger N)_{2l} + (D_C^\dagger D)_{21} (U_C^\dagger N)_{1l} \right] + B_2 \left[ (U_C^\dagger D)_{12} (D_C^\dagger N)_{1l} + (D_C^\dagger D)_{12} (U_C^\dagger N)_{1l} \right] \right|^2$$



# Numerical results

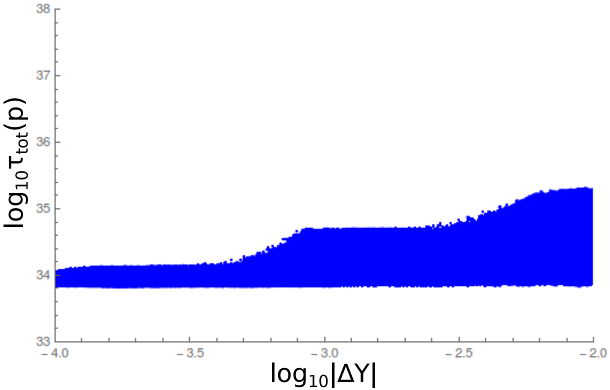
Channels $p \to$ charged meson $+ \bar{\nu}$ summed, SO(10)

**Proton decay into neutrinos can not be "hidden" due to small perturbations in the Yukawa interactions!**



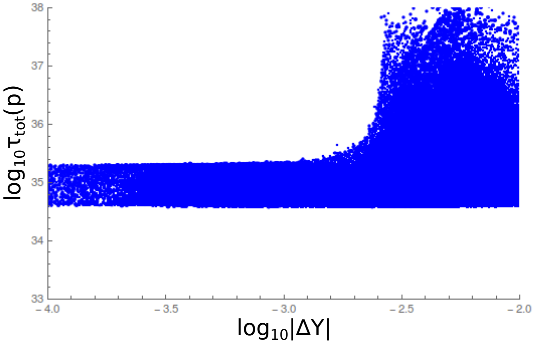
# Numerical results

## Total proton lifetime in SO(10)



# Numerical results

## Total proton lifetime in flipped SU(5) ($SU(5) \times U(1)_X$ gauge group) [Michal Malinský talk]




- Proton decay might be completely "hidden" due to small perturbations in the Yukawa interactions!
- $d = 5$ Planck-scale-suppressed operators can not be built within simplest models $\Rightarrow$ the size of the corrections expected to be $\mathcal{O}(M_G^2/M_{Pl}^2) \sim 10^{-4}$

# Conclusions

- Cabibbo-like suppression may play an important role in proton lifetime determination
- If the Yukawa couplings are symmetric, the flavour structure of the proton decay widths for channels with neutrinos in the final state is fully determined by the CKM matrix
- In order to determine the decay width for channels with charged leptons in the final state (like the "golden" channel $p \to \pi^0 e^+$), fits to Yukawa sector are necessary
- The predictions for the charged lepton channels, however, get blurred by adding the Planck-suppressed higher-dimensional operators
- The predictions for the neutrino channels (hence, also for the total proton lifetime) are robust!