MAX-PLANCK-INSTITUT FÜR PHYSIK

TEV WINDOW TO GRAND UNIFICATION: HIGGS' LIGHT COLOR TRIPLET PARTNER

Anja Stuhlfauth (MPP & LMU)

May 28, 2025

PLANCK 2025

Based on arXiv:2411.14051 [hep-ph]

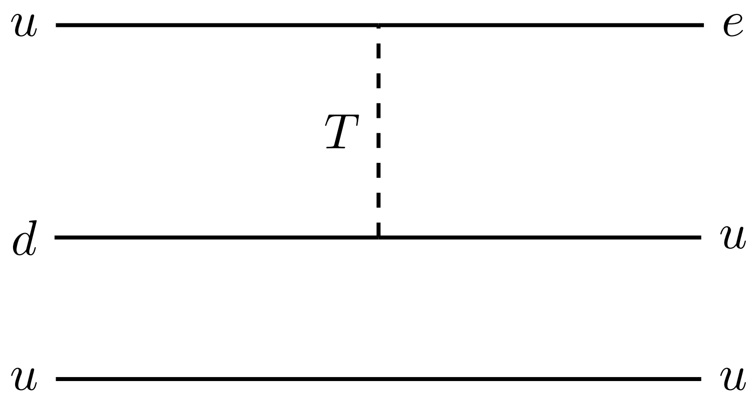
In collaboration with Gia Dvali and Otari Sakhelashvili

HIGGS' COLOR TRIPLET PARTNER

Grand Unification

- Unification of electroweak and color force
- GUT scale $M_{\text{GUT}} \sim 10^{16}\ \text{GeV}$ [Georgi, Quinn, Weinberg '74]
- Universal feature: existence of color triplet T

  Example SU(5) [Georgi, Glashow '74]: $5_H = \begin{pmatrix} T \\ H \end{pmatrix}$



T leads to proton decay

- Leptoquark
- Usually assumed to be heavy ("doublet-triplet splitting problem")

  Alternative possibility: T can be light due to suppressed Yukawa couplings [Dvali '92, '96]

HIGGS' LIGHT COLOR TRIPLET PARTNER

T can be light due to suppressed Yukawa couplings [Dvali '92, '96]:

- splitting in Yukawa couplings, not in mass
- $m_T \sim \text{TeV}$ [Atlas '23, '21, CMS '18] $\longleftarrow$ Window to grand unification!

➡ **Correlations of signatures in 3 different categories of experiments**:

- Direct production at high energy accelerators
- Proton decay experiments
- Cold neutron experiments

SU(5)

Symmetry breaking pattern: $SU(5) \xrightarrow{\langle 24_H \rangle} SU(3)_C \times SU(2)_w \times U(1)_Y \xrightarrow{\langle 5_H \rangle} SU(3)_C \times U(1)_e$

Scalars: adjoint Higgs $\langle 24_H \rangle \propto M_{\text{GUT}}\,\text{diag}\left(1,1,1,-\frac{3}{2},-\frac{3}{2}\right)$, $\quad 5_H = \begin{pmatrix} T_r & T_g & T_b & H^+ & H^0 \end{pmatrix}^T$

Fermions: $\bar{5}_F = \begin{pmatrix} d_r^c & d_g^c & d_b^c & e^- & -\nu \end{pmatrix}$, $\quad 10_F = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_b^c & -u_g^c & -u_r & -d_r \\ -u_b^c & 0 & u_r^c & -u_g & -d_g \\ u_g^c & -u_r^c & 0 & -u_b & -d_b \\ u_r & u_g & u_b & 0 & e^+ \\ d_r & d_g & d_b & -e^+ & 0 \end{pmatrix}$, $\quad \nu^c$

YUKAWA COUPLINGS

In minimal model:

$$\mathscr{L}_{\text{Yuk}} = Y_d\, 5^*_H 10_F \bar{5}_F + Y_u\, 10_F 10_F 5_H$$

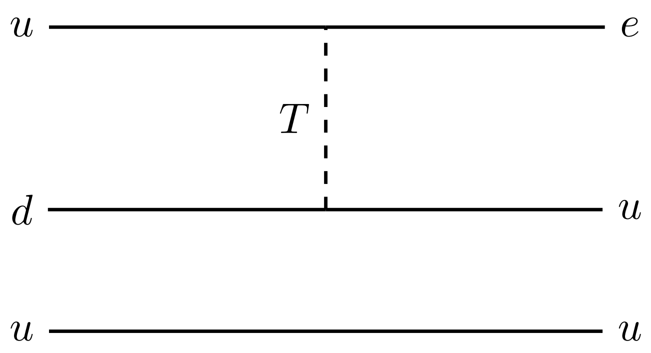
- SM Yukawa couplings for doublet
- Triplet has quark-quark and quark-lepton couplings
- Doublet and triplet have same Yukawa coupling strength set by SM fermion masses
- Predicts wrong mass relation $m_d = m_e$, fixed with higher-dimensional operators [Ellis '79]

Proton decay amplitude: $\mathscr{M} \sim \frac{Y^2}{m_T^2}$

Comparing with experimental proton lifetime

$\tau_p > 10^{34} y$ [Super-Kamiokande '20]

$\Rightarrow m_T > 10^{11}$ GeV



EFFECTIVE YUKAWA COUPLINGS

In minimal model:

$$\mathscr{L}_{\text{Yuk}} = Y_d\, 5^*_H 10_F \bar{5}_F + Y_u\, 10_F 10_F 5_H$$

Higher-dimensional operators split couplings of doublet and triplet

Gravity gives $\Lambda < M_P/\sqrt{N_{species}} \sim 10^{17}\text{GeV}$ in SM

[Dvali ’07, Dvali, Redi ’07]

Example:

$$\mathscr{L}_{\text{5-dim}} \supset \frac{g}{\Lambda} 5^*_H\, 24_H\, 10_F\, \bar{5}_F$$

Plug in $\langle 24_H \rangle \propto M_{\text{GUT}}\, \text{diag}\left(1,1,1,-\frac{3}{2},-\frac{3}{2}\right)$

$$\mathscr{L}_{\text{Yuk}} \supset \left(Y_d + g\frac{M_G}{\Lambda}\right) T^*\left(u^c d^c + QL\right) + \left(Y_d - g\frac{3M_G}{2\Lambda}\right) H^*\left(Qd^c + Le^c\right)$$

EFFECTIVE YUKAWA COUPLINGS

Effective Lagrangian [Dvali, Shifman '96]:

$$\begin{aligned}\mathscr{L}_{\text{Yuk}} \supset\ & g_{Tud}\, T^*\, u^c d^c + g_{TQL}\, T^*\, QL \\ & + g_{Tue}\, T\, u^c e^c + g_{TQQ}\, T\, QQ + g_{Td\nu}\, T\, d^c \nu^c \\ & + Y'_d\, H^*\, Q d^c + Y'_e\, H^*\, L e^c + Y'_u\, H\, Q u^c \\ & + Y'_\nu\, H\, L \nu^c\end{aligned}$$

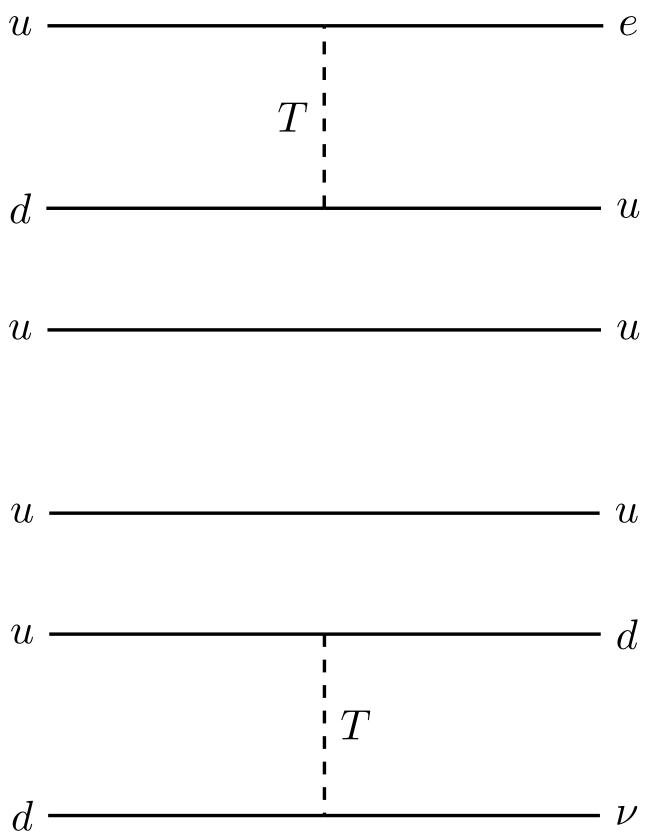
➡ **Independent couplings of triplet and doublet**

PROTON DECAY

- Proton decay channels: $p \rightarrow \pi^0 e^+$, $p \rightarrow \pi^+ \nu$, …
- Amplitude: $\mathscr{M} \sim \frac{g_{Tqq} g_{Tql}}{m_T^2}$
- Assume phenomenologically interesting regime $m_T \sim \mathrm{TeV}$
- Comparing with experimental proton lifetime

  $\tau_p > 10^{34} y$ [Super-Kamiokande '20]

  $\Rightarrow \; g_{Tqq} g_{Tql} < 10^{-26}$



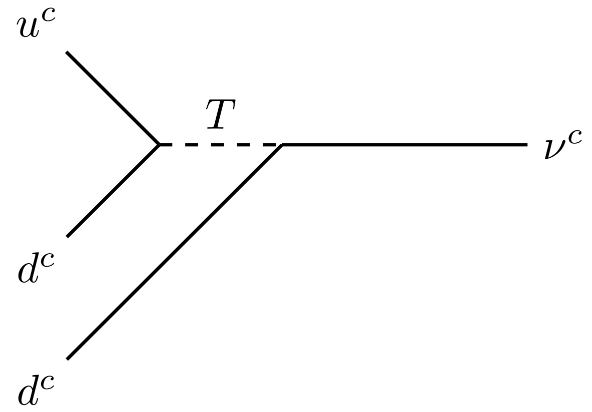
NEUTRON OSCILLATIONS INTO STERILE NEUTRINO

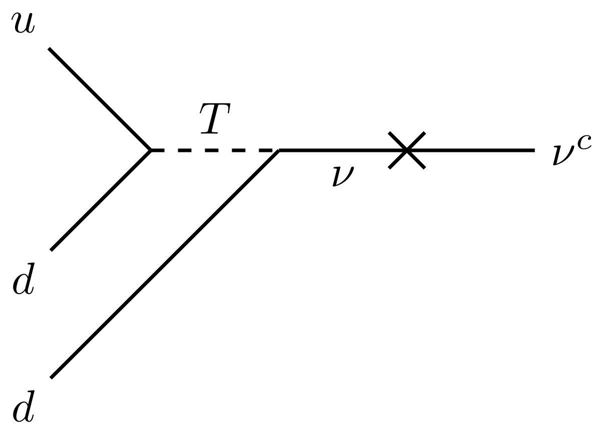
- If mass of sterile neutrino m_R is close to neutron mass m_n

$$m_R \simeq m_n$$

- Mixing mass term through diagrams on the right

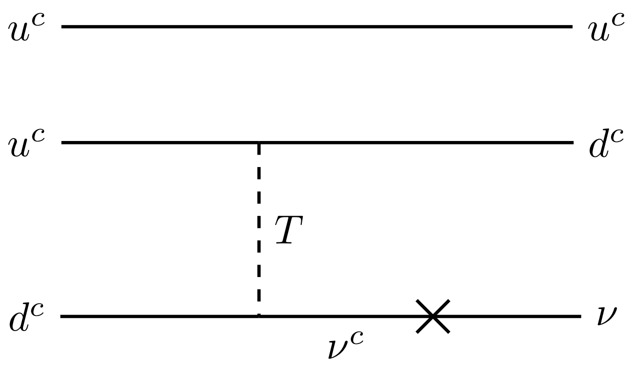
- **Directly correlated with proton decay $p \to \pi^+ \nu$**





NEUTRON OSCILLATIONS INTO STERILE NEUTRINO

Proton decay

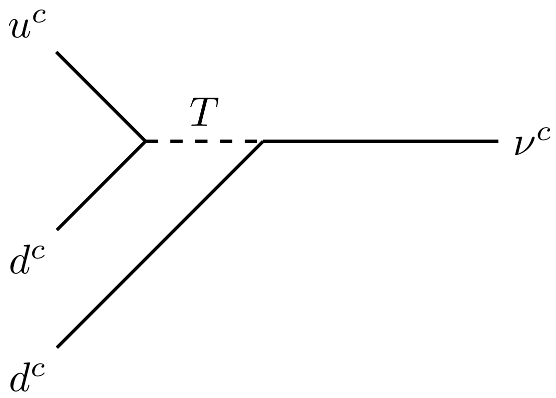


$$\tau_{n\nu^c} \simeq m_n^{-1}\sqrt{\tau_p m_\nu}$$

$\tau_p \sim 10^{32}\text{y}$ [Super-Kamiokande ’14]

$\Rightarrow\ \tau_{n\nu^c} \sim 10^2 - 10^3\text{s}$

$n - \nu^c$ oscillations



Experiments measuring neutron disappearance into hidden species [nEDM ’21, Ban et al. ’23]

- Ultra cold neutrons in magnetic field (magnetic resonance imaging)
- Oscillation time is within range of interest

Color triplet can be probe of neutrino mass!

T-PRODUCTION AT LHC

- Can be pair-produced at LHC
- Bound on new colored particles and R-hadrons around TeV [Atlas ’23, ‘21, CMS ’18]
- T is long-lived:

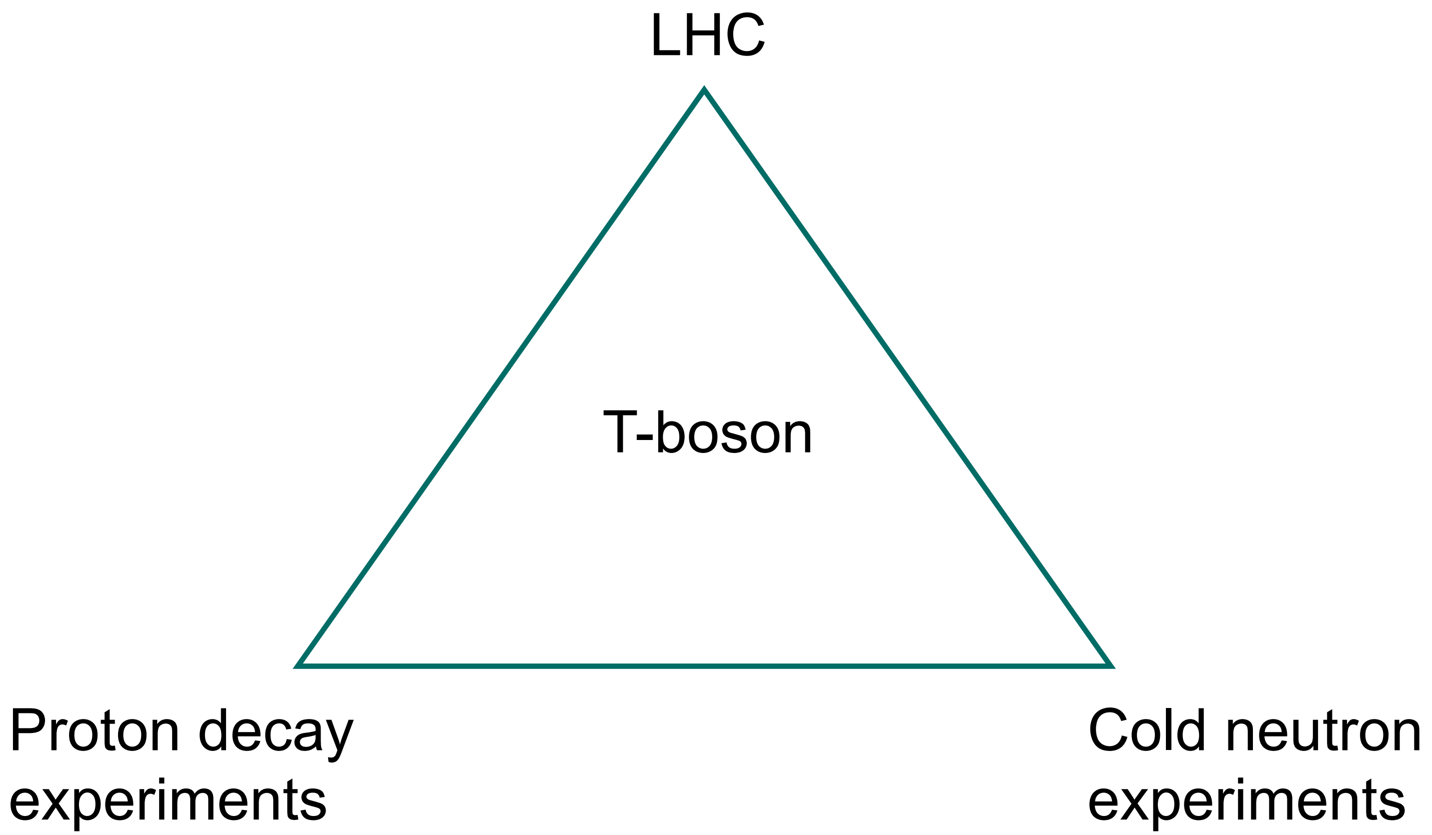
  $\tau_T \sim 10^{-11}\mathrm{s} \sim 1\mathrm{mm}$
- Triplet hadronizes, e.g., Td^c
  - T-baryon $Tqq, T^*q^cq^c$
  - T-meson Tq^c, T^*q

- Decays via displaced vertex
- Decay is accompanied by jets

  $(Td^c) \to \pi^0 + \nu^c$

  $(T^*u^cd^c) \to \bar{n} + \nu^c$
- For more suppressed couplings, T-hadron can decay outside of detector

CORRELATION OF SIGNATURES



EFFECTIVE YUKAWA COUPLINGS

In minimal model:

$$\mathscr{L}_{\text{Yuk}} = Y_d \, 5^*_H 10_F \bar{5}_F + Y_u \, 10_F 10_F 5_H$$

Add higher-dimensional operators:

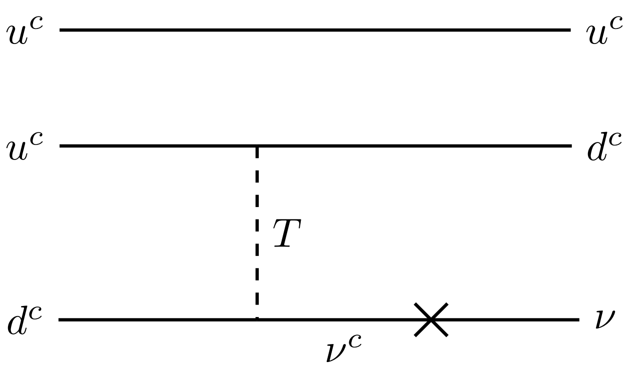
$$\mathscr{L}_{\text{5-dim}} \supset \frac{g_1}{\Lambda} 5^*_H 10_F 24_H \bar{5}_F + \frac{g_2}{\Lambda} 5^*_H 24_H 10_F \bar{5}_F + \\ + \frac{g_3}{\Lambda} 10_F 10_F 24_H 5_H + \frac{g_4}{\Lambda} 24_H 10_F 10_F 5_H + \\ + \frac{g_5}{\Lambda} 5_H 24_H \bar{5}_F \nu^c$$

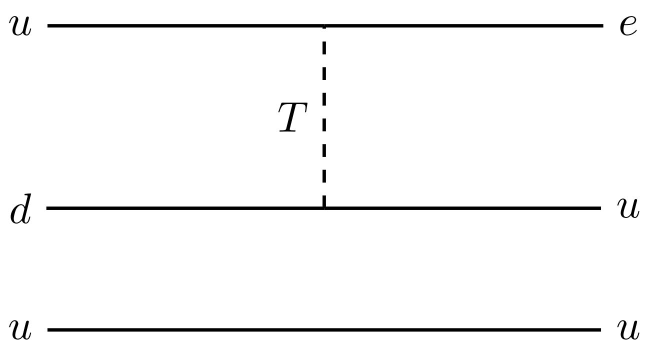
Effective Lagrangian:

$$\mathscr{L} \supset g_{Tud} \, T^* u^c d^c + g_{TQL} \, T^* QL + \\ + g_{Tue} \, T u^c e^c + g_{TQQ} \, T QQ + g_{Td\nu} \, T d^c \nu^c + \\ + Y'_d \, H^* Q d^c + Y'_e \, H^* L e^c + Y'_u \, H Q u^c + \\ + Y'_\nu \, H L \nu^c$$

➡ Independent couplings of triplet and doublet

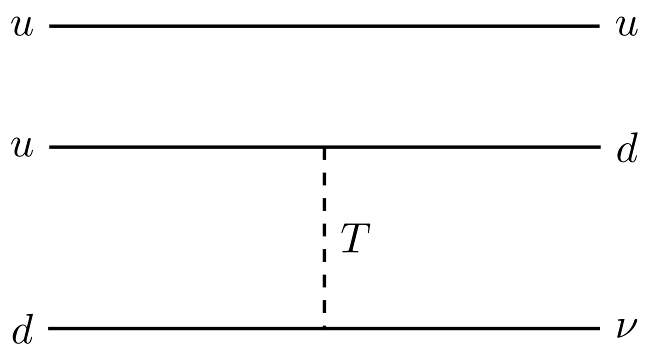
PROTON DECAY





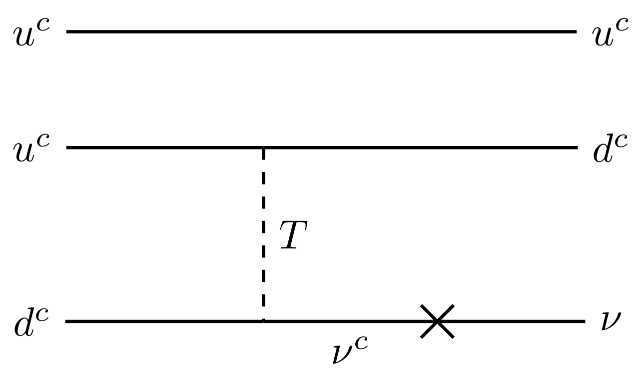
If $p \to \pi^+ \nu$ goes through ν^c, proton lifetime extra enhanced:

$$\tau_p \sim \frac{m_R}{m_\nu} \frac{m_T^4}{g_{Tqq}^2 g_{Tql}^2}$$

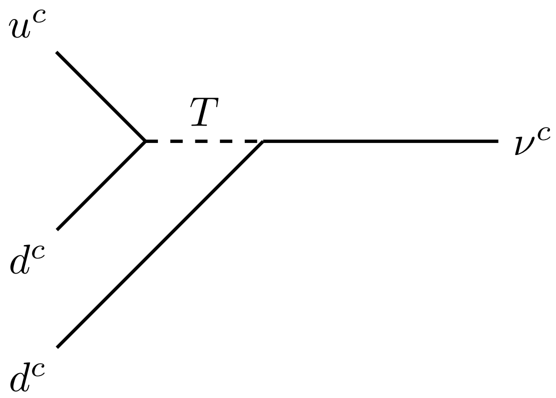


NEUTRON OSCILLATIONS INTO STERILE NEUTRINO

Proton decay

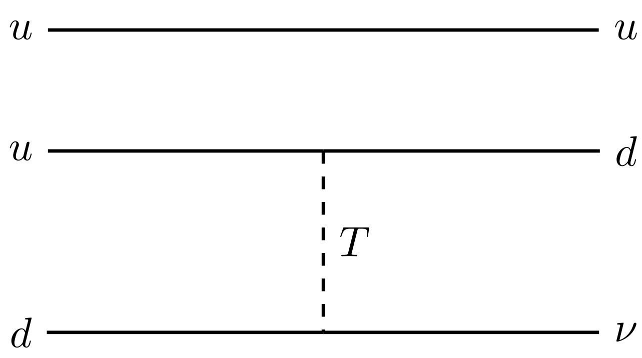


$n - \nu^c$ oscillations

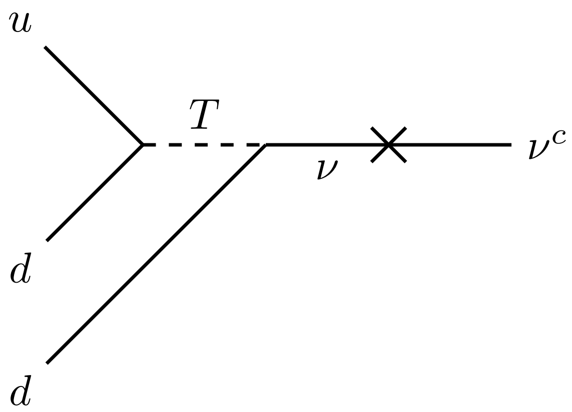


$$\tau_{n\nu^c} \simeq m_n^{-1}\sqrt{\tau_p m_\nu}$$

$$\tau_p \sim 10^{32}\text{y} \Rightarrow \tau_{n\nu^c} \sim 10^2 - 10^3\text{s}$$



$$\tau_{n\nu^c} \simeq \sqrt{\frac{\tau_p}{m_\nu}}$$



NEUTRON DISAPPEARANCE EXPERIMENTS

Ultracold neutrons in magnetic field

Magnetic field changes energy $\Delta E = \mu_n B$

Ban et al.: scan with magnetic field in steps $\Delta B = 3\mu T$ in range $50 - 1100\mu T$, corresponds to mass splitting $2 - 69\text{peV}$

Bound on neutron disappearance time $\tau > 1\text{s}$

Experiments with bound neutron:

GERDA and LEGEND, Germanium detectors

NEUTRON-ANTINEUTRON OSCILLATIONS

Oscillation time $\tau_{n\bar{n}} \sim \tau^2_{n\nu^c} m_n \sim 10^{30}\mathrm{s}$

Far from experimental limits $\sim 10^8\mathrm{s}$ [Super-Kamiokande '21]