NATIONAL SCIENCE CENTRE
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Faculty of Physics

A fresh look at proton decay in SUSY SU(5)

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Outline of talk

- Motivation
  - Proton decay
  - Minimal SUSY SU(5)
- Experimental status of proton decay
- SUSY SU(5) contribution in Proton decay
- Set up
- Numerical analysis
- Results for two decay modes

Motivation

- After the success of electroweak unification, we are motivated to study a unified theory of electroweak and strong interactions, called Grand Unified Theory (GUT).

- SU(5) is the minimal large (simple) gauge group that can contain all the SM gauge groups as subgroups. Baryon number violation is the most impressive prediction of GUT models and it leads to proton decay.

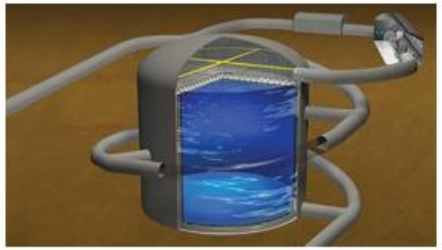
- The GUT scale energy is not attainable by accelerators, but we can indirectly probe such a high scale through proton decay measurements.

- The minimal SU(5) GUT predicts $p \to \pi^0 e^+ \sim 10^{31}$ years as the dominant decay mode of proton decay, now completely ruled out from experimental limit. It also doesn't give us correct value of $sin^2(\theta_w)$.

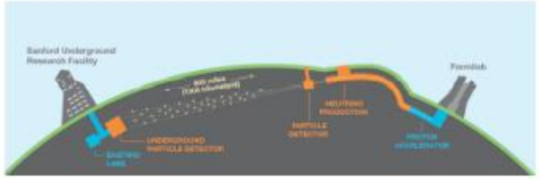
- One of the phenomenological consequences of the supersymmetric SU(5) is the prediction of $sin^2(\theta_w)$, which is supported by the precision measurements and have exact unification.

Proton decay

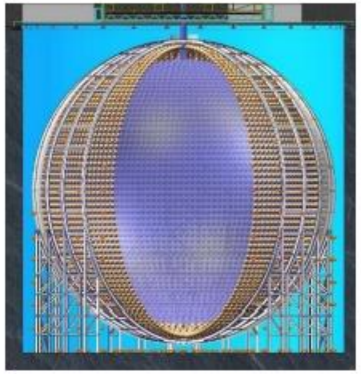
- In this decade, proton decay searches will be improved by O(10) by 3 different neutrino detectors and maybe discovery.



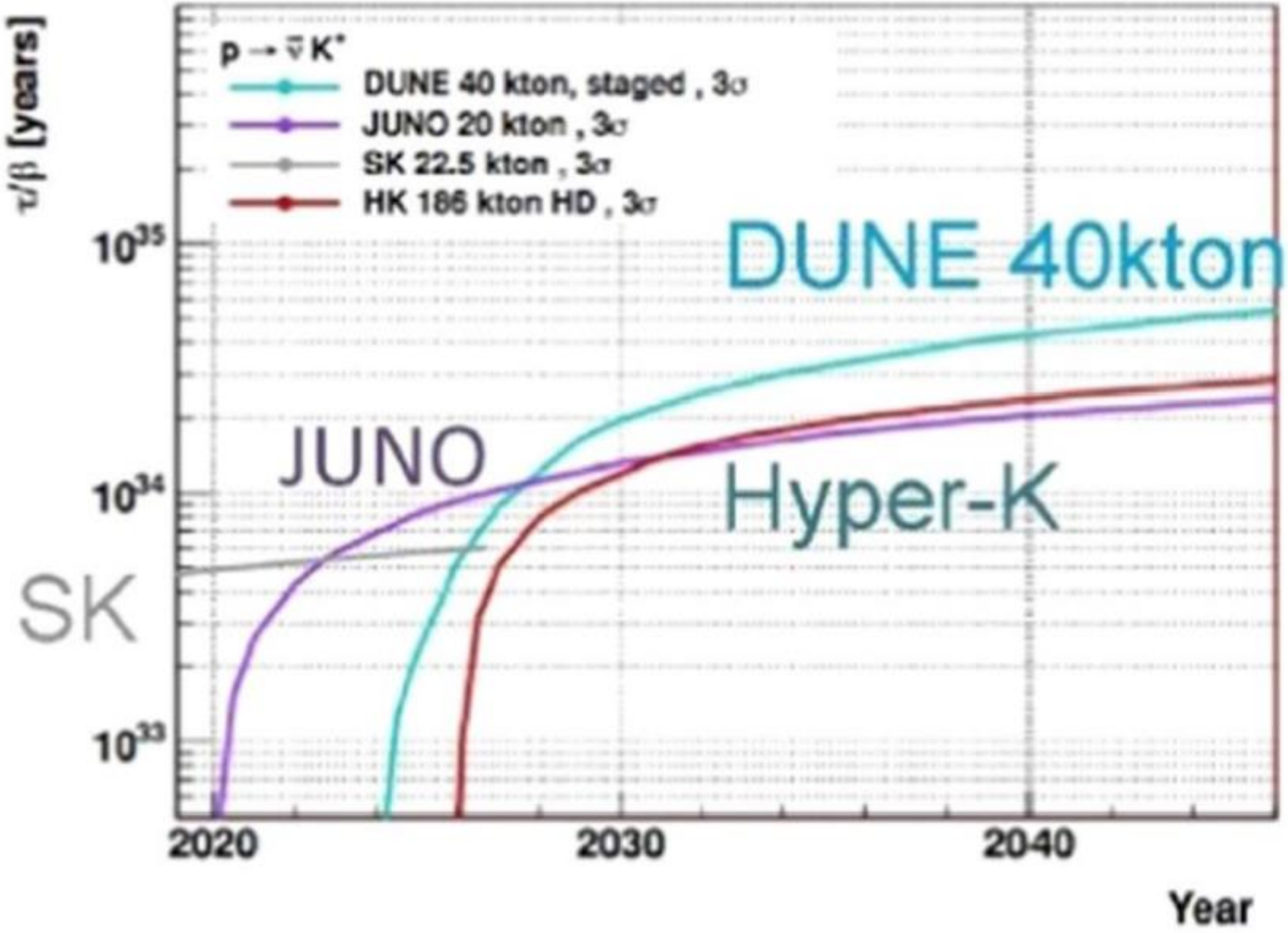
Hyper-K: 185 Kton water in Japan



DUNE: 40 Kton Liquid Argon in US



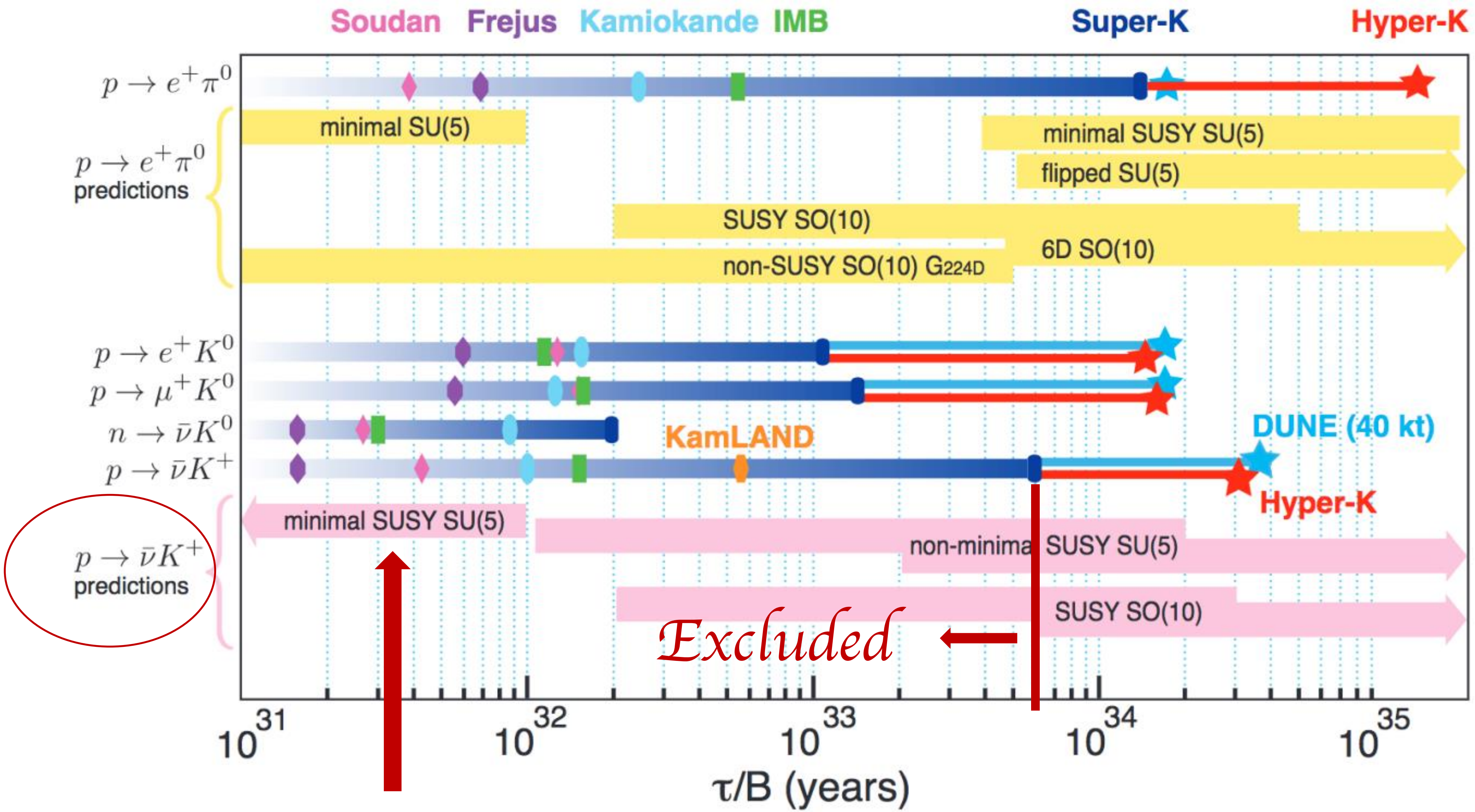
JUNO: 20 kton Liquid Scintillator in China



Hyper-K Design Report arXiv:1805.04163

Experimental status of proton decay

p Decay Modes	Partial mean life (10^{33} years)		
	Current (90% CL)	Future (3σ discovery)	Future (90% CL)
$p \to \pi^0 e^+$	16	DUNE: 15 (25) Hyper-K: 63 (100)	DUNE: 20 (40) Hyper-K: 78 (130)
$p \to K^+ \bar{\nu}$	5.9	JUNO: 12 (20) DUNE: 30 (50) Hyper-K: 20 (30)	JUNO: 19 (40) DUNE: 33 (65) Hyper-K: 32 (50)



$$\tau_{p\to k^+\bar{\nu}} \simeq 4\times 10^{35}\times \sin^4(2\beta)\left(\frac{0.1}{\bar{A}_R}\right)^2\left(\frac{M_S}{10^2\mathrm{TeV}}\right)^2\left(\frac{M_{H_c}}{10^{16}\mathrm{GeV}}\right)^2 yrs$$

Refs: Hisano, Kobayashia , Kuwaharaa , and Nagataa

Sunny Seo, IBS

Baryon and Lepton number violating operator in SUSY SU(5)

❖ D=4, supersymmetric terms in MSSM superpotential

$$L_i Q_j D_k^c, U_i^c D_j^c D_k^c$$

⇨ Lead fast proton decay
but protected by R- parity

❖ Assuming R-parity conservation, SU(5) superpotential has Yukawa terms

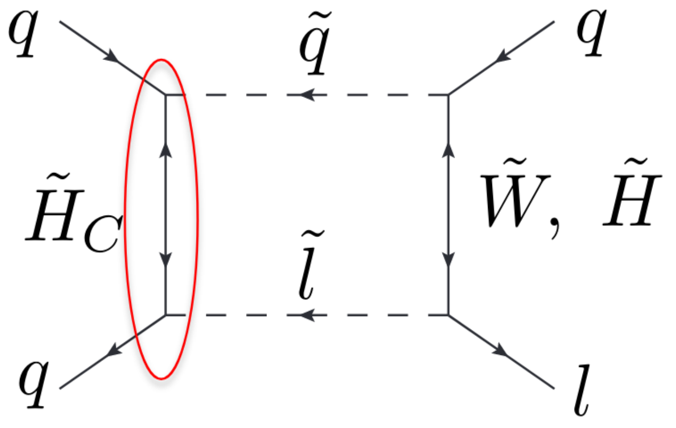
$$W_Y^{SU(5)} = \frac{1}{4} h^{ij} \epsilon_{abcde} \chi_i^{ab} \chi_j^{cd} H^e + \sqrt{2} f^{ij} \chi_i^{ab} \phi_{ja} \bar{H}_b$$

❖ D=5, Integrating out color Higgsino leads dim-5 BNV terms in SU(5) superpotential

$$W_{BV}^{SU(5)} = -\frac{1}{M_{H_C}}\left[C_{5L}^{ijkl}\frac{1}{2}\epsilon^{\alpha\beta\gamma}(Q'_{i\alpha}Q'_{j\beta})(Q'_{k\gamma}L_l) + C_{5R}^{ijkl}\epsilon^{\alpha\beta\gamma}(u^c_{i\alpha}d^c_{j\beta})(u^c_{k\gamma}e^c_l)\right]$$

$$C_{5R}^{ijkl} = \frac{2}{M_{H_C}}(V_{CKM}\hat{Y}_d)^{ij}\hat{Y}_u^k(V_{CKM}^{kl})^\dagger$$

$$C_{5L}^{ijkl} = \frac{2}{M_{H_C}}(\hat{Y}_u^i\delta^{ij})(V_{CKM}\hat{Y}_d)^{kl}$$



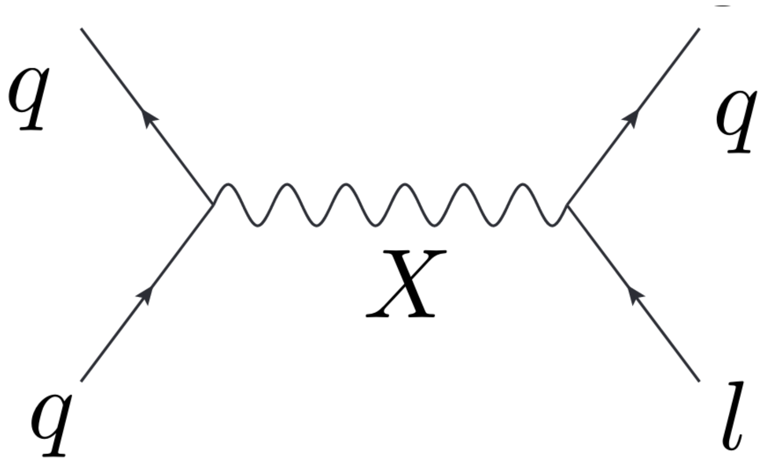
Sensitive to GUT scale and Yukawas

➢ Naïve formula for proton decay rate

$$\Gamma(p\to K^+\bar{\nu}) \approx \frac{\tan\beta^2 m_p^5}{M_{GUT}^2 m_{SUSY}^2}$$

Large enhancement in the decay rates

❖ D=6, Integrating out X-bosons leads to dim-6 BNV operators



$$C^{(6)ijk}_{RL}(ud_id_j\nu_k)(ud_i)_R(d_j\nu_k)_L, \qquad C^{(6)ijk}_{RL}(ud_id_j\nu_k) = \frac{g^2_{GUT}}{M^2_V}V^{1j}_{CKM}\delta^{ik}$$

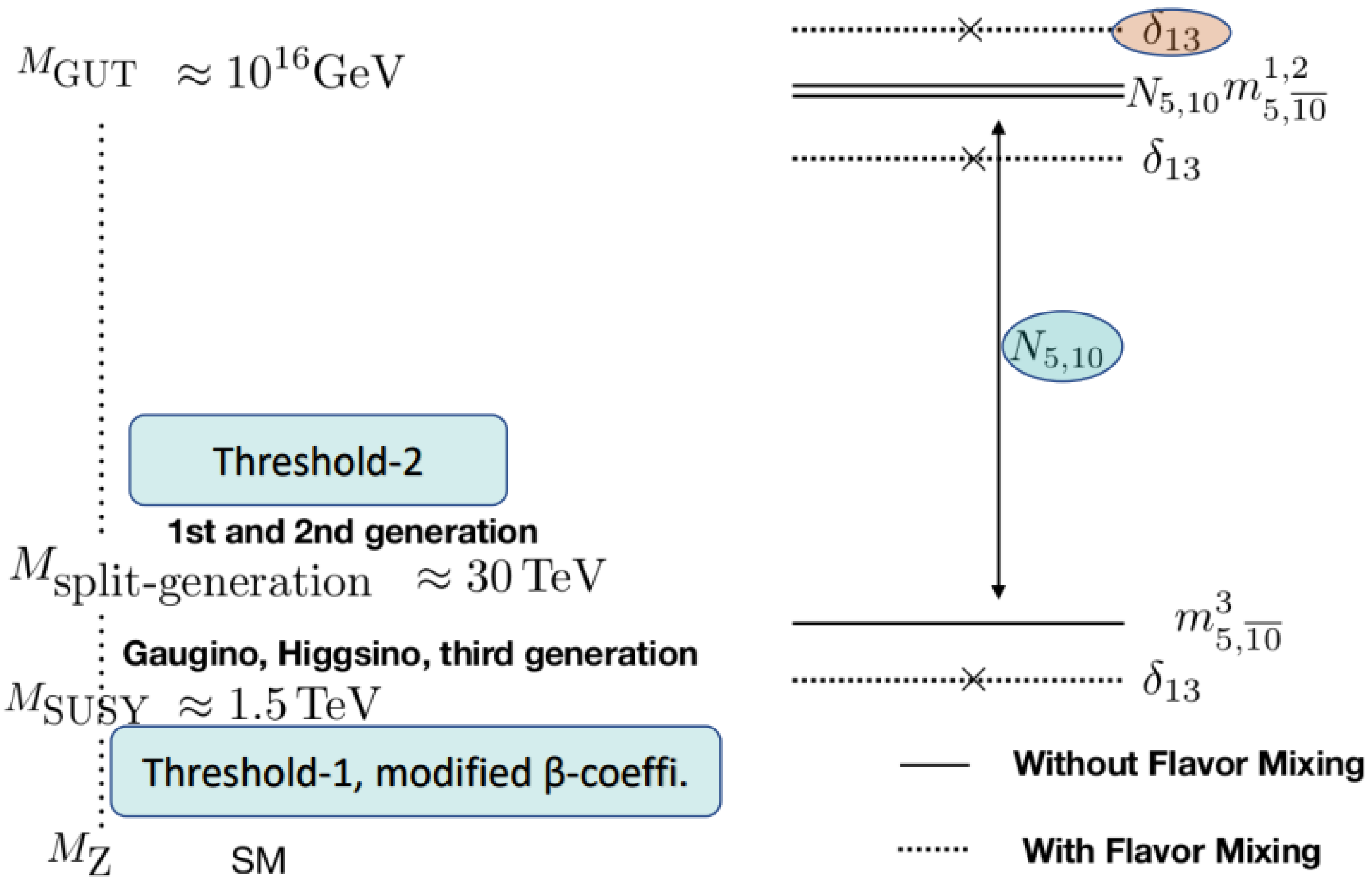
$$C^{(6)ik}_{RL}(ud_iul_k)(ud_i)_R(ul_k)_L, \qquad C^{(6)ik}_{RL}(ud_iul_k) = \frac{g^2_{GUT}}{M^2_V}\delta^{ik}$$

$$C^{(6)ik}_{LR}(ud_iul_k)(ud_i)_L(ul_k)_R, \qquad C^{(6)ik}_{LR}(ud_iul_k) = \frac{g^2_{GUT}}{M^2_V}(\delta^{ik} + V^{1i}_{CKM}(V^{\dagger}_{CKM})^{k1})$$

$$\Gamma(p \to K^+\bar{\nu}) \propto \frac{g^4_{GUT}}{M^4_V}$$

⟹ Supressed by vector boson masses & sensitive to gauge coupling

SET UP



Questions

- Can we decouple first two generation completely?
- How much running of gauge coupling will effect in this set-up??
- Threshold correction??
- How proton decay will effect due to flavour violation?

Refs:
L. Randall and M. Reece
H. Murayama and A. Pierce
N. Nagata and S. Shirai

- Perhaps the most probable structure of supersymmetric mass spectrum considering all low energy constraints

Boundary values for soft masses in this set up

$$m_{\tilde{Q}}^2 = m_{10}^2 \begin{pmatrix} 1 & 0 & \frac{\delta_{13}^{10}}{N_{10}} \\ 0 & 1 & 0 \\ \frac{\delta_{13}^{10}}{N_{10}} & 0 & \frac{1}{(N_{10})^2} \end{pmatrix}$$

$$m_{\tilde{d}}^2 = m_{\bar{5}}^2 \begin{pmatrix} 1 & 0 & \frac{\delta_{13}^{\bar{5}}}{N_{\bar{5}}} \\ 0 & 1 & 0 \\ \frac{\delta_{13}^{\bar{5}}}{N_{\bar{5}}} & 0 & \frac{1}{(N_{\bar{5}})^2} \end{pmatrix}$$

- (Q, u, e) superfields are elements of same 10-plet supermultiplet of SU(5)

$$m_{\tilde{Q}}^2 = m_{\tilde{u}}^2 = m_{\tilde{e}}^2$$

- (d, L) superfields are also elements of same 5-plet supermultiplet of SU(5).

$$m_{\tilde{d}}^2 = m_{\tilde{L}}^2$$

Precision computations require

Need precision calculation of gauge unification scale

- Compute 2-loop β-Coeff. For split spectrum

One-loop: $b_a = \begin{pmatrix} 79/15 & -1/3 & -13/3 \end{pmatrix}$

$$B_{ab} = \begin{pmatrix} 407/75 & 21/5 & 176/15 \\ 7/5 & 89/3 & 16 \\ 22/15 & 6 & 58/3 \end{pmatrix} \quad C_a^{u,d,e} = \begin{pmatrix} 26/5 & 14/5 & 18/5 \\ 6 & 6 & 2 \\ 4 & 4 & 0 \end{pmatrix}$$

Two-loop

- Split SUSY threshold at two scale

Partial decay width of proton decay

$$\Gamma(B_i \to M_j l_k) = \frac{m_i}{32\pi}\left(1 - \frac{m_j^2}{m_i^2}\right)^2 \left| \sum_I C_I^{ijk} W_{0I}^{ijk}(B_i \to M_j) \right|^2$$

Hadronic matrix elements at 2 GeV
Y. Aoki, T. Izubuchi, E. Shintani, and A. Soni,

- Compute Wilson coefficient of 5-dim operator at GUT scale

RGE running of 5-dim Wilson Coeff till SUSY Scale

- Matching at SUSY scale to dim-6 four fermion operator

RGE running till 2 GeV

- Compute partial decay width at 2 GeV

SUSEFLAV-H suited for heavy supersymmetry

will be public soon

Sprotondecay: computing dim 5 and dim 6 proton decay in supersymmetric models

Numerical Analysis details

- We implement split-generation scenario in SuSeFlav code which is a supersymmetric spectrum calculator.
- We interface the proton decay calculations routines with the adapted SuSeFlav version.

Paramter	Range
m_{hu}, m_{hd}	$[-30, 30]$ TeV
$m_{10}, m_{\bar{5}}$	$[1, 30]$ TeV
$M_{1/2}$	$[0.7, 3]$ TeV
A_0	$[-8, 8]$ TeV
$N^1_{10}, N^1_{\bar{5}}$	$[1, 20]$
$\delta^{10}_{13}, \delta^{\bar{5}}_{13}$	$[-1, 1]$
$\tan\beta$	5

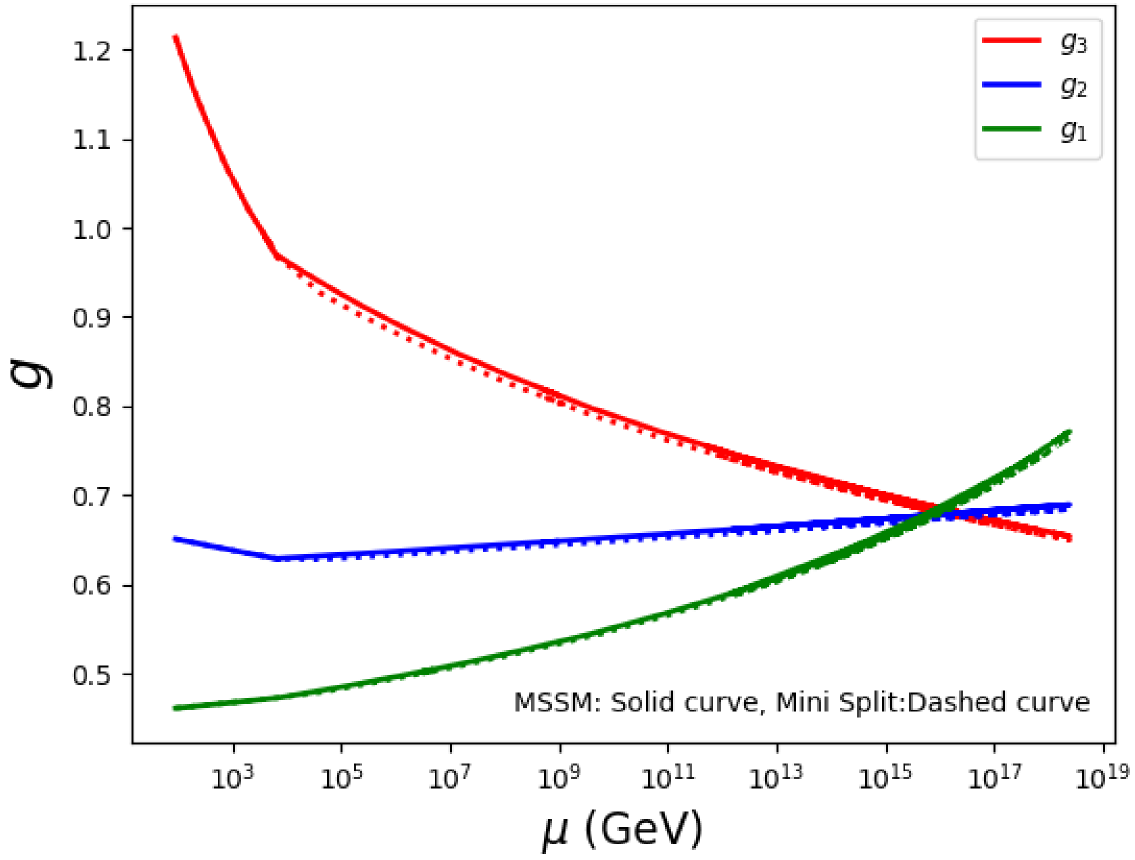
Spectrum selection criteria

- Correct Higgs masses
- LHC bounds on sfermions and gauginos masses
- LEP bounds
- Vacuum stability
- $\text{Br}(\tau \to e\,\gamma)$

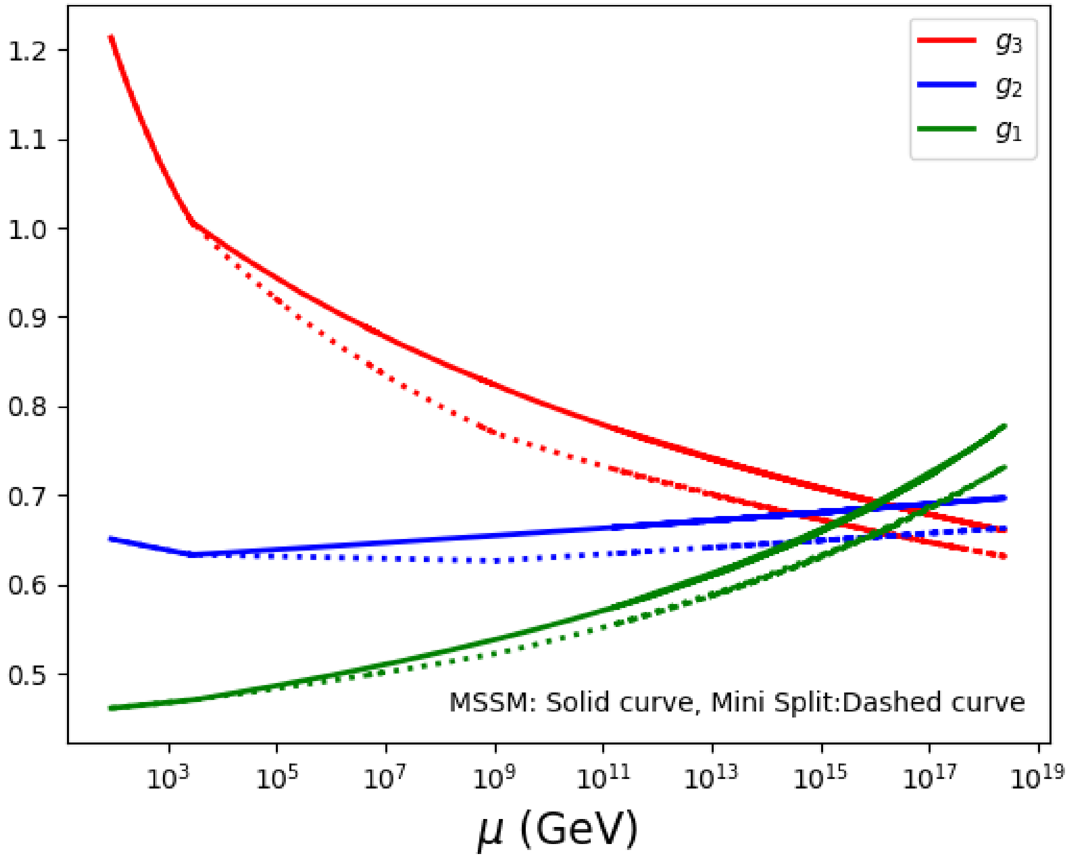
- Results are presented here only for case $m_{10} = m_{\bar{5}}$, $N_{10} = N_{\bar{5}}$

Results: Gauge Unification in generation-split scenario

Split-Gen scale 10 TeV

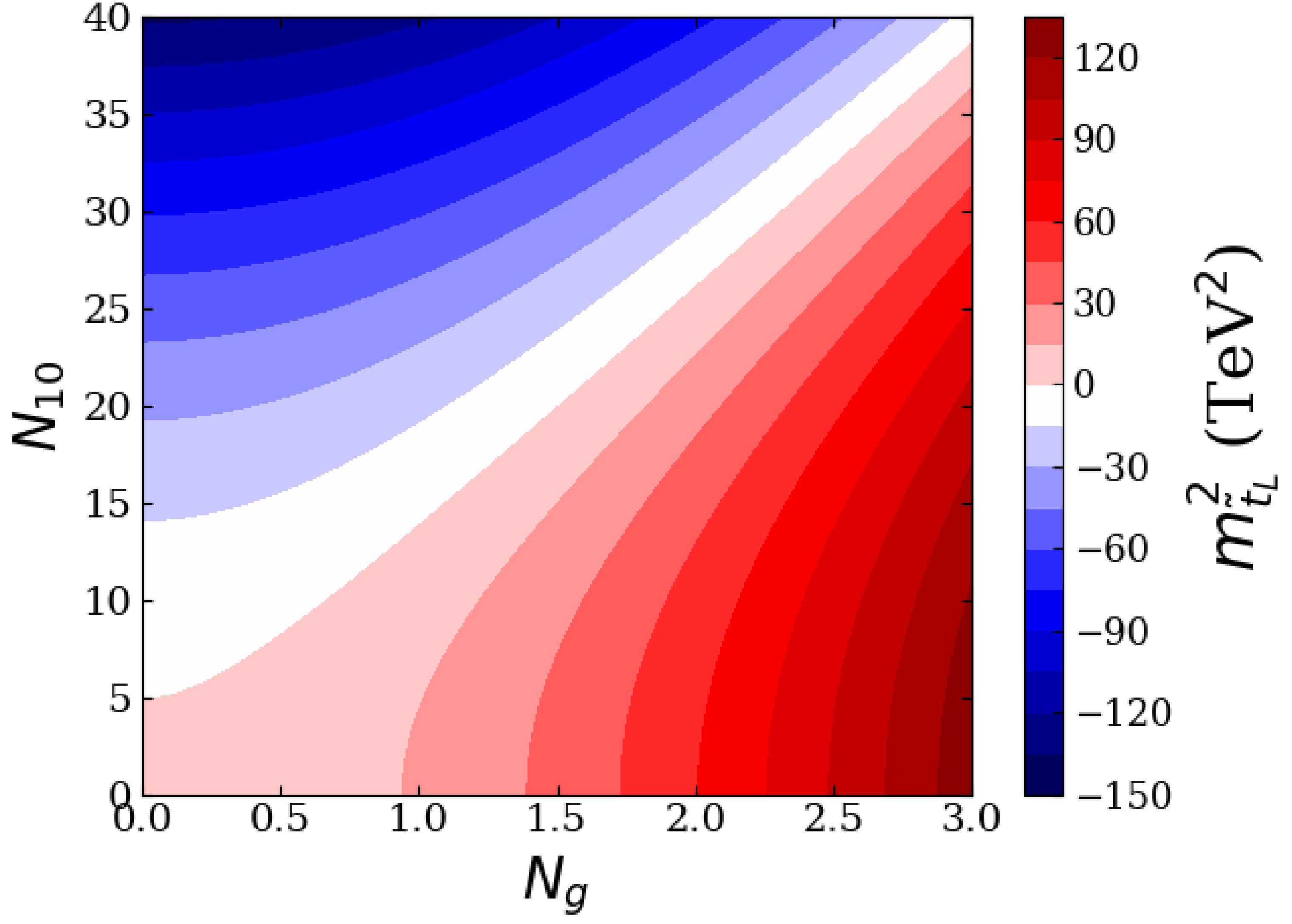


Split-Gen scale 10^6 TeV



- For large splitting, modified β-coeff. Contribution become important, specially for unified gauge coupling

Can first two generation scalars completely decouple?



At GUT scale, N_{10} is ratio between first two gen and third gen.

$$N_g = \frac{M_3}{m_{\tilde{t}}}$$

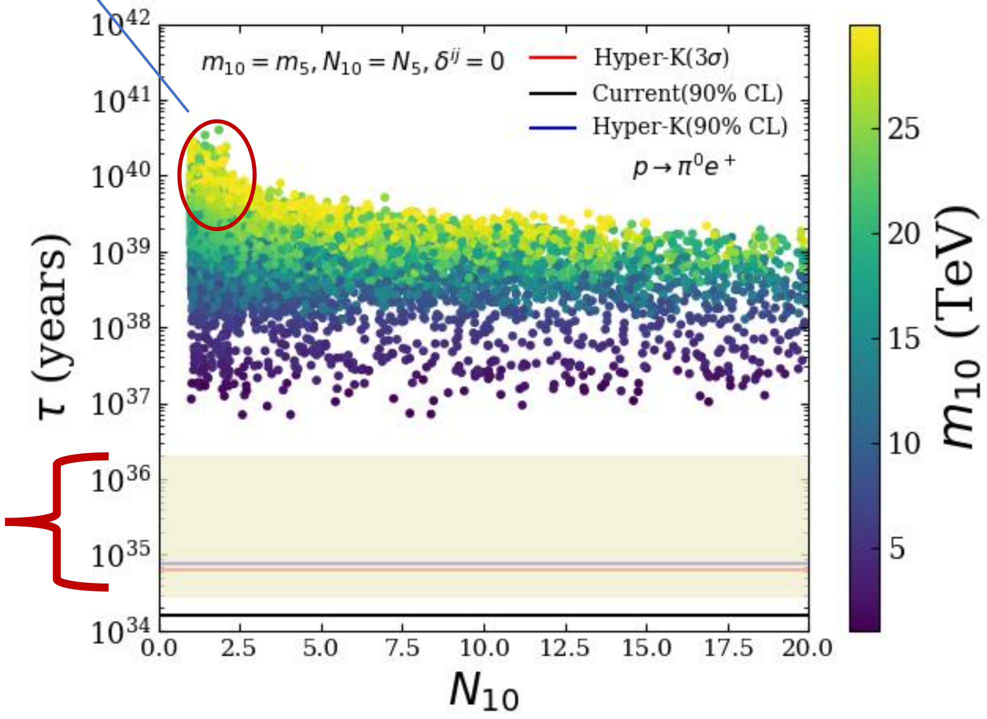
Refs: N. Arkani-Hamed and H. Murayama, 1997 && K. Agashe and M. Graesser, 1999

Results: for the decay mode $p \to \pi^0 e^+$

Ref: Shirai et al

❖ Without δ's insertion

D=6

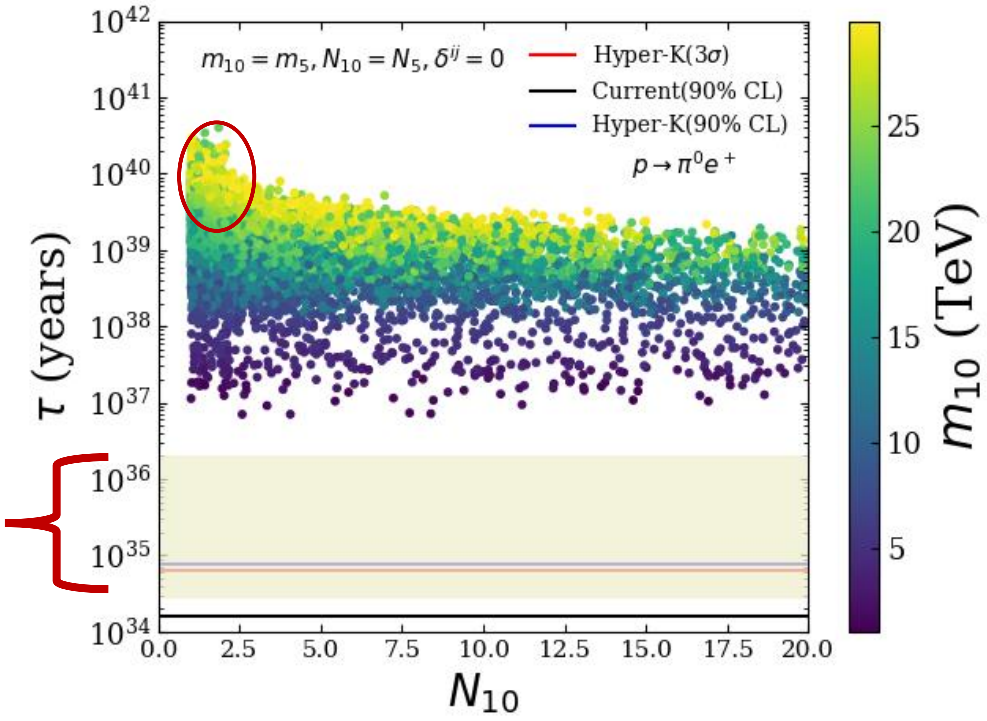


- Splitting doesn't effect life time.
- As expected, Dim 6 operator have large contribution then dim 5 operator.
- Both dim 5 and dim 6 operator contribution is not in reach of current experimental limit.
- Some parameter space of Dim 6 contribution can be probed in future Hyper-K
- Dim 5 contribution is even not in reach of future contribution.

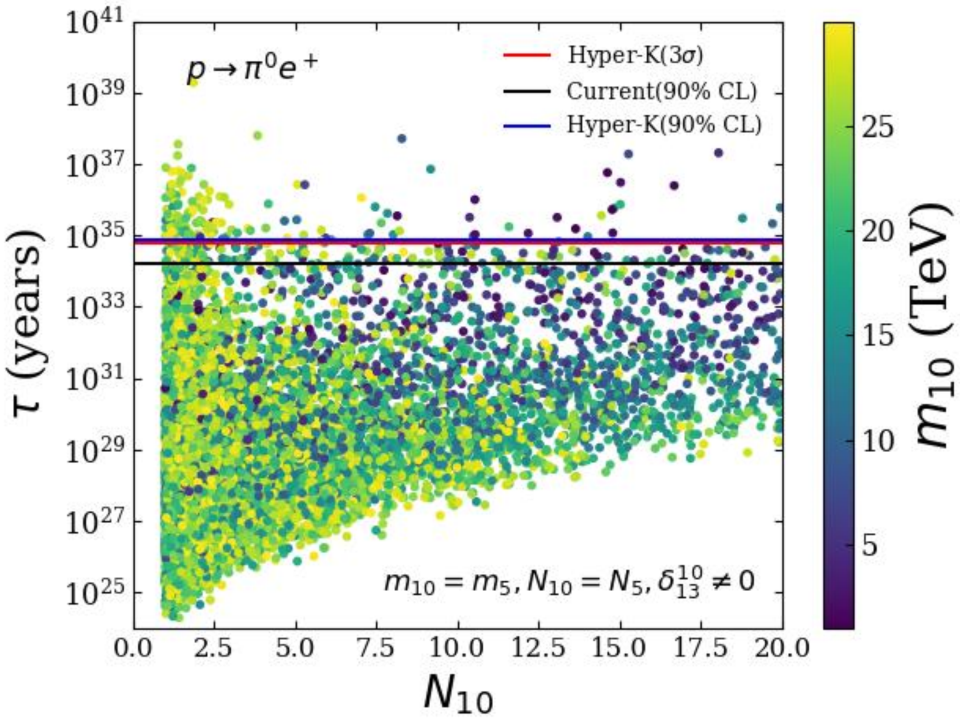
Results: for the decay mode $p \to \pi^0 e^+$

❖ Without δ's insertion

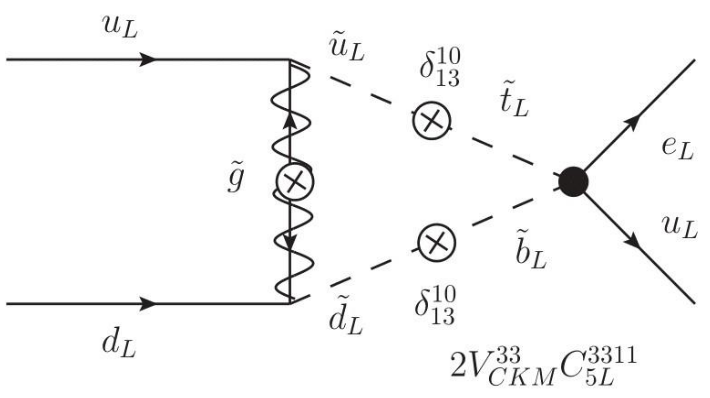
D=6

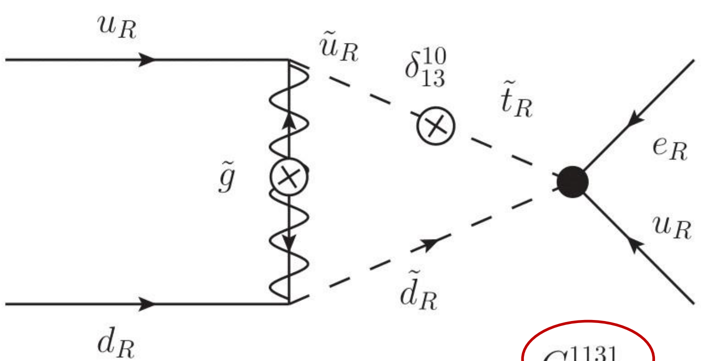


❖ With δ's insertion in 10-plet



Results: for the decay mode $p \to \pi^0 e^+$

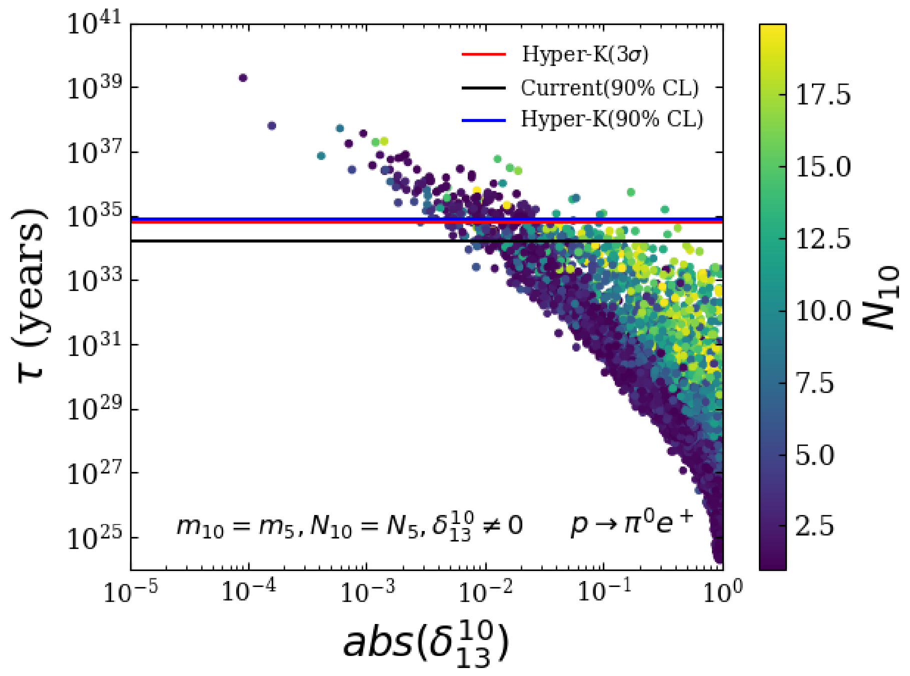




- Gluino-dressing diagrams becomes the most dominating contribution.

C^{1131}_{5R}

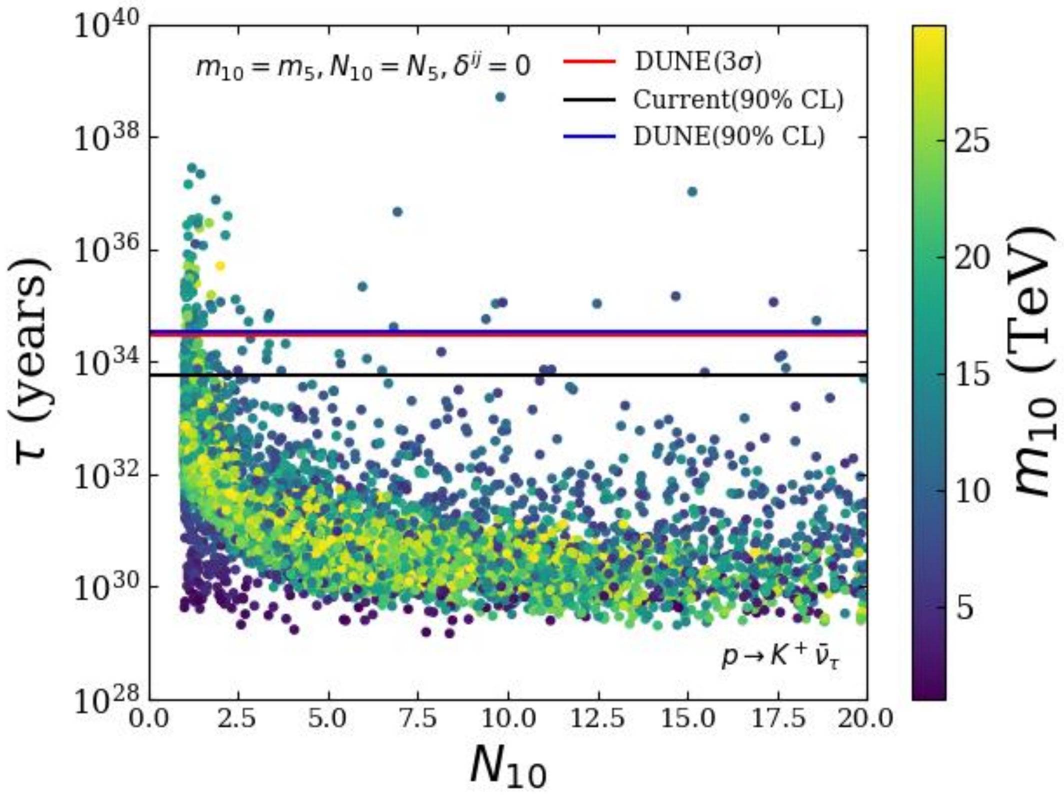
$$C^{ijkl}_{5R} = \frac{2}{M_{H_C}} (V_{CKM}\hat{Y}_d)^{ij} \hat{Y}^k_u (V^{kl}_{CKM})^\dagger$$



- Dim-5 operator contribution become important.
- Lot of parameter space is already rule out by current experiment.
- Put strong constraint on flavor violation for non-degenerate spectrum at susy scale
- Sensitive for future proton decay experiment.

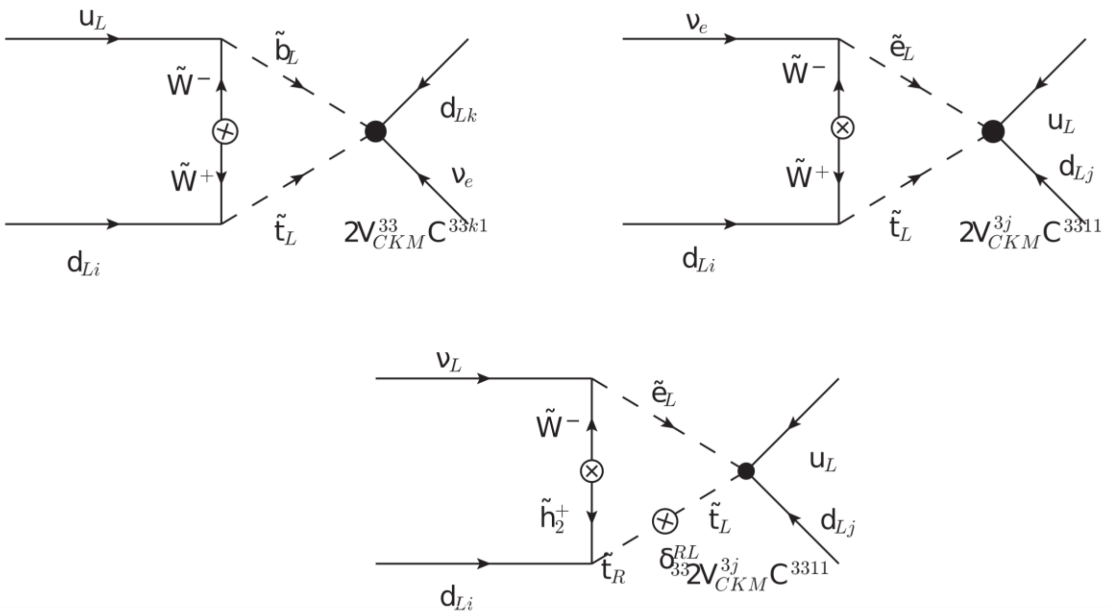
Results: for the decay mode $p \to K^+ \bar{\nu}_\tau$

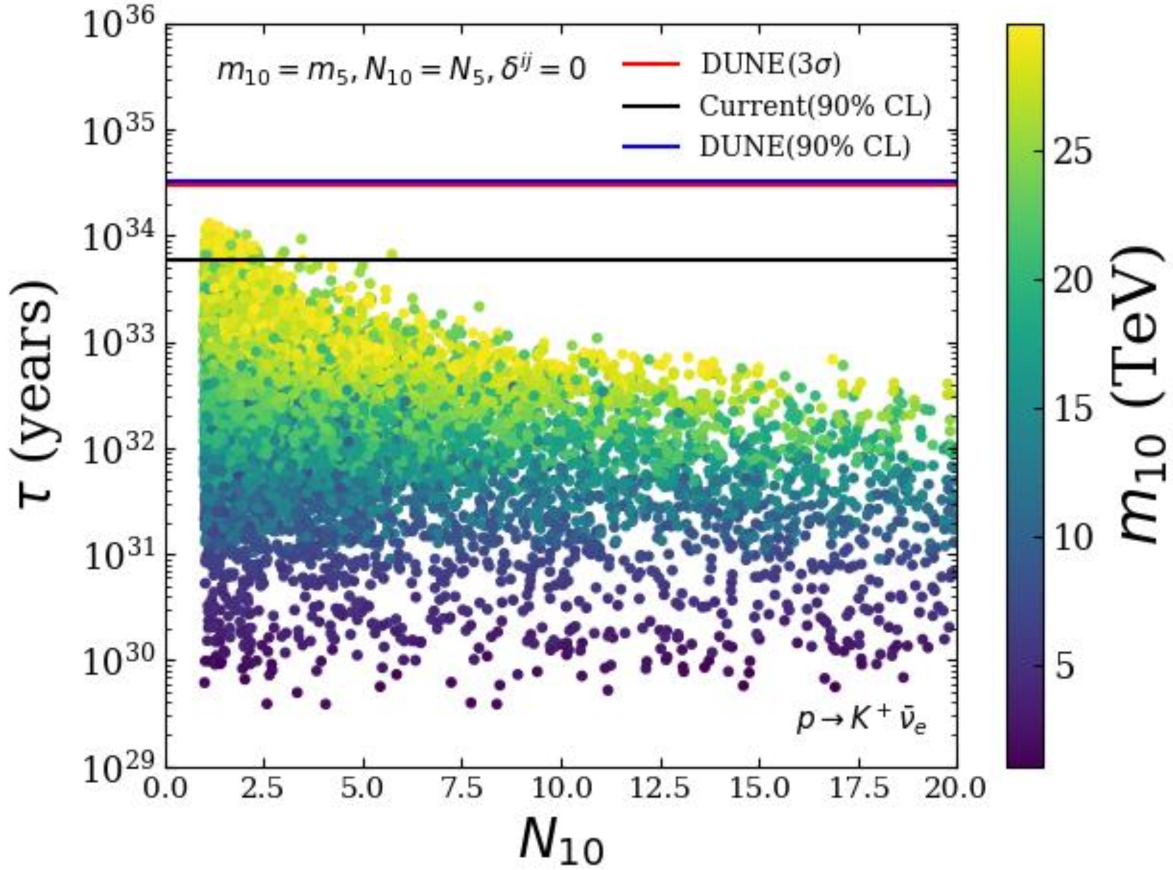
- In $p \to K^+ \bar{\nu}_\tau$ channel, due to of relatively larger τ Yukawa coupling, chargino dressed diagram also contributes in RL fermion operators in addition to LL operator .
- Even without including flavor mixing, gluino and neutralino have relevant contribution in LL operators because tau have larger C5L, C5R contributions as compared to the electron case.
- There is already cancellation region without δ



Results: for the decay mode $p \to K^+ \bar{\nu}_e$

Dressing Diagrams for $p \to K^+ \bar{\nu}_e$ without δ's:



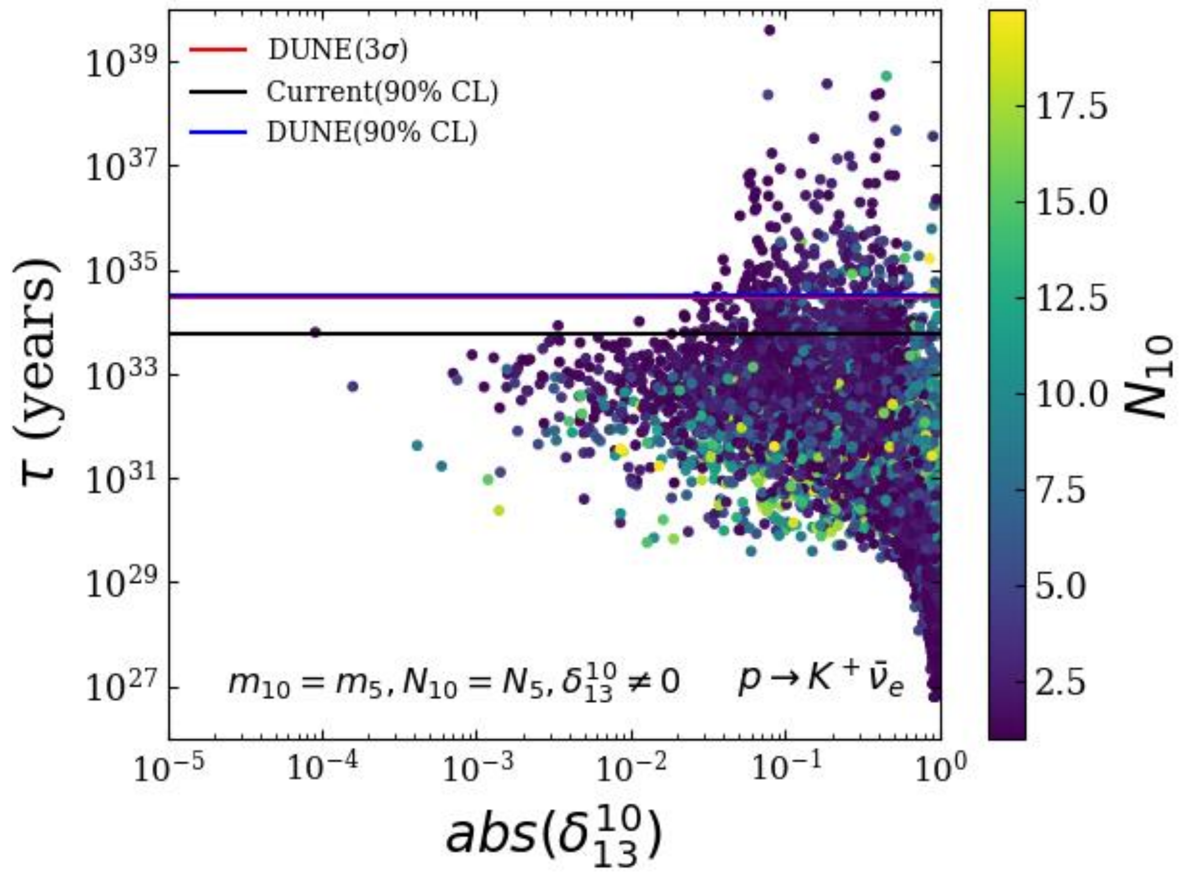


- ❖ Most constrained channel of minimal SUSY SU(5) model and almost rule out by current experimental limits except for degenerate spectrum.

Results: for the decay mode $p \to K^+ \bar{\nu}_e$

$p \to K^+ \bar{\nu}_e$ with δ's:

- Gluino and neutralino diagrams contribution become relevant in addition to chargino contribution.
- New contributions have opposite signs w.r.t the chargino contribution which lead to both enhancement as well as cancellation in the decay rate depending on δ sign.



Summary

- Gauge unification scale does not change with this spectrum and Exact Unification still holds, after taking thresholds correctly into account.

- The decay mode $p \to \pi^0 e^+$, which has sensitivity beyond that of DUNE and Hyper-K, is brought within the reach of these experiments in this model.

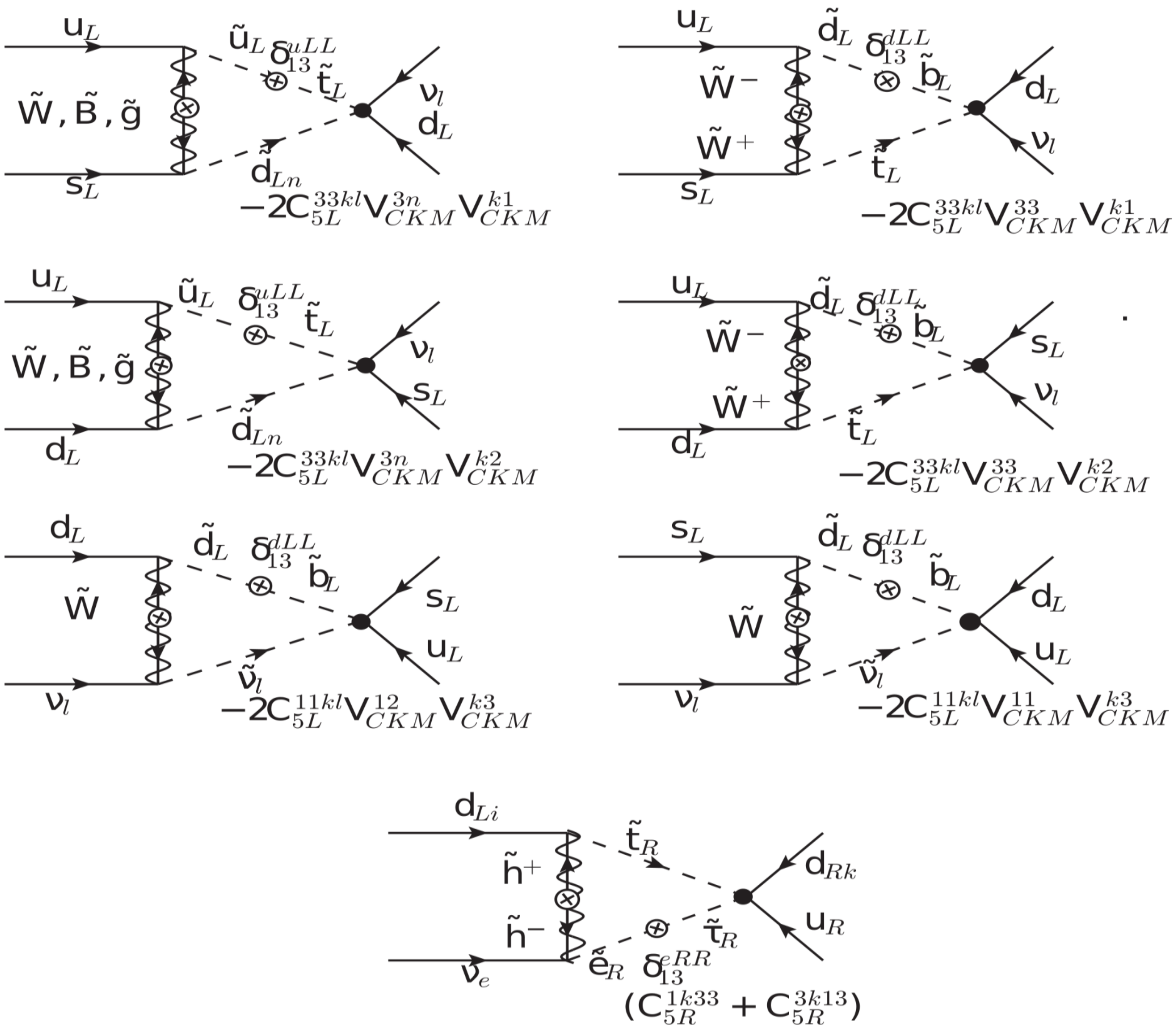
- The most dominating decay mode $p \to K^+ \bar{\nu}_e$ of this model, which essentially rules this model out for this range of masses, is now able to survive and further, interestingly, can be explored at DUNE and Hyper-K.

- Flavoured decoupling gives interesting results in which the flavour of the neutrino could play an important role in distinguishing the model

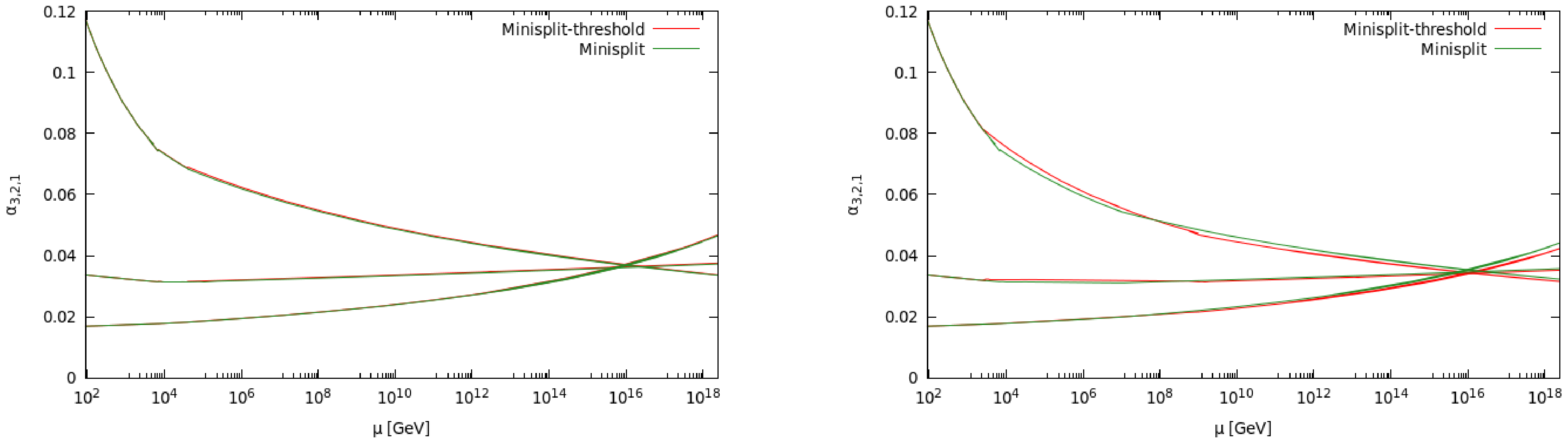
- SUSEFLAV_H is updated for two scale thresholds and mini-split beta coefficients, will be public soon.


Thank you for the attention!

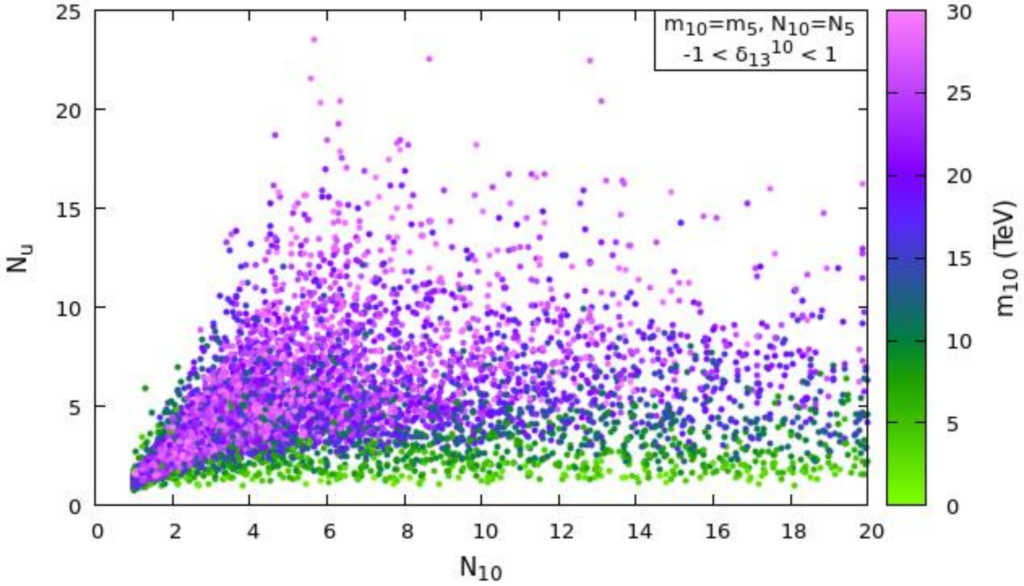
Back up sides



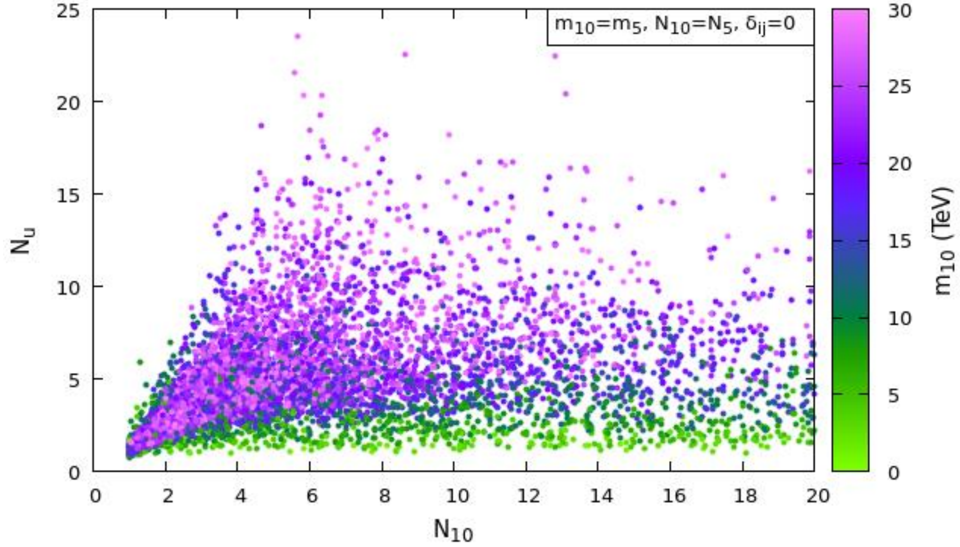
u_L $\tilde{u}_L$ δ_{13}^{uLL} $\tilde{t}_L$ ν_l d_L
$\tilde{W}, \tilde{B}, \tilde{g}$
s_L $\tilde{d}_{Ln}$
$-2C_{5L}^{33kl}V_{CKM}^{3n}V_{CKM}^{k1}$
u_L $\tilde{d}_L$ δ_{13}^{dLL} $\tilde{b}_L$ d_L ν_l
$\tilde{W}^-$ $\tilde{W}^+$
s_L $\tilde{t}_L$
$-2C_{5L}^{33kl}V_{CKM}^{33}V_{CKM}^{k1}$
u_L $\tilde{u}_L$ δ_{13}^{uLL} $\tilde{t}_L$ ν_l s_L
$\tilde{W}, \tilde{B}, \tilde{g}$
d_L $\tilde{d}_{Ln}$
$-2C_{5L}^{33kl}V_{CKM}^{3n}V_{CKM}^{k2}$
u_L $\tilde{d}_L$ δ_{13}^{dLL} $\tilde{b}_L$ s_L ν_l
$\tilde{W}^-$ $\tilde{W}^+$
d_L $\tilde{t}_L$
$-2C_{5L}^{33kl}V_{CKM}^{33}V_{CKM}^{k2}$
d_L $\tilde{d}_L$ δ_{13}^{dLL} $\tilde{b}_L$ s_L u_L
$\tilde{W}$
ν_l $\tilde{\nu}_l$
$-2C_{5L}^{11kl}V_{CKM}^{12}V_{CKM}^{k3}$
s_L $\tilde{d}_L$ δ_{13}^{dLL} $\tilde{b}_L$ d_L u_L
$\tilde{W}$
ν_l $\tilde{\nu}_l$
$-2C_{5L}^{11kl}V_{CKM}^{11}V_{CKM}^{k3}$
d_{Li} $\tilde{t}_R$ d_{Rk} u_R
$\tilde{h}^+$ $\tilde{h}^-$
ν_e $\tilde{e}_R$ δ_{13}^{eRR} $\tilde{\tau}_R$
$(C_{5R}^{1k33} + C_{5R}^{3k13})$



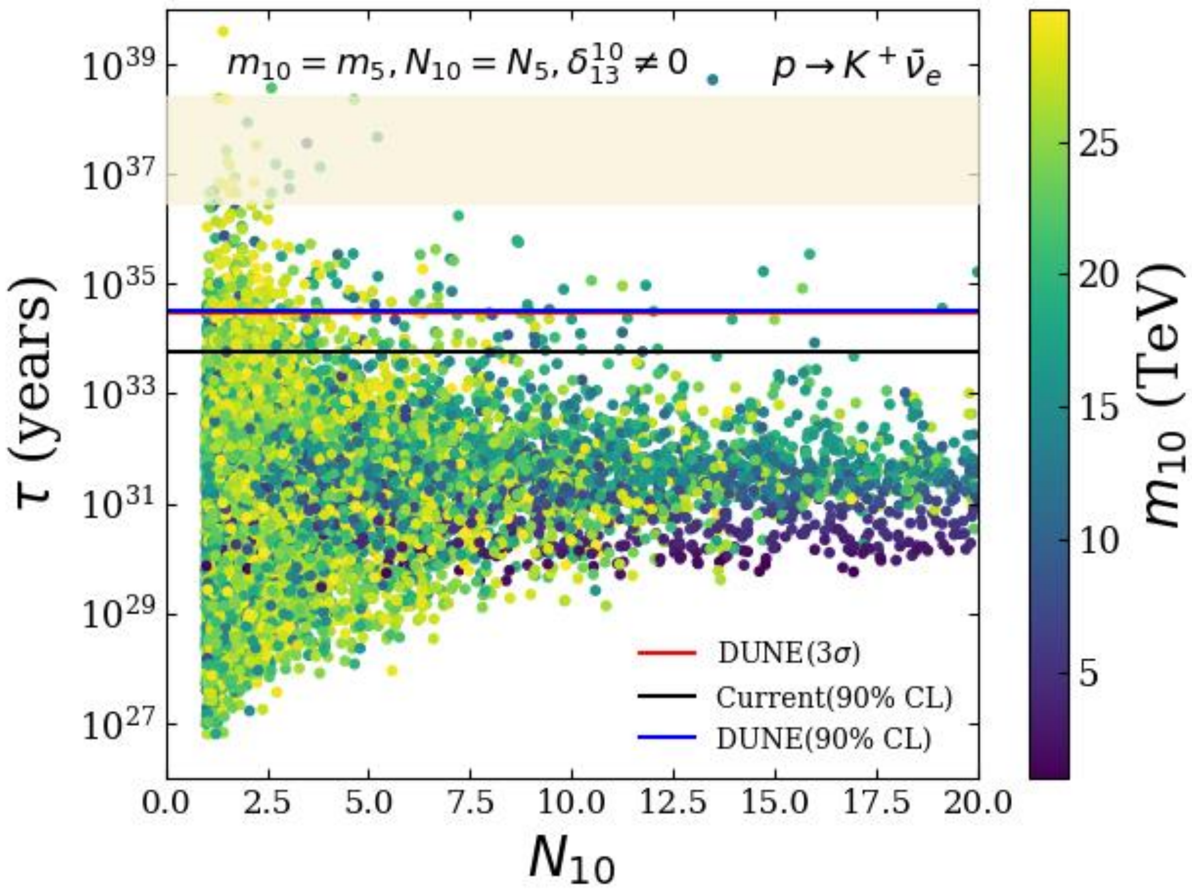
Minisplit-threshold
Minisplit
$\alpha_{3,2,1}$
μ [GeV]
0.12
0.1
0.08
0.06
0.04
0.02
0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Minisplit-threshold
Minisplit
$\alpha_{3,2,1}$
μ [GeV]
0.12
0.1
0.08
0.06
0.04
0.02
0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}



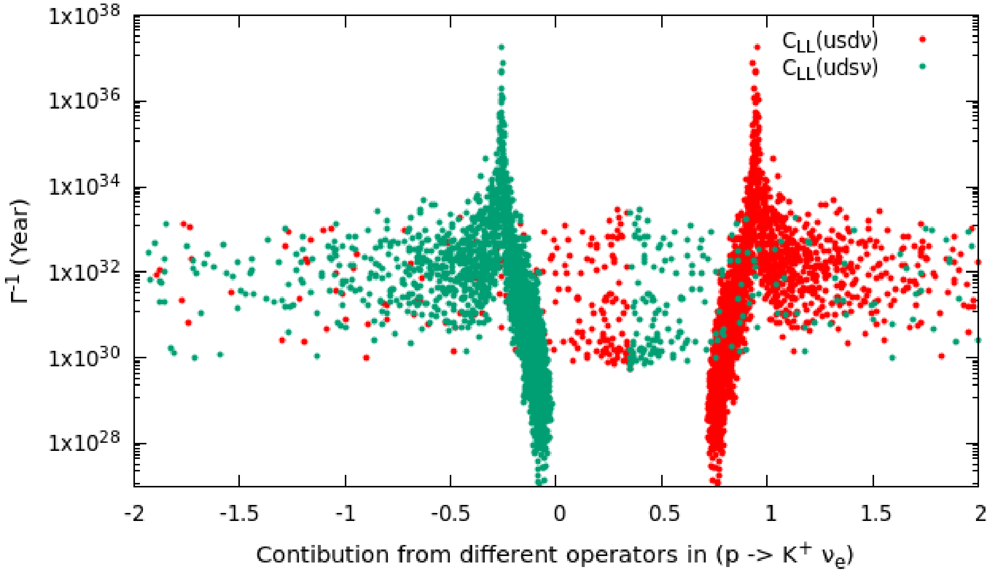
m10=m5, N10=N5
-1 < δ13^10 < 1
N_u
N_10
m_10 (TeV)



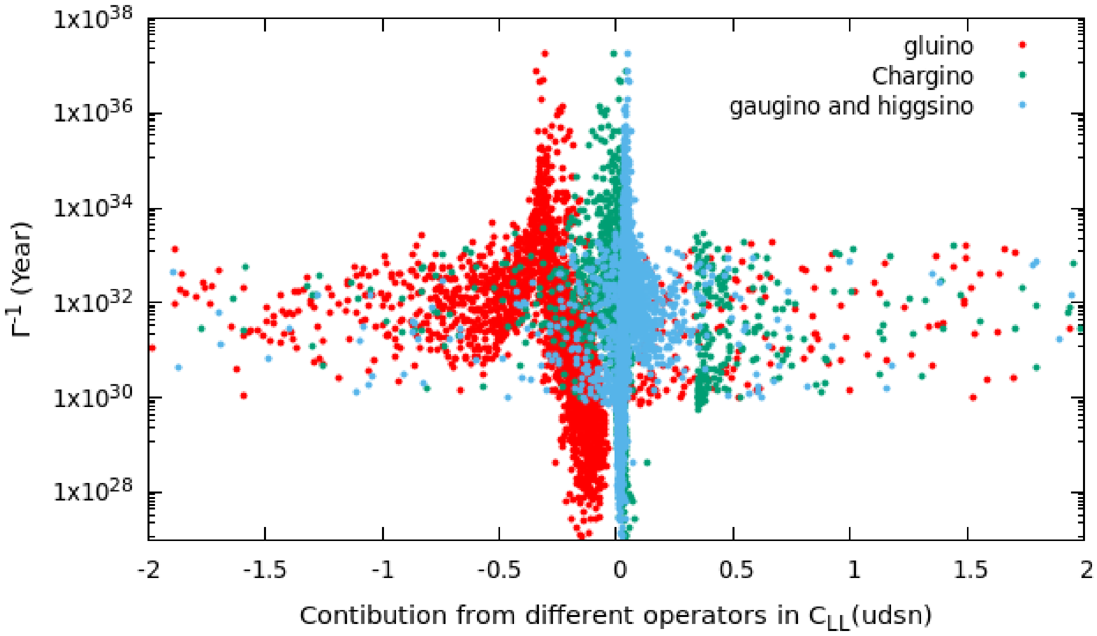
m10=m5, N10=N5, δij=0
N_u
N_10
m_10 (TeV)



$m_{10} = m_5, N_{10} = N_5, \delta_{13}^{10} \neq 0$
$p \to K^+ \bar{\nu}_e$
τ (years)
10^{39}
10^{37}
10^{35}
10^{33}
10^{31}
10^{29}
10^{27}
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
N_{10}
DUNE(3σ)
Current(90% CL)
DUNE(90% CL)
m_{10} (TeV)
25
20
15
10
5



1x10^38
1x10^36
1x10^34
1x10^32
1x10^30
1x10^28
Γ^-1 (Year)
C_LL(usdν)
C_LL(udsν)
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Contibution from different operators in (p -> K^+ ν_e)



1x10^38
1x10^36
1x10^34
1x10^32
1x10^30
1x10^28
Γ^-1 (Year)
gluino
Chargino
gaugino and higgsino
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Contibution from different operators in C_LL(udsn)