Nucleons and New Physics

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IBS Workshop (Daejeon, South Korea)
December 3-6, 2018

We want to look for ways to stress-test or “break” the Standard Model.

Simple question:

What could happen that is forbidden by the SM?

Theory role includes:

- Articulate the SM-forbidden phenomena
- Give good reasons why it should/could happen
- Show how to interpret experimental searches (mapping frontier)

There are a lot of behaviors forbidden by the SM.

For example, $Z \rightarrow \gamma + e^-$

Not very interesting to mount big effort to test this because

- Violates charge conservation
- Violates Lorentz symmetry

To have “good reason” identify the most vulnerable symmetries …. accidental symmetries

Two prime candidates: baryon number and lepton number conservation (or Z_2 lepton).

Shaky baryon number conservation is all that protects the neutron from oscillating to an antineutron.

Shaky lepton number (or Z_2 lepton) and baryon number conservation are all that protects the proton from decaying.

These two observational possibilities should be relentlessly pursued experimentally and fully explored theoretically.

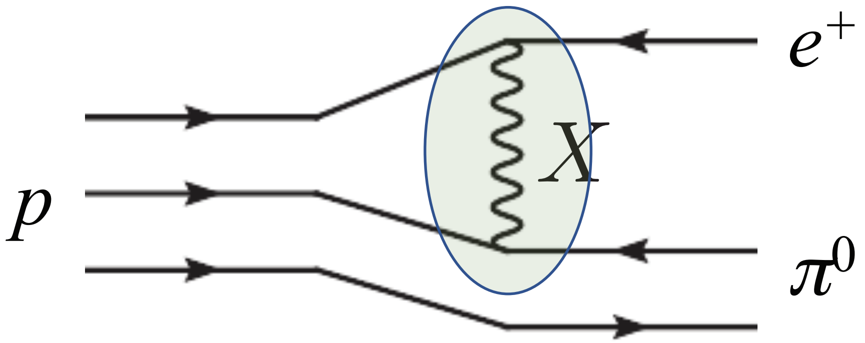
What is the current situation?

What are the future prospects?

Proton decay can occur by higher-dim operator. $\frac{1}{\Lambda_p^2}(\bar{d}^c \bar{u}^c\, q\, \ell) + \cdots$

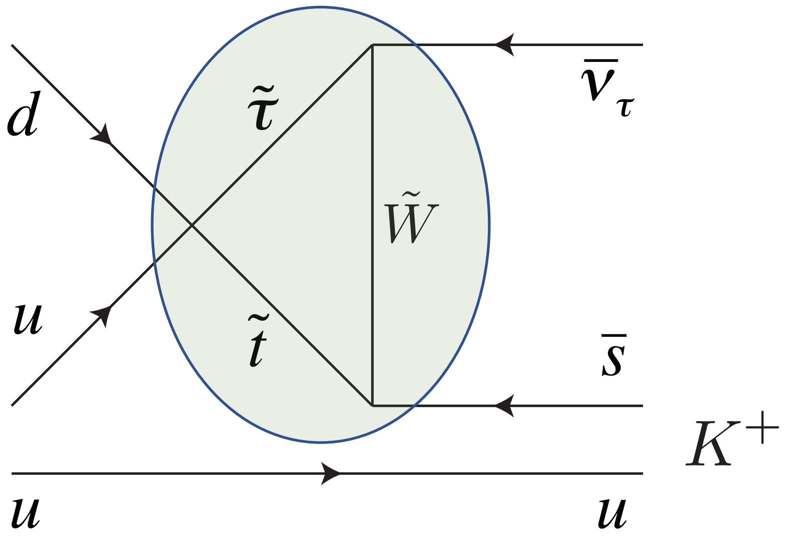
This operator likely exists with Planck suppressed couplings at least.

This operator could exist with smaller scale suppression in GUT theories.



$p \to e^+\pi^0$

(SUSY and Non-SUSY GUTs)



$p \to \bar{\nu} K^+$

(SUSY GUTs)

Gauge couplings measured at low scale

Exact unification tests require matching at high scale and RG flow to low scale across thresholds (e.g., superpartners)

MATCHING. ($\mu_* = 10^{16}\,\mathrm{GeV}$)

$$\left(\frac{1}{g_i^2(\mu_*)}\right)_{\overline{MS}} = \left(\frac{1}{g_U^2(\mu_*)}\right)_{\overline{MS}} - \left(\frac{\lambda_i(\mu_*)}{48\pi^2}\right)_{\overline{MS}}$$

where $$(\lambda_i(\mu))_{\overline{MS}} = l_i^{V_n} - 21\, l_i^{V_n} \ln \frac{M_{V_n}}{\mu} + l_i^{S_n} \ln \frac{M_{S_n}}{\mu} + 8\, l_i^{F_n} \ln \frac{M_{F_n}}{\mu}$$

Relations that are independent of unified coupling:

$$\left(\frac{\Delta\lambda_{ij}(\mu_*)}{48\pi^2}\right)_{\overline{MS},\ \overline{DR}} \equiv \left(\frac{1}{g_i^2(\mu_*)} - \frac{1}{g_j^2(\mu_*)}\right)_{\overline{MS},\ \overline{DR}} = \left(\frac{\lambda_j(\mu_*) - \lambda_i(\mu_*)}{48\pi^2}\right)_{\overline{MS},\ \overline{DR}}$$

$$\left(\frac{\Delta\lambda_{ij}(\mu_*)}{48\pi^2}\right)_{\overline{MS},\ \overline{DR}} \equiv \left(\frac{1}{g_i^2(\mu_*)} - \frac{1}{g_j^2(\mu_*)}\right)_{\overline{MS},\ \overline{DR}} = \left(\frac{\lambda_j(\mu_*) - \lambda_i(\mu_*)}{48\pi^2}\right)_{\overline{MS},\ \overline{DR}}$$

The couplings $g_i(\mu_*)$ determined from flowing precision IR couplings up (including thresholds, if applicable).

What neighborhood of values of $\Delta\lambda_{ij}(\mu_*)$ do we expect?

→ Approximately Dynkin indices of GUT representations.

For minimal SU(5) models $\Delta\lambda$ ~ 10 or so

For SO(10) models $\Delta\lambda$ ~ 100 or so

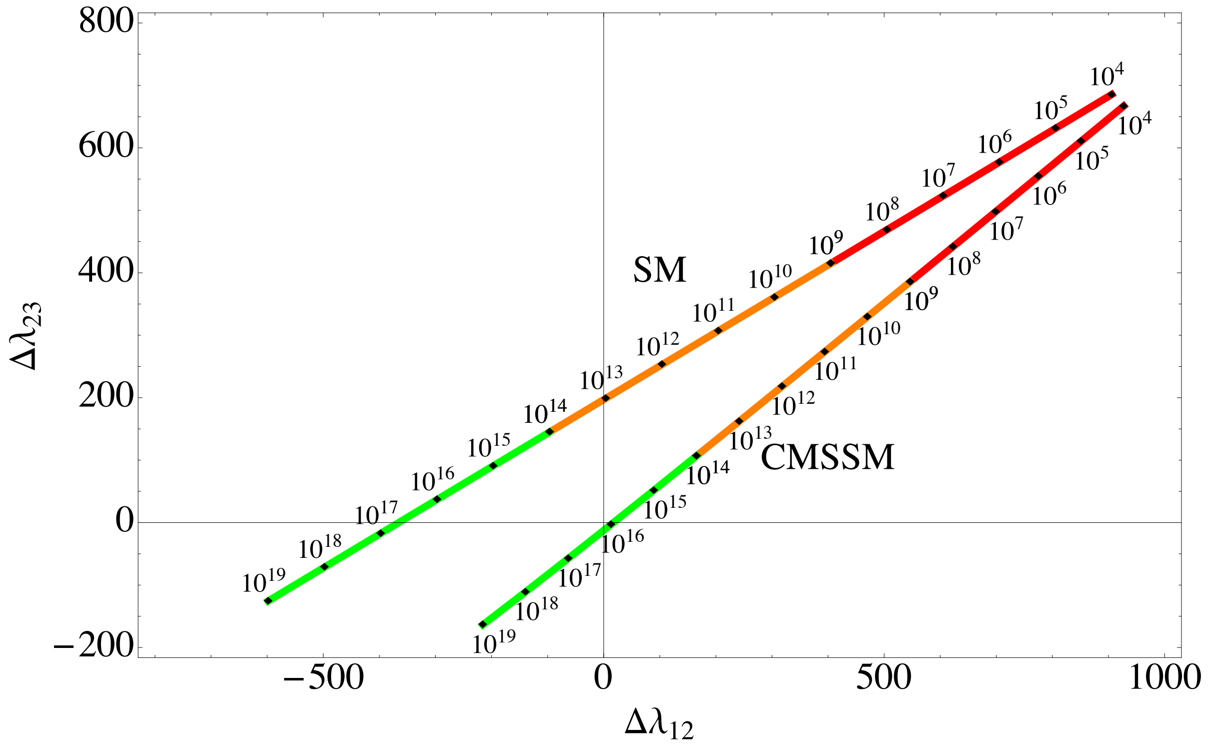


FIG. 2. This key visualization plot shows $\Delta\lambda_{23}(\mu)$ as a function of $\Delta\lambda_{12}(\mu)$ for the Standard Model and a CMSSM-like SUSY model. Labels on the line indicate the scale μ. Green regions indicate that a unification scale around those values is moderately safe from constraints. Orange indicates relatively unsafe, Red indicates very unsafe.

(Ellis, Wells, `15)

(Unexpectedly?) small thresholds needed for CMSSM

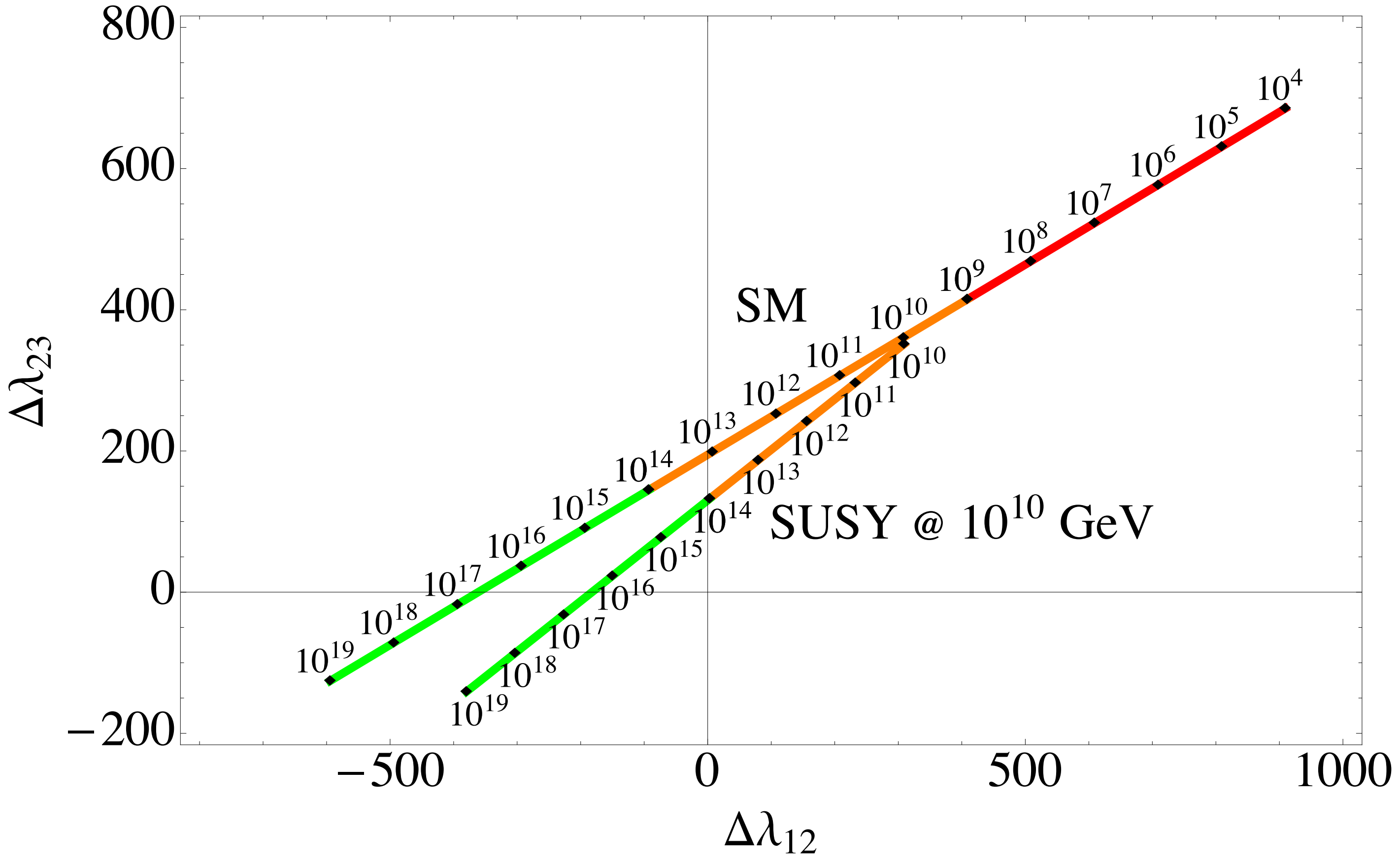


Figure 16: Plot of the threshold corrections needed for exact gauge coupling unification. The numbers along the line are the scales μ_* at which the IR couplings are evaluated for unification and at which point the needed threshold corrections are computed and then plotted in the plane. The long straight line is assuming only the SM up to the highest scale. The second line that branches downward is for the case of superpartners existing at 10^{10} GeV, which lowers the needed threshold corrections at high scales.

[Ellis, Wells, ‘17]

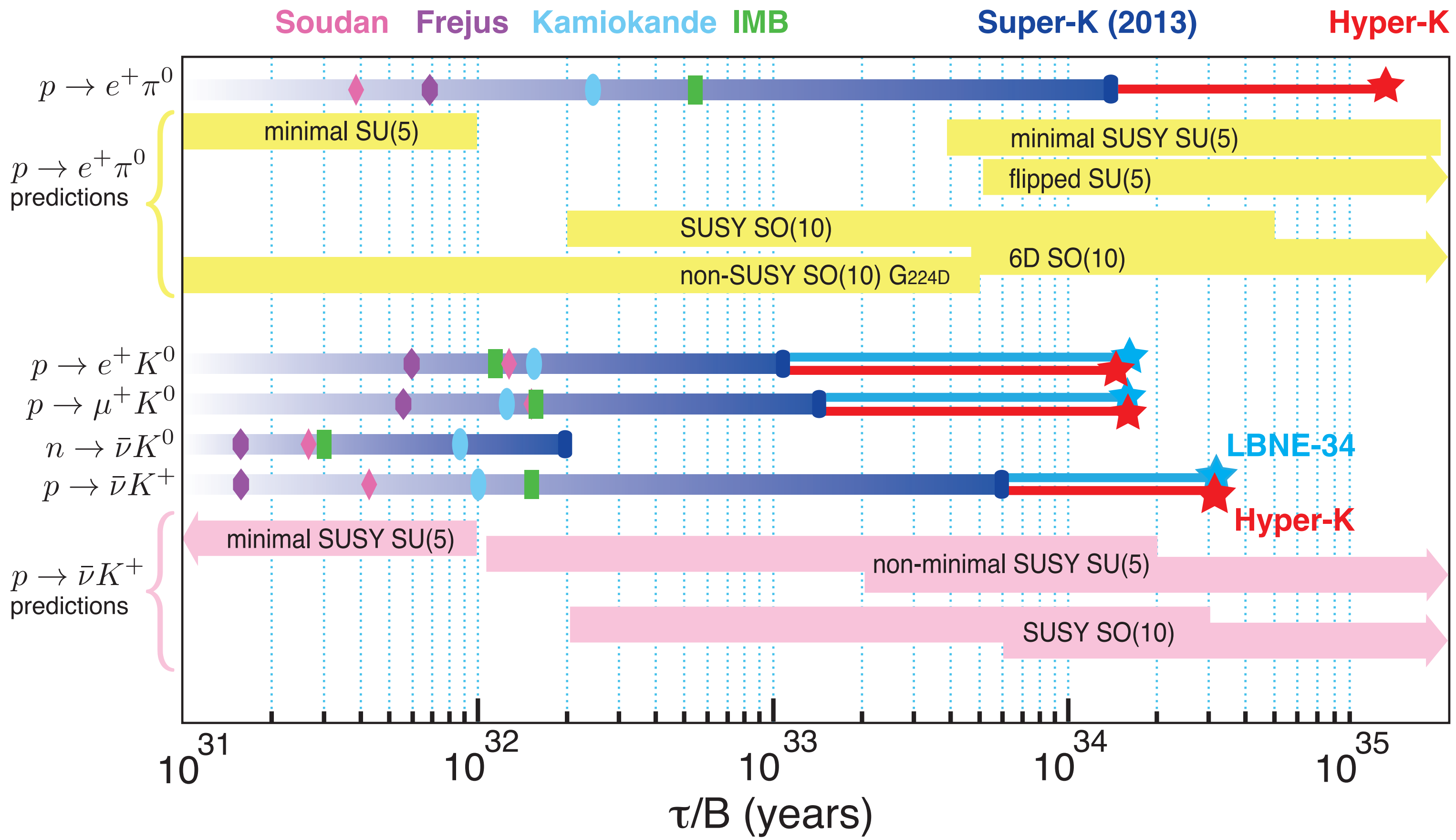
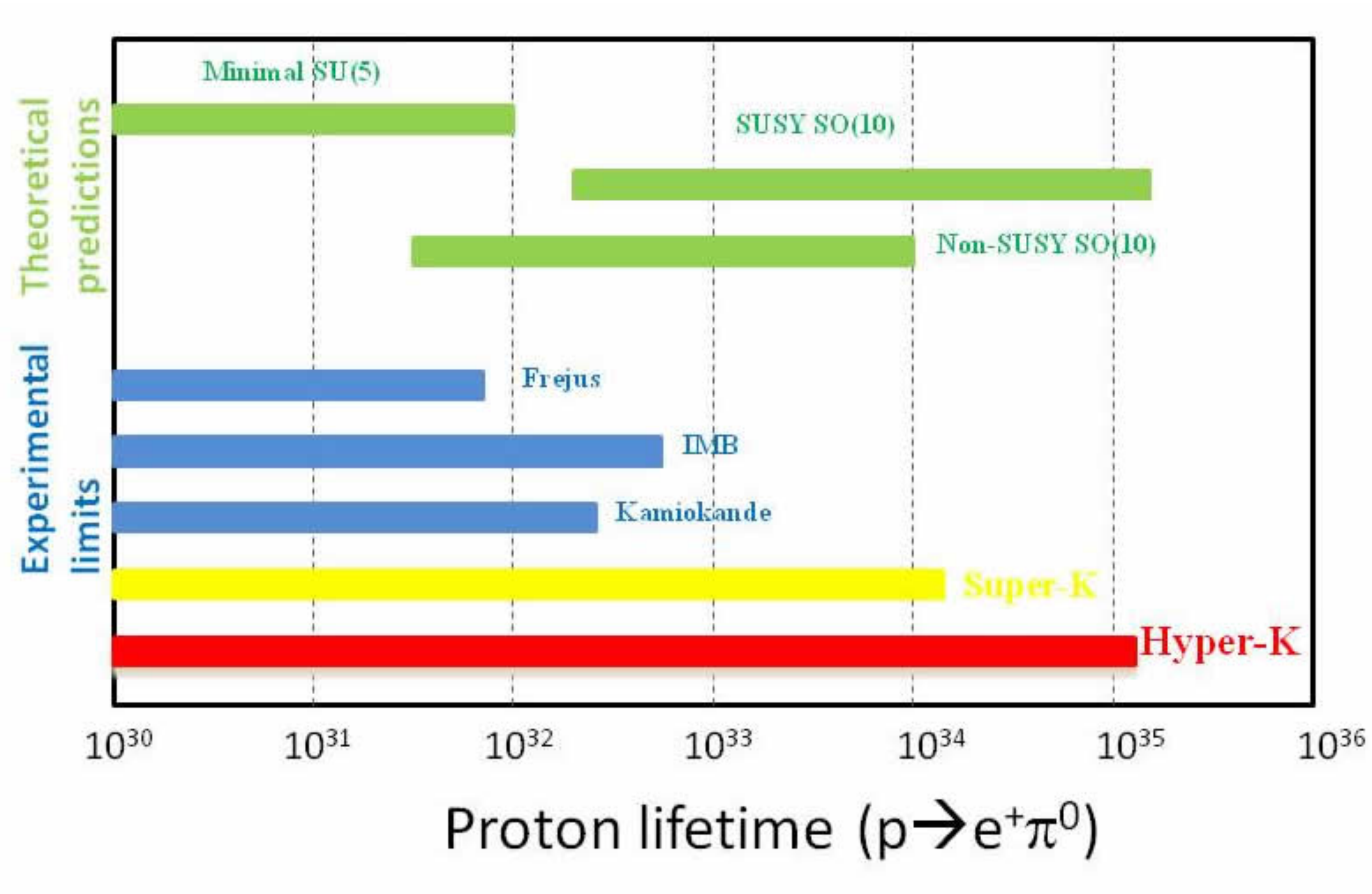


Figure 2-4. *The experimental reach of Hyper-Kamiokande and a 34-kton LBNE LArTPC are compared to prior experiments and the rough lifetime predictions from a wide range of GUT models. The projected limits are for 10 live years of running, at 90% C.L., calculated for a Poisson process including background assuming the detected events equal the expected background.*

Hewett, Weerts (eds.). Intensity Frontier, 2013.

$\tau/B(p \to e^+\pi^0) > 1.6 \times 10^{34}$ years (SK-2016 result at 90% CL)



Hyper-K website (accessed 2018/11/26)

GUTs and proton decay (ignoring potential naturalness concerns)

- non-SUSY unification is fine, but uncomfortably large threshold corrections

- SUSY unification is fine, but perhaps uncomfortably small threshold corrections

- PeV scale up to intermediate scale SUSY slight advantage?

- Proton decay limits have not nor will not in our lifetimes rule out even minimal GUT theories

- Nevertheless, proton decay probes are right in *terra prima* for GUTs (an extraordinary accident…) --- each push forward is a good risk

Consider the following criticism:

Hyper-K and DUNE improvements on proton decay sensitivity appear impressive if you focus on lifetimes (gains of over an order of magnitude).

However, the gains are not impressive since there improved reach in fundamental scale is not impressive due to the power law dependence.

A factor of 10 improvement in $p \to e^+\pi^0$ is only a factor of 1.8 improvement in M_X.

A factor of 10 improvement in $p \to K^+\nu$ is only a factor of 3.3 improvement M_{Hc}.

$$\tau(p \to e^+\pi^0) \sim M_X^4 \qquad\qquad \tau(p \to K^+\bar{\nu}) \sim \frac{M_{H_c}^2 \tilde{m}^4}{M_{\text{ino}}^2} \sim (M_{H_c} m_{\text{susy}})^2$$

Criticism is unfounded.

- There is no known rigorous metric by which to meaningfully discuss "big improvements"

- What matters is if improvements are being made still within *terra prima* (i.e., region where theory suggests signals most likely to appear)

- Proton decay limits in these two complementary modes are in *terra prima* and improvements are needed (even if "modest" by some misguided definition)

- Separate justification: super high payoff must accompany high risk (yes in this case)

- Comment on Standard Practice: The commonly accepted requirement of "order of magnitude" improvement design before investing in new experiment translates to more than a factor of ~2 improvement in parameters from common functions (x^2, $\ln(x)$, etc.).

<u>Neutron-antineutron oscillations</u>

The issues of investments, improvements, and *terra prima* are also present in n-nbar oscillations.

Recall, only a suspect symmetry (baryon number conservation) is keeping the neutron from oscillating into an anti-neutron.

1) We want to press this experimentally. Are improvements to be had?

2) Are we in *terra prima* for n-nbar oscillation signals? I.e., are the "modest" improvements worth it?

Answer to 1) is YES.

Answer to 2) is more tricky.

Neutron-antineutron oscillations at free neutron experiments

$$\begin{aligned}\mathcal{H}_{\text{eff}}|n\rangle &= \left(m_n - i\frac{\Gamma}{2} + \mathcal{E}_n\right)|n\rangle + \delta|\bar{n}\rangle \\ \mathcal{H}_{\text{eff}}|\bar{n}\rangle &= \left(m_n - i\frac{\Gamma}{2} + \mathcal{E}_{\bar{n}}\right)|\bar{n}\rangle + \delta|n\rangle\end{aligned}$$

$$\langle\mathcal{H}_{\text{eff}}\rangle = \begin{pmatrix} m_n - i\frac{\Gamma}{2} + \mathcal{E}_n & \delta \\ \delta & m_n - i\frac{\Gamma}{2} + \mathcal{E}_{\bar{n}} \end{pmatrix}$$

$$E_{1,2} = m_n - i\frac{\Gamma}{2} + \frac{\mathcal{E}_n + \mathcal{E}_{\bar{n}}}{2} \pm \frac{1}{2}\sqrt{(\mathcal{E}_n - \mathcal{E}_{\bar{n}})^2 + 4\delta^2}$$

The probability that a neutron at t=0 will be measured as an anti-neutrino at time t is.

$$P[\bar{n}(t)] = e^{-\Gamma t}\left(\frac{2\delta}{\mathcal{E}_n - \mathcal{E}_{\bar{n}}}\right)^2 \sin^2\left(\frac{(\mathcal{E}_n - \mathcal{E}_{\bar{n}})t}{2}\right)$$

$$P[\bar{n}(t)] = e^{-\Gamma t}\left(\frac{2\delta}{\mathcal{E}_n - \mathcal{E}_{\bar{n}}}\right)^2 \sin^2\left(\frac{(\mathcal{E}_n - \mathcal{E}_{\bar{n}})t}{2}\right)$$

Make substitution: $\tau_{n\bar{n}} \equiv 1/\delta$

At ILL

$$\begin{aligned} F &= \text{Flux of neutrons} \simeq 1.25 \times 10^{11}\,\text{neutrons}/s \\ v_{\text{avg}} &= \text{average neutron velocity} \simeq 600\,\text{m}/s \\ L &= \text{distance to annihilation target} \simeq 60\,\text{m} \\ B &= \text{ambient magnetic field} \simeq 10^{-8}\,\text{T} \end{aligned}$$

Average time it takes for neutron to make it to the annihilation target is $t_{\text{avg}} = L/v_{\text{avg}} \simeq 0.1\,s$

$$\mathcal{E}_n = -\mathcal{E}_{\bar{n}} = -\mu_n \cdot B \simeq 6 \times 10^{-22}\,\text{MeV} \qquad P[\bar{n}(t_{\text{avg}})] \simeq \delta^2 t_{\text{avg}}^2 = 10^{-18}\left(\frac{10^8\,s}{\tau_{n\bar{n}}}\right)^2\left(\frac{t_{\text{avg}}}{0.1\,s}\right)^2$$

To estimate oscillation sensitivity: $P[\bar{n}(t_{\text{avg}})]FT_{\text{run}} \simeq 1$ (assumes 1 nbar produced and seen)

$$\tau_{n\bar{n}} \simeq (2 \times 10^8\,s)\left(\frac{F}{1.25 \times 10^{11}\,\text{neutrons/s}}\right)^{1/2}\left(\frac{T_{\text{run}}}{1\,\text{yr}}\right)^{1/2}$$

Actual ILL limit achieved:

$\tau_{n\bar{n}} > 0.86 \times 10^8\,\text{s at } 90\%\ \text{C.L.}$

ILL (high flux neutron reactor) achieved oscillation time limit of

$$\tau_{n\bar{n}} > 0.86 \times 10^8\,\mathrm{s\ at\ 90\%\ C.L.}$$

There is a prospect to improve this at the ESS (European Spallation Source), currently under construction in Lund, Sweden.

ESS might be able to improve sensitivity to

$\tau_{nn} > 10^{10}$ s (ESS projected sensitivity)

through dedicated experiment.

On the surface it appears obviously “worth it” to do these improvements.

However,

- It is costly in both money and career investment
- Improvements in the probe of new physics scale appears “modest” or even “small”

Let’s look at this second point more closely.

There are 12 independent operators that contribute to n-$\bar{n}$ oscillation at tree level.

$$\boxed{\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\text{eff}}|n\rangle\right| \equiv \frac{\Lambda_{\text{QCD}}^6}{\Lambda_{n\bar{n}}^5}}$$

$$\mathcal{L}_{\text{eff}} \supset \sum_{i=1}^{6} c_i \mathcal{O}_i + \bar{c}_i \bar{\mathcal{O}}_i + \text{h.c.}$$

$$\mathcal{O}_1 = \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,,$$
$$\mathcal{O}_2 = \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,,$$
$$\mathcal{O}_3 = \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \,,$$
$$\mathcal{O}_4 = \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,,$$
$$\mathcal{O}_5 = \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_R d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,,$$
$$\begin{aligned}\mathcal{O}_6 = {} & \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \\ & + \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_L d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'})\end{aligned}$$

$\bar{\mathcal{O}}_i$ is obtained by exchanging $P_L \leftrightarrow P_R$ in $\mathcal{O}_i$.

Neuron-antineutron oscillation times vs. scale of "new physics"

$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right| \equiv \frac{\Lambda_{\rm QCD}^6}{\Lambda_{n\bar{n}}^5}$$

$$\Lambda_{n\bar{n}} = \boxed{4.25 \times 10^5\ \mathrm{GeV}} \left(\frac{\tau_{n\bar{n}}}{2.7 \times 10^8\ \mathrm{s}}\right)^{1/5}$$

$$= 5.53 \times 10^5\ \mathrm{GeV} \left(\frac{\tau_{n\bar{n}}}{10^9\ \mathrm{s}}\right)^{1/5} = 8.76 \times 10^5\ \mathrm{GeV} \left(\frac{\tau_{n\bar{n}}}{10^{10}\ \mathrm{s}}\right)^{1/5} = \boxed{1.39 \times 10^6\ \mathrm{GeV}} \left(\frac{\tau_{n\bar{n}}}{10^{11}\ \mathrm{s}}\right)^{1/5}$$

The quantic root (from dim-9 operators) gives "very small" gains in $\Lambda_{\rm nn}$ even with orders of magnitude gain in oscillation time.

Two orders of magnitude improvement in τ_{nn} translates into only a factor of $(100)^{1/5}$ = 2.5 improvement in Λ_{nn} (scale of new physics).

Nevertheless, this is “significant” since it reaches the magic threshold of improving underlying mass scales/parameters by more than a factor of 2 as is implicitly required through “standard practice” when deciding if planned improvement is enough.

Experimental improvement is impressive. (That’s answer to my original question 1).

Question 2), whether that improvement is taking place within *terra prima*, or perhaps within *terra deserta*, requires more discussion.

In the case of new physics at EW scale, LHC experiment is in *terra prima* from naturalness arguments. Factors of 2 improvement in superpartner masses or PNGB masses or compositeness factors is highly sought.

In the case of proton decay, Hyper-K and DUNE are within *terra prima* since motivated GUT scenarios and the scale of gauge coupling unification put predictions right in the vicinity.

What’s the equivalent for n-nbar? What might want n-nbar to be where experimental limits currently are at?

Current sensitivities and future searches are in the neighborhood of Λ_{nn} ~ 100 – 1000 GeV.

This can be interpreted as *terra prima* for PeV scale supersymmetry. Good.

However, is there a more direct argument for Λ_{nn} ~ 1 PeV?

Perhaps explanation of baryon asymmetry --- baryogenesis.

Most scales can accommodate baryogenesis. Good (sort of).

<u>Raise the bar a little</u>: Can a very simple, full model of baryogenesis yield n-nbar signal at ESS but nowhere else? That would put ESS search at least somewhere above *terra deserta* if not into *terra prima*.

Answer: yes (Grojean, Shakya, JW, Zhang, ’17 and others)

A minimal extension that can accommodate both $n-\bar{n}$ oscillation and the observed baryon asymmetry involves two Majorana fermions X_1, X_2 (with $M_{X_1} < M_{X_2}$), each having a B violating interaction $\frac{1}{\Lambda^2} X u d d$. In addition, a B conserving coupling between the two is necessary to evade constraints from unitarity relations. In the context of RPV SUSY, this corresponds to the presence of a wino or gluino in addition to the bino, which is known to allow for sufficient baryogenesis [64–66].

Guided by minimality, we assume $X_{1,2}$ are both SM singlets, and consider just one of the many possible B conserving operators in addition to the two B violating ones. Our minimal EFT thus consists of the following dimension-six operators that couple $X_{1,2}$ to the SM:[2]

$$\begin{aligned}\mathcal{L} \supset\ & \eta_{X_1}\, \epsilon^{ijk}(\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_1) \\ & + \eta_{X_2}\, \epsilon^{ijk}(\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_2) \\ & + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}\,, \\ & \text{with } |\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,,\ |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,,\ |\eta_c| \equiv \Lambda_c^{-2}\,. \end{aligned} \quad (3)$$

Both X_1 and X_2 mediate n-$\bar{n}$ oscillation — integrating them out at tree level gives

$$c_1 = \frac{1}{\left(\Lambda_{n\bar{n}}^{(1)}\right)^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}\,. \tag{4}$$

$$\mathcal{L} \supset c_1\,\frac{1}{2}\,\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) + \text{h.c.}\,,$$

$$\text{with}\;\; c_1 \equiv \left(\Lambda_{n\bar{n}}^{(1)}\right)^{-5}\,. \tag{1}$$

Calculation of the baryon asymmetry — The relevant processes for baryogenesis include

- B violating processes: single annihilation $uX_{1,2} \to \bar{d}\bar{d}$, $dX_{1,2} \to \bar{u}\bar{d}$, decay $X_{1,2} \to udd$, and off-resonance scattering $udd \to \bar{u}\bar{d}\bar{d}$;

- B conserving processes: scattering $uX_1 \to uX_2$, co-annihilation $X_1X_2 \to \bar{u}u$, and decay $X_2 \to X_1\bar{u}u$;

as well as their inverse and CP conjugate processes. CP violation arises from interference between tree and one-loop diagrams in $uX_{1,2} \leftrightarrow \bar{d}\bar{d}$, $uX_1 \leftrightarrow uX_2$ and $X_2 \leftrightarrow uud$, and additionally from $udd \leftrightarrow \bar{u}\bar{d}\bar{d}$ (in a way that is related to $X_2 \leftrightarrow uud$ by unitarity). In each case, CP violation is proportional to $\mathrm{Im}(\eta^*_{X_1}\eta_{X_2}\eta_c) \sim \Lambda^{-6}$.

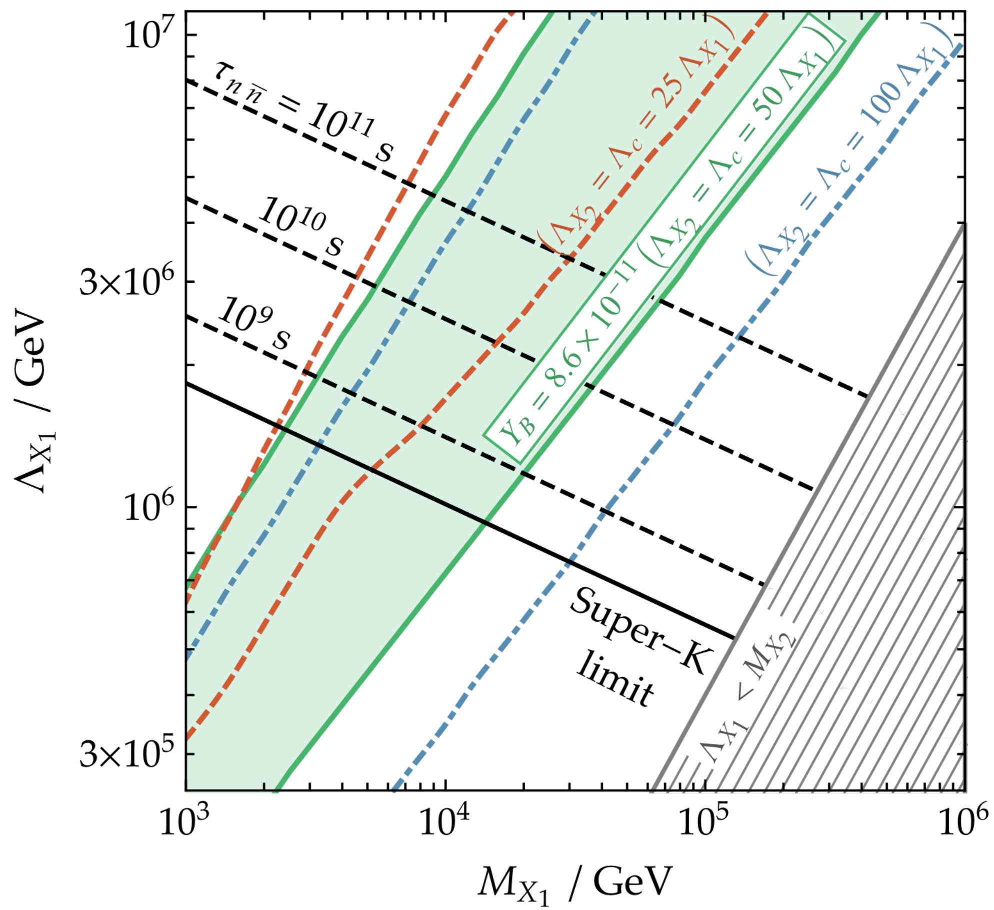


FIG. 2. Parameter space of the minimal EFT probed by n-$\bar{n}$ oscillation for the late decay scenario, assuming $M_{X_2} = 4\,M_{X_1}$. For $\Lambda_{X_2} = \Lambda_c = 50\,\Lambda_{X_1}$, the green shaded region can accommodate $Y_B = 8.6\times10^{-11}$. For $\Lambda_{X_2} = \Lambda_c = 25\,\Lambda_{X_1}$ ($100\,\Lambda_{X_1}$), viable region is between dashed red (dot-dashed blue) lines. The gray shaded region marks $\Lambda_{X_1} < M_{X_2}$, where EFT validity requires greater than $\mathcal{O}(1)$ coupling.

Baryogenesis is indeed possible with n-nbar signals, and the parameter space for such increases with higher oscillation time sensitivity.

Conclusions

Accidental symmetries (here, B and L violation) are vulnerable principles to be attacked experimentally

Nucleon decays and oscillations provide penetrating stress-tests

Proton decay experiments operate in *terra prima* for B (and L) violation. Improvements have great discovery potential and are not incremental.

There is no obvious *terra prima* for n-nbar oscillation experiments, but one can show that future improvements could lead to discovery signal (huge payoff) for simple theories of baryogenesis.