Probing the Supersymmetric Grand Unified Theories at the Future Proton-Proton Colliders and Hyper-Kamiokande Experiment

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The 2022 Mitchell Conference on Collider, Dark Matter, and Neutrino Physics, TAMU, May 24-27 2022

Waqas Ahmed, TL, Shabbar Raza and Fang-Zhou Xu, Phys. Lett. B **819**, 136378 (2021) [arXiv:2007.15059 [hep-ph]]; in preparation.

Supersymmetry and the SSMs with R-Parity

- A natural solution to the gauge hierarchy problem in the SM.
- Gauge coupling unification can be achieved.
- The Lightest Supersymmetric Particle (LSP) such as the LSP neutralino etc can be a dark matter candidate.
- The electroweak gauge symmetry can be broken radiatively due to the large top quark Yukawa coupling.
- ....

The Grand Unified Theories: $SU(5)$ and $SO(10)$

- Gauge interaction unification.
- In $SO(10)$ model, one family of the SM fermion forms a spinor **16** representation.
- Yukawa coupling unification.
- Charge quantization.
- Weak mixing angle at weak scale M_Z.
- Neutrino masses and mixings by seesaw mechanism.
- Prediction: dimension-six proton decay via heavy gauge boson exchange.

Problems

- Gauge symmetry breaking.
- Doublet-triplet splitting problem.
- Proton decay problem.
- Fermion mass problem.

  The wrong prediction on the fermion mass ratios: $m_e/m_\mu = m_d/m_s$.

String Models

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory
- D-brane models on Type II orientifolds
- Free fermionic string model builing
- $\mathcal{F}$-Theory Model Building

Supersymmetry is a bridge between the promising low energy phenomenology and high-energy fundamental physics.

Grand Particle Physics Paradigm

String Theory $\rightarrow$ String Models $\rightarrow$ SUSY GUTs $\rightarrow$ SSMs $\rightarrow$ SM

Can we probe this grand particle physics paradiagm via the future pp colliders and other experiments? If yes, what is the center-of-mass energy needed?

We can probe the SUSY GUTs at the future experiments!

Future Colliders

- Lepton colliders: CEPC, CLIC, $FCC_{\rm ee}$, and ILC.
- Hadron colliders: HL-LHC, HE-LHC, $FCC_{\rm hh}$, SppC, and VLHC.

To probe the new physics beyond the SM, we do need future proton-proton colliders.

Future Proton-Proton Colliders

- Question: what is the concrete scientific goal for the future pp colliders?
- Question: what is the center-of-mass energy needed for this scientific goal?

The Scientific Goal for the Future PP Colliders

- Supersymmetry cannot be the scientific goal since the sparticles can be very heavy and then we cannot probe supersymmetry.
- The supersymmetric GUTs with grand desert hypothesis can be the scientific goal [1].

[1] Waqas Ahmed, TL, Shabbar Raza and Fang-Zhou Xu, Phys. Lett. B **819**, 136378 (2021) [arXiv:2007.15059 [hep-ph]]; in preparation.

The Proof

- Grand desert hypothesis: no new physics between the sparticle mass scale and the GUT scale.
- For the GUTs with the GUT scale $M_{GUT} \leq 1.0 \times 10^{16}$ GeV, we can probe the dimension-six proton decay via heavy gauge boson exchange at the Hyper-Kamiokande experiment.
- For the GUTs with $M_{GUT} \geq 1.0 \times 10^{16}$ GeV, we can probe the gluino and/or squarks at the future pp colliders.
- Providing the "Concrete Scienctific Goal" for the future pp colliders and Hyper-Kamiokande experiment.

The First Part of the Proof

For the GUTs with the GUT scale $M_{GUT} \leq 1.0 \times 10^{16}$ GeV, we can probe the dimension-six proton decay via heavy gauge boson exchange at the Hyper-Kamiokande experiment.

The Predictions of the SUSY GUTs: Proton Decays

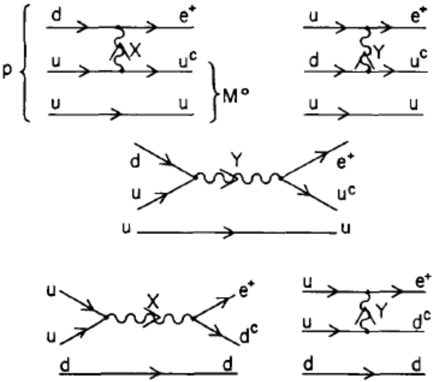
- The dimension-six proton decay via superheavy $(X_\mu, \ Y_\mu)$ gauge boson exchanges

$$SU(5) \ = \ \left(\begin{array}{cc} SU(3)_C & (\overline{X}_\mu, \overline{Y}_\mu) \\ (X_\mu, Y_\mu) & SU(2)_L \end{array} \right) .$$

- The dimension-five proton decays via colored Higgsino exchanges in the supersymmetric GUTs.
- We do not consider the dimension-five proton decays.

We can have the dimension-five proton decays at renormalizable level by introducing vector-like particles, and can nelect the dimension-five proton decays in some models such as the flipped $SU(5)$ models.

The Dimension-Six Proton Decay via $(X_\mu, \ Y_\mu)$ Exchanges



The GUTs with $M_{GUT} \leq 1.0 \times 10^{16}$ GeV

- The proton lifetime from the dimension-six proton decay $p \to e^+\pi^0$ via heavy gauge boson exchange is

$$\tau_p \simeq 1.0 \times 10^{34} \times \left(\frac{2.5}{A_R}\right)^2 \times \left(\frac{0.04}{\alpha_{\rm GUT}}\right)^2 \times \left(\frac{M_{\rm GUT}}{1.0 \times 10^{16}~{\rm GeV}}\right)^4 ~{\rm years}~.$$

- The current lower limit from the Super-Kamiokande experiment gives $\tau_p > 2.4 \times 10^{34}$ years [2], and thus we obtain $M_{\rm GUT} \geq 1.0 \times 10^{16}~{\rm GeV}$.
- At the future Hyper-Kamiokande experiment, we can probe the proton lifetime at least above 1.0×10^{35} years [3]. Therefore, the GUTs with $M_{\rm GUT} \leq 1.0 \times 10^{16}~{\rm GeV}$ is definitely within its reach.

[2] K. Abe *et al.* [Super-Kamiokande], Phys. Rev. D **95**, no.1, 012004 (2017) [arXiv:1610.03597 [hep-ex]]; A. Takenaka *et al.* [Super-Kamiokande], Phys. Rev. D **102**, 112011 (2020) [arXiv:2010.16098 [hep-ex]].

[3] K. Abe *et al.* [Hyper-Kamiokande], [arXiv:1805.04163 [physics.ins-det]].

Comment

- In fact, if we did not observe the dimension-six proton decay from the Super-Kamiokande experiment and future Hyper-Kamiokande experiment, we obtain $M_{X_\mu/Y_\mu} \geq 1.0 \times 10^{16}~\mathrm{GeV}$, not $M_{\mathrm{GUT}} \geq 1.0 \times 10^{16}~\mathrm{GeV}$.
- There indeed exists some subtleties to define the GUT scale due to threshold corrections.
- Because $M_{X_\mu/Y_\mu} \leq M_{GUT}$, our study is not affected by these subtleties.

The Second Part of the Proof

For the GUTs with $M_{GUT} \geq 1.0 \times 10^{16}$ GeV, we can probe the gluino and/or squarks at the future pp colliders.

The supersymmetry breaking mediation mechanisms

- Gravity mediated supersymmetry breaking.
- Anomaly mediated supersymmetry breaking.
- Gauge mediated supersymmetry breaking.

The Supersymmetry Searches at the Future pp Colliders

- At the future 100 TeV pp Colliders such as $\mathrm{FCC_{hh}}$ and SppC, gluino $\tilde{g}$ via heavy flavor decay, gluino via light flavor decay, and the first-two generation squarks $\tilde{q}$ can be discovered for their masses up to about 11 TeV, 17 TeV, and 14 TeV, respectively. If the gluino and first-two generation squark masses are similar, they can be probed up to 20 TeV.
- To discover the gluino $\tilde{g}$ with mass around 15 TeV via heavy flavor decay, we need the 160 TeV pp collider such as the VLHC.

The Phenomenological Constraints

- The SM-like Higgs boson mass $m_h \subset [123,\ 127]\ \mathrm{GeV}$, and gluino mass $m_{\tilde{g}} \geq 2.2\ \mathrm{TeV}$.
- The constraints from rare decay processes $B_s \to \mu^+\mu^-$, $b \to s\gamma$, and $B_u \to \tau\nu_\tau$.
- To be general, we do not require the relic abundance of the LSP neutralino to satisfy the Planck bound within 5σ $0.114 \leq \Omega_{\mathrm{CDM}} h^2 \leq 0.126$.

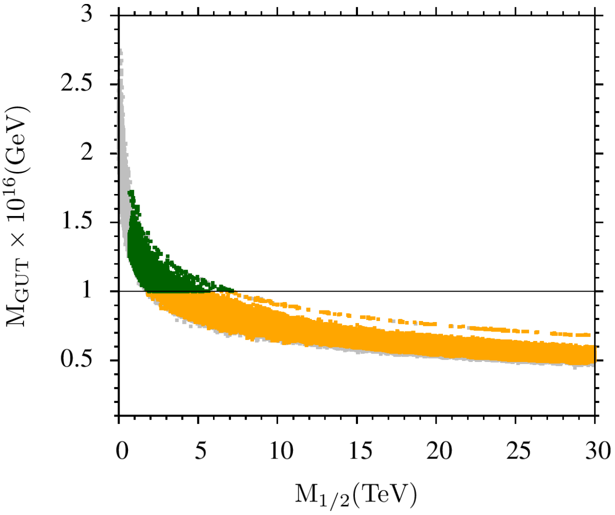
Gravity Mediated Supersymmetry Breaking

We perform the random scans for the following mSUGRA/CMSSM parameter space

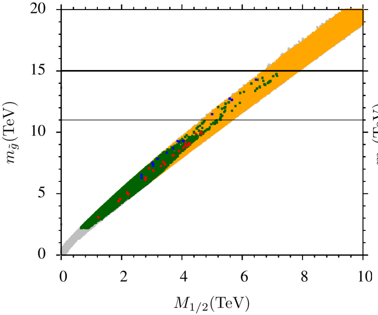
$$
\begin{aligned}
0 \leq M_0 \ &\leq 90 \, \mathrm{TeV}, \\
0 \leq M_{1/2} &\leq 30 \, \mathrm{TeV}, \\
-3 \leq A_0/M_0 &\leq 3, \\
2 \leq \tan\beta \ &\leq 60
\end{aligned}
$$

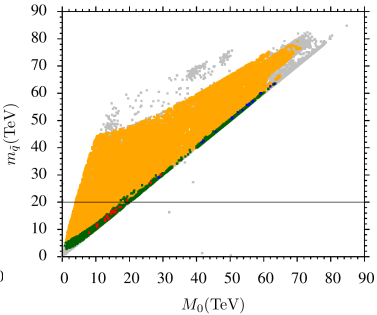
with $\mu > 0$ and $m_t = 173.2 \, \mathrm{GeV}$.

Gravity Mediated Supersymmetry Breaking

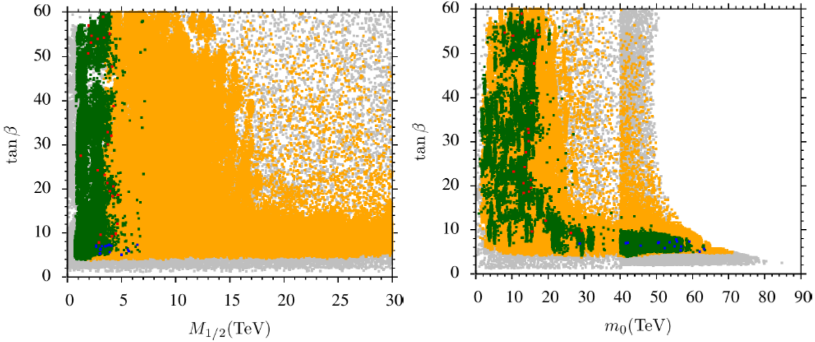


Gravity Mediated Supersymmetry Breaking





Gravity Mediated Supersymmetry Breaking



Gravity Mediated Supersymmetry Breaking

- The upper bound on the universal gaugino mass $M_{1/2}$ is about 7 TeV, and then the upper bound on gluino mass is 15 TeV.
- In our viable parameter space, the lightest squark is generically to be light stop, and thus we do have gluino via heavy flavor decay. To probe such gluino with mass up to 15 TeV, we find that the center-of-mass energy of the future pp collider needs to be about 160 TeV.
- The needed center-of-mass energy is 160 TeV.
- In the viable parameter space with correct dark matter relic density and $\tan\beta > 7.5$, gluino mass is less than 10 TeV. Thus, we can probe it at the $\mathrm{FCC_{hh}}$ and SppC.

Anomaly Mediated Supersymmetry Breaking

We perform the random scans over the following parameter space of the minimal AMSB

$$1\,\mathrm{TeV} \leq M_0 \leq 7.5\,\mathrm{TeV},$$
$$100\,\mathrm{TeV} \leq M_{3/2} \leq 3000\,\mathrm{TeV},$$
$$2 \leq \tan\beta \leq 60$$

with $\mu > 0$ and $m_t = 173.2\,\mathrm{GeV}$.

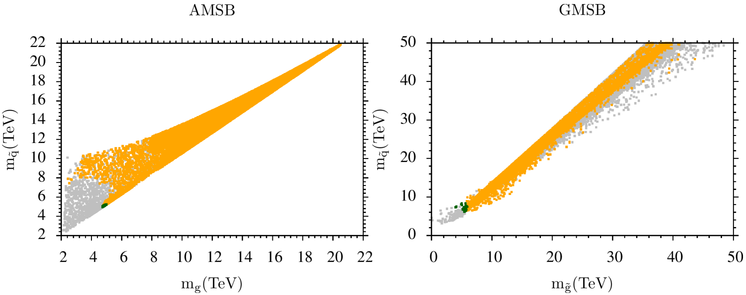
Gauge Mediated Supersymmetry Breaking

With one pair of the messenger fields in the **5** and $\overline{\mathbf{5}}$ representations of $SU(5)$, we perform random scans over the following parameter space

$$5 \times 10^5 \,\mathrm{GeV} \leq \Lambda \equiv F/M_{\mathrm{mess}} \leq 10^{10} \,\mathrm{GeV},$$
$$2 \times \Lambda \leq M_{\mathrm{mess}} \leq 10^{15} \,\mathrm{GeV},$$
$$2 \leq \tan\beta \leq 60$$

with $\mu > 0$ and $m_t = 173.2 \,\mathrm{GeV}$.

Anomaly and Gauge Mediated Supersymmetry Breakings



Anomaly and Gauge Mediated Supersymmetry Breakings

- For anomaly mediation, the squark and gluino masses are less than about 5 TeV.
- For anomaly mediation, the squark and gluino masses are less than about 8 TeV and 6 TeV, respectively.
- The GUTs with anomaly and gauge mediated supersymmetry breakings are well within the reaches of the future 100 TeV pp colliders such as the $\mathrm{FCC_{hh}}$ and SppC.

String Models

- We cannot probe the Pati-Salam models and SM-like models from four-dimensional free-fermionic string constructions as well as the Pati-Salam models from D-brane models on Type II orientifolds.

  No dimension-six proton decay.

- All the other string models might be probed except the models with one-step string-scale gauge coupling unification.
- The $\mathcal{F} - SU(5)$ can be probed and is under investigation.

  The flipped $SU(5)$ model with vector-like particles and string-scale gauge coupling unification from

  F-theory model building or free-fermionic string constructions.

Summary

- Supersymmetry is a bridge between the low energy phenomenology and high-energy fundamental physics, and thus is the promising new physics beyond the SM.
- Gauge coupling unification in the supersymmetric SM strongly implies the GUTs.
- With the grand desert hypothesis, we show that the supersymmetric GUTs and some string models can be probed at the future pp colliders and Hyper-Kamiokande experiment.

Thank You Very Much
for Your Attention!