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

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Waqas Ahmed, TL, Shabbar Raza and Fang-Zhou Xu, arXiv:2007.15059 [hep-ph]; in preparation.

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Motivation for New Physics beyong the Standard Model

The convincing evidence

Dark energy; dark matter; neutrino masses and mixing; baryon asymmetry; inflation; ...

Fine-tuning problems

Cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...

Aesthetic problems

Interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters;

...

The electroweak vacuum stability problem

The stability problem can be easily solved in the new physics models.

- New Physics beyond the SM!
- Question: why do we still believe in supersymmetry?

- Generalization of the Poincare Algebra; The most general symmetry of the S-matrix; The local supersymmetry includes gravity naturally, *i.e.*, supergravity, etc.
- Supersymmetry provides a natural solution to the gauge hiearchy problem.
- Supersymmetry partially solves the cosmological constant problem: $M_{\rm Pl} \rightarrow M_{SUSY}$.
- Supersymmetry is a bridge between the promising low energy phenomenology and the high-energy fundamental physics such as the Grand Unified Theory (GUT) and string theory.

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking
- Natural dark matter candidates
- Electroweak baryogenesis
- Electroweak precision: R parity
- μ problem in the MSSM: $\mu H_d H_u$.

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

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa coupling unification
- Radiative electroweak symmetry breaking due to the large top quark Yukawa coupling
- 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.

- Gauge symmetry breaking
- Doublet-triplet splitting problem
- Proton decay problem
- Fermion mass problem: $m_e/m_\mu = m_d/m_s$

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- 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
- *F*-Theory Model Building

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

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!

Scientific Goal: If we propose a future pp collider, what is the center-of-mass energy needed to probe the supersymmetry?

The Predictions of the SUSY GUTs: Proton Decays

The dimension-six proton decay via superheavy (X_μ, Y_μ) gauge boson exchanges

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

- The dimension-five proton decays via colored Higgsino exchanges in the supersymmetric GUTs.
- ► The operators for dimension-four proton decays from U^c_iD^c_jD^c_k + Q_iL_jD^c_k + E^c_iL_jL_k are forbidden by Z₂ R parity.

The Dimension-Six Proton Decay via (X_{μ}, Y_{μ}) Exchanges





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The current bounds from Super-Kamiokande (SK)

 $au_{p \to e^+ \pi^0} \ge 2.4 \times 10^{34} \ {
m yrs} \ , \ \ au_{p \to ar{
u} K^+} \ge 5.9 \times 10^{33} \ {
m yrs} \ .$

► The expected bounds from Hyper-Kamiokande (HK)

 $au_{p \to e^+ \pi^0} \ge 1.0 \times 10^{35} \text{ yrs} , \ au_{p \to \bar{\nu} K^+} \ge 2.5 \times 10^{34} \text{ yrs} .$

¹K. Abe et al. [Super-Kamiokande], Phys. Rev. D **95**, no.1, 012004 (2017) [arXiv:1610.03597 [hep-ex]]; M. Yokoyama [Hyper-Kamiokande Proto Collaboration], arXiv:1705.00306 [hep-ex]; K. Abe et al. [Hyper-Kamiokande], [arXiv:1805.04163 [physics.ins-det]]; A. Takenaka et al. [Super-Kamiokande], Phys. Rev. D **102**, 112011 (2020) [arXiv:2010.16098 [hep-ex]].

- The SM-like Higgs boson mass is around 125 GeV.
- The tree-level Higgs boson mass is smaller than M_Z .
- The Higgs boson mass is enhanced by the top quark/squark loop corrections.
- The maximal stop mixing is needed to relax the fine-tuning.

Problem: the $SU(3)_C \times U(1)_{EM}$ symmetry breaking.

 Implication: the SM-like Higgs boson mass prefers the heavy sparticle spectrum.

- The first two-generation squark mass low bounds are around 1.8 TeV.
- ► The gluino mass low bound is around 2.3 TeV.
- The stop and sbottom mass low bounds are around 1.2 and 1.3 TeV, respectively.

The SSMs are fine-tuned!!!

The ATLAS SUSY Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary

Model		Signature			£ dt [fb-	'1	Ma	Mass limit					Reference
Inclusive Searches	$qq, q \rightarrow q \ell_1^0$	0 e.μ mono-jet	2-6 jets 1-3 jets	$\frac{E_{T}^{min}}{E_T^{min}}$	139 36.1	2 [10x Degen 2 [1x, 8x Deg	L] Jen.]	0.43	0.71		1.9	m($\tilde{t}_{1}^{0})_{\leq}400\text{GeV}$ m(\tilde{q})-m(\tilde{t}_{1}^{0})=5 GeV	ATLAS-CONF-2019-040 1711.03301
	$33.3 \rightarrow q\bar{q}\bar{t}_1^{\bar{q}}$	0 <i>e.µ</i>	2-6 jets	E_7^{mins}	139	22			Forbidden		2.35 1.15-1.95	m(\tilde{t}_1^0)=0 GeV m(\tilde{t}_1^0)=1000 GeV	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
	$32.3 \rightarrow q\bar{q}W^{2}_{1}$	1 e.µ	2-6 jets		139	5					2.2	m(2)<600 GeV	ATLAS-CONF-2020-047
	$88, 8 \rightarrow qq(\ell\ell)R_1^0$	ee, µµ	2 jets	E _T	36.1	3				1.2		m(g)-m(t ²)=50 GeV	1805.11381
	$32, 3 \rightarrow qqW22_1^-$	55 r. µ	6 jets	£7	139	2				1.15	1.97	m(i;) <600 GeV m(i)=m(i)=200 GeV	ATLAS-CONF-2020-002 1909.08457
	${\mathfrak f}{\mathfrak g}, {\mathfrak z}{\to} {\mathfrak s}{\mathfrak l}{\mathfrak f}_1^0$	0-1 ε.μ SS ε.μ	3 <i>b</i> 6 jets	E_T^{mins}	79.8 139	2				1.25	2.25	m(\tilde{r}_1^0)<200 GeV m(\tilde{r}_1^0)=300 GeV	ATLAS-CONF-2018-041 1909-08457
31" gen. squarks dreat production	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} \delta \tilde{t}_1^0 / t \tilde{t}_1^*$		Multiple Multiple		36.1 139	h h	Forbidden	Forbidden	0.9		$m(\hat{t}_1^2)$ =20	$m(\tilde{t}_{1}^{0})$ = 300 GeV, BR(\tilde{t}_{1}^{0})= 1 0 GeV, $m(\tilde{t}_{1}^{1})$ = 200 GeV, BR(\tilde{t}_{1}^{0})= 1	1708.09266, 1711.00301 1909.08457
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\ell}_2^0 \rightarrow b b \tilde{\ell}_1^0$	0 ε.μ 2 τ	6 b 2 b	E_{T}^{max}	139 139	5 / /	Forbidden		0.13-0.85	3.23-1.35	Δ.	$n(\hat{k}_{2}^{0}, \hat{k}_{1}^{0}) = 130 \text{ GeV}, m(\hat{k}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\hat{k}_{2}^{0}, \hat{k}_{1}^{0}) = 130 \text{ GeV}, m(\hat{k}_{1}^{0}) = 0 \text{ GeV}$	1908.03122 ATLAS-CONF-2020-031
	$I_1I_1, I_1 \rightarrow t \hat{t}_1^0$	0-1 e. µ	≥ 1 jet	E_T^{max}	139	I ₁				1.25		m(k ²)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$r_1r_1, r_1 \rightarrow Wh \ell_1^{\prime\prime}$	14,4	3 jets/1 5	Equin.	139	11		0.44-0.	59	1.10		m(t)=400 GeV	ATLAS-CONF-2019-017
	$nn, n \rightarrow nw, n \rightarrow ns$	0 e.u	20	Emin	36.1	2			0.85			miC1=0GeV	1805.01649
	and a set of the set	0 <i>e</i> .µ	mono-jet	E_T^{minn}	36.1	î1 Î1		0.46				m(i, /)-m(²)_150 GeV m(i, /)-m(²)+5 GeV	1805.01649 1711.02301
	$\tilde{r}_1\tilde{r}_1, \tilde{r}_1 \rightarrow t \tilde{\ell}_2^0, \tilde{\ell}_2^0 \rightarrow Z/h \tilde{\ell}_1^0$	1-2 e, µ	1-4 b	E_T^{mint}	139	î ₁			0.067-	-1.18		m(2)=500 GeV	SUSY-2018-09
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e.µ	1.6	E ₇	139	î ₁		Forbidden	0.86	_	m(t ^ν ₁)=360 GeV, π(t ₁)-π(t ₁ ^ν)= 40 GeV	SUSY-2018-09
EW direct	$\mathcal{R}_1^+ \mathcal{R}_2^0$ via WZ	3 e.μ ee.μμ	≥ 1 jet	E_T^{minn} E_T^{minn}	139 139	$\hat{\chi}_{1}^{*} \hat{\chi}_{2}^{*}$ $\hat{\chi}_{1}^{*} \hat{\chi}_{2}^{*}$	0.205		0.64			$\substack{ m(\widehat{r}_1^n)=0\\ m(\widehat{r}_1^n)=m(\widehat{r}_1^n)=5 \text{ GeV} }$	ATLAS-CONF-2020-015 1911.12605
	$\hat{x}_{1}^{*}\hat{x}_{1}^{*}$ via WW	2 e.µ		E ₇	139	81		0.42				m(k ²)=0	1908.08215
	X1X2 via Wh S*S ^T via Z. In	0-1 e. µ	2 1/2 7	ET.	139	X_1X_1 Portic	dcharn		0.74			m(tr)=70 GeV	2004.10894, 1909.09226
	er energi	2.7		Emin	139	T PL TRL	0.16-0.3	0.12-0.39	1.0			m(2)10	1911.06660
	$l_{L,R}l_{L,R}$, $l \rightarrow \ell \ell_1^0$	2 e. µ	0 jets	Enin	139	1			0.7			m(x ²)=0	1908.08215
		ee, µµ	≥ 1 jet	E'man	139	1	0.256					m(?)-m(?)=10 GeV	1911.12505
	$HH, H \rightarrow hG/ZG$	0ε.μ 4ε.μ	≥ 3 <i>b</i> 0 jets	$E_T^{\rm finn}$	38.1 139	h h	0.13-0.23	0.55	0.29-0.88			$BR(\tilde{t}_1^0 \rightarrow h\tilde{G}) = 1$ $BR(\tilde{t}_1^0 \rightarrow 2t\tilde{G}) = 1$	1806.04030 ATLAS-CONF-2020-040
Long-lived particles	Direct $\hat{x}_1^* \hat{x}_1^-$ prod., long-lived \hat{x}_1^*	Disapp. trk	1 jet	E_7^{max}	36.1	8 8 0.15		0.46				Pure Wino Pure higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable 3 R-hadron		Multiple		36.1	3				_	2.0		1902.01636,1808.04095
	Metastable § H-hadron, §→qqX1		Multiple		36.1	g (ng) =10 m	6, 9.2 ABJ			_	2.05 2.4	m(t_)=100 GeV	1710.04901,1808.04095
RPV	$\hat{x}_{1}^{*}\hat{x}_{1}^{*}/\hat{x}_{1}^{*}, \hat{x}_{1}^{*} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e.µ			139	$\hat{x}_{1}^{a}/\hat{x}_{1}^{b}$ [BR/Z)	$r_{i=1}$, $BR(Z_{i})=1$]	٥	625 1.0	6		Pure Wino	ATLAS-CONF-2020-009
	$Lrvpp \rightarrow v_r + x, v_r \rightarrow e\mu/e\tau/\mu\tau$	ep,et.pt A = 0	() into	armins.	3.2	P.					1.9	A111+0.11, A112(13)(210+0.07	1607.00079
	$\chi_1 \chi_1 / \chi_2 \rightarrow WW/ZIIIIrr$ $\chi_1 \chi_1 / \chi_2 \rightarrow WW/ZIIIIrr$	4	-5 large-R is	6 ⁷⁷	36.1	2 1m(F) - 200	6, 4 ₂₀ # 6 GeV 1100 GeV1		0.02	1.33	19	Large X.	1804.03502
	9919 - Hellin 1 - 144		Multiple		36.1	2 12 20-4	2e-5]		1.0	6	2.0	m(t ²)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\pi, r \rightarrow c \hat{\tau}_1^0, \hat{\tau}_1^0 \rightarrow abs$		Multiple		36.1	T [1" = 20-4, 1	le-2]	0.55	1.0	6		m(t ²)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\overline{u}, \overline{i} \rightarrow b \overline{\ell}_1^*, \overline{\ell}_1^* \rightarrow b b x$		≥ 4b		139	î		Forbidden	0.95			m(\hat{x}_1^*)=500 GeV	ATLAS-CONF-2020-016
	$r_1r_1, r_1 \rightarrow or$ $\tilde{r}_1\tilde{r}_1, \tilde{r}_1 \rightarrow or$	200	2 juna + 2 b 2 h		36.7	T1 [\$\$\$, \$4]		0.42 0	.01	0414	15	BDG. and a Ball SDM.	1/10.07171
	and the	1,0	DV		136	<i>t</i> ₁ [10-10 < <i>X</i> ₂]	<10-0, 30-10< X	<30-9]	1.0		1.6	BR(r_i-sga)=100%, cosit,+1	2003.11956
										_			
													J
*Only	Only a selection of the available mass limits on new states or 10 ⁻¹											Mass scale [TeV]	

phenomena is shown. Many of the limits are based on simplified models. c.f. refs. for the assumptions made.

The CMS Squark Searches



The CMS Gluino Searches



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The CMS Gluino Searches



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The CMS Stop and Sbottom Searches



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Supersymmetry at the Current and Future Colliders

- The wrong impression is that supersymmetry was excluded at the LHC?
- Can we rule out supersymmetry at the LHC, VLHC, FCC_{hh} and SppC?
 No! No!! No!!!
- Point: supersymmetry breaking soft mass scale can be pushed to be much higher than 1 TeV, while gauge coupling unification can still be preserved due to the logarithmic RGE running and threshold corrections around the GUT scale.
- Conclusion: supersymmetry will definitely not die in the near future!!!

The interesting question: can we rule out or discover the natural supersymmetry at the FCC_{hh} and SppC? Or can we solve the supersymmetry electroweak fine-tuning problem naturally?

The EENZ-BG Fine-Tuning Measure ²

- Because we study the SUSY GUTs, we shall consider the EENZ-BG fine-tuning measure.
- Definition: the quantitative measure Δ^{EENZ-BG}_{FT} for fine-tuning is the maximum of the logarithmic derivative of *M_Z* with respect to all the fundamental parameters *a_i* at the GUT scale

$$\Delta_{\mathrm{FT}}^{\mathrm{EENZ-BG}} = \mathrm{Max}\{\Delta_i^{\mathrm{GUT}}\}, \quad \Delta_i^{\mathrm{GUT}} = \left|rac{\partial \mathrm{ln}(M_Z)}{\partial \mathrm{ln}(a_i^{\mathrm{GUT}})}
ight|.$$

² J. R. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A **1**, 57 (1986); R. Barbieri and G. F. Giudice, Nucl. Phys. B **306**, 63 (1988).

Can we propose a supersymmetry scenario whose the EENZ-BG fine-tuning measure is automatically 1 or order 1 (O(1))?

Fundamental physics principles: simplicity and naturalness.

Fine-Tuning Definition:

$$\Delta_{\mathrm{FT}} = \mathrm{Max}\{\Delta_i^{\mathrm{GUT}}\}, \quad \Delta_i^{\mathrm{GUT}} = \left|\frac{\partial \mathrm{ln}(M_Z)}{\partial \mathrm{ln}(a_i^{\mathrm{GUT}})}\right|$$

Natural Solution:

$$M_Z^n = f_n\left(\frac{M_Z}{M_*}\right) M_*^n .$$

$$\frac{\partial \ln(M_Z^n)}{\partial \ln(M_*^n)} \simeq \frac{M_*^n}{M_Z^n} \frac{\partial M_Z^n}{\partial M_*^n} \simeq \frac{1}{f_n} f_n \simeq \mathcal{O}(1) \ .$$

For no-scale supergravity and M-theory on S^1/Z_2 , we have $M_* = M_{1/2}$ and $M_* = M_{3/2}$, respectively.

³T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B 740, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D 92, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]]; T. Li, S. Raza and X. C. Wang, Phys. Rev. D 93, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

Supernatural Supersymmetry

The *F* - *SU*(5) ⁴ and the MSSM ⁵ with no-scale supergravity ⁶ and Giudice-Masiero Mechanism ⁷.

 $\mathcal{F} - SU(5)$: the flipped SU(5) model with vector-like particles and string-scale gauge coupling unification from F-theory model building.

No-scale Supergravity: $M_{1/2} \neq 0$, and $M_0 = A_0 = B_{\mu} = 0$.

Giudice-Masiero Mechanism: generating μ term from supersymmetry breaking effect, *i.e.*, $\mu \propto M_{1/2}$.

Prolem: we cannot predict the exact mass ratio $\mu/M_{1/2}$?

• The NMSSM ⁸ with supersymmetry breaking soft terms from M-theory on S^1/Z_2 ⁹.

The NMSSM: an singlet S, and a discrete Z_3 symmetry.

⁴T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B 740, 66 (2015) [arXiv:1408.4459 [hep-ph]].

⁵G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]].

⁰E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B **133**, 61 (1983); A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145**, 1 (1987).

⁷G. F. Giudice and A. Masiero, Phys. Lett. B **206**, 480 (1988).

⁸T. Li, S. Raza and X. C. Wang, Phys. Rev. D 93, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

⁹T. Li, Phys. Rev. D 59, 107902 (1999) [hep-ph/9804243].

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- The Kähler potential and superpotential can be calculated in principle or at least inspired from a fundamental theory such as string theory with suitable compactifications. In other words, one cannot add arbitrary high-dimensional terms in the Kähler potential and superpotential.
- There is one and only one chiral superfield or modulus whose F-term breaks supersymmetry. And all the supersymmetry breaking soft terms are obtained from the above Kähler potential and superpotential.
- All the other mass parameters, if there exist such as the µ term in the MSSM, must arise from supersymmetry breaking.

There exist the correlations among the GUT-scale parameters with large fine-tuning measures 10 .

¹⁰R. Ding, T. Li, F. Staub and B. Zhu, Phys. Rev. D **93**, no. 9, 095028 (2016) doi:10.1103/PhysRevD.93.095028 [arXiv:1510.01328 [hep-ph]]. ← □ ▷ ← □ ▷ ← □ ▷

- The SUSY electroweak fine-tuning problem can be solved by the super-natural supersymmetry.
- Can we probe supersymmetry at the future pp colliders? No?
- Can we probe the supersymmetric GUTs at the future pp colliders? Yes!!! ¹¹

¹¹W. Ahmed, T. Li, S. Raza and F. Z. Xu, [arXiv:2007.15059 [hep-ph]]. < □ → < ♂ → < ≧ → < ≧ → ≧ → ○ < ♡

The Exceptions in String Models

The D-brane models: the Pati-Salam Model

In one of our models, the gauge coupling unification for $SU(4)_C \times SU(2)_L \times SU(2)_R$ can be achieved, while gaugino mass unification cannot.

The F-theory models

Gauge coupling unification can be realized in the SO(10) model with $U(1)_X$ flux while not necessary in the SU(5) model with $U(1)_Y$ flux and the SO(10) model with $U(1)_{B-L}$ flux.

$$\frac{1}{\alpha_2} - \frac{1}{\alpha_3} = k \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_3} \right) ,$$

$$\frac{M_2}{\alpha_2} - \frac{M_3}{\alpha_3} = k \left(\frac{M_1}{\alpha_1} - \frac{M_3}{\alpha_3} \right) ,$$

where k = 5/3.

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- Grand desert hypothesis: no new physics between the sparticle mass scale and the GUT scale.
- ▶ For the GUTs with the GUT scale $M_{GUT} \le 1.0 \times 10^{16}$ GeV, we can probe the dimension-six proton decay via heavy gauge boson exchange at the Hyper-Kamiokande experiment.
- ▶ For the GUTs with $M_{GUT} \ge 1.0 \times 10^{16}$ 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 GUTs with $M_{GUT} \leq 1.0 \times 10^{16}$ GeV

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

$$egin{array}{r_p} &\simeq & 1.0 imes 10^{34} imes \left(rac{2.5}{A_R}
ight)^2 imes \left(rac{0.04}{lpha_{
m GUT}}
ight)^2 \ & imes \left(rac{M_{
m GUT}}{1.0 imes 10^{16} \ {
m GeV}}
ight)^4 \ {
m years} \; . \end{array}$$

- The current lower limit from the Super-Kamiokande experiment gives τ_p > 2.4 × 10³⁴ years ¹², and thus we obtain M_{GUT} ≥ 1.0 × 10¹⁶ GeV.
- At the future Hyper-Kamiokande experiment, we can probe the proton lifetime at least above 1.0 × 10³⁵ years ¹³. Therefore, the GUTs with M_{GUT} ≤ 1.0 × 10¹⁶ GeV is definitely within its reach.
- ¹²K. 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]]. ¹³K. Abe *et al.* [Hyper-Kamiokande], [arXiv:1805.04163 [physics.ins-det]]. □ ▷ < ⑦ ▷ < ≧ ▷ < ≧ ▷

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

The supersymmetry breaking mediation mechanisms

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

- ▶ For the 100 TeV pp Colliders such as 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 *g̃* via heavy flavor decay with mass around 15 TeV, we need the 160 TeV pp collider such as the VLHC.

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

We perform the random scans for the following mSUGRA/CMSSM parameter space $% \mathcal{M} = \mathcal{M} = \mathcal{M} + \mathcal{M} +$

$$\begin{array}{l} 0 \leq M_0 \leq 90 \, {\rm TeV}, \\ 0 \leq M_{1/2} \leq 30 \, {\rm TeV}, \\ -3 \leq A_0/M_0 \leq 3, \\ 2 \leq \tan\beta \, \leq 60 \end{array}$$

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



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- 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.
- In the viable parameter space with correct dark matter relic density and tan β > 7.5, gluino mass is less than 10 TeV. Thus, we can probe it at the FCC_{hh} and SppC.

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

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

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

We perform random scans over the following minimal GMSB parameter space

$$\begin{split} 5\times 10^5\,{\rm GeV} &\leq \Lambda \,\leq 10^{10}\,{\rm GeV},\\ 2\times\Lambda \,\leq M_{mess} \leq 10^{15}\,{\rm GeV},\\ 2\leq \tan\beta \,\leq 60 \end{split}$$

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

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Anomaly and Gauge Mediated Supersymmetry Breakings



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- For anomaly mediation, the squark and gluino masses are less than 6 TeV.
- For anomaly mediation, the squark and gluino masses are less than 10 TeV and 8 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 FCC_{hh} and SppC.

- 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 can be probed at the future pp colliders and Hyper-Kamiokande experiment.
- ► The super-natural supersymmetry can definitely be probed at the FCC_{hh} and SppC.

Thank You Very Much for Your Attention!

