Snowmass EF08 Report

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CONTENTS

I. INTRODUCTION

The Standard Model (SM) works astoundingly well up to energy scales of the order of $\sim$ TeV. However there are some tantalizing anomalous experimental results as well as theoretical considerations which may point us to the type of new physics (NP) that may be present. In this report, we aim to summarize the experimental prospects at future colliders of exploring NP possibilities that arise in some of the most well-motivated models of Beyond the Standard Model physics.

As a guide to NP possibilities, below we summarize some motivations guiding our explorations in Sec. II. The theory model space is huge and many models exist which we will not be able to include, hence we will focus on prospects for a few types of models which qualitatively capture generic features of new physics possibilities III. Summary plots and tables of current status and prospects of probing the particle content of selected models at future colliders are presented in Sec. IV.

II. MOTIVATIONS

A. Naturalness

M. Reece

The Standard Model contains many unexplained small parameters, such as the electroweak hierarchy (the ratio of electroweak and Planck energies), small Yukawa couplings, and the strong CP angle $\bar{\theta}$. Finding a more fundamental explanation of these parameters is one of the major goals of high-energy physics. The QCD scale provides an example of what such an explanation could look like: it is generated dynamically, through dimensional transmutation, as the scale $\propto \exp[-8\pi^2/(bg_s^2)]$ at which a mildly small coupling g_s at high energies runs to become strong, triggering confinement. The electroweak hierarchy has been a particular focus of efforts to build similarly compelling dynamical models and to experimentally test them. There are two especially prominent classes of examples: supersymmetric (SUSY) extensions of the Standard Model (reviewed in [1]), in which SUSY can be dynamically broken at a low scale explained by dimensional transmutation and SUSY breaking can, in turn, trigger electroweak symmetry breaking [2, 3]; and models in which the Higgs boson is a composite particle, especially those in which it is a pseudo-Nambu-Goldstone boson [4–6] (see [7] for a modern review). These models provide *natural* explanations of the electroweak hierarchy, and in particular they are technically natural in the sense that radiative corrections to the Higgs boson mass are at most logarithmically divergent in such theories.

Natural models for the electroweak scale typically replace the quadratic *divergence* of the Higgs mass with a quadratic *sensitivity* to the mass scale of new particles. Because the Higgs field interacts much more strongly with third generation fermions than with the light generations, many models correlate the flavor puzzle with the electroweak hierarchy problem. For example, in supersymmetry, the electroweak hierarchy is obviously sensitive to the higgsino mass [8], but it is also very sensitive to the stop masses, motivating models in which the third-generation squarks are the lightest [9–12] and prompting a number of experimental searches targeting such models. In the context of composite Higgs models, the leading paradigm involves "partially composite" fermions [13, 14], with the top quark mixing strongly with composite states and fermionic top partners providing some of the first expected signals in collider experiments. So far, the LHC has not discovered any of these predicted signals. This has spurred investigation of variant models in which the collider signals are more difficult to observe, such as R-parity violating or Stealth SUSY models (see, e.g., [15–18] for natural simplified models the LHC can target) or "neutral naturalness" models where quadratic divergences are canceled by particles without strong Standard Model interactions, e.g., the Twin Higgs scenario [19]. However, given the continued lack of new physics signals at the LHC, including in measurements of Higgs couplings, many of these models must be at least mildly tuned to fit the data.

The lack of experimental evidence so far for any natural explanation of the electroweak hierarchy has resulted in the concept of naturalness itself becoming a subject of much debate. Various claims that naturalness predicted particles below a particular mass scale have been falsified by data, leading some to conclude that the concept of naturalness itself should be abandoned. It is important to keep in mind, however, that naturalness was never the source of a quantitative no-lose theorem. Rather, it is a heuristic, and one based on simple logic. A natural theory is one in which a large part of parameter space leads to qualitatively similar physics to the world around us, e.g., to an exponentially large hierarchy between the electroweak and Planck scales. An unnatural theory, like the Standard Model, is one in which ultraviolet parameters must be chosen in an exponentially tiny sliver of parameter space to lead to physics like the world around us. The *naturalness heuristic* is the simple statement that, all else being equal, a theory that describes a universe like the one we live in over a substantial portion of its UV parameter space is more likely to be correct than one that describes a universe like the one we live in over only a tiny sliver of parameter space. One could use the language of Bayesian reasoning to formalize this notion, but fundamentally it is just common sense. Overly formal treatments of this idea are, to some extent, obfuscations of the underlying logic, because we lack any sharp measure on the space of theories to define agreed-upon priors. Naturalness, then, is an argument about what new physics is most *plausible*. This heuristic has had successes in the past. One prominent example of a successful prediction of the naturalness heuristic in particle physics was the prediction that the charm quark should exist with $m_c \lesssim 1.5\,\mathrm{GeV}$, based on the quadratically divergent mass difference between the K_L and K_S mesons in the theory without charm [20, 21] (see also [22]).

The naturalness heuristic continues to be an important guide toward physics beyond the Standard Model which might exist near the TeV scale. The harshest critics and the staunchest proponents of naturalness have both made the mistake of taking this heuristic *too* seriously, as if it is a sharp quantitative prediction. However, the absence of superpartners or other signs of natural new physics at the LHC so far cannot invalidate the naturalness heuristic. Conversely, the naturalness heuristic cannot produce a precise upper bound on the mass scale of new physics. It is a guideline, and its failure in experiments so far suggests that we may live in a universe that is somewhat fine-tuned. That said, the heuristic would still indicate that supersymmetry with 10 TeV superpartners, despite its mild fine tuning, is a more plausible theory of nature than a theory where the Standard Model is valid up to the Planck scale.

In the context of minimal supersymmetry, further support for a mildly fine-tuned spectrum arises from the observation that the Higgs mass of 125 GeV points to somewhat heavier superpartners, with stops at the 10 TeV scale or above (though a large left-right stop mixing could allow lighter squarks to be compatible with the measured Higgs mass; see [23] for a review of Higgs mass calculations in SUSY). Such moderately tuned spectra could simply be an accident of the universe in which we live, or could be argued for from the perspective of the landscape of a more complete theory (see, e.g., the Snowmass white paper [24]). The connection between the Higgs mass and heavy scalar superpartners has led to an increased interest in "split" supersymmetric spectra [25, 26] in which the gaugino (and possibly higgsino) masses could remain at the TeV scale while the scalar superpartners are at the 10 TeV to 1 PeV scale [27, 28]. Such spectra are predicted by many simple models of SUSY breaking. A mildly long-lived gluino could provide a key collider signal of such a scenario.

Although moderately tuned, but mostly natural, scenarios remain compelling search targets that are compatible with all existing data, theorists have also begun to investigate more radical deviations from older paradigms. A key example is the cosmological relaxation scenario [29], in which dynamics in the early universe drives a light scalar field to become trapped at a value at which the effective Higgs potential appears to be fine-tuned from the viewpoint of traditional effective field theory. See the Snowmass White Paper [30] for a more thorough discussion of novel approaches to naturalness, many of which have interesting experimental consequences.

B. Anomalies in Indirect Measurements (g-2, m_W, etc)

S. Baum

III. MODELS

A. Extra Dimensions

K. Agashe

Extra dimensions (see review in [31], for example) and SUSY are the only possible extensions of relativistic space-time in field theory. Both concepts feature in super-string theory, which is perhaps the only well-developed, consistent theory of quantum gravity. In light of the above facts, it is quite likely that extra dimensions exist in Nature: obviously, the crucial question then is are there any observable effects of extra dimensions? The answer depends on the size of the extra dimensions: first of all, extra dimensions much be compact, otherwise the inverse square law of gravitational and electrostatic forces would be modified at long distances, in contradiction with observations. An SM (including gravitational) field propagating in such a finite-size extra dimension manifests as a tower of Kaluza-Klein (KK) modes from the four-dimensional (4d) viewpoint, with masses quantized increasingly in units of inverse size of extra dimension (called the compactification or KK scale). The zero-mode (typically massless) of this KK decomposition is identified with the observed SM field/particle. Whereas, the other/heavier modes are the new, beyond SM, particles in this framework, whose effects are potentially observable. In addition, there is a particle called the radion, which corresponds to the modulus associated with the fluctuations of the size of the extra dimension.

One can then ask which KK scales are motivated from theory and experimental perspectives? In particular, the lightest KK scale being $\sim \mathcal{O}$ (TeV) would be relevant for the solving the Planck-weak hierarchy problem of the SM: the lightest KK top quark could cancel the quadratic divergence in the SM Higgs mass^2 from the SM top quark loop. It could also provide a dark matter candidate in the form of the lightest KK particle. On the other hand, if the KK scale is much heavier than $\sim \mathcal{O}$ (TeV), then such an extra dimension could still address, for example, the flavor hierarchy of the SM via varying profiles for the SM fermions in the extra dimension. Moving onto signals from these KK particles, in case of the lightest KK scale being $\sim \mathcal{O}$ (TeV), these KK particles might of course be *directly* accessible to the LHC/future colliders. In addition (and this point is valid even if KK particles are beyond LHC/future collider reach), there are indirect/virtual effects of these KK particles on flavor/CP violation and electroweak (EW) fits of the SM. Indeed, $\sim \mathcal{O}$ (TeV) KK scale could be strongly constrained by such precision tests; remarkably, this tension might be ameliorated by implementing suitable symmetries, which could be simple extensions of well-known protection mechanisms of the SM itself, thus rendering $\sim \mathcal{O}$ (TeV) KK scale viable. Overall, the above discussion strongly motivates direct search at the LHC/future colliders for such KK particles.

In fact, current extensive direct searches at the LHC are already probing $\sim$ TeV mass scale, say, for KK gauge bosons/gravitons, produced in $q\bar{q}$ or gg annihilation, followed by vanilla decay into 2 SM particles. Note that, unlike universal Z'/W', these KK particles often decay preferentially into heavier SM particles, such as top quark/Higgs particles (including longitudinal W/Z). Given the hierarchy between KK scale and masses of these SM particles, the top quarks/Higgs bosons are produced boosted, so their decay products (in turn) merge. This direction has resulted in development of sophisticated jet-substructure techniques to identify such novel objects (from the detector angle), which could be useful in other contexts as well. More recently, non-standard decays of such KK particles have also been studied, for example, decay into other new particles, such as heavier into lighter KK particles or KK particles into radion (see, for example, [32]), which subsequently decay into SM particles.

In summary, extra dimensions have a a variety of motivations and lead to a rich set of signals, especially from direct production at the LHC/future colliders, where there remains a reasonable chance of their discovery (possibly via non-standard modes), in spite of the current bounds (direct and indirect). Thus, continuing and diversifying such searches at the LHC is justified.

B. Composite Higgs

T. Gherghetta

C. Supersymmetry (SUSY)

C. .E. M. Wagner

IV. FUTURE PROSPECTS

A. Sensitivity Studies

1. Extra Dimensions

2. Composite Higgs

The phenomenology in CH models is basically governed by the compositeness scale m_* and the overall coupling strength g_*. Generically, in such models, the top quark may be

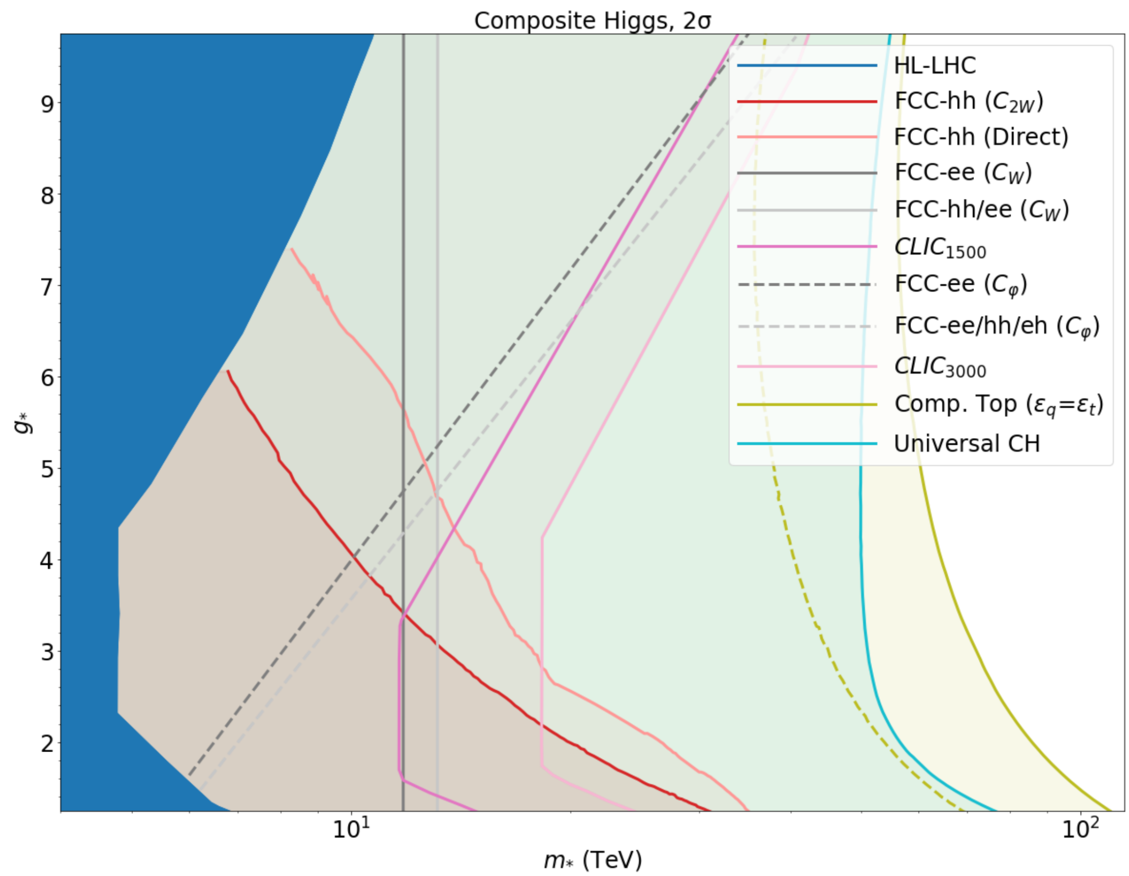

FIG. 1: Composite Higgs for 2 σ CI. The lower boundary of Comp. Top is indicated by a dashed line.

expected to be partially composite as well, hence the top compositeness can be an additional parameter.

3. SUSY

Squarks and Gluinos

Charginos

Sleptons

B. pMSSM Scans

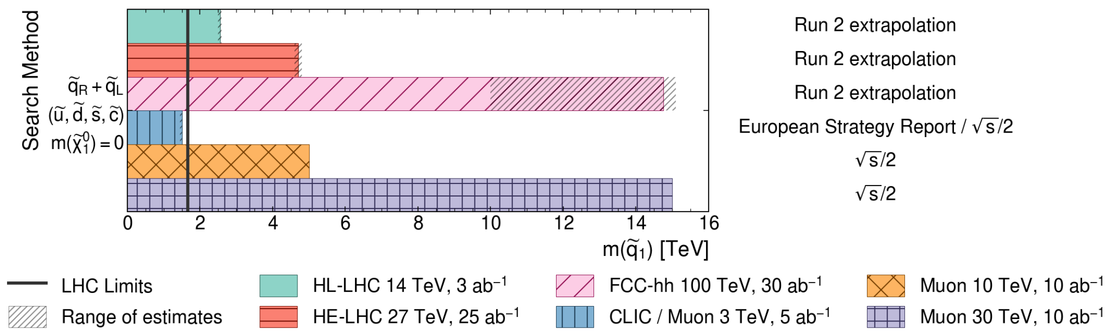

FIG. 2: Light-squark sensitivity comparison for various collider scenarios. *specifics here.* A table detailing the origin of each line is given in Table I

TABLE I: Sources for Light Squark Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[33]
	CMS data analysis	[34]
HL-LHC	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
HE-LHC (27 TeV)	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
FCC-hh (100 TeV)	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
	Dedicated Study	[35]
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	[36]
Muon (10 TeV)	$\sqrt{s}/2$	[36]
Muon (30 TeV)	$\sqrt{s}/2$	[36]

V. CONCLUSION

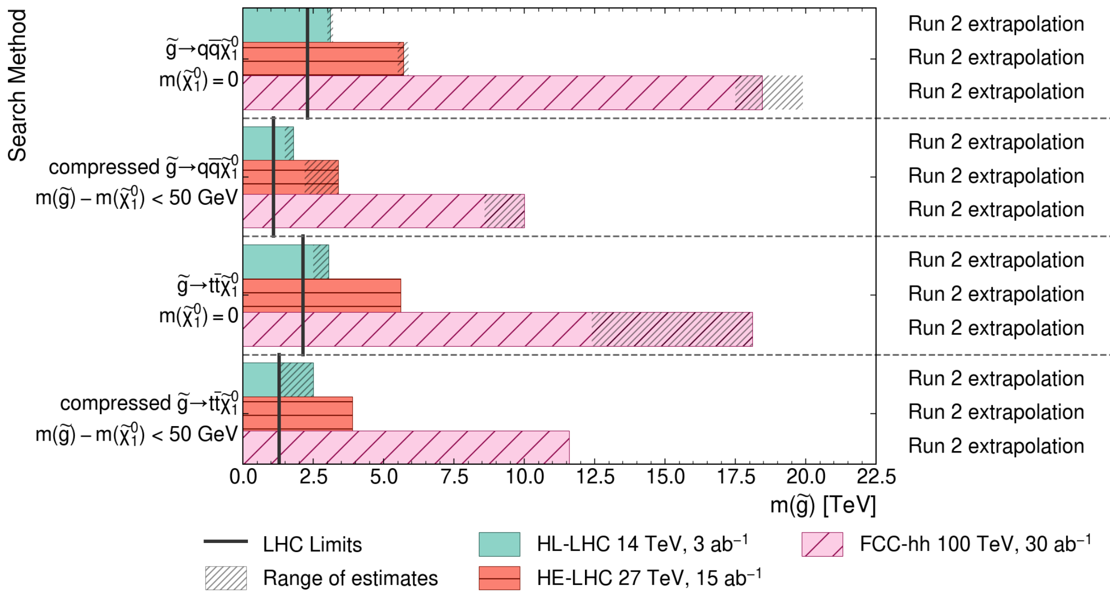

FIG. 3: Gluino sensitivity comparison for various collider scenarios. *specifics here.* A table detailing the origin of each line is given in Table II

TABLE II: Sources for Gluino Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[33]
	CMS data analysis	[34]
HL-LHC	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
	Dedicated Study	[37]
HE-LHC (27 TeV)	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
	Dedicated Study	[37]
FCC-hh (100 TeV)	ATLAS Collider Reach	Run-2 [33] re-scaled
	CMS Collider Reach	Run-2 [34] re-scaled
	Dedicated Study	[35]

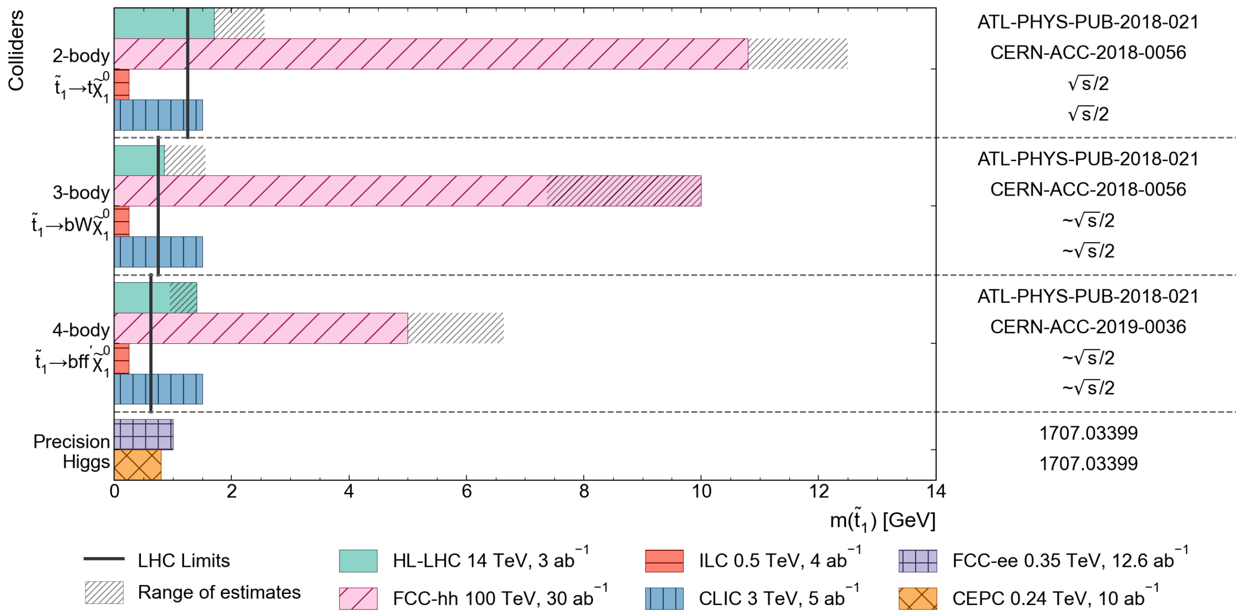

FIG. 4: Estimated stop exclusion reaches for various colliders and search methods. The two, three, and four-body decay searches target the regions $\Delta m(\widetilde{t}_1, \widetilde{\chi}_1^0) \in (m_t, \infty)$, $(m_b + m_W, m_t)$, and $(0, m_b + m_W)$ respectively. The bars show the largest limit on $m(\widetilde{t}_1)$ in the $m(\widetilde{t}_1) - m(\widetilde{\chi}_1^0)$ phase-space for each region. The Precision Higgs constraints are based on measuring production rates of the Higgs boson assuming the only BSM contributions are from stops. References for each exclusion estimate are shown on the right as either the CDS report number or arXiv identifier. ILC and CLIC limits are estimated to be $\sqrt{s}/2$, with slight inefficiencies in the three and four-body decay searches due to soft decay products. Current limits from the LHC [38] are shown as vertical lines. A table detailing the origin of each line is given in Table III.

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TABLE III: Sources for Stop Squark Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[38]
	CMS data analysis	[39]
HL-LHC	ATLAS Study	[40]
	ATLAS Collider Reach	Run-2 [38] re-scaled
	CMS Collider Reach	Run-2 [39] re-scaled
HE-LHC (27 TeV)	ATLAS Collider Reach	Run-2 [38] re-scaled
	CMS Collider Reach	Run-2 [39] re-scaled
FCC-hh (100 TeV)	ATLAS Collider Reach	Run-2 [38] re-scaled
	CMS Collider Reach	Run-2 [39] re-scaled
	Dedicated Study	[41]
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	n/a
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	n/a
Muon (10 TeV)	$\sqrt{s}/2$	n/a
Muon (30 TeV)	$\sqrt{s}/2$	n/a
FCC-ee Precision	. Analysis of precision measurement predictions	[42]
CEPC Precision	. Analysis of precision measurement predictions	[42]

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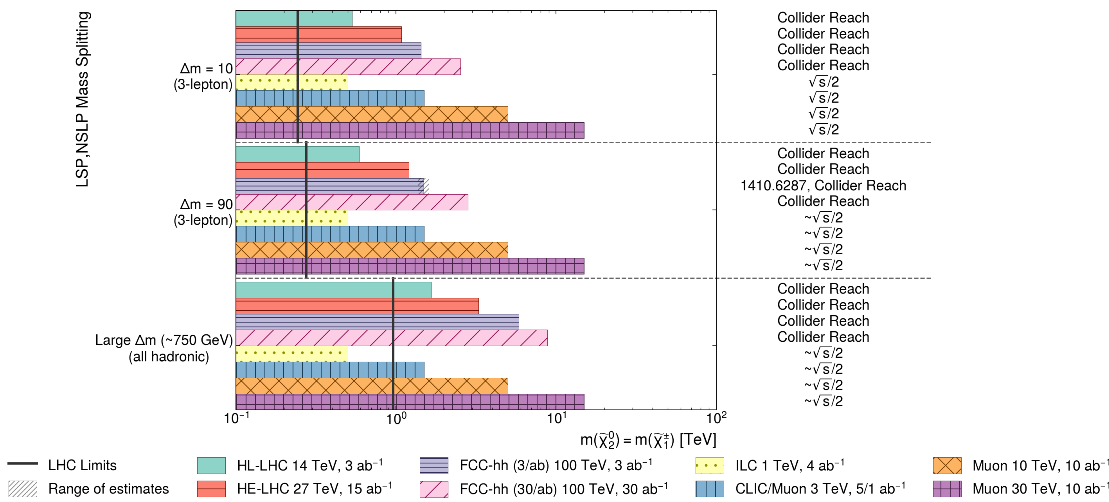

FIG. 5: Wino NLSP bino LSP sensitivity comparison for various collider scenarios. *specifics here.* A table detailing the origin of each line is given in Table IV

TABLE IV: Sources for Wino-Chargino Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[43]
	CMS data analysis	[44]
HL-LHC	ATLAS Collider Reach	[43]
	CMS Collider Reach	[37]
HE-LHC (27 TeV)	ATLAS Collider Reach	[43]
	CMS Collider Reach	[37]
FCC-hh (100 TeV)	ATLAS Collider Reach	[43] re-scaling
	CMS Collider Reach	n/a
	Dedicated Study	[35]
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	[45]
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	[46]
Muon (10 TeV)	$\sqrt{s}/2$	n/a
Muon (30 TeV)	$\sqrt{s}/2$	n/a

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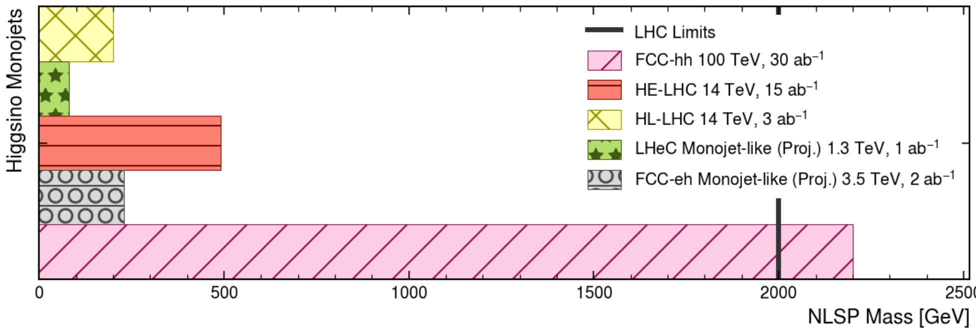

FIG. 6: Higgsino monojet sensitivies for various colliders. Plot references are included in Table V.

TABLE V: Sources for Higgsino Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[47]
	CMS data analysis	[48]
HL-LHC	ATLAS Collider Reach	[49]
	CMS Collider Reach	[50]
HE-LHC (27 TeV)	ATLAS Collider Reach	[49]
	CMS Collider Reach	[50]
FCC-hh (100 TeV)	ATLAS Collider Reach	[49]
	CMS Collider Reach	[50]
	Dedicated Study	[51]
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	
Muon (10 TeV)	$\sqrt{s}/2$	
Muon (30 TeV)	$\sqrt{s}/2$	

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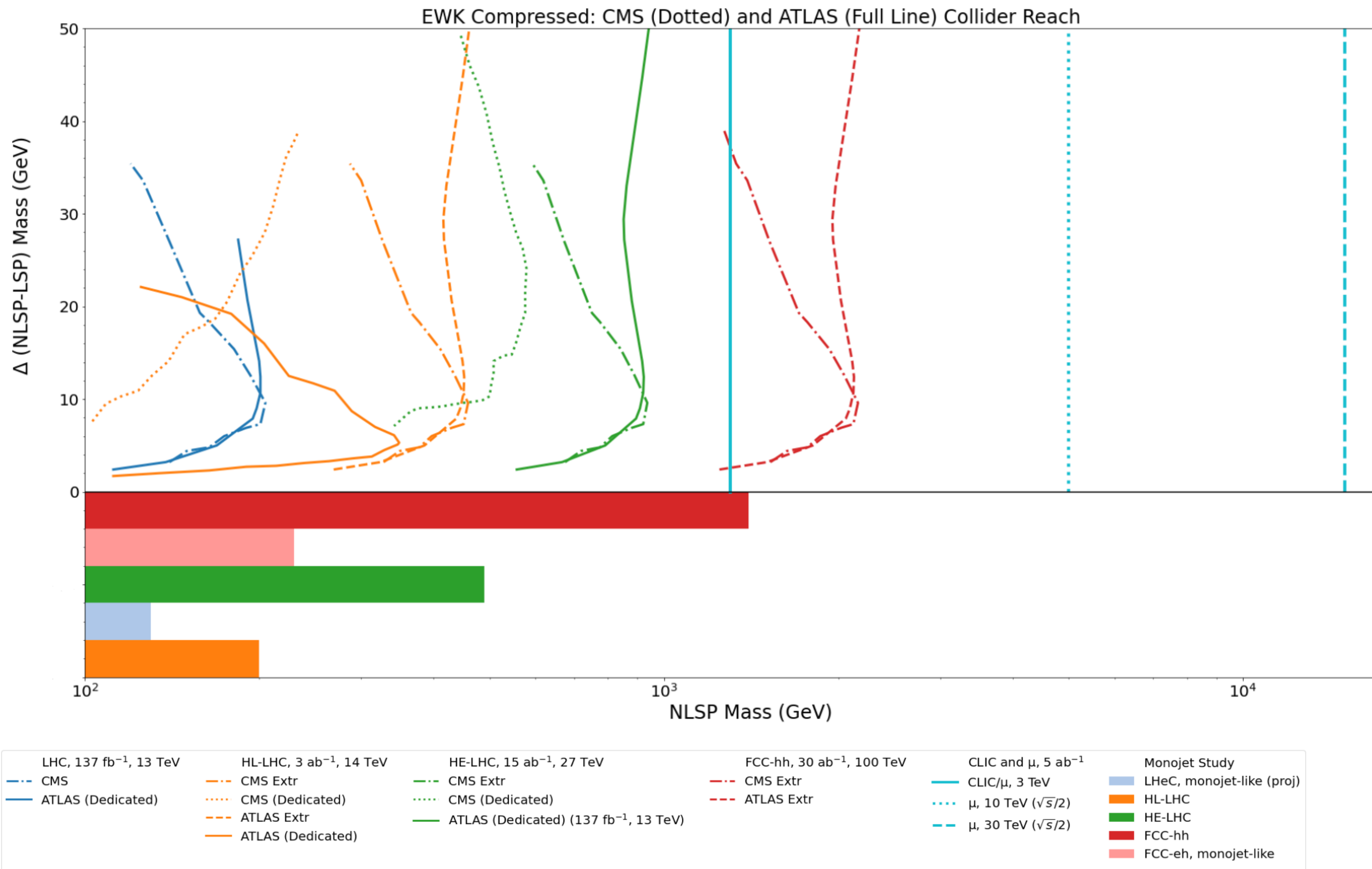

FIG. 7: Compressed EWK reaches for CMS (Dotted) ATLAS (Full Line). Plot references are included in Table V.

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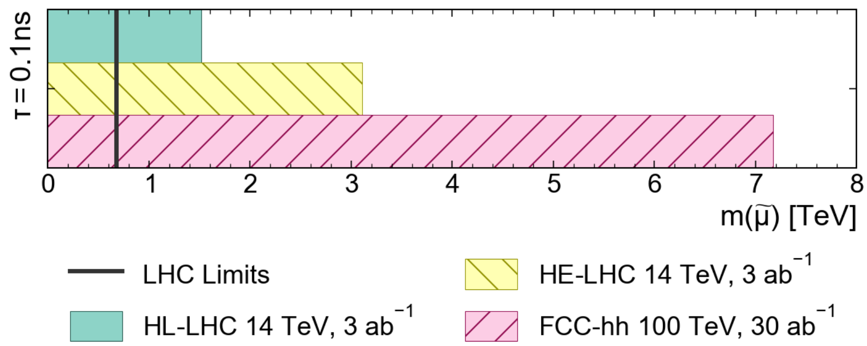

FIG. 8: Smuon sensitivity comparison for various collider scenarios. All values were obtained by re-scaling Run-2 limits [52] with a $\tau = 0.1$ns model. A table detailing the origin of each line is given in Table II

.

TABLE VI: Sources for Smuon Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[52]
	CMS data analysis	[53]
HL-LHC	ATLAS Collider Reach	Run-2 [52] re-scaled
	CMS Collider Reach	Run-2 [53] re-scaled
	Dedicated Study	[37]
HE-LHC (27 TeV)	ATLAS Collider Reach	Run-2 [52] re-scaled
	CMS Collider Reach	Run-2 [53] re-scaled
FCC-hh (100 TeV)	ATLAS Collider Reach	Run-2 [52] re-scaled
	CMS Collider Reach	Run-2 [53] re-scaled
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	
Muon (10 TeV)	$\sqrt{s}/2$	
Muon (30 TeV)	$\sqrt{s}/2$	

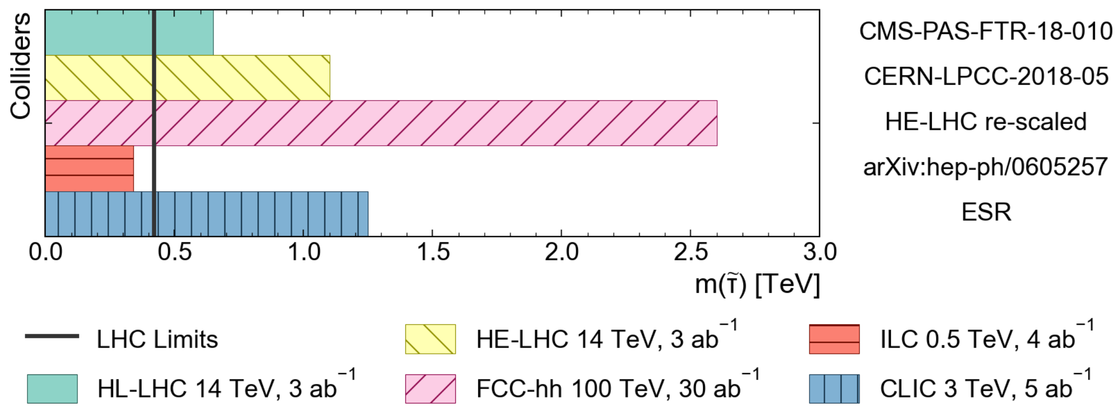

FIG. 9: Stau sensitivity comparison for various collider scenarios. A table detailing the origin of each line is given in Table VII

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TABLE VII: Sources for Stau Limits

Collider	Method	Reference
LHC Run-2	ATLAS data analysis	[54]
	CMS data analysis	
HL-LHC	ATLAS Collider Reach	
	CMS Collider Reach	
HE-LHC (27 TeV)	ATLAS Collider Reach	
	CMS Collider Reach	
FCC-hh (100 TeV)	ATLAS Collider Reach	
	CMS Collider Reach	
	Dedicated Study	[41]
ILC/C^3 (1 TeV)	$\sqrt{s}/2$	
CLIC/Muon (3 TeV)	$\sqrt{s}/2$	[51]
Muon (10 TeV)	$\sqrt{s}/2$	
Muon (30 TeV)	$\sqrt{s}/2$	

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