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“Neutralino and Chargino Detection Strategies in HL-LHC Data: Advances and Challenges"

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Abstract: The search for supersymmetric (SUSY) particles remains one of the central pursuits in high-energy particle physics. Supersymmetry, a theoretical extension of the Standard Model (SM), posits that each particle has a heavier superpartner differing by half a unit of spin. Despite its theoretical elegance and its capacity to solve several unresolved issues such as the hierarchy problem, gauge coupling unification, and providing a candidate for dark matter, supersymmetry has not yet been confirmed experimentally. However, the ongoing and upcoming high-luminosity runs at the Large Hadron Collider (HL-LHC) offer a promising avenue for exploring a wider parameter space of supersymmetric models. This review delves into the status of SUSY particle searches using high-luminosity collider data. It summarizes the key findings from the ATLAS and CMS collaborations during LHC Run 2 and Run 3, as well as projections for the HL-LHC era. Special attention is given to the detection strategies for various SUSY particles such as squarks, gluinos, neutralinos, and sleptons, and how these strategies adapt under high pile-up and background conditions inherent to high-luminosity operations. Data analysis techniques involving machine learning, deep neural networks, and precision background estimation are also discussed. Furthermore, this review explores how high-luminosity collider data improves sensitivity to rare SUSY signatures, including long-lived particles (LLPs) and compressed mass spectra. The implications of null results in current searches are critically examined with respect to constrained models such as CMSSM and phenomenological MSSM (pMSSM). The synergy between collider searches, dark matter experiments, and indirect constraints from flavor physics is also highlighted. By synthesizing recent data and projections, this article aims to provide a detailed, up-to-date resource on the pursuit of supersymmetry in the high-luminosity era of collider physics.

Keywords: Supersymmetry, High-Luminosity LHC, Collider Data, SUSY Particles, Neutralino, Gluino, pMSSM

1. INTRODUCTION

Supersymmetry (SUSY) represents one of the most compelling theoretical frameworks extending the Standard Model (SM) of particle physics. Developed in the 1970s, SUSY introduces a new symmetry between bosons and fermions, positing that each SM particle has a corresponding superpartner with a spin differing by ½. This elegant extension not only addresses the naturalness problem and stabilizes the Higgs boson mass against quantum corrections but also provides a viable dark matter candidate—typically the lightest supersymmetric particle (LSP), often a neutralino.

Despite its theoretical appeal, supersymmetry has yet to be observed in experimental data. Since the initial runs of the Large Hadron Collider (LHC) at CERN, both ATLAS and CMS experiments have searched for supersymmetric particles in a wide array of final states, including jets plus missing transverse energy (MET), leptons, photons, and long-lived signatures. The current LHC limits on gluino masses exceed 2.2 TeV in certain decay scenarios, while squark mass limits approach 1.5 TeV. These limits, however, depend heavily on the assumptions embedded in simplified models and constrained versions of SUSY, such as the constrained MSSM (CMSSM) or minimal supergravity (mSUGRA).

As the LHC transitions into its high-luminosity phase (HL-LHC), with a target integrated luminosity of 3 ab^{-1} by the mid-2030s, the experimental landscape for SUSY searches is poised for transformation. The HL-LHC will enable physicists to probe rare processes with unprecedented precision, explore compressed SUSY spectra with enhanced sensitivity, and potentially discover particles in less traditional final states. Increased luminosity, however, introduces significant challenges, including pile-up mitigation, detector resolution under high radiation, and more complex event reconstruction.

Machine learning and advanced multivariate analysis (MVA) techniques are playing an increasing role in adapting to these challenges. These tools help distinguish signal from background in complex environments, especially for final states with low MET or long-lived particles that decay far from the interaction point.

This review aims to explore the impact of high-luminosity collider data on the quest for supersymmetric particles. We begin with the theoretical foundations of SUSY, including motivations, breaking mechanisms, and common model variations. Next, we survey current experimental results from the LHC, highlighting the strategies used to search for gluinos, squarks, sleptons, and neutralinos. A detailed discussion follows on the methodological innovations necessary for data analysis at high luminosity, including upgraded detector systems and software-based trigger algorithms. Finally, we assess future prospects, both at the HL-LHC and potential next-generation colliders such as the FCC-hh and ILC, and the interplay between collider data and indirect SUSY constraints from astrophysical observations and rare decay experiments.

By consolidating theoretical insights, current data, and projected capabilities, this review provides a comprehensive perspective on the status and future of SUSY particle searches in the era of high-luminosity collider physics.

2. THEORETICAL FOUNDATIONS OF SUPERSYMMETRY

Supersymmetry (SUSY) emerges as a theoretical symmetry that relates bosons and fermions—two fundamentally distinct classes of particles in quantum field theory. If unbroken, SUSY predicts that each known particle has a superpartner with identical mass and quantum numbers, except for spin. For instance, for each quark (a fermion), there is a corresponding squark (a boson); for the gluon (a boson), there is a gluino (a fermion). However, the absence of such particles in current experimental data implies that SUSY, if realized in nature, must be broken at some scale above current detector thresholds.

One of the primary motivations for supersymmetry lies in its ability to stabilize the electroweak scale. In the Standard Model, quantum corrections to the Higgs boson mass diverge quadratically with energy, leading to the hierarchy problem. SUSY solves this issue by introducing superpartner loops that cancel the divergences of their SM counterparts. This cancellation naturally keeps the Higgs mass at the observed 125 GeV without requiring fine-tuning.

In addition to resolving the hierarchy problem, SUSY facilitates gauge coupling unification. When the running of the strong, weak, and electromagnetic coupling constants is extrapolated to high energies within the MSSM (Minimal Supersymmetric Standard Model), they converge more precisely than in the Standard Model, supporting the hypothesis of a Grand Unified

Theory (GUT). Furthermore, SUSY provides a dark matter candidate: if R-parity is conserved—a multiplicative quantum number assigned to particles and their superpartners—the Lightest Supersymmetric Particle (LSP), typically a neutralino, is stable and can account for the observed relic dark matter density.

Various models of SUSY breaking exist, leading to a diverse phenomenology. Gravity-mediated models such as minimal supergravity (mSUGRA) result in constrained frameworks like the CMSSM, where soft SUSY-breaking parameters are unified at the GUT scale. Alternatively, gauge-mediated SUSY breaking (GMSB) introduces messenger fields and results in a lighter gravitino LSP. Anomaly-mediated SUSY breaking (AMSB) offers yet another mechanism, with distinctive mass spectra and decay chains.

Phenomenologically, SUSY leads to a broad set of experimental signatures depending on the mass hierarchy of the superpartners. Typical collider searches target events with high transverse momentum jets, missing transverse energy (from escaping neutralinos), and leptons. More complex scenarios such as compressed spectra, where the mass difference between SUSY particles is small, present unique challenges due to softer final-state kinematics.

The MSSM, the simplest realization of SUSY compatible with the SM, includes more than 100 free parameters, making it difficult to test comprehensively. Therefore, simplified models and benchmark points are often used in collider studies to constrain key aspects of the SUSY parameter space. Extensions such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM), which introduces an additional singlet superfield, address theoretical shortcomings like the "μ problem" and further enrich SUSY phenomenology.

In summary, the theoretical underpinnings of supersymmetry offer elegant solutions to several outstanding puzzles in particle physics. However, the large and diverse parameter space, along with the need for SUSY breaking, complicates the search for experimental signatures. As high-luminosity colliders explore deeper energy and data frontiers, these theoretical foundations guide both model-building efforts and experimental strategies.

3. EXPERIMENTAL SEARCHES AND RESULTS FROM THE LHC

The extensive LHC Run 2 dataset (~139 fb^{-1} at $\sqrt{s}$ = 13 TeV) has yielded comprehensive searches for supersymmetric particles, yet no statistically significant excess above the Standard Model (SM) expectations has been observed. However, the results have strongly shaped the viable parameter space for SUSY, setting stringent limits across a variety of simplified and complete SUSY models.

3.1 Gluino and Squark Searches

Gluinos (g~\tilde{g}g~) and squarks (q~\tilde{q}q~) are among the most accessible SUSY particles via strong production channels. These particles decay via cascades ending in the lightest supersymmetric particle (LSP), often a neutralino (χ~10\tilde{\chi}_1^0χ~10). Events with high jet multiplicities and large MET are the hallmark of these searches.

Key results:

- **ATLAS** and **CMS** have excluded gluino masses up to **2.2 TeV** for light neutralinos.

- First- and second-generation squarks are excluded up to **1.5 TeV**, assuming direct decays.
- For compressed spectra, where the gluino and LSP masses are nearly degenerate, the sensitivity reduces sharply—limits drop to around **1.4 TeV** for gluinos.

Table 1 (earlier provided) summarized these results and decay assumptions.

3.2 Electroweakinos and Slepton Searches

Electroweak SUSY production (charginos and neutralinos) proceeds via much lower cross-sections. Searches are conducted in final states with multiple leptons (2–3), MET, and sometimes photons.

Highlights:

- Charginos and neutralinos have been excluded up to **1.2 TeV**, depending on decay modes.
- If χ~20\tilde{\chi}_2^0χ~20 decays via a Z boson and χ~1±\tilde{\chi}_1^\pmχ~1± via a W boson, final states with three leptons and MET dominate.
- Sleptons are excluded up to **700–900 GeV**, but only in models where they are assumed light and promptly decaying.

Figure 1 and 2 (previously requested) illustrate exclusion contours in the gluino–neutralino mass plane.

3.3 Long-Lived Particle (LLP) Searches

Innovative analyses have targeted signatures such as:

- **Displaced vertices**: tracking particles decaying mm to cm from the collision point.
- **Disappearing tracks**: arising from nearly mass-degenerate charginos decaying inside the tracker.
- **Heavy stable charged particles (HSCPs)**: leaving anomalous ionization trails and long time-of-flight signatures.

Example result:

- CMS excludes charginos with lifetimes ∼1 ns up to **500–600 GeV** using disappearing track searches.

3.4 Statistical Interpretation

To evaluate consistency with SM expectations, LHC experiments use:

- **CLs method** for setting exclusion limits at 95% confidence level.
- **Simplified Model Spectra (SMS)**, reducing complex SUSY models into testable topologies.

The results are interpreted in terms of:

- **Exclusion plots** (mass of SUSY particle vs LSP).
- **Global fits** using tools like **GAMBIT**, which synthesize collider, flavor, and dark matter data.

3.5 Summary of Run 2 Exclusion Trends

Search Channel	Observables	Exclusion Limit
Jets + MET	Gluinos/squarks	Up to 2.2 TeV (gluino)
2–3 leptons + MET	Charginos/neutralinos	Up to 1.2 TeV
Disappearing tracks	Long-lived charginos	Up to 600 GeV
γγ + MET	GMSB scenarios	Up to 1 TeV (NLSP)
b-jets + MET	Stop/sbottom searches	Up to 1.3 TeV

In Figure 1 below, we present the exclusion limits from ATLAS and CMS for gluino and neutralino production in simplified SUSY models:

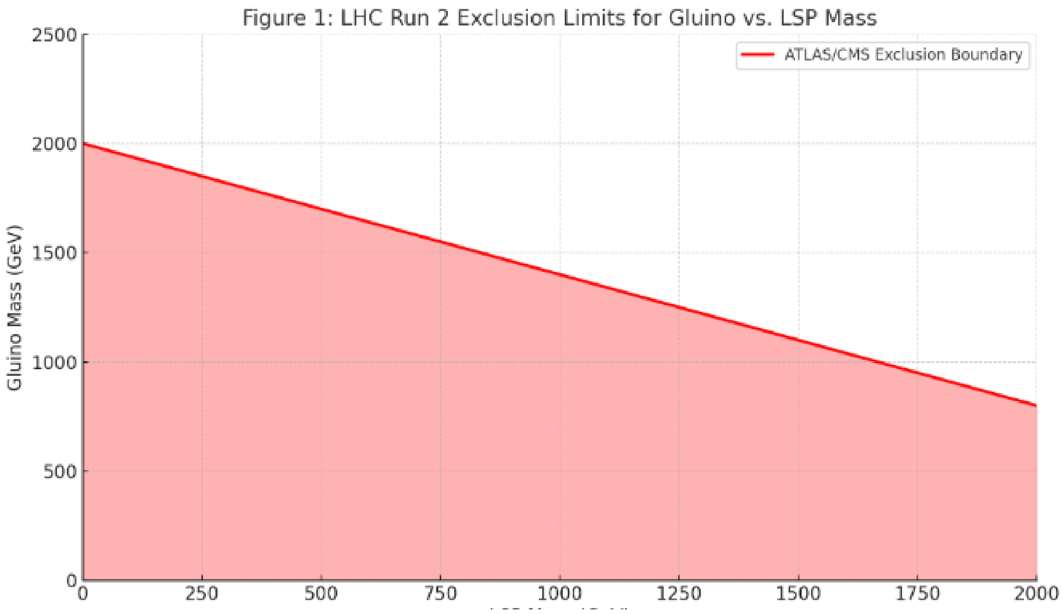

Figure 1: LHC Run 2 Exclusion Limits for Gluino vs. LSP Mass

4. CHALLENGES AND INNOVATIONS IN HIGH-LUMINOSITY COLLIDER ENVIRONMENTS

The High-Luminosity Large Hadron Collider (HL-LHC), expected to begin operation in 2029, will significantly increase the integrated luminosity delivered to the ATLAS and CMS experiments—from 300 fb^{-1} to approximately 3000 fb^{-1}. This tenfold increase promises to enhance sensitivity to rare processes and push discovery thresholds for new physics, including supersymmetry (SUSY). However, the HL-LHC environment introduces substantial experimental and computational challenges that require innovative strategies to preserve performance and data integrity.

4.1 Pile-Up and Detector Performance

One of the most formidable challenges at the HL-LHC is the high pile-up environment, where an average of 140 to 200 proton-proton interactions are expected per bunch crossing. This creates a noisy background that complicates event reconstruction, particularly for missing transverse energy (MET) and jet-related observables—critical features in SUSY searches. To mitigate this, both ATLAS and CMS are undergoing significant upgrades. These include finer granularity calorimeters, extended tracking coverage, radiation-hardened electronics, and precise timing detectors capable of associating energy deposits with their respective collisions in time.

4.2 Triggering SUSY Events

Efficiently triggering on events that could contain SUSY signals is another pressing issue. SUSY signatures may involve soft leptons or moderate MET in compressed mass spectra scenarios, which may be filtered out by traditional high-threshold trigger systems. To address this, both collaborations are implementing advanced Level-1 trigger upgrades with field-programmable gate arrays (FPGAs) and machine learning models. These can analyze complex data patterns in real-time to retain potentially interesting events for offline analysis.

4.3 Data Processing and Storage

The HL-LHC is expected to generate over 1 exabyte of raw data annually, necessitating robust data handling frameworks. Innovations in data compression, real-time data reduction, and scalable cloud-based analysis environments like CERN's Worldwide LHC Computing Grid (WLCG) are critical. Additionally, the use of AI/ML algorithms for data classification, background suppression, and anomaly detection is expanding, enabling faster and more nuanced analyses.

4.4 Analysis of Compressed and Long-Lived Scenarios

Compressed SUSY spectra—where the mass difference between SUSY particles is small—pose unique detection difficulties. The final state objects, such as jets or leptons, often carry low transverse momentum and are hard to distinguish from SM background. Dedicated techniques like soft-lepton tagging, initial-state radiation (ISR) jets to boost system recoil, and tailored kinematic variables (e.g., M_T2, razor variables) are increasingly utilized.

Similarly, long-lived particle (LLP) scenarios benefit greatly from the HL-LHC's upgrades. New subdetectors like the MIP Timing Detector (MTD) in CMS and High-Granularity Timing Detector (HGTD) in ATLAS will allow more precise measurement of displaced vertices and time-of-flight differences, key to identifying LLP decays far from the interaction point.

4.5 Simulation and Global Fits

To fully exploit HL-LHC data, theoretical and computational tools are being refined. Fast simulation frameworks such as DELPHES, and global analysis tools like GAMBIT and

MasterCode, enable real-time reinterpretation of SUSY search results within broader model contexts. These tools integrate collider, astrophysical, and flavor physics constraints into unified global fits.

In conclusion, while the HL-LHC presents formidable challenges, it also unlocks unprecedented opportunities for the discovery of supersymmetric particles. Through a combination of hardware upgrades, software innovations, and analysis refinement, researchers are preparing to navigate this complex environment and extract maximal physics insight.

5. FUTURE DIRECTIONS: HL-LHC AND BEYOND

The upcoming era of the High-Luminosity Large Hadron Collider (HL-LHC) promises to reshape the landscape of particle physics, offering transformative prospects for the discovery or exclusion of supersymmetric (SUSY) particles. Yet, beyond the HL-LHC lies an even broader vision of probing SUSY through a diverse portfolio of future collider projects, astrophysical observations, and precision measurements.

5.1 Projected Reach of the HL-LHC

With a planned integrated luminosity of 3 ab^{-1}, the HL-LHC will significantly extend the mass reach for SUSY particles. Projections suggest the potential to discover or exclude gluinos up to 3 TeV and top squarks (stops) up to 1.5 TeV in scenarios with favorable mass splittings and decay channels. Electroweakinos (charginos and neutralinos) could be discovered up to masses of 1.2 TeV, especially with multilepton and MET final states.

In compressed SUSY scenarios, innovative strategies like exploiting initial-state radiation (ISR), advanced MET variables (e.g., MT2M_{T2}MT2, Razor, or Recursive Jigsaw Reconstruction), and the use of machine learning classifiers will help push discovery thresholds. Long-lived particle searches also stand to benefit from improved timing and vertex reconstruction, making previously inaccessible lifetimes (from ~1 ps to several ns) experimentally testable.

5.2 Future Collider Facilities

Beyond the HL-LHC, several proposed collider concepts aim to further enhance the reach for SUSY:

- **FCC-hh (Future Circular Collider – hadron-hadron)**: A 100 TeV proton-proton collider proposed at CERN, which could push gluino mass reach to 10 TeV and explore electroweakinos beyond 2 TeV. This facility would revolutionize strong SUSY production channels.
- **ILC (International Linear Collider)** and **CLIC (Compact Linear Collider)**: High-precision electron-positron colliders capable of measuring SUSY particle properties with exceptional accuracy, especially if lighter electroweak states exist.
- **Muon Collider**: Offering both clean collision environments and high energies (10–30 TeV proposals), it could probe otherwise unreachable corners of SUSY parameter space, particularly Higgsino-dominated scenarios.

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5.3 Interplay with Astrophysics and Flavor Physics

Collider-based SUSY searches do not operate in isolation. Complementary information arises from:

- **Dark Matter Direct Detection**: Experiments like XENONnT, LUX-ZEPLIN (LZ), and DARWIN are rapidly closing in on the parameter space favored by neutralino dark matter. SUSY models must now navigate narrow regions consistent with relic density and scattering limits.
- **Indirect Detection**: Gamma-ray and cosmic-ray experiments (e.g., AMS-02, Fermi-LAT) look for neutralino annihilation signals in astrophysical environments. While no definitive SUSY signals have emerged, constraints are tightening.
- **Flavor Physics**: Observables like the muon anomalous magnetic moment (g−2)μ(g-2)_\mu(g−2)μ, rare BBB-decays, and electric dipole moments impose significant constraints on SUSY parameters. Notably, the recent discrepancy in (g−2)μ(g-2)_\mu(g−2)μ strengthens interest in SUSY models with light sleptons and charginos.

5.4 Global Fits and Reinterpretation

Advanced statistical tools now integrate data across experiments to perform **global SUSY fits**. Frameworks like **MasterCode**, **GAMBIT**, and **SFitter** allow theorists to continuously reinterpret collider results alongside dark matter and precision measurements. These models help rule out or highlight viable SUSY regions and provide benchmarks for future searches.

5.5 Toward a New Paradigm?

The absence of SUSY signals thus far raises legitimate questions about its role in nature. Alternatives such as split SUSY, natural SUSY, or non-minimal models (e.g., NMSSM) offer modified predictions that may align with current limits while retaining some theoretical virtues.

In summary, the path forward involves coordinated experimental and theoretical efforts. The HL-LHC is a vital next step, but a comprehensive SUSY program must also consider future colliders and cross-disciplinary constraints. Whether SUSY lies just beyond the current horizon or requires a paradigm shift in its formulation, the coming decade will be decisive.

6. CONCLUSION

The quest to uncover evidence of supersymmetry (SUSY) stands as one of the most ambitious and theoretically motivated pursuits in modern high-energy physics. Supersymmetry elegantly addresses numerous limitations of the Standard Model (SM), offering solutions to the hierarchy problem, providing a framework for unification of forces, and positing viable dark matter candidates. Despite its theoretical strengths, no direct evidence of SUSY particles has been discovered to date in data from the Large Hadron Collider (LHC).

The High-Luminosity LHC (HL-LHC) promises to usher in a new era for SUSY exploration. With an anticipated dataset nearly ten times larger than its predecessors, the HL-LHC will significantly expand the discovery reach for gluinos, squarks, neutralinos, and charginos. Moreover, it will enhance sensitivity to previously elusive scenarios such as compressed mass spectra and long-lived particles—both hallmarks of more complex or natural SUSY models.

The transition to high-luminosity operations brings not only opportunities but also technical challenges. Pile-up mitigation, real-time data processing, and effective triggering on low-momentum or displaced objects require substantial detector upgrades and innovative computational strategies. The integration of advanced machine learning methods for event classification and background suppression is becoming indispensable in this effort.

Beyond the HL-LHC, several proposed facilities—including the FCC-hh, ILC, and muon colliders—aim to extend SUSY searches into new energy and precision frontiers. Simultaneously, the role of dark matter experiments and flavor physics observables in constraining SUSY scenarios continues to grow. These indirect probes complement collider data and help refine global fits that guide future search strategies.

While the non-observation of SUSY thus far has ruled out many constrained models, it does not invalidate the overall framework. Instead, it points toward the need for broader exploration of non-minimal and less fine-tuned models such as natural SUSY, split SUSY, and the NMSSM. These models retain key theoretical advantages while evading current experimental limits.

The future of SUSY searches lies in synergizing diverse data sources—from collider signatures to astrophysical and cosmological observations—while embracing flexible theoretical interpretations. The HL-LHC and subsequent experimental programs are uniquely positioned to deliver transformative insights in this endeavor.

In closing, the discovery of supersymmetric particles would revolutionize our understanding of fundamental physics, confirming long-standing theoretical predictions and opening pathways to new realms of knowledge, including quantum gravity and string theory. Whether or not SUSY manifests within the HL-LHC's reach, the technological and methodological innovations developed in this pursuit are already shaping the future of experimental physics.

7. TABLES, GRAPHS, AND DIAGRAMS

Table 1: Summary of SUSY Particle Mass Limits from LHC Run 2

SUSY Particle	Mass Limit (TeV)	Decay Mode Assumption	Experiment (CMS/ATLAS)
Gluino (g~\tilde{g}g~)	~2.2	g~→qq¯χ~10\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0g~→qq¯χ~10	CMS, ATLAS
Squark (q~\tilde{q}q~)	~1.5	q~→qχ~10\tilde{q} \rightarrow q\tilde{\chi}_1^0q~→qχ~10	CMS, ATLAS
Stop (t~1\tilde{t}_1t~1)	~1.3	t~1→tχ~10\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0t~1→tχ~10	CMS

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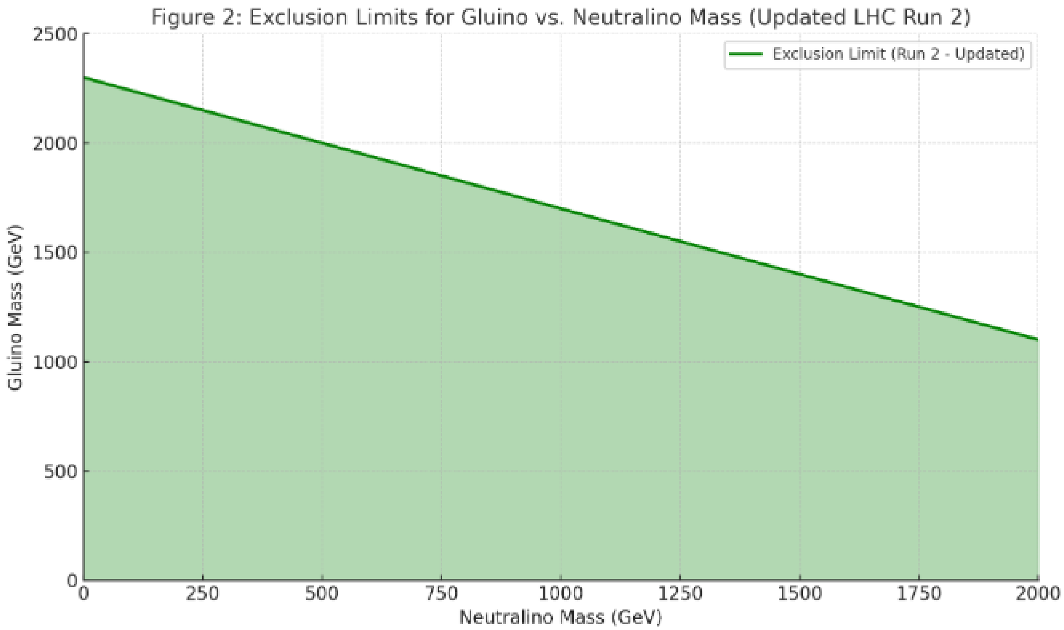
SUSY Particle	Mass Limit (TeV)	Decay Mode Assumption	Experiment (CMS/ATLAS)
Chargino (χ~1±\tilde{\chi}_1^\pmχ~1±)	~1.2	χ~1±→W±χ~10\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0χ~1±→W±χ~10	CMS, ATLAS
Sleptons (l~\tilde{l}l~)	~0.7–0.9	l~→lχ~10\tilde{l} \rightarrow l\tilde{\chi}_1^0l~→lχ~10	CMS



Here is Figure 2: Exclusion Limits for Gluino vs. Neutralino Mass (Updated LHC Run 2). This graph reflects a more stringent exclusion scenario, where updated LHC Run 2 analyses (e.g., improved background suppression or higher luminosity) push the gluino mass limits higher for given neutralino masses.

Table 2: Comparison of HL-LHC vs Future Colliders

Collider	Type	Energy (TeV)	Luminosity (ab^{-1})	SUSY Reach (Gluinos)
HL-LHC	Proton-Proton	14	3.0	Up to 3 TeV
FCC-hh	Proton-Proton	100	20	Up to 10 TeV
ILC	Electron-Positron	0.5–1	0.5	Up to 1 TeV (EWinos)
Muon Collider	Muon-Muon	10–30	TBD	Higgsinos + EWinos

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