LHC luminosity and energy upgrades confront natural supersymmetry models

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arXiv : 1808.04844 with : Howard Baer, Vernon Barger, James S. Gainer, Hasan Serce and Xerxes Tata

Energy Frontier in Particle Physics: LHC and Future Colliders

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Overview

1. Supersymmetry : A BSM Theory
2. Naturalness
3. Confronting natural SUSY models at the LHC and its upgrades

SUSY as a BSM Theory

Till today, though, the Standard Model (SM) is the most celebrated and established theory, there are several reasons to expect new physics beyond SM. **Weak Scale Supersymmetry** is one of the most attractive ways to deal with these problems. Supersymmetry or SUSY is a highly motivated extension of SM which obeys a new quantum symmetry which relates fermions to bosons. Supersymmetrizing the SM leads to the MSSM.

- One of the main advantage of SUSY is that quadratic divergences in Higgs Mass due to each SM particle is cancelled by its *Superpartner*.
- In addition to this, the MSSM receives impressive support from *data* via several different virtual effects: the gauge coupling unification, $m_h \sim 125$ GeV, $m_t \sim 175$ GeV for REWSB.
- Naively one may expect sparticles at or near weak scale m_{weak} ~100 GeV.
- **Current LHC Limits :** $m_{\tilde{g}} > 2.2 TeV$, $m_{\tilde{t}_1} > 1.1 TeV$
- Do these limits rule out SUSY? if not, what collider is needed to verify or rule out weak scale SUSY?

Supersymmetry and its Breaking

Since no superpartners have been observed (e.g. a bosonic electron with mass m(e)), then SUSY must be broken, with a breaking scale not too far from the weak scale m_{weak} ~100 GeV.

$m_{sparticles} >> m_{SMparticles} \implies$ SUSY broken $\implies$ Soft SUSY breaking (SSB) terms $\implies$ Log divergences introduced

How does these SSB terms originate ?

$$\left.\begin{array}{l}\text{Gravity-mediation} \\ \text{Anomaly-mediation}\end{array}\right\} \rightarrow \text{Mirage-mediation}$$

Gauge-mediation

Gaugino-mediation

Naturalness

$$m_{sparticles} >> m_{SMparticles}$$

LHC Limits : $m_{\tilde{g}} > 2.2 TeV$, $m_{\tilde{t}_1} > 1.1 TeV \implies$ **Is SUSY Unnatural?**

The notion of *Practical Naturalness* states that

> *An Observable $\mathcal{O}$ is natural if all independent contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.*

The measure of Naturalness is the Electroweak fine-tuning parameter (Δ_{EW}) which is defined as

$$\Delta_{EW} = max_i |C_i| / (M_Z^2/2) \tag{1}$$

Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{2}$$

A SUSY model is said to be natural if $\Delta_{EW} < 30$. This choice $\Delta_{EW} < 30$ is not ad-hoc, rather it arises from anthropic requirements for life to sustain (See Howard Baer's talk on Oct 5, 9-9:30 AM).

arXiv : 1702.06588 by H. Baer et. al.

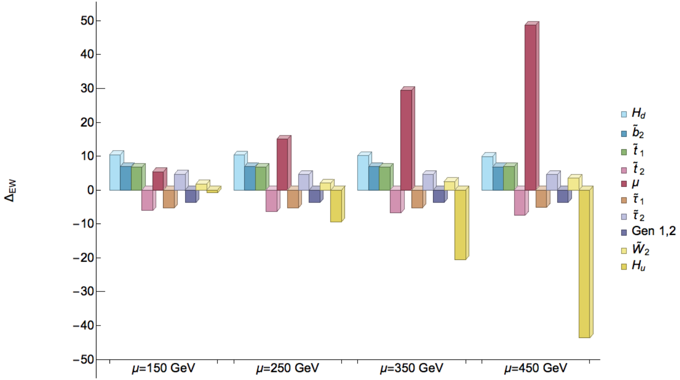

Figure: 3. Top ten contributions to Δ_{EW} from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV.

$\Delta_{EW} < 30$ requires $\mu \sim$ 100-350 GeV.

SUSY μ problem

- The MSSM superpotential contains term $\mu H_u H_d$ which leads to $\mu \approx m_P$.
- $\mu \approx$ **100 - 350 GeV** phenomenologically for naturalness (no large cancellations in Equation (2))

This is the famous SUSY μ problem

- A promising approach to solve the SUSY μ problem is to first forbid μ, perhaps via some symmetry, and then re-generate it of order the scale of soft SUSY breaking terms.
- However, present LHC limits suggest the soft breaking scale m_{soft} lies in the multi-TeV regime whilst naturalness requires $\mu \sim m_{W,Z,h} \sim$ 100 GeV so that a Little Hierarchy (LH) appears with $\mu \ll m_{soft}$.

$\mathbb{Z}_{24}^{R}$ solution to μ problem

$\mu_{eff} \sim m_{weak}$ is generated

~~R-Parity Violating operators~~

~~Dim-5 proton decay operators~~

Solves the gravity-spoliation problem because no terms with suppression less than $1/m_P^8$ are allowed in the scalar potential

SUSY saves PQ solution to strong CP problem from the gravity spoliation problem via the introduction of $\mathbb{Z}_{24}^{R}$ discrete symmetry as the fundamental symmetry.

arXiv:1810.03713 by H. Baer, V. Barger and **D.S.**

arXiv:1902.10748 by K.J. Bae, H. Baer, V. Barger and **D.S.**

arXiv : 1602.07697 by H. Baer et. al.

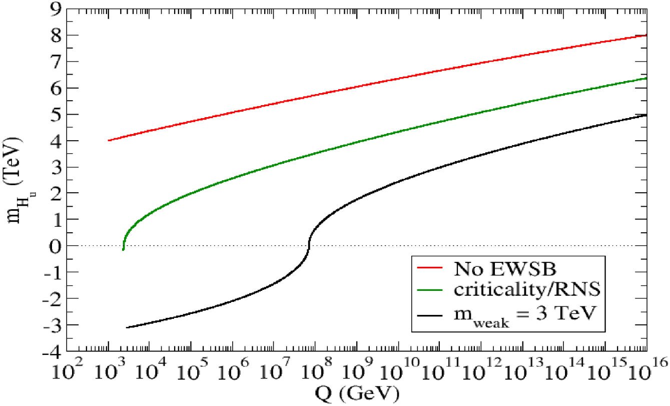

Figure: 4. Evolution of the term $sign(m^2_{H_u})\sqrt{m^2_{H_u}}$ for the case of *No EWSB*, criticality as in *RNS* and $m_{weak} = 3$ TeV. Supersymmetric models with **radiatively-driven naturalness** enjoy modest electroweak fine-tuning while respecting LHC sparticle and Higgs mass constraints.

nNUHM2,3 Model

In the two- or three- extra parameter non-universal Higgs models, nNUHM2 or nNUHM3,

- The SSB parameters arise from tree level gravitational interactions of observable sector superfields with gauge singlet hidden sector fields. This mechanism is called **Gravity-mediated SUSY breaking**.
- The gaugino masses are unified to $m_{1/2}$, the matter scalar soft masses are unified to m_0 and the trilinear couplings are unified to A_0 at the GUT scale.
- In the NUHM3 model, it is further assumed that the third generation matter scalars are split from the first two generation $m_0(1,2) \neq m_0(3)$.
- The soft Higgs masses m_{H_u} and m_{H_d} are independent of m_0.Typically the parameter freedom in m_{H_u} and m_{H_d} is traded for the more convenient weak scale parameters μ and m_A.

NUHM2

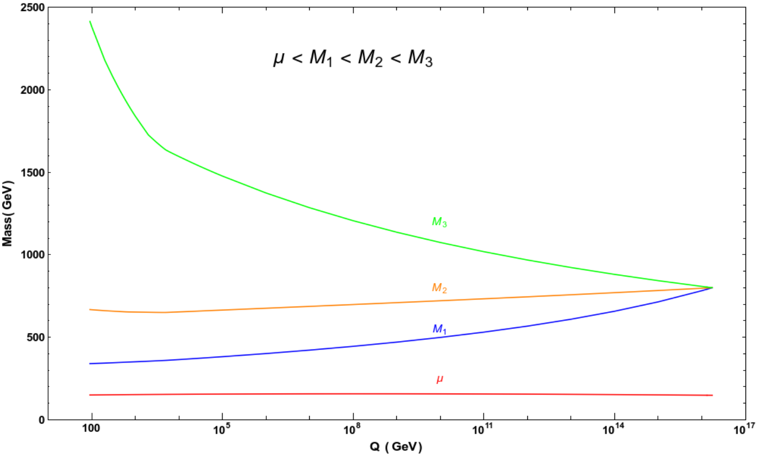

Figure: 5. This hierarchy leads to a novel, rather clean same-sign diboson signature from wino pair production at hadron colliders.

nAMSB Model

arXiv : 1801.09730 by H. Baer, V. Barger and **D. S.**

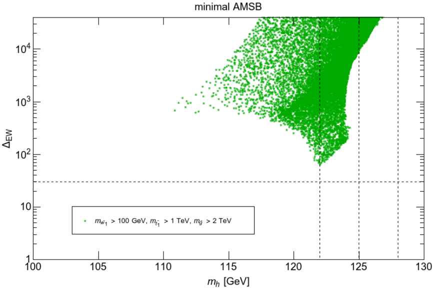

Figure: 6(a) Parameter Space : m_0, $m_{3/2}$, tan β and sign(μ)

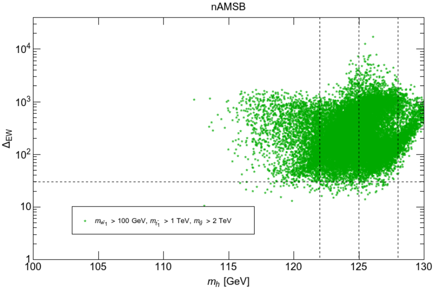

Figure: 6(b) Parameter Space : m_0, $m_{3/2}$, A_0, tan β, μ, m_A

The nAMSB parameter space allows $m_h \sim 125$ GeV due to including bulk A term and allows naturalness by independent bulk Higgs masses. Winos are still lightest gauginos but $\mu \ll M_2 < M_1$ and M_3.

nGMM Model

In this model, SUSY is broken through **mirage-mediation** which is a mixed gravity/moduli plus anomaly-mediated soft SUSY breaking (SSB) mechanism where we can choose how much each of gravity/moduli-mediated and anomaly-mediated SUSY breaking contribute.

A distinctive feature of this model is that gaugino(and scalar) masses evolve from non-universal values at the GUT scale to apparently universal values at some intermediate scale
$\mu_{mir} = m_{GUT} \times e^{-8\pi^2/\alpha}$
where the introduced parameter α measures the relative moduli- versus anomaly-mediated contributions to gaugino masses.

The natural generalized MM model is characterized by the parameter set :

$$\alpha,\ m_{3/2},\ c_m,\ c_{m3},\ a_3,\ \tan\beta,\ \mu,\ m_A$$

Mirage Mediation

arXiv : 1610.06205 by H. Baer et. al.

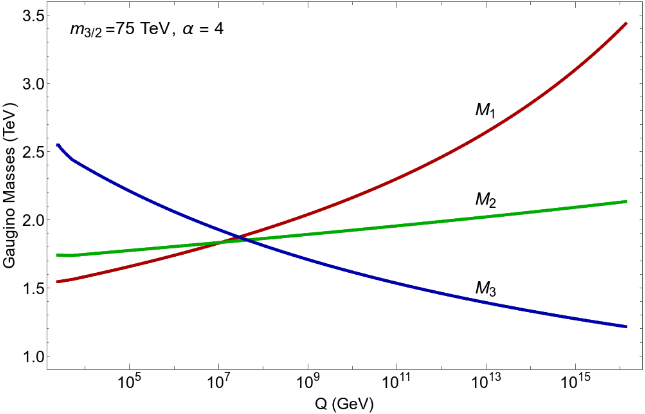

Figure: 7. Evolution of gaugino masses from the nGMM benchmark point with $m_{3/2}$= 75 TeV, α= 4.

RNS Models

- nNUHM2 Model *(Nucl.Phys. B435 (1995) 115-128; JHEP 0507 (2005) 065.)*
  m_0, $m_{1/2}$, A_0, $\tan\beta$, μ, m_A
- nNUHM3 Model *(Nucl.Phys. B435 (1995) 115-128; JHEP 0507 (2005) 065.)*
  $m_0(1,2)$, $m_0(3)$, $m_{1/2}$, A_0, $\tan\beta$, μ, m_A
- nGMM Model *(Phys. Rev. D 94 (2016) no.11, 115017.)*
  α, $m_{3/2}$, c_m, c_{m3}, a_3, $\tan\beta$, μ, m_A
- nAMSB Model *(Nucl. Phys. B 557 (1999) 79; Phys. Rev. D 98 (2018) no.1, 015039.)*
  m_0, $m_{3/2}$, A_0, $\tan\beta$, μ, m_A

arXiv : 2002.03013 by H. Baer, V. Barger, S. Salam, **D. S.** and K. Sinha.

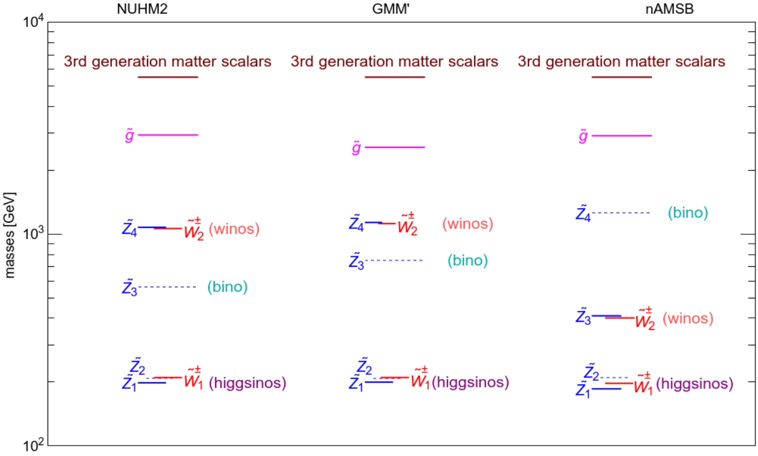

Figure: 8. Typical mass spectra from natural SUSY in the case of NUHM2 (with gaugino mass unification), nGMM with mirage unification and compressed gauginos and natural AMSB where the wino is the lightest gaugino. In all cases, the higgsinos lie at the bottom of the spectra.

Search Channels

The four most important search channels for natural SUSY at the LHC or its upgrades are the following :

- Gluino pair production : $pp \to \tilde{g}\tilde{g}X$ followed by $\tilde{g} \to \tilde{t}_1^* t$, $\tilde{t}_1 \bar{t}$ or if these are closed, then $\tilde{g} \to t\bar{t}\tilde{Z}_i$, $t\bar{t}\tilde{Z}_i$ or $t\bar{b}\tilde{W}_i^+ + c.c.$
- Top squark pair production : $pp \to \tilde{t}_1\tilde{t}_1^* X$ followed by $\tilde{t}_1 \to t\tilde{Z}_i$ or $b\tilde{W}_j^+$
- Higgsino pair production : $pp \to \tilde{Z}_i\tilde{Z}_j j, \tilde{W}_1\tilde{Z}_i j, \tilde{W}_1\tilde{W}_1 j$ channels is unlikely to be visible above SM Zj background. However, the $pp \to \tilde{Z}_1\tilde{Z}_2 j$ channel (with contributions from $pp \to \tilde{W}_1\tilde{Z}_2 j$) , where $\tilde{Z}_2 \to \ell\bar{\ell}\tilde{Z}_1$ with a soft OS dilepton pair and where the hard initial state radiated jet supplies a trigger, offers a promising search channel for low mass higgsinos with $m_{\tilde{Z}_{1,2}} \sim 100 - 300$ GeV.
- Wino pair production : $pp \to \tilde{W}_2^{\pm}\tilde{Z}_{3 \text{ or } 4}X$ followed by $\tilde{W}_2 \to W\tilde{Z}_{1,2}$ and $\tilde{Z}_{3 \text{ or } 4} \to W^{\pm}\tilde{W}_1^{\mp}$ leading to a clean same-sign diboson signal.

Total production cross sections for gluinos and top squarks at 14 and 27 TeV

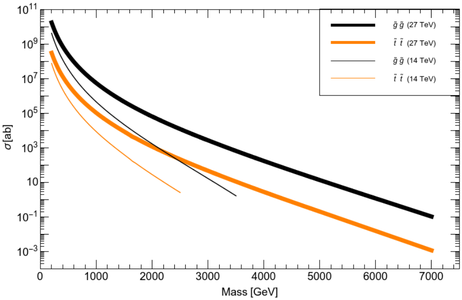

Figure: 9.Plot of NLL+NLO predictions of $\sigma(pp \to \tilde{g}\tilde{g}X)$ and $\sigma(pp \to \tilde{t}_1\tilde{t}_1^* X)$ production at LHC for $\sqrt{s} = 14$ and 27 TeV.

Eur. Phys. J. C **74** (2014) no.12, 3174. by C. Borschensky et. al.

Phys. ReV. D. **98** (2018) no.7, 075010 by H. Baer et. al.

Updated top squark analysis for $\sqrt{s} = 27$ TeV

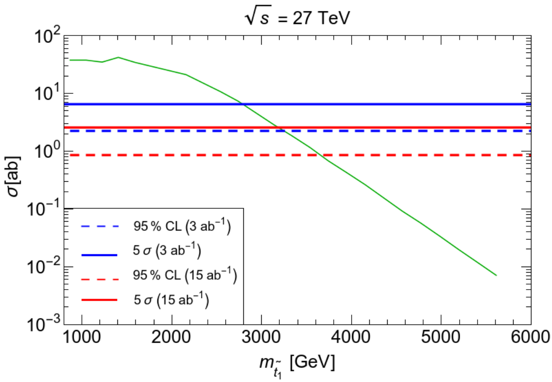

Figure: 10.Plot of top-squark pair production cross section vs. $m_{\tilde{t}_1}$ after cuts at HE-LHC with $\sqrt{s} = 27$ TeV (green curve). We also show the 5σ and 95% CL reach lines assuming 3 and 15 ab^{-1} of integrated luminosity (for a single detector).

Updated gluino analysis for $\sqrt{s} = 27$ TeV

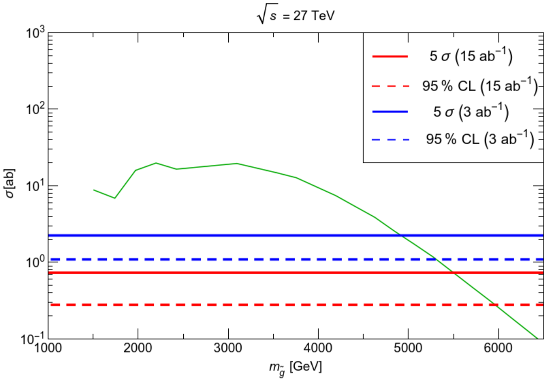

Figure: 11.Plot of gluino pair production cross section vs. $m_{\tilde{g}}$ after cuts at HE-LHC with $\sqrt{s} = 27$ TeV (green curve). We also show the 5σ and 95% CL reach lines assuming 3 and 15 ab^{-1} of integrated luminosity.

Gluino pair production

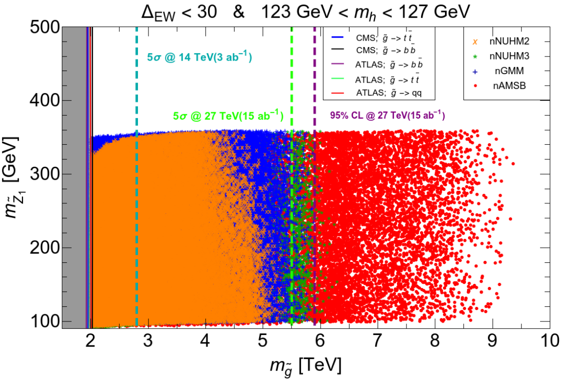

Figure: 12.Plot of points in the $m_{\tilde{g}}$ vs. $m_{\tilde{z}_1}$ plane from a scan over nNUHM2, nNUHM3, nGMM and nAMSB model parameter space. We compare to recent search limits from the ATLAS/CMS experiments (solid vertical lines) and future LHC upgrade options (dashed vertical lines).

Top squark pair production

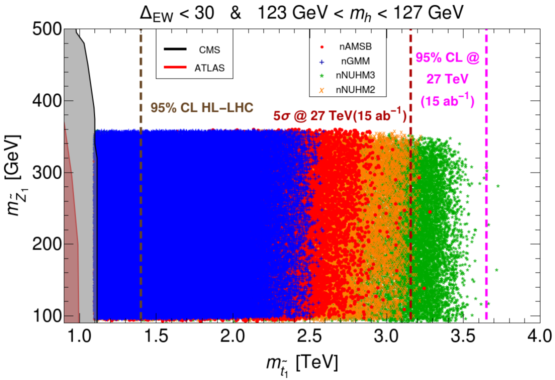

Figure: 13.Plot of points in the $m_{\tilde{t}_1}$ vs. $m_{\tilde{z}_1}$ plane from a scan over nNUHM2, nNUHM3, nGMM and nAMSB model parameter space. We compare to recent search limits from the ATLAS/CMS experiments (solid contours) and to projected future limits (dashed lines).

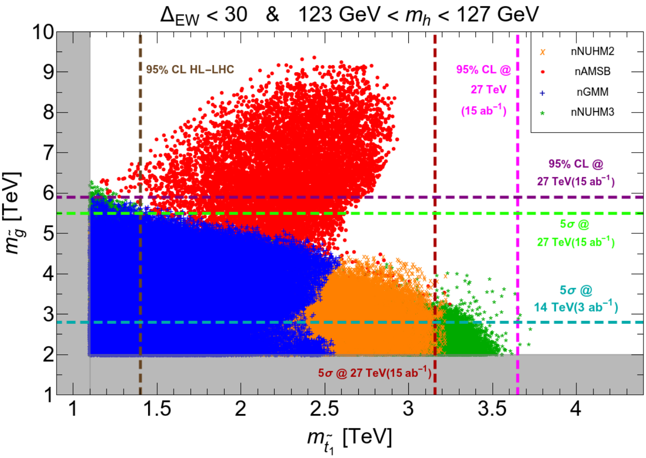

Figure: 14.Plot of points in the $m_{\tilde{t}_1}$ vs. $m_{\tilde{g}}$ plane from a scan over nNUHM2, nNUHM3, nGMM and nAMSB model parameter space. We compare to projected future search limits from the LHC experiments.

Higgsino pair production

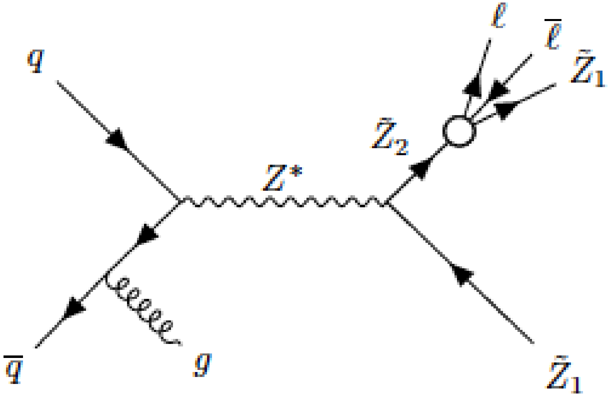

Figure: 15.

Higgsino pair production ATLAS result

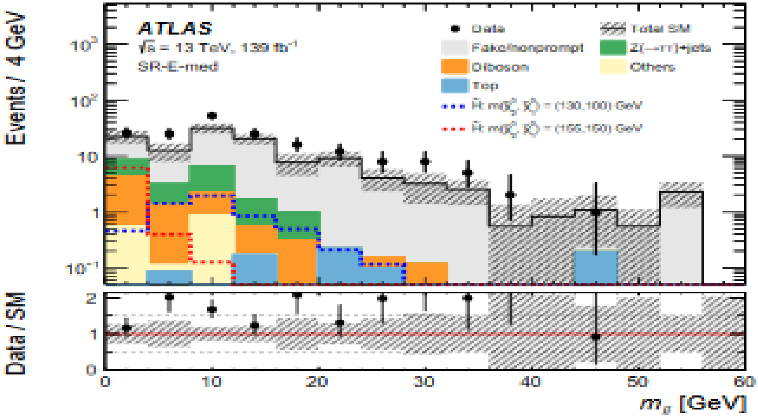

Figure: 16. *arXiv : 1911.12606 ATLAS Collaboration*

Higgsino pair production

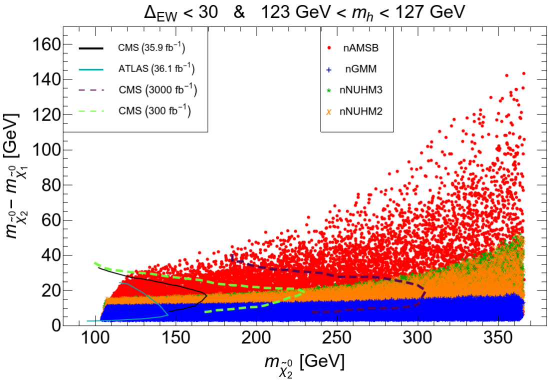

Figure: 17.Plot of points in the $m_{\tilde{z}_2}$ vs. $m_{\tilde{z}_2} - m_{\tilde{z}_1}$ plane from a scan over nNUHM2, nNUHM3, nGMM and nAMSB model parameter space. We compare to recent search limits from the ATLAS/CMS experiments and some projected luminosity upgrades as computed by CMS.

Wino pair production

arXiv : 1710.09103 by H. Baer, V. Barger, J.S. Gainer, M. Savoy, **D. S.** and X. Tata.

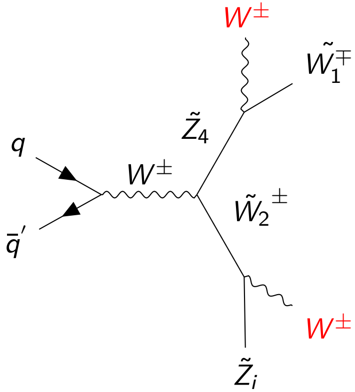

Figure: 18. Same-sign diboson production at LHC in SUSY models with light higgsinos ($\tilde{W}_1^\mp$ and $\tilde{Z}_i$). Here, $\tilde{Z}_4$ and $\tilde{W}_2^\pm$ in the intermediate step are winos.

Wino pair production

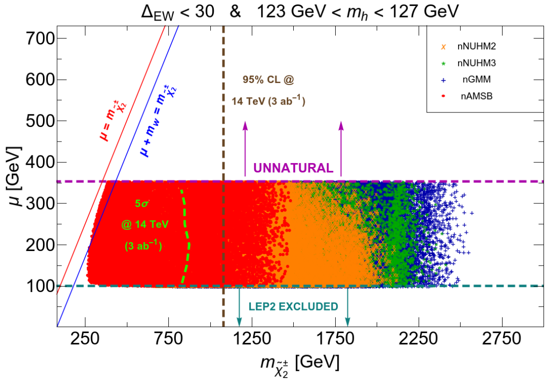

Figure: 19.Plot of points in the $m_{\tilde{w}_2^-}$ vs. μ plane from a scan over nNUHM2, nNUHM3, nGMM and nAMSB model parameter space. We compare to projected search limits for the ATLAS/CMS experiments at HL-LHC.

Summary

- Our goal, in this paper, was to ascertain what sort of LHC upgrades might be sufficient to either discover or falsify natural supersymmetry.
- We scanned over four different natural SUSY models: nNUHM2,3 nAMSB and nGMM. We obtained $m_{\tilde{t}_1} \leq 3.5$ TeV, $m_{\tilde{g}} \leq 6$ TeV in nNUHM2,3 and nGMM, but $m_{\tilde{g}} \leq 9$ TeV in nAMSB and upper limits on higgsino and wino masses.
- We compared these against current LHC constraints and found large regions of natural SUSY parameter space remain to be explored.
- We also compared against the HL-LHC upgrade: the HL-LHC with $\sqrt{s} = 14$ TeV and 3 ab^{-1} of integrated luminosity and also updated the HE-LHC reach using the revised energy and integrated luminosity targets as suggested by the ongoing European Strategy study: $\sqrt{s} = 27$ TeV and IL$= 15$ ab^{-1}.
- We found that HL-LHC is likely to see a OSDLMET signal arising from higgsino pair-production. May need HE-LHC to see (natural) gluinos and top squarks and winos.


Thank you ...

QUESTIONS ?

BACK UP SLIDES

Δ_{EW}, Δ_{HS}, Δ_{BG}

$\mathcal{O} = \mathcal{O}$ + b - b

When evaluating fine-tuning, it is not permissible to claim fine-tuning of dependent quantities one against another.

The Electroweak Measure Δ_{EW}

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{3}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{4}$$

Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \tag{5}$$

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \tag{6}$$

where Λ is a high energy scale up to which MSSM is valid. Λ can be as high as m_{GUT} or even m_P.
A simple fix for Δ_{HS} is to regroup the dependent terms as follows :

$$m_h^2 \approx \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) \tag{7}$$

This regrouping now leads back to Δ_{EW} measure because now $(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) = m_{H_u}^2(Weak)$.

Updated top squark analysis for $\sqrt{s} = 27$ TeV

Cuts : $n(b - jets) \geq 2$, $n(isol.\ leptons) = 0$,
$E_T^{miss} > max(1500\ \mathrm{GeV}, 0.2M_{eff})$, $E_T(j_1) > 1000$ GeV, $E_T(j_2) > 600$ GeV,
$S_T > 0.1$ and $\Delta\phi(\vec{E}_T^{miss}, \mathrm{jet\ close}) > 30$ deg.
Where, M_{eff} is the usual effective mass variable, S_T is transverse sphericity and the $\Delta\phi$ cut is on the transverse opening angle between the missing E_T vector and the closest jet. The surviving background rates in ab are listed below :

process	σ (ab)
$b\bar{b}Z$	1.87
$t\bar{t}Z$	1.1
t	4.4×10^{-2}
$t\bar{t}$	3.3×10^{-2}
$t\bar{t}b\bar{b}$	2.3×10^{-2}
$t\bar{t}t\bar{t}$	1.7×10^{-3}
$t\bar{t}h$	6.8×10^{-4}
total	3.07

Updated gluino analysis for $\sqrt{s} = 27$ TeV

Cuts : $n(b-jets) \geq 2$, $n(isol.\ leptons) = 0$,
$E_T^{miss} > max(1900\ \mathrm{GeV}, 0.2M_{eff})$, $E_T(j_1) > 1300$ GeV, $E_T(j_2) > 900$ GeV,
$E_T(j_3) > 200$ GeV, $E_T(j_4) > 200$ GeV, $S_T > 0.1$ and
$\Delta\phi(\vec{E}_T^{miss}, \mathrm{jet\ close}) > 10$ deg.

The corresponding backgrounds in ab after cuts are listed below :

process	σ (ab)
$b\bar{b}Z$	0.061
$t\bar{t}Z$	0.037
t	0.003
$t\bar{t}$	0.026
$t\bar{t}b\bar{b}$	0.0046
$t\bar{t}t\bar{t}$	0.0
$t\bar{t}h$	8.1×10^{-4}
total	0.132