New angular (and other) cuts to improve the higgsino signal at the LHC

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Overview

1. The Standard Model and its drawbacks
2. SUSY as a BSM Theory
   - Naturalness
   - Radiatively-Driven Natural SUSY models
3. SUSY Signal and SM Backgrounds
   - New Angle cuts
   - Improved efficiency due to new Angle cuts
   - Mass reach
4. Conclusion

The Standard Model and its drawbacks

Although, the Standard Model is the most celebrated theory till date, it has certain drawbacks as follows :

- Existence of Dark Matter [LSP from RPC SUSY + QCD Axion]
- The Higgs mass instability problem in the EW sector [SUSY]
- Gravity, Dark energy, Cosmological Constant [Landscape]

SUSY as a BSM Theory

- Softly Broken supersymmetry or SUSY is a highly motivated extension of SM which obeys a new quantum symmetry which relates fermions to bosons.
- In SUSY, the SM fields are elevated to superfields containing both fermionic and bosonic components. Supersymmetrizing the SM leads to the MSSM.
- Quadratic Divergences in Higgs Mass due to each SM particle is cancelled by its *Superpartner*. This idea solves the Big Hierarchy problem which is one of the main motivations of SUSY.
- But **no** sparticles have been seen in LHC yet.

Naturalness

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

Unless the spectrum is compressed,

LHC Limits: $m_{\tilde{g}} > 2.2$ TeV, $m_{\tilde{t}_1} > 1.3$ TeV $\Longrightarrow$ **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

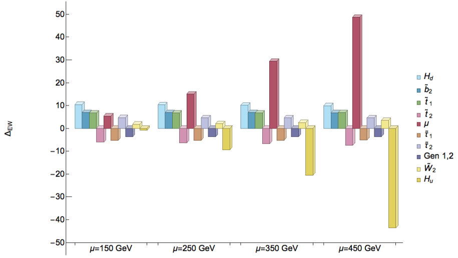
$$\Delta_{EW} = max_i |C_i|/(M_Z^2/2) \quad (1)$$

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

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) tan^2\beta}{tan^2\beta - 1} - \mu^2 \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \quad (2)$$

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.

Naturalness



Top ten contributions to $\Delta_{EW} = max_i|C_i|/(M_Z^2/2)$ from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV.

arXiv: 1509.02929 by Baer, Barger and Savoy.

arXiv: 1702.06588 by Baer, Barger, Gainer, Huang, Savoy, Serce and Tata.

Requiring $\Delta_{EW} < 30$ implies

- $\mu \leq 300$ GeV $\Longrightarrow$ Light higgsinos.
- top squarks must be highly mixed $\Longrightarrow m_h \sim 125$ GeV.

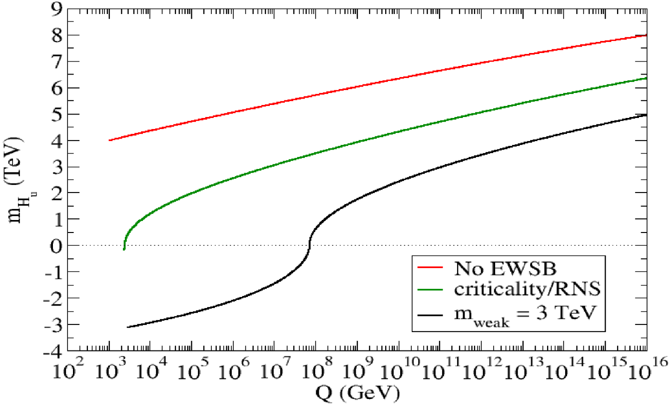
SUSY μ problem

- 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 μ $\sim m_{W,Z,h} \sim$ 100 GeV so that a Little Hierarchy (LH) appears with $\mu \ll m_{soft}$.

arXiv : 1602.07697 by H. Baer et. al.



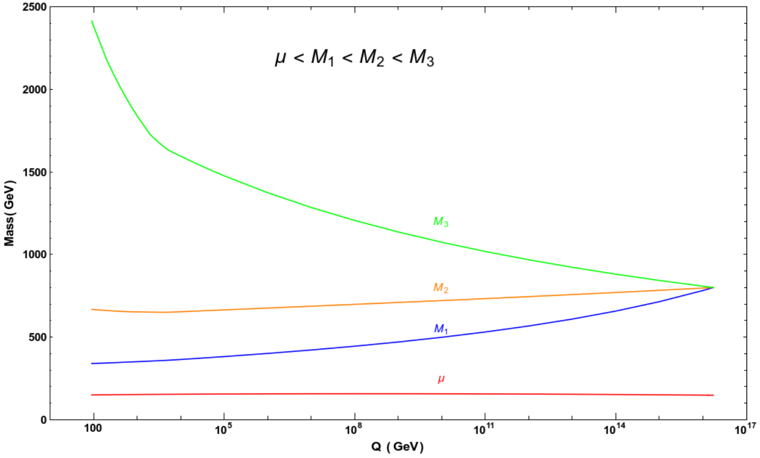
Evolution of the term $sign(m^2_{H_u})\sqrt{m^2_{H_u}}$ for the case of $No\ EWSB$, criticality as in RNS and $m_{weak} = 3$ TeV. Supersymmetric models with **radiatively-driven naturalness** enjoy modest electroweak fine-tuning while respecting LHC sparticle and Higgs mass constraints.

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

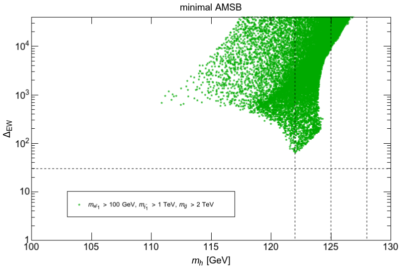


This hierarchy leads to a novel, rather clean same-sign diboson signature from wino pair production at hadron colliders.

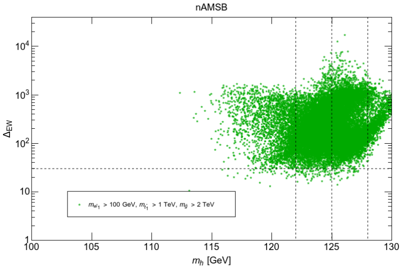
nAMSB Model

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

In this model, one-loop contribution to the SSB parameters originates in the super-Weyl anomaly always when SUSY is broken. This mechanism is called the **anomaly-mediated SUSY breaking**. Though loop suppressed, this contribution is always present.



minimal AMSB



Natural AMSB

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.

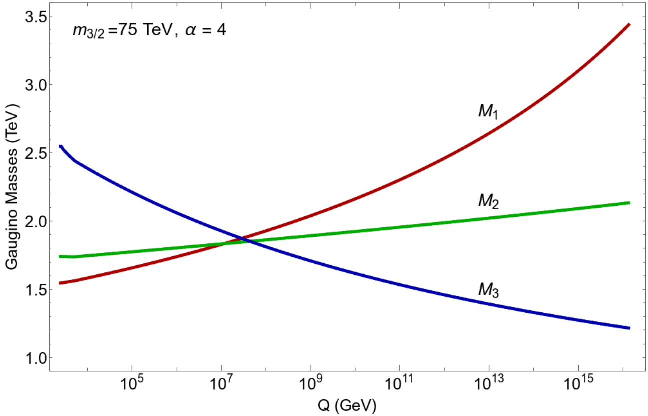
A distinctive feature of this model is that gaugino(and scalar) masses evolve from non-universal values at the GUT scale to apparently universal values at some intermediate scale
$\mu_{mir} = m_{GUT} \times e^{-8\pi^2/\alpha}$
where the introduced parameter α measures the relative moduli- versus anomaly-mediated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



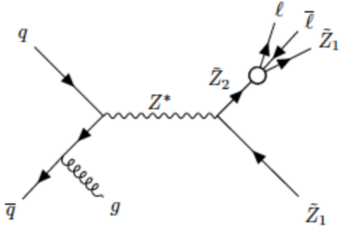
Evolution of gaugino masses from the nGMM benchmark point with $m_{3/2}$= 75 TeV, α= 4.

Radiatively-Driven Natural SUSY models

- nNUHM2 Model *(Nucl.Phys. B435 (1995) 115-128; JHEP 0507 (2005) 065.)*
  m_0, $m_{1/2}$, A_0, tan β, 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 β, μ, m_A
- nGMM Model *(Phys. Rev. D 94 (2016) no.11, 115017.)*
  α, $m_{3/2}$, c_m, c_{m3}, a_3, tan β, 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 β, μ, m_A

Signal and Background processes

Despite large cross-section of pair production of higgsinos, the signal is swamped by backgrounds because the decay products are soft. Hence the focus is on monojet + soft dilepton + $\not{E}_T$ signal, triggered by monojet.



A generic feynman diagram for opposite-sign dilepton+jets+MET signature from higgsino pair production at hadron colliders

SM Backgrounds: $\tau\bar{\tau}j$, $t\bar{t}$, WWj, $W\ell\bar{\ell}j$, $Z\ell\bar{\ell}j$

Benchmark points

We have chosen 3 Benchmark points as follows:

- BM1 (NUHM2): $m_0 = 5$ TeV, $m_{1/2} = 1$ TeV, $A_0 = -8$ TeV, $tan\beta = 10$, $\mu = 150$ GeV, $m_A = 2$ TeV
  $\Longrightarrow m_{\tilde{\chi}_2^0} = 157.6$ GeV, $m_{\tilde{\chi}_1^0} = 145.4$ GeV,
  $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 12.2$ GeV, $\Delta_{EW} = 13.9$
- BM2 (NUHM2): $m_0 = 5$ TeV, $m_{1/2} = 1$ TeV, $A_0 = -8$ TeV, $tan\beta = 10$, $\mu = 300$ GeV, $m_A = 2$ TeV
  $\Longrightarrow m_{\tilde{\chi}_2^0} = 310.1$ GeV, $m_{\tilde{\chi}_1^0} = 293.7$ GeV,
  $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 16.4$ GeV, $\Delta_{EW} = 21.7$
- BM3 (GMM'): $tan\beta = 10$, $m_{3/2} = 75$ TeV, $\alpha = 4$, $c_m = c_{m3} = 6.9$, $a_3 = 5.1$, $\mu = 200$ GeV, $m_A = 2$ TeV
  $\Longrightarrow m_{\tilde{\chi}_2^0} = 207.0$ GeV, $m_{\tilde{\chi}_1^0} = 202.7$ GeV,
  $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 4.3$ GeV, $\Delta_{EW} = 26.0$

Signal and Background evaluation

- For simulations, we have used MadGraph5_aMC@NLO for event generation, interfaced with Pythia 8 for parton showering and hadronization, followed by Delphes 3.4.2 for detector simulation where the default Delphes ATLAS parameter card is employed.
- The anti-k_T jet algorithm has been used with $R = 0.6$. We consider only jets with $E_T(\text{jet}) > 40$ GeV and $|\eta(jet)| < 3.0$ in our analysis.
- We identify leptons with $E_T > 5$ GeV and $|\eta(\ell)| < 2.5$ as isolated leptons if if the sum of the transverse energy of all other objects (tracks, calorimeter towers, etc.) within $\Delta R = 0.5$ of the lepton candidate is less than 10% of the lepton E_T.
- We have used Isajet 7.88 to generate the Les Houches Accord (LHA) file for the signal BM points and pass it through the above-mentioned simulation chain.

Basic cuts and $C1$ cuts

Basic cuts (cuts at Madgraph level): $p_T(j) > 80$ GeV, $p_T(\ell) > 1$ GeV, $\Delta R(\ell\bar{\ell}) > 0.01$ and $m(\ell\bar{\ell}) > 1$ GeV for the backgrounds including $\gamma^*, Z^* \to \ell\bar{\ell}$

Next, we implement cut set **C1**:

- require two OS/SF isolated leptons with $p_T(\ell) > 5$ GeV, $|\eta(\ell)| < 2.5$,
- $n(jets) \geq 1$ with $p_T(j1) > 100$ GeV for identified calorimeter jets,
- $\Delta R(\ell\bar{\ell}) > 0.05$ (for $\ell = e$ or μ),
- $\not{E}_T > 100$ GeV and
- $n(b - jet) = 0$.

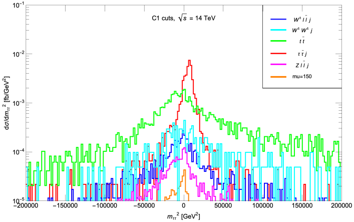
$m^2_{\tau\tau}$

$Z \to \tau\bar{\tau}j$ is a significant SM BG and earlier studies had proposed $m^2_{\tau\tau} < 0$ cut to reduce this BG. This cut is also used by ATLAS/CMS. $m^2_{\tau\tau}$ is calculated as:

$$m^2_{\tau\tau} = (1 + \xi_1)(1 + \xi_2)m^2_{\ell\ell} \tag{3}$$

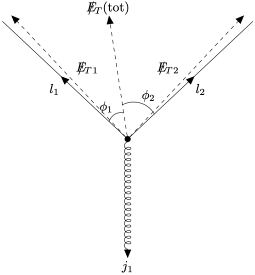
where ξ_1 and ξ_2 are calculated as follows:

$$-\sum_{jets} \vec{p}_T(j) = (1 + \xi_1)\vec{p}_T(\ell_1) + (1 + \xi_2)\vec{p}_T(\ell_2) \tag{4}$$



Distribution in $m^2_{\tau\tau}$ for three SUSY BM models with $\mu = 150,\ 200$ and 300 GeV along with SM backgrounds after $C1$ cuts with $n_J \geq 1$.

Angle cuts



Sketch of the ditau background, decay products and MET configuration.

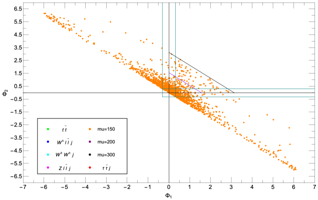
$\not{E}_T(tot)$ is expected between the direction of leptons, as long as both τs are fast moving. For a case of very asymmetric τ pair, $\not{E}_T(tot)$ would be close to the fast τ direction. Then mismeasurements can cause $\not{E}_T(tot)$ to be slightly outside the two leptons, motivating the strip cuts.

Angle cuts:

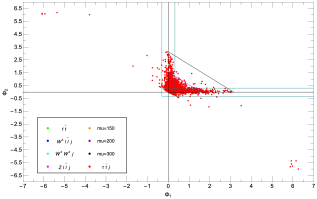
veto ϕ_1, $\phi_2 > 0$, $\phi_1 + \phi_2 < \pi/2$,

veto $|\phi_1| \leq \pi/10$ and $\phi_2 \geq -\pi/10$ or $|\phi_2| \leq \pi/10$ and $\phi_1 \geq -\pi/10$. [strip cuts]

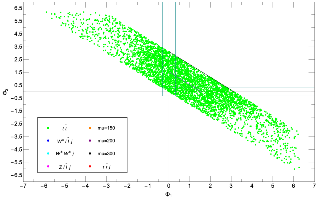
Angle cuts



SUSY BM point $\mu = 150$ GeV



SM BG $\tau\tau j$



SM BG $t\bar{t}$

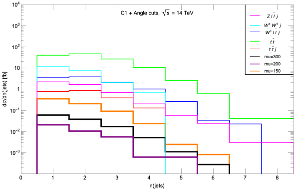
$m^2_{\tau\tau}$ vs. new angular cuts

cuts/process	$BM1$	$BM2$	$BM3$ $_{GMM'}$	$\tau\bar{\tau}j$	$t\bar{t}$	WWj	$W\ell\bar{\ell}j$	$Z\ell\bar{\ell}j$
BC	83.1	9.3	31.3	43800.0	41400	9860.0	1150.0	311
$C1$	1.2	0.19	0.07	94.2	179	35.9	14.7	5.9
$C1 + m^2_{\tau\tau} < 0$	0.92	0.13	0.043	23.1	75.6	12.8	7.7	3.2
$C1 + angle$	0.69	0.12	0.04	2.2	130	22.1	11.0	4.9

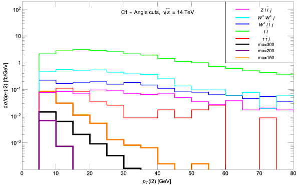
Table: Cross sections (in fb) for signal benchmark points and the various SM backgrounds listed in the text after various cuts.

This shows that the angle cuts reduce the $\tau\tau j$ BG more efficiently than the $m^2_{\tau\tau}$ cut, though the more of the other SM BGs get through. We impose further cuts, namely **C2** and **C3**, to reduce the other SM BGs.

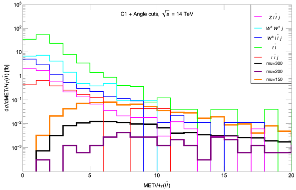
Distributions after C1+Angle cuts



$n(jets)$ distribution $\longrightarrow$ $n(jets) = 1$

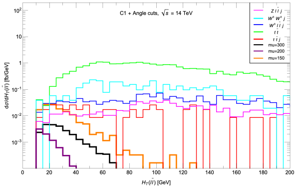


$p_T(\ell_2)$ distribution $\longrightarrow$ $p_T(\ell_2)$: $5 - 15$ GeV

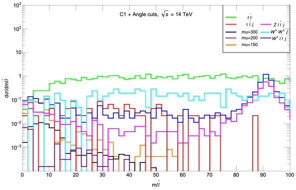


$\not{E}_T/H_T(\ell\bar{\ell})$ distribution $\longrightarrow$ $\not{E}_T/H_T(\ell\bar{\ell}) > 4$

Distributions after C1+Angle cuts



$H_T(\ell\bar{\ell})$ distribution $\longrightarrow H_T(\ell\bar{\ell}) < 60$ GeV

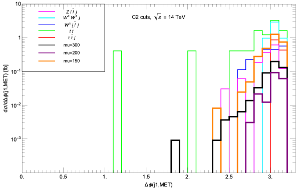


$m(\ell\bar{\ell})$ distribution $\longrightarrow m(\ell\bar{\ell}) < 50$ GeV

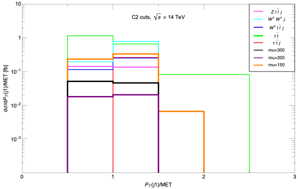
In light of the above distributions, we next include the following cut set **C2**:

- **C1** plus angle cuts
- $p_T(\ell_2) : 5 - 15$ GeV
- $\not{E}_T / H_T(\ell\bar{\ell}) > 4$,
- $n(jets) = 1$
- $H_T(\ell\bar{\ell}) < 60$ GeV
- $m(\ell\bar{\ell}) < 50$ GeV

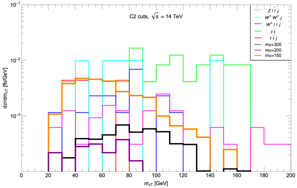
Distributions after C2 cuts



$\Delta\phi(j1, \not{E}_T)$ distribution $\longrightarrow \Delta\phi(j1, \not{E}_T) > 2.0$

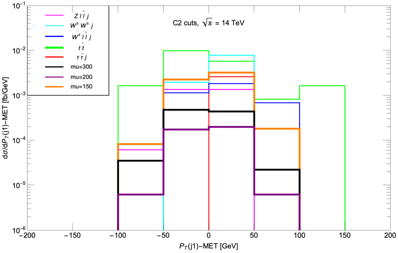


$p_T(j1)/\not{E}_T$ distribution $\longrightarrow p_T(j1)/\not{E}_T < 1.5$



$m_{cT}(\ell\bar{\ell}, \not{E}_T)$ distribution $\longrightarrow m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV

Distributions after C2 cuts



$|p_T(j1) - \not{E}_T|$ distribution $\longrightarrow$ $|p_T(j1) - \not{E}_T| < 100$ GeV

In light of the above distributions, we next include the following cut set **C3**:

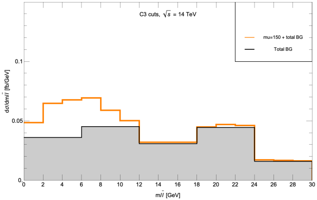
- apply all **C2** cuts,
- $\Delta\phi(j1, \not{E}_T) > 2.0$
- $m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV
- $p_T(j1)/\not{E}_T < 1.5$
- $|p_T(j1) - \not{E}_T| < 100$ GeV

Cut flow table

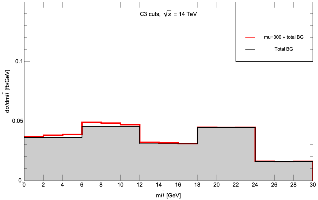
cuts/process	$BM1$	$BM2$	$BM3$ $_{GMM'}$	$\tau\bar{\tau}j$	$t\bar{t}$	WWj	$W\ell\bar{\ell}j$	$Z\ell\bar{\ell}j$
BC	83.1	9.3	31.3	43800.0	41400	9860.0	1150.0	311
$C1$	1.2	0.19	0.07	94.2	179	35.9	14.7	5.9
$C1 + m^2_{\tau\tau} < 0$	0.92	0.13	0.043	23.1	75.6	12.8	7.7	3.2
$C1 + angle$	0.69	0.12	0.04	2.2	130	22.1	11.0	4.9
$C2$	0.29	0.049	0.019	0.13	0.99	0.49	0.18	0.14
$C3$	0.25	0.033	0.017	0.13	0.29	0.39	0.15	0.07

Table: Cross sections (in fb) for signal benchmark points and the various SM backgrounds listed in the text after various cuts.

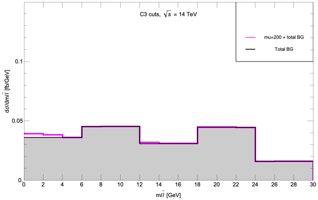
Distributions after C3 cuts



$m(\ell\bar{\ell})$ distribution for BM1 ($\Delta m \sim 12$ GeV)

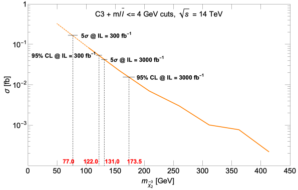


$m(\ell\bar{\ell})$ distribution for BM2 ($\Delta m \sim 16$ GeV)

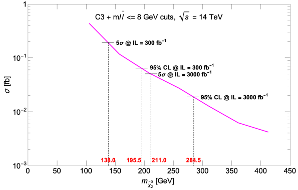


$m(\ell\bar{\ell})$ distribution for BM3 ($\Delta m \sim 4$ GeV)

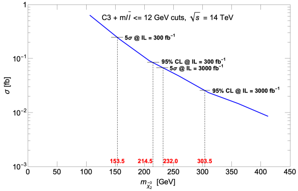
Mass reach after C3 + $m(\ell\bar{\ell}) \leq \Delta m$ cuts



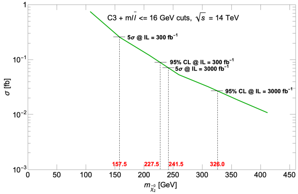
$\Delta m = 4$ GeV



$\Delta m = 8$ GeV

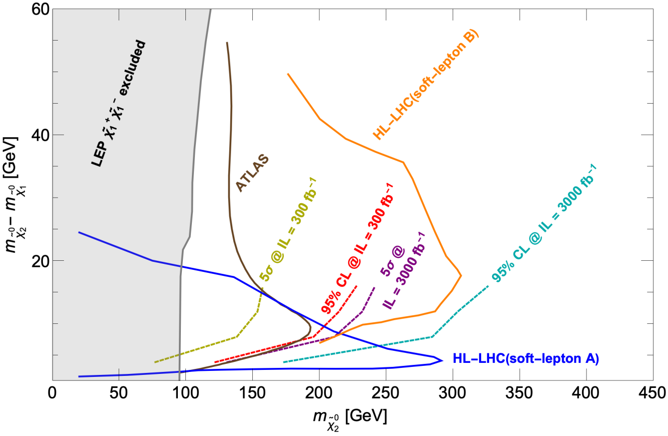


$\Delta m = 12$ GeV



$\Delta m = 16$ GeV

Summary plot



The 5σ and 95% CL reach of LHC with 300 and 3000 fb^{-1} in the μ vs. Δm plane after $C3 + m(\ell\bar{\ell}) \leq \Delta m$ cuts.

Conclusion

- Naturalness require the higgsino mass parameter $\mu \sim m_{weak}$ but allow the other soft terms (which are pulled to large values by string landscape) to be large such that sparticles other than higgsinos are well beyond HL-LHC reach.
- Such a stringy naturalness picture provides strong motivation for higgsino pair production reactions as an avenue to SUSY discovery at LHC14.
- Here, we re-examine higgsino pair production reactions leading to soft opposite-sign/same flavor dilepton pairs $+ \not{E}_T$ at LHC with $\sqrt{s} = 14$ TeV.
- We propose a new set of angular cuts which eliminate ditau backgrounds much more efficiently than $m^2_{\tau\tau} < 0$ cut. Several other cuts have been devised to further reduce the other SM backgrounds and yield a clean signal.

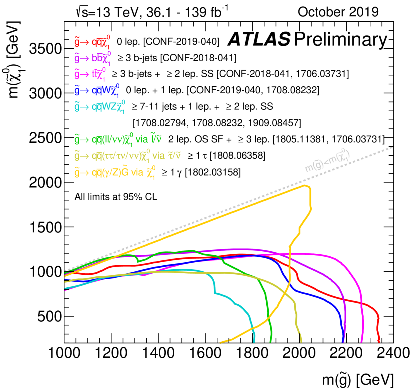
- After the final set of cuts, namely the **C3** cuts, we expect higgsino pair production to manifest itself as a low end excess in the $m(\ell\bar{\ell})$ distribution with a cutoff at the $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ value.
- Therefore, after the **C3** cuts we impose a cut of requiring $m(\ell\bar{\ell}) \leq \Delta m$ and evaluate the reach of LHC14 for 300 and 3000 fb^{-1} of integrated luminosity.
- We see that the reach is strongest for larger Δm values up to $15 - 20$ GeV but drops off for smaller mass gaps.
- However, some significant portion of natural parameter space with $\mu \sim m_{\tilde{\chi}_2^0} \sim 200 - 350$ GeV and $\Delta m \sim 4 - 10$ GeV can still be evaded by HL-LHC.

Thank You

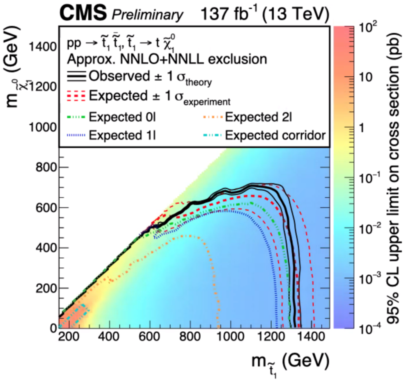
Questions ?

Back Up Slides

Where are the sparticles ?



Results of ATLAS searches for gluino pair production in SUSY for various simplified models with up to 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV.



Results of CMS searches for top squark pair production in SUSY for various simplified models with up to 137 fb^{-1} of data at $\sqrt{s} = 13$ TeV.

Naturalness

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

LHC Limits: $m_{\tilde{g}} > 2.2$ TeV, $m_{\tilde{t}_1} > 1.3$ TeV $\Longrightarrow$ **Is SUSY Unnatural?**

Various notions of Naturalness found in literature include : Δ_{BG}, Δ_{HS} and Δ_{EW}.

Δ_{HS} and Δ_{BG} measure put a stringent upper bound on the masses of the sparticles. Hence, these notions of naturalness, along with the above-mentioned experimental limits, render weak scale SUSY unnatural/highly fine-tuned.

However, a critical assessment of these older measures of Naturalness reveal that they must be updated to the model-independent electroweak measure of Naturalness (Δ_{EW}) so as to follow the notion of *Practical Naturalness* which states that

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

Δ_{EW}

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

$$\Delta_{EW} = max_i |C_i| / (M_Z^2/2) \tag{5}$$

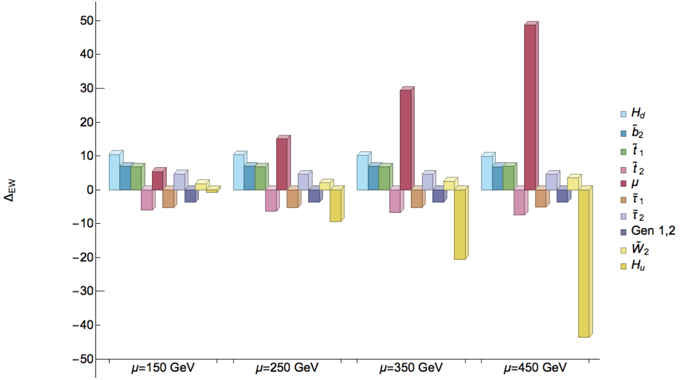
Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{6}$$

Since all the terms on RHS of Eqn. 6 must be comparable to $M_Z^2/2$, it implies

- $\mu \leq 300$ GeV $\Longrightarrow$ Light higgsinos.
- top squarks must be highly mixed

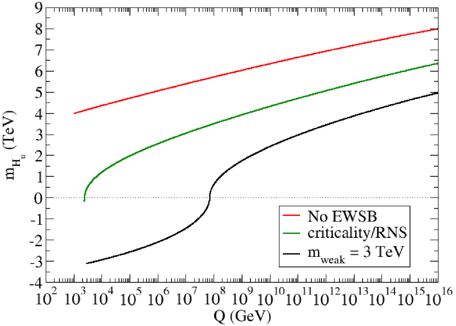
Understanding Δ_{EW}



Top ten contributions to $\Delta_{EW} = max_i|C_i|/(M_Z^2/2)$ from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV.

arXiv: 1702.06588 by Baer, Barger, Gainer, Huang, Savoy, Serce and Tata.

Radiatively-Driven Natural SUSY



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.

arXiv: 1602.07697 by Baer, Barger, Savoy and Serce.