ATLAS Z + MET Excess in the MSSM

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Higgs mass and SUSY

Higgs mass (experiment)

$$m_h = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}. \tag{1}$$

[Aad et al., 2015a]

Higgs mass (SUSY)

It is bounded by the Z mass at the tree level.

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{6m_t^4}{(2\pi)^2 v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2} \tag{2}$$

[Okada et al., 1991]

Large radiative corrections from heavy stops are expected.

ATLAS 3σ Excess of leptonic Z, jets, and MET

ATLAS Run I data (20.3fb^{-1}) [Aad et al., 2015b]

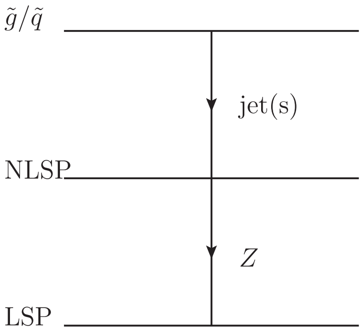
- Same flavor, opposite sign dilepton peaked on the Z mass (81 GeV $< m_{ll} < 101$ GeV),
- At least 2 jets,
- Large missing transverse energy (MET), $E_{\mathrm{T}}^{\mathrm{miss}} > 225$ GeV,
- Large scalar sum of transverse momenta, $H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}}^{\mathrm{jet},i} + p_{\mathrm{T}}^{\mathrm{lepton},1} + p_{\mathrm{T}}^{\mathrm{lepton},2} > 600$ GeV,
- Large angular separation, $\Delta\phi(\mathrm{jet}_{1,2}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$.

	ee	$\mu\mu$	combined
Observed	16	13	29
Expected	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2

basic requirements

- Particle with strong int. cross section lighter than ~ 1.2 TeV,
- which produces at least 1 Z boson in the decay chain.

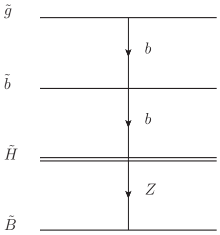
[Barenboim et al., 2015]

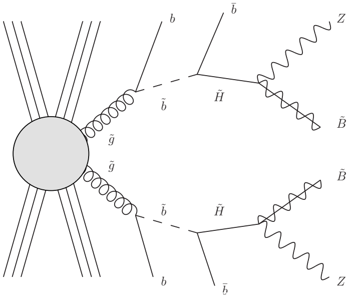


Theoretical approaches (1/6)

light sbottom scenario [Kobakhidze et al., 2015]

- The 3rd generation squarks tend to be light.
- $\tilde{t}$ typically produces $bW\tilde{\chi}_1^0$, while $\tilde{b}$ can produces $bZ\tilde{\chi}_1^0$.
- However, many b-jets are produced.



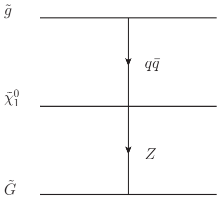


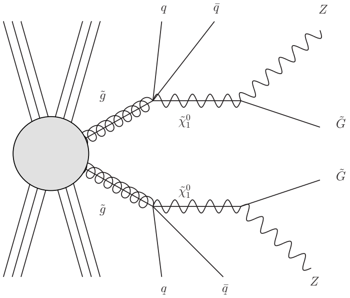
Theoretical approaches (2/6)

general gauge mediation (GGM) scenario

[Barenboim et al., 2015, Allanach et al., 2015]

- gravitino LSP ($\tilde{g}$ does not decay directly into it)
- NLSP is a Wino-Bino mixture s.t. BF($\tilde{\chi}_1^0 \to Z\tilde{G}$) $\simeq 1$.
- excluded by multijet, multilepton and CMS Z+jets+MET searches.

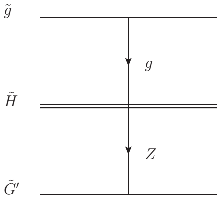


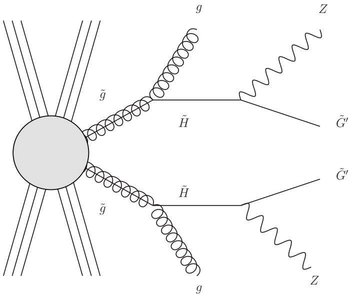


Theoretical approaches (3/6)

goldstini scenario [Liew et al., 2015]

- Two SUSY breaking sectors
  – massless goldstino (irrelevant) and
  – massive pseudo-goldstino.
- Gluino radiative decay → low jet multiplicity.

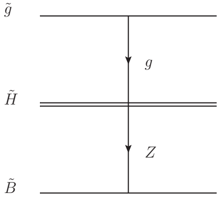


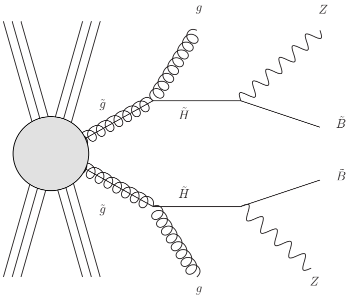


Theoretical approaches (4/6)

mini-split SUSY scenario [Lu et al., 2015]

- gluon radiative decay to g and $\tilde{\chi}^0_{2,3}$ $\rightarrow$ low jet multiplicity.
- Its BF is enhanced by $\log(m_{\tilde{t}}/m_t)$.

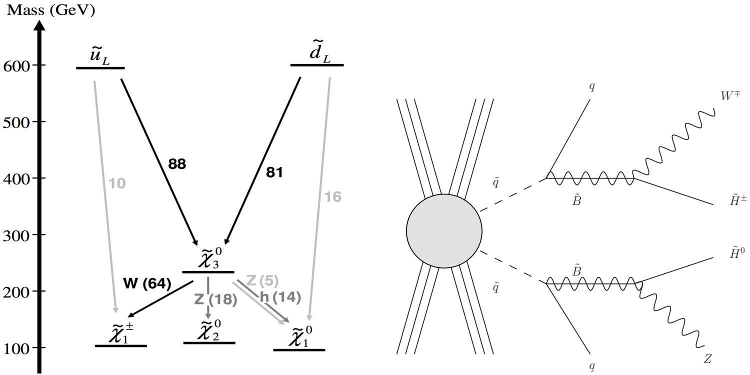




Theoretical approaches (5/6)

pMSSM scan [Cahill-Rowley et al., 2015]

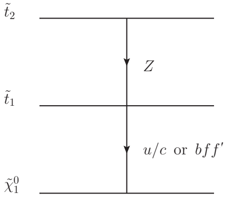
Light 1st, 2nd gen. squarks, Bino-like $\tilde{\chi}_3^0$, Higgsino-like $\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_1^{\pm}$.

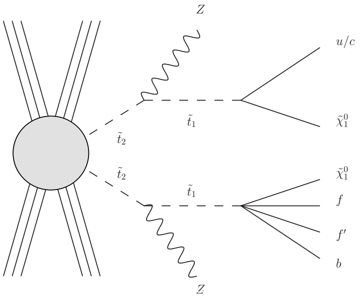


Theoretical approaches (6/6)

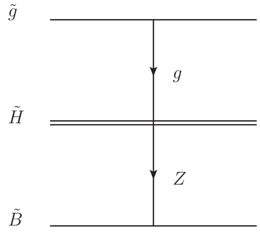
mixed-stops scenario [Collins et al., 2015]

- Z is emitted in the first step of decay chain.
  $\rightarrow$ This may lead to contamination of CMS background.
- Stops are mixed s.t. BF$(\tilde{t}_2 \rightarrow \tilde{t}_1 Z) \gtrsim 0.8$.
- Flavor changing decay of $\tilde{t}_1$ reduces hadronic activity.





Neutralino decay



Higgsino-like neutralinos $\tilde{\chi}^0_{2,3}$ decay into $\tilde{\chi}^0_1$ and Z or h.
When $m_Z < m_{\tilde{\chi}^0_{2,3}} - m_{\tilde{\chi}^0_1} < m_h$, BF$(\tilde{\chi}^0_{2,3} \to Z\tilde{\chi}^0_1) \simeq 1$.

$\to$ We fix $|\mu| = M_1 + 100\text{GeV}$ (s.t. $m_{\tilde{\chi}^0_{2,3}} \simeq m_{\tilde{\chi}^0_1} + 100\text{GeV}$).

Gluino radiative decay into Higgsino

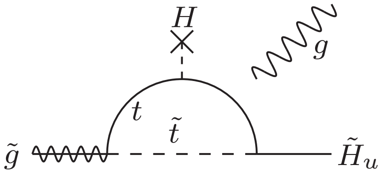
Low jet multiplicity compared to the tree-level decay, $\tilde{g} \to q\bar{q}\tilde{\chi}$.

- consistent with the N_{jets}-distribution of the excess [Liew et al., 2015]
- helpful to evade other SUSY searches

$$\Gamma(\tilde{g} \to q\bar{q}\tilde{\chi}) \sim m_{\tilde{g}}^5/m_{\tilde{q}}^4$$

$$\Gamma(\tilde{g} \to g\tilde{B}) \sim m_{\tilde{g}}^5/m_{\tilde{q}}^4$$

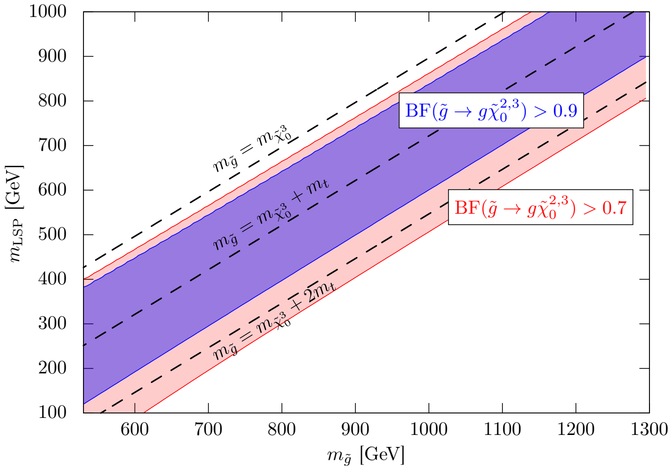
$$\Gamma(\tilde{g} \to g\tilde{H}) \sim (m_{\tilde{g}}^3 m_t^2/m_{\tilde{t}}^4) \log(m_{\tilde{t}}^2/m_t^2)$$



$$\frac{\Gamma(\tilde{g} \to g\tilde{H})}{\Gamma(\tilde{g} \to t\bar{t}\tilde{\chi})} \sim \frac{m_t^2}{m_{\tilde{g}}^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

[Toharia and Wells, 2006, Gambino et al., 2005, Sato et al., 2012, Sato et al., 2013]

Gluino- (as well as LSP-) mass dependence



$(\mathsf{sgn}(\mu),\, \tan\beta,\, m_{\tilde{t}_r}/\mathsf{TeV}) = (-,\, 2,\, 100)$

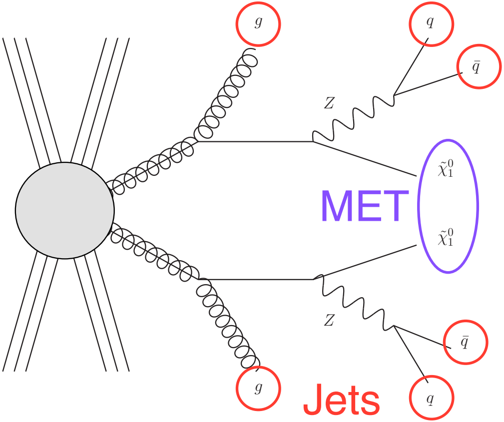
LHC constraints

$\text{BF}(Z \to q\bar{q}) = 69.2\%$

$\text{BF}(Z \to \nu\bar{\nu}) = 20.5\%$

$\text{BF}(Z \to e\bar{e}$ or $\mu\bar{\mu}) = 6.8\%$

Relevant search:
multijet+MET
[Aad et al., 2014]



LHC constraints

$\text{BF}(Z \to q\bar{q}) = 69.2\%$

$\text{BF}(Z \to \nu\bar{\nu}) = 20.5\%$

$\text{BF}(Z \to e\bar{e}$ or $\mu\bar{\mu}) = 6.8\%$

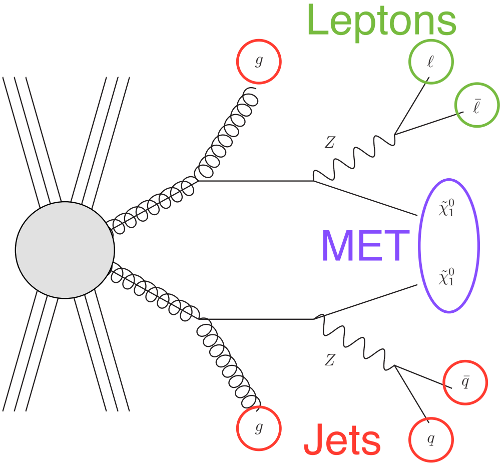
Relevant searches:

Z+dijet+MET

[Khachatryan et al., 2014]

CMS Z+jets+MET

[Khachatryan et al., 2015]



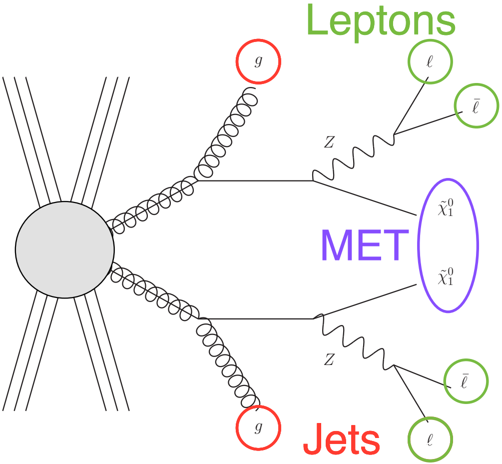
LHC constraints

$\mathrm{BF}(Z \to q\bar{q}) = 69.2\%$

$\mathrm{BF}(Z \to \nu\bar{\nu}) = 20.5\%$

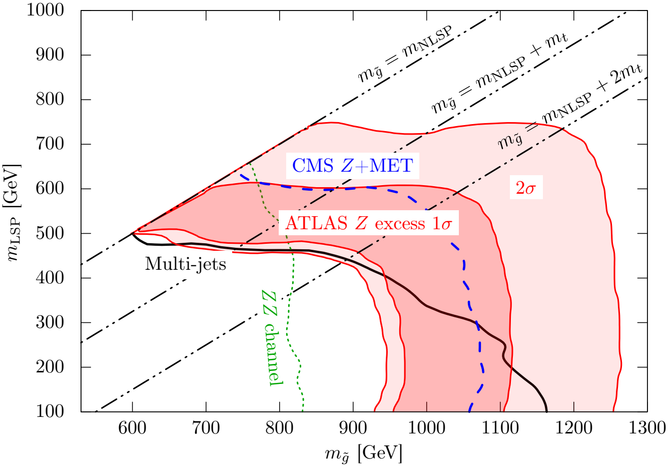
$\mathrm{BF}(Z \to e\bar{e}$ or $\mu\bar{\mu}) = 6.8\%$

Relevant search:
four-lepton+MET
[Aad et al., 2014,
Chatrchyan et al., 2014]



LHC constraints [Result]

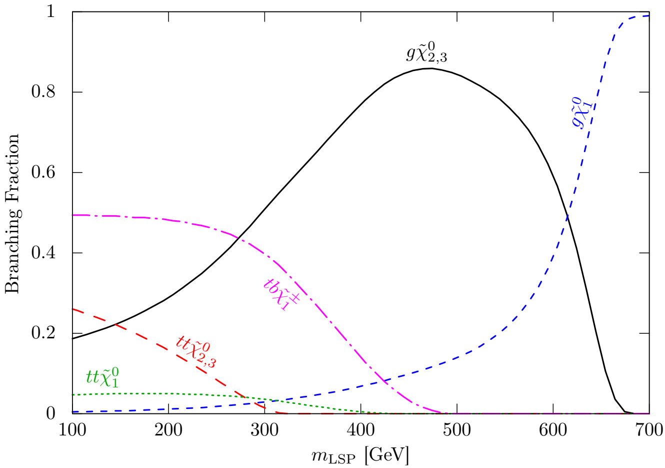
Simplified model:
$\tilde{g} \to g\tilde{\chi}_2^0 \to gZ\tilde{\chi}_1^0$ with 100% branching fractions.



Conclusion

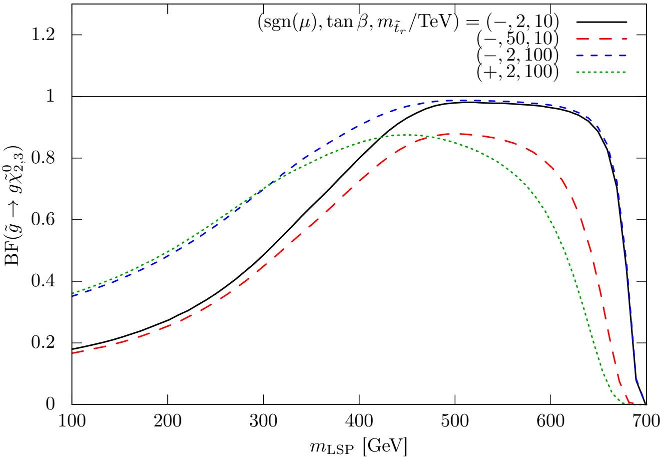
- The (mini-)split SUSY is well-motivated by the Higgs mass. The ATLAS Z+jets+MET excess can be well explained in the mini-split framework apart from the similar search by CMS.
- There are small parameter regions satisfying all the constraints.
- MET, H_{T}, and N_{jets} distributions are consistent with data. [Ellwanger, 2015, Liew et al., 2015]
- Dark matter could be explained by Bino-like LSP.
- Run II will make it clear soon!

Efficiency of the gluino radiative decay

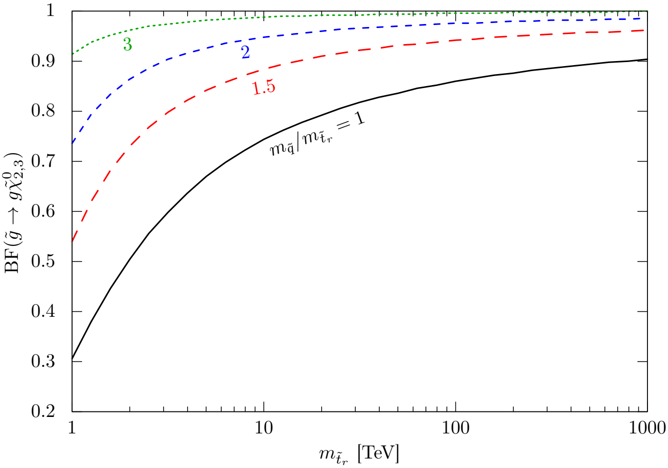


$(\mathsf{sgn}(\mu),\, \tan\beta,\, m_{\tilde{t}_r}/\mathsf{TeV}) = (+,\, 2,\, 10),\, m_{\tilde{g}} = 800\,\mathsf{GeV}$

Efficiency of the gluino radiative decay



Not so split spectrum is OK.



$\mu = -600\text{GeV},\ M_1 = 500\text{GeV},\ \tan\beta = 2$

Method of analysis

Simplified model

$\tilde{g} \to g\tilde{\chi}_2^0 \to gZ\tilde{\chi}_1^0$ with 100% branching fractions.

Method of analysis

- MADGRAPH 5 v2.1.2 + Pythia 6.4 + Delphes 3
- MLM matching (scale parameter= $m_{\tilde{g}}/4$)
- PDFs from CTEQ6L1
- gluino production: NLO+NLL in g_s using NLL-fast v2.1

CMS Z+jets+MET search

[Khachatryan et al., 2015]

It is consistent with the SM.

cuts/bins for on-Z counting experiment

- $N_{\text{jets}} \geq 2$ or $N_{\text{jets}} \geq 3$.
- $100\text{GeV} < E_{\text{T}}^{\text{miss}} < 200\text{GeV}$, $200\text{GeV} < E_{\text{T}}^{\text{miss}} < 300\text{GeV}$, or $300\text{GeV} < E_{\text{T}}^{\text{miss}}$.

NOTE:

- H_{T} cut is not applied.
- Jet-Z Balance (JZB) is utilized in the SM BG estimation. $\text{JZB} \equiv \left|\sum_{i\in\text{jets}} \vec{p}_{\text{T}}^{\,i}\right| - \left|\vec{p}_{\text{T}}^{\,Z}\right| = \left|\vec{p}_{\text{T}}^{\,\text{miss}} + \vec{p}_{\text{T}}^{\,Z}\right| - \left|\vec{p}_{\text{T}}^{\,Z}\right|$.

RGE effects in gluino decay (1/2)

Effective Lagrangian (relevant for gluino decay) after integrating out squarks

$$\mathcal{L} = C_7^{\tilde{B}} O_7^{\tilde{B}} + C_{2,33}^{\tilde{H}_u} O_{2,33}^{\tilde{H}_u} + C_5^{\tilde{H}_u} O_5^{\tilde{H}_u}, \qquad (3)$$

where $O_7^{\tilde{B}} \equiv (\tilde{B}\sigma^{\mu\nu}\tilde{g})G_{\mu\nu}$, $O_5^{\tilde{H}_u} \equiv (\tilde{H}_u\sigma^{\mu\nu}\tilde{g})HG_{\mu\nu}$, and $O_{2,33j}^{\tilde{H}_u} \equiv (\tilde{H}_u\sigma^{\mu\nu}\tilde{g})(Q_{L,3}\sigma_{\mu\nu}u_{R,3}^c)$. [Toharia and Wells, 2006, Gambino et al., 2005, Sato et al., 2012, Sato et al., 2013]

RGE effects in gluino decay (2/2)

boundary conditions at the lightest squark mass

$$C_7^{\tilde{B}} = \frac{g_s^2 g'}{384\pi^2}(m_{\tilde{g}} - m_{\tilde{B}}) \sum_i \left(\frac{1}{m_{\tilde{q}_{Li}}^2} - \frac{2}{m_{\tilde{u}_{Ri}}^2} + \frac{1}{m_{\tilde{d}_{Ri}}^2} \right), \quad (4)$$

$$C_{2,33}^{\tilde{H}_u} = \frac{g_s y_t}{4\sqrt{2}\sin\beta} \left(\frac{1}{m_{\tilde{q}_{L3}}^2} + \frac{1}{m_{\tilde{t}_R}^2} \right), \quad (5)$$

$$C_5^{\tilde{H}_u} = \frac{g_s^2 y_t^2}{32\sqrt{2}\pi^2 \sin\beta} \left(\frac{1}{m_{\tilde{q}_{L3}}^2} + \frac{1}{m_{\tilde{t}_R}^2} \right). \quad (6)$$

RGEs

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu} C_7^{\tilde{B}} = \frac{-14 g_s^2}{16\pi^2} C_7^{\tilde{B}}, \quad (7)$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu} \begin{pmatrix} C_{2,33}^{\tilde{H}_u} \\ C_5^{\tilde{H}_u} \end{pmatrix} = \frac{1}{16\pi^2} \begin{pmatrix} -\frac{37}{3} g_s^2 + \frac{3}{2} y_t^2 & 2 g_s y_t \\ 4 g_s y_t & -14 g_s^2 + 3 y_t^2 \end{pmatrix} \begin{pmatrix} C_{2,33}^{\tilde{H}_u} \\ C_5^{\tilde{H}_u} \end{pmatrix}. \quad (8)$$

[Toharia and Wells, 2006, Gambino et al., 2005, Sato et al., 2012, Sato et al., 2013]

“too large split” is problematic

decay length

$$c\tau_{\tilde{g}} \sim O(10)\mu\text{m}\left(\frac{m_{\tilde{g}} - m_{\text{NLSP}}}{300\ \text{GeV}}\right)^{-3}\left(\frac{m_{\tilde{t}_r}}{100\ \text{TeV}}\right)^{4}. \qquad (9)$$

Severely constrained if $c\tau_{\tilde{g}} \gtrsim O(1)$mm [Nagata et al., 2015].

Other theoretical approaches

NMSSM scenario

[Ellwanger, 2015, Cao et al., 2015b, Cao et al., 2015a, Ding et al., 2015]

- Bino-like NLSP and singlino-like LSP
- more or less similar power of explanation.
  (*e.g.* compressed spectrum is often required.)

Composite Higgs/RS scenario [Vignaroli, 2015]

- many b-jet signatures and severely constrained.

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