LHC Signatures of Natural SUSY

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**EW Fine-tuning**

- Minimization condition for higgs scalar potential (1-loop)

\[
\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2
\]

- Naturalness requires all terms on RHS comparable to LHS 
  \[\Rightarrow\] fine-tuning parameter

\[
\Delta_{EW} \equiv \max \left( \frac{m_{H_u}^2}{M_Z^2/2 \tan^2 \beta - 1}, \frac{\Sigma_u^u}{M_Z^2/2 \tan^2 \beta - 1}, \frac{\mu^2}{M_Z^2/2}, \ldots \right)
\]

- \(\Delta_{EW}=100\) corresponds to 1\% EWFT, \(\Delta_{EW}=30\) is \(~3\%\) EWFT

- Limited value of \(\Delta_{EW}\) \(\Rightarrow\) upper limit on \(m_{H_u}^2\) and \(\mu^2\)

- \(\Delta_{EW}\) is a bound on FT, it measures minimal FT present in given spectrum (see X.Tata talk)
Summary of Natural spectrum

- For $m_h \sim 125$ GeV and $\Delta_{EW} < 30$:
  - $\mu \sim 100$-300 GeV
  - $\text{stop}_1 \sim 1$-2 TeV, $\text{stop}_2 = \text{sbottom}_1 \sim 2$-4 TeV
  - gluino $\sim 1$-5 TeV
  - $1^{\text{st}}/2^{\text{nd}}$ generation squarks $\sim 1$-10 TeV
  - sleptons $\sim 1$-30 TeV

- This can be realized in a simple extension of mSUGRA, NUHM2
  
  $$m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A$$

- Here small $m_{H_u}^2 \simeq -M_Z^2$ and lighter stops are generated by RGE evolution, hence Radiatively-driven Natural SUSY (RNS) name
Current ATLAS/CMS limits done in simplified models and not applicable to the light higgsino case
Hard trilepton signals

- Trileptons are golden channel for gaugino searches that relies on 3-body decay of neutralinos:
  - ATLAS/CMS exclude up to mass \( \sim 700 \text{GeV} \)
  - or up to \( \sim 300 \text{GeV} \) via WZ for 100\% BF
- In RNS sleptons are heavy and the 3-body decays closed,
  \[
  pp \rightarrow \tilde{W}_2 \tilde{Z}_4 \rightarrow (\tilde{W}_1 Z) + (\tilde{W}_1 W) \rightarrow WZ + E_T^{\text{miss}} \rightarrow \ell^+ \ell^- \ell' + E_T^{\text{miss}}
  \]

  
- No reach at LHC8 beyond LEP2 bound
- At LHC14 the reach extends to \( m_{1/2} = 500 \ (630) \ \text{GeV} \) for 300 (1000) fb\(^{-1}\)
Gluino cascades

- $pp \rightarrow \tilde{g}\tilde{g}X$ followed by gluino cascades
  lead to multi-jets + multi-leptons + MET signature

- LHC14 can only probe part of natural gluino mass range, up to
  1700 GeV (1900 GeV)
  for 300 (1000)fb$^{-1}$

- $\tilde{Z}_2 - \tilde{Z}_1$ mass gap
  (if >25 GeV)
  can be measured from OS/SF dileptons

**NUHM2:** $m_0=5$ TeV, $A_0=-1.6m_0$, $\tan\beta=15$, $\mu=150$ GeV, $m_A=1$ TeV

![Graph showing the dependence of $\sigma(gg)$ on $m_{1/2}$](image-url)
Mono-jets and mono-photons

- Higgsinos have compressed spectrum with mass gap 10-30 GeV – only soft visible decay products

\[ pp \rightarrow \tilde{Z}_{1,2} \tilde{Z}_{1,2}/\tilde{Z}_{1,2} \tilde{W}_1/\tilde{W}_1 \tilde{W}_1 + (j \text{ or } \gamma) \]

- Contact interaction, used in ATLAS/CMS search, not applicable: mediator mass \( M_Z \ll \sqrt{s} \sim p_T(jet) + E_T^{miss} \)
leading to extra 1/s suppression for ME
(see X.Tata talk)

- Signal has same shape as BG
and \( S/B \approx 1\% \)
detection is very challenging
Same-sign Dibosons

- Sizeable production cross section (~10-100 fb) for wino-like $\tilde{Z}_4\tilde{W}_2$ and $\tilde{W}_2\tilde{W}_2$
- Each decays into $W$ about 50%
- Two $W$'s are not charge correlated
- Same-sign $WW$ is novel signature, characteristic of light higgsinos
- No $2\to2$ SM production of $ssWW$
- BG from $WZ$ and $t\bar{t}$bar removed by $m_T>125$ GeV cut
- $2lSS+MET$ is not probed by existing di-lepton searches that require significant hadronic activity
ssWW prospects

- Reach for 100 (1000) fb$^{-1}$ extends to $m_{1/2} \sim 680$ (1000) GeV
- Better than canonical 3-lepton reach
- Exceeds direct gluino production reach (if gaugino masses are unified)
- Independent of gluino search!

**NUHM2**: $m_0=5$ TeV, $A_0=-1.6m_0$, $\tan\beta=15$, $\mu=150$ GeV, $m_A=1$ TeV

arXiv: 1302.5816, 1310.4858
4-lepton signal

- Winos also have significant BF to Z, 25-50%
- Novel channel for low $|\mu|$ models: 4 isolated leptons + MET and no jets
- BGs controlled by MET $> 200$ GeV cut
- Reach for 300 (1000) fb$^{-1}$
  extends to $m_{1/2} \simeq 500$ (650) GeV
  - confirmatory channel for same-sign WW
- Current 4-lepton searches are optimized for glunio cascades in RPV with many leptons and jets

arXiv: 1310.4858
Conclusions

- Although FT is intrinsically model dependent, generic pheno studies of natural SUSY are possible with \( \Delta_{EW} \) – lower bound on FT.

- Small \( \mu \) is necessary (but not sufficient) condition for naturalness. It is more fundamental than light stops!

- Higgsino-like chargino and neutralinos are difficult to detect at LHC due to low visible energy release from their decays.

- Diboson productions are novel signatures characteristic of light higgsino scenario. They depend only on EW-ino spectrum.

- Same-sign WW can probe wino masses up to 550 (800) GeV, for 100 (1000) fb\(^{-1}\) at LHC14. Larger reach than in canonical trilepton channel.

- LHC can cover large portion of para space with FT >3% by ssWW, but ILC with ~600 GeV is necessary to complete the test of SUSY naturalness.
Cuts for ssWW

- **b-jet veto** (60% eff.)
- 2 isolated **same-sign** leptons $p_T(l_1) > 20\text{GeV}$, $p_T(l_2) > 10\text{GeV}$
- $m_T^{min} \equiv \min [m_T(l_1, E_T), m_T(l_2, E_T)] > 125\text{GeV}$ removes WZ and ttbar due to kinematic cutoff for on-shell W
- **MET>200GeV**
Cuts for ZZ

- b-jet veto (60% eff.)
- 4 isolated leptons with $p_T(l) > 10$ GeV, $|\eta(l)| < 2.5$
- $\text{MET} > 100$ (200) GeV
Soft trileptons

- Mass gap between higgsinos is $<30$ GeV $\Rightarrow$ very soft leptons for higgsino pair production

$$pp \rightarrow \tilde{W}_1 \tilde{Z}_2 \rightarrow (e \nu_e \tilde{Z}_1) + (\mu^+ \mu^- \tilde{Z}_1)$$

- A shape analysis may allow to claim a signal with high luminosity