# Hunting Natural SUSY at LHC

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# EW Fine-tuning

arXiv: 1207.3343, 1404.1386

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

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

- Sparticles contribute via radiative corrections inside Σ

$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \times \left[ f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

$$F(m^2) = m^2 \left( \log(m^2/Q^2) - 1 \right), \text{ with } Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

- Naturalness requires no large cancellations ⇒ fine-tuning parameter

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

- Limited value of $\Delta_{EW}$ ⇒ upper limit on $m_{H_u}^2$ and $\mu^2$

- $\Delta_{EW}$ is determined by the spectrum and does not depend on high-scale dynamics

# Properties of $\Delta_{EW}$

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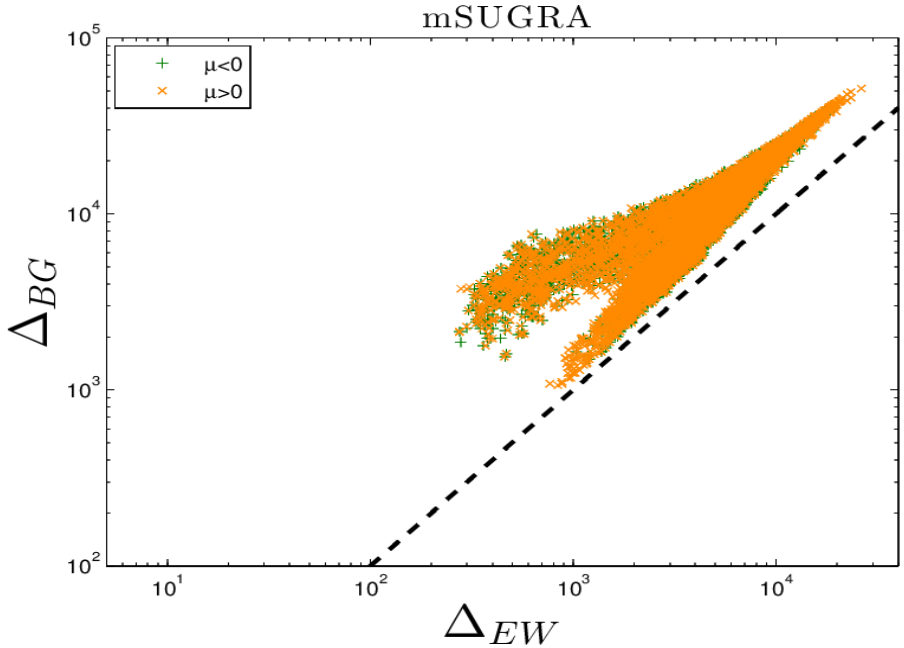
- FT is a property of the model and can be quantified by measure

Ellis, Enqvist, Nanopoulos, Zwirner '86
Barbieri, Giudice '88

$$\Delta_{BG} \equiv max_i \left| \frac{\Delta M_Z^2/M_Z^2}{\Delta a_i/a_i} \right| = max_i \left| \frac{\partial \ln M_Z^2}{\partial \ln a_i} \right|$$

- $\Delta_{EW}$ provides a bound on FT, that can be saturated with specific model para correlations

$$\Delta_{BG} > \Delta_{EW}$$




- If $\Delta_{EW}$ is large, any underlying theory that leads to the spectrum will be fine-tuned.

- Small $\Delta_{EW}$ does not imply no FT, but leaves open the possibility of finding a theory with low FT.

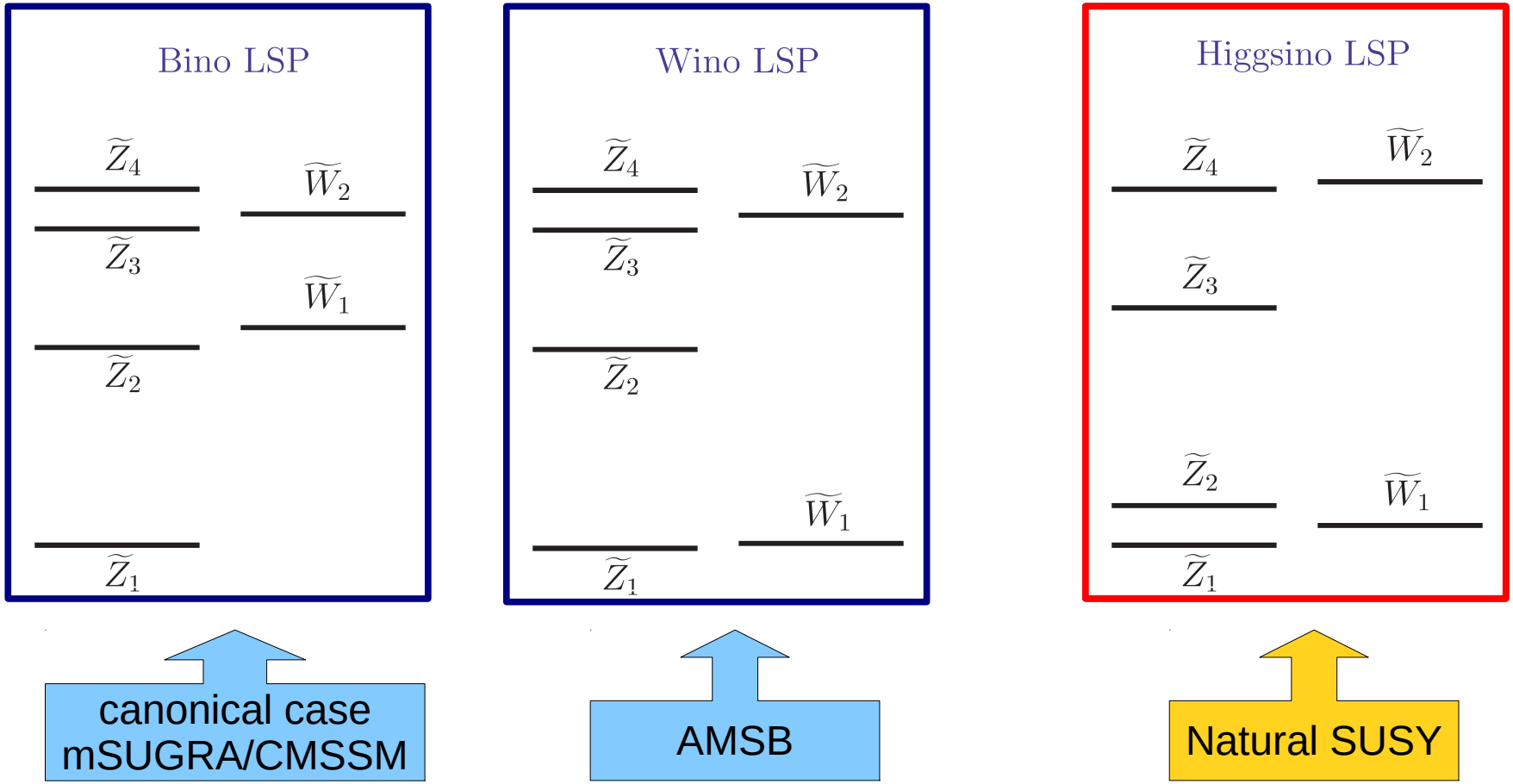
# Summary of Natural spectrum

- For $m_h$ ~ 125 GeV and $\Delta_{EW} < 30$:
  - $\mu$ ~ 100-300 GeV
  - stop_1 ~ 1-2 TeV, stop_2 = sbottom_1 ~ 2-4 TeV, highly mixed by large $A_t$
  - gluino ~ 1-5 TeV
  - 1st/2nd generation squarks ~ 1-10 TeV
  - sleptons ~ 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)

# EW-ino spectrum




- Current ATLAS/CMS limits done in simplified models and not applicable to the light higgsino case

# Hard trilepton signals

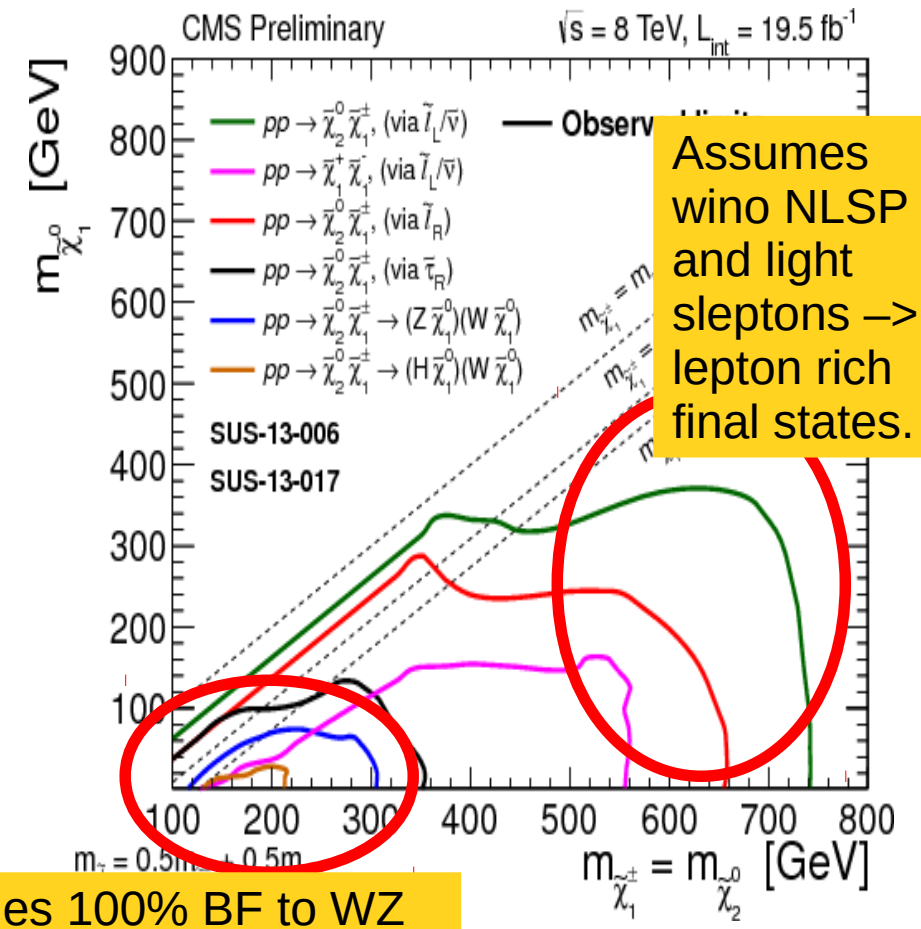
arXiv: 1310.4858

- Trileptons are golden channel for gaugino searches that relies on 3-body decay of neutralinos:
- In RNS sleptons are heavy and 3l only appear from

$$pp \to \widetilde{W}_2 \widetilde{Z}_4 \to (\widetilde{W}_1 Z) + (\widetilde{W}_1 W)$$

25%

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




Assumes wino NLSP and light sleptons –> lepton rich final states.

Assumes 100% BF to WZ

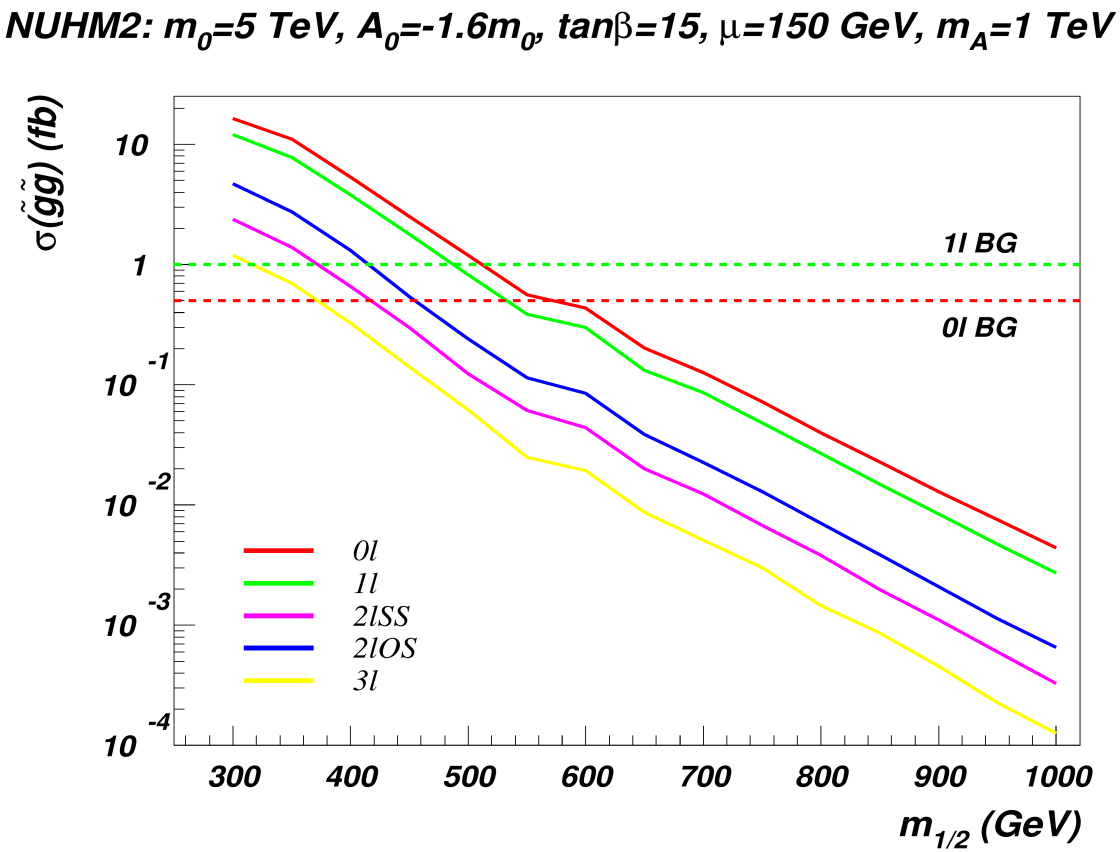
# EW-inos in gluino cascades

arXiv: 1310.4858

- $pp \to \tilde{g}\tilde{g}X$ followed by gluino cascade decays 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$^{-1}$

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

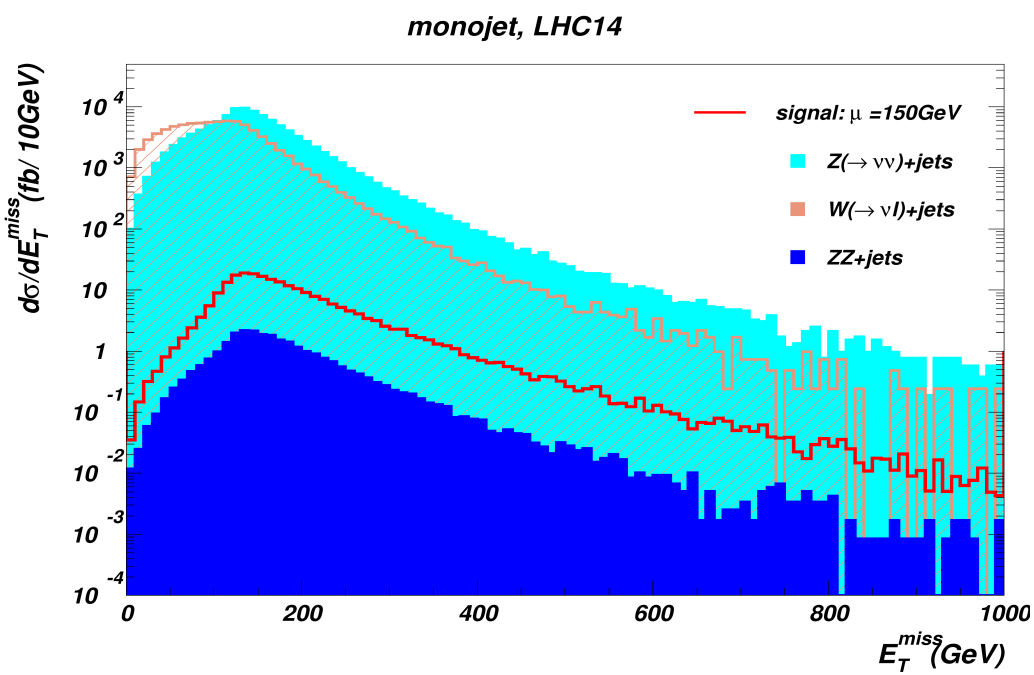


# Mono-jets and mono-photons

arXiv: 1401.1162

- Higgsinos have compressed spectrum with mass gap 10-30 GeV – only soft visible energy ==> higgsinos mostly appear as MET.
- $pp \to \widetilde{Z}_{1,2}\widetilde{Z}_{1,2}/\widetilde{Z}_{1,2}\widetilde{W}_1/\widetilde{W}_1\widetilde{W}_1 + (j \text{ or } \gamma)$
- Contact interaction, used in ATLAS/CMS search, not applicable: mediator mass $M_Z \ll \sqrt{\hat{s}} \sim p_T(jet) + E_T^{miss}$ leading to extra 1/s suppression for ME
- Signal has same shape as BG and S/B ≈1%.

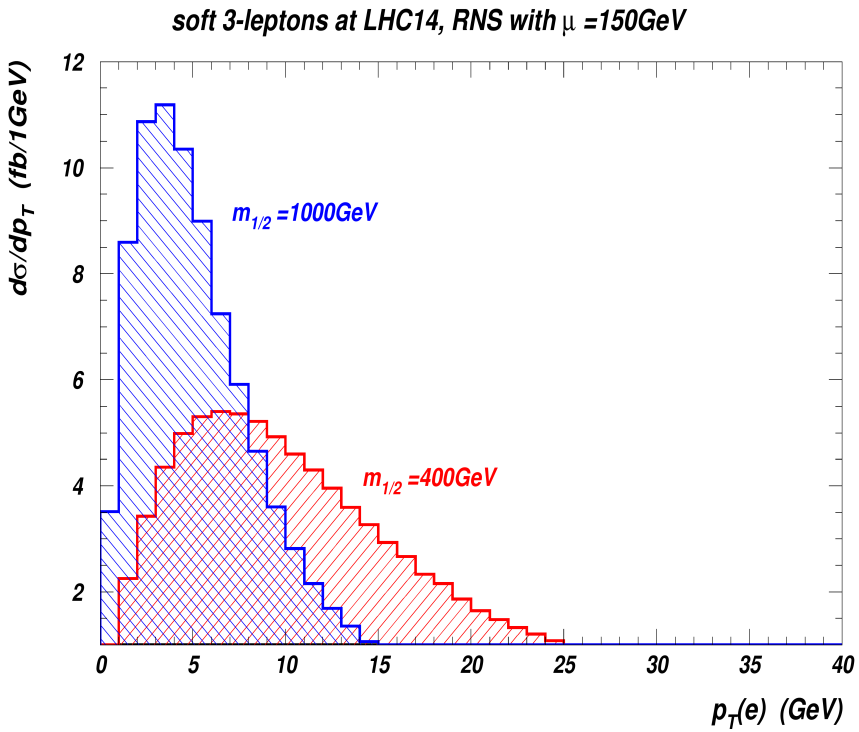
  Detection is very challenging.



# Soft trileptons

arXiv: 1302.5816

- Mass gap between higgsinos is <30 GeV $\Rightarrow$ very soft leptons for higgsino pair production. But ATLAS/CMS can detect soft leptons $p_T(\mu) > 5\ \mathrm{GeV},\ p_T(e) > 10\ \mathrm{GeV}$
- $pp \longrightarrow \widetilde{W}_1 \widetilde{Z}_2 \longrightarrow (e\nu_e \widetilde{Z}_1) + (\mu^+\mu^- \widetilde{Z}_1)$
- For $m_{1/2} < 400 - 500\ \mathrm{GeV}$
  and $\mu$=150GeV
  most e pass trigger threshold



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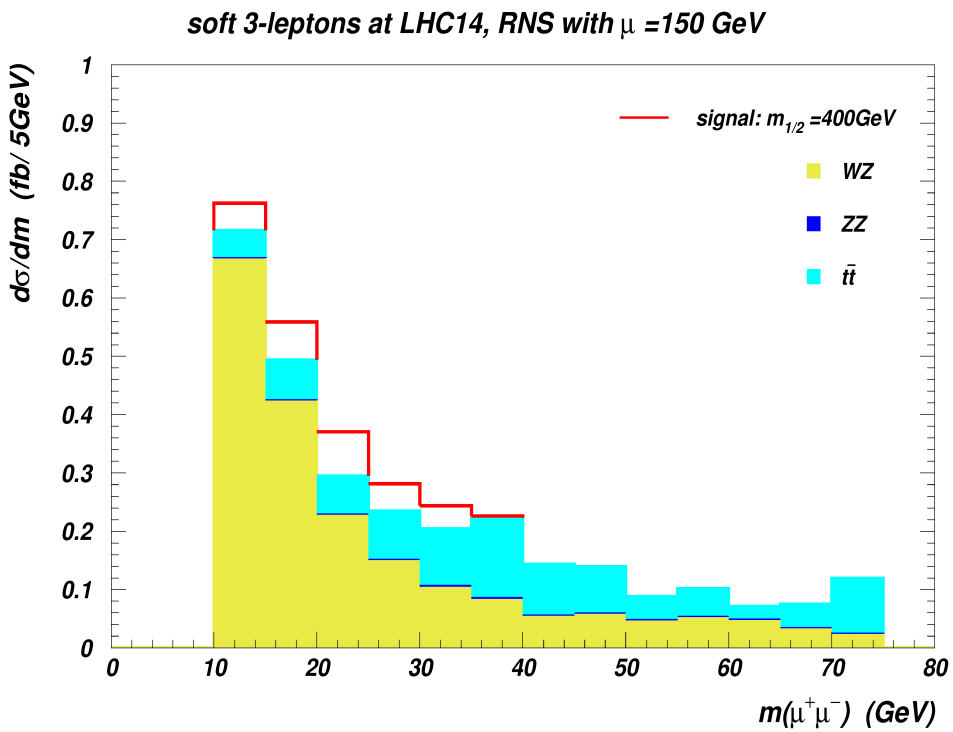
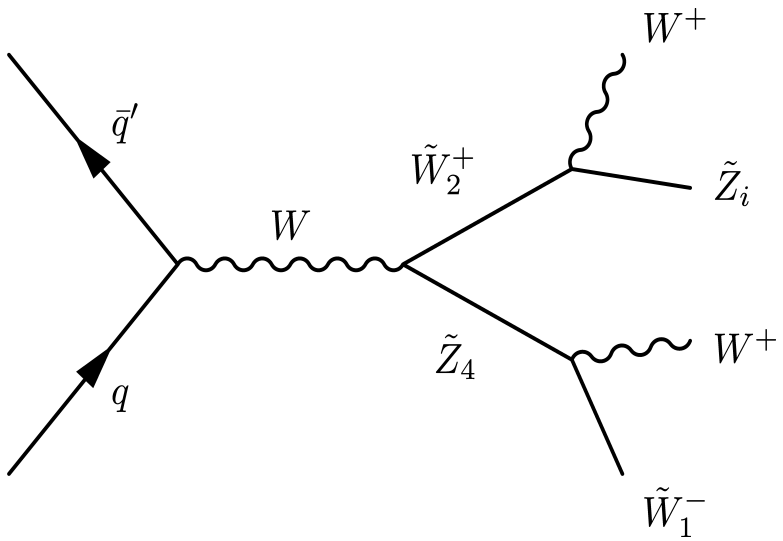
- For $m_{1/2} < 400 - 500\ \mathrm{GeV}$ and $\mu$=150GeV most e pass trigger threshold
- A shape analysis may allow to claim a signal with high luminosity – confirmation channel



# Same-sign Dibosons

arXiv: 1302.5816

- Sizeable production cross section (~10-100 fb) for wino-like $\widetilde{Z}_4\widetilde{W}_2$ and $\widetilde{W}_2\widetilde{W}_2$
- Each decays into W about 50%
- Two W's are not charge correlated
- Same-sign WW is novel signature, charcteristic of light higgsinos
- No 2->2 SM production of ssWW
- BG from WZ and ttbar removed by mT>125 GeV cut

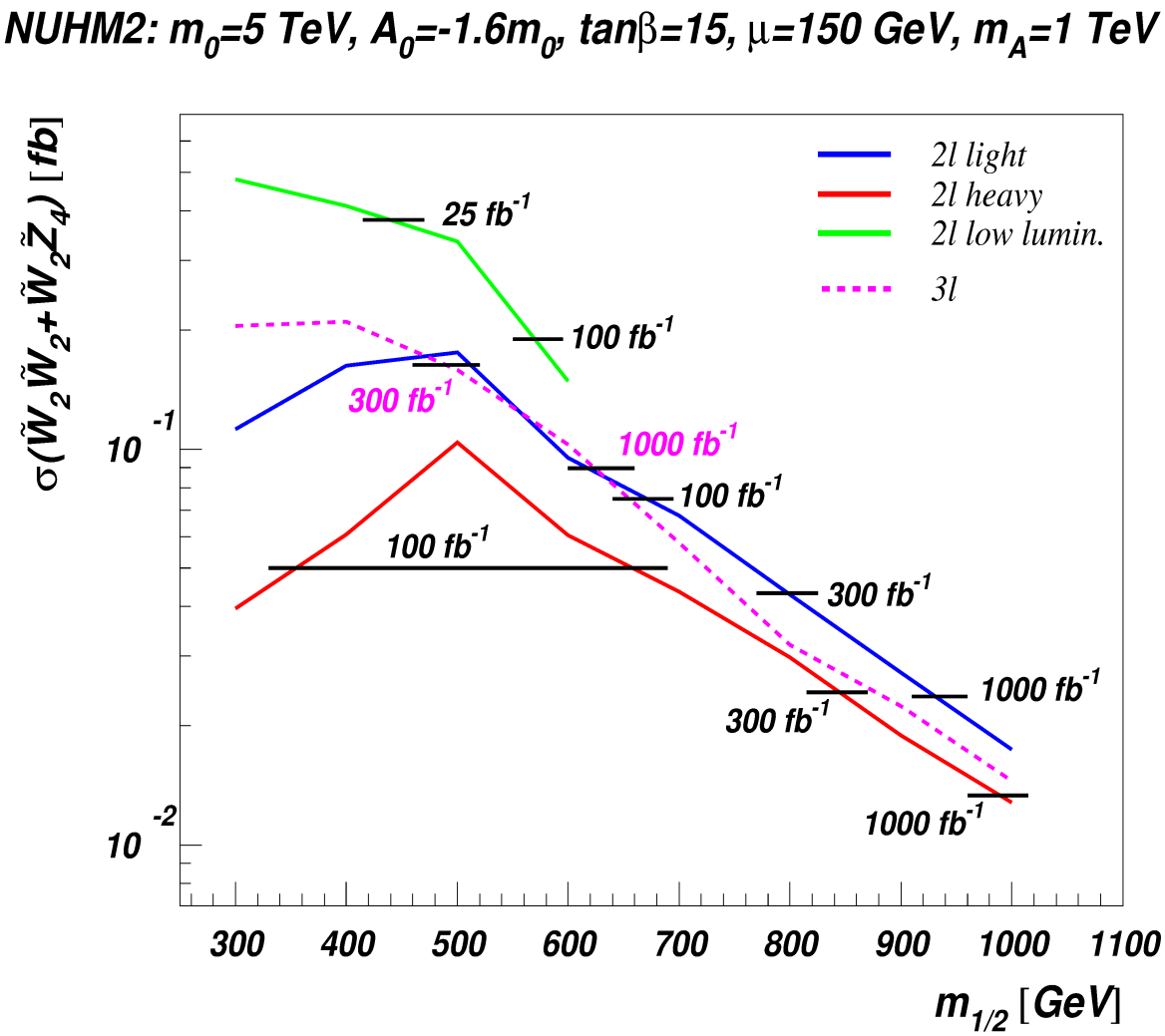



- 2lSS+MET is not probed by existing di-lepton searches that require significant hadronic activity

# ssWW prospects

arXiv: 1302.5816, 1310.4858

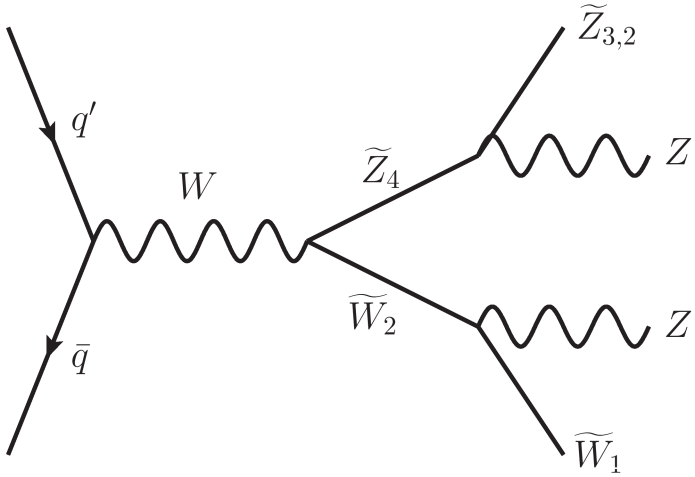
- Reach for 100 (1000) $fb^{-1}$ extends to $m_{1/2} \sim 680\ (1000)\ \mathrm{GeV}$
- Much better than canonical 3-lepton reach
- Exceeds direct gluino production reach, $m_{1/2} \sim 700\mathrm{GeV}$ with $300\mathrm{fb}^{-1}$ (if gaugino masses are unified)
- Independent of gluino search!



# 4-lepton signature

arXiv: 1310.4858

- Winos also have significant BF to Z, 25-50%
- Novel channel for low |μ| models: 4 isolated leptons + MET and no jets
- BGs controlled by MET > 200 GeV cut
- Reach for 300 (1000) $fb^{-1}$ extends to
  $m_{1/2} \sim 500\ (650)\ \mathrm{GeV}$
  comparable to canonical 3-leptons
  -> confirmatory channel
  for same-sign WW

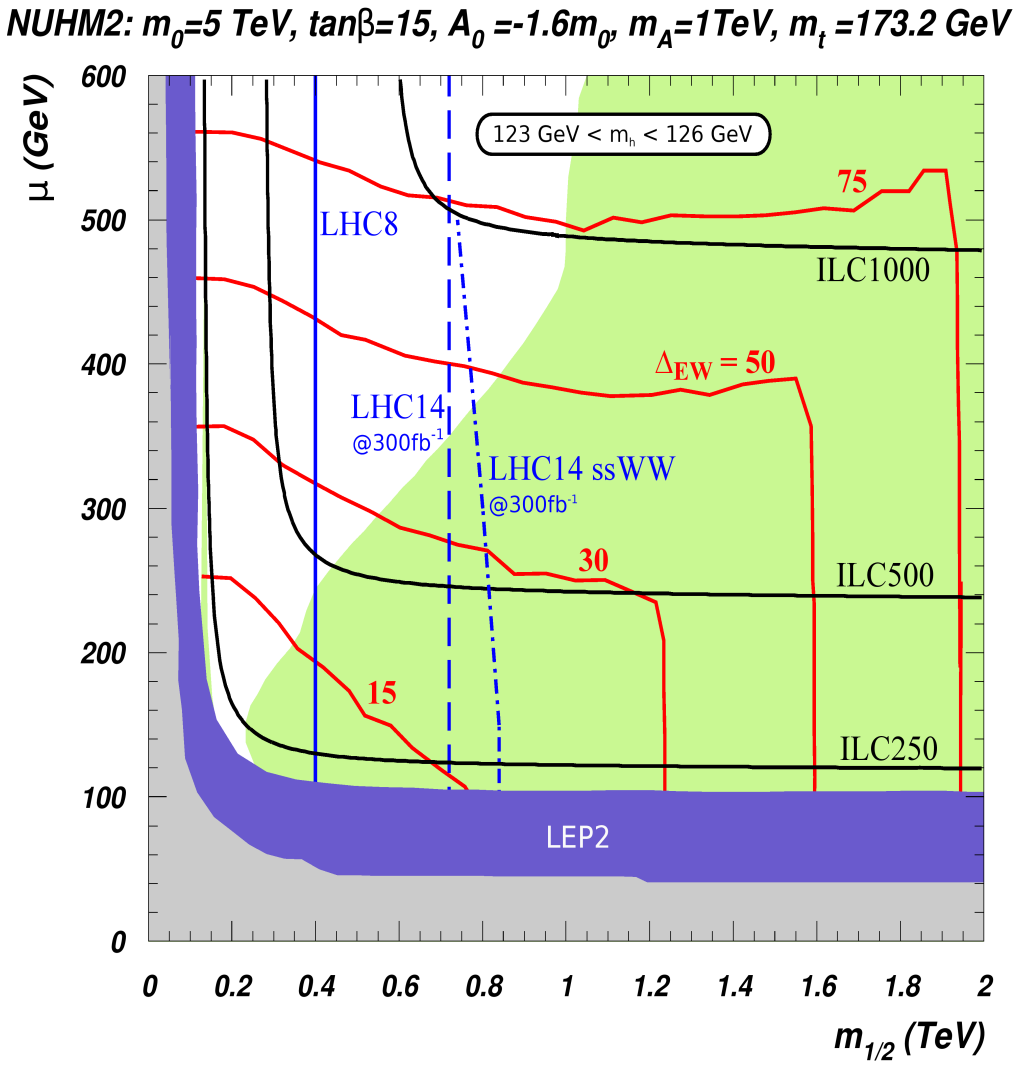



- Current 4-lepton searches are optimized for glunio cascades in RPV with many leptons and jets

# LHC-ILC complimentarity

arXiv: 1310.4858

- In light higgsino models, ssWW offers the largest reach $m_{1/2} \sim 1$ TeV for HL-LHC
- Still not enough to fully probe <3% EWFT region
- ILC with $\sqrt{s} \sim 600$ GeV is needed for complete check of FT in MSSM
- ILC can measure higgsino masses with sub-GeV precision (see arXiv:1404.7510)

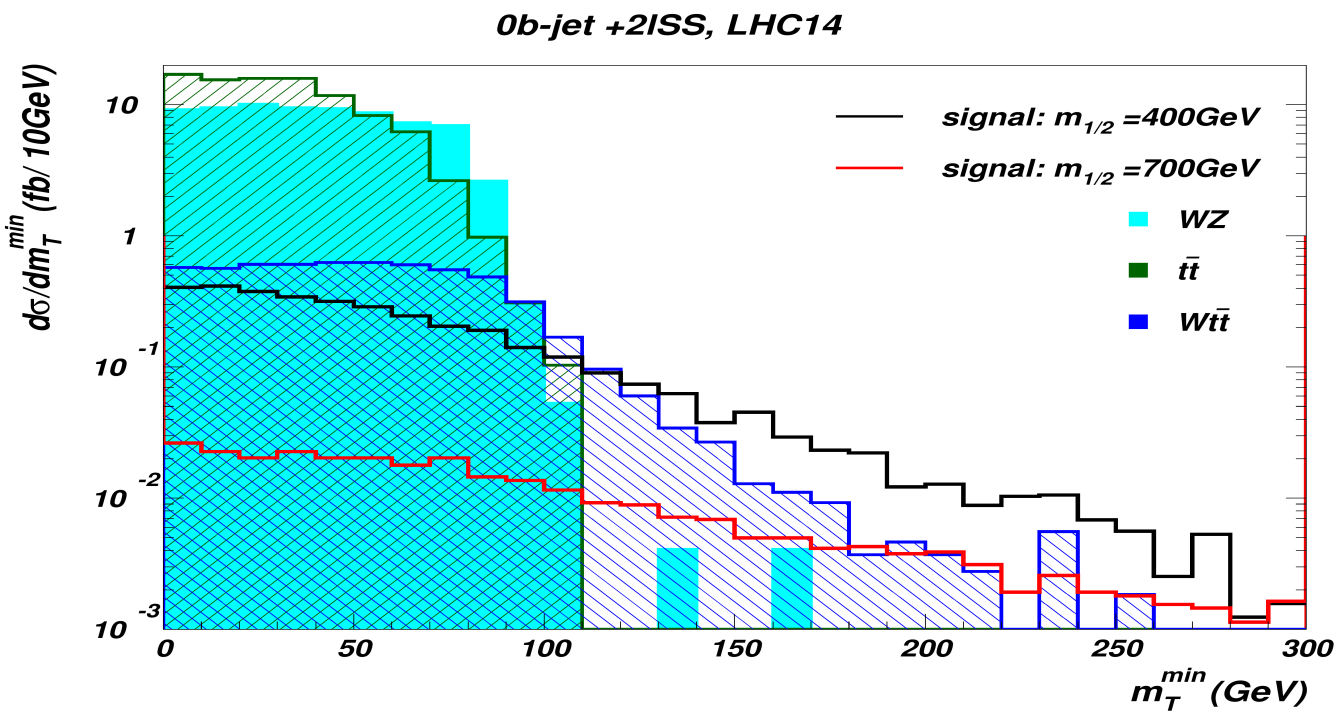


# *Conclusions*

- 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 by ssWW, but ILC with ~600 GeV is necessary to complete the test of SUSY naturalness with FT >3%.

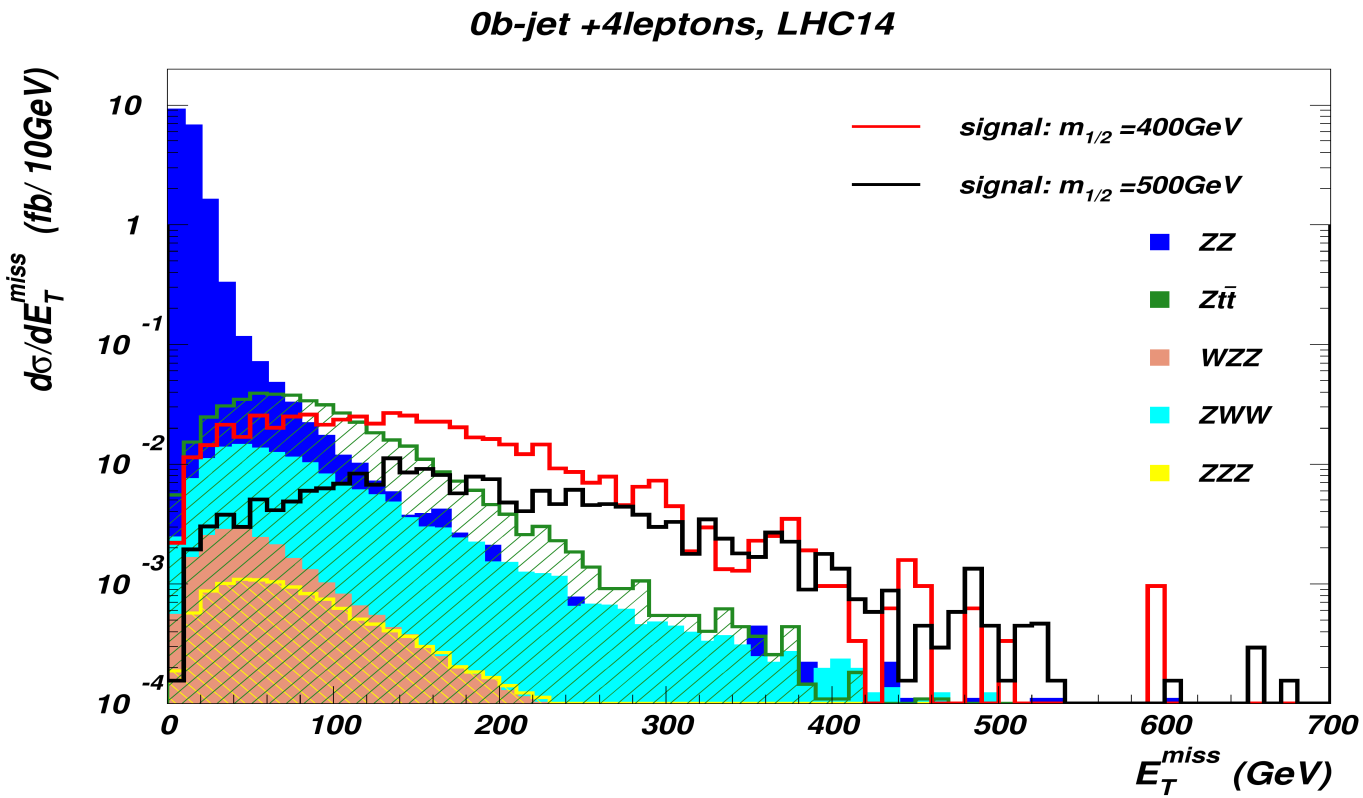
# Cuts for ssWW

- b-jet veto (60% eff.)
- 2 isolated same-sign leptons $p_T(l_1) > 20GeV,\ p_T(l_2) > 10GeV$
- $m_T^{min} \equiv \min\left[m_T(l_1, \not{E}_T), m_T(l_2, \not{E}_T)\right] > 125GeV$
  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 $p_T(l) > 10\ \mathrm{GeV},\ |\eta(l)| < 2.5$
- MET > 100 (200) GeV



# Higgsinos mass gap

arXiv: 1404.7510