SUSY benchmark after LHC8

Post LHC8 SUSY benchmark points for ILC physics

Howard Baer[1], *Jenny List*[2]

[1]University of Oklahoma, Norman, OK 73019, USA
[2]DESY, Notkestraße 85, 22607 Hamburg, Germany

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http://www-flc.desy.de/ilcphysics/postLHC8-SUSYbenchmarks.php

Akiya Miyamoto

for

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Theoretical motivation

- Supersymmetry is a symmetry between bosonic and fermionic field
- Appealing for theorists because it reduces quadratic divergences of scalar field to logarithmic.
- A solution for gauge hierarchy problem
  - weak scale stable against quantum corrections.
  - Stable extrapolation of SM to GUT scale
  - Provides a route to unification with gravity via local SUSY, supergravity model.

Indirect experimental evidence

- Guage coupling unification
  - SM gauge coupling at electro-weak scale meat at GUT point
- Precision electroweak measurements
  - consistent with a SUSY model with heavy SUSY particles
  - Top quark mass and electroweak symmetry breaking
  - Mt=150 ~ 200 GeV
- Light Higgs mass
- Dark matter: no SM particles are the candidate of cold dark matter, SUSY offers several candidates, such as the neutralino, the gravitino, a singlet sneutrino
- Baryogenesis: not possible to explain in the SM, but SUSY theories offer some candidates

Some problems for SUSY models

- LHC
  - No evidence with ~ 5fb^{-1} at 7 TeV and ~ 20fb^{-1} at 8 TeV
  - CMS (11.7 fb^{-1}@8 TeV) excluded $m_{\tilde{g}} \lesssim 1500\,\text{GeV}$ in the mSUGRA for $m_{\tilde{q}} \simeq m_{\tilde{g}}$
    $m_{\tilde{g}} \lesssim 1000\,\text{GeV}$ for $m_{\tilde{q}} \gg m_{\tilde{g}}$.

    in the mSUGRA (=CMSSM)

    Scenario with a universal light squark mass is excluded

- mSUGRA fits on EWPO, $(g-2)_\mu$, B-meson decay BR, neutralino CDM excluded similar mass region.

- Mh=125 GeV ➔ ruled out minimal version of gauge-mediated SUSY and anomaly mediated SUSY (lightest MSSM particle exceeded 5 TeV)

BP1:Natural SUSY

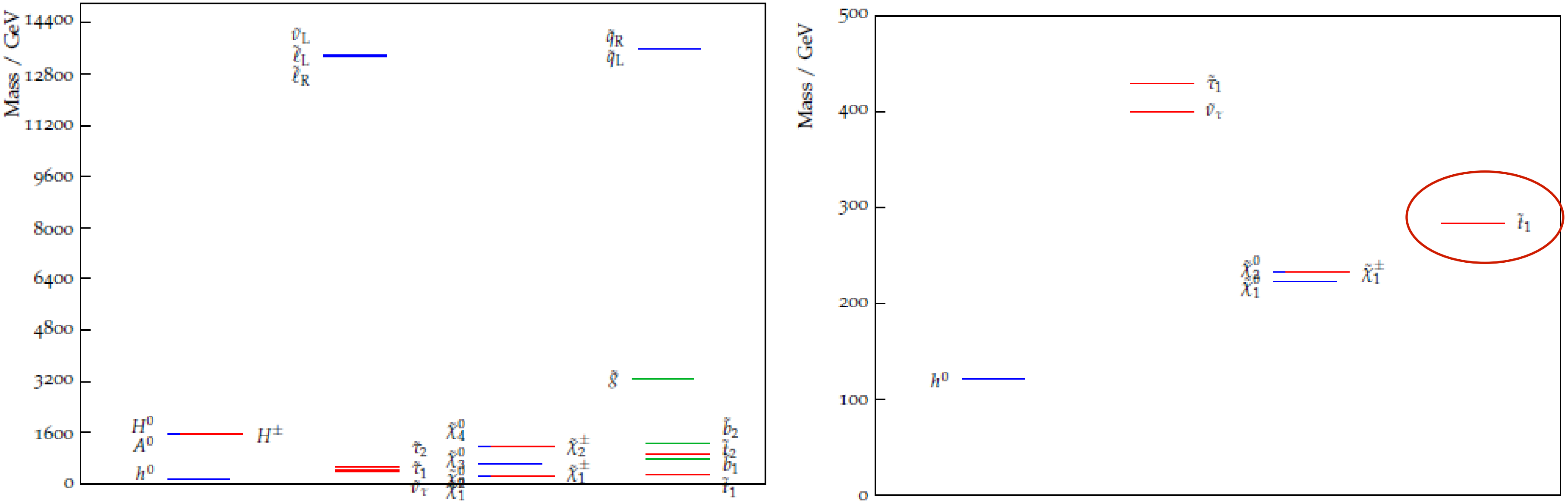
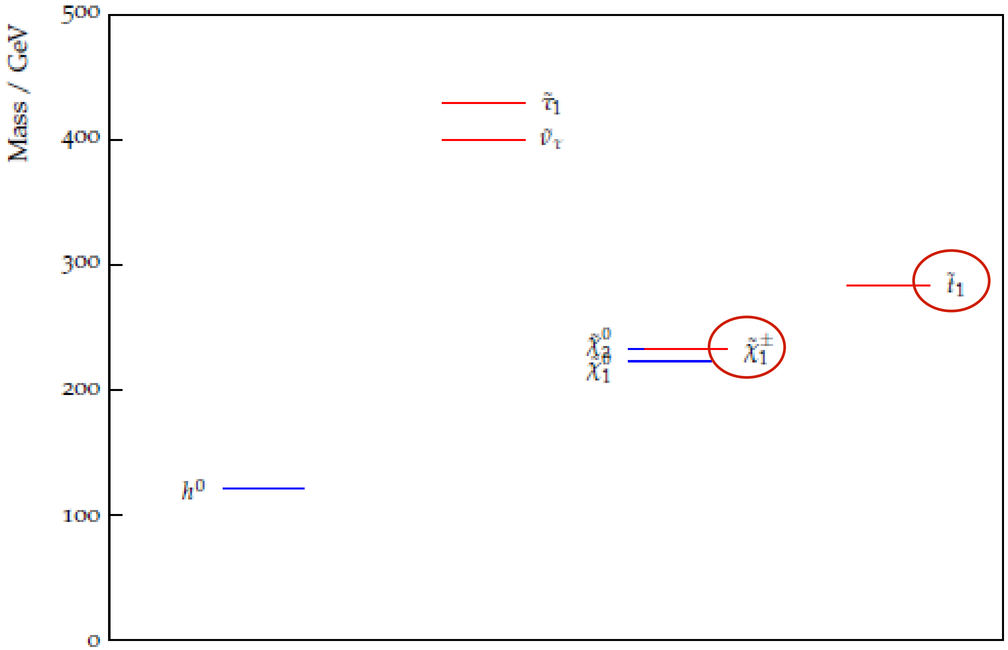


Figure 2: Left: Full spectrum of the natural SUSY benchmark. Right: Zoom into the spectrum below 500 GeV.

- a superpotential higgsino mass parameter $\mu \lesssim 100 - 300\,\text{GeV}$,
- a sub-TeV spectrum of third generation squarks $\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$,
- an intermediate scale gluino $m_{\tilde{g}} \lesssim 1.5 - 3\,\text{TeV}$ with $m_A \lesssim |\mu| \tan\beta$ and
- multi-TeV first/second generation matter scalars $m_{\tilde{q},\tilde{\ell}} \simeq 10 - 50\,\text{TeV}$.



At LHC,

- higgsino-like electroweakinos production at LHC → missing Et events
- next heavier particle is the $\tilde{t}_1$. small mass difference

$m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$ < top mass

→ $\tilde{t}_1 \to b\tilde{\chi}^\pm_1$ dominates,

missing Et + 2 acollinear b-jets

At ILC the spectrum of higgsino-like $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ will be accessible for $\sqrt{s} \geq 320$ GeV

$\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2\tilde{\chi}^0_2$ pair production and $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production

a mass gap $m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} \sim m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \sim 7.5$ GeV: → small visible energy

a hard ISR photon radiated from the initial state may help

Cross section is typically in the few tens of fb region

As $\sqrt{s}$ is increased past $600 - 800$ GeV, $\tilde{t}_1\bar{\tilde{t}}_1$, $\tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$ and $\tilde{\tau}_1\bar{\tilde{\tau}}_1$ become successively accessible.

BP2:Radiatively-driven natural SUSY (RNS)

- Motivated to minimize Δ_{EW}, with large squark mass

requiring $\mu \simeq 100 - 300\,\text{GeV}$ $\quad m_{\tilde{t}_{1,2}} \simeq 1 - 4\,\text{TeV}.$

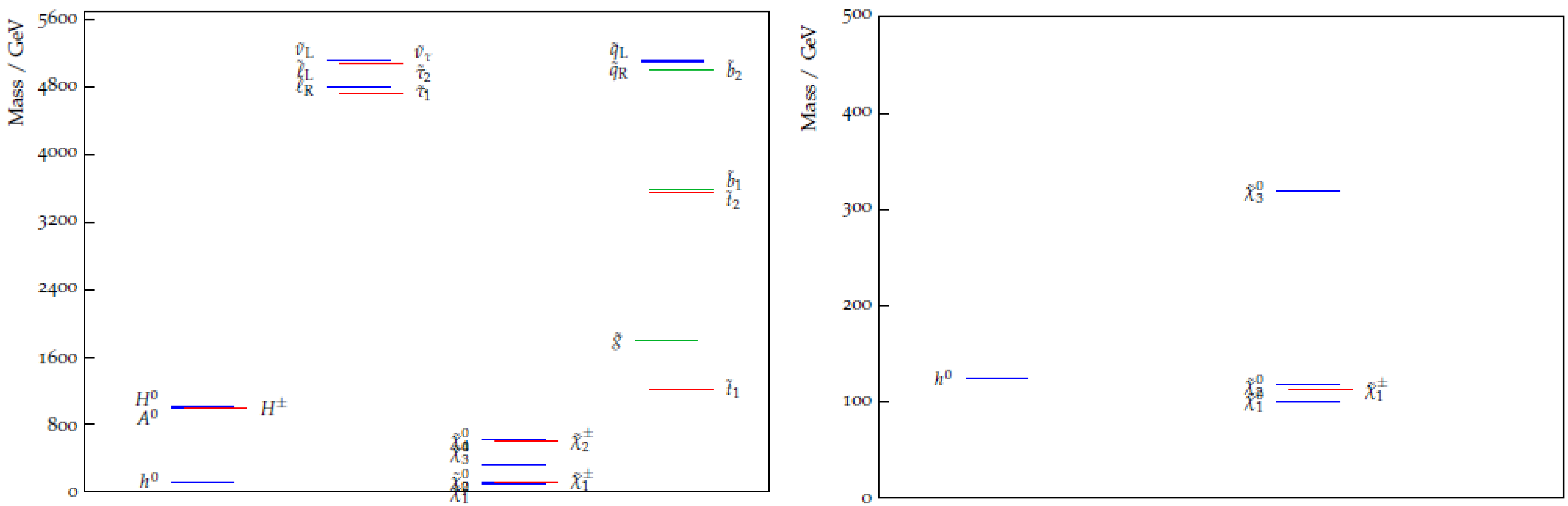


Figure 3: Left: Full spectrum of the RNS benchmark. Right: Zoom into the spectrum below 500 GeV.

- Observable at LHC as gluino cascade decay if gluino mass is low, but it could be 5 TeV. Could be seen as same sign di-boson production : $pp \to \tilde{\chi}_2^{\pm}\tilde{\chi}_4^0 \to (W^{\pm}\tilde{\chi}_2^0) + (W^{\pm}\tilde{\chi}_1^{\mp})$
- ILC: $\tilde{\chi}_1^+\tilde{\chi}_1^-$ or $\tilde{\chi}_1^0\tilde{\chi}_2^0$. "The small mass gap, angular distribution and polarization dependence of the signal cross sections may all be used to help establish the higgsino-like nature…"

BP3: NUHM2 with light A, H, H+-

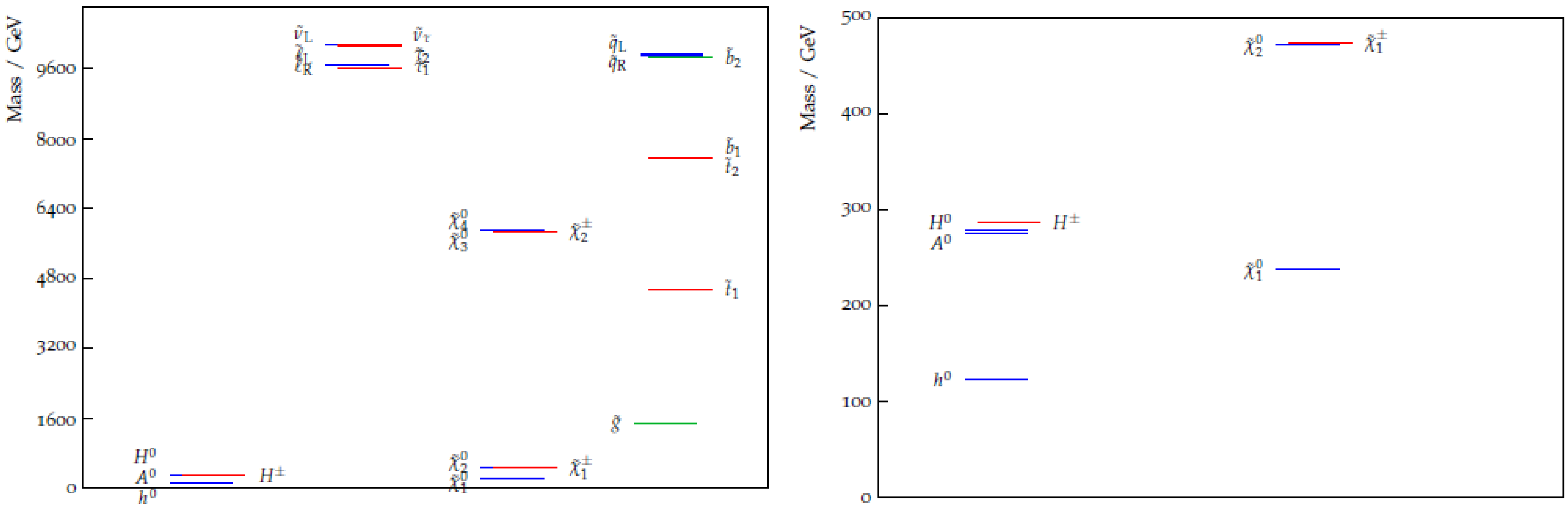


Figure 4: Left: Full spectrum of the NUHM2 benchmark. Right: Zoom into the spectrum below 500 GeV.

- Light A, H, H+-, but remaing sparticles beyond LHC reach
- Br(b->sγ) would be large due to tH+ loop contribution
- LHC: may be light gluino (~ 1.46TeV)
  - need a dedicated analysis for $\tilde{g} \to \tilde{\chi}_1^0 t\bar{t}$ $\tilde{g} \to (\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm) tb,$
  - LHC14 should observe $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to Wh + E_T^{\rm miss} \to \ell\nu_\ell + b\bar{b} + E_T^{\rm miss}$
- ILC 0.5TeV, Ah, ZH at an observable rate
  Accessible to AH, H+-, Electroweakino (decays to real W+, Z)

BP4:mSUGRA/CMSSM

- Large portion of parameter space were ruled out by
  - direct search of gluino and squakrs at LHC8
  - mh~125 GeV ➔ excluded $m_{1/2}$<1 TeV for low m_0 and m_0<2.5 TeV for low $m_{1/2}$
- Some remaining dark matter allowing parameter space (still fine tuned)

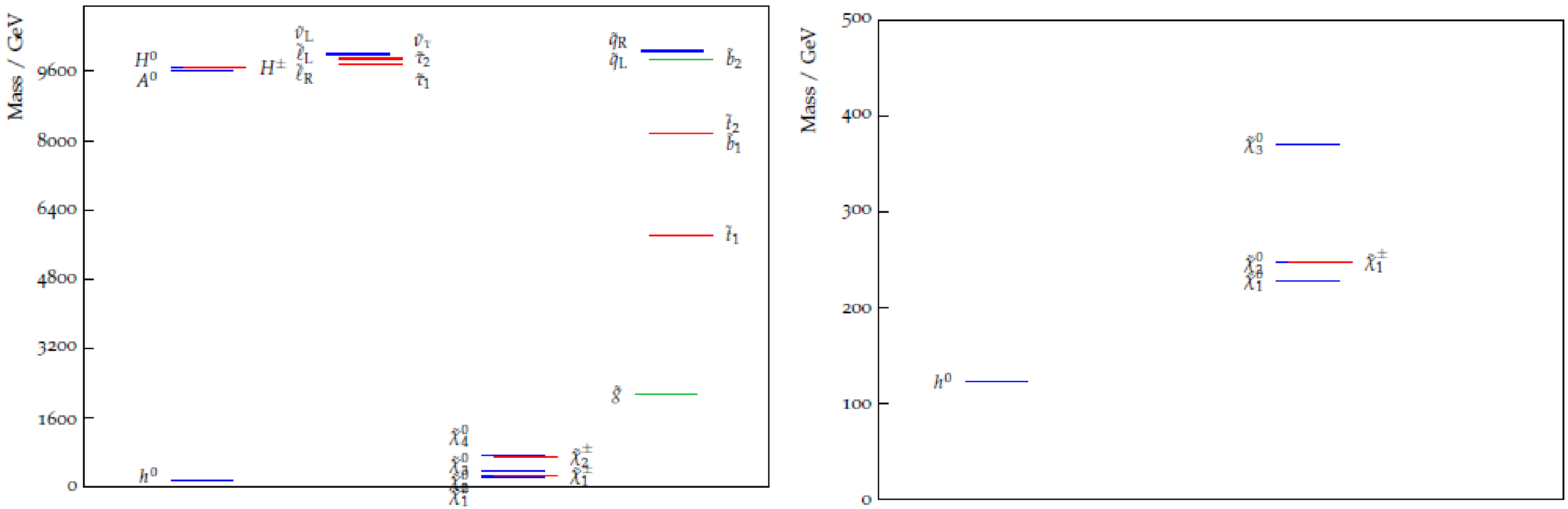


Figure 5: Left: Full spectrum of the mSugra benchmark. Right: Zoom into the spectrum below 500 GeV.

For LHC14, missing Et $pp \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \to W^* h^* + E_T^{\rm miss}$.

ILC0.5 for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$. $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass gap is just 19 GeV.

BP5: Non-universal gaugino mass (NUGM)

- Gaugino mass at GUT scale:
  - m0=3TeV, M1=0.3TeV, M2=0.25TeV, M3=0.75TeV were selected

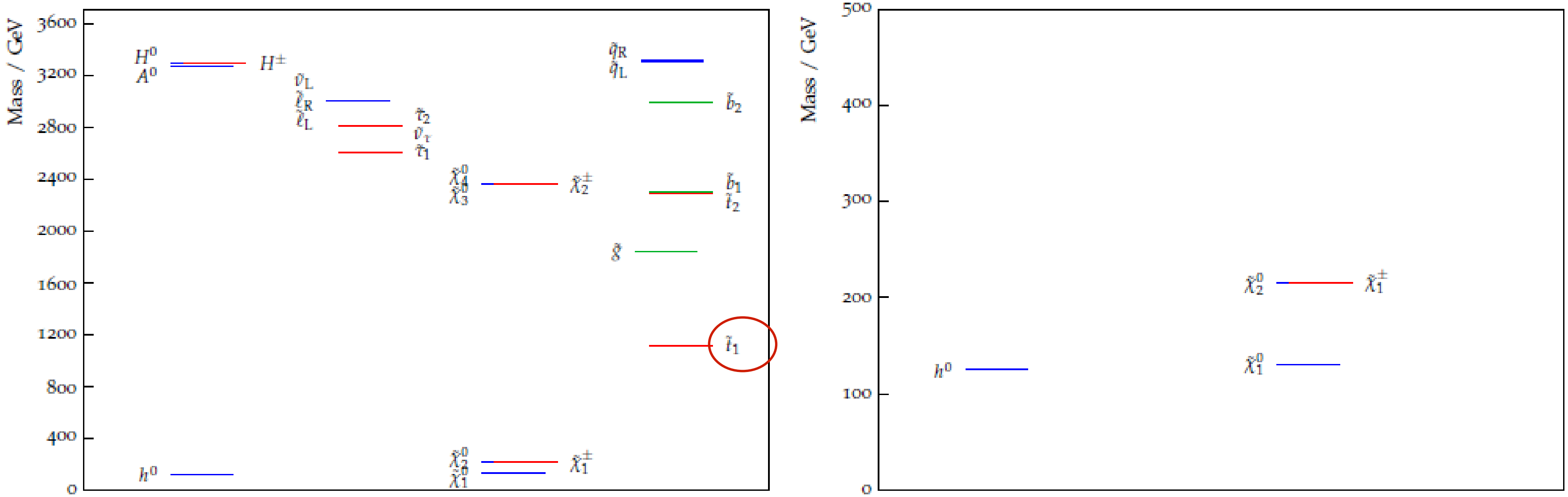


Figure 6: Left: Full spectrum of the NUGM benchmark. Right: Zoom into the spectrum below 500 GeV.

model should be testable in future LHC searches, not only in the standard jets plus missing E_t analyses, but also via searches tailored for very high multiplicity final states and using b-jet tagging [163], since the gluino almost exclusively decays via $\tilde g \to \tilde t_1 t$ followed by $\tilde t_1 \to \tilde\chi_1^0 t$. In addition, the production channel $pp \to \tilde\chi_1^\pm \tilde\chi_2^0 \to WZ + E_T^{miss}$ may be testable in the near future [164].

- ILC0.5: chargino pair production, $\tilde\chi_1^\pm \to \tilde\chi_1^0 W$ $\quad W^+W^- + \not{E}$

BP6: stau-coannihilation (STC)

- pMSSM (phenomenological MSSM model)
  - scenario with light τ ↓1 : allows efficient dark matter annihilation mechanism & consistency with (g-2)μ anomaly and Br(b→sγ)
  - parameters
    - m_{gluino}, μ, m_A, $\tan\beta$, (2 or 3)x(m_Q, m_U, m_D, M_L, M_E), M_1,M_2, A_t, A_b, $A\tau$: 19 or 24 parameters

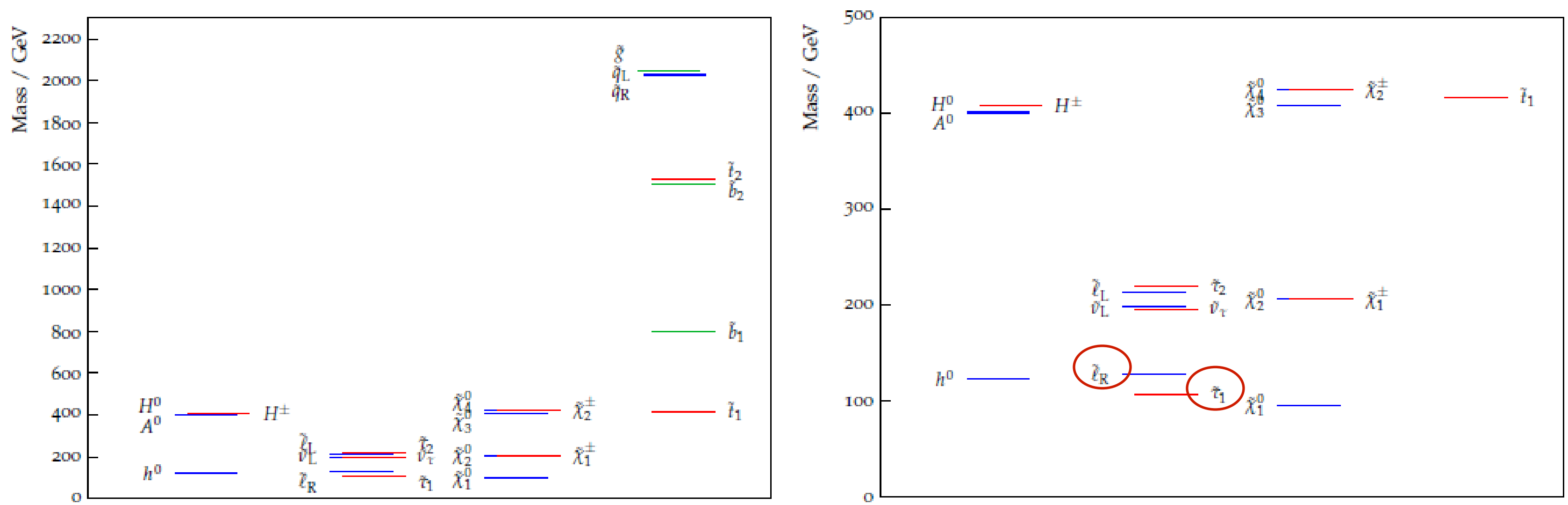
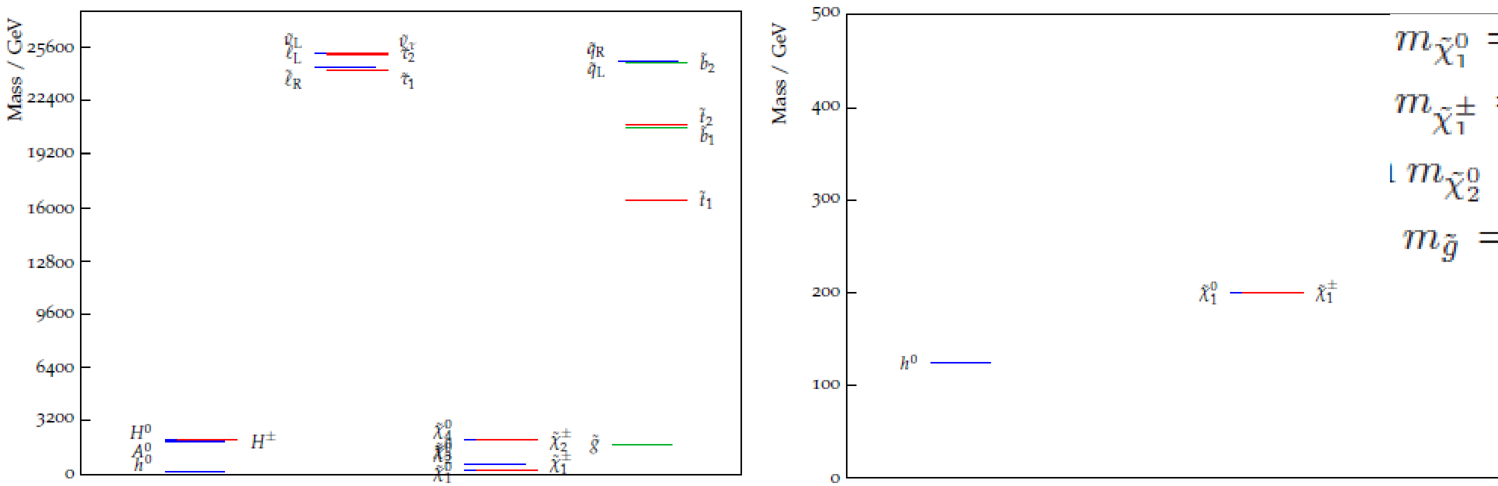


Figure 7: Left: Full spectrum of the STC benchmark. Right: Zoom into the spectrum below 500 GeV.

- gluino and light squarks beyond current LHC8 limit
- light slepton is not detectable due to soft tau lepton
- many sleptons and electroweakinos obsable at ILC0.5, and further more at ILC1.0, but experimentally challenging to identify each of them due to cascade decay.

BP7:Kallosh-Linde(KL), G2MSSM, spread SUSY benchmark

- A model to avoid difficulty of minimal anomaly-mediation model which predict a ligh Higgs scalar (< 120 GeV)
- various scalar particles are heavy, similar to the gravitino mass ~ 100TeV, the gaugino remains O(1)TeV



$$m_{\tilde{\chi}_1^0} = 200.07\ \text{GeV}$$
$$m_{\tilde{\chi}_1^\pm} = 200.4\ \text{GeV}.$$
$$m_{\tilde{\chi}_2^0} = 616.5\ \text{GeV}$$
$$m_{\tilde{g}} = 1788\ \text{GeV}.$$

Figure 8: Left: Full spectrum of the KL benchmark. Right: Zoom into the spectrum below 500 GeV.

- LHC14 accessible to the gluino pair production with O(100)fb-1
- ILC: wino-like chargino is quasi-stable: Highly ionizing track+decay into soft product pair production of chargino could be detected with ISR photon tagging
- ILC1.0: $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production opens up $\tilde{\chi}_2^0 \to W\tilde{\chi}_1^\pm$ or $\tilde{\chi}_1^0 h$ to occur.

BP8: Brummer-Buchmuller(BB) BM

- A model inspired by GUT-scale string compactification

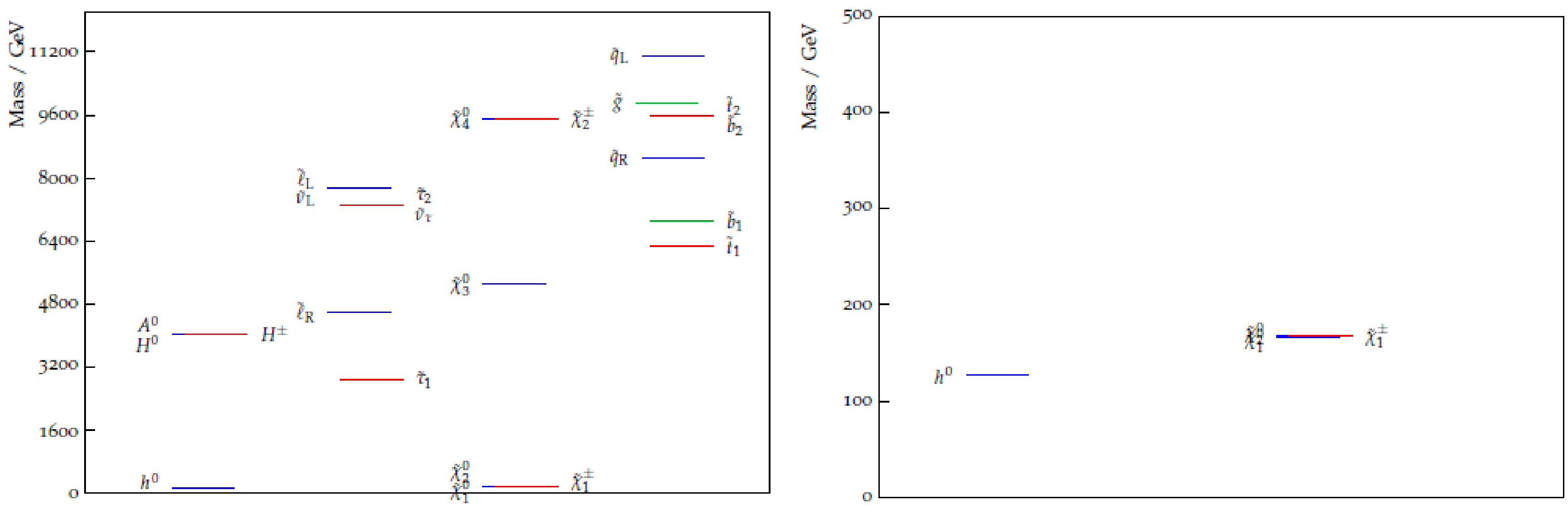


Figure 9: Left: Full spectrum of the BB benchmark. Right: Zoom into the spectrum below 500 GeV.

- gluino and squarks in several TeV range and escape LHC detection
- the model include higgsino-like light chargino and neutralino, accessible at ILC

  $mass(\chi_{1,2}^{0})$ = 167, 168 GeV, $mass(\chi_{1,2}^{\pm})$=167, 9520 GeV

BP9: Normal scalar mass hierarchy (NMH)

- Normal scalar mass hierarchy: $m_0(1) \sim m_0(2) << m_0(3)$
- Motivated by
  - >3σ discrepancy of $(g-2)_\mu$ (requires light smuons)
  - lack of a large discrepancy in $Br(b \to s\gamma)$ (requires 3rd generation squarks beyond TeV)
- Need degeneration among first/second generation sfremions to suppress FCNC
- first/second generation squarks, light at GUT scale, get high mass value by renomalization group running to EW scale due to strong coupling, but sleptons remain light.

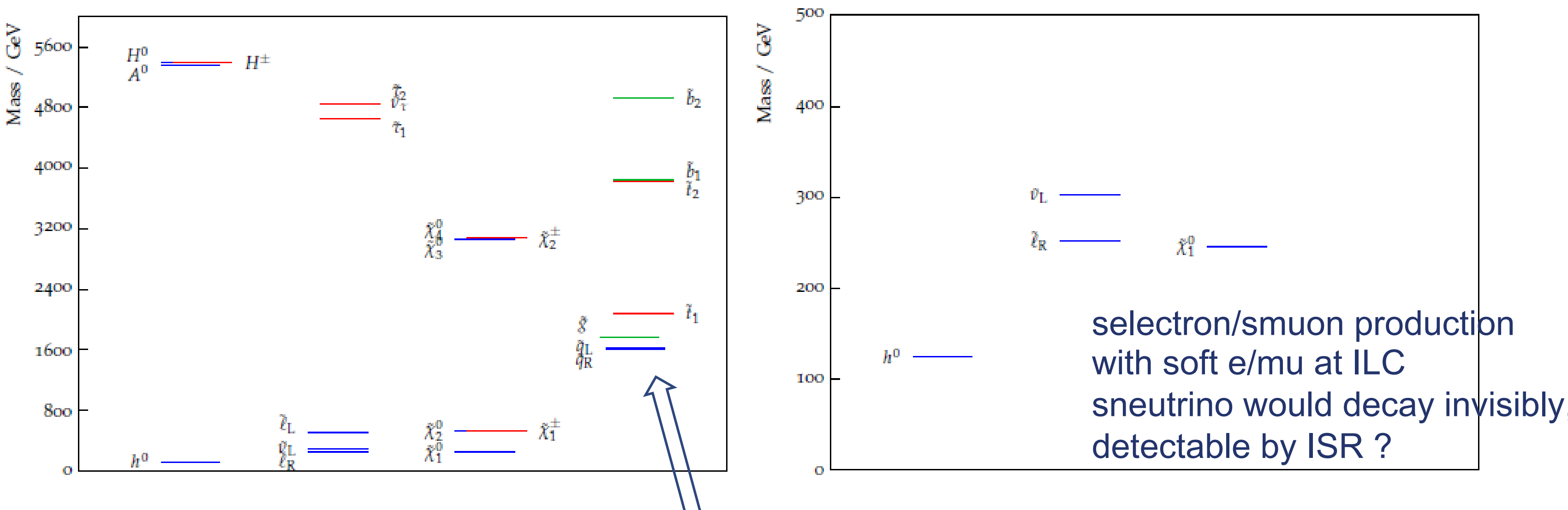


Figure 10: Left: Full spectrum of the NMH benchmark. Right: Zoom into the spectrum below 500 GeV.

Compatible with LHC8 result, but tested at LHC14

BP10: Low mH scenario(LMH)

- Assume 125 GeV particle is heavy CP-even Higgs boson
- m_A=110GeV, tanβ=6.2, μ=1.7TeV : production rates for H is at least 90% of SM

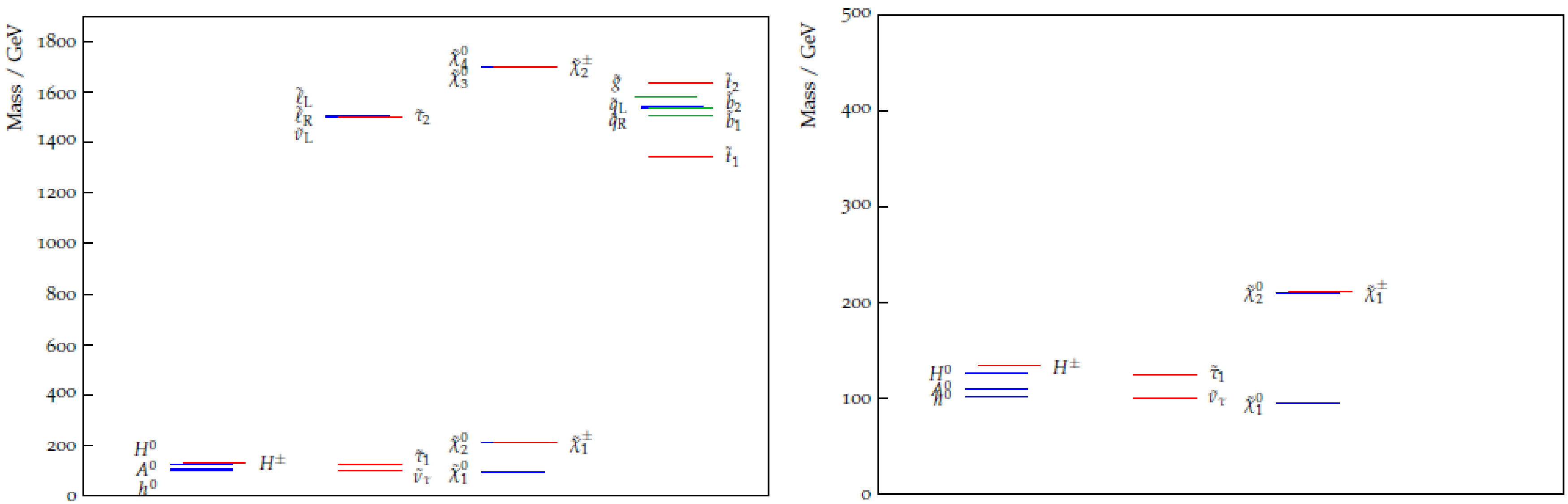


Figure 11: Left: Full spectrum of the lowMH benchmark. Right: Zoom into the spectrum below 500 GeV.

- $\nu\downarrow\tau$ is NLSP(101GeV) and τ is126GeV.
  Both of them contribute to a sufficiently high co-annihilation for the observed relic density.
- τ decays 100% to $\tau+\nu\downarrow\tau$, $\nu\downarrow\tau$ decays invisibly($\nu\downarrow\tau+\chi\downarrow 1\uparrow 0$).
- $\nu\downarrow\tau$ mass measurement is important for cosmological measurement.
- Light CP-even higgs: 103 GeV. low cross section and escape LEP detection.
- M_A=110GeV, $M_{H\pm}$=134 GeV. Due to low tanβ, they are difficult to detect at LHC.

Conclusion

- Good motivation to SUSY despite non-observation at LHC8.
- SUSY : area of many speculation
- which model do you bet ?