SUSY prospects for Linear Colliders in view of LHC results

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LHC2TSP Workshop, July 2012, CERN

Main implication of LHC:

Evidence for a new particle at a mass of $\simeq 125$ GeV!

- Is it “a” Higgs boson?
- Is it “the” SM Higgs boson?
- Is it part of a more complex Higgs sector? Which part?
- Has it a non-Higgs admixture?
- If it is the SM Higgs, how can its mass be so light?

$\Rightarrow$ Rich bread & butter physics program of Higgs and top precision measurements and indirect searches for an $\sqrt{s} \simeq 0.25 \ldots 0.5 \ldots (1.0)$ TeV e^+e^- Linear Collider

$\rightarrow$ c.f. talk by R. Pöschl on Friday

Question here:
Can we still expect some BSM “cream topping” in addition?

Take SUSY as example

SUSY Goodies

- solution to hierarchy problem
- gauge coupling unification
- radiative electroweak symmetry breaking
- dark matter candidates
- baryogenesis
- theoretically well understood
- calculable & predictive

SUSY Problems

- SUSY flavour problem: e.g. $\Delta M(K)$, $b \to s\gamma$, $\mu \to e\gamma$
- SUSY CP problem: EDMs
- gravitino problem: overproduction of Dark Matter or late $\tilde{G}$ decays spoiling BBN
- fine-tuning: creeps in again if SUSY partners too massive
- **no SUSY partners seen (identified?) sofar!**

Indirect Constraints

- $(\mathbf{g}-\mathbf{2})_\mu$: hints towards light $\tilde{\mu}$ or large $\tan\beta$
- $\mathbf{b}\to\mathbf{s}\gamma$: BR above SM would hint towards large $\tan\beta$ and light $H^\pm$, $\tilde{\chi}^\pm$
- $\mathbf{B_s}\to\mu^+\mu^-$: constrains $\tan^6\beta/m_A^4$
- $\mathbf{B_u}\to\tau^+\nu_\tau$: agrees with SM, but some room for SUSY contributions within errors.
- **Dark Matter:** Could consist of several particle species. Don't forget light moduli or axions (and thus axinos, saxions)
- **Higgs:** right mass for the MSSM - but need to solve hierarchy problem more than ever!

Grand Picture of LHC SUSY searches (I)

- **Gluinos:** LHC $m_{\tilde{g}} \gtrsim 1.4$ TeV for $m_{\tilde{g}} \simeq m_{\tilde{q}}$
  $\Rightarrow$ fine with "naturalness" prefering $m_{\tilde{g}} \lesssim 3-4$ TeV
- **1st /2nd Gen. Squarks:** LHC $m_{\tilde{q}} \gtrsim 1.4$ TeV for $m_{\tilde{g}} \simeq m_{\tilde{q}}$ in simplest case. Could be in tens of TeV regime from theory & flavour point of view. Could have different masses!
- **Sleptons:** Constrained by LHC in some specific cascades with specific mass differences. Need to be light to explain $(g-2)_\mu$. Light $\tilde{\tau}$ best candidate to enhance $h \to \gamma\gamma$ (c.f. talks Sat. afternoon!)
  best "watertight" limit still from LEP: $\mathbf{m_{\tilde{l}} \gtrsim 100}$ GeV

Grand Picture of LHC SUSY searches (II)

- **Electroweakinos:** Hardly constrained by LHC unless in conjunction with light gluinos / 1st or 2nd gen. squarks - or with light sleptons with $m_{\tilde{l}} = 1/2(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$. Naturalness motivates Higgsino nature for light ewkinos - but wino/bino possible as well
- **3rd Gen. Squarks:** LHC limits far below those for 1st / 2nd generation, no conflict yet with naturalness regime.
- **SUSY Higgses:** If light Higgs SM-like $\rightarrow A$, H and $H^\pm$ could be heavy. Direct search: $m_A > 500$ GeV at $\tan\beta = 50$, $m_A > 220$ GeV (or $m_A < 120$ GeV) at $\tan\beta = 10$. This is exactly corner where heavy H at 125 GeV.

A word on constraints & “fine-tuning”

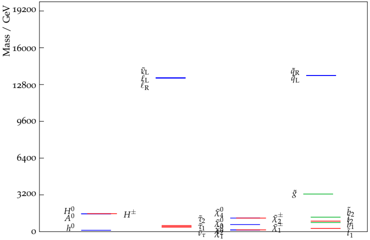
- when a lot of tweaking of a model is needed to fulfill *theoretical* boundary conditions → “fine-tuning” – beyond some point should question “naturalness” of model
- **this is not true for experimental limits!**
- nature only chose *one* point
- so even if you picked the right model, you expect to *experimentally* exclude everything around this true point before pinning it down
- c.f. Higgs discovery: nothing unnatural in excluding huge mass range before discovery at the right mass!

⇒ The experimentally relevant question is whether certain characteristic phenomenological features are excluded or allowed, but not how “often” they occur!

In this spirit

- will present several examples of valid scenarios featuring
  - light Higgsinos
  - light gauginos
  - light sleptons
- all have $m_h \simeq 125$ GeV....
- all are compatible with LHC direct searches
- but only some of them fulfill all indirect constraints (esp. $(g-2)_\mu$)

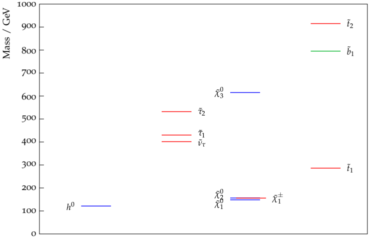
Natural SUSY



Characteristics:

- naturalness constrains $\mu, m_{\tilde{t}}, m_{\tilde{g}}$
- multi-TeV 1st / 2nd gen squarks avoid SUSY flavour problem

zoom:



Linear Collider:

- $\sqrt{s} = 500$ GeV:
  $|\mu|, M_2$ via $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$
- $\sqrt{s} = 1$ TeV:
  $\tilde{t}_1\bar{\tilde{t}}_1$, $\tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$, $\tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{\tau}_1\tilde{\tau}_2$ and $\tilde{\chi}_{1/2}^0\tilde{\chi}_3^0$

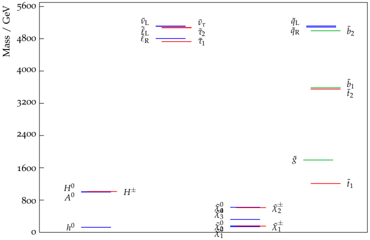
Hidden SUSY

Characteristics:

- allow slightly larger Λ_{NS}, but keep $|\mu|$ small
- higgsinos similar as before, $\Delta M \simeq 10$ GeV
- but 3rd gen scalars more heavy, lighter $\tilde{\chi}_3^0$

Linear Collider:

- $\sqrt{s} = 500$ GeV: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_{1,2}^0\tilde{\chi}_3^0$
- $\sqrt{s} = 1$ TeV: $\tilde{\chi}_{1,2}^0\tilde{\chi}_4^0$



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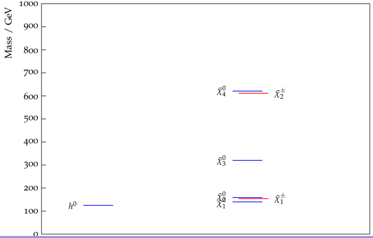
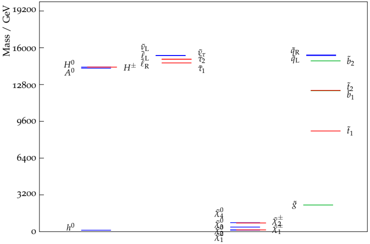


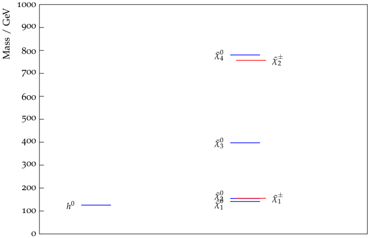
A typical example of what is left of mSUGRA



Characteristics:

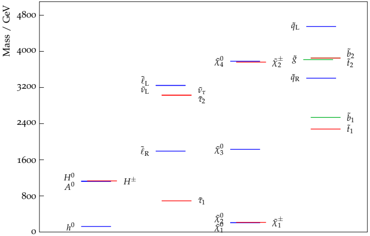
- example for remaining DM allowed regions of mSUGRA with $m_h = 126$ GeV and obeying LHC limits
- interestingly, this is very close to the Hidden SUSY case
- but even more challenging at LHC since $m_{\tilde{g}} = 2.3$ TeV, lightest squark $m_{\tilde{t}_1} = 8.8$ TeV

zoom:



Mixed gravity-gauge mediation arXiv: 1201.4338 [hep-ph]

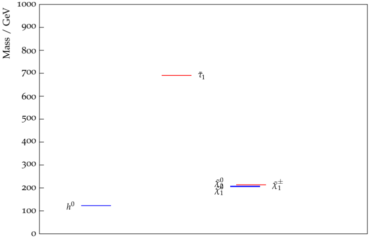
dedicated talk tomorrow by F. Brümmer!



Characteristics:

- inspired by GUT-scale string compactifications
- higgsinos similar as before, but $\Delta M \simeq 1...3$ GeV
- $m_{\tilde{g}} = 3.8$ TeV, lightest squark $m_{\tilde{t}_1} = 2.3$ TeV $\rightarrow$ "LHC nightmare"

zoom:



Linear Collider:

- $\sqrt{s} = 500$ GeV: $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$
- $\tilde{\tau}_1$ could be light in addition

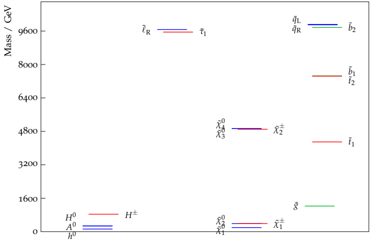
Non-universal Higgs masses

Characteristics:

- light ewkinos: Wino / Bino mixture
- light SUSY Higgses at low $\tan\beta = 6$, $m_A = 275$ GeV
- $m_{\tilde{g}} = 1.2$ TeV, decay to $t\bar{t}\tilde{\chi}_1^0$ / $tbW^{\pm}\tilde{\chi}_1^0$

Linear Collider:

- $\sqrt{s} = 500$ GeV: Ah, ZH
- $\sqrt{s} = 1$ TeV: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$



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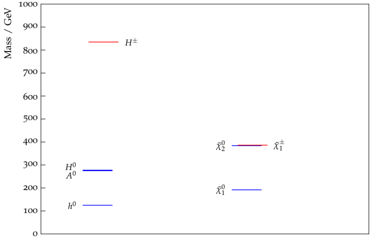


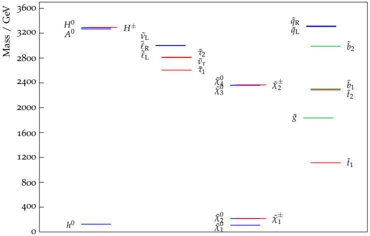
Non-universal Gaugino masses

Characteristics:

- light ewkinos: Wino / Bino mixture
- $m_{\tilde{g}} = 1.2$ TeV, decay to $t\bar{t}\tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ decays to $W^\pm / Z\tilde{\chi}_1^0$
- testable at LHC in near future

Linear Collider:

- $\sqrt{s} = 500$ GeV: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$ (at low rate)



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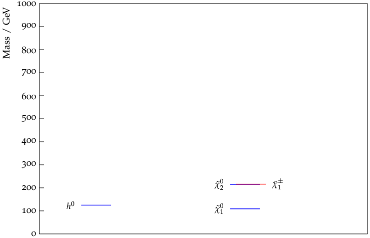


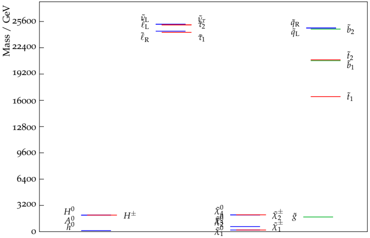
Kallosh-Linde models

Characteristics:

- from stabilisation of moduli fields
- scalar fields order of $m_{3/2} \simeq 100$ TeV
- gauginos sub-TeV, AMSB form
- with extreme mass degeneracy: $\Delta M = 0.3$ GeV

Linear Collider:

- $\sqrt{s} = 500$ GeV: $\tilde{\chi}_1^+ \tilde{\chi}_1^-$
- $m_{\tilde{\chi}_1^\pm}$ from ISR recoil, ΔM from decay to $\pi \tilde{\chi}_1^0$
- studied for TESLA TDR



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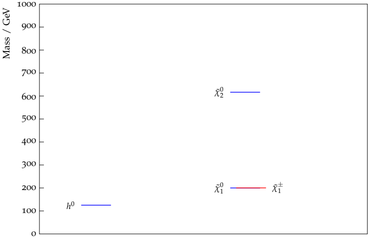
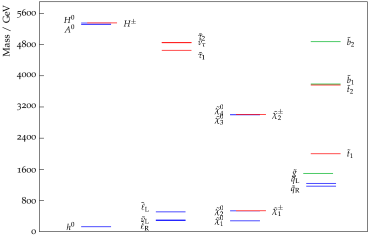


Normal Mass Hierarchy

Characteristics:

- reconcile $(g-2)_\mu$ with $BR(b \to s\gamma)$
- light $\tilde{\mu}$, 3rd gen squarks beyond TeV-scale
- $\simeq$ 1.5 TeV gluino / 1st and 2nd gen squarks $\Rightarrow$ testable this year?



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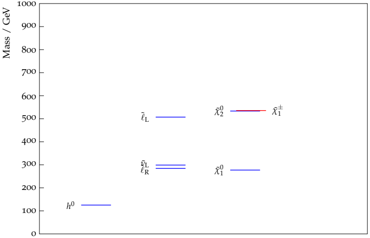


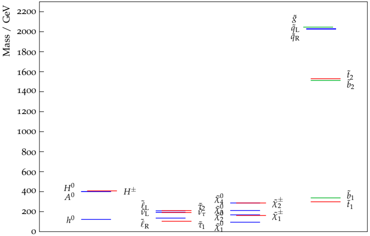
Linear Collider:

- $\sqrt{s} = 600$ GeV: $\tilde{\chi}^0_1\tilde{\chi}^0_1\gamma$, $\tilde{\mu}^+_R\tilde{\mu}^-_R$, $\tilde{e}^+_R\tilde{e}^-_R$
- $\sqrt{s} = 1$ TeV: $\tilde{\mu}^+_L\tilde{\mu}^-_L$, $\tilde{e}^+_L\tilde{e}^-_L$

pMSSM

Characteristics:

- from a phenomenological point of view, everything is still allowed
- fulfill all constraints, esp. $(g-2)_\mu$, $BR(b \to s\gamma)$, Dark Matter, Higgs,...
- small $\delta m_{\tilde{\tau}} = 7$ GeV



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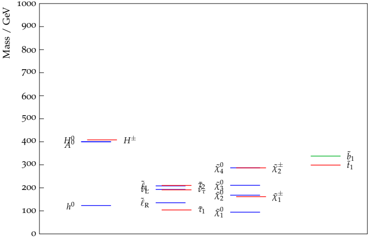

Linear Collider:

- $\sqrt{s} = 500$ GeV: ewkinos, sleptons
- $\sqrt{s} = 1$ TeV: $\tilde{\chi}_2^+ \tilde{\chi}_2^-$, SUSY Higgses, $\tilde{t}_1 \bar{\tilde{t}}_1$, $\tilde{b}_1 \bar{\tilde{b}}_1$

Favoured by current data

- light electroweakinos
- could be Higgsinos, and mass degenerate
- optionally augmented by
  - light $\tilde{t}_1$ (naturalness)
  - light $\tilde{\mu}$ ($(g-2)_\mu$)
  - light $\tilde{\tau}_1$ (dark matter, $h \to \gamma\gamma$)

- model-independent SUSY parameter determination with “just” electroweakinos?
  - obviously: gaugino-sector
  - precision measurements: sensitivity to non-gaugino sector parameters through loop-contributions

    $\rightarrow$ *c.f. talk by A. Barucha at ICHEP*
  - needs polarised cross-sections ($P(e^-)$ and $P(e^+)$)
  - and threshold scans

Prospects

- still a lot for LHC to discover
- even at low sparticle masses
- some scenarios will be extremely difficult for LHC
- so the “cream topping” for a Linear Collider is more probable than ever
  - for precision measurements of particles discovered at LHC
  - for discovering additional particles after LHC discovered BSM
  - and even for first-hand discovery
    (or a “watertight” exclusion...)

Still very good reason to expect answers at the TeV scale - but will need comprehensive access to electroweak BSM sector