Proposals for (revised) SUSY CLIC benchmarks.

To fulfill the popular demand for benchmarks with heavier masses, we'll first propose a single SUSY model that could serve for all three of the slepton, squark, and heavy Higgs benchmark processes. Using a single model for several different benchmark processes has several possible advantages:

- Synergy: different analyses can feed off of each other, just as in the real world.
- Choosing some masses somewhat below the maximal reach gives a "safety margin" for early studies, while still clearly beating what ILC can do.
- A single complete SUSY simulation can be used for "SUSY backgrounds" to each process, if desired.

Also, in the real world, luminosity requirements may demand that staying at one fixed $\sqrt{s}$ will be necessary, even if it is not quite the optimal $\sqrt{s}$ for all physics analyses.

In the following, models are defined and constraints checked using the output of Softsusy3.1.3 and micrOmegas2.2. Branching ratios come from SDECAY1.1, and cross-sections from Madgraph4. NOTE: ISR and beamstrahlung effects not included!

To make a model that is simultaneously appropriate for the slepton, squark, and heavy Higgs benchmark processes, use a Minimal Supersymmetry model with parameters at the GUT scale as follows:

$$M_1 = 780\,\mathrm{GeV}, \quad M_2 = 940\,\mathrm{GeV}, \quad M_3 = 540\,\mathrm{GeV},$$
$$A_0 = -750\,\mathrm{GeV}, \quad m_0 = 303\,\mathrm{GeV}, \quad \tan\beta = 24, \;\; \mu > 0,$$
$$m_t = 173.3\,\mathrm{GeV}, \;\; M_b(M_b) = 4.25\,\mathrm{GeV}, \;\; \alpha_S(M_Z) = 0.118.$$

Note this is *not* an mSUGRA model, instead having non-unified gaugino masses [specifically, in a pattern found in models with an F-term that is part singlet and part adjoint under $SU(5)$]. This allows sleptons to be relatively heavier compared to squarks than the ratio found in mSUGRA within the stau-coannihilation region.

Indirect constraints for this model:

$$\begin{aligned}\Omega_{\rm DM}h^2 &= 0.1105\\ \Delta a_\mu &= 6.04\times 10^{-10}\\ BR(b\to s\gamma) &= 3.01\times 10^{-4}\\ BR(B_s\to\mu^+\mu^-) &= 3.9\times 10^{-9}\end{aligned}$$

Complete mass spectrum:

```
h, H, A, Hpm = 119.13  902.4  902.6  906.3
Neutralinos = 328.3  701.8  760.2  816.2
Charginos = 701.6  816.1
stau1, stau2, snutau = 330.2  674.3  666.8
stop1, stop2 = 739.4  1121.8
sbot1, sbot2 = 1043.3  1096.0
seR, seL, snue = 422.8  696.1  691.3
suR, suL, sdR, sdL = 1125.7  1257.7  1116.1  1260.0
Gluino = 1239.7
```

Slepton production benchmark

Relevant Masses:
$$
\begin{aligned}
m_{\tilde{e}_R} &= m_{\tilde{\mu}_R} = 422.8 \text{ GeV} \\
m_{\tilde{e}_L} &= m_{\tilde{\mu}_L} = 696.1 \text{ GeV}
\end{aligned}
$$

At $\sqrt{s} = 3$ TeV:
$$
\begin{aligned}
e^+e^- &\to \tilde{e}^+_R\tilde{e}^-_R \quad 24.2 \text{ fb} \\
e^+e^- &\to \tilde{e}^+_R\tilde{e}^-_L \quad 2.98 \text{ fb} \quad (\times 2 \text{ for } R \leftrightarrow L) \\
e^+e^- &\to \tilde{e}^+_L\tilde{e}^-_L \quad 10.8 \text{ fb} \\
e^+e^- &\to \tilde{\mu}^+_R\tilde{\mu}^-_R \quad 2.60 \text{ fb} \\
e^+e^- &\to \tilde{\mu}^+_L\tilde{\mu}^-_L \quad 2.29 \text{ fb}
\end{aligned}
$$

Branching ratios (for both $\ell = e, \mu$):
$$
\begin{aligned}
\tilde{\ell}_R &\to \ell\tilde{N}_1 \quad (100\%) \\
\tilde{\ell}_L &\to \ell\tilde{N}_1 \quad (100\%)
\end{aligned}
$$

Note also $\tilde{\nu}_\ell \to \nu_\ell\tilde{N}_1$ is 100% and invisible in this model.

Physics observables include:

masses of $\tilde{e}_R, \tilde{e}_L, \tilde{\mu}_R, \tilde{\mu}_L, \tilde{N}_1$ from kinematic edges.

polarization to separate $\tilde{\ell}_L$ from $\tilde{\ell}_R$.

cross-section measurements for $\tilde{e}_R, \tilde{e}_L$ to indirectly constrain neutralino masses entering in t-channel.

Right-handed squark production benchmark

$$\text{Relevant Masses:} \qquad m_{\tilde{u}_R} = m_{\tilde{c}_R} = 1126 \text{ GeV}$$
$$m_{\tilde{d}_R} = m_{\tilde{s}_R} = 1116 \text{ GeV}$$

At $\sqrt{s} = 3$ TeV:

$$\begin{array}{lclll} e^+e^- & \to & \tilde{u}_R\bar{\tilde{u}}_R & 1.14 \text{ fb} & (\times\ 2 \text{ for } \tilde{c}_R) \\ e^+e^- & \to & \tilde{d}_R\bar{\tilde{d}}_R & 0.291 \text{ fb} & (\times\ 2 \text{ for } \tilde{s}_R) \end{array}$$

Branching ratios:

$$\tilde{q}_R \to q\tilde{N}_1 \quad (99.7\%).$$

Physics observables include: $m_{\tilde{q}_R}$ from kinematic distributions, angular distribution for production, check presence of $\tilde{u}_R, \tilde{c}_R$ vs. $\tilde{d}_R, \tilde{s}_R$ using polarization.

Heavy Higgs pair production benchmark

$$\text{Relevant Masses:} \quad \begin{aligned} m_{A^0} &= 902.6 \text{ GeV} \\ m_{H^0} &= 902.4 \text{ GeV} \\ m_{H^\pm} &= 906.3 \text{ GeV} \end{aligned}$$

(Note: this is not quite up to the desired 1 TeV, but hopefully 900 GeV will be deemed close enough. If not, it is much easier to make a dedicated model with $m_A = 1$ TeV, rather than to try to squeeze it into a single model that also works well with the slepton and squark benchmarks. However, I would argue that the advantages of having a single common benchmark model for the different processes outweigh advantages of the extra 100 GeV in m_A.)

$$\text{At } \sqrt{s} = 3 \text{ TeV:} \quad \begin{aligned} e^+e^- &\rightarrow H^+H^- & 1.67 \text{ fb} \\ e^+e^- &\rightarrow H^0A^0 & 0.692 \text{ fb} \end{aligned}$$

Branching ratios:

$$
\begin{array}{rcl}
H^{+} & \rightarrow & t\bar{b}\ (81.8\%), \quad \tau^{+}\nu_{\tau}\ (18.2\%) \\
H^{0} & \rightarrow & b\bar{b}\ (81.8\%), \quad \tau^{+}\tau^{-}\ (17.3\%), \quad t\bar{t}\ (0.9\%), \\
A^{0} & \rightarrow & b\bar{b}\ (81.7\%), \quad \tau^{+}\tau^{-}\ (17.3\%), \quad t\bar{t}\ (1.0\%),
\end{array}
$$

Physics observables include: m_{A^0}, m_{H^0}, $m_{H^\pm}$

$\sigma \times BR$ for $H^0/A^0 \rightarrow b\bar{b},\ \tau^+\tau^-$

$\sigma \times BR$ for $H^+ \rightarrow t\bar{b},\ \tau^+\bar{\nu}_\tau$

angular distribution for production (to get spin)

Chargino, Neutralino pair production benchmark

The model proposed above for the slepton, squark, and heavy Higgs processes unfortunately does not have, and cannot be tweaked to have, nice simple decays for charginos and neutralinos. More generally it is very difficult to have ~ 1 TeV wino-like neutralinos and charginos with simple branching fractions to W, Z, h in models that have good dark matter and reasonable chances for discovery at LHC. Also, it might be wise to leave room for studying heavier Higgsino-like states.

Therefore, we propose a model with $\sim$640 GeV wino-like states and $\sim$910 GeV higgsino-like states, defined by mSUGRA parameters as follows:

$$m_{1/2} = 800\,\mathrm{GeV}, \qquad A_0 = 0, \qquad m_0 = 966\,\mathrm{GeV}$$
$$\tan\beta = 51, \qquad \mu > 0$$

The relevant neutralino and chargino masses are:

$$\begin{aligned} m_{\tilde{N}_{1,2,3,4}} &= 340.3,\ 643.1,\ 905.5,\ 916.7\ \mathrm{GeV} \\ m_{\tilde{C}_{1,2}} &= 643.2,\ 916.7\ \mathrm{GeV} \end{aligned}$$

Indirect constraints:

$$\begin{aligned} \Omega_{\rm DM} h^2 &= 0.110 \\ \Delta a_\mu &= 7.92 \times 10^{-10} \\ BR(b \to s\gamma) &= 3.30 \times 10^{-4} \\ BR(B_s \to \mu^+\mu^-) &= 1.55 \times 10^{-8} \end{aligned}$$

Complete mass spectrum:

```
h, H, A, Hpm = 118.52  742.0  742.8  747.6
Neutralinos = 340.3  643.1  905.5  916.7
Charginos = 643.2  916.7
stau1, stau2, snutau = 670.4  973.7  962.0
stop1, stop2 = 1392.9  1598.1
sbot1, sbot2 = 1544.4  1609.7
seR, seL, snue = 1010.8  1100.4  1097.2
suR, suL, sdR, sdL = 1817.7  1870.3  1812.3  1871.8
Gluino = 1811.8
```

Important branching ratios for the lighter, gaugino-like, states:

$$\begin{aligned}\tilde{C}_1 &\rightarrow W\tilde{N}_1\ (100\%)\\ \tilde{N}_2 &\rightarrow h\tilde{N}_1\ (90.6\%),\quad Z\tilde{N}_1\ (9.4\%)\end{aligned}$$

Note that the dominance of $\tilde{N}_2 \rightarrow h\tilde{N}_1$ over $\tilde{N}_2 \rightarrow Z\tilde{N}_1$ is generic.

For the heavier, higgsino-like, states:

$$\begin{aligned}\tilde{C}_2 &\rightarrow W\tilde{N}_2\ (27.5\%),\quad W\tilde{N}_1\ (11.8\%),\quad h\tilde{C}_1\ (24.2\%),\\ &\quad\ Z\tilde{C}_1\ (25.8\%),\quad \tilde{\tau}_1\nu_\tau\ (10.7\%)\end{aligned}$$

$$\begin{aligned}\tilde{N}_3 &\rightarrow W^{\pm}\tilde{C}_1^{\mp}\ (51.4\%),\quad Z\tilde{N}_2\ (23.1\%),\quad Z\tilde{N}_1\ (10.9\%),\\ &\quad\ h\tilde{N}_1\ (1.95\%),\quad \tilde{\tau}_1^{\pm}\tau^{\mp}\ (12.1\%)\end{aligned}$$

$$\begin{aligned}\tilde{N}_4 &\rightarrow W^{\pm}\tilde{C}_1^{\mp}\ (52.8\%),\quad h\tilde{N}_1\ (9.8\%),\quad h\tilde{N}_2\ (23.3\%),\\ &\quad\ Z\tilde{N}_2\ (0.8\%),\quad Z\tilde{N}_1\ (2.1\%),\quad \tilde{\tau}_1^{\pm}\tau^{\mp}\ (11.2\%)\end{aligned}$$

Important production modes at $\sqrt{s} = 3$ TeV:

$$
\begin{array}{rclr}
e^+e^- & \to & \tilde{N}_1\tilde{N}_2 & 2.75 \text{ fb} \\
e^+e^- & \to & \tilde{N}_1\tilde{N}_3 & 0.043 \text{ fb} \\
e^+e^- & \to & \tilde{N}_1\tilde{N}_4 & 0.124 \text{ fb} \\
e^+e^- & \to & \tilde{N}_2\tilde{N}_2 & 3.90 \text{ fb} \\
e^+e^- & \to & \tilde{N}_2\tilde{N}_3 & 0.291 \text{ fb} \\
e^+e^- & \to & \tilde{N}_2\tilde{N}_4 & 0.270 \text{ fb} \\
e^+e^- & \to & \tilde{N}_3\tilde{N}_4 & 4.78 \text{ fb}
\end{array}
$$

$$
\begin{array}{rcll}
e^+e^- & \to & \tilde{C}_1^+\tilde{C}_1^- & 10.5 \text{ fb} \\
e^+e^- & \to & \tilde{C}_1^+\tilde{C}_2^- & 0.492 \text{ fb} \quad (\times 2 \text{ for } 1 \leftrightarrow 2) \\
e^+e^- & \to & \tilde{C}_2^+\tilde{C}_2^- & 11.8 \text{ fb}
\end{array}
$$

Physics observables include $\tilde{N}_2$ and $\tilde{C}_1$ masses, through

$$\begin{aligned} e^+e^- &\rightarrow \tilde{C}_1^+\tilde{C}_1^- \rightarrow W^+W^-\tilde{N}_1\tilde{N}_1 \\ e^+e^- &\rightarrow \tilde{N}_2\tilde{N}_2 \rightarrow hh\tilde{N}_1\tilde{N}_1, \quad hZ\tilde{N}_1\tilde{N}_1 \end{aligned}$$

For extra credit, if that's too easy, also reconstruct $\tilde{N}_{3,4}$ and/or $\tilde{C}_2$ using additional W, Z, h from their decays.

Note: in this model,

$$\begin{aligned} h &\rightarrow b\bar{b}\,(68.8\%), \\ &\rightarrow \tau^+\tau^-\,(21.0\%), \\ &\rightarrow WW\,(11.8\%), \\ &\rightarrow ZZ\,(0.9\%) \end{aligned}$$