SUSY at the ILC

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Muon Collider Physics Workshop:
November 11, 2009

SUSY at the ILC: Implications for a Muon Collider

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A discussion of some lessons from a study of the pMSSM at the ILC and a study of the pMSSM in general.

Not a review of SUSY at the ILC (which would take a slightly longer talk to say the least).

Based on work described in

- arXiv:0711.1374 [hep-ph]. Phys.Lett.B677:48-53,2009.
- arXiv:0712.2965 [hep-ph]. (PRD).
- arXiv:0812.0980 [hep-ph]. JHEP 0902:023,2009.

Work done with Carola Berger, JoAnne Hewett, Ben Lillie, and Tom Rizzo.

- Supersymmetry (SUSY) has many motivations: the hierarchy problem, dark matter, unification, connection with string theory, etc.
- The simplest supersymmetric extension of the standard model is the Minimal Supersymmetric Standard Model (MSSM).
- After SUSY breaking, the MSSM has **105 parameters** beyond those of the standard model.
- The large number of parameters can be problematic.
- One approach is to study particular SUSY breaking scenarios.
  - **Advantages: few parameters, unifying principle.**

However focusing on particular SUSY breaking scenarios means not exploring much of the 105 parameter MSSM space.

What are we missing with this approach? Are there SUSY signatures which differ greatly from those found from standard scenarios and benchmarks?

The Big Question:

How can one study SUSY phenomenology without assuming a particular SUSY breaking scenario, but without needing to e.g. scan over 105 parameters?

- Assume
  - **CP conservation** (removes phases)
  - **Minimal Flavor Violation** (removes off-diagonal terms in mass matrices)
  - **1st and 2nd generation sfermion masses are degenerate** (reduces number of mass parameters)
  - **1st and 2nd generation trilinear couplings negligible** (removes A_e, A_μ, A_u, A_d by setting $= 0$.)

- End up with the **pMSSM** (phenomenological MSSM).
- **19 Parameters**

- Gaugino masses: $M_1,\ M_2,\ M_3$
- Sfermion masses: $m_{q1,2}, m_{u1,2},\ m_{d1,2}, m_{l1,2},$
  $m_{e1,2},\ m_{q3}, m_{u3}, m_{d3}, m_{l3}, m_{e3}.$
- 3^{rd} generation trilinears: A_t, A_b, A_τ
- Higgs/ Higgsino parameters: $\mu, m_A, \tan\beta$

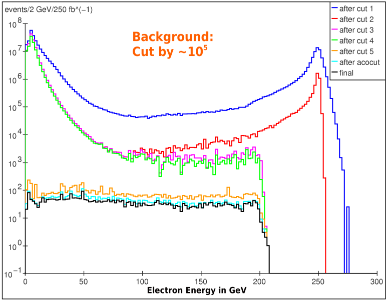
- **Notes:** All parameters specified $\sim$ the weak scale.

No high scale assumptions.

- Arkani-Hamed, Kane, Thaler, and Wang (JHEP 0608:070,2006) explored how well the LHC can uniquely determine SUSY parameters by generating $\sim 43,000$ pMSSM points.
  - They then found LHC signatures of each "model" (10 fb^{-1}, no BG).
  - Found the number of distinct signatures, models.
  - With some definition of "distinct", found that each model would be degenerate with $\mathcal{O}(10)$ others at LHC.
- In particular, in their set of $\sim 43,000$ models, there were 383 models which were degenerate with at least one other model in the set.
- As these models were in some sense "difficult" at LHC, we explored how well the ILC could distinguish these models.
- Provided an opportunity to study the ILC's capabilities for the exploration of a more general class of SUSY models.

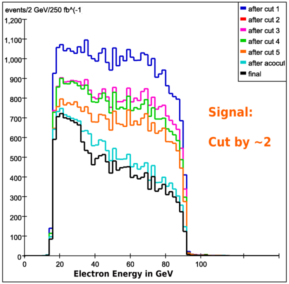
- For each model, we generated 250 fb^{-1} of data for each of 80% left and 80% right electron beam polarization.
- Considered $\sqrt{s} = 500$ GeV.
- Used a design-specific beamstrahlung spectrum for both signal and background.
- Used backgrounds developed by Tim Barklow which included all $2 \rightarrow 2$, $2 \rightarrow 4$, and $2 \rightarrow 6$ SM processes from e^+e^-, $e^\pm\gamma$, and $\gamma\gamma$ initial states
- Used the org.lcsim package to simulate the SiD.
- Used PYTHIA, included More accurate treatment of chargino, neutralino production with associated photons, chargino decays.
- Detailed study...
- BUT: No positron polarization, energy upgrade to 1 TeV. No threshold scans.

- Had trouble initially using “standard cuts”.
- Developed (with help from the literature) sets of cuts designed to optimize signal in various channels (see bonus slides for details, cites).



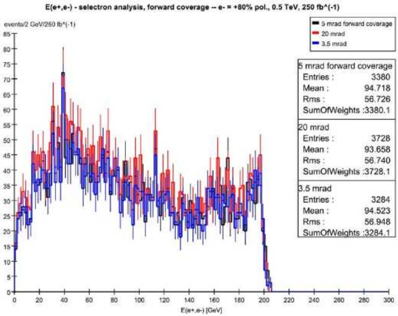
Electron Energy

Selectron Analysis



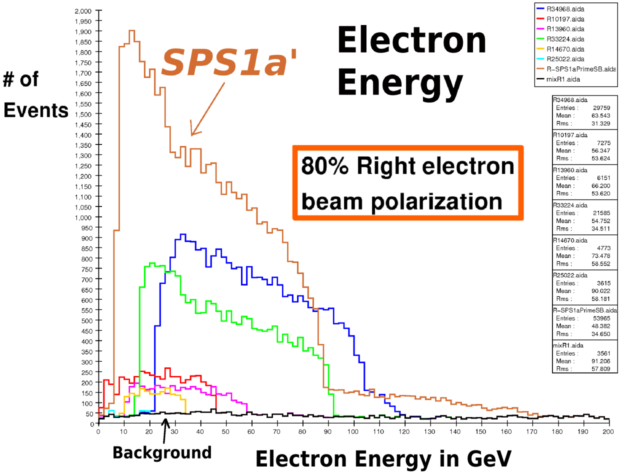
Forward Coverage

- For initial values of the forward tracking cutoff, we found unmanageably large backgrounds for many models.
- Needed to go to lower values for this cutoff.
- Important to see if this is a problem for muon colliders.

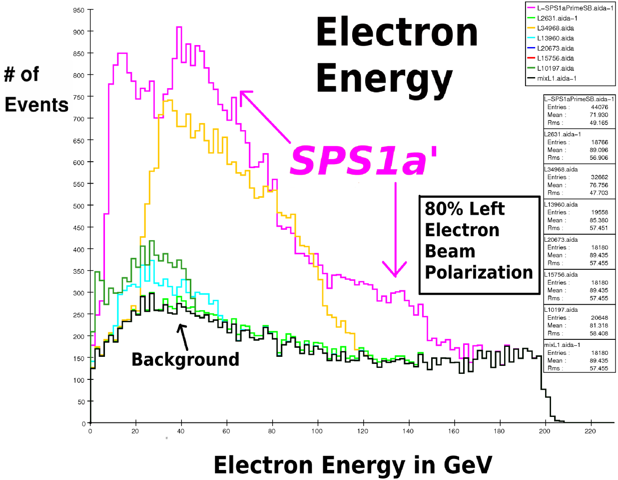


20 mrad $\xrightarrow{-9\%}$ **5 mrad** $\xrightarrow{-3\%}$ **3.5 mrad**

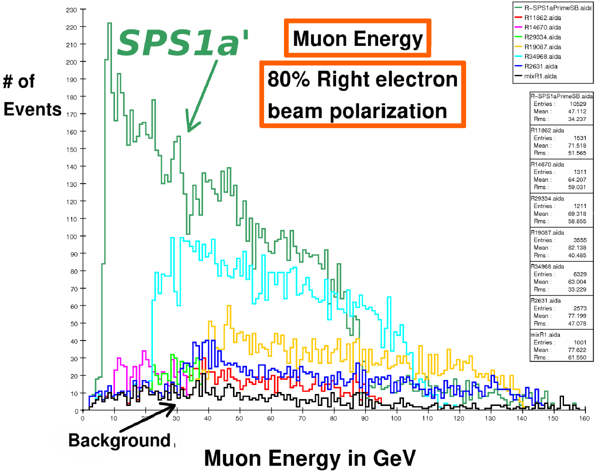
Selectron Results



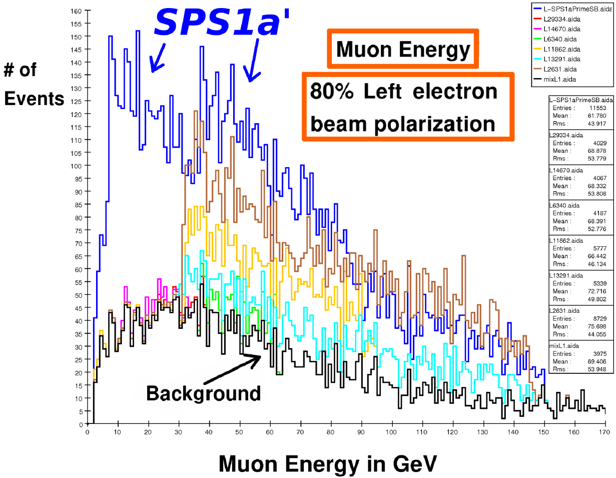
Selectron Results



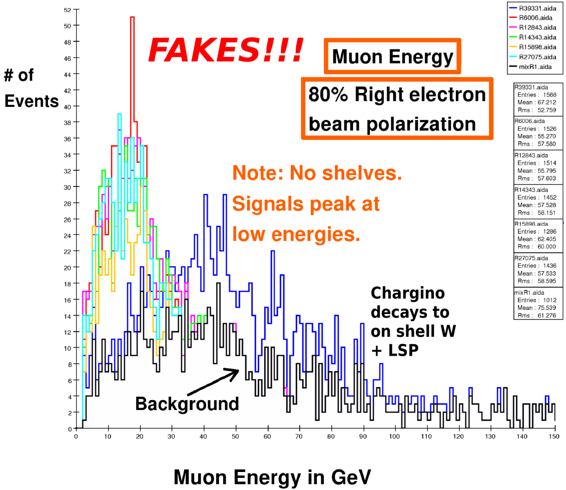
Smuon Results



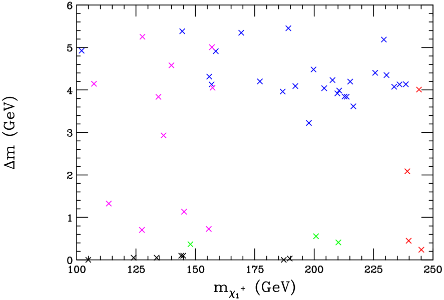
Smuon Results



Smuon Results



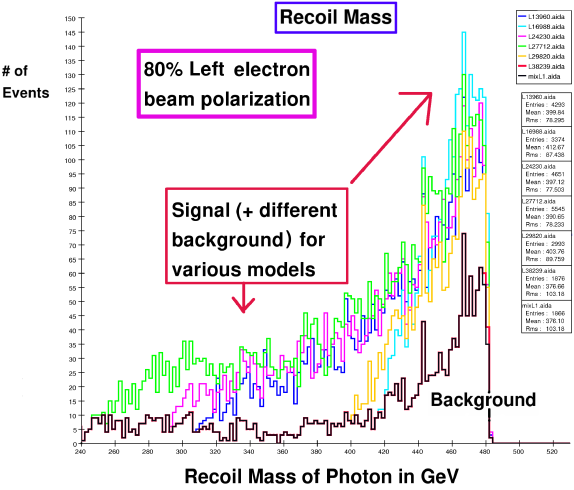
In general, the LSP is not necessarily a Bino; if the LSP is Wino or Higgsino, there will be a chargino nearly degenerate in mass with the LSP. One can also have e.g. $M_2 \approx M_1$.



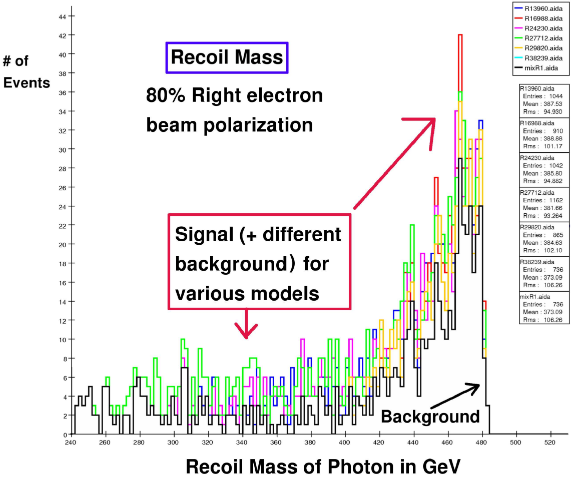
Especially if LSP is Wino or Higgsino we will need radiative chargino search or stable particle search to determine chargino mass and Δm.

blue	chargino decay through off-shell W
green	radiative chargino production
magenta	radiatve & off-shell W
black	stable chargino analysis
red	not observable

Radiative Chargino Search: Results



$$M_{recoil} = \sqrt{s}\sqrt{(1 - 2E_\gamma/\sqrt{s})}$$



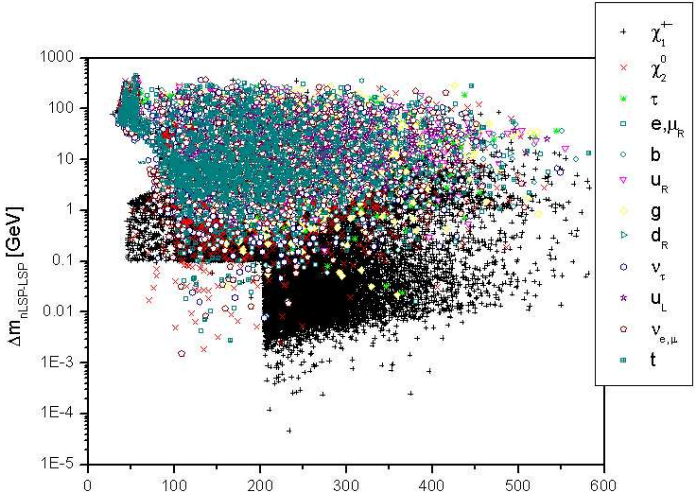
$$M_{recoil} = \sqrt{s}\sqrt{(1 - 2E_\gamma/\sqrt{s})}$$

- As noted above many of the models studied have features which make them more difficult to study at the ILC.
  - Sparticles with small mass separations with LSP.
  - Wino and Higgsino LSPs
- But how representative are these models?
- To find out we performed a scan over all 19 parameters, generating 10 million parameter space points using flat priors and 2 million parameter space points using log priors.
- Checked whether each point satisfied many theoretical, experimental, and observational constraints, including

Constraints

- Spectrum tachyon free
- LSP the lightest neutralino
- $\Delta\rho$ within experimental limits
- $g-2$ within experimental limits (wide range due to SM/experiment tension)
- $b \to s\gamma$ within experimental limits
- $B \to \mu\mu$ within experimental limits
- No CCB, potential not UFB
- $B \to \tau\nu$ within experimental limits
- Sfermions, charginos would not have been discovered at LEP
- Invisible Width of Z less than LEP bound
- Stable charged would not have been discovered at Tevatron.
- LEP/ Tevatron would not have discovered charged Higgs.
- LEP would not have discovered neutral Higgs
- WIMP would not have been discovered by CDMS, XENON10
- Thermal relic density not greater than dark matter density (WMAP).
- Model would not cause excess of trilepton events at Tevatron.
- Model would not cause excess of jet + missing energy events at Tevatron.

- $\sim 68,000$ out of $10,000,000$ models satisfied all constraints in the flat prior sample.
- $\sim 2,000$ out of $2,000,000$ models satisfied all constraints in the flat prior sample.



Many models have LSPs which are close to being pure weak eigenstates. Additionally many models have Higgsino or Wino LSPs.

LSP Type	Definition	Fraction of Models
Bino	$\lvert Z_{11}\rvert^2 > 0.95$	0.14
Mostly Bino	$0.8 < \lvert Z_{11}\rvert^2 \leq 0.95$	0.03
Wino	$\lvert Z_{12}\rvert^2 > 0.95$	0.14
Mostly Wino	$0.8 < \lvert Z_{12}\rvert^2 \leq 0.95$	0.09
Higgsino	$\lvert Z_{13}\rvert^2 + \lvert Z_{14}\rvert^2 > 0.95$	0.32
Mostly Higgsino	$0.8 < \lvert Z_{13}\rvert^2 + \lvert Z_{14}\rvert^2 \leq 0.95$	0.12
All other models		0.15

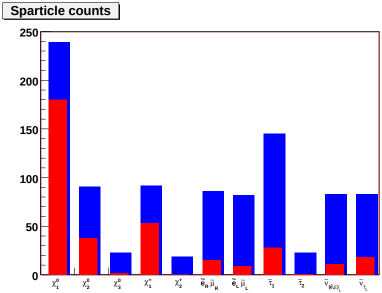
Conclusions

- MSSM models may have features which require more work at lepton colliders than e.g. SPS1a$'$.
- When designing analyses, we should be mindful of possibilities like small mass splittings between sparticles and the LSP.
- If there are charginos nearly degenerate with the LSP (such as when the LSP is Wino or Higgsino) it may take a variety of search strategies to study these charginos.
- Such studies will be important for understanding how SUSY relates to dark matter.
- These points hold for muon colliders as well.
- Forward coverage was important in reducing backgrounds at ILC: detailed studies needed to quantify its importance at a muon collider.

- ILC Results
- Cuts
- Parameter Ranges
- Sample Mass Spectra

Many of these slides are from my ALCPG07 talk.

AKTW Degenerate Models: Accessible Particles



- Of the 242 models (383-models with artificially set chargino-LSP mass splitting), 181 have sparticles accessible at 500 GeV.
- 85 have charged sparticles accessible at 500 GeV.
  - These models have a total of 140 accessible charged sparticles.
- At 1 TeV, all but 1 of the 242 models have accessible sparticles; many more charged sparticles are also accessible at this energy.

- Due to a PYTHIA feature, we only had 242 total models.
- Of these models (181 of which have sparticles accessible at 500 GeV), 82 are visible in our analyses.
- Of the 85 models with charged particles accessible, 78 are visible.

- Among these 242 models there are 162 pairs of models degenerate at LHC in which at least one of the models has at least one sparticle accessible at 500 GeV.
- Of these 162 pairs, 90 involve two models with only neutral sparticles accessible at 500 GeV. We are unable to resolve any of these degeneracies.
- Of the 72 pairs in which at least 1 model has an accessible charged sparticle at 500 GeV, 55 may be distinguished at ILC.

Cuts!!!

Following Goodman. (See 0712.2965 for fuller bibliography)

1. Exactly two leptons, identified as an electron and a positron, in the event and no other charged particles.
2. $E_{vis} < 1$ GeV for $|\cos\theta| \geq 0.9$
3. $E_{vis} < 0.4\sqrt{s}$ in the forward hemisphere.
4. $\cos\theta > -0.96$ for the reconstructed electron-positron pair.
5. We demand that the visible transverse momentum $> 0.04\sqrt{s}$.
6. Acoplanarity angle $\Delta\phi^{e^+e^-} > 40$ degrees
7. $M_{e^+,e^-} < M_Z - 5$ GeV or $M_{e^+,e^-} > M_Z + 5$ GeV.

Smuon Cuts

Following Martyn and Bambade et al.

1. No electromagnetic energy (or clusters) $> 0.01\sqrt{s}$ in $|\cos\theta| > 0.995$
2. Two muons weighted by their charge within the polar angle $-0.9 < Q_\mu \cos\theta_\mu < 0.75$ and no other visible particles
   This removes a substantial part of the W-pair-background.
3. Acoplanarity angle $\Delta\phi^{\mu\mu} > 40$ degrees.
   This reduces both the W-pair and $\gamma\gamma$-backgrounds.
4. $|\cos\theta_{p_{missing}}| < 0.9$
5. muon energy $E_\mu > 0.004\sqrt{s}$
6. transverse momentum of dimuon system, or equivalently, visible transverse momentum (since there is only the muon pair visible),
   $p_{T\,\mathrm{vis}} = p_T^{\mu\mu} > 0.04\sqrt{s}$
   This remove a significant portion of the remaining $\gamma\gamma$- and $e^\pm\gamma$ backgrounds.

Radiative Chargino Search: Cuts

Following OPAL, as well as Gunion and Mrenna (2001), our cuts are

1. Exactly one photon with $p_T > 0.035\sqrt{s}$ and no other charged tracks within 25 degrees
2. No identified (i.e. above 142 mrad) electrons or muons in the event
3. $1 <$ number of charged tracks < 11
4. $E_{\text{vis, other particles}} - E_\gamma < 0.35\sqrt{s}$
5. We demand $\frac{p_{T,vis}}{E_{T,vis}} > 0.4$ and $\frac{p_{T,vis}}{p_{tot}} > 0.2$.
6. We require that $M_{recoil} = \sqrt{s}\sqrt{\left(1 - 2E_\gamma/\sqrt{s}\right)} > 160$ GeV

Parameter Ranges!!!

Parameters and Parameter Ranges: AKTW

Parameter	Min.	Max.
$M_1,\ M_2,\ \mu$	100 GeV	1 TeV
$m_{l1,2},\ m_{e1,2},\ m_{l3},\ m_{e3}$	100 GeV	1 TeV
M_3	600 GeV	1 TeV
$m_{q1,2},\ m_{u1,2},\ m_{d1,2}$	600 GeV	1 TeV
$m_{q3},\ m_{u3},\ m_{d3}$	600 GeV	1 TeV
$\tan\beta$	2	50
M_A	800 GeV	800 GeV
A_τ	0	0
A_b, A_t	850 GeV	850 GeV

19 Parameters

- Sfermion mass terms (10; first and second degeneration sfermions taken to be degenerate).
- Gaugino masses (3)
- Third generation trilinears (3: A_t, A_τ, A_b)
- μ, m_A, $\tan\beta$

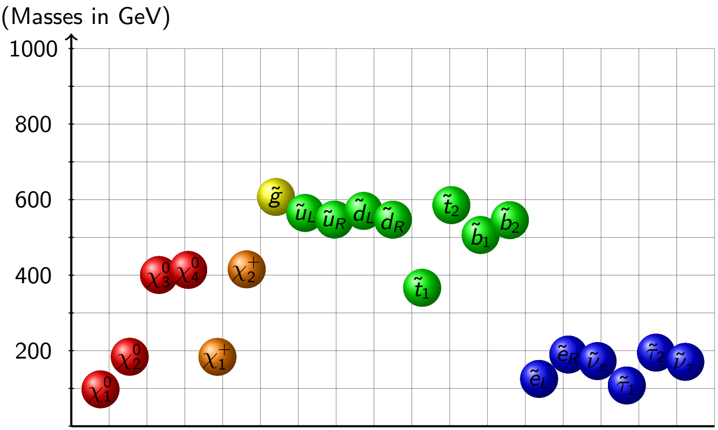
Flat Priors 10^7 points

$$
\begin{aligned}
100\,\mathrm{GeV} \leq m_{\tilde{f}} &\leq 1\,\mathrm{TeV}\,,\\
50\,\mathrm{GeV} \leq |M_{1,2}, \mu| &\leq 1\,\mathrm{TeV}\,,\\
100\,\mathrm{GeV} \leq M_3 &\leq 1\,\mathrm{TeV}\,,\\
|A_{b,t,\tau}| &\leq 1\,\mathrm{TeV}\,,\\
1 \leq \tan\beta &\leq 50\,,\\
43.5\,\mathrm{GeV} \leq m_A &\leq 1\,\mathrm{TeV}\,.
\end{aligned}
$$

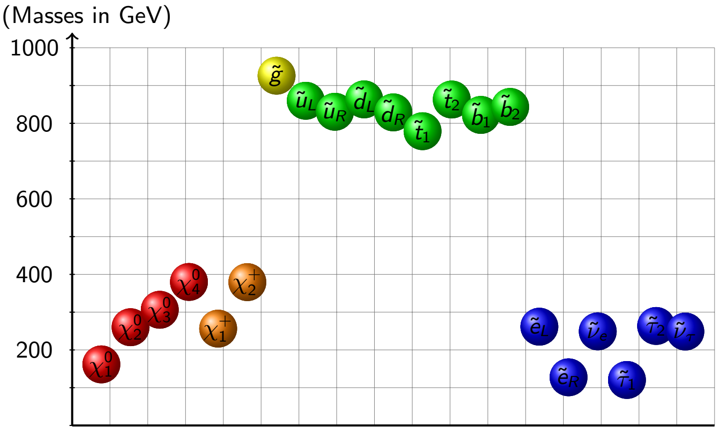
Log Priors 2×10^6 points

$$
\begin{aligned}
100\,\mathrm{GeV} \leq m_{\tilde{f}} &\leq 3\,\mathrm{TeV}\,,\\
10\,\mathrm{GeV} \leq |M_{1,2}, \mu| &\leq 3\,\mathrm{TeV}\,,\\
100\,\mathrm{GeV} \leq M_3 &\leq 3\,\mathrm{TeV}\,,\\
10\,\mathrm{GeV} \leq |A_{b,t,\tau}| &\leq 3\,\mathrm{TeV}\,,\\
1 \leq \tan\beta &\leq 60\,,\\
43.5\,\mathrm{GeV} \leq m_A &\leq 3\,\mathrm{TeV}\,.
\end{aligned}
$$

Spectra!!!



mSUGRA: $m_{1/2} = 250$ GeV, $m_0 = 70$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, sign $\mu = +1$

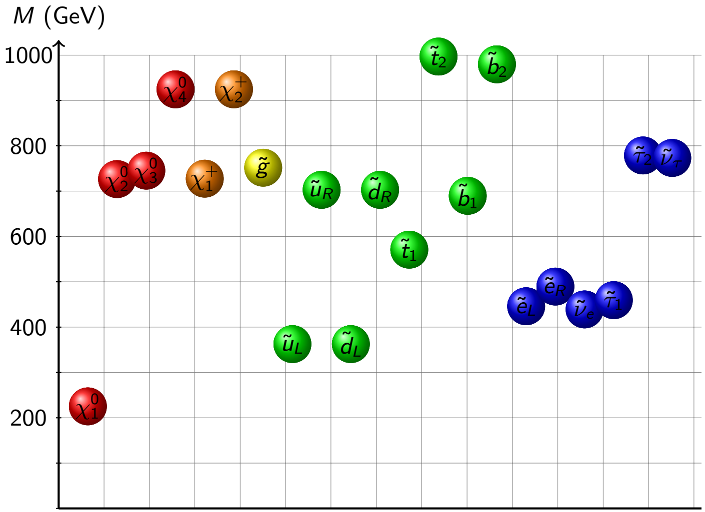


GMSB: $\Lambda = 40$ TeV, $M_{mess} = 80$ TeV, $N_{mess} = 3$, $\tan\beta = 15$, sign $\mu = +1$

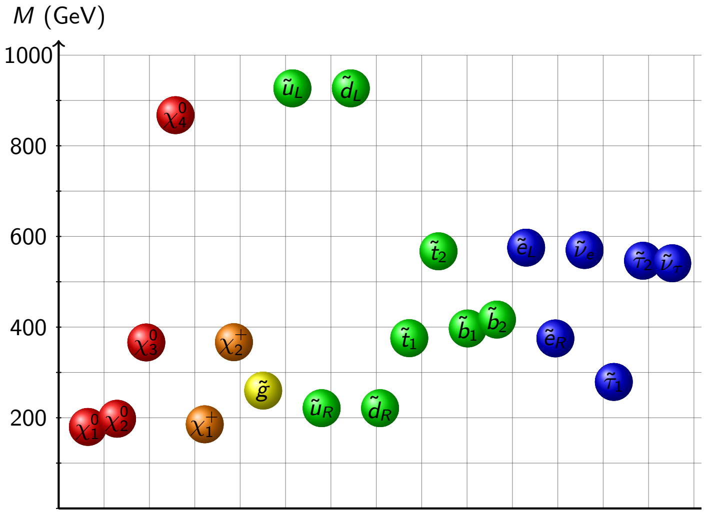
Stau NLSP

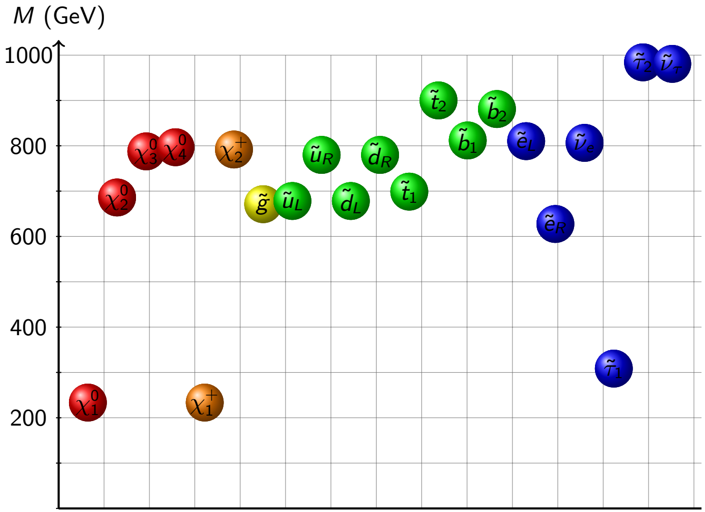
Gravitino LSP (not pictured)

pMSSM 1



M (GeV)
1000
800
600
400
200
χ_4^0
χ_2^+
$\tilde{t}_2$
$\tilde{b}_2$
χ_2^0
χ_3^0
χ_1^+
$\tilde{g}$
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{b}_1$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{t}_1$
$\tilde{e}_R$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{\tau}_1$
$\tilde{u}_L$
$\tilde{d}_L$
χ_1^0


M (GeV)
1000
800
600
400
200
χ_4^0
$\tilde{u}_L$
$\tilde{d}_L$
$\tilde{t}_2$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
χ_3^0
χ_2^+
$\tilde{t}_1$
$\tilde{b}_1$
$\tilde{b}_2$
$\tilde{e}_R$
$\tilde{\tau}_1$
$\tilde{g}$
χ_1^0
χ_2^0
χ_1^+
$\tilde{u}_R$
$\tilde{d}_R$



M (GeV)
1000
800
600
400
200
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{t}_2$
$\tilde{b}_2$
χ_3^0
χ_4^0
χ_2^+
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{b}_1$
$\tilde{e}_L$
$\tilde{\nu}_e$
χ_2^0
$\tilde{g}$
$\tilde{u}_L$
$\tilde{d}_L$
$\tilde{t}_1$
$\tilde{e}_R$
$\tilde{\tau}_1$
χ_1^0
χ_1^+