SUSY tools and Predictions

by

Ben Allanach (University of Cambridge)

Talk outline

- Bestiary of public codes only: supposedly impartial
- Apology: no author lists
- Predictions for the LHC: partial
MSSM Tools

Theory BC

SUSY Spectrum calculator

Input observables: M_Z, m_t,

Decays

Event generator

Detector simulation

Dark matter

Indirect observables

EW/flavour etc

(NMSSM, RPV, FV, CPV)

SUSY Tools and LHC Predictions: SUSY 2007
Spectrum and decays

- **ISASUSY** decouples particles at the mass thresholds but misses some finite terms in the matching: re-sums log splittings.
- **SOFTSUSY, sPHENO, SUSPECT** all catch the finite terms but do the splittings to leading log in RPC-MSSM.
- **CPsuperH, FeynHiggs** do Higgs mass spectrum and decays with of CP violating MSSM
- **NMSPEC** does the **CNMSSM** spectrum, **NMHDECAY** gives the decays widths etc
- **PYTHIA, ISASUSY, sPHENO and SusyHIT** do decays of Higgs and SUSY particles in MSSM.
Matrix Element Generators

- Additional hard jets *cannot* be modelled reliably using the parton shower - you need to simulate the matrix element.

- **SMADGRAPH**, **compHEP**, **calcHEP**, **GRACE** do SUSY and more general models at tree level. 2 to 4 possible. **BRIDGE** can be used to remember spin information in the decays.

- **WHIZARD**, **SUSYGEN** - polarisation included for $e^+e^-$

- **PROSPINO** does NLO-QCD sparticle production
Event Generation

- Can pass matrix-element generated events to event generators with the (original) *Les Houches Accord*
  - **PYTHIA** used extensively. Includes RPV. phase-space decays. **ISAJET** too.
  - **HERWIG** maintains spin info down cascade decays. RPV too.
  - **SHERPA** matches up ME with more standard event generation.
- Shift toward C++
SUSY Prediction of $\Omega h^2$

- Assume relic in thermal equilibrium with $n_{eq} \propto (MT)^{3/2} \exp(-M/T)$.
- Freeze-out with $T_f \sim M_f/25$ once interaction rate $< \text{expansion rate ($t_{eq}$ critical)}$.
- microMEGAs uses calcHEP to automatically calculate relevant Feynman diagrams for some given model Lagrangian: flexible.
- darkSUSY has MSSM annihilation channels hard-coded. Much work on (in)-direct detection possibilities.
Implementation

Input parameters are: $m_0$, $A_0$, $M_{1/2}$, $\tan \beta$,

- $m_t = 171.4 \pm 2.9$, $m_b(m_b) = 4.24 \pm 0.11 \text{ GeV}$,
- $\alpha_s(M_Z)^{\overline{MS}} = 0.1176 \pm 0.002$,
- $\alpha^{-1}(M_Z)^{\overline{MS}} = 127.918 \pm 0.018$

For the likelihood, we also use

- $\Omega_{DM} h^2 = 0.104^{+0.0073}_{-0.0128} \text{ micrOMEGAs, darkSUSY}$
- $\delta(g - 2)_\mu / 2 = (22 \pm 10) \times 10^{-10} \text{ Stöckinger et al}$
- $BR[b \rightarrow s \gamma] = (3.55 \pm 0.38) \times 10^{-5} \text{ Misiak et al}$
- $\sin^2 \theta_w^{\text{eff}} = 0.23153 \pm 0.000175$
- $M_W = 80.392 \pm 0.031 \text{ GeV} \text{ W Hollik, A Weber et al}$
b Observables


\[ BR(B_u \rightarrow \tau \nu), \Delta M_{B_s} \]
Constraints on SUSY Models

Fit Development

- Typically done 2d scans with $2\sigma$ exclusion regions, but in general we have $\alpha(M_Z)$, $\alpha_s(M_Z)$, $m_t$, $m_b$, $m_0$, $M_{1/2}$, $A_0$, $\tan\beta$ to vary
- Effective 3d type scan done which parameterises a 2d surface of central $\Omega h^2$
- 4d scan used the impressive *Markov Chain Monte Carlo technique* like in cosmology.
- Combine likelihoods from all of the different measurements.

---

\[ a \] Ellis *et al*, arXiv:0706.0652  
\[ b \] Baltz, Gondolo, JHEP 0410 (2004) 052
Markov-Chain Monte Carlo

Metropolis-Hastings Markov chain sampling consists of list of parameter points \( x^{(t)} \) and associated posterior probabilities \( p^{(t)} \).

\[
P = \min \left( \frac{p^{(t+1)}}{p^{(t)}}, 1 \right)
\]

Final density of \( x \) points \( \propto p \). Required number of points relatively *insensitive* to number of dimensions.
Killer Inference for Susy METeorology


http://users.hepforge.org/~allanach/benchmarks/kismet.html

SUSY Tools and LHC Predictions: SUSY 2007

B.C. Allanach

– p.12/33
Killer Inference for Susy METeorology


Bayesian 1

Bayesian 2

http://users.hepforge.org/~allanach/benchmarks/kismet.html

Frequentist
Figure 0: Including (LHS) or not including (RHS) the LEP2 direct Higgs mass constraints on the CMSSM.
Other literature

R. R. de Austri, R. Trotta and L. Roszkowski, arXiv:0705.2012, including some NNLO $b \rightarrow s\gamma$ pieces. susyBayes
Fitting to SUSY Breaking Model

- Experimenters pick a SUSY breaking point
- They derive observables and errors after detector simulation
- We fit this “data” with our codes

Fits to future collider data

Assume edge measurements from some SUSY point: what constraints exist on the phenomenological MSSM?

SFITTER/FITTINO: see talks by Rauch, Bechtle in SUSY pheno 1.
Summary

- There is now a bewildering multitude of codes for calculating SUSY related observables.
- There has been some organisation and consolidation between them, notably in the form of Les Houches Accord.
- SUSY fitting in the multi-dimensional régime, currently. Could easily still be in this situation after early LHC data.
- Markov Chain Monte Carlos are a very useful tool for exploring such a régime.
- Current dependence on priors should not be a surprise: probably only eliminated after ILC data.
Likelihood and Posterior

Q: What’s the chance of observing someone to be pregnant, given that they are female?

Likelihood

\[ p(\text{pregnant} \mid \text{female, human}) = 0.01 \]

Posterior

\[ p(\text{female} \mid \text{pregnant, human}) = 1.00 \]
Sanity Check

---

**SUSY Tools and LHC Predictions: SUSY 2007**

B.C. Allanach

---

### Plots

1. **Top-Left Plot:**
   - X-axis: $m_h$ (GeV)
   - Y-axis: $m_{\chi_1^0}$ (TeV)
   - L/L(max)

2. **Top-Right Plot:**
   - X-axis: $m_A$ (TeV)
   - Y-axis: $m_{\chi_1^0}$ (TeV)
   - L/L(max)

3. **Bottom-Left Plot:**
   - X-axis: $m_{\tau}$ (TeV)
   - Y-axis: $m_{\chi_1^0}$ (TeV)
   - L/L(max)

4. **Bottom-Right Plot:**
   - X-axis: $m$ (TeV)
   - Y-axis: L per bin
   - Data points for RH slepton, gluino, LH squark, light stop
Electroweak Observables

They prefer light SUSY. Be careful of 1-loop approx.

Caveats

• Implicitly assumed that LSP constitutes *all* of dark matter

• Assumed radiation domination in post-inflation era. No clear evidence between freeze-out+BBN that this is the case ($t_{eq}$ changes).

• Examples of non-standard cosmology that would change the prediction:
  • Extra degrees of freedom
  • Low reheating temperature
  • Extra dimensional models
  • Anisotropic cosmologies
  • Non-thermal production of neutralinos (late decays?)
Collider SUSY Dark Matter Production

Strong sparticle production and decay to dark matter particles.

Q: Can we measure enough to predict $\sigma$?
Collider SUSY Dark Matter Production

Strong sparticle production and decay to dark matter particles.

Any dark matter candidate that couples to hadrons can be produced at the LHC.
Collider Check

Need corroboration with *direct detection*. If we can pin particle physics down, a comparison between the predicted relic density and that observed is a test of the cosmological assumptions used in the prediction. Thus, if it doesn’t fit, you change the cosmology until it does.

Predicting $\Omega h^2$

Not much left that’s allowed but edge measurements allow reasonable $\Omega h^2$ error for 300 fb$^{-1}$.

$\chi^2$/ndf  59.34 / 54
Constant    38.39
Mean        0.1046
Sigma       0.1966E-01

Q: What about other bits of parameter space?

Volume Effects

Can’t rely on a good $\chi^2$ in non-Gaussian situation
Comparison

- **LHS:** allowing non thermal-$\chi^0_1$ contribution
- **RHS:** only $\chi^0_1$ dark matter
- (flat priors)
Comparison

- Fix $\tan \beta = 10$ and all SM inputs
- Restrict $m_0, M_{1/2} < 1$ TeV.
- Same fits!
Priors

We have assumed a flat prior in $\tan \beta$, implies a measure:

$$p(m_0|\text{data}) = \int dM_{1/2} \, dA_0 \, d\tan \beta \, ds$$

$$p(m_0, M_{1/2}, A_0, \tan \beta, s|\text{data}).$$

$$\mu B = \frac{\sin 2\beta}{2}(\tilde{m}_{H_1}^2 + \tilde{m}_{H_2}^2 + 2\mu^2),$$

$$\mu^2 = \frac{\tilde{m}_{H_1}^2 - \tilde{m}_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{M_Z^2}{2}.$$

Change variables: $\int d\mu dB \rightarrow \int dM_Z d\tan \beta|J|$
EWSB prior

\[ p(\text{all data}|m_0, M_{1/2}, A_0, \mu, B, s) \]
\[ \approx p(\text{data}|m_0, M_{1/2}, A_0, \mu, B, s) \times \]
\[ p(M_Z|m_0, M_{1/2}, A_0, \mu, B, s). \]
\[ \approx p(\text{data}|m_0, M_{1/2}, A_0, \mu, B, s) \times \delta(M_Z - M_Z^{cen}) \]

Change variables

\[ \int d\mu dB \delta(M_Z - M_Z^{cen}) \rightarrow \int d\tan \beta |J| : \]

\[ J = \frac{B \tan^2 \beta + 1}{\mu \tan \beta \tan^2 \beta - 1} \]
Same order prior

We wish to encode the idea that “SUSY breaking terms should be of the same order of magnitude”

\[
p(m_0 | M_S) = \frac{1}{\sqrt{2\pi w^2 m_0}} \exp \left( -\frac{1}{2w^2} \log^2 \left( \frac{m_0}{M_S} \right) \right),
\]

\[
p(A_0 | M_S) = \frac{1}{\sqrt{2\pi e^{2w} M_S}} \exp \left( -\frac{1}{2e^{2w}} \frac{A_0^2}{M_S^2} \right),
\]

We don’t know SUSY breaking scale \( M_S \):

\[
p(m_0, M_{1/2}, A_0, \mu, B) = 
\int_0^\infty dM_S \ p(m_0, M_{1/2}, A_0, \mu, B | M_S) \ p(M_S)
\]