Status of SUSY after LHC Run I

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Contents...

1. SUSY and the CMSSM
2. Experimental constraints on SUSY
3. Bayesian statistics
4. Favoured regions of CMSSM
5. Viability & naturalness

Lots of topics =>
Lots of details and caveats missing...

Flavour of our work...

SUSY Motivation

- Solves hierarchy problem between Planck and EW scales (stabilises Higgs sector). Radiative top loops cancel with new stop loops
- Lightest neutralino (if lightest SUSY particle) is a WIMP; explains dark matter
- Predicts light Higgs at $\lesssim 130$ GeV
- Unification of gauge couplings (by extended Higgs sector)
- "Predicts" heavy top quark (big Yukawa required for REWSB)
- Explains anomalous magnetic moment of muon, by neutralino/smuon or chargino/muon-sneutrino loops

Summary of CMSSM

- SUSY is broken. General breaking MSSM has ~>100 free parameters
- CMSSM: Four free continuous parameters at GUT:

m_0 = universal soft scalar mass

$m_{1/2}$ = universal soft gaugino mass

A_0 = universa soft trilinear

$\tan\beta$ = the ratio of the two Higgs vevs

Also looking at pheno pMSSM with 8 params at SUSY scale

- Neutralino-1:

$$m_\chi = 0.4 m_{1/2}$$

- Neutralino-2:

$$m_\chi = 0.8 m_{1/2}$$

- Gluino:

$$m_{\tilde{g}} = 2.7 m_{1/2}$$

- Stau-1:

$$m_{\tilde{\tau}} = \sqrt{0.15 m_{1/2}^2 + m_0^2}$$

Bayesian statistics

- Consider posterior probability - probability density of the CMSSM's parameter space given the experimental data
- cf. frequentist statistics (e.g. chi^2) - probability of data given the theory
- Posterior proportional to likelihood times prior (Bayes' theorem):

$$p(p_1, p_2, \ldots | D) = \mathcal{L}(D | p_1, p_2, \ldots) \times \pi(p_1, p_2, \ldots)$$

- Likelihood contains experimental information, often Gaussian:

$$\mathcal{L} = \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

- Prior contains belief in parameter space before seeing data
- Bayesian stats is a calculus for beliefs –won't tell us what our prior beliefs ought to be, but how to update them once we see experiments

Experimental constraints...

SUSY constrained by:

- Direct searches
- Higgs mass
- Dark matter
- EWPO
- g-2 anomaly
- B-physics

- Perhaps also non-SM Higgs rates...

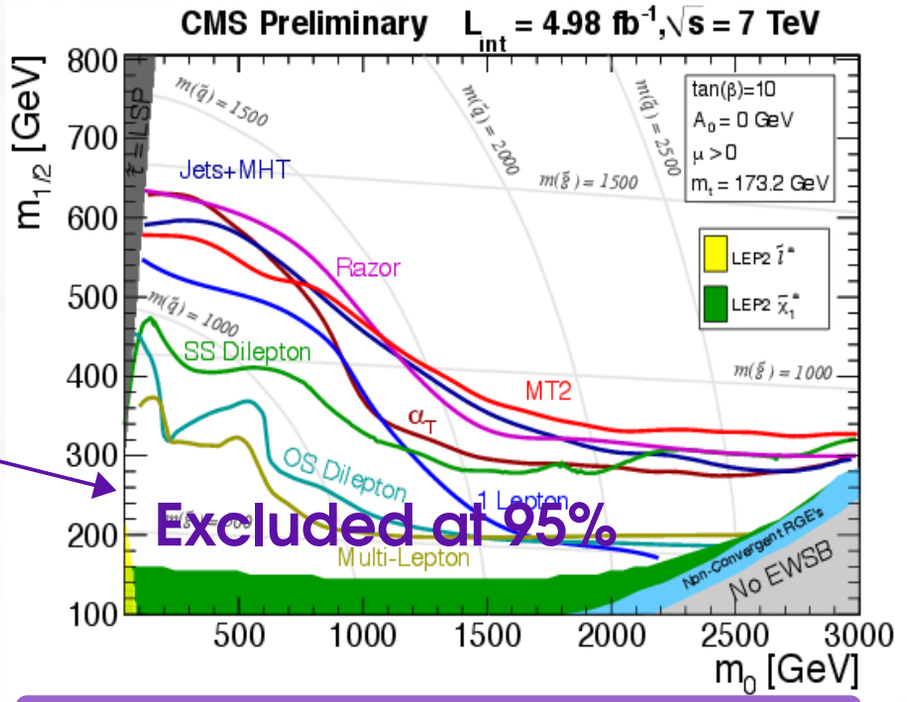
Measurement	Mean	Error: Exp., Th.	Likelihood
CMS razor 4.4/fb	Explained later		Poisson
m_h (GEV)	125	2, 2	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\sin\theta_{\rm eff}$	0.23116	0.00013, 0.00015	Gaussian
m_W(GeV)	80.399	0.023, 0.015	Gaussian
$\delta(g-2)_\mu^{\rm SUSY}\times10^{10}$	28.7	8.0, 1.0	Gaussian
$\mathrm{BR}(\overline{\mathrm{B}}\to \mathrm{X_s}\gamma)\times10^4$	3.60	0.23, 0.21	Gaussian
$\mathrm{BR}(\mathrm{B_u}\to\tau\nu)\times10^4$	1.66	0.66, 0.38	Gaussian
ΔM_{B_s}(GeV)	17.77	0.12, 2.40	Gaussian
$\mathrm{BR}(\mathrm{B_s}\to\mu^+\mu^-)$	$< 4.5\times10^{-9}$	0, 14%	Error Fn.

Theory error now > exp't

Updated to LHCb measurement in recent BayesFits papers

Including direct LHC SUSY searches

- Signature jets and missing energy, from cascade decay of heavy coloured sparticle, with 2 neutralinos in final state
- No statistically significant excess of events. Takes a large bite out of CMSSM
- We simulated expected SUSY events by MC, including detector efficiency and acceptance, across the m0, m12 plane of the CMSSM



Now a little out-of-date...

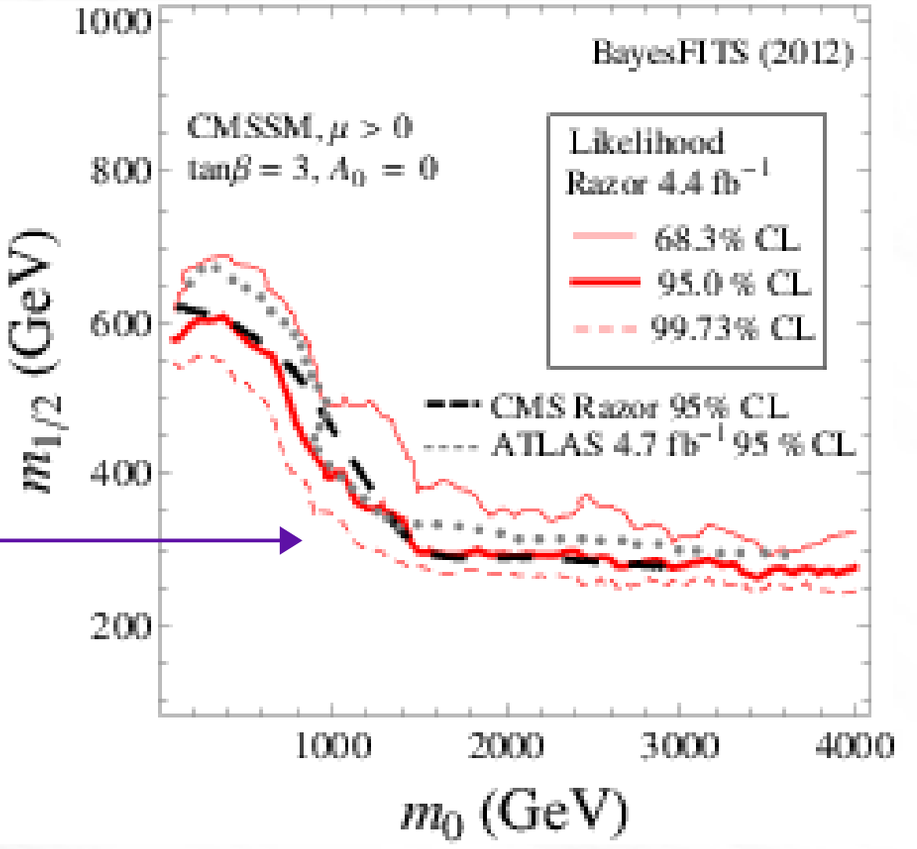
Exclusion slightly higher

Likelihood from LHC SUSY search

- Calculated our likelihood with a Poisson, plus systematics on background predictions

$$\mathcal{L} = \mathrm{Po}(o|s+b) \times \mathrm{Syst}(b'|b)$$

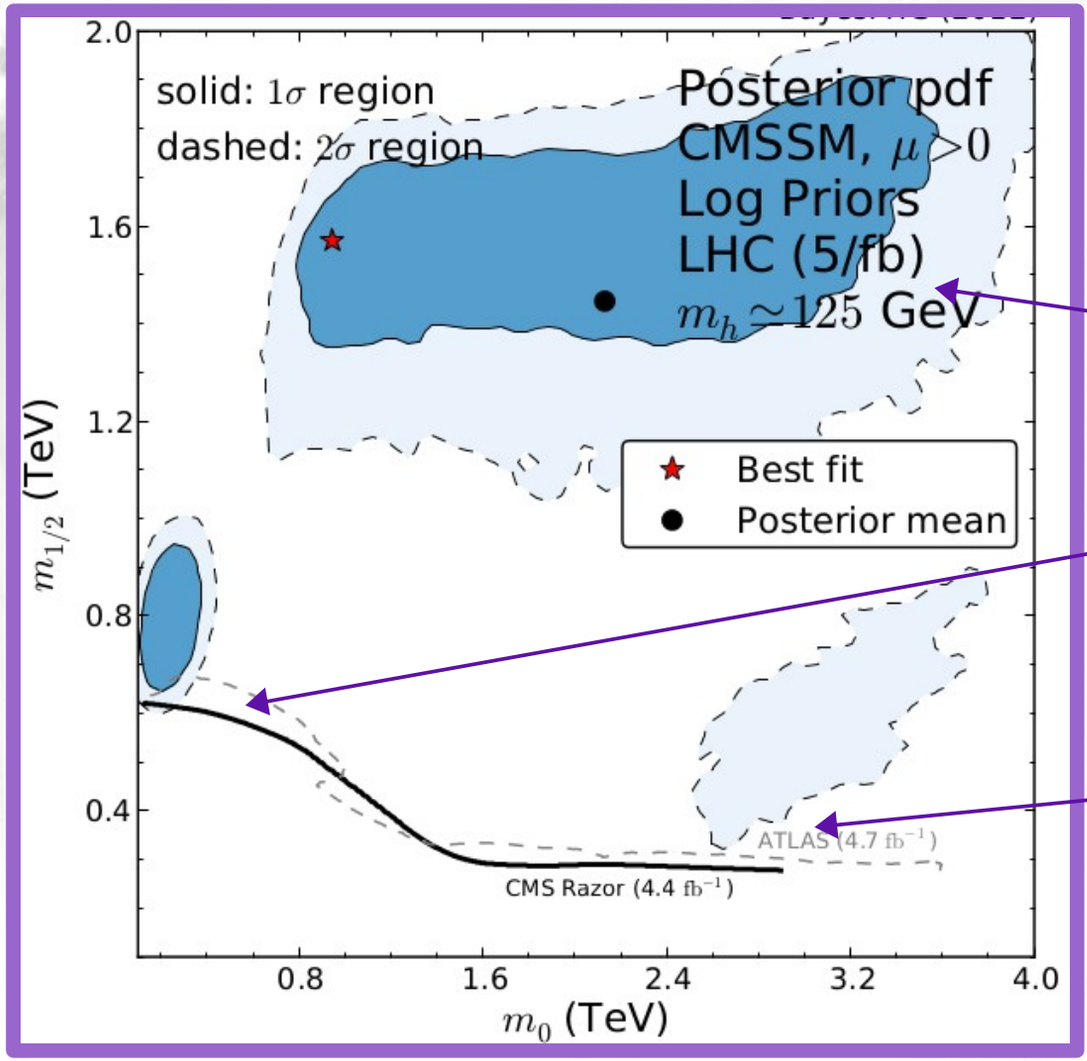
- Official likelihood not published
- Our 95% exclusion contour agrees well with official result for CMSSM (m0, m12); this validates method
- We can re-interpret SUSY searches in ANY model! Including ph'cal pMSSM, NMSSM etc



Results...

- Scan parameter space with "MultiNest" MC algorithm
- Now present results as 68% and 95% two-dimensional "credible regions"
- These regions contain 68% and 95% of the posterior pdf
- Reflect degree of belief
- But don't indicate any (frequentist) coverage (cf. Confidence interval)
- We choose non-informative log or flat priors for the CMSSM parameters (no "correct" choice, but some choices are bad...)
- Prior dependence <=> "weak" data

Results (m0 , m12)



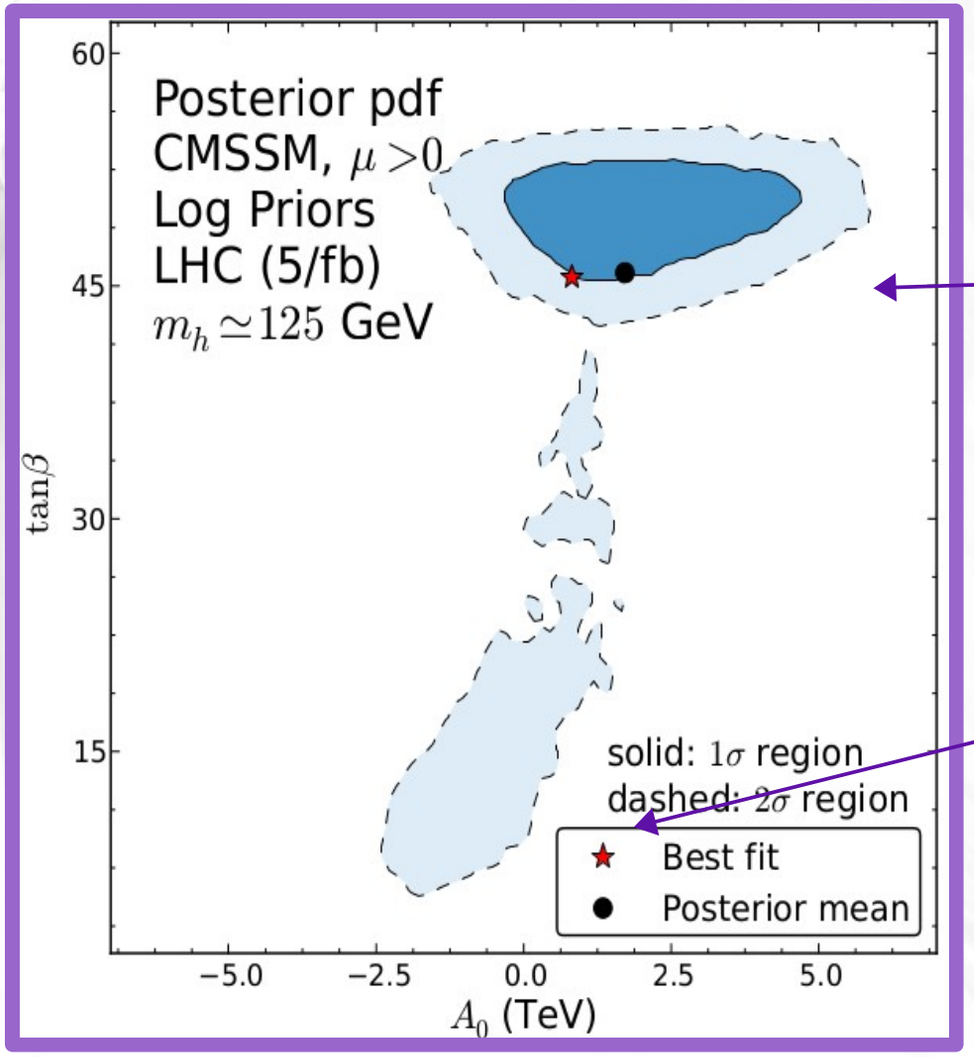
- DM annihilation mechanism shapes plot:

A-funnel region. Neutralinos annihilate via heavy-Higgs resonance

Stau co-annihilation region. Neutralinos co-annihilate with staus to reduce relic density,

Focus point at 2 sigma (sizable Higgsino component)

Results (A0, tan beta)



- DM annihilation again shapes plot:

A-funnel prefers large tan beta, to lower mA and open Higgs resonance.

At the expense of flavour physics, which likes small tan beta.

Stau co-annihilation prefers smaller tan beta.

"Viability"

- Frequentist: Find minimum chi-squared => find the probability of obtaining a chi-squared that large (p-value)
- If less than, e.g., 5%, reject model
- Problem: don't know the distribution of the chi-squared, so guess?!
- Problem: frequentist quantities are properties of experiment
- "Let data speak for itself?! <=> frequentist statistics properties of hypothetical, unrealised experiments -information that is NOT in data
- We (+"rivals") so far find CMSSM p-value>5 %, even with g-2, we are making a (sensible) guess for chi-squared dist'n

"Viability"

- Bayesian: find probability of model given the data!

$$p(M|D) = p(D|M)p(M)/p(D) \propto \mathcal{Z}$$

- Problem: don't know normalisation p(D) or prior for model p(M), so compare evidence Z=P(D|M) with a reference model, and these factors cancel
- If evidence of, e.g., CMSSM much less than reference model (e.g. SM augmented with DM candidate?!), reject model
- e.g. if $\mathcal{Z}(M1)/\mathcal{Z}(M2)$> critical value, model 1 is significantly favoured over model 2
- Common interpretation is Jeffreys scale
- This is ongoing...

Naturalness

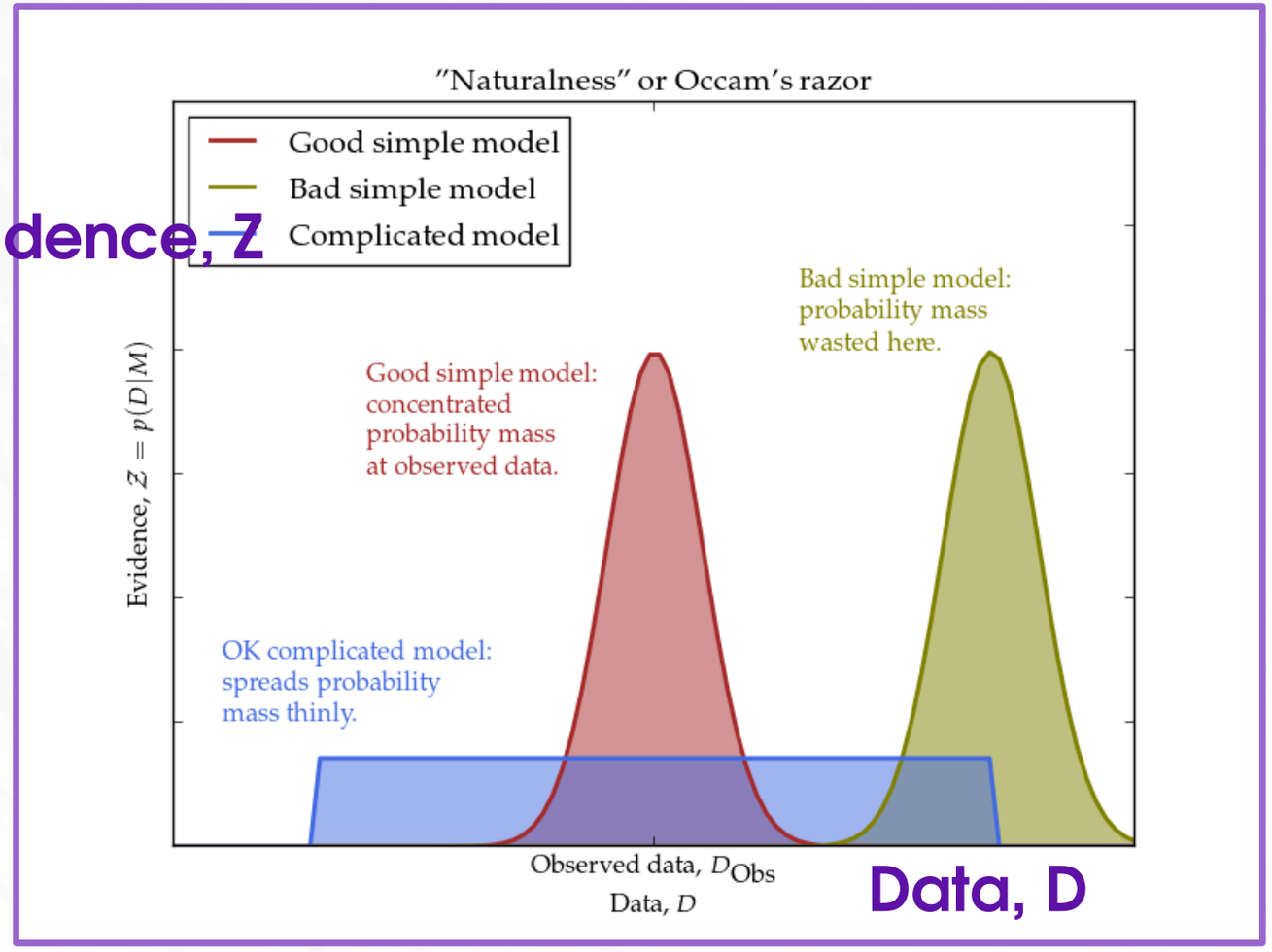
- Naturalness – fine-tuning of EW scale wrt SUSY parameters.
  Barbieri & Giudice measure: $\Delta = \max_i \frac{p_i}{M_Z} \frac{\partial M_Z}{\partial p_i}$
- Failed SUSY searches => large radiative corrections to EW scale
  => "unnatural"
- Naturalness is a statistical argument (Strumia '99)- formalised by Bayesian stats. Bayesian evidence measures naturalness:

$$\mathcal{Z} = p(D|M) = \int \mathcal{L}(D|p_1, p_2, \ldots)\pi(p_1, p_2, \ldots)dp_1 \mathrm{d}p_2 \ldots$$

BIG CAVEAT: "CMSSM" $b,\ \mu \mapsto \tan\beta,\ M_Z$
To measure naturalness wrt MZ, need "fair" priors in $b,\ \mu$
rather than $\pi(M_Z) = \delta(M_Z - 91.18\ldots)$

Naturalness (cont.)

- Naturalness – Ill-defined? Aesthetic principle? No! Statistical argument, formalised with Bayesian stat.
- Links with Occam's razor & falsifiability → lots of insights



Summary

1. Have powerful statistical tools to explore rich parameter space.
2. Even simplest CMSSM viable
3. Though mass scales now high
4. Typical masses: neutralino ~ 0.5 TeV, squarks & gluinos ~ 3 TeV.
5. Naturalness formalised with Bayesian stats

Lots of topics =>
Lots of details and caveats missing...

Search Fowlie or Roszkowski on arXiv for full picture