The CMSSM after 2 years of the LHC

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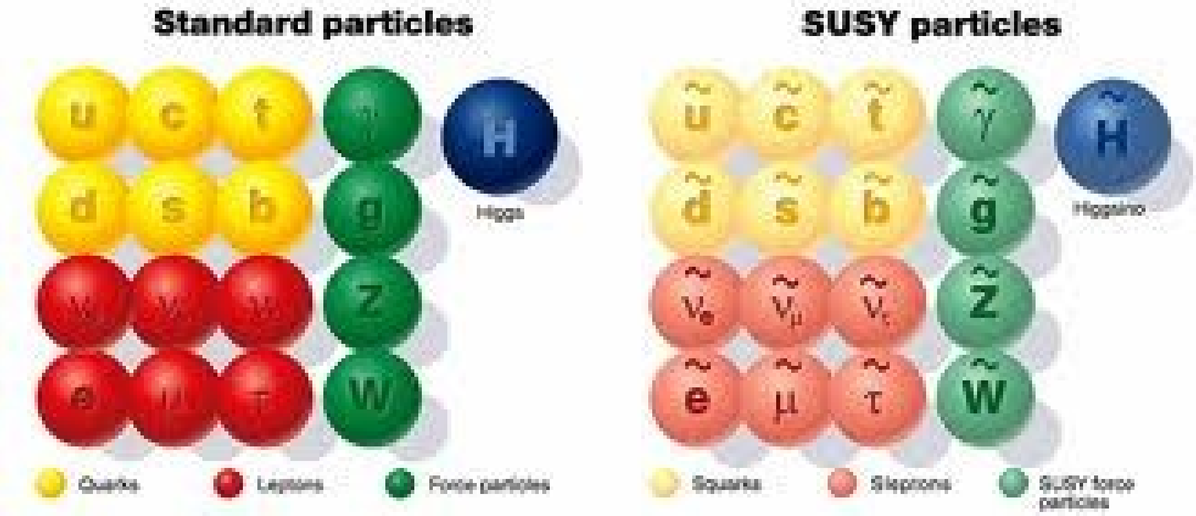
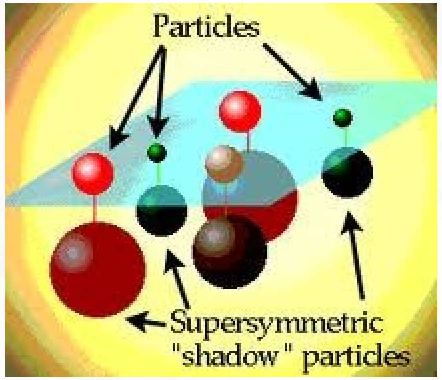
Contents

1. SUSY and the CMSSM in a few slides!
2. Bayesian statistical methodology.
3. BayesFits results.
4. Prospects for SUSY detection.
5. Conclusions.

Summary of SUSY

- Supersymmetry links fermions with bosons!
- Suspersymmetrize SM, by adding particles with spins differing by ½ .
- Quarks (½) are partnered with scalar quarks, squarks (0) etc.
- Need enlarged Higgs sector (2 Higgs doublets).
- After EWSB, gauginos and Higgsinos mix in neutralinos and charginos.





Summary of CMSSM

- SUSY is broken, but general breaking has ~>100 free parameters.
- **CMSSM**: Four free continuous parameters:

m_0 = universal scalar mass

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

A_0 = universal trilinear

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

- These are Lagrangian parameters defined at the GUT scale.

- Approximate mass relations:

Neutralino-1: $m_{\chi_1} \sim 0.4 \times m_{1/2}$

Neutralino-2: $m_{\chi_2} \sim 0.8 \times m_{1/2}$

Gluino: $m_{\tilde{g}} \sim 2.7 \times m_{1/2}$

Stau-1: $m_{\tilde{\tau}} \sim \sqrt{0.15 \times m_{1/2}^2 + m_0^2}$

- Masses calculated at SUSY scale (~EW).

CMSSM is (was?) pretty appealing…

- Solves hierarchy problem between Planck and EW scales (stabilises Higgs sector). Radiative top loops cancel with new stop loops.
- If the lightest neutralino is the lightest SUSY particle, it is a WIMP; explains dark matter.
- Unification of gauge couplings (dominantly through extended Higgs sector).
- Explains anomalous magnetic moment of muon, with extra neutralino/smuon or chargino/muon-sneutrino loops.
- Links with gravity.
- "Predicts" heavy top quark (big Yukawa required for REWSB).

CMSSM theorist after LHC searches...

- Failed SUSY searches (ATLAS & CMS @ 4.4/fb).
- "Discovery" 125 GeV Higgs (which is heavy for the CMSSM, forthcoming).
- Constraints on flavour physics.
- (Picture stolen from talk by Hitoshi Murayama @ SUSY12.)

Testing the CMSSM

- CMSSM has a large phase space (m0, m12, A0, tan beta) with rich and varied phenomenology.
- Calculate CMSSM predictions for physical observables (Higgs mass, relic density, g-2 etc) at a given parameter point with publically available tools.
- Compare those predictions in with experiments, including the latest SUSY searches and Higgs result!
- Find the Bayesian posterior credible regions of the CMSSM's parameter space.
- **i.e. We test the CMSSM against all experiments.**

Bayesian Statistics

- We consider posterior probability, the probability density of the CMSSM's phase space given the experimental data.
- cf. Frequentist statistics, in which one considers probability of data given the theory.
- Posterior is proportional to the likelihood times the prior (Bayes' theorem):

$$p(\vec{x}|d) \propto L(d|\vec{x}) \times \pi(\vec{x})$$

- Likelihood contains experimental information.
- Prior contains theoretical prejudices. We use non-informative priors, that equally weight linear or logarithmic intervals.

Bayesian Statistics

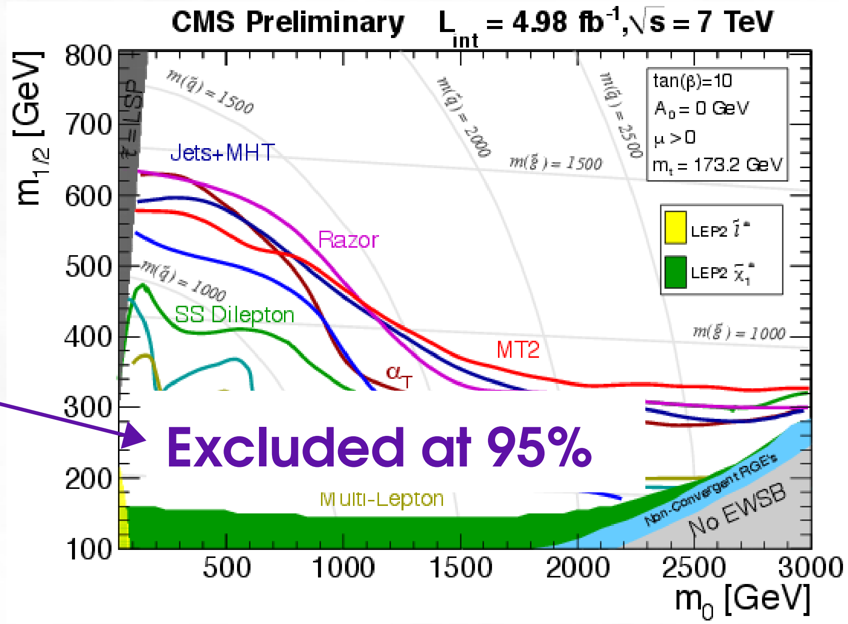
- We find the posterior density with a Monte Carlo algorithm, nested sampling.
- Too time consuming to use e.g. a grid-scan.
- Our Bayesian credible regions are the smallest regions that contain a given fraction of the posterior. e.g. the credible region A on the (m0, m12) plane:

$$\int_A p(m_{0,} m_{1/2}|d)\, dm_0\, dm_{1/2} = 0.95$$

$$A \text{ is such that } \int_A dm_0\, dm_{1/2} \text{ is minimized}$$

Including direct LHC SUSY searches

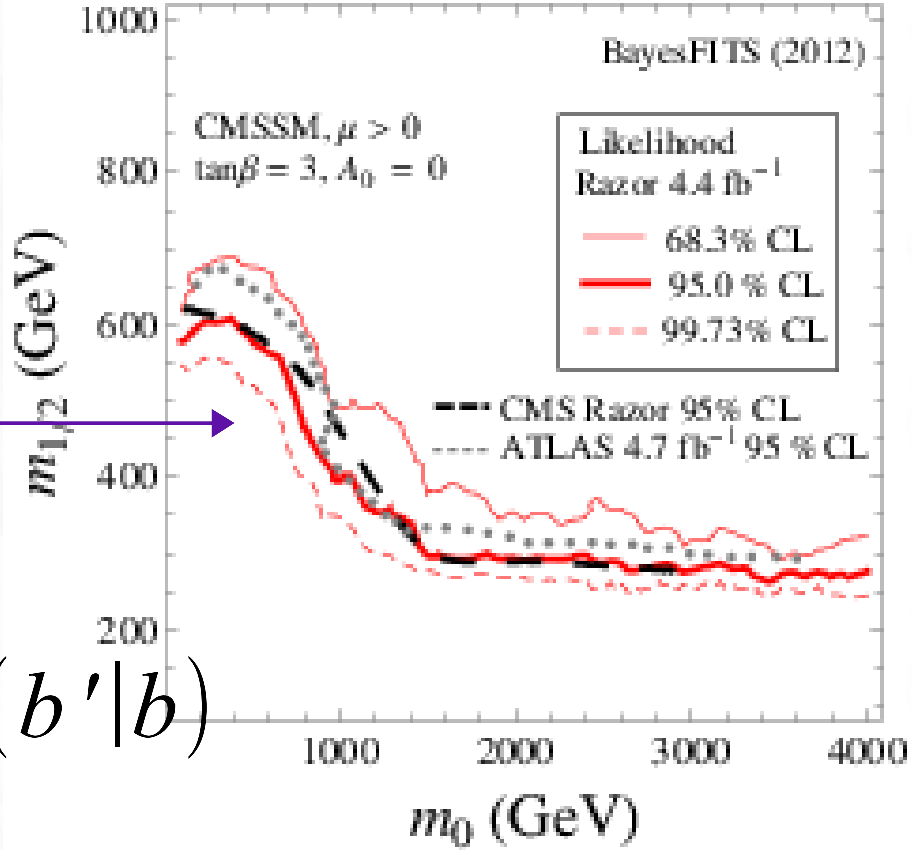
- Signature is jets and missing energy, from cascade decay of heavy coloured sparticle, with 2 neutralinos in final state.
- No statistically significant excess of events. Takes a large bite out of CMSSM.
- We simulated expected SUSY events by MC, including detector efficiency and acceptance, across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



"Spaghetti plot" of LHC SUSY 95% limits.

Likelihood from LHC SUSY search

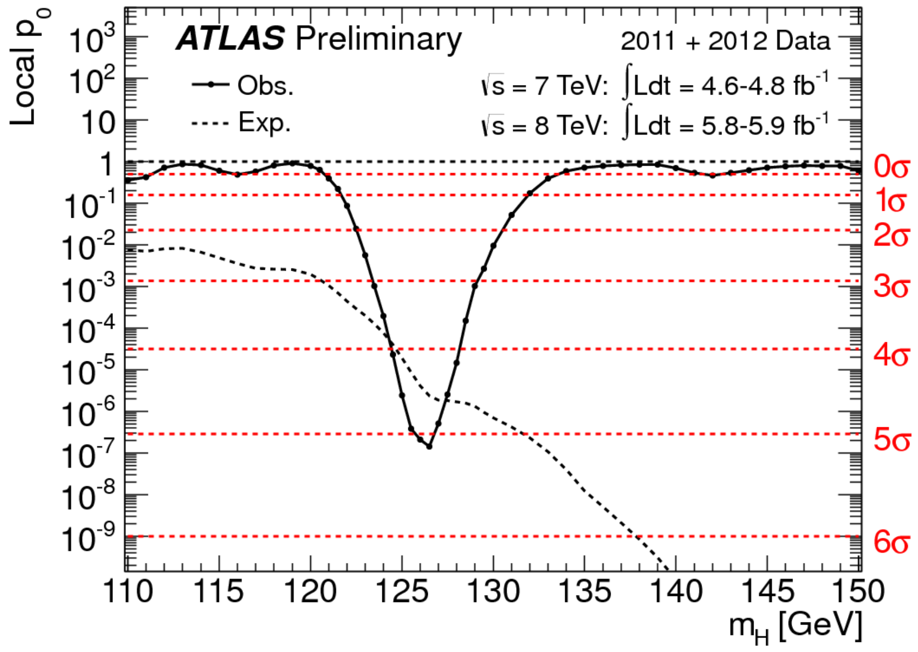
- Calculated our likelihood with a Poisson, plus systematics on background predictions.
- (Official likelihood not published.)
- Our 95% exclusion contour agrees well with official result; this validates method.



$$L = \text{Poisson}(o|s+b) \times \text{Systematic}(b'|b)$$

Including "Higgs discovery"

- The CMSSM Higgs is SM-like.
- CMSSM predicts a light Higgs. Tree-level < MZ, but with loops from stop squarks <~130 GeV.
- Likelihood function for Higgs discovery is Gaussian with mean 125 GeV and experimental error 2 GeV.
- But we add another 2 GeV theoretical error in quadrature: estimated from scheme and scale dependence of Higgs mass calculation.



"Higgs discovery" at > 5 sigma

Including dark matter constraints

- Neutralino is a brilliant DM candidate (stability by LSP and R-parity).
- Number density of neutralino: Boltzmann rate equation with thermal bath of particles, but include expansion of universe. As universe cools, neutralinos are frozen out.
- Relic density ~ mass/thermally averaged annihilation cross section.
- Need annihilation mechanism to reduce relic density.
- WMAP measurement included as Gaussian, but we add in quadrature a ~10% theoretical error (missing orders, propagating errors in sparticle masses).
- Also include Xenon-100 90% limit on WIMP mass and SI scattering cross section.

Summary of priors

CMSSM parameter	Prior Range	Prior Distribution
m_0	100 - 4000 (GeV)	Log
$m_{1/2}$	100 - 2000 (GeV)	Log
A_0	-7000 - 7000 (GeV)	Linear
$\tan\beta$	3 - 62	Linear
$\text{sgn}\,\mu$	$+1$ or -1	Fixed in a scan

Log: 1-10 weighted equally to 100-1000, etc. **Linear**: 0-10 weighted equally to 10-20 etc. NB probability " piles-up" at infinity.

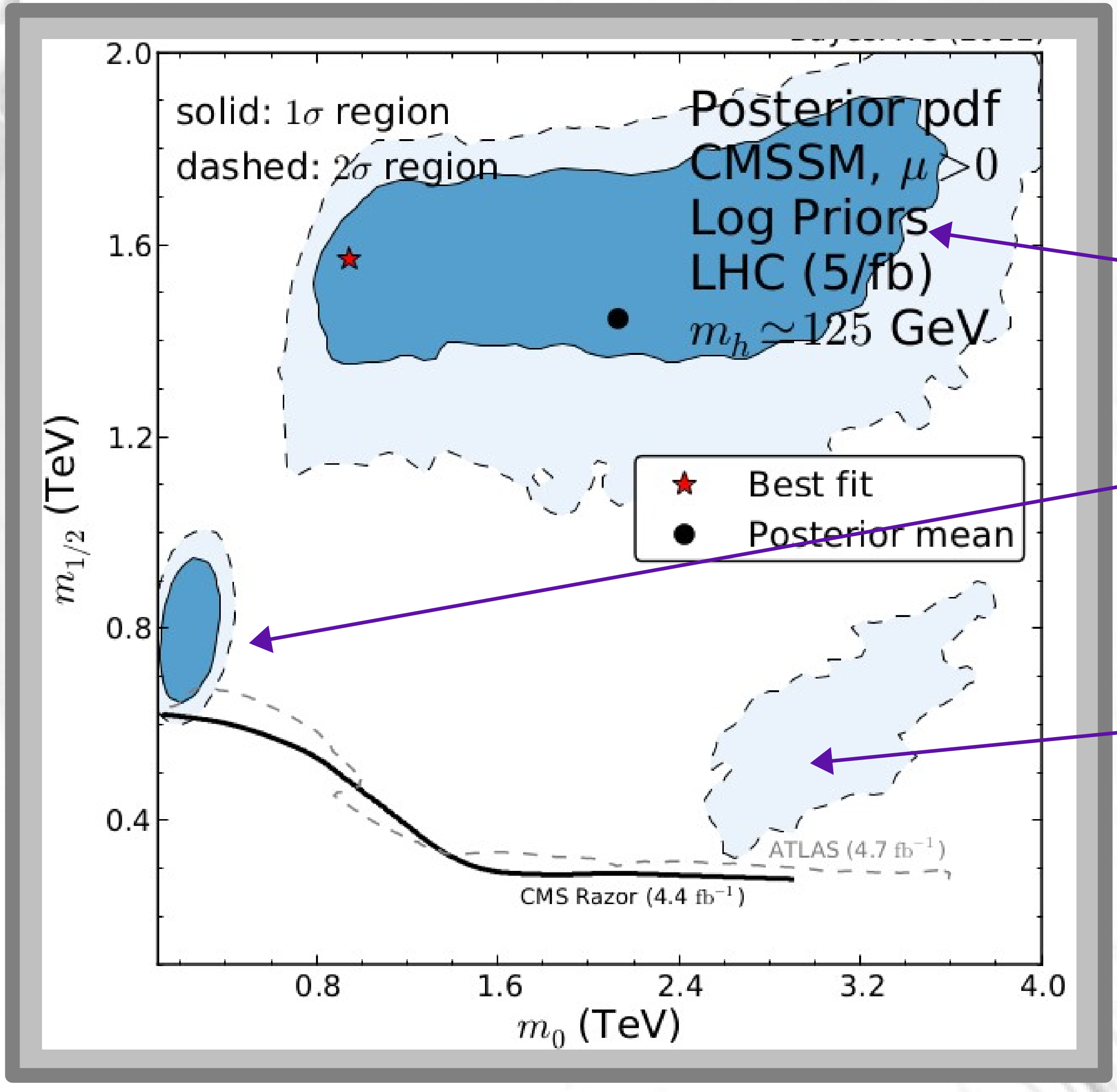
Summary of likelihoods

Gaussian: the likelihood is

$$L \sim e^{-(\mu - x)^2/\sigma^2}$$

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
$\sin\theta_{\text{eff}}$	0.23116	0.00013, 0.00015	Gaussian
m_W(GeV)	80.399	0.023, 0.015	Gaussian
$\delta(g-2)_\mu^{\text{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
$\text{BR}(\overline{\text{B}} \to \text{X}_s\gamma) \times 10^4$	3.60	0.23, 0.21	Gaussian
$\text{BR}(\text{B}_u \to \tau\nu) \times 10^4$	1.66	0.66, 0.38	Gaussian
ΔM_{B_s}(GeV)	17.77	0.12, 2.40	Gaussian
$\text{BR}(\text{B}_s \to \mu^+\mu^-)$	$< 4.5 \times 10^{-9}$	0, 14%	Error Fn.

Results (m0 , m12)



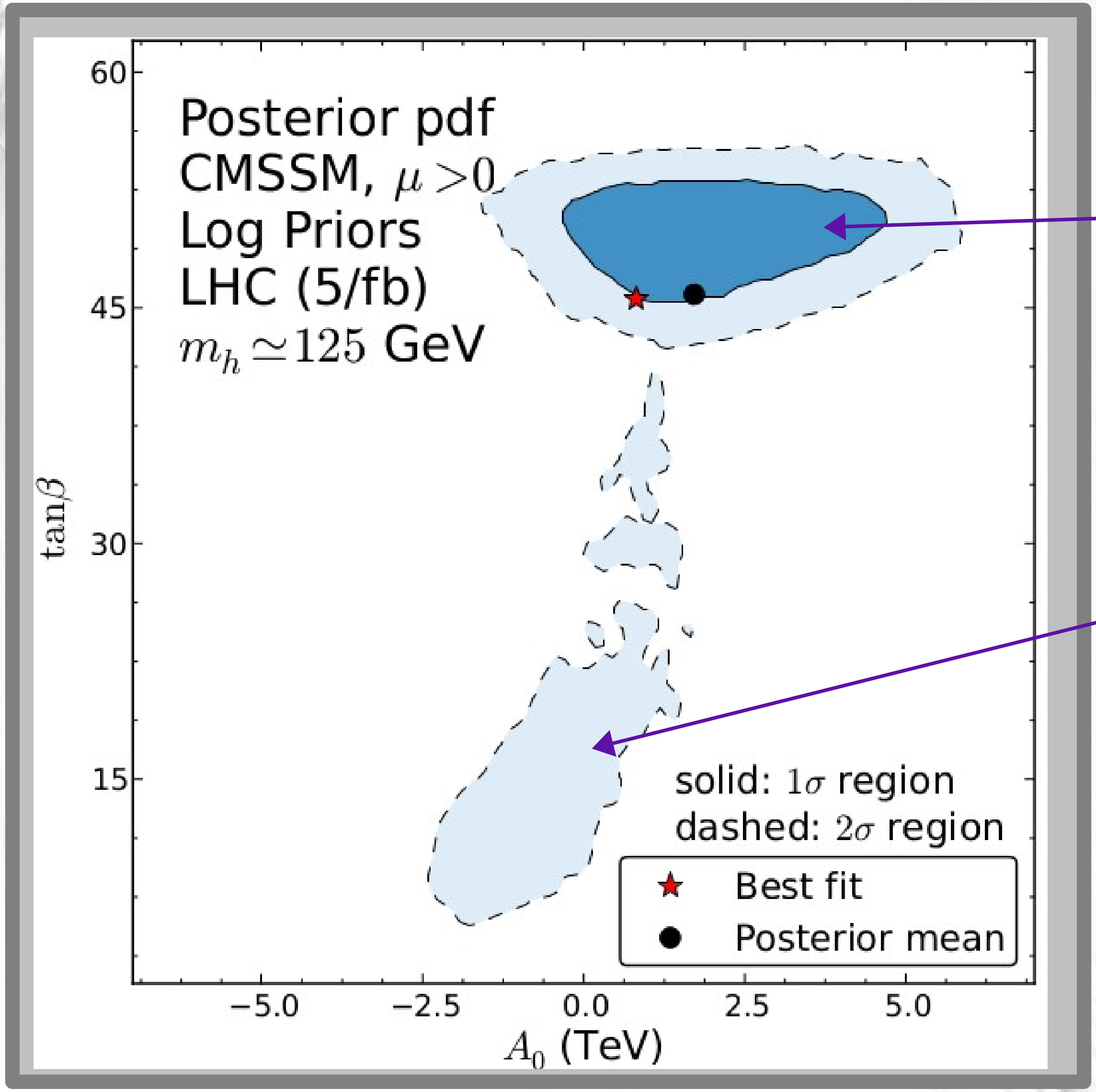
- DM annihilation mechanism shapes plot:

A-funnel region. Neutralinos annihilate via heavy-Higgs resonance $2m_\chi \sim m_A$

Stau co-annihilation region. Neutralinos co-annihilate with staus to reduce relic density, $m_\chi \sim m_{\tilde{\tau}}$

Focus point at 2 sigma (sizable Higgsino component, WW and ZZ enhanced).

Results (A0, tan beta)



- DM annihilation again shapes plot:

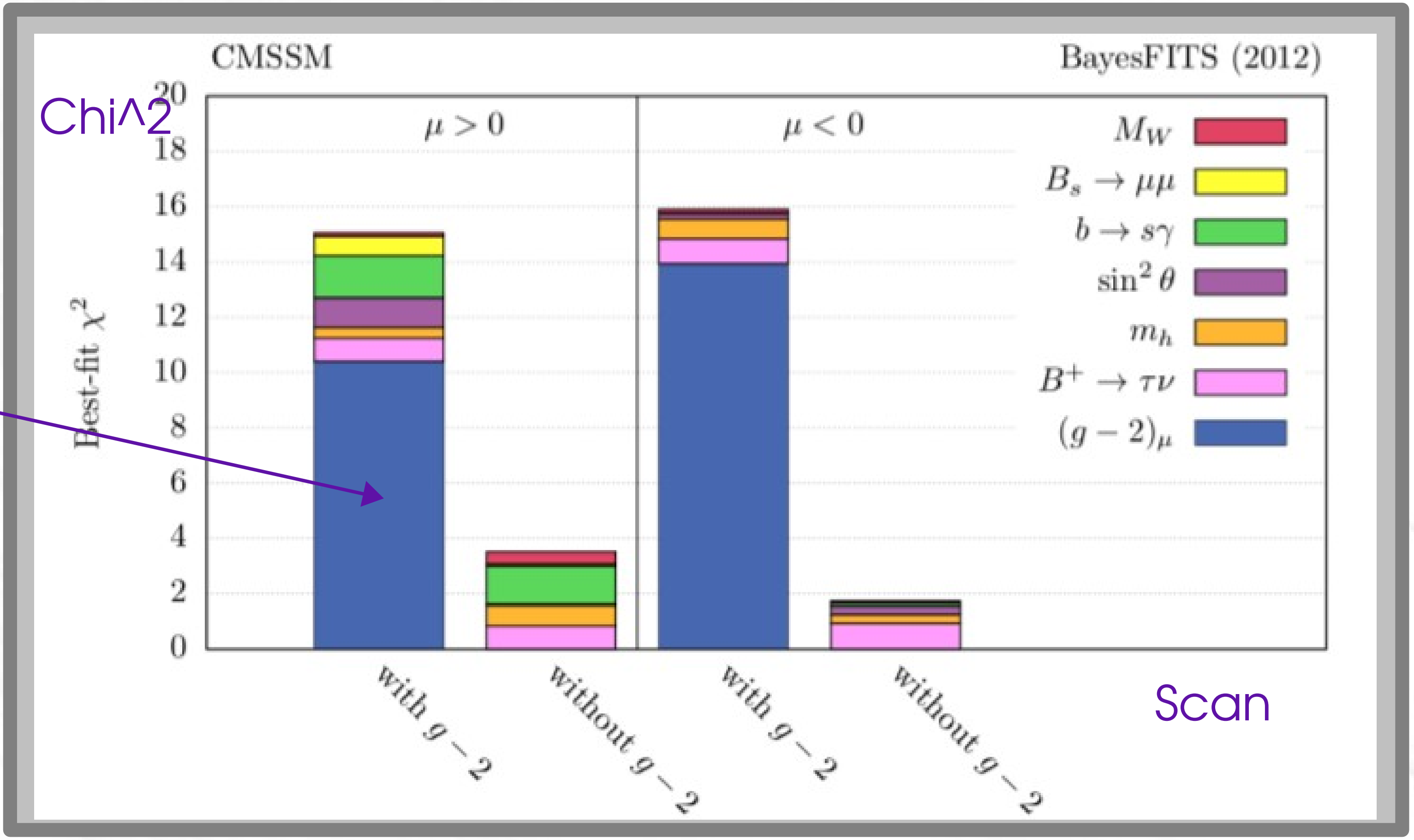
  A-funnel prefers large tan beta, to lower mA and open Higgs resonance.

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

  Stau co-annihilation prefers smaller tan beta.

Breakdown of contributions

- Chi^2 contributions to best-fit point.
- g-2 has biggest contribution (likes light smuons).
- Higgs contributions small.
- EWPO and flavour moderate.

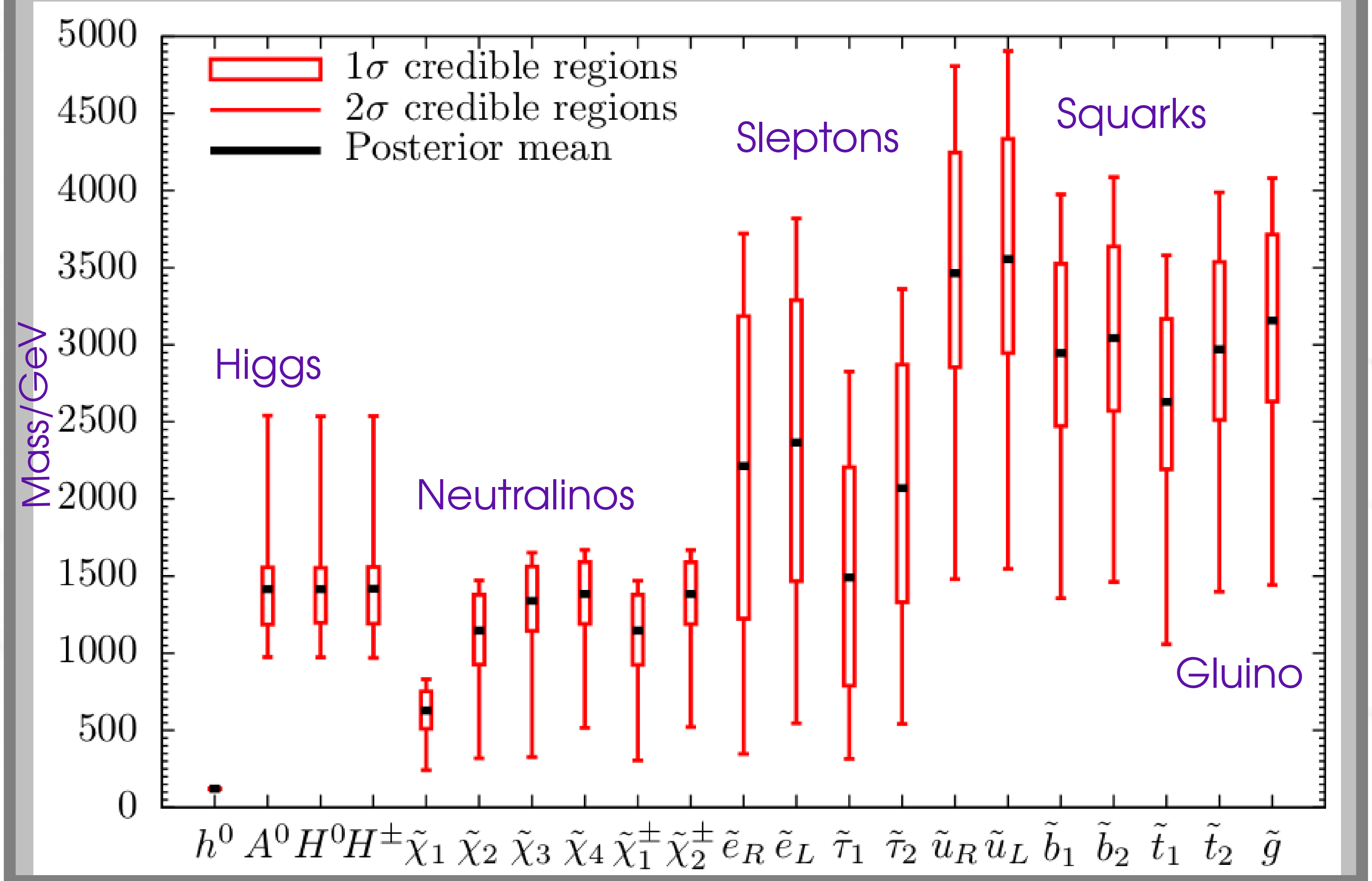


Tension between observables...

- Null LHC searches are pushing (m0, m12) to larger values.
- g-2 likes light smuons, to give signficant enhancements to g-2 via loops.
- Relic density requires particular annihilation mechanisms, and there is a tension with Higgs ~ 125 GeV, which needs large tan beta.
- Flavour physics likes small tan beta.
- => Things are getting difficult.
- But CMSSM is still viable (acceptable agreement with experiments).
- If we suppose that g-2 anomaly has other explanation, things are fine.

Preferred sparticle masses

- Neutralino ~ 0.5 TeV
- Stops ~ 2.5 TeV
- Gluino ~ 3 TeV
- Getting quite heavy, especially for naturalness!



Prospects

- CMSSM has retreated to higher sparticle masses.
- Most credible-regions ought to be within reach of the LHC with 100/fb (currently SUSY limits with 5/fb).
- Measurements of Higgs couplings could further constrain the CMSSM.
- But effect of precision mass measurements limited by Higgs mass calculation in CMSSM (also relic density).
- Credible regions are within reach of Xenon-1 Tonne.

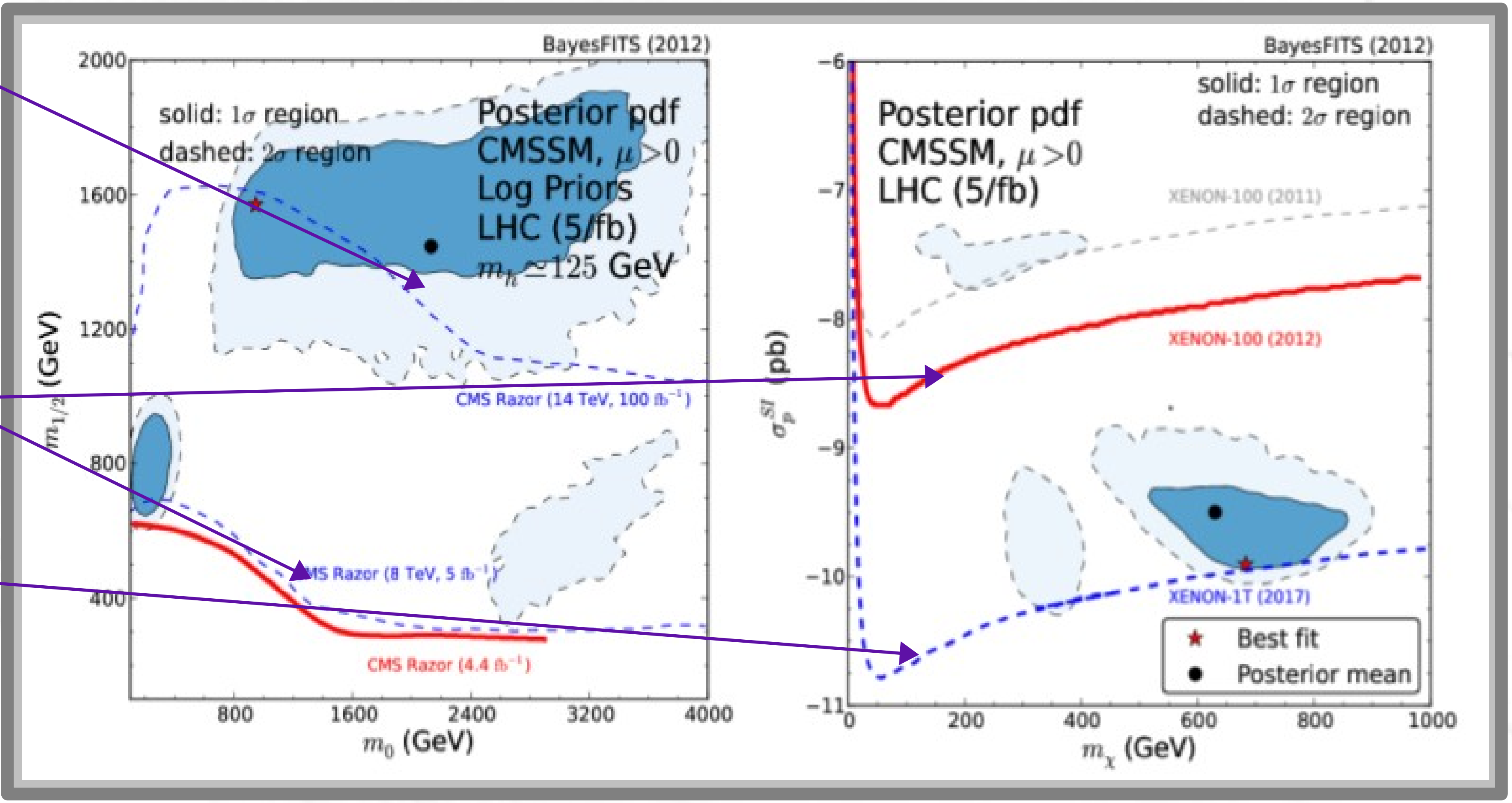
Prospects (m0,12) & (mchi, x-section)

LHC @ 14 TeV 100/fb, ~>2015, projected sensitivity.

Current LHC.

Xenon direct detection current.

Xenon 1 Tonne 2017 projected sensitivity.



Conclusions

- Compared CMSSM against experimental data, including 2 years of LHC.
- Simulated CMS LHC SUSY search at the event level.
- Have powerful statistical tools to explore rich parameter space.
- CMSSM is retreating quickly up (m0, m12) plane.
- But still just viable, especially if g-2 is omitted.
- Typical masses: neutralino ~ 0.5 TeV, squarks & gluinos ~ 3 TeV.
- Prospects: Most of favoured parameter space can be reached in ongoing experiments.