# SUSY tools and Predictions

by

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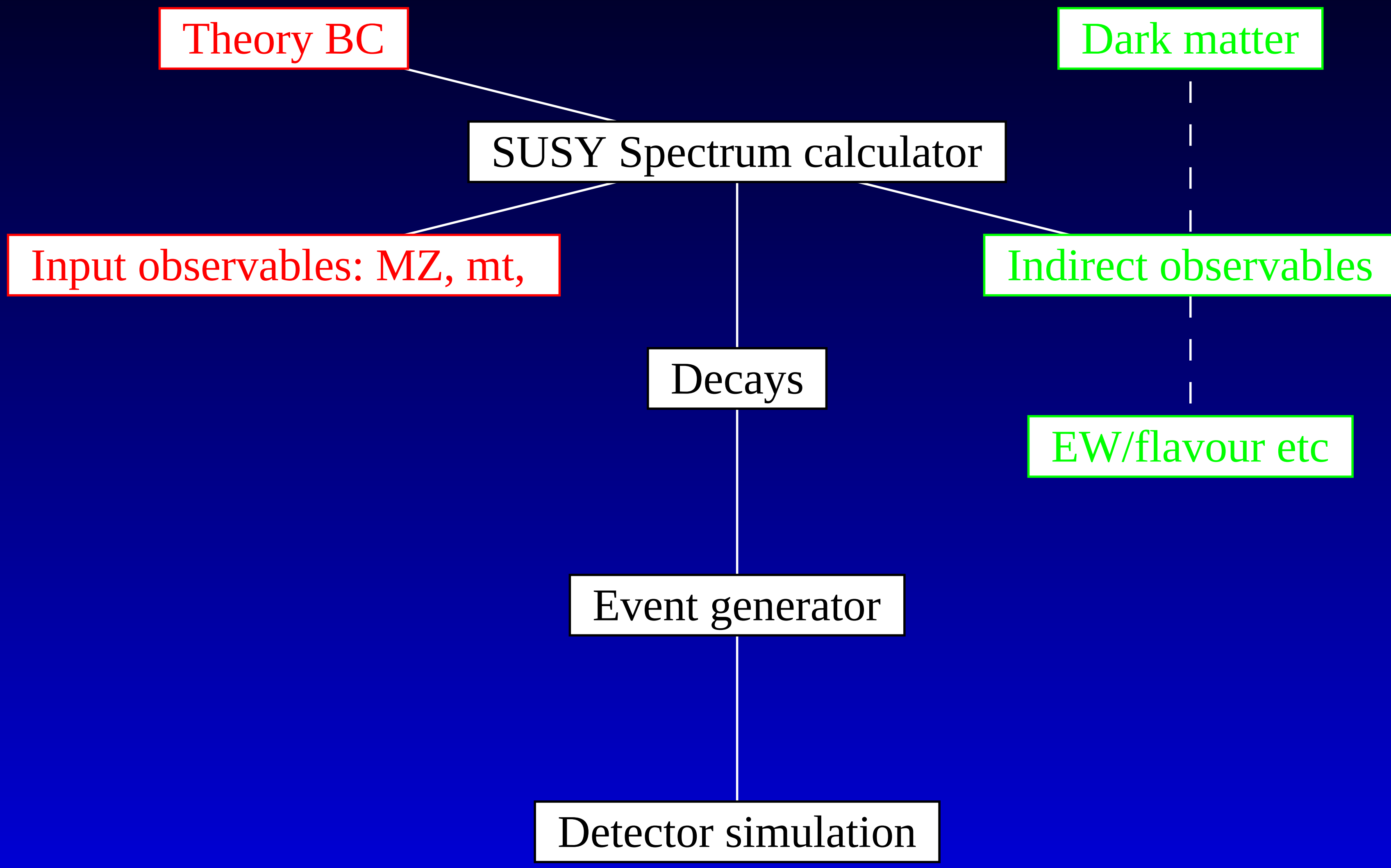
## Talk outline

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

# MSSM Tools



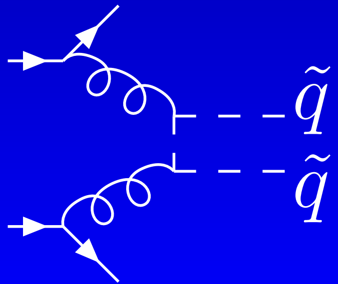

SLHA: Skands *et al*, JHEP 0407 (2004) 036, SLHA2 on its way (NMSSM, RPV, FV, CPV)

# 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.

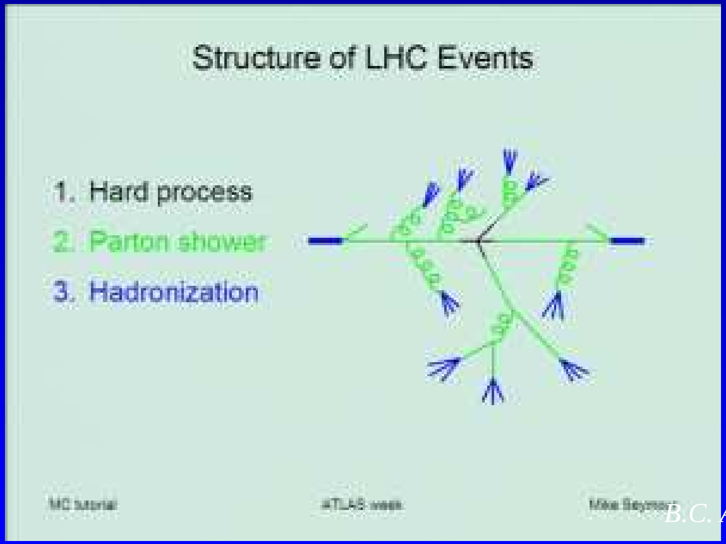
# Matrix Element Generators

- 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 $<$ 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: $m_0$, $A_0$, $M_{1/2}$, $\tan\beta$,

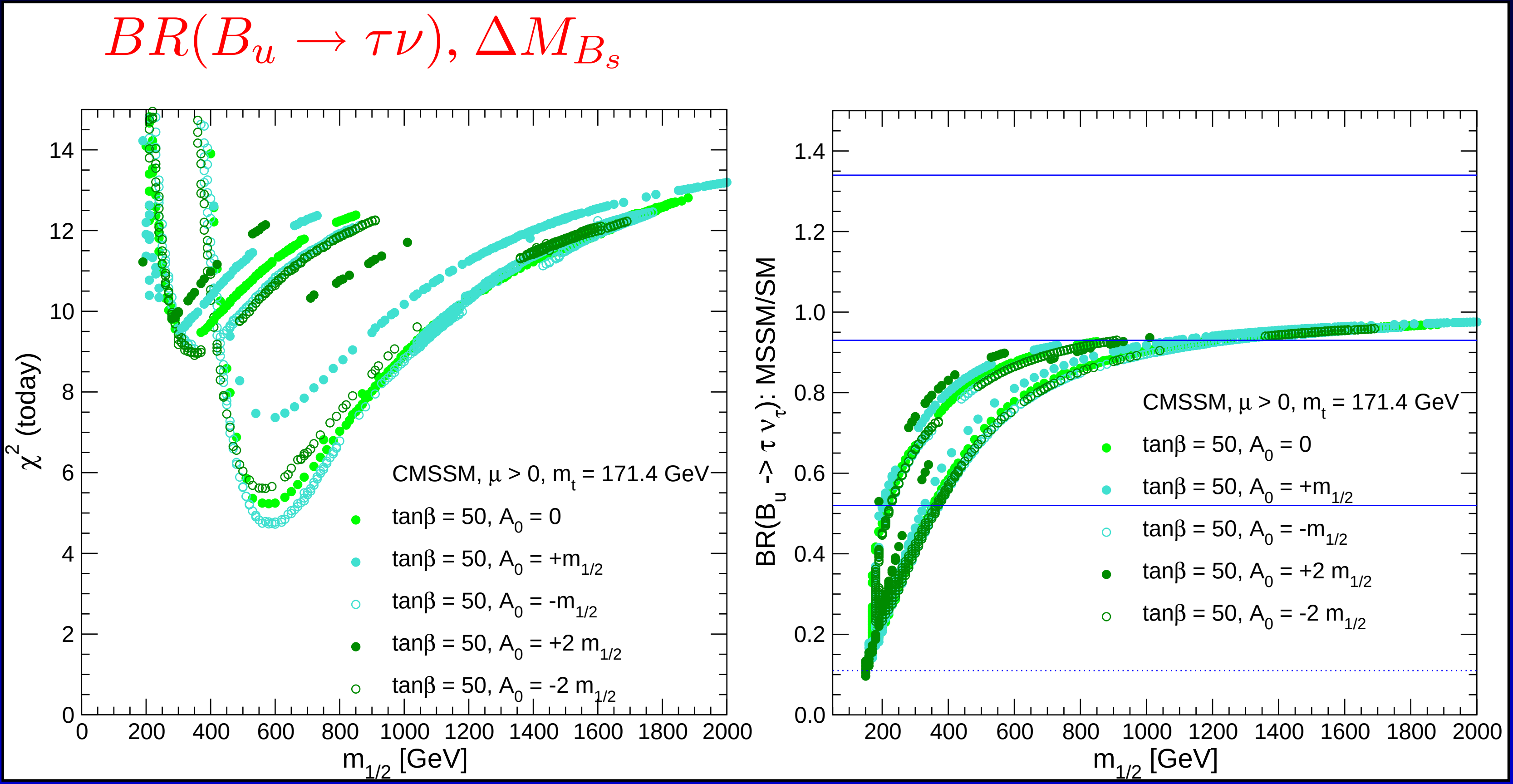
- $m_t = 171.4 \pm 2.9$, $m_b(m_b) = 4.24 \pm 0.11$ GeV,
- $\alpha_s(M_Z)^{\overline{MS}} = 0.1176 \pm 0.002$,
  $\alpha^{-1}(M_Z)^{\overline{MS}} = 127.918 \pm 0.018$

For the likelihood, we also use

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

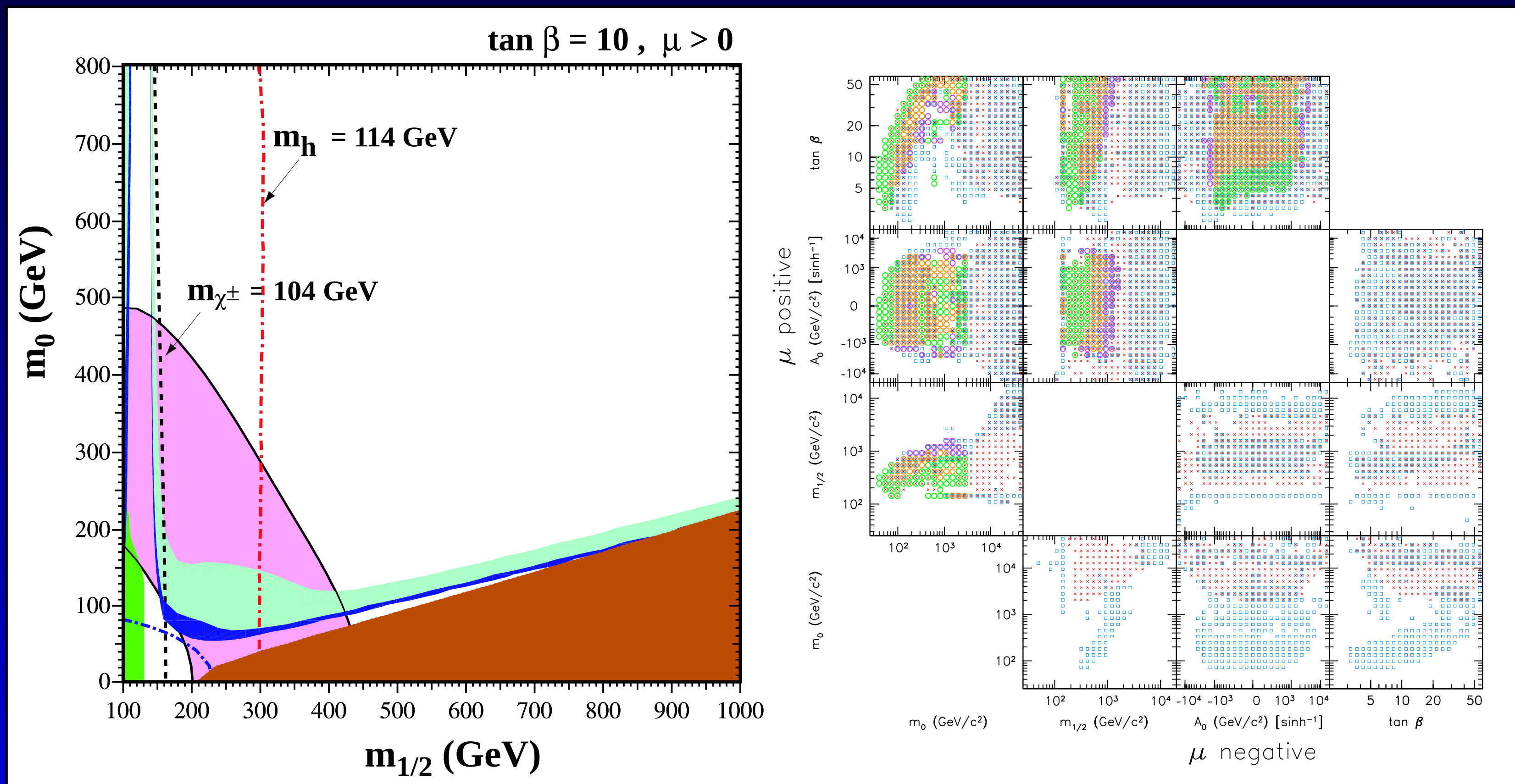
# $b$ Observables

CMSSM: Ellis, Heinemeyer, Olive, Weber, Weiglein, arXiv:0706.0652



# Constraints on SUSY Models

CMSSM well-studied in literature: eg Ellis, Olive *et al* PLB565 (2003) 176; Roszkowski *et al* JHEP 0108 (2001) 024; Baltz, Gondolo, JHEP 0410 (2004) 052;…

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# Fit Development

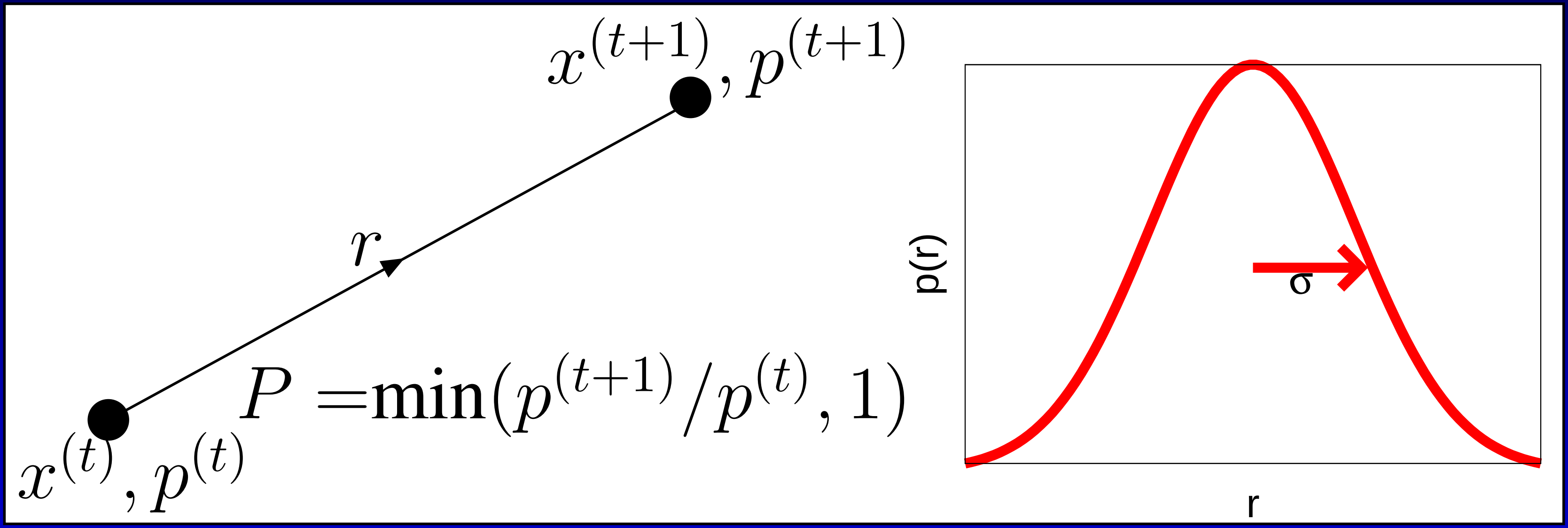
- Typically done 2d scans with $2\sigma$ exclusion regions, but in general we have $\alpha(M_Z), \alpha_s(M_Z)$, $m_t$, $m_b$, $m_0$, $M_{1/2}$, $A_0$, $\tan\beta$ to vary
- Effective 3d type scan done [a] which parameterises a 2d surface of central $\Omega h^2$
- 4d scan [b] used the impressive *Markov 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

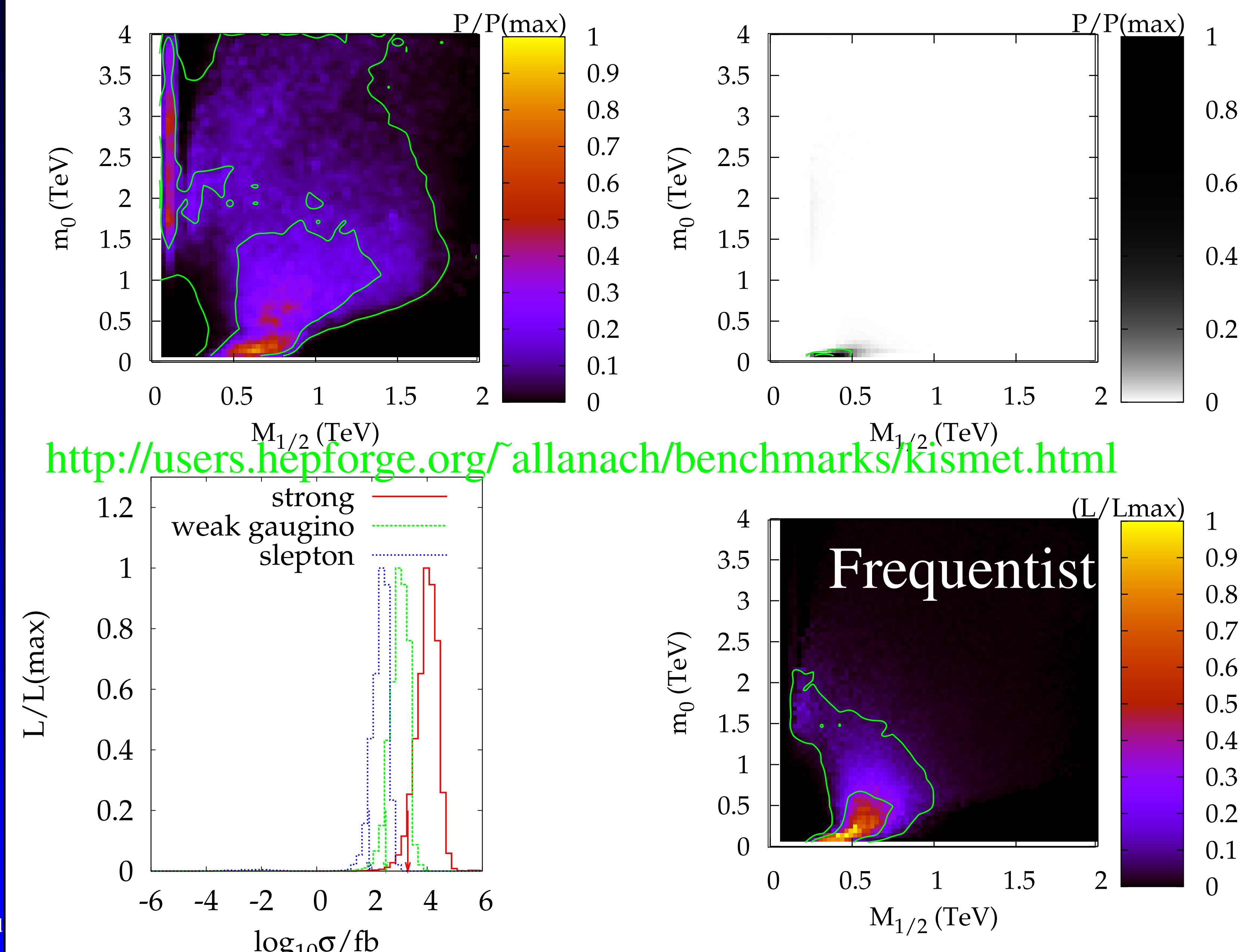
Metropolis-Hastings Markov chain sampling consists of list of parameter points $x^{(t)}$ and associated posterior probabilities $p^{(t)}$.




Final density of $x$ points $\propto p$. Required number of points relatively *insensitive* to number of dimensions.


# Killer Inference for Susy METeorology

BCA, Cranmer, Weber, Lester, arXiv:0705.0487




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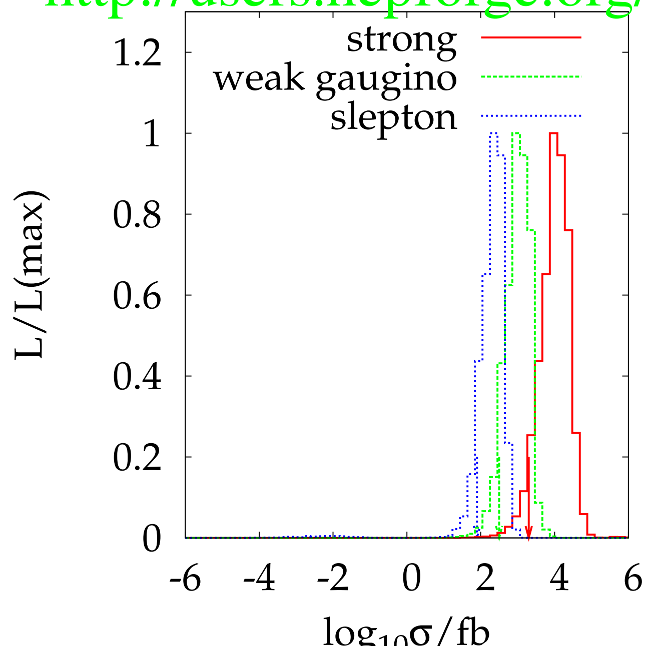
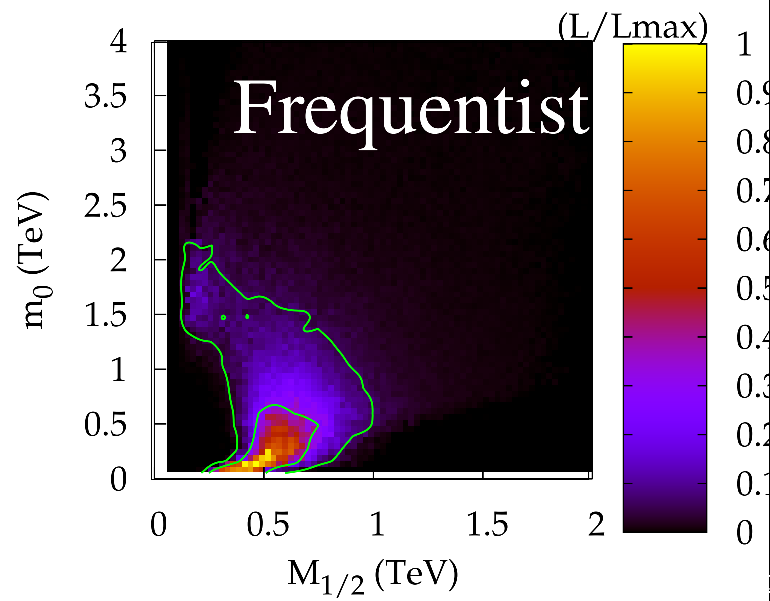


# Higgs Meteorology

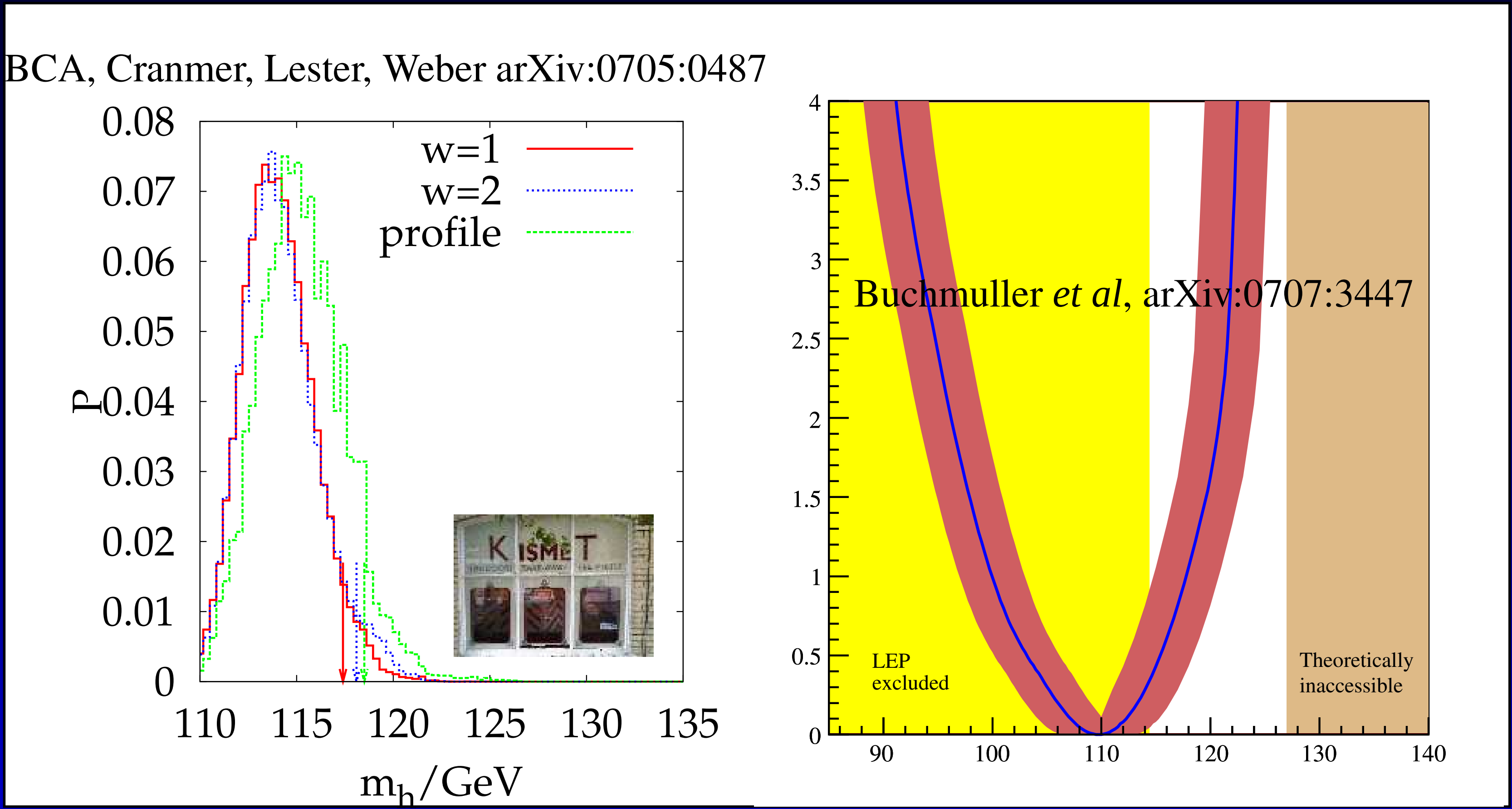
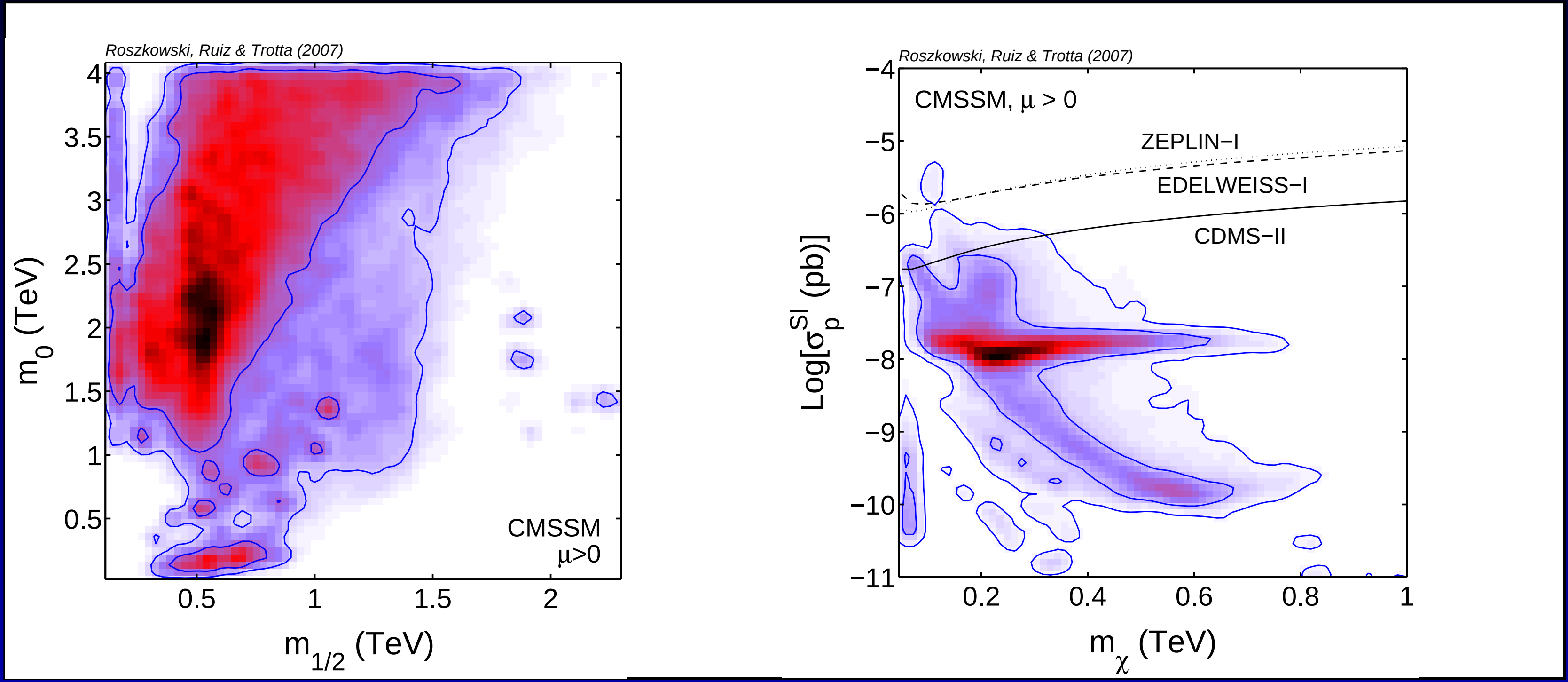


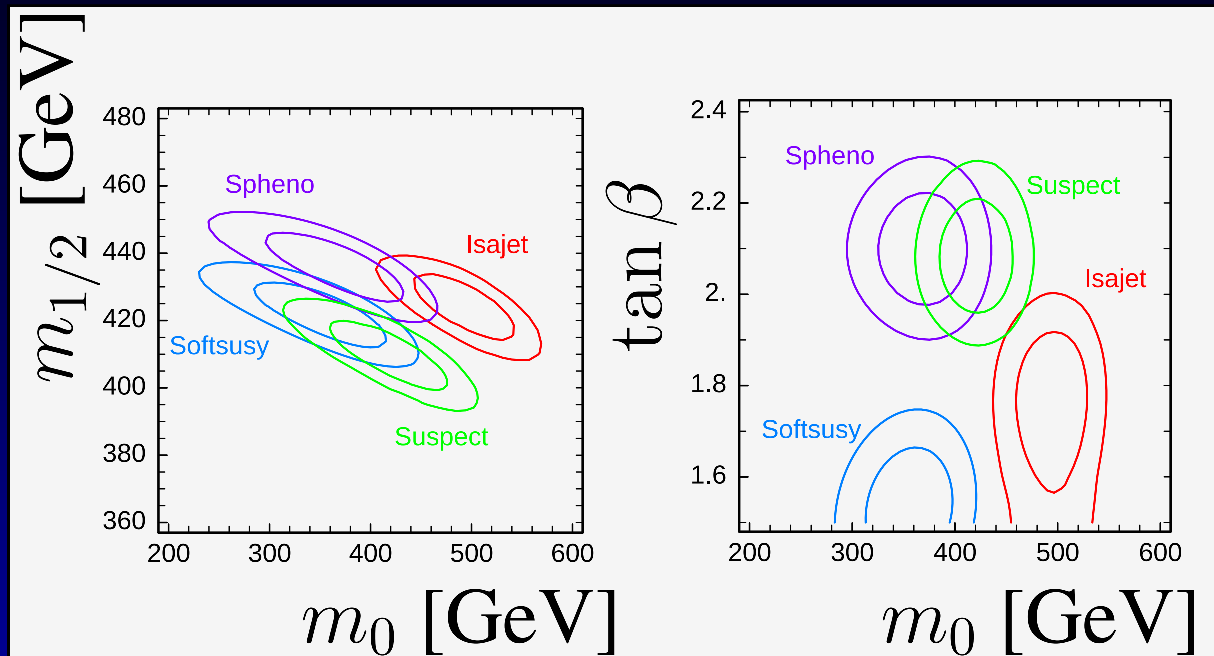

Figure 0: Including (LHS) or *not* including (RHS) the LEP2 direct Higgs mass constraints on the CMSSM.

# Other literature




R. R. de Austri, R. Trotta and L. Roszkowski, `arXiv:0705.2012`, including some NNLO $b \rightarrow s\gamma$ pieces. susyBayes

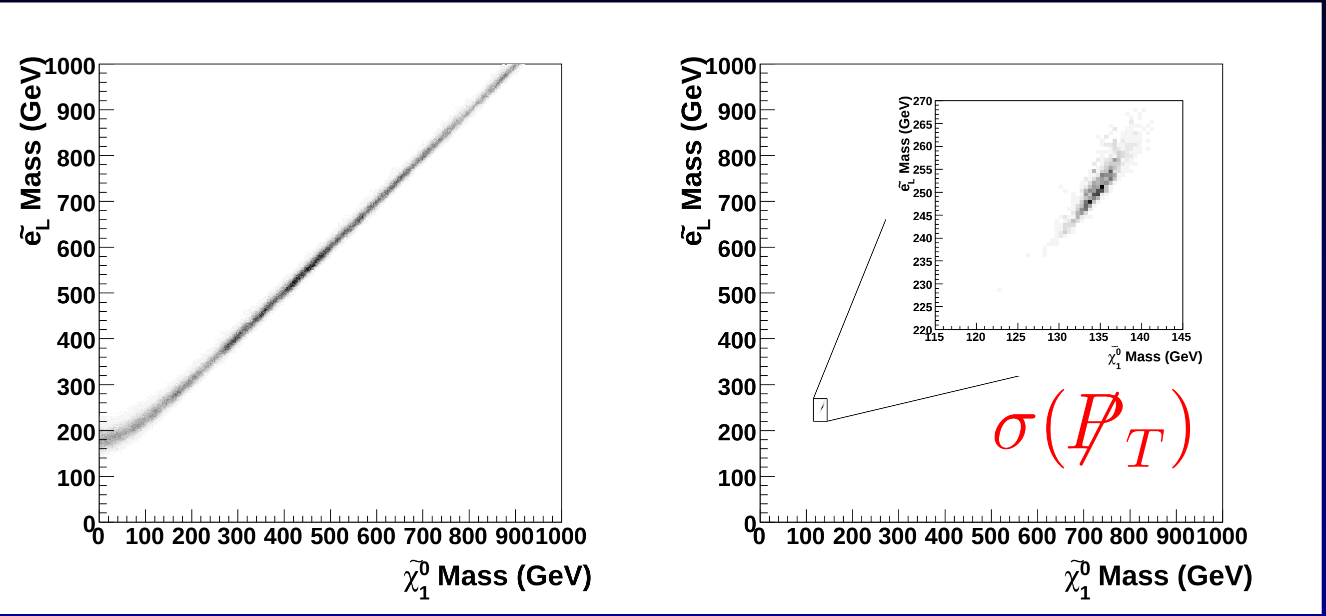
# Fitting to SUSY Breaking Model




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

BCA, S Kraml, W Porod, JHEP 0303 (2003) 016

# Fits to future collider data




Lester, Parker, White, JHEP 0601 (2006) 080

- 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 Accords*.
- 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.

# Supplementary Material

# Likelihood and Posterior

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

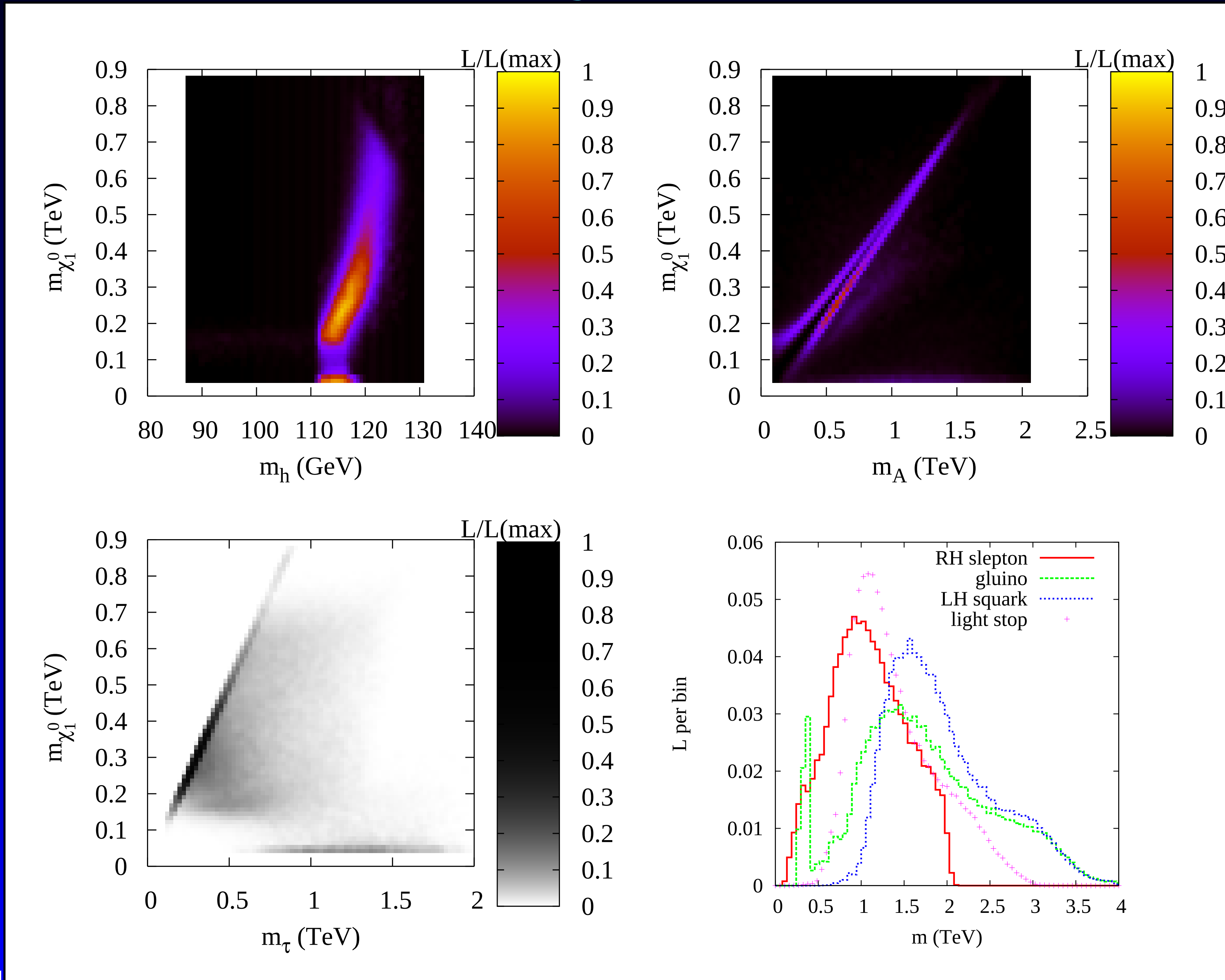
Likelihood

$p$(pregnant | female, human) = 0.01

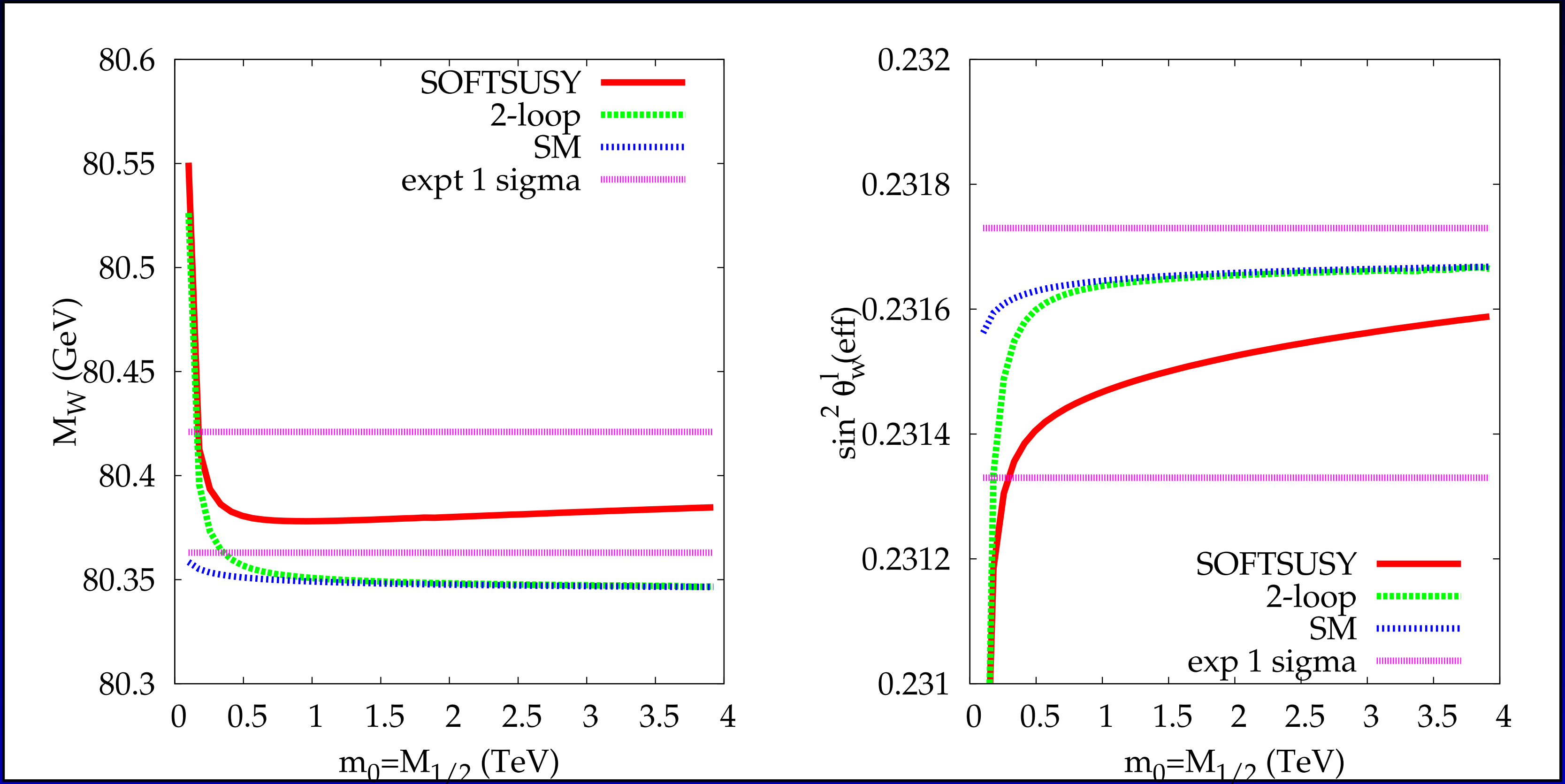
Posterior

$p$(female | pregnant, human) = 1.00

# Sanity Check



# Electroweak Observables




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

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Ellis *et al*, hep-ph/0411216; hep-ph/0602220.

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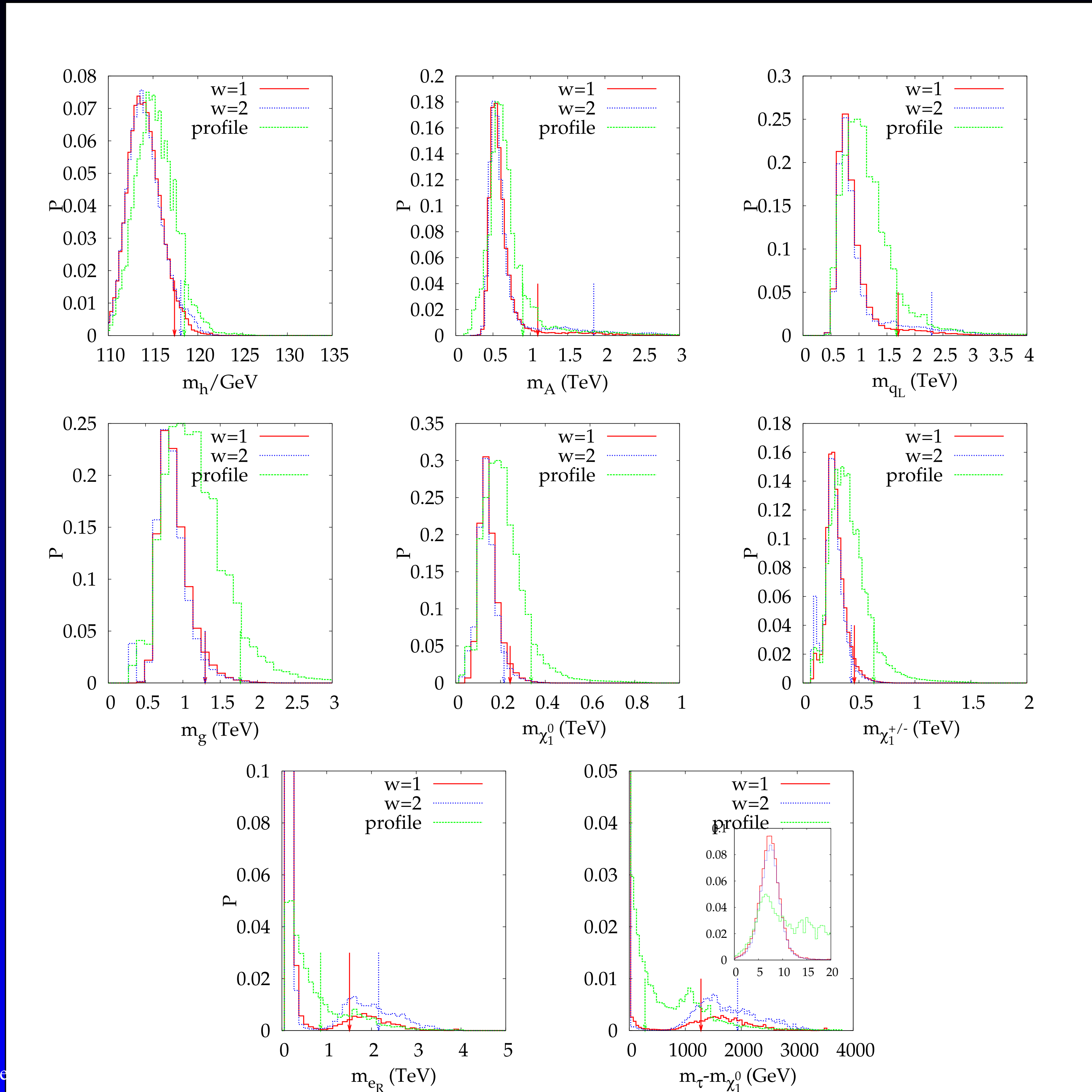


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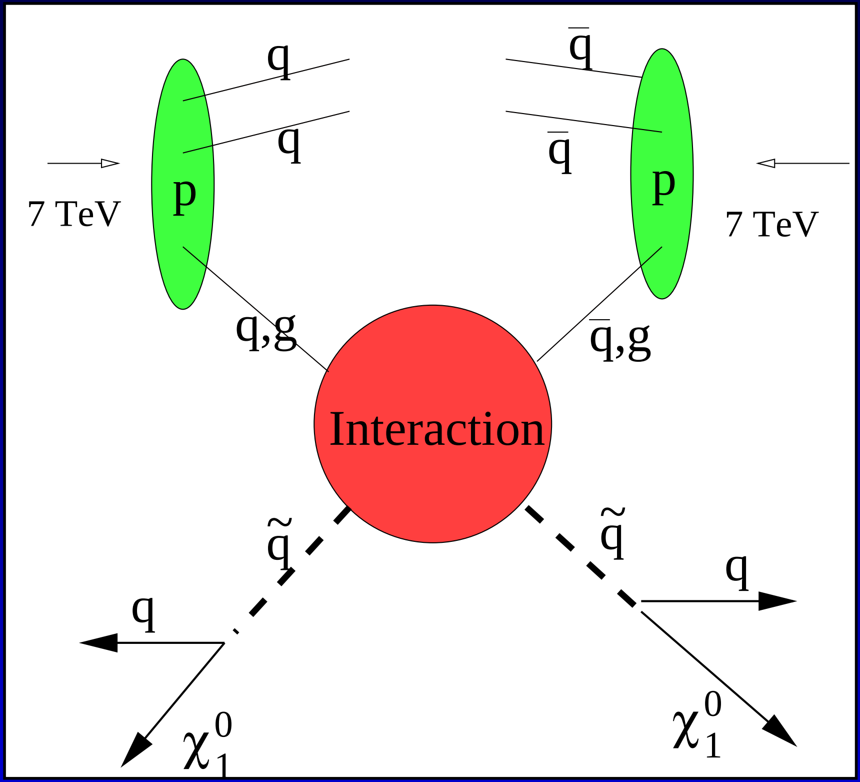
# Caveats

- 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.




$\mathcal{Q}$: Can we measure enough to predict $\sigma$?

# Collider SUSY Dark Matter Production

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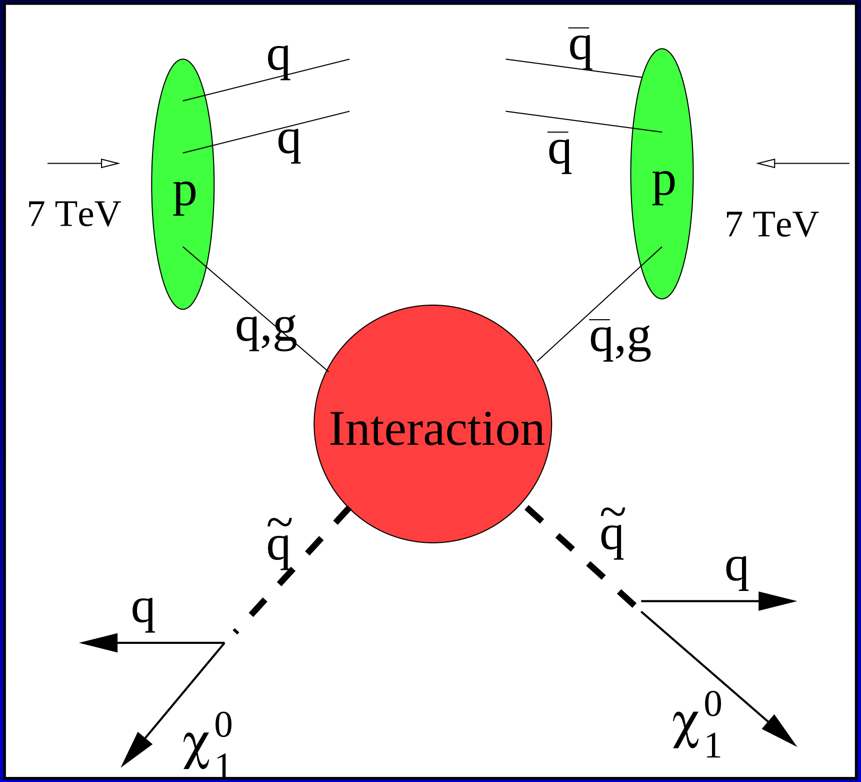


*Any dark matter candidate that couples to hadrons can be produced at the LHC*

# 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.

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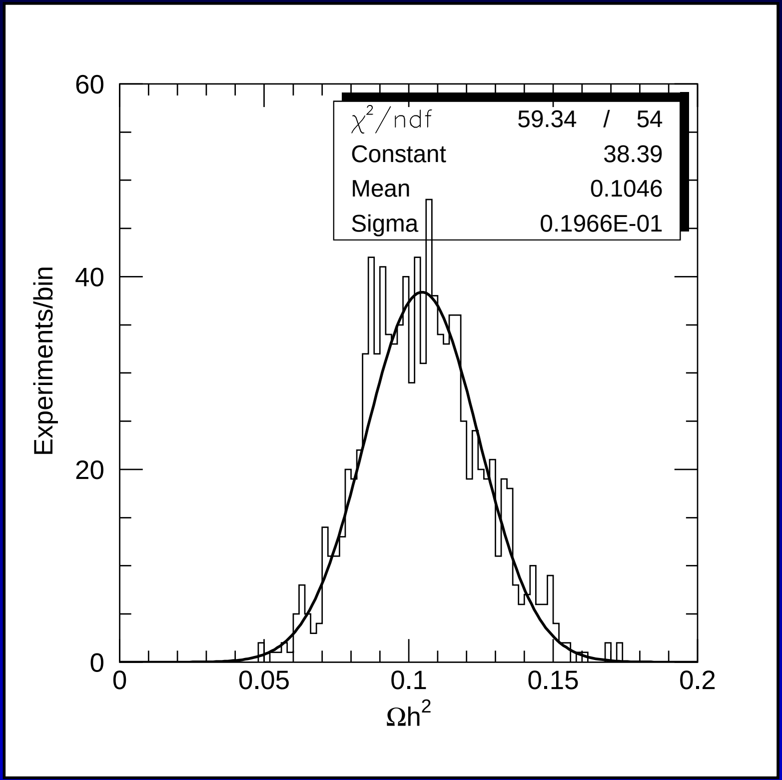
BCA, G. Belanger, F. Boudjema, A. Pukhov, JHEP 0412 (2004) 020.; M. Nojiri, D. Tovey, JHEP 0603 (2006) 063

# Predicting $\Omega h^2$

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




*Q*: What about other bits of parameter space?

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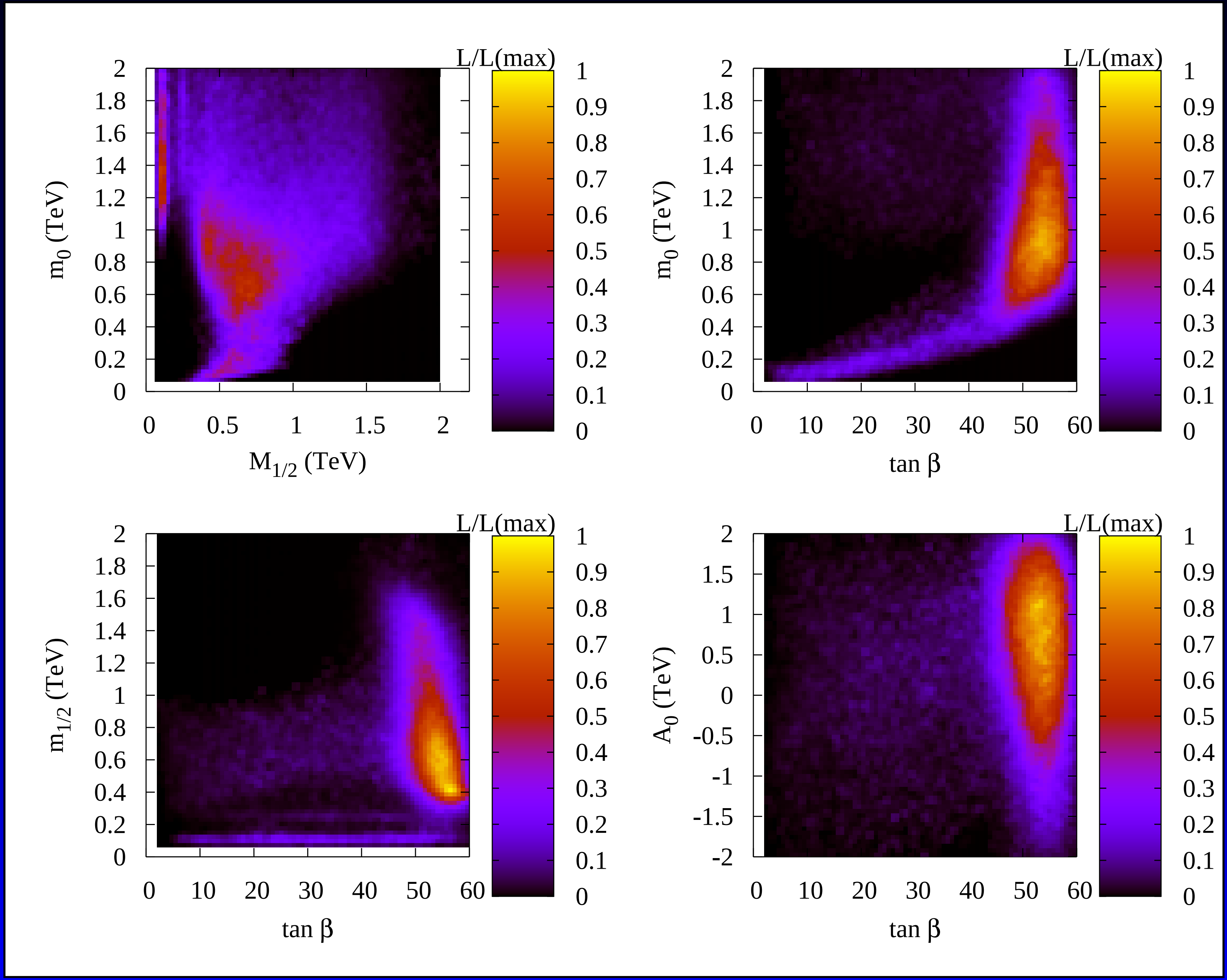
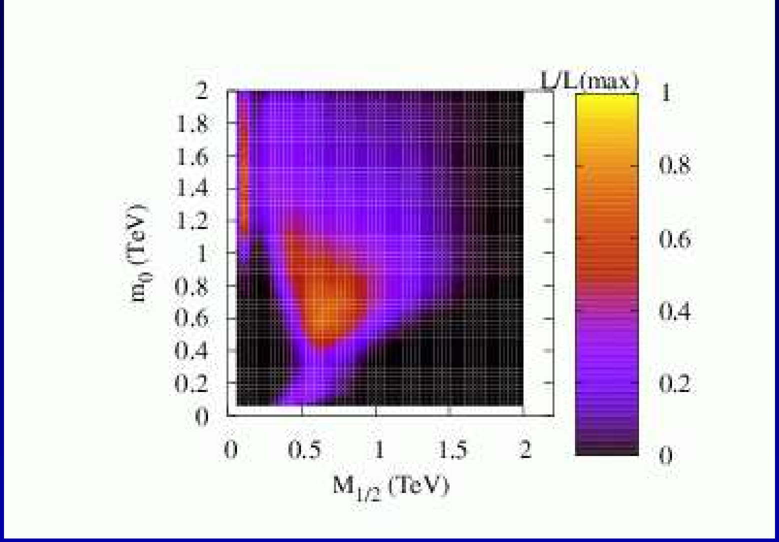
M Nojiri, G Polesello, D Tovey, JHEP 0603 (2006) 063, `hep-ph/0512204`.

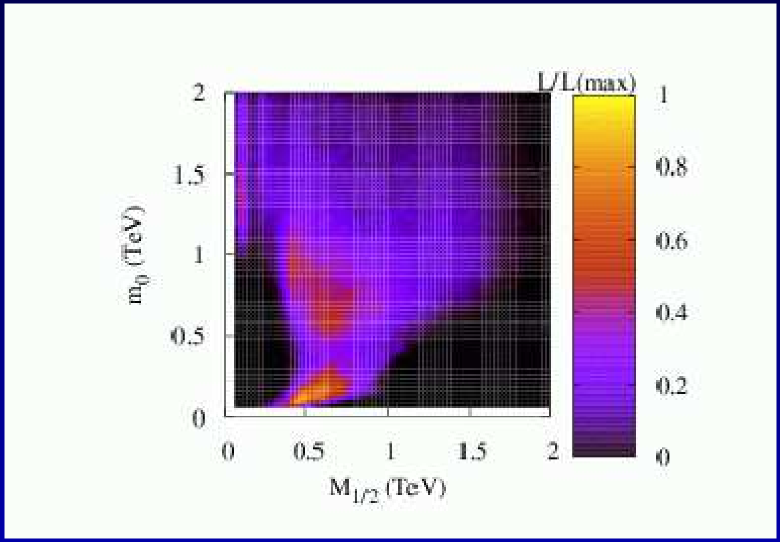

L/L(max)
$m_0$ (TeV)
$M_{1/2}$ (TeV)
tan β
$m_{1/2}$ (TeV)
$A_0$ (TeV)

# Volume Effects

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

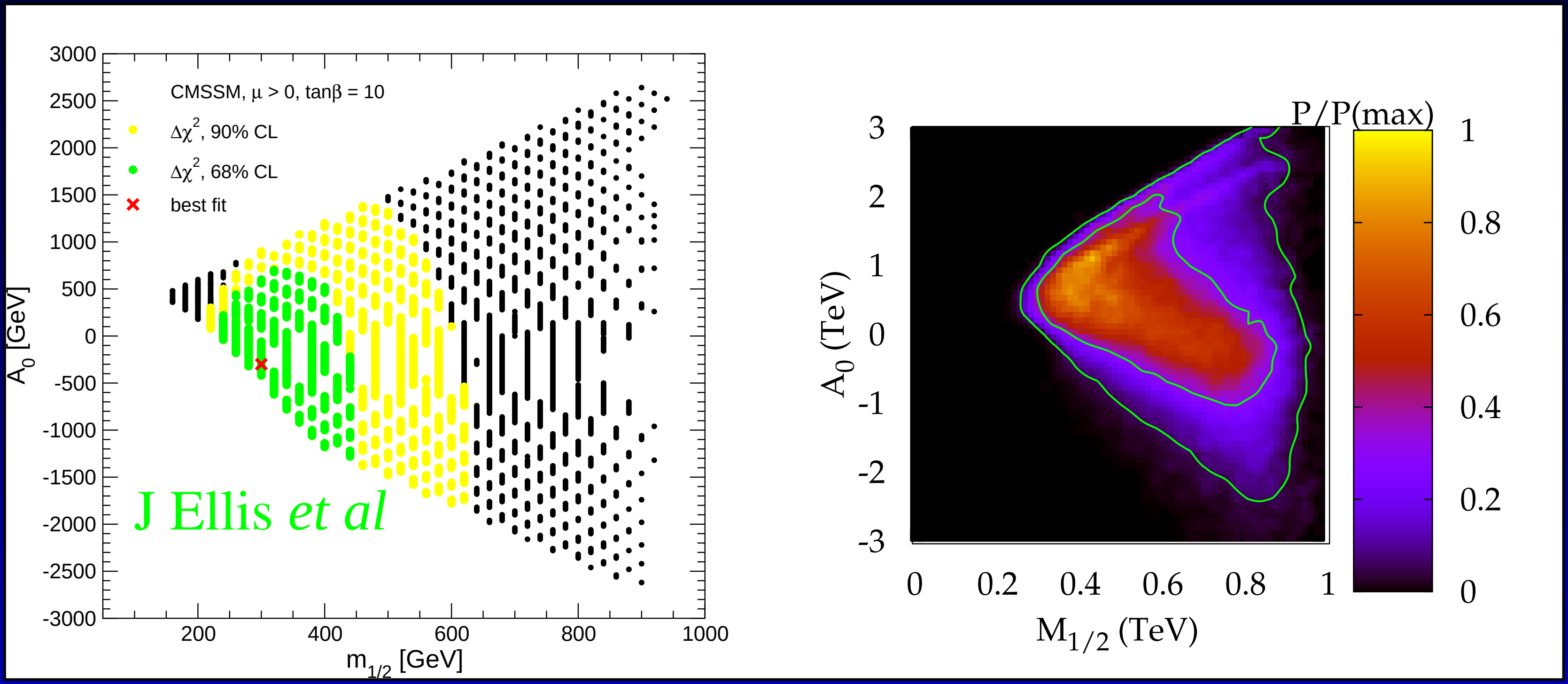
# Comparison




- LHS: allowing non thermal-$\chi_1^0$ contribution
- RHS: only $\chi_1^0$ 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:

$$
\begin{aligned}
p(m_0|\text{data}) &= \int dM_{1/2}\, dA_0\, d\tan\beta\, ds \\
&\quad p(m_0, M_{1/2}, A_0, \tan\beta, s|\text{data}). \\
\mu B &= \frac{\sin 2\beta}{2}(\bar{m}_{H_1}^2 + \bar{m}_{H_2}^2 + 2\mu^2), \\
\mu^2 &= \frac{\bar{m}_{H_1}^2 - \bar{m}_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{M_Z^2}{2}.
\end{aligned}
$$

Change variables: $\int d\mu dB \to \int dM_Z d\tan\beta |J|$

# EWSB prior

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

Change variables
$\int d\mu dB \delta(M_Z - M_Z^{cen}) \to \int d \tan\beta |J|$:

$$
J = \frac{B}{\mu \tan\beta} \frac{\tan^2\beta + 1}{\tan^2\beta - 1}
$$

# Same order prior

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

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

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

We don't know SUSY breaking scale $M_S$:

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