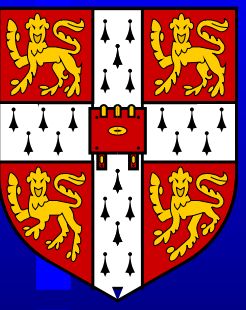


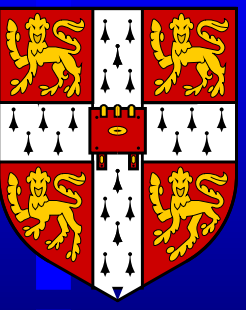
Tools for Supersymmetric Phenomenology

by

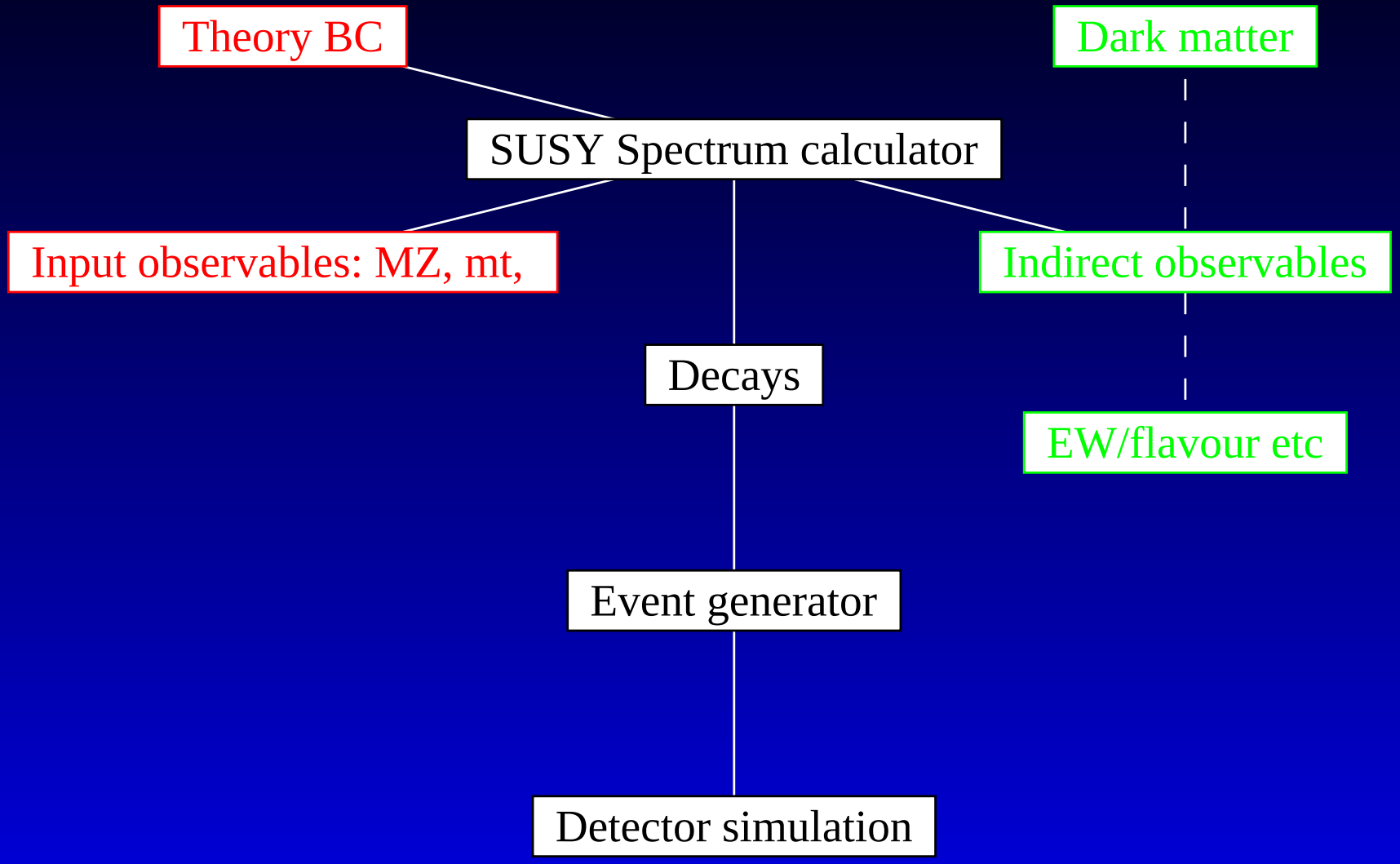
Ben Allanach (University of Cambridge)

Talk outline

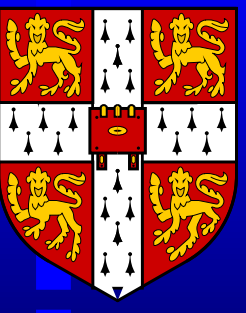
- SPA project http://spa.desy.de/spa/, http://www.ippp.dur.ac.uk/montecarlo/BSM
- Bestiary of public codes only: supposedly impartial
- Predictions for the LHC: partial



MSSM Tools



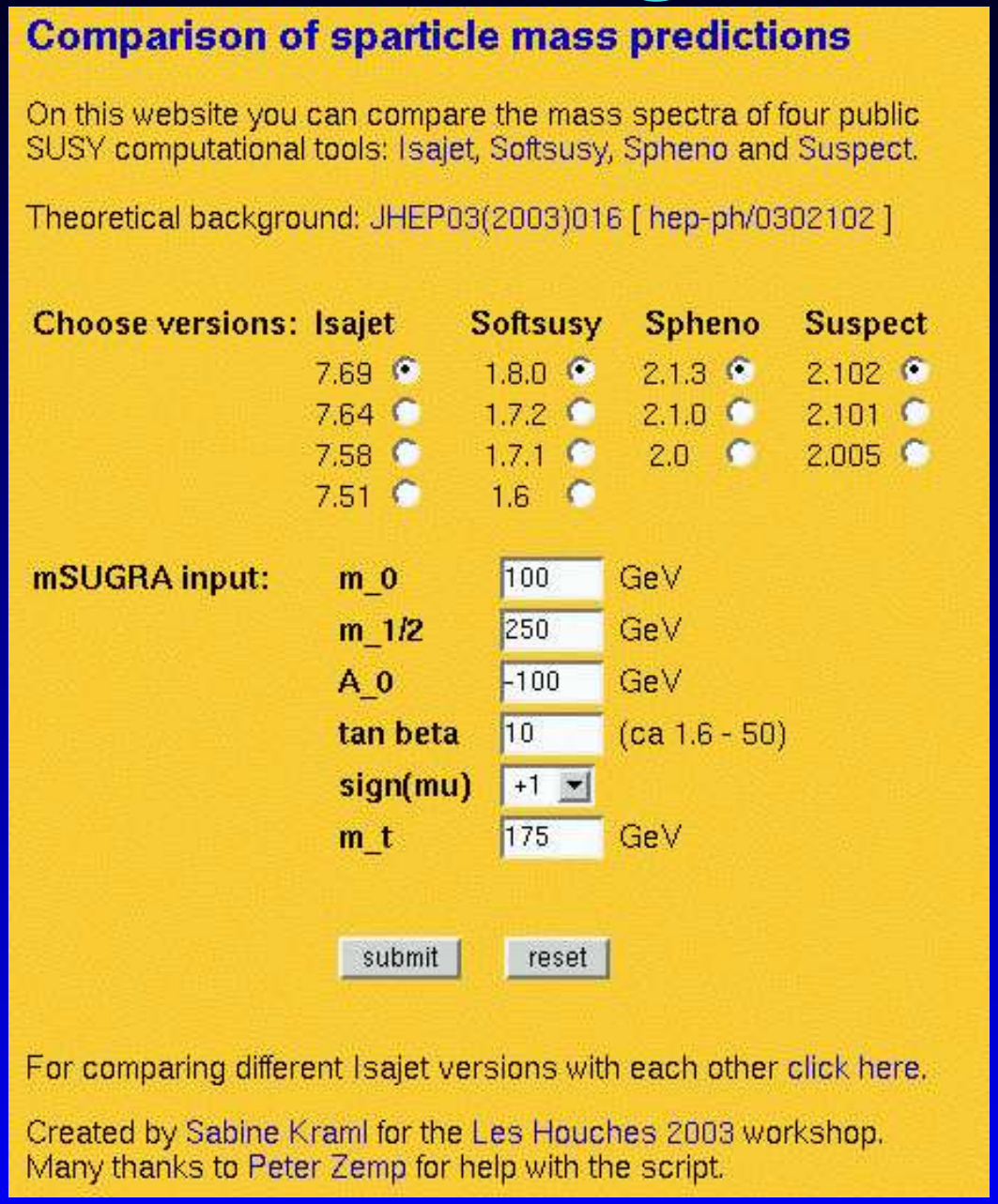
SLHA: Skands *et al*, JHEP 0407 (2004) 036, SLHA2 on here (NMSSM, RPV, FV, CPV), arXiv:0801.0045



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.

Web Page



Comparison of sparticle mass predictions

On this website you can compare the mass spectra of four public SUSY computational tools: Isajet, Softsusy, Spheno and Suspect.

Theoretical background: JHEP03(2003)016 [hep-ph/0302102]

Choose versions:	Isajet	Softsusy	Spheno	Suspect
	7.69	1.8.0	2.1.3	2.102
	7.64	1.7.2	2.1.0	2.101
	7.58	1.7.1	2.0	2.005
	7.51	1.6		

mSUGRA input:			
	m_0	100	GeV
	m_1/2	250	GeV
	A_0	-100	GeV
	tan beta	10	(ca 1.6 - 50)
	sign(mu)	+1	
	m_t	175	GeV

submit reset

For comparing different Isajet versions with each other click here.

Created by Sabine Kraml for the Les Houches 2003 workshop.
Many thanks to Peter Zemp for help with the script.

http://kraml.home.cern.ch/kraml/comparison/

BCA, S Kraml in hep-ph/0402295

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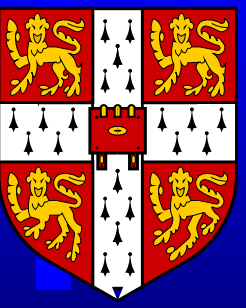
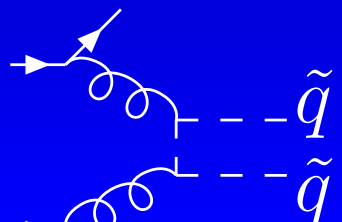


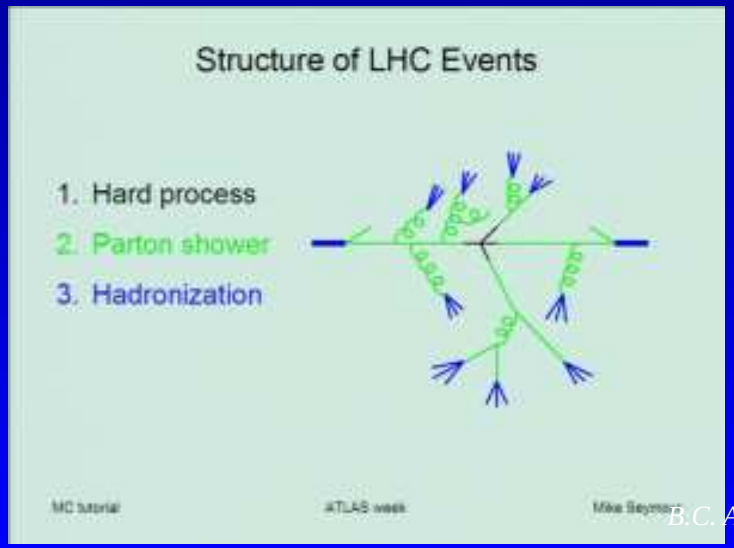
Matrix Element Generators

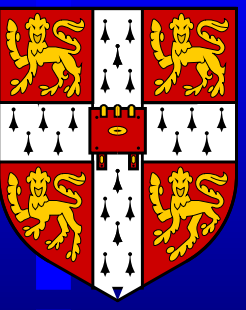
- Feyn Arts/Feyn Calc
- Additional hard jets *cannot* be modelled reliably using the parton shower - you need to simulate the matrix element.
- SMADGRAPH, compHEP, calcHEP, GRACE do SUSY and more general models at tree level. 2 to 4 possible. BRIDGE can be used to remember spin information in the decays.
- 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++



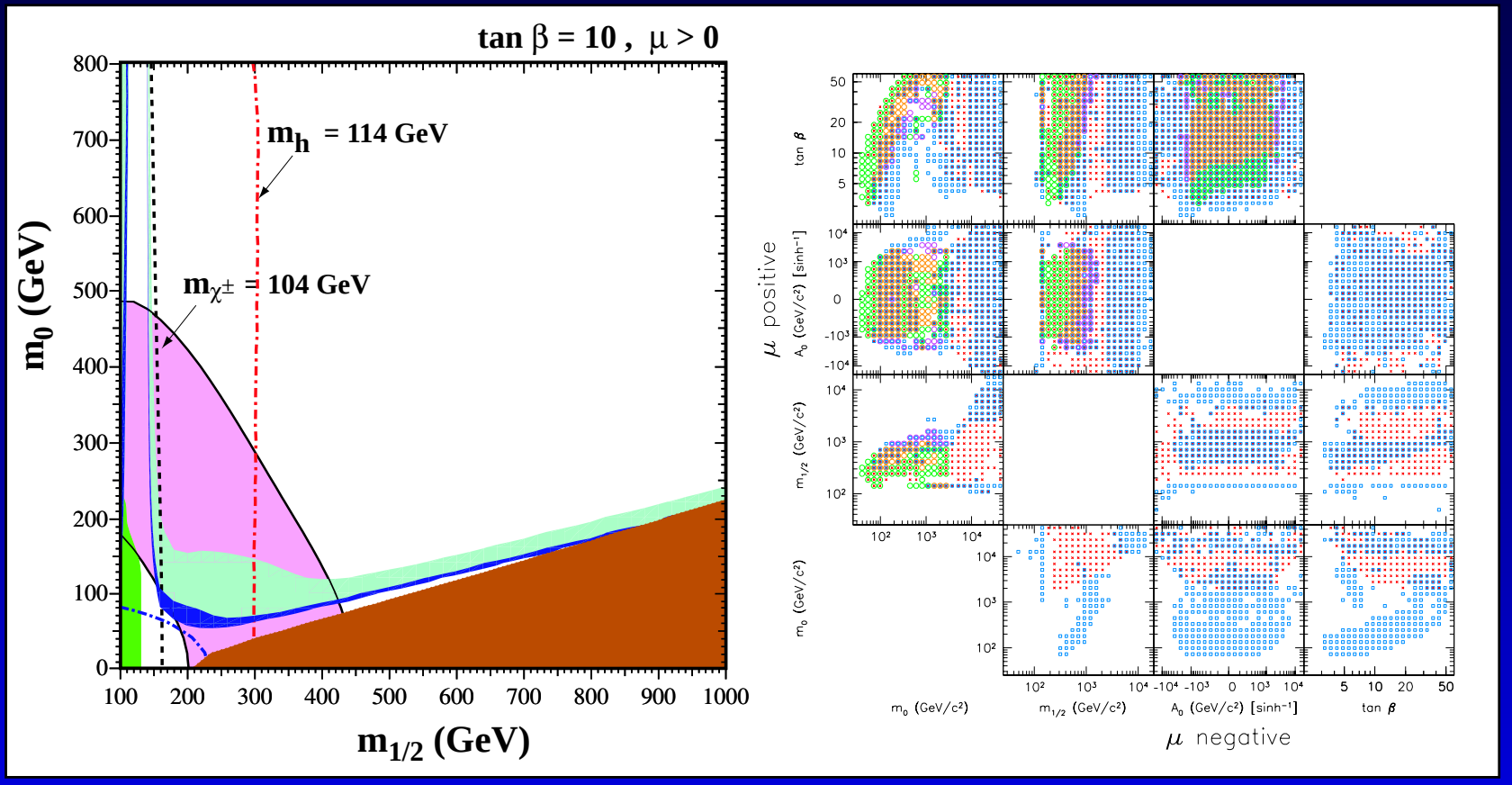


SUSY Prediction of Ωh^2

- 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*. `susyBSG`
- `darkSUSY`, `ISATOOLS` has MSSM annihilation channels hard-coded. Much work on (in)-*direct* detection possibilities.

Constraints on SUSY Models

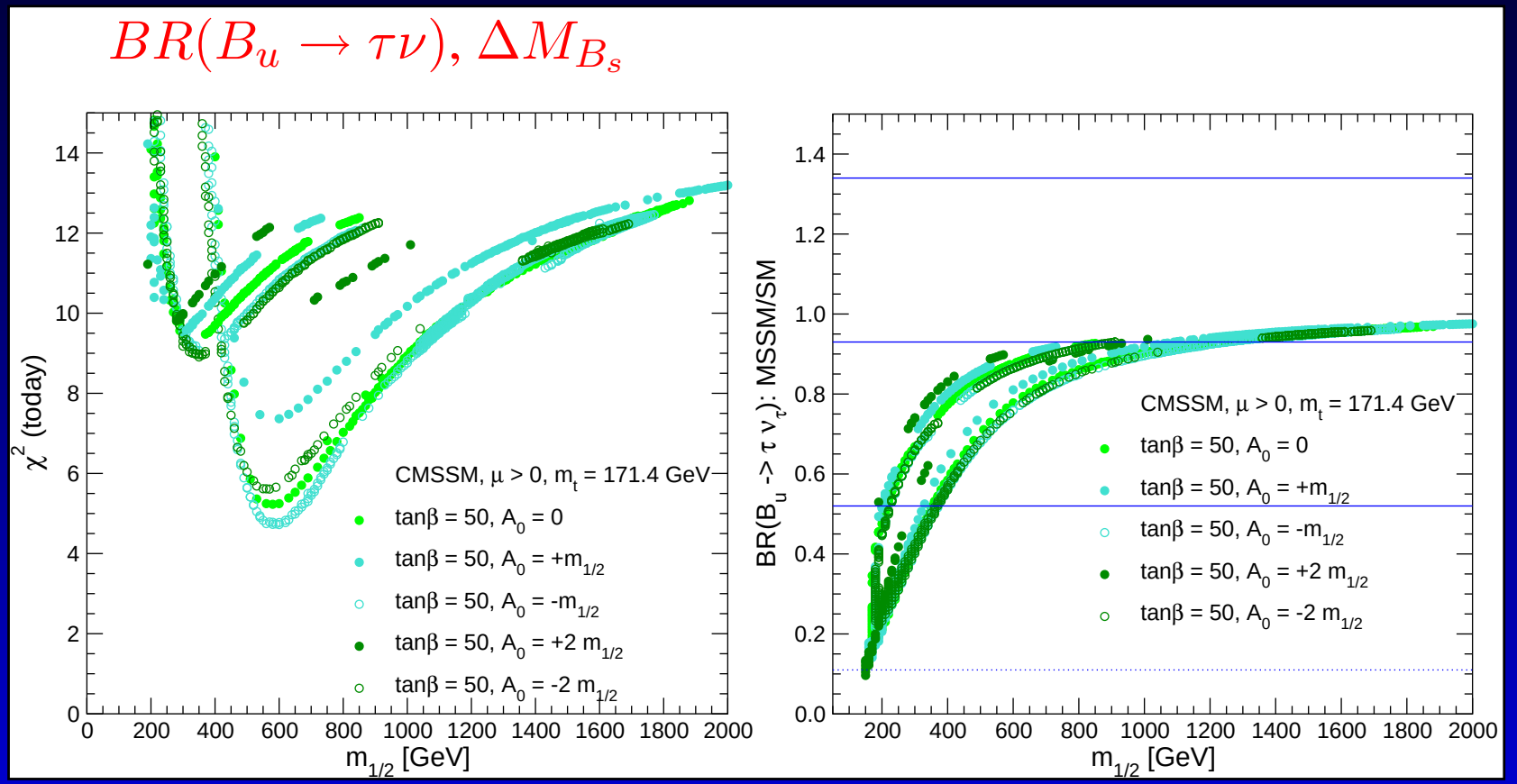
CMSSM well-studied in literature: eg Ellis, Olive *et al* PLB565 (2003) 176; Roszkowski *et al* JHEP 0108 (2001) 024; Baltz, Gondolo, JHEP 0410 (2004) 052;...

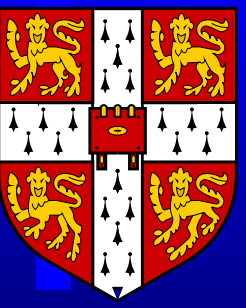


b Observables

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

$BR(B_u \to \tau\nu), \Delta M_{B_s}$



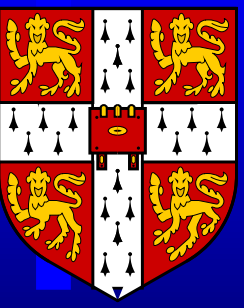


Fit Development

- Typically done 2d scans with 2σ 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 Ωh^2
- 4d scan [b] used the impressive *Markov Chain Monte Carlo technique* like in cosmology.
- Combine likelihoods from all of the different measurements.

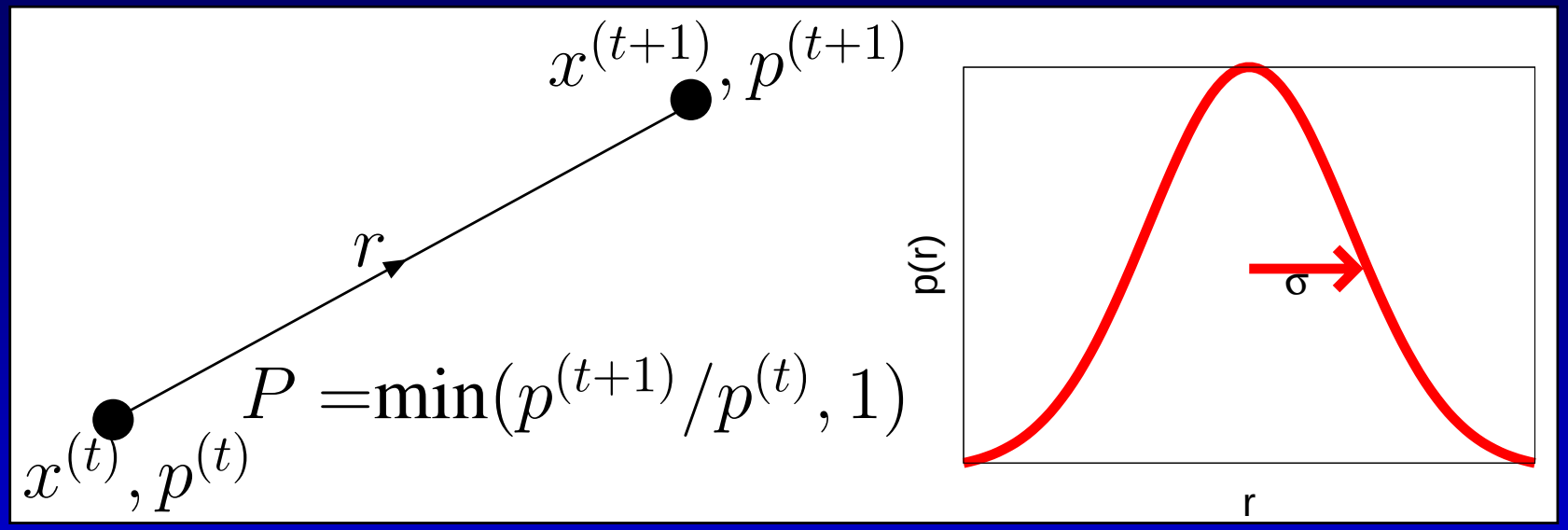
[a] Ellis *et al*, arXiv:0706.0652

[b] Baltz, Gondolo, JHEP 0410 (2004) 052

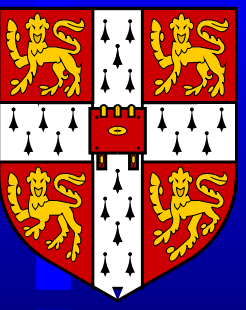


Markov-Chain Monte Carlo

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.



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
- $\delta(g-2)_\mu/2 = (22 \pm 10) \times 10^{-10}$ Stöckinger *et al*
- $BR[b \to s\gamma] = (3.55 \pm 0.38) \times 10^{-4}$ susyBSG
- $\sin^2\theta_w^l(\text{eff}) = 0.23153 \pm 0.000175$
- $M_W = 80.392 \pm 0.031$ GeV W Hollik, A Weber *et al*

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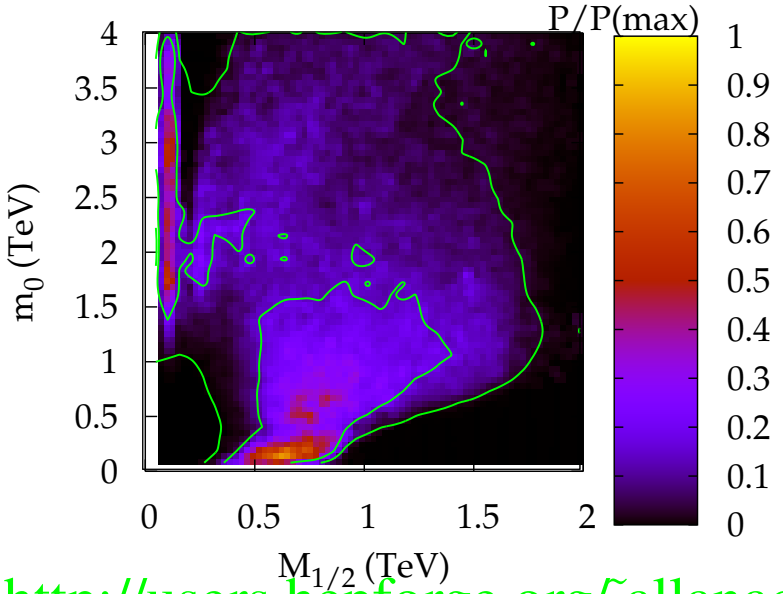
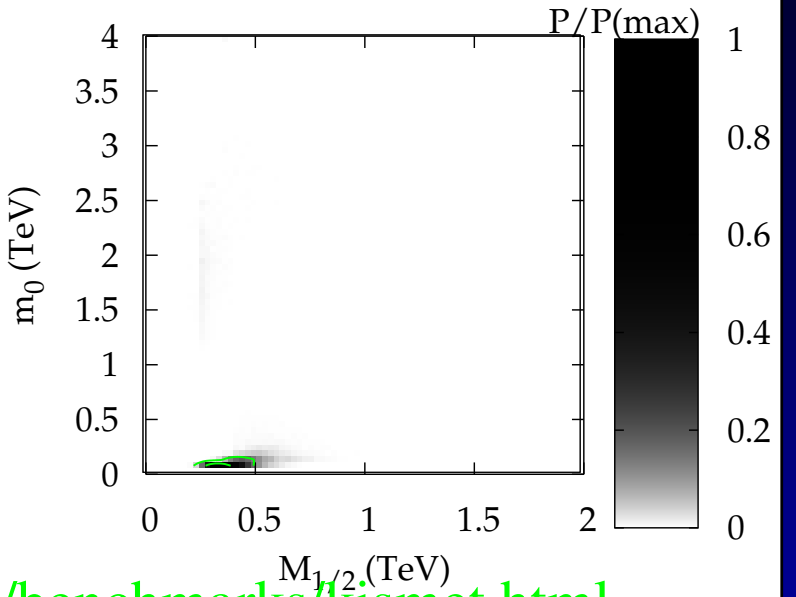
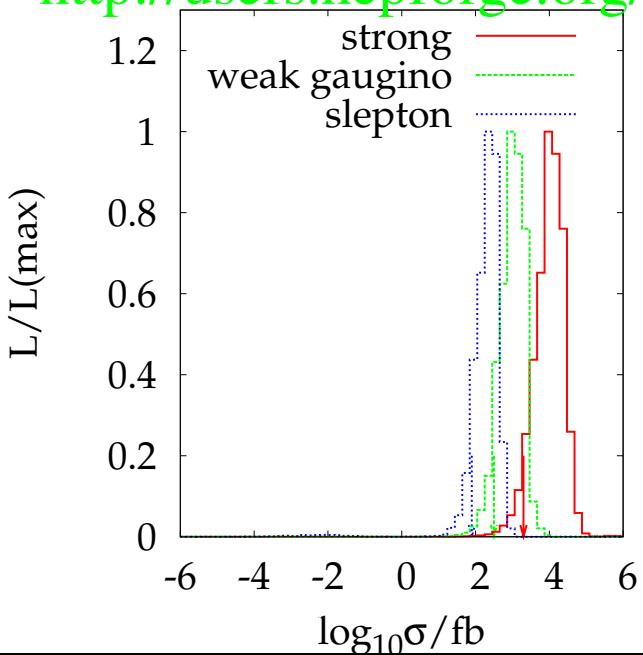
Killer Inference for Susy METeorology

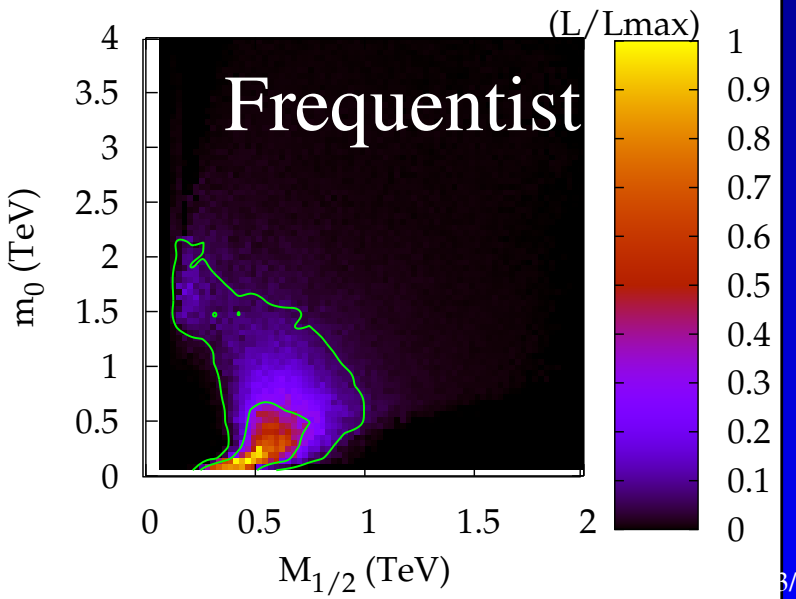
BCA, Cranmer, Weber, Lester, arXiv:0705.0487





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





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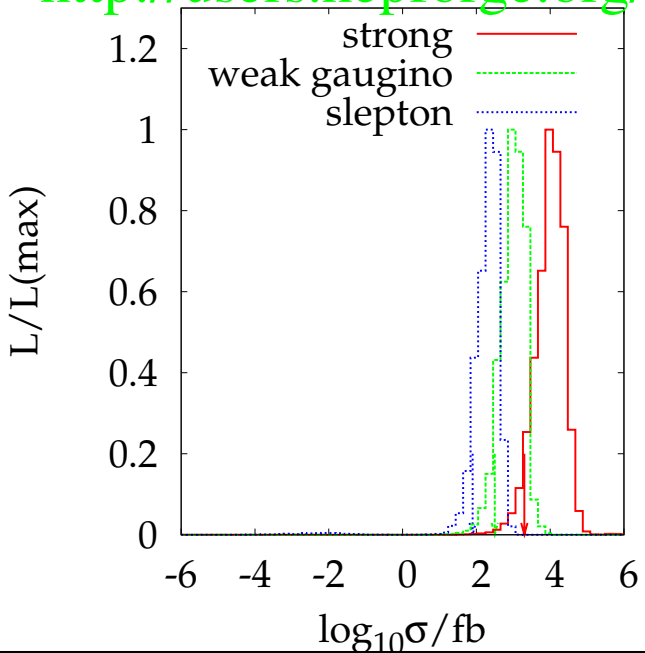

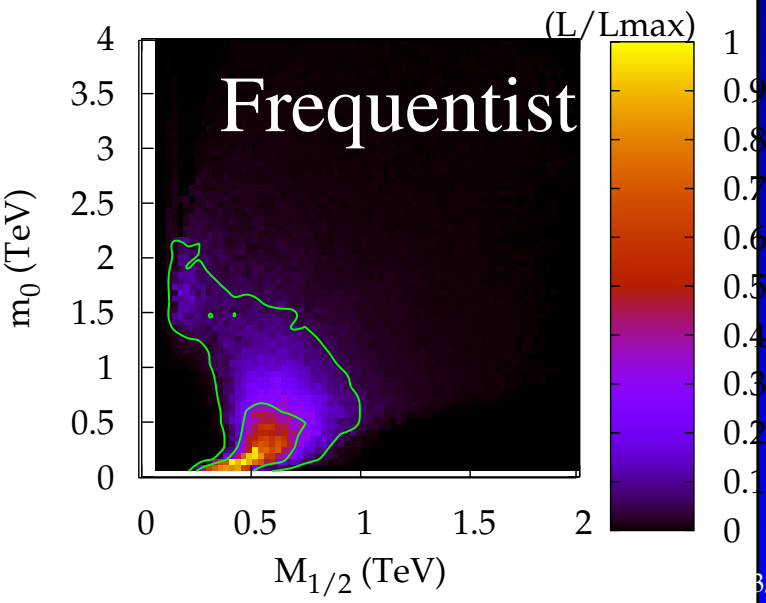

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Higgs Meteorology

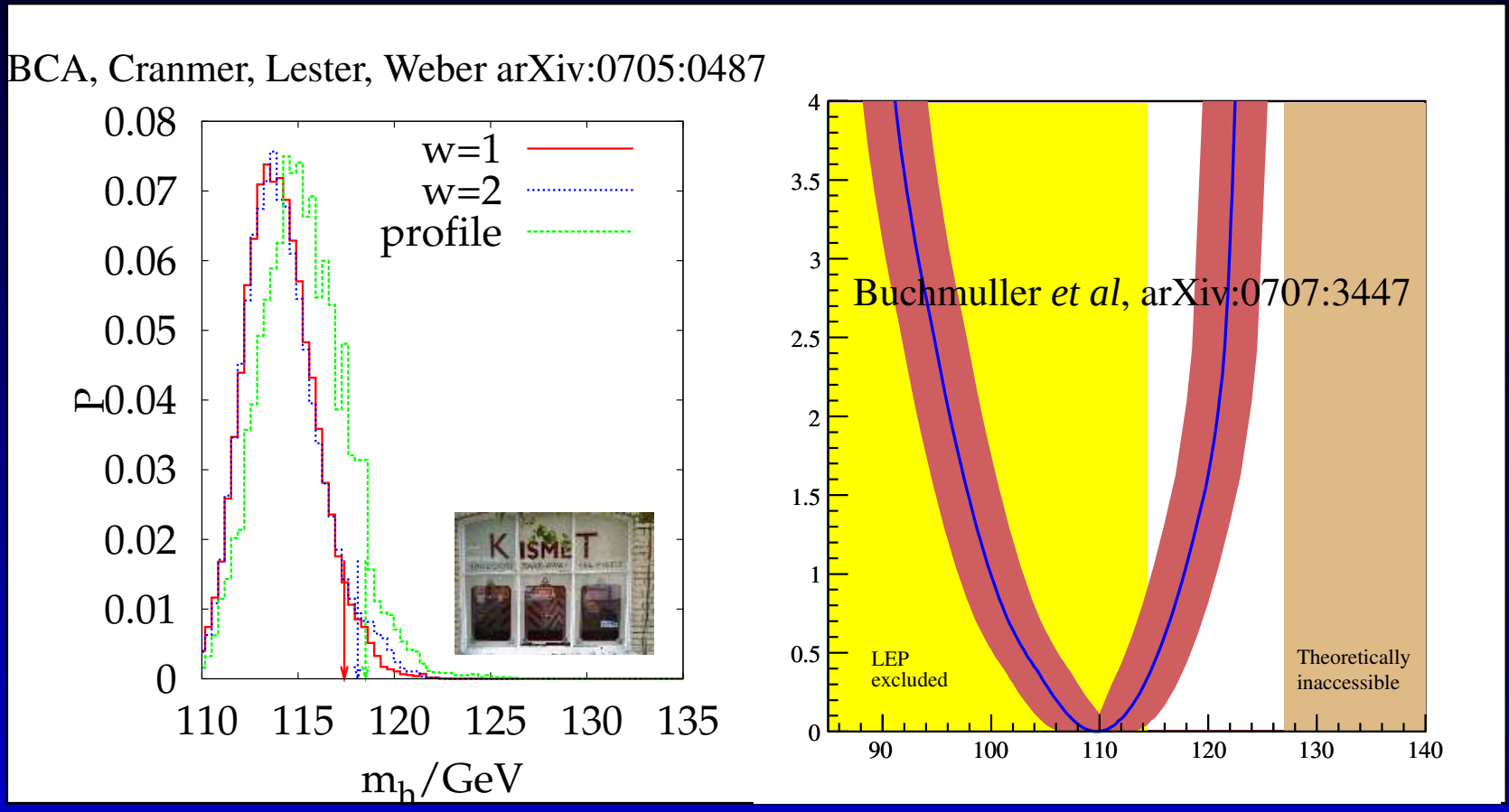
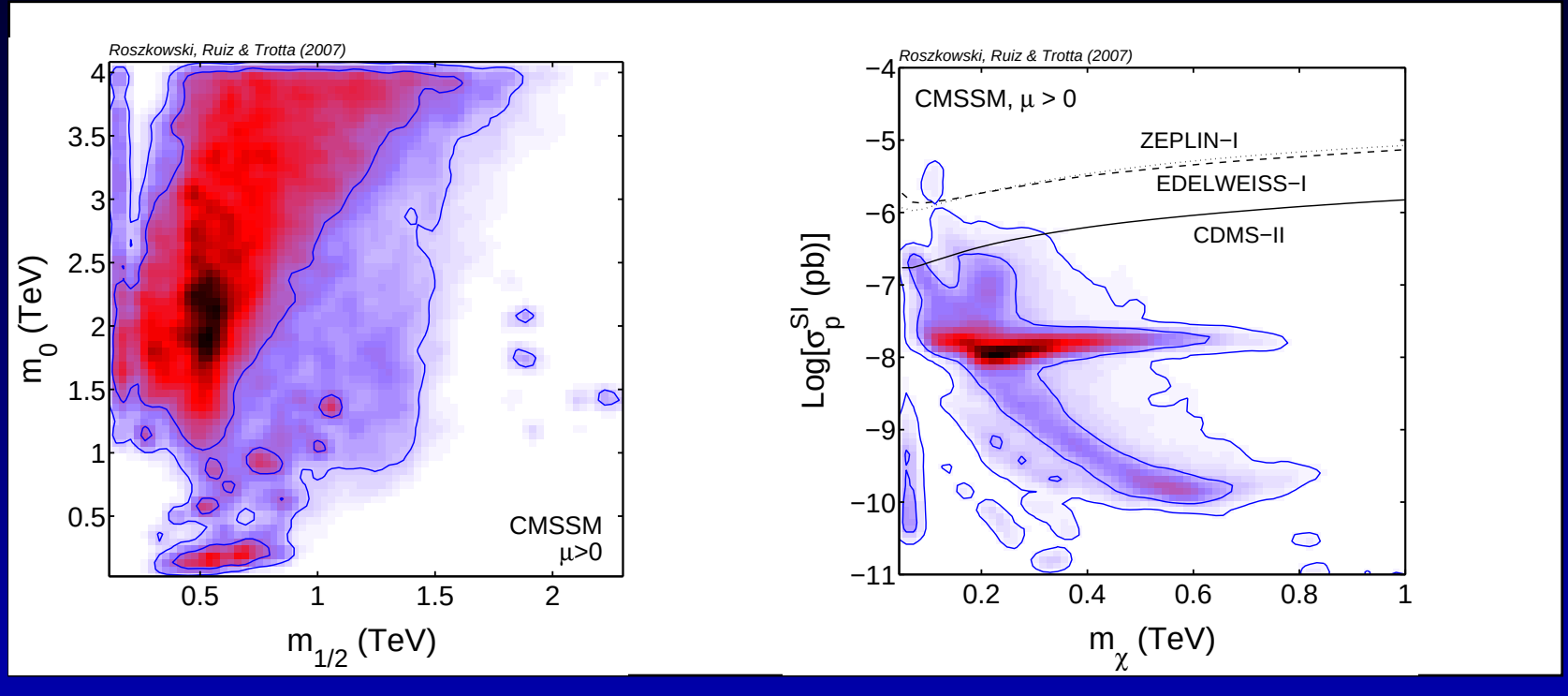


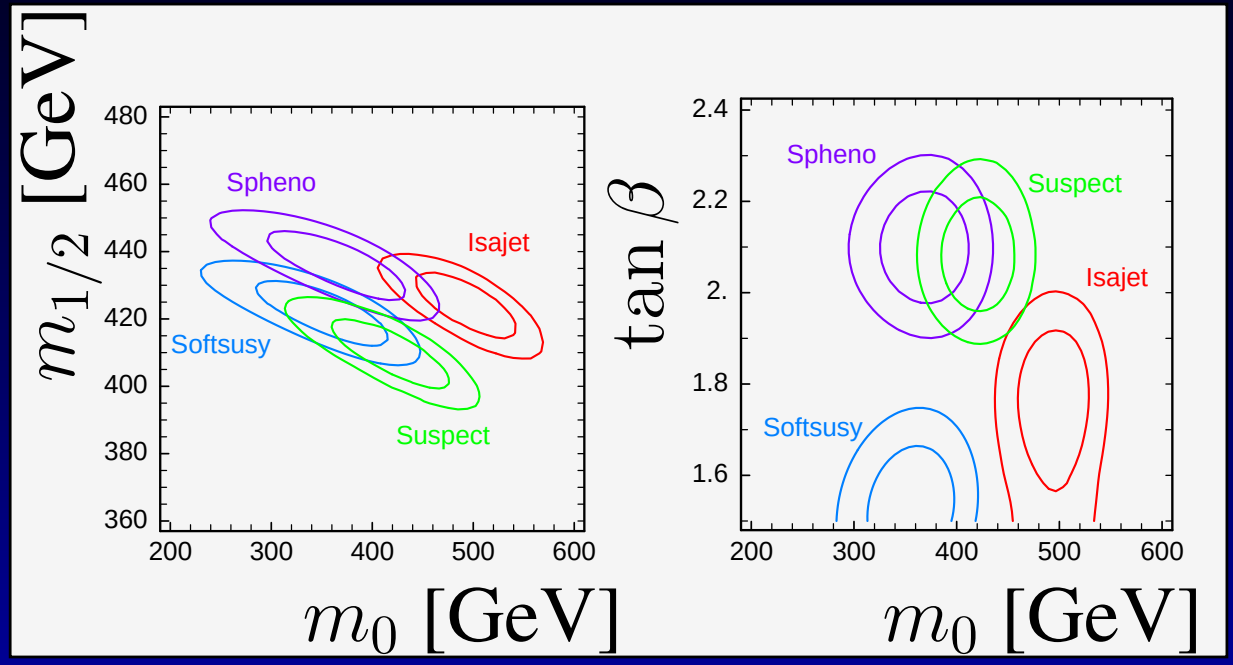
Figure 0: Including (LHS) or *not* including (RHS) the LEP2 direct Higgs mass constraints on the CMSSM.

Other literature



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

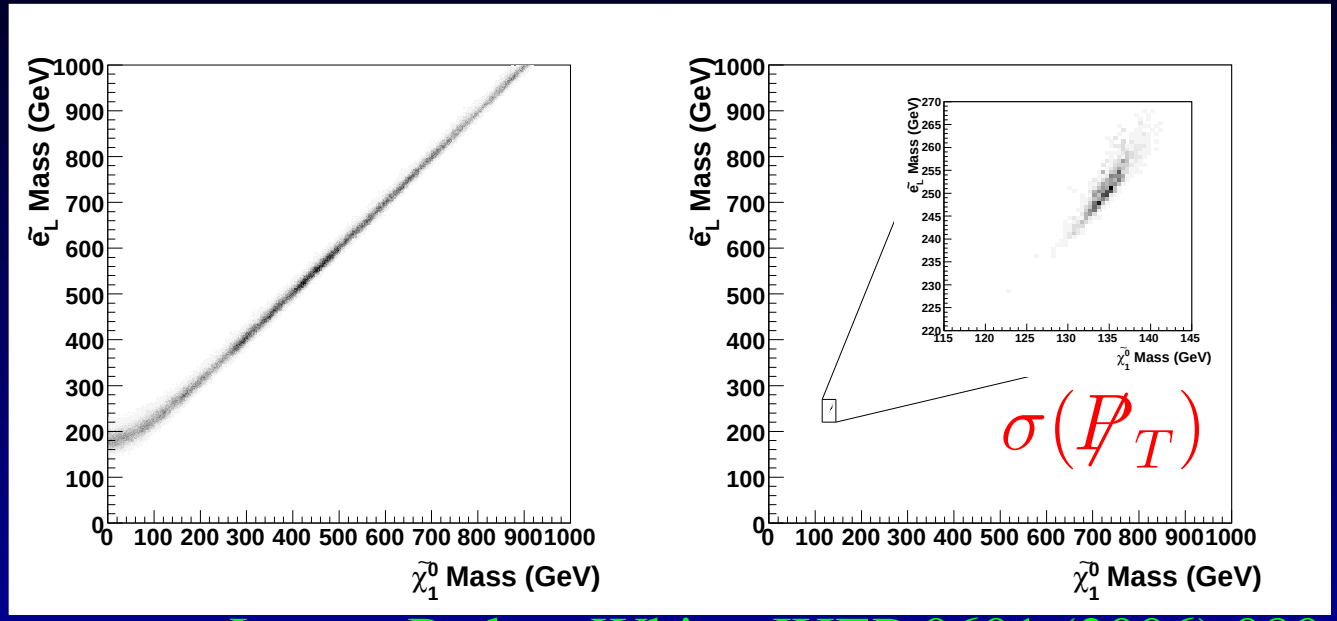
Fitting to SUSY Breaking Model



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

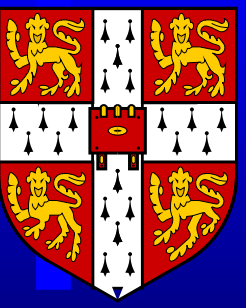
BCA, S Kraml, W Porod, JHEP 0303 (2003) 016

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



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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.

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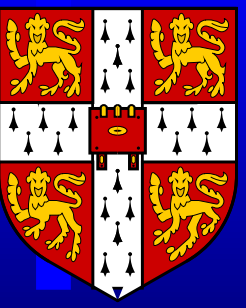
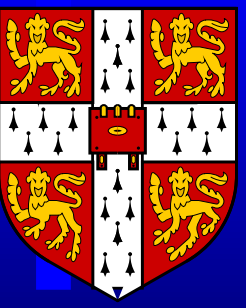


Supplementary Material



Likelihood and Posterior

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

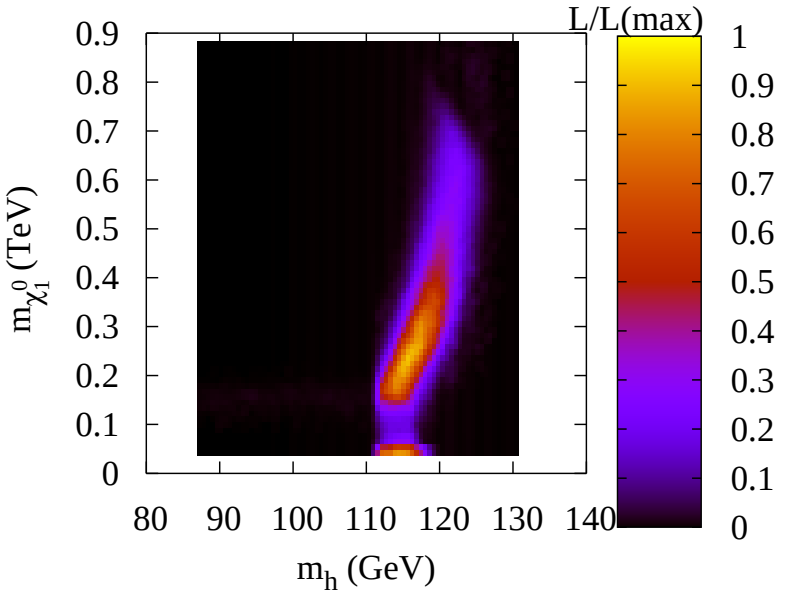
Likelihood

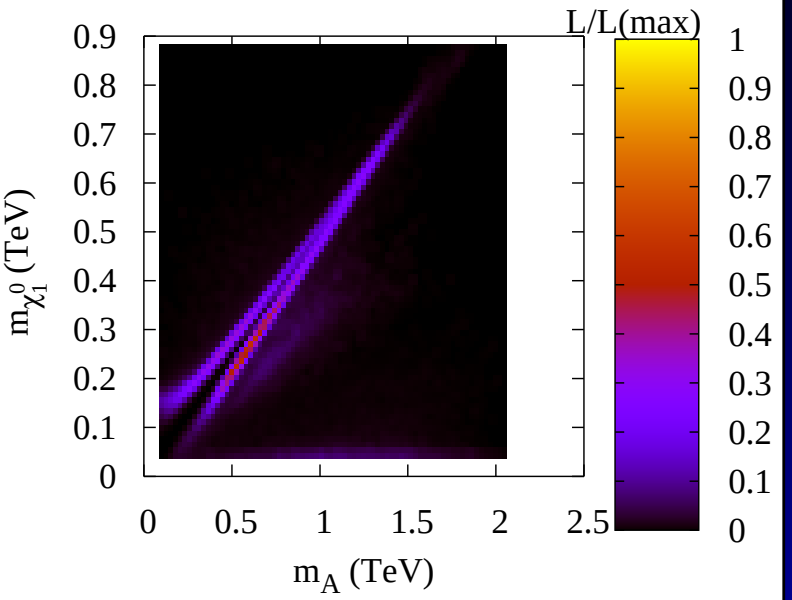
$p(\text{pregnant} \mid \text{female, human}) = 0.01$

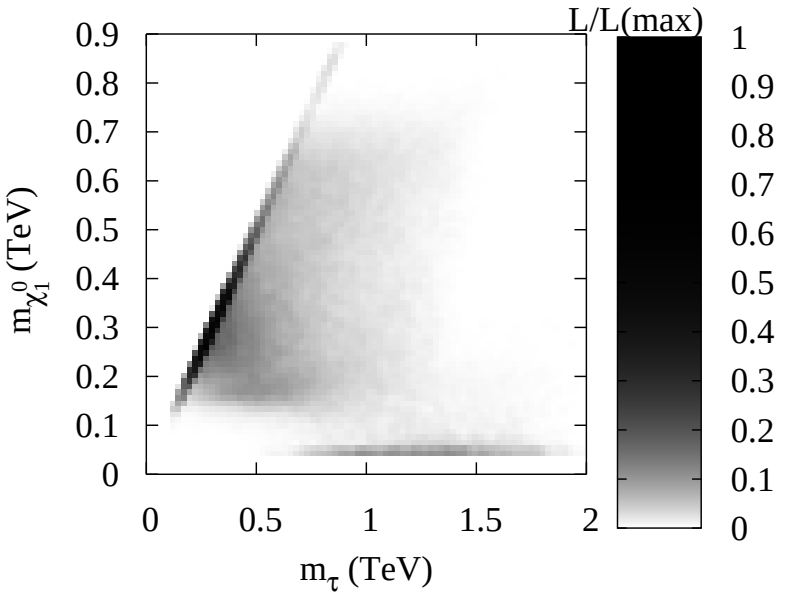
Posterior

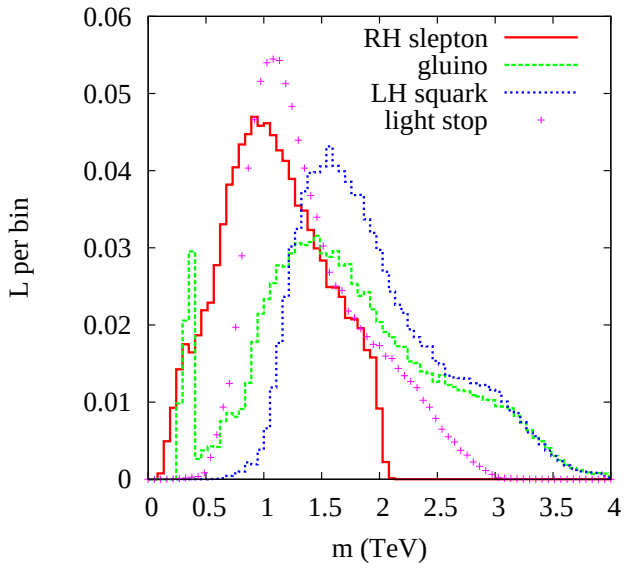
$p(\text{female} \mid \text{pregnant, human}) = 1.00$

Sanity Check

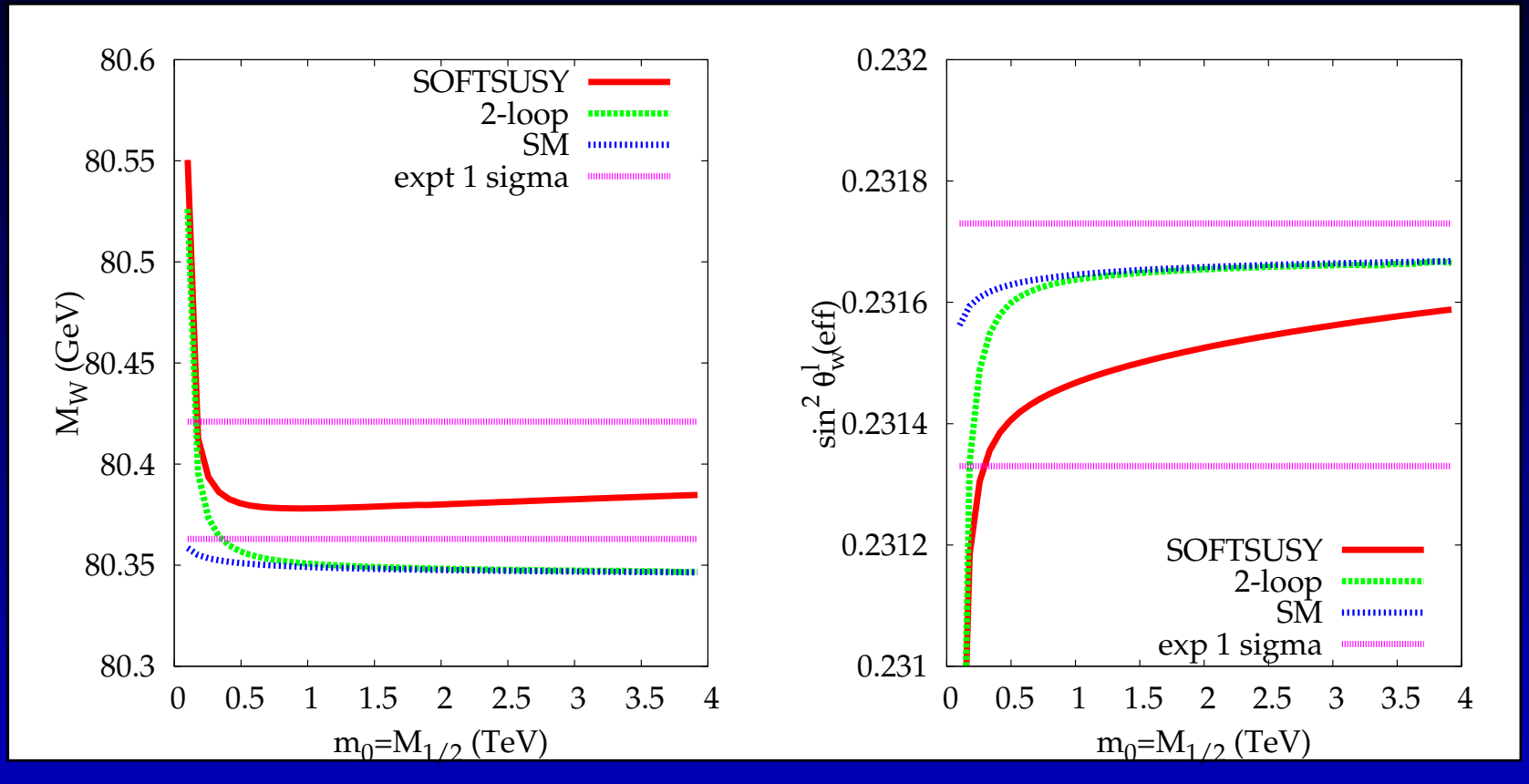






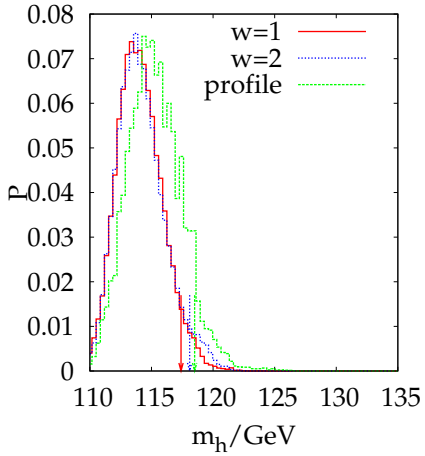


Electroweak Observables



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

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


w=1
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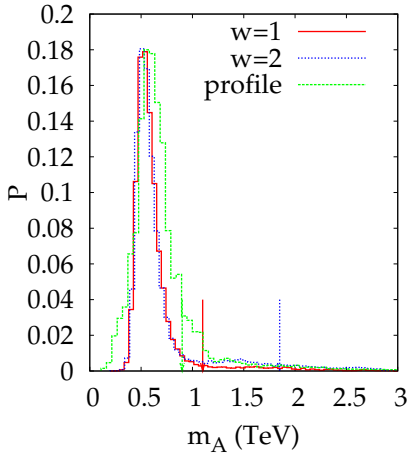
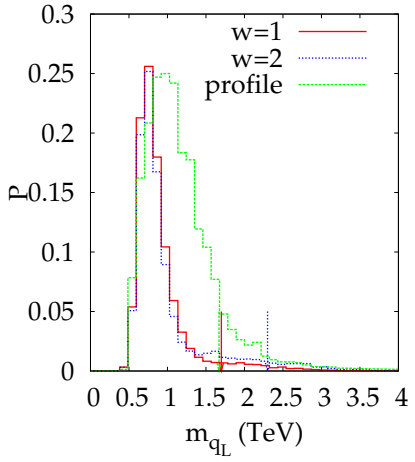
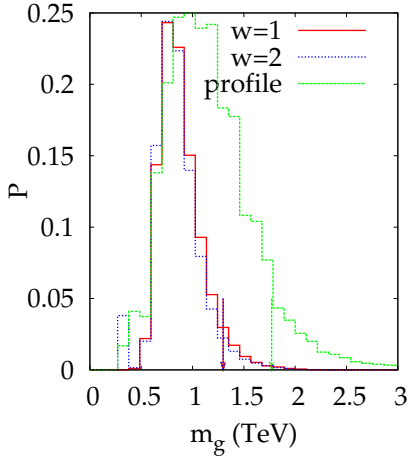
profile
P
m_h/GeV


w=1
w=2
profile
P
m_A (TeV)


w=1
w=2
profile
P
m_{q_L} (TeV)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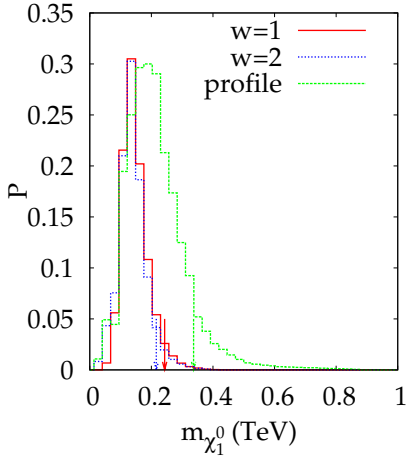
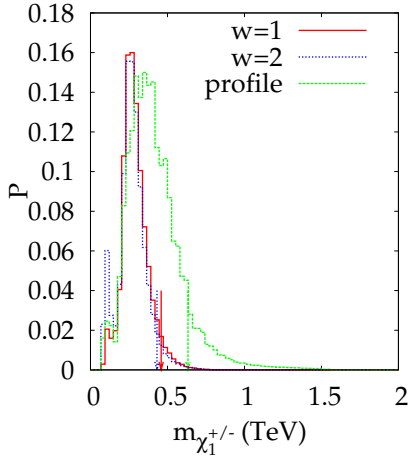
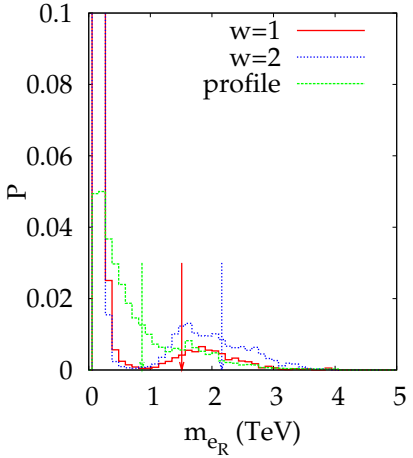
w=2
profile
P
m_g (TeV)


w=1
w=2
profile
P
$m_{\chi_1^0}$ (TeV)


w=1
w=2
profile
P
$m_{\chi_1^{+/-}}$ (TeV)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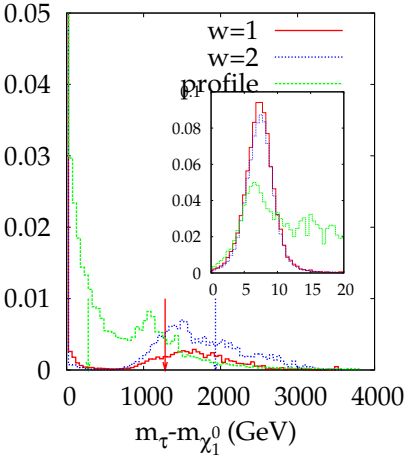
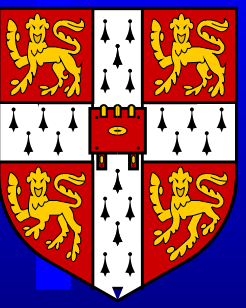
w=2
profile
P
m_{e_R} (TeV)


w=1
w=2
profile
P
m_τ-$m_{\chi_1^0}$ (GeV)



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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?)

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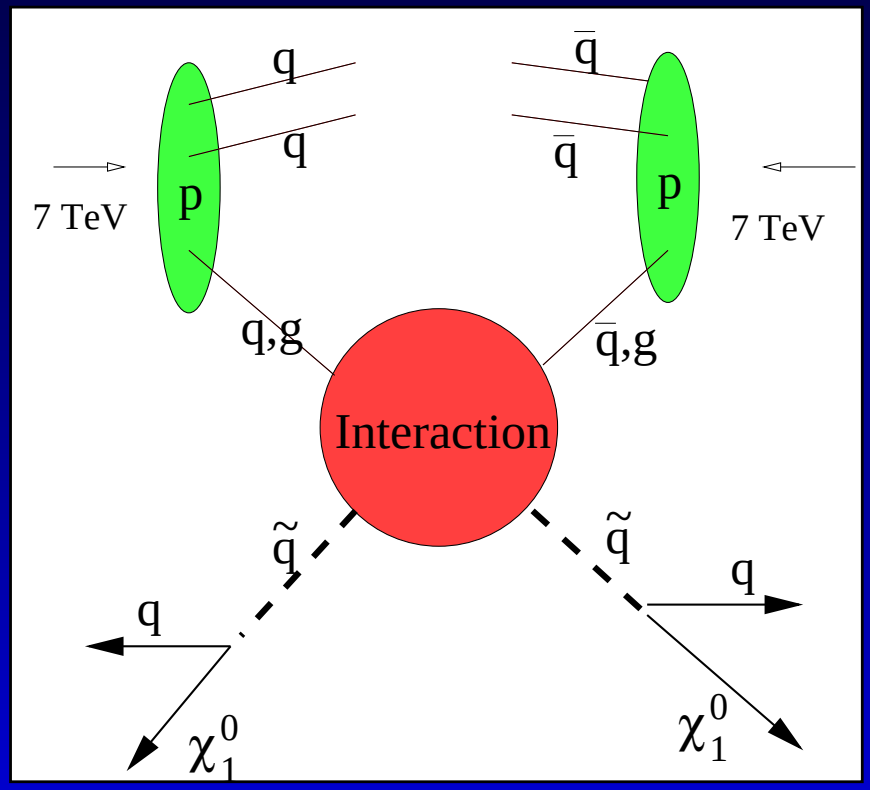
Collider SUSY Dark Matter Production

Strong sparticle production and decay to dark matter particles.



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

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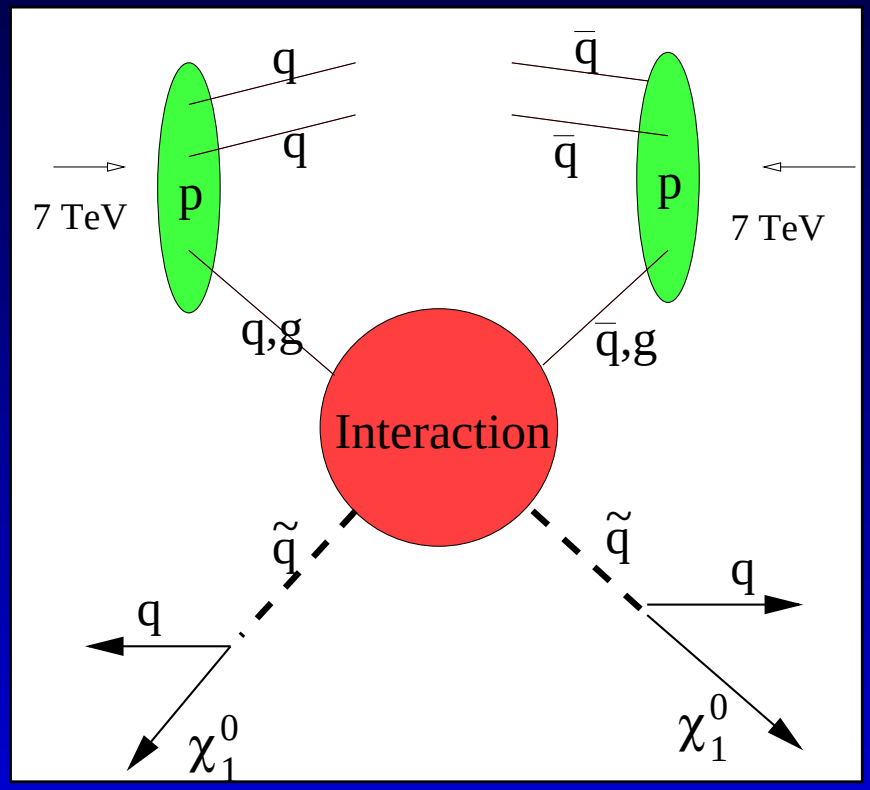
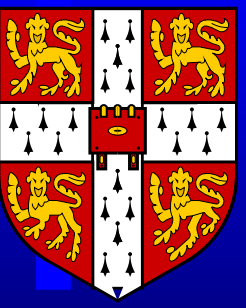


Any dark matter candidate that couples to hadrons can be produced at the LHC



Collider Check

Need corroboration with *direct detection*.

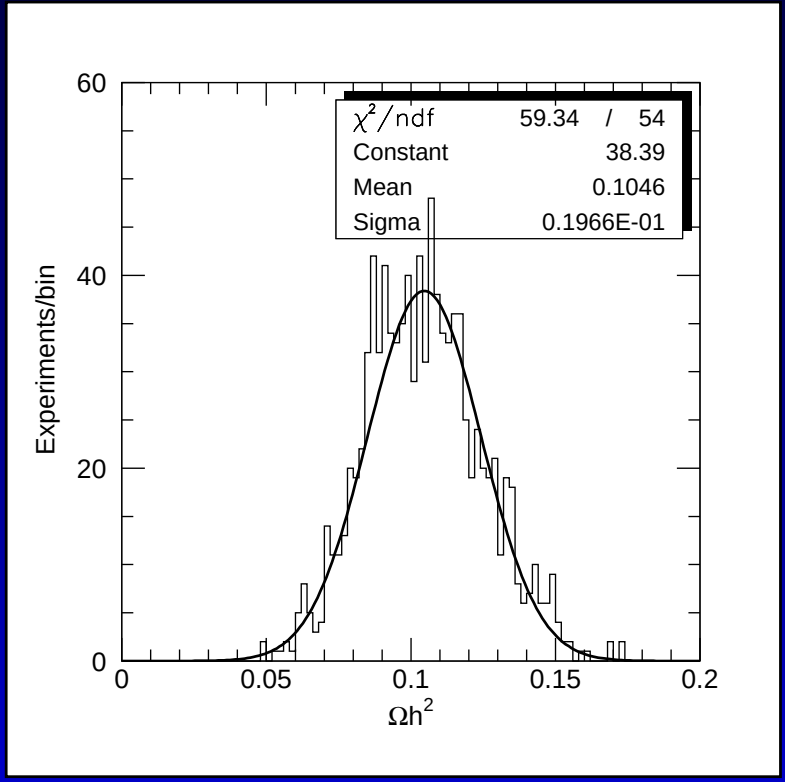
If we can pin particle physics down, a comparison between the predicted relic density and that observed is a test of the cosmological assumptions used in the prediction.

Thus, if it doesn't fit, you change the cosmology until it does.

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

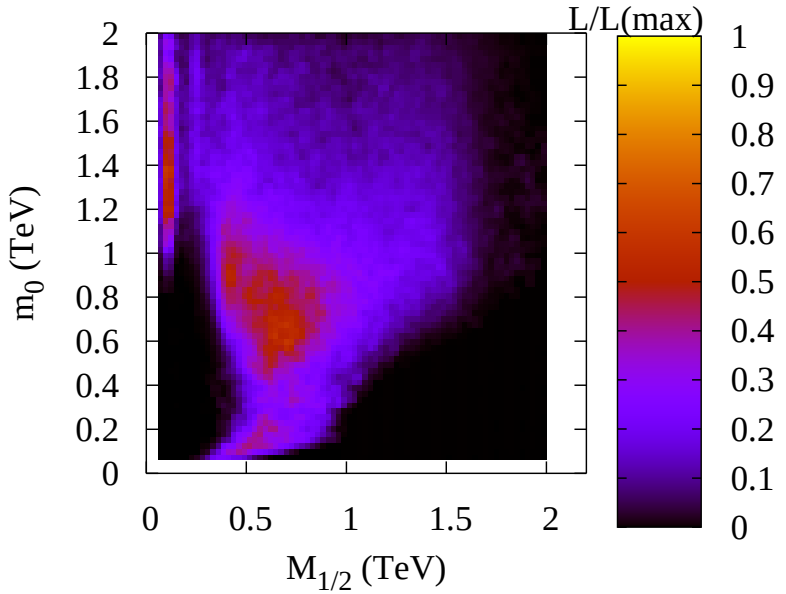
Predicting Ωh^2

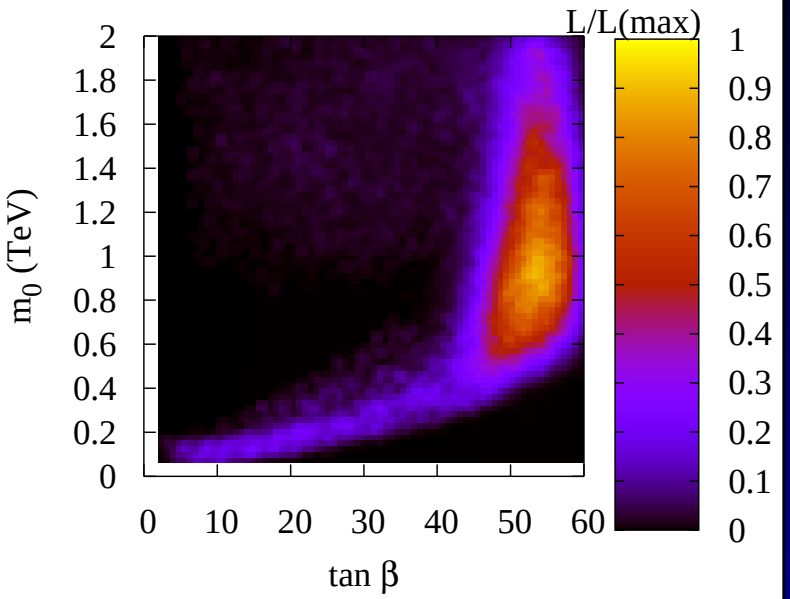
Not much left that's allowed but edge measurements allow reasonable Ωh^2 error for 300 fb^{-1}.

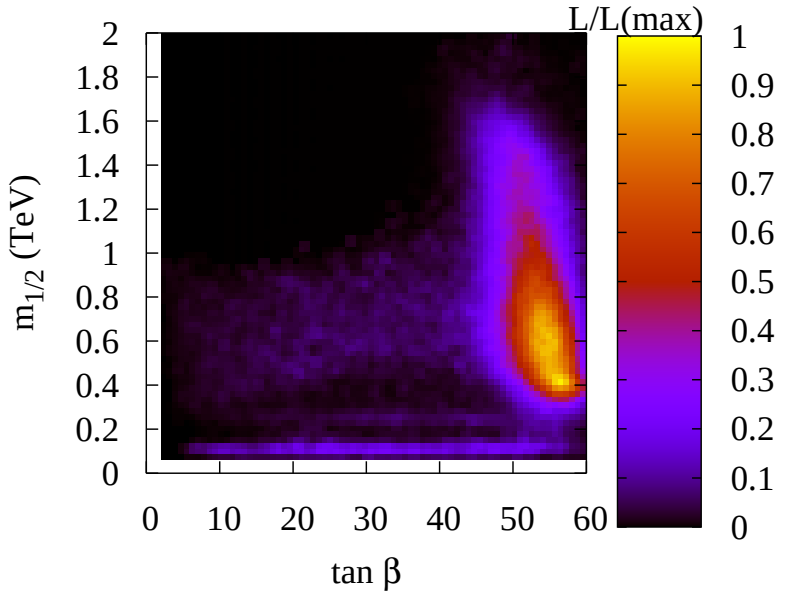


Q: What about other bits of parameter space?

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


L/L(max)
m0 (TeV)
M1/2 (TeV)
0
0.5
1
1.5
2
0.2
0.4
0.6
0.8
1.8
1.6
1.4
1.2
0.1
0.3
0.5
0.7
0.9


L/L(max)
m0 (TeV)
tan β
0
10
20
30
40
50
60
0.2
0.4
0.6
0.8
1.8
1.6
1.4
1.2
0.1
0.3
0.5
0.7
0.9


L/L(max)
m1/2 (TeV)
tan β
0
10
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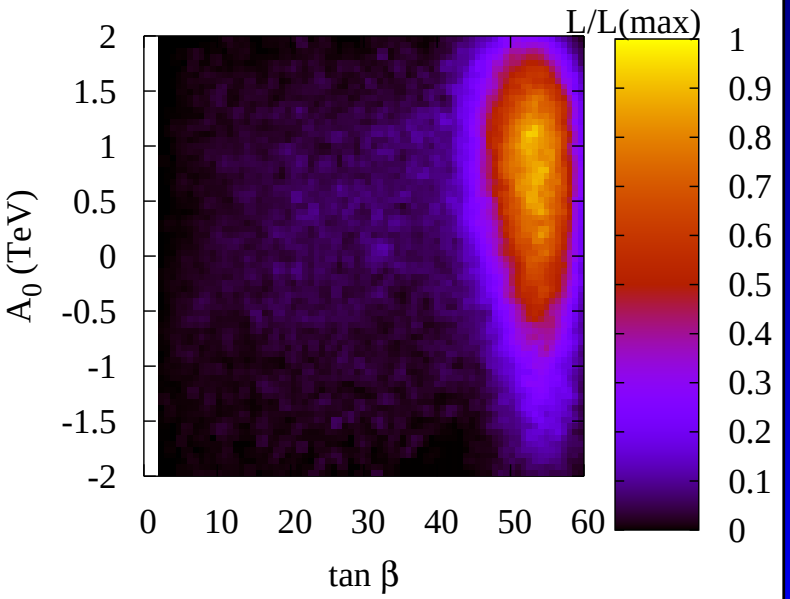
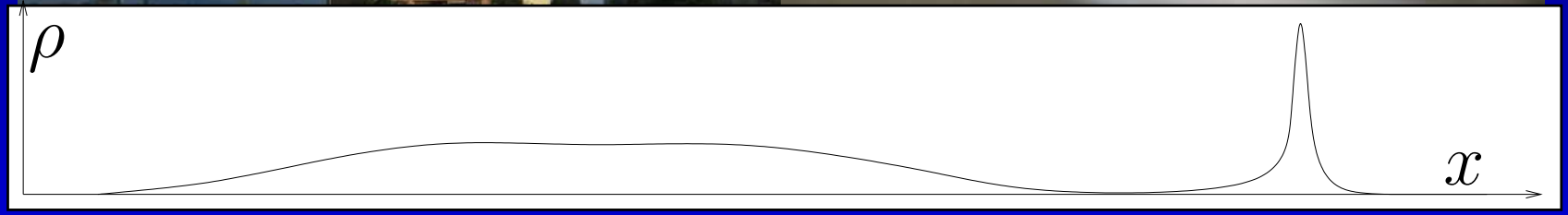
0.9

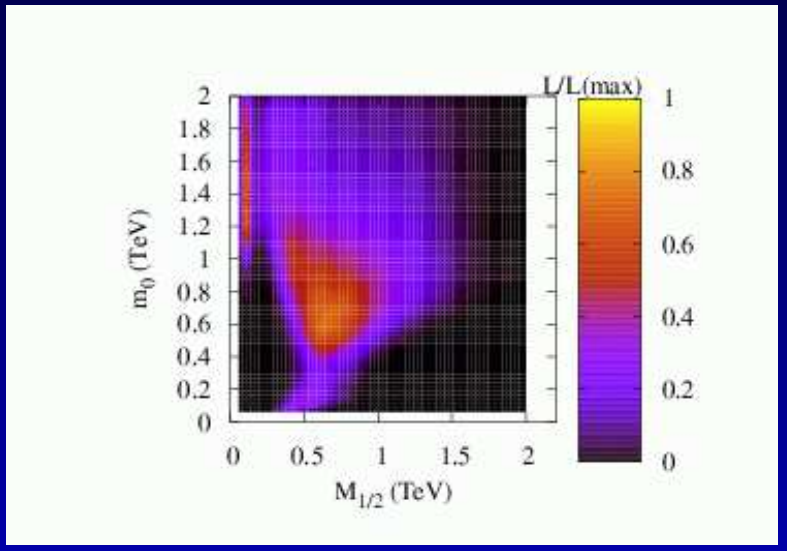

L/L(max)
A0 (TeV)
tan β
0
10
20
30
40
50
60
-0.5
-1
-1.5
0.5
1.5
0.1
0.3
0.5
0.7
0.9

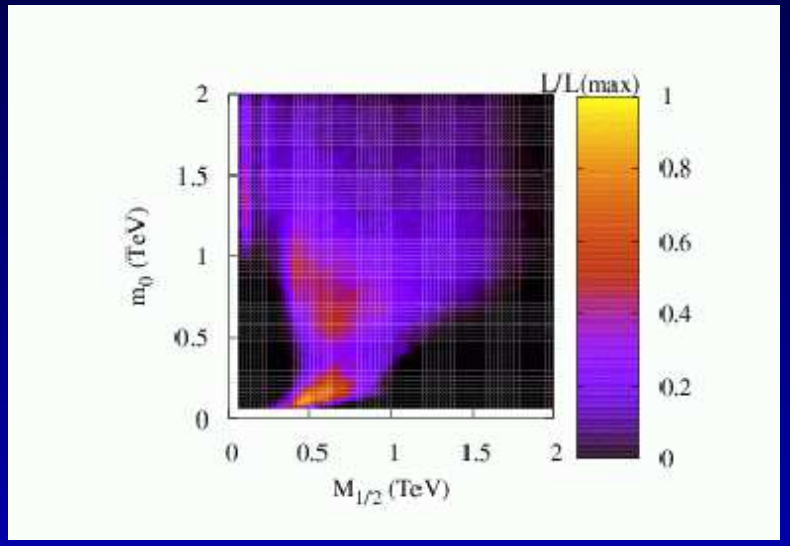
Volume Effects

Can't rely on a good χ^2 in non-Gaussian situation



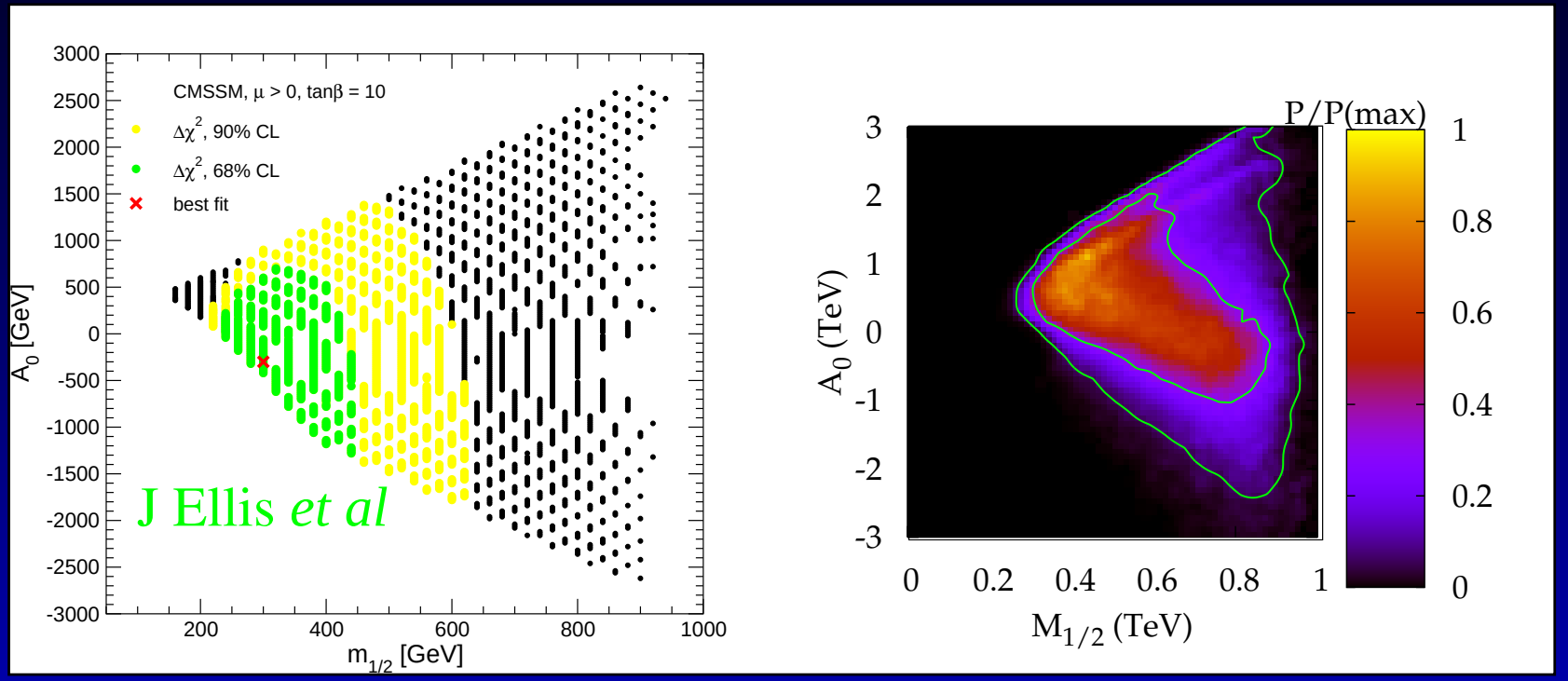
Comparison



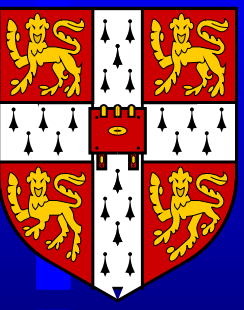


- LHS: allowing non thermal-χ_1^0 contribution
- RHS: only χ_1^0 dark matter
- *(flat priors)*

Comparison



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



Priors

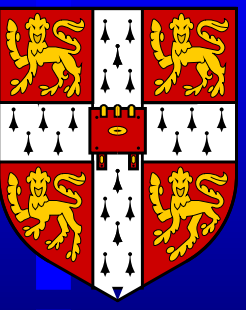
We have assumed a flat prior in $\tan\beta$, implies a measure:

$$p(m_0|\text{data}) = \int dM_{1/2}\, dA_0\, d\tan\beta\, ds\; p(m_0, M_{1/2}, A_0, \tan\beta, s|\text{data}).$$

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

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

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

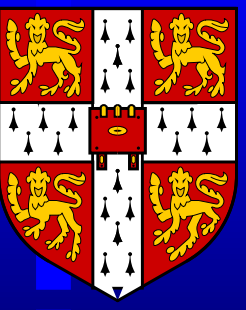


EWSB prior

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

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:

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