SOFTSUSY and Phenomenology

by

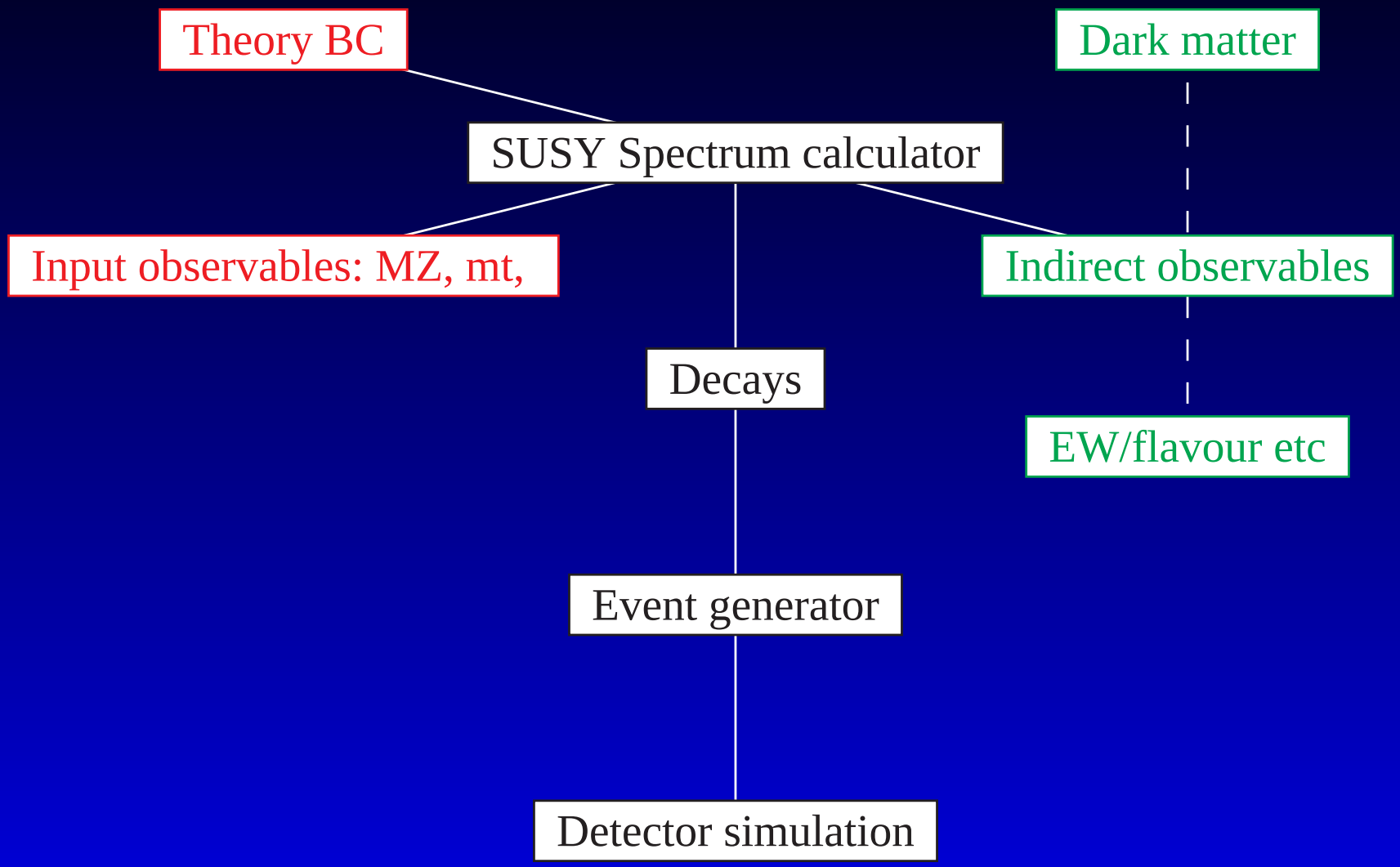
Ben Allanach (University of Cambridge)

Talk outline

- Context
- How SOFTSUSY works
- SOFTSUSY Update
- Comparison with other spectrum generators

Please ask questions while I'm talking

MSSM Tools



SLHA: Skands *et al*, `hep-ph/0311123`, SLHA2: BCA *et al*, `arXiv:0801.0045` (NMSSM, RPV, FV, CPV)

Spectrum and decays

- ISASUSY, SOFTSUSY, sPHENO, SUSPECT calculate the MSSM spectrum.
- 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, Herwig++, ISASUSY, sPHENO and SusyHIT do decays of Higgs and SUSY particles in MSSM.

SUSY Les Houches Accords

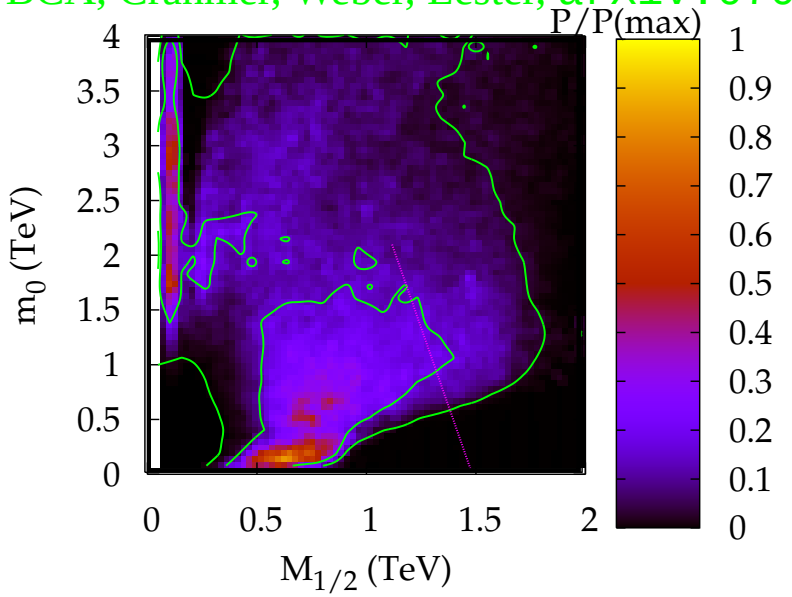
A set of physics conventions and an ASCII format to allow all of the codes exchange information about SUSY masses, mixings, decays and couplings.

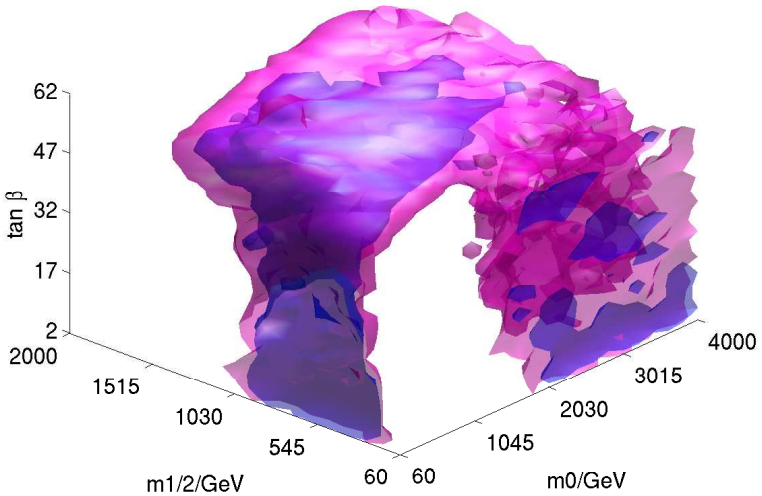
```
Block MODSEL  # Select model
     1    1   # sugra
Block SMINPUTS   # Standard Model inputs
     1    1.27934000000000e+02   # alpha_em^(-1)(MZ) SM MSbar
          [ ... ]
Block MINPAR  # SUSY breaking input parameters
     3    1.00000000000000e+01   # tanb
          [ ... ]
Block MASS   # Mass spectrum
# PDG code     mass                    particle
   1000021     6.09569684199012e8e+02   # ~g
          [ ... ]
#      PDG   Width
DECAY      2000013      2.78438e-05    # ~mu_R-
   0.9638490   2     1000022    13     # ~mu_R->~chi_10,mu-;
   0.0361508   2    -1000024    14     # ~mu_R->~chi_1-,nu_mu;
          [ ... ]
```

Killer Inference for Susy METeorology

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

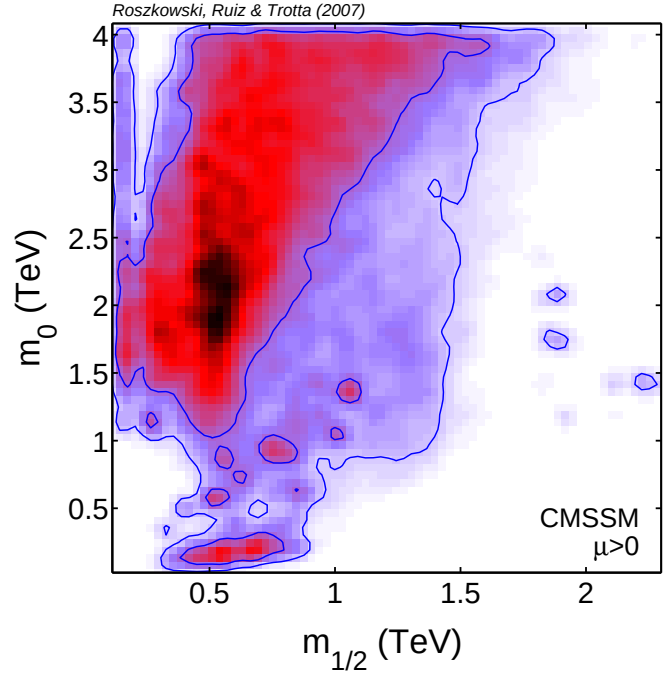
BCA, Cranmer, Weber, Lester, arXiv:0705.0487



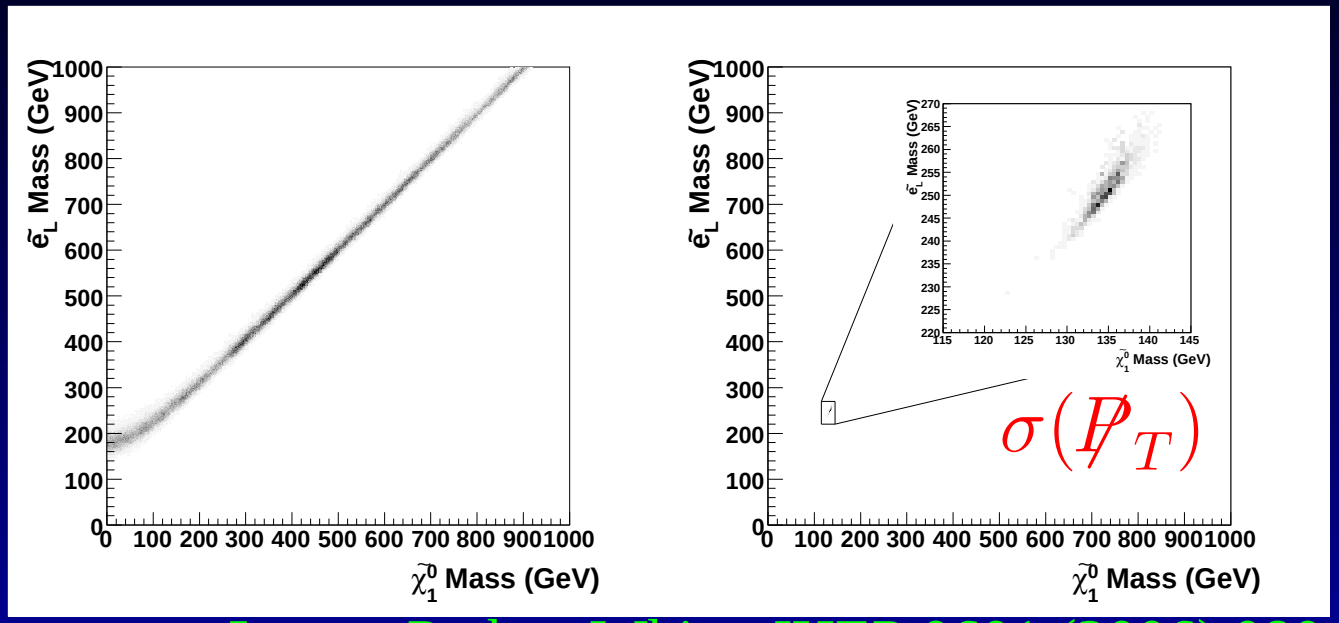


AbdusSalam *et al*, arXiv:0904.2548

Observable	Measurement	Fit(Log)
m_W [GeV]	80.399 ± 0.025	80.402
Γ_Z [GeV]	2.4952 ± 0.0025	2.4964
$\sin^2\theta^{eff}_{lep}$	0.2324 ± 0.0012	0.2314
$\delta(g\text{-}2)_\mu \times 10^{10}$	30.20 ± 9.02	26.74
R^0_l	20.767 ± 0.025	20.760
R_b	0.21629 ± 0.00066	0.21962
R_c	0.1721 ± 0.0030	0.1723
A_e	0.1513 ± 0.0021	0.1483
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.685
A^b_{FB}	0.0992 ± 0.0016	0.1040
A^c_{FB}	0.071 ± 0.035	0.074
$BR(B \to X_s\gamma) \times 10^4$	3.55 ± 0.42	3.42
$R_{BR(B_u \to \tau\nu)}$	1.11 ± 0.32	1.00
$R_{\Delta M_{B_s}}$	1.15 ± 0.40	1.00
Δ_{0-}	0.0375 ± 0.0289	0.0748
$\Omega_{CDM}h^2$	0.11 ± 0.02	0.13



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?

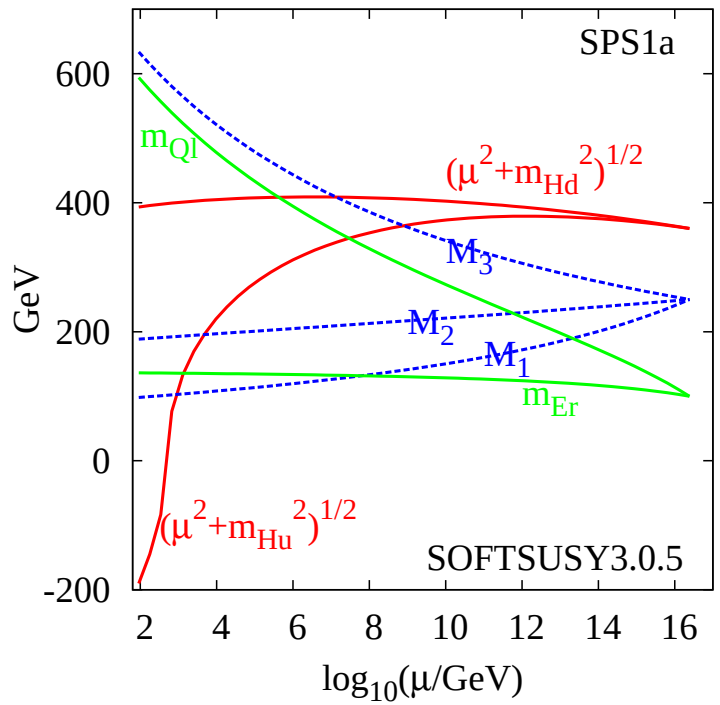
SOFTSUSY Program

- The updated SOFTSUSY manuals (one RPV, one RPC) can be found on the SOFTSUSY homepage
- Written in C++ with emphasis on generlisability and speed
- Fine-tuning calculation provided
- Stand-alone, no external packages required.
- Latest version is 3.1.5
- Full 3-family flavour dependence of Yukawa and soft terms but *real* parameters only
- R_p conserving and R_p *violating* couplings.
- Options for: user defined SUSY breaking boundary conditions, mSUGRA, mAMSB, mGMSB, non-universal mSUGRA

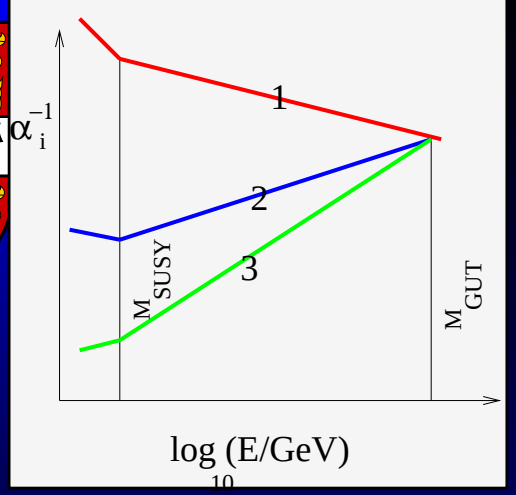
SOFTSUSY

SOFTSUSY is an MSSM spectrum generator. Like 3 other public spectrum generators, it predicts MSSM masses and couplings consistent with weak-scale data and an assumed high-scale boundary condition on SUSY breaking.

BCA, hep-ph/0104145



SOFTSUSY



Get $g_i(M_Z)$, $h_{t,b,\tau}(M_Z)$.

↓

Run to M_S.

↓

REWSB, iterative solution of μ

↓

M_X. Soft SUSY breaking BC.

↓

Run to M_S. Calculate[a] sparticle pole masses.

↓

Run to M_Z

[a] BCA, Comp. Phys. Comm. 143 (2002) 305.

The Problem

$M_{GUT} \sim 10^{16}$ GeV

Theory boundary condition on SUSY breaking parameters

Renormalisation group equations

$M_{SUSY} \sim \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

Match electroweak symmetry breaking, calculate sparticle masses

$M_Z = 91$ GeV

Match to Standard Model data on gauge/Yukawa couplings

Theory Boundary Condition

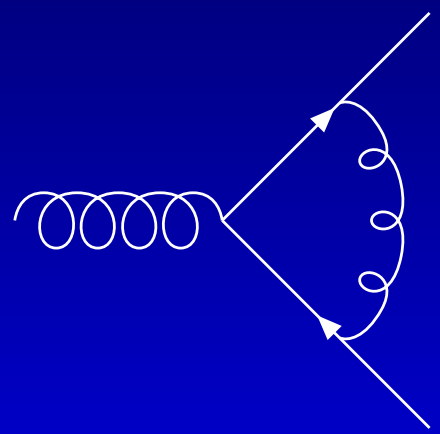
This is a condition on the SUSY breaking parameters eg:

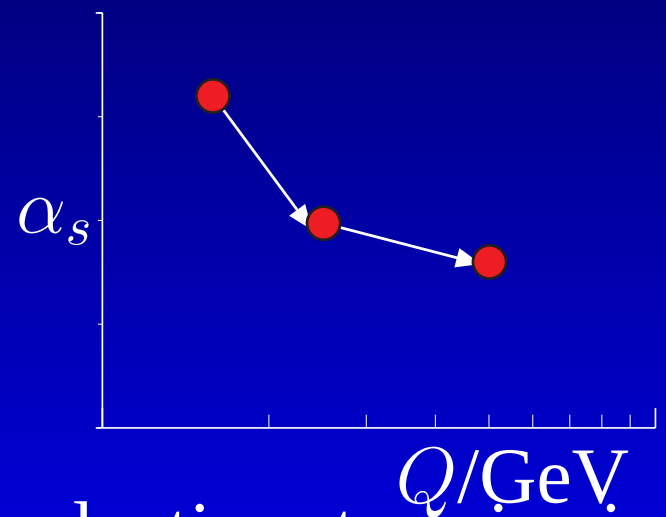
- *mSUGRA*: common scalar mass m_0, common gaugino mass $M_{1/2}$, common trilinear scalar coupling A_0 at electroweak gauge unification scale
- *mAMSB*: common scalar mass m_0, gravitino mass $M_{3/2}$
- *mGMSB*: Number of messengers n_5, mass of messengers M_{Mess}, SUSY scale Λ: sets scale of SUSY breaking
- *pMSSM*: *Weak scale* SUSY breaking terms: most general MSSM

Renormalisation Group Equations

Tell us how to calculate masses etc at *another energy scale* Q via differential equations, eg:

$$\frac{d\alpha_s(Q)}{d\ln Q} = -\frac{3}{16\pi^2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$





5th order Runge-Kutta with adaptive step-size is used in practice as it's *fast*

Electroweak Symmetry Breaking

We have H_1^0, H_2^0 in the Standard Model, and we must make sure that their VEVs give M_Z correctly:

$$< H_1^0 >^2 + < H_2^0 >^2 = 4\frac{M_Z^2}{g'^2 + g_2^2}$$

We also input the ratio of VEVs

$$\tan\beta = < H_2^0 > / < H_1^0 >,$$

and this fixes the other one. The Higgs potential must have a minimum corresponding to these VEVs, and this fixes 2 Higgs potential parameters (μ, m_3).

Higgs Potential Minimisation

Done at $M_S \sim \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ as it tends to minimise scale dependence, so higher loops hopefully smaller there. User may change this, though.

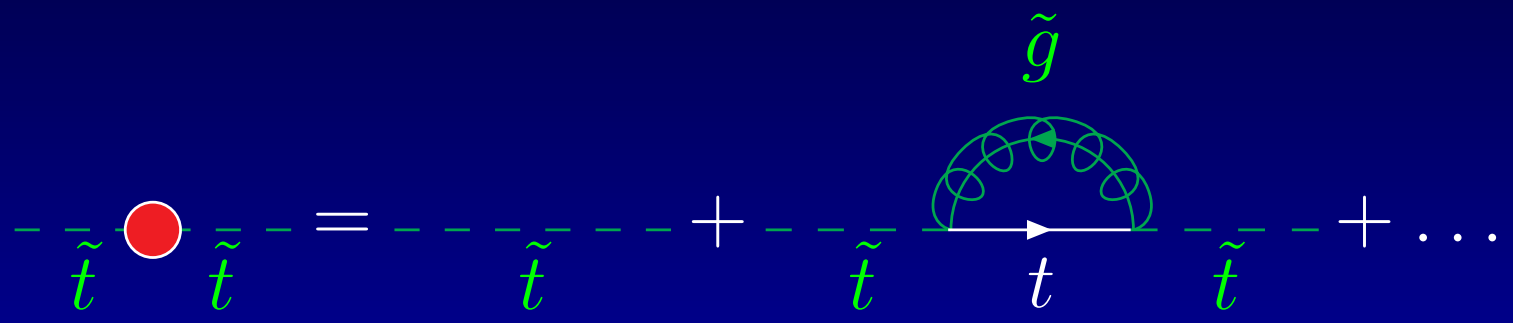
$$\mu^2 = \frac{1}{2}\left(\tan 2\beta \left[m^2_{\bar{H}_2} \tan\beta - m^2_{\bar{H}_1} \cot\beta\right] - M^2_{\bar{Z}}\right),$$

$$m_3^2 = \frac{s_{2\beta}}{2}\left(m^2_{\bar{H}_1} + m^2_{\bar{H}_2} + 2\mu^2\right).$$

Corrected by loop tadpoles, which depend in turn on μ. Use iteration to determine it, then calculate m_3^2.

Calculating Sparticle Pole Masses

We must add radiative corrections[a] to the Born-level masses that we have in the Lagrangian to get pole sparticle masses:

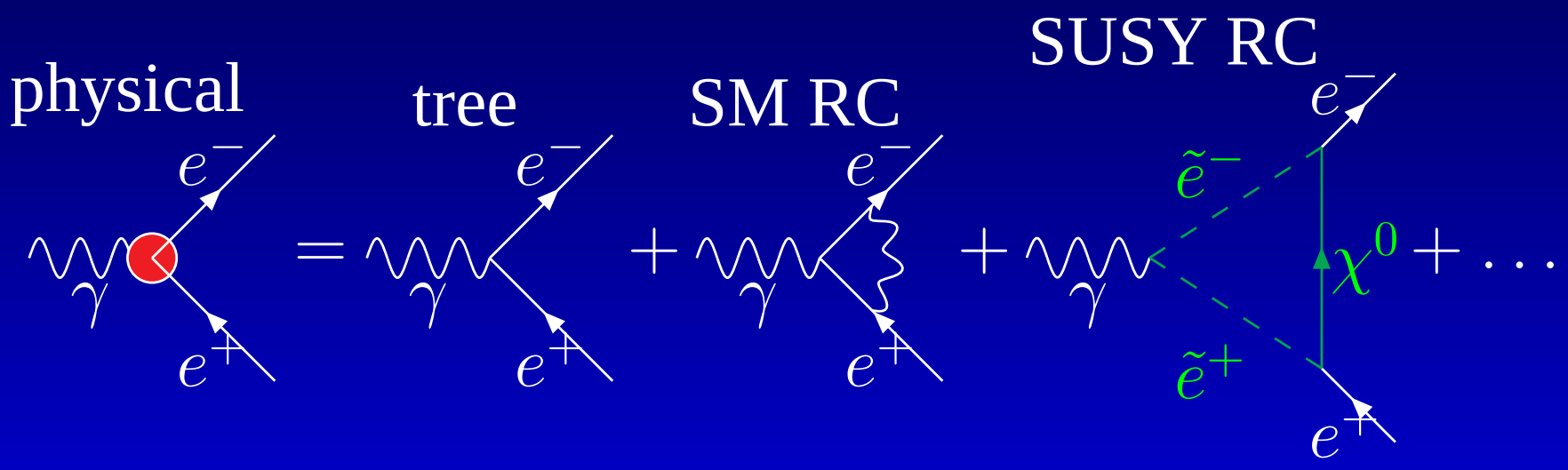


This is a complicated part of the calculation, since all (s)particles can be in the loops. The two stops mix, and you have to calculate the mass eigenstates.

[a] Bagger, Matchev, Pierce and Zhang, NPB491 (1997) 3

Standard Model Data

We match the model to SM gauge couplings (G_μ, α_{em}, M_Z), Yukawa couplings. But the values obtained in SM are got without sparticles, so we must subtract their radiative corrections



All of these radiative corrections depend on sparticle masses and couplings.

Thresholds

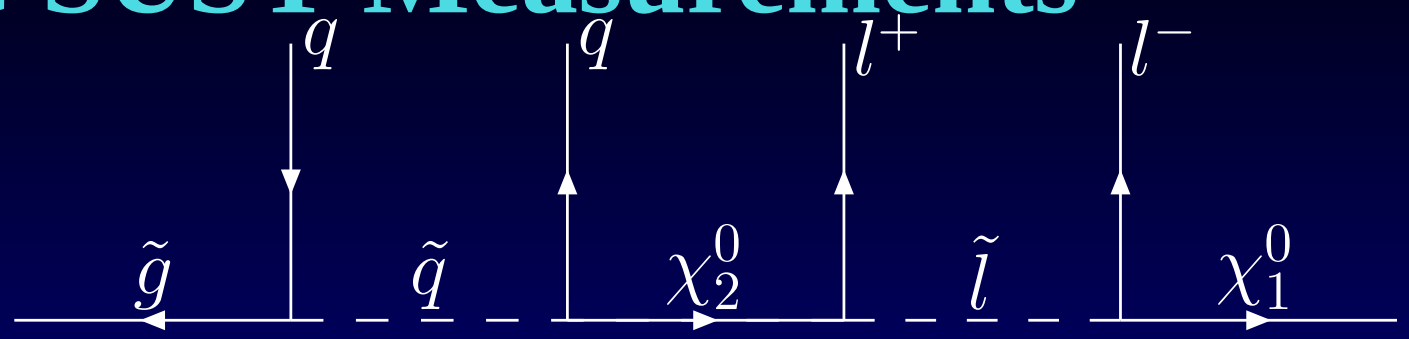
Loops involving sparticles renormalise masses/couplings at 1-loop level have two pieces: logarithmic (ISAJET) and finite. SOFTSUSY includes both (in leading-log approximation)

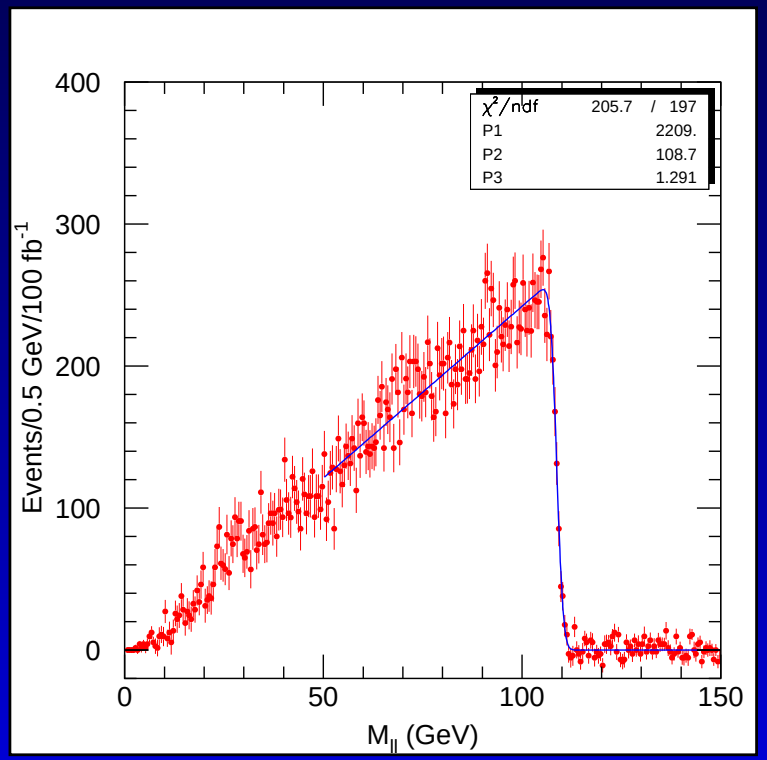
- All one-loop (important) MSSM corrections included.
- Additionally, added 2-loop QCD corrrections to m_t and m_b
- All full one-loop flavour diagonal corrections are included

Level of Approximation

- MSSM $Renormalisation Group Equations$: Full 2-loop, below M_Z we have 3-loop QCD$\otimes$1-loop QED
- Thresholds: 1-loop for most things, some 2-loop terms for Higgs': zero-momentum limit of h_t^4, $h_t^2 g_3^2$, $h_b^2 g_3^2$, h_b^4, $h_b^2 h_t^2$, h_τ^4, $h_\tau^2 h_b^2$ corrections.
- Higgs potential: 1-loop plus same 2-loop terms as Higgs',
- Gauge couplings: 1-loop MSSM corrections and leading (top) 2-loop corrections

LHC SUSY Measurements





$$m_{ll}^2(max) = \frac{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}$$

$\mathcal{Q}$: Can we measure enough of these to pin SUSY[a] down?

[a] BCA, Lester, Parker, Webber, JHEP 0009 (2000) 004

Other Observables

Often more complicated, eg m_{llq} edge:

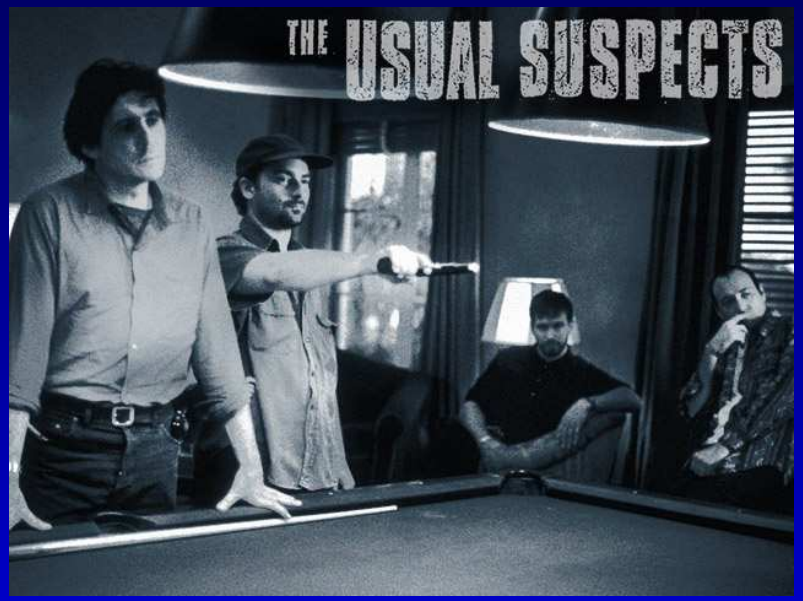
$$\max\left[\frac{(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)(m_{\chi_2^0}^2 - m_{\chi_1^0}^2)}{m_{\chi_2^0}^2}, \frac{(m_{\tilde{q}}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}, \frac{(m_{\tilde{q}} m_{\tilde{l}} - m_{\chi_2^0} m_{\chi_1^0})(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)}{m_{\chi_2^0} m_{\tilde{l}}}\right]$$

Also m_{lq}^{high}, m_{lq}^{low}, llq *threshold* [a], $M_{T_2}^2(m) =$

$$\min_{\not{p}_1+\not{p}_2=\not{p}_T}\left[\max\left\{m_T^2(p_T^{l_1}, \not{p}_1, m), m_T^2(p_T^{l_2}, \not{p}_2, m)\right\}\right],$$

$\max[M_{T_2}(m_{\chi_1^0})] = m_{\tilde{l}}]$ for dislepton production.

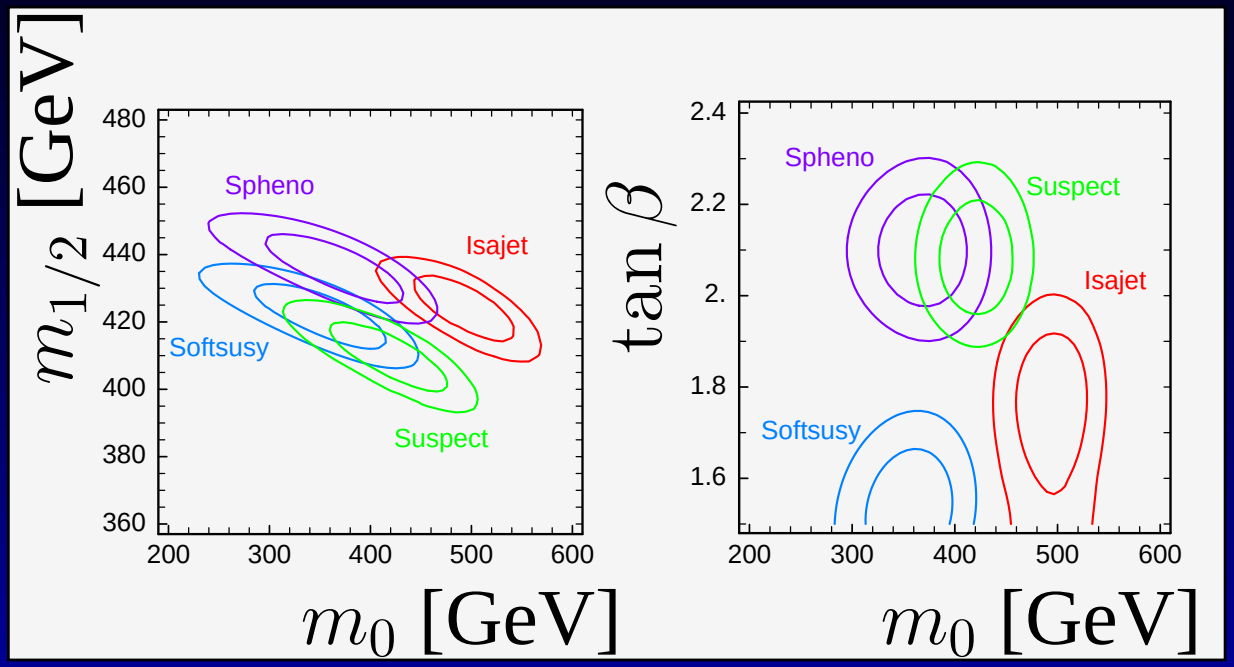
The Codes



- IsaSugra: `f77` H Baer, F E Paige, S D Protopescu and X Tata, hep-ph/001086
- SoftSusy: `C++` BCA, CPC 143 (2002) 305
- SusPect: `f77` A Djouadi, J L Kneur and G Moultaka, hep-ph/0211331
- SPheno: `f90` W Porod, CPC 153 (2003) 275

IsaSugra re-sums logs in sparticle mass splittings by having step functions in RGEs. The others all include finite terms $\sim 1/(16\pi^2)(m_{\tilde{p}_1}/m_{\tilde{p}_2})$.

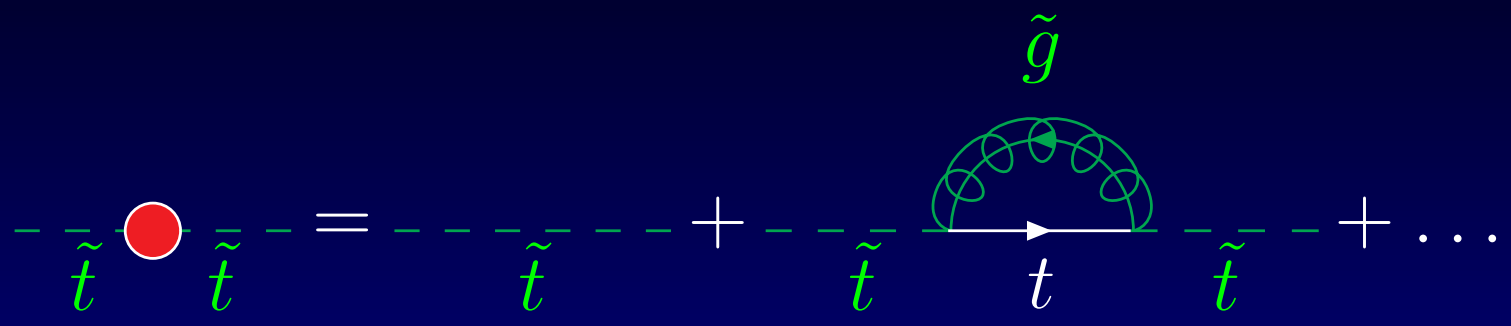
Fitting to SUSY Breaking Model



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

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

Reasons For Spectrum Differences



$\mathcal{Q}$: Which couplings/masses to use in L?

$$m_{\tilde{t}}^{pole} = m_{\tilde{t}}^{tree}(Q) + \alpha_s L(m_{\tilde{t}}^{pole}, m_{\tilde{g}}, m_t, Q),$$

$\mathcal{A}$: The pole mass? The tree mass? $\alpha_s(Q)$? $\alpha_s(m_{\tilde{t}})$? The difference is of higher order. The codes make different choices, corresponding to differences at higher orders.

Higgs

Higgs are important because of:

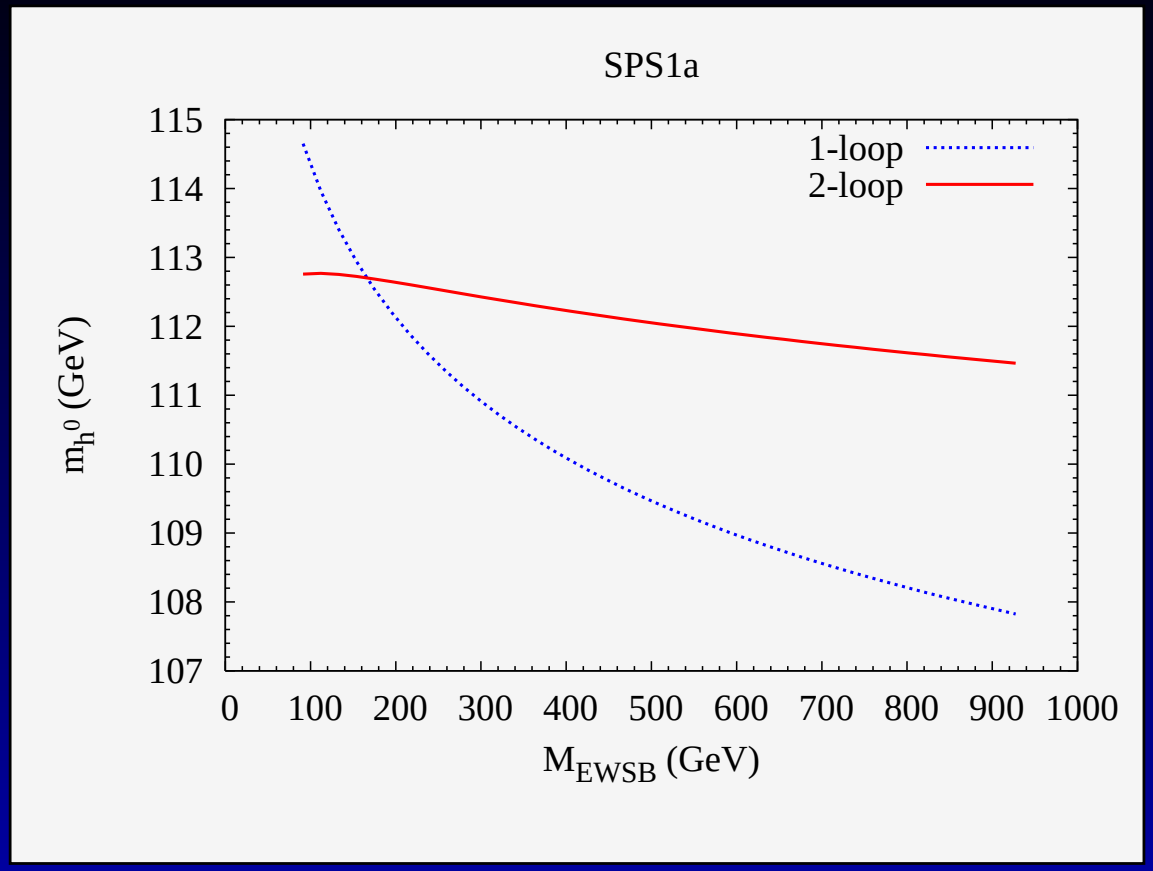
- LEP2 constraints: $m_h > 114.4$ GeV
- Discriminating variable between eg mGMSB, mAMSB, mSUGRA
- It's a handle on $\tan\beta = v_u/v_d$.

Fortunately[a], $\overline{DR}$ computation is under control, eg SPS1a[b] $m_0 = 100, m_{1/2} = 250, A_0 = -100, \tan\beta = 10, \mu > 0$

mass	SoftSusy	SPheno	SuSpect
m_h	112.1	112.2	112.1
m_A	406.2	405.7	405.6

[a] BCA, A Djouadi, J-L Kneur, W Porod, P Slavich, *to appear*

[b] BCA *et al*, EPJ C25 (2002) 113



The picture is actually not so rosy! Compare m_h:

	SPS1a	SPS2	SPS4	SPS8
SuSpect$^{\overline{DR}}$	112.1	116.8	114.1	115.4
FeynHiggs^{OS}[a]	113.8	118.3	116.1	117.3

[a] Heinemeyer, Hollik, Weiglein, CPC 124 (2000) 76

Higgs Meteorology

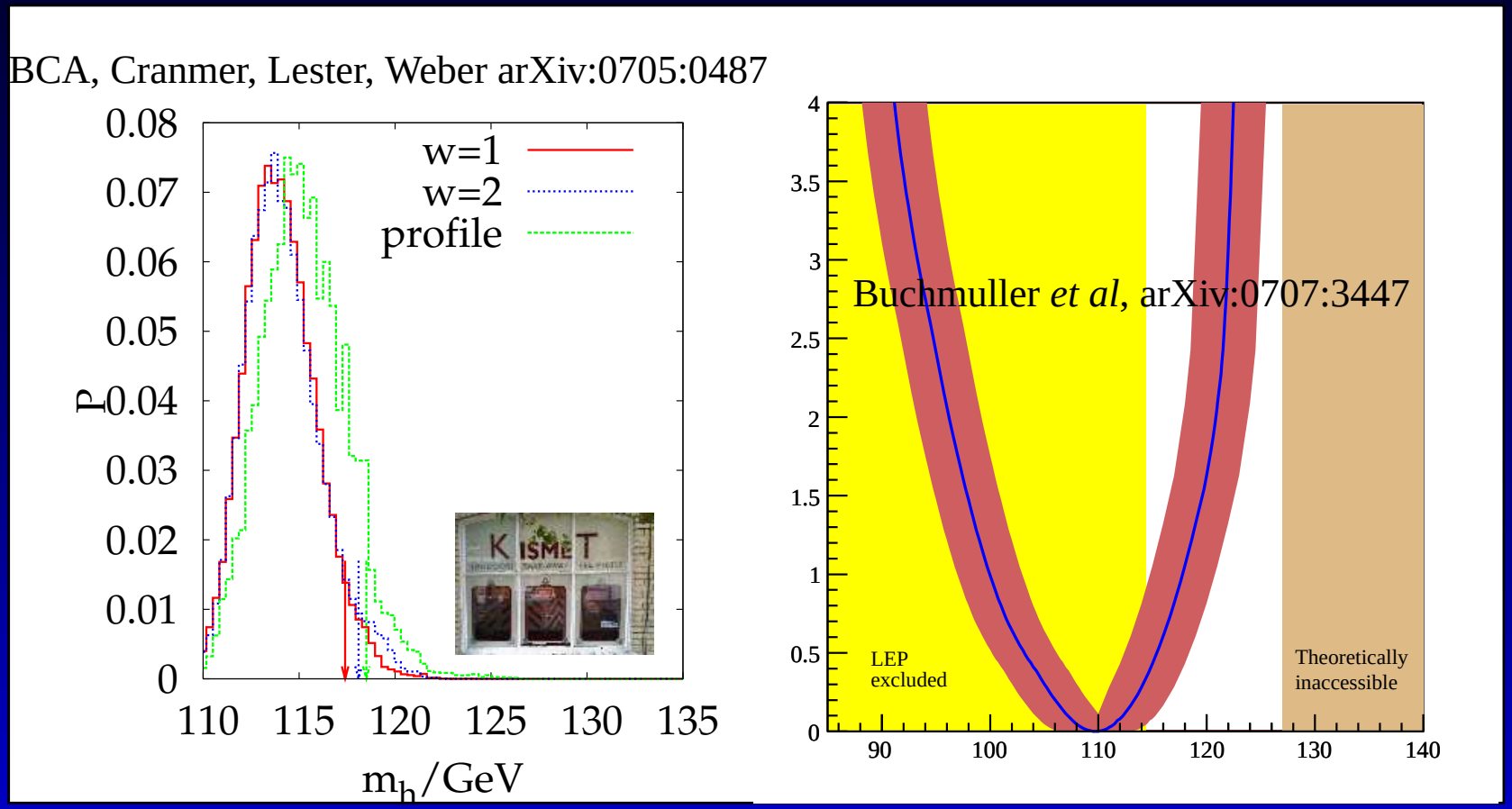


Figure 1: Including (LHS) or *not* including (RHS) the LEP2 direct Higgs mass constraints on the CMSSM.

Web Page

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

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

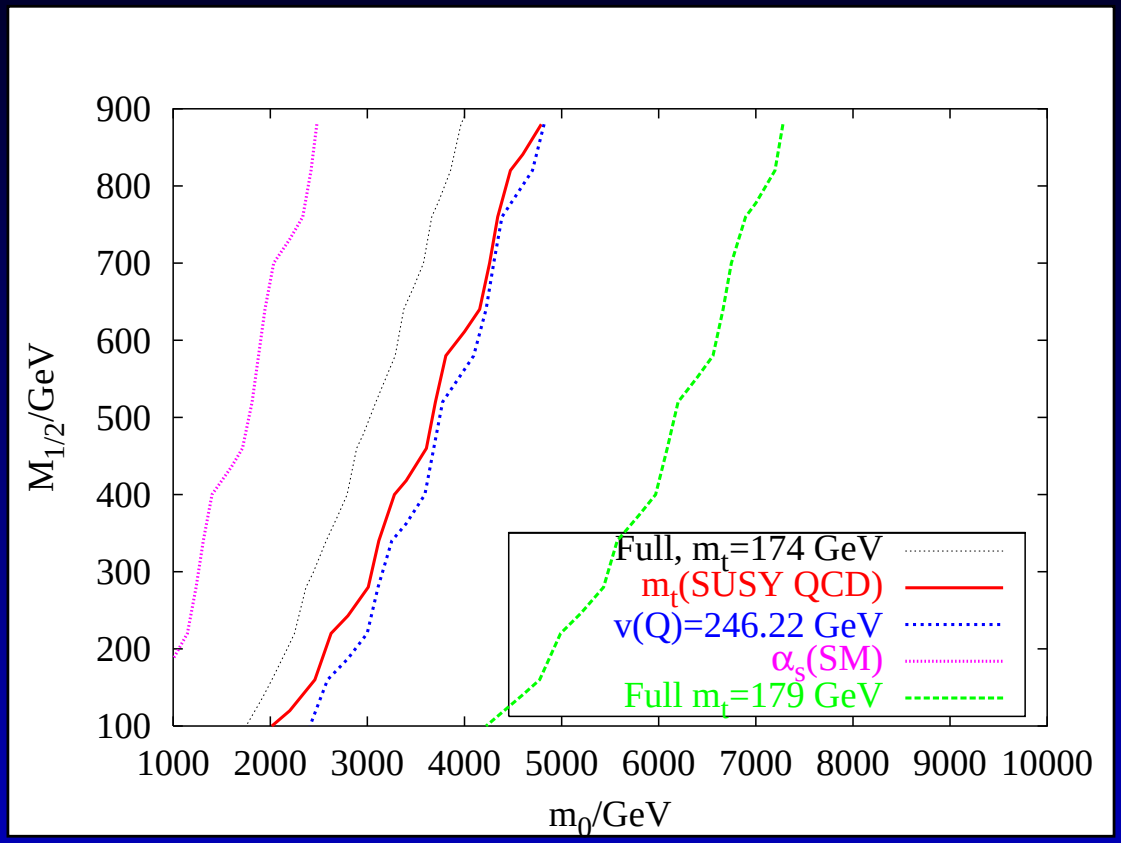
submit reset

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.

BCA, S Kraml in hep-ph/0402295

Focus Point



BCA, Hetherington, Parker, Webber, `arXiv:hep-ph/0005186`

$$\frac{1}{2}M_Z^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \qquad (1)$$

High $\tan\beta$

BCA, Belanger, Boudjema, Pukhov, Porod, hep-ph/0402161. Baer *et al*

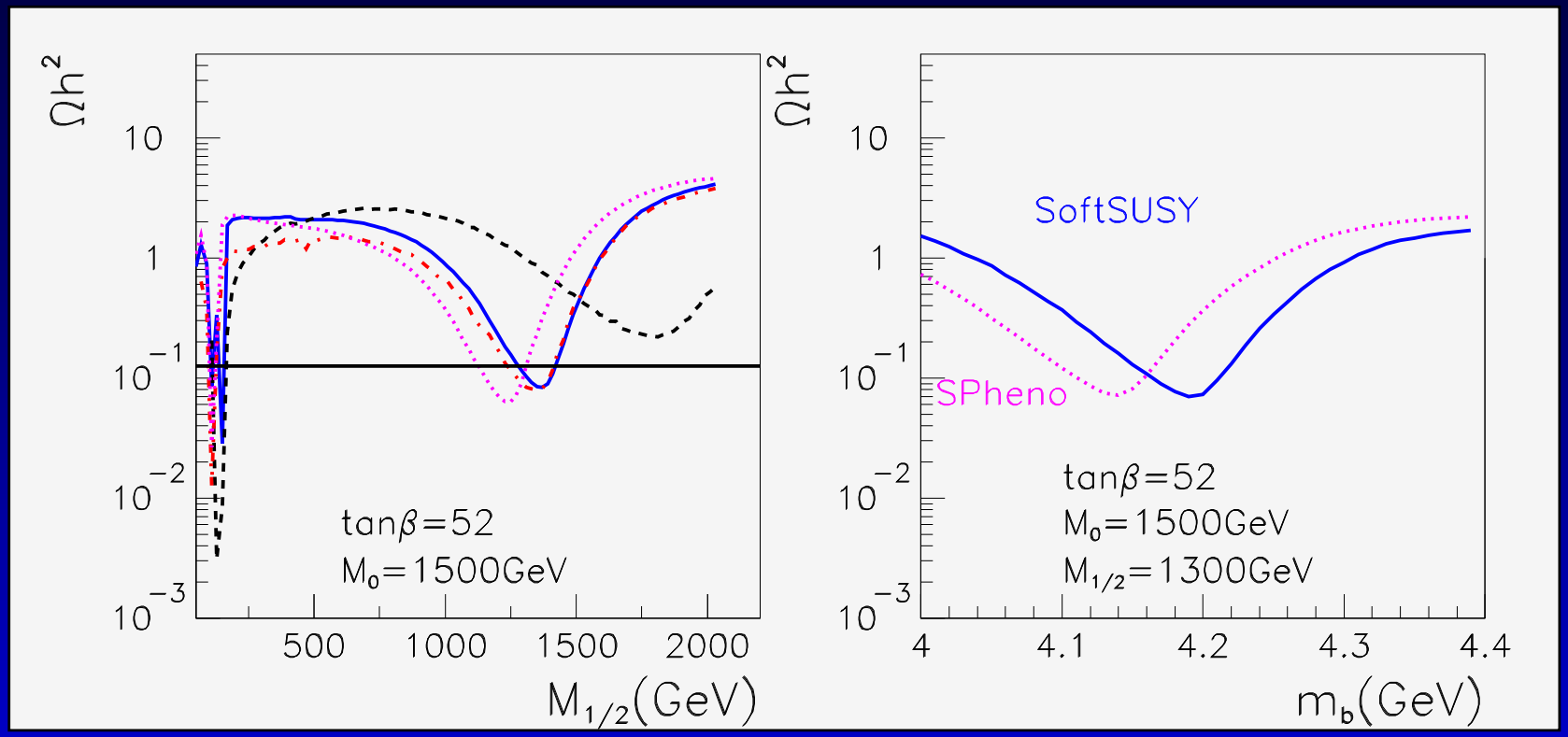


Figure 2: High $\tan\beta$ region. Full: `SoftSusy`, dotted: `SPheno`, dashed: `SuSpect`. Get annihilation into A.

Uncertainties in Relic Density

Bulk region: $\tilde{B}\tilde{B} \to Z, h \to l\bar{l}$. Coannihilation: $\tilde{\tau}\chi_1^0 \to \tau + X$

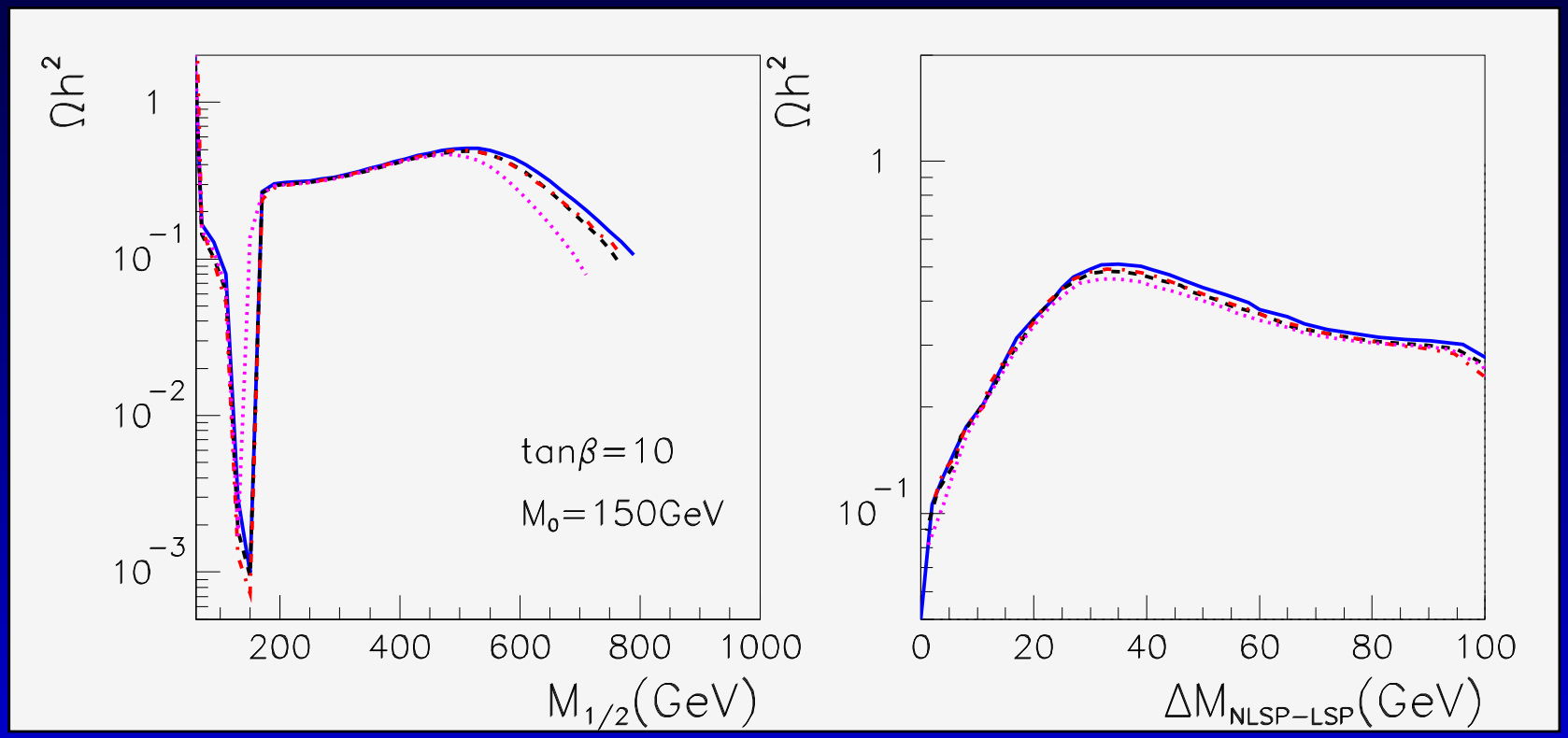


Figure 3: Bulk/coannihilation region. Full: `SoftSusy`, dotted: `SPheno`.

Focus Point

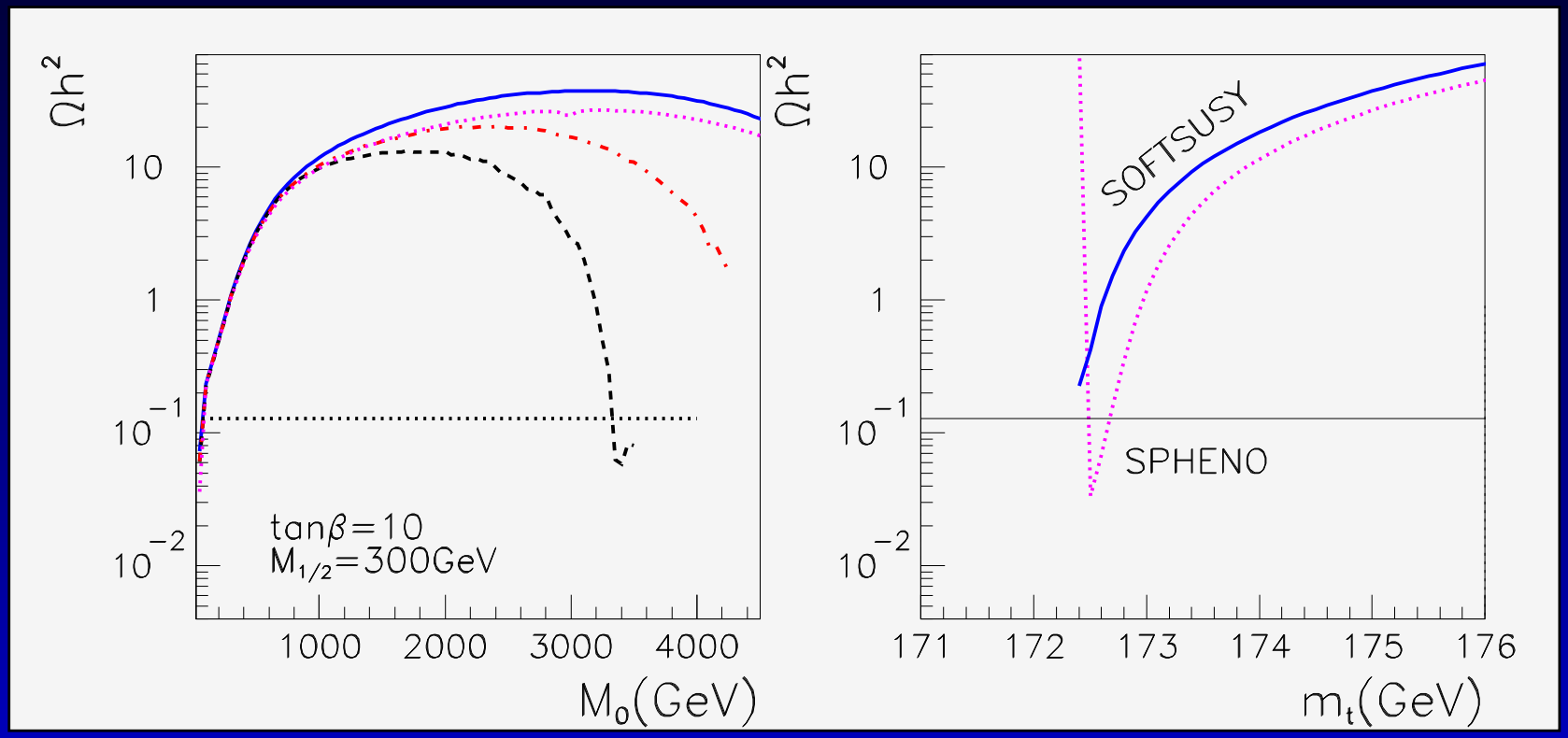


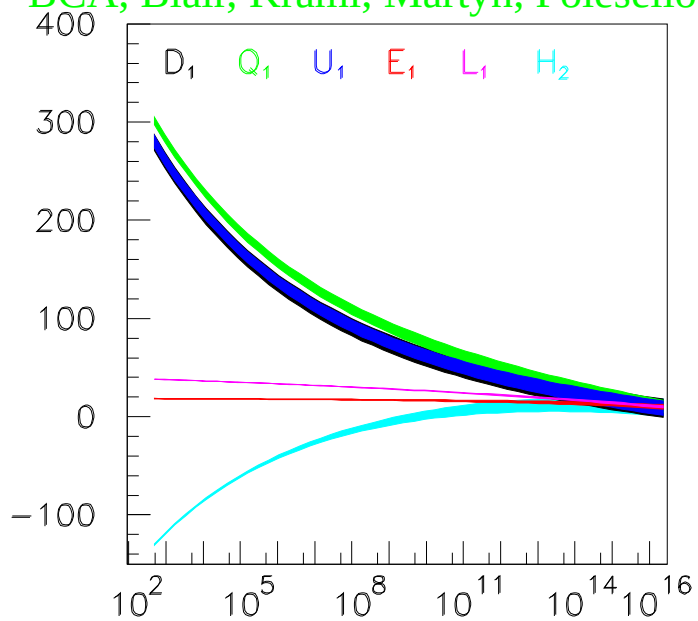
Figure 4: Focus point region. Full: `SoftSusy`, dotted: `SPheno`, dashed: `SuSpect`. Higgsino LSP annihilates into ZZ/WW

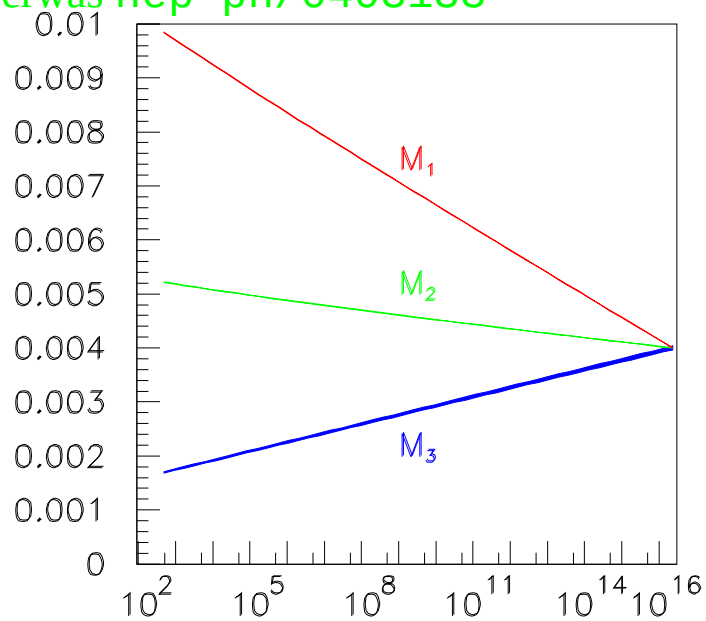
Summary

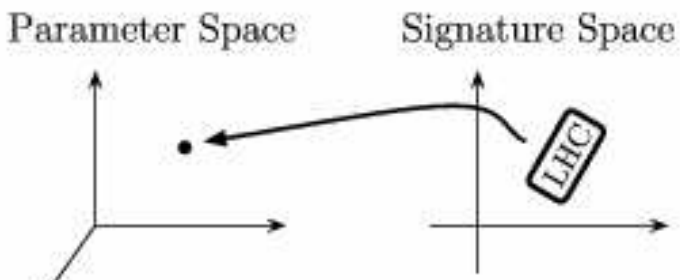
The Inverse Problem

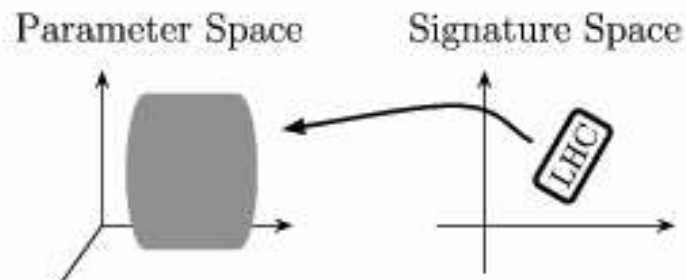
Want to do this with LHC+ILC data:

BCA, Blair, Kraml, Martyn, Polesello, Porod, Zerwas hep-ph/0403133







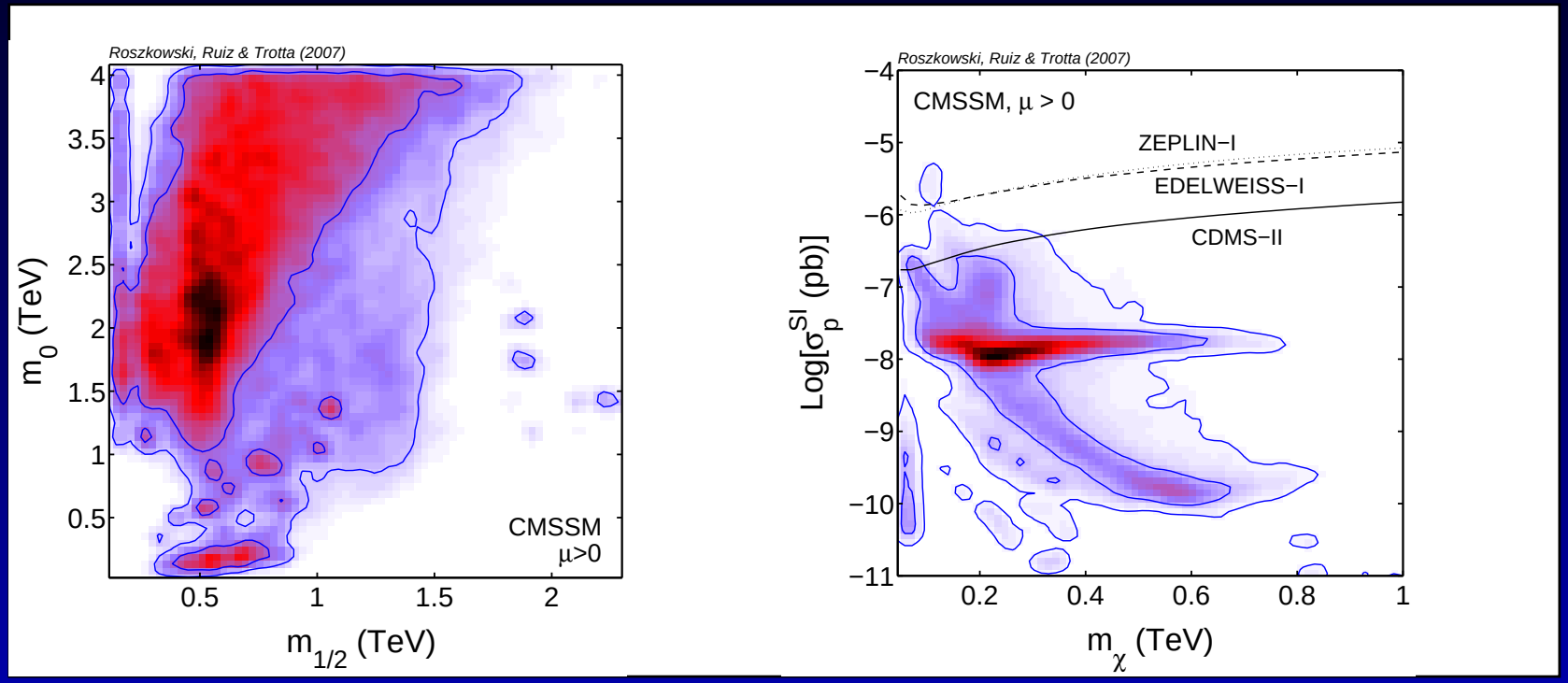


Arkani-Hamed, Kane, Thaler, Wang, hep-ph/05120190

Summary II

- 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*.
- Current theoretical errors in spectrum calculation are present but not *too bad*, but more loops are being calculated.

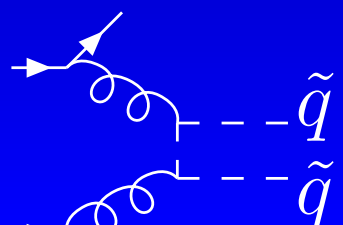
Other literature



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

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++