SUSY CALCULATIONAL TOOLS

Abdelhak DJOUADI (LPMT Montpellier)

1. Introduction
2. General codes for spectrum calculation
   - ISASUSY
   - SUSPECT
   - SOFTSUSY
   - SPHENO
3. Codes for NLO spectrum, production, decay and cosmology
   - NLO Higgs and sparticle mass calculations
   - NLO Higgs and SUSY particle production and decay
   - Codes for analytical calculations
   - Dark Matter calculations
4. Monte–Carlo event generators
5. Summary.

Introduction/Motivations

Unconstrained MSSM: minimal gauge group, minimal particle content, R_p conservation and minimal set of soft SUSY-breaking parameters:

$\gtrsim$ 100 free parameters.

Non viable phenomenology $\rightarrow$ constraints from theory and experiment: no intergeneration mixing, no new source of C$\not{P}$, 1st/2d gen. universality.

still $\gtrsim$ 22 free parameters !!

This large number of parameters enters in:

– The evaluation of the masses of $\geq$ 33 SUSY/Higgs particles.
– The complicated couplings (mixing, diagonalis., Majorana, RC..)
– The many possible decay modes (including higher order).
– The various production channels in $pp, ep, e^+e^-, e\gamma, \gamma\gamma$ and $\mu^+\mu^-$.

Very difficult to make detailed study of spectra and to compare with expectation and/or outcome in experimental searches and/or simulations: unification boundary conditions at the high–energy scale (ex: $\Lambda_{\rm GUT}$):

Only a few $\mathcal{O}(5)$ parameters $\Rightarrow$ constrained/predictive models.

However, even in this case the situation is still rather complicated:

– Many possibilities: mSUGRA, AMSB, GMSB, strings, $\tilde{\nu}_R$, extra dim...
– RGE (coupled) evolution from the high to low energy scales.
– Proper and complicated breaking of electroweak symmetry (EWSB).
– Still calculate mass, coupling, decay, production of 33 particles.

A very tricky situation indeed.... This needs:

– Very sophisticated programs to encode all the information.
– Pass to MC event generators to link with experiment.

General Codes for Spectrum Calculation

- Purpose: Calculation of SUSY and Higgs particle spectrum in:

– Constrained models: mSUGRA, GMSB, AMSB, etc...

– Unconstrained MSSM but with boundary conditions at high–scale.

- There are several programs available on the market:
  - **ISASUSY**: H. Baer, F. Paige, S. Protopopescu and X. Tata.
    http://paige.home.cern.ch/paige
  - **SUSPECT** : A. Djouadi, J.L. Kneur, G. Moultaka.
    http://www.lpm.univ-montp2.fr:6714/˜kneur/suspect.html
  - **SOFTSUSY** : B. Allanach.
    http://allanach.home.cern.ch/allanach/softsusy.html
  - **SPHENO**: W. Porod.
    to be made public soon
  - A number of private codes.

- They have different features in general (good for checks!):
  - Some are in Fortran, some are in C++ (Softsusy).
  - Some are interfaced with event generators (Isajet/Suspect).
  - Have different options for models and flexibility.
  - Use different approximations (ex: NLO corrections, etc...)

- They in principle involve at least four main ingredients:

– RGE of parameters between low and high scales (M_Z and $M_{\rm GUT}$).

– Consistent implementation of electroweak symmetry breaking (REWSB).

– Calculation of the physical masses (including radiative corrections).

– Check conformity of obtained spectrum with theory and experiment.

ALGORITHM

Choice of low energy inputs: $\alpha(M_Z), \sin^2\theta_W, \alpha_S(M_Z)$, $m_{t,b,\tau}^{\rm pole}$; $\tan\beta(M_Z)$

Radiative corrections $\rightarrow g_{1,2,3}^{\overline{\rm DR}}(M_Z)$, $\lambda_\tau^{\overline{\rm DR}}(M_Z), \lambda_b^{\overline{\rm DR}}(M_Z), \lambda_t^{\overline{\rm DR}}(m_t)$

First iteration: no SUSY Radiative Corrections

Two–loop RGE for $g_{1,2,3}^{\overline{\rm DR}}$ and $\lambda_{\tau,b,t}^{\overline{\rm DR}}$ with choice: $-g_1 = g_2 \cdot \sqrt{3/5}$ $-M_{\rm GUT} \sim 2 \cdot 10^{16}$ GeV

Include all SUSY thresholds via step functions in β functions.

First iteration: Unique threshold guessed.

Here your can chose your model (mSUGRA, GMSB, AMSB, or pMSSM).
Fix your high–energy inputs (mSUGRA: $m_0, m_{1/2}, A_0$, sign(μ), etc...).

Run down with RGE to: $-M_Z(m_t)$ for $g_{1,2,3}$ and $\lambda_{\tau,b}(\lambda_t)$ $-M_{\rm EWSB}$ for $\tilde{m}_i, \tilde{M}_i, A_i$

First iteration: Guess for $M_{\rm EWSB} = M_Z$.

$\mu^2, \mu B = F_{\rm non-linear}(m_{H_1}, m_{H_2}, \tan\beta, V_{\rm loop})$

$V_{\rm loop} \equiv$ Effective potential at 1–loop with all masses.

First iteration: No V_{loop} included

Here you can check μ convergence, CCB, UFB, etc...

Diagonalisation of mass matrices and calculation of masses and couplings

Radiative corrections to the physical Higgs, sfermion, gaugino masses.

First iteration: No Radiative Corrections.

Here you can check that you obtain a reasonable spectrum:

– no tachyonic masses (from RGE, EWSB or mixing), good LSP,
– not too much fine-tuning (for instance in M_Z, λ_t w.r.t $\mu^2, \mu B$),
– agreement with experiment: EW precision data, $(g-2)$, etc...

– Small iteration on μ: $\mu_i - \mu_{i-1} \leq \epsilon$.

– Long iteration RGE/RC: 3 to 4 iterations (larger for $\tan\beta \geq 40$).

MAIN FEATURES OF THE VARIOUS PROGRAMS

ITEM	ISASUSY	SUSPECT	SOFTSUSY	SPHENO*
Models	mS,AM,GM	mS,AM,GM*	mS,AM,GM	mS,AM,GM
	MSSM(25)	MSSM(22)	–	–
	$\tilde{\nu}_R$, strings	–	–	string sc.
RGE	2–loop g_i, λ_i	2–loop g_i, λ_i	2–loop g_i, λ_i	2–loop g_i, λ_i
	2 loop soft	1–loop soft	1–loop soft	2–loop soft
EWSB	$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$	flexible*	$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$	$\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$
$V_{\rm loop}$/tad.	$t, b, \tilde{t}, \tilde{b}$	1–loop	1–loop	1–loop
Thresholds	Steps	Steps	in RC	in RC
SM	leading	lead/full	lead/full	full
RC SUSY	approx.	$\sim$ PBMZ	$\sim$ PBMZ	full
Higgs	1Loop EP	SUBH/BDSZ*	FHF	BDSZ
Checks	–	CCB,UFB,FT	FineTuning	CCB,UFB
	–	EW,a_μ	–	EW,a_μ, $bs\gamma$
Decays	Yes	hdecay/sdecay*	–	Yes
Production	pp and e^+e^-	ee susygen	–	e^+e^-

* To come soon.

– PBMZ: D. Pierce, J. Bagger, K. Matchev and R. Zhang, hep-ph/9606211.
– FHF: S. Heinemeyer, W. Hollik and G. Weiglein, hep-ph/9903404.
– SUBH: M. Carena, M. Quiros and C. Wagner, hep-ph/9508343.
– BDSZ: A. Brignole, G. Degrassi, P. Slavitch and F. Zwirner, hep-ph/0112177.

SCANS AND CONSTRAINTS ON MODELS

Possibility of link with other routines, imposing theoretical and experimental constraints and make scans on the parameter space of the models:

$\to$ strong constraints on the parameter space of the various models.

$\to$ delineate regions of par. space where SUSY signals can be expected.

Example: mSUGRA with Suspect*

- Theory Constraints:
  - proper EWSB (μ converge and good M_A^2), no tachyons from RGE.
  - simple CCB and UFB, no tachyons from mixing, χ_1^0 LSP.

- Experimental constraints:
  - Bounds on sparticle masses from LEP2 ($\chi, \tilde{\ell}$) and Tevatron ($\tilde{q}, \tilde{g}$).
  - Bounds on Higgs masses from LEP ($M_{H^0} \gtrsim 114$ GeV, $M_{h,A} \gtrsim M_Z$).
  - Precision measurements of $M_W, \sin^2\theta_W$: $\Delta\rho^{\rm SUSY} \lesssim 2 \cdot 10^{-3}$.
  - SUSY/Higgs Contributions to $b \to s\gamma$: $2.10^{-4} \lesssim$ BR $\lesssim 5.10^{-4}$.

    (Routine provided by Ciuchini, Degrassi, Gambino, Giudice).

- Additional requirements:
  - 2σ evidence for SM Higgs at LEP: 113 GeV $\lesssim M_{h,H} \lesssim$ 117 GeV.
  - 1.6 σ contribution to $(g-2)_\mu$: $6 \cdot 10^{-10} \lesssim a_\mu \lesssim 60 \cdot 10^{-10}$.
  - χ_1^0 solution for CDM problem: $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$.

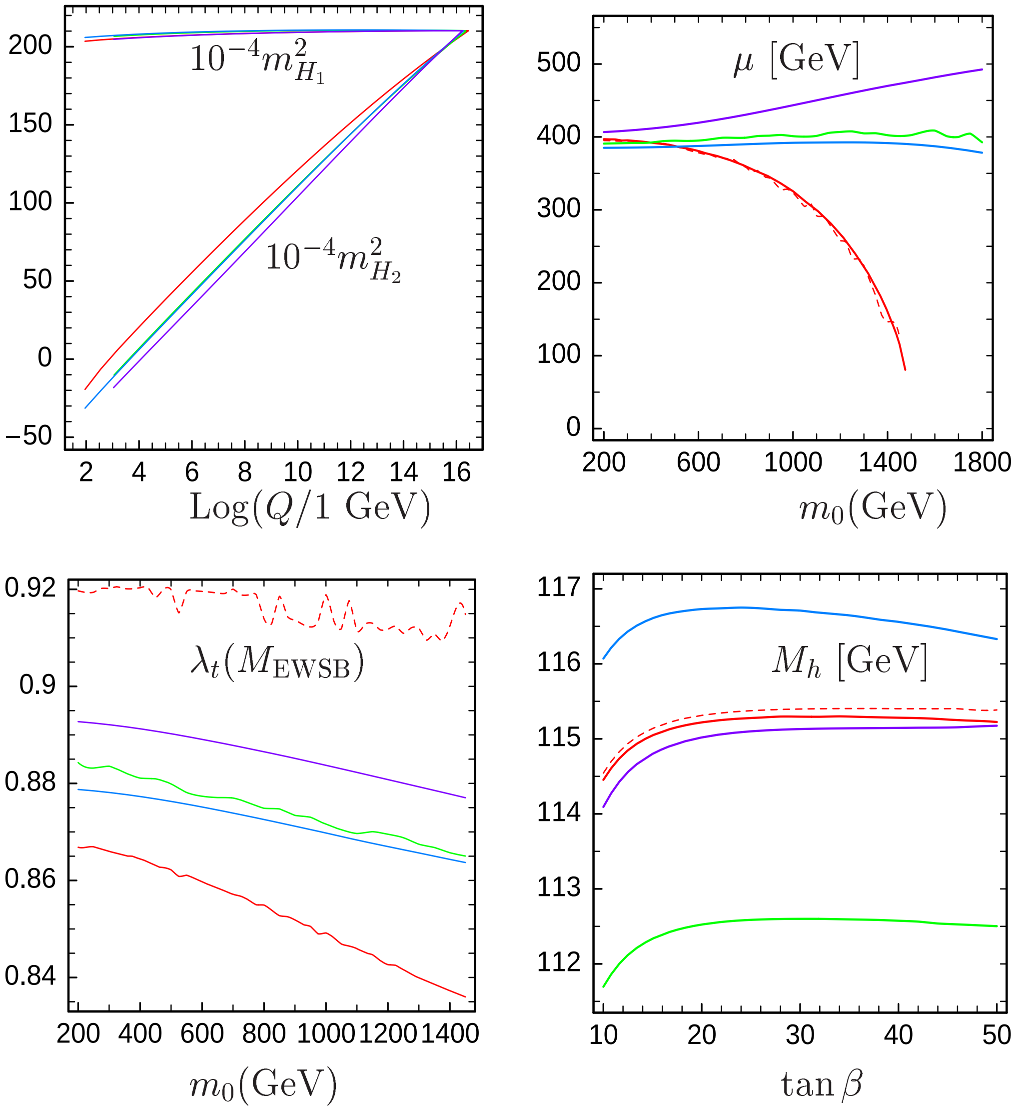
    (Routine for χ_1^0 (co)–annihilation and relic density by M. Drees)

- Expectations for sparticle/Higgs production at colliders.

* Manuel Drees, Jean-Loic Kneur and A. Djouadi, JHEP 0108:055,2001.
See also many other analyses in the recent years: Ellis, Ganis, Nanopoulos and Olive; Battaglia et al.; Arnowitt, Dutta, Hu and Santoso; Roszkowski, Ruiz de Austri and Nihei; Lahanas and Spanos; Gomez, Lazarides and Pallis; Feng, Matchev and Wilczek; Bottino, Donato, Fornengo and Scopel; Baltz and Gondolo; Chattopadhyay and Pran Nath; Barger and Kao; de Boer, Huber, Sander and Kazakov; Belanger, Boudjema, Cottrant, Godbole and Semenov, ...

COMPARISON BETWEEN THE VARIOUS PROGRAMS

From Sabine Kraml (see talk in // session).



red:	**Isajet 7.63 (7.58)**	**blue:**	**SoftSusy 1.4**
green:	**SuSpect 2.005**	**violet:**	**SPheno 1.0**

– Top–Letft: $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\sin(\mu) > 0$, $m_0 = 1450$ GeV.
– Top–Right: $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\sin(\mu) > 0$.
– Bottom–Left: $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\sin(\mu) > 0$.
– Bottom–Right: $m_{1/2} = 300$ GeV, $A_0 = 0$, $\sin(\mu) > 0$,. $m_0 = 4000$ GeV.

$\tan\beta = 40 \ , \ \ A_0 = 0 \ , \ \ \mathrm{sign}(\mu) > 0$

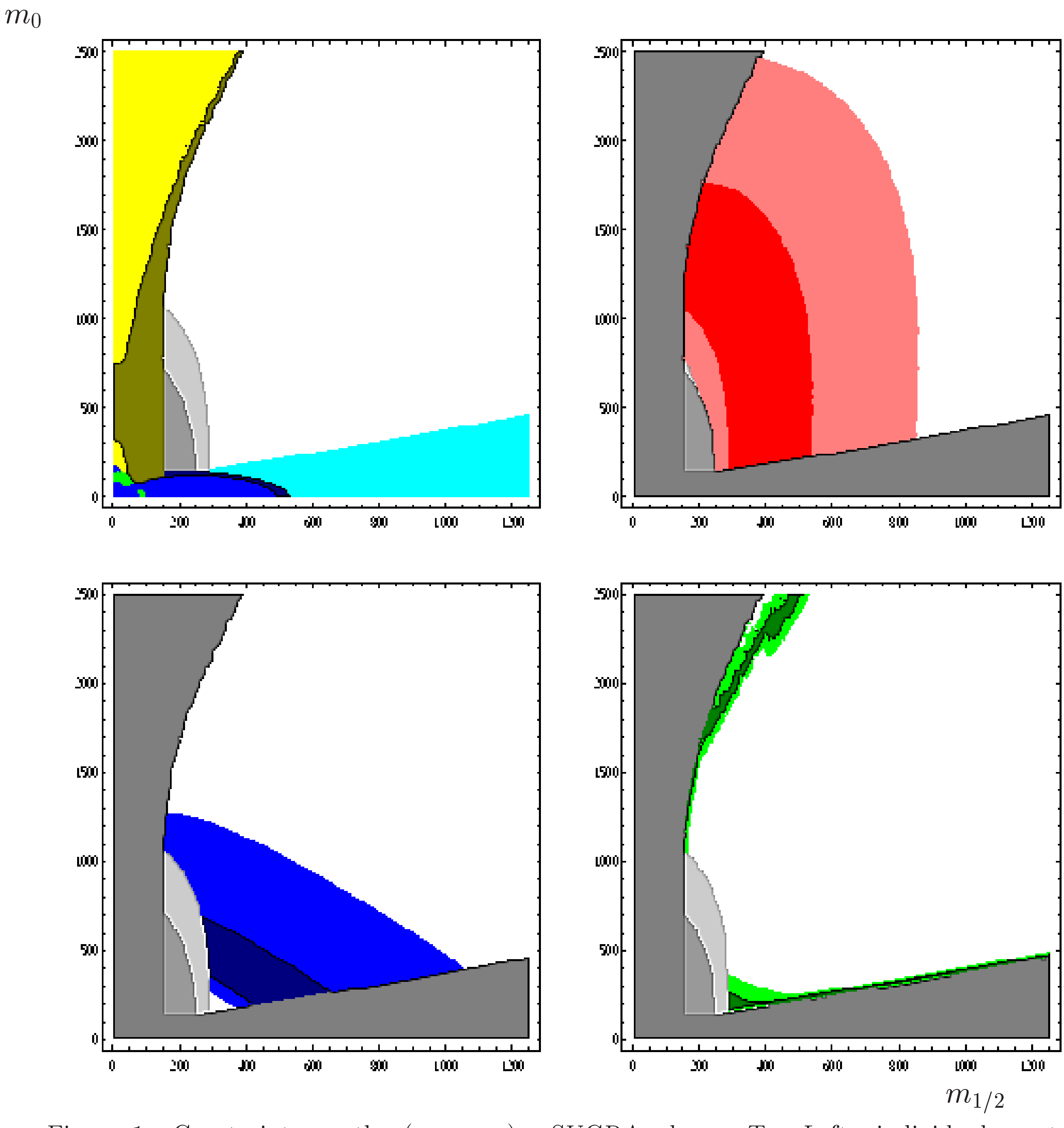


Figure 1: Constraints on the $(m_{1/2}, m_0)$ mSUGRA plane. Top–Left: individual constraints from non–convergent μ (yellow region), tachyonic M_A (green), tachyonic sfermions (blue), light sfermions (dark), light charginos (brown), $\tilde{\chi}_1^0$ non–LSP (light blue), BR$(b \to s\gamma)$ (medium grey) and light h boson (light and medium grey). The three other plots are for the 1σ (dark colors) and 2σ (light colors) "evidence" for, the Higgs boson (but with larger error bars, Top–Right), the $(g_\mu - 2)$ (Bottom–Left) and the Dark Matter (Bottom–Right).

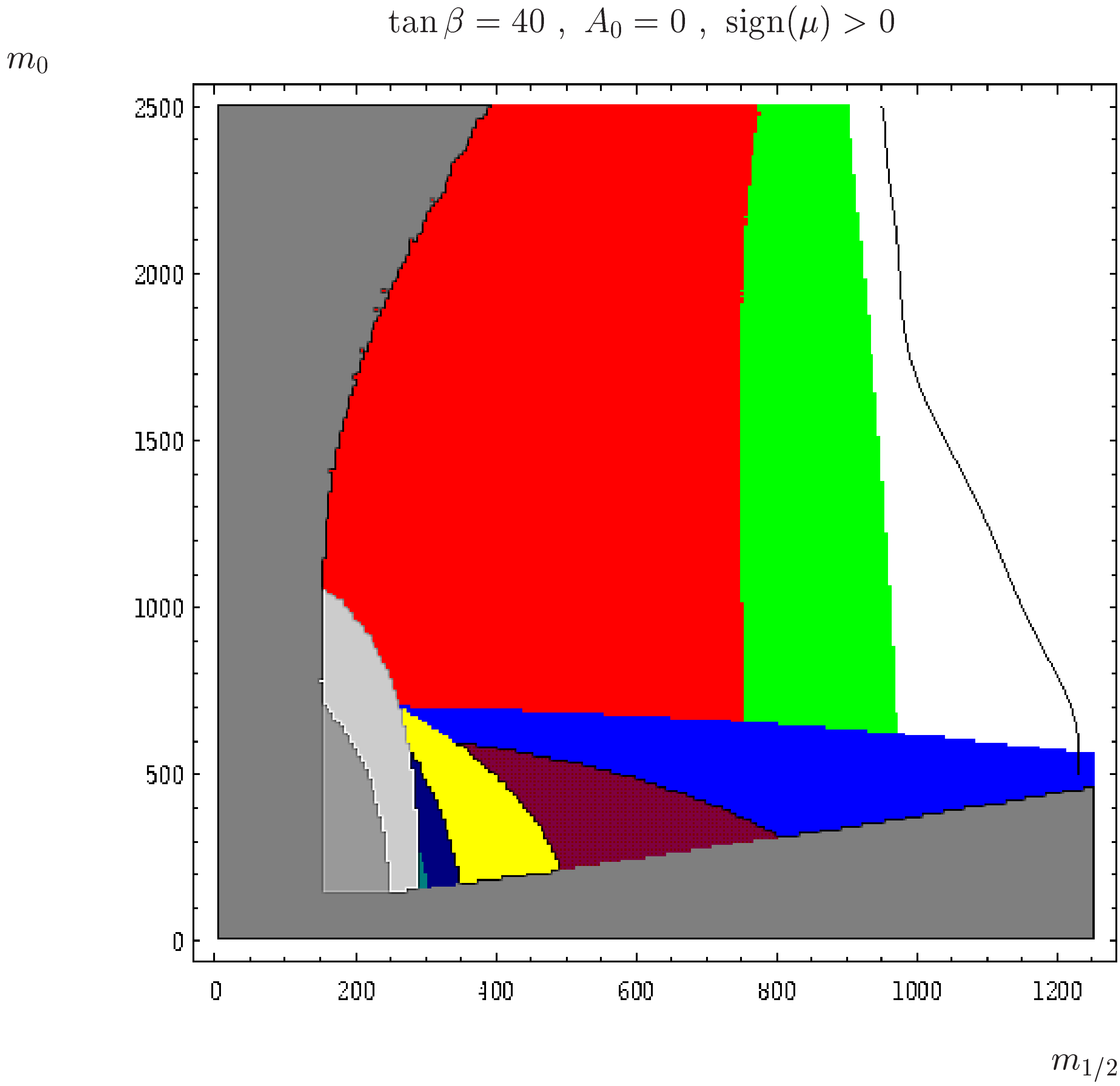


Figure 2: The $(m_{1/2}, m_0)$ mSUGRA plane where SUSY and Higgs particles can be produced at an e^+e^- collider with a c.m. energy $\sqrt{s} = 1.2$ TeV. The grey areas are those excluded by theoretical and experimental constraints. The colored regions are those where then cross sections are large enough for the particles to be produced: $\tilde{\chi}_1^0\tilde{\chi}_2^0$ (green), $\tilde{\chi}_1^+\tilde{\chi}_1^-$ (red), $\tilde{l}^+\tilde{l}^-$ (blue), $\tilde{\nu}\tilde{\nu}^*$ (purple), $\tilde{t}_1\tilde{t}_1^*$ (dark blue), $\tilde{b}_1\tilde{t}_1^*$ (dark blue) and the heavy MSSM $H, A, H^\pm$ bosons (yellow). Note that some of these regions are overlapping. The lines are the 5σ reach contours for sparticles at the LHC in the missing E_T channel with a luminosity $\int \mathcal{L}100$ fb^{-1} adapted from Ref. [?].

Codes for spectrum, decay & production

1. NLO Higgs and Sparticle mass calculations

- Very important for Higgs boson and also for SUSY particle masses:
  – Possibly large (QCD, λ_t): alters reach at colliders (Higgs at LEP).
  – Alters search strategy: allows or not some decay modes ($\tilde{t}_1 \to b\chi_1^+$)
  – $m_{\tilde{P}} - m_{\rm LSP} \propto E_T^{\rm mis}$: important for experimental searches.
  – $m_{\tilde{P}} - m_{\rm LSP}$ important for relic density (co–annihilation).

- For sparticle masses: see previous codes for spectrum calculation.

- For the MSSM Higgs boson masses (also included in previous codes):

1. SUBH (M. Carena, M. Quiros and C. Wagner):

http://gate.hep.anl.gov/cwagner/subh.f

– Eff. Pot. approach + QCD RG improvement + leading λ_t^2 corrections.
– Includes now gluino corrections to m_b, m_t

2. FeynHiggs (S. Heinemeyer, W. Hollik and G. Weiglein):

http://www-itp.physik.uni-karlsruhe.de/feynhiggs/

– Feynman diag. approach: full 1 loop + 2 loop SUSY–QCD at $q^2 = 0$.
– Version FeynHiggsFast has leading 1–loop and app. 2–loop (faster).

3. BDSZ* (A. Brignole, G. Degrassi, P. Slavich and F. Zwirner):

Hopefully to be released soon (hein Pietro?).

– Leading one–loop corrections (full corrections to come).
– Full $\alpha_s \lambda_t^2$ corrections including gluino contributions.
– Full λ_t^4 and $\alpha_s \lambda_b^2$ corrections including gluino contributions.

4. Some approximate and private codes ....

2. NLO Higgs and SUSY particle production calculations

– NLO QCD corrections are very important for Higgs and SUSY particle production at hadron colliders: $K \sim 2$ at LHC (see talk by M. Spira).

– Decays of SUSY and Higgs particles can be complicated: many channels, higher order decays, important radiative corrections, etc...

(Non–exhaustive) list of public codes:

- NLO Higgs production at hadron colliders (M. Spira[1]):

– HIGLU: $pp \to gg \to h, H, A$ (NLO).
– VV2H/V2HV: $qq \to h, H + qq$ and $W, Z + h, H$ (NLO).
– HQQ: $pp \to q\bar{q}, gg \to h, H, A + Q\bar{Q}$ (LO, NLO to come).
– HPAIR: $pp \to q\bar{q}, gg \to hh, HH, hA, HA, AA$ (partly NLO).

- NLO SUSY particle production at hadron colliders (M. Spira et al.):

– PROSPINO: $pp \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ (NLO).
– Pair and associated production of gauginos at NLO to come...

- Production of Higgs and SUSY particles at e^+e^- colliders:

– SUSYGEN (S. Katsanevas et al.): also MC generator, see later.
– HZHA (P. Janot): MC generator for Higgs production at LEP2.
– Many four or six fermion production processes at e^+e^- colliders....

- Decays of Higgs and SUSY particles:

– ISASUSY: two–body Higgs and SUSY decays available.
– HDECAY[2]: SM and MSSM Higgs decays with higher order effects.
– SDECAY*[3]: SUSY particle decays including higher order effects.
– SPHENO* (W. Porod): 2 and 3–body SUSY particle decays.

[1]http://www.desy.de/ spira/
[2]AD, Jan Kalinowski, Michael Spira.
[3]AD, Yann Mambrini, Margarete Mühlleitner.

3. Automatic Matrix Element Generators

– Multi–particle processes are very important for pp and e^+e^- physics. Ex: pp or $e^+e^- \to Ht\bar{t} \to$ 8 or 10 fermions if $H \to b\bar{b}$ or WW.

– Large MEs for the full process: needs to be calculated automatically and interfaced to MC event generators for a full simulation.

There are two major codes for SM and SUSY Physics

- **CompHEP**: A. Pukhov, E. Boos, A. Semenov et al.

  http://theory.sinp.msu.ru/comphep

  – Uses trace techniques and Vegas for PS integration.

  – Calculates its own SUSY Feynman rules and spectra (Semenov).

  – Easy interface with MC generators. Rapid development.

- **GRACE–SUSY**: Minami-Tateya Group (T. Kon et al.)

  http://www-sc.kek.jp/minami

  – Only e^+e^- processes (pp to come) with Form/Reduce for traces.

  – Has only selected processes and needs model files for the others.

  – No (SUSY) news since some time...

There exist other codes but do not include SUSY processes yet:

- **MadGraph**: http://pheno.physics.wisc.edu/Software/MadGraph/
- **AMEGIC++**: F.Krauss, R.Kuhn, G. Soff
- **O'MEGA/WHIZARD**: T. Ohl and W. Kilian
- **FeynCalc**: http://www.feyncalc.org/

......

4. Dark Matter Codes

Several experiments for Dark Matter searches are in progress or planed. Low energy SUSY (MSSM) has a very good candidate: the LSP (χ_1^0).

Important ingredients: (un)constrained MSSM predictions for:

– the relic density of the LSP: $\sigma(\chi_1^0\chi_1^0 + \chi_1^0\tilde{P})$.

– the rate for direct detection: $\chi_1 N \to \chi_1^0 N$.

– the rate for indirect detection: $\chi_1^0\chi_1^0 \to \gamma\gamma, \gamma Z$ and $\bar{p}, e^+, \nu + X$.

For relic density: needs SUSY–Higgs spectra, annihilation/co–annihilation cross sections, pair production thresholds, effects of resonances...

Needs also: modeling of the halo, hadronisation, nuclear matrix elements, particle flux, interaction and propagation, etc...

There are two main multi–purpose codes which include all these[4]:

- **DarkSUSY** (Gondolo, Edjso, Bergström, Illio, Baltz):

http://www.physto.se/ edsjo/darksusy/

– Own spectra pMSSM calculation but can be linked to SUSPECT.

– Hadronisation and SM particle decays from PITHYA.

- **NeutDriver** (G. Jungman):

http://t8web.lanl.gov/people/jungman/neut-package.html

– Has only unconstrained MSSM (69 parameters).

– Seems to have bugs and no recent upgrade.

There is also a new code which calculates the relic density in the MSSM:

- **MicrOmegas** (G. Belanger, F. Boudjema, A. Pukhov, A. Semenov):

– (co)–annihilation calculation with all channels based on ComHEP.

– Includes isasusy/feynhiggs/hdecay/suspect* for spectra.

A number of private codes for one or all items is available....

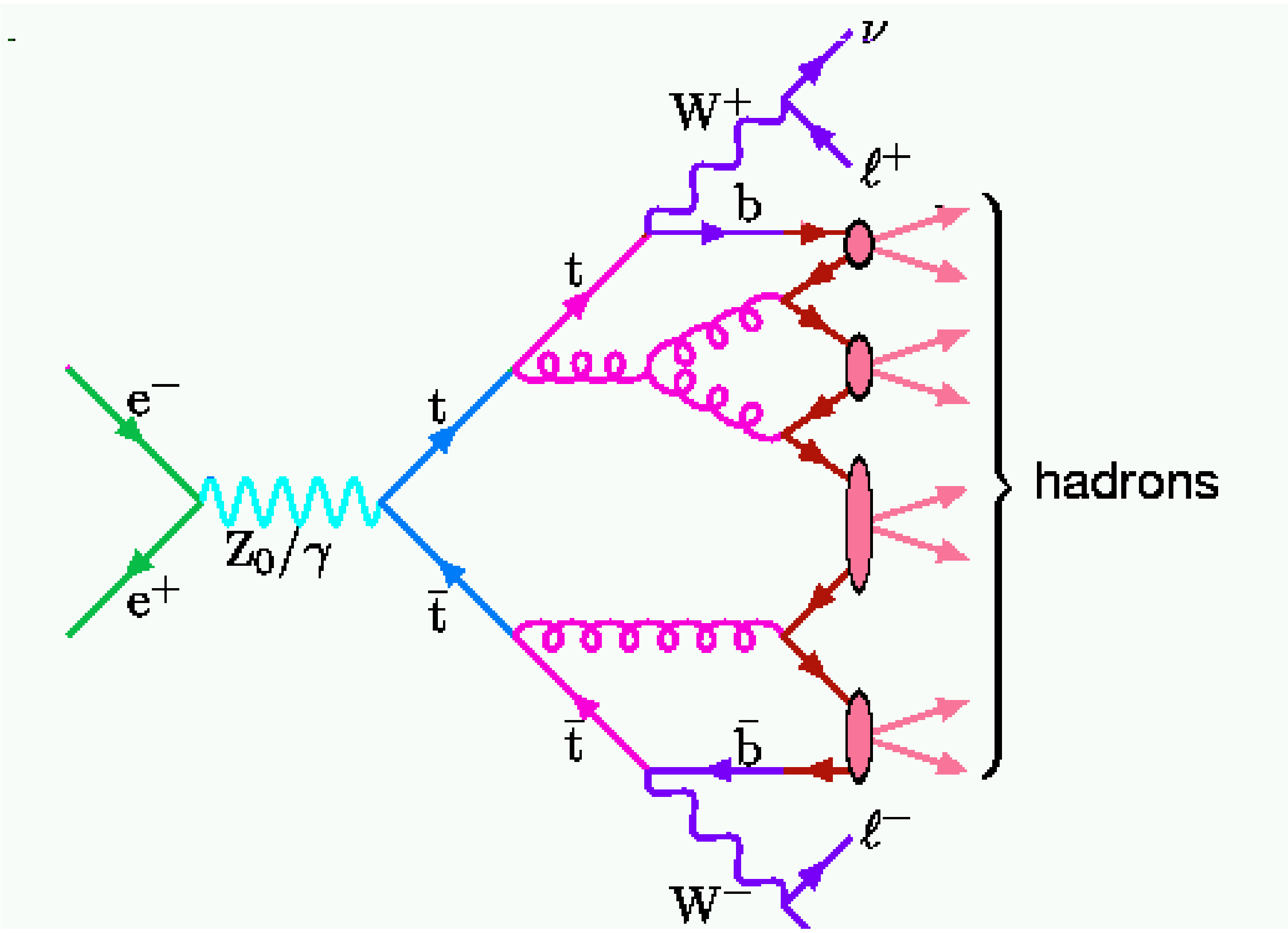
[4] See talk of Emanuel Nezri in // sessions.

Monte–Carlo Event generators

– Big mastodons which do everything from production to hadron decay and simulate the signals and the backgrounds.

– Five phases in simulation: 1) Hard production processes, 2) Parton Shower, 3) Heavy particle decays, 4) Hadronisation, 5) Hadron decays.

– I discuss only production (1) and decays (3) of SUSY/Higgs particles. The rest of the simulation is as in the Standard Model.



There are three + one multipurpose MC generators[5]:

- **ISAJET**: H. Baer, F. Paige, S. Protopopescu and X. Tata.

http://paige.home.cern.ch/paige

– Oldest and most used of SUSY generators.
– All SUSY production channels (including some $R\!\!\!/_p$) are built in.
– Linked with ISASUSY for spectrum and decay BR's calculation.
* Rather poor description of SM processes.

- **(S)PYTHIA**: T. Sjostrand et al. and S. Mrenna.

http://www.thep.lu.se/ torbjorn/Pythia.html

– Gives the best description of SM physics.
– Calculates the 2–body decay rates of SUSY and Higgs particles.
– Wide range of production processes (including $R\!\!\!/_p$) implemented.
* Approximate SUSY spectrum calculation (analytical formulae).

- **HERWIG**: S. Moretti, P. Richardson (for SUSY) et al.

http://hepwww.rl.ac.uk/theory/seymour/herwig/

– Good for SM but SUSY aspect is developing very rapidly.
– Has many production channels, good treatment of $R\!\!\!/_p$
– Has spin correlations in all processes and polarisation in e^+e^-.
* No built–in code for spectra or decay (interface with Isajet/Hdecay).

- **SUSYGEN:** N.Ghodbane, S.Katsanevas, P.Morawitz, E.Perez

http://lyoinfo.in2p3.fr/susygen/susygen3.html

– Specialized in e^+e^- but now includes some processes in pp, ep.
– Spectrum from SuSpect; calculates SUSY decays and uses Hdecay.
– Has full spin correlations and includes all parity violation processes.
-* Interfaced with PYTHIA for parton shower and hadronisation.
* Cannot simulate the SM backgrounds.

[5]Thanks to Peter Richardson for his help here.

Summary

- More and more programs are available for public use:
  – Good for check/comparison (not so good to have only one gun...).
  – Makes healthy competition between codes (upgrade or perish...).

- Programs get more and more sophisticated (and no sparticle yet!)

  – Only a few or some aspects of SUSY (theoretical, phenomenological or experimental) are dealt with by one single program.

  – This calls for complementarity between various programs (spectra calculation, NLO corrections, matrix elements, Monte–Carlos...).

  – Big efforts for clarity, simplicity, speed, user–friendly, interface..

  – Time consuming and not very safe....

- More interplay between theory and experiment (good for the field!):
  – Many workshops on Tools (GdR-SUSY, SUSY-Tools, LesHouches..)
  – Many discussions for interfacing (Les Houches Accord...).

- There is a rapid development:
  – Many new codes have appeared in the recent years.
  – Recent changes in the major generators and spectra codes.
  – Move to C++ (good news or bad news?).

Ready for the next round of experiment!

Hope that SUSY is also ready...