

SUSY CALCULATIONAL TOOLS

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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
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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 CP, 1st/2d gen. universality.

still $\gtrsim 22$ free parameters !!

This large number of parameters enters in:

- The evaluation of the masses of ≥ 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: Λ_{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_{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: $\alpha(M_Z), \sin^2 \theta_W, \alpha_S(M_Z), m_{t,b,\tau}^{\text{pole}} ; \tan \beta(M_Z)$

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

First iteration: no SUSY Radiative Corrections

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

Include all SUSY thresholds via step functions in β functions.

First iteration: Unique threshold guessed.

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

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

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

$\mu^2, \mu B = F_{\text{non-linear}}(m_{H_1}, m_{H_2}, \tan \beta, V_{\text{loop}})$
 $V_{\text{loop}} \equiv$ 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 MSSM(25) $\tilde{\nu}_R$, strings | mS,AM,GM* MSSM(22) – | mS,AM,GM – – | mS,AM,GM – string sc. |
| RGE | 2-loop g_i, λ_i 2 loop soft | 2-loop g_i, λ_i 1-loop soft | 2-loop g_i, λ_i 1-loop soft | 2-loop g_i, λ_i 2-loop soft |
| EWSB $V_{\text{loop}}/\text{tad.}$ | $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ $t, b, \tilde{t}, \tilde{b}$ | flexible* 1-loop | $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ 1-loop | $\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ 1-loop |
| Thresholds | Steps | Steps | in RC | in RC |
| RC SM SUSY Higgs | leading approx. 1Loop EP | lead/full \sim PBMZ SUBH/BDSZ* | lead/full \sim PBMZ FHF | full full BDSZ |
| Checks | – – | CCB,UFB,FT EW, a_μ | FineTuning – | CCB,UFB EW, $a_\mu, bs\gamma$ |
| 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:

- strong constraints on the parameter space of the various models.
- 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 $M_W, \sin^2 \theta_W$: $\Delta \rho^{\text{SUSY}} \lesssim 2 \cdot 10^{-3}$.
- SUSY/Higgs Contributions to $b \rightarrow s\gamma$: $2 \cdot 10^{-4} \lesssim \text{BR} \lesssim 5 \cdot 10^{-4}$.
(Routine provided by Ciuchini, Degrandi, Gambino, Giudice).

- Additional requirements:

- 2σ evidence for SM Higgs at LEP: 113 GeV $\lesssim M_{h,H} \lesssim 117$ GeV.
- 1.6σ 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)

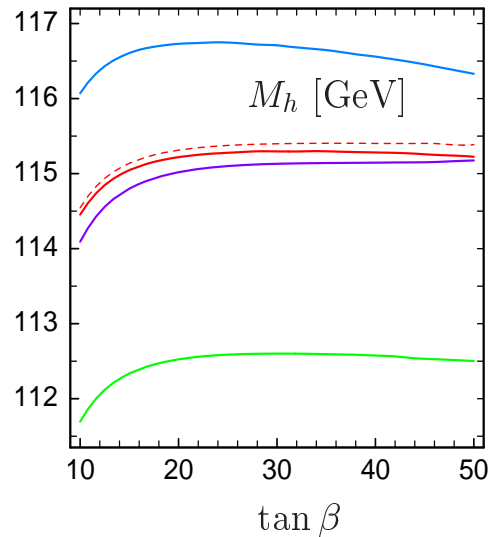
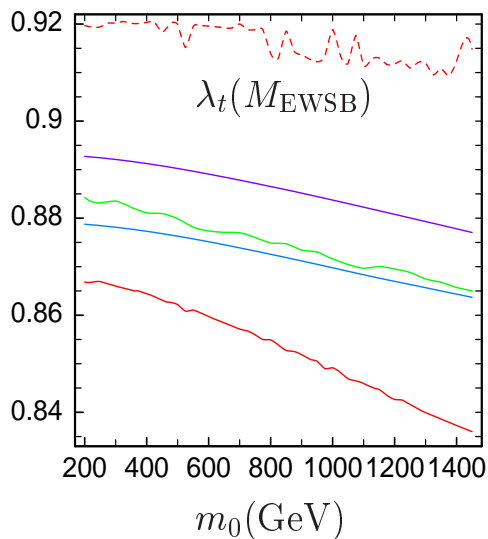
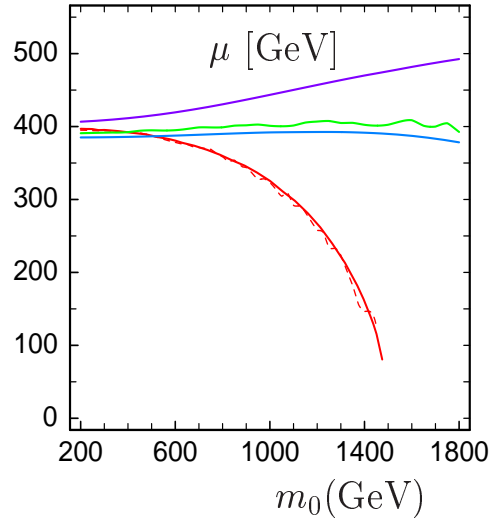
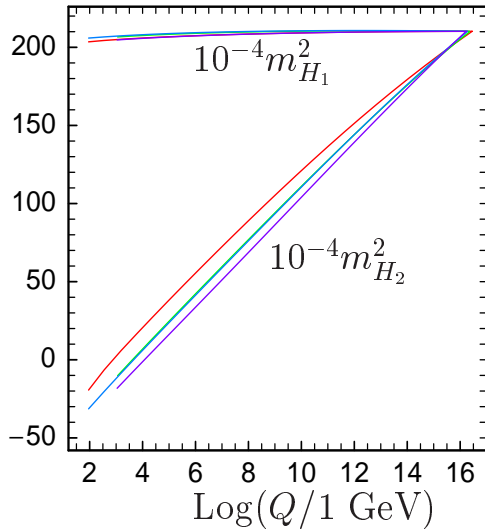
- Expectations for sparticle/Higgs production at colliders.

* Manuel Drees, Jean-Loic Kneur and A. Djouadi, JHEP 0108:055,2001.

See also many other analyses in the recent years: Ellis, Ganiis, 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-Left: $m_{1/2} = 300 \text{ GeV}$, $A_0 = 0$, $\tan \beta = 10$, $\sin(\mu) > 0$, $m_0 = 1450 \text{ GeV}$.
- Top-Right: $m_{1/2} = 300 \text{ GeV}$, $A_0 = 0$, $\tan \beta = 10$, $\sin(\mu) > 0$.
- Bottom-Left: $m_{1/2} = 300 \text{ GeV}$, $A_0 = 0$, $\tan \beta = 10$, $\sin(\mu) > 0$.
- Bottom-Right: $m_{1/2} = 300 \text{ GeV}$, $A_0 = 0$, $\sin(\mu) > 0$, $m_0 = 4000 \text{ GeV}$.

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

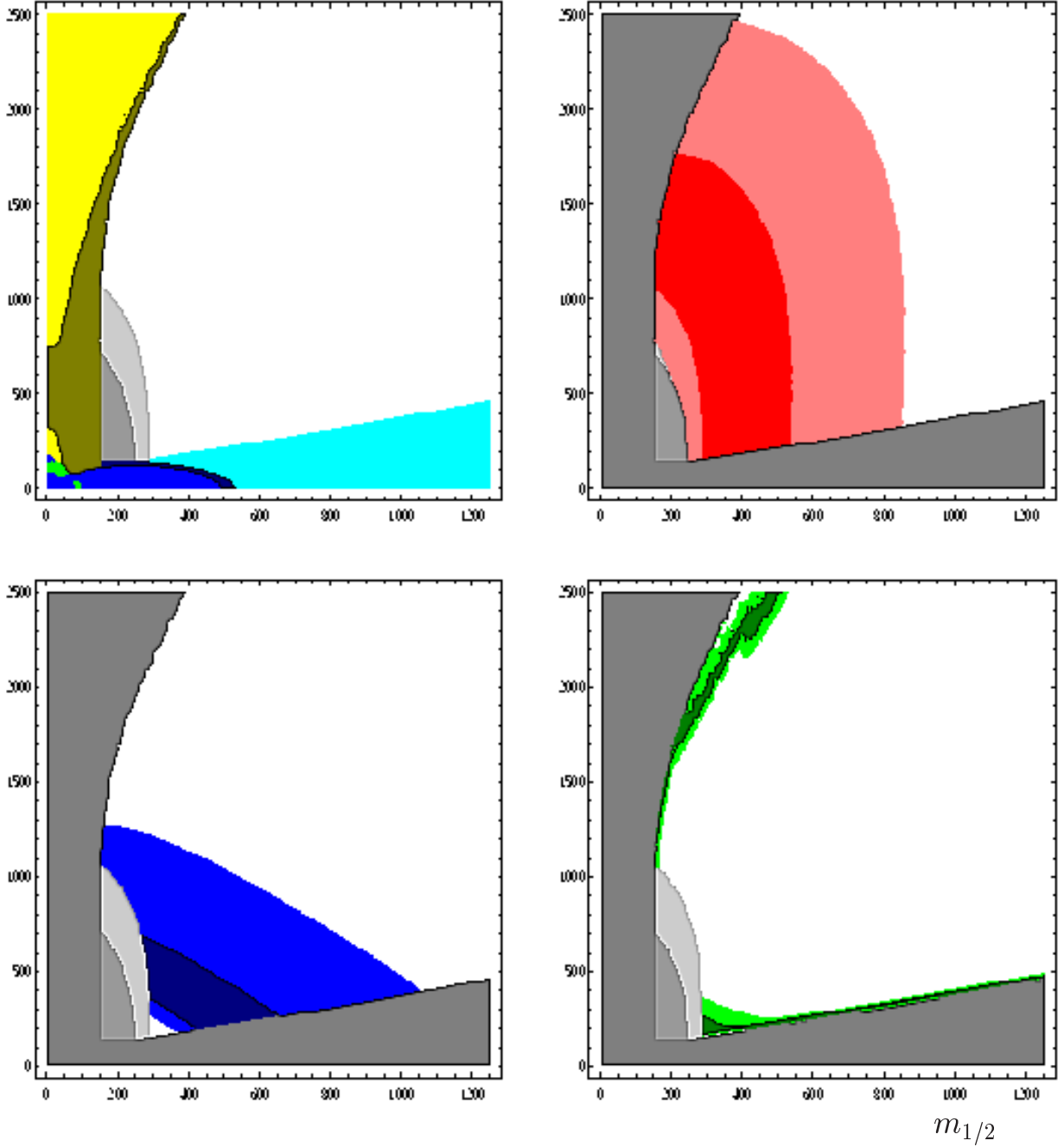
 m_0


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), $\text{BR}(b \rightarrow s\gamma)$ (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).

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

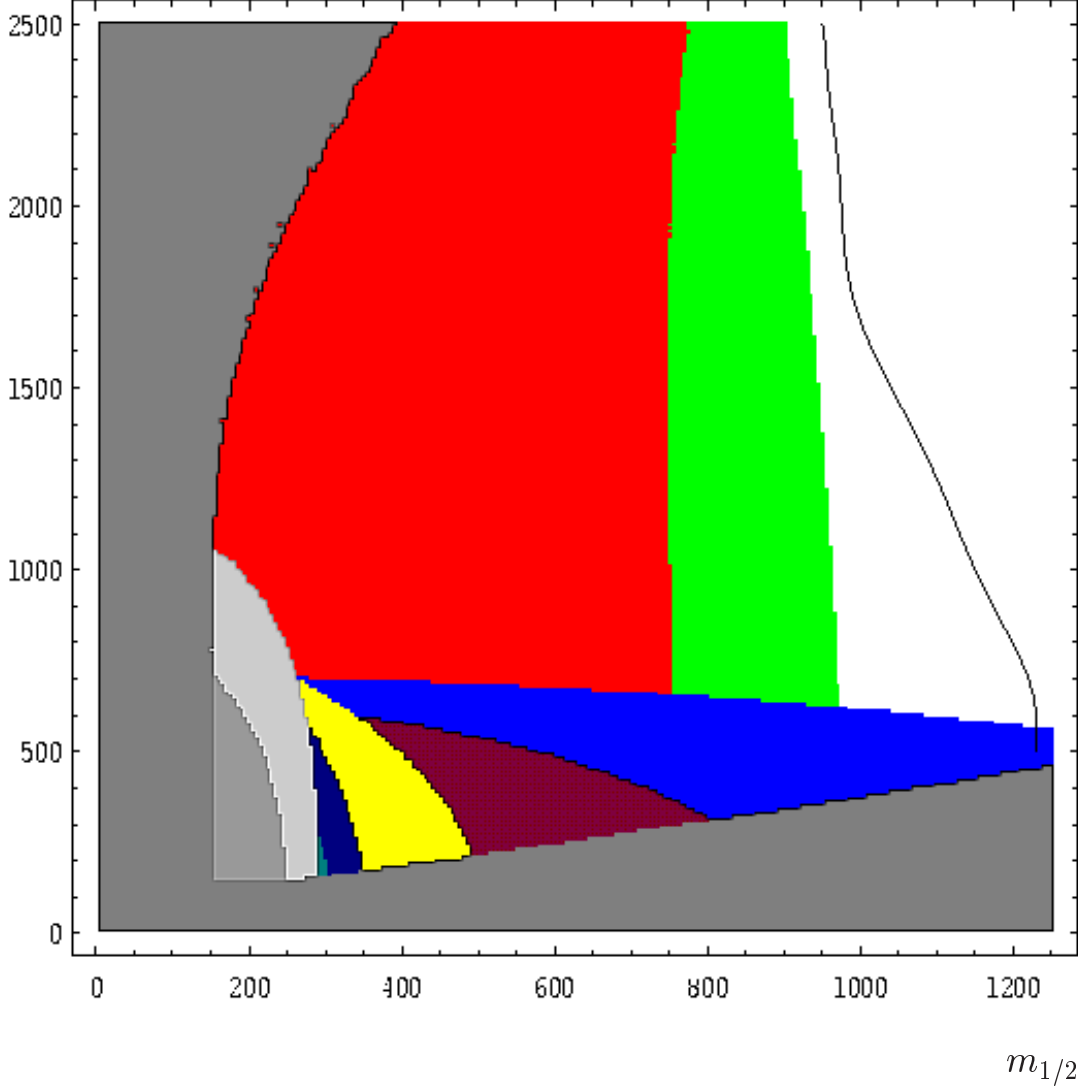
 m_0


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 $\int \mathcal{L} 100 \text{ fb}^{-1}$ 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 ($\tilde{t}_1 \rightarrow b\chi_1^+$)
 - $m_{\tilde{p}} - m_{\text{LSP}} \propto E_T^{\text{mis}}$: important for experimental searches.
 - $m_{\tilde{p}} - m_{\text{LSP}}$ 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. Spira¹):
 - HIGLU: $pp \rightarrow gg \rightarrow h, H, A$ (NLO).
 - VV2H/V2HV: $qq \rightarrow h, H + qq$ and $W, Z + h, H$ (NLO).
 - HQQ: $pp \rightarrow q\bar{q}, gg \rightarrow h, H, A + Q\bar{Q}$ (LO, NLO to come).
 - HPAIR: $pp \rightarrow q\bar{q}, gg \rightarrow hh, HH, hA, HA, AA$ (partly NLO).
- **NLO SUSY particle production at hadron colliders** (M. Spira et al.):
 - PROSPINO: $pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ (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.
 - HDECAY²: 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/>

²AD, Jan Kalinowski, Michael Spira.

³AD, Yann Mambrini, Margarete Mühlleitner.

3. Automatic Matrix Element Generators

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

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4. Dark Matter Codes

Several experiments for Dark Matter searches are in progress or planned. 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: $\chi_1 N \rightarrow \chi_1^0 N$.
- the rate for indirect detection: $\chi_1^0\chi_1^0 \rightarrow \gamma\gamma, \gamma Z$ 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 these⁴:

- **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):

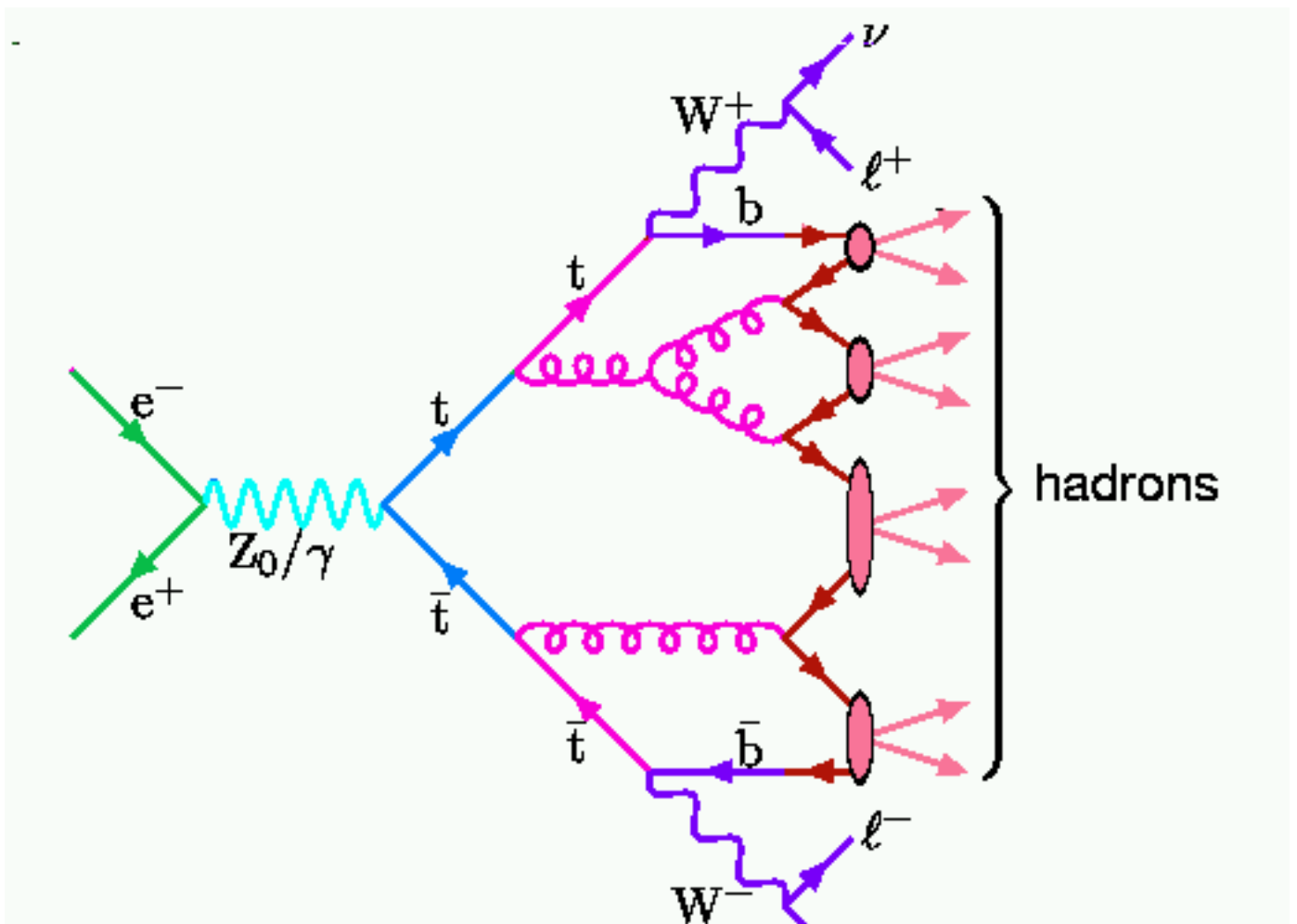
- (co)–annihilation calculation with all channels based on ComHEP.
- Includes isasusy/feynhiggs/hdecay/suspect* for spectra.

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

⁴See 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 generators⁵:

- **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.

⁵Thanks 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...