The mhMSSM and SuSpect3

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- **Introduction**
- **mHMSSM** Rima El-Kosseifi, Jean-Loic Kneur, Gilbert Moultaka, Dirk Zerwas
- **SUSPECT3** Jean-Loic Kneur, Gilbert Moultaka, Michael Ughetto, Dirk Zerwas, Abdelhak Djouadi
- **Conclusions and Outlook**

Introduction

A brief history:

- 1997 GDR Supersymmetry (Pierre Binetruy)
  - Working group MSSM
- 1997-2002 Definition of phenomenological MSSM (pMSSM)
  - sfermions: 1st and 2nd generation universality
  - No new sources of FCNC and CP violation
- 1999 Publication MSSM report: arXiv:hep-ph/9901246 (406 citations)
- 2002 Publication of Spectrum Calculator SuSpect: Comput.Phys.Commun.176:426-455,2007
  - Abdelhak Djouadi, Jean-Loic Kneur, Gilbert Moultaka
  - pMSSM (of the MSSM WG +3 parameters), mSUGRA, mGMSB,….
- 2003 Susy Les Houches Accord (SLHA): JHEP 0407:036,2004
  - Interoperability of Spectrum, Decay and Cross section calculators
- 2012 Discovery a R=+1 particle: h
- 2013 Relic density MSSM with SuSpect2: Phys. Rev. D 89, 055017 (2014)
- 2013 Start on major rewrite in C++ (SuSpect3)
- 2015 Relic density NMSSM with SFitter: Phys. Rev. D 93, 015011 (2016)

Introduction

- fermion ↔ boson
- has "no" problems with radiative corrections (quadrat. div.)
- has a light Higgs Boson (<140GeV)
- interesting pheno at the TeV scale

spin-0	spin-1/2	spin-1
Squarks $\tilde{q}_R, \tilde{q}_L$	q	
	Gluino: g	$\tilde{g}$
Sleptons: $\tilde{\ell}_R, \tilde{\ell}_L$	ℓ	
h,H,A	Neutralino $\chi_{i=1-4}$	Z, γ
$H^{\pm}$	Charginos: $\chi^{\pm}_{i=1-2}$	$W^{\pm}$

3 neutral Higgs bosons: h, A, H
1 charged Higgs boson: $H^{\pm}$
and supersymmetric particles

MSSM LowScale

Higgs sector	Gauge sector	trilinear couplings
$\tan\beta(Q = M_{Z^0})$	$M_1(Q = M_{\rm EWSB})$	$A_t(Q = M_{\rm EWSB})$
$m^2_{H_u}(Q = M_{\rm EWSB})$	$M_2(Q = M_{\rm EWSB})$	$A_b(Q = M_{\rm EWSB})$
$m^2_{H_d}(Q = M_{\rm EWSB})$	$M_3(Q = M_{\rm EWSB})$	$A_\tau(Q = M_{\rm EWSB})$
$\mu(Q=M_{\rm EWSB})$		
m_{A^0}		

$SU(2)_L$ doublets	$SU(2)_L$ singlets
$m_{\tilde{q}1_L}(Q = M_{\rm EWSB})$	$m_{\tilde{u}_R}(Q = M_{\rm EWSB})$
$m_{\tilde{q}2_L}(Q = M_{\rm EWSB})$	$m_{\tilde{d}_R}(Q = M_{\rm EWSB})$
$m_{\tilde{q}3_L}(Q = M_{\rm EWSB})$	$m_{\tilde{c}_R}(Q = M_{\rm EWSB})$
$m_{\tilde{\ell}1_L}(Q = M_{\rm EWSB})$	$m_{\tilde{s}_R}(Q = M_{\rm EWSB})$
$m_{\tilde{\ell}2_L}(Q = M_{\rm EWSB})$	$m_{\tilde{t}_R}(Q = M_{\rm EWSB})$
$m_{\tilde{\ell}3_L}(Q = M_{\rm EWSB})$	$m_{\tilde{b}_R}(Q = M_{\rm EWSB})$
	$m_{\tilde{e}_R}(Q = M_{\rm EWSB})$
	$m_{\tilde{\mu}_R}(Q = M_{\rm EWSB})$
	$m_{\tilde{\tau}_R}(Q = M_{\rm EWSB})$

Many different models:

- (p)MSSM (minimal supersymmetric extension of the standard model)
- mSUGRA
- GMSB
- AMB
- NMSSM

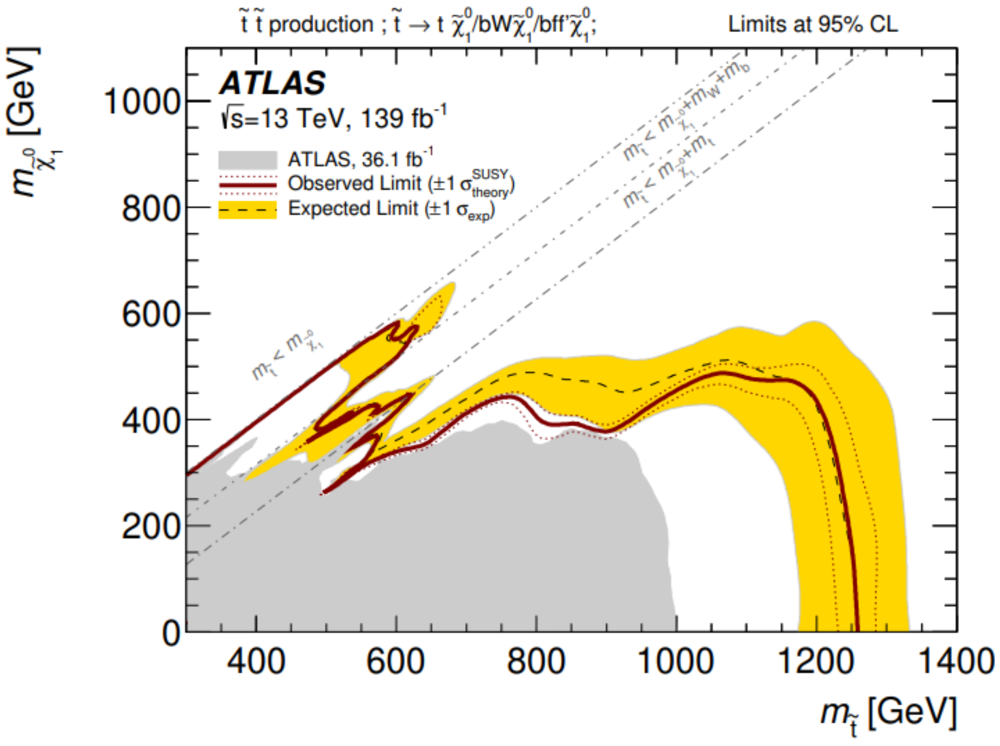
R-Parity conserved:

- Production of SUSY particles in pairs
- (Cascade-) decays to the lightest SUSY particle
- LSP stable, neutral and weakly interacting: neutralino (χ_1)
- LSP candidate for CDM
- less than half of the particles observed
- Great hope for discovery due to LHC CM increase to 13.6TeV (Depeche Mode "I can just can't get enough")

The Stop Cliff

An example point:

- Heavy squarks and sleptons
- Light LSP (Bino)



EW	2.0 TeV
$m^2_{H_d}$	3.65740418 TeV^2
$m^2_{H_u}$	-0.213361994 TeV^2
sign(μ)	+
A_t	3.610 TeV
$m_{\tilde{t}_R}$	1.27 TeV
$m_{\tilde{q}3_L}$	3 TeV
M_1	300 GeV
M_2	2 TeV
M_3	3 TeV
$A_b,\ A_\tau$	0 GeV
$\tan\beta$	10
$m_{\tilde{e}_L} = m_{\tilde{\mu}_L} = m_{\tilde{\tau}_L} = m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{\tau}_R}$	2 TeV
$m_{\tilde{q}1_L} = m_{\tilde{q}2_L} = m_{\tilde{u}_R} = m_{\tilde{c}_R} = m_{\tilde{d}_R} = m_{\tilde{s}_R} = m_{\tilde{b}_R}$	3 TeV
m_h	125.012 GeV
$m_{\tilde{t}_1}$	1306 GeV
$m_{\tilde{\chi}_1^0}$	294 GeV

Stop sector:

- Lightest stop at detection mass limit
- At=3610 GeV

Higgs mass:

- Experimental error ~ 0.15GeV
- Typical non-parametric error: 2GeV
- GeV level rounding: 125GeV

Calculating a Supersymmetric Spectrum

GUT scale ~10^{16}GeV

$m^2_{H_d}$ $A_b,\ A_\tau\ \ A_t$ M_1

$m^2_{H_u}$ M_2

$\mathrm{sign}(\mu)$ $Ae,\ A\mu,\ Ad,\ As,\ Au,\ Ac$ M_3

$m_{\tilde{e}_L}$ $m_{\tilde{\mu}_L}$ $m_{\tilde{\tau}_L}$ $m_{\tilde{e}_R}$ $m_{\tilde{\mu}_R}$ $m_{\tilde{\tau}_R}$

$m_{\tilde{q}1_L}$ $m_{\tilde{q}2_L}$ $m_{\tilde{q}3_L}$ $m_{\tilde{u}_R}$ $m_{\tilde{c}_R}$ $m_{\tilde{t}_R}$

$m_{\tilde{d}_R}$ $m_{\tilde{s}_R}$ $m_{\tilde{b}_R}$

RGE

RGE

Derived:

EWSB scale ~10^3GeV

$m^2_A(Q),\ \mu$

RGE

Z scale ~10^2GeV

$\tan\beta$

Boundary conditions:
- **High scale: SUSY breaking masses**
- **EWSB scale: μ, m^2A(EWSB)**
- **Z scale: tanβ**

Numerical solution of coupled RGE:
- **High Scale to Low Scale in N steps**

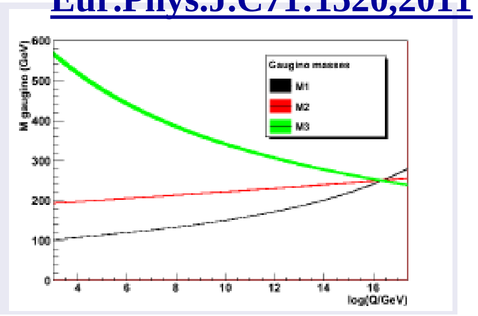
Ensure EWSB
- **Iteration at EWSB scale**

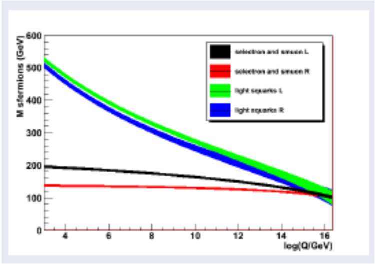
Radiative corrections EWSB scale:
- **Higgs Potential**
- **Higgs and SUSY running masses to pole masses**

Radiative corrections Z scale:
- **Corrections to SM couplings (yukawa, W, Z**

Measuring Unification:
Eur.Phys.J.C71:1520,2011

SUSPECT3





Low Scale MSSM

RGE

EWSB scale ~10^3GeV

RGE

Z scale ~10^2GeV

mSUGRA, SUGRA

GUT scale ~10^{16}GeV

RGE

RGE

EWSB scale ~10^3GeV

RGE

Z scale ~10^2GeV

High Scale MSSM, GMSB, mGMSB, AMSB, mAMSB

GUT scale ~10^{16}GeV

RGE

High scale ~10^{15}GeV-10^6GeV

RGE

RGE

EWSB scale ~10^3GeV

RGE

Z scale ~10^2GeV

INFLATION NEW

GUT scale ~10^{16}GeV

RGE

High scale ~10^{15}GeV

RGE

Inflation scale ~10^{14}GeV

RGE

RGE

EWSB scale ~10^3GeV

RGE

Z scale ~10^2GeV

MSSM: ~30 parameters scan
Reduce parameter space by 1: mh replaces a parameter

Replacing At with mh

EWSB determines iteratively:

- **Higgs mass parameter mu**
- **CP-odd running mass**

$$\overline{m}_A^2(M_{EWSB}) = \frac{1}{\cos 2\beta}\left(\hat{m}_{H_u}^2 - \hat{m}_{H_d}^2\right) - \overline{m}_Z^2,$$

$$\mu^2(M_{EWSB}) = \frac{1}{2}\Big(\left(\hat{m}_{H_u}^2 \tan\beta - \hat{m}_{H_d}^2 \cot\beta\right)\tan 2\beta - \overline{m}_Z^2\Big).$$

A_t replaced by m_h

- **Need to invert Higgs mass dependence on A_t**

$$M_s^2(p^2) = \begin{pmatrix} \overline{m}_{11}^2 - \Pi_{11}(p^2) + \frac{t_1}{v_1} & \overline{m}_{12}^2 - \Pi_{12}(p^2) \\ \overline{m}_{12}^2 - \Pi_{12}(p^2) & \overline{m}_{22}^2 - \Pi_{22}(p^2) + \frac{t_2}{v_2} \end{pmatrix}$$

$$\overline{m}_{11}^2 = \overline{m}_Z^2 \cos^2\beta + \overline{m}_A^2 \sin^2\beta,$$
$$\overline{m}_{22}^2 = \overline{m}_Z^2 \sin^2\beta + \overline{m}_A^2 \cos^2\beta,$$
$$\overline{m}_{12}^2 = -\frac{1}{2}(\overline{m}_Z^2 + \overline{m}_A^2)\sin 2\beta.$$

Add the determination of A_t:

- **A_t determined from a pole mass**
- **Need all radiative corrections**
- **Can only be implemented post-EWSB**

Important:

- **A spectrum calculation is iterative:**
  - **RGE: high scale, low scale, Z scale**
  - **EWSB**

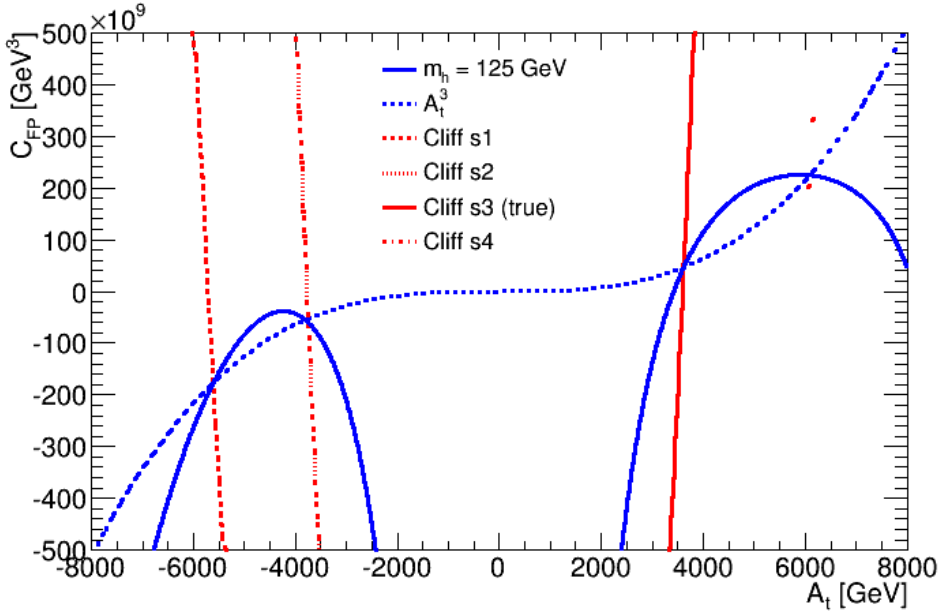
Higgs Molar:

$$\mathrm{HiggsMolar}(A_t) = C_3A_t^3 + C_2A_t^2 + C_1A_t + C_0 + (R_2A_t^2 + R_1A_t + R_0)\sqrt{a_sA_t^2 + b_sA_t + c_s} = 0$$

Replacing At

Solve for A_t:

- Not possible analytically in general
- Step through the function in steps on 1MeV (just kidding)



FixedPoint problem:

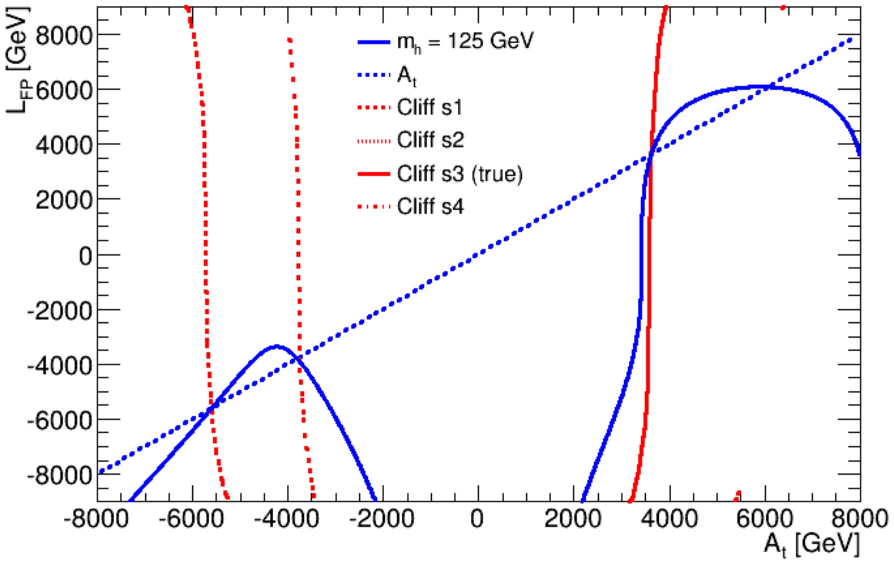
$$C_{\rm FP}(A_t) = -\frac{1}{C_3}[C_2A_t^2 + C_1A_t + C_0 + (R_2A_t^2 + R_1A_t + R_0)\sqrt{a_sA_t^2 + b_sA_t + c_s}],$$

$$A_t = \sqrt[3]{C_{\rm FP}(A_t)}.$$

$$L_{\rm FP}(A_t) \equiv \sqrt[3]{C_{\rm FP}(A_t)},$$

C_{FP} and LFP:

- Strong local dependence guides convergence
- But to converge need |LFP'| < 1 (against repulsive FPs etc)
- Define convergence parameter and function:



$$L_{\rm FP_\tau}(A_t) = \frac{1}{\tau}(L_{\rm FP}(A_t) - A_t) + A_t.$$

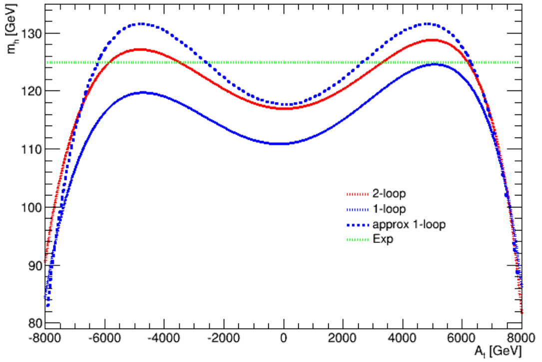
2-loop (and higher orders):

- Enter in the mass matrix
- Soft dependence

Remnants, log(A_t) and 2-loop:

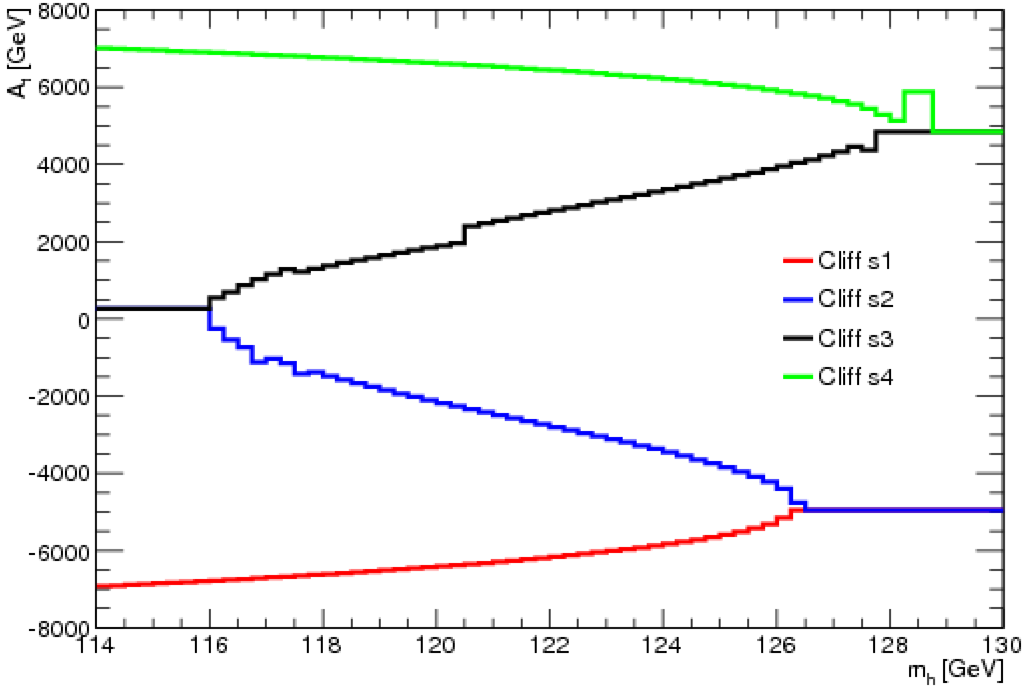
- Taken into account exactly in the EWSB iterations
- EWSB iterations are standard also in "standard" MSSM!

Proof of Concept: Beyond the benchmark point



Proof of complete Inversion in more than 1 point:

- Stepping through mh
- Specifying s1, s2, s3, s4
- Necessitates a stepper function applied regularly to identify the local minima and maxima in m_h
- Close to extremal FP is complemented by a standard Bisection algorithm



It works (better than expected):

- Regions are separated
- continuous
- Small steps corresponding to changes in pseudoscalar mass and μ leads to a <2GeV deviation in mh
- 3 points (of 256) not converged

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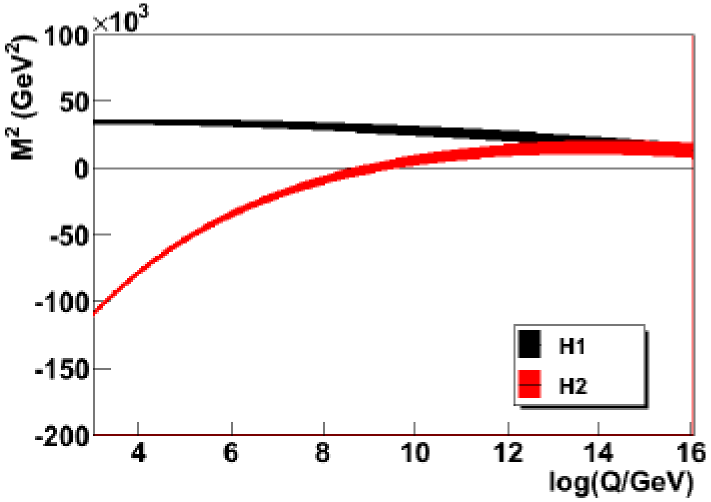
Inversion works: from $m_h(A_t)$ to $A_t(m_h)$

EWSB

Variant 1:
- m^2Hu
- m^2Hd
- sign(μ)
- At,….

Determine:
- μ
- m^2A(EWSB)



Variant 2:
- μ
- m^2A(EWSB)
- At,…

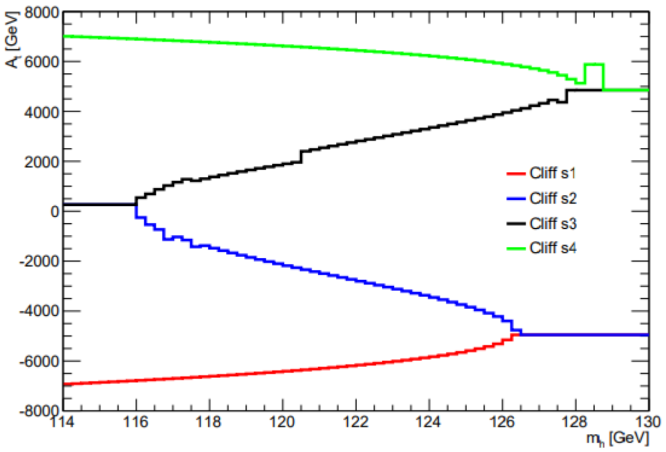
Determine:
- m^2Hd
- m^2Hu

Variant 3: NEW
- μ
- mA
- At,…

Determine:
- m^2Hd
- m^2Hu

Variant 4: NEW
- m^2Hu
- m^2Hd
- sign(μ)
- mh,…

Determine:
- μ
- m^2A(EWSB)
- At(EWSB)



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Variant 5: NEW
- μ
- m^2A(EWSB)
- mh,…

Determine:
- m^2Hd
- m^2Hu
- At(EWSB)

Variant 6: NEW
- μ
- mA
- mh,…

Determine:
- m^2Hd
- m^2Hu
- At(EWSB)

C++ Inheritance: Models and EWSB

Models:

- Base for initialization
- Generic bottom up running NEW
- Generic models as function of the number of scales (up to 5)
- Generic models implement the algorithm:
  - RGE running
  - Calculating rad corrs at the right scale
  - Calculating pole masses
- Specific models implement boundary conditions (set the SUSY breaking parameters)
- Minimal models inherit from larger models of the same type

Examples:

- Base → 2scales →LowScaleMSSM
- Base → 4scales → GMSB →mGMSB
- Base → 4scales → AMSB →mAMSB
- ….

EWSB

- Base for initialization
- 3 classes EWSBclassic → Base
  - Algorithm specific part
  - m^2H_u m^2H_d
  - μ, mA^2(EWSB) (BC at 3 scales)
  - μ, mA
- 1 class EWSBmh→ Base
  - mh NEW
- EWSBclassic+EWSBmh
  - Alg developed for 1 EWSB variant, worked for all 3
  - Difficulty: diamond inheritance (virtual solved the problem)

Upgrades wrt SuSpect2 and Technicalities

Upgrades:

- EWSB decoding automatic
- EWSB with Higgs inversion
- Closer to respecting full SLHA specifications:
  - EXTERNAL Block index 0: non standard in SuSpect2, now standard treatment
- 1st and 2nd generation sfermion parameters separated
- Complete rad corr Charginos Neutralinos calculated on pole masses instead of previous approximations
- Kept SLHA+ capability of fixed EWSB and GUT scales
- Implemented inflation model

Code maintenance:

- Started with disk
- Moved to svn@LAL
- Moved to gitlab.in2p3.fr
- Implemented CI tests for example files

Testing:

- Comparisons with SuSpect2 (will be maintained)
- Compilation gcc 4.8.5 and 8.1.0 with severe flags (well kind of)
- Checked all example Models with valgrind

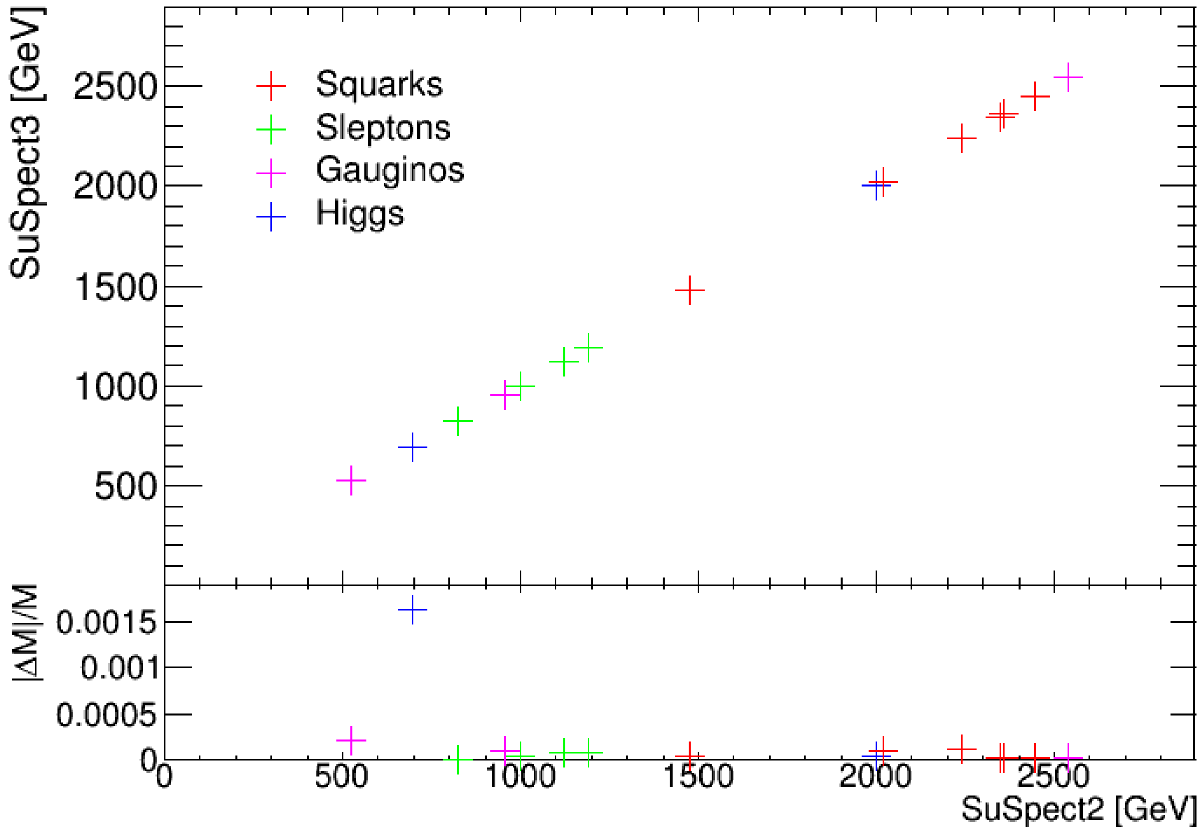
User feedback:

- in memory initialization: example code and HowTo on web page
- adding mixture of file input +in memory: use of copy constructor with HowTo on webpage

Availability:

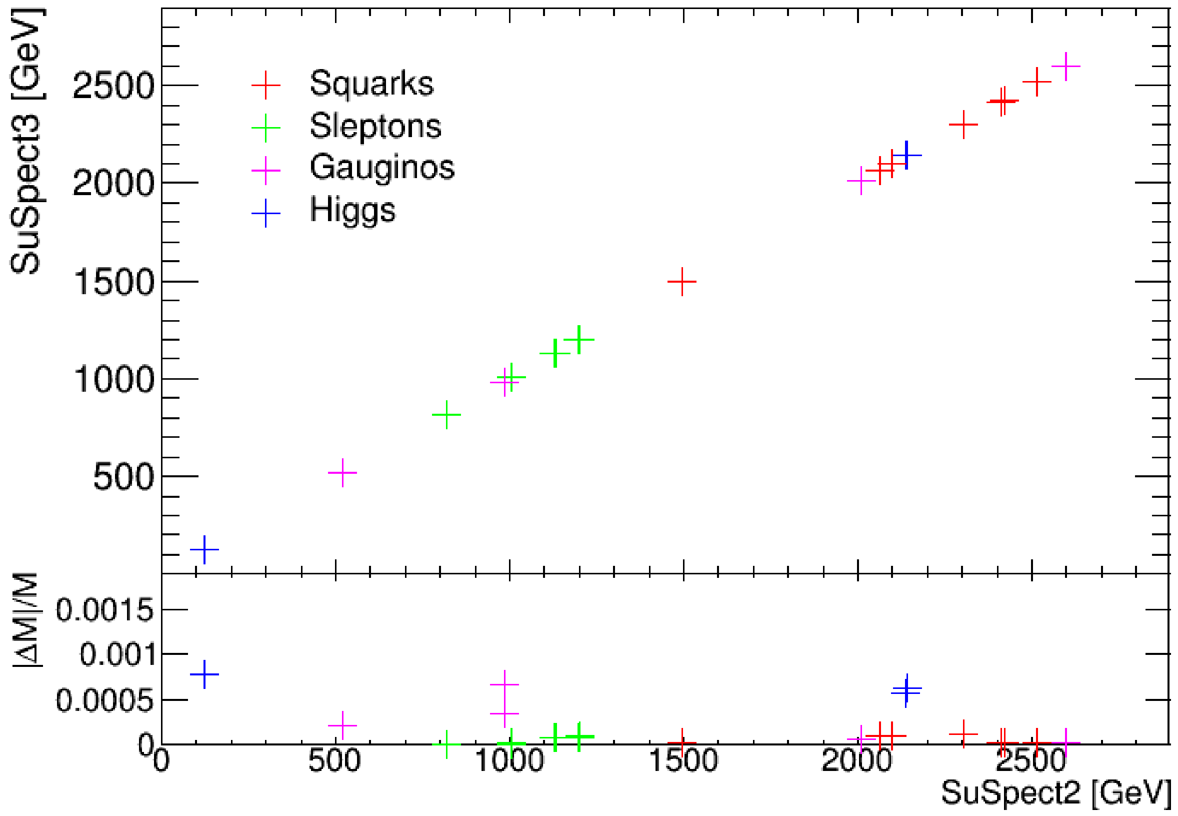
- v3.1.1
- http://suspect.in2p3.fr
- wget http://suspect.in2p3.fr/tar/suspect3.tar.gz
- tar xvfz suspect3.tar.gz
- ./configure
- make
- suspect3 –d examples/mSUGRA.in

Comparisons SuSpect2 and SuSpect3



MSOFT:

- **Test of RGE solutions**
- **permil level agreement (excellent)**
- **largest deviation in the Higgs sector mHd**
- **due to YD(3,3) at low scale**



Pole masses

- **test of RGE+Diagonalization+RadCorrs**
- **permil level agreement and better**

Conclusions and outlook

Proof of concept:

- m_h as fundamental parameter of the MSSM: doable
- Correct to all orders
- Stop cliff benchmark: works
- 1d scan: works

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SuSpect3:

Excellent collaboration between theorists and experimentalists lead to:

- Major rewrite of SuSpect
- Support for more models
- New variants of EWSB

arXiv:2211.16956

Future work:

- Improvements on the Higgs Inversion

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