CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Next-to-Minimal SOFTSUSY

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- NMSSM model
- NMSSM Spectrum calculation
- Code structure
- Download and install
- Running the code
- Conclusions

Spectrum generators

Solve boundary value problem finding:

$\overline{DR}$ Parameters (masses and couplings) at low energies

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consistent with:

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Low energy data ($m_Z, G_F, m_{top} \ldots$)

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➢ Spectrum generators play a crucial role in SUSY phenomenology

- Allow fast exploration of the parameter space with high precision

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  e.g. Dark matter calculators, low energy observables, decay tools

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- Allow fast exploration of the parameter space with high precision
- Provides required input for many other HEP tools

  e.g. Dark matter calculators, low energy observables, decay tools

- Typically appears at the top of a long calculation tool chain for doing phenomenology

NMSSM Spectrum generation

SOFTSUSY: popular, fast, precise, reliable tool for MSSM spectra

Next-to-Minimal SOFTUSY update provides all this in NMSSM too

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NMSSM previously had one public spectrum generator NMSPEC

(Can also auto-generate codes with FlexibleSUSY, SARAH)

(see talk by A. Voigt next)

Many MSSM spectrum generators

SOFTSUSY, ISASUSY, SPheno, SUSEFLAV, SUSPECT

bug catching, cross-checks, different capabilities, approaches

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bug catching, cross-checks, different capabilities, approaches

With Next-to-Minimal SOFTUSY now get this benefit in NMSSM

NMSSM Spectrum generation

- The μ–problem

$$\text{Why } \mu \approx 0.1 - 1 \text{ TeV?}$$

$$\mathcal{W}_{MSSM} = Y_u \hat{\bar{Q}}_L \hat{H}_u \hat{u}_R - Y_d \hat{\bar{Q}}_L \hat{H}_d \hat{d}_R - Y_e \hat{\bar{E}} \hat{H}_d \hat{d}_R - \mu \hat{H}_u \hat{H}_d$$

NMSSM Spectrum generation

- Solve μ-problem

$$\text{generate } \mu \approx 0.1 - 1 \text{ TeV}$$

$$\mathcal{W}_{PQNMSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L H_d d_R - Y_e \bar{E} H_d d_R - \lambda S H_u H_d$$

NMSSM Spectrum generation

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- Increase the Higgs mass (low $\tan\beta$, high λ)

$$m_h^2 \approx \underbrace{M_Z^2 \cos^2 2\beta}_{\mathrm{MSSM}} + \frac{\lambda^2}{2} v^2 \sin^2 2\beta$$

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- Improved naturalness

e.g. [M.Bastero-Gil, C.Hugonie, S.F.King, D.P.Roy , S.Vempati, PLB 489, 359; S. F. King, M. Mhlleitner, R. Nevzorov and K. Walz,Nucl. Phys. B 870 323,;T. Gherghetta, B. von Harling, A. D. Medina,M. A. Schmidt, JHEP 02, 032; D.Kim, PA, C.Balázs, B.Farmer, E.Hutchison arXiv:1312.4150]

NMSSM

$$SU(3)_C \times SU(2)_W \times U(1)_Y$$

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Chiral superfields

$$\hat{\Psi}_i \to e^{iQ_i^{PQ}\theta} \hat{\Psi}_i$$

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
$\hat{Q}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	-1
$\overline{u}_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0
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$\hat{L}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
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NMSSM

Break PQ symmetry explictly with cubic term: $\frac{\kappa}{3}S^3$

$\Rightarrow$ usual $\mathcal{Z}_3$ symmetric NMSSM

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$\mathcal{Z}_3$ symmetric

$$\mathcal{W}_{\mathcal{Z}_3} = \left[Y_E L H_1 \bar{E} + Y_D Q H_1 \bar{D} + Y_U Q H_2 \bar{U} + \lambda S(H_2 H_1)\right] + \frac{\kappa}{3} S^3$$

$$= \mathcal{W}_{\text{MSSM}}^{\mu=0} + \lambda S(H_2 H_1) + \frac{\kappa}{3} S^3$$

NMSSM

Break PQ symmetry explictly with cubic term: $\frac{\kappa}{3} S^3$

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Use all renormalisable terms

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$$\begin{aligned} \mathcal{W}_{\mathcal{Z}_3} &= \left[Y_E L H_1 \bar{E} + Y_D Q H_1 \bar{D} + Y_U Q H_2 \bar{U} + \lambda S (H_2 H_1)\right] + \frac{\kappa}{3} S^3 \\ &= \mathcal{W}^{\mu=0}_{\mathrm{MSSM}} + \lambda S (H_2 H_1) + \frac{\kappa}{3} S^3 \end{aligned}$$

NMSSM

Break PQ symmetry explictly with cubic term: $\frac{\kappa}{3}S^3$

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$$\mathcal{W}_{\not{\mathcal{Z}}_3} = \mathcal{W}^{\mu=0}_{MSSM} + \lambda S H_2 H_1 + \mu H_2 H_1 + \xi_F S + \frac{\mu'}{2}S^2 + \frac{\kappa}{3}S^3$$

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Next-to-Minimal SOFTSUSY can generate spectra in both cases

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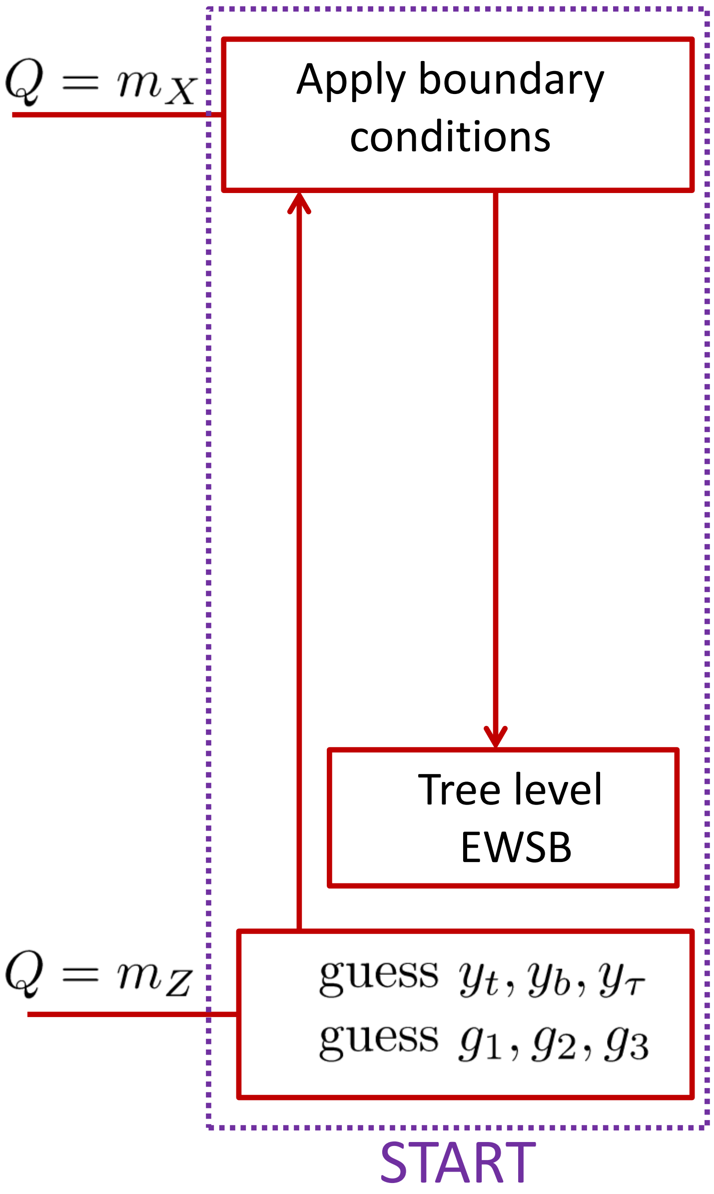
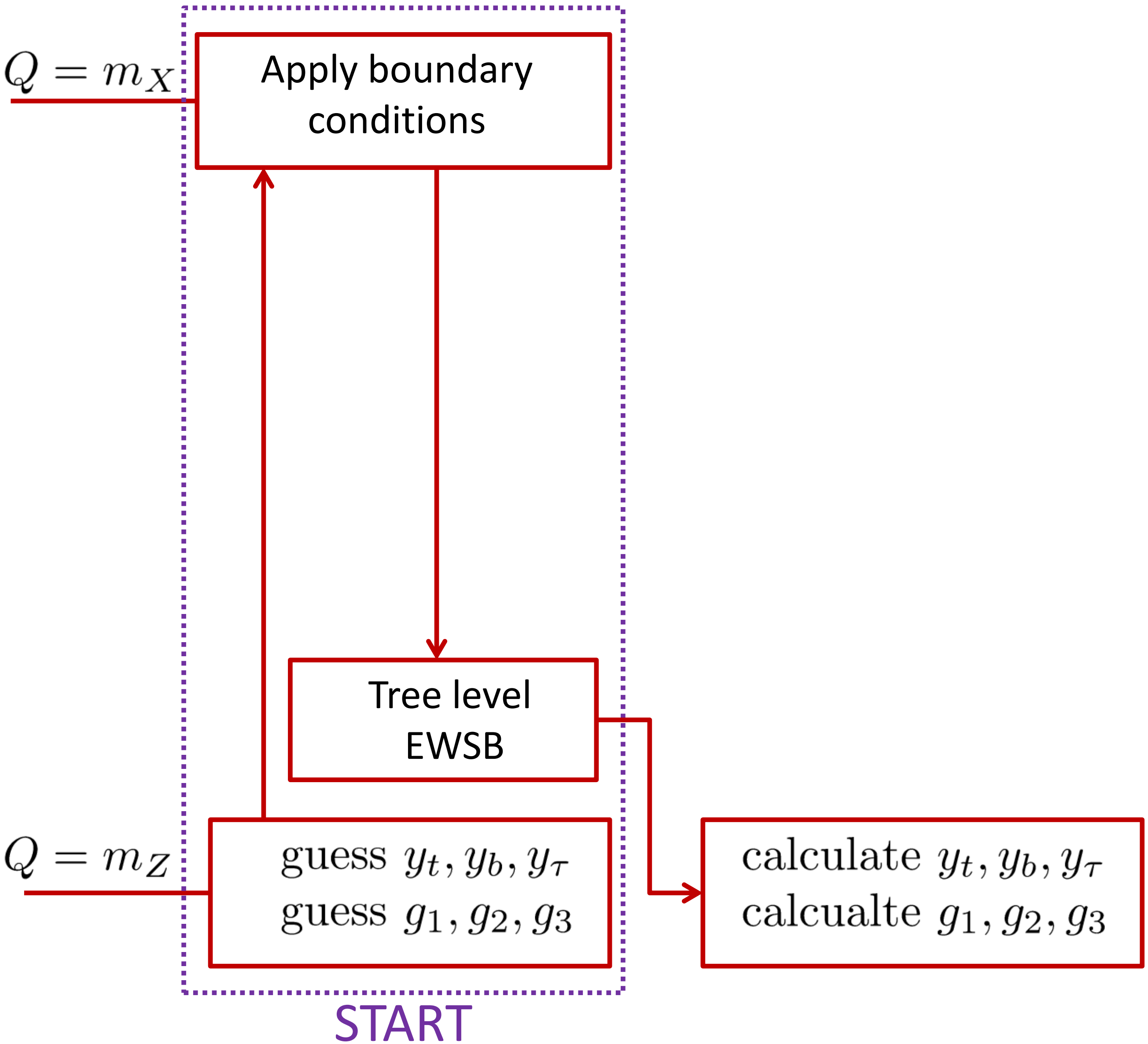
Algorithm



$Q = m_X$
Apply boundary conditions
Tree level EWSB
$Q = m_Z$
guess y_t, y_b, y_τ
guess g_1, g_2, g_3
START

Algorithm



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calcualte g_1, g_2, g_3
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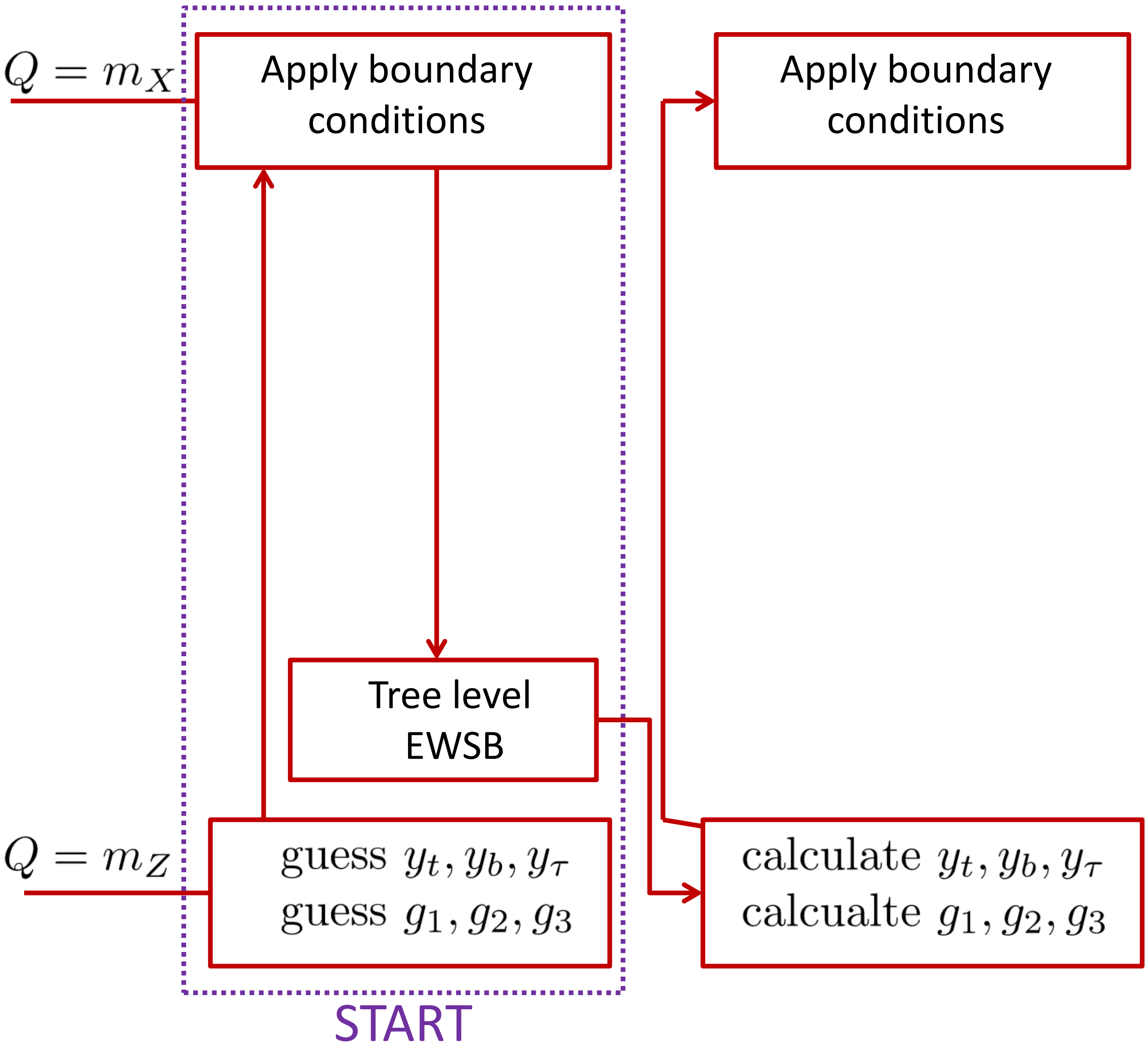
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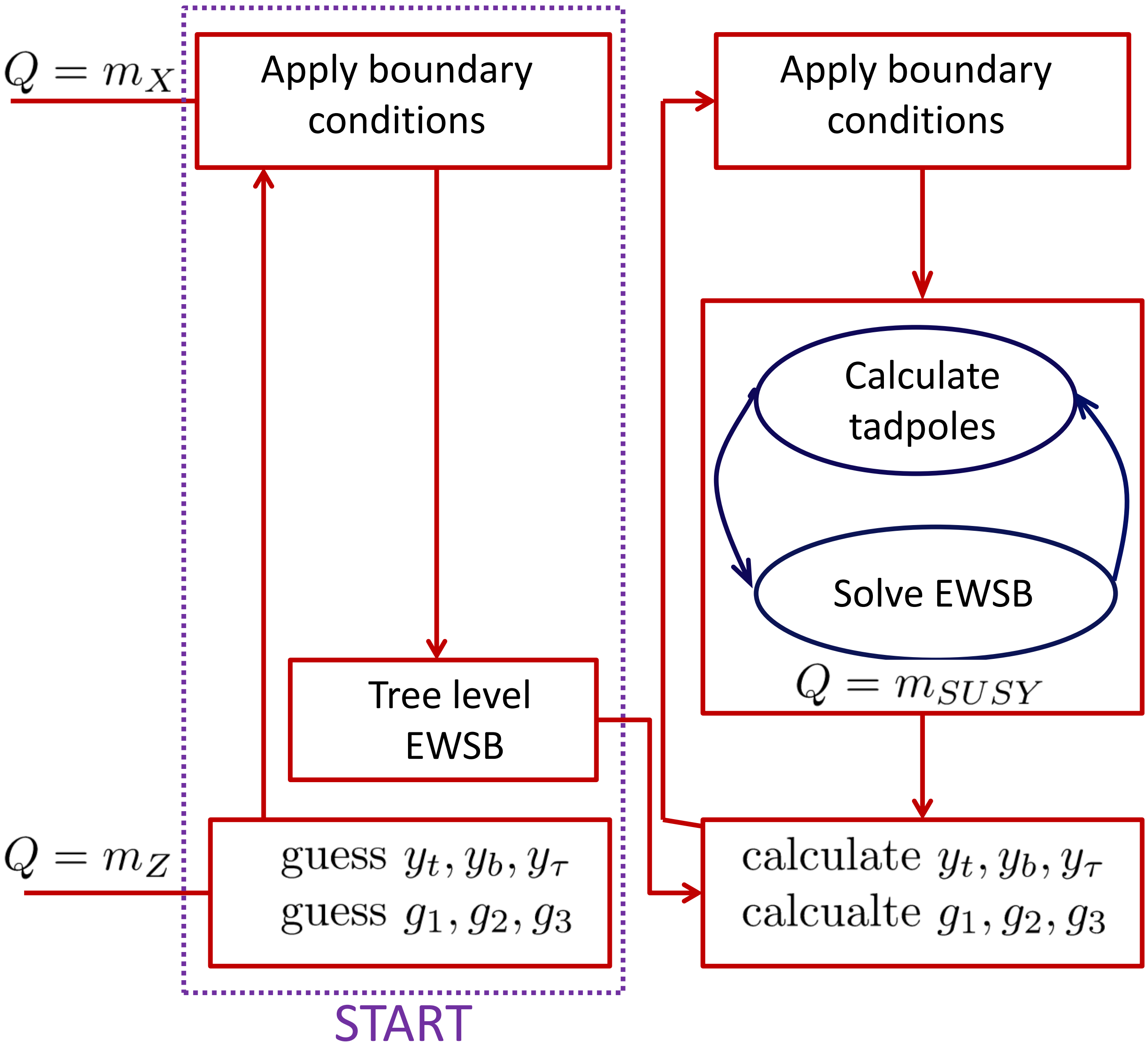

$Q = m_X$
Apply boundary conditions
Apply boundary conditions
Calculate tadpoles
Solve EWSB
$Q = m_{SUSY}$
Tree level EWSB
$Q = m_Z$
guess y_t, y_b, y_τ
guess g_1, g_2, g_3
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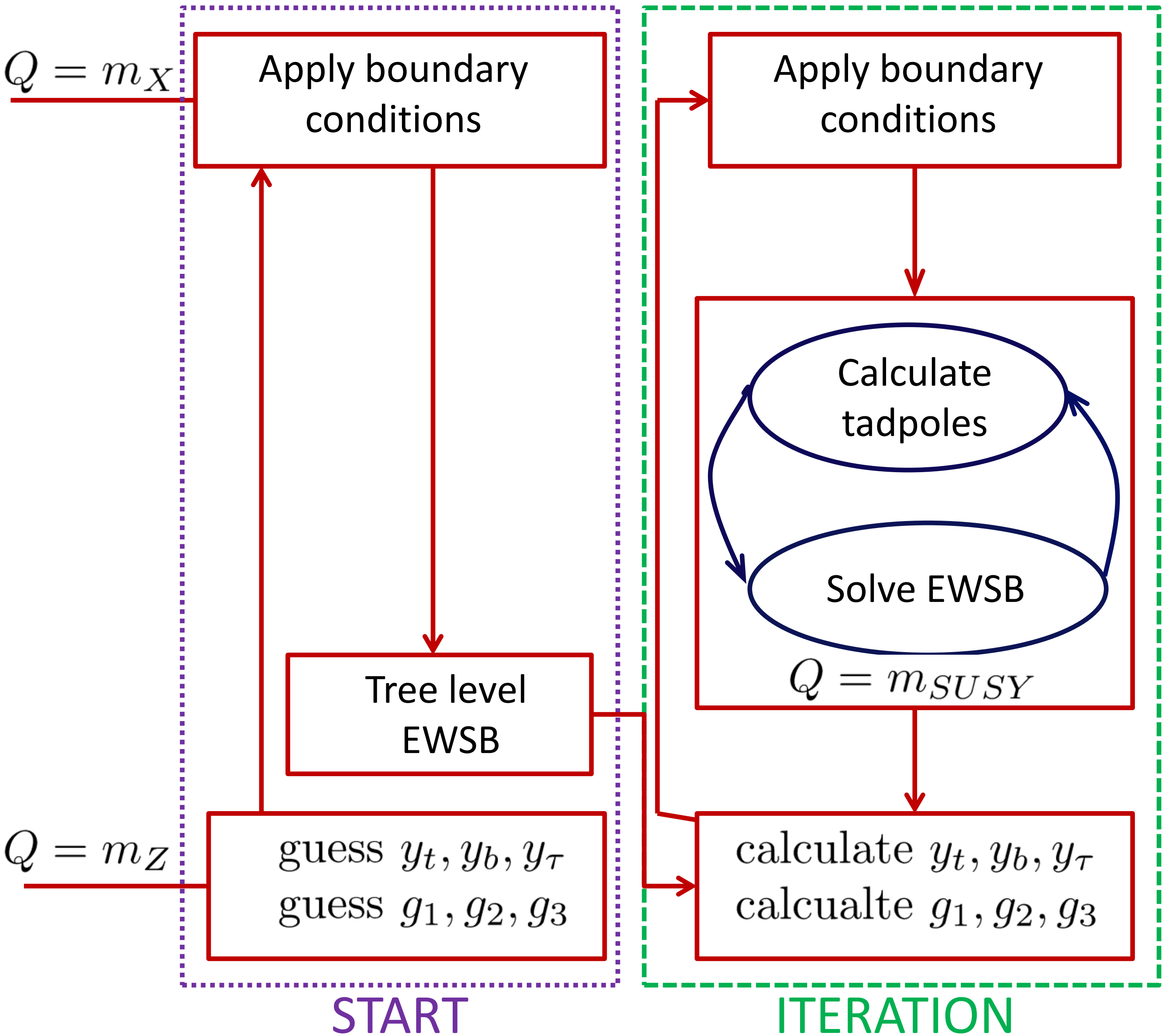

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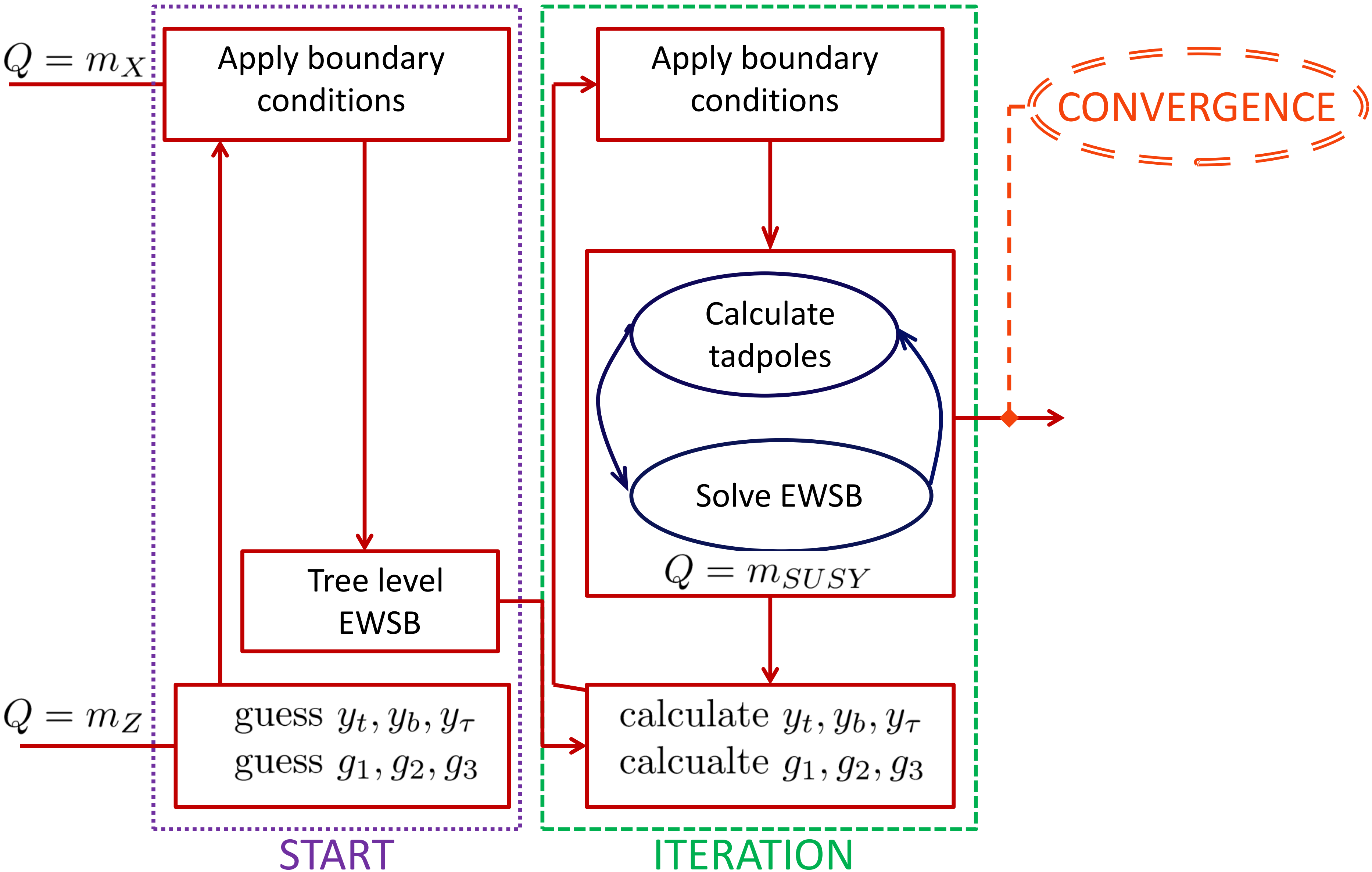
ITERATION

Algorithm



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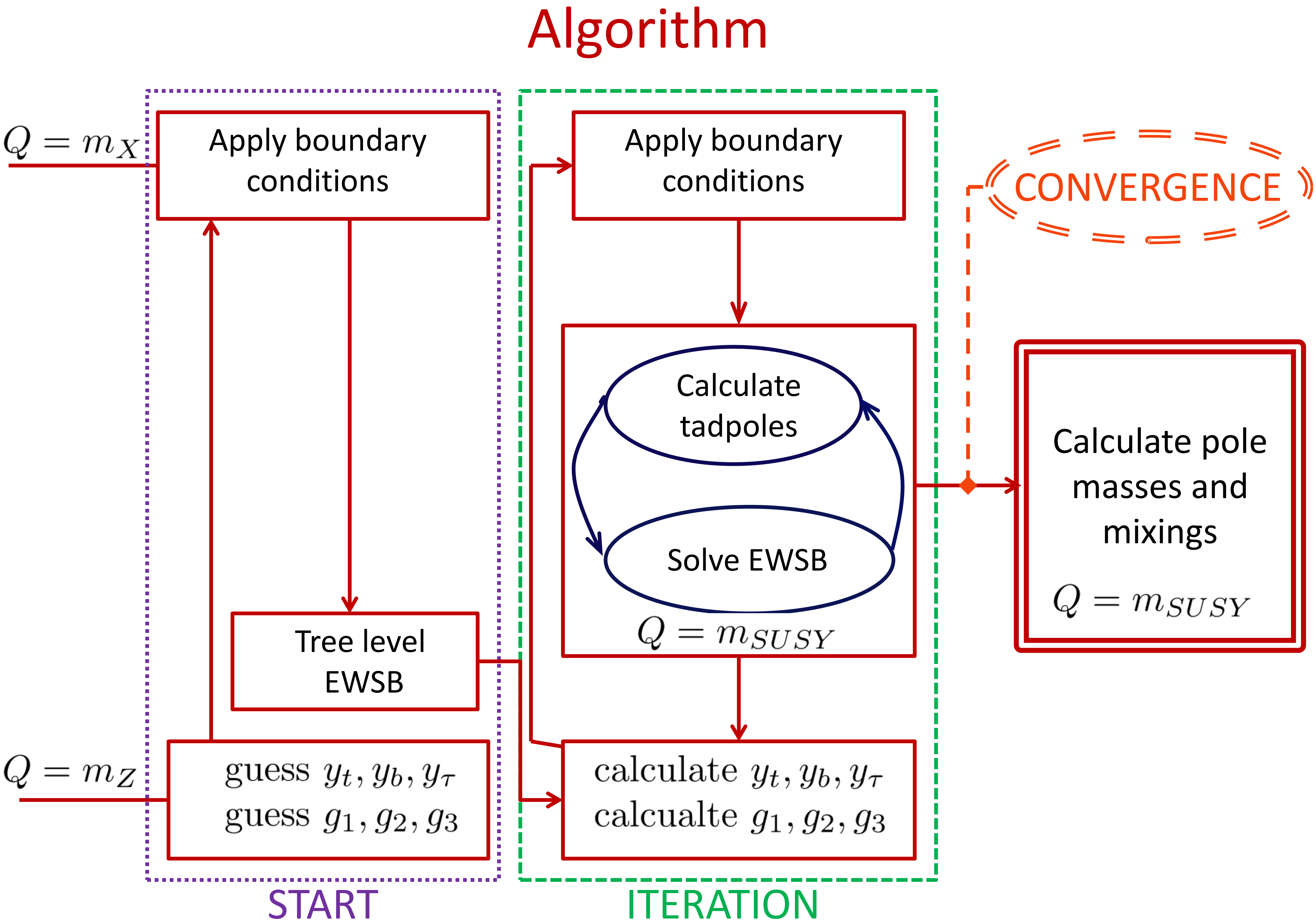

Algorithm
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CONVERGENCE
Calculate pole masses and mixings
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Technical pieces

- Two-loop Renormalisation group equations (full 3 family)
  - Needed for evolution between scales e.g, GUT and EW
  - Obtained from gen. expressions [Martin,Vaughn PRD 50, 2282]
  - checked against NMSSM rev. [Ellwanger,Hugonie,Teixeira Phys.Rept. 96, 1]

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[PA,Park,Stöckinger ,Voigt, arXiv:1406.2319]

(see also talk by A. Voigt)

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- Full one loop self energies and tadpoles
  - $\mathcal{Z}_3$ expr. taken from literature [G.Degrassii, P.Slavich Nucl.Phys. B 825, 119]

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- Full one loop self energies and tadpoles
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  - — Checked numerically via two independent implementations (most cases)
  - — Checked numerically against FlexibleSUSY (all cases)

Higgs Mass accuracy

- Obtain $\overline{\text{DR}}$ mass matrix
- Full one loop self energies for all Higgs states
- Two loop corrections using files from Pietro Slavich (for neutral Higgs states)

$\mathcal{O}(\alpha_s\alpha_b)$, $\mathcal{O}(\alpha_s\alpha_t)$ NMSSM zero momentum
[G.Degrassii, P.Slavich Nucl.Phys. B 825, 119]

$\mathcal{O}\left((\alpha_t+\alpha_b)^2\right)$, $\mathcal{O}(\alpha_\tau^2)$ MSSM parts zero momentum

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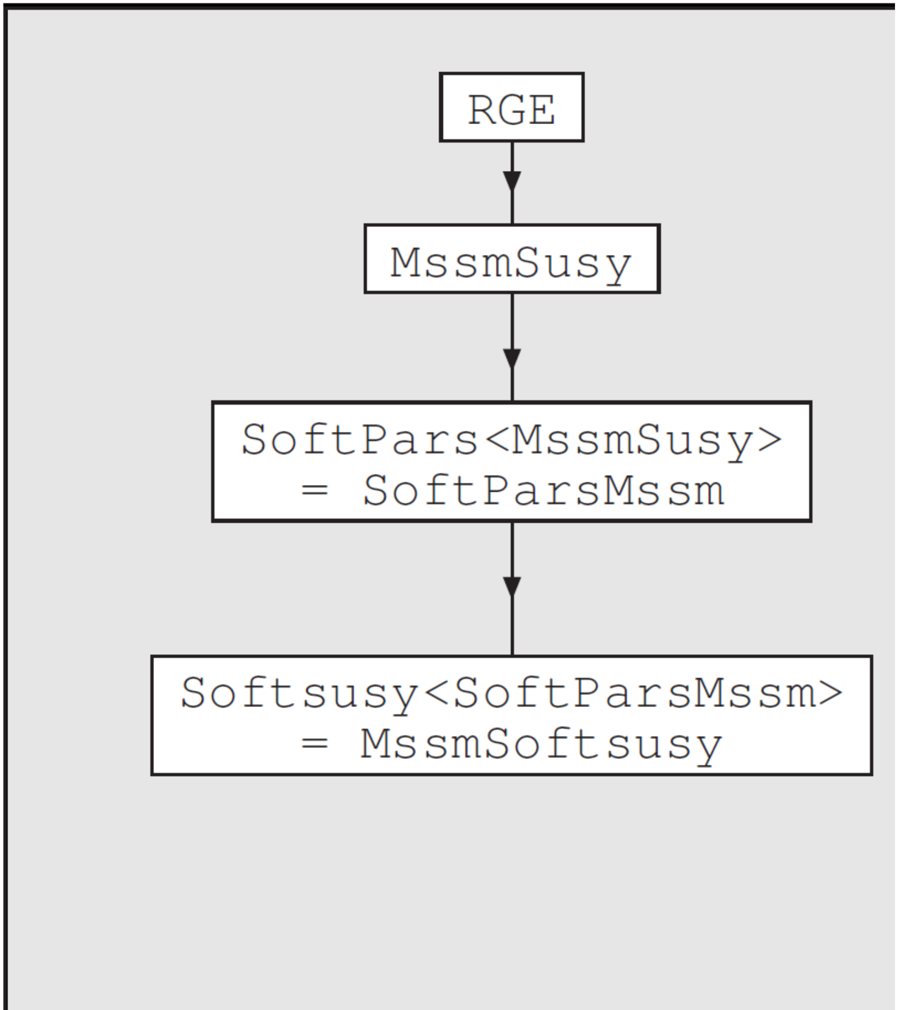
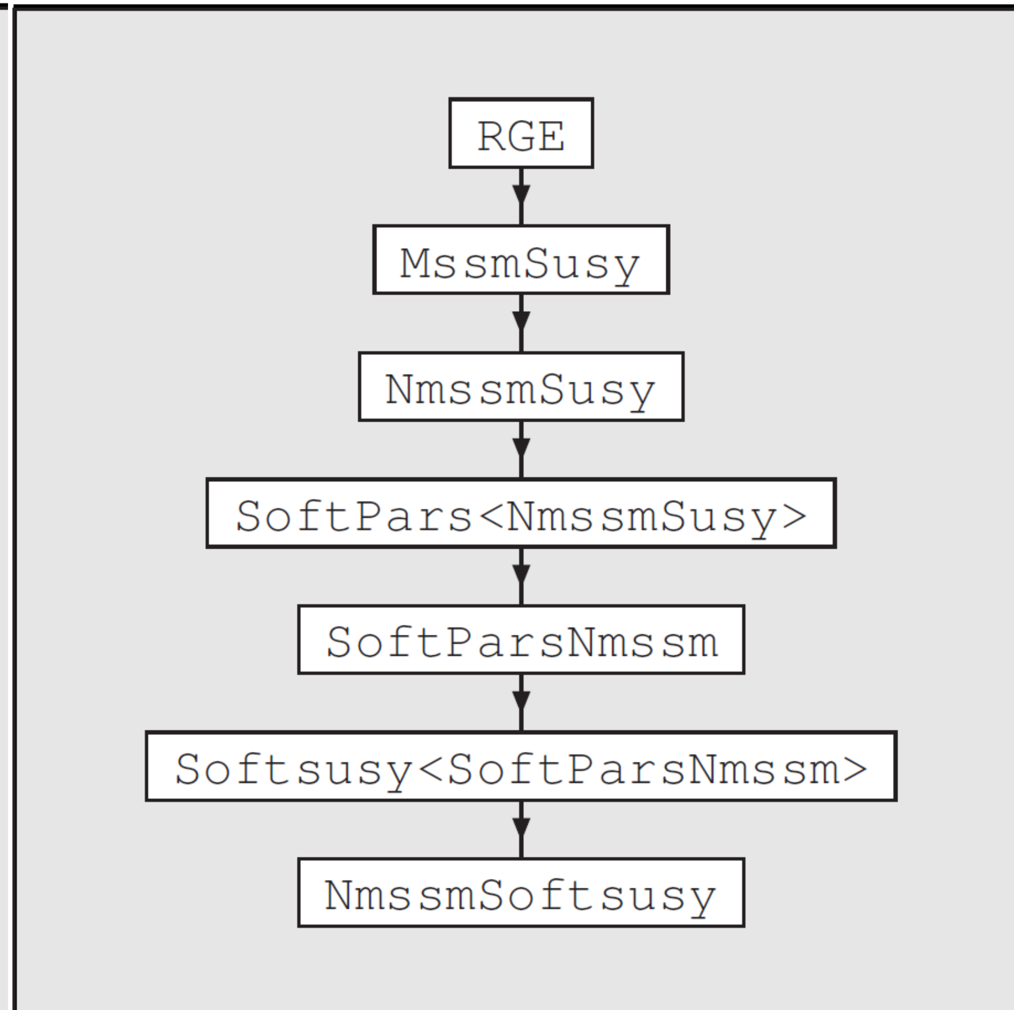
- one loop self energies use at $p^2 = m_{h_i^2}$ via iteration:

$$M_H^2 + \Sigma(p^2 = m_{h_i}^2) \xrightarrow[\text{for eigenvalues}]{\text{diagonalise}} m_{h_i}^2$$

Code structure

- SOFTSUSY code structure has been updated a little
- minimises code duplication, errors
- methods maintain familiarity for expert users





Download and install

Next-to-Minimal SOFTSUSY is an extension of SOFTSUSY

Distributed as part of SOFTSUSY from version 3.4.0 onwards

View/Download latest version from: http://softsusy.hepforge.org/

Download

```
wget http://www.hepforge.org/archive/softsusy/softsusy-3.4.1.tar.gz
tar -xvzf softsusy-3.4.0.tar.gz
cd softsusy
```

Install

```
./configure
make -jN
```

N is the number of jobs to run simultaneously for parallel make

Test Run

```
./softsusy-nmssm.x > inOutFiles/outputTest-nmssm
./softpoint.x leshouches < inOutFiles/nmssmSLHAnoZ3Input > nmSLHAnoZ3Output
./softpoint.x leshouches < inOutFiles/nmssmSLHAZ3Input > nmSLHAZ3Output
```

Running the code

Option 1

Use the SLHA interface by passing an SLHA2 Input file

[CPC 180 (2009) 8]

To run:

call the softpoint executable as shown on the last slide:

```
./softpoint.x leshouches < inOutFiles/nmssmSLHAnoZ3Input > nmSLHAnoZ3Output
./softpoint.x leshouches < inOutFiles/nmssmSLHAZ3Input > nmSLHAZ3Output
```

User written SLHA2 input file

SLHA2 output file

Running the code

WARNING: this interface has changed in version 3.4.0 onwards
Details here are for the new version for 3.4.0 and later

Option 2

Use the command line interface

To run:
call the softpoint executable again
but now without leshouches option
and passing parameters as options like:

```
./softpoint.x  --m0=<m0> --m12=<m12> --a0=<a0> --tanBeta=<tb> --lambda=<lam>
```

Running the code

NMSSM flags	description
`--lambdaAtMsusy`	input λ at scale M_{SUSY}

NMSSM parameters	description
`--m0=<value>`	unified soft scalar mass
`--m12=<value>`	unified soft gaugino mass
`--a0=<value>`	unified trilinear coupling
`--tanBeta=<value>`	$\tan\beta$
`--mHd2=<value>`	soft down-type Higgs mass squared $m_{H_1}^2$
`--mHu2=<value>`	soft up-type Higgs mass squared $m_{H_2}^2$
`--mu=<value>`	μ parameter
`--m3SqrOverCosBetaSinBeta=<value>`	$m_3^2/(\cos\beta\sin\beta)$
`--lambda=<value>`	trilinear superpotential coupling λ
`--kappa=<value>`	trilinear superpotential coupling κ
`--Alambda=<value>`	trilinear soft coupling A_λ
`--Akappa=<value>`	trilinear soft coupling A_κ
`--lambdaS=<value>`	$\lambda\langle S\rangle = \lambda s/\sqrt{2}$
`--xiF=<value>`	linear superpotential coupling ξ_F
`--xiS=<value>`	linear soft coupling ξ_S
`--muPrime=<value>`	bilinear superpotential coupling μ'
`--mPrimeS2=<value>`	bilinear soft coupling $m_S'^2$
`--mS2=<value>`	bilinear soft mass m_S^2

Running the code

Option 3

Write program calling the fixed point iteration e.g distributed sample program: src/main-nmssm.cpp

This sample code was called earlier in the TestRun example:

```
./softsusy-nmssm.x > inOutFiles/outputTest-nmssm
```

Running the code

Option 3

Write program calling the fixed point iteration e.g distributed sample program: src/main-nmssm.cpp

This sample code was called earlier in the TestRun example:

```
./softsusy-nmssm.x > inOutFiles/outputTest-nmssm
```

Call fixed point iteration

```
NmssmSoftsusy n;
n.lowOrg(SemiMsugraBcs, mGutGuess, pars, nmpars, sgnMu, tanb, oneset, uni);
```

Using the code

Get SM inputs at MZ:

```
QedQcd oneset; ///< See "lowe.h" for default definitions parameters
double alphasMZ = 0.1187, mtop = 173.5, mbmb = 4.18;
oneset.setAlpha(ALPHAS, alphasMZ); oneset.setPoleMt(mtop);
oneset.setMass(mBottom, mbmb);
oneset.toMz(); ///< Runs SM fermion masses to MZ
```

Fix parameters :

```
double m12 = 300., a0 = -300., mGutGuess = 2.0e16, tanb = 10.0, m0 = 500.;
int sgnMu = 1; ///< sign of effective mu parameter
double lambda = 0.1, s = 0.0, xiF = 0.0, mupr = 0.0;
```

Fill

```
DoubleVector pars(5), nmpars(5);
pars(1) = m0; pars(2) = m12; pars(3) = a0; pars(4) = a0, pars(5) = a0;
nmpars(1) = lambda; nmpars(2) = kappa; nmpars(3) = s; nmpars(4) = xiF; nmpars(5) = mupr;
bool uni = true; // MGUT defined by g1(MGUT)=g2(MGUT)
softsusy::Z3 = true; // choose Z3 conserving case (selects EWSB conditions)
```

Call fixed point iteration

```
NmssmSoftsusy n;
n.lowOrg(SemiMsugraBcs, mGutGuess, pars, nmpars, sgnMu, tanb, oneset, uni);
```

Using the code

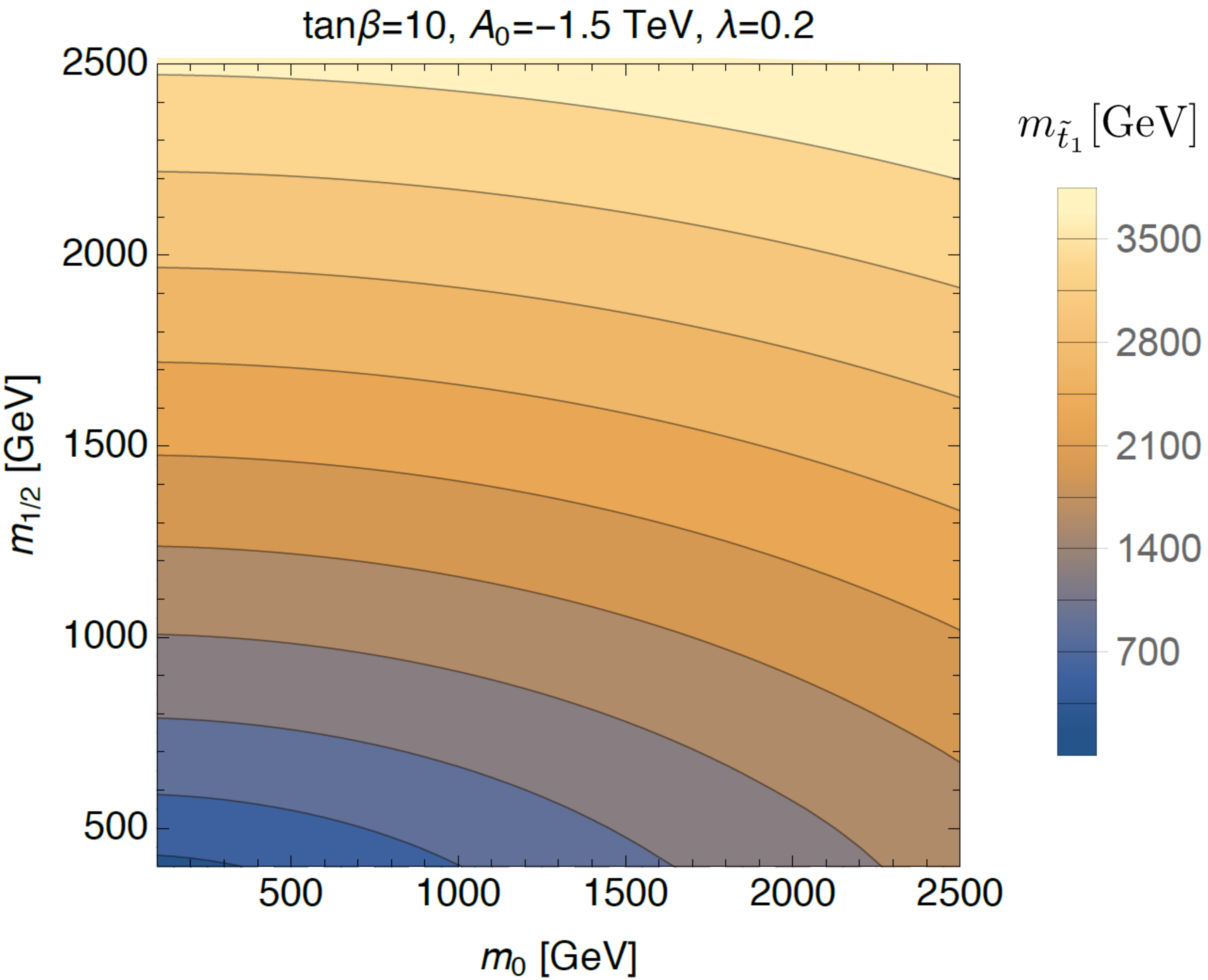
Option 3

Gives great flexibility and control to the user
Wrap grid or random scan of parameters
around last step

→ Produce plots of the physics

For example...

Using the code



Running the code

Interface with NMSSMTools

Setup:

```
$ cd /path/to/NMSSMTools/
$ wget http://www.th.u-psud.fr/NMHDECAY/NMSSMTools_4.1.2.tgz
$ tar xf NMSSMTools_4.1.2.tgz
$ cd /path/to/softsusy/
$ ./setup_nmssmtools.sh \
     --nmssmtools-dir=/path/to/NMSSMTools/NMSSMTools_4.1.2 \
     --compile
```

Run:

```
$ ./softsusy_nmssmtools.x leshouches < slhaInput > slhaOutput
```

SLHA options:

```
Block SOFTSUSY
   15    1       # NMSSMTools compatible output (default: 0)
   16    4       # Select Micromegas option for NMSSMTools
   17    1       # 1:sparticle decays via NMSDECAY (default: 0)
```

Conclusions

- Next-to-Minimal SOFTSUSY is here now!
- Next-to-Minimal SOFTSUSY is fast, reliable, easy to use
- Go to the SOFTSUSY website now!

Download it!

Install it!

Use it!

Hack it!

Tell us what you think of it!

Back up slides

EWSB

$$V_{\rm Higgs} = V_F^H + V_D^H + V_{\rm soft}^H$$
$$= V_{\rm MSSM}^{\mu=0} + V_F^{HN} + V_{\rm soft}^{HN}$$

$$\langle H_1^0 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle H_2^0 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix},$$
$$\langle S \rangle = \frac{1}{\sqrt{2}} s$$

$$V_F^{HN} = |\lambda S + \mu|^2 (|H_2|^2 + |H_1|^2) + |\lambda H_2 H_1 + \kappa S^2 + \mu' S + \xi_S|^2 ,$$
$$V_{\rm soft}^{HN} = m_S^2 |S|^2 + \left(\lambda A_\lambda S H_2 H_1 + \frac{\kappa}{3} A_\kappa S^3 + \frac{m_S'^2}{2} S^2 + \xi_S S + \text{h.c.} \right) .$$

$$\mu_{\rm eff} \equiv \mu + \frac{\lambda s}{\sqrt{2}}, \quad B_{\rm eff} \equiv A_\lambda + \frac{\kappa s}{\sqrt{2}} \quad (m_3^2)_{\rm eff} \equiv \frac{\lambda s}{\sqrt{2}} B_{\rm eff} + \widehat{m}_3^2 \quad \widehat{m}_3^2 \equiv m_3^2 + \lambda\left(\frac{\mu' s}{\sqrt{2}} + \xi_F \right)$$

$$m_{H_1}^2 = -\frac{M_Z^2}{2}\cos(2\beta) - \frac{\lambda^2}{2} v_2^2 + (m_3^2)_{\rm eff} \tan\beta - |\mu_{\rm eff}|^2 ,$$
$$m_{H_2}^2 = \frac{M_Z^2}{2}\cos(2\beta) - \frac{\lambda^2}{2} v_1^2 + \frac{(m_3^2)_{\rm eff}}{\tan\beta} - |\mu_{\rm eff}|^2 ,$$
$$m_S^2 = -\kappa^2 s^2 - \frac{\lambda^2}{2} v^2 + \kappa\lambda v_2 v_1 + \lambda A_\lambda \frac{v_2 v_1}{\sqrt{2} s} - \kappa A_\kappa s - m_S'^2 - \mu'^2 + 2\kappa\xi_F - 3\kappa s \mu'$$

EWSB

Options for parameters fixed by EWSB conditions:

$\mathcal{Z}_3$ (covering $\{s, \kappa, m_S\}$ and $\{m_{H_u}^2, m_{H_d}^2, m_S^2\}$)

$\not{\mathcal{Z}_3}$ (covering $\{m_{H_u}^2, m_{H_d}^2, m_S^2\}$ and $\{\mu, m_3^2, \xi_S\}$)

$$\{s, \kappa, m_S\} \qquad \{m_{H_u}^2, m_{H_d}^2, m_S^2\} \qquad \{\mu, m_3^2, \xi_S\}$$

$$\mu_{\rm eff} \equiv \mu + \frac{\lambda s}{\sqrt{2}} \quad B_{\rm eff} \equiv A_\lambda + \frac{\kappa s}{\sqrt{2}} \quad (m_3^2)_{\rm eff} \equiv \frac{\lambda s}{\sqrt{2}} B_{\rm eff} + \widehat{m}_3^2 \quad \widehat{m}_3^2 \equiv m_3^2 + \lambda\left(\frac{\mu' s}{\sqrt{2}} + \xi_F\right)$$

$$m_{H_1}^2 = -\frac{M_Z^2}{2}\cos(2\beta) - \frac{\lambda^2}{2} v_2^2 + (m_3^2)_{\rm eff} \tan\beta - |\mu_{\rm eff}|^2 ,$$

$$m_{H_2}^2 = \frac{M_Z^2}{2}\cos(2\beta) - \frac{\lambda^2}{2} v_1^2 + \frac{(m_3^2)_{\rm eff}}{\tan\beta} - |\mu_{\rm eff}|^2 ,$$

$$m_S^2 = -\kappa^2 s^2 - \frac{\lambda^2}{2} v^2 + \kappa\lambda v_2 v_1 + \lambda A_\lambda \frac{v_2 v_1}{\sqrt{2} s} - \kappa A_\kappa s - m_S'^2 - \mu'^2 + 2\kappa\xi_F - 3\kappa s \mu'$$