FlexibleSUSY

A spectrum generator generator

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ARC Centre of Excellence for Particle Physics at the Terascale

FlexibleSUSY: Precise automated calculations in any BSM theory

Peter Athron (Monash University, CoEPP)

FlexibleSUSY
A spectrum generator generator

https://flexiblesusy.hepforge.org/
[CPC 190 (2015) 139-172, JHEP 1701 (2017) 079, CPC 230 (2018) 145-217]

<u>Collaboration</u>

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Model specific details from:

SARAH

[F.Staub arXiv:0806.0538, CPC 181 (2010) 1077-1086, CPC 182 (2011) 808-833]

FlexibleSUSY

- Precision corrections for spectrum generators known in general form
- Exploit this abstraction to aid theory and phenomenology.

SARAH ⟶ Feynman rules, RGEs, Self Energies, tadpoles... [F. Staub]

↑

FlexibleSUSY ⟶ C++ code, fast, modular, adaptable, reliable.

```
$ ./install-sarah # if not already installed
$ ./createmodel --name=NMSSM
$ ./configure --with-models=NMSSM
$ make
```

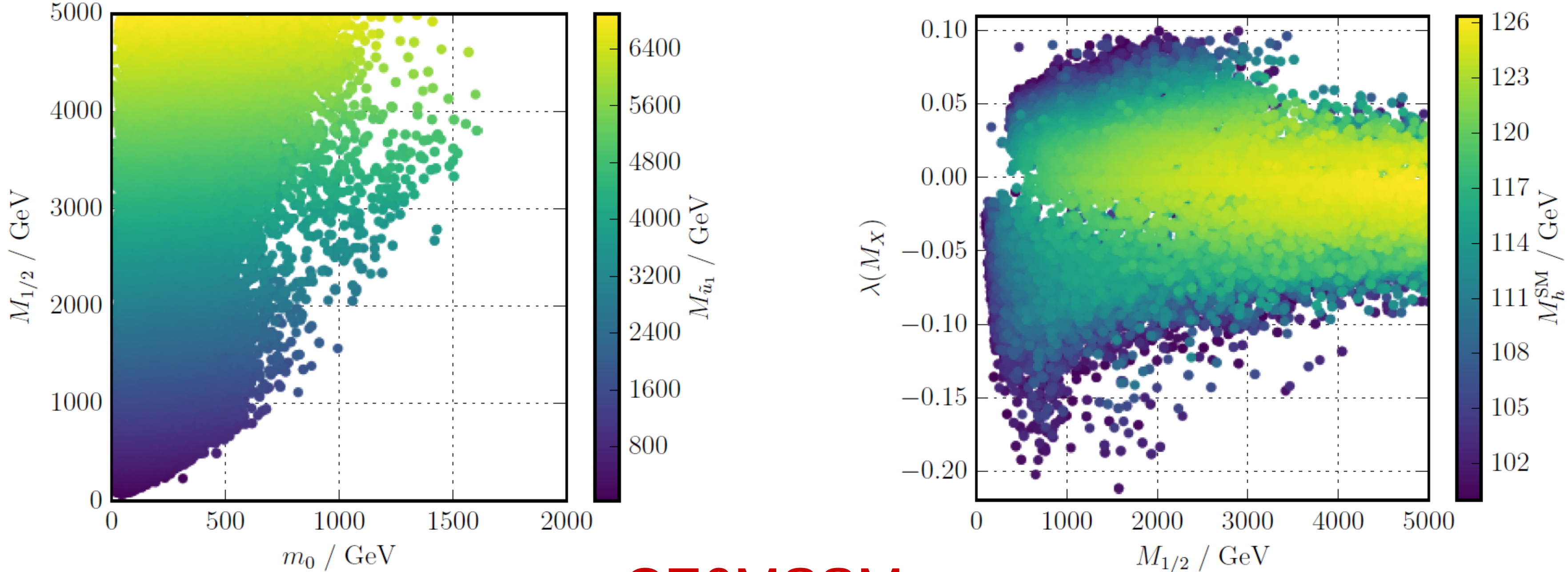
- Many prebuilt spectrum generators: MSSM,NMSSM,USSM,E6SSM...

(No SARAH / MATHEMATICA dependence) https://flexiblesusy.hepforge.org/models.html

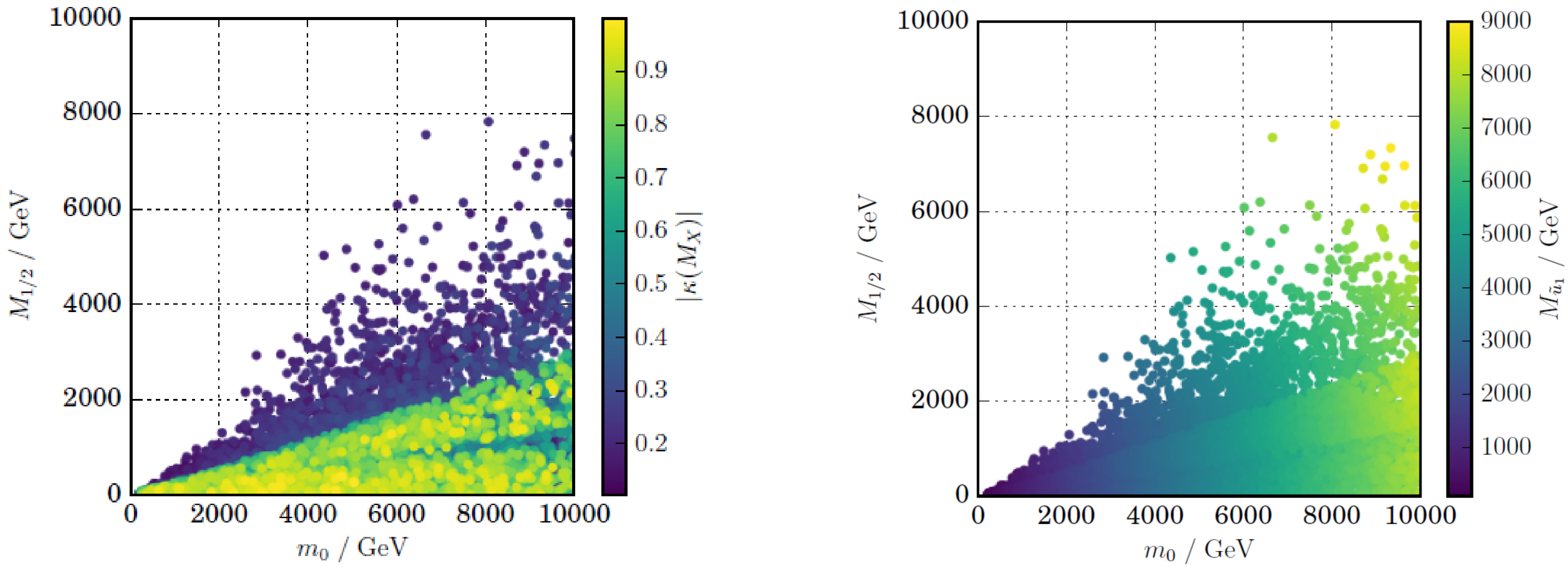
- Web interface (go play): https://flexiblesusy.hepforge.org/online/online.php

Interface with a scanner, e.g. Multinest

CNMSSM scan



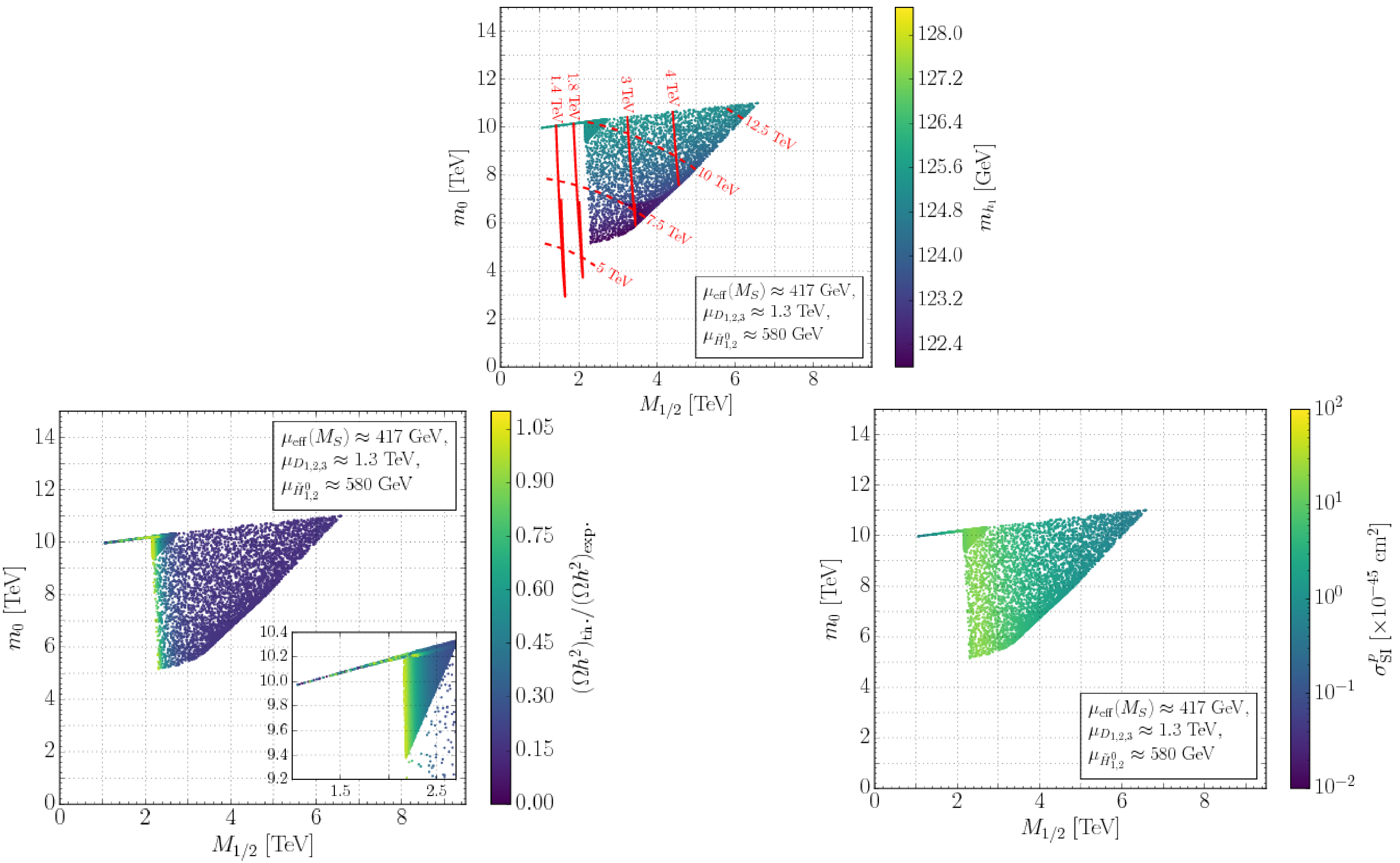
CE6MSSM scan



Interface with Micromegas...
using SARAH to write CalcHEP files for Micromegas

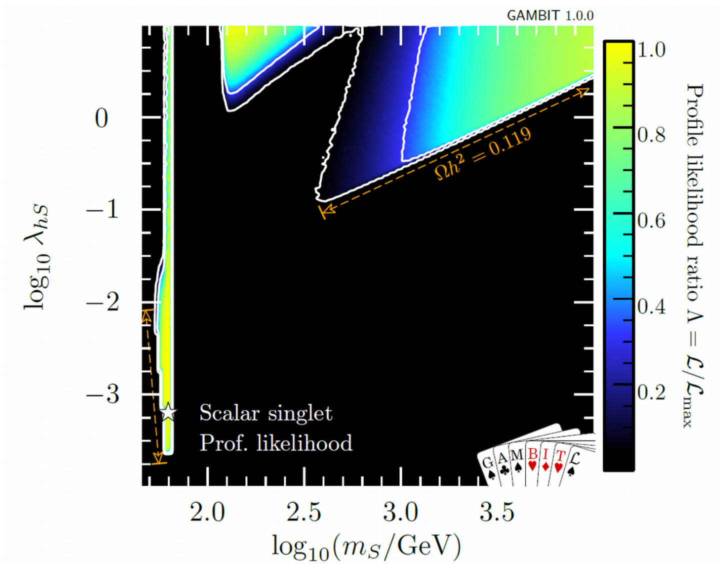
CSE6MSSM scan

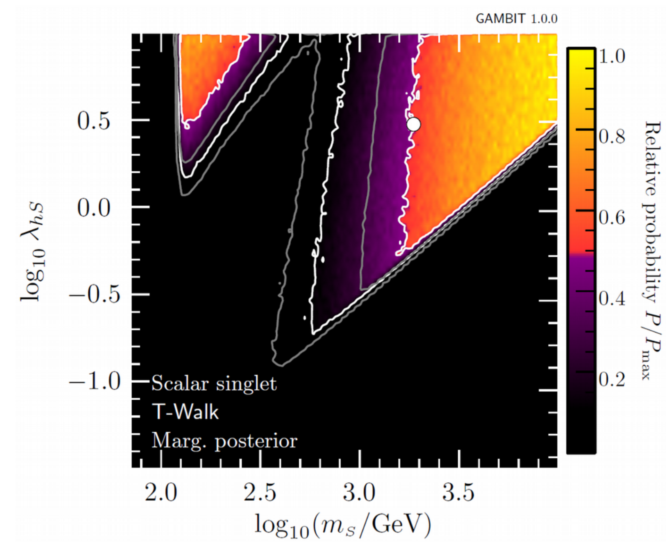
[PA, Dylan Harries, Roman Nevzorov and Anthony G. Williams, JHEP 1612 (2016) 128]



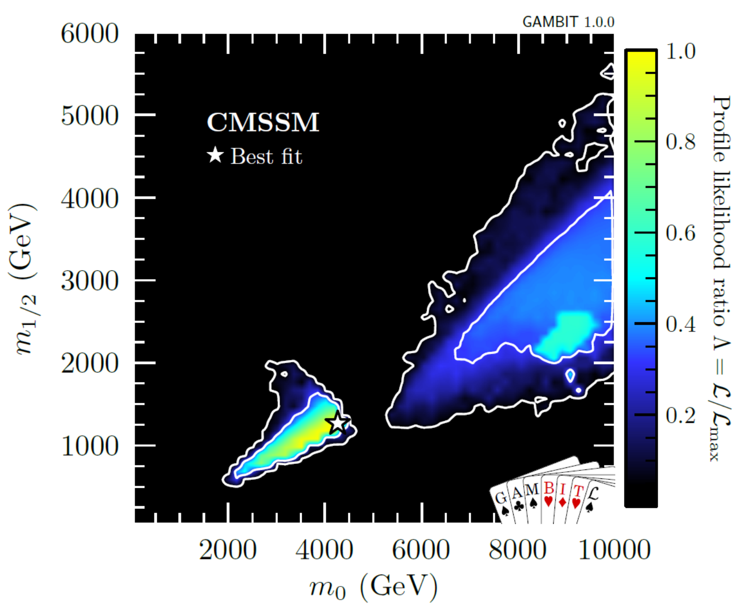
Interface with GAMBIT...

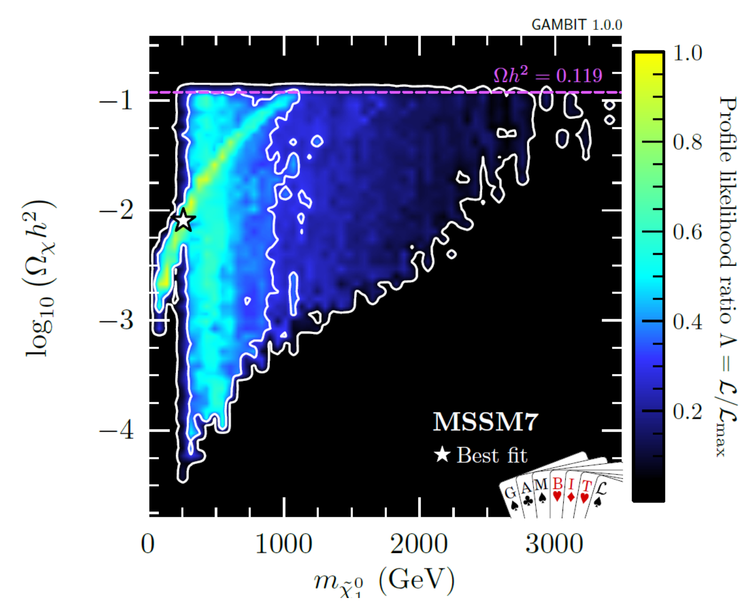
To combine with a huge array of observable calculations
and scanners and produce high quality global fits





[The GAMBIT Collaboration, EPJC 77 (2017) no.8, 568]





[The GAMBIT Collaboration, EPJC 77 (2017) no.12, 824] [The GAMBIT Collaboration, EPJC 77 (2017) no.12, 879]

See talk and poster by Anders Kvellestad and Are Raklev for details and latest work

FlexibleSUSY is precise

ALL BSM
Models

- Full three family 2-loop RGEs
- Full 1-loop self energies, threshold corrections and tadpoles
- Pure QCD 2-loop corrections for running top/bottom
- FlexibleEFTHiggs Hybrid EFT/fixed order precision Higgs mass calculation
- 1-loop Anomalous magnetic moment of the muon
- 1-loop Electric dipole moments
- Partial 2-loop W mass prediction
- Decays of Higgs / BSM states (work in progress)
- Tower of effective field theories (C++ level manual matching conditions, auto-generated matching is work in progress)

FlexibleSUSY is precise

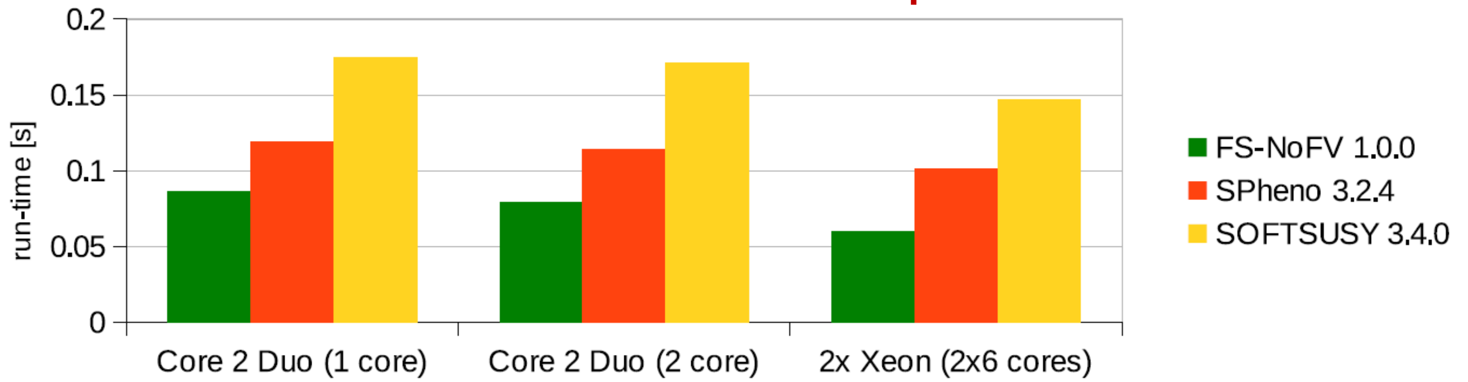
STATE OF THE ART MODEL SPECIFIC CORRECTIONS

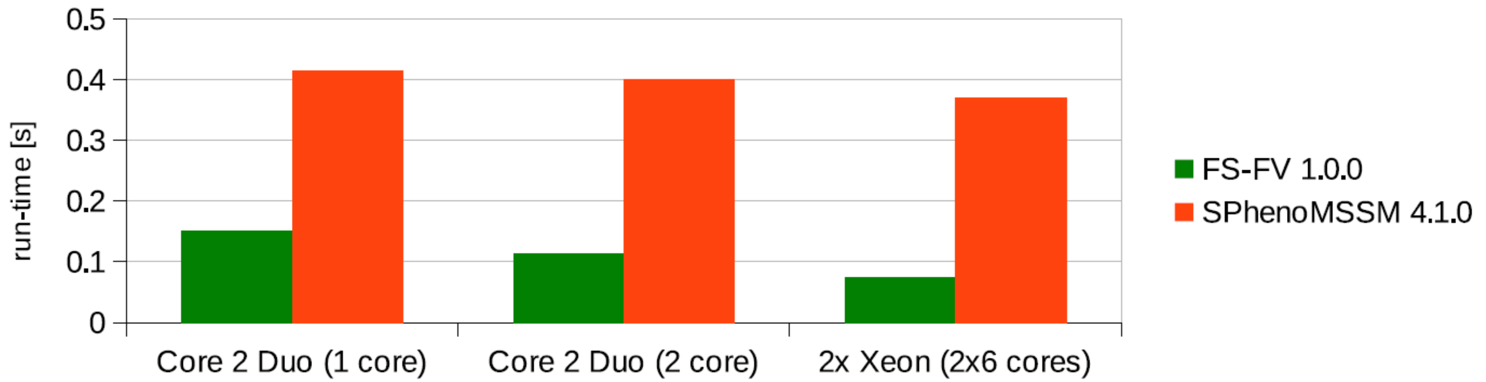
- 3-loop RGEs in SM and MSSM
- 2-loop (SUSY) QCD correc. to top, bottom Yukawas in SM, MSSM
- 2-loop (SUSY) QCD correc. to strong gauge coupling in SM, MSSM
- 2-loop fixed order Higgs mass corrections SM, MSSM, NMSSM
- 3-loop fixed order Higgs mass corrections SM, MSSM (via Himalaya)
- 3-loop Higgs mass corrections in Split-MSSM

FlexibleSUSY is fast

- Smart linear algebra package (Eigen3)
- Multi-threading

CMSSM run-time comparison





g++ 4.8.0, ifort 13.1.3 20130607

FlexibleSUSY is adaptable

Examples of easy meta-code adaption:

- Specify your own high scale boundary conditions

```
EXTPAR = { {61, LambdaInput},
           {63, ALambdaInput} };

HighScaleInput = {
    ...
    {T[\[Lambda]], ALambdaInput LambdaInput},
    ...
};
```

- Define the high scale, with fixed number or analytic condition

```
Highscale = g1 == g2;
HighScale = Ye[3,3] == Yd[3,3];
Highscale = Qin;
```

gauge coupling unification OR
Tau-bottom Yukawa unification OR
Fixed scale entered as input parameter

- Choose EWSB output parameters

```
EWSBOutputParameters = { B[\[Mu]], \[Mu] };
```

Common MSSM choice

- Select EWSB solvers (FPI vs gsl Broyden, Newton etc)

```
FSEWSBSolvers = { FPITadpole };
FSEWSBSolvers = { GSLBroyden };
FSEWSBSolvers = { GSLNewton };
```

Default setting is to try all, starting with FPI

- Build tower of effective field theories

C++ code level only so far

Fixed Order Higgs mass Calculations in FlexibleSUSY

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

Included precison with FlexibleSUSY:

$$\Sigma(p^2) = \Sigma^{\text{1-loop}}(p^2) + \Sigma^{\text{2-loop}}(0) + \Sigma^{\text{3-loop}}(0)$$

$\Sigma^{\text{1-loop}}$: complete All models

$\Sigma^{\text{2-loop}}$: $\mathcal{O}(y_t^2 g_s^2, y_b^2 g_s^2)$ MSSM, NMSSM

: $\mathcal{O}(y_t^4, y_t^2 y_b^2, y_b^4, y_\tau^4)$ MSSM

$\Sigma^{\text{3-loop}}$: $\mathcal{O}(y_t^2 g_s^4, y_b^2 g_s^4)$ MSSM

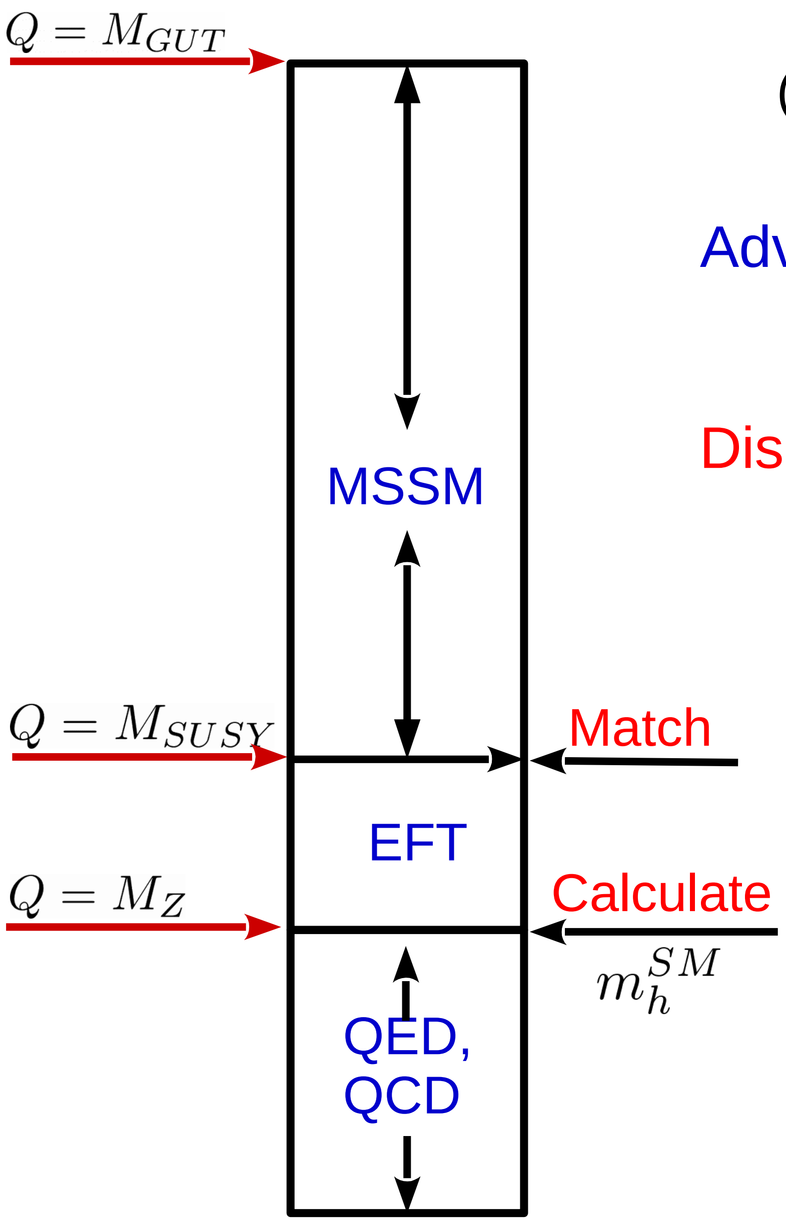
[via Himalaya: R.V.Harlander, J.Klappert and A.Voigt EPJC 77, no. 12, 814 (2017)]

$$\Sigma(p^2) = \Sigma(p^2, Q^2)$$

$Q^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$ - chosen to minimise largest logarithmic corrections

Pure EFTs

Resum large logs with EFT matching and running



For MSSM FlexibleSUSY has many pure EFT Higgs mass calculators (with different EFTs for different hierarchies)

Advantage: resums large logs
can include two-loop matching

Disadvantage: Misses p^2/M_{SUSY}^2 terms
Suffers if $M_{SUSY} \approx M_Z$

$$\lambda = \frac{1}{4}\left(g_Y^2 + g_2^2\right)\cos^2 2\beta + \Delta\lambda^{(1)} + \Delta\lambda^{(2)}$$

Pure EFTs for MSSM models

- FlexibleSUSY/HSSUSY [1407.4081, 1512.07761, 1703.08166]
  SM EFT: 2L matching, 3L RGEs , partial 3L and 4L SM self energy
  $\Longrightarrow$ **M_h prediction at full NLO + NNLO $\mathcal{O}(\alpha_t(\alpha_s + \alpha_t)$ full NLL + NNLL $\mathcal{O}(\alpha_t(\alpha_s + \alpha_t)$ resummation.**
  Note: Same setup and formal precision as SUSYHD

- FlexibleSUSY/SplitMSSM [1407.4081, 1512.07761]
  SplitSUSY EFT: 2L matching, 2L RGEs and 2L+ 3L QCD EFT self energy
  $\Longrightarrow$ **M_h prediction at full NLO + NNLO $\mathcal{O}(\alpha_t\alpha_s)$ full NLL resummation.**

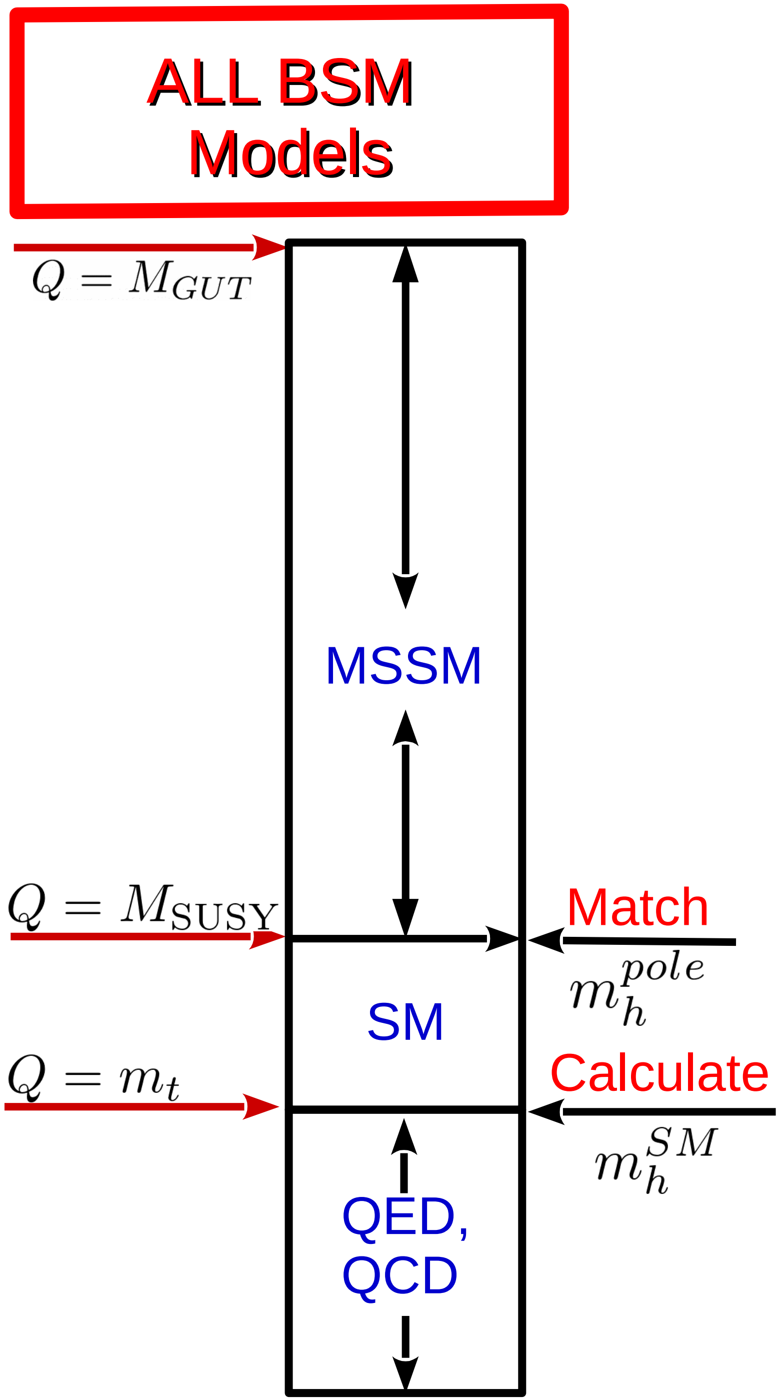
- FlexibleSUSY/THDMIIMSSMBCFull [0901.2065, 1508.00576]
  THDMII EFT: 2L matching, 2L RGEs and 1L EFT self energy
  $\Longrightarrow$ **M_h prediction at full NLO with full NLL resummation.**

- FlexibleSUSY/HTHDMIIMSSMBC [hep-ph/9307201, 1508.00576]
  THDMII + light Higgsinos EFT: 2L matching, 2L RGEs, 1L EFT self energy
  $\Longrightarrow$ **M_h prediction at full NLO with full NLL resummation.**

- FlexibleSUSY/HGTHDMIIMSSMBCFull [0901.2065, 1508.00576]
  THDMII + Higgsinos + gauginos EFT: 2L matching, 2L RGEs, 1L EFT self energy
  $\Longrightarrow$ **M_h prediction at full NLO with full NLL resummation.**

See also talk by Jae-hyeon Park later this session
for application of HSSUSY and SplitMSSM

FlexibleEFTHiggs: Hybrid EFT / Fixed order



Special pole mass matching condition
Avoids EFT uncertainty

Advantage: Resums logs
Includes p^2/M_{SUSY}^2
Can be used in any model

Disadvantage: two-loop matching
work in progress

$$M_h^{\mathrm{SM}} = M_h^{\mathrm{BSM}}$$

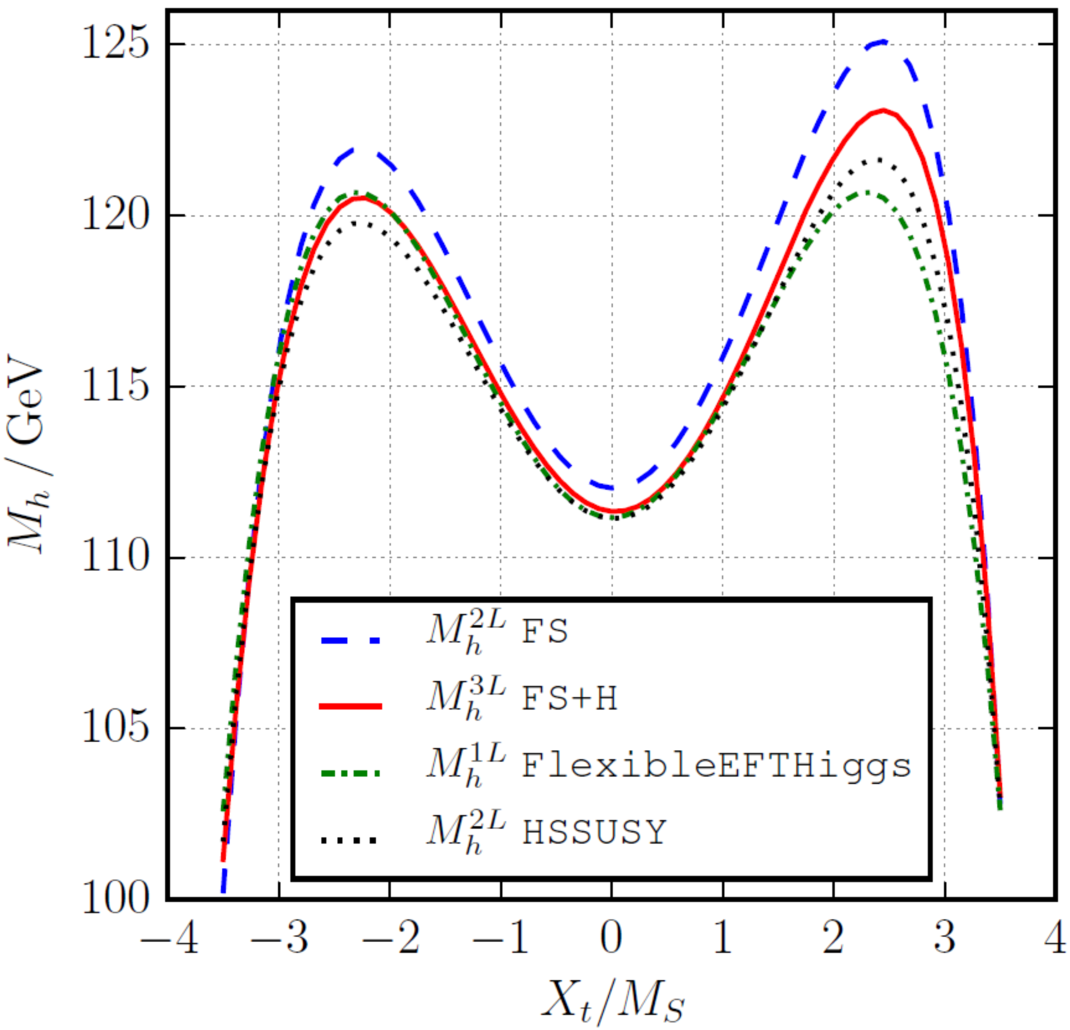
$$(m_h^{\mathrm{SM}})^2 - \Sigma_h^{\mathrm{SM}}(m_h^{\mathrm{BSM}}) = (m_h^{\mathrm{BSM}})^2 - \Sigma_h^{\mathrm{BSM}}(m_h^{\mathrm{BSM}}),$$

$$\lambda(M_{\mathrm{SUSY}}) = \frac{1}{v^2}\left[(m_h^{\mathrm{BSM}})^2 - \Sigma_h^{\mathrm{BSM}}(m_h^{\mathrm{BSM}}) + \Sigma_h^{\mathrm{SM}}(m_h^{\mathrm{BSM}})\right]$$

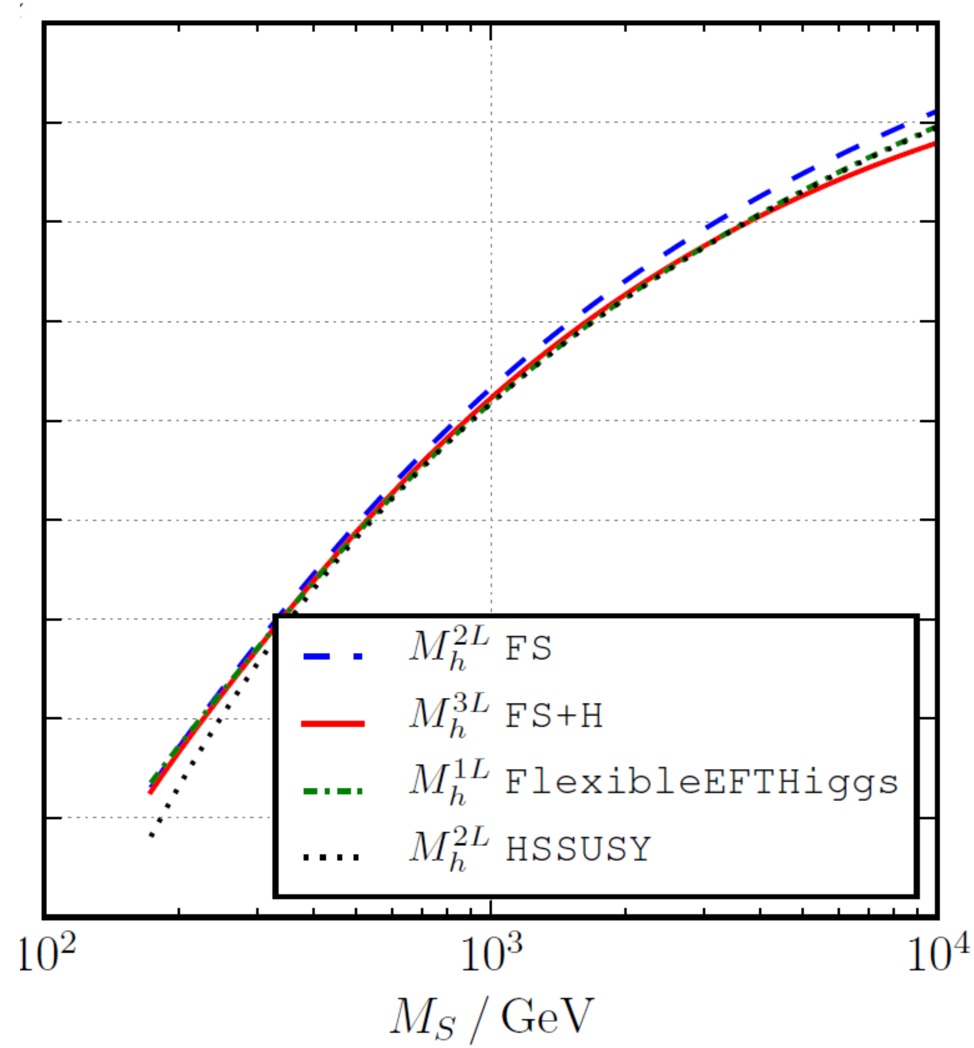
FlexibleSUSY Higgs mass calculations comparison

Note: $\alpha_s \alpha_t$ two-loop matching corrections vanish when $X_t = 0$

$M_S = 2\,\text{TeV}, \tan\beta = 5$



$X_t = 0, \tan\beta = 5$



Summary

- FlexibleSUSY is precise, adaptable to many problems and very fast.
- FlexibleSUSY creates a spectrum generator in any user specified BSM model and calculate:
  - Running parameters via 2-loop RGEs and 1-loop thresholds and tadpoles
  - All pole masses at one-loop precision
  - Precise Higgs mass at for low and high SUSY (BSM) scales
  - Anomalous magnetic moment of the muom
  - Fermion Electric Dipole Moments
  - W mass and muon decay
- FlexibleSUSY has state-of-the-art Higgs mass calculations in all models including MSSM,
  - Pure EFT calculation, e,g. HSSUSY
  - Fixed order calcuation up to 3-loop via Himalaya
  - FlexibleEFTHiggs Hybrid EFT / Fixed order calculations
- FlexibleSUSY is easy to interface with many codes to calculate other observables, e.g. relic density of dark matter
- FlexibleSUSY is interfaced within GAMBIT for use in global fits of BSM models (see talk by Anders Kvellestad and poster by Are Raklev)

FlexibleSUSY is adpaptable

Spectrum generator may be adapted at:

Meta-code level

- Change particle content, gauge structure, mixing, etc
- Change boundary conditions
- Change EWSB output parameters
- Change boundary value solver (two scale solver or semi-analytic solver)
- Build effective tower of different models

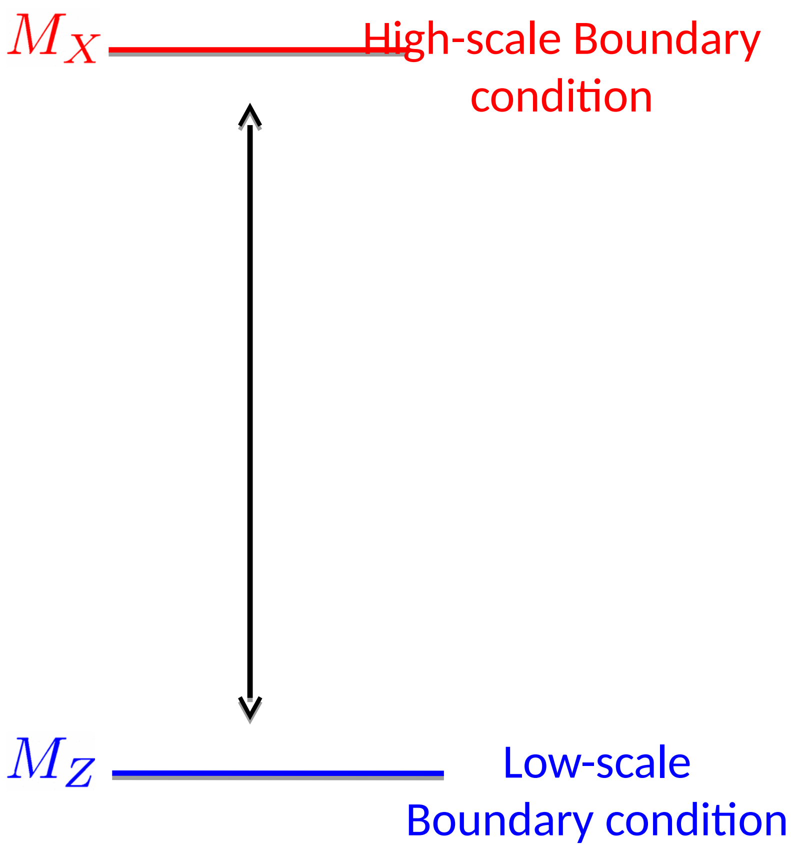
Generated code (C++) level

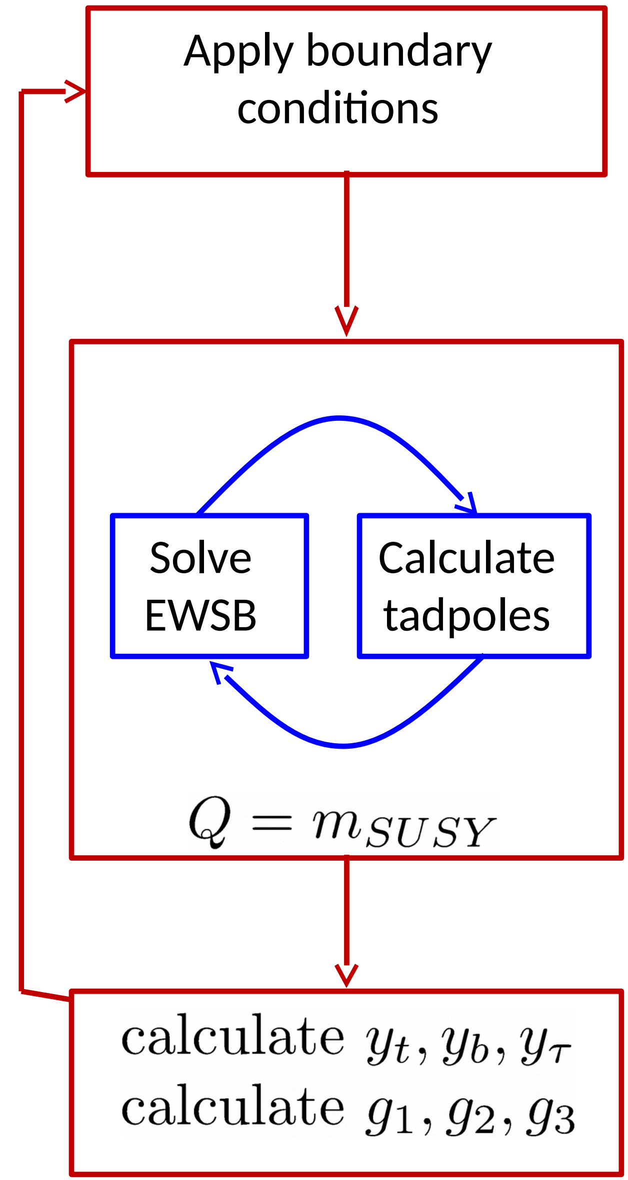
- Replace components
- Extend components (i.e. add new corrections)
- Use components in your own code
- Replace algorithm
- Build effective tower of different models

FlexibleSUSY is adaptable

Can also change the boundary value solver itself!

boundary-value solver → Two-scale fixed point iteration





Advantages: fast, finds solutions for most points in many models.

FlexibleSUSY is adaptable

- FlexibleSAS (Dylan Harries)

FlexibleSUSY has been designed to allow new boundary-value problem solvers

<u>Semi-Analytic Solver</u>

Use semi-analytic solutions for running masses at EWSB scale

$$
\begin{aligned}
m_i^2 &= a_i m^2 + b_i M^2 + c_i A M + d_i A^2 \\
M_j &= e_j A + f_j M \\
A_k &= p_k A + q_k M
\end{aligned}
$$

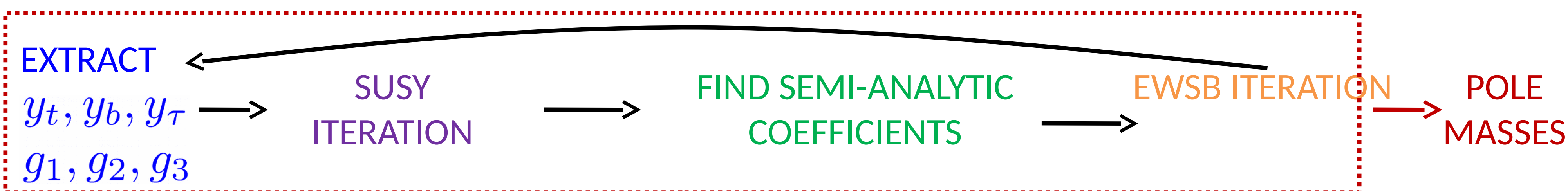
where m, M, A are input parameters in high scale constraints

$a_i = a_i(y_m, g_n)$ etc Coefficients depend only on dimensionless couplings

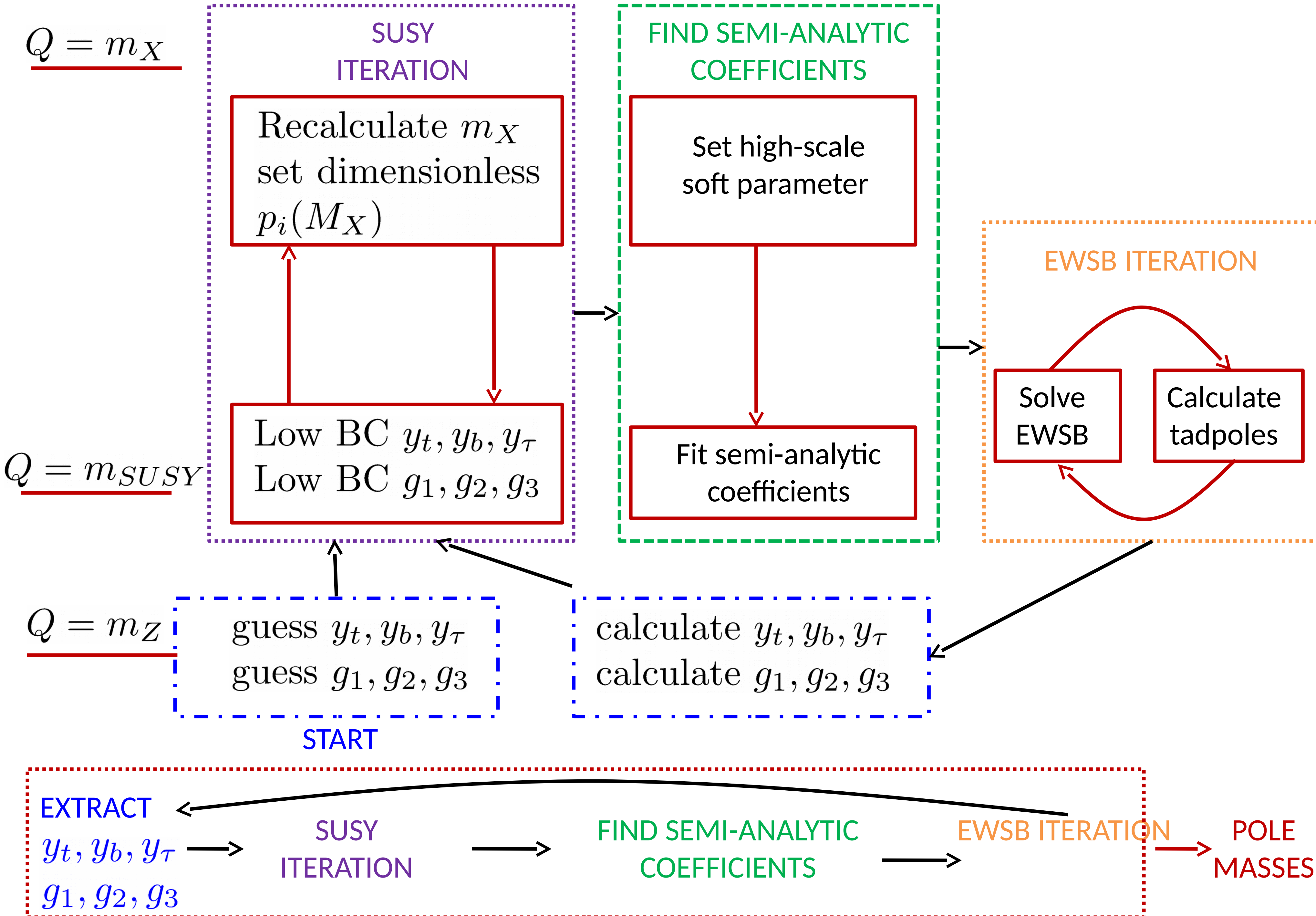
Rewrite EWSB in terms of universal (m, M, A) parameters

Now the EWSB outputs may include universal parameters set at the high scale.

This makes it possible to find solutions in the CNMSSM, CE6SSM.



Semi-analytic fixed point iteration



Comparison to public codes

Why is Spheno so different?

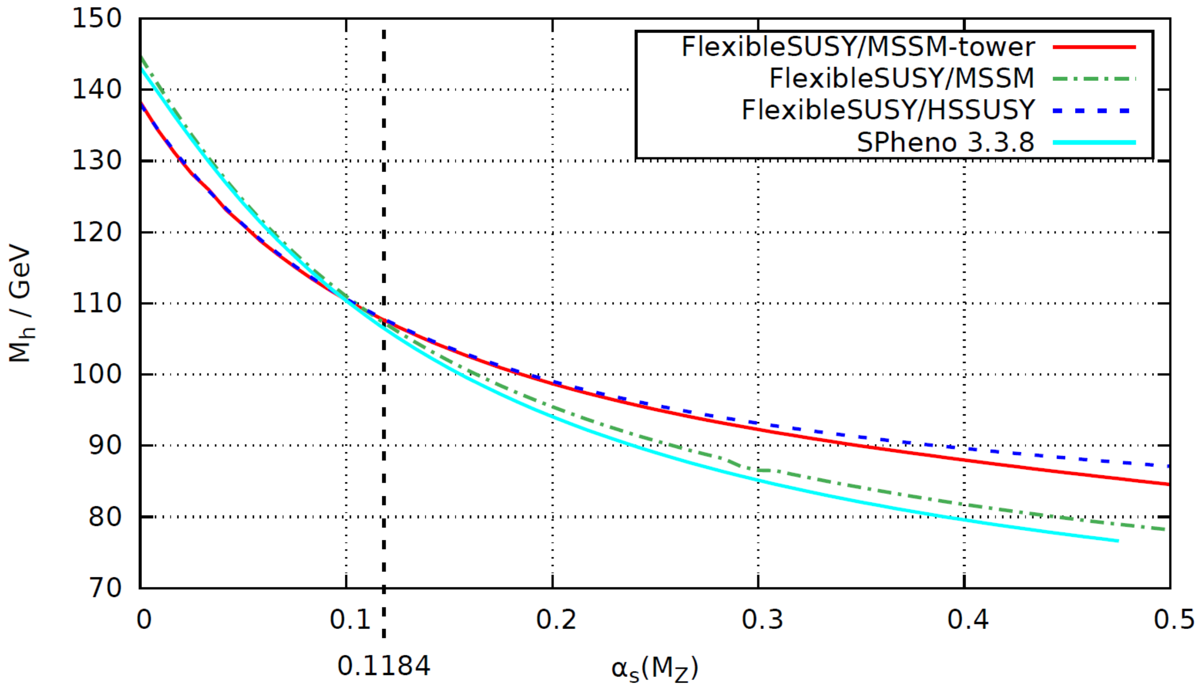
Or

Why do FlexibleSUSY and SOFTSUSY agree so well with FlexibleEFTHiggs?

Cause of difference:
higher order differences from calculation of $m_t^{\overline{\mathrm{DR}}}$

$$\text{FS: } m_t^{\overline{\mathrm{DR}}} = M_t + \left[\widetilde{\Sigma}_t^{(1),S}(M_t)\right] + M_t\left[\widetilde{\Sigma}_t^{(1),L}(M_t) + \widetilde{\Sigma}_t^{(1),R}(M_t)\right] + M_t\left[\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}}) + \left(\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right)^2 + \widetilde{\Sigma}_t^{(2),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right],$$

$$\text{SP: } m_t^{\overline{\mathrm{DR}}} = M_t + \left[\widetilde{\Sigma}_t^{(1),S}(m_t^{\overline{\mathrm{DR}}})\right] + m_t^{\overline{\mathrm{DR}}}\left[\widetilde{\Sigma}_t^{(1),L}(m_t^{\overline{\mathrm{DR}}}) + \widetilde{\Sigma}_t^{(1),R}(m_t^{\overline{\mathrm{DR}}})\right] + m_t^{\overline{\mathrm{DR}}}\left[\widetilde{\Sigma}_t^{(1),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}}) + \widetilde{\Sigma}_t^{(2),\mathrm{qcd}}(m_t^{\overline{\mathrm{DR}}})\right].$$



Cause of agreement:
must be an accidental cancellation!

Comparison to public codes

Why is Spheno so different?

Or

Why do FlexibleSUSY and SOFTSUSY agree so well with FlexibleEFTHiggs?

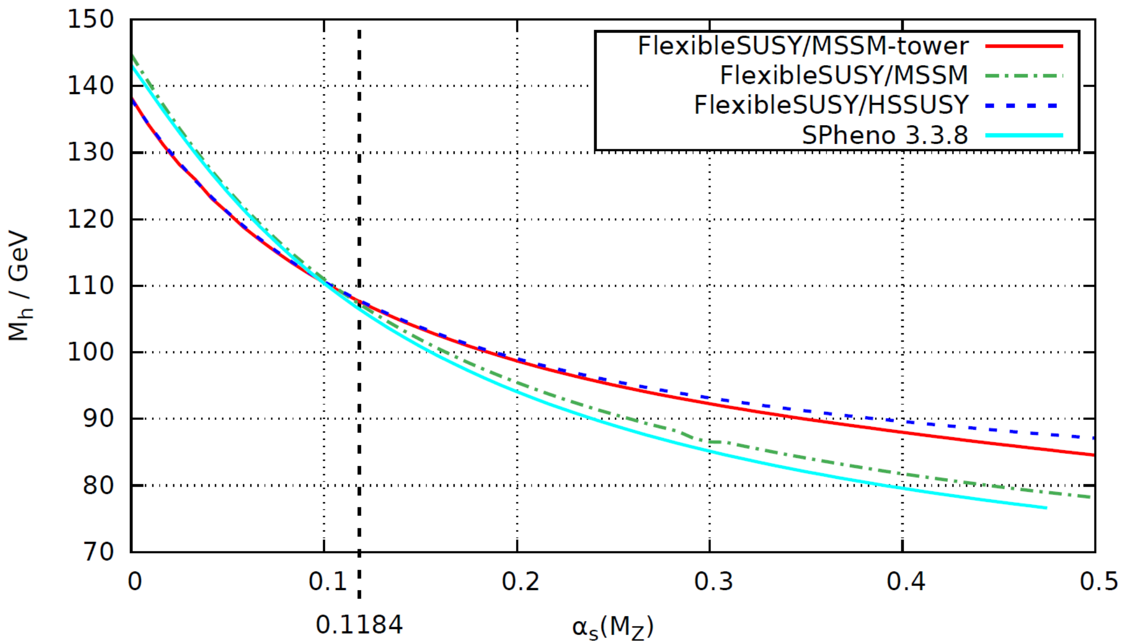
Fixed order expansion:

$$(M_h^2)^{\text{EFT}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(736 g_3^4 - 672 g_3^2 y_t^2 + 90 y_t^4\right) + \dots \Big],$$

$$(M_h^2)^{\text{FlexibleSUSY}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(\frac{736}{3} g_3^4 - 288 g_3^2 y_t^2 + \frac{27}{2} y_t^4\right) + \dots \Big],$$

$$(M_h^2)^{\text{SPheno}} = m_h^2 + v^2 y_t^4 \Big[12 t_S \kappa_L + 12 t_S^2 \kappa_L^2 \left(16 g_3^2 - 9 y_t^2\right) + 4 t_S^3 \kappa_L^3 \left(\frac{992}{3} g_3^4 - 192 g_3^2 y_t^2 + \frac{81}{2} y_t^4\right) + \dots \Big].$$

Large coefficients suggest both FlexibleSUSY and Spheno have a larger uncertainty than the difference between the suggests



Cause of agreement:
must be an accidental cancellation!

Pure EFTs for MSSM models

- FlexibleSUSY/HSSUSY [1407.4081, 1703.08166]
  SM EFT: 2L mathcing, 3L RGEs , partial 3L and 4L SM self energy
  Mh at NLO + NNLO(only g3^n yt^m) with
  NLL + NNLL(only g3^n yt^m).
  Note: Same setup and fomal precison as SUSYHD

- FlexibleSUSY/SplitMSSM [1407.4081]
  SplitSUSY EFT: 2L matching, 2L RGEs and 2L+ 3L QCD EFT self energy
  Mh at NLO(full) + NNLO(only at*as) with NLL(full)

- FlexibleSUSY/THDMIIMSSMBCFull [0901.2065, 1508.00576]
  THDMII EFT: 2L matching, 2L RGEs and 1L EFT self energy
  Mh at NLO + NNLL

- FlexibleSUSY/HTHDMIIMSSMBC [hep-ph/9307201, 1508.00576]
  THDMII + light Higgsinos EFT: 2L matching, 2L RGEs, 1L EFT self energy
  Mh at NLO + NNLL

- FlexibleSUSY/HGTHDMIIMSSMBCFull [0901.2065, 1508.00576]
  THDMII + Higgsinos + gauginos EFT: 2L matching, 2L RGEs, 1L EFT self energy
  Mh at NLO + NNLL

Comparison of uncertainties

Note: combining errors linearly is quite conservative, so these are likely an overestimate

Full model approach (2L):

(C_3 and Q uncertainties added linearly)

M_S/TeV	X_t/M_S	ΔM_h/GeV	X_t/M_S	ΔM_h/GeV
1	0	±1.3	2	±2.0
2	0	±2.1	2	±3.0
10	0	±4.5	2	±5.5

EFT-M_h approach (1L):

($y_t^{(i)}$ and Q uncertainties added linearly)

M_S/TeV	X_t/M_S	ΔM_h/GeV	X_t/M_S	ΔM_h/GeV
1	0	±1.0	2	±3.1
2	0	±1.0	2	±3.1
10	0	±1.1	2	±2.8