NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

FlexibleSUSY Developments

Peter Athron (Nanjing Normal University)

On behalf of the

FlexibleSUSY collaboration

FlexibleSUSY

A spectrum generator generator

What is FlexibleSUSY?

In a nutshell:

You choose and specify the SM extension

FlexibleSUSY automatically gives you the calculations and code to predict observables!

~ Almost *any* extension including non-SUSY extensions,
not only SUSY extensions

What is FlexibleSUSY?

For user specified models FlexibleSUSY automates calculations of:

- BSM masses,
- Higgs and W masses,
- Scalar decay widths and BRs
- muon g-2,
- electric dipole moments,
- Flavour changing observables

and…. if you have an observable we don’t currently support:

- FlexibleNPF – NPointFunctions:

Incorporate:

- New amplitudes and
- New observables

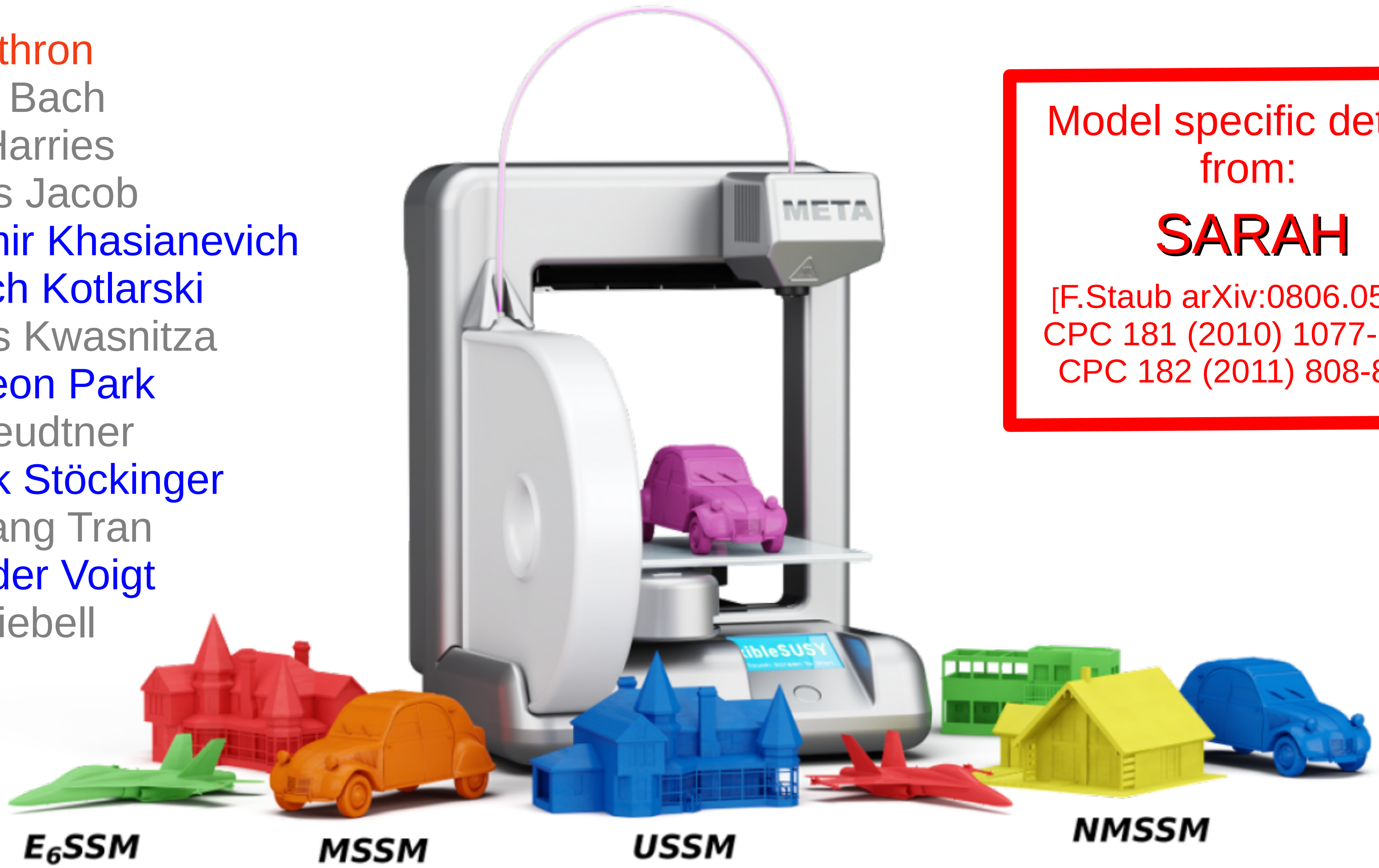
in FlexibleSUSY

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>

Peter Athron
Markus Bach
Dylan Harries
Douglas Jacob
Uladzimir Khasianevich
Wojciech Kotlarski
Thomas Kwasnitza
Jae-hyeon Park
Tom Steudtner
Dominik Stöckinger
Kien Dang Tran
Alexander Voigt
Jobst Ziebell



Model specific details from:

SARAH

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

FlexibleSUSY

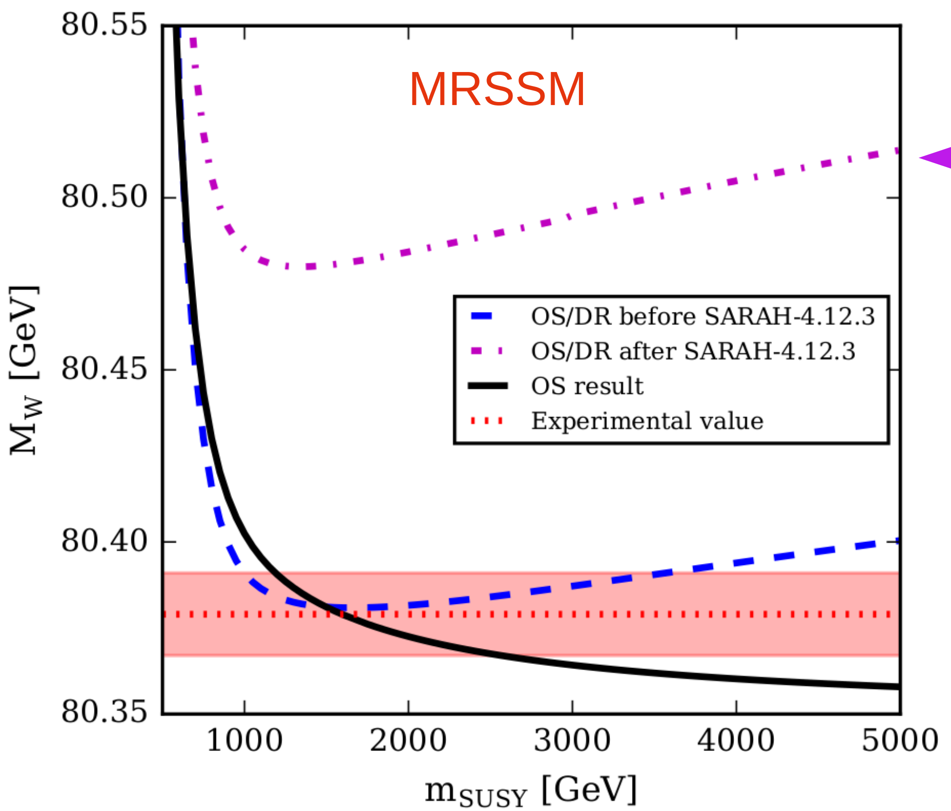
FlexibleSUSY delivers C++ calculations of the mass spectra and precision obeservables that is:

- **Precise** Same precision or higher as model dedicated codes
- **Fast** Care taken for fast evaluation, e.g. fast LA package Eigen
- **Adaptable**
  - ➔ Change particle content, algorithms, boundary conditions constraints on parameters at with model files,
  - ➔ adjust many settings at runtime, precisions, calculation options etc, what observabkes to include
  - ➔ Now you can even add your own observables...

New MW calculation

Previous MW calculations implememted based on generalsiations of Msbar/Drbar calculations in Bagger, Pierce, Matchev, Zhang Nucl.Phys.B 491 (1997) 3-67

Problem with non-decoupling logs when new physics scale is large pointed out in contxt of MRSSM



This is the SARAH-4.12.3 calculation, which was essentially the same as our old Msbar/Drbar calculation

[Diessner, Weiglein, JHEP 07 (2019) 011]

How did we get it so wrong?

The non-decoupling problem

Basic relation between muon decay and MW

$$G_F = \frac{\pi\, \alpha_{\rm em}(M_Z)}{\sqrt{2}\, M_W^2 \left(1 - \frac{M_W^2}{\hat{\rho} M_Z^2}\right)} (1 + \Delta \hat{r}_W)$$

This includes e.g.

$$\alpha_{\rm em}(M_Z) = \frac{\alpha_{{\rm em},SM}^{(5),\overline{MS}}(M_Z)}{1 - \Delta\alpha_{\rm em}^{SM} - \Delta\alpha_{\rm em}^{BSM}}\,,$$

Well known that this resums important
higher order corrections

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Also resums BSM corrections

Well known that this resums important higher order corrections

$$G_F = \left[\frac{\pi\, \alpha_{\rm em}(M_Z)}{\sqrt{2}\, M_W^2 \left(1 - \frac{M_W^2}{\hat\rho M_Z^2}\right)} (1 + \Delta\hat r_W)\right]_{\Delta\alpha_{\rm em}^{BSM}=0} \times \left[1 + \Delta\alpha_{\rm em}^{BSM} + (\Delta\alpha_{\rm em}^{BSM})^2 + \cdots\right]\,,$$

Contains large non-decoupling logs that should cancel order by order

Issue only showed up when looking at high scales

New MW calculation

So to avoid the large non-decoupling logs which realy ruined the precision in that example:

We implememted a new calculation which decouples properly.

Idea: Split SM and Bsm contribtions, $M_W^2 = (M_W^{\mathrm{SM}})^2\,(1+\Delta_W)$

Include state-of-the-art SM contributions, via fit formlae

Strict one-loop expansion of BSM contributions,

$$\Delta_W = \frac{s_W^2}{c_W^2 - s_W^2}\left[\frac{c_W^2}{s_W^2}\,(\Delta\hat{\rho}_{\mathrm{tree}} + \Delta\hat{\rho}_{\mathrm{BSM}}) - \Delta\hat{r}_{W,} - \Delta\alpha\right]$$

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Note: we treat tree-level rho corrections like one-loop corrections since they should be very small based on expermental constraints.

With this strict one-loop expansion of the BSM corrections, we successfully avoid the non-decoupling logs

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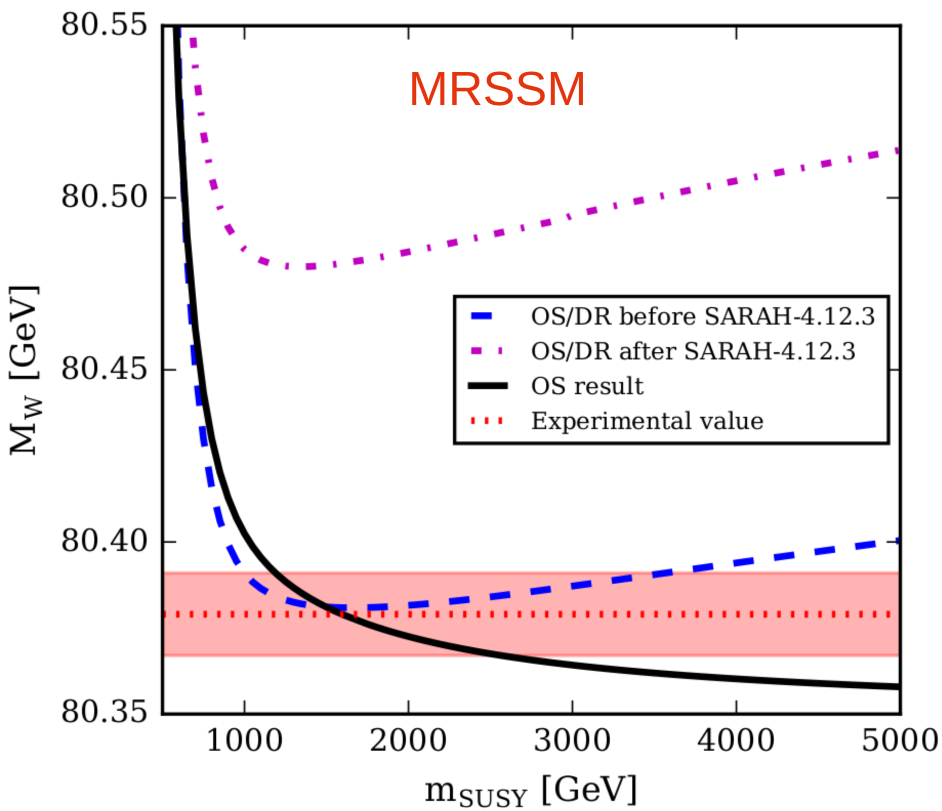
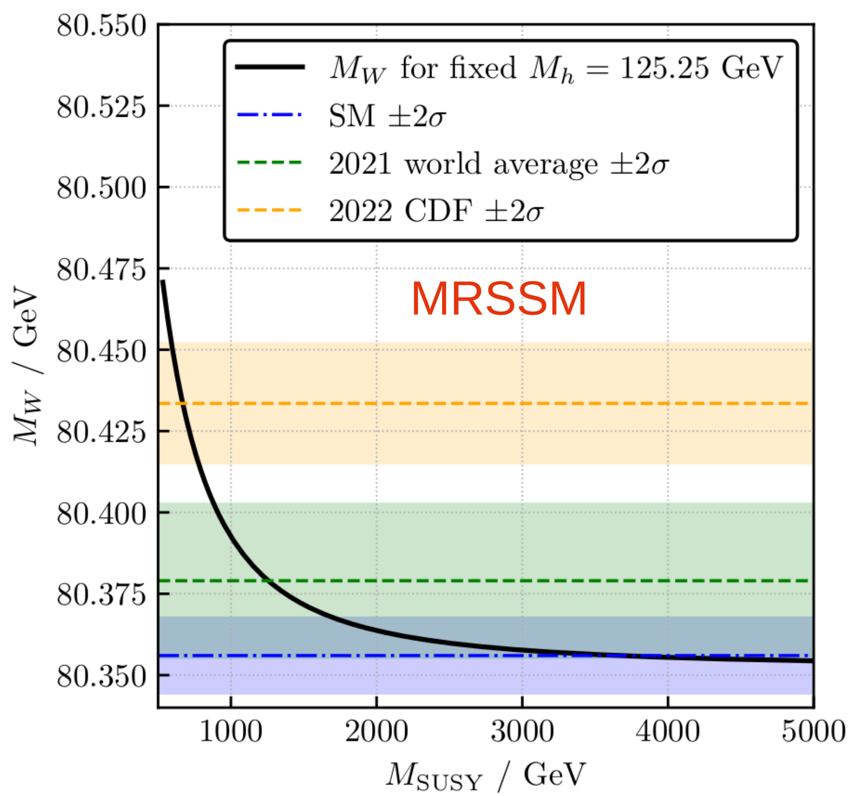


[Diessner, Weiglein, JHEP 07 (2019) 011]



[PA, M. Bach, D.H.J. Jacob, W.Kotlarski, D. Stoeckinger and A.Voigt, Phys.Rev.D 106 (2022) 9, 095023]

Higgs mass calculations

FlexibleSUSY really specialises in (MSSM) Higgs mass calculations

1) Fixed order calculations $M_H^2 + \Sigma(p^2 = m_{h_i}^2)$ —diagonalise for eigenvalues→ $m_{h_i}^2$

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

$\Sigma^{\text{1-loop}}$: 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)]

Most precise fixed order DRbar MSSM calculation

Common problem: large logs may spoil the precision

Higgs mass calculations

FlexibleSUSY really specialises in (MSSM) Higgs mass calculations

2) EFT approach   Its quite easy to build EFT calculations in FlexibleSUSY

We already have many of these for MSSM scenarios, including

Most precise EFT calculation in MSSM (similar to SUSYHD but with extra contributions) →

- FlexibleSUSY/HSSUSY [1407.4081, 1512.07761, 1703.08166] SM EFT: 2L matching, 3L RGEs, partial 3L and 4L SM self energy
- FlexibleSUSY/SplitMSSM [1407.4081, 1512.07761] SplitSUSY EFT: 2L matching, 2L RGEs and 2L+ 3L QCD EFT self energy

Advantage: resums large logs can include two-loop matching

Disadvantage: Misses $p^2/M^2_{\rm BSM}$ terms, suffers if $M_{\rm BSM} \approx M_Z$

Higgs mass calculations

FlexibleSUSY really specialises in (MSSM) Higgs mass calculations

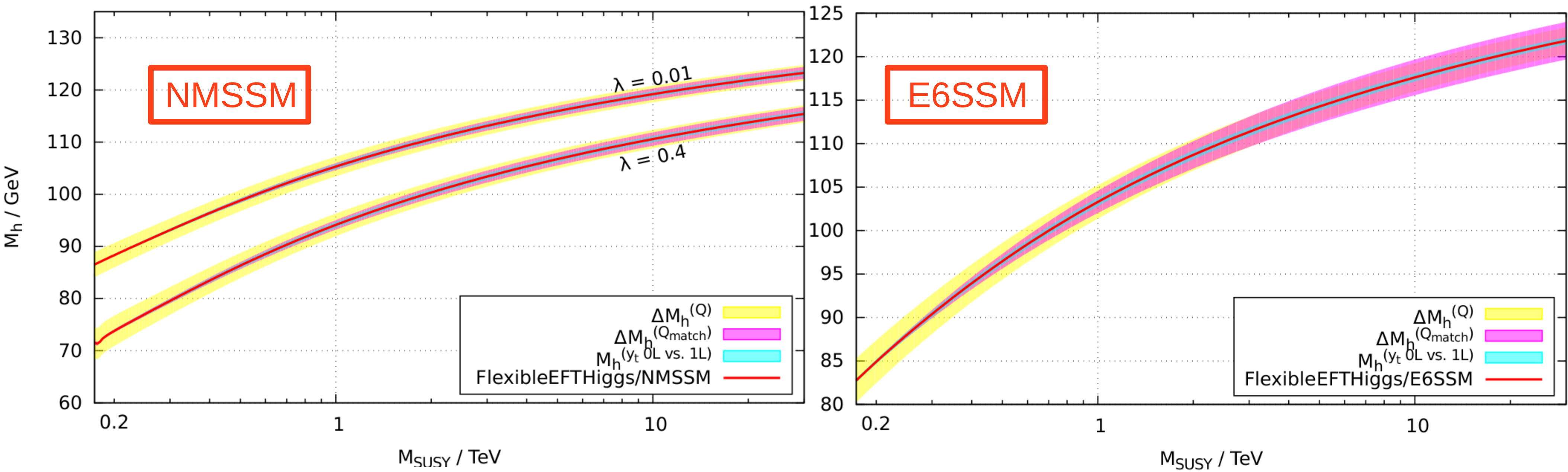
3) FlexibleEFTHggs - Hybrid EFT/Fixed order

Resums large logs and matches fixed order at $M_{\text{BSM}} \approx M_Z$

Best of both worlds

All models 2-loop RGEs, full 1-loop matching and 1-loop self energy

[PA, J-h. Park, T. Steudtner, D. Stoeckinger and A. Voigt, JHEP 01 (2017) 079,
PA, M.Bach, D.Harries, T.Kwasnitza, J-h. Park, T.Steudtner, D.Stoeckinger, A.Voigt & J.Ziebell, Comput.Phys.Commun. 230 (2018) 145-217]



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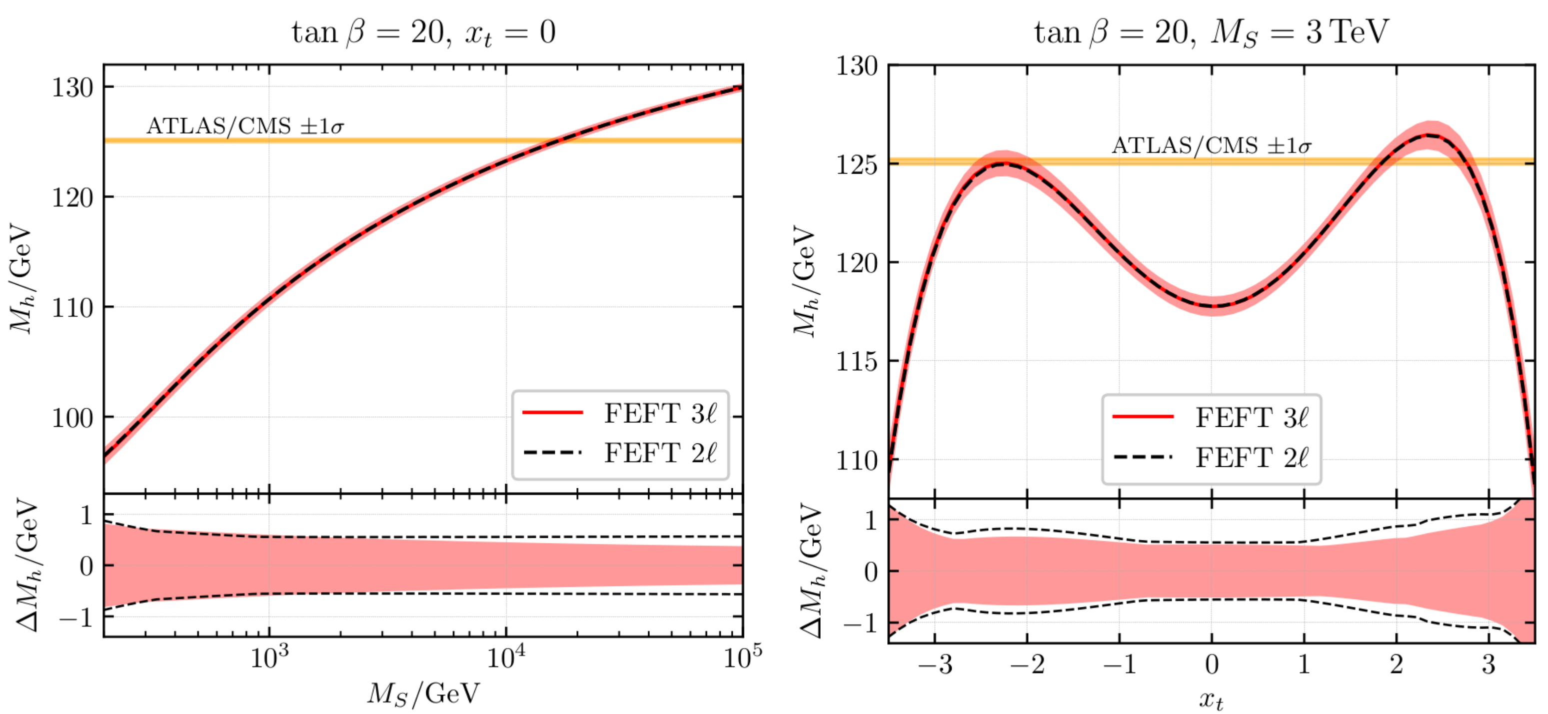
Best of both worlds

MSSM 4-loop RGEs, 3-loop matching and 3-loop self energy

M_h calculated at $\mathrm{N^3LL}$ and $\mathrm{N^3LO}$

[T. Kwasnitza, D. Stoeckinger and A. Voigt, JHEP 06 (2023) 201, JHEP 07 (2020) 07, 197]



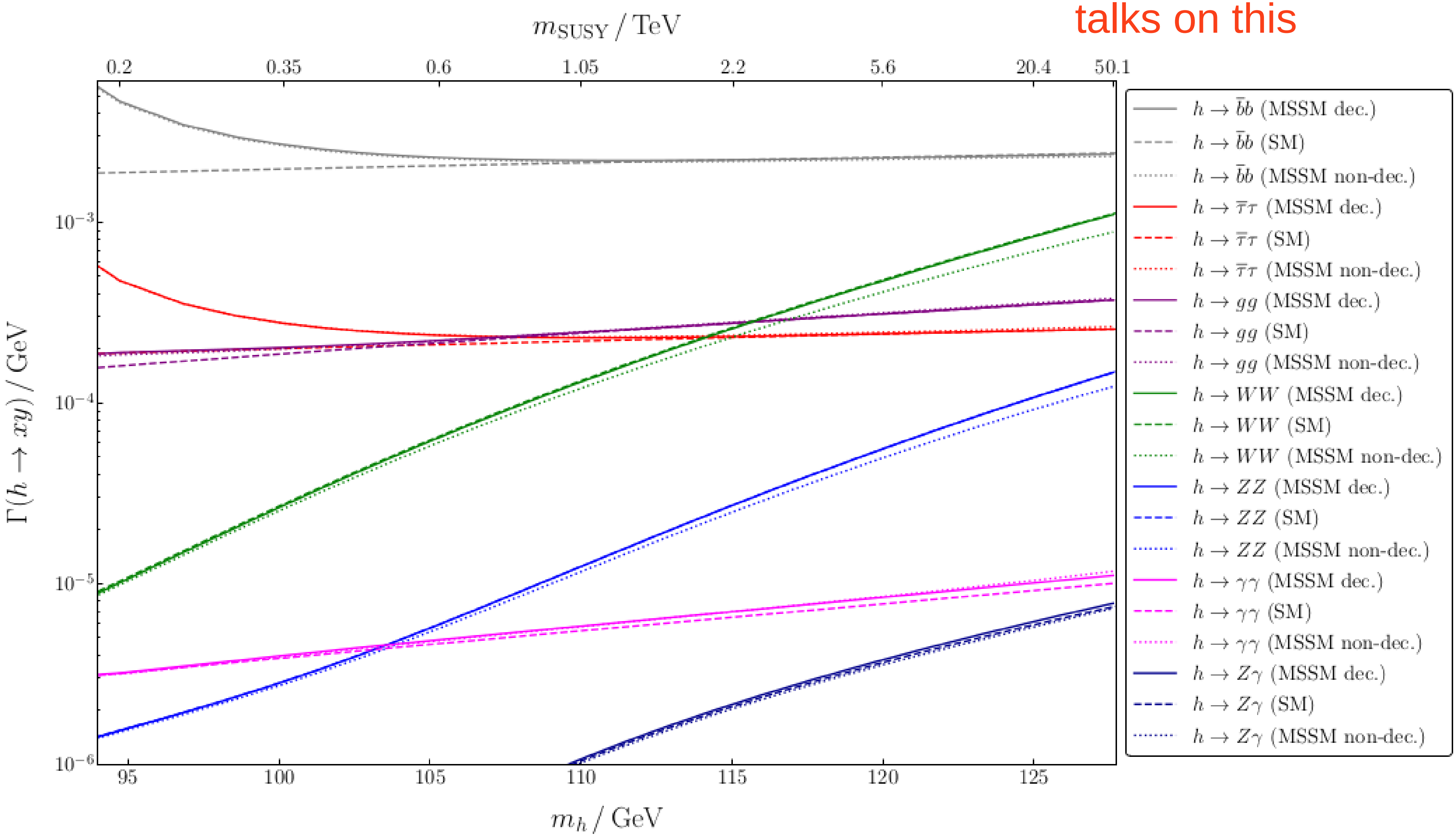
State-of-the-art MSSM Precision

FlexibleDecay

Precise scalar decays, special treatment for SM-like Higgs decays

[P.Athron, A.Buechner, D.Harries, W. Kotlarski, D. Stoeckinger and A.Voigt, Comput.Phys.Commun. 283 (2023) 108584]

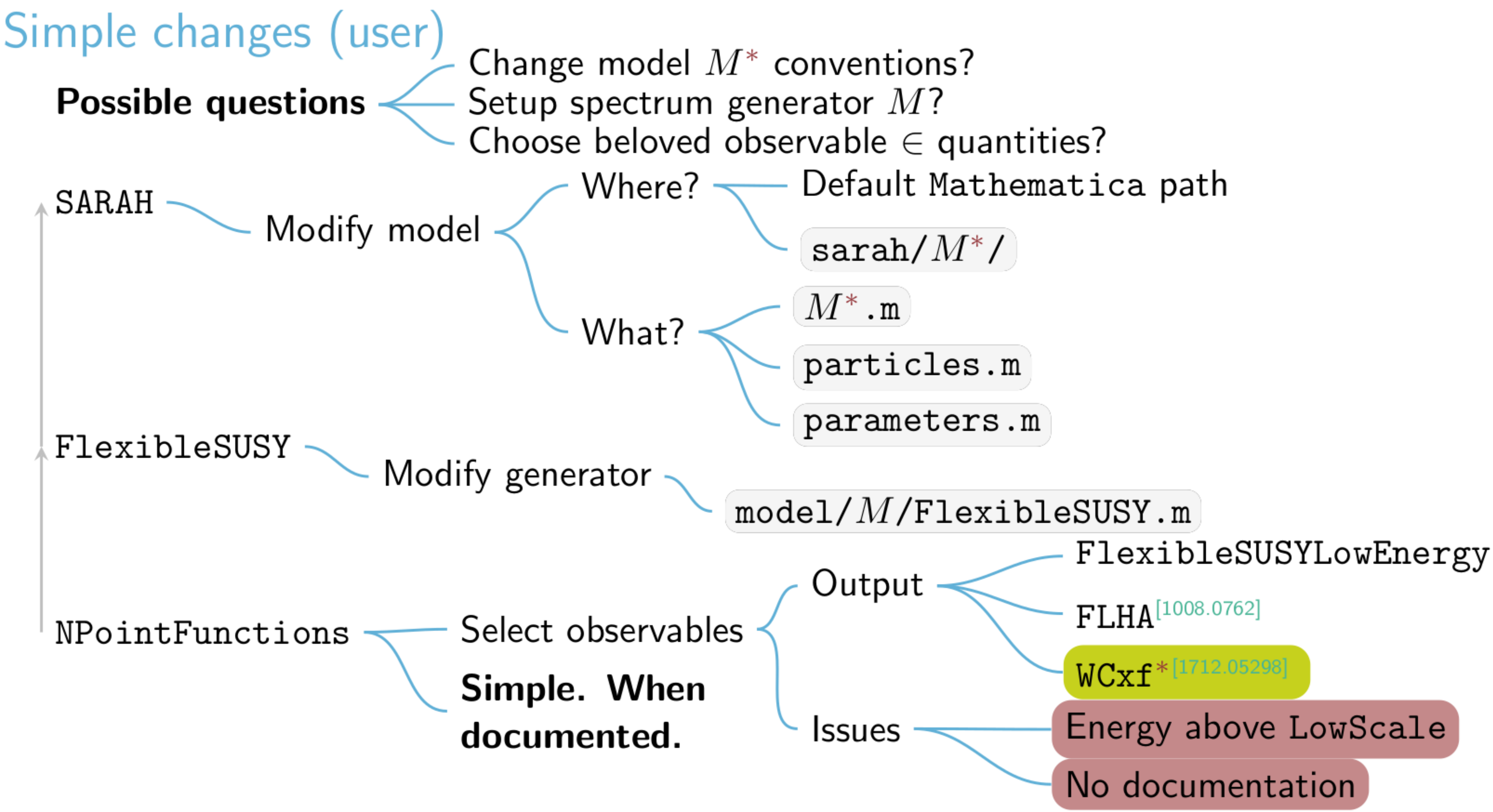
Wojtek has given many talks on this



NPointFunctions

Uladzimir Khasianevich, Wojciech Kotlarski and Dominik Stöckinger, + earlier contributions from Jobst Ziebell and Kien Dang Tran

FlexibleSUSY is now so Flexible the user can specify the observable as well as the model!



More updates

Vector field contribution for muon g-2 and lepton EDMs,

Two-loop Barr-Zee contributions for muon g-2

Electron and tau g-2 now available (not just muon)

New flavour violating processes:

- $\ell \to \ell' \gamma$
- $b \to s\gamma$

HiggsSignals/HiggsBounds interface

Option to choose loop libraries:

- SOFTSUSY
- FFLITE
- LOOPTOOLS
- Collier

Conclusions

- FlexibleSUSY is awesome
- If FlexibleSUSY is not in your life that is very sad :(
- But you can fix this :)

```
$ git clone https://github.com/FlexibleSUSY/FlexibleSUSY
$ cd FlexibleSUSY
```

OR

```
$ wget https://www.hepforge.org/archive/flexiblesusy/FlexibleSUSY-2.7.1.tar.gz
$ tar -xf FlexibleSUSY-2.7.1.tar.gz
$ cd FlexibleSUSY-2.7.1
```

Then setup and run it, e.g.

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

Go forth and make excellent physics with FlexibleSUSY!

The End

Thanks for listening!

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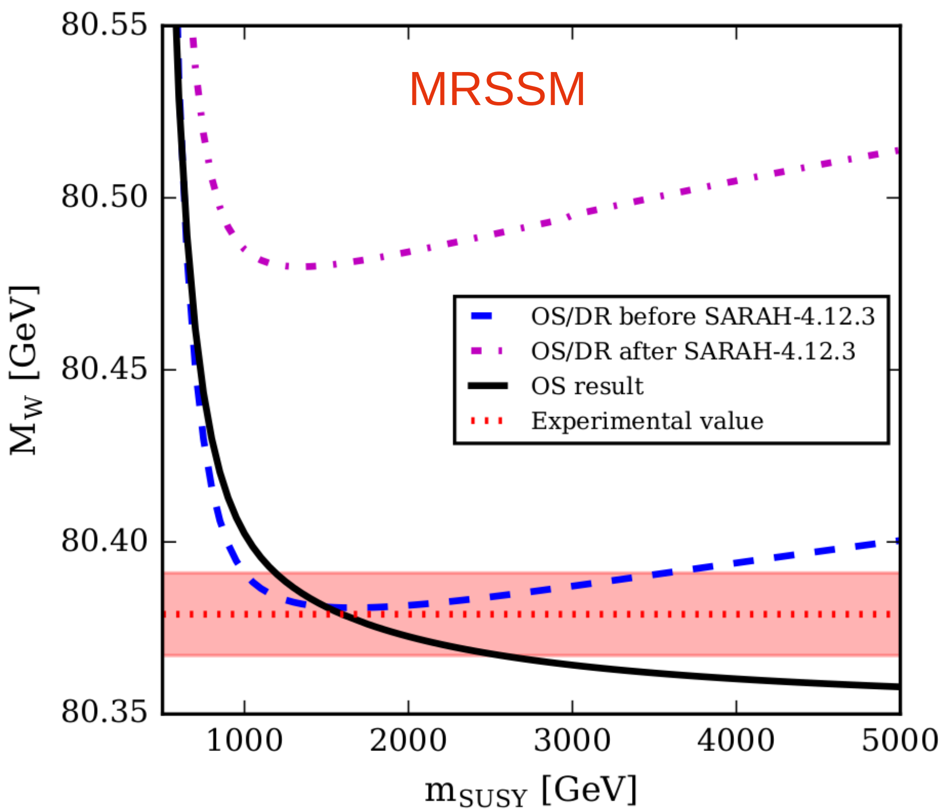

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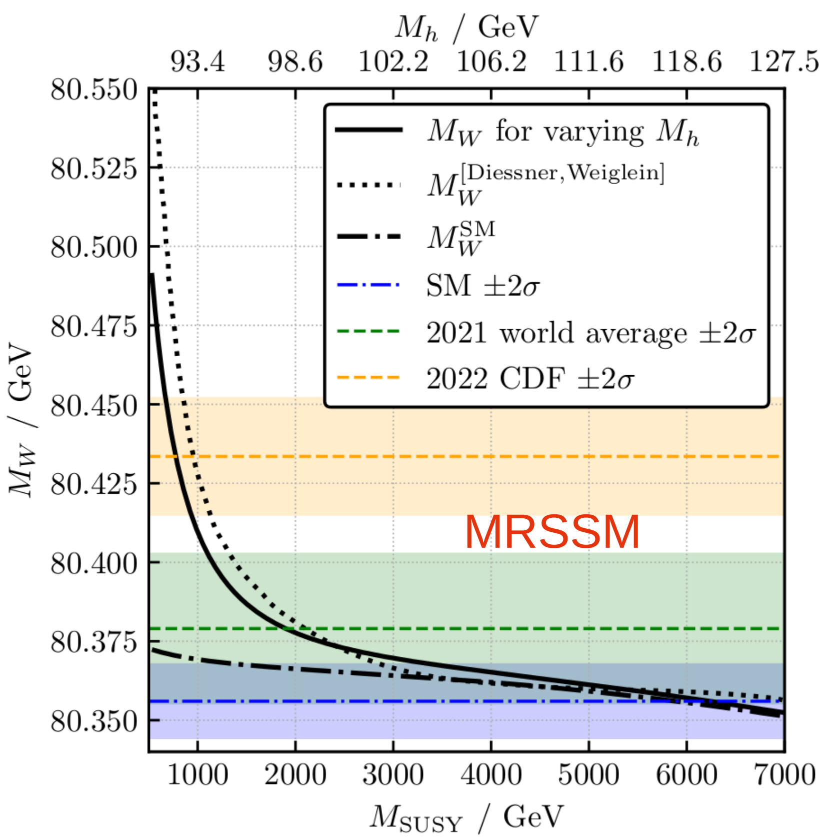

[PA, M. Bach, D.H.J. Jacob, W.Kotlarski, D. Stoeckinger and A.Voigt, Phys.Rev.D 106 (2022) 9, 095023]

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

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Resums large logs and matches fixed order at $M_{\text{BSM}} \approx M_Z$

Best of both worlds

MSSM 4-loop RGEs, 3-loop matching and 3-loop self energy

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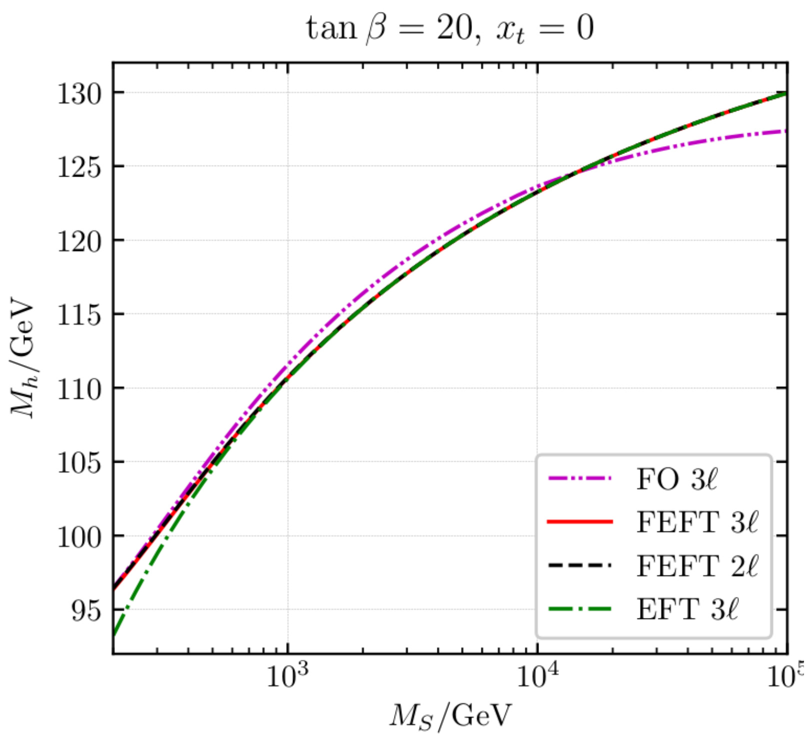
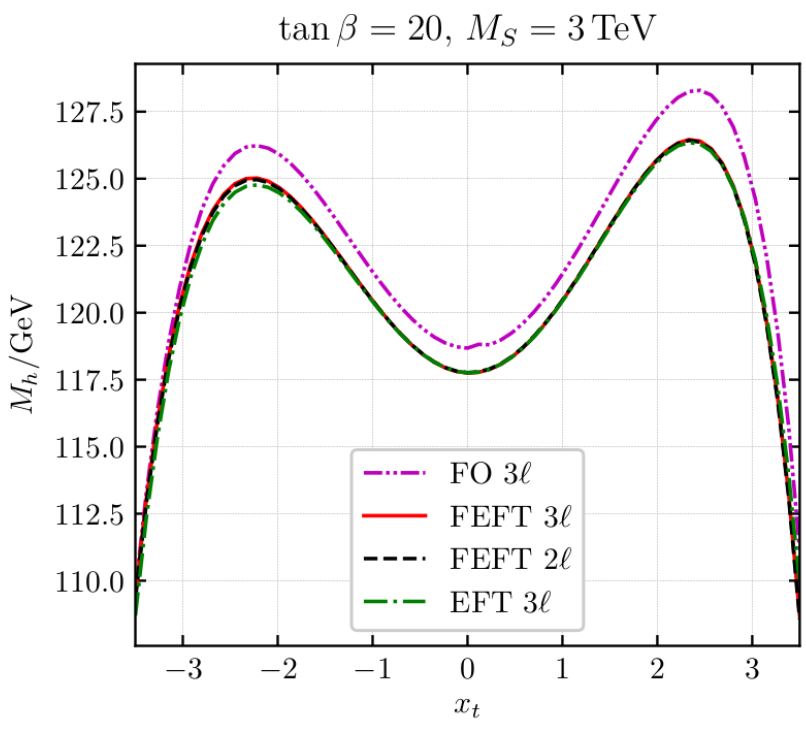




State-of-the-art MSSM Precision

MRSSM explanation of CDF MW measurement

This effect is really essential if you want explain the recent CDF MW measurement

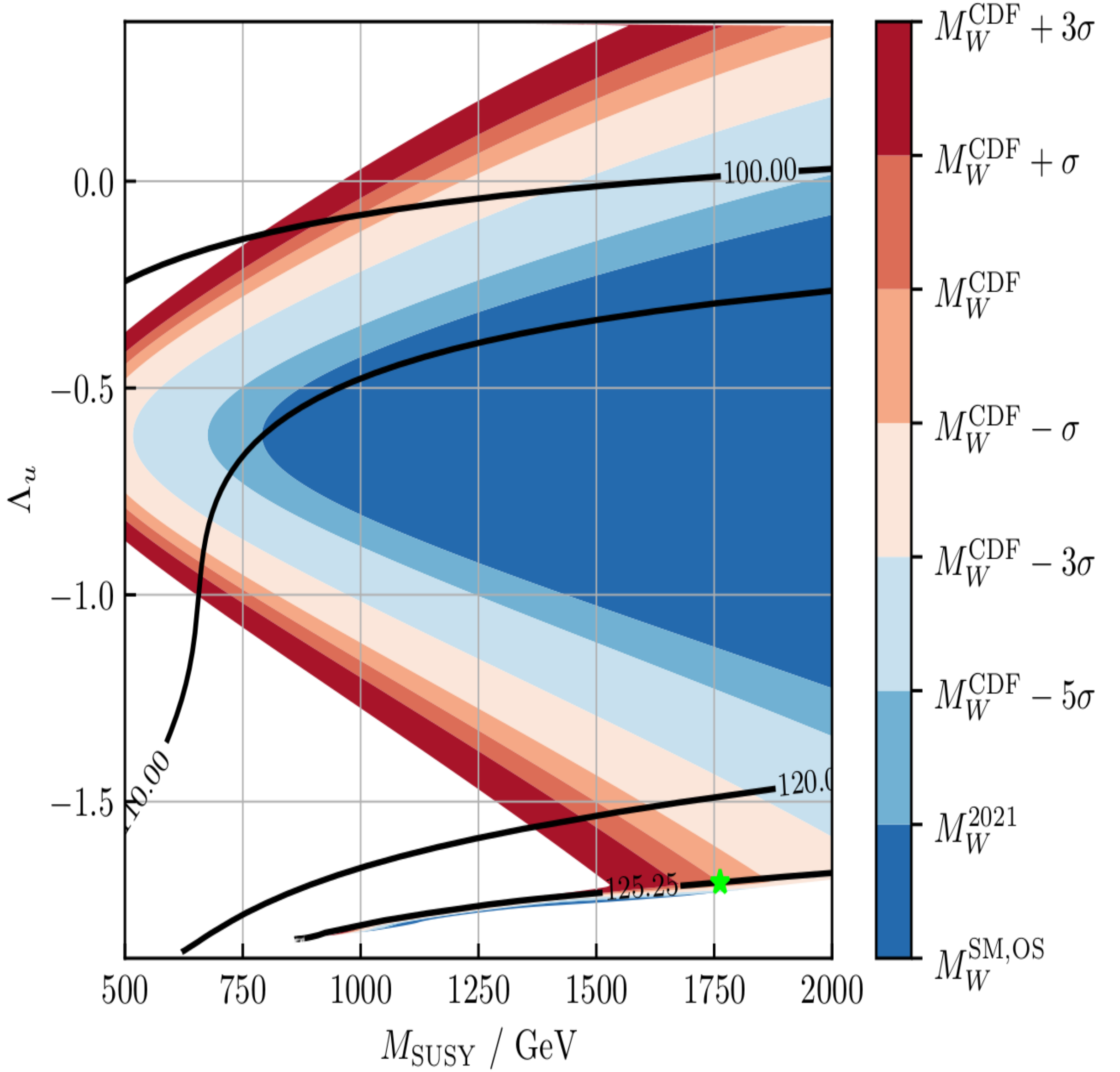
Tree level contribution:

$$\hat{\rho}_{\text{tree}} = 1 + \frac{4v_T^2}{v_d^2 + v_u^2}$$

$$\Rightarrow m_W^2 = m_Z^2 \cos^2\theta_W + g_2^2 v_T^2$$

Explaining CDF W mass measurement is easy

Higgs mass is quite constraining though



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
- Precise W mass prediction (all known SM contributions + one-loop BSM)
- Decays of scalars
- Tower of effective field theories (C++ level manual matching conditions, auto-generated matching is work in progress)

FlexibleSUSY is precise

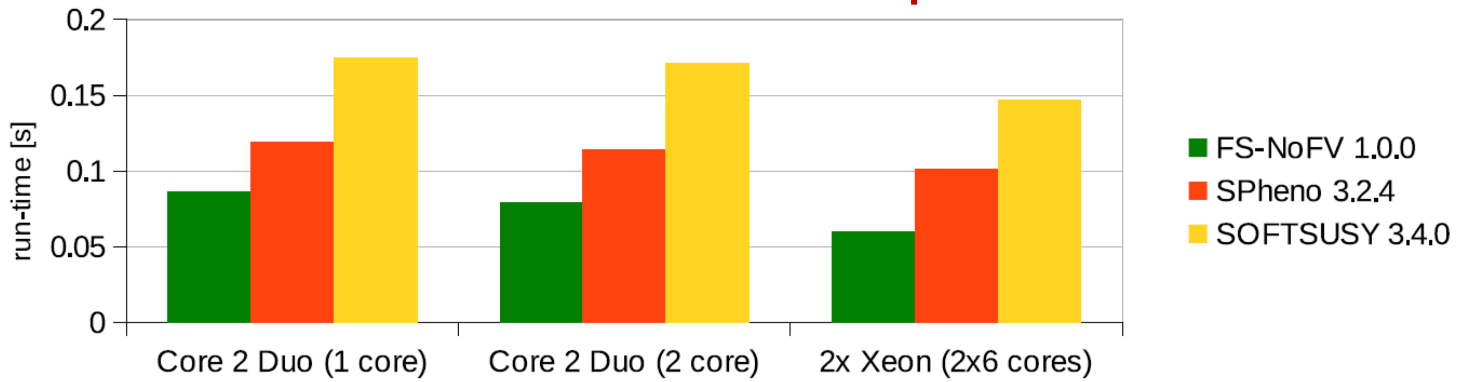
STATE OF THE ART MODEL SPECIFIC CORRECTIONS

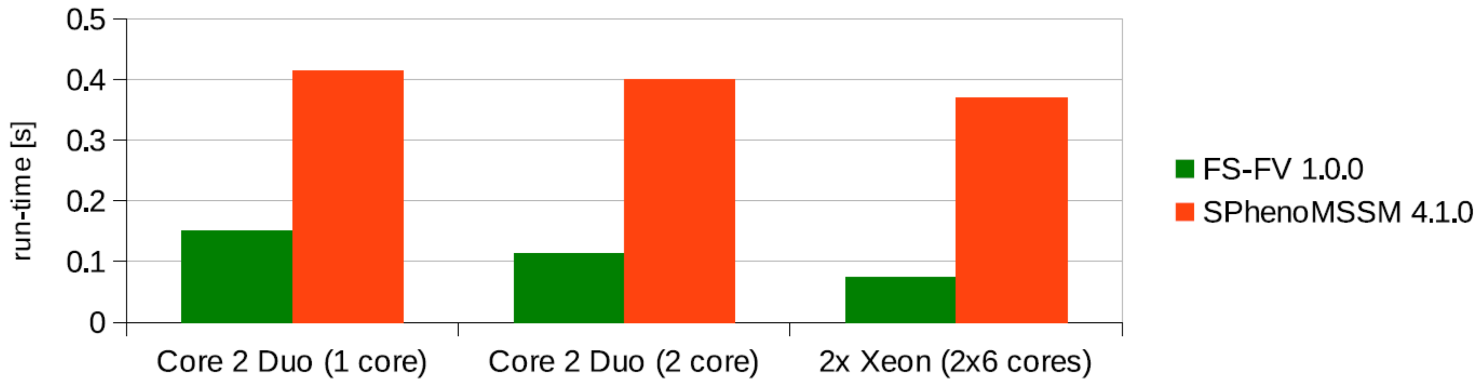
- 3-loop RGEs in SM and MSSM
- 2-loop (SUSY) QCD correc. to top, bottom Yukawas in SM, MSSM
- 2-loop (SUSY) QCD correc. to strong gauge coupling in SM, MSSM
- 2-loop fixed order Higgs mass corrections SM, MSSM, NMSSM
- 3-loop fixed order Higgs mass corrections SM, MSSM (via Himalaya)
- 3-loop Higgs mass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

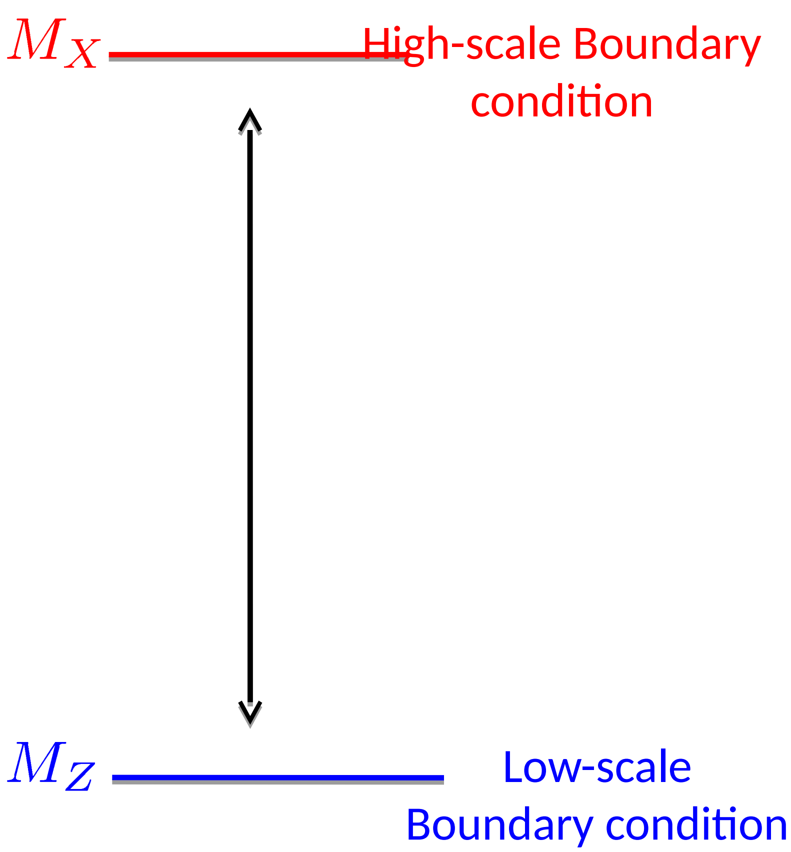
- Build tower of effective field theories

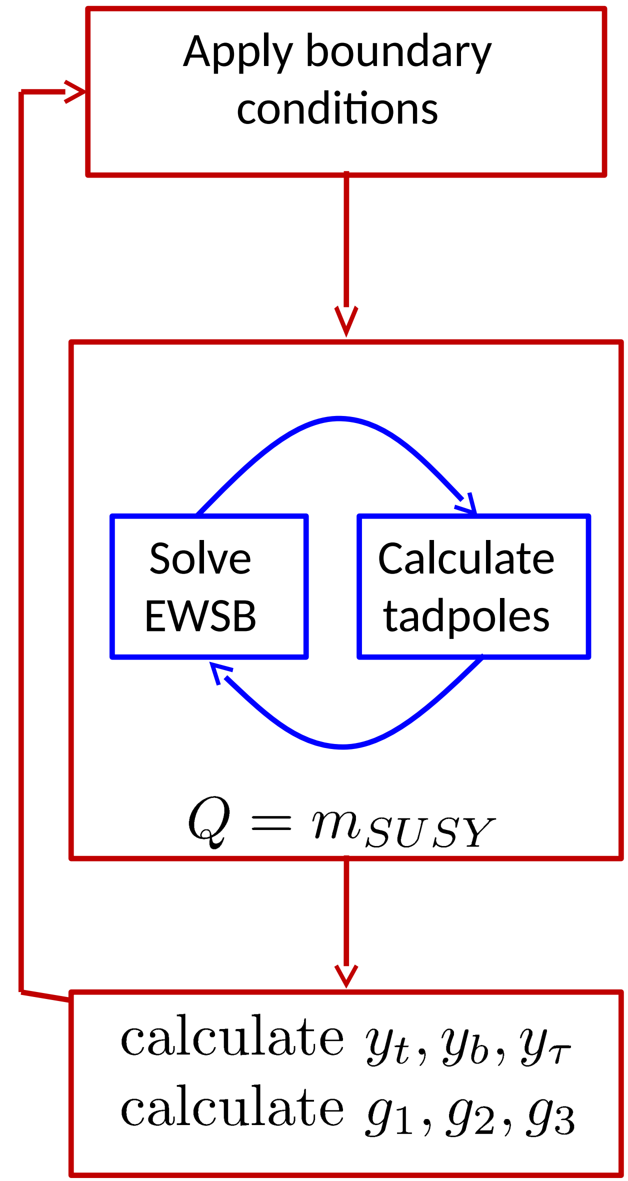
C++ code level only so far

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