CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

FlexibleTools

Understanding new physics from the LHC with next generation software

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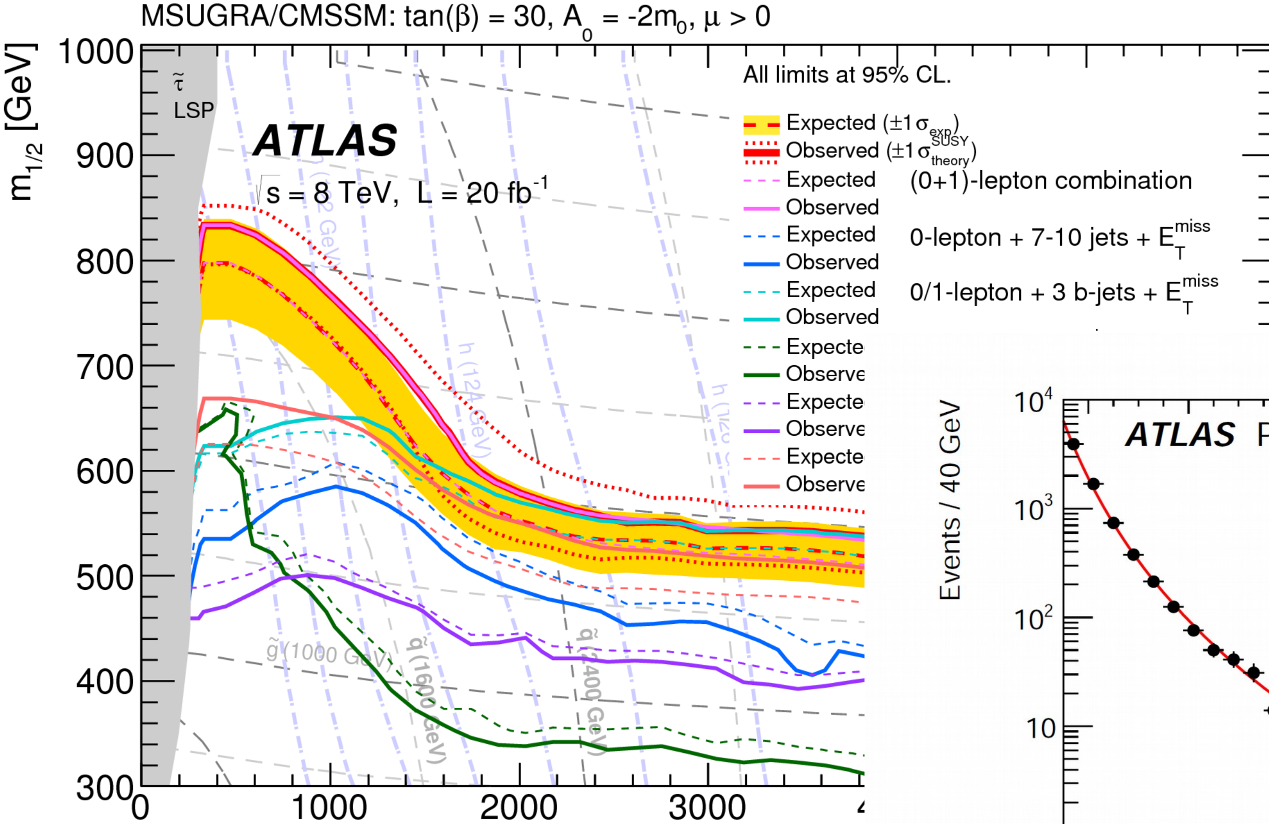
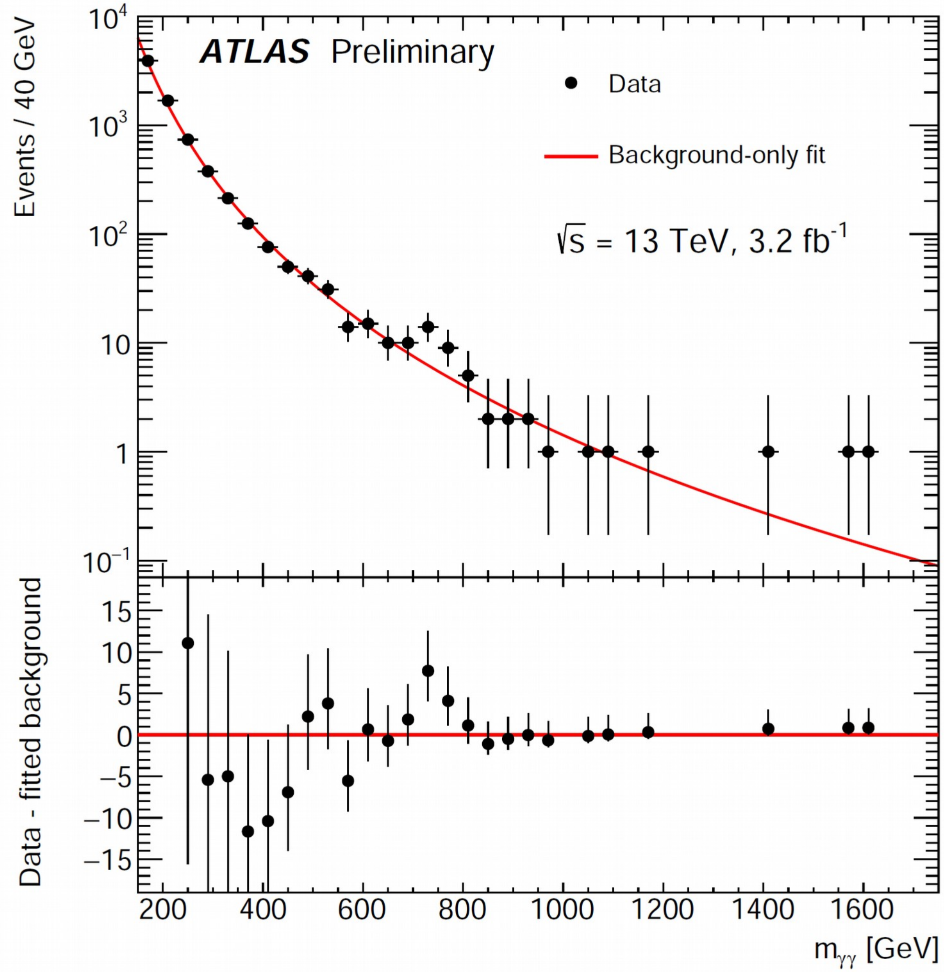
LHC results



CMSSM now heavily constrained



New physics hint that cannot be explained by the MSSM

Minimality is not required by fundamental motivations of SUSY

- Large Hierarchy Problem ← Just needs SUSY + little hierarchy problem can be improved
- Gauge Coupling Unification ← Just depends on incomplete SU(5) Multiplets (Higgs fields)
- Dark Matter candidate ← Appropriate LSP from Z2 symmetry
- Explaining the matter-antimatter asymmetry ← Can have extra contributions
- Radiative EWSB ← Need large Yukawas to drive soft terms negative

Non-minimal models can solve problems with the MSSM

- mu problem
- little hierarchy problem
- Explaining the matter-antimatter asymmetry
- Flavour physics problems
- boredom: exciting new phenomenology

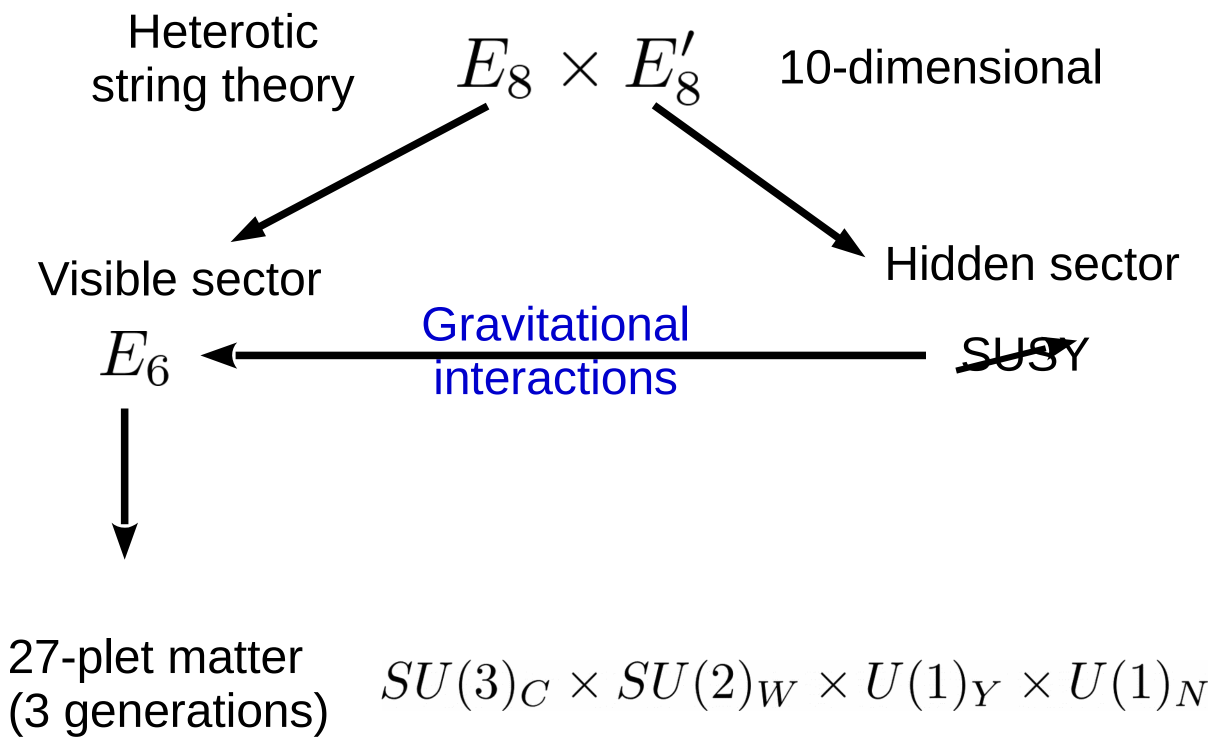
Beyond SUSY

SUSY models are not the only possibility

- Higgs extensions (scalar singlet, two Higgs doublet, triplet Higgs)
- Dark matter models (e.g. Minimal Dark Matter)
- Gauge extensions
- Proposals to fit new LHC excesses
- Extra dimensions
- (non-SUSY) GUT models
- Family symmetry models
- Composite Higgs

Let me explain my own story...

Once upon a time I was a young, naive PhD student.
The idea of E6 SUSY models really captured my imagination
(thanks in part to Roman Nevzorov)



Propaganda

Elegant string inspired model

SUSY solves hieratchy problem

E6 forbids mu-problem

E6 ensures anomaly free

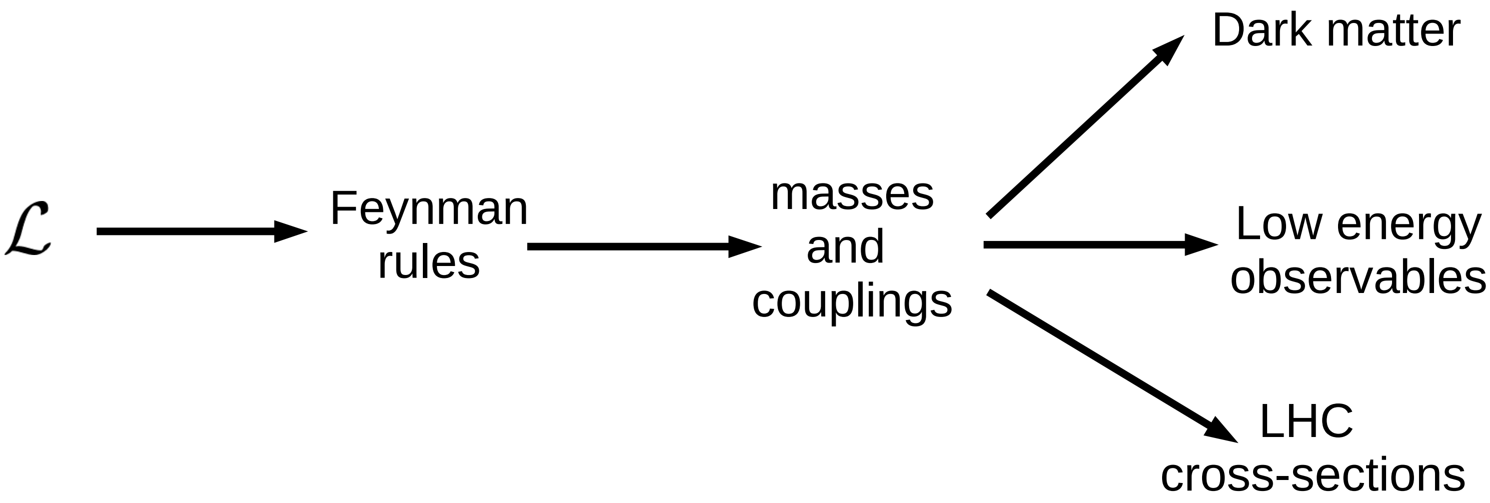
Exotic D- and F-terms raise Higgs mass

String picture motivation for hidden sector

So, I thought, wouldn't it be great to understand the phenomenology...

That is not such an easy thing...

Understanding the consequences of a new physics model involves:



Long before I started there had been a huge effort by many people to do this in just the MSSM

Example: MSSM

The most popular extention of the Standard Model has been the Minimal Supresymmetric extension of the Standard Model (MSSM).

To test the MSSM on must calculate many observables:

- masses,
- LHC cross-sections,
- decay rates,
- relic density of dark matter,
- amomalous magnetic moment of the muon
- etc …

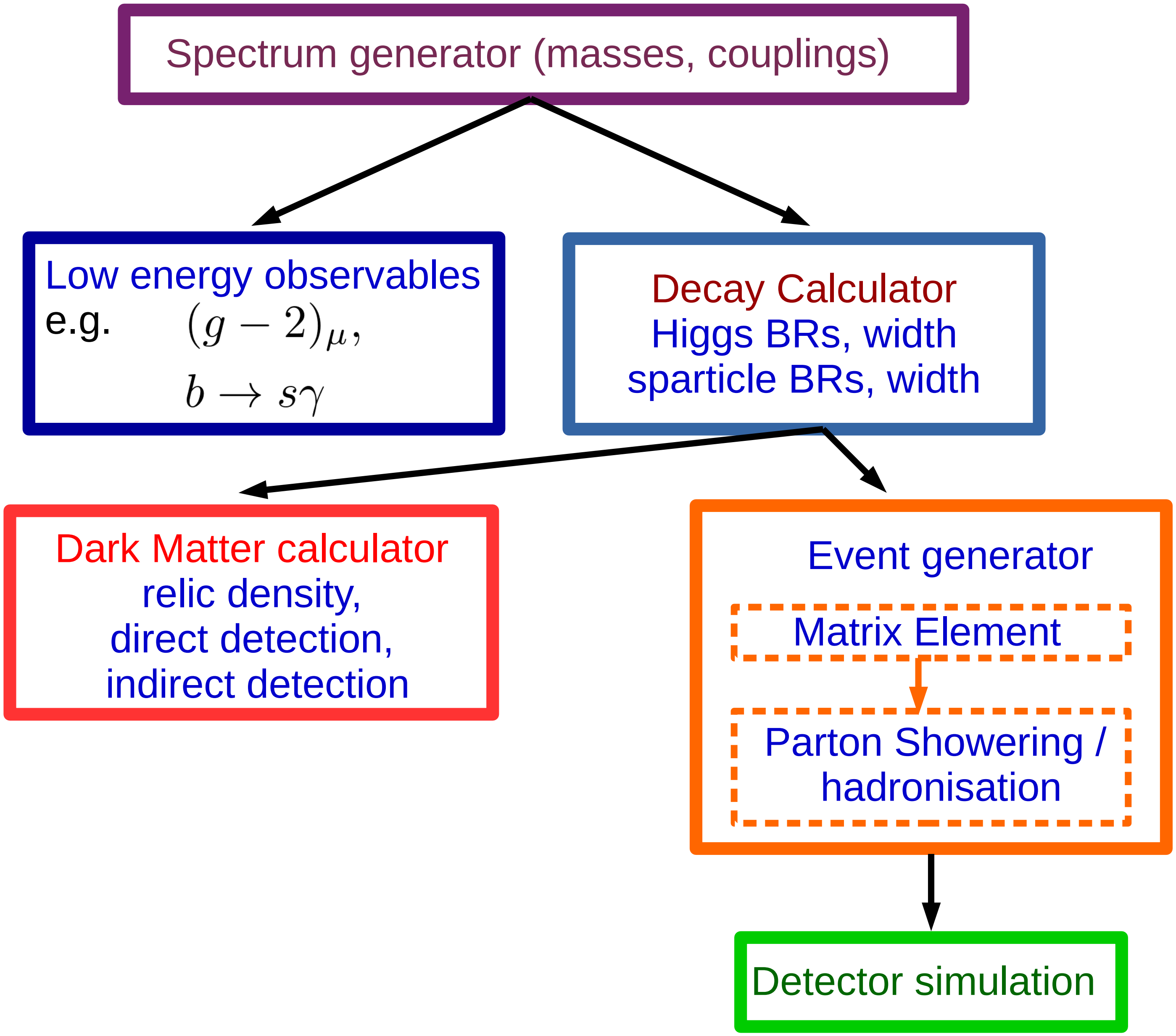
These are very complicated calculations.

A huge number of papers have been written on each one.

And the parameter space of the model is huge

⟶ Computational tools

Example: MSSM Tool Chain



Example: MSSM Tools

SOFTSUSY, SPHENO, SUSPECT, ISASUSY, (FeynHiggs)

MICROMEGAS, DARKSUSY

HDECAY, SDECAY, FeynHiggs, SPHENO

SUPERISO, FeynHiggs, GM2calc

MADGRAPH/EVENT, WHIZARD, PYTHIA, HERWIG, SHERPA, ISAJET

Each contains many lines of code

Multiple codes needed for: cross-checks, bug finding and different physics approaches, renomalisations schemes, indications of level of uncertainty

Before code could be written many expressions needed to be derrived for the MSSM (Feynman Rules, Mass matrices, RGEs, loop corrections…)

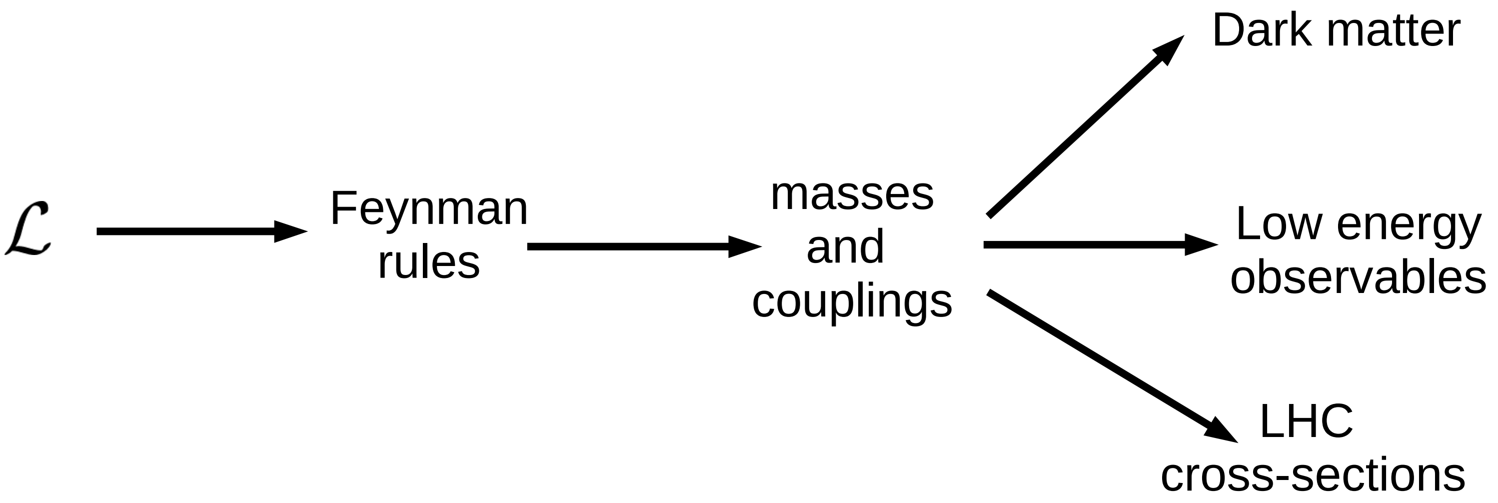
E6 SUSY models are significantly more complicated than the MSSM..

Repeating all of this for every model is a huge calculational hurdle.

Solution: Auto-generation of code, using symbolic algebra package (ie mathematica) and specialise general results to specific models.

This talk is about one of the most exciting developments in particle physics in the last ten years...

There has been remarkable progress in automating all these steps:



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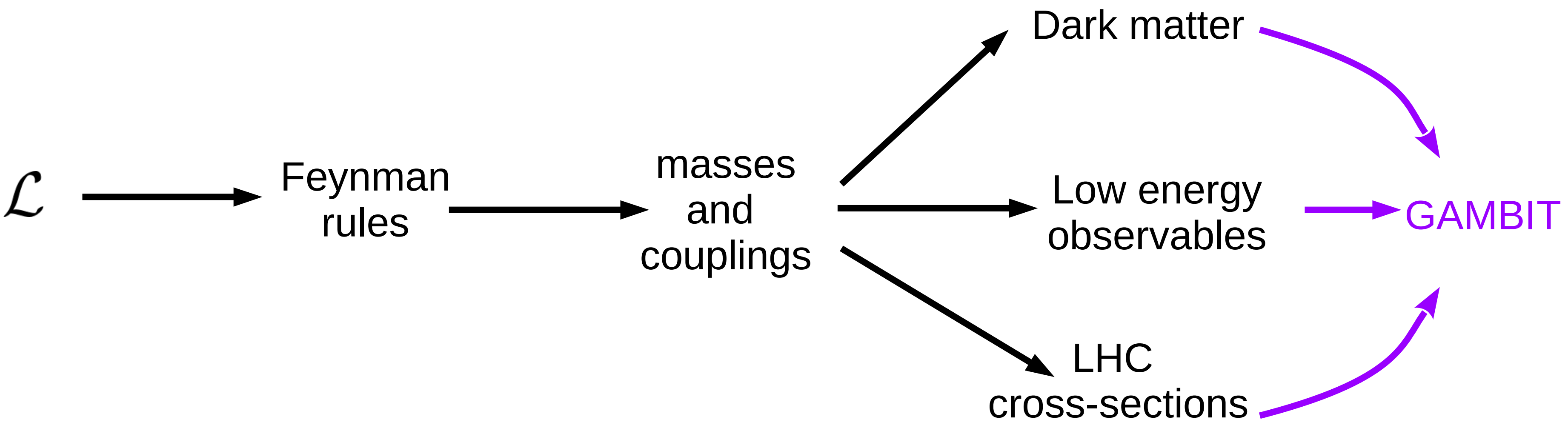


Martin already talked about using GAMBIT for the global fit at the end, but we need to calculate observables before we can do any fit.

This is why we need FlexibleTools!

General Model Tools (incomplete list)

Mathematica packages to derive Feynman rules (and more)	SARAH FeynRules CalcHEP
Spectrum generators	FlexibleSUSY/BSM Spheno-3
Decay Calculator	FlexibleDecay Spheno-3
Event Generator	MADGRAPH WHIZARD PYTHIA SHERPA
Dark Matter	micrOMEGAs
Signals/Limits	HiggsBounds/Signals CheckMate MadAnalysis ATOM
Global Fits	GAMBIT

Content

Introduction:

- Why E6 SUSY models are great (meanderings on the past)
- doing particle physics properly is hard!

FlexibleSUSY, a spectrum generator generator for any* BSM model

Extensions and new tools:

FlexibleHiggs, EFT approach for two loop corrections in any* BSM model

FlexibleDecay, tool to calculate partial widths / BRs in any** BSM model

Diphoton Tools, set of useful tools that can be used specifically to study the diphoton excess

* some caveats apply
** some caveats may apply (work in progress)

FlexibleTools

[PA, M.Bach, D.Harries, J.H.Park, T.Steudtner, D.Stöckinger, A.Voigt, J.Ziebell]

Aim: create precise computational tools
for phenomenology in most or all BSM models

Process

Build general algorithms with flexibility in mind

Specialise to specific user specified model and generate C++ implementation

Allow flexible adaption at every level: adapt model input,
shape tool structure,
adapt generated code,
configure options via input

FlexibleSUSY = spectrum generator generator

FlexibleSUSY

Spectrum generators

<u>Components</u>

RGEs

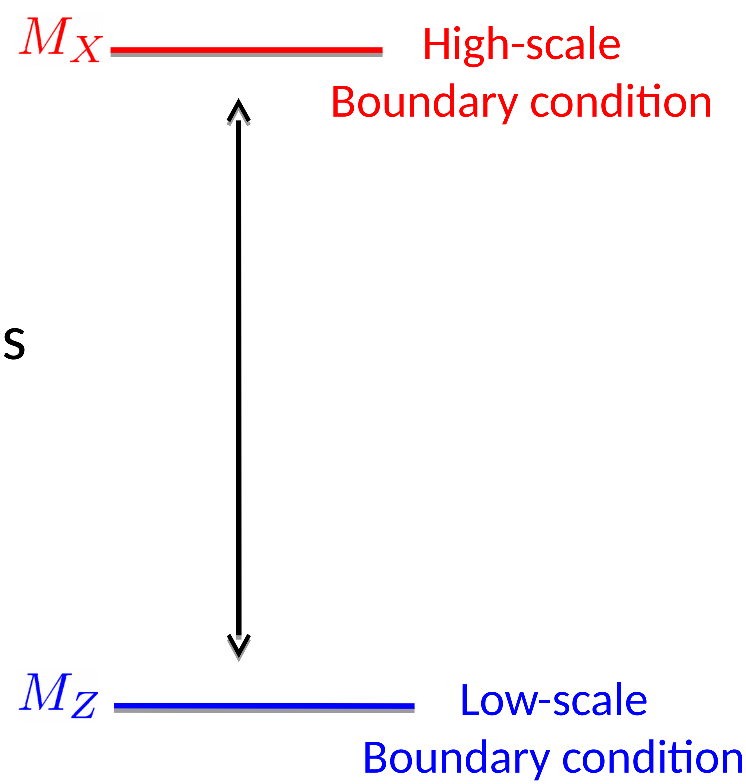
EWSB equations

Tadpoles corrections

Mass matrices

Self energies

<u>boundary-value solver</u>



<u>Output</u>

Pole masses, mixing angles / matrices, couplings

FlexibleSUSY

https://flexiblesusy.hepforge.org/

[PA, J.H.Park, D.Stöckinger, A.Voigt CPC 190 (2015) 139-172]

- 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.

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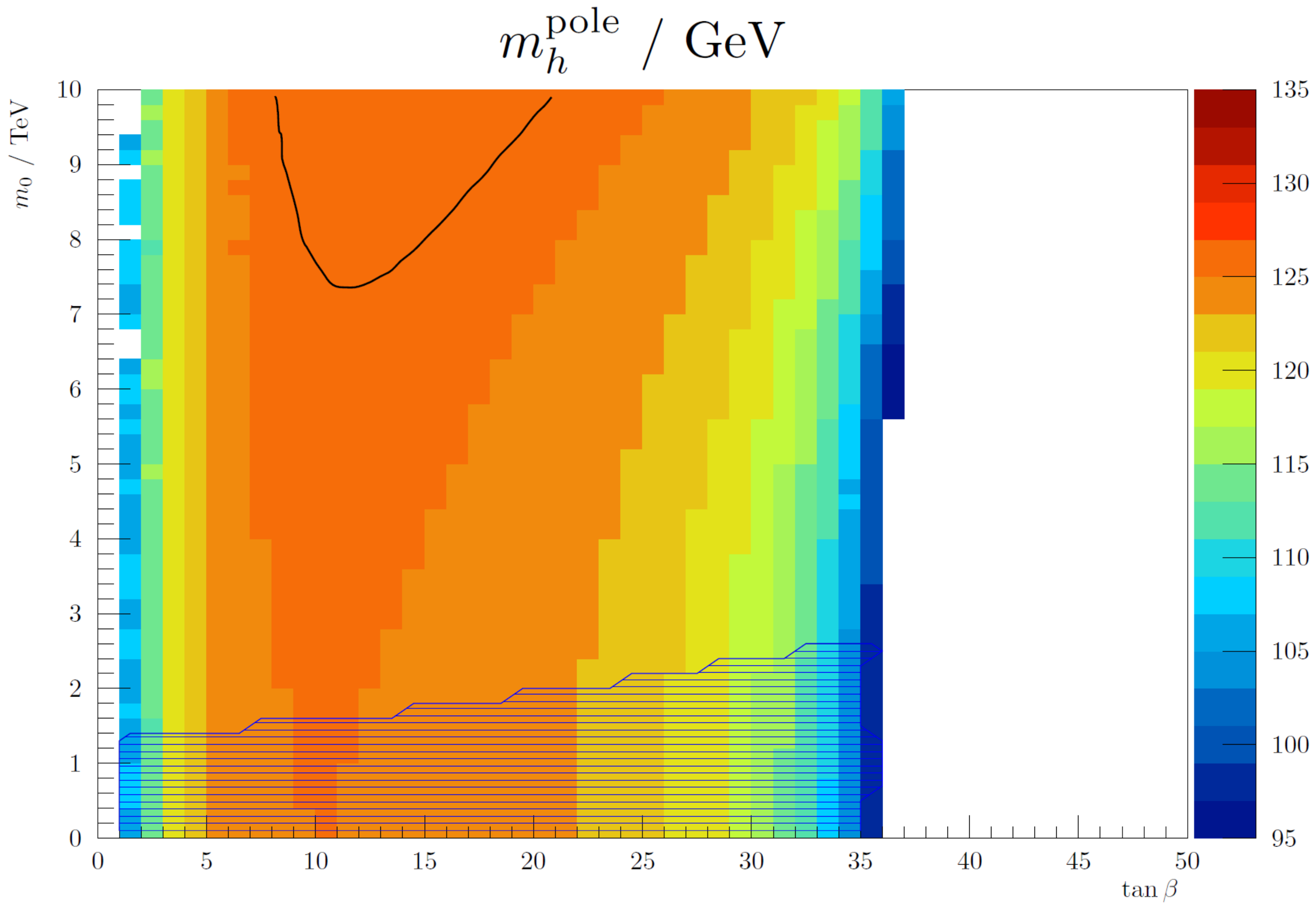
```
$ ./install-sarah # if not already installed
$ ./createmodel --name=NMSSM
$ ./configure --with-models=NMSSM
$ make
```

NMSSM parameter scan



$M_{1/2} = -A_0 = 5\,\text{TeV}, \lambda(M_X) = 0.1, \text{sign}\, v_s = +1.$

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$ 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

FlexibleSUSY is precise

- FlexibleSUSY spectrum generators are as precise as leading public spectrum generators for MSSM and NMSSM:

  SOFTSUSY, SPheno, SUSPECT, NMSSMTools…

- Full three family two loop RGEs
- Full one loop self energies for all states and mass mixing
- Pure QCD two loop corrections for running top/bottom
- Neutral Higgs can get two loop corrections (optional):

(files from Pietro Slavich)

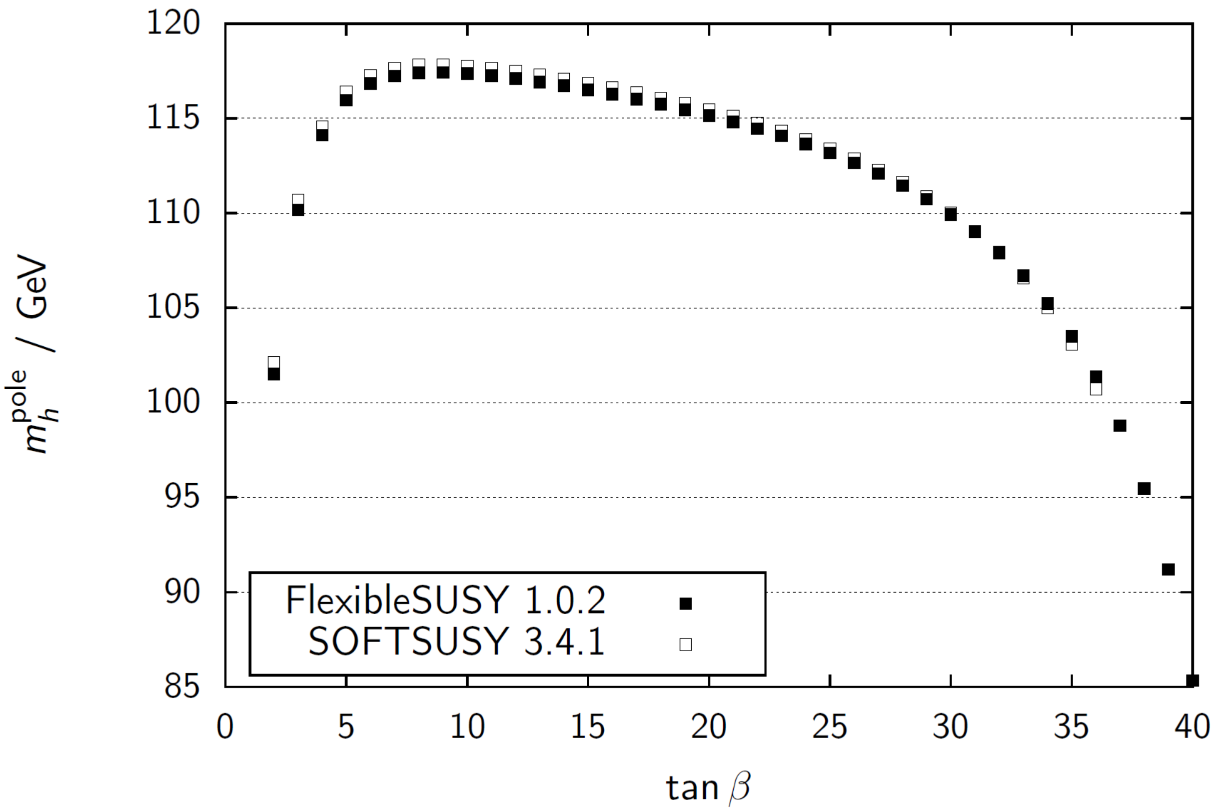
$\mathcal{O}(\alpha_s \alpha_b)$, $\mathcal{O}(\alpha_s \alpha_t)$ (N)MSSM zero momentum [G.Degrassi, P.Slavich Nucl.Phys. B 825, 119]

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

- one loop self energies use $p^2 = m^2$ via iteration (optional):

$$M^2 + \Sigma(p^2 = m^2) \xrightarrow[\text{for eigenvalues}]{\text{diagonalise}} m^2$$

Higgs Mass in NMSSM



$$m_0 = M_{1/2} = -A_0 = 1\,\text{TeV}, \lambda(M_X) = 0.1, \text{sign}\, v_s = +1.$$

Default FlexibleSUSY closely matched to SOFTSUSY

→ FlexibleSUSY and SOFTSUSY agree more closely than most spectrum generators

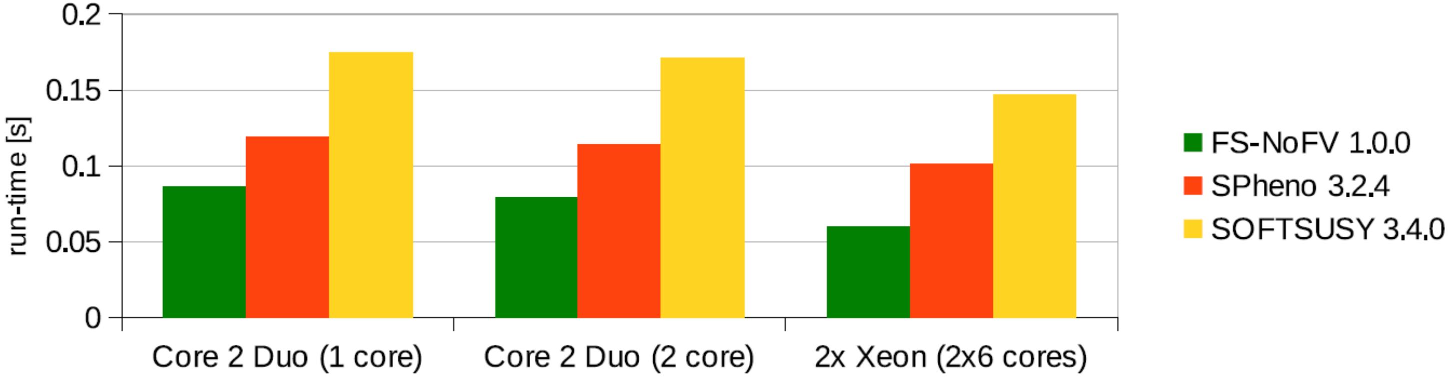
FlexibleSUSY and other NMSSM Spectrum generators were compared here:

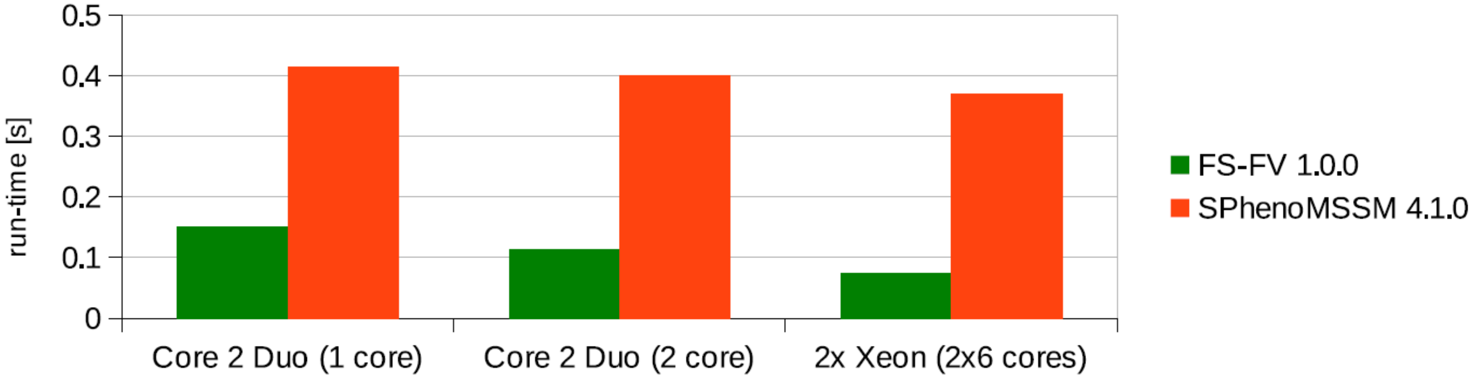
[F.Staub, PA, U.Ellwanger, R.Grober, M.Muhlleitner, P.Slavich , A.Voigt, arXiv:1507.05093 [hep-ph].]

FlexibleSUSY is fast

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

CMSSM run-time comparison

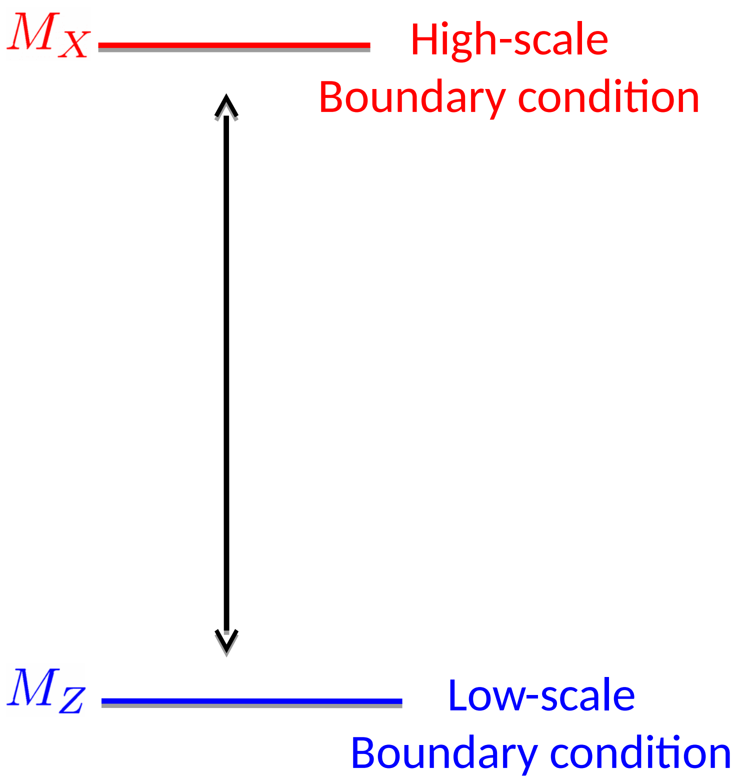


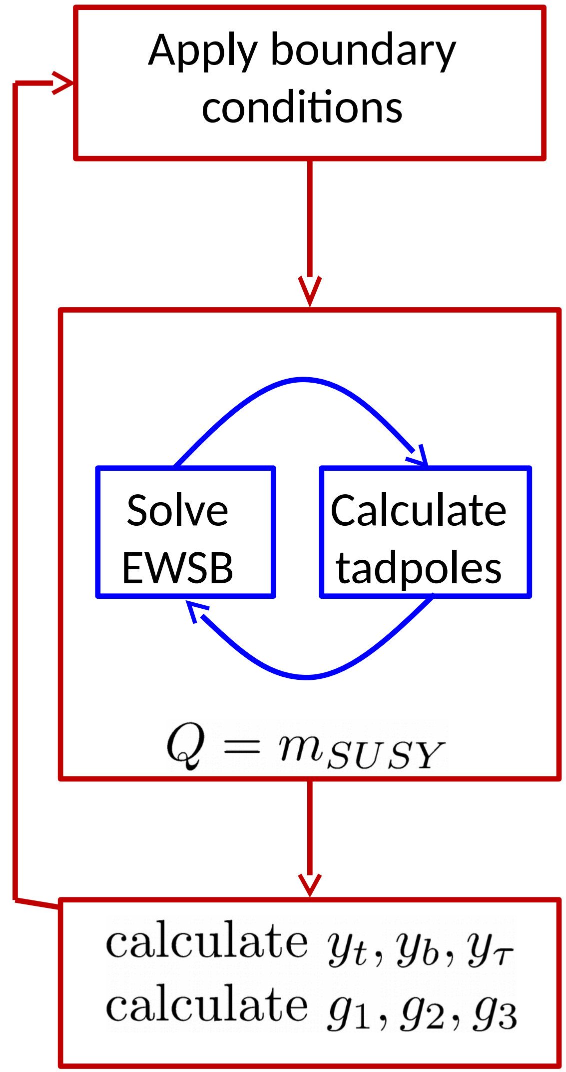


g++ 4.8.0, ifort 13.1.3 20130607

FlexibleSUSY is adaptable

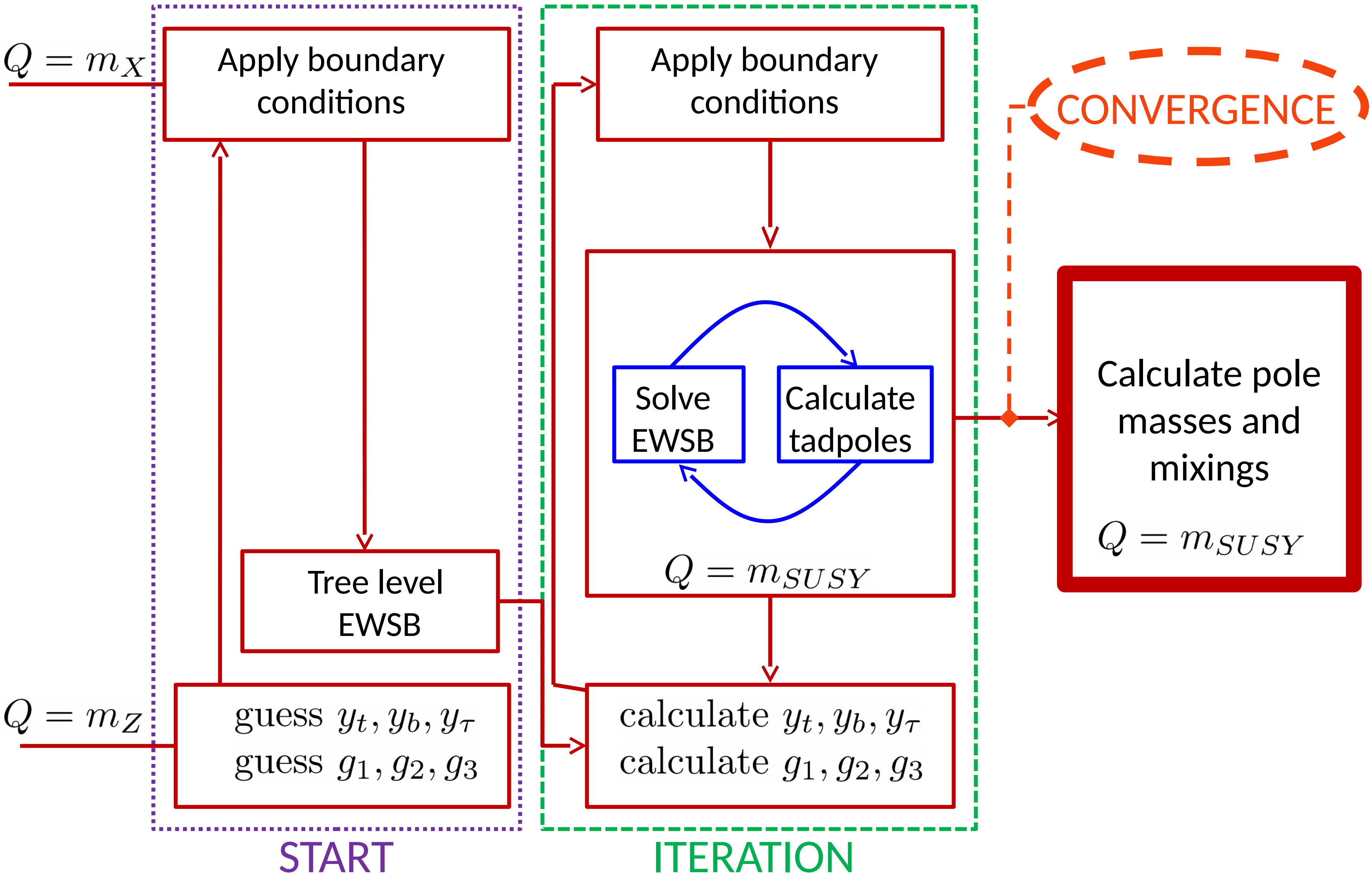
boundary-value solver → Two-scale fixed point iteration





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

Two-scale fixed point iteration



FlexibleSUSY is adaptable

Two-scale boundary solver may be set in non-standard ways:

- 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

Extensions and other FlexibleTools

A Flexible Future

- FlexibleCPV (v1.1.0+)
  FlexibleSUSY can now generate models with complex parameters.

- FlexibleMW (Markus Bach)
  New calculation of muon decay to be implemented, making MW a prediction that can be used in precision tests.

- FlexibleAMU (Jobst Ziebell)
  Calculation of new physics contributions to g-2 specialised to the user chosen model

- FlexibleSAS (Dylan Harries)
  New (semi-analytic) boundary value solver to find solutions where usual method fails

- FlexibleBSM (v1.1.0+)
  FlexibleSUSY extension so it now works for non-SUSY models as well.

- FlexibleHiggs (Tom Steudtner)
  An effective field theory calculation of the two-loop Higgs mass for a generic model

- FlexibleDecay (Dylan Harries, Markus Bach) (help for diphoton excess)
  Calculate BRs for Higgs and new BSM states

Beyond SUSY

SUSY models are not the only possibility

- Higgs extensions (scalar singlet, two Higgs doublet, triplet Higgs)
- Dark matter models (e.g. Minimal Dark Matter)
- Gauge extensions
- Proposals to fit new LHC excesses
- Extra dimensions
- (non-SUSY) GUT models
- Family symmetry models
- Composite Higgs

FlexibleSUSY is not just for SUSY

- FlexibleBSM update (v1.1.0+)

$\Rightarrow$ FlexibleSUSY now works for non-SUSY models as well.

Very similar to SUSY structure but $\overline{MS}$ parameters, RGEs and shifts to pole used.

Default executable is based on two-scale solver shaped using the model file

Beyond this the C++ code may be adapted or used as a library of C++ routines,
⟶ you can exploit routines to:

- Solve EWSB
- Extract DRbar / MSbar parameters
- Calculate tree level mass eigenstates
- Calculate Pole mass eigenstates using one loop self energies
- Run DRbar / MSbar parameters with 2 loop RGEs

Usage examples:

- Calculate spectrum where some SUSY partners are very heavy and a non-SUSY model is used as a low energy effective theory (e.g. Split-SUSY)
- Study vacuum stability in the model

FlexibleHiggs

The Higgs mass is a very important prediction in SUSY models

Quartic coupling in MSSM is fixed:

$$V_{\phi}^{SM} = \mu^2|\phi|^2 + \lambda|\phi|^4$$

$$V_{H^0}^{MSSM} = m_1^2|H_u^0|^2 + m_2^2|H_d^0|^2 - m_3^2(H_u^0 H_d^0 + h.c.) + \frac{1}{8}(g'^2 + g^2)v^2$$

$$\Rightarrow m_h \leq M_Z$$ Tree level upperbound on lightest Higgs mass

Radiative corrections are large and play crucial role

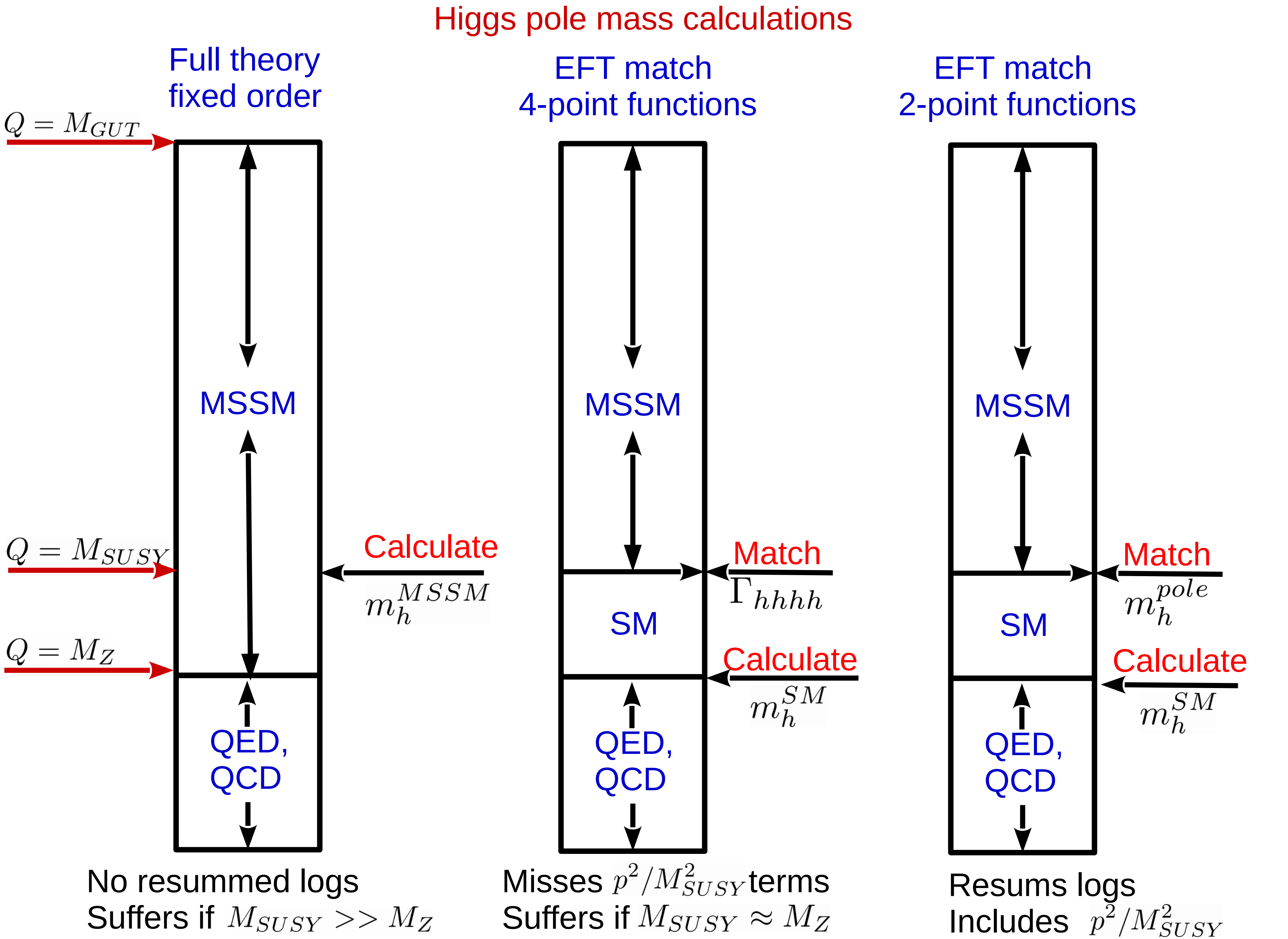
To test if 125 GeV is possible two-loop corrections are essential!

Furthermore Higgs mass and sparticle limits imply large logs need resummed

There is already a huge literature on precision Higgs mass in the MSSM

Many alternatives (NMSSM, E6SSM, MRSSM) raise the Higgs mass.

But then two-loop corrections are also essential to check.



Higgs pole mass calculations
Full theory
fixed order
EFT match
4-point functions
EFT match
2-point functions
$Q = M_{GUT}$
$Q = M_{SUSY}$
$Q = M_Z$
MSSM
QED,
QCD
Calculate
m_h^{MSSM}
MSSM
SM
QED,
QCD
Match
Γ_{hhhh}
Calculate
m_h^{SM}
MSSM
SM
QED,
QCD
Match
m_h^{pole}
Calculate
m_h^{SM}
No resummed logs
Suffers if $M_{SUSY} >> M_Z$
Misses p^2/M_{SUSY}^2 terms
Suffers if $M_{SUSY} \approx M_Z$
Resums logs
Includes p^2/M_{SUSY}^2

FlexibleSUSY MSSM Higgs mass options

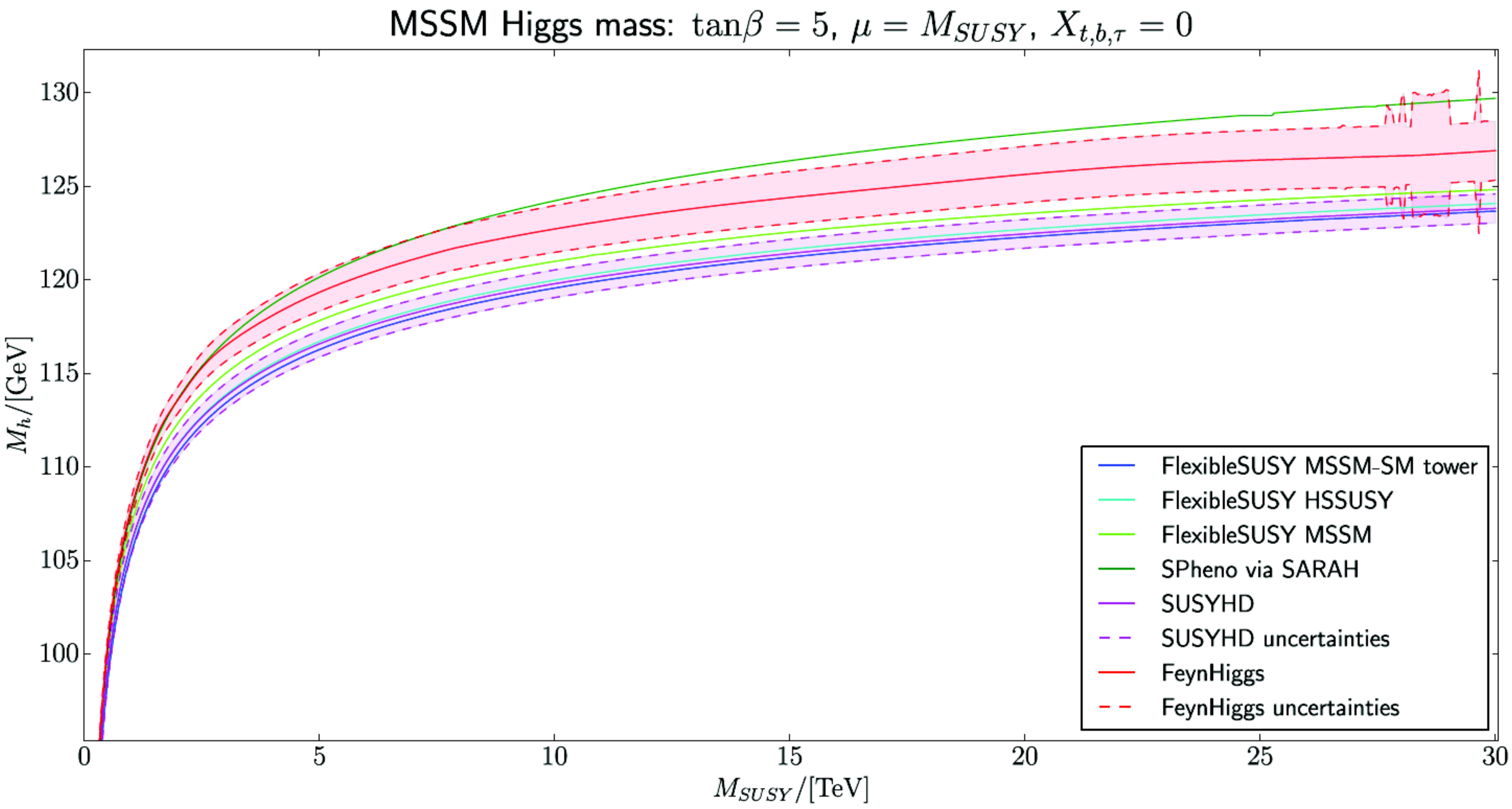
(see arxiv:1512.07761 Bagnaschi, Brummer, Buchmuller, Voigt, Weiglein for first application of EFTs)

Model	RGEs	h self-energy contributions	matching conditions to the MSSM
MSSM ("full model")	3L	$1L + 2L\ O((\alpha_t + \alpha_b)\alpha_s)$ $+ 2L\ O((\alpha_t + \alpha_b)^2)$	–
THDM	2L	1L	$1L\ \lambda_i\ O((\alpha_t + \alpha_b + \alpha_\tau)\alpha_i)$ $+ 2L\ \lambda_i\ O(\alpha_t^2 \alpha_s)$ [1508.00576]
THDM + $\tilde{h}_i$	2L	1L	$1L\ \lambda_i\ O((\alpha_t + \alpha_b + \alpha_\tau)\alpha_i)$ $+ 2L\ \lambda_i\ O(\alpha_t^2 \alpha_s)$ [1508.00576]
THDM + split	2L	1L	$1L\ \lambda_i\ O((\alpha_t + \alpha_b + \alpha_\tau)\alpha_i)$ $+ 2L\ \lambda_i\ O(\alpha_t^2 \alpha_s)$ [1508.00576]
SM + split	2L	$1L + 2L\ O(\alpha_t(\alpha_s + \alpha_t))$ $+ 3L$ gluino $O(\alpha_t \alpha_s^2)$	$1L\ \tilde{g}_{ij}\ O(\alpha_t + \alpha_i)$ $+ 1L\ \lambda\ O((\alpha_t + \alpha_i)^2)$ $+ 2L\ \lambda\ O(\alpha_s \alpha_t^2)$ [1407.4081]
SM ("EFT")	3L	$1L + 2L\ O(\alpha_t(\alpha_s + \alpha_t))$	$1L\ \lambda\ O((\alpha_t + \alpha_i)^2 + \alpha_b^2 + \alpha_\tau^2)$ $+ 2L\ \lambda\ O((\alpha_s + \alpha_t)\alpha_t^2)$ [1407.4081, 1504.05200]
SM ("automatic EFT")	3L	1L	$1L\ \lambda + O(p^2/M_S^2)$ terms

FlexibleHiggs

EFT calculation, but uses pole mass matching

→ smooth interpolation between: EFT result at high MSUSY and full theory calculation at low MSUSY



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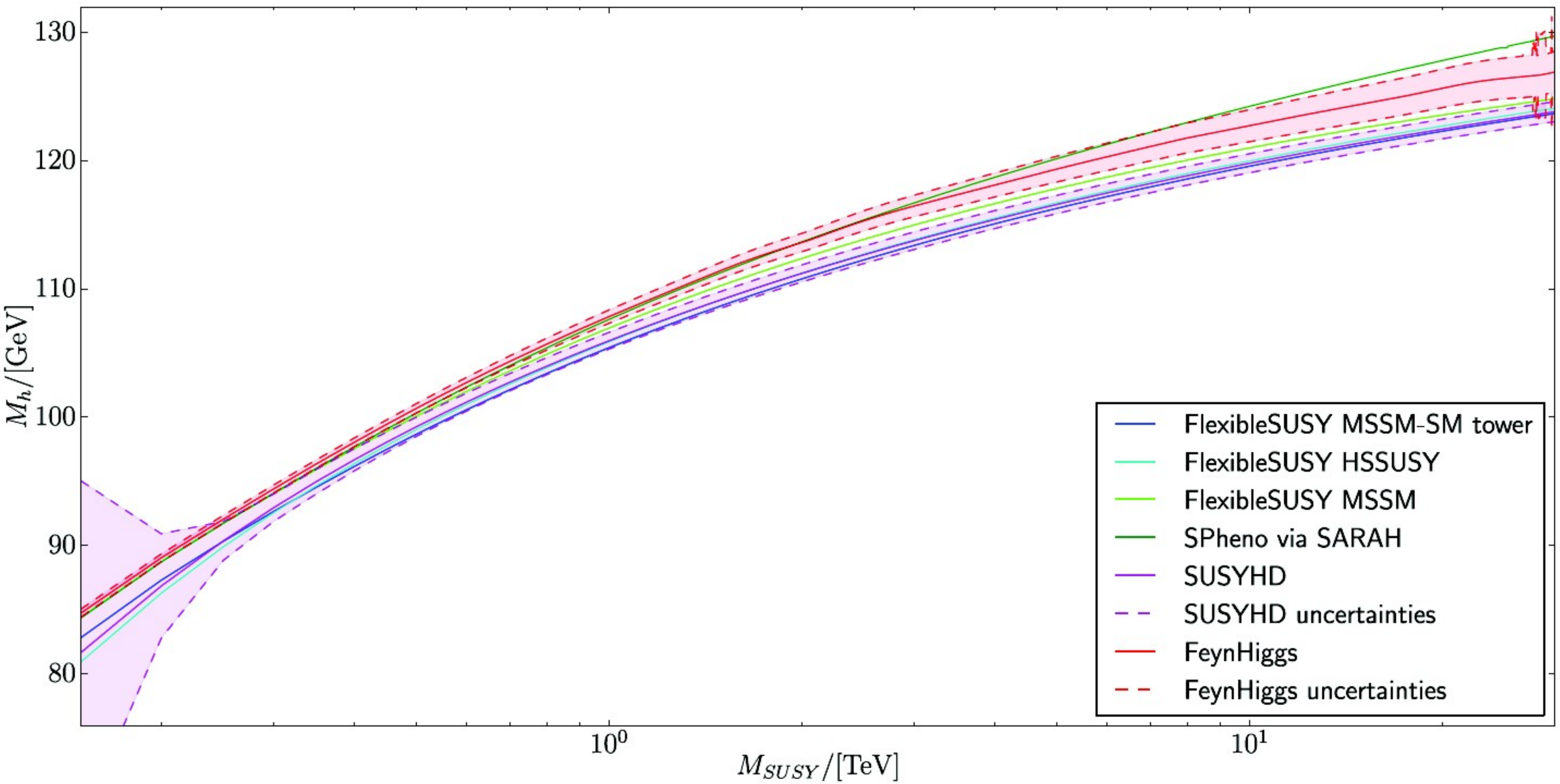

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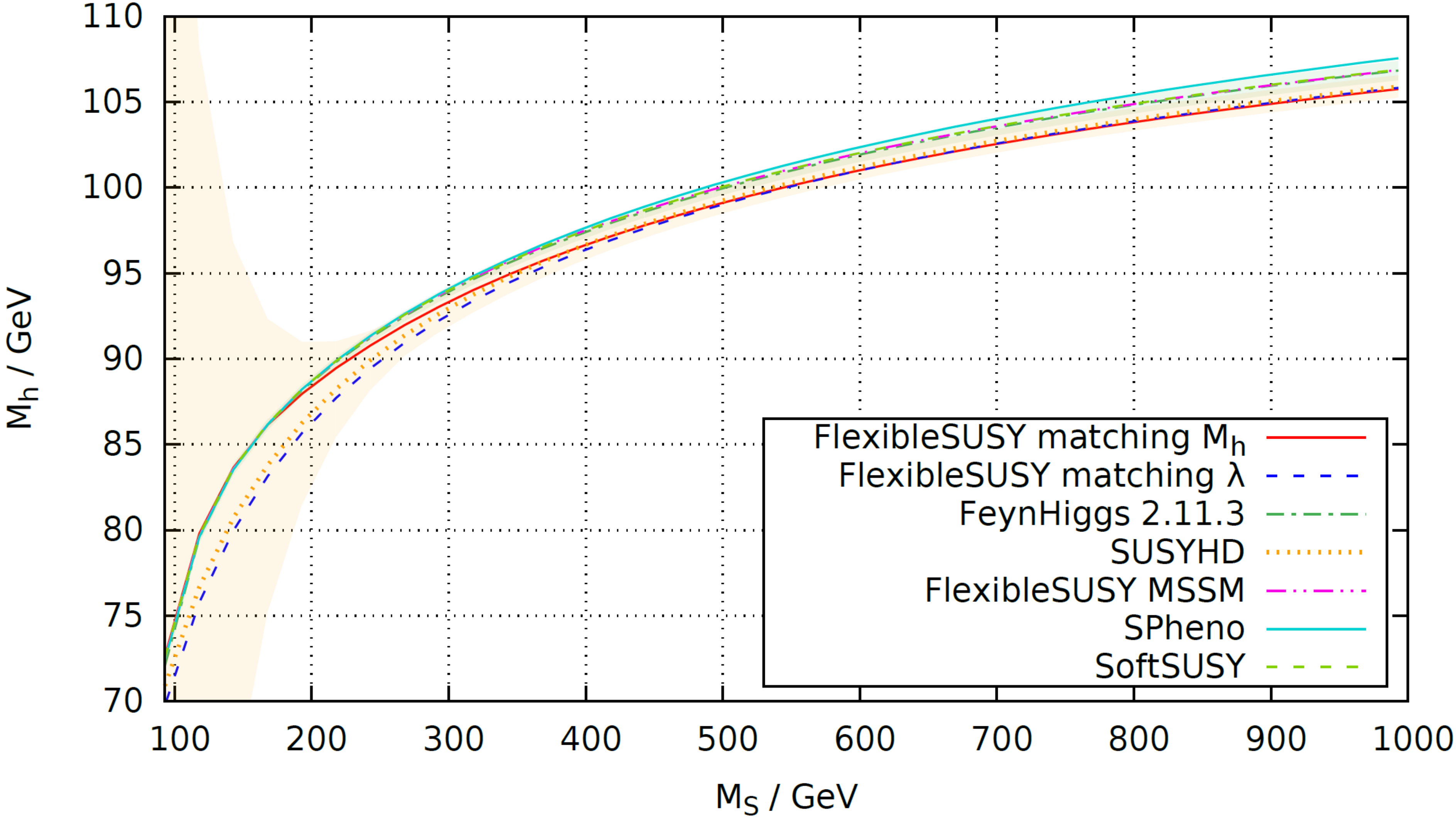

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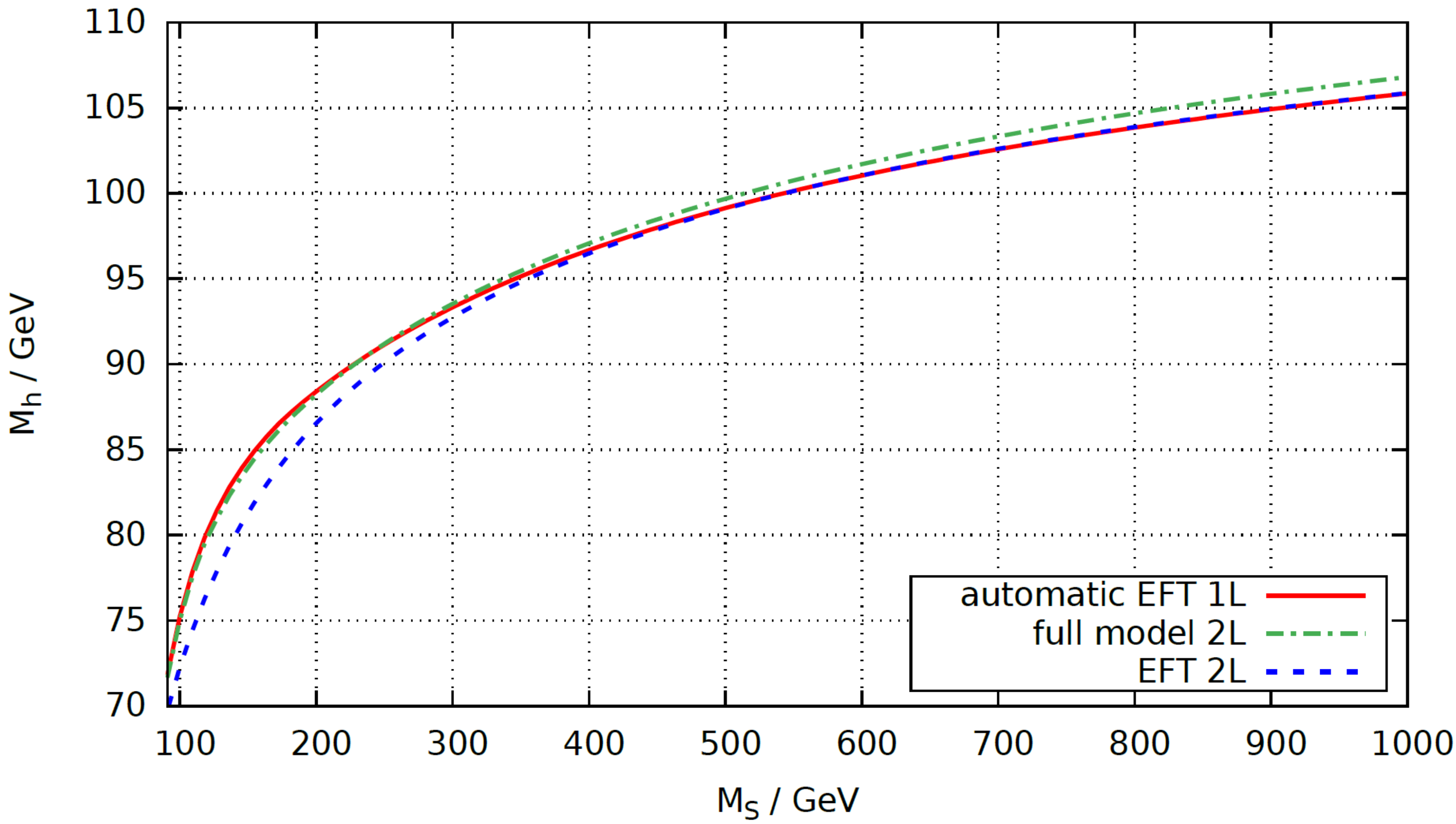

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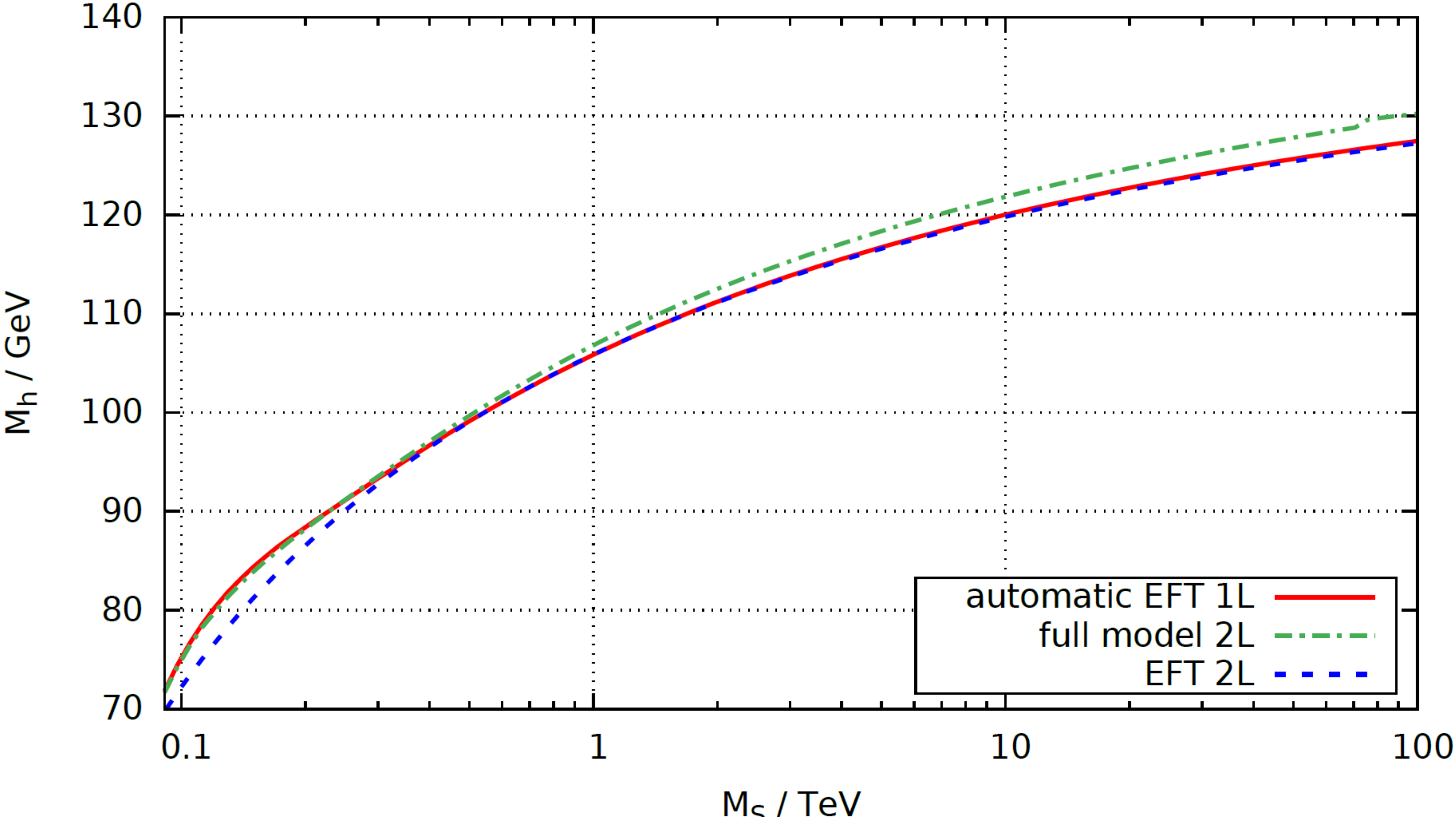

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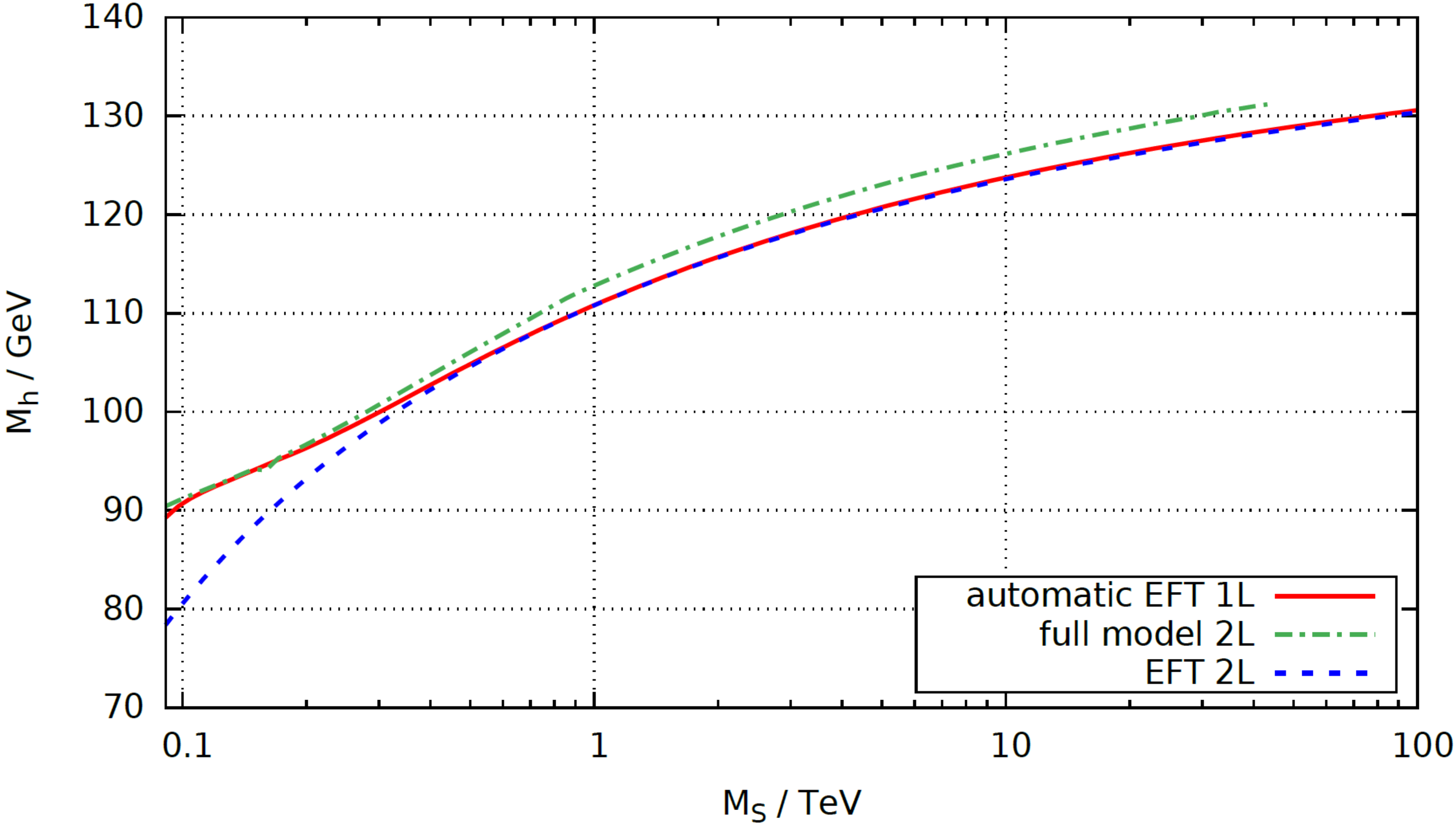


FlexibleHiggs

1) In MSSM we added specific 3-loop RGEs and two-loop matching

$\longrightarrow$ Reproduces SUSYHD result at high MSUSY precisely

Understand all differences between general model FlexibleHiggs and SUSYHD

2) Matching to SM using pole Higgs masses rather tha n 4-point functions

$\longrightarrow$ Automatically get p^2/M_{SUSY} contributions even at 1-loop

Interpolate between EFT result at $M_{SUSY} >> M_{EW}$

and full theory Fixed order calculation at $M_{SUSY} \approx M_{EW}$

3) Difference between the full theory calcs of FlexibleSUSY/SoftSUSY and Spheno

Entirely due to two-loop differences in extraction of top Yukawa from masses used

Both consistent one-loop calculations with only 2-loop pure qcd corrections

4) Results seem to indicate that nonetheless FlexibleSUSY/SOSFTSUSY secretly contain some correct higher order logs through their choice

This needs to be investigated still.

5) 1st automated procedure to improve Higgs mass precsison with EFT approach, resumming logs

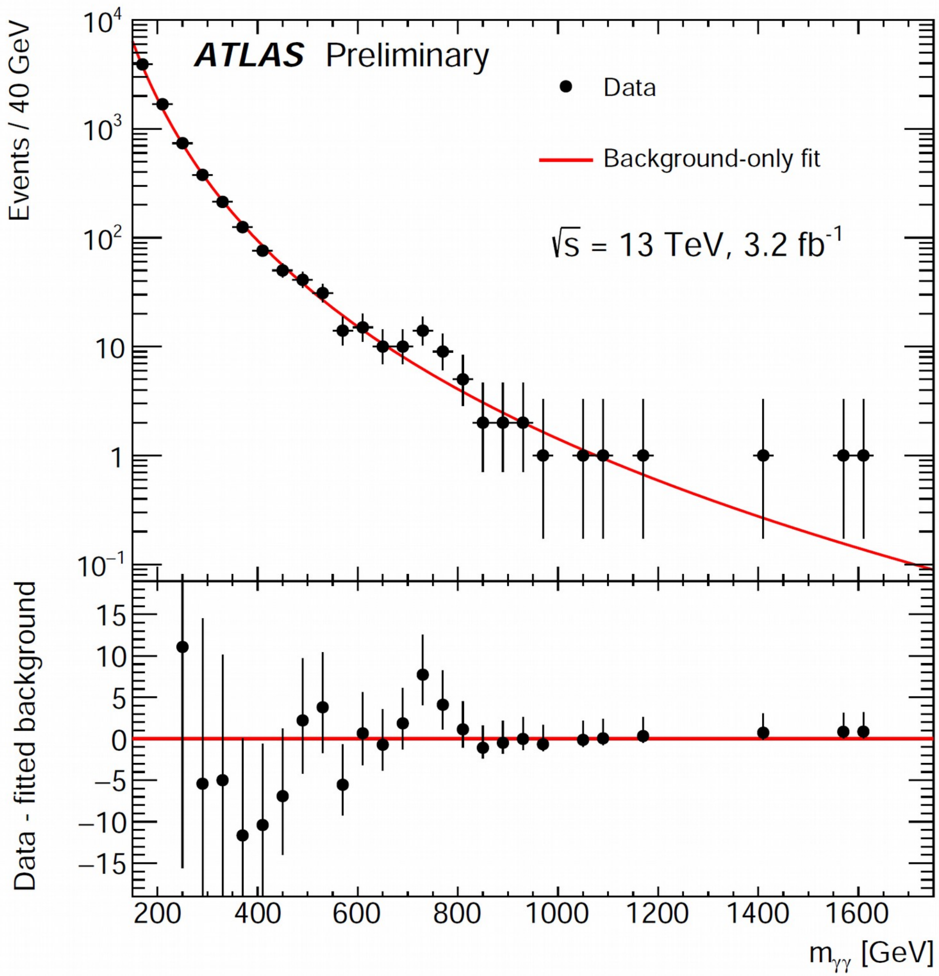
Can be applied to any SUSY model.

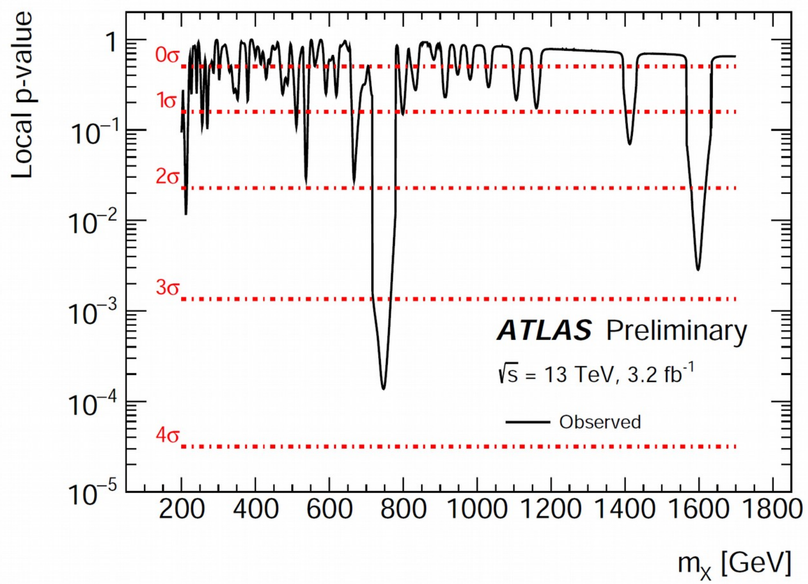
Procedure should even be applied to non-SUSY models (if there is a need)

FlexibleDecay

And tools to study the diphoton excess

750 GeV diphoton excess





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Australia

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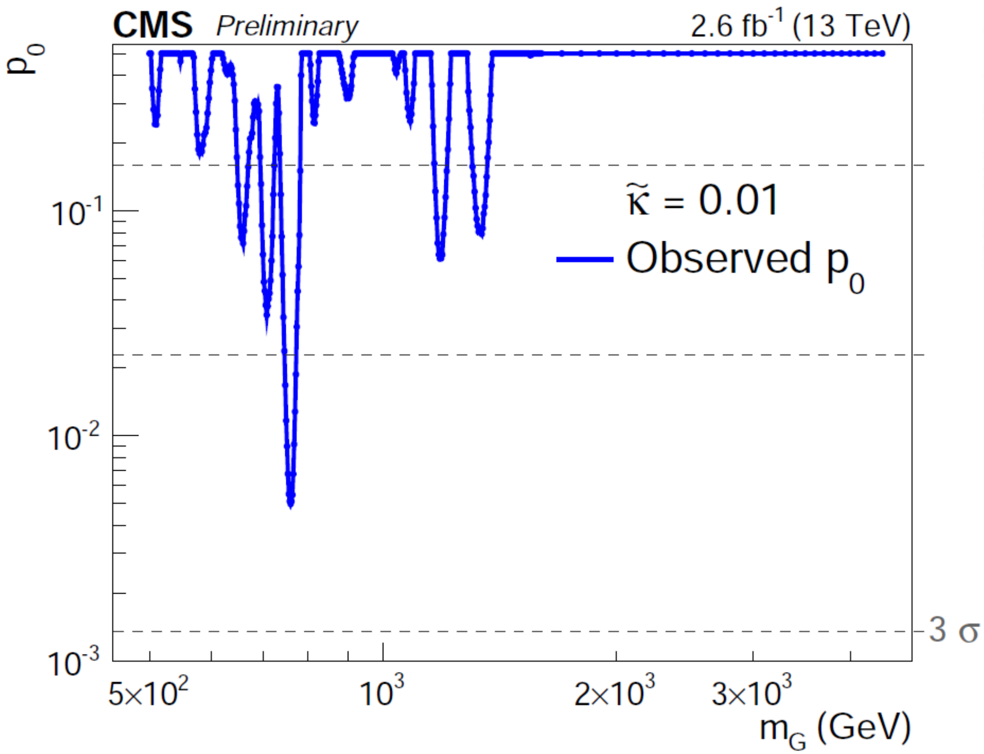
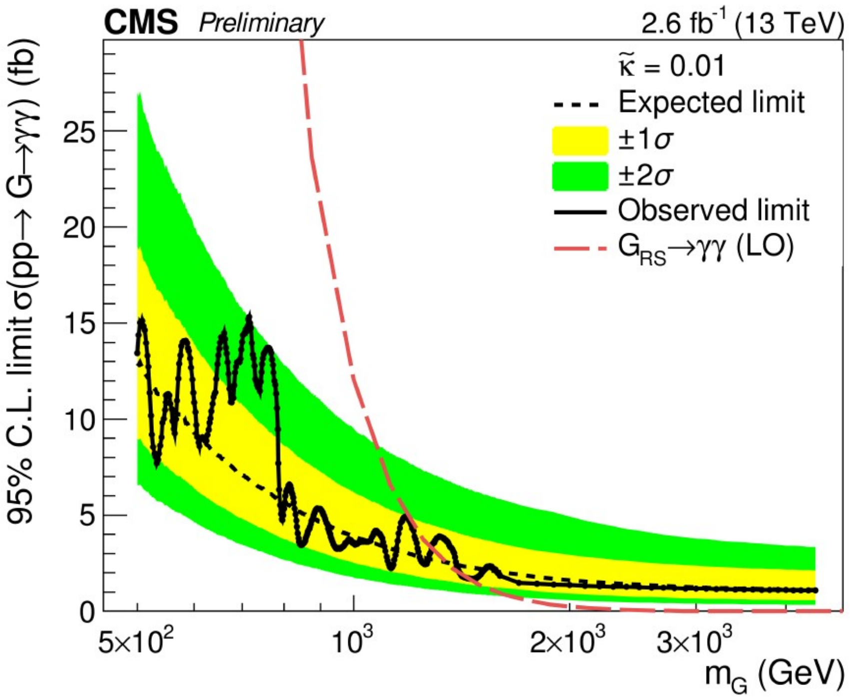
Monash University
Victoria 3800
Australia

750 GeV diphoton excess

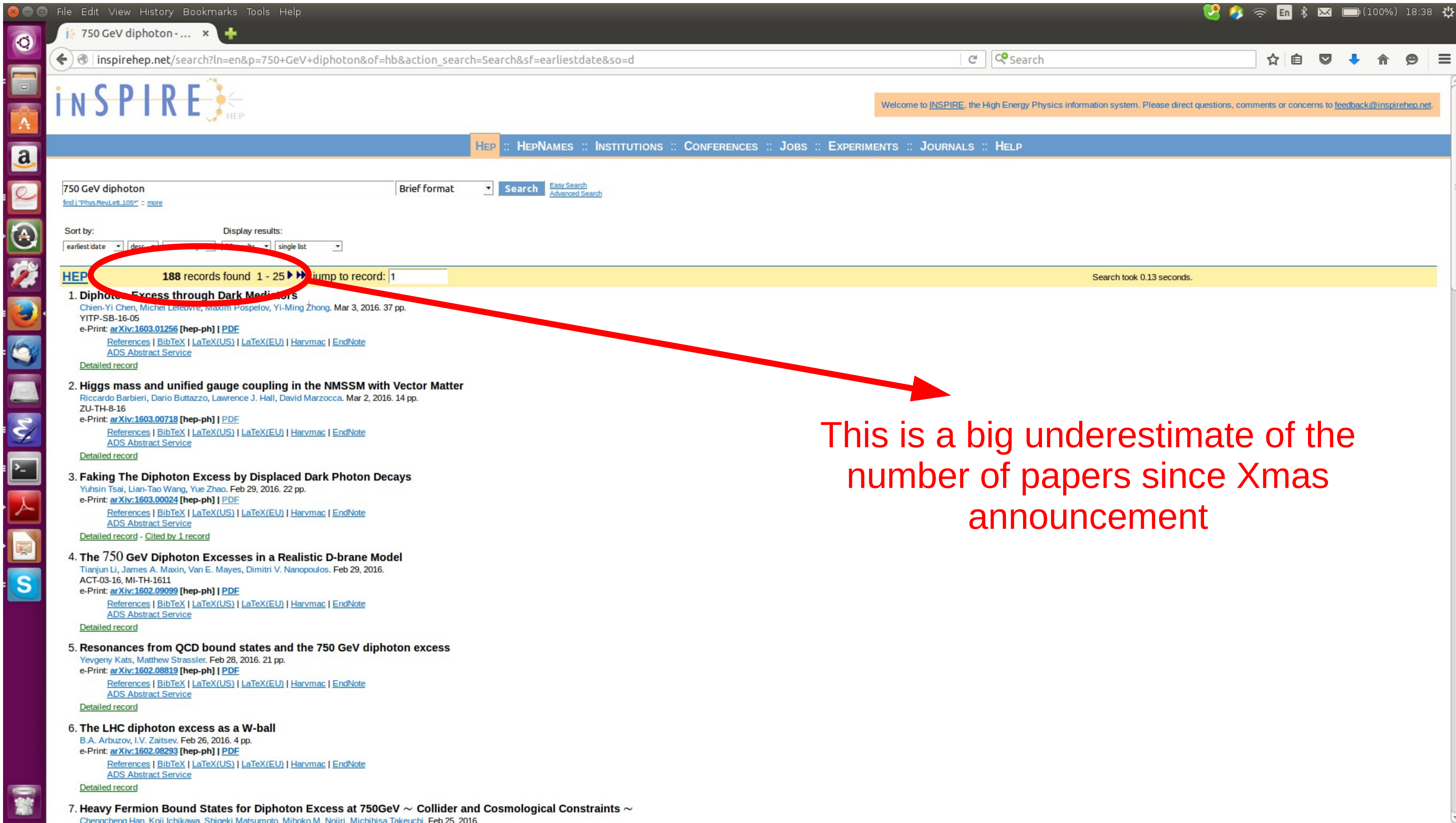
CMS also see something in the same place!





750 GeV diphoton excess

The particle physics community is clearly excited…



This is a big underestimate of the number of papers since Xmas announcement

750 GeV diphoton excess

- the local significance seen by ATLAS is quite large (3.9 sigma)

- CMS sees a milder excess in the same place (2.6 sigma, local)

- the signal could plausibly originate from well motivated BSM physics

- the ingredients people are using to fit this model (new scalar + exotics fermions) are exoected in E6 models

<u>My attitude</u>

If you gave me even odds I'd bet against this being real (I'm sorry)
But give me 2-1 and I would seriously consider betting for
3-1 and I snap call that bet.

Of course those odds are based on intuition and guessing.
If we really want to access my degree of belief we need GAMBIT ;)

FlexibleDecay

Long term goal

produce general model decay codes with as high (or higher) precision as leading MSSM Higgs and sparticle decay codes

Short term update
(Dylan Harries)

extend FlexibleSUSY to calculate diphoton and digluon effective vertices

This quick update was done as part of a larger joint project with SARAH developers and many others (see next slide) to create and illustrate the use of tools for studying the diphoton excess

$$\Gamma(\Phi \to \gamma\gamma)_{LO} = \frac{G_F \alpha^2(0) m_\Phi^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c^f Q_f^2 r_f^\Phi A_f(\tau_f) + \sum_s N_c^s r_s^\Phi Q_s^2 A_s(\tau_s) + \sum_v N_c^v r_v^\Phi Q_v^2 A_v(\tau_v) \right|^2$$

$$\Gamma(\Phi \to gg)_{LO} = \frac{G_F \alpha_S^2(\mu) m_\Phi^3}{36\sqrt{2}\pi^3} \left| \sum_f \frac{3}{2} D_2^f r_f^\Phi A_f(\tau_f) + \sum_s \frac{3}{2} D_2^s r_s^\Phi A_s(\tau_s) + \sum_v \frac{3}{2} D_2^v r_v^\Phi A_v(\tau_v) \right|^2 .$$

$$\Gamma(A \to \gamma\gamma)_{LO} = \frac{G_F \alpha^2 m_A^3}{32\sqrt{2}\pi^3} \left| \sum_f N_c^f Q_f^2 r_f^A A_f^A(\tau_f) \right|^2 \qquad \Gamma(A \to gg)_{LO} = \frac{G_F \alpha_S^2 m_A^3}{36\sqrt{2}\pi^3} \left| \sum_f 3 D_2^f r_f^A A_f^A(\tau_f) \right|^2$$

$$r_f^\Phi = \frac{v}{2M_f}(C_{\bar{f}f\Phi}^L + C_{\bar{f}f\Phi}^R), \qquad r_s^\Phi = \frac{v}{2M_s^2} C_{ss^*\Phi}, \qquad r_v^\Phi = -\frac{v}{2M_v^2} C_{vv^*\Phi}.$$

FlexibleDecay

+ important SM QCD corrections

$$\Gamma(\phi \to gg) = \Gamma(\phi \to gg)(1 + C_\phi^{NLO} + C_\phi^{NNLO} + C_\phi^{N^3LO})$$

$$\Gamma(A \to gg) = \Gamma(A \to gg)(1 + C_A^{NLO} + C_A^{NNLO})$$

$$C_\Phi^{\rm NLO} = \left(\frac{95}{4} - \frac{7}{6}N_F\right)\frac{\alpha_s}{\pi}\,,$$

$$C_\Phi^{\rm NNLO} = \Bigg(370.196 + (-47.1864 + 0.90177N_F)N_F + (2.375 + 0.666667N_F)\log\frac{m_\Phi^2}{m_t^2}\Bigg)\frac{\alpha_s^2}{\pi^2}\,,$$

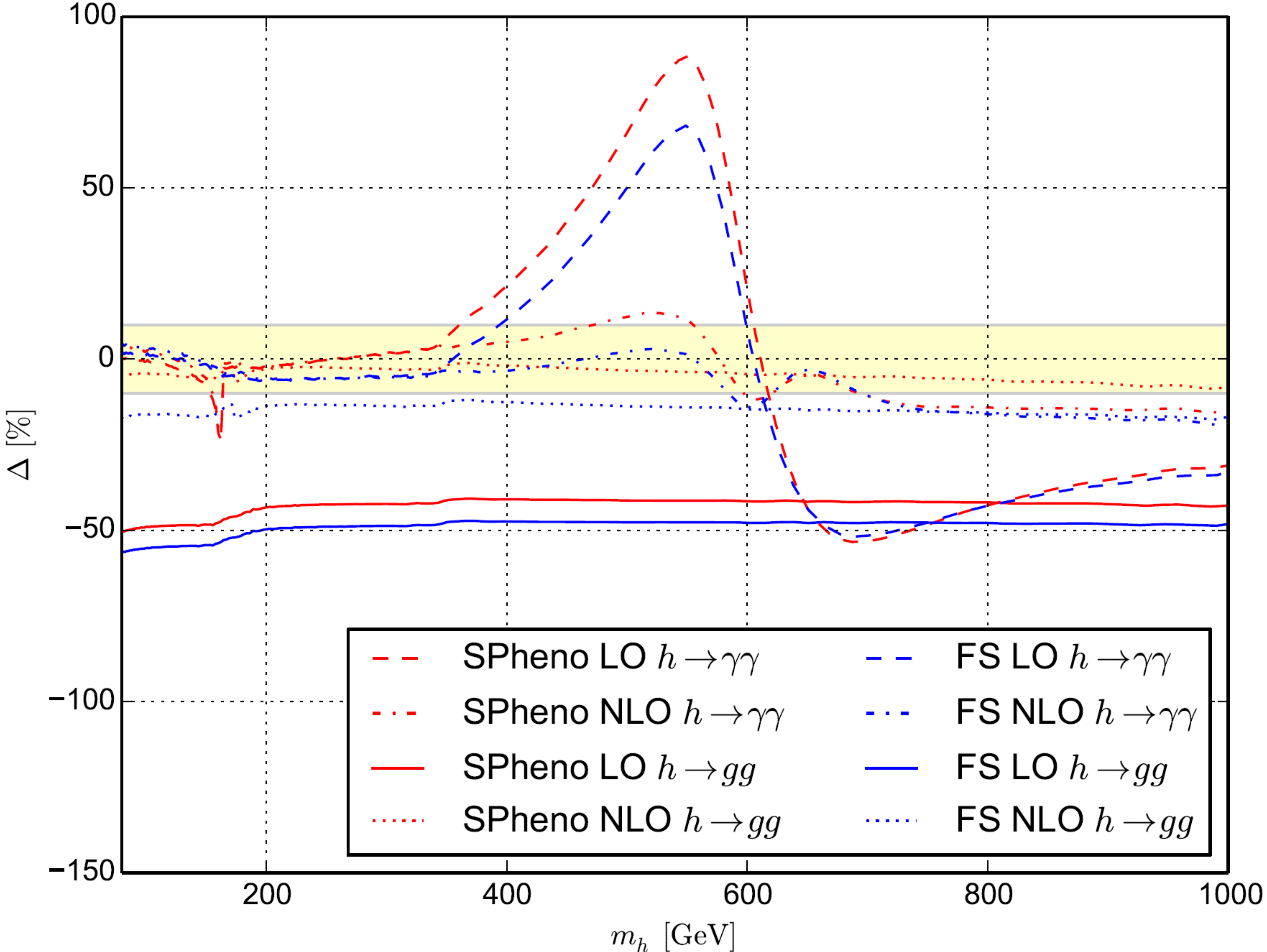
$$C_\Phi^{\rm N^3LO} = \left(467.684 + 122.441\log\frac{m_\Phi^2}{m_t^2} + 10.941\left(\log\frac{m_\Phi^2}{m_t^2}\right)^2\right)\frac{\alpha_s^3}{\pi^3}$$

$$C_A^{\rm NLO} = \left(\frac{97}{4} - \frac{7}{6}N_F\right)\frac{\alpha_s}{\pi}\,,$$

$$C_A^{\rm NNLO} = \left(171.544 + 5\log\frac{m_\Phi^2}{m_t^2}\right)\frac{\alpha_s^2}{\pi^2}$$

We also apply NLO corrections to the diphoton decays, using expressions from hep-ph/9504378 in appropriate limits and elsewhere extract numerical results from HDECAY, based on a computation of the full expressions.

SM comparison to Higgs Cross-section Working group results



Diphoton excess tools
(arXiv:1602.05581)

Precision tools and models to narrow in on the 750 GeV diphoton resonance

Florian Staub,[a] Peter Athron,[b] Lorenzo Basso,[c] Mark D. Goodsell,[d] Dylan Harries,[e] Manuel E. Krauss,[f] Kilian Nickel,[f] Toby Opferkuch,[f] Lorenzo Ubaldi,[g] Avelino Vicente,[h] Alexander Voigt[i]

Huge project in very short time frame to:

- add library of 40 models proposed in literature to explain diphoton
  With model files for SARAH, Spheno and FlexibleSUSY

- implement/check diphoton/digluon vertices in FlexibleSUSY / Spheno

- present use of tool chain interfaced by SARAH to get BRs:
  Spheno/FlexibleSUSY $\rightarrow$ MonteCarlo Tools

We even present a nice new model and show using these tools that it can explain the diphoton excess! But you will have to read the paper...

Conclusions

- Important to consider more exotic BSM models than MSSM, with high precision.
- FlexibleTools are precise, fast and adaptable and can be used in any* model!
- FlexibleTools can help!

    Calculate mass spectra with FlexibleSUSY

    Calculate precise Higgs mass FlexibleHiggs

    Calculate precise decays with FlexibleTools or...

- Use the diphoton tool chain to have careful and rigorous prediction of BSM diphoton partiial width and BR and check consistency with data in other channels
- FlexibleTools are already being used in GAMBIT

*Some caveats apply

Happy 60th Birthday Tony!

The End

Backup slides

A Flexible Future

- FlexibleSAS (Dylan Harries) auto generation available: October

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

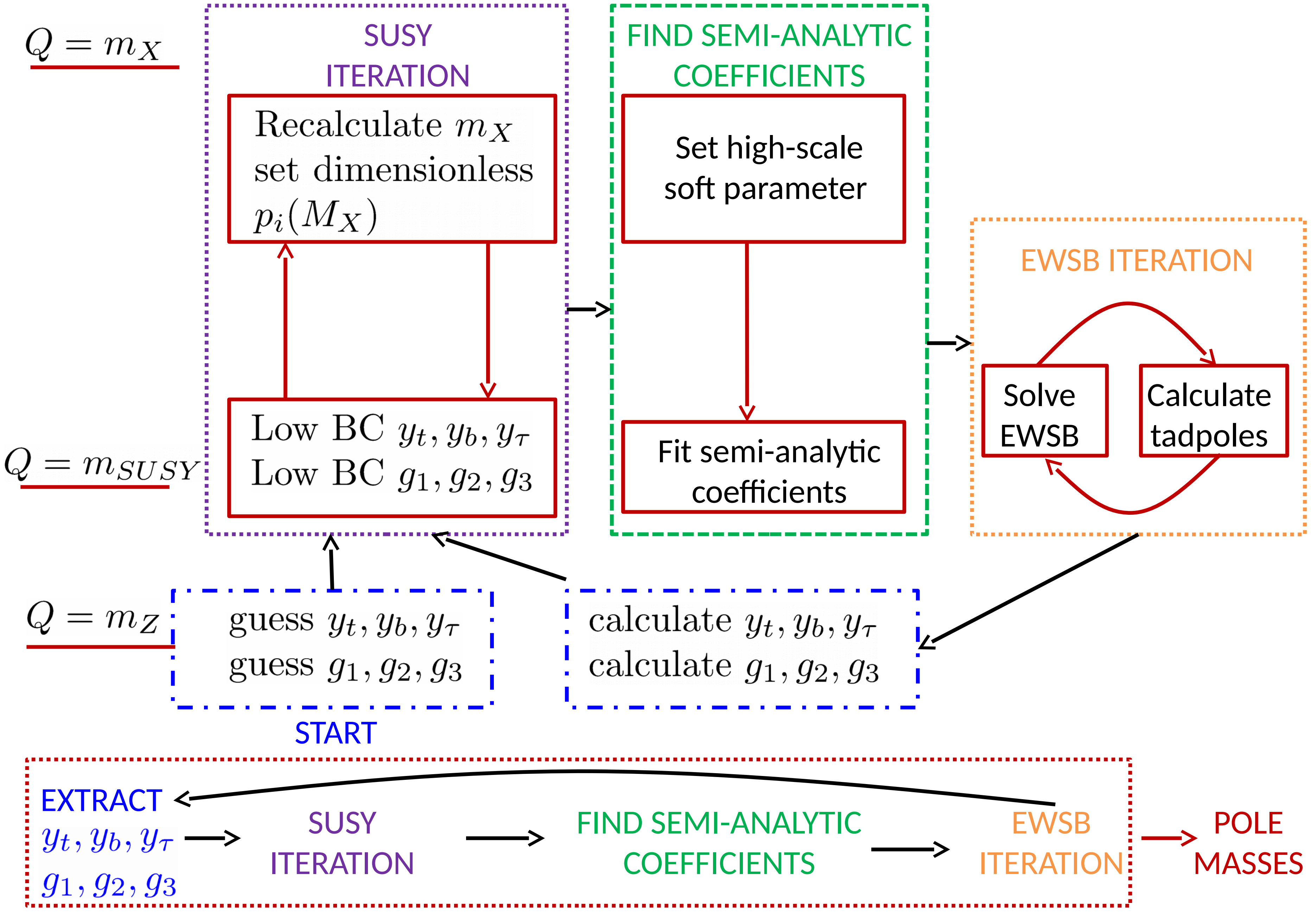
$a_i = a_i(y_m, g_n)$ etc Coefficients depend only on dimensionless couplings

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

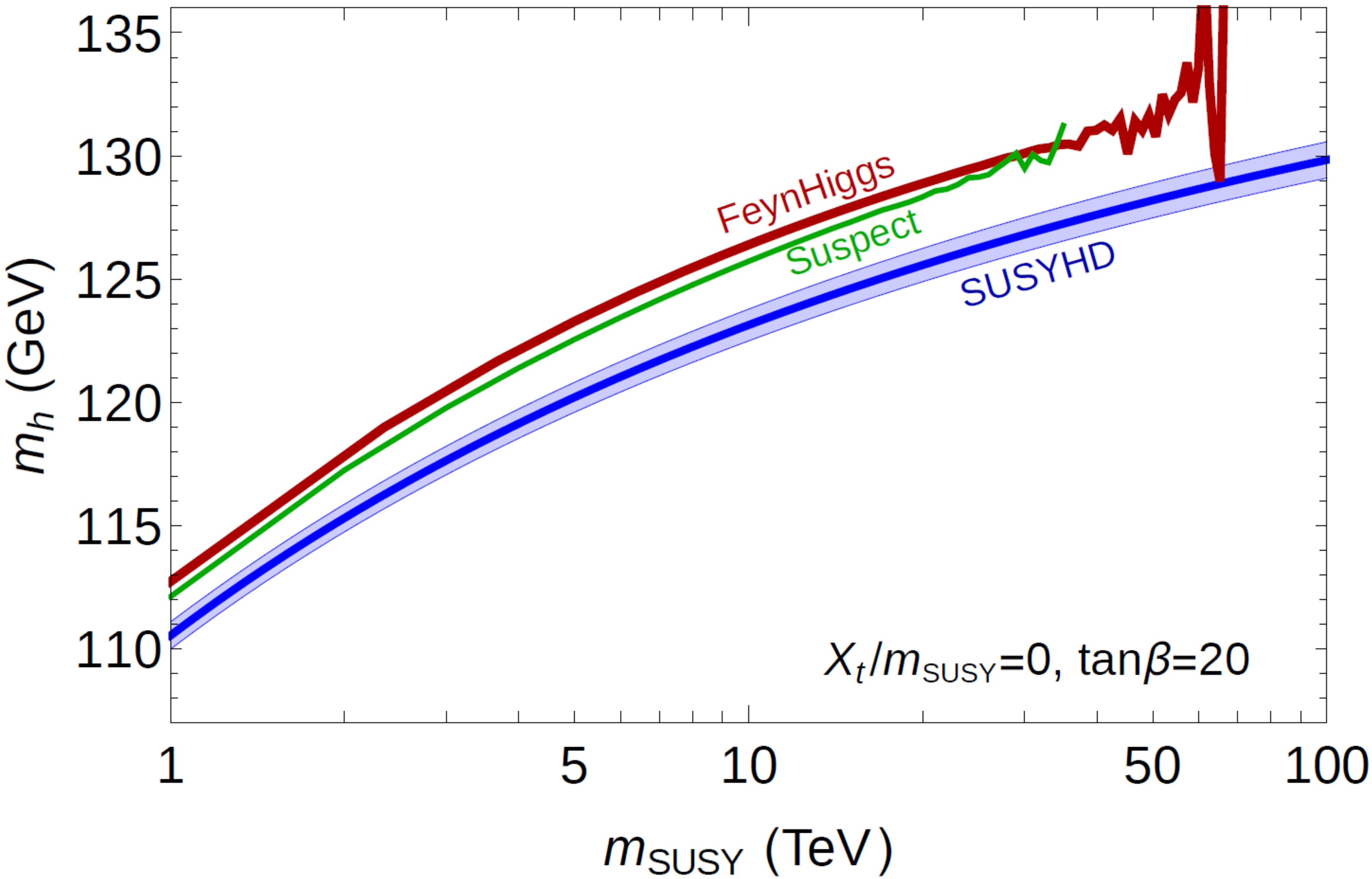
Now the EWSB outputs may include universal parameters set at the high scale.

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

Semi-analytic fixed point iteration



In MSSM preferred calculation currently depends on MSUSY:



FlexibleSUSY

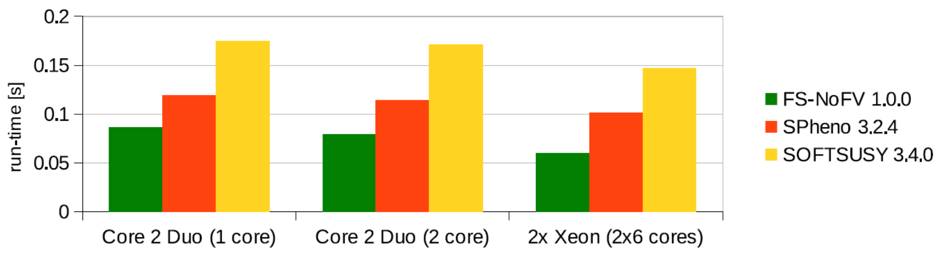
FlexibleSUSY is precise

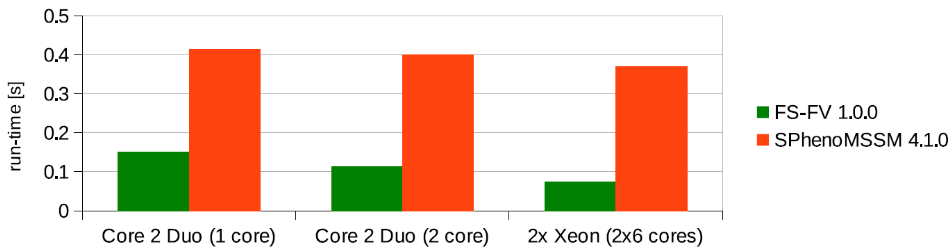
Full three family two-loop RGEs including gauge kinetic mixing
Full one-loop self energies, including all states, for shifts to pole
Full one-loop threshold corrections, and two-loop pure QCD corrections for y_t, y_b
Special boundary conditions for EFT two loop Higgs in MSSM via JHEP 1409 (2014) 092
(matches SUSYHD precision)
Partial 3 loop corrections for SplitSUSY

FlexibleSUSY is fast

Smart linear algebra (eigen)

Safe Multi-threading





g++ 4.8.0, ifort 13.1.3 20130607

FlexibleSUSY is adaptable

FlexibleSUSY is adaptable

Two-scale boundary solver may be set in non-standard ways:

- 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 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 algorithm
- 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 adpaptable

Object orientation ⟶ modularity

<u>Replaceable/extendable/reusable components:</u>

- RGEs
- Self energies
- Tadpoles
- Mass matrices
- RGE + BC solver:
  - ✓ two scale fixed point iteration
  - ✓ Lattice method.
- linear algebra package
- SUSY or soft breaking parameter objects
- Passarino-veltman functions
- I am sure there are more if you are smart…