

FlexibleSUSY 2.0 and FlexibleMW: Automated calculation of the muon decay

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in collaboration with:

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11th Annual Meeting of the Helmholtz Alliance
“Physics at the Terascale”

Hamburg, 28 November 2017



What is a spectrum generator?

Definition

tool for calculation of pole masses, mixings and couplings of particles within a specific model from theory input parameters

⇒ information can be used for further phenomenological studies

consideration of conditions at different scales, e. g.

- M_Z : matching to the SM (gauge and Yukawa couplings)
- M_{SUSY} : electroweak symmetry breaking conditions
- M_{GUT} : parameter constraints for gauge coupling unification

⇒ boundary value problem (BVP) with running of parameters via renormalization group equations (RGEs) has to be solved

spectrum generators available for some SUSY models, e. g. (N)MSSM



- spectrum generator generator based on Mathematica and C++
- model specification within a SARAH model file containing superpotential, soft-breaking terms, gauge structure and field content
- non-supersymmetric models can also be investigated (FlexibleBSM)

New features in FlexibleSUSY 2.0

increase the generality and capabilities

⇒ larger number of models and observables can be investigated

Extensions:

New features in FlexibleSUSY 2.0

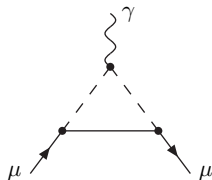
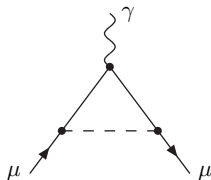
increase the generality and capabilities

⇒ larger number of models and observables can be investigated

Extensions:

FlexibleAMU

- provides calculator for $a_\mu = (g - 2)_\mu/2$
- includes model-specific 1-loop and universal leading logarithmic 2-loop QED contributions
- generic diagram types:



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Extensions:

FlexibleAMU

FlexibleCPV

- adds option of complex parameters
- allows study of models with new sources of CP violation
- application: calculation of electric dipole moments of fermions

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Extensions:

FlexibleAMU

FlexibleCPV

FlexibleSAS

- up to now only one BVP solver:
two-scale solver using fixed point iteration
- introduces new solver which makes use of semi-analytic solutions to RGEs for dimensionful running parameters
- enables broader exploration of parameter space and investigation of specific models, e. g. of the CNMSSM and CE₆SSM

New features in FlexibleSUSY 2.0

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⇒ larger number of models and observables can be investigated

Extensions:

FlexibleAMU

FlexibleCPV

FlexibleSAS

FlexibleEFTHiggs

- method to predict lightest Higgs pole mass in any BSM model
- achieves NLO + NLL accuracy through hybrid calculation combining:
 - ▶ full 1-loop fixed-order computation including suppressed terms of $\mathcal{O}(m_t^2/M_S^2)$
 - ▶ effective field theory approach resumming logarithms of M_S/m_t to all orders

New features in FlexibleSUSY 2.0

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Extensions:

FlexibleAMU

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FlexibleMW

automated calculation of the muon decay to determine weak mixing angle and W pole mass

Determination of the running weak mixing angle θ_W

- required for calculation of gauge couplings, e. g. $g_2 = e / \sin \theta_W$
- electroweak precision quantities: θ_W, M_W, M_Z, G_F (2 indep.)

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- electroweak precision quantities: $\theta_W, \underbrace{M_W, M_Z, G_F}_{\text{input}}$ (2 indep.)
- 1. method: computation via e. g.

$$\cos^2 \theta_W = \frac{m_W^2}{m_Z^2}$$

$$\text{with } m_V^2(Q) = M_V^2 + \text{Re } \Sigma_{V,T}(p^2 = M_V^2, Q) \quad (V = W, Z)$$

- ▶ implemented since FlexibleSUSY 1.0
- + easily applicable to any BSM model with a W and Z boson
- parametric uncertainty limited by that of M_W ($\approx 0.02\%$)
⇒ no meaningful computation of electroweak precision observables

Determination of the running weak mixing angle θ_W

- required for calculation of gauge couplings, e. g. $g_2 = e / \sin \theta_W$
- electroweak precision quantities: $\theta_W, M_W, \underbrace{M_Z, G_F}_{\text{input}}$ (2 indep.)
- 2. method: computation via muon decay [Nucl. Phys. B **351**, 49 (1991)]

$$\sin^2 \theta_W \cos^2 \theta_W = \frac{\pi \alpha_{\text{em}}}{\sqrt{2} M_Z^2 G_F (1 - \Delta\hat{r})}$$

- more complicated to automatize because model-specific 1-loop vertex and box diagrams contribute
 - ▶ implemented as FlexibleMW in FlexibleSUSY 2.0 for all BSM models
 - + smaller parametric uncertainty limited by that of M_Z ($\approx 0.002\%$)
 - + allows calculation of M_W as a model prediction
 - \Rightarrow comparison with experimental value to constrain parameter space

Detailed 1-loop formalism of FlexibleMW

generalization of MSSM formulas [Nucl. Phys. B **491**, 3 (1997)]:

$$\sin^2 \theta_W \cos^2 \theta_W = \frac{\pi \alpha_{\text{em}}}{\sqrt{2} M_Z^2 G_F (1 - \Delta \hat{r}) \hat{\rho}_{\text{tree}}}$$

$$\Delta \hat{r} = \frac{1}{1 - \Delta \hat{\rho}} \frac{\text{Re} \Sigma_{W,T}(0)}{M_W^2} - \frac{\text{Re} \Sigma_{Z,T}(M_Z^2)}{M_Z^2} + \delta_{\text{VB}}$$

$$\Delta \hat{\rho} = 1 - \left(1 + \frac{\text{Re} \Sigma_{W,T}(M_W^2)}{M_W^2} \right) / \left(1 + \frac{\text{Re} \Sigma_{Z,T}(M_Z^2)}{M_Z^2} \right)$$

(leading SM 2-loop corrections to $\Delta \hat{r}$ and $\Delta \hat{\rho}$ are also implemented)

\Rightarrow iteration for self-consistent determination of θ_W

$$\text{finally: } M_W = \sqrt{M_Z^2 \cos^2 \theta_W \frac{\hat{\rho}_{\text{tree}}}{1 - \Delta \hat{\rho}}}$$

What is $\hat{\rho}_{\text{tree}}$?

$$\hat{\rho}_{\text{tree}} = \rho_0 \frac{m_{Z,\text{SM}}^2}{m_{Z,\text{mix}}^2}$$

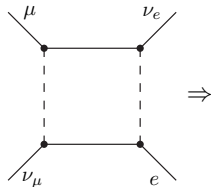
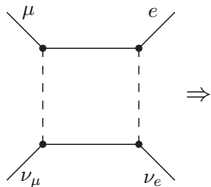
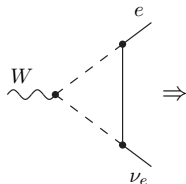
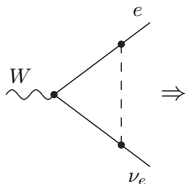
- includes corrections from higher dimensional Higgs multiplets via

$$\rho_0 = \frac{\sum_i (t_i^2 - t_{3i}^2 + t_i) |v_{\varphi_i}|^2}{\sum_i 2 t_{3i}^2 |v_{\varphi_i}|^2}$$

- ▶ sum over neutral Higgs fields φ_i with vacuum expectation values v_{φ_i}
 - ▶ t_i denotes weak isospin and t_{3i} its third component
- includes corrections from extra $U(1)$ gauge groups via the ratio of
 - ▶ $m_{Z,\text{SM}}$ – SM-like tree-level Z boson mass
 - ▶ $m_{Z,\text{mix}}$ – tree-level Z boson mass including mixing with Z' bosons

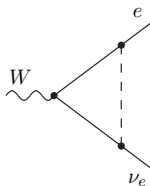
Model-specific contributions to δ_{VB}

calculate generic diagrams \Rightarrow insert model-dependent information

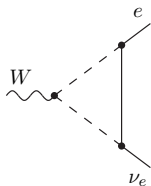
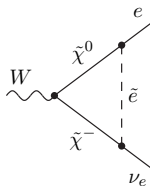


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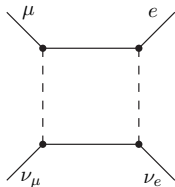
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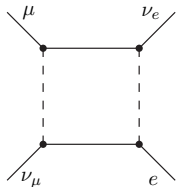
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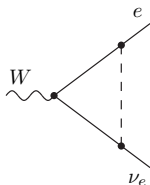
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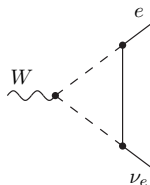
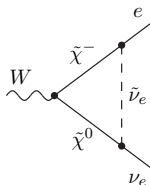
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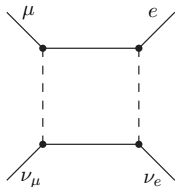
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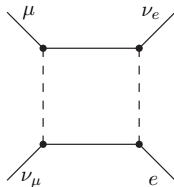
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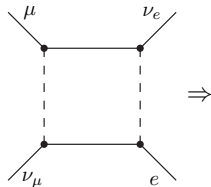
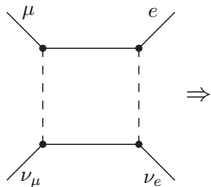
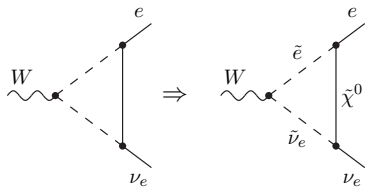
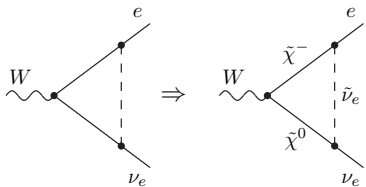
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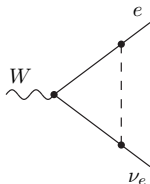
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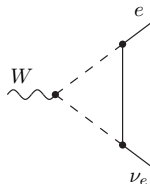
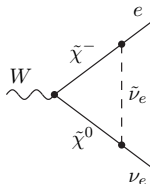


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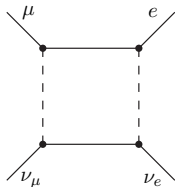
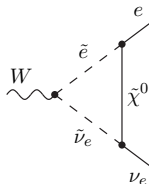
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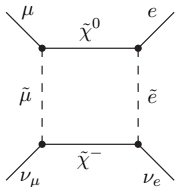
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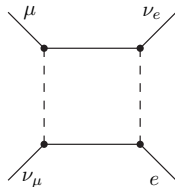
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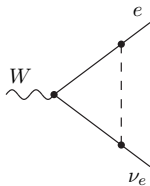


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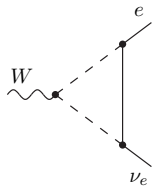
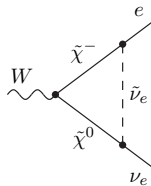


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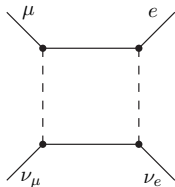
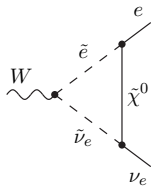
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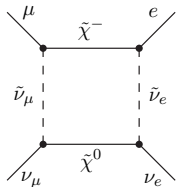
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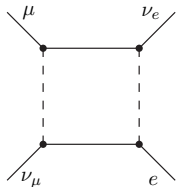
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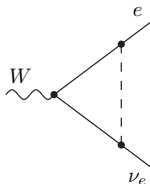


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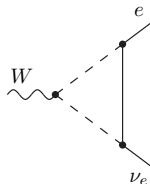
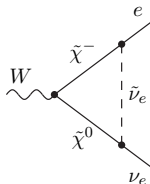


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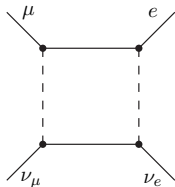
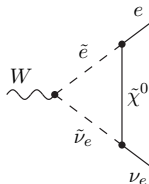
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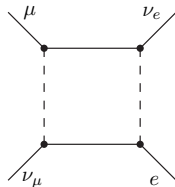
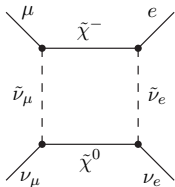
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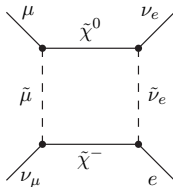
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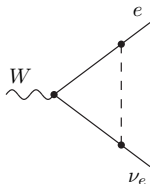


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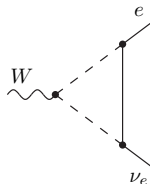
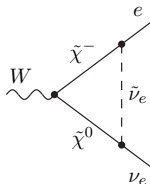


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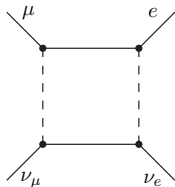
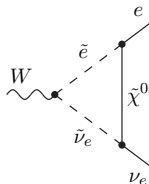
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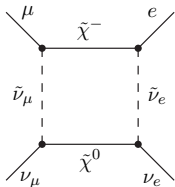
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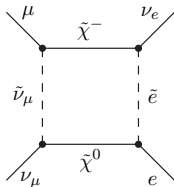
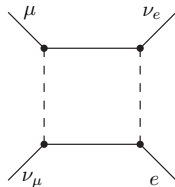
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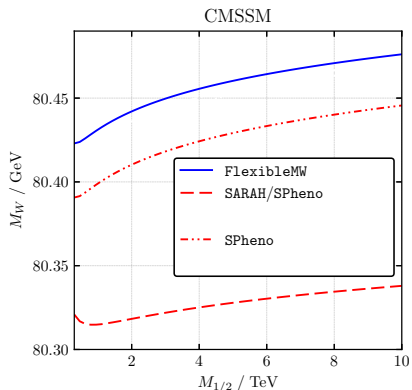
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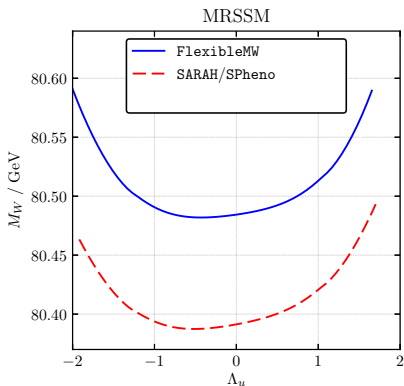
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Comparison to SPheno and SARAH/SPheno

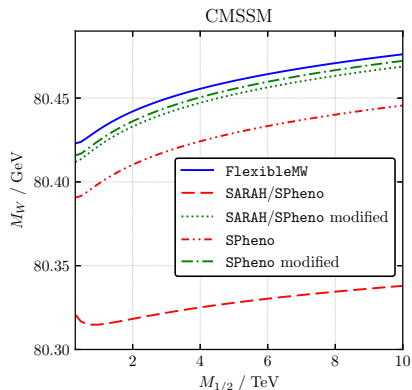


$$m_0 = 1 \text{ TeV}$$
$$\tan \beta = 10$$
$$\text{sign } \mu = +1$$
$$A_0 = 0$$

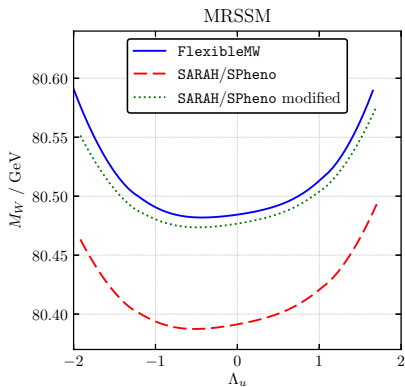


other parameters fixed as for BMP1 in
Table 2 from [JHEP **1412**, 124 (2014)]

Comparison to SPheno and SARAH/SPheno



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Conclusions

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- FlexibleSUSY 2.0 with several new features is now available at <https://flexiblesusy.hepforge.org>
- muon decay method for determination of weak mixing angle decreases parametric uncertainty and allows prediction of M_W
- FlexibleMW is an implementation of this method for general models
- comparison to SPheno and SARAH/SPheno revealed inconsistencies in these codes and finally shows good agreement

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Thanks for your attention!