NPointFunctions: a calculator of amplitudes and observables in FlexibleSUSY

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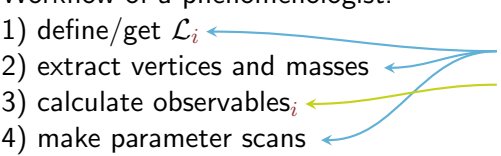
Overview

- Motivation
- What is `FlexibleSUSY`?
- What is `NPointFunctions`?
- Some applications
- Conclusions

Workflow of a phenomenologist:

1) define/get $\mathcal{L}_i$
2) extract vertices and masses
3) calculate observables$_i$
4) make parameter scans



A spectrum generator - generator

A calculator of amplitudes and observables

MRSSM, leptoquarks*, Grimus-Neufeld model*

FlexibleSUSY?[1406.2319], [1710.03760] The end-user side.

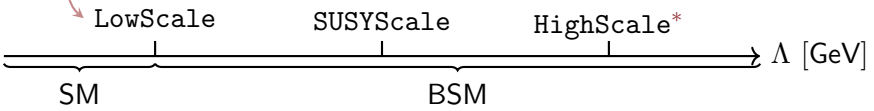
- Define $\mathcal{L}_i$ —1) create→ #1 #2 #3 —2) SARAH→ `Mathematica` code: vertices, masses, 2-loop RGE, EWSB

`MODEL.m`	`parameters.m`	`particles.m`
model definition	additional information	additional information

- Setup model$_i$ —3) create→ #1 #2 —4) `FlexibleSUSY`→ `C++`* code, which: solves BVP*, finds mixings, finds masses, finds observables*

`FlexibleSUSY.m`	`LesHouches.in.MODEL`
restrictions*, extra*, settings	numerical values for the input parameters

A nice place for something new! —5) ...→ `FlexibleSUSY.m`



NPointFunctions?[soon] The end-user side.

- Setup observable$_i$ —5) configure→ #1 —6) NPointFunctions→ 1) `Mathematica`* code,
  2) `C++` code, which:
  adds*, new input blocks
  evaluates observable$_i$
  evaluates Wilson coefficients

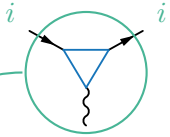
settings.m*

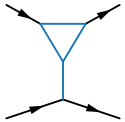
```
topologies[LOOPS]
diagrams[LOOPS, TYPE]
amplitudes[LOOPS, TYPE]
regularization[LOOPS]
momenta[LOOPS]
order[]
sum[LOOPS]
chains[LOOPS]
mass[LOOPS]
```

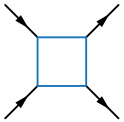
- Main* dependencies
  `FeynArts`
  `FormCalc`
  `ColorMath`
- Implemented*
  $l_i \to l_j l_k l_k^C$
  $l_i \to l_j$ conversion
  connected to $l_i \to l_j \gamma$

LFV processes

What is about $(g-2)_i$?







$$\mathcal{L}_{\text{LEFT}} \ni m_\mu C_X^{\mathcal{D}} [\bar{e}\sigma^{\mu\nu} P_X \mu] F_{\mu\nu} + C_{XY,f}^{\Gamma} [\bar{e}\Gamma_X \mu][\bar{f}\Gamma_Y f]$$

$$\Gamma_{\mu\to e\gamma}^{[\text{any}]} \propto \sum |C^{\mathcal{D}}|^2$$

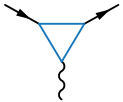
$$\Gamma_{\mu\to 3e}^{[\text{hep-ph/9510309}]} \propto 0.006 \cdot \Gamma_{\mu\to e\gamma} + \sum \left(\text{Re}\, C_e^{\mathcal{V}} C^{\mathcal{D}*} + |C_e^{\mathcal{S},\mathcal{V}}|^2 \right)$$

$$\omega_{\mu-e}^{[\text{hep-ph/0203110}]} \propto \sum |DC_X^{\mathcal{D}} - \sum (S^{(N)} g^{\mathcal{S}} + V^{(N)} g^{\mathcal{V}})|^2$$

Motivation by ...

- New bounds / results

$(g-2)_\mu$
BNL + FNAL:
$(25.1 \pm 5.9) \cdot 10^{-10}$



$\mu \to e$ conversion COMETs: 3,4
$\mu \to 3e$ Mu3es: 2,4
$\mu \to e\gamma$ MEG-II: 1

They are connected! ... **?**

Q: Do we need / How to use all of that?

- SUSY — Extension of Poincaré algebra | No quadratic divergences | ...
- MRSSM — Different SUSY realization | Absence of MSSM limit | R-symmetry
- Rich phenomenology[2014-...] — Electroweak precision observables | Higgs boson mass | Dark matter relic density | Coloured sector
- Other models? — Leptoquarks S_1 and R_2 | Grimus-Neufeld model

Well motivated!

Q: What's the model contribution / parameter dependence?

MRSSM?[0712.2039]

$U(1)_R$ symmetry: $\theta \to e^{i\alpha Q_\theta}\theta, \quad Q_\theta := +1$

Same superfield $\to$ related Q_*

Assertion	$Q_{\mathsf{V}} = 0$	$Q(v_{d,u}) = 0$	Yukawas form	All previous
Result	**no** Majorana gauginos	**no** μ-term	Q_{SM} are* fixed	**no** L/R mixing **no** A-terms
Consequence	Dirac masses			sfermion masses*
$-\mathcal{L} \ni$	$M_B^D(\tilde{B}\tilde{S} - \sqrt{2}D_B S)$			$(m_{\tilde{l}}^2)_{ij}\tilde{l}_i^*\tilde{l}_j$
		higgsino masses	usual Yukawas	new "Yukawas"
$W \ni$		$\mu_u R_u \cdot H_u$	$-Y_{ij}^e\ \bar{E}_i L_j \cdot H_d$	$\lambda_u S R_u \cdot H_u$

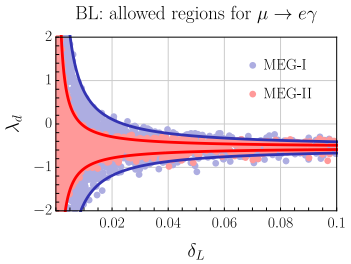
Parameters

Dirac masses	higgsino masses	sfermion masses*	new "Yukawas"
$M_B^D(\tilde{B}\tilde{S} - \sqrt{2}D_B S)$	$\mu_u R_u \cdot H_u$	$(m^2_{\tilde{l}})_{ij}\tilde{l}^*_i\tilde{l}_j$	$\lambda_u S R_u \cdot H_u$
M_B^D or M_W^D should be light!	μ_d – dipole μ_u – restricted	$\delta_L = \frac{(m^2_{\tilde{l}})_{12}}{(m_{\tilde{l}})_{11}(m_{\tilde{l}})_{22}}$ and / or $\delta_R = \frac{(m^2_{\tilde{e}})_{12}}{(m_{\tilde{e}})_{11}(m_{\tilde{e}})_{22}}$	λ_d, λ_u, Λ_d, Λ_u – dependent

So many! **Q:** What to do?

Simplified scenarios: i.e. BHL

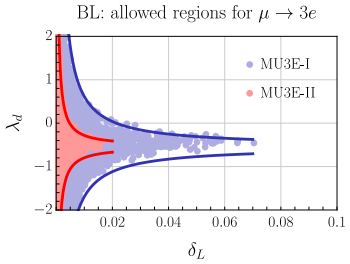
Scattering plots



expectation:

$\mathrm{Br}_{\mu\to e\gamma} \propto \delta_L^2(\lambda_d + \Delta)^2$

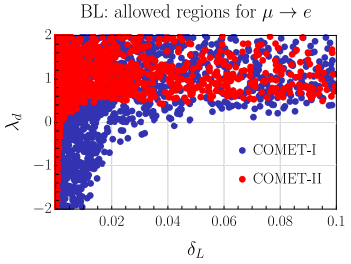
check!



expectation:

dipole dominance if

$\mathrm{Br}_{\mathsf{MEG}} \to \mathrm{Br}_{\mathsf{MU3E}}/0.006$

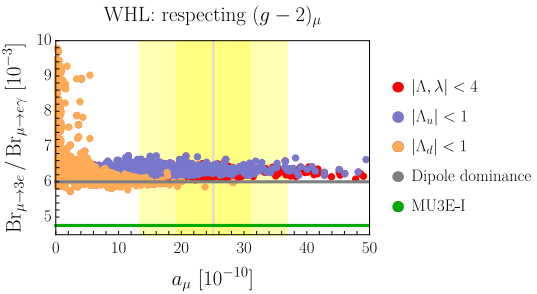


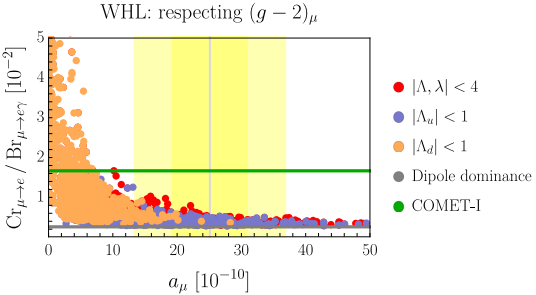
correlation?

cancellations,

non-correlation!

What if ... $(g-2)_\mu$?





$$\frac{\mathrm{Br}_{\mu\to 3e}}{\mathrm{Br}_{\mu\to e\gamma}} \approx 0.006$$

$$\frac{\mathrm{Cr}_{\mu\to e}}{\mathrm{Br}_{\mu\to e\gamma}} \approx 0.0026$$

Chirality flip *aka* $\sigma_{\mu\nu}$, **no** μ-term $\to \Lambda_d, \lambda_d$ enhancement.

Conclusions

- **N**PointFunctions @ FlexibleSUSY
  - Fast / customizable
  - Extendable / modular structure
  - Consistent checks / constraints from different scales
- M**R**SSM @ SUSY
  - Different realization of SUSY
  - No MSSM limit
  - Rich phenomenology
- **c**LFV @ MRSSM
  - Interplay of $(g-2)_\mu$, $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion
  - Constructive region coverage by experiments
  - Interesting enhancement / interference patterns