aSuperIso_DM:
a new toolbox for dark matter calculations

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An automisation of SuperIso Relic

SuperIso Relic

- Computation of flavour observables
- Relic density within the framework of adjustable cosmological models (dark energy, dark entropy, ...)
- Indirect detection (Fermi-LAT dSphs, AMS-02 antiprotons)
- Direct detection (Xenon1T, LUX, PANDA-X,PICO60...)
- **But specific to the MSSM and NMSSM**

aSuperIso_DM (automated SuperIso for Dark Matter)

A generalisation of SuperIso Relic to any quantum field theory that can be cast under a Lagrangian form and that features a dark matter particle

An automisation of SuperIso Relic

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Warning:
The following is a preliminary presentation,
the final code and manual is coming soon!

FeynRules Interface

Previously on
SuperIso Relic

Squared Amplitudes for DM (co-)annihilations generated with FormCalc from the (N)MSSM LanHEP model files.

$\rightarrow$ **Flavour-expanded diagrams**:
similar squared amplitudes were calculated multiple times ($\chi\,\chi \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ ...)

$\rightarrow$ Large amount of files and large compilation time

Now on
aSuperIso_DM

Squared amplitudes are generated from a FeynRules model file using Mathematica routines interfaced with FeynRules.

$\rightarrow$ **Diagrams not flavour-expanded**

$\rightarrow$ Small amount of files and reduced compilation time

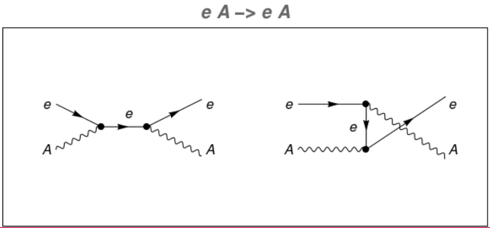
Diagrams

Simple Mathematica interface to obtain and visualise 2→2 processes from a list of Feynman Rules

In[1]:= **diag**=**Diagram22**[**feynmanrules**,{**e**,**A**,**e**,**A**}]

Out[1]={DiagramList[{e,A,e,A},
{{e,A,e,A,m$s},e}, {{e,1},$-ie\gamma_{s_5,s_1}{}^{\mu_2}$,
{A,2},{e, m$s}},{e,3}, $-ie\gamma_{s_3,s_6}{}^{\mu_4}$,{A,4}}},
{{e,A,e,A,m$u,e},{{e,1}, $-ie\gamma_{s_5,s_1}{}^{\mu_4}$,
{A,4},{e,m$u},{A,2}, $-ie\gamma_{s_3,s_6}{}^{\mu_2}$,{e,3}}}]]

In[2]:= **PaintDiagramList**[**diag**]
Out[2]=



Diagrams

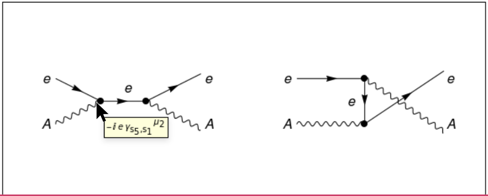
Simple Mathematica interface to obtain and visualise 2→2 processes from a list of Feynman Rules

```
In[1]:= diag=Diagram22[feynmanrules,{e,A,e,A}]

Out[1]={DiagramList[{e,A,e,A},
        {{e,A,e,A,m$s},e}, {{e,1},−ieγ_{s5,s1}^{μ2} ,
        {A,2},{e, m$s}},{e,3}, −ieγ_{s3,s6}^{μ4} ,{A,4}}},
        {{e,A,e,A,m$u,e},{{e,1}, −ieγ_{s5,s1}^{μ4} ,
        {A,4},{e,m$u},{A,2}, −ieγ_{s3,s6}^{μ2} ,{e,3}}}]]

In[2]:= PaintDiagramList[diag]
Out[2]=
```

e A -> e A



Squared Amplitude

`AmpSquared22` is a function to obtain explicit formulae for squared amplitudes, as a function of particle masses and Mandelstam variables S,T, U ($m\$s$, $m\$t$, $m\$u$).
It makes use of abbreviations and sum over propagator generation numbers to gain computation time.
$\Rightarrow$ compared to `FeynCalc` for processes in the Standard Model

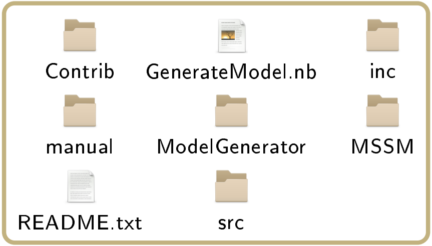
```
In[1]:= AmpSquared22[diag]

Out[1]=
```

$$\frac{2e^4\left(6\text{Me}^8-\text{Me}^4\left(3\text{m\$s}^2+14\text{m\$sm\$u}+3\text{m\$u}^2\right)+\text{Me}^2\left(\text{m\$s}^3+7\text{m\$s}^2\text{m\$u}+7\text{m\$sm\$u}^2+\text{m\$u}^3\right)-\text{m\$sm\$u}\left(\text{m\$s}^2+\text{m\$u}^2\right)\right)}{(\text{Me}^2-\text{m\$s})^2(\text{Me}^2-\text{m\$u})^2}$$

Model generation

As an example, let's generate the MSSM model:



1. Create a new folder named after your model
2. Move your FeynRules model file to the model directory
3. Open GenerateModel.nb and run every block

Model generation

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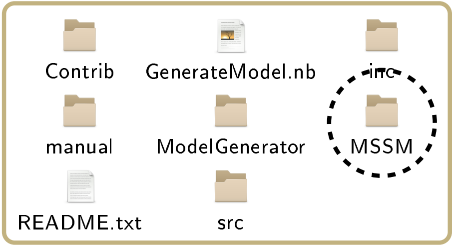

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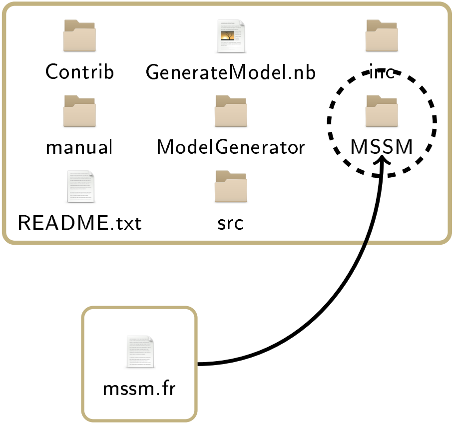

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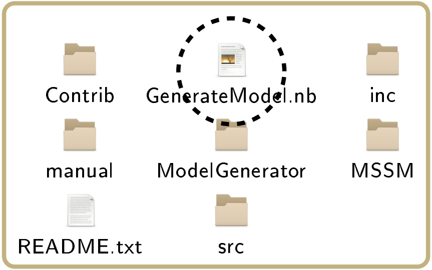


1. Create a new folder named after your model
2. Move your `FeynRules` model file to the model directory
3. Open GenerateModel.nb and run every block

Model generation

GenerateModel.nb * - Wolfram Mathematica 11.0

File Edit Insert Format Cell Graphics Evaluation Palettes Window Help

```
Quit[]

directory=NotebookDirectory[];
$FeynRulesPath=SetDirectory[directory<>"Contrib/feynrules2.4.68"];
<<FeynRules`;
 SetDirectory[directory<>"Contrib/feynrules2.4.68/Core"];
 <<Decay.m;
SetDirectory[directory<>"ModelGenerator"];
<<DMI.m;
```

Load FeynRules and squared amplitude calculation routines

```
(*This block needs to be modified by the user*)
ModelDirectory = "MSSM"; (*Please write here the directory name containing the FeynRules model file *)
ModelFileName = "mssm.fr"; (*Please write here the FeynRules model file name*)
FR$AmpSquaredParallelize = True; (*Set to True if you want the calculation of square
                     to be parallelized, False otherwise*)
FR$CPDiagrams = True; (*Set to True if the considered model conserves CP-parity.
                In this case, if a diagram is not self-conjugate, the conjugate
                The calculation time is thus significantly reduced.*)
printdiag = False; (*Set to True if you want to print all the 2-2 Feynman diagrams in "diagrams.pdf" *)
```

Block to be modified by the user

```
(*load model*)
directory = directory <> ModelDirectory;
SetDirectory[directory];
LoadModel[ModelFileName];
```

Load model

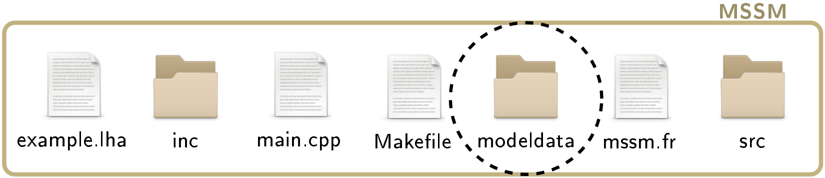
```
GenerateModel[directory, ModelFileName, PrintDiagrams → printdiag];
```

Generate C++ code

Code structure

The Mathematica interface generates:

- Lagrangian and Feynman rules
- Model parameter structure definition and initialisation routine
- C++ files for the calculation of (co-)annihilation squared amplitudes, decay widths and branching ratios and DM-quark effective couplings



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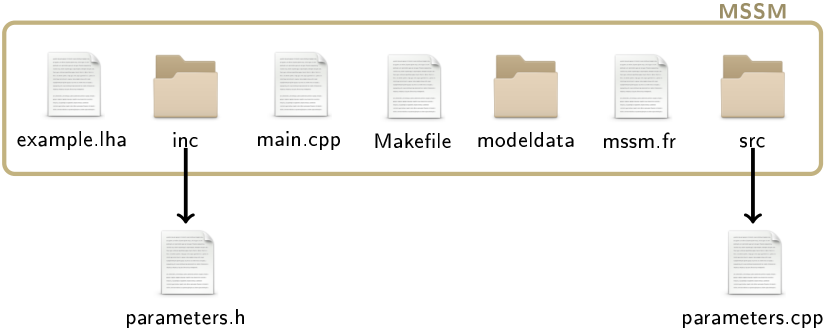

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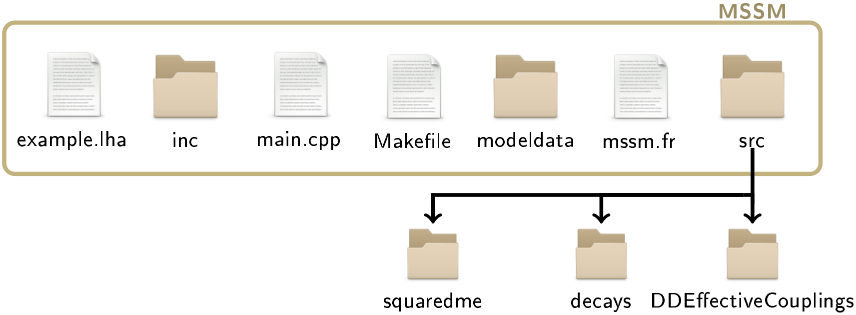


Relic density

Alternative cosmological scenarios:

- Possibility to chose among several QCD equations of state
- Modification of the expansion rate: Dark density
- Modification of the entropy content:
  - Dark entropy
  - Reheating (radiation entropy)
- Decaying scalar field

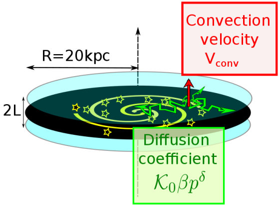
Big Bang Nucleosynthesis constraints:

$\Rightarrow$ using AlterBBN

Indirect detection

AMS-02 antiprotons

- Propagation code by Boudaud et al., interface with USINE coming soon
- **Two-zone diffusion model**



- **Semi-analytical resolution of the propagation equation**
- **Flexible DM halo density profile** (only needs to respect cylindrical symmetry)
- **Flexible propagation parameter values** (Diffusion coefficients, convection velocity...)

Fermi-LAT dwarf spheroidal galaxies (dSphs)

- Likelihoods interpolated from the tabulated likelihoods provided by Fermi-LAT collaboration.
- Flexible sets of dSphs

Direct detection

Spin-Dependent (SD) and spin-independent (SI) cross-sections

- Calculation for non-coloured particles with spin 0, 1/2, 1.
- Similarly to `micrOmegas`, SD and SI contributions to the DM-quarks effective couplings are extracted from the 2-2 DM-quark scattering diagrams by applying projection operators.

Constraints from XENON1T, PANDAX-2, PICO60...

- Flexible DM local density and velocity distriution
- Flexible nucleon and nuclear form factors

Comparison to similar codes

- $\sim$**30 minutes to generate whole MSSM model** on 4 cores, compared to a couple of hours to generate a CalcHep model from the same FeynRules model file (needs flavour-expansion in the latter case).
- Computation time of DM observables similar to SuperIso Relic
- Compilation time reduced to a couple of minutes
- Very close results compared to SuperIso Relic and micrOmegas in the MSSM (comparison to MadDM and in the frame of other models coming soon)

Prospects

- Complete resolution of the relic density Boltzmann equations for **multi-component dark matter**, including **semi-annihilations**.
- **Sommeferfeld Effect** for relic density and indirect detection.
- Models with **spin 3/2 and 2 fields**.
- Implementation of **flavour observables**.

Conclusions

- As supersymmetric scenarios are currently very challenged by expermimental constraints,
  `SuperIso Relic` transforms into `aSuperIso_DM`:
  - works for any particle physics model with a DM candidate respecting a Z2 symmetry
  - compilation time strongly reduced
  - a new way to visualise diagrams and obtain squared amplitude explicit formulae
  - conserves all the features for dark matter specific to `SuperIso Relic`
- **Public code and manual coming very soon!**