MARTY

Modern ARtificial Theoretical phYsicist

Automated loop-level BSM calculations

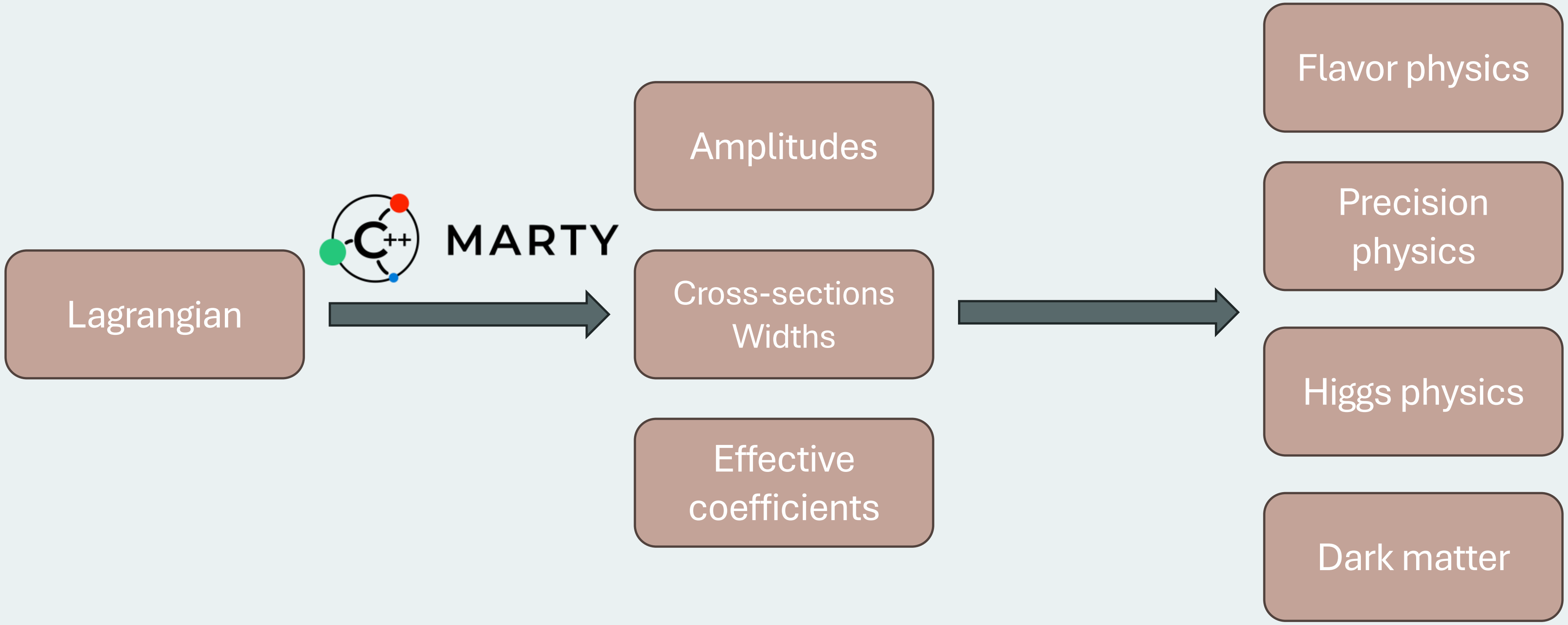
Website: https://marty.in2p3.fr
Main Publication: G. Uhlrich, N. Mahmoudi, A. Arbey, Comp. Phys. Commun. 264 (2021) 107928 [arXiv: 2011.02478]

Niels Fardeau (IP2I)

June 16 2025

Introduction

BSM phenomenology

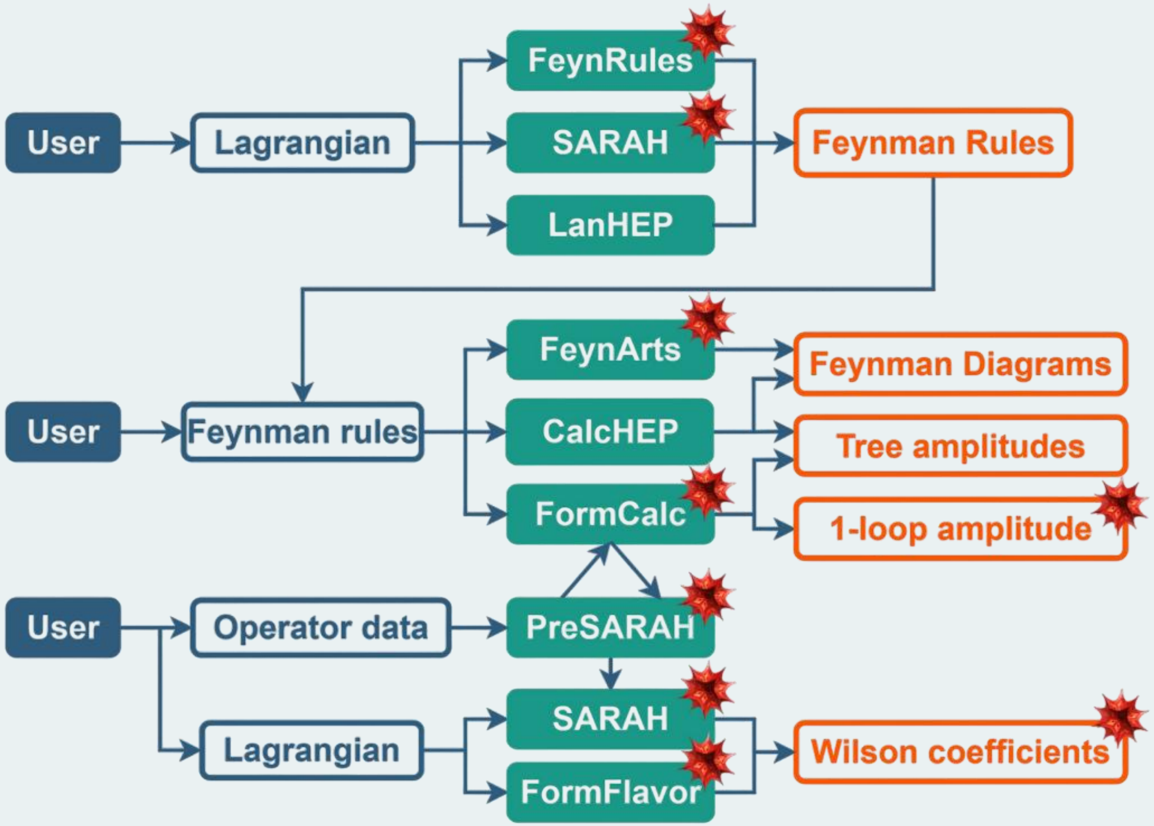


- Model dependent
- Analytical calculations
- Tedious and error-prone

- (Mostly) model independent
- Numerical calculations
- Widely-used existing codes

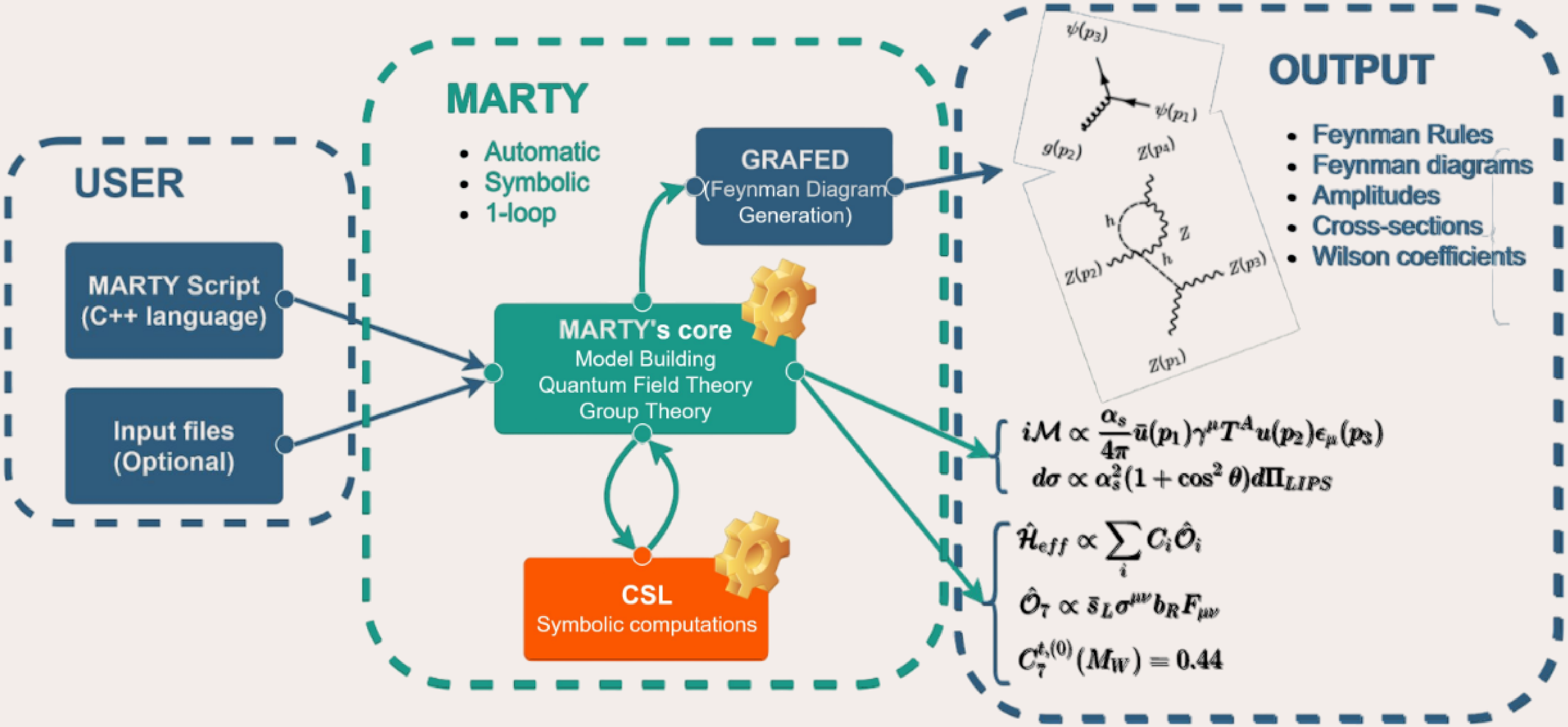
Present ecosystem

- Efficient and well-known codes
- Many distinct codes
- Several user inputs
- Mostly dependent on Mathematica



MARTY Generalities

The MARTY Pipeline



MARTY's capabilities

Model-building

- 4D Flat space-time (Minkowski)
- Spin representations
  - Spin 0 : (pseudo)-scalars
  - Spin ½ : Weyl, Dirac, Majorana
  - Spin 1 : Vectors
- Gauge groups
  - Semi-simple Lie groups SU(N), SO(N), Sp(N)
  - Exceptional Lie groups E, F, G

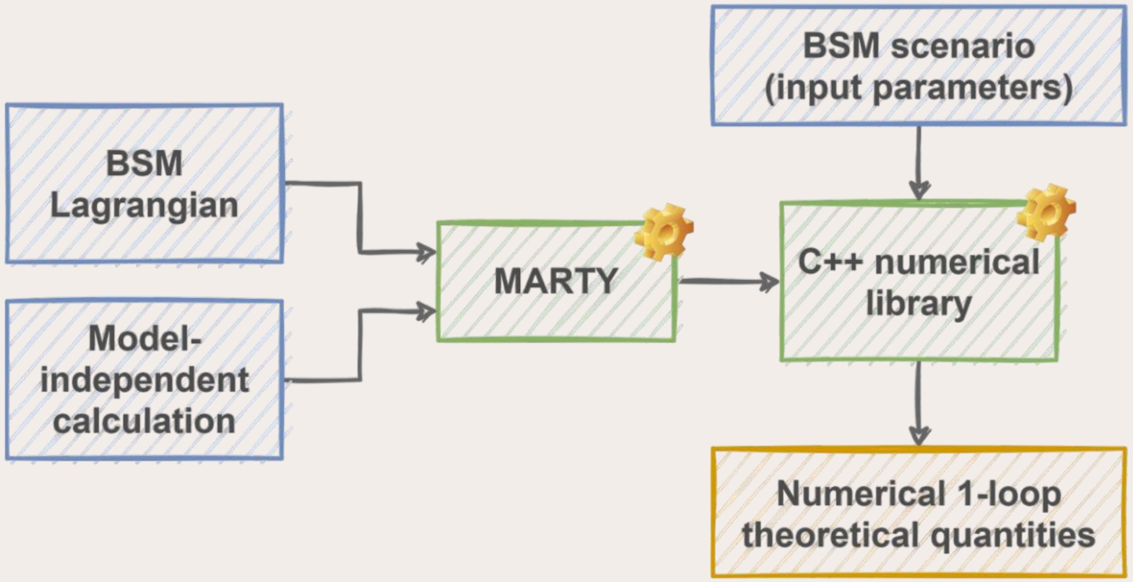
Calculations

- Squared amplitudes, Wilson Coefficients
- Up to 1-loop (fully automated)

- Index contractions
- Dirac and gauge group algebra/traces
- Equations of motion
- Tensor reduction, master integrals
- Abbreviations to speed up calculations

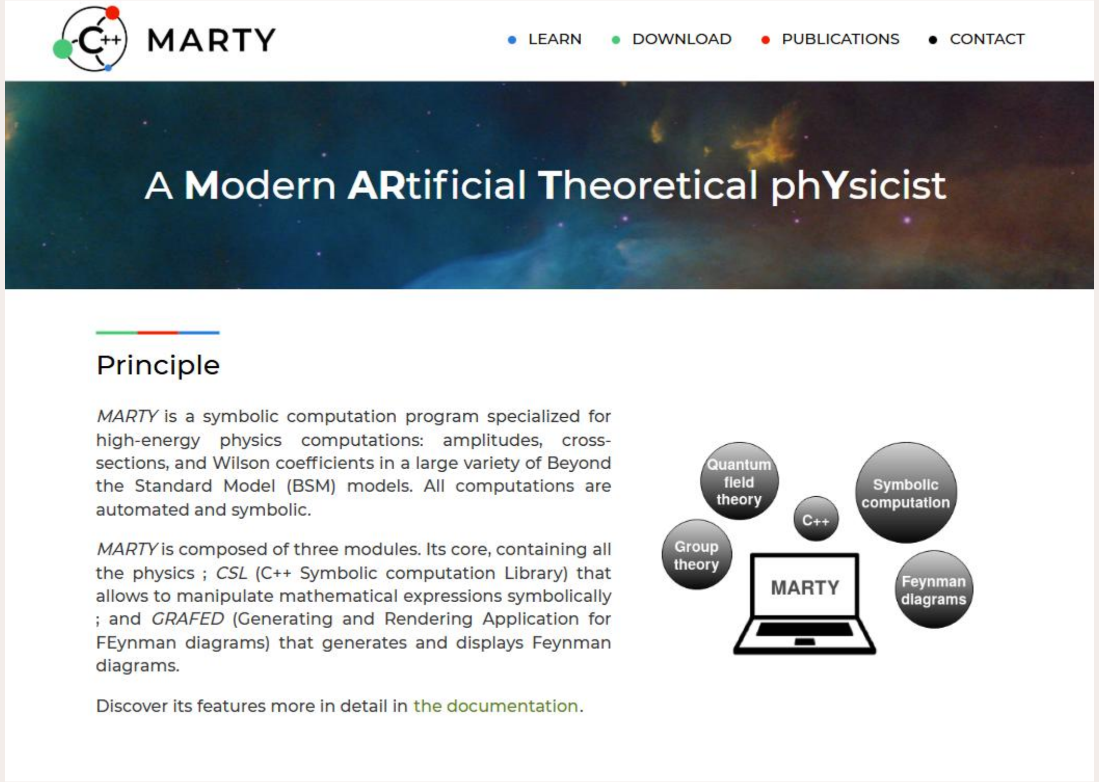
Numerical libraries

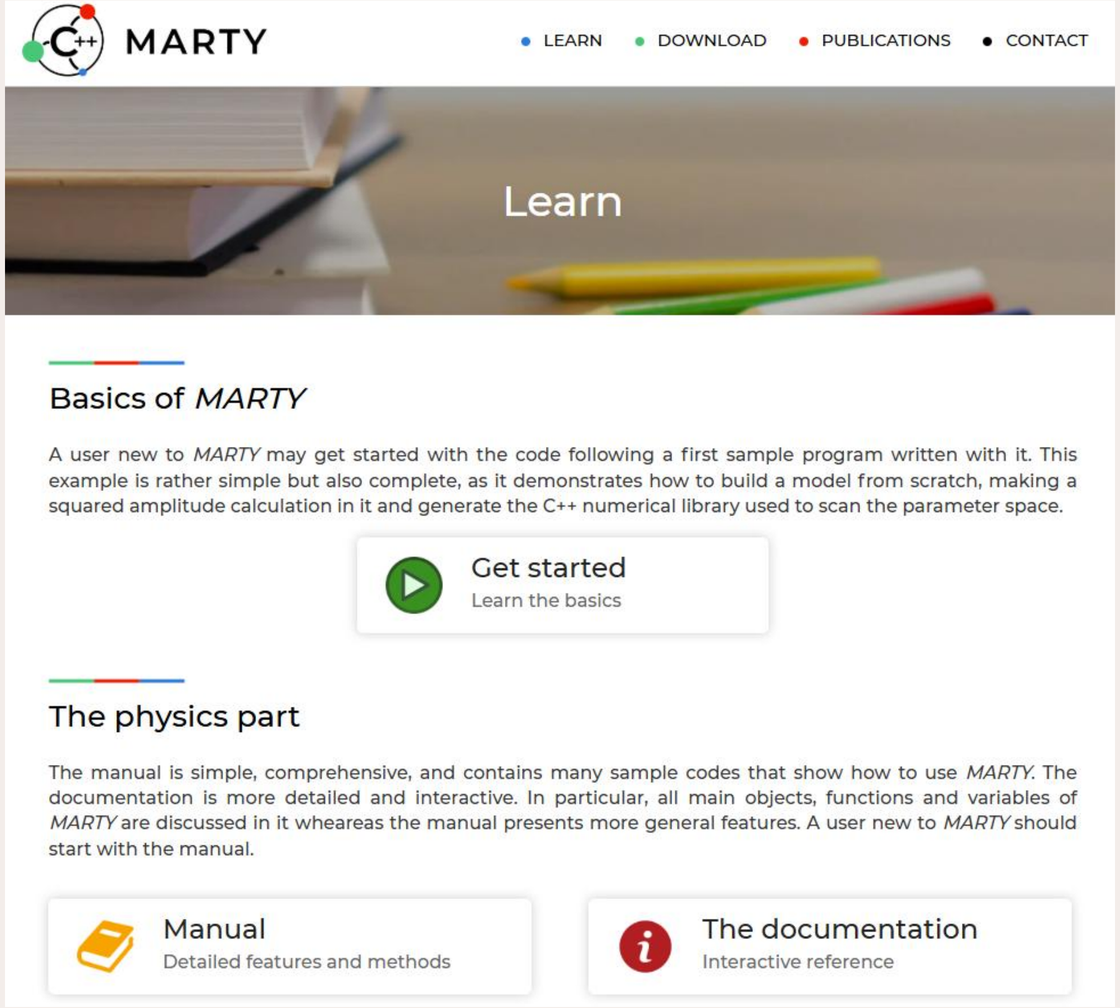
- Main output of MARTY
- Translate analytical results into C++ functions
- Only scalar expression
  - Squared amplitudes
  - Wilson coefficients
- Self-contained library
  - Spectrum generator
  - Numerical phase-space integration



Documentation

https://marty.in2p3.fr





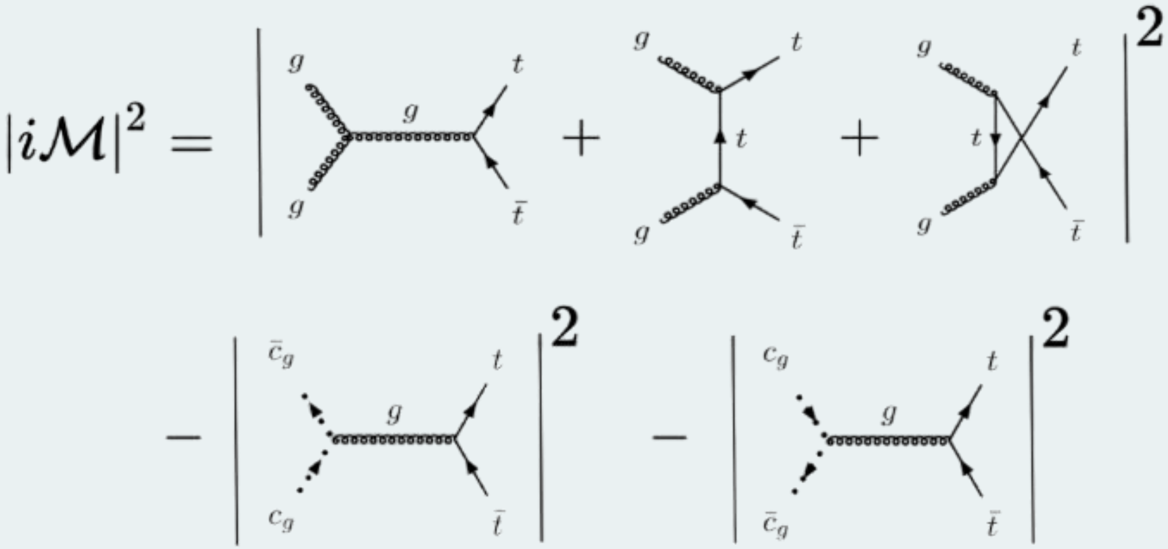
Selection of results

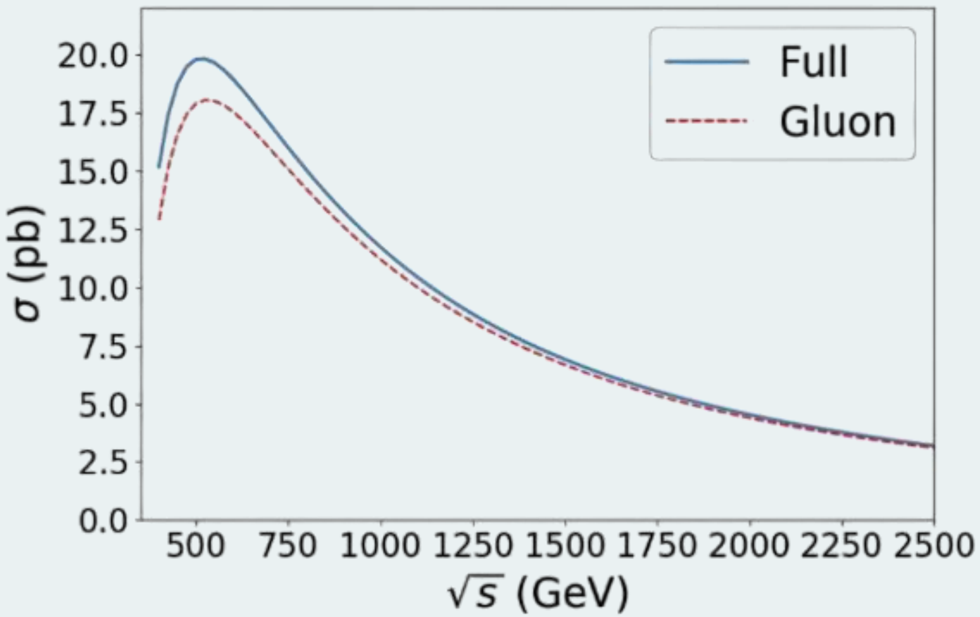
Validation principle

Gallery of the possible applications of MARTY

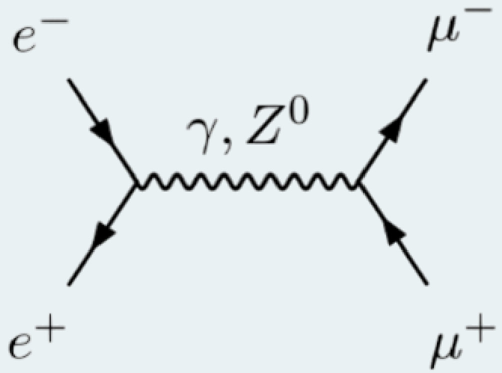
- Only known examples from the literature
- Squared amplitudes and Wilson coefficients
- Tree-level and one-loop results
- Fully simplified results
- Straightforward generalization to other BSM scenarii
- All the code for these examples can be downloaded from MARTY's website

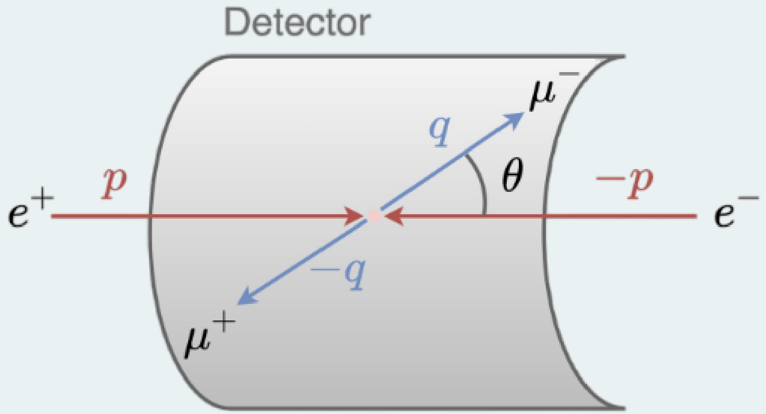
$gg \to \bar{t}t$ (SM)



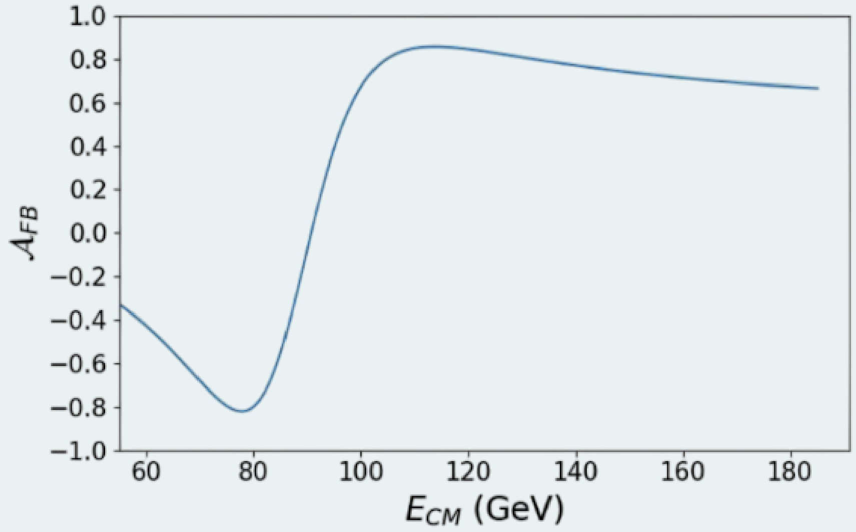


Forward-backward asymmetry (SM)



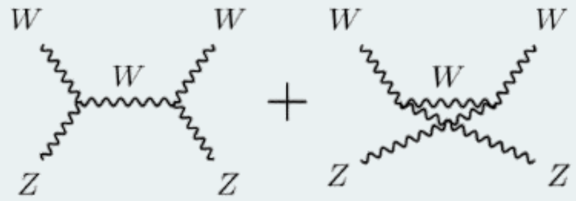


$$\mathcal{A}_{FB} \equiv 2\pi \frac{\int_0^{\pi/2} \frac{d\sigma}{d\theta} d\theta - \int_{\pi/2}^{\pi} \frac{d\sigma}{d\theta} d\theta}{\sigma}$$



Vector boson scattering and Unitarity

$i\mathcal{M}_{3V} =$



$\propto E^4$

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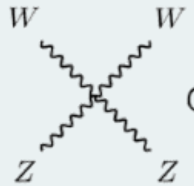
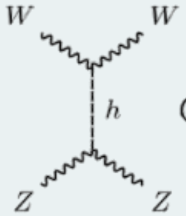


$\propto E^4$

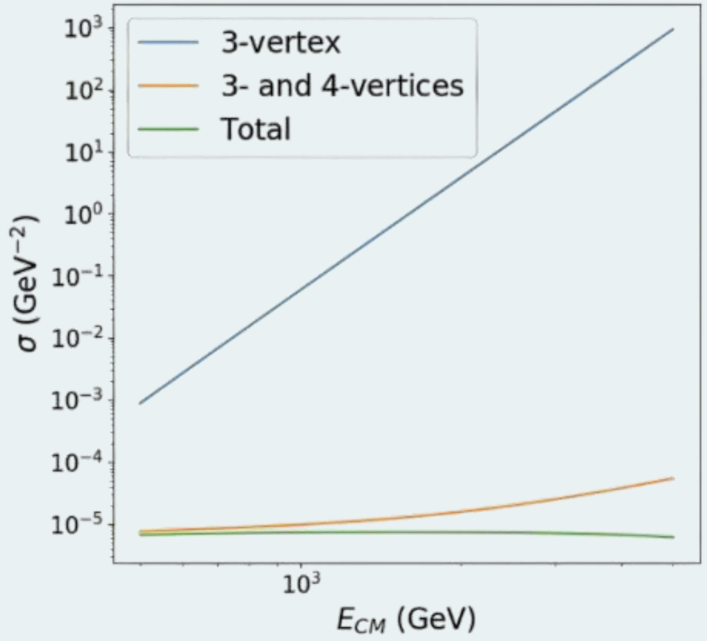
$i\mathcal{M}_h =$



$\propto E^2$

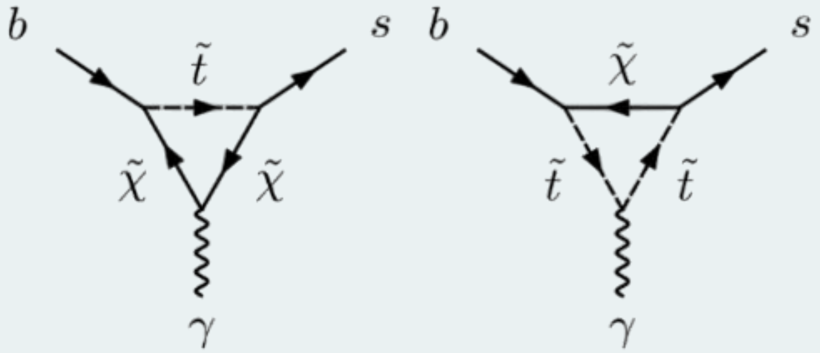
Cancellations

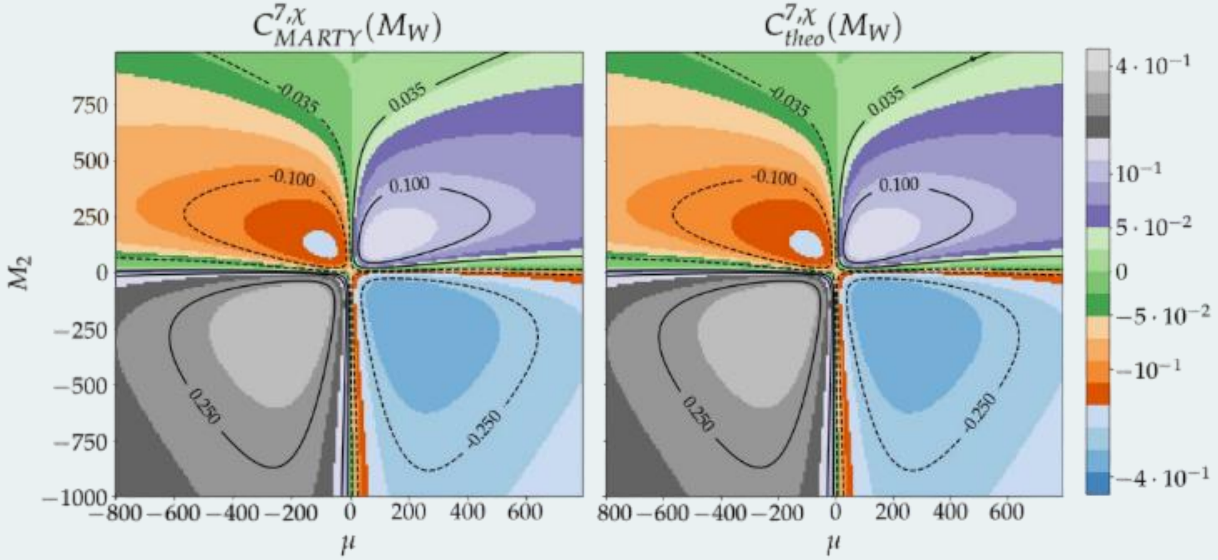
$$i\mathcal{M}_{3V+4V} \propto E^2$$
$$i\mathcal{M}_{3V+4V+h} \propto E^0$$



$b \to s\gamma$ (pMSSM)

$$i\mathcal{M} \propto C_7 \left(\bar{s}\sigma^{\mu\nu} P_R b\right) F_{\mu\nu}$$

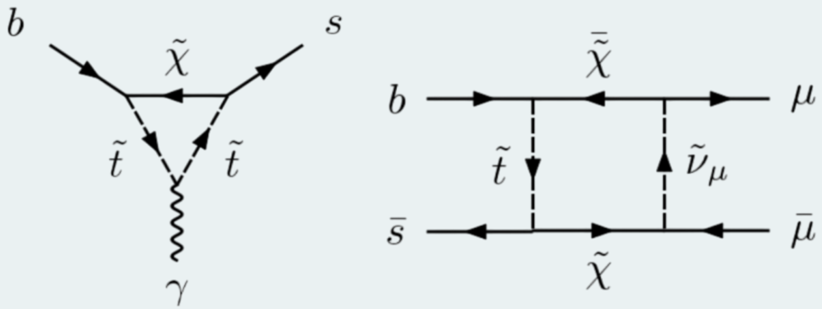




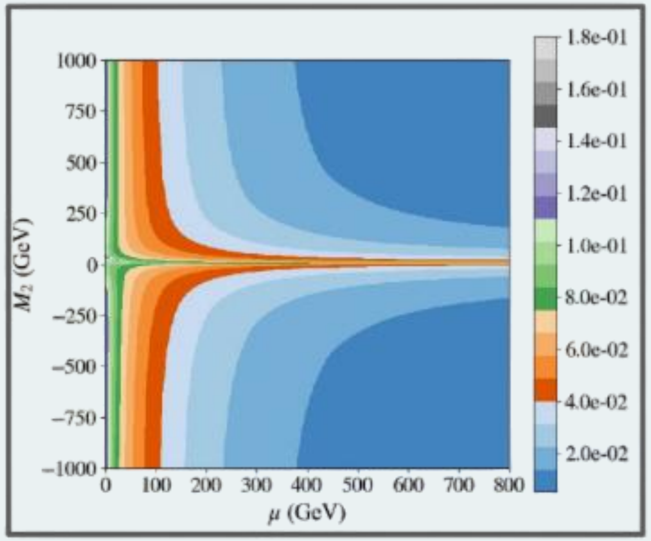
(Spectrum generated by MARTY)

$b \to s\bar{\mu}\mu$ (pMSSM)

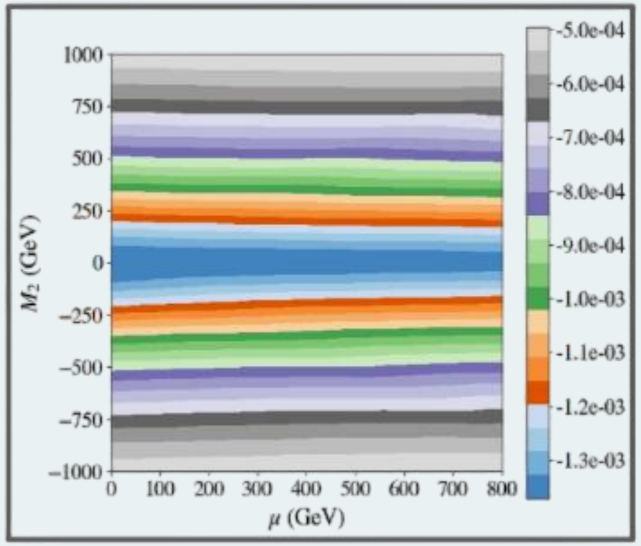
$$i\mathcal{M} \propto C_9\,(\bar{s}\gamma^{\mu}P_L b)\,(\bar{\mu}\gamma_{\mu}\mu)$$



Photon penguins



Boxes



Conclusion

- Clear and growing need for **automated calculations** in **generic BSM scenarii**
- **MARTY** can contribute to this need
  - Unique C++ program, **Mathematica-independent**
  - High-level **Model Building** features
  - Fully automated **one-loop, 5 legs** calculations
- **Validated** on very diverse examples
- **Embedding** within broader pipelines
  - Dark matter : **DarkPack**
  - Flavor physics : ***Hyperiso*** *(still in dev)*

Thanks !

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MARTY and DarkPACK
How to compute relic density in user-defined models

Marco Palmiotto

16th June 2025

Motivations

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How to verify if a given BSM model can describe some dark matter observables…
…and how do cosmological assumptions influence dark matter prodution?

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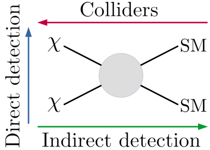
To compute:

- Relic density
- Direct and indirect detection observables
- Collider observables



DarkPack's philosophy

DarkPACK is conceived to have a **unique** and **modular** workflow

Unique

Lagrangian density $\longrightarrow$ amplitudes, ... $\longrightarrow$ DM observables

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Modular

- Possibility of stopping at any point of the chain...
- ...to link it with external software
- Object-oriented structure $\rightarrow$ more ease in writing custom functionalities
- **New:** detailed documentation with doxygen from the next version

References: (M.P., A.Arbey, N.F.Mahmoudi, CPC) user manual
(M.P., thesis) full reference

MARTY (Recap)

With MARTY the user can:

- Write a Lagrangian symbolically in a C++ source file
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  $\longrightarrow$ up to 1 loop level
- Output those results in a **numerical** C++ library

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How to get DarkPACK

DarkPACK and its documentation can be downloaded at

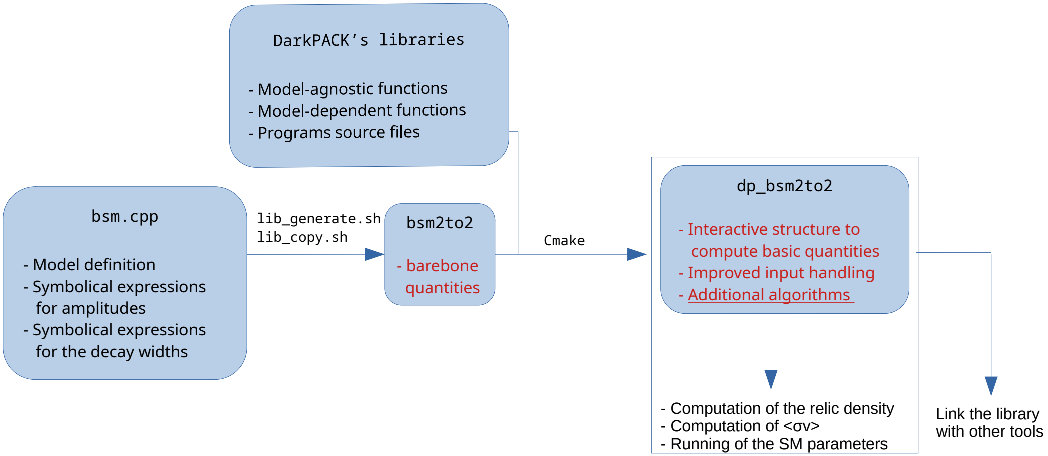
https://gitlab.in2p3.fr/darkpack/darkpack-public

(2211.10376 M.P., A.Arbey, N.F.Mahmoudi)

For this workshop, we’ll use the pre-release of the next version here:

https://github.com/marco-palmiotto/darkpack-cmake-public

How it works


DarkPACK's libraries
- Model-agnostic functions
- Model-dependent functions
- Programs source files
bsm.cpp
- Model definition
- Symbolical expressions for amplitudes
- Symbolical expressions for the decay widths
lib_generate.sh
lib_copy.sh
bsm2to2
- barebone quantities
Cmake
dp_bsm2to2
- Interactive structure to compute basic quantities
- Improved input handling
- Additional algorithms
- Computation of the relic density
- Computation of <σv>
- Running of the SM parameters
Link the library with other tools

Capabilities' overview

Observables:

- $\sum |M|^2, \Gamma \quad \longrightarrow \quad$ @LO if $\leq$ 1-loop
- $W_{\text{eff}}, \langle \sigma v \rangle \quad \longrightarrow \quad$ improved stability at low T
- $\Omega h^2 \quad \longrightarrow \quad$ from `SuperIso Relic`
  $\longrightarrow$ well-tested, reliable in MSSM, NMSSM
  $\longrightarrow$ allows for **modified cosmology**

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- user-friendly
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released MSSM

- performance
- consistency

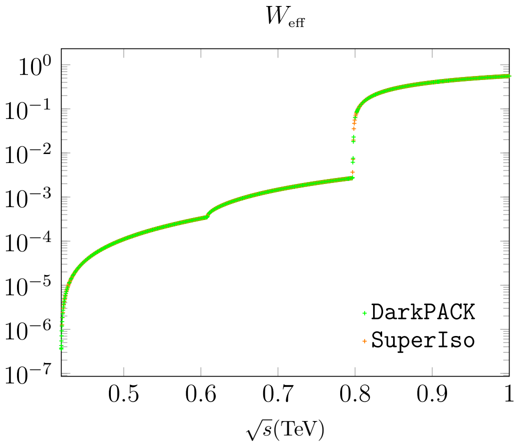
released "scalar" model

- stability
- ease of use

Next:

- new models
- submodule for parameter space sampling

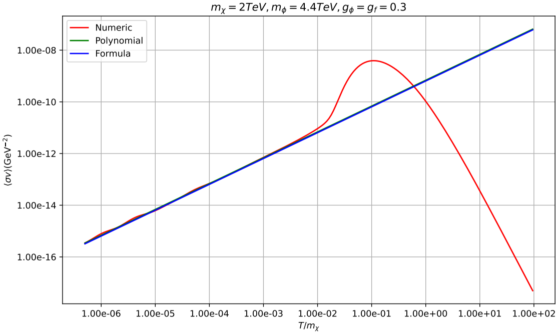
Example: W_{eff} in the MSSM



Example: $\langle\sigma v\rangle$ in the "scalar" model

$$\mathcal{L} \supset -g_\chi \phi \bar{\chi}\chi + \sum_{f\in\{\text{SMfermions}\}} \frac{y_f}{\sqrt{2}} g_f \phi \bar{f} f$$

- ϕ parity-even scalar mediator
- χ Dirac fermion



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Questions we would like to answer

- What is the impact of **modified cosmology** on DM relic density?
- Can sampling the parameter space be easier if we know more about each species’ abundance?
- How much do thermodynamical assumptions influence the DM abudance?

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$$\dot{n}_i + 3Hn_i = -\sum_{j=1}^{N}\sum_{a,b}\left[\langle\sigma v_{\text{Møl}}\rangle_{ij\to ab}n_in_j - \langle\sigma v_{\text{Møl}}\rangle_{ab\to ij}n_an_b\right] + $$
$$- \sum_{j\neq i}\sum_{a,b}\left[\langle\sigma v_{\text{Møl}}\rangle_{ia\to jb}n_in_a - \langle\sigma v_{\text{Møl}}\rangle_{jb\to ia}n_jn_b\right] + \quad \Rightarrow \quad \dot{n} + 3Hn = \langle\sigma v_{\text{Møl}}\rangle\left(n^2 + n_{\text{eq}}^2\right)$$
$$- \sum_{j\neq i}\sum_{a,b}\left[\langle\Gamma_{i\to jab}\rangle\left(n_i - n_i^{\text{eq}}\right) - \langle\Gamma_{j\to iab}\rangle\left(n_j - n_j^{\text{eq}}\right)\right]$$

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Modified cosmology: energy density

- It is possible to modify the energy density:

$$\rho = \rho_{\Lambda CDM} + \rho_D$$

- Among the various possibilities, $\rho_D(T)$ can be:
  - parametrised
  - taken from a table of values defined by the user

Modified cosmology: entropy density

It is possible to modify the entropy density:

$$s = s_{\mathrm{rad}} + s_D$$

With 3 scenarios:

1. Standard entropy injection (Σ_r given)

$$\dot{s}_{\mathrm{rad}} = -3Hs_{\mathrm{rad}} + \Sigma_r$$

   this modifies the relation between t and T

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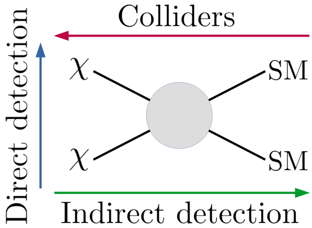
2. Dark entropy production ($s_D \neq 0$ given, can overlap with 1)
3. Dark entropy injection ($\Sigma_D \neq 0$ given, can overlap with 1)

$$\dot{s} = -3Hs_{\mathrm{rad}} + \Sigma_r + \Sigma_D$$

Development roadmap

- Releasing new models
- Improving the model-agnostic algorithms
- Native functions for indirect searches
  $\longrightarrow$ required amplitudes already provided
  $\longrightarrow$ already possible to link it with external software
- More general forms of the Boltzmann equation
  $\longrightarrow$ Solving a system of equations: one for every species
  $\longrightarrow$ Supporting models with multiple DM candidates
  $\longrightarrow$ Considering more general scenarios, i.e. freeze-in
- Native functions for direct searches
  $\longrightarrow$ `MARTY` provides Wilson coefficients



Before the tutorial session

If you want to follow the tutorial session, and you have not installed the dependencies yet, I recommend you to

- Or go on the workshop’s github page and install them locally
- Or proceed with the container-based setup. You will only need:
    1. Docker
    2. Visual Studio Code
    3. The devcontainer extension for VScode

Thank you for the attention!