Hazma☆

Adam Coogan[a,b,c], Logan A. Morrison[b,c]

[a] *GRAPPA, Institute of Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*
[b] *Department of Physics, 1156 High St., University of California Santa Cruz, Santa Cruz, CA 95064, USA*
[c] *Santa Cruz Institute for Particle Physics, 1156 High St., Santa Cruz, CA 95064, USA*

Abstract

Hazma does many wonderful things.

Keywords: Dark matter, indirect detection

1. Introduction

Hazma. Hazma is great.

2. Installation and Package Structure

2.1. Installation

Before installing `hazma`, the user needs to have a few of well-established packages : cython, scipy, numpy, and scikit-image. Theses are easily installed by using PyPi. If the user has PyPi installed on their system, then these packages can be installed using

```
pip install cython, scipy, numpy, scikit-image
```

Hazma can be installed in the same way, using:

```
pip install hazma
```

☆Code and tutorials available at github.com/LoganAMorrison/Hazma.

Email addresses: `a.m.coogan@uva.nl` (Adam Coogan), `loanmorr@ucsc.edu` (Logan A. Morrison)

This will download a tarball from the PyPi repository, compile all the c-code and install `hazma` on the system. Alternatively, the user can install `hazma` by downloading the package from `https://github.com/LoganAMorrison/Hazma.git`. Once downloaded, navigate to the package directory using the command line and run either

```
pip install .
```

or

```
python setup.py install
```

Note that since `hazma` makes extensive usage of the package cython, the user will need to have a c-compiler installed on their system. For more information, see the cython installation guide: `https://cython.readthedocs.io/en/latest/src/quickstart/install.html`

3. Overview: The `theory` Class

Instances of the `theory` class represent dark matter models, and are the main objects used to perform analyses in Hazma.

3.1. Built-in Theories

Present Lagrangians for scalar and vector models. Link to github with FR and FC calculations.

This section briefly describes the two models currently implemented `hazma`. Each model contains two BSM particles:

- A dark matter particle;
- A mediator that interacts with the dark matter as well as Standard Model particles.

Both the dark matter and the mediator are uncharged under the Standard Model gauge group. Each model is defined in terms of a Lagrangian written in terms of the microscopic degrees of freedom of the Standard Model (quarks, leptons and gauge bosons). However, at the energy scale of interest for self-annihilations of nonrelativistic MeV dark matter, quarks and gluons are not the current strongly-interacting degrees of freedom. Instead, the microscopic Lagrangian must be matched onto the effective Lagrangian for pions and other mesons using the techniques of chiral perturbation theory (chPT). The models currently implemented in `hazma` utilize leading-order chPT.

Observables in chPT are computed in terms of an expansion in a small parameter, the meson momentum p divided by the mass scale $\Lambda_{\mathrm{ChPT}} \sim 4\pi f_\pi \sim 1$ GeV, where f_π is the pion decay constant. As with an effective field theory (EFT), chPT has a limited range of validity: as $p^2 \to \Lambda_{\mathrm{ChPT}}$, higher-order Feynman diagrams in the chPT expansion provide contributions to observables comparable to leading order ones. This suggests that leading-order chPT cannot be trusted for computing dark matter self-annihilation cross sections when $m_{\mathrm{DM}} \gtrsim 500$ GeV. In fact, the convergence of the chPT expansion is disrupted at a lower mass scale by the lowest-lying hadronic resonances, the ρ ($m_\rho = 770$ GeV) and the $f_0(500)$ ($m_{f_0(500)} \sim 450$ MeV). Figure **??** illustrates where the leading-order chPT calculations can and cannot be trusted in the $(m_{\mathrm{DM}}, m_{\mathrm{mediator}})$ plane. This is important to keep in mind when using the models provided with `hazma`.

In this manual we state the microscopic Lagrangian as well as the chiral Lagrangian for each of the following theories without justification. The particular forms chosen for the interaction Lagrangians and the matching procedure are described and justified in detail in a companion papers [**?**].

3.1.1. Scalar model

The

3.1.2. Vector model

3.2. Using `theory`

3.2.1. Annihilation cross sections, decay widths and branching fractions

3.2.2. Gamma ray and positron spectra

3.2.3. Gamma ray limits

Explain procedure

3.2.4. Cosmic Microwave Background limits

Explain procedure

3.3. Gamma-ray and Positron Spectra

In `hazma`, their are two main types of spectra: Final state radiation (FSR) and decay spectra. Processes where there is a photon or electron in the immediate final state are classified as FSR. For example, the process of two dark matter particles annihilating through a scalar mediator into two charged fermions or mesons and a photon, i.e. $\overline{\chi}\chi \to S^* \to \overline{f}f\gamma$ or $\overline{\chi}\chi \to S^* \to \pi^+\pi^-\gamma$. Decay spectra arise when one of the final state particles is unstable and is able to decay radiatively, like the muon, charged pion or neutral pion. If this is the case, the spectrum for the state A decaying or annihilating into the state XB with X being some state and B then decaying radiatively to the state $C\gamma$, can be approximated using the narrow width approximation as

$$\frac{dN(A \to XB \to XC\gamma)}{dE} \sim \mathrm{BF}(A \to XB)\frac{dN(B \to X\gamma)}{dE} \tag{1}$$

An example of such a proccess is two dark matter particles annihilating into two muons or two pions: $\overline{\chi}\chi \to S^* \to \mu^+\mu^-$ or $\overline{\chi}\chi \to S^* \to \pi^+\pi^-$. For both cases, the final state particles are unstable and will decay. For the decay spectra, it is easiest to compute the gamma-ray or positron spectra in the rest frame of the decaying particle. Then, to compute the spectra in another frame, the spectrum must be boosted.

3.3.1. Boost Integrals

4. How Hazma Works

5. Advanced Usage

6. Conclusion

7. Bibliography

Here are two sample references: [1, 2].

References

[1] R. Feynman, F. Vernon Jr., Annals of Physics 24 (1963) 118–173. doi:10.1016/0003-4916(63)90068-X.

[2] P. Dirac, Physica 19 (1953) 888–896. doi:10.1016/S0031-8914(53)80099-6.