Ph.D. Thesis

Indirect study of electroweakly interacting particles at 100 TeV hadron colliders

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Abstract

(♣ To be written ♣)

Acknowledgments

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Section 1

Introduction

(♣ Unit: $\hbar = c = k_B = 1$ ♣)
(♣ Definition of "SM" ♣)
(♣ Definition of "WIMP" ♣)

Section 2

Weakly interacting massive particles

2.1 WIMPs as a dark matter candidate

One of the most important evidences of the beyond SM is the existence of dark matter (DM) [1]. DM is an unknown object that occupies a non-negligible ratio of the total energy of our universe, but has not yet been directly observed because of its weak interaction with the SM particles.[♮1] In spite of its invisibility, the existence of DM is confirmed by several astrophysical observations such as the mass measurement using the gravitational lensing effect caused by galaxies and clusters [2, 3], the flatness of galactic rotation curves further the optical radius [4, 5], the measurement of the power spectrum of the cosmic microwave background (CMB), and so on. In particular, the observation of CMB allows us the precise determination of various cosmological parameters [6, 7] including the density of the non-relativistic matter and baryon, which is currently determined as [8]

$$\Omega_m h^2 = 0.1430 \pm 0.0011, \tag{2.1}$$
$$\Omega_b h^2 = 0.02237 \pm 0.00015, \tag{2.2}$$

where $h \sim \mathcal{O}(1)$ is the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The difference between $\Omega_m h^2$ and $\Omega_b h^2$ implies the existence of DM and its abundance $\Omega_\chi h^2 \simeq 0.12$.

In cosmology, DM production mechanisms that try to explain the DM abundance are divided into two main categories: thermal and non-thermal production. The former assumes the equilibrium between the DM and the thermal bath in the early universe. As the universe expands, the interaction rate that maintains the thermal equilibrium becomes smaller and the DM decouples from the thermal bath at some time, which is the so-called *freezeout*. As

[♮1] At worst DM interacts with the SM particles through the gravity, which is considerably weaker than all the other known interactions. **(♣ Mention to Ema paper?? ♣)**

we will see below, the resulting abundance of the DM in this scenario is mainly controlled by the temperature of the thermal bath T_f when the freezeout occurs. On the other hand, non-thermal production assumes the DM production by some processes irrespective of the thermal bath such as decay of a heavy particle. Since the thermal production scenario can be realized in relatively simple setup and WIMPs are well motivated in connection with this kind of scenario, we focus on it.

We assume the stable DM particle χ with mass m_χ can pair annihilate into SM particles with some cross section σ. When DM is in thermal equilibrium with the thermal bath of temperature T, DM has some fixed velocity distribution. **(♣ More clearly ♣)** Let v be the relative velocity of annihilating DM particles and $\langle \sigma v \rangle$ be the thermal average of the product of σ and v. By using this quantity, we can write down the Boltzmann equation for the DM number density n as

$$\frac{d(na^3)}{dt} = -(n^2 - n_{\mathrm{eq}}^2)a^3 \langle \sigma v \rangle \,, \tag{2.3}$$

where t and a are the time coordinate and the scale factor of the Friedmann Robertson Walker metric

$$ds^2 = -dt^2 + a(t)^2 d\boldsymbol{x}^2, \tag{2.4}$$

while n_{eq} denotes the number density of DM in equilibrium.

Here we assume that the freezeout occurs when the relativistic radiation dominates the total energy of the universe, which will be verified to be correct later. Then we can use the Einstein equation together with the knowledge of thermodynamics to derive $a \propto T^{-1}$ and

$$dt = -2\sqrt{\frac{3}{16\pi G g_* a_B}}\frac{dT}{T^3}, \tag{2.5}$$

with G and a_B being the gravitational constant and the coefficient of the Stefan-Boltzmann law. g_* represents the effective degrees of freedom of relativistic particles in the thermal bath

$$g_* \equiv \sum_{\text{bosons}} g_B + \frac{7}{8}\sum_{\text{fermions}} g_F, \tag{2.6}$$

where both g_B and g_F denote the spin degrees of freedom of each particle in the summation. Finally, by defining dimensionless parameters $x \equiv T/m_\chi$ and $u(x) \equiv n/T^3$ and substituting $a_B = \pi^2/15$, Eq. 2.3 is deformed as

$$test \tag{2.7}$$

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