Simulating the Behaviour of a R-Parity Violating SUSY Neutralino in the FASER Detector at CERN

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Abstract

RPV SUSY is a concept in physics beyond the standard model that could eventually assist in solving the most fundamental unknown questions in physics. An experiment with possibly high potential of discovering RPV SUSY particles is the FASER experiment at CERN. In this specific project, the capabilities of using the FASER MC simulation framework for examining RPV SUSY in FASER has been studied by simulating the RPV SUSY particle neutralino. The results show that the framework is capable of handling RPV SUSY, although that some slight adjustments might be needed to increase the general ability of the framework.

1 Introduction

The Standard Model (SM) is the so far most successful theory for describing the physical world we live in. However, despite the model's success, it is not perfect. There are still fundamental questions that the theory is incapable of answering: What is all dark matter? Why is there an imbalance in matter and anti-matter? How do we resolve the hierarchy problem? To find the resolution to these questions, physics beyond the Standard Model (BSM) needs to be studied.

One BSM theory, which eventually could lead to the answers to these questions, is R-Parity Violating (RPV) Supersymmetry (SUSY). In this project, the hypothetical particle neutralino, which receives interesting properties in RPV SUSY, has been studied. This has been done by implementing it in the FORESEE software package used by the FASER collaboration at CERN. RPV SUSY has never before been implemented in the FASER Monte Carlo (MC) simulation framework. Consequently, this project has tested the limits of the software, with the purpose of finding possible improvements, potentially allowing RPV SUSY searches to be performed with the FASER detector.

2 Background

2.1 RPV SUSY

To start with, SUSY is an extension of the Standard Model which predicts an associated partner particle, a so called superpartner, for each particle. In most SUSY models, the two superpartners share most properties except spin, which they differ in by a half. This creates an important link between fermions and bosons. SUSY is a promising addition to the Standard Model, as it could, for example, assist in resolving the hierarchy problem [1]. However, so far, all searches for SUSY have been unsuccessful [2].

In SUSY models, the concept of R-Parity is important. Simply put, R-Parity conservation ensures the preservation of baryon and lepton number by forbidding their associative renormalizable couplings [3]. Mathematically, R-Parity can be described as

$$\text{R-Parity of a particle} = (-1)^{3(B-L)+2s}$$

where B is baryon number, L is lepton number, and s is spin. This takes on the values 1 and -1 for SM particles and their superpartners, respectively. A consequence of R-Parity is that it ensures that the lightest superpartner can not decay into standard model particles [4].

On the other hand, in R-Parity violating models, this is no longer true. This means that the lightest neutralino, which is assumed to be the lightest superpartner, can decay into SM particles via RPV couplings and thus be detectable. The RPV couplings allows the rare production of neutralinos through D- and B-meson decays via R-Parity violating $LQ\bar{D}$ couplings [2]. These are described by the $LQ\bar{D}$ operator, given by the third term in the following addition to the superpotential, added by RPV SUSY,

$$W_{RPV} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c.$$

2.2 FASER

FASER, or ForwArd Search ExpeRiment, is an experiment at CERN associated with the LHC and ATLAS. The FASER detector is located in the beam collision line of sight of ATLAS, roughly 480 meters behind its interaction point, see figure 1 [5]. This location is strategically chosen to look for light and weakly-interacting particles traveling in the far-forward direction after being created in the LHC collisions. These are the properties of the neutralino, thus FASER has the capability of potentially being able to detect the neutralino.

The detector itself can be seen in figure 2. Following is a simple overview of the detectors functionality. A complete description of the detector is given in [5].

The particles from the LHC collisions come into the detector from the right in the figure. The particles first come in contact with two scintillator counters, making up the VetoNu station, and the FASERν detector, used for detecting neutrinos and suppressing backgrounds. Next, there is another Veto scintillator station before the particles reach the 1.5 meters long decay volume, where optimally, the particle in question should decay. Following the decay volume is a set of two one meter long 0.57 T magnets intertwined with three tracking stations. The magnets bend the tracks of the electrically charged decay products, and the track can then be reconstructed with the information from the tracking stations. Lastly, at the most downstream part of the detector, there is a pre-shower and an electromagnetic calorimeter for measuring the energy.

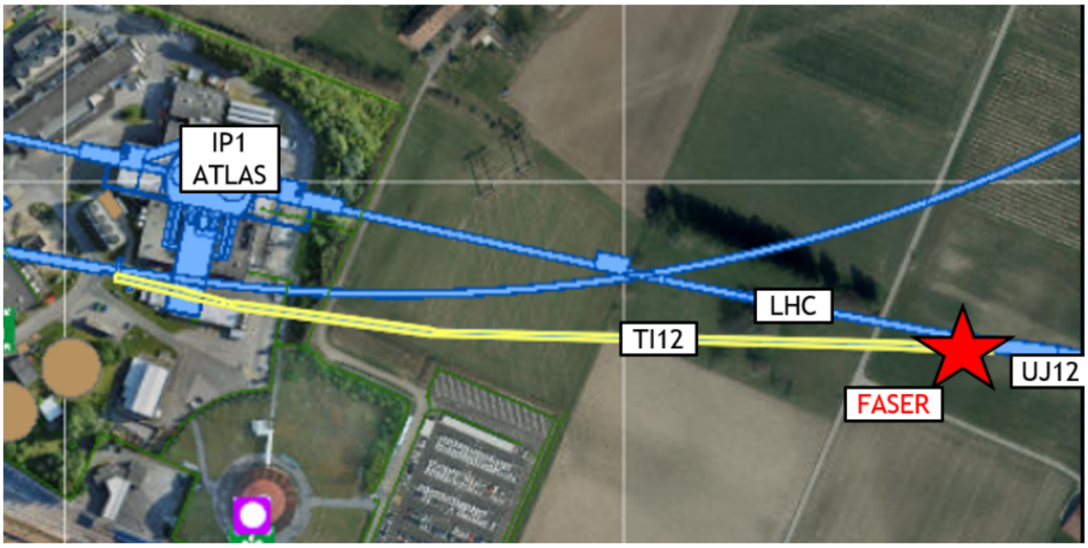


Figure 1: Location of the FASER detector. Figure from [5].

3 Model

Since the neutralino is a hypothetical particle, there are different models with it that can be considered. To make a detailed analysis, extending from the general properties of the neutralino, one specific scenario, out of these possibilities, needs to be decided on. Specifically, its production and decay routes ought to be specified.

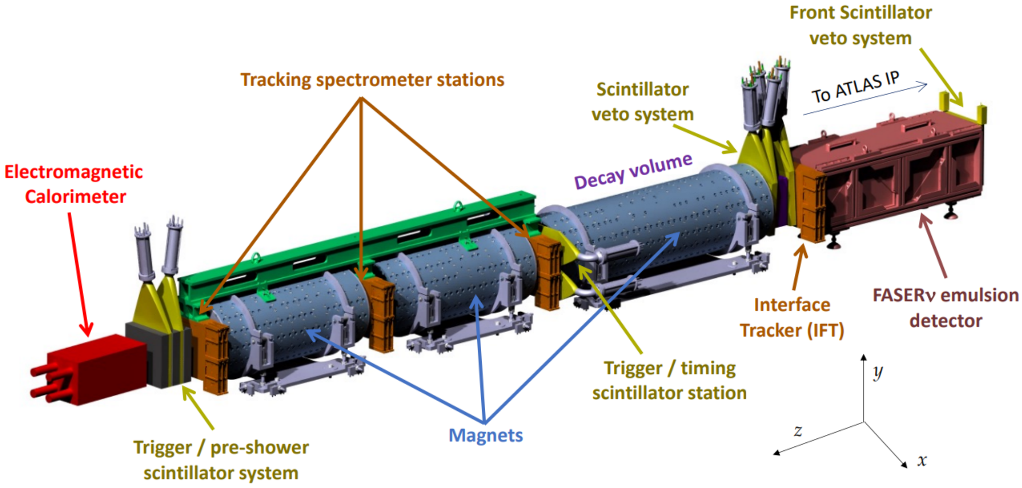


Figure 2: The FASER detector. Figure from [5].

For this project, benchmark scenario 2 in [2], described in more detail in [6], was analysed. In this framework, it is assumed that the neutralino, $\tilde{\chi}_1^0$, is produced via a $D^{\pm}$-meson in the decay

$$D^{\pm} \rightarrow \tilde{\chi}_1^0 + e^{\pm}.$$

The branching fraction for this decay is given by

$$\Gamma(D^{\pm} \rightarrow \tilde{\chi}_1^0 + e^{\pm}) = \frac{9g_2^2}{256\pi}\left(Z_{12} + \tan\theta_W Z_{11}\right)^2 \frac{|\lambda'_{121}|^2}{m_{\tilde{f}}^4} f_D^2 \frac{m_{D^{\pm}}^2\left(m_{D^{\pm}}^2 - m_{\tilde{\chi}_1^0}^2 - m_{e^{\pm}}^2\right)}{(m_c + m_d)^2}\left|\vec{p}_{\tilde{\chi}_1^0}\right|,$$

where g_2 is the coupling, Z_{12} and Z_{11} are neutralino mixing matrix elements (set to $Z_{12} = 0$ and $Z_{11} = 1$), θ_W is the weak mixing angle, λ'_{121} is one of the $LQ\bar{D}$-couplings, $m_{\tilde{f}}$ is sfermion mass (the ratio $\frac{\lambda_{121}}{m_{\tilde{f}}^2}$ is set to 10^{-7} GeV^{-2}), $f_D = 207$ MeV is the decay constant of the D meson, $m_{D^{\pm}}$, $m_{\tilde{\chi}_1^0}$, $m_{e^{\pm}}$, m_c (charm quark), and m_d (down quark) are the masses of the respective particles, and $\vec{p}_{\tilde{\chi}_1^0}$ is given by $\lambda^{\frac{1}{2}}(m_{D^{\pm}}, m_{\tilde{\chi}_1^0}, m_{e^{\pm}})/(2m_{D^{\pm}})$, with $\lambda^{\frac{1}{2}}(a,b,c) = \sqrt{a^2 + b^2 + c^2 - 2ab - 2ac - 2bc}$.

Furthermore, in the specified scenario, the decays of the neutralino are given by

$$\tilde{\chi}_1^0 \rightarrow K_{S/L}^0 + \overset{(-)}{\nu}$$

for the "invisible" decay and

$$\tilde{\chi}_1^0 \rightarrow K^{\mp} + e^{\pm}$$

for the visible. The corresponding branching fractions are given by

$$\Gamma(\tilde{\chi}_1^0 \rightarrow K_{S/L}^0 + \overset{(-)}{\nu}) = \frac{g_2^2}{512\pi}\left(3Z_{12} - \tan\theta_W Z_{11}\right)^2 \frac{|\lambda'_{121}|^2}{m_{\tilde{f}}^4} f_K^2 \frac{m_{K_0}^4\left(m_{\tilde{\chi}_1^0}^2 - m_{K^0}^2\right)}{m_{\tilde{\chi}_1^0}^2\left(m_s + m_d\right)^2}\left|\vec{p}_{\nu}\right|$$

and

$$\Gamma(\tilde{\chi}_1^0 \rightarrow K^{\mp} + e^{\pm}) = \frac{9g_2^2}{256\pi}\left(Z_{12} + \tan\theta_W Z_{11}\right)^2 \frac{|\lambda'_{112}|^2}{m_{\tilde{f}}^4} f_K^2 \frac{m_{K^+}^4\left(m_{\tilde{\chi}_1^0}^2 - m_{K^+}^2 - m_e^2\right)}{m_{\tilde{\chi}_1^0}^2\left(m_s + m_u\right)^2}\left|\vec{p}_e\right|,$$

with $\vec{p}_{\nu} = (m_{\tilde{\chi}_1^0}^2 - m_{K^0}^2)/2m_{\tilde{\chi}_1^0}$ and $\vec{p}_e = \lambda^{\frac{1}{2}}(m_{K^+}, m_{\tilde{\chi}_1^0}, m_e)/2m_{\tilde{\chi}_1^0}$.

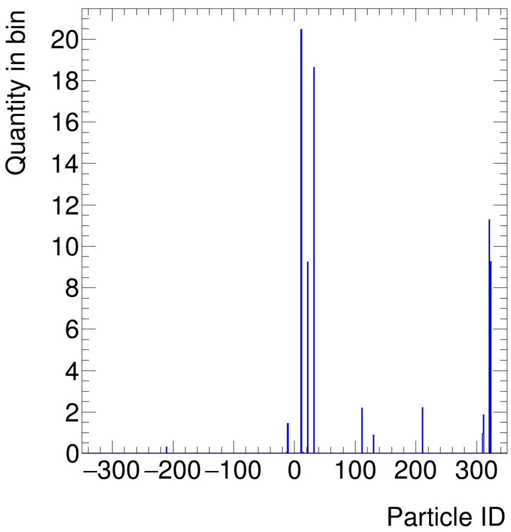
4 Results and Conclusion

The model described above was implemented in the FORESEE software package and then ran through the whole FASER analysis chain. As mentioned in the introduction, a RPV SUSY model, such as this one, has never before been implemented in the FASER MC simulation framework. Moreover, the full analysis chain has so far mostly been used to study dark photons. It is therefore important that the program, for RPV SUSY neutralinos, gives logical results that differ from those for the dark photon.

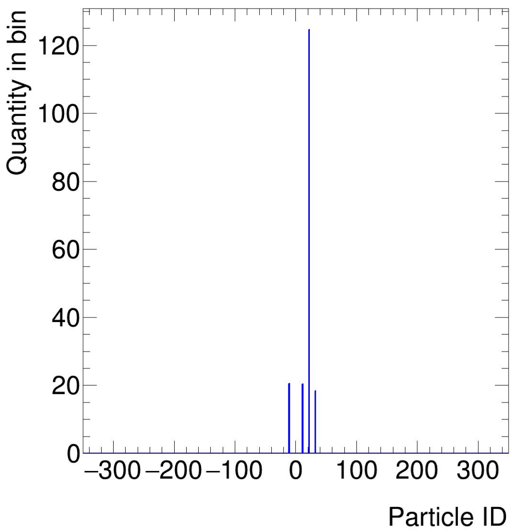
In figure 3, a histogram of the involved particles' IDs can be seen. These are summarised in table 1 and 2. It can be seen that the program accounts for the relevant particles mentioned in the the previous section, for instance the kaons. Additionally, it is clear that the results for the neutralino and the dark photon are different. However, the plot for the neutralino still includes the particle ID 32, which refers to the dark photon, and not 1000022, which would refer to the neutralino. This indicates that something in the software is hard coded for the value 32 to represent the particle being studied. This issue was found to originate from the FORESEE code.

In figure 4, histograms of the truth values of the momentum in the z-direction for the particles can be seen. The plots for the two particles are similar in shape, which is a positive indication that the program functions correctly for the neutralino. Important to note is that the values for the neutralino do not necessarily have to be exact. When implementing the model for the neutralino in FORESEE, somewhat arbitrary values were used for it's lifetime, because we had difficulties getting in contact with the theoretical physicists behind the model.

To conclude, it appears that FORESEE and the FASER MC simulation framework is capable of handling RPV SUSY. Thus, it should be able to assist in the search for RPV SUSY with the FASER detector.



(a) Neutralino.



(b) Dark photon.

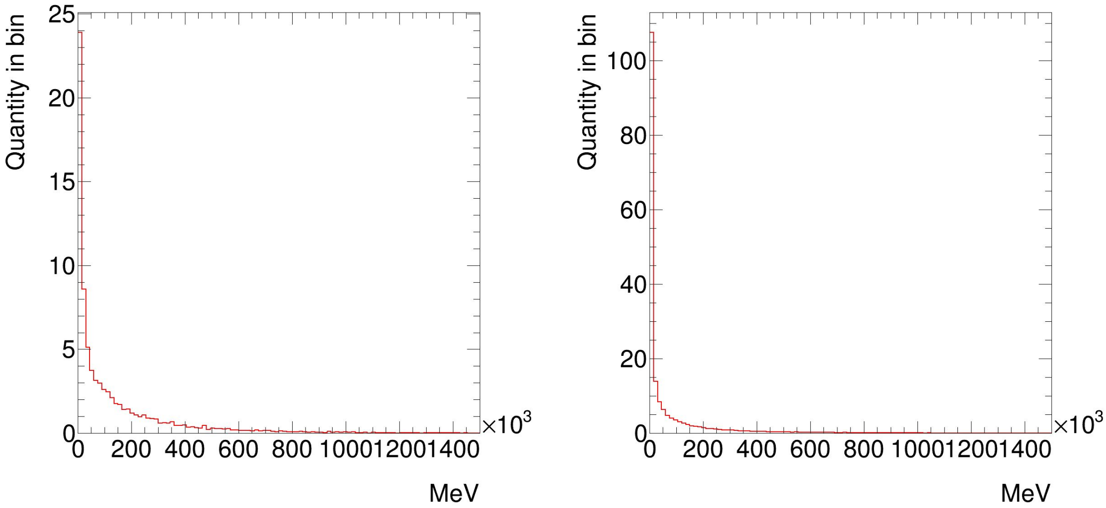
Figure 3: Histograms of the particle IDs.

PID	-11	11	22	32
Particle	e^+	e^-	γ	A'

Table 1: The particle IDs, with corresponding particle, for the case with the dark photon.

PID	-211	-13	-11	11	14	22	32	111	130	211	310	311	321	323
Particle	π^-	μ^+	e^+	e^-	ν_μ	γ	$\tilde{\chi}_1^0$	μ^0	K_L^0	π^+	K_S^0	K^0	K^+	K^{*+}

Table 2: The particle IDs, with corresponding particle, for the case with the neutralino.



(a) Neutralino.

(b) Dark photon.

Figure 4: Histogram of the truth values of the momentum in the z-direction for the particles.

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