Effects of diffractive collisions on predictions of the number of muons in the air shower

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Introduction

A hadronic interaction plays an important role in air shower development, and detailed understanding is key to solve the muon excess observed in UHECR observations and to understand the mass composition. Diffractive collision is one of the proposed sources of the problem. Recently, some studies show the effects of diffractive collisions on the air shower simulation. In Ref. [1], the effect of diffractive collisions are discussed using extreme assumption, turning off the diffractive collisions in air shower simulation. They found that lateral distribution of the number of muons decrease at the shower core and increase by 10% at 1,000 m far from the shower core for 10^{19} eV proton primary with 60^{o} zenith angle by turning off the diffractive collisions. However, it is not clear that what in diffractive collisions makes the number of muons larger or smaller. Diffractive collisions are characterized by the four collision types (as shown in Figure 1) and diffractive mass. In this work, we try to understand the effects of each characteristic of diffractive collisions on the number of muons.

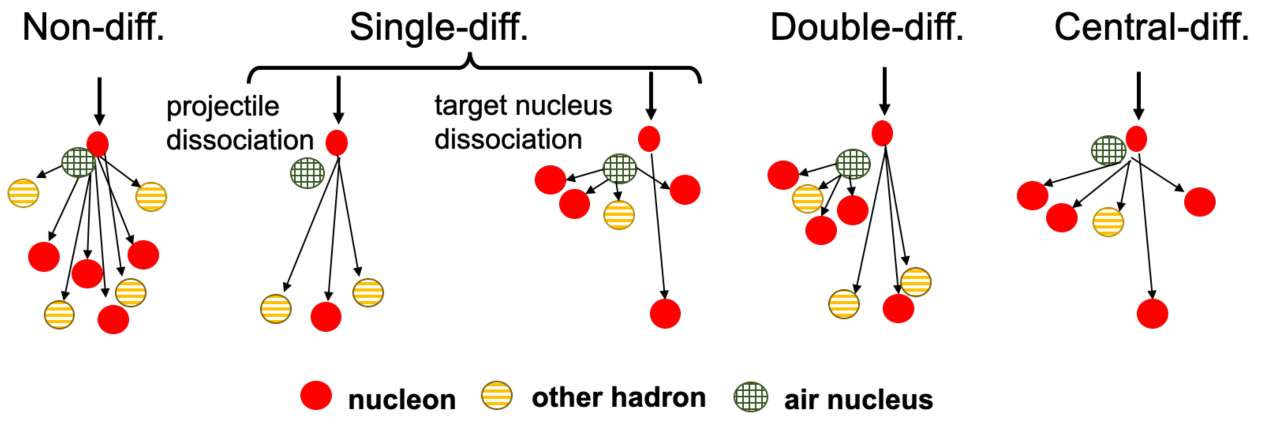

Figure 1: the schematic view of each collision type of diffractive collisions. [3]

Simulation setup

simulation settings

- CONEX 6.40
- primary particles: 10^{19} eV protons,
- Zenith angle: 60^{o}
- 40,000 air showers
- categorize events using the collision type at the first interaction

Since large statistics are needed to understand the effects of each characteristic, we use one-dimensional simulation CONEX v6.40 [2]. We cannot calculate the lateral distribution, however, we can understand the effects of detailed characteristics of diffractive collisions with enough statistics.

The number of muons with the collision type

Firstly, we checked the effects of collision type on the number of muons categorized by the collision type at the first interaction. The longitudinal profile and the number of muons on the ground are shown in Figures 2 and 3, respectively. With categorization at the first interactions, categories of projectile single diffraction and double-diffraction show a smaller number of muons than the average of all collision types.

Categories of target single diffraction and central diffraction show a smaller number than average for X < 1000 g/cm^2, then these categories show a larger number of muons for deeper parts. For target single diffraction and central diffraction, the projectile cosmic ray is intact, and shower developments become one interaction deeper.

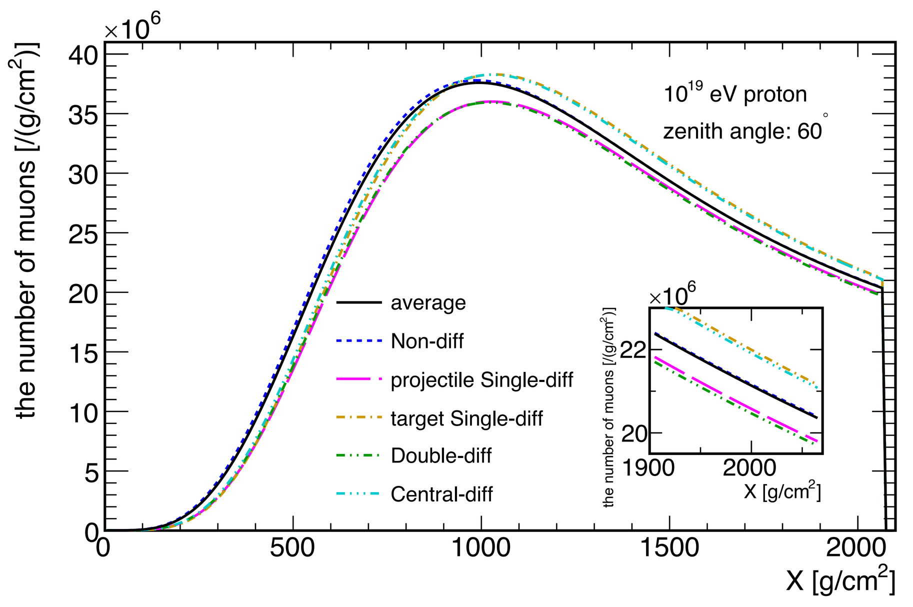

Figure 2: the predictions of longitudinal profiles of the number of muon with categorization at the first interaction. EPOS-LHC is used for the interaction model. [3]

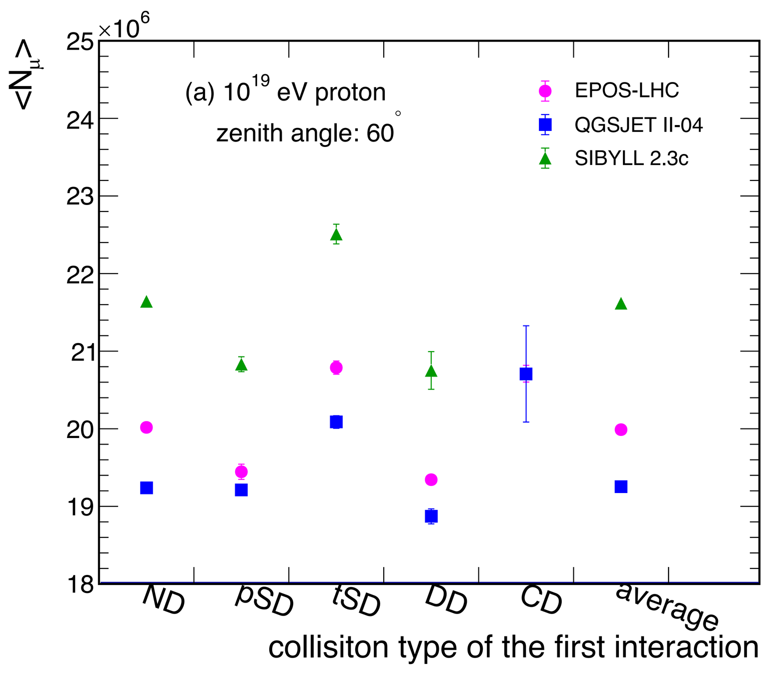

Figure 3: The number of muons at the ground for each interaction model. [3]

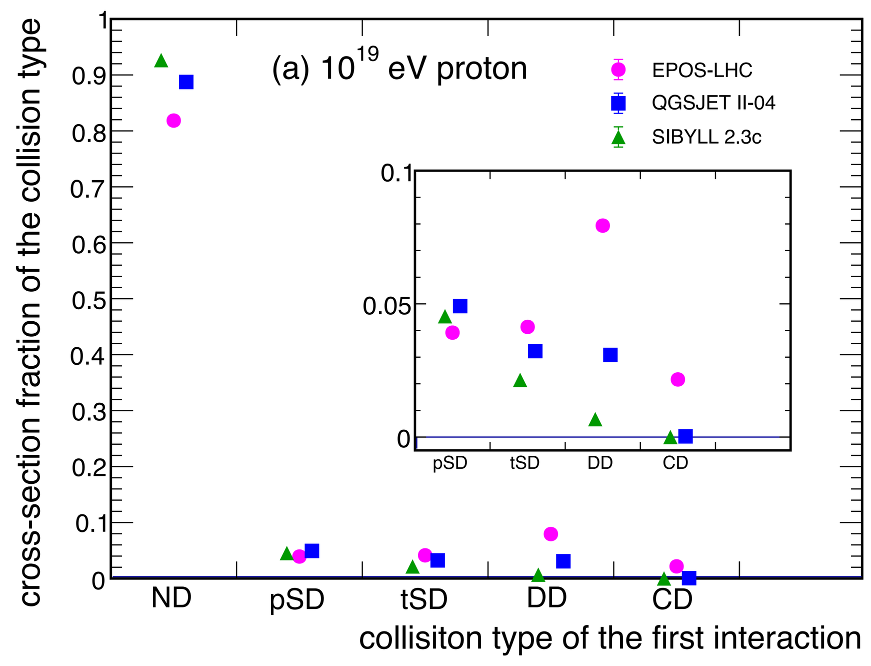

Figure 4: cross-sectional fraction of each collision type at the first interaction . [3]

The fraction of collision types and the number of muons

Next, to understand the effects of fractions of each collision type, we artificially change the fraction of diffractive collisions and estimate the number of muons after modification.

$$N_{\mu}^{modified} = \sum_{i=collision\ type} F^{i} N_{\mu}^{i}$$

$$R_1 = \frac{Diffractive\ collisions}{ALL\ collisions}$$

$$R_2 = \frac{SD}{SD + DD}$$

$$R_3 = \frac{projectile\ SD}{all\ SD}$$

$$R_4 = \frac{CD}{diffractive\ collisions}$$

where F^{i} is the fraction of each collision type after modification and N_{μ}^{i} is the number of muons of each collision type. To modify the fraction, we use ratios R_i (i = 1-4).

When the ratio of diffractive collisions R_1 is changed from the original prediction to the prediction by EPOS-LHC in SIBYLL 2.3c, N_{μ} becomes 0.16% smaller at the first interaction.

Diffractive mass dependencies

Differences between the category of projectile single diffraction and the average strongly depend on the hadronic interaction models, as shown in Fig. 3. These model dependencies are caused by the diffractive mass dependencies. In this section, we check the diffractive mass at the first interaction for the categories of projectile single diffraction. Diffractive mass is the invariant mass of the dissociation system of the diffractive collision. The diffractive mass is calculated from the momentum of produced particles.

Differential cross-sections of diffractive mass (diffractive-mass spectrum) and diffractive mass dependencies of N_{μ} are shown in Figures 5 and 6, respectively. Diffractive mass dependencies are small for EPOS-LHC and QGSJET II-04 cases, while SIBYLL 2.3c shows a dip structure at the low diffractive mass region.

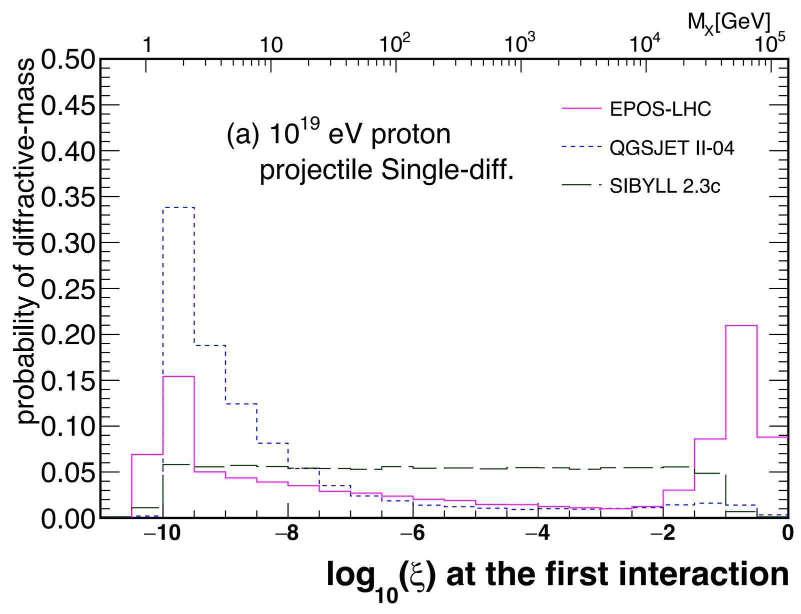

Figure 5: differential cross section of diffractive mass for three interaction models. [3]

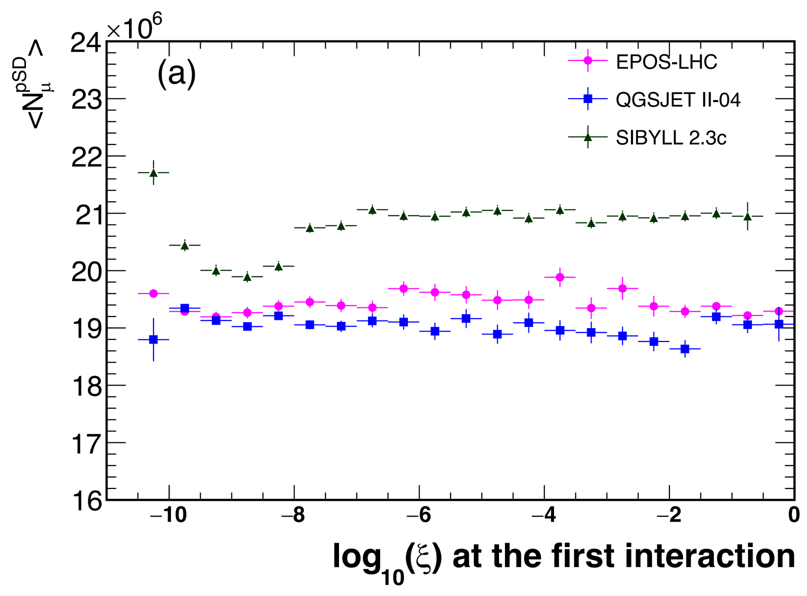

Figure 6: diffractive mass dependencies of the number of muons on the ground. [3]

To estimate the effect of the diffractive-mass spectrum, we artificially change the spectrum and calculate modified N_{μ}.

$$N_{\mu}^{pSD,modified} = \sum P^{i} N_{\mu}^{pSD,i},$$

where P^{i} is the probability of i-th bin in Figure 5 and $N_{\mu}^{pSD,i}$ is the number of muons in i-th bin in Figure 6. When the diffractive mass spectrum is changed to the spectrum by QGSJET II-04 for SIBYLL 2.3c, the number of muons becomes 2.0 % larger for pSD case. The diffractive mass affects for pSD and DD cases, therefore N_{μ} is expected to be 0.2 % larger at the first interaction.

Summary

We discussed the effect of each characteristic of diffractive collisions at the first interaction. The effects of the cross-sectional fraction and the diffractive mass spectrum were 0.16% and 0.2% at the first interaction. For the number of muons, both cross-sectional fractions and the diffractive mass dependencies are important.

In this work, we only focused on the first interaction. It is important to discuss the effects of interactions of secondary particles in the future.

[1] L.B. Arbeletche *et al.*, Int. J. Mod. Phys. A **33**, 1850153 (2018)

[2] T. Bergmann *et al.*, *One-dimensional hybrid approach to extensive air shower simulation*, Astropart. Phys. **26**(2007) 420-432.

[3] K. Ohashi *et al*, arXiv:2005.12594.