MC study for the effect of diffractive events on the air shower developments

Ken Ohashi, Yoshitaka Itow, and Hiroaki Menjo (ISEE, Nagoya Univ., Japan)

abstract

To understand the origin of ultra-high energy cosmic-rays (UHECRs), mass composition of cosmic-rays is very important. The depth of shower maximum, $X_{\max}$, is an indicator of the mass composition. The prediction of $X_{\max}$ by an air shower simulation is shifted significantly by the choice of hadronic interaction models. Diffractive events are one of the proposed sources of model differences in X_{max} predictions. In this work, we study the effect of parameters of diffractive events, such as the fraction of single/double diffraction, on $X_{\max}$ using the air shower simulation package COSMOS. 50000 air showers are simulated and categorized by the collision type of first interaction. We estimate the effect of diffractive events on air shower developments quantitatively by replacing the fraction and <X_{max}>,.

Introduction

The origin of ultra-high energy cosmic-rays is unknown. Ultra-high energy cosmic rays (UHECRs) with > 10^{18} eV are expected to be accelerated in energetic extra-galactic object such as AGNs and star burst galaxies, however, these accelerators of UHECRs are not identified experimentally yet. To understand the origin, the mass composition of cosmic-rays, protons, iron nuclei, or other nuclei, is one of the key observable. During the propagation from the source to the Earth, UHECRs are bended by the magnetic field of the inner/outer galaxy, and they interact with cosmic microwave background. These effect strongly depends on the mass composition. As a result of interactions between a cosmic-ray and air nuclei, a large number of particles are produced in the atmosphere, and this phenomenon is called "air shower" (Fig. 1). UHECR experiments observe air-showers by using particle detector arrays and/or fluorescence telescopes on the ground. The energy and the depth of maximum of the air shower developments, X_{max}, is one of the indicators of the mass composition, and the mass composition is estimated by comparing the prediction and an experimental data of X_{max}(Fig. 2). However, a prediction of X_{max} depends on the choice of hadronic interaction models in simulation, and that makes difficult to interpret mass composition.
Verification of hadronic interaction models is needed, and several components of the models are proposed as sources of the <X_{max}> discrepancy among the models. One proposed source is the different modeling of diffractive collisions among the models.

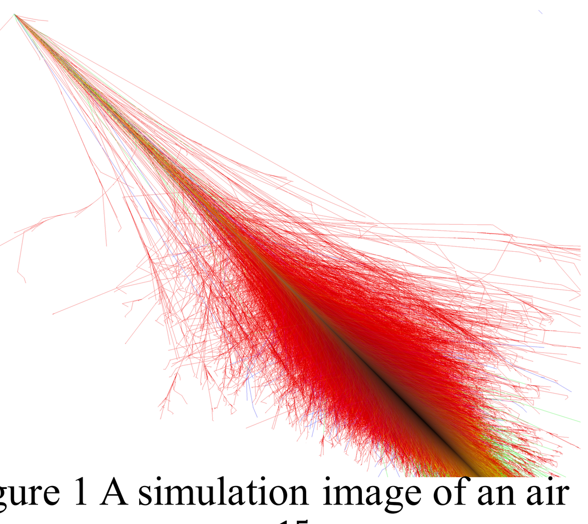

Figure 1 A simulation image of an air shower event by 10^{15} eV proton cosmic-ray.
Image credit: CORSIKA web page

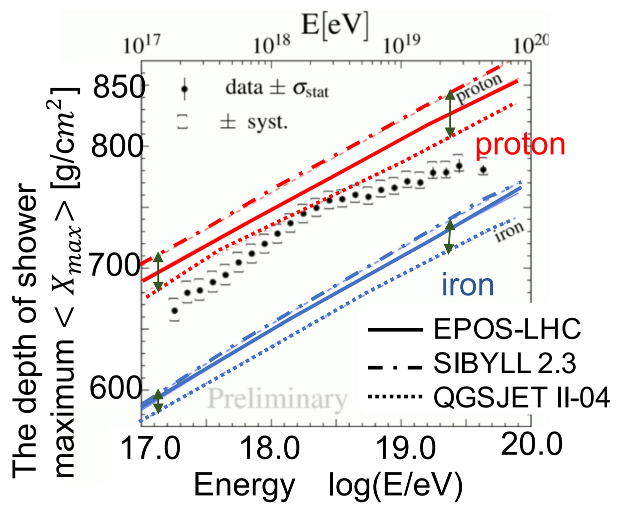

Figure 2 Experimental data and predictions of mean X_{max} (<X_{max}>). Exp. data are results by PAO [1]. Predictions are results of air shower simulations with several hadronic interaction models.

Diffractive collisions

Diffractive collisions is one of the event categories in inelastic collisions of hadrons and 16 to 22% of collisions between 10^{15} eV proton and an air nucleus are diffractive events. There are three types of diffractive events as shown in Fig. 3. A single diffractive event is a diffractive event with one proton dissociation, while a double diffractive event is with both proton dissociations. In this study, we focus on only single and double diffraction. Diffractive events are characterized by a smaller number and higher energy of produced particles than non-diffractive events.

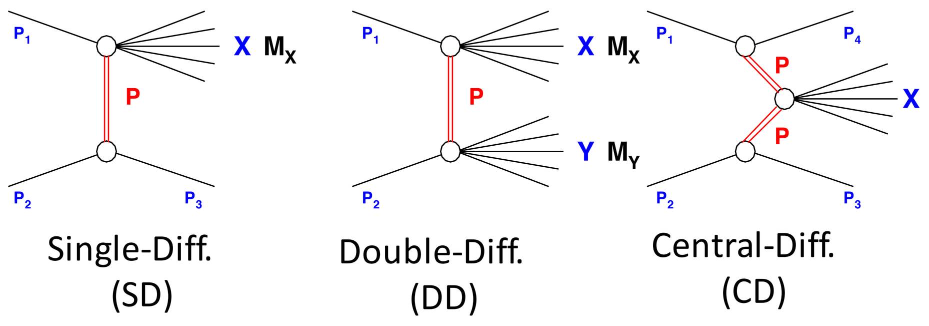

Figure 3
The feynman diagram of diffractive collisions.[1]

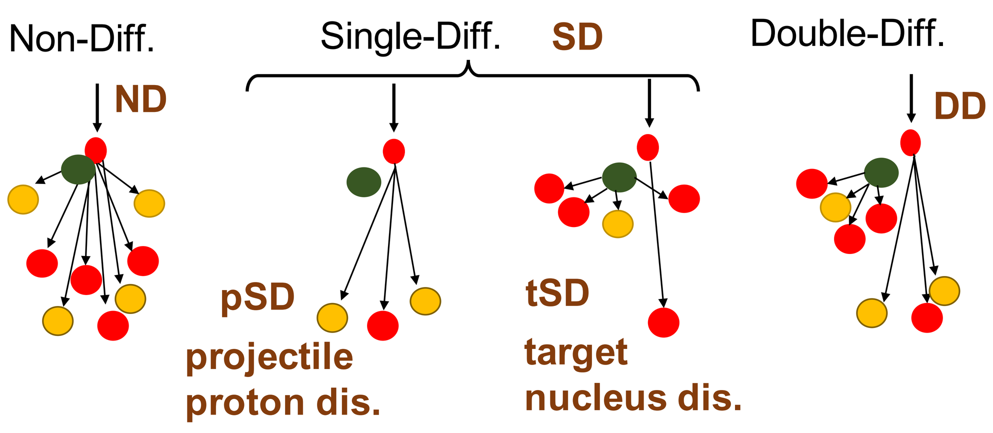

Figure 4 The schematic view of the diffractive event of non-diffractive (left, ND), projectile single diffractive (middle-left, pSD), target single diffractive (middle-right, tSD), and double diffractive (right, DD) at lab frame.

A few simulation studies about the effect of diffractive collisions on the air-shower development have been performed. The effect of the shift of diffractive cross section on $X_{\max}$ is estimated $\pm 5\ \mathrm{g/cm^2}$ in Ref. 2. In Ref. 3, the maximum effect of diffractive events is estimated with an extreme assumption, and that is $15\ \mathrm{g/cm^2}$. However, the assumption in Ref. 3 is not realistic, and the effect of parameters of diffractive events on $X_{\max}$ is not well understood. These parameters are important to improve the models.
In this work, we discuss the effect of parameters of diffractive events on the air shower development.

The effect of diffractive events on the air shower development

In this work, we simulate air showers by using the air shower simulation package COSMOS 8.035, and estimate the effect of parameters of diffractive events on mean X_{max} (<X_{max}>).

In parameters of diffractive events, we focus on the fraction of each category of diffractive events in inelastic collisions. The energy of each produced particle in diffractive events is different among the types, and that of SD with target nucleus dissociation is highest. This feature affects shower developments of each type of diffractive events, therefore the fraction of each type in inelastic collisions is one of important parameters.

simulation settings

- 50000 air showers
- categorize events using the first interaction information
- primary particle: 10^{15} eV proton
- Energy of the first interaction: $\sqrt{s_{NN}} \approx 1.3$ TeV

the predictions of <X_{max}>

By using the first interaction information, we divide the events into four or five categories, and calculate <X_{max}> for each category. Table 1 shows the <$X_{\max}$> and fractions of each category. The effect of diffractive events is different among the diffractive types. <$X_{\max}$> predictions of diffractive events are larger than that of ND, and that of tSD are largest in four or five categories.

Table 1 <$X_{\max}$> and the fraction of each category of diffraction for three interaction models

	ND	SD (proton dis.)	SD (air nucleus dis.)	DD	CD	total
SIBYLL 2.3c						
fraction [%]	84.2±0.4	10.5±0.1	4.20±0.09	1.10±0.05		100.0
mean $X_{\max}$ [g/cm^2]	577.0±0.4	609.9±1.3	648.1±2.5	605.7±3.8		583.8±0.4
difference from ND	-	+32.9	+71.1	+28.7		
QGSJET II-04						
fraction [%]	84.7±0.4	7.2±0.1	4.20±0.09	4.00±0.09		100.0
mean $X_{\max}$ [g/cm^2]	561.1±0.4	612.4±1.6	634.8±2.5	602.8±2.0		569.9±0.4
difference from ND	-	+50.9	+73.3	+41.3		
EPOS-LHC						
fraction [%]	78.9±0.4	4.7±0.1	5.0±0.1	9.2±0.1	2.27±0.07	100.0
mean $X_{\max}$ [g/cm^2]	565.5±0.4	611.1±1.9	632.8±2.2	606.1±1.3	627.1±3.2	576.1±0.4
difference from ND	-	+45.6	+67.3	+40.6	+61.6	

the effect of the fraction of each category of diffraction

To estimate the effect of the fraction, we replace fractions in QGSJET II to EPOS-LHC or SIBYLL 2.3c, and calculate total X_{max} using Eq. 1.

$$< X_{max}^{total} > = < X_{max}^{ND} > + f^{pSD}\alpha^{pSD} + f^{tSD}\,\alpha^{tSD} + f^{DD}\alpha^{DD} \quad \text{(Equation 1)}$$

where $< X_{max}^{total} >$ is <$X_{\max}$> of all events, and $< X_{max}^{ND} >$ is that of ND category. f^i (i = pSD, tSD, DD) is the fraction of each category and α^i is a difference of <$X_{\max}$> of category i from ND. When we use $< X_{max}^{ND} >$ and α^i in SIBYLL 2.3c and f^i in QGSJET II and calculate $< X_{max}^{total} >$ (replacing the fraction in QGSJET II to SIBYLL 2.3c), the result is 570.4 g/cm^2, which is 0.5 g/cm^2 larger than the original one. From table 1, EPOS-LHC only has the category of CD. We ignore the fraction of CD and renormalize each fraction in order to make total fraction 100%, then replace the fraction in QGSJET II to EPOS-LHC. The result is 571.6 g/cm^2, which is 1.7 g/cm^2 larger than the original one. From these results, the effect of model differences of the fraction between SIBYLL 2.3c (EPOS-LHC) and QGSJET II on <$X_{\max}$> is 0.5 g/cm^2 (1.7 g/cm^2), which is 3.5 % (27.1 %) of the current model discrepancy.

the effect of <X_{max}> of each category of diffractive events

To estimate the effect of diffractive events other than the fraction, which is a difference in particle production, we replace in α^i of each category in QGSJET II to EPOS-LHC or SIBYLL 2.3c. We estimate that effect by replacing α^i in Table 1 and calculate with Eq. 1. Replacing α^i in QGSJET II to SIBYLL 2.3c (EPOS-LHC), the result is 568.0 g/cm^2 (569.2 g/cm^2), which is 1.9 g/cm^2 (0.6 g/cm^2) smaller than original one. This shift is 13.6 % (10.7 %) of the current model discrepancy between two models.

Conclusion

<u>We studied the effect of diffractive events on air shower developments.</u>

- The effect of model differences in the fraction of each category between SIBYLL 2.3c (EPOS-LHC) and QGSJET II on X_{max} is 0.5 g/cm^2 (1.7 g/cm^2).
- The effect of model differences of each category of diffractive events between SIBYLL 2.3c (EPOS-LHC) and QGSJET II on X_{max} is 1.9 g/cm^2 (0.6 g/cm^2).

References

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