Impact of diffractive collisions on air shower development

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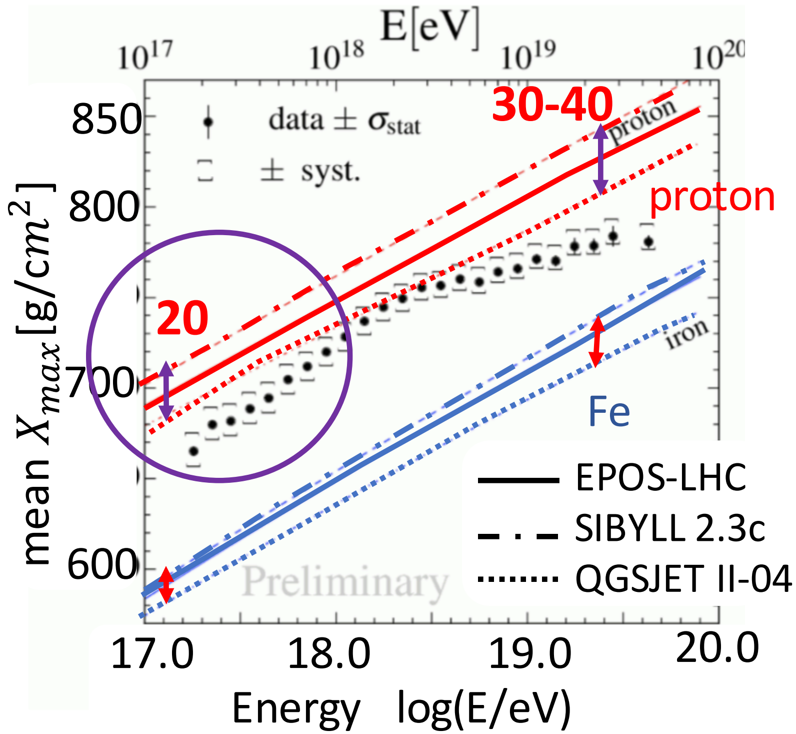
3/25 **第三回 空気シャワー観測による宇宙線の起源探索勉強会**
@ICRR, Univ. of Tokyo

Mass composition and hadronic interaction models



The Pierre Auger Collaboration
PoS (ICRC 2017) 506

Hadronic interaction models:
composed by theory and phenomenological models

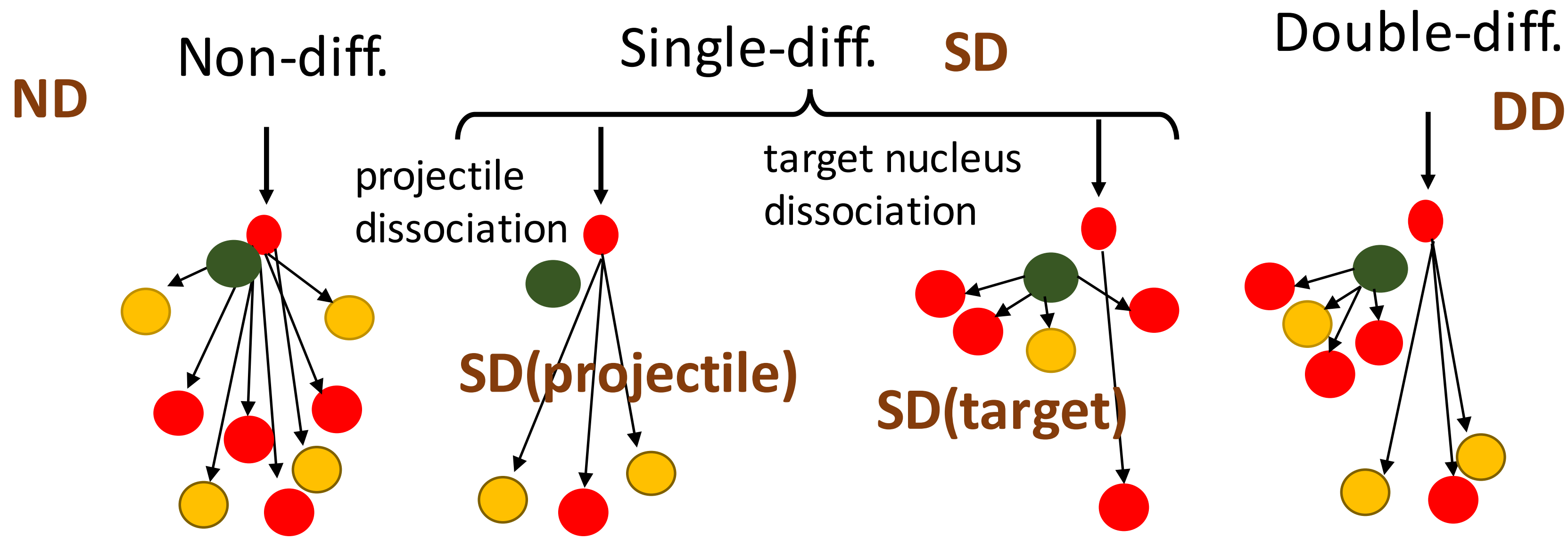
<possible sources of model uncertainty>

- production of high energy particles
- interaction between pions and air nuclei
- **diffractive collisions** etc.

To reduce model uncertainty, we need to understand the effect of each components in model on air shower developments.

Diffractive collisions and air shower

schematic view of the interaction between a cosmic-ray proton and an air nucleus



SIBYLL 2.3c $K_{el} \sim 0.39$ $K_{el} \sim 0.56$ $K_{el} \sim 0.997$ $K_{el} \sim 0.52$

=> the effect of each collision in air shower is different

fraction

	ND	SD(projectile)	SD(target)	DD
SIBYLL 2.3c	88.2 %	7.9 %	3.2 %	0.8 %
EPOS-LHC	84.4 %	3.3 %	3.8 %	8.4 %

=> Model differences in fractions of each collision type.

The effect of diffractive collisions on air shower developments

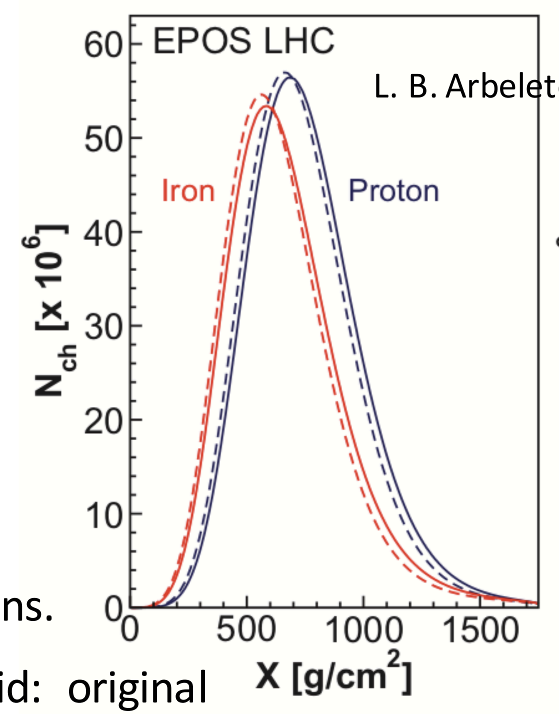
Previous work

L. B. Arbeletche et al.,
International Journal of Modern Physics A
Vol. 33, No. 26 (2018) 1850153

Estimate the effect by simulate air showers without diffractive collisions.

In previous work, differences of each type of diffraction is not considered.

➡ We need detail study to understand the effect of each collision type such as fractions.



L. B. Arbeletche et al.,

solid: original
dashed: diffractive collisions are artificially turn OFF

In this work

Estimate the effect of fractions and diffractive mass on air shower developments quantitatively.

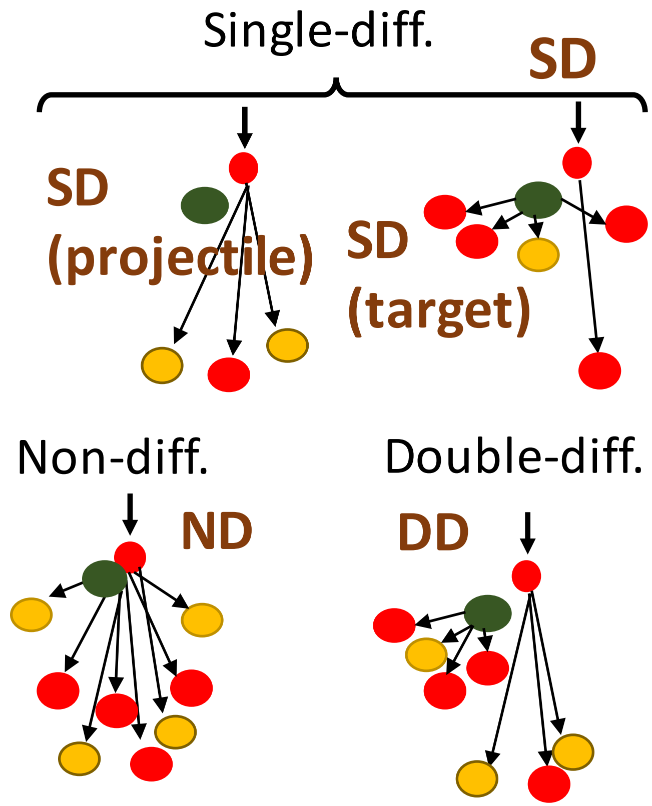
Air shower simulation

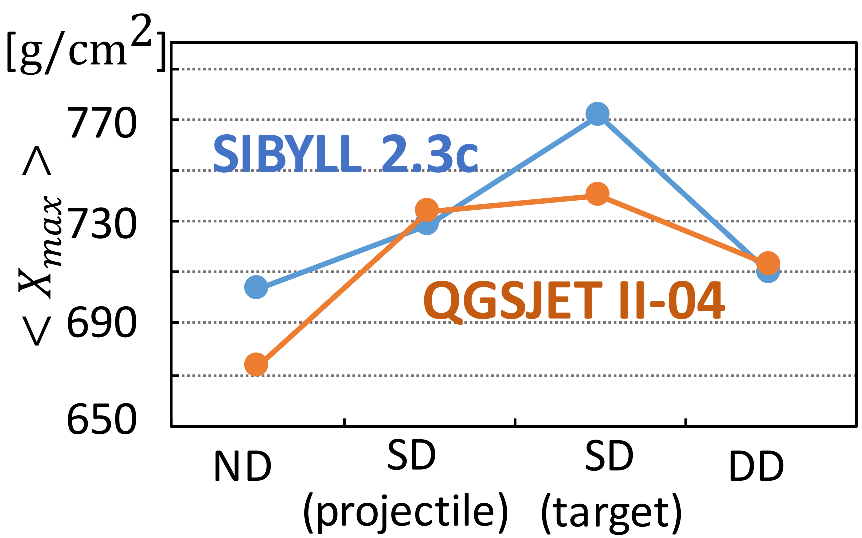
COSMOS 8.035

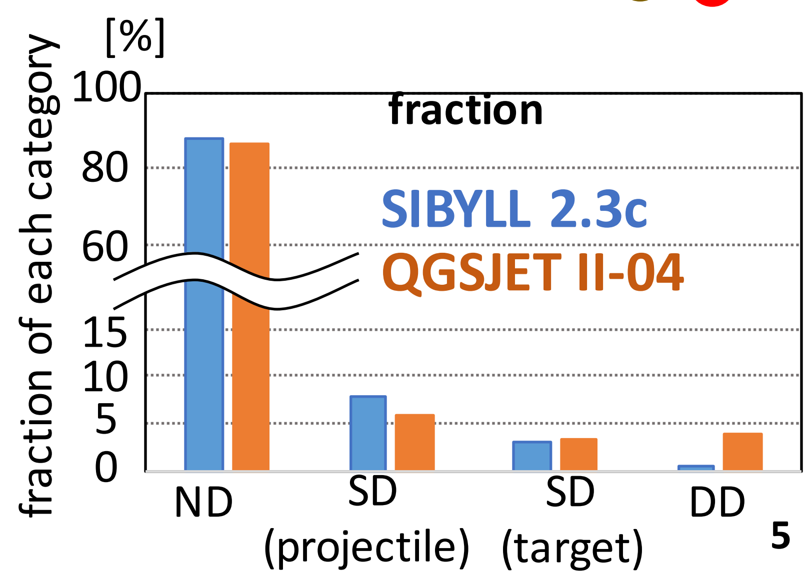
primary: proton, 10^{17} eV
\# of events: 3000 events

For each events, we use

- X_{max}
- Collision type at the **first interaction**







categorized by collision type at the first interaction

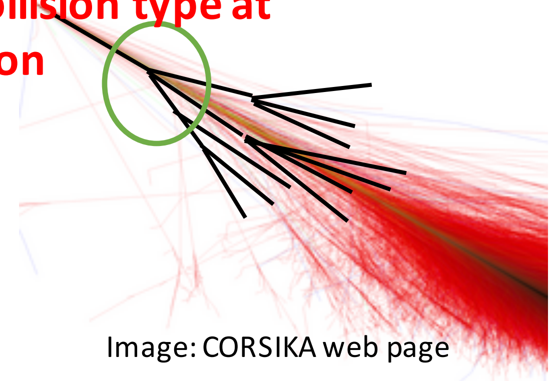
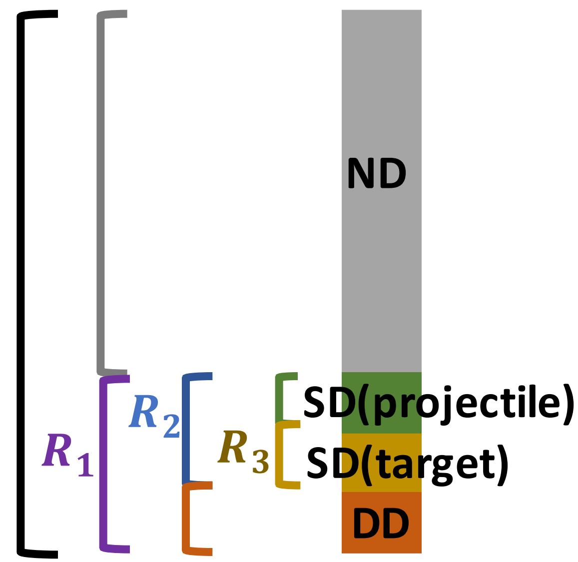


Image: CORSIKA web page

The effect of fraction

To estimate the effect of fractions of **each category**, I use three ratios of the fraction.

R_1=(# of diff.)/(# of all events)
R_2=(# of single-diff.)/(# of single- and double-diff.)
R_3=(# of target single-diff.)/(# of single-diff.)



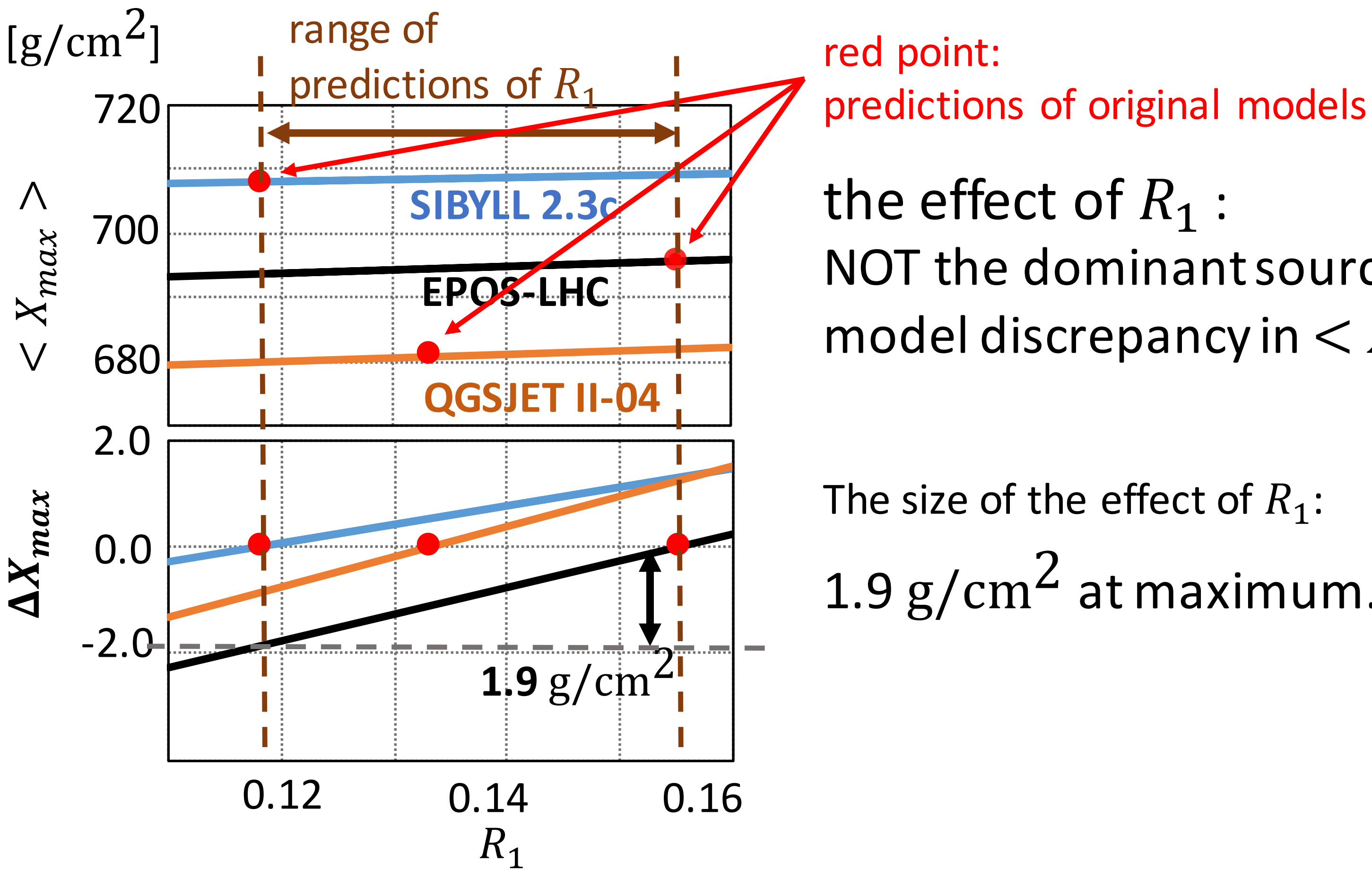
predictions of each ratio in models.

	SIBYLL 2.3c	QGSJET II-04	EPOS-LHC	range of predictions
R_1	**0.12**	**0.13**	**0.16**	**0.12 - 0.16**
R_2	**0.94**	**0.71**	**0.46**	**0.46 - 0.94**
R_3	**0.29**	**0.38**	**0.53**	**0.29 - 0.53**

Estimate the shift of $< X_{max}^{total} >$ when we change R_i artificially within the range of predictions

$$< X_{max}^{total} > = \sum_{i}^{i=ND,SD(target,projectile),DD} F^i(R_1,R_2,R_3) < X_{max}^i >$$

The effect of R_1



the effect of R_1 :
NOT the dominant source of model discrepancy in $< X_{max} >$

The size of the effect of R_1:

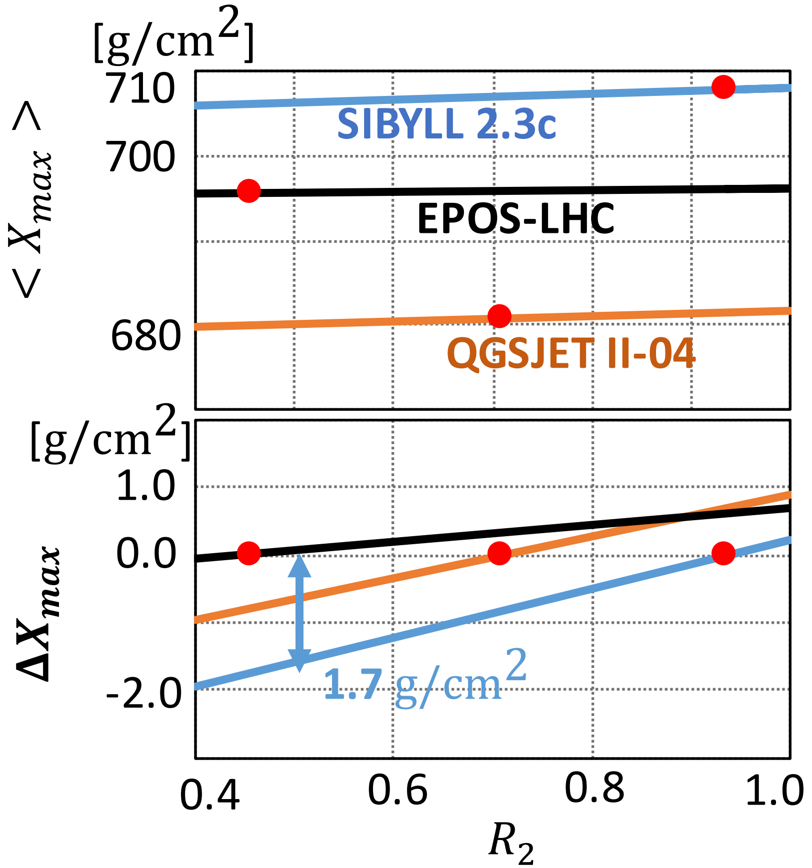
1.9 g/cm^2 at maximum.

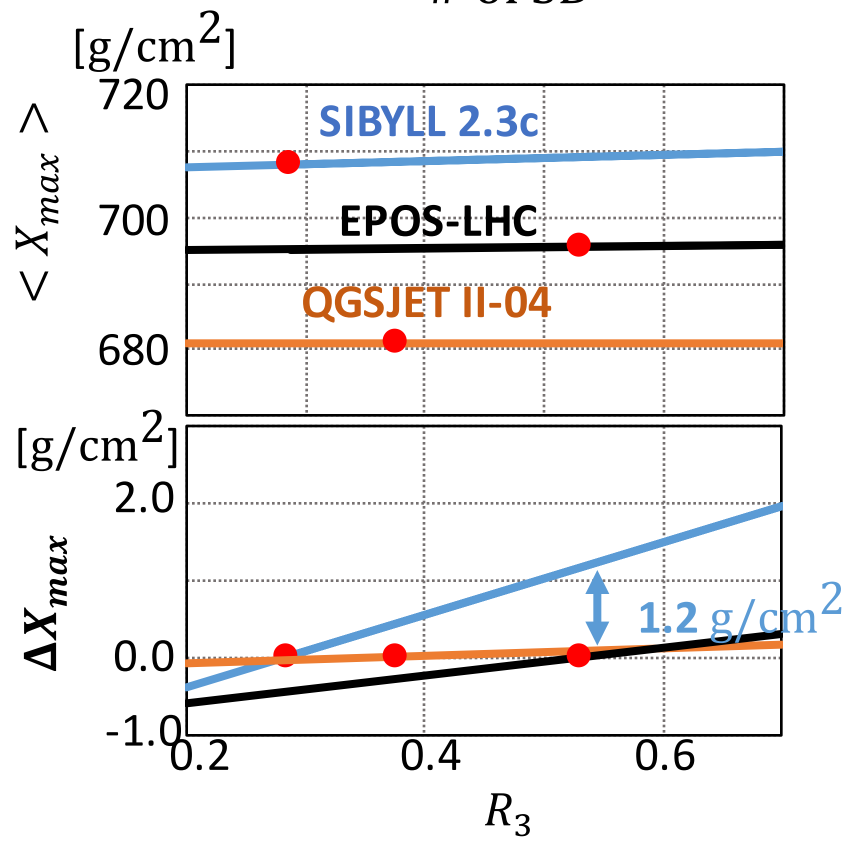
$$\Delta X_{max} = X_{max}^{modified} - X_{max}^{original}$$

The effect of R_2 and R_3

$$R_2 = \frac{\#\text{ of } SD}{\#\text{ of SD and DD}}$$

$$R_3 = \frac{\#\text{ of target SD}}{\#\text{ of SD}}$$





$$\Delta X_{max} = X_{max}^{modified} - X_{max}^{original}$$

red point: prediction of original model

The effect of fractions

If two or three ratios are changed…

	range of predictions	combination: X_{max} maximum	combination: X_{max} minimum
R_1	**0.12 – 0.16**	**0.16**	**0.12**
R_2	**0.46 – 0.94**	**0.94**	**0.46**
R_3	**0.29 – 0.53**	**0.53**	**0.29**

	combination: X_{max} maximum	combination: X_{max} minimum	**difference Δ**
SIBYLL 2.3c $[\mathrm{g/cm^2}]$	**710.8**	**706.2**	**4.6**
EPOS-LHC $[\mathrm{g/cm^2}]$	**683.1**	**679.3**	**3.8**
QGSJET II-04 $[\mathrm{g/cm^2}]$	**696.2**	**693.4**	**2.8**

current model discrepancy in $< X_{max} >$ predictions :

27.1 $\mathbf{g/cm^2}$ (COSMOS 8.035, 10^{17} eV proton primary)

uncertainty caused by the fraction is **4.6 $\mathbf{g/cm^2}$** at max.

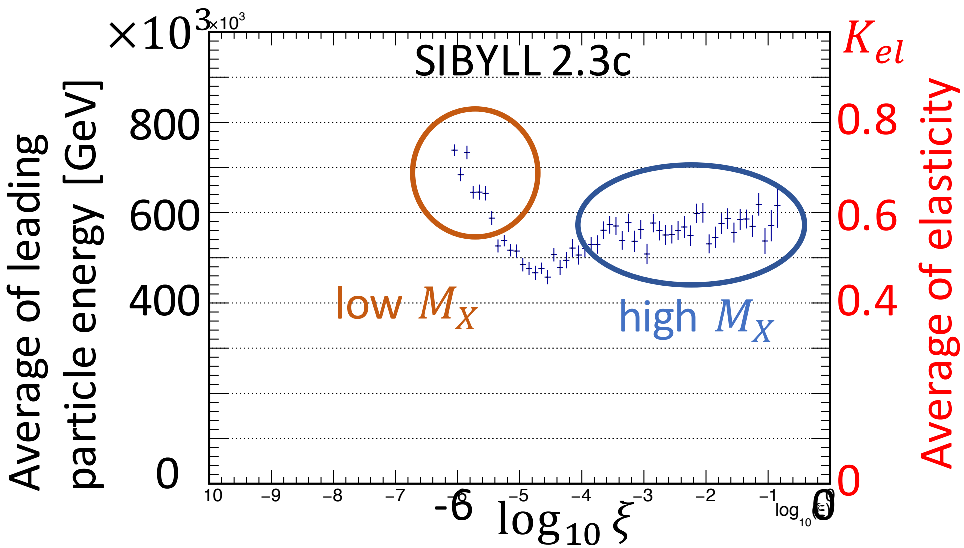
(17 % of current model discrepancy in $< X_{max} >$)

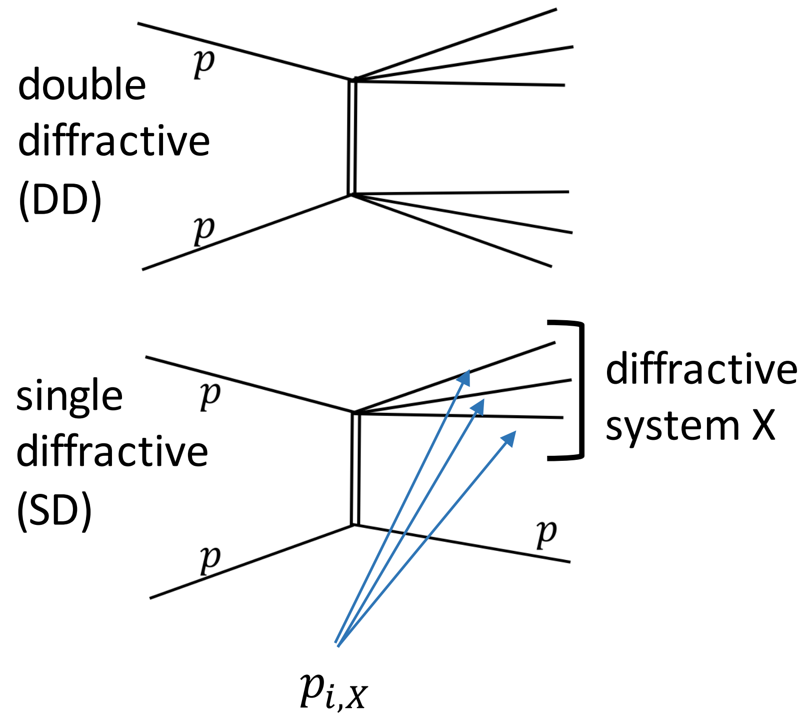
diffractive mass dependency of $< X_{max} >$ of projectile SD

diffractive mass

$$M_X^2 = \left(\sum_i p_{i,X}\right)^2$$

low M_X -> high elasticity
high M_X -> low elasticity





$$\log\left(\frac{M_X^2}{s}\right) = \log(\xi)$$

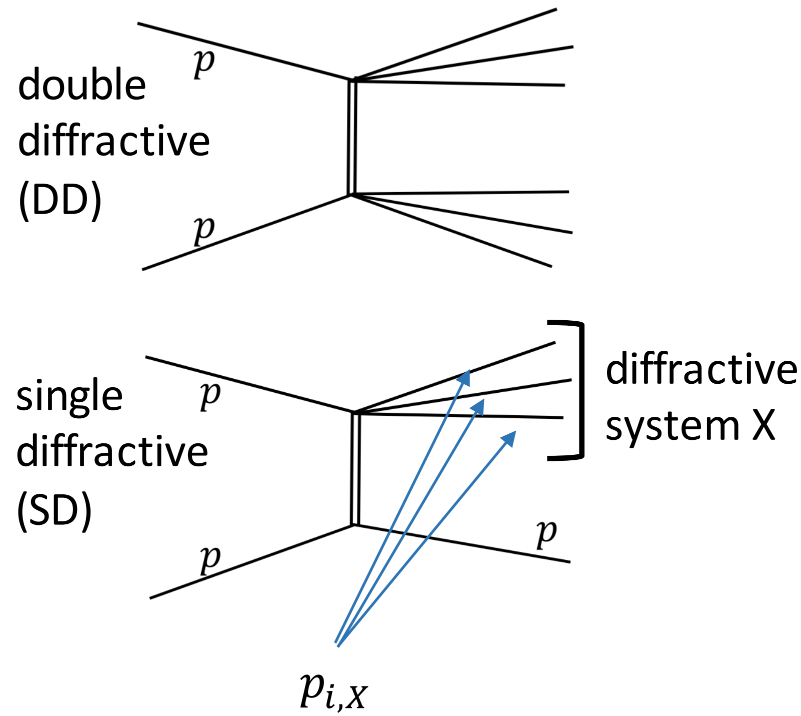
s: center of mass energy

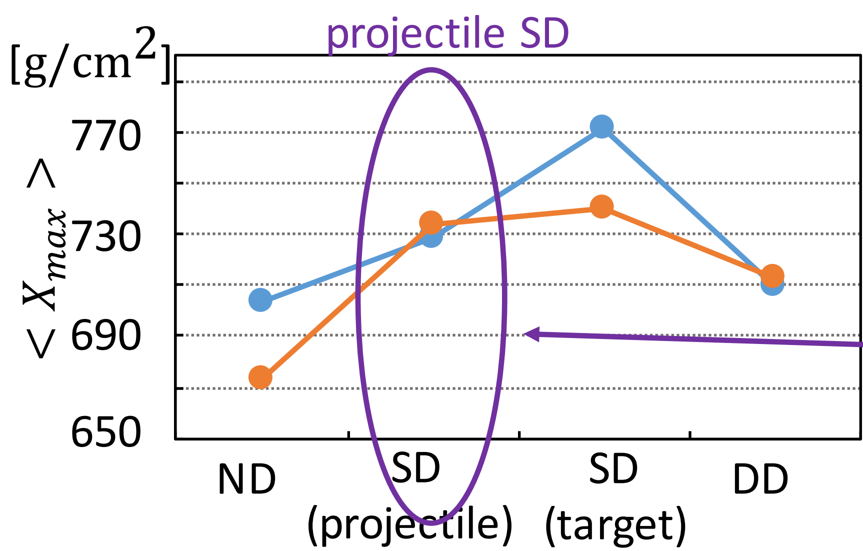
diffractive mass dependency of $< X_{max} >$ of projectile SD

diffractive mass

$$M_X^2 = \left(\sum_i p_{i,X} \right)^2$$

low M_X -> high elasticity
high M_X -> low elasticity



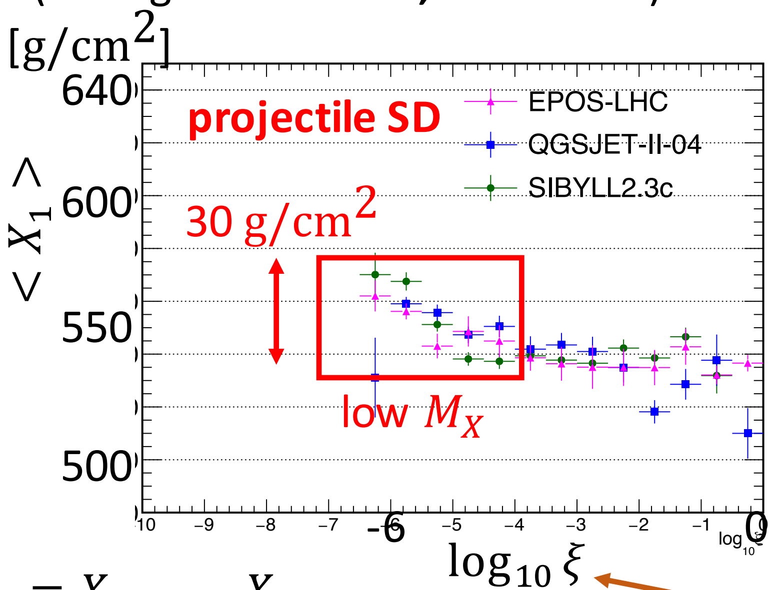


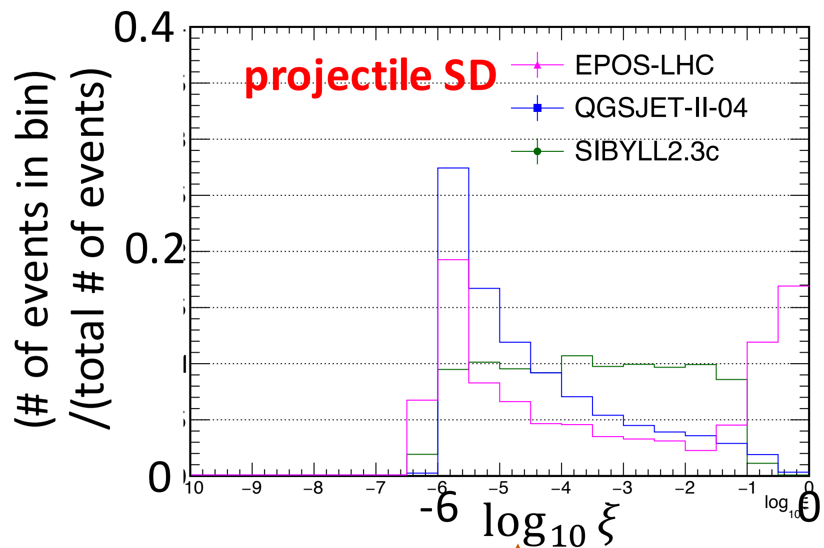
check the diffractive mass dependency of projectile SD

diffractive mass dependency of $< X_{max} >$ of projectile SD

$\mathbf{10^{15}}$ **eV** proton primary, COSMOS 8.035
(total generated: **50,000 events**)

select projectile SD by collision type of the first interaction





$X_1 = X_{max} - X_0$,
X_0: the depth of the first interaction

diffractive mass of the first interaction

Diff. mass dependency of X_1 are same among the models.
Large model discrepancies can be seen in the diff. mass spectrum.

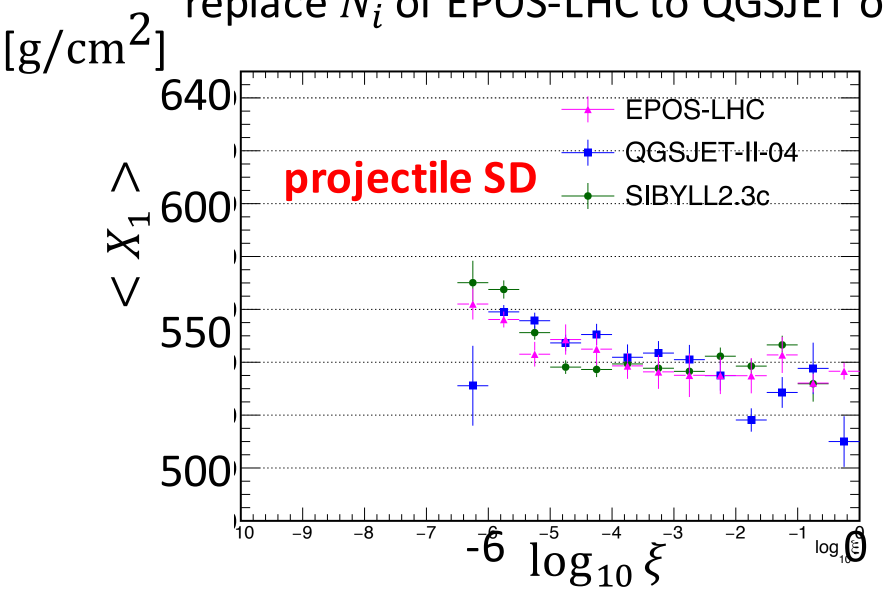
the effect of diffractive mass

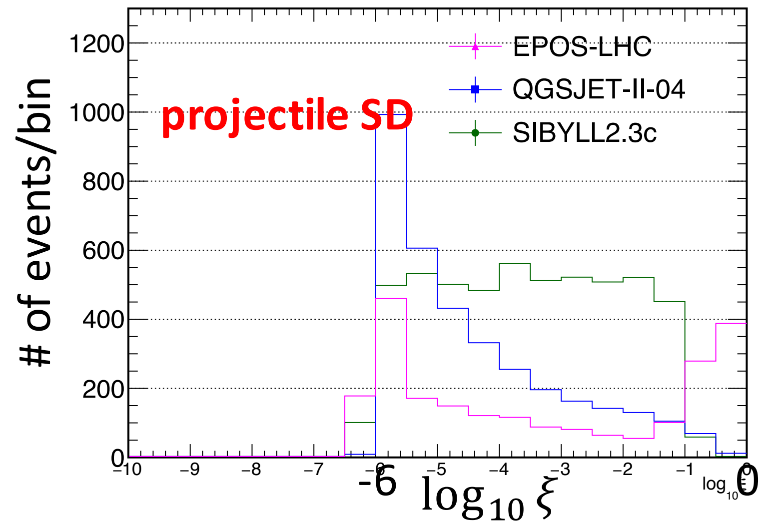
$$< X_{max}^{projectile\ SD} > = < X_0 > + \frac{\sum N_i * C_i}{\sum N_i}$$

N_i: # of events of i-th bin in diff. mass spectrum
C_i : factor of i-th bin in $\log_{10}\xi - X_1$ plot

replace N_i of EPOS-LHC to QGSJET or SIBYLL

10^{15} eV proton primary, COSMOS 8.035





$< X_0 >$ and C_i: use original predictions in EPOS-LHC

diff. mass spectrum **projectile SD**	EPOS-LHC	QGSJET II-04	SIBYLL 2.3c	prediction by EPOS-LHC
$< X_{max}^{pSD} >$ [g/cm^2]	611.0	614.0	609.4	**611.1**

4.6 g/cm^2

fraction of projectile SD: 8% at max. ➡ the effect to total X_{max}: < 0.5 g/cm^2

summary

- The effect of diffractive collisions on air shower developments are estimated quantitatively.
- Simulated events are categorized by collision type at **<u>the first interaction</u>**.
- The effect of fraction is estimated by using ratios of the fraction of each category, and uncertainty caused by fraction is 4.6 $\mathrm{g/cm^2}$ at max.
- The effect of diffractive mass spectrum is 4.6 $\mathrm{g/cm^2}$ for projectile Single-diff.

backup

the effect of diffractive mass

$$< X_{max}^{projectile\ SD} > = < X_0 > + \frac{\sum N_i * C_i}{\sum N_i}$$

N_i: # of events of i-th bin in diff. mass spectrum
C_i : factor of i-th bin in $\log_{10}\xi - X_1$ plot

replace N_i (diff. mass spectrum)

$< X_0 >$ and C_i are same as predictions by EPOS-LHC

diff. mass spectrum	EPOS-LHC	QGSJET II-04	SIBYLL 2.3c
$< X_{max}^{pSD} >$ $[\mathrm{g/cm^2}]$	611.0	614.0	609.4

$4.6\ \mathrm{g/cm^2}$

$< X_0 >$ and C_i are same as predictions by QGSJET II-04

$-6\ \mathrm{g/cm^2}$

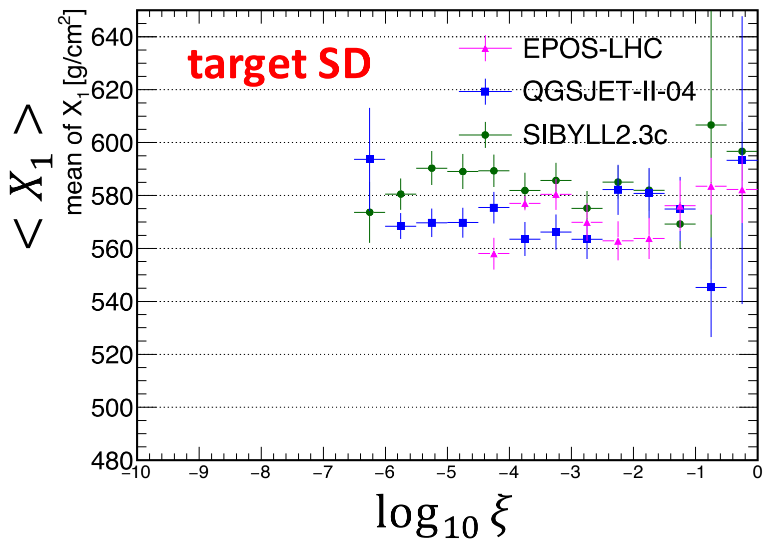
diff. mass spectrum	EPOS-LHC	QGSJET II-04	SIBYLL 2.3c
$< X_{max}^{pSD} >$ $[\mathrm{g/cm^2}]$	605.2	613.0	603.0

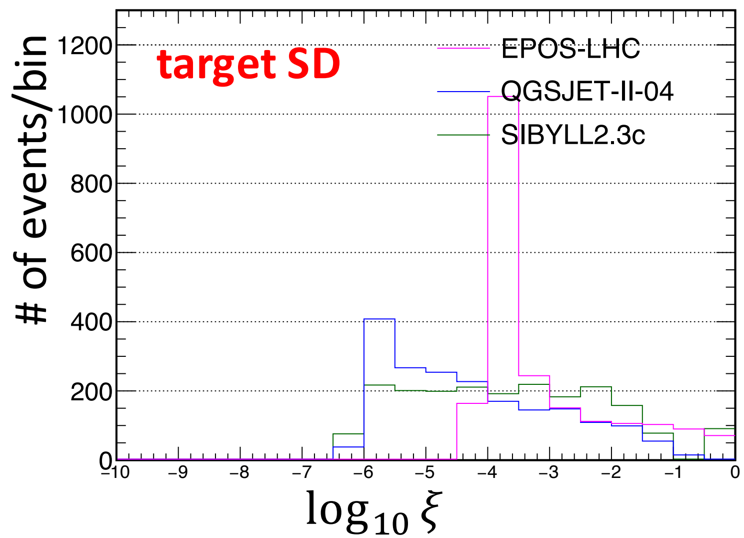
$10.0\ \mathrm{g/cm^2}$

$< X_{max}^{pSD} >$	prediction by EPOS-LHC	prediction by QGSJET II-04
$[\mathrm{g/cm^2}]$	**611.1**	**612.4**

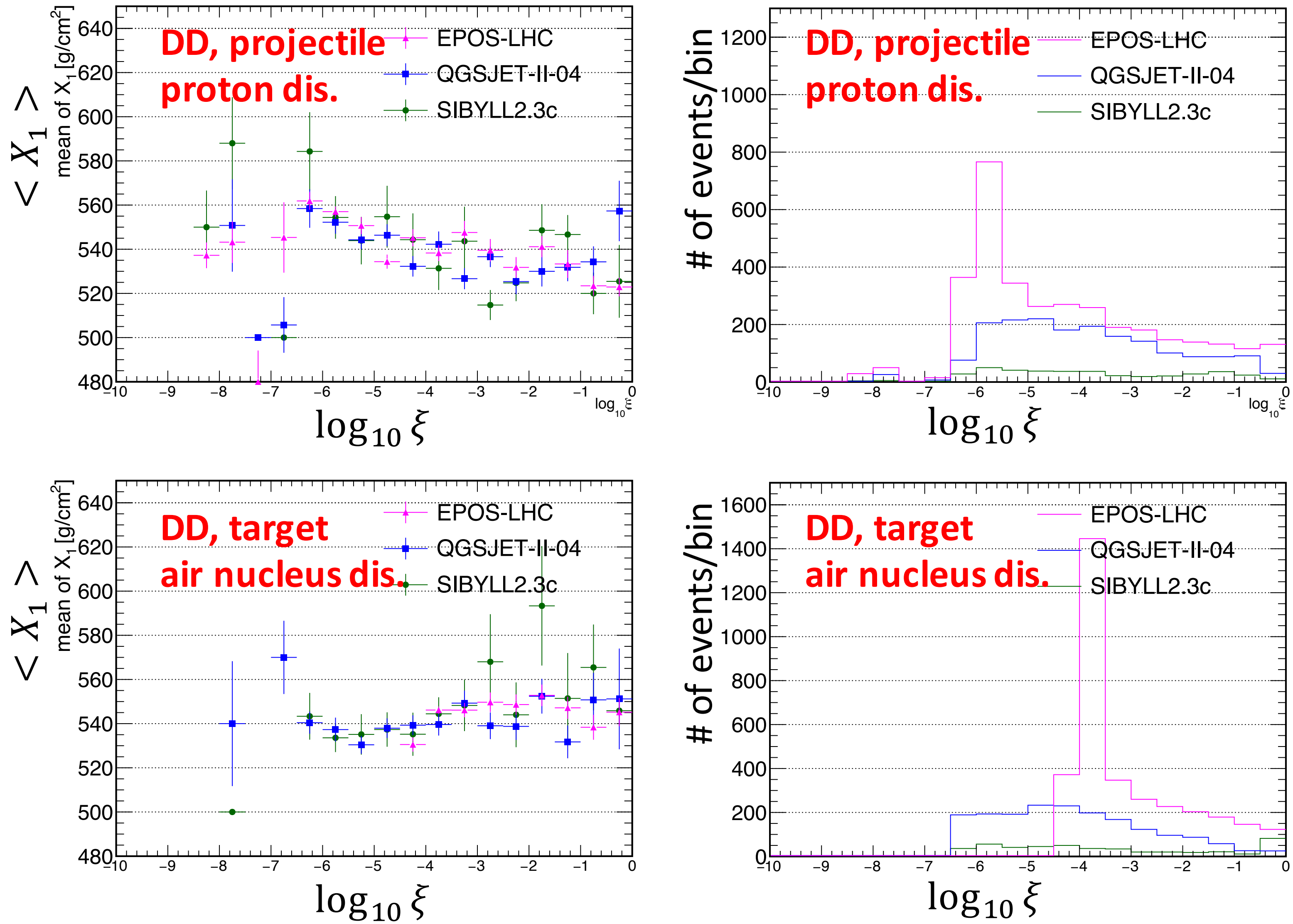
diffractive mass spectrum of target SD

diffractive mass





Double-diff.



DD, projectile
proton dis.
EPOS-LHC
QGSJET-II-04
SIBYLL2.3c
mean of X1 [g/cm2]
< X1 >
log10 ξ
# of events/bin
DD, target
air nucleus dis.