A simulation study of the effects of diffractive collisions on observables of air showers experiments

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Ken Ohashi - CORSIKA workshop 2020 (virtual)

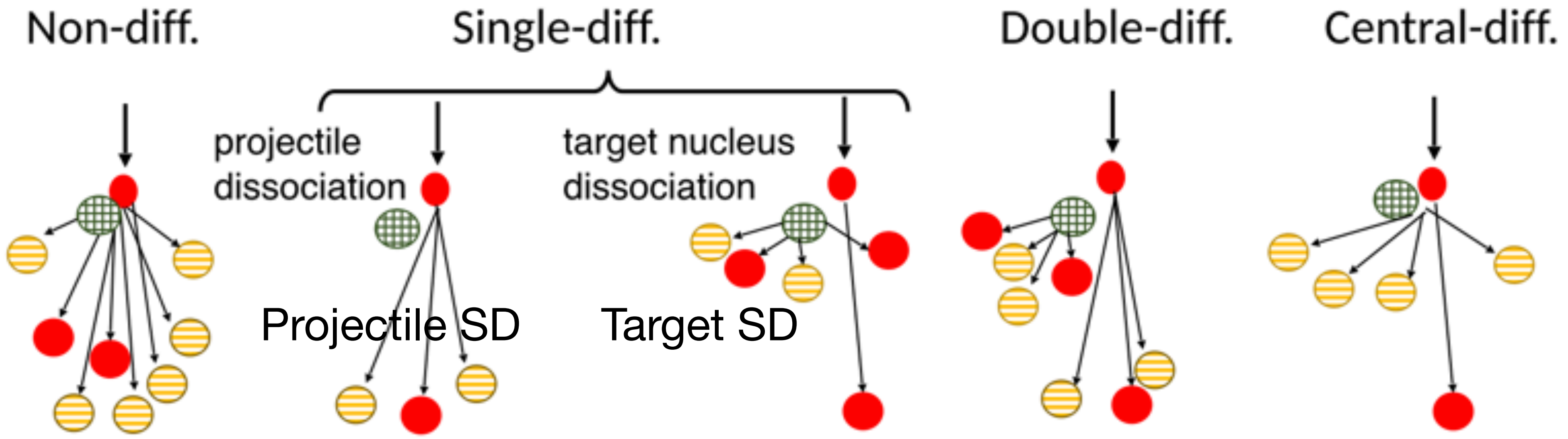
The paper of this study have uploaded on arXiv: 2005.12594

Diffractive collision

One of collision types of inelastic collisions

Elasticity of diffractive collision is higher than other collision types.

Schematic view of the diffractive collision :



elasticity: K_{el} ~ 0.39 | K_{el} ~ 0.56 | K_{el} ~ 1 | K_{el} ~ 0.52 | K_{el} ~ 1

SIBYLL 2.3c

10^{17} eV proton

High elasticity | Intact proton | High elasticity | Intact proton

Differences between Non-diff. and diffractive

Differences in diffractive collisions

Differences between interaction models

- Cross-sections of each type
- Modeling of diffractive dissociation (mainly affect for pSD and DD cases)

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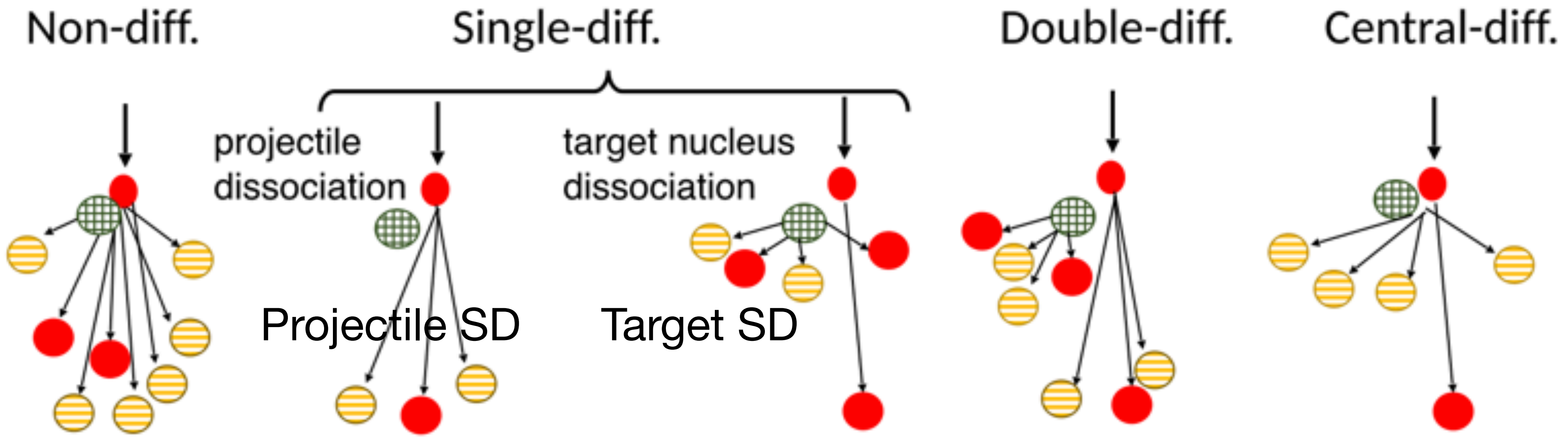

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Differences between interaction models

- Cross-sections of each type
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<u>Large model differences:</u>

Fraction of diffractive collisions in inelastic collisions

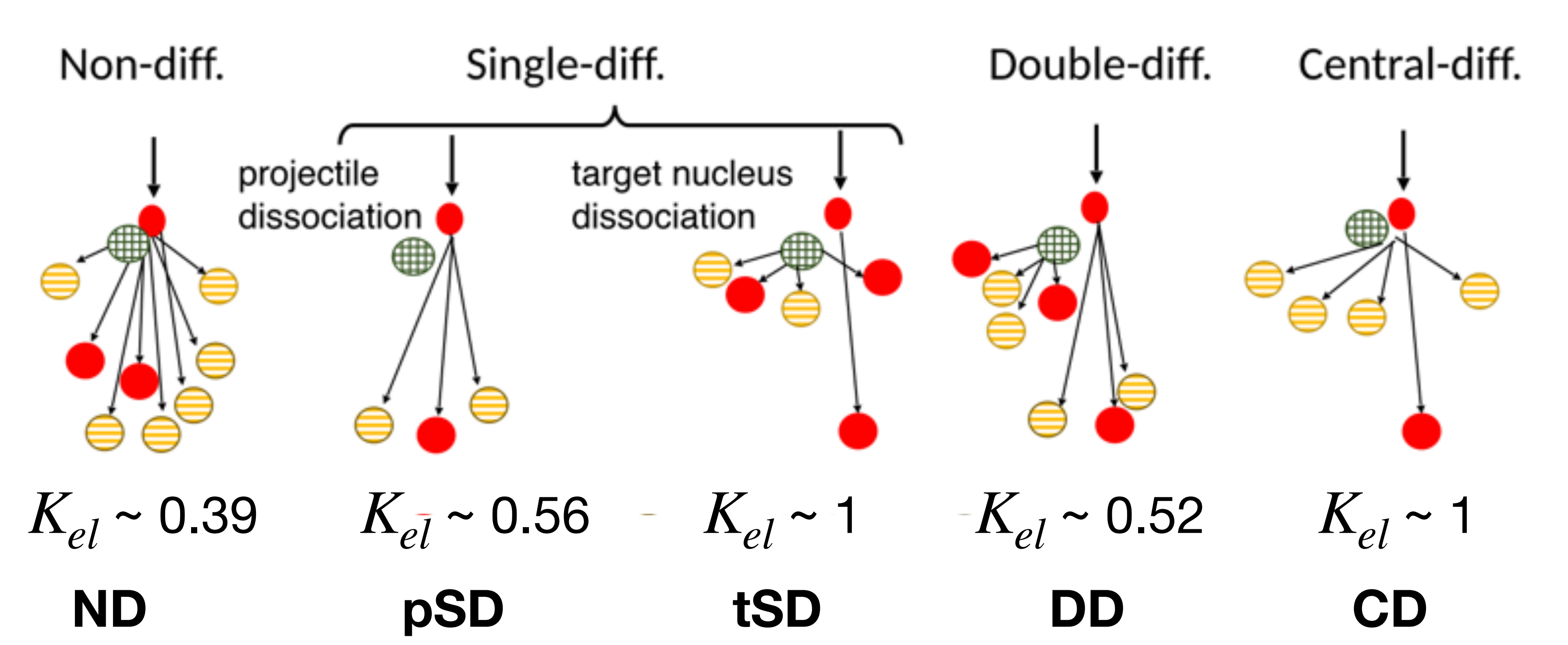
0.07 for SIBYLL 2.3c

0.18 for EPOS-LHC

10^{19} eV proton primary

→ **one of the source of uncertainty in air shower simulations**

Diffractive collision



<u>Three differences:</u>

1. **Difference between Non-diffractive and diffractive collisions**
2. **Difference between collision types in diffractive collisions**
3. **Difference between models**

Differences between interaction models

- Cross-sections of each type
- Modeling of diffractive dissociation (mainly affect for pSD and DD cases)

Modeling of diffractive dissociation can change the elasticity for pSD and DD cases, while they does not change the elasticity for tSD and CD cases.

<u>How these differences affect air showers?</u>

simulation: CONEX 6.40, 40,000 events

Primary particle is proton.

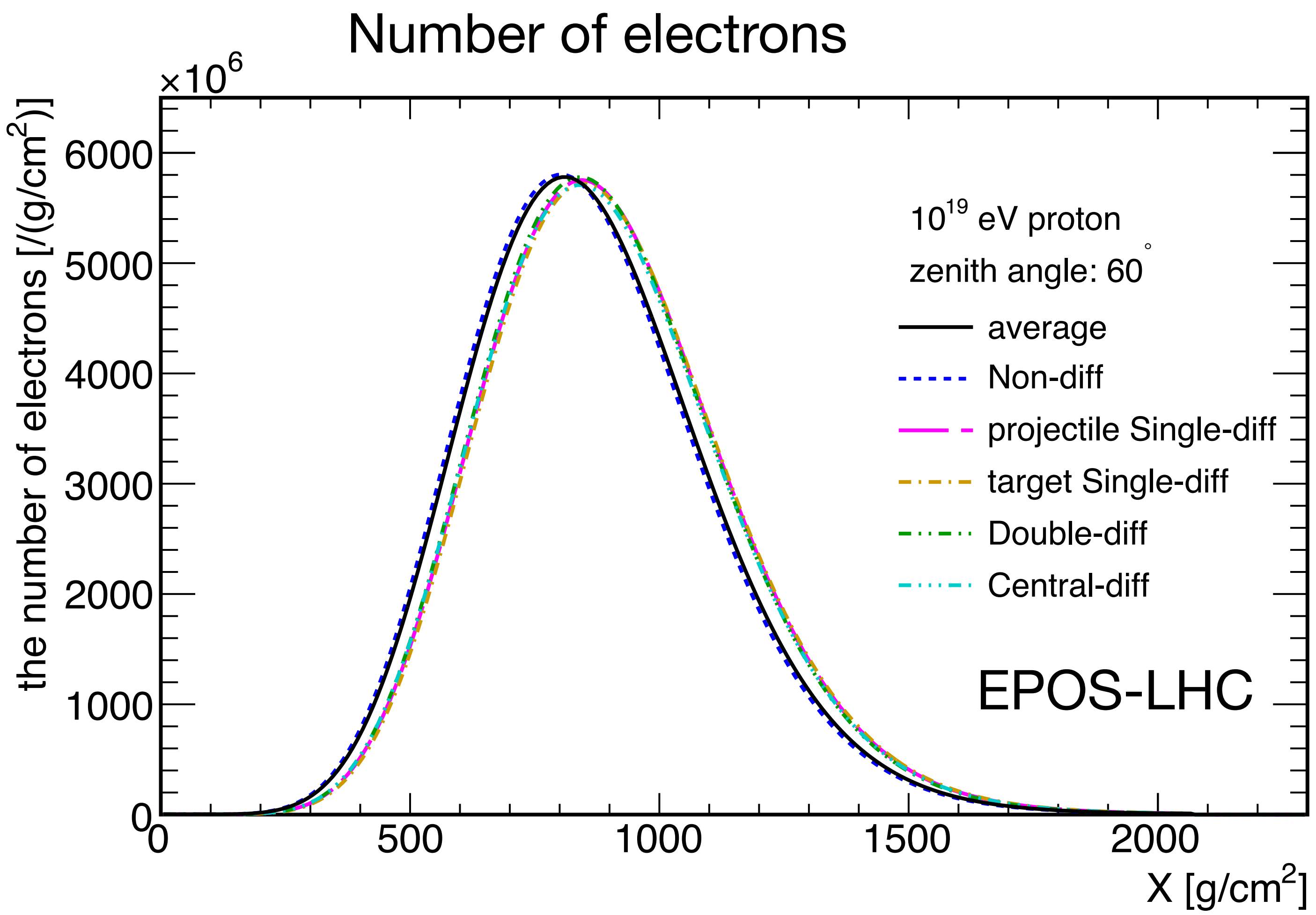
Modify outputs:

1. **Collision type information**
2. **Diffractive mass (important parameter of diffractive dissociation)**

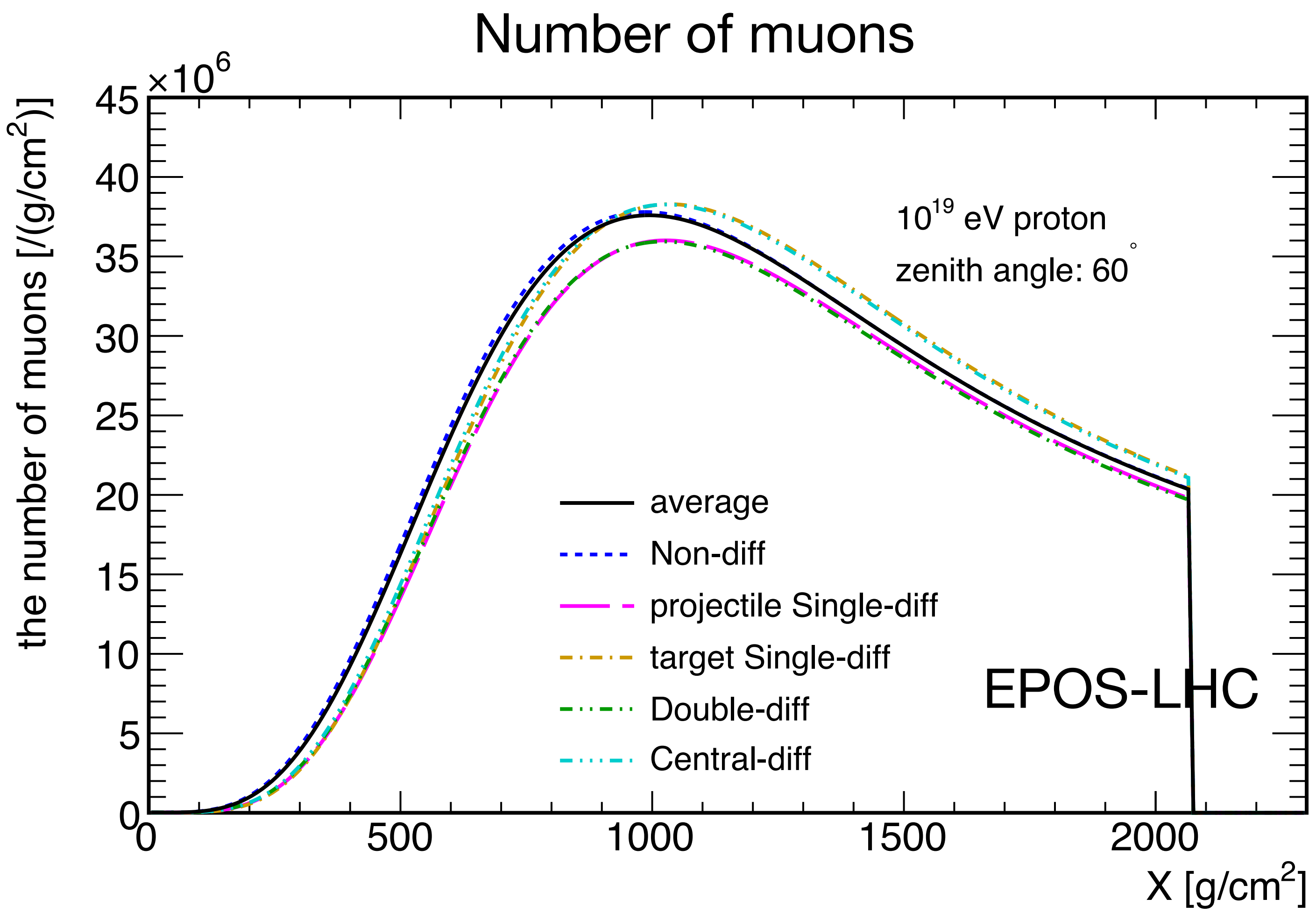
Focus on the first interaction for simplicity in this presentation

Effects of collision types on air shower profiles

Using the collision type at the first interaction



If the first interaction is the diffractive collision, Air shower developments are deeper.

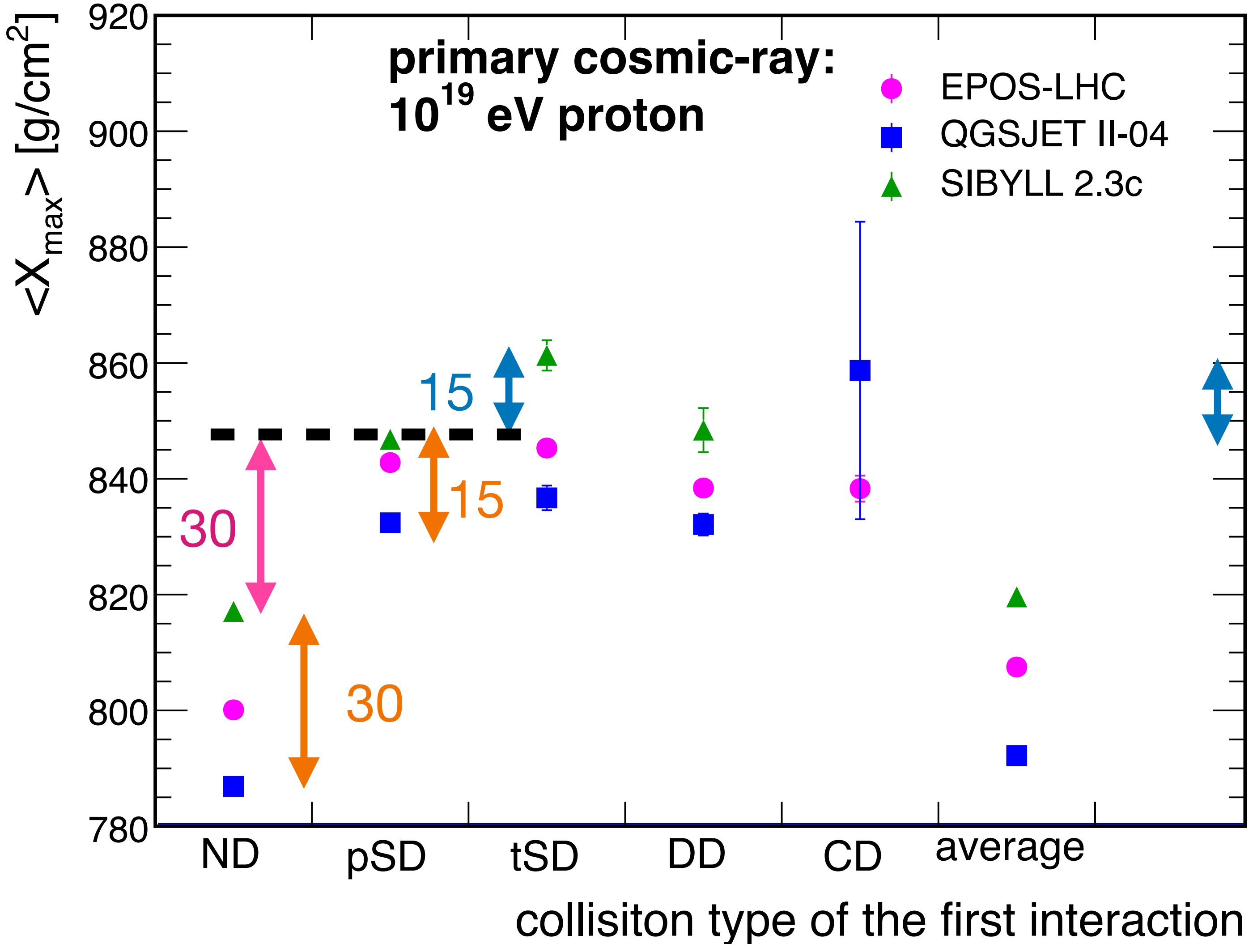


pSD and DD: number of muons are decreased.

tSD and CD: number of muons are larger for deeper part.

Effects of collision types on $\langle X_{\rm max} \rangle$

Using the collision type at the first interaction



$\langle X_{\rm max} \rangle$

Differences between ND and pSD are 30-40 $\rm g/cm^2$.

Differences in diffractive collisions is 15 $\rm g/cm^2$ for SIBYLL 2.3c case and very small for EPOS-LHC and QGSJET II-04 cases.

Size of differences between models depend on the collision type.

Large differences in $\langle X_{\rm max} \rangle$ between ND and diffractive collisions

=> differences in cross-section fractions between models affect $\langle X_{\rm max} \rangle$

Differences between models depend on the collision type

=> modeling of diffractive dissociation affect $\langle X_{\rm max} \rangle$

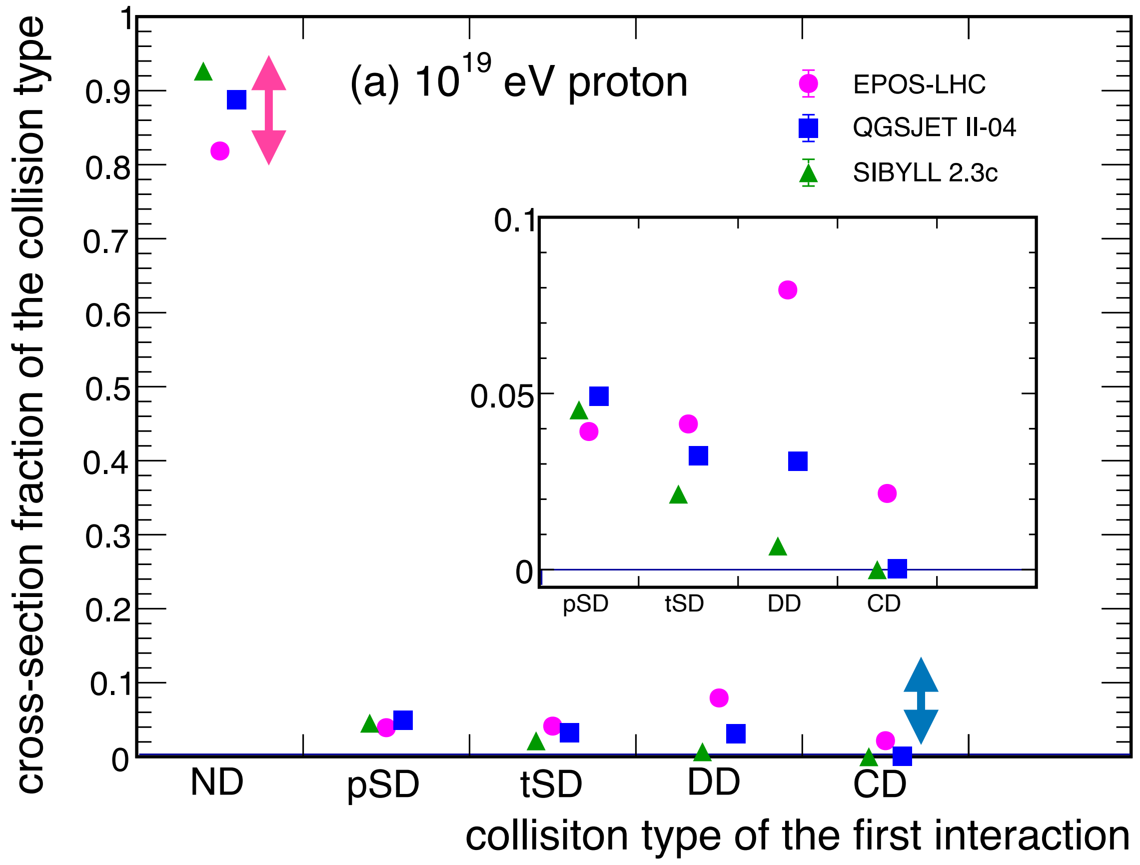
Effects of differences between models

Differences in cross-sections

Cross-sections

Total inelastic cross-sections
(not discussed in this presentation)

Cross-section fractions



Differences in modeling of diffractive dissociation

Differential cross-section of diffractive mass (diffractive mass spectrum)

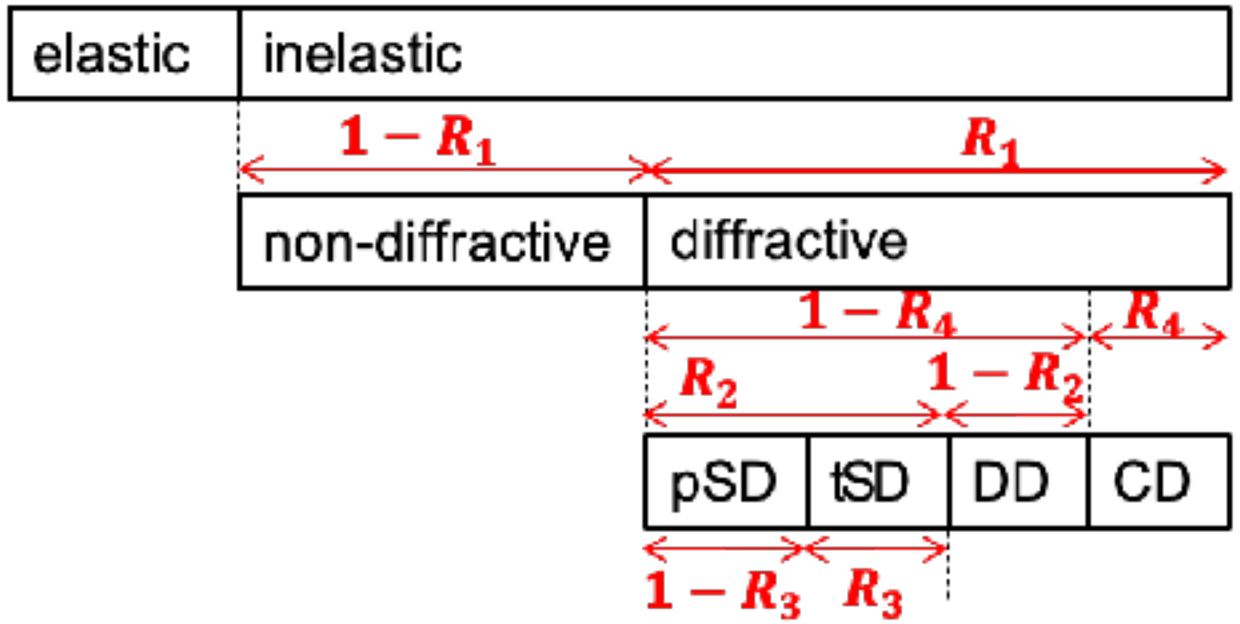
Diffractive mass dependent particle productions

How these differences affect air shower simulation?

Effects of cross-section fractions

Cross-section Fractions

To understand the effects of differences in cross-section fractions between models, Calculate $\langle X_{\mathrm{max}} \rangle$ for each collision type at the first interaction and change weight of cross-section fractions artificially.



$$\langle X_{max}^{modified} \rangle = \sum f^i \langle X_{max}^i \rangle$$

<u>Predictions of ratios by 3 interaction models</u>

Ratio	Minimum	Maximum
R_1	0.07	0.18
R_2	0.50	0.91
R_3	0.32	0.51

Use as uncertainty in ratios:

R_1: 0.07 - 0.18

R_2: 0.50 - 0.91

R_3: 0.32 - 0.51

Effects of cross-section fractions

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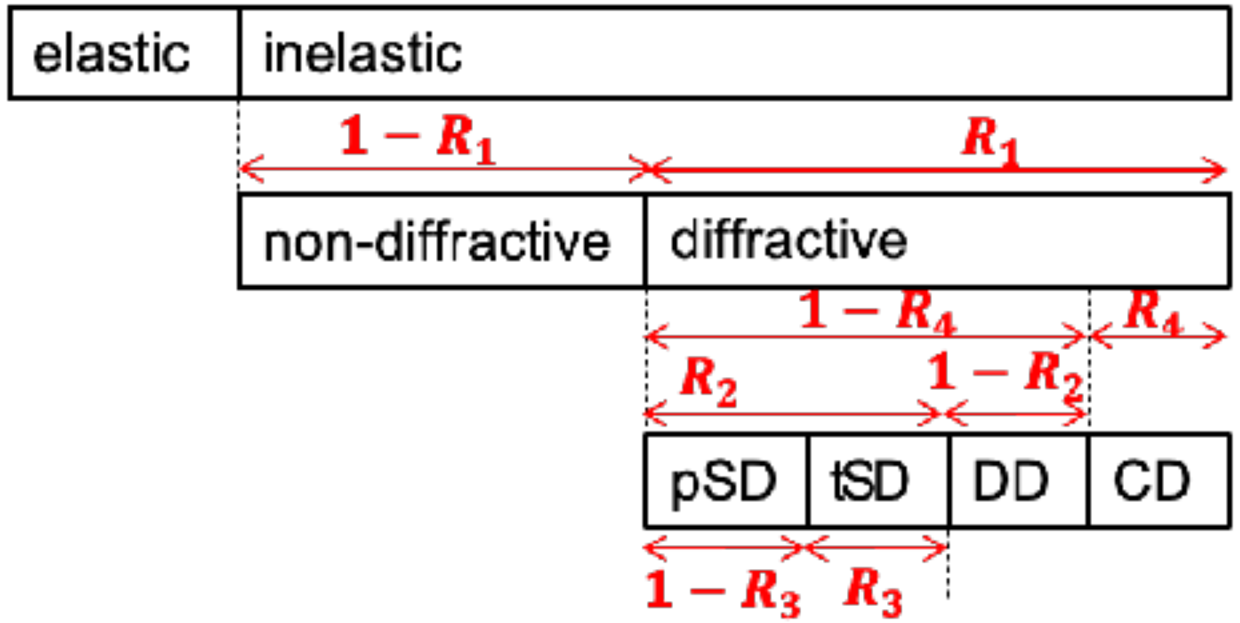

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Predictions of ratios by 3 interaction models

Ratio	Minimum	Maximum
R_1	0.07	0.18
R_2	0.50	0.91
R_3	0.32	0.51

uncertainty in ratios:	Difference of $\langle X_{\max}^{modified} \rangle$ between maximum R_i and minimum R_i
R_1: 0.07 - 0.18	**4.4** $\mathrm{g/cm^2}$
R_2: 0.50 - 0.91	**0.4** $\mathrm{g/cm^2}$
R_3: 0.32 - 0.51	**Less than 0.1** $\mathrm{g/cm^2}$

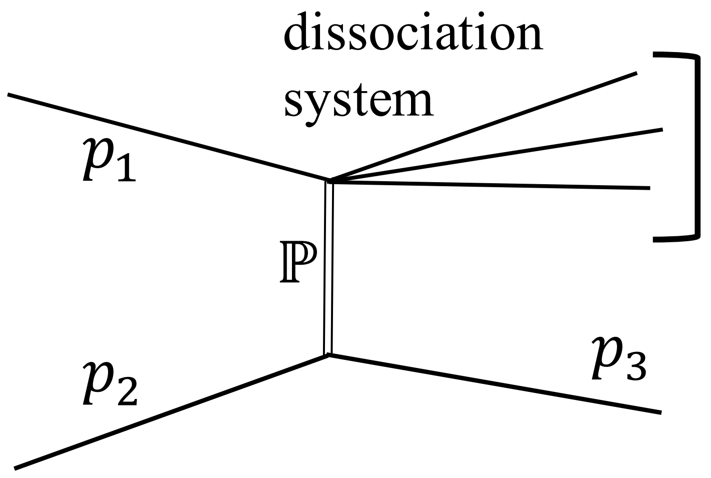
Statistical error: $\pm 0.4\ \mathrm{g/cm^2}$

For EPOS-LHC case

Differences between Non-diff and diffractive show large effects, while differences in diffractive collision show small effects.

Effects of diffractive mass

Diffractive mass



Diffractive mass:
Invariant mass of
Dissociation system M_X

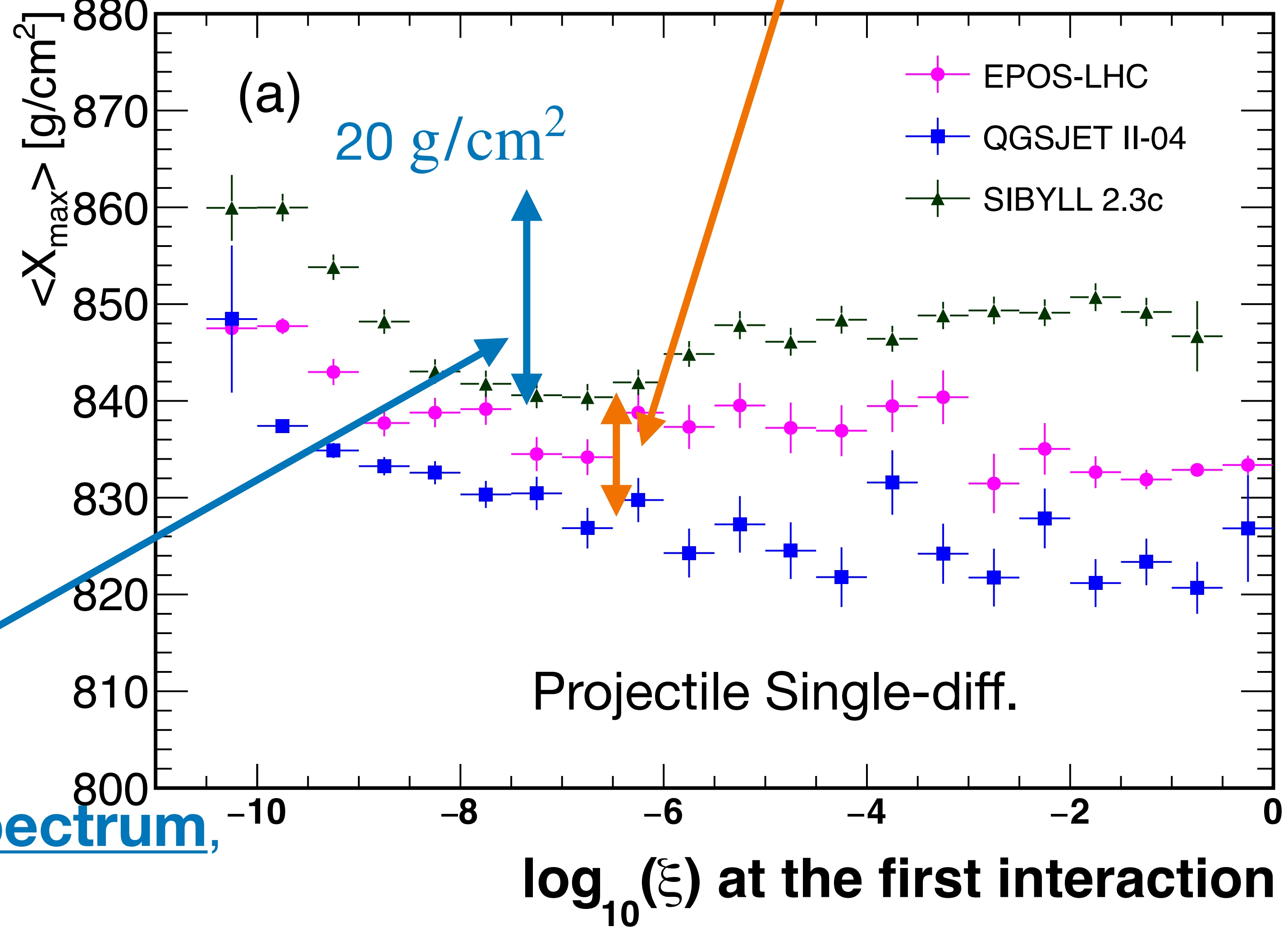
Important parameter in modeling of diffractive dissociation

Low M_X -> higher elasticity

High M_X -> lower elasticity

$\log_{10}(\xi) = \log_{10}(M_X^2/s)$,
$\sqrt{s}$: center of mass energy

Due to differences in modeling of particle productions and secondary interactions.



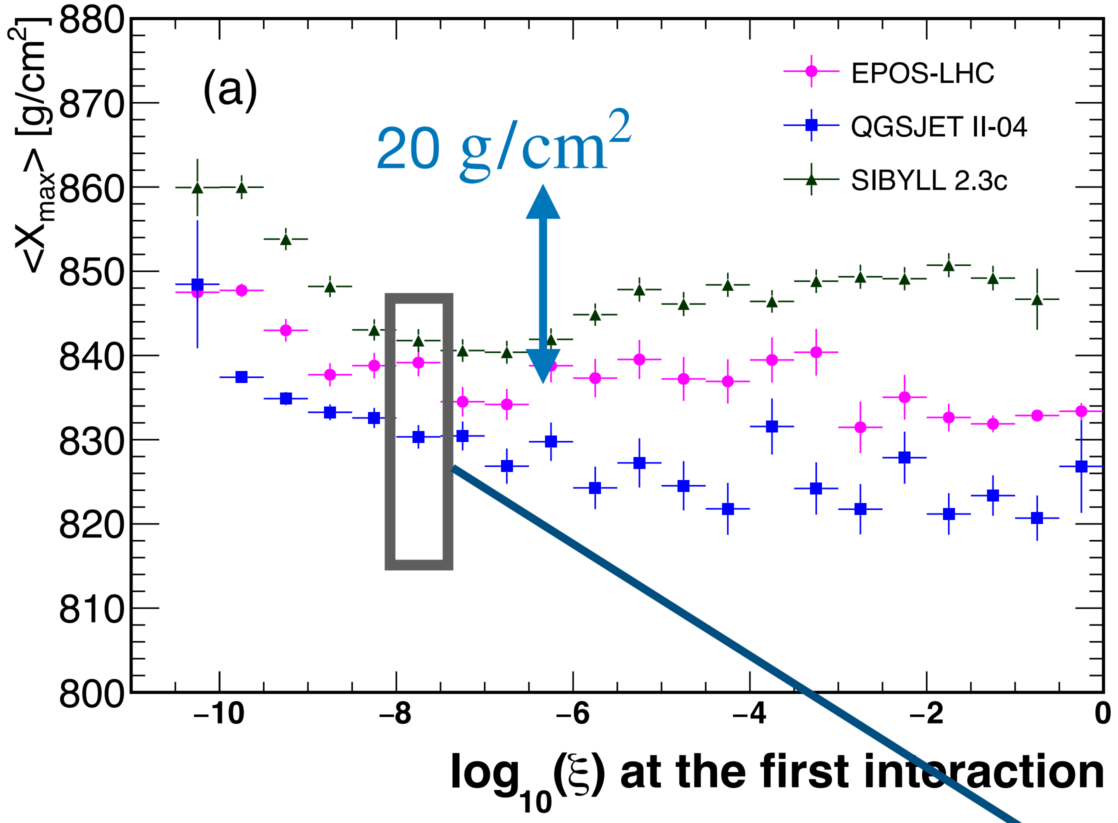
If we assume an extreme diffractive mass spectrum,
size of effects for pSD is 20 $\mathrm{g/cm^2}$.

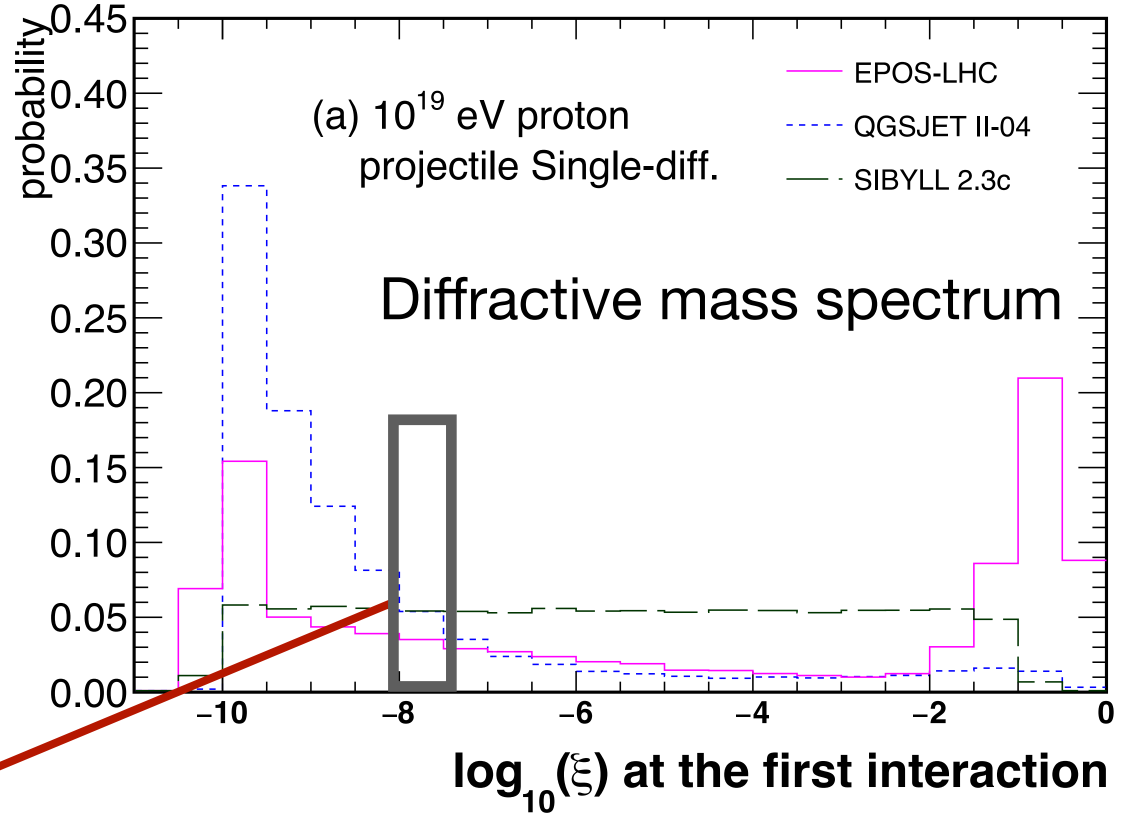
Projectile particles dissociate only for pSD and DD (~10% in total)

-> **effects of an extreme diffractive mass spectrum on $\langle X_{max}\rangle$ is 2 $\mathrm{g/cm^2}$ at max. (at first interaction)**

Effects of uncertainty in diffractive mass

Effects of differences in diffractive mass spectrum





Projectile particles dissociate only for pSD and DD (~10% in total)

$$\langle X_{max}^{modified} \rangle = \sum P^i(M_X)\ \langle X_{max}^i \rangle$$

Use predictions of $\langle X_{max}^i \rangle$ by EPOS-LHC and change weight $P^i(M_X)$ by other model

EPOS-LHC original : $838.0 \pm 0.3\ \mathrm{g/cm^2}$

Using QGSJET weight : $841.7 \pm 0.5\ \mathrm{g/cm^2}$

Using SIBYLL weight : $837.6 \pm 0.5\ \mathrm{g/cm^2}$

Difference $4.1\ \mathrm{g/cm^2}$

effects of uncertainty diffractive mass spectrum on $\langle X_{\mathrm{max}} \rangle$ is ~0.4 $\mathrm{g/cm^2}$ at first interaction.

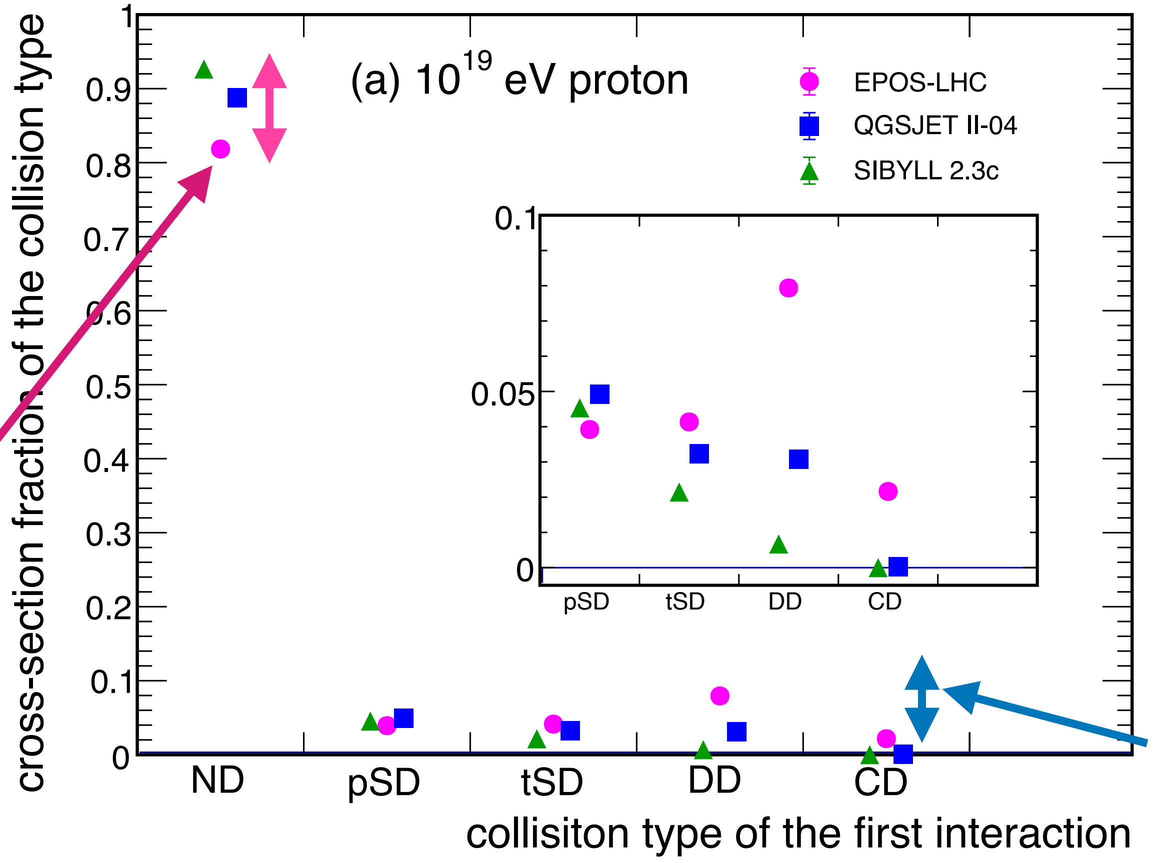
Effects of differences between models

Differences in cross-sections

Cross-sections → Cross-section fractions

↓

Total inelastic cross-sections
(not discussed in this presentation)



At the first interaction:
4.4 $\mathrm{g/cm^2}$ on $\langle X_{max} \rangle$

At the first interaction:
0.4 $\mathrm{g/cm^2}$ on $\langle X_{max} \rangle$

Differences in modeling of diffractive dissociation

- **Differential cross-section of diffractive mass (diffractive mass spectrum)**
  At the first interaction:
  0.4 $\mathrm{g/cm^2}$ on $\langle X_{max} \rangle$
- **Diffractive mass dependent particle productions**

Differences in cross-section fractions between ND and diffractive collisions show large effects while differences in diffractive collisions show smaller effects at the first interaction.

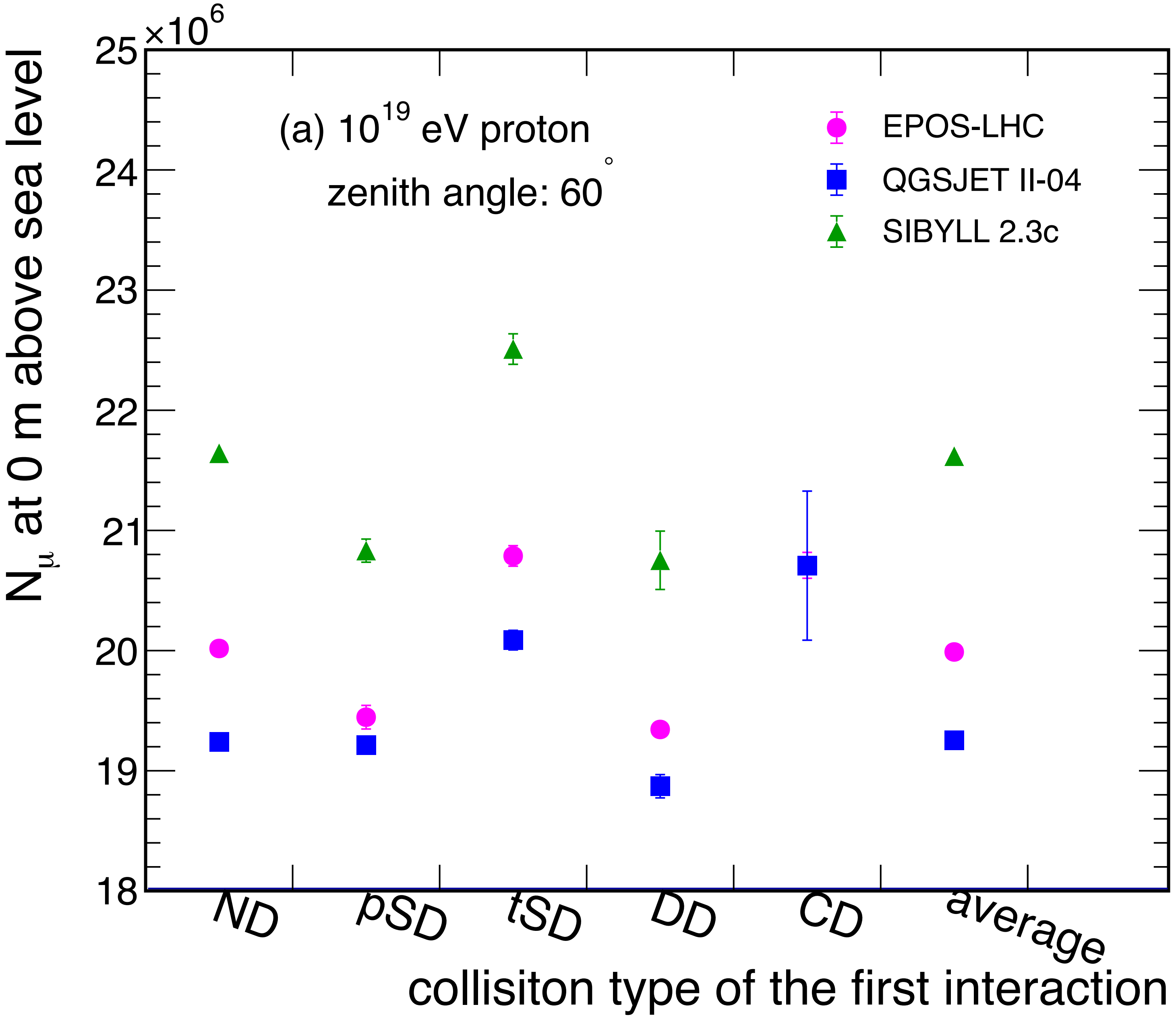
Summary

- Diffractive collision is one of the source of uncertainty in air shower simulations.
- Diffractive collisions show larger elasticity than others, and there are large differences in elasticity between collision types in diffractive collisions.
- To understand the effects of uncertainty of diffractive collisions between models, we estimate the effects of uncertainty at the first interactions.
- Differences in cross-section fractions between ND and diffractive collisions show large effects on $\langle X_{max} \rangle$ while differences in diffractive collisions show smaller effects at the first interaction.
- We have uploaded the paper on arXiv. [arXiv: 2005.12594]
  - including discussion about effects on $\langle X^{\mu}_{max} \rangle$ and N_{μ}.
  - Not only at the first interaction, but also effects for whole air shower are discussed.

Backup

Effects of collision types (N_μ)

Using the collision type at the first interaction



$\langle X_{\max} \rangle$

Differences between ND and pSD are 20-30 $\mathrm{g/cm^2}$.

Differences in diffractive collisions are 20 $\mathrm{g/cm^2}$ for 10^{17} eV proton primary cases while 10 $\mathrm{g/cm^2}$ for 10^{19} eV cases.

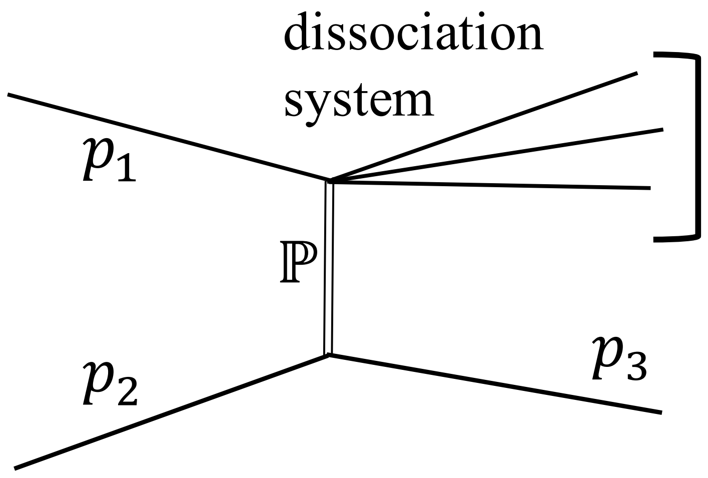
N_μ

Differences between ND and tSD (CD) are ~2%.

Differences between ND and pSD (DD) depend on model, ~2% for SIBYLL 2.3c and very small difference for QGSJET II-04

Effects of differences between models (N_μ)

Diffractive mass



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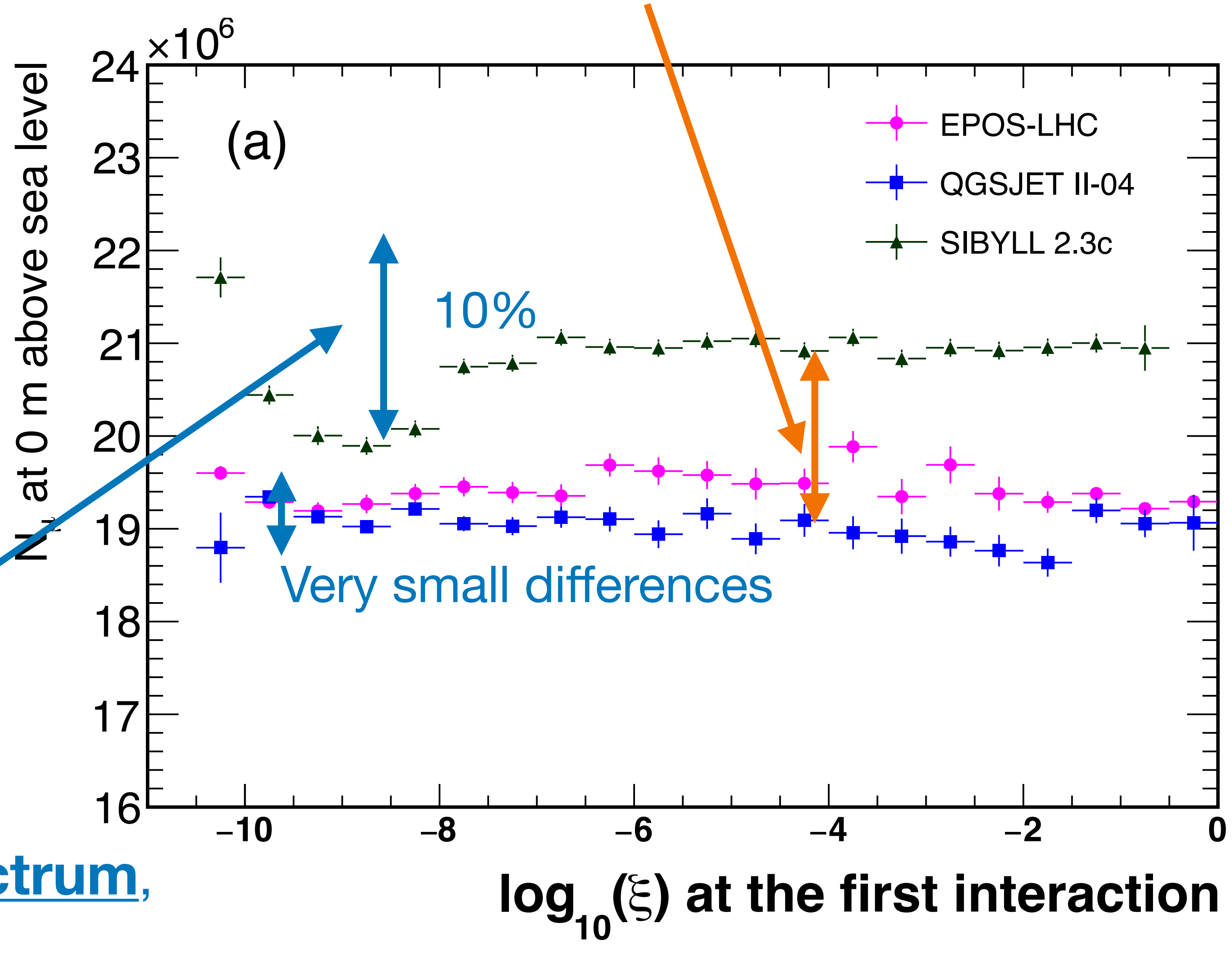
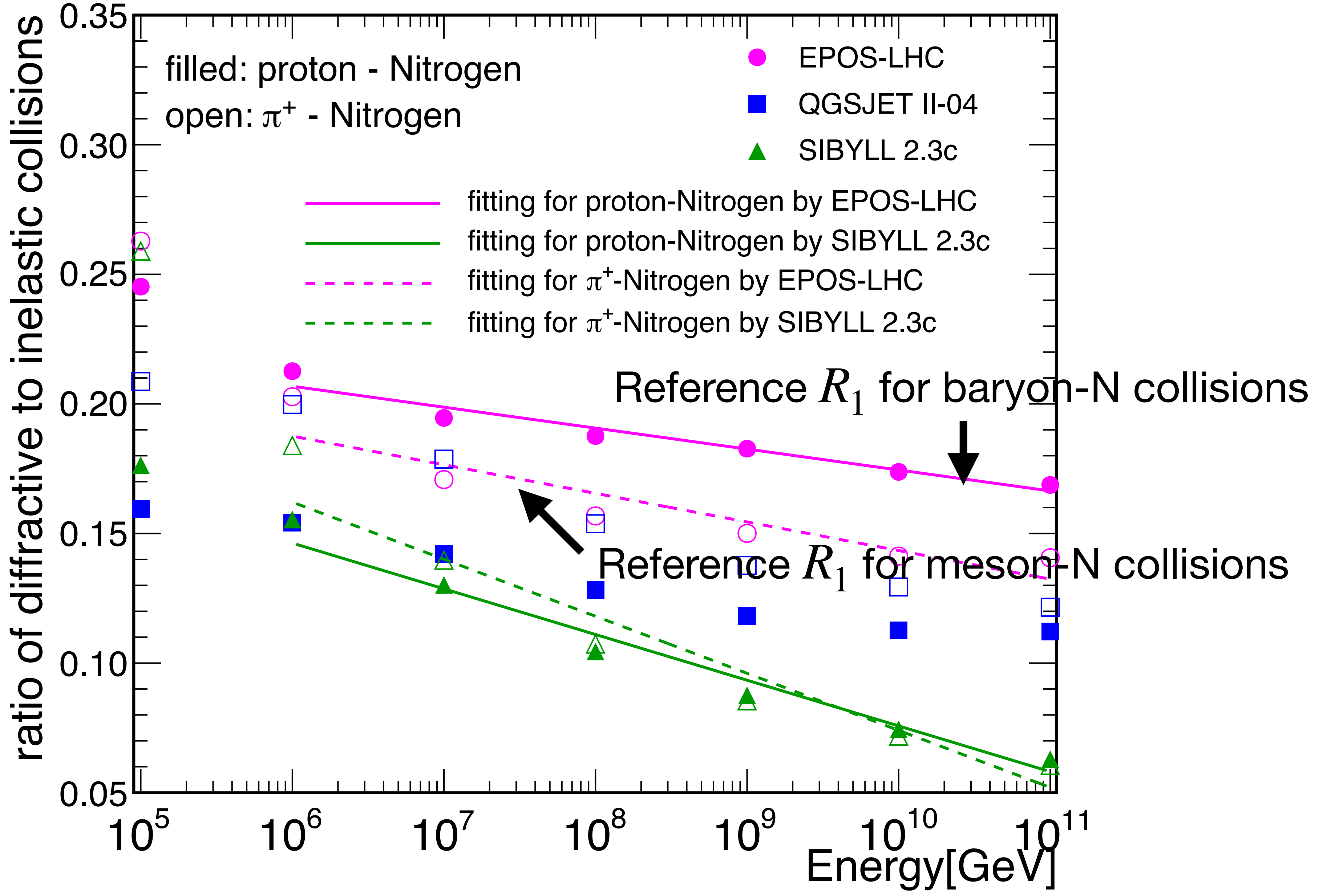


If we assume an extreme diffractive mass spectrum, size of effects on pSD is 10 %.

Projectile particles dissociate only for pSD and DD (~10% in total)
-> effects on $\langle X_{max} \rangle$ is 1% at max. (at the first interaction)

Effects of cross-section fraction for whole air shower

Change R_1 for collisions with energy > 10^{15} eV



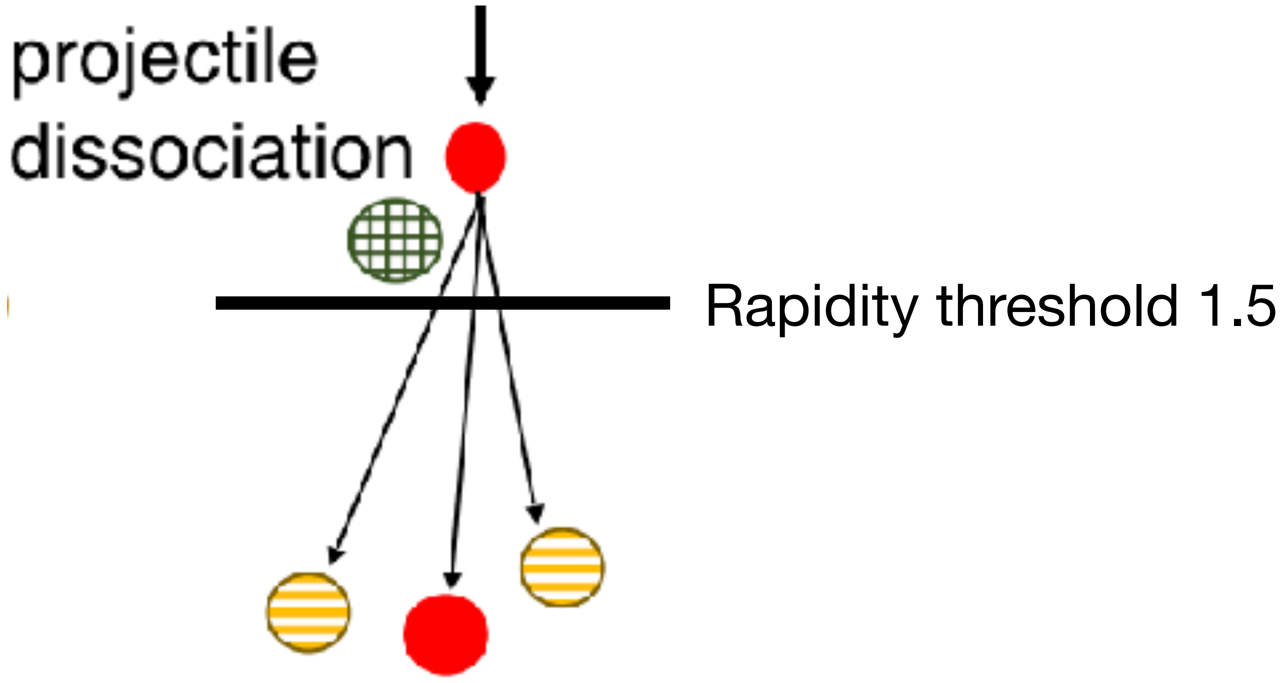
If collision with energy > 10^{15} eV..

1. Randomly select the collision type using reference R_1
2. Generate a collision. If the collision type is not same as selected in (1), regenerate a collision.

	Original	Modified	Difference
EPOS-LHC	807.5	809.5	2.0
SIBYLL 2.3c	819.6	828.5	4.4
QGSJET II-04	792.2	796.6	8.9
	27.4	+4.5 → 31.9	

Size of statistical errors: ± 0.3 $\mathrm{g/cm^2}$

Calculation of diffractive mass



$$M_X^2 = |\sum p^i|^2$$