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High-energy photonuclear interactions and muon content of extensive air showers

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Muon puzzle

Muon content *z*-measure:

$$z = \frac{\ln N_\mu^{\rm exp} - \ln N_\mu^{\rm theor}(\text{primary } p)}{\ln N_\mu^{\rm theor}(\text{primary Fe}) - \ln N_\mu^{\rm theor}(\text{primary } p)]}$$

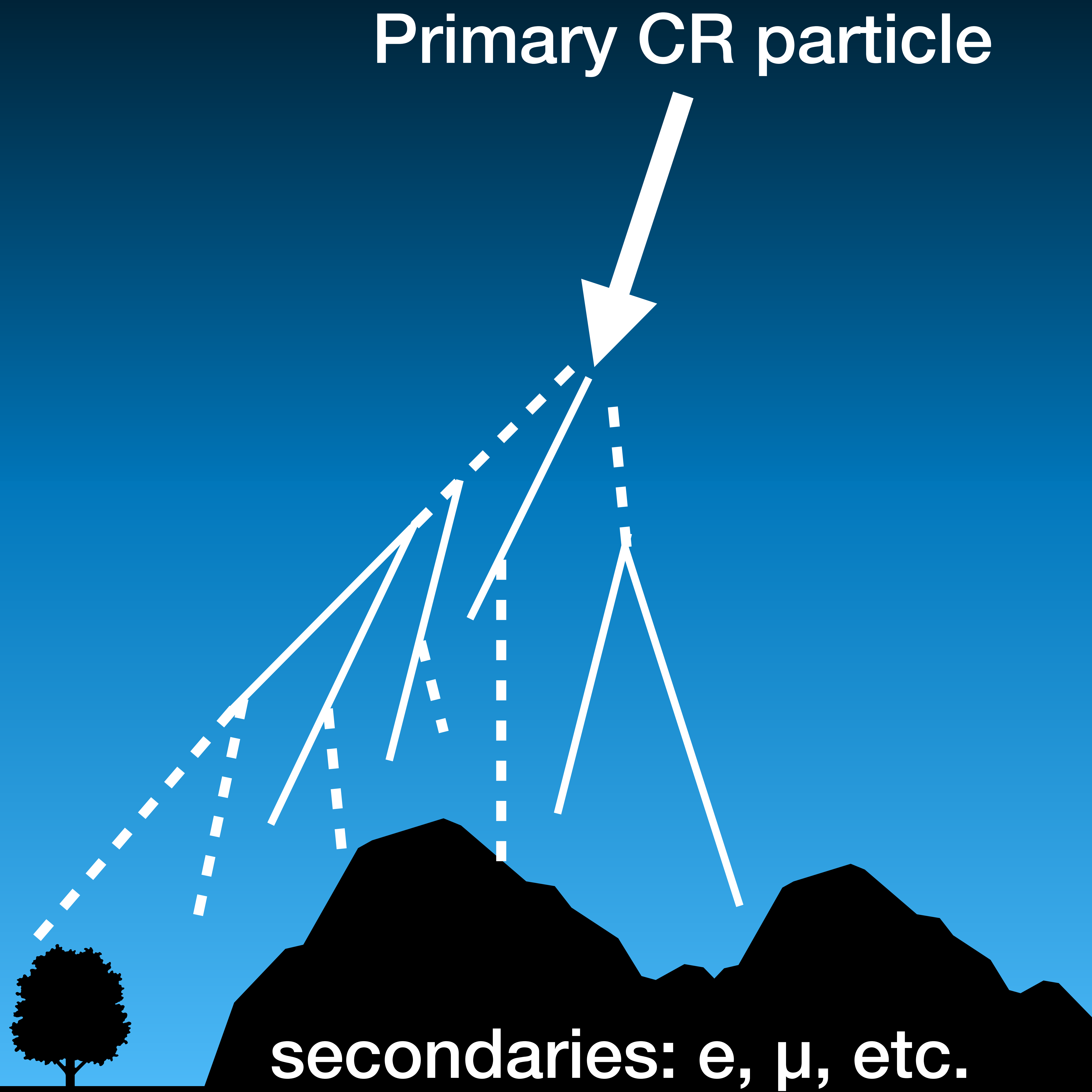
Expectation: 0 < *z* < 1

0 = pure protons

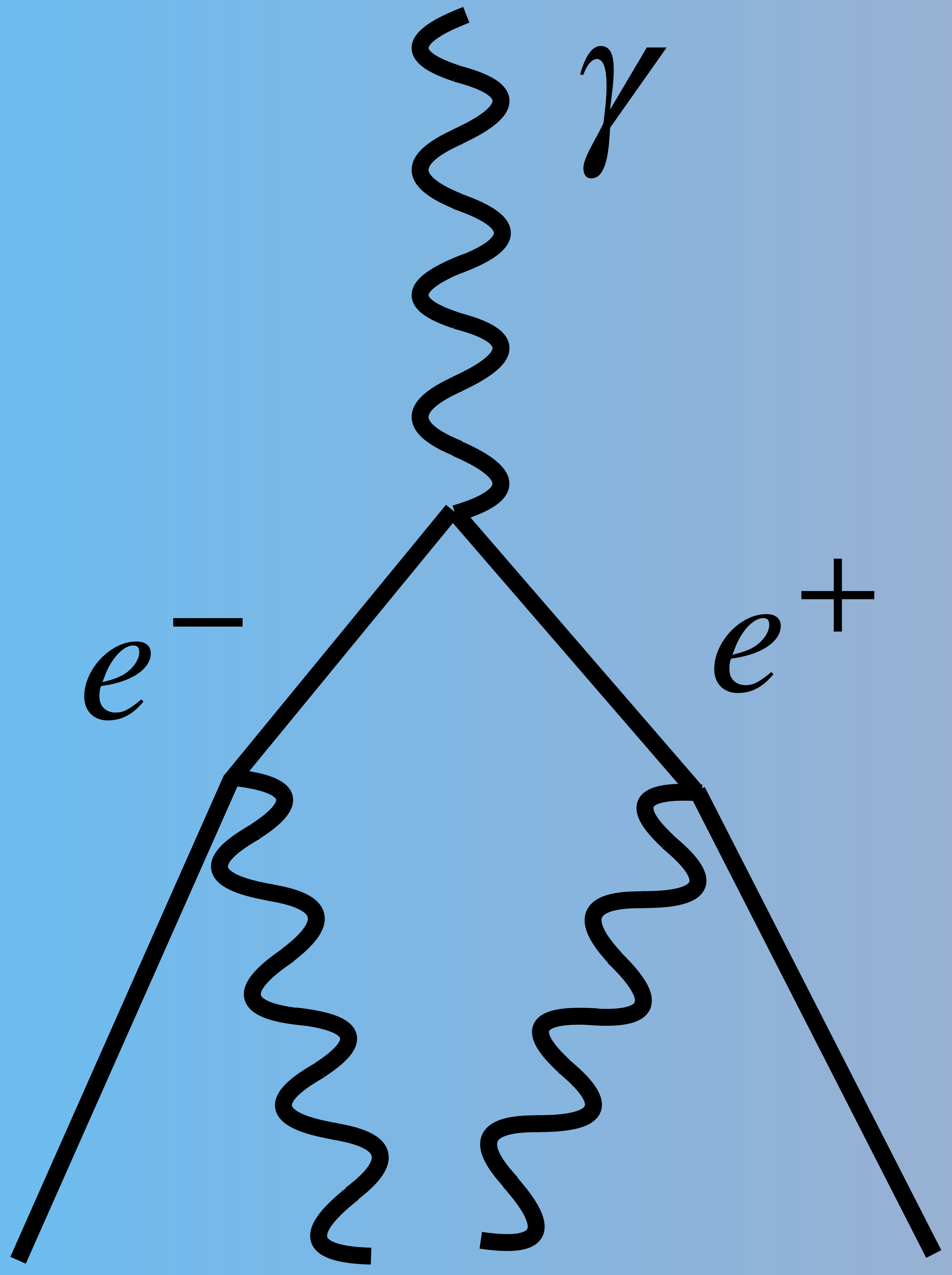
1 = pure iron

In fact: *z* > 1 is observed sometimes!

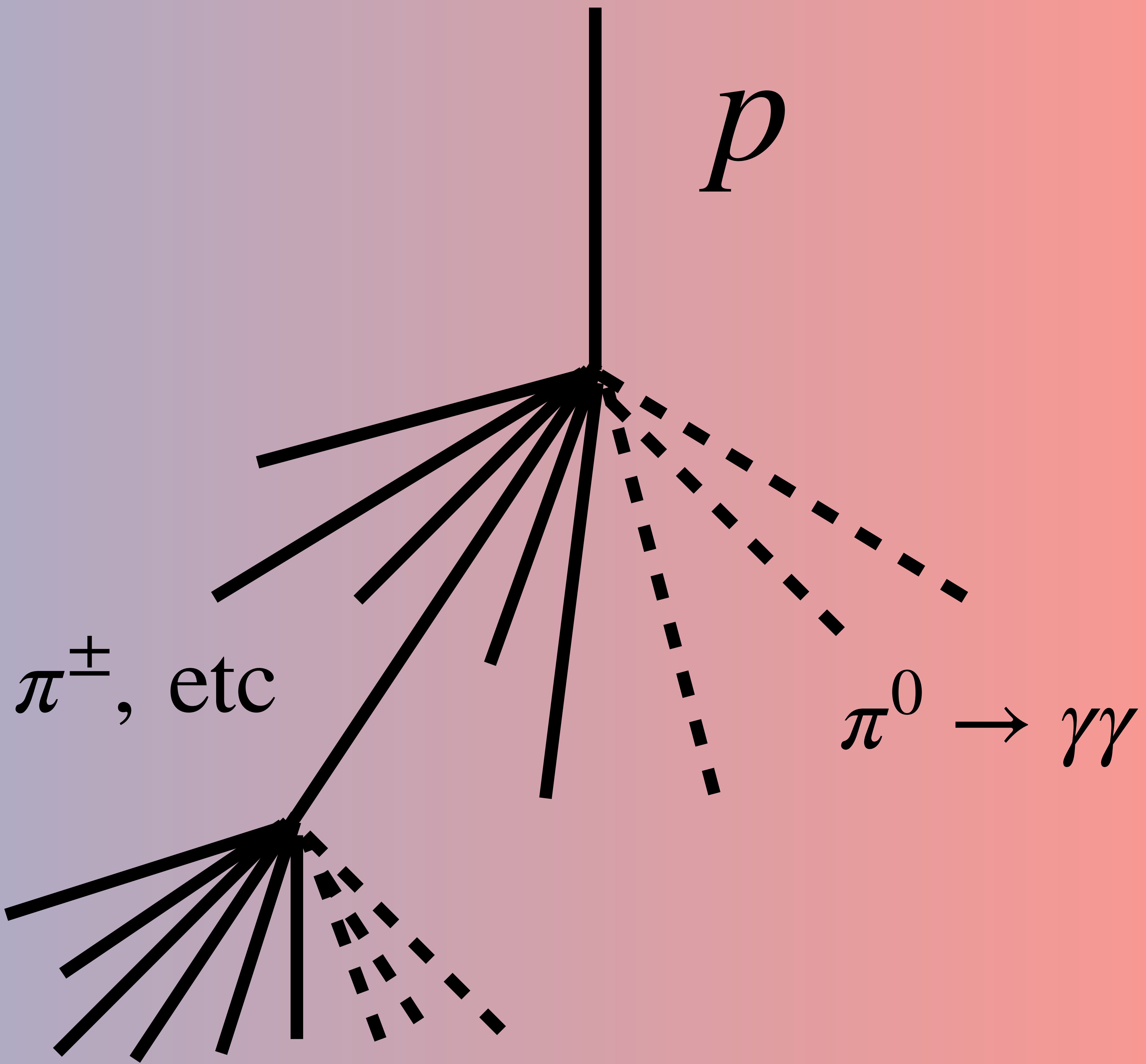
[arXiv:2105.06148v2]



Electromagnetic cascades



Hadronic cascades



Dominant muon producers:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$$

Electromagnetic cascades?

Dominant muon producers:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$$

Photonuclear reaction!

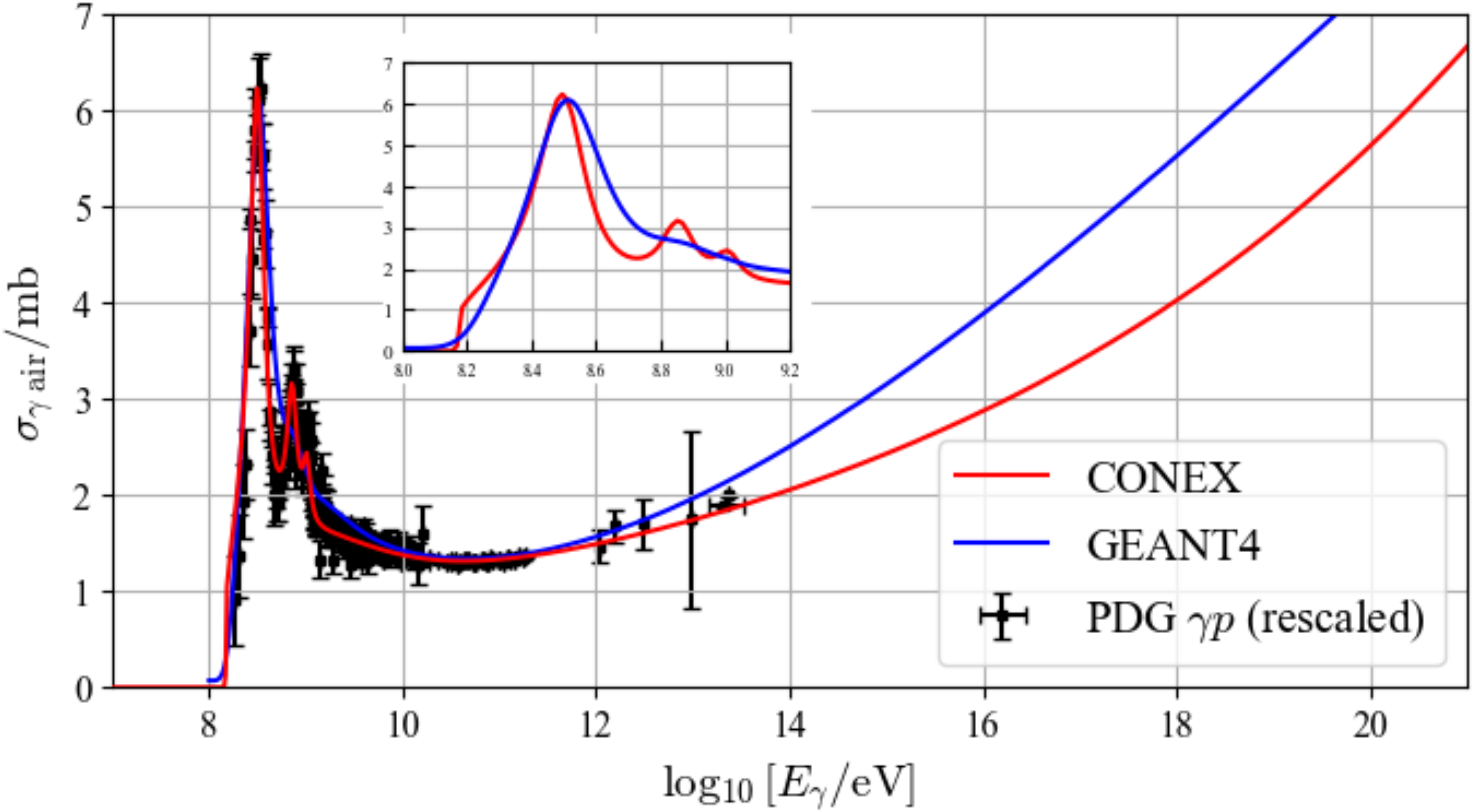
Dominant muon producers:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

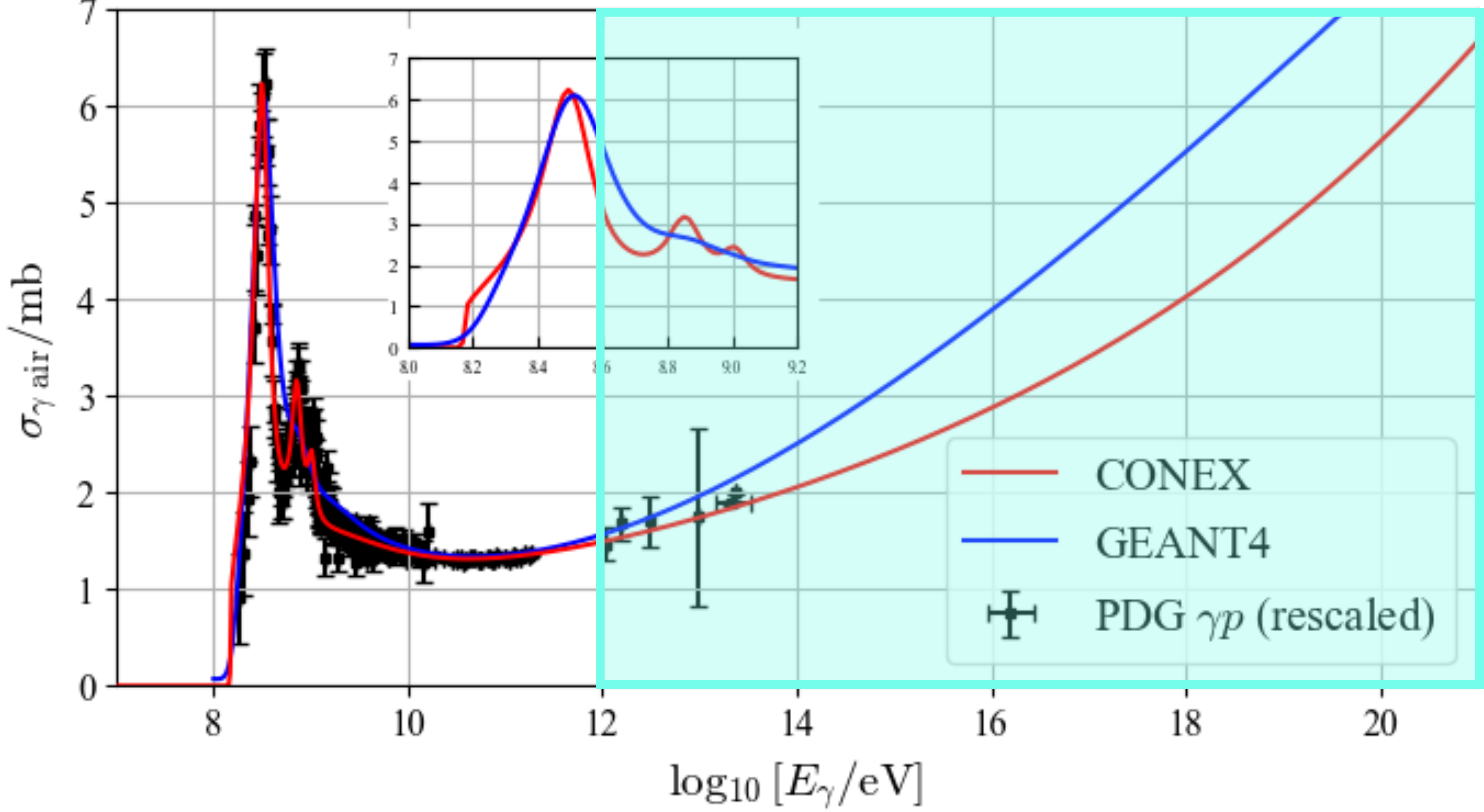
$$\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$$

$$\gamma + A \rightarrow \pi + \ldots$$

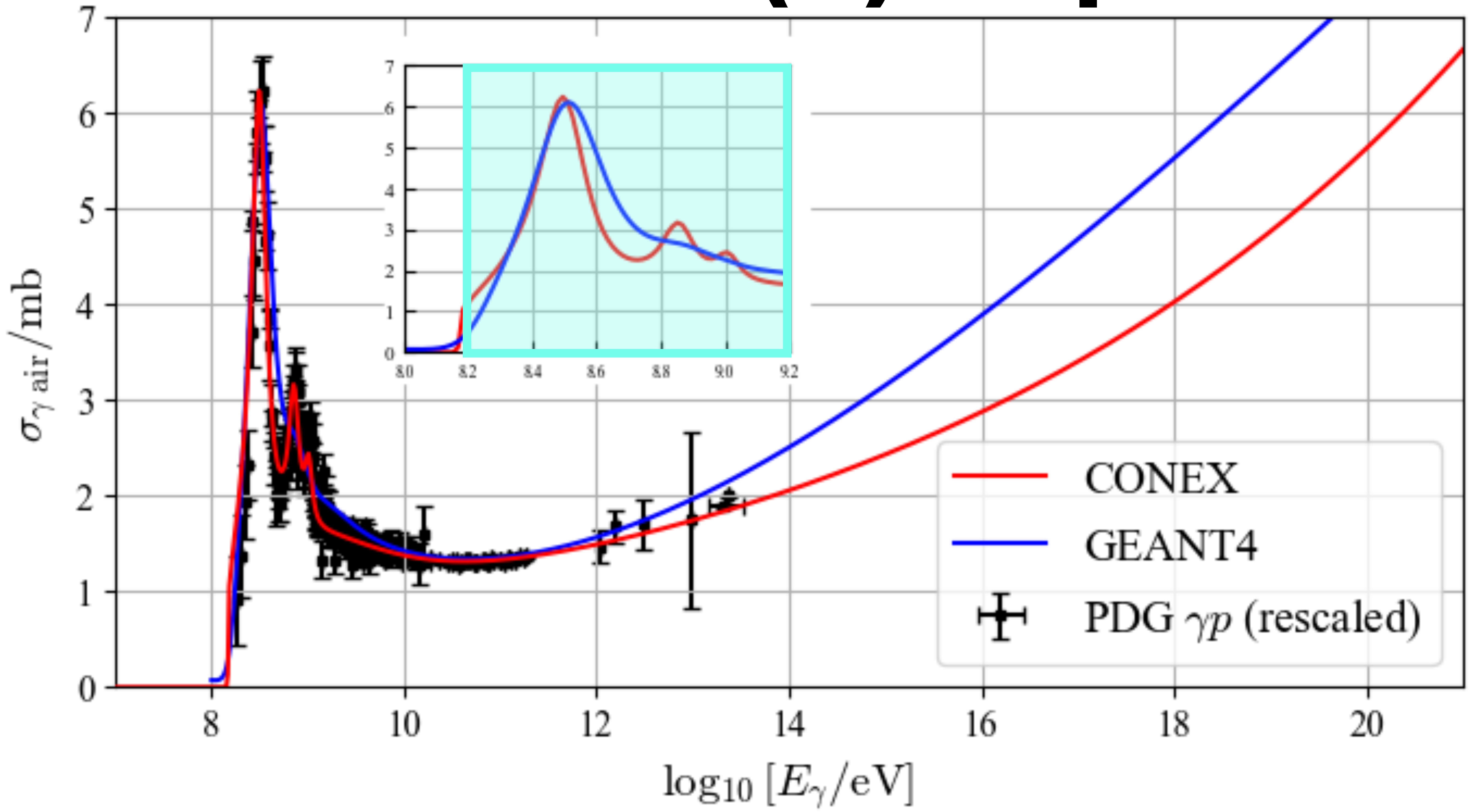
Photon+air (weighted) photonuclear cross-section



Systematic uncertainty:
1. asymptotic behavior



Systematic uncertainty: 2. mass number (A) dependence



Semi-analytical approach to study photonuclear cross-section models

$$\frac{dN_\mu}{dE_\gamma} = \sigma_{\gamma\ \mathrm{air}}(E_\gamma) \cdot f(E_\gamma, E_i, X)$$

E_i — primary photon energy

E_γ — (grand-)mother reaction energy

X — slant depth [g cm^{-2}]

We assume that f does not depend on the photonuclear interaction model, unless the latter one significantly affects an electromagnetic shower development.

Parametrization of the universal function

$$f(E_\gamma, E_i, X) = \mathcal{N}(E_\gamma, E_i) \;\cdot\; p(X \,|\, X_{\max}(E_\gamma, E_i), E_\gamma) \;\cdot\; \Theta(E_i - E_\gamma)$$

E_i — primary photon energy

E_γ — (grand-)mother reaction energy

X — slant depth [g cm^{-2}]

$\mathcal{N}$ accounts for number of muons at maximum (by slant depth)

p describes the longitudinal profile (we assume generalized Gaisser—Hillas shape)

Parametrization of the universal function

$$\frac{dN_\mu}{dE_\gamma}(E_\gamma, E_i, X) = \left(\frac{\sigma_{\gamma\ \mathrm{air}}(E_\gamma)}{\mathrm{mb}}\right) \times N_0 \left(\frac{E_\gamma}{\mathrm{eV}}\right)^{-\gamma_1+\gamma_2 \ln\left(\frac{E_\gamma}{\mathrm{eV}}\right)} \left(\frac{E_i}{\mathrm{eV}}\right)^{i} \times$$

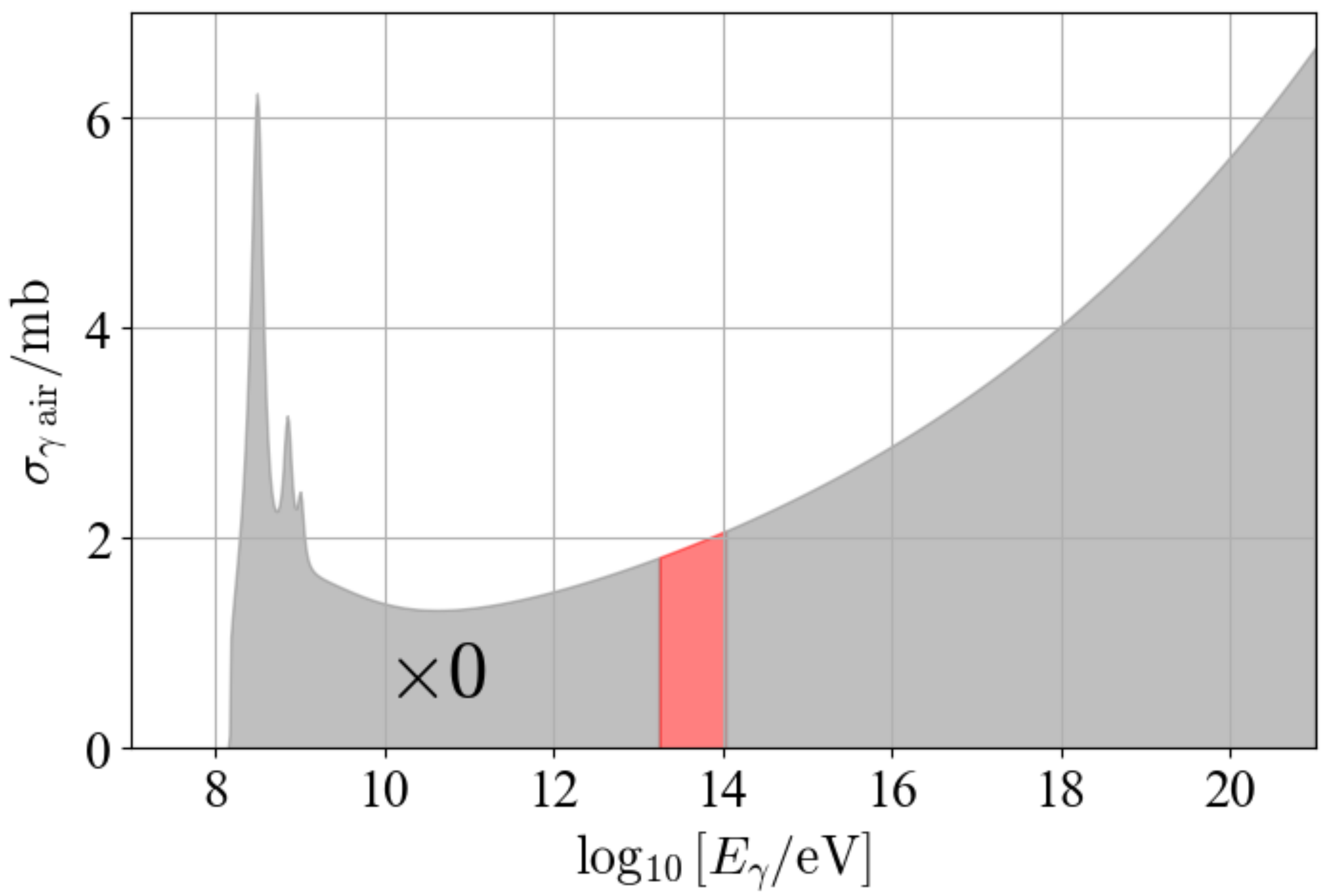
$$\times \left(\frac{X}{X_{\max}}\right)^{\frac{X_{\max}}{\Lambda\left(\frac{X}{X_{\max}}, E_\gamma\right)}} \exp\left[\frac{X_{\max} - X}{\Lambda\left(\frac{X}{X_{\max}}, E_\gamma\right)}\right] \times \Theta(E_i - E_\gamma),$$

$$X_{\max} = -X_0 + X_\gamma \ \ln\left(\frac{E_\gamma}{\mathrm{eV}}\right) + X_i \ln\left(\frac{E_i}{\mathrm{eV}}\right),$$

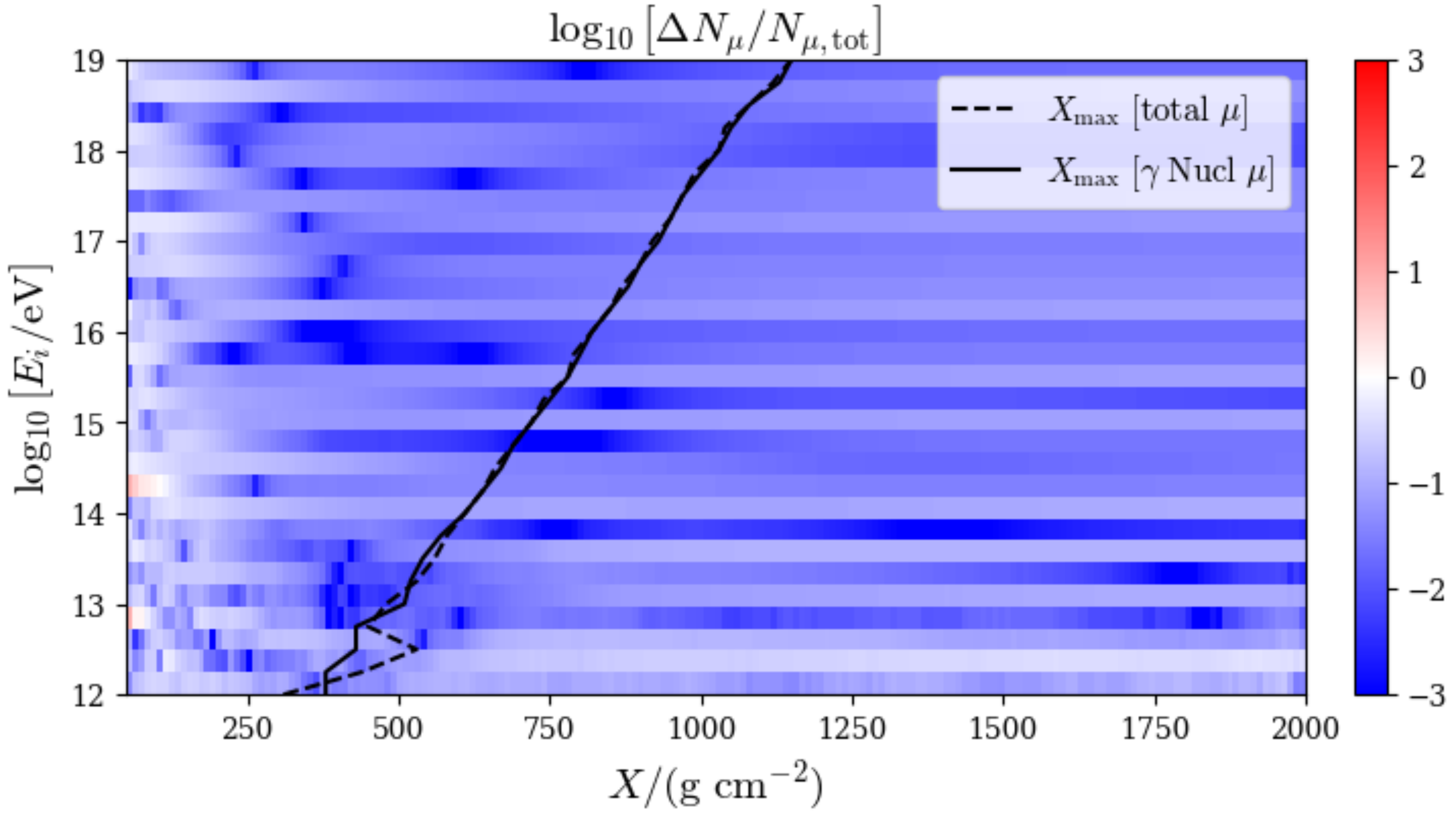
$$\Lambda(\xi) = -\left(\Lambda_0 - \Lambda_1\xi + \Lambda_2\xi^2\right) + \ln\left(\frac{E_\gamma}{\mathrm{eV}}\right) \times \left(\lambda_0 - \lambda_1\xi + \lambda_2\xi^2\right).$$

— 13 parameters in total

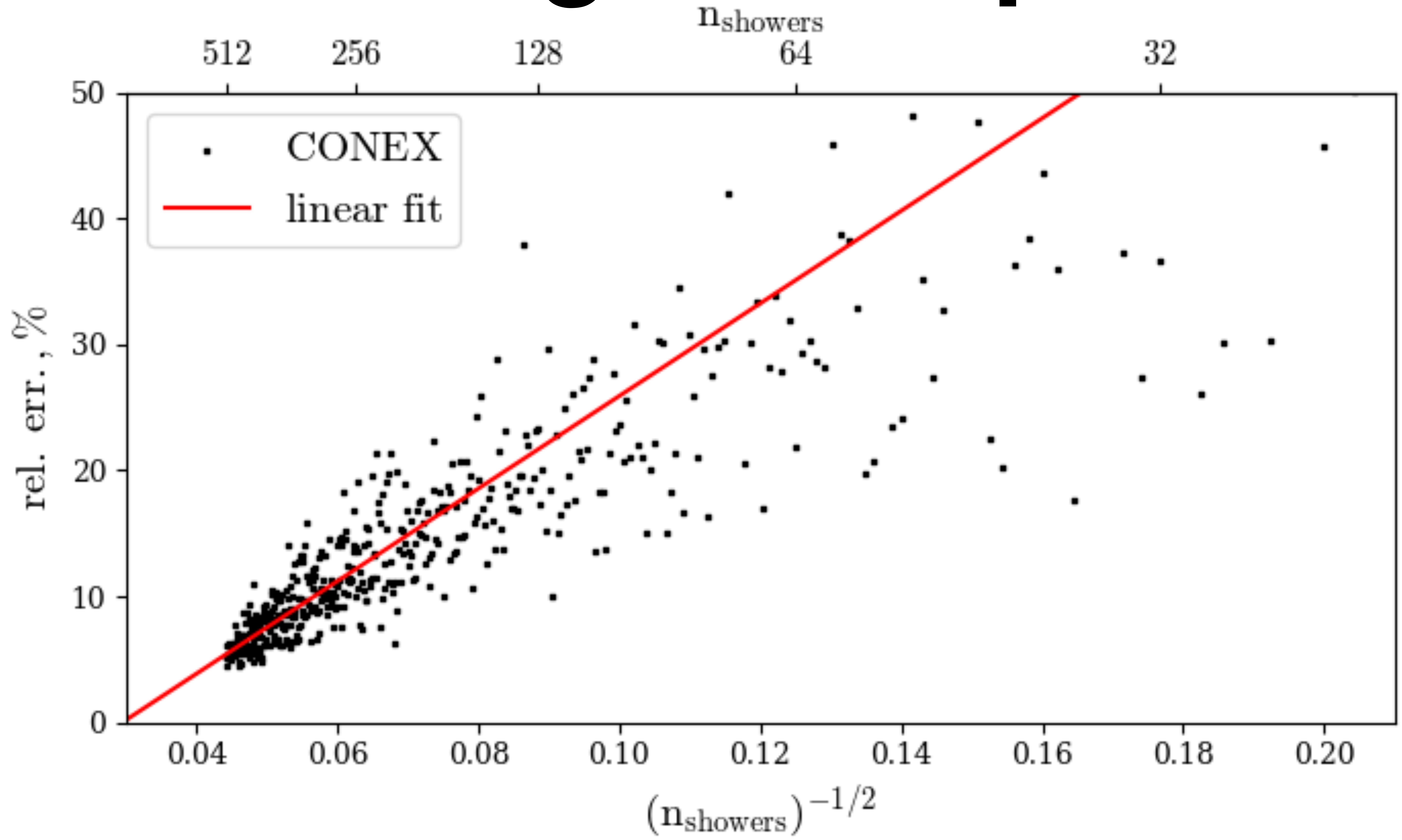
— only Linear Regression



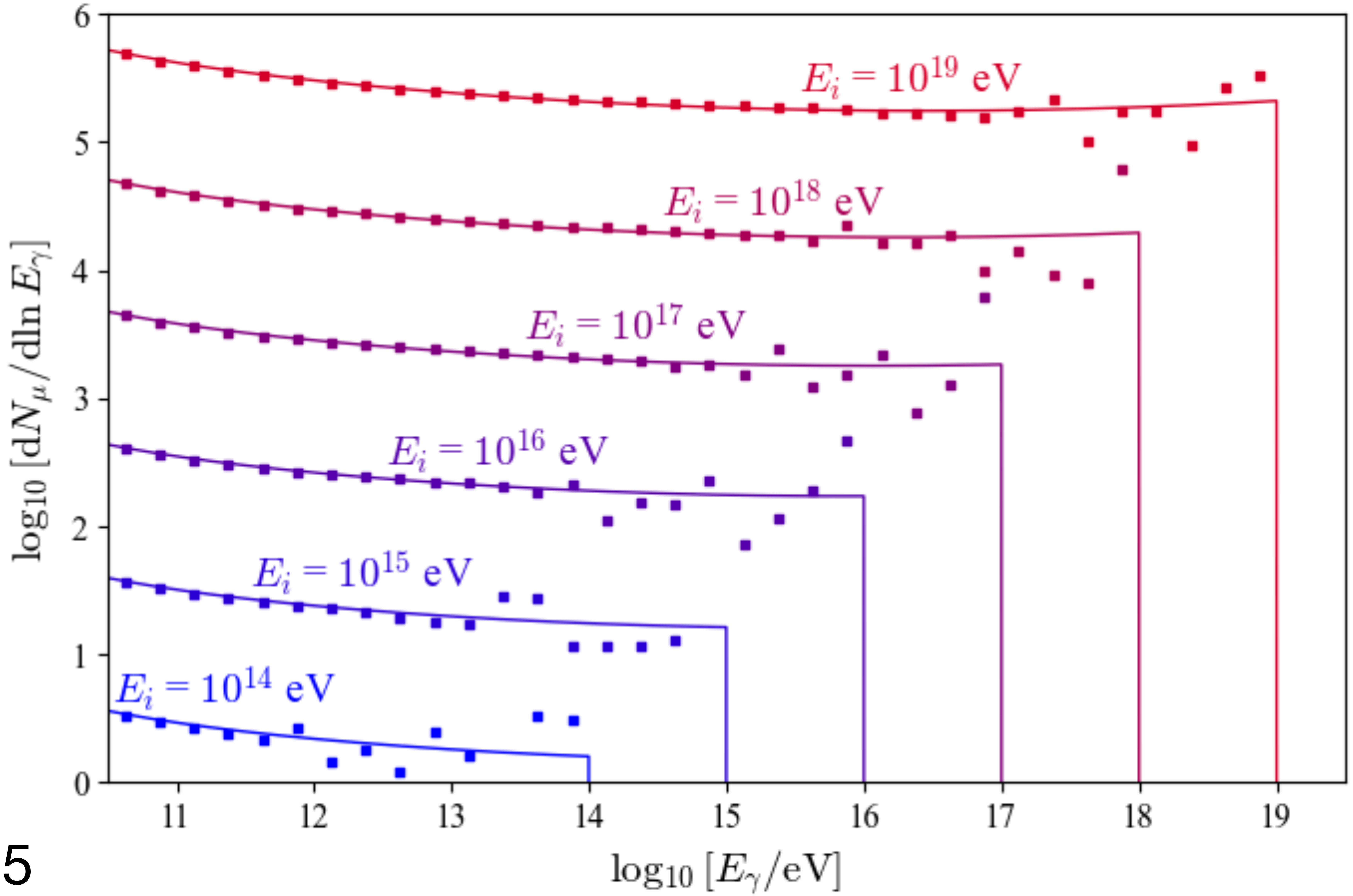
Results: testing assumptions



Results: testing assumptions



Results: train set



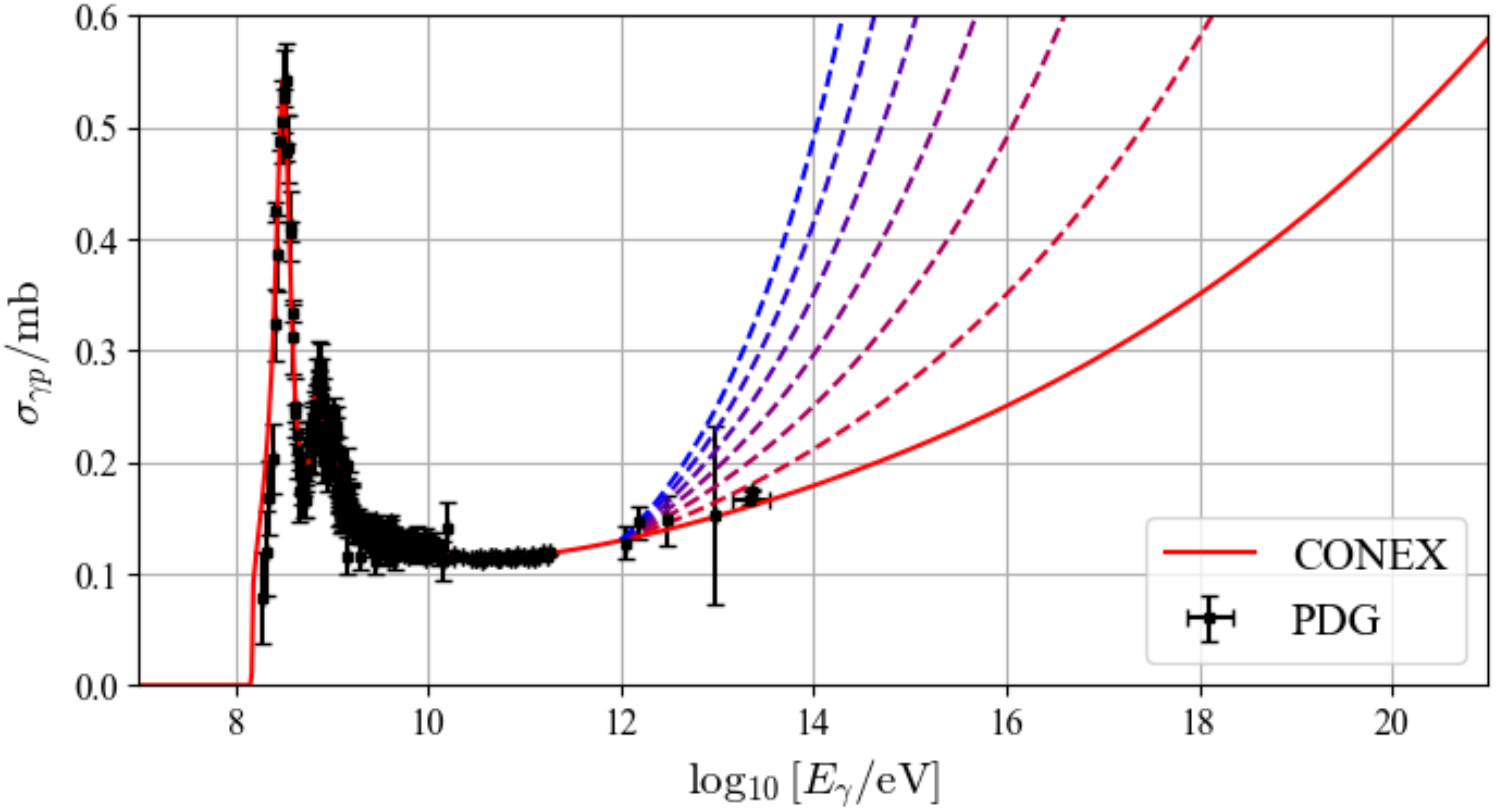
CONEX:

EPOS-LHC, $\theta = 30°$

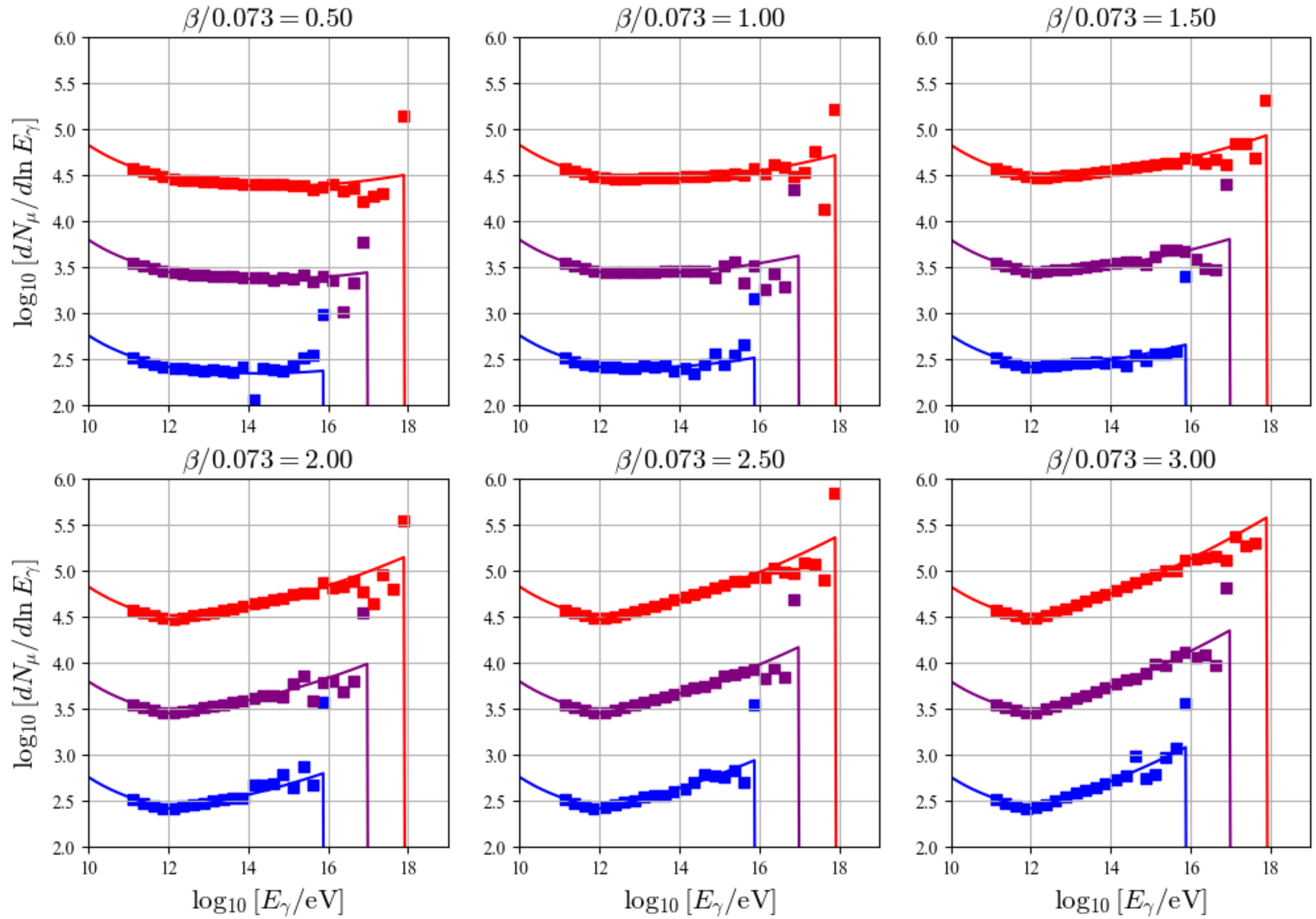
512 photon EAS

$X \cos\theta = 10^3$ g cm^{-2}

Results: test set



Results: test set



CONEX:

EPOS-LHC, $\theta = 30°$

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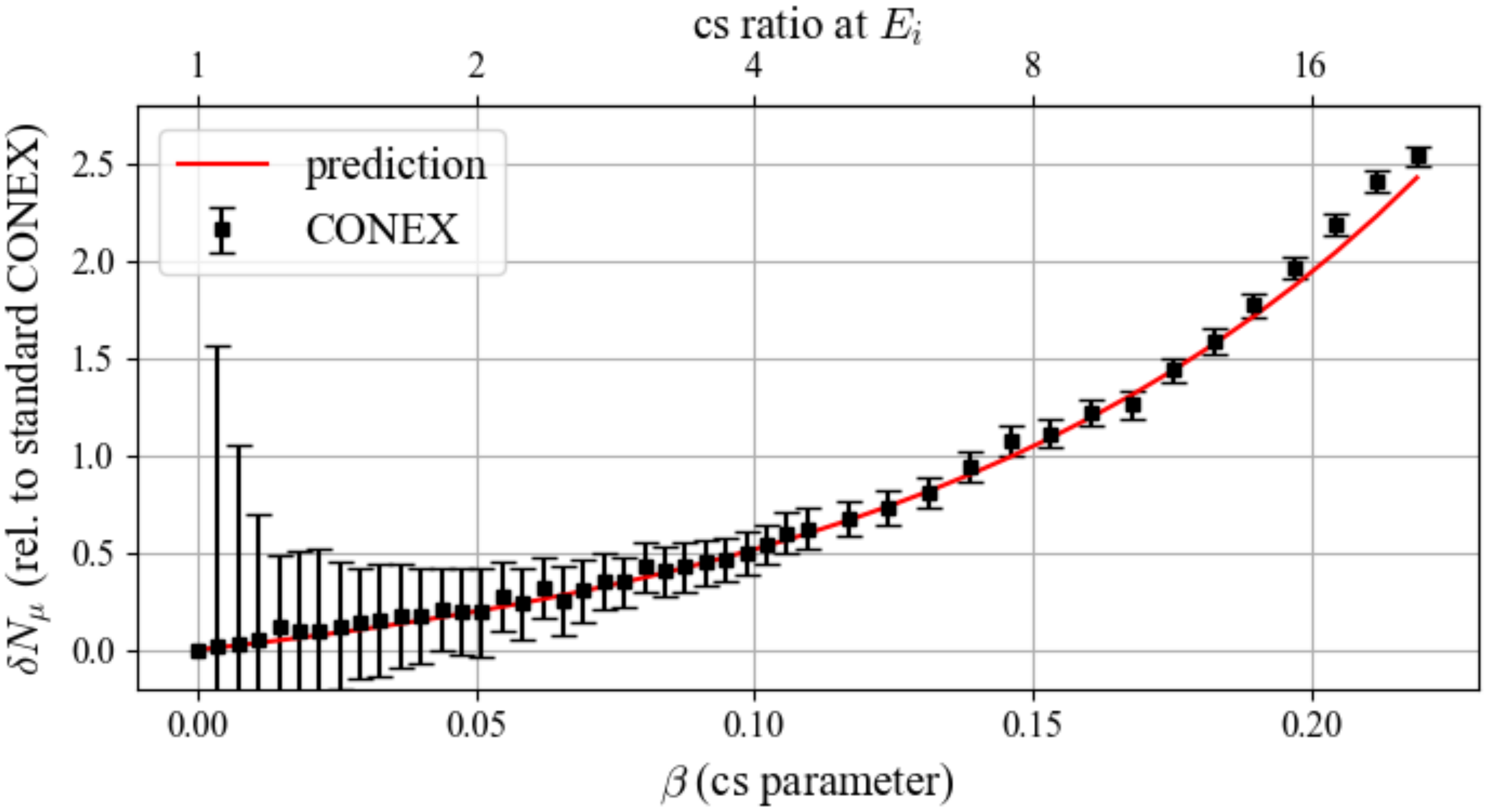
Results: test set



CONEX:

EPOS-LHC, $\theta = 30°$

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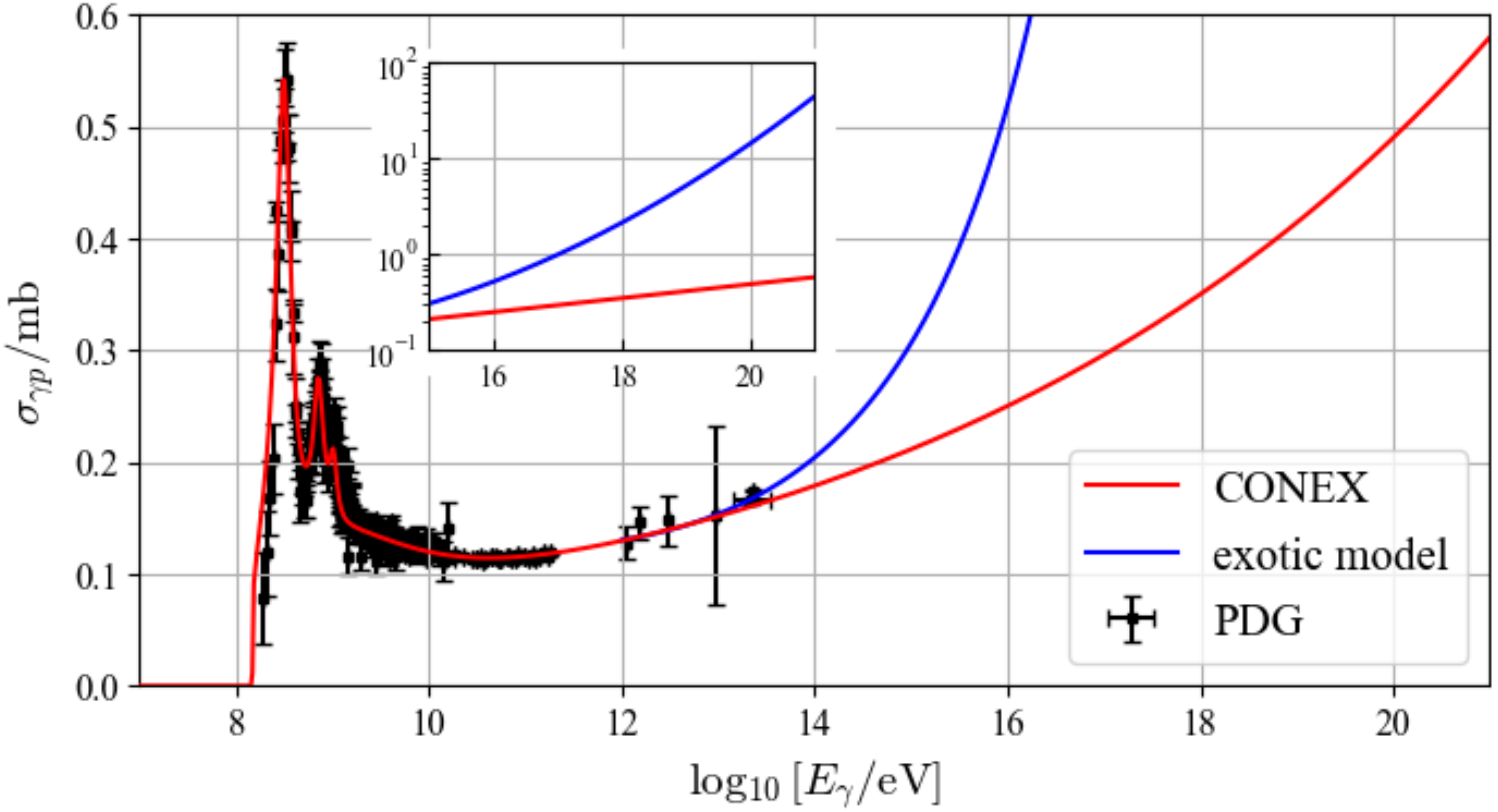
$X \cos\theta = 10^3$ g cm^{-2}

Results: ‘exotic’ model



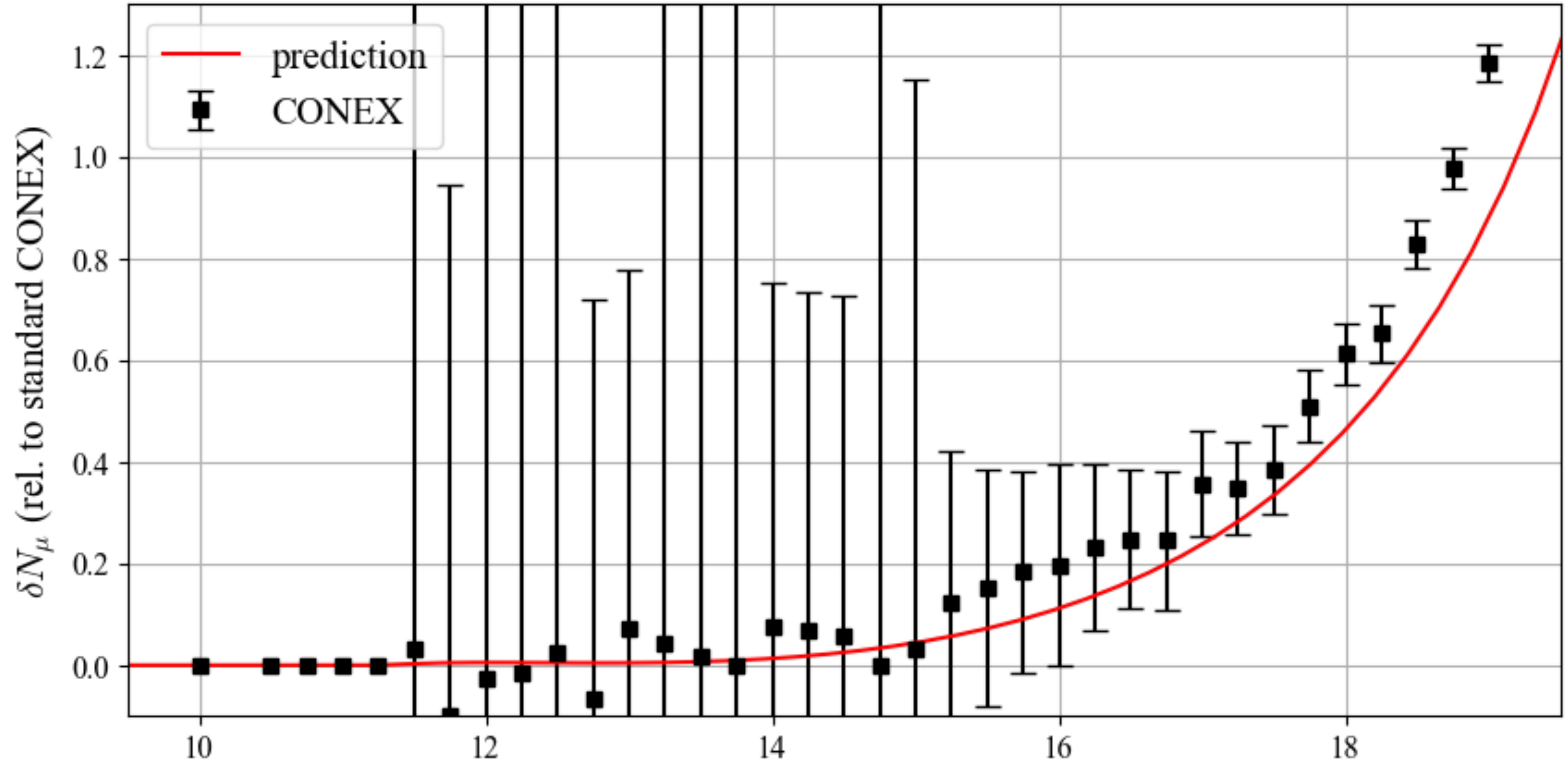
CONEX:

EPOS-LHC, $\theta = 30°$

2048 photon EAS

$X \cos\theta = 10^3\ \mathrm{g\ cm^{-2}}$

Results: ‘exotic’ model



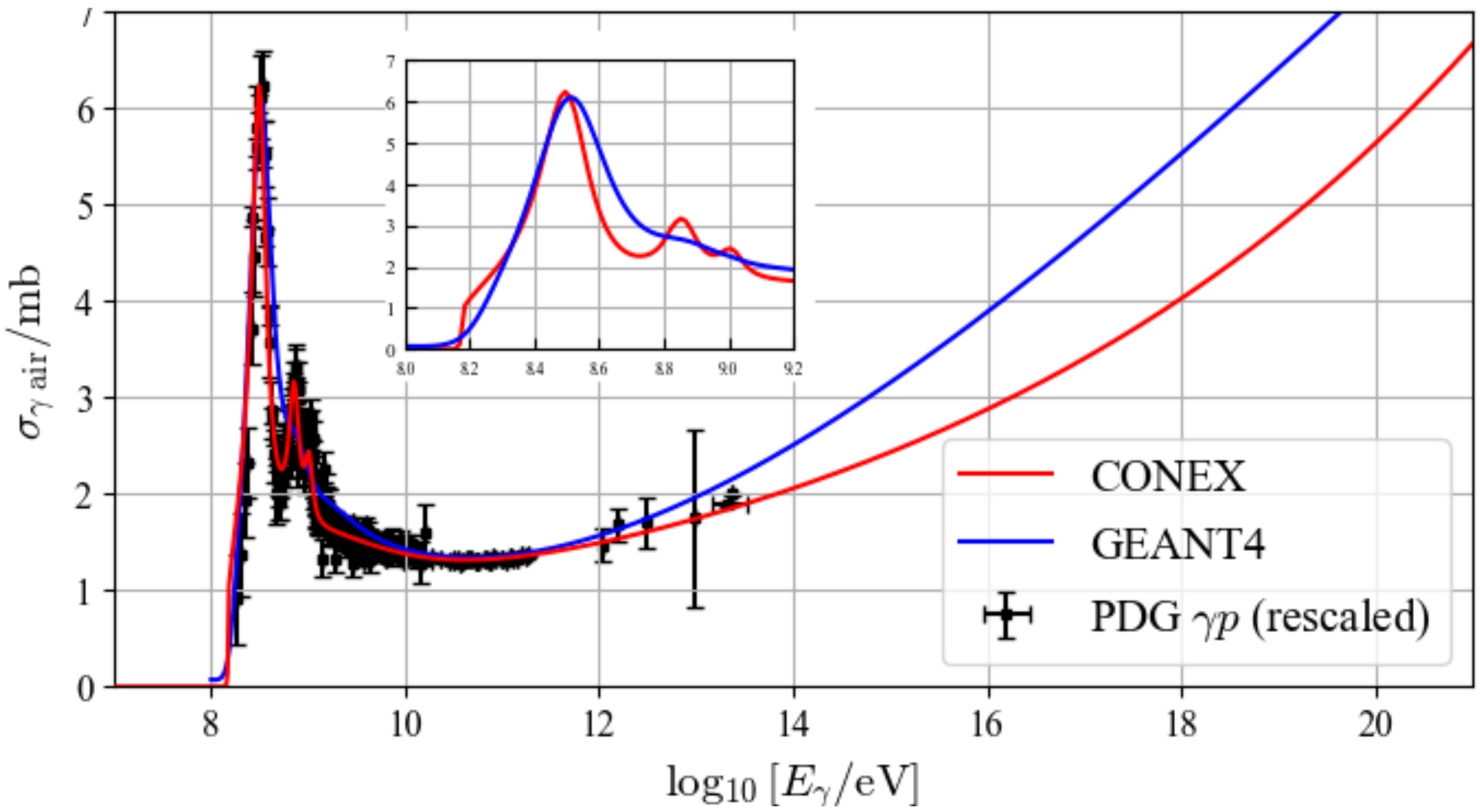
CONEX:

EPOS-LHC, $\theta = 30°$

2048 photon EAS

$X \cos\theta = 10^3 \text{ g cm}^{-2}$

Results: A-scaling* (GEANT4)



CONEX:

EPOS-LHC, $\theta = 30°$

512 photon EAS

$X\cos\theta = 10^3\ \mathrm{g\ cm^{-2}}$

Results: A-scaling* (GEANT4)

Here one should be careful: our prediction works only for high-energy photonuclear reactions.

We observe an insignificant departure of simulation results from our prediction.

Thus lower-energy corrections (in particular, the contribution of the resonance region) are small enough.

This indicates that CONEX A-scaling is reasonable at near-resonance energies.

CONEX:

EPOS-LHC, $\theta = 30°$

512 photon EAS

$X \cos\theta = 10^3$ g cm^{-2}

Summary

The developed analytical technique allows to study a wide range of photonuclear cross-section models in terms of photon-initiated EAS muon content **without using simulations!**

By-product: the code made by GR and NM is compatible with almost arbitrary EGS4 cross-section modification, which now can be easily implemented to CONEX and CORSIKA (see e.g. Andrey Sharofeev’s talk on LIV effects in EAS).

detailed and multi-purpose

CORSIKA

CONEX

$$\frac{dN_\mu}{dE_\gamma} = \sigma_{\gamma\ \mathrm{air}}(E_\gamma) \cdot f(E_\gamma, E_i, X)$$

and similar analytical formulae

time-saving and easily-controlled

Work in progress…

— Account for higher-order corrections. Probably this can be done using electromagnetic cascade equations. This would allow to describe even more extreme cross-section modifications and UHE regime analytically.

— Explore the spectrum and spatial structure of additional muons. Which fraction of them is actually detectable?

— Use toy-model of hadron EAS to predict the number of additional muons(?): results are sufficiently model-dependent…