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High-energy Photonuclear Reactions Contribution to the Ground-level Muon Content of Extensive Air Showers

Nickolay S. Martynenko [1,2], Grigory I. Rubtsov [2,1], and Sergey V. Troitsky [2,1]

[1]Lomonosov MSU, Faculty of Physics

[2]Institute for Nuclear Research of RAS

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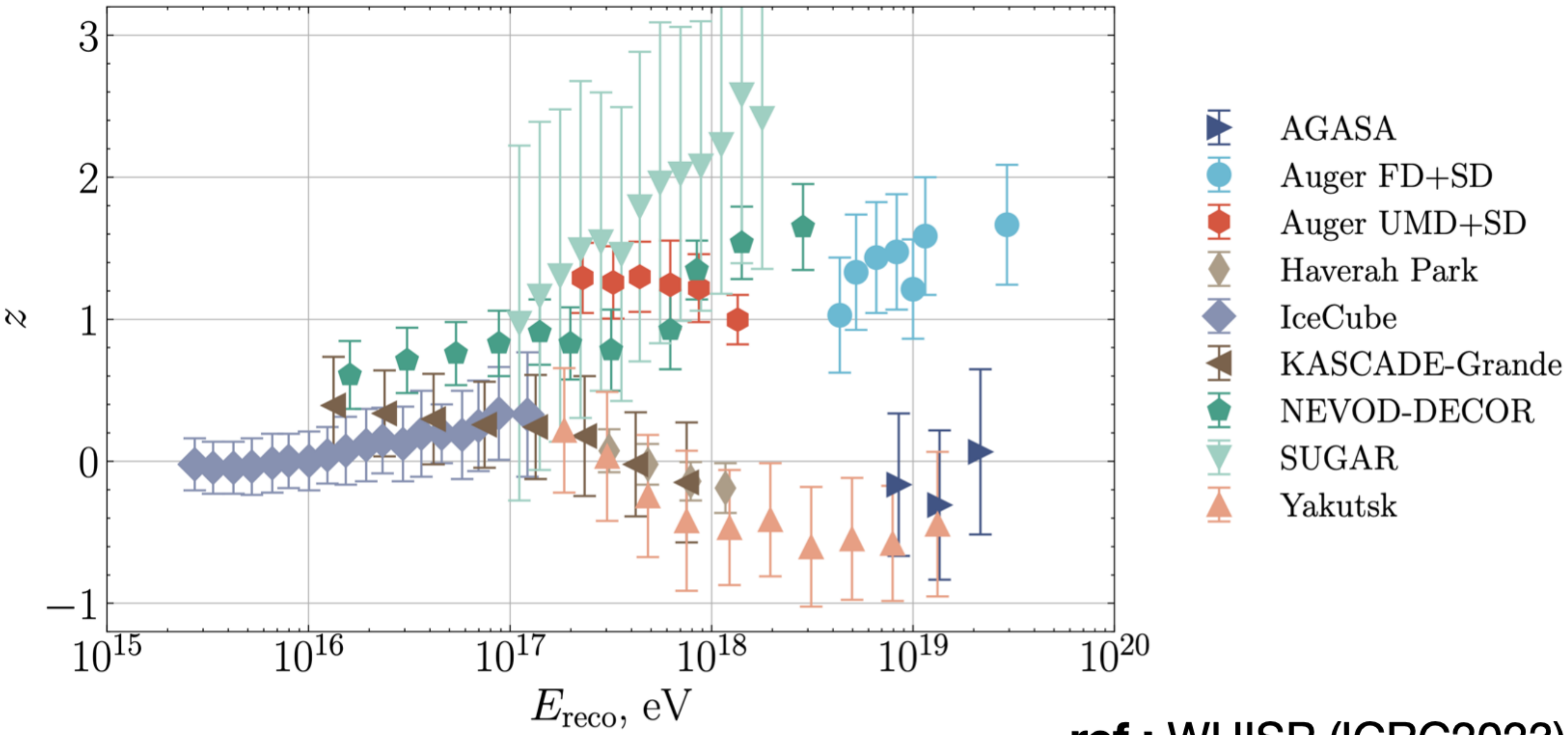
Motivation: Muon Puzzle



ref.: WHISP (ICRC2023)

Motivation: Muon Puzzle

- **Hadronic Models:** years of efforts, dozens of models, but… no definitive solution [yet]

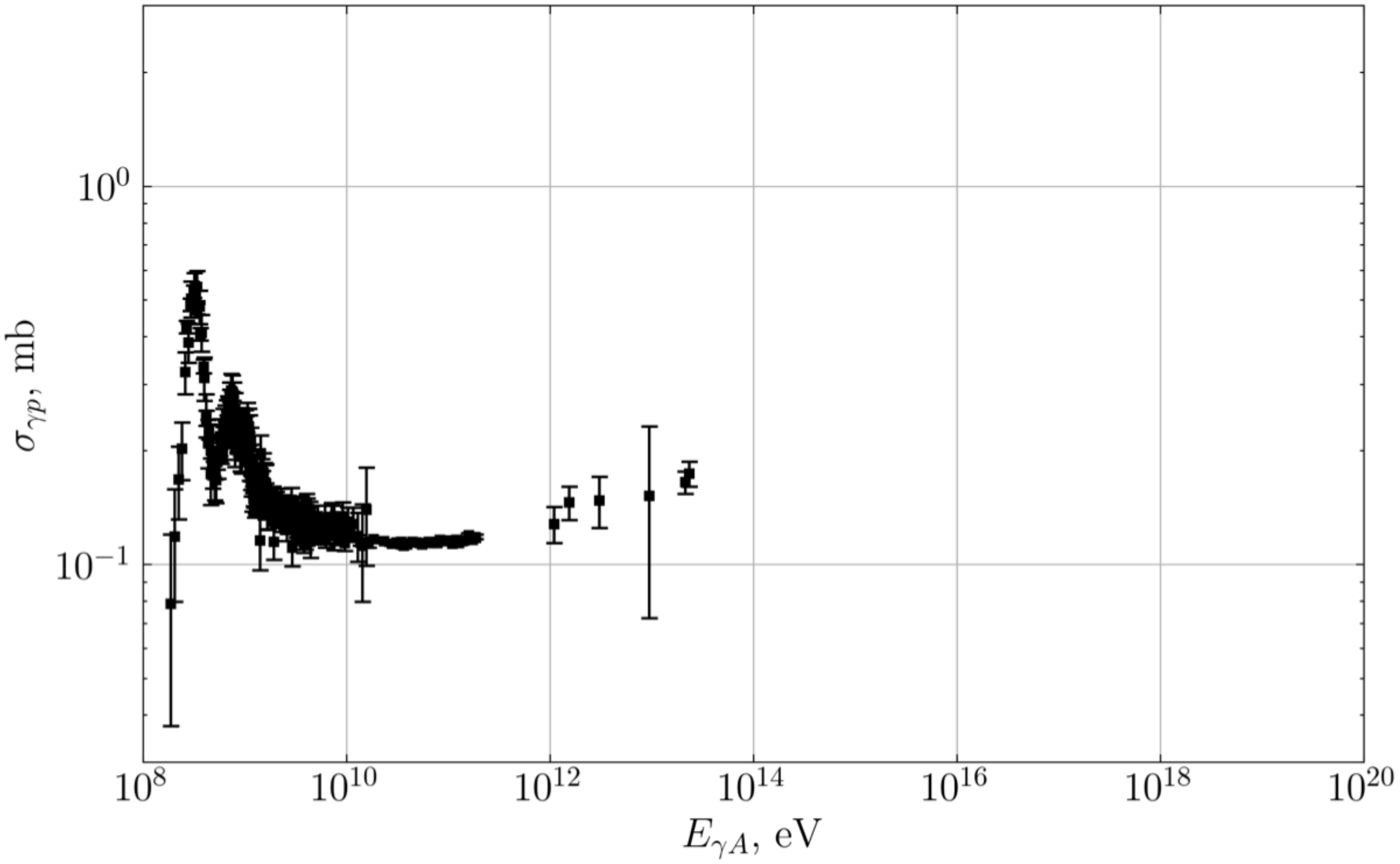
- **Electromagnetic models:** also deserve attention, but not much research done to date

We focus on the **photonuclear process:**

$$\gamma + ({}^{14}\mathrm{N}, {}^{16}\mathrm{O}, {}^{40}\mathrm{Ar}, \dots) \to \mathrm{hadrons} + \dots$$

A hadronic sub-cascade arises and, eventually, $\mu^{\pm}$ are produced in the decays of $\pi^{\pm}$, $K^{\pm}$, …

Photonuclear Reaction Cross-section



ref.: Particle Data Group (2025)

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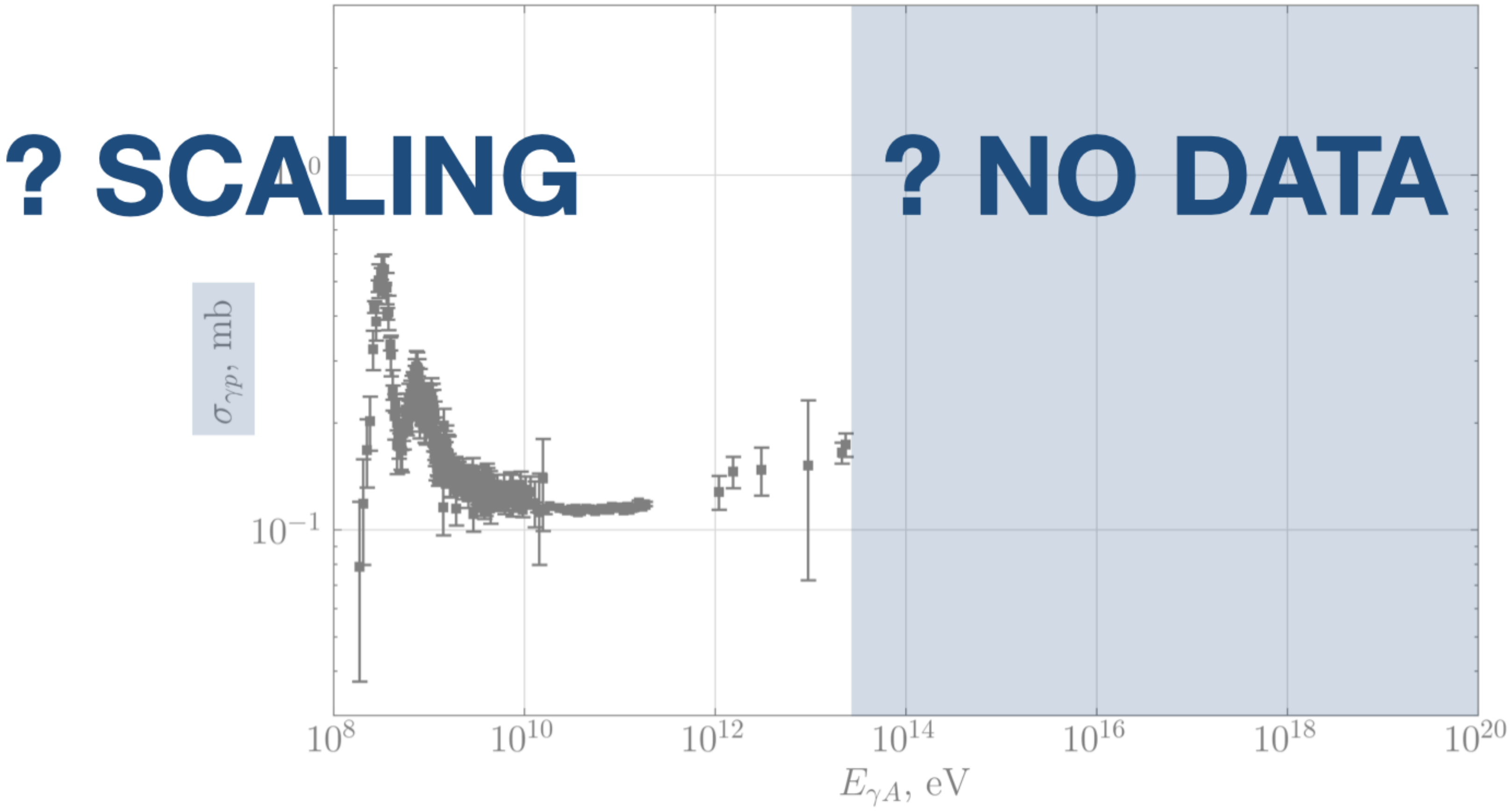

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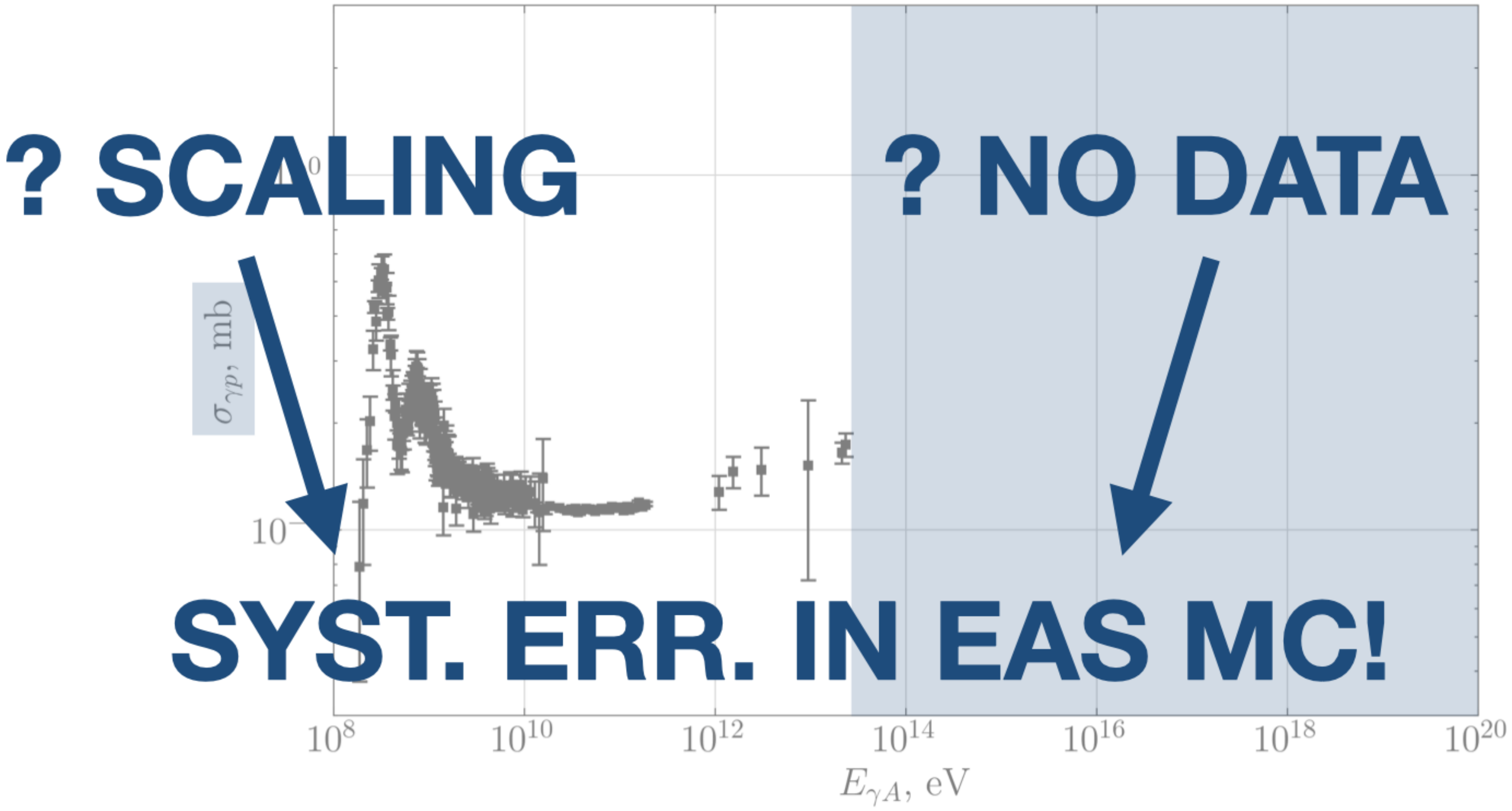
Photonuclear Reaction Cross-section



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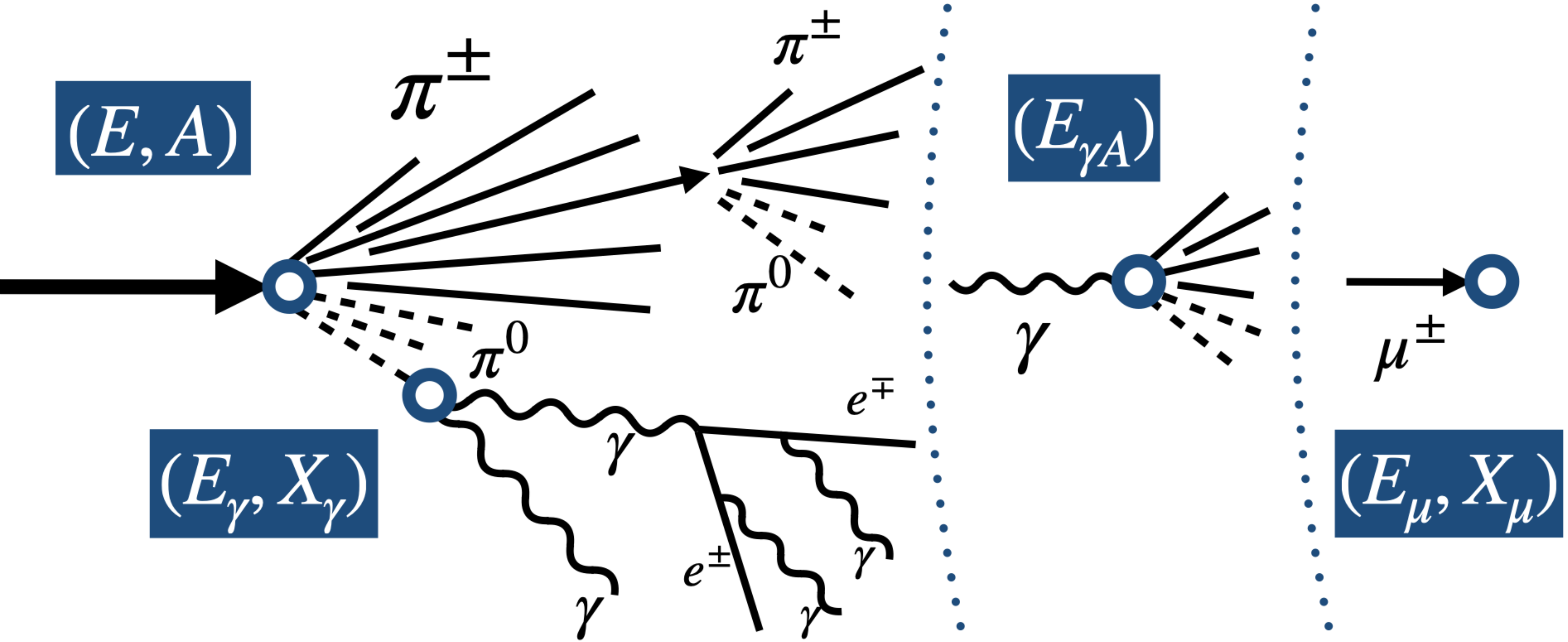
Systematic Uncertainty Estimation



Systematic Uncertainty Estimation

Assumption 1. The average number of muons produced by (grand-)^n parent high-energy photonuclear reactions in EAS is a linear functional of the photonuclear cross-section:

$$N_{\mu[\leftarrow\gamma A]}(E_\mu > E_{\mu,\mathrm{thr}})\Big|_{X_\mu} = \int\limits_{E_{\gamma A,\mathrm{thr}}}^{E} dE_{\gamma A}\,\sigma_{\gamma A}(E_{\gamma A}) \cdot G(E_{\gamma A}\,|\,E, A)\Big|_{X_\mu}$$

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‘Green Function’

Systematic Uncertainty Estimation

Assumption 2. For the Green Function defined above, the following parametrization is applicable:

$$G(E_{\gamma A}\,|\,E,1)\Big|_{X_\mu} = \int\limits_{\ln E_{\gamma A}}^{\ln E} d\ln E_\gamma \int_0^{X_\mu} dX_\gamma \,\frac{dN_\gamma}{d\ln E_\gamma\, dX_\gamma} \cdot \Gamma(E_{\gamma A}\,|\,E_\gamma)\Big|_{X_\mu - X_\gamma}$$

$$G(E_{\gamma A}\,|\,E,A)\Big|_{X_\mu} = A \cdot G(E_{\gamma A}\,|\,A^{-1}E,1)\Big|_{X_\mu}$$ (superposition model)

Systematic Uncertainty Estimation

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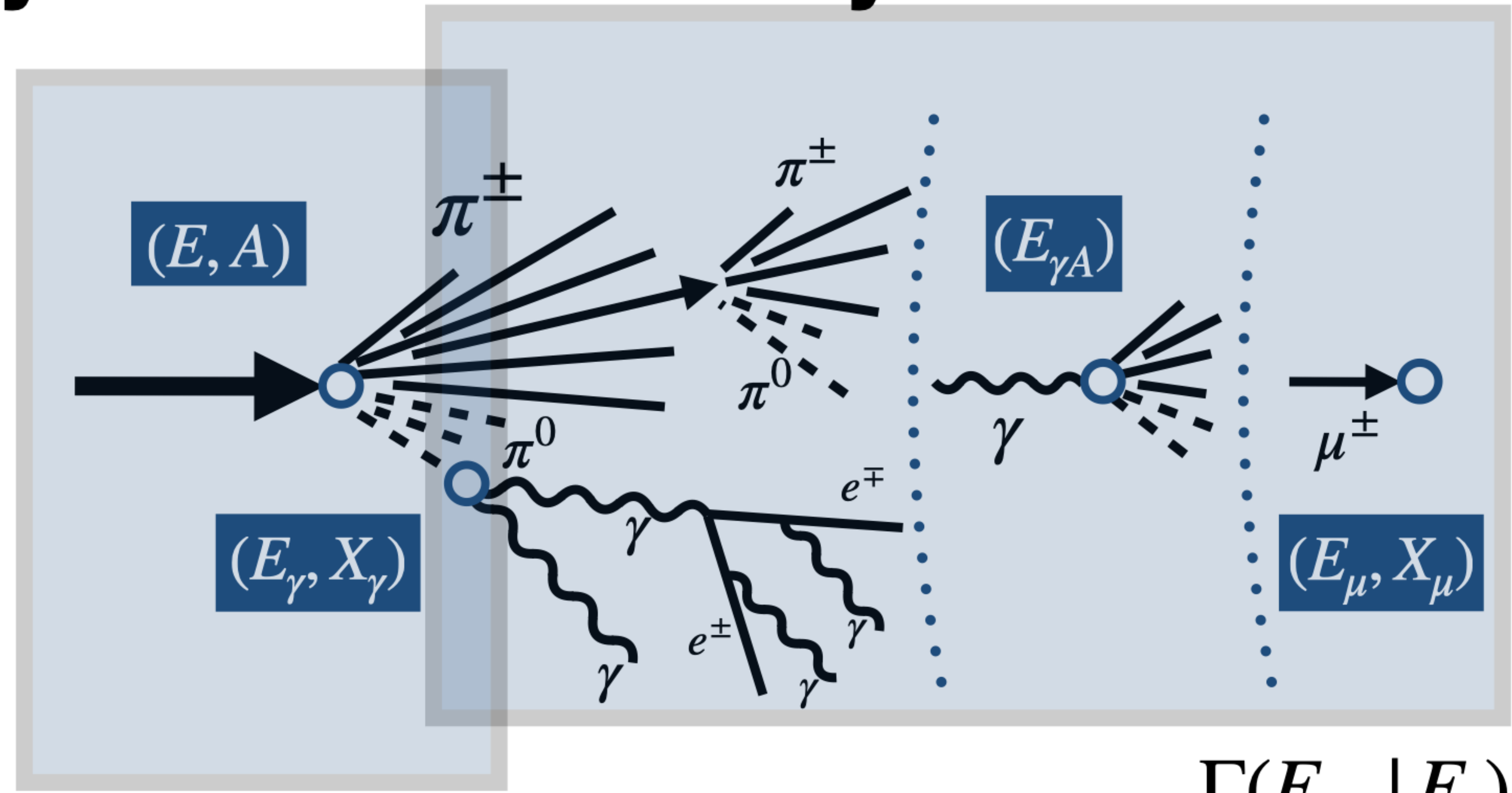
'High-energy Photons Distribution'

$$G(E_{\gamma A} \,|\, E, 1)\Big|_{X_\mu} = \int\limits_{\ln E_{\gamma A}}^{\ln E} d\ln E_\gamma \int_0^{X_\mu} dX_\gamma \, \boxed{\frac{dN_\gamma}{d\ln E_\gamma\, dX_\gamma}} \cdot \boxed{\Gamma(E_{\gamma A} \,|\, E_\gamma)\Big|_{X_\mu - X_\gamma}}$$

'Gamma Green Function'

$$G(E_{\gamma A} \,|\, E, A)\Big|_{X_\mu} = A \cdot G(E_{\gamma A} \,|\, A^{-1}E, 1)\Big|_{X_\mu}$$ (superposition model)

Systematic Uncertainty Estimation



$\Gamma(E_{\gamma A} \,|\, E_\gamma)$

$dN_\gamma / (d \ln E_\gamma \, dX_\gamma)$

Monte-Carlo Simulations

CONEX v7.60 in default configuration (EPOS-LHC+UrQMD 1.3+EGS4)

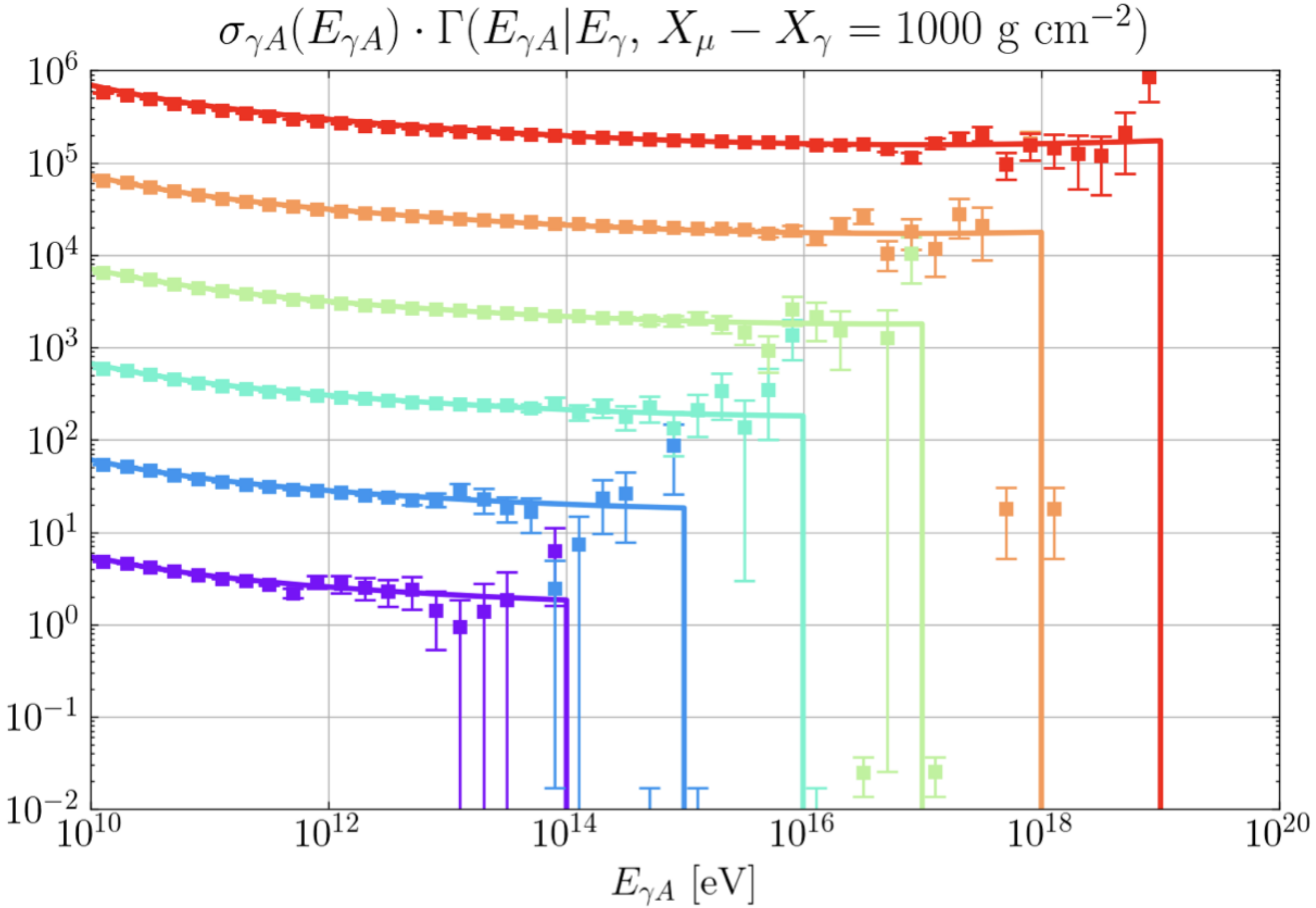
Gamma Green Function: overwrite EGS4 tables and scan the high-energy photonuclear cross-section bin-by-bin.

Since the photonuclear process in EGS4 is much less probable than electron-positron pair production, such a calculation is reasonable.

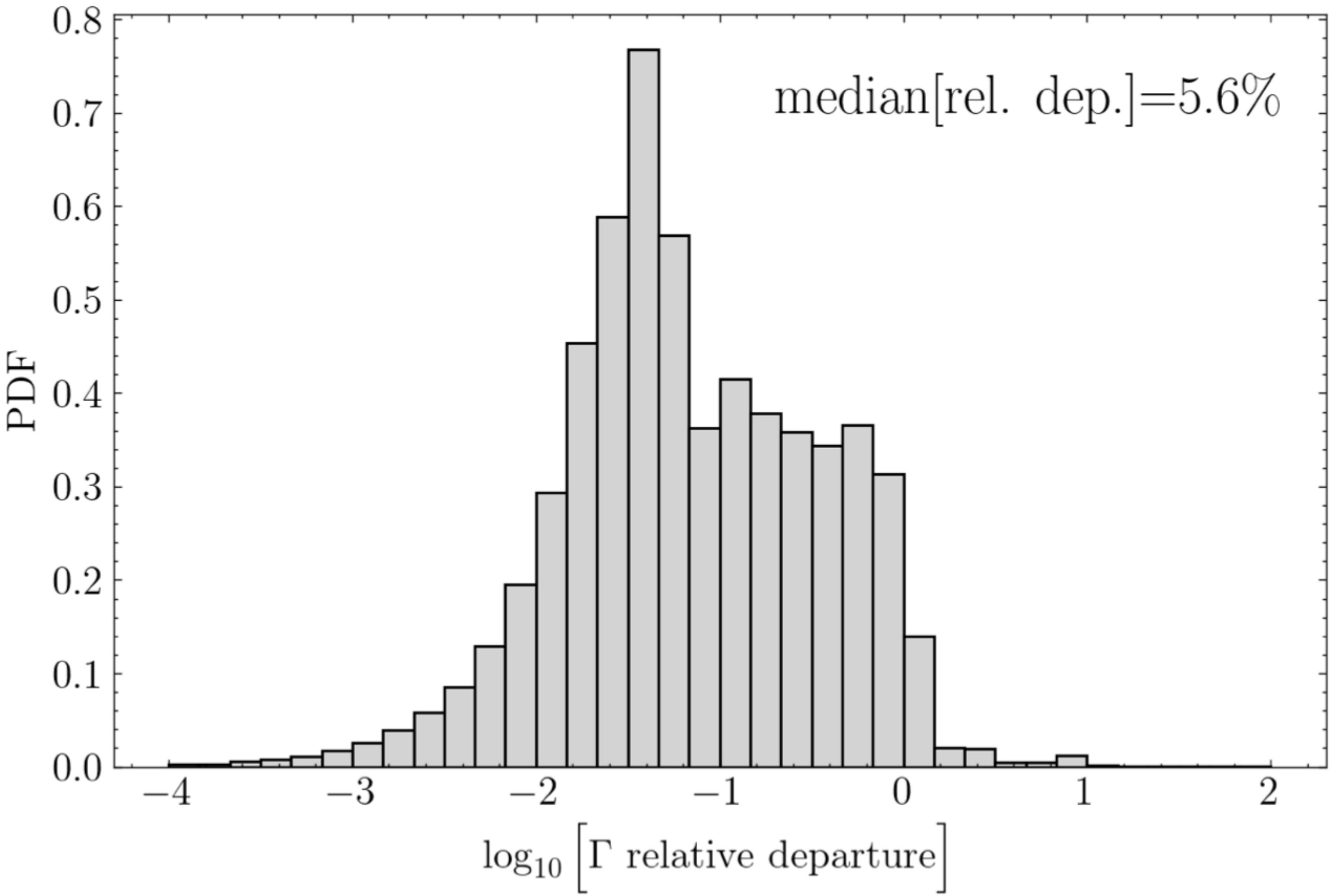
High-Energy Photons Distribution: disable photon-air interactions and record Leading Interactions Tree (CONEX option).

«Leading particle» carries away ~50% of the total reaction energy, thus ~10 most energetic leading interactions produce the dominant contribution. The energy of forthcoming leading reactions is comparable to the average energy of the first interaction secondaries.

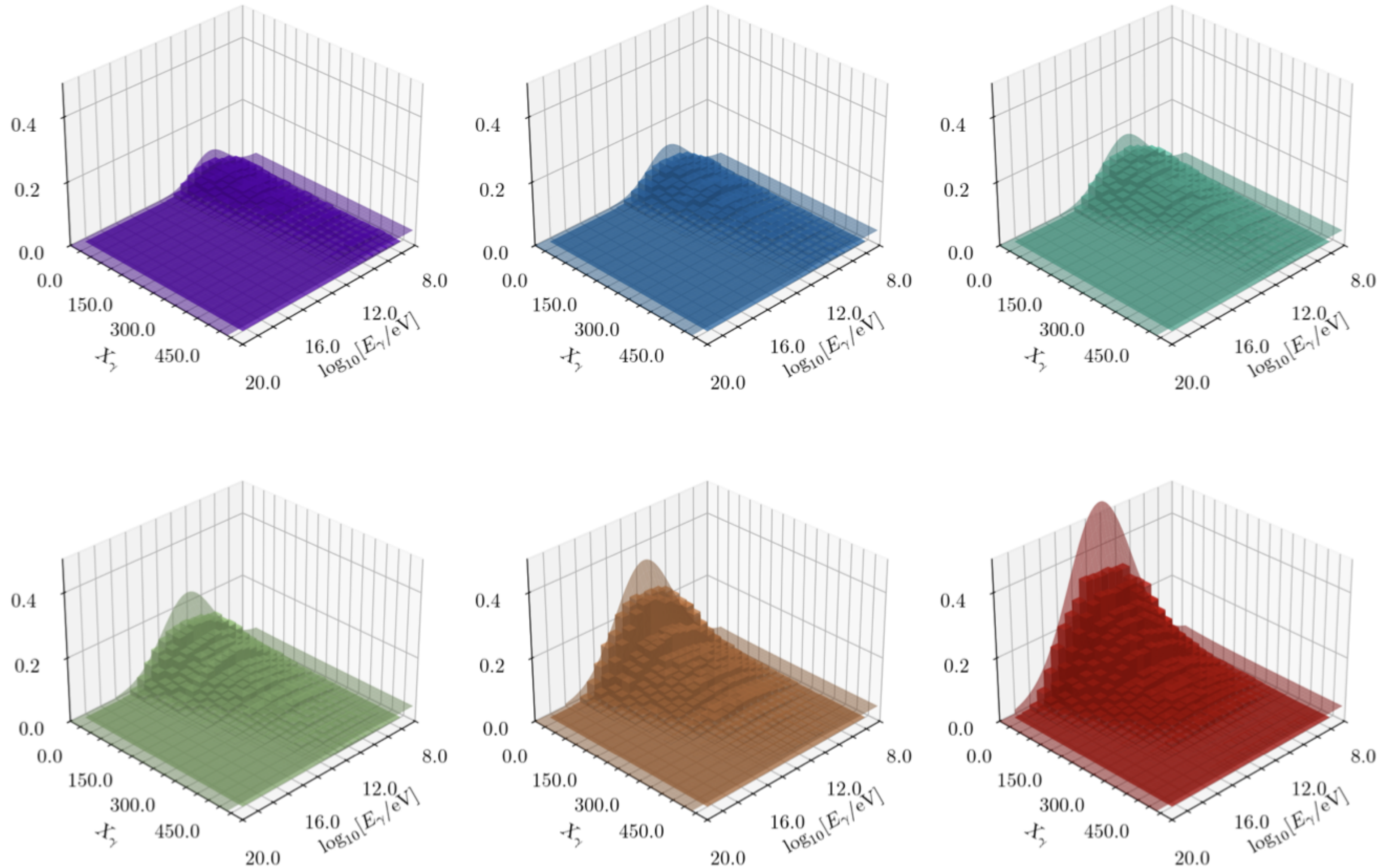
Results: Gamma Green Function



Results: Gamma Green Function



Results: High-Energy Photons Distribution



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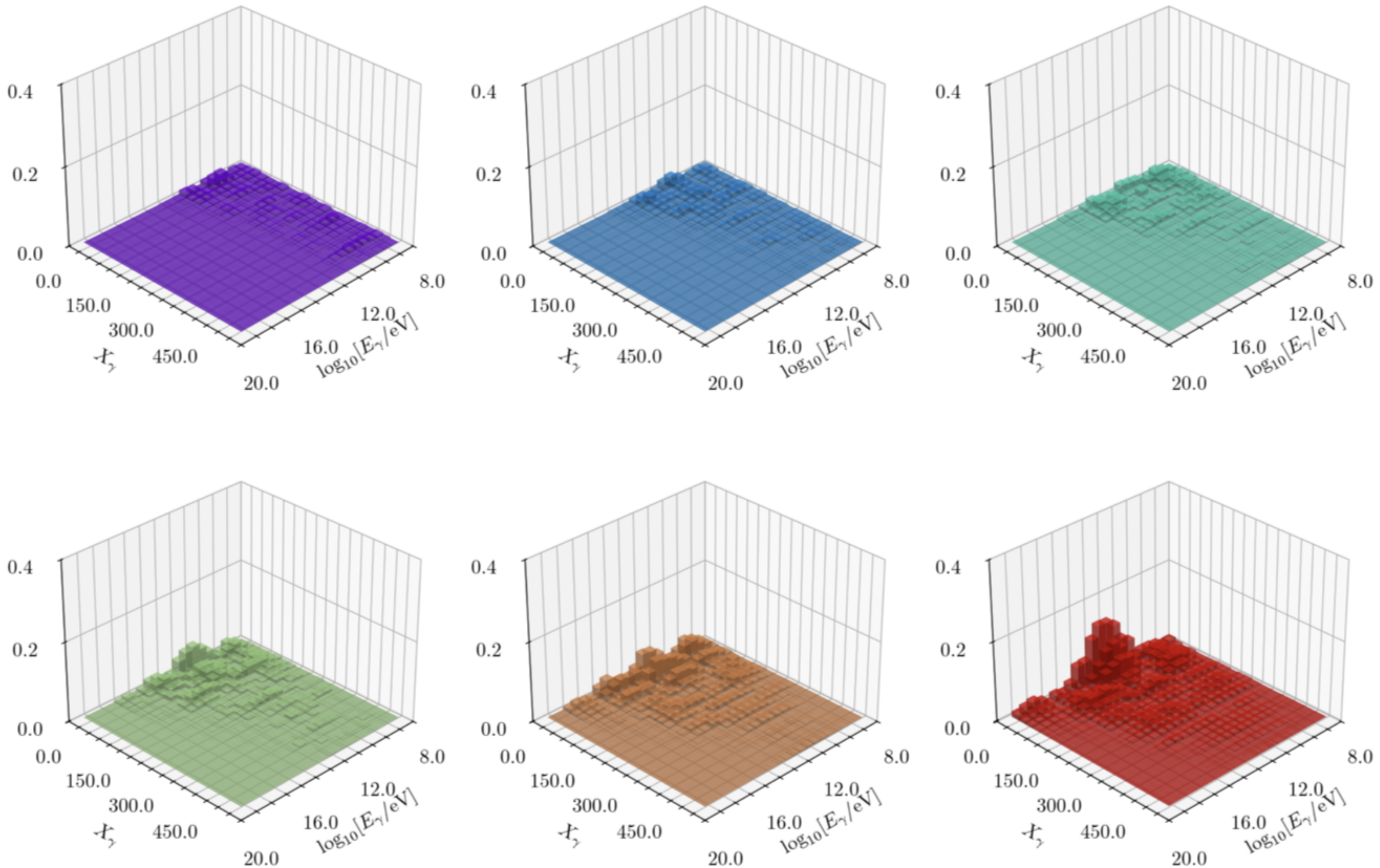

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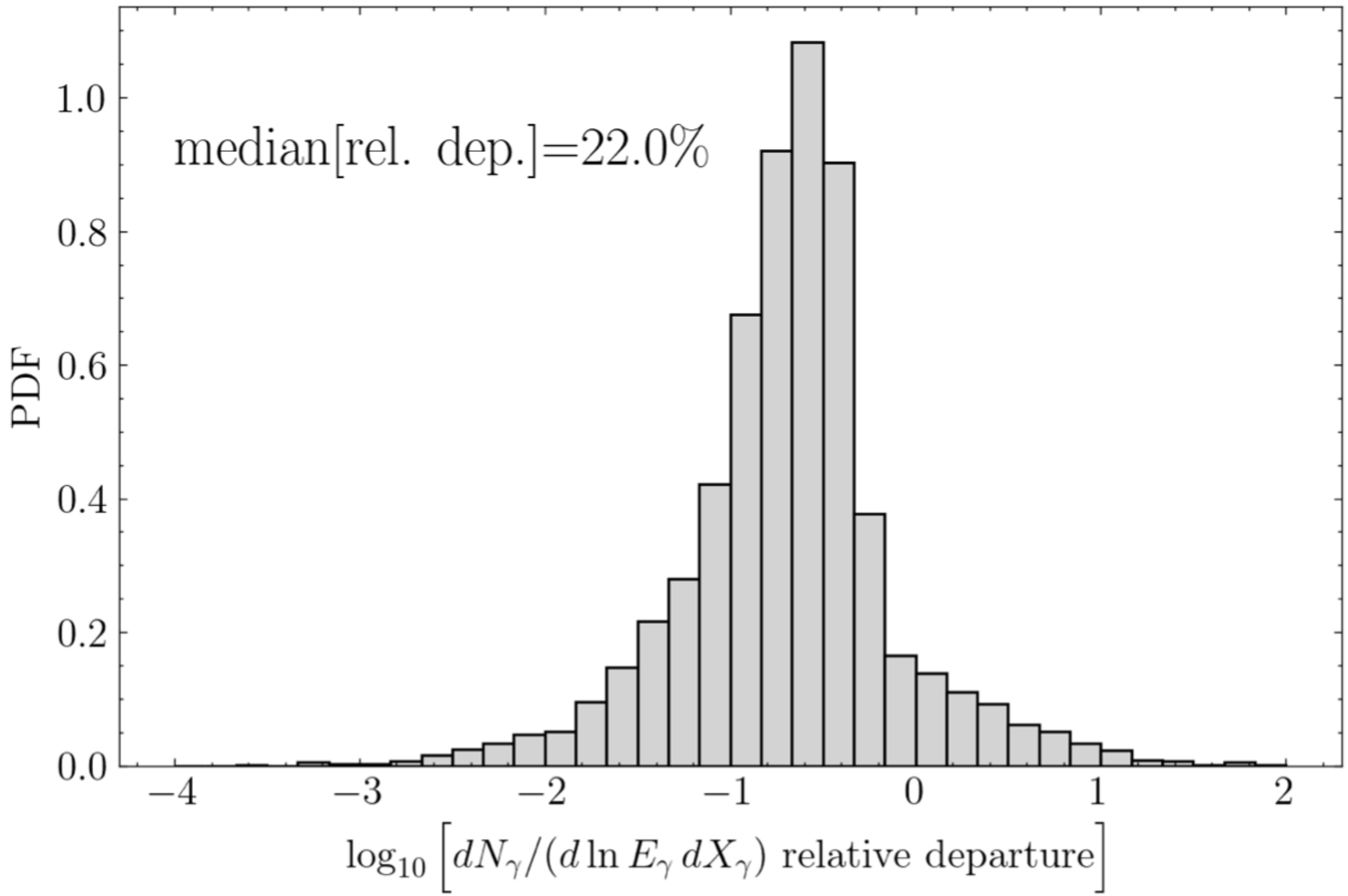
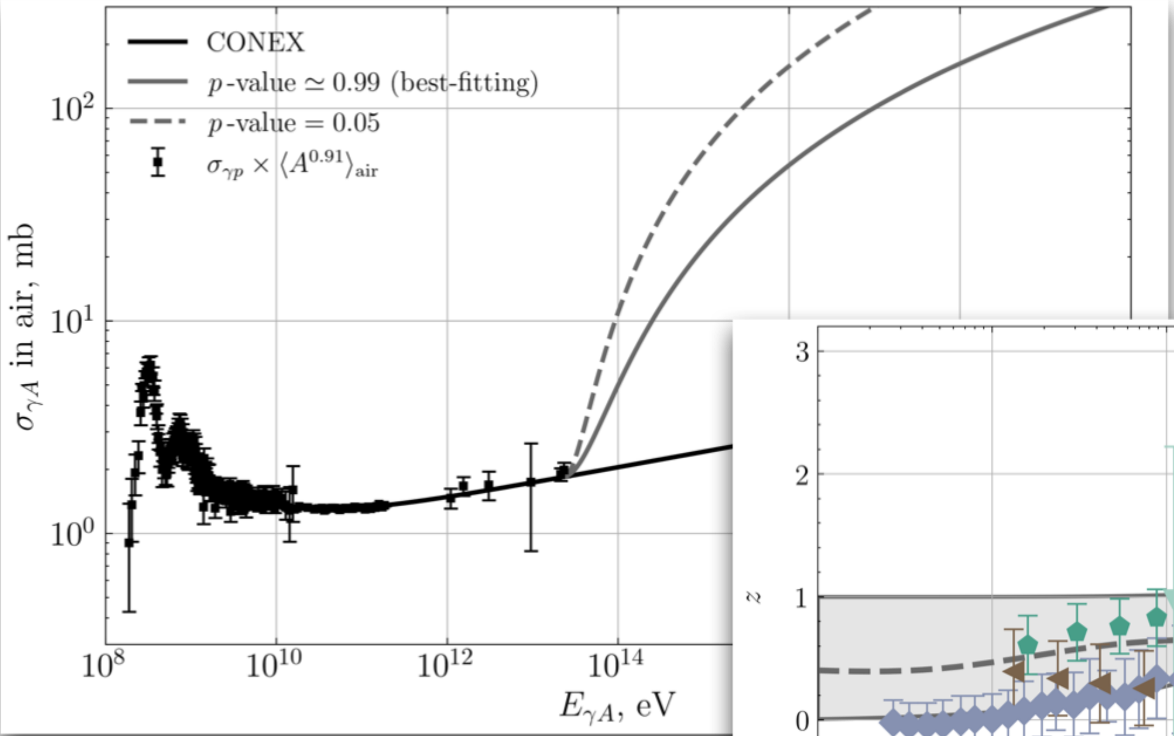
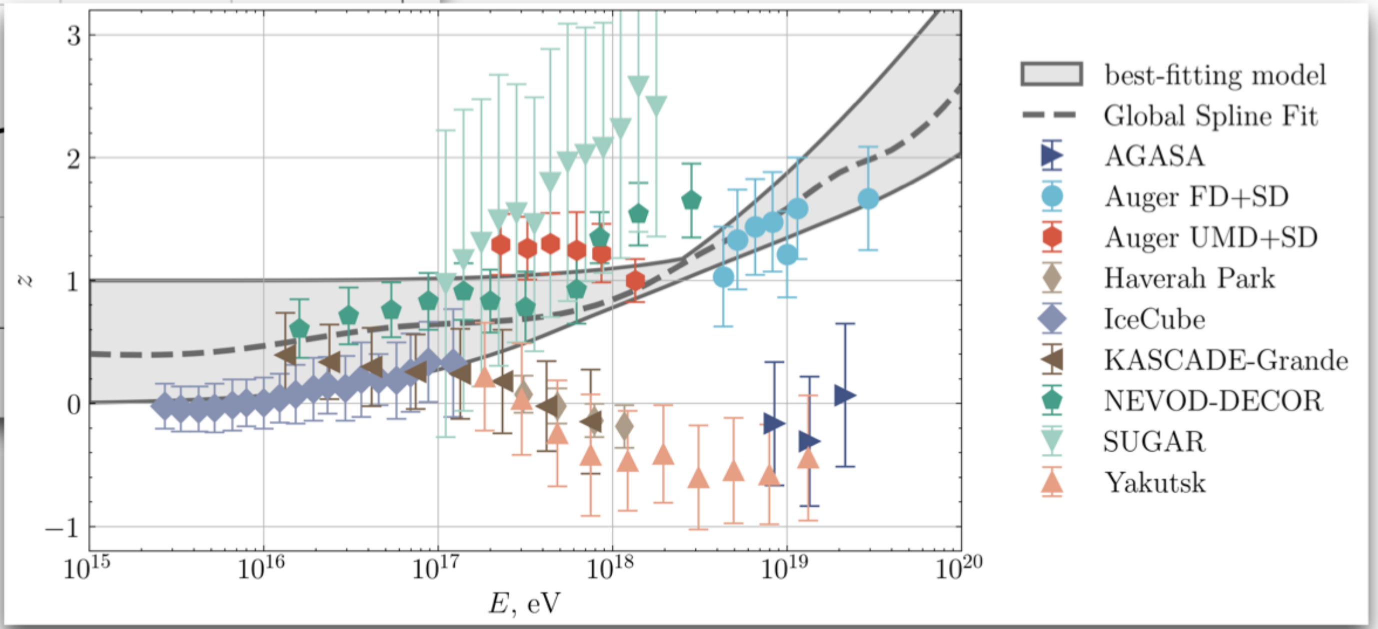


Results: Photonuclear Cross-section



$$\sigma_{\gamma A} \sim \ln(s)^2$$



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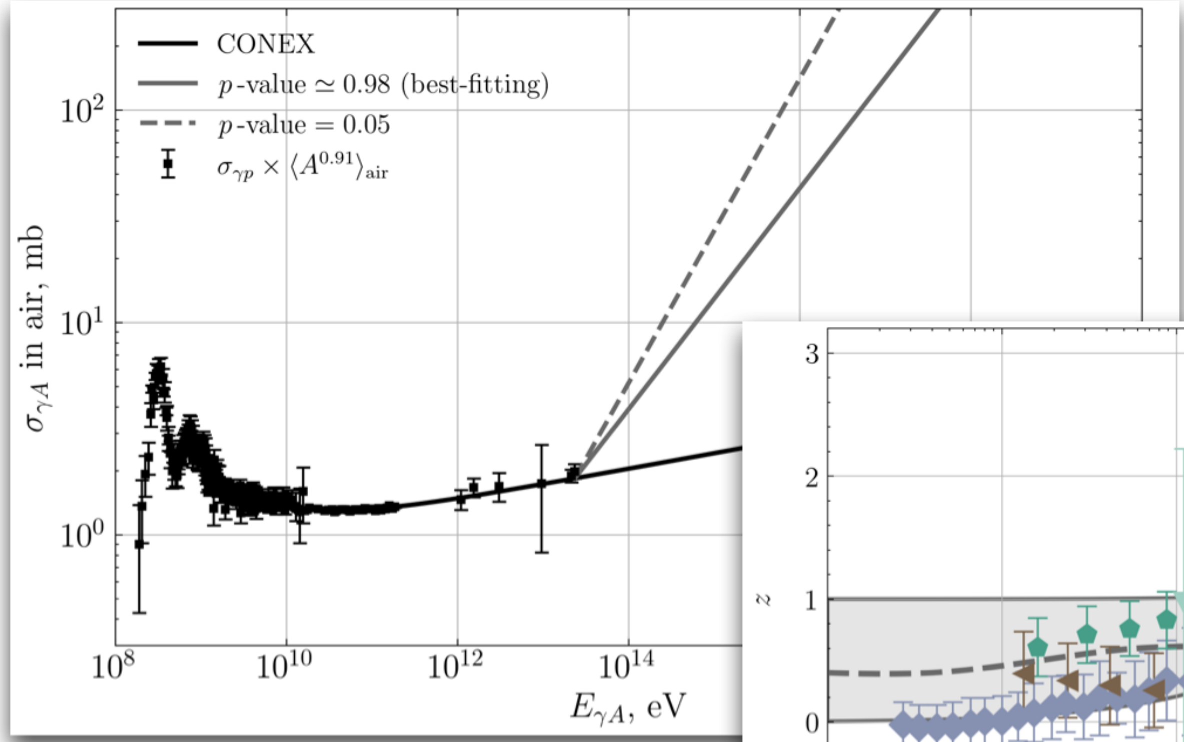
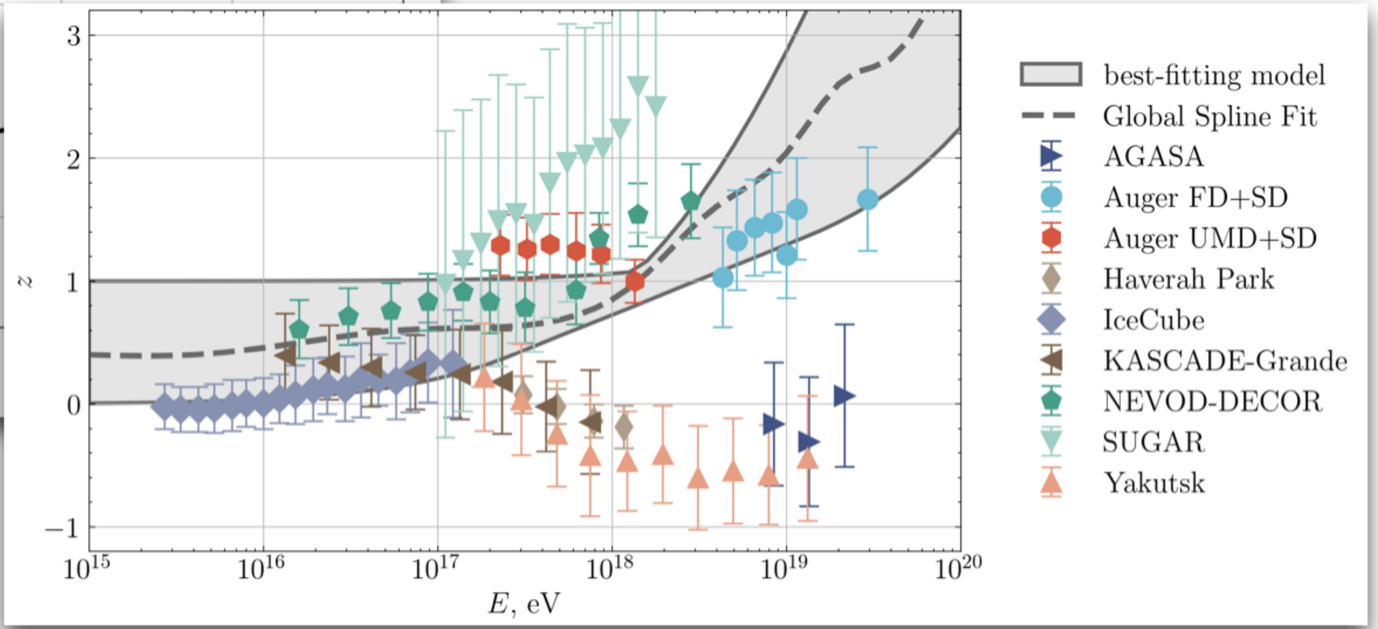


$$\sigma_{\gamma A} \sim s^{\beta}$$



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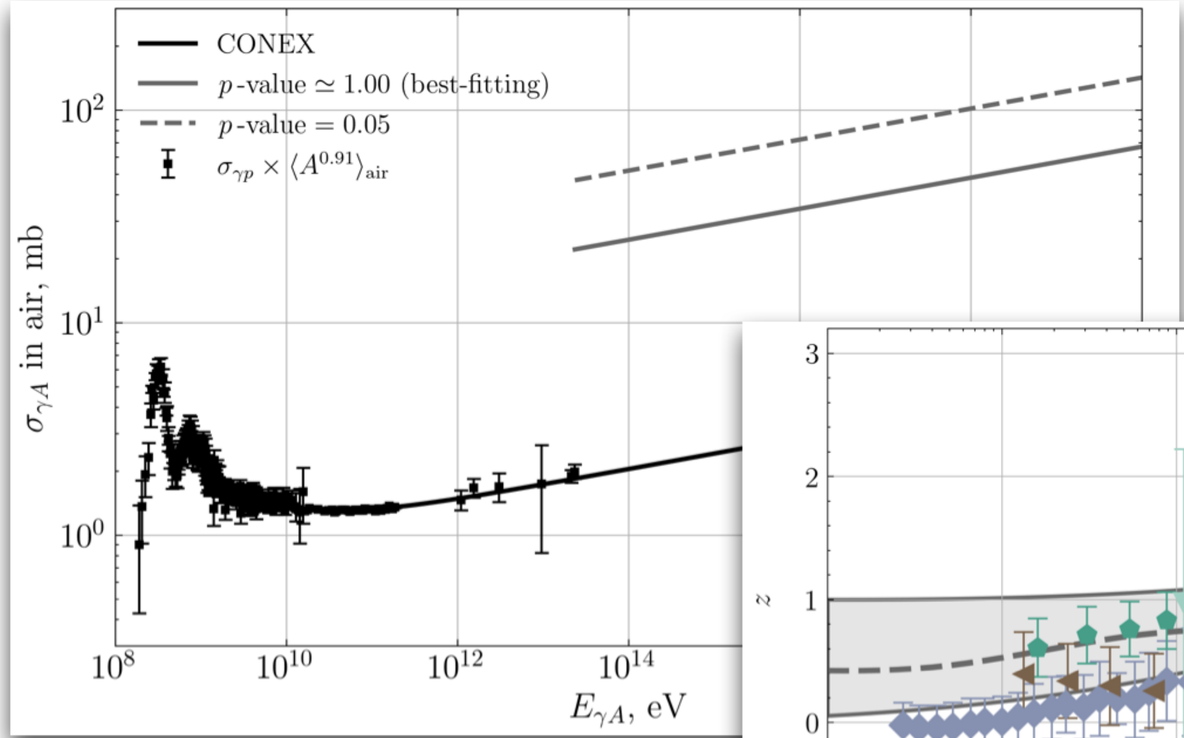
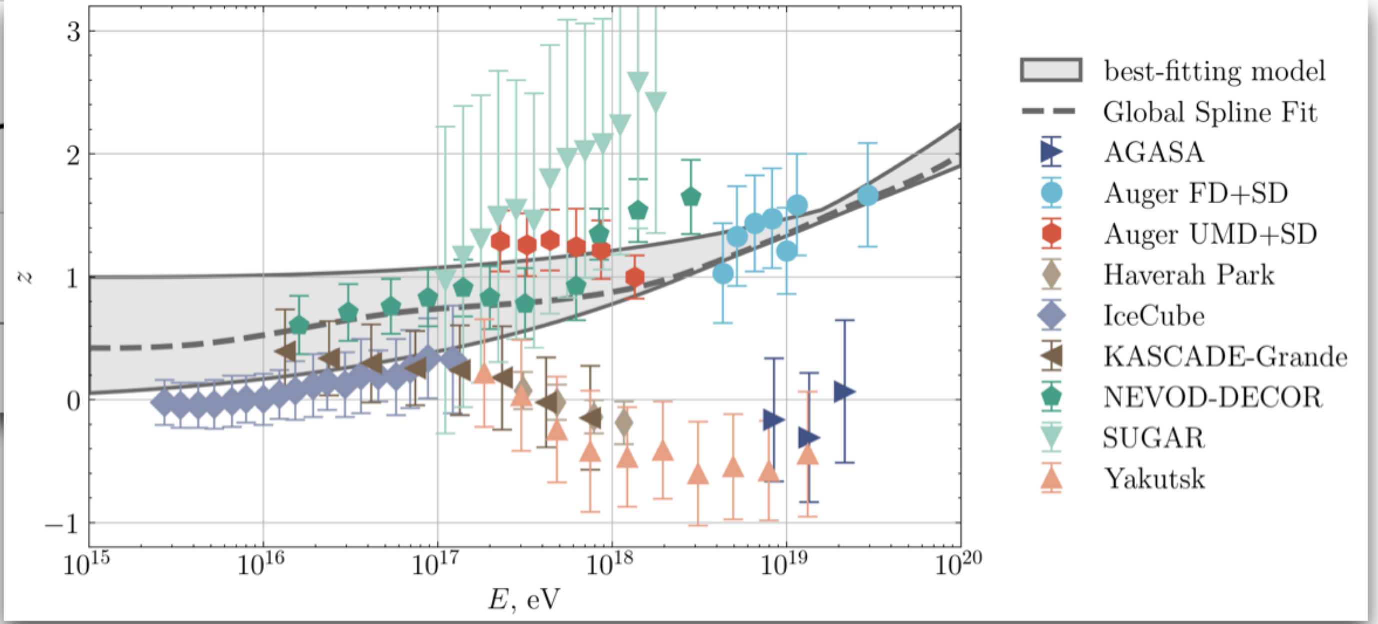


$$\sigma_{\gamma A} \sim k \cdot \sigma_{\gamma A}^{\rm CONEX}$$



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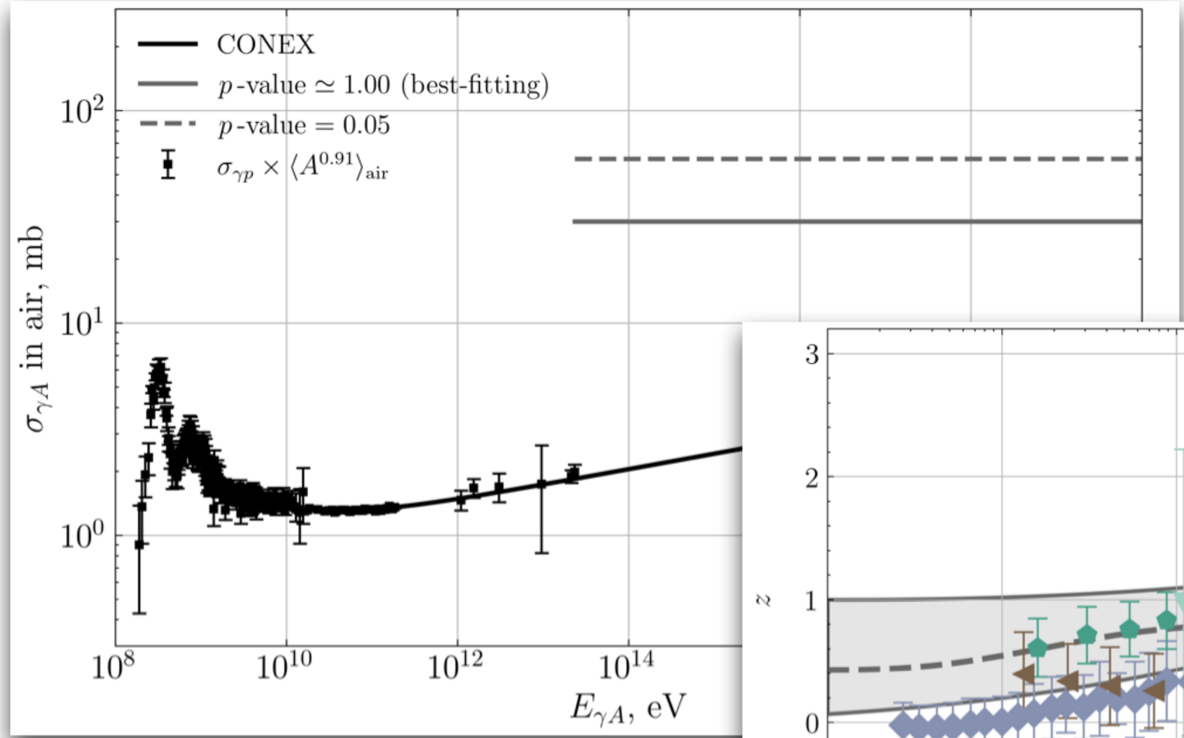
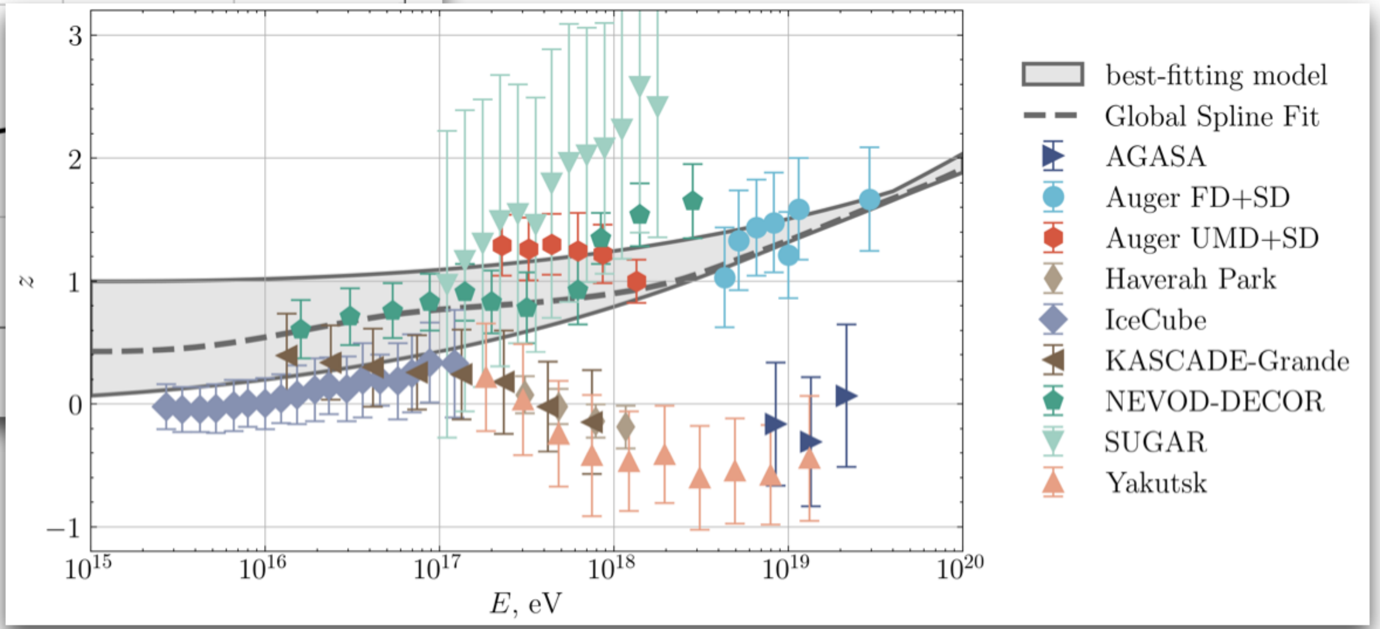


$$\sigma_{\gamma A} \sim \text{const}$$



Conclusion

- The developed 'Green Function' approach is an effective and fast method for studying the systematic uncertainty of the EASs' muon content over a wide class of photonuclear process models
- An enormous modification of the high-energy photonuclear reaction cross-section, $\sigma_{\gamma A}(E_{\gamma A} > 10^{13}\ \mathrm{eV}) \sim (10\ldots100)\ \mathrm{mb}$, could lead to a number of 'additional' muons large enough to explain $z \sim (1\ldots2)$
- On the other hand, $\sigma_{\gamma A}(E_{\gamma A} > 10^{13}\ \mathrm{eV}) \gtrsim 100\ \mathrm{mb}$ is excluded at high confidence level from observations (direct constraints on the photonuclear cross-section from the EASs' muon content!)
- Further detailed analysis is needed: inclined showers?.. modification threshold?.. muon-rich gamma showers?..

Muon-rich Gamma Showers: Preliminary