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High-energy Photonuclear Reactions & Muon Content of Extensive Air Showers

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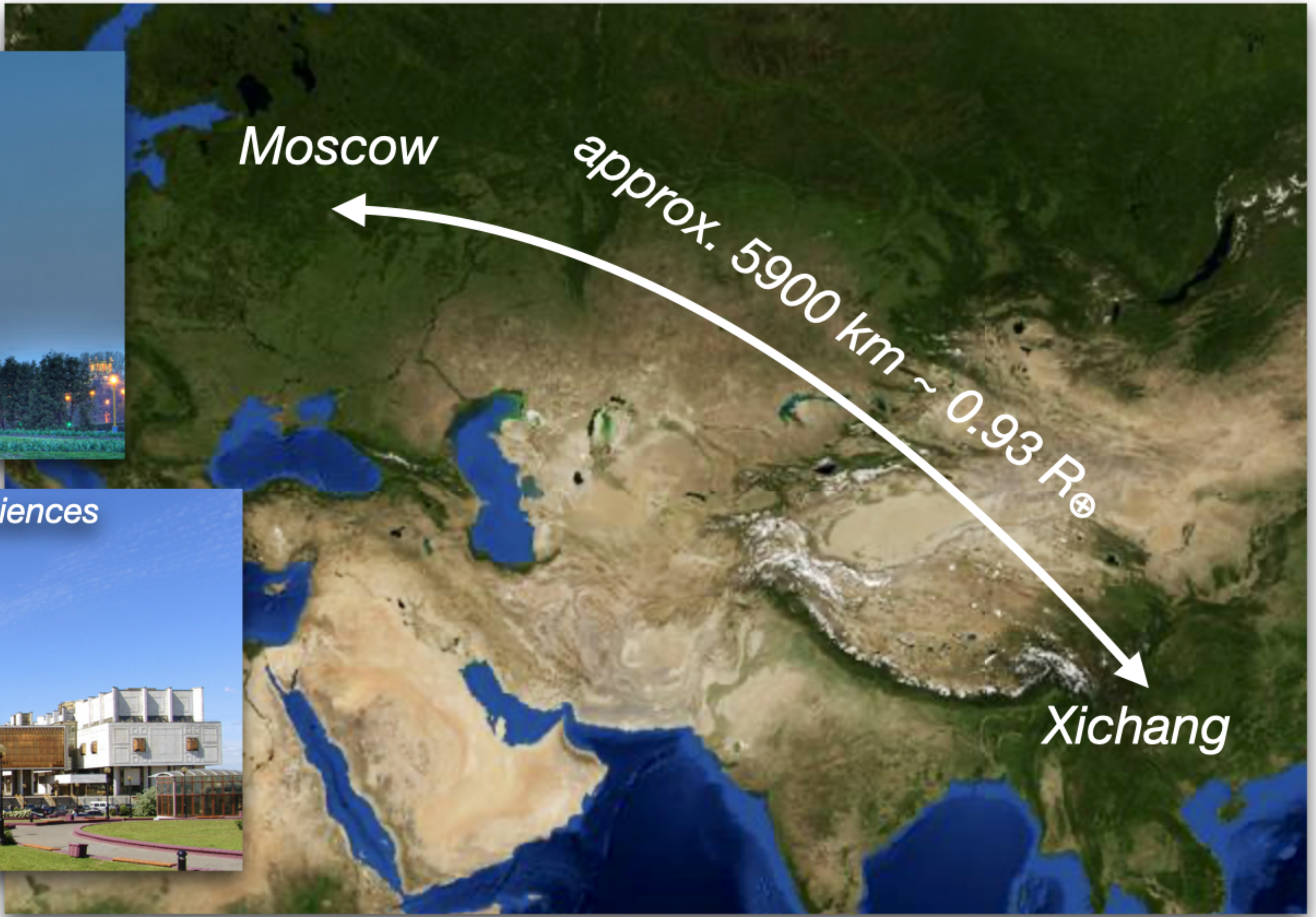
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approx. 5900 km ~ 0.93 R⊕
Xichang

Outline of the Talk

- Motivation: Muon Puzzle
- Photonuclear Reaction Cross-section
- Muon Profiles Systematic Uncertainty
- Limitations & Interesting Physical Implications
- Conclusions

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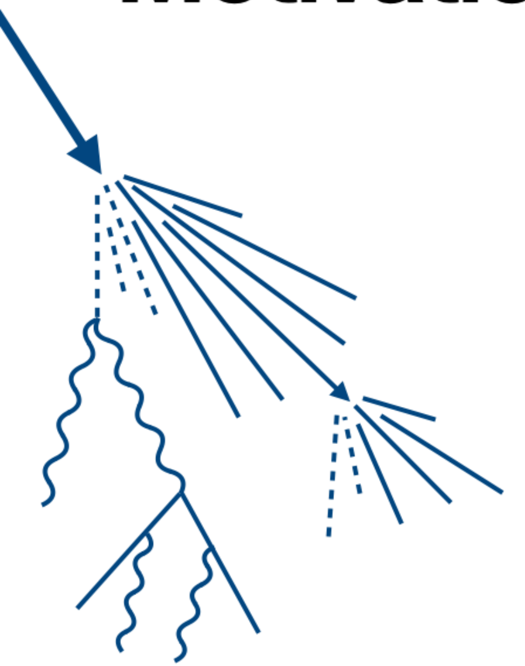

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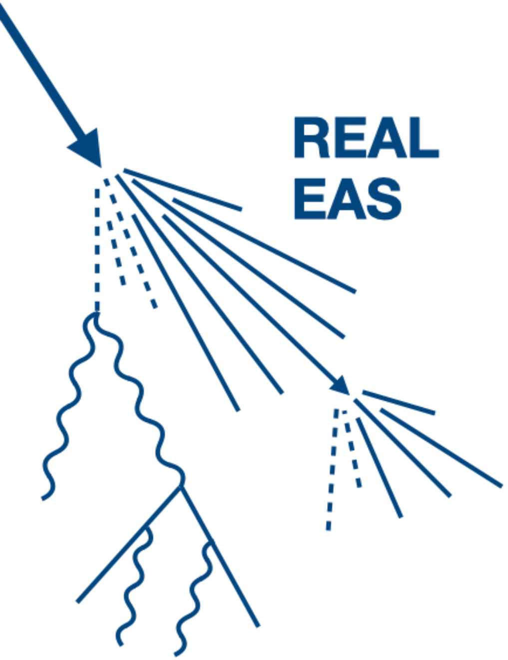

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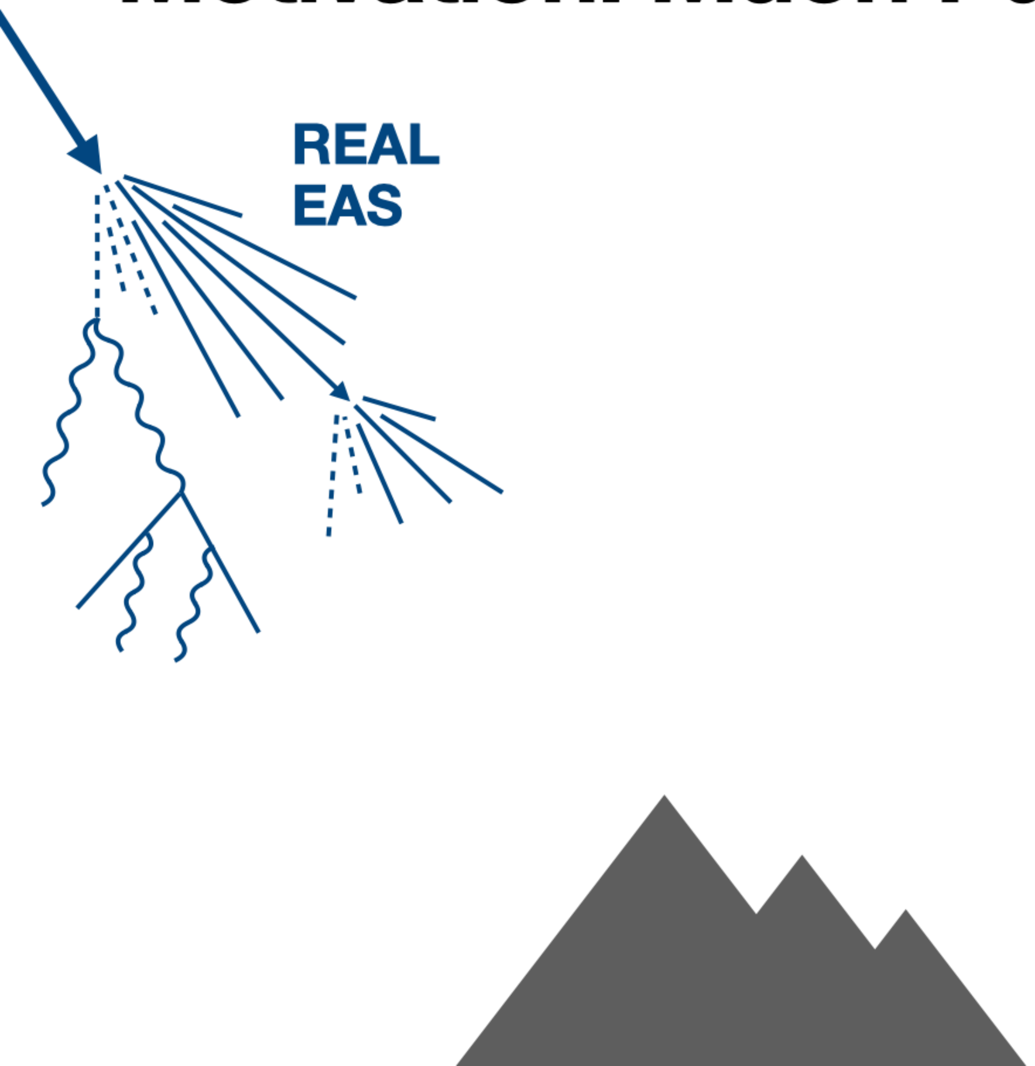

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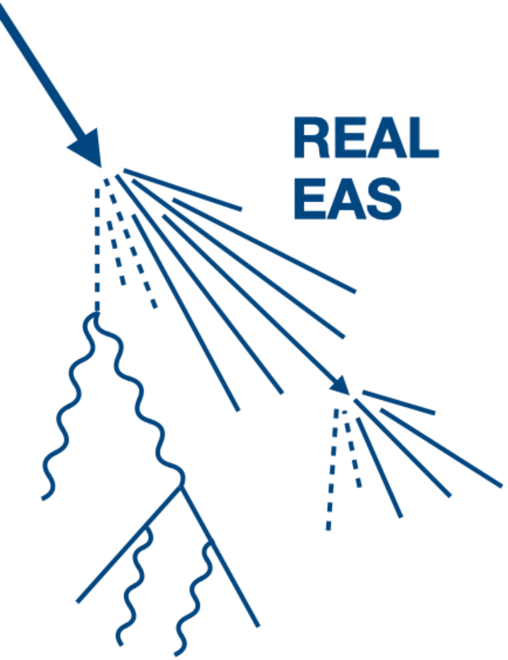

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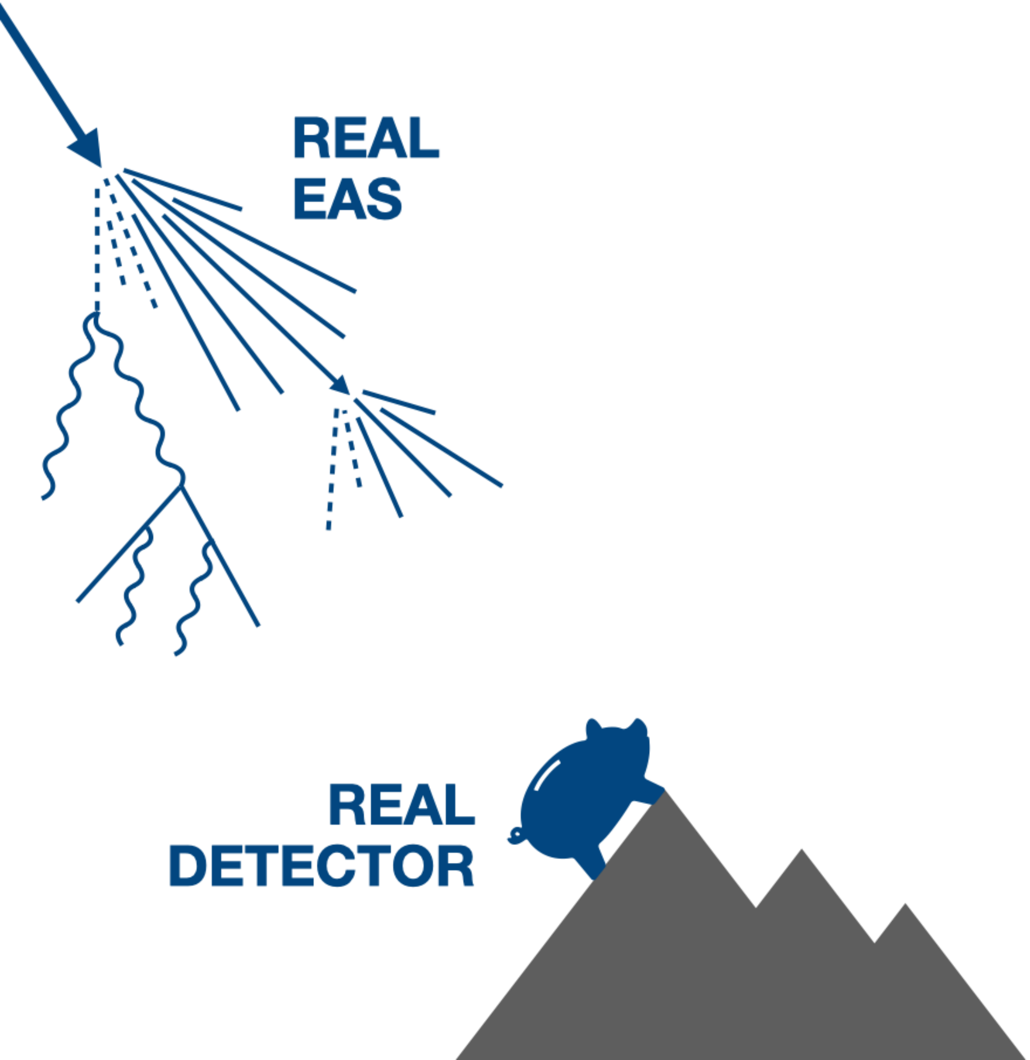

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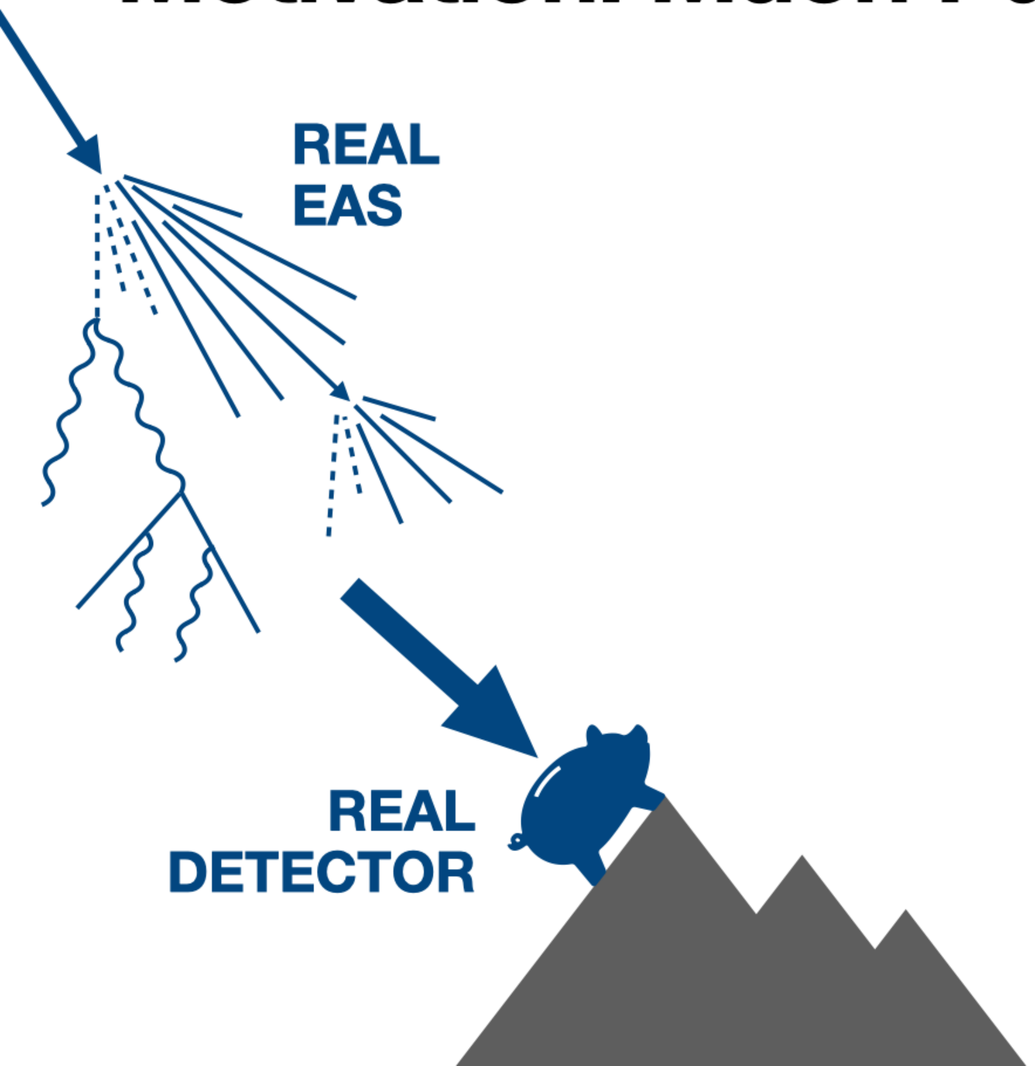

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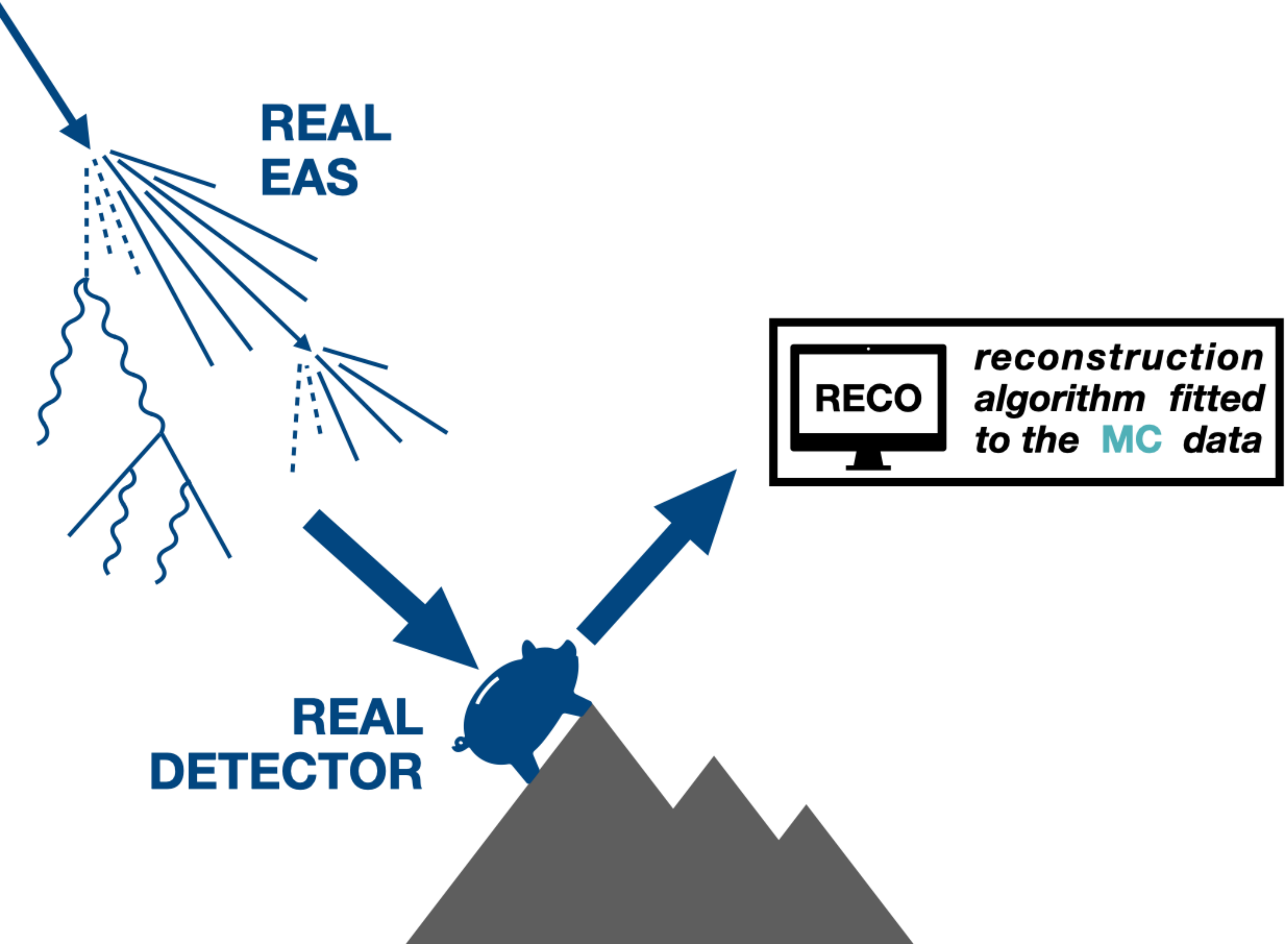

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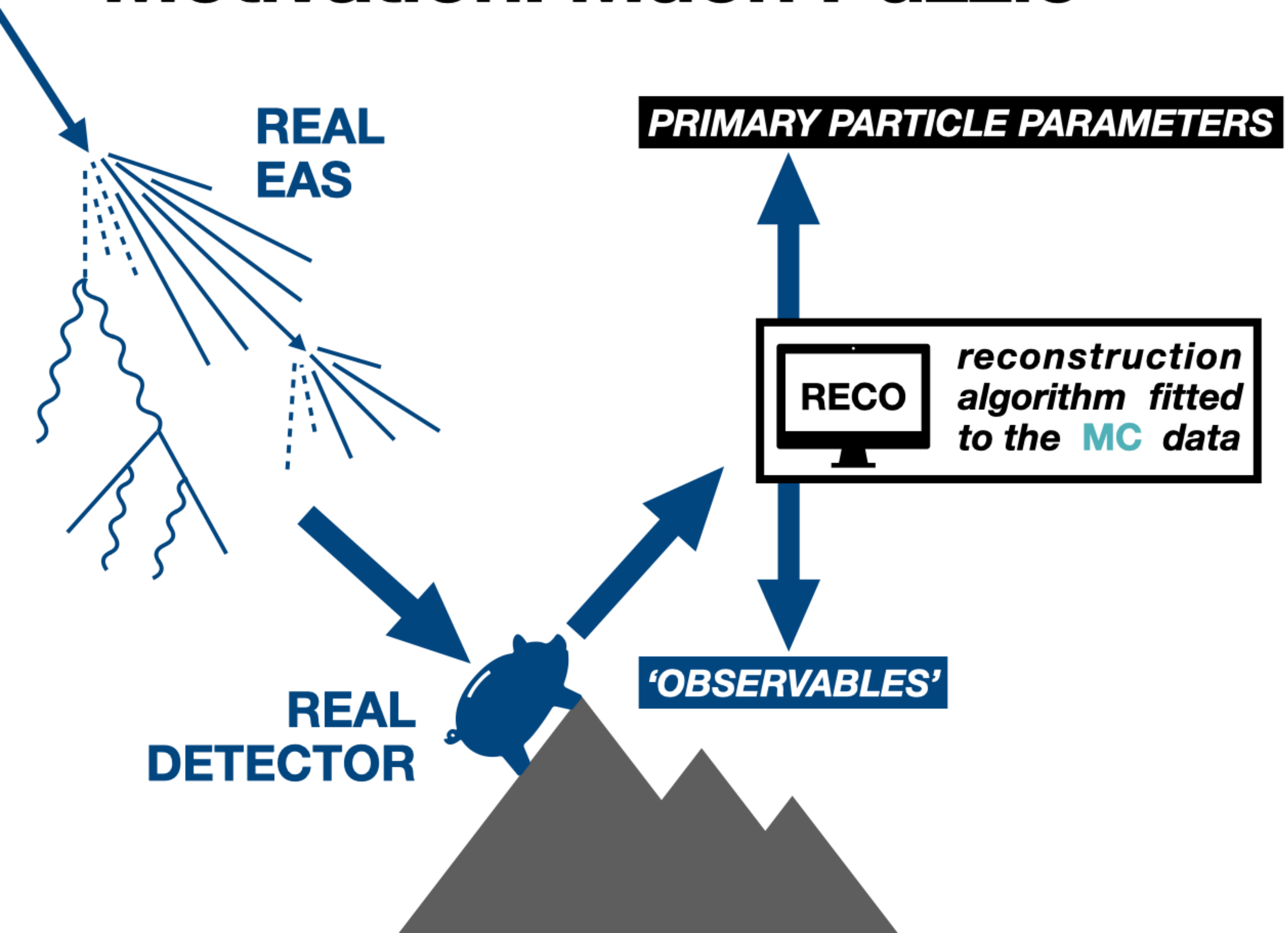

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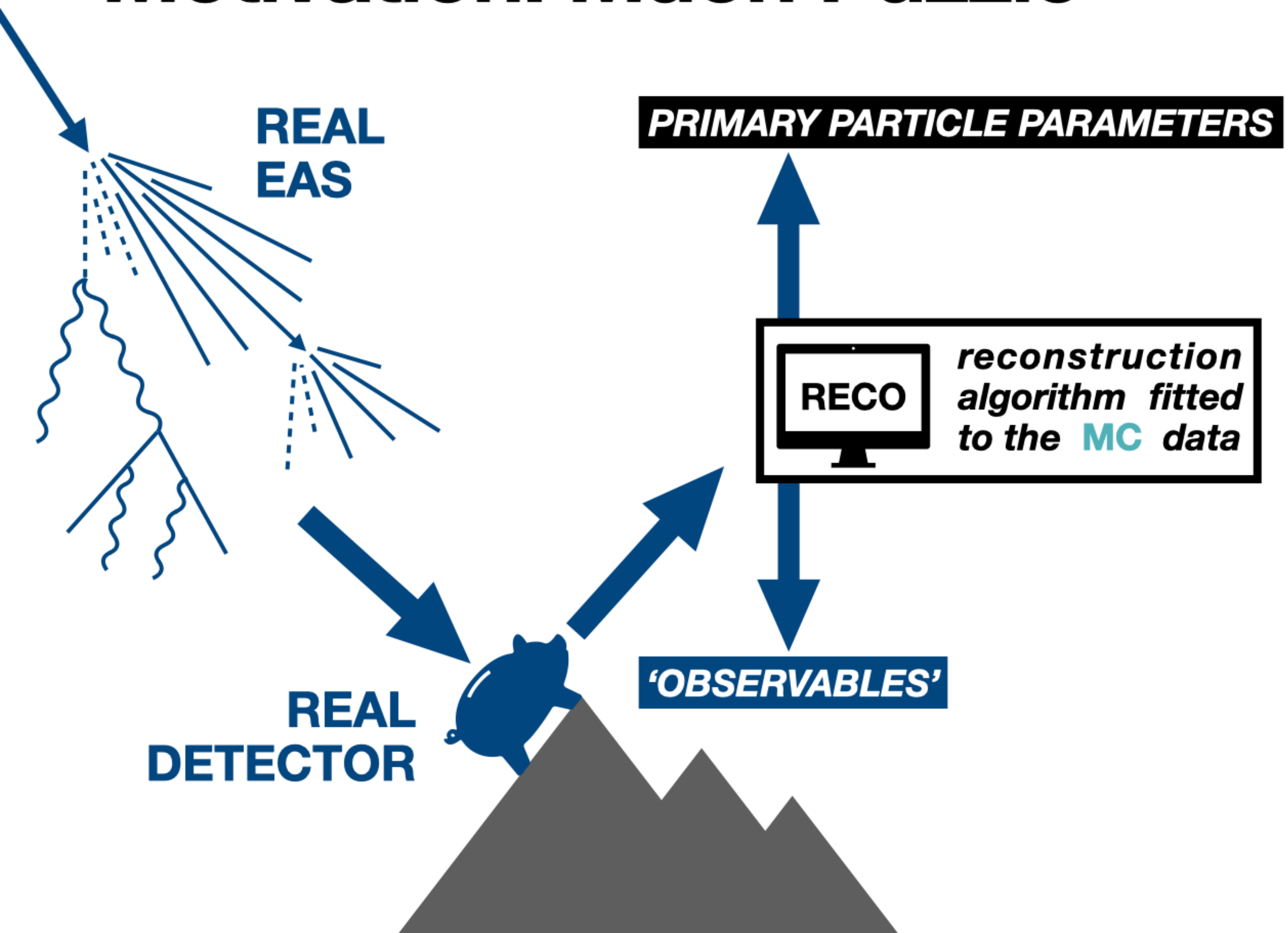
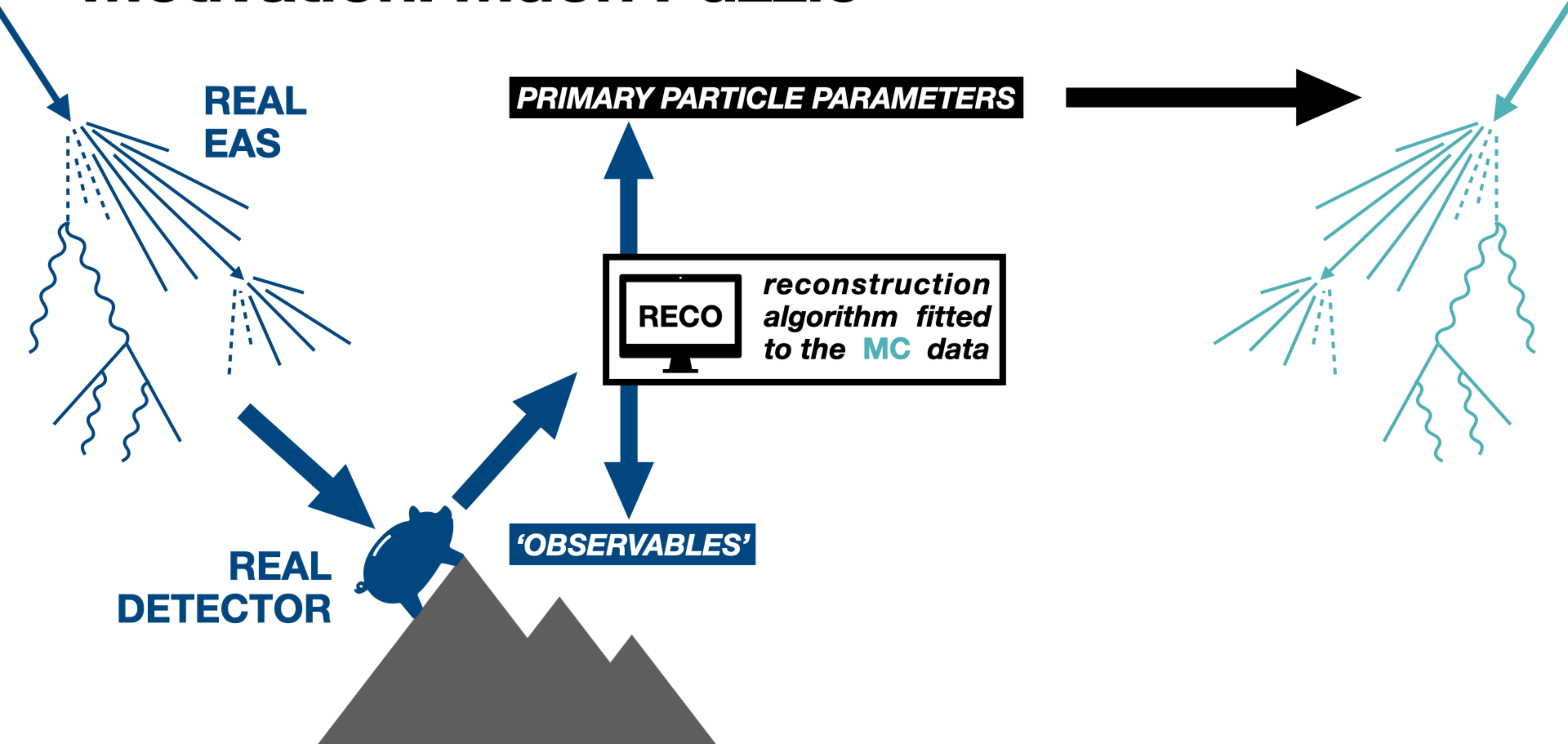


?

can one trust these outputs?

Motivation: Muon Puzzle



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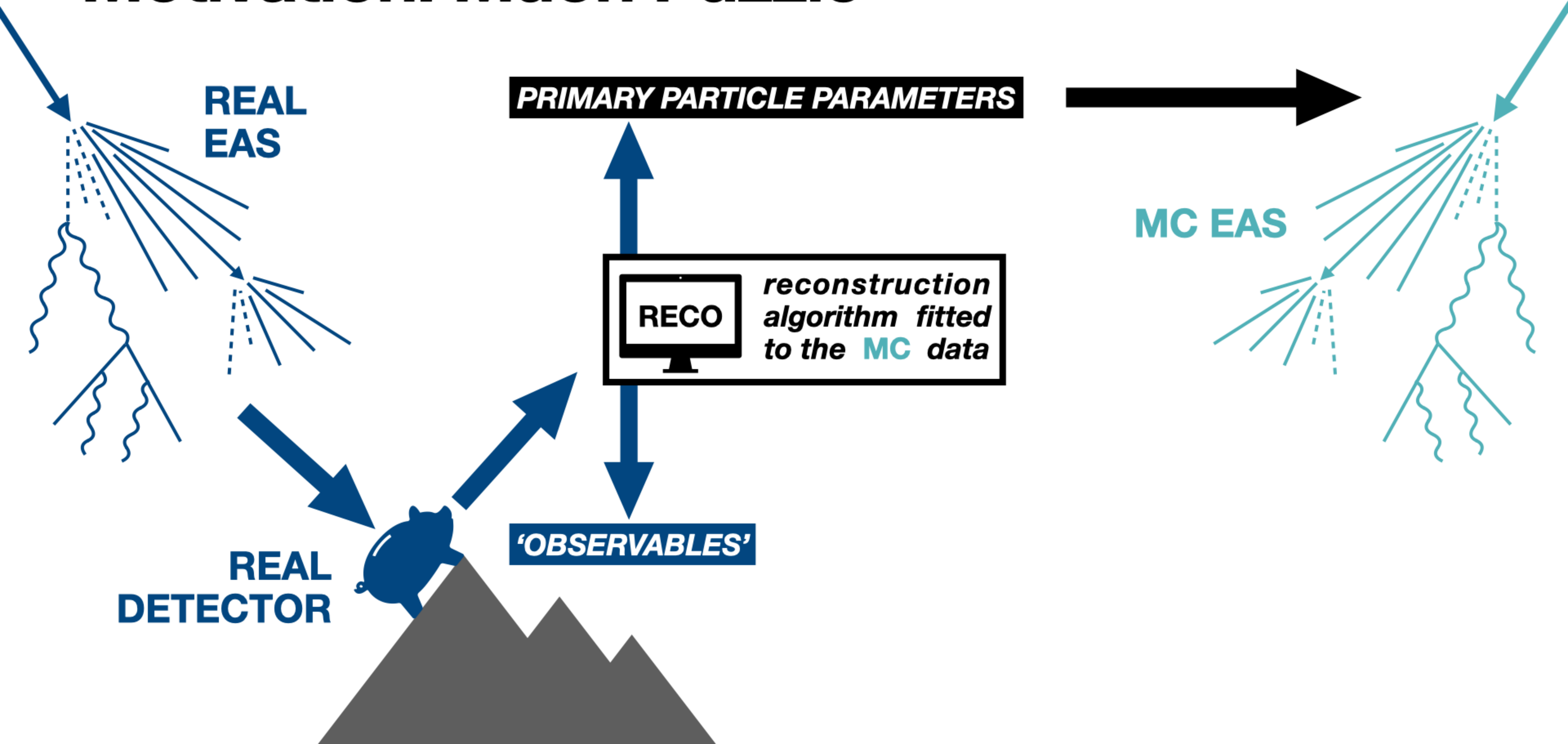

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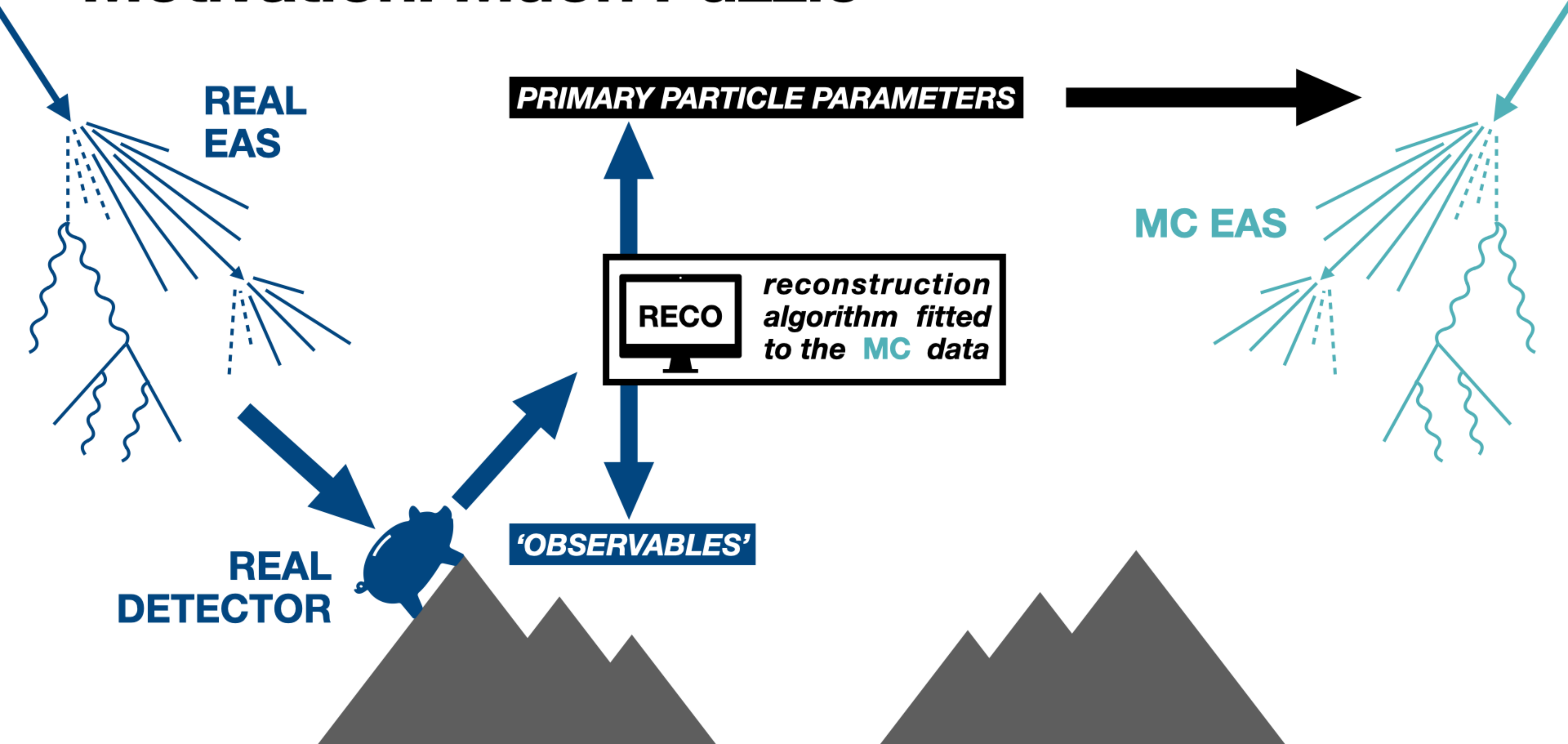

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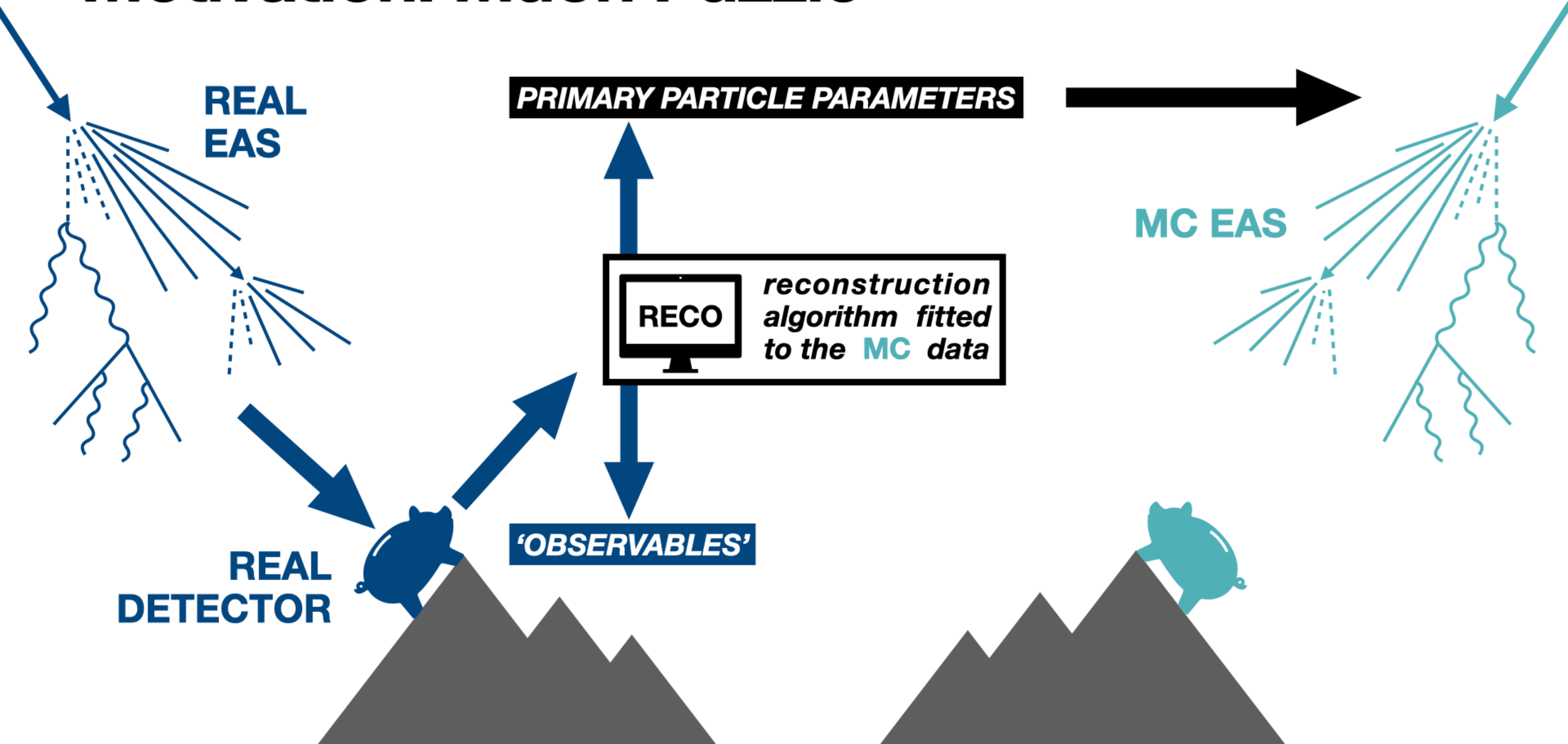

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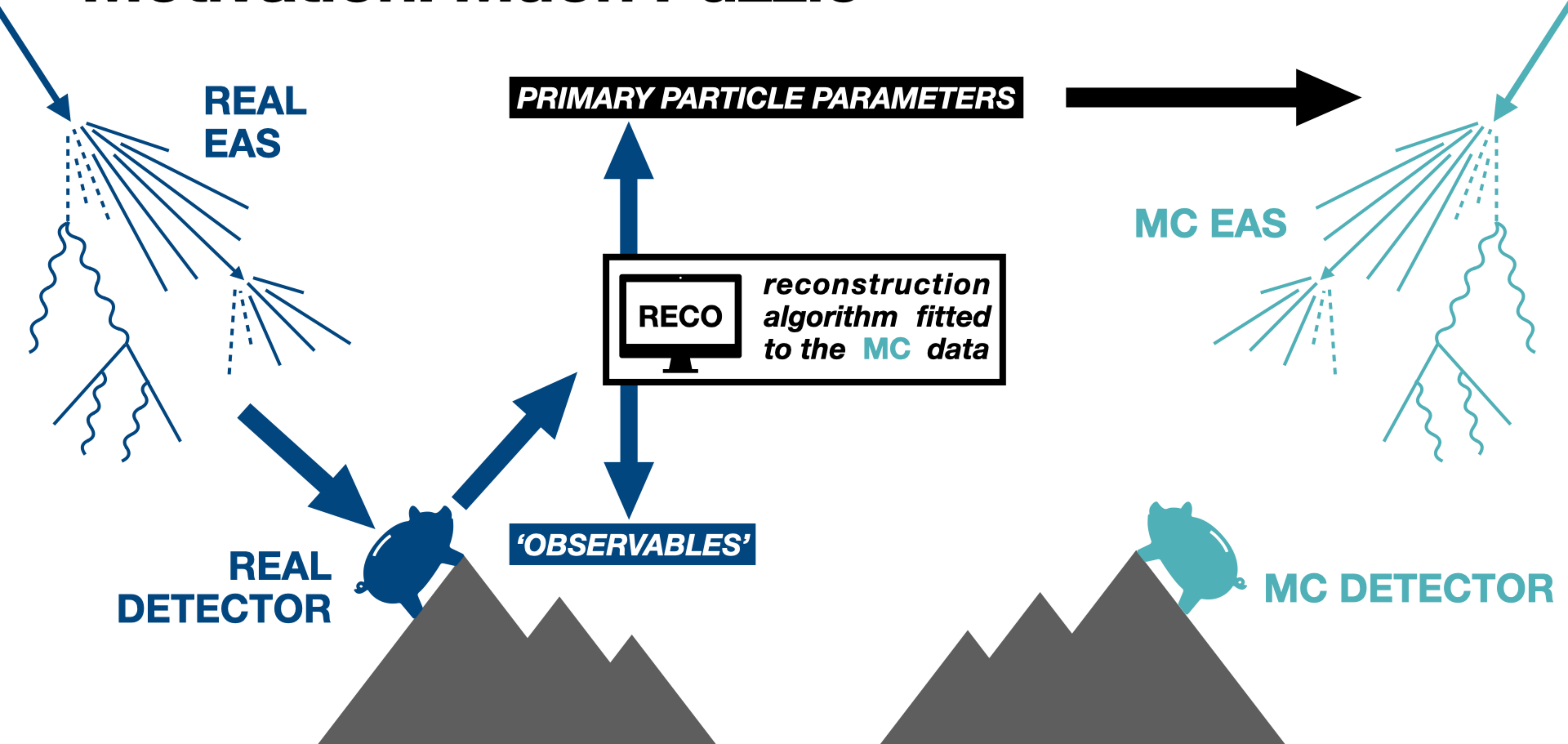

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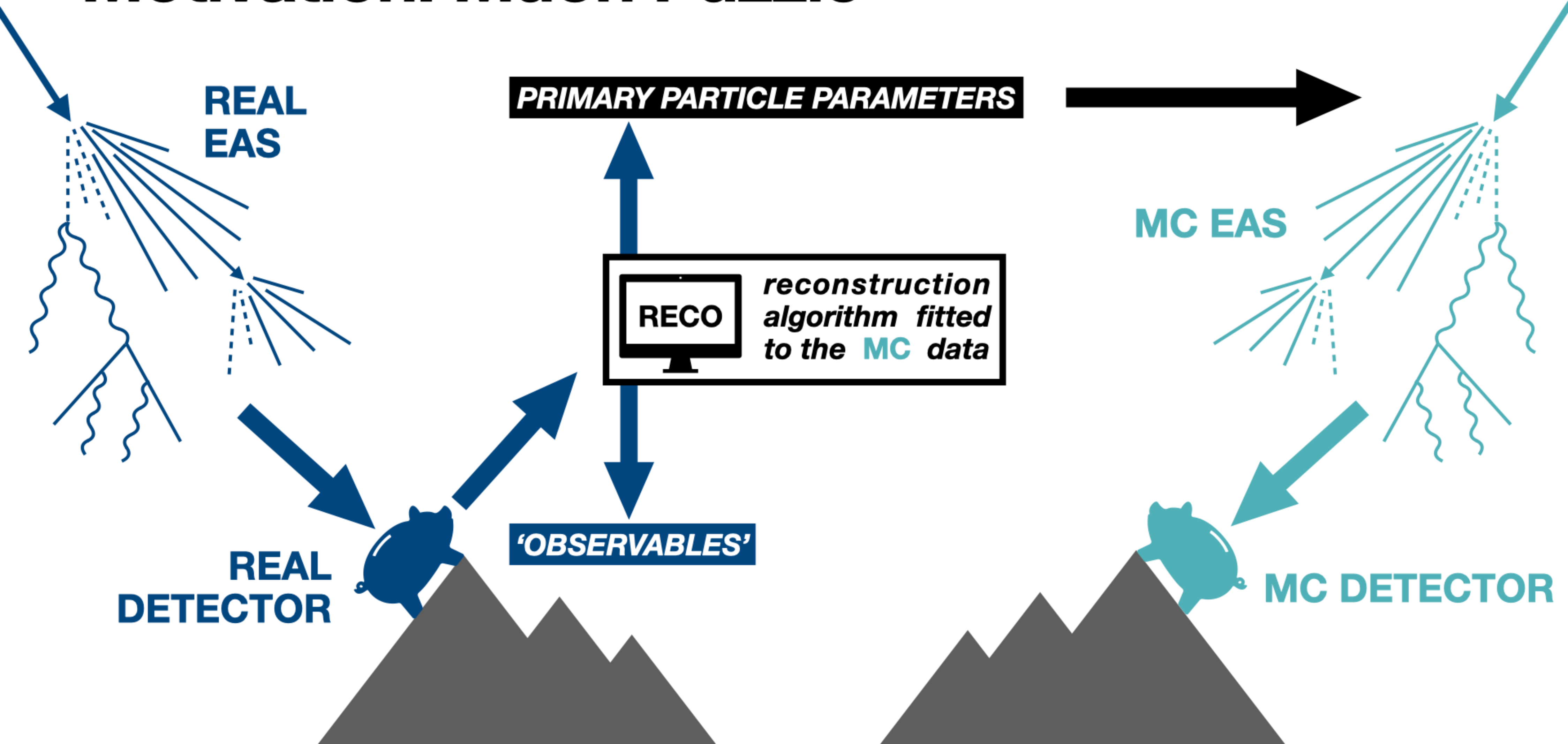

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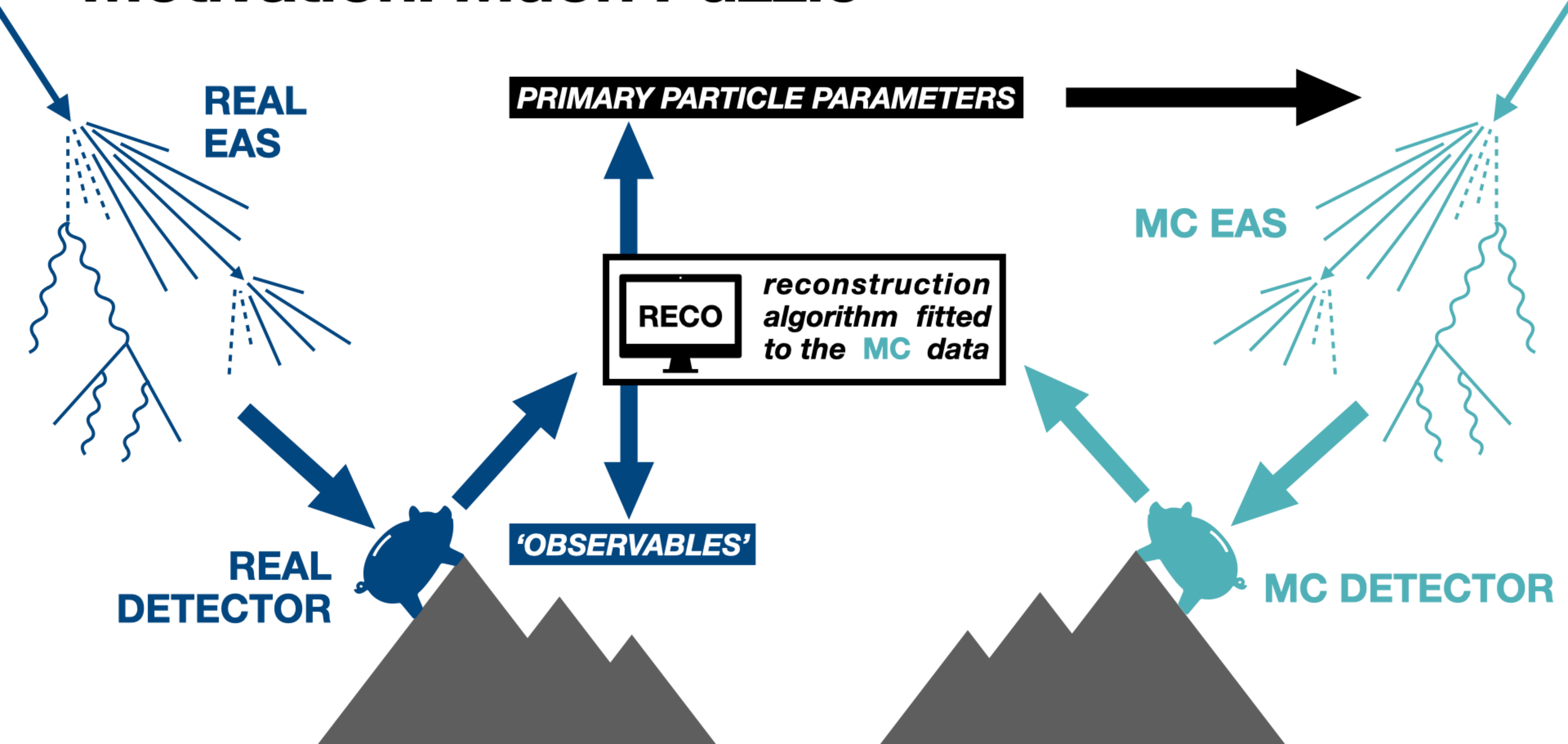

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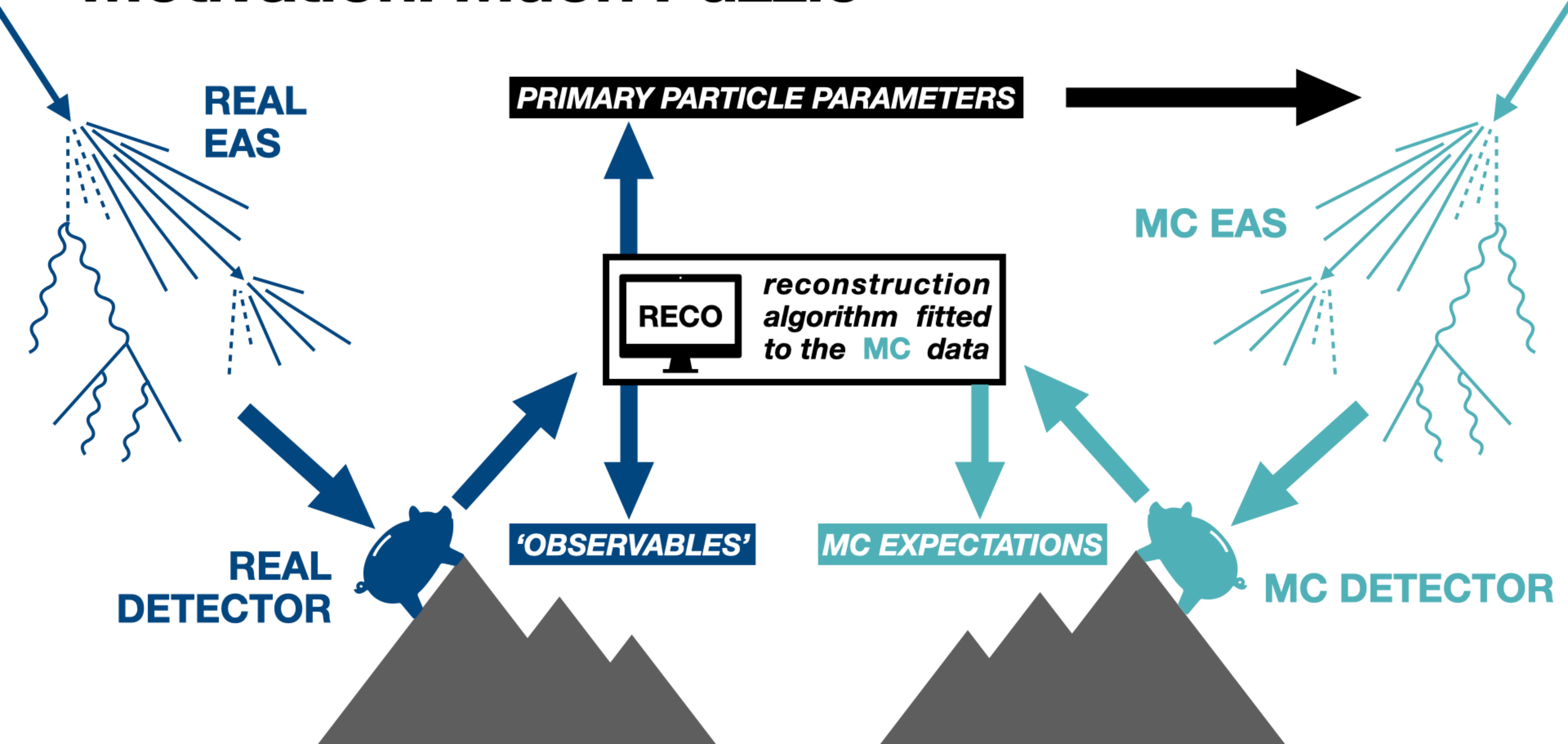

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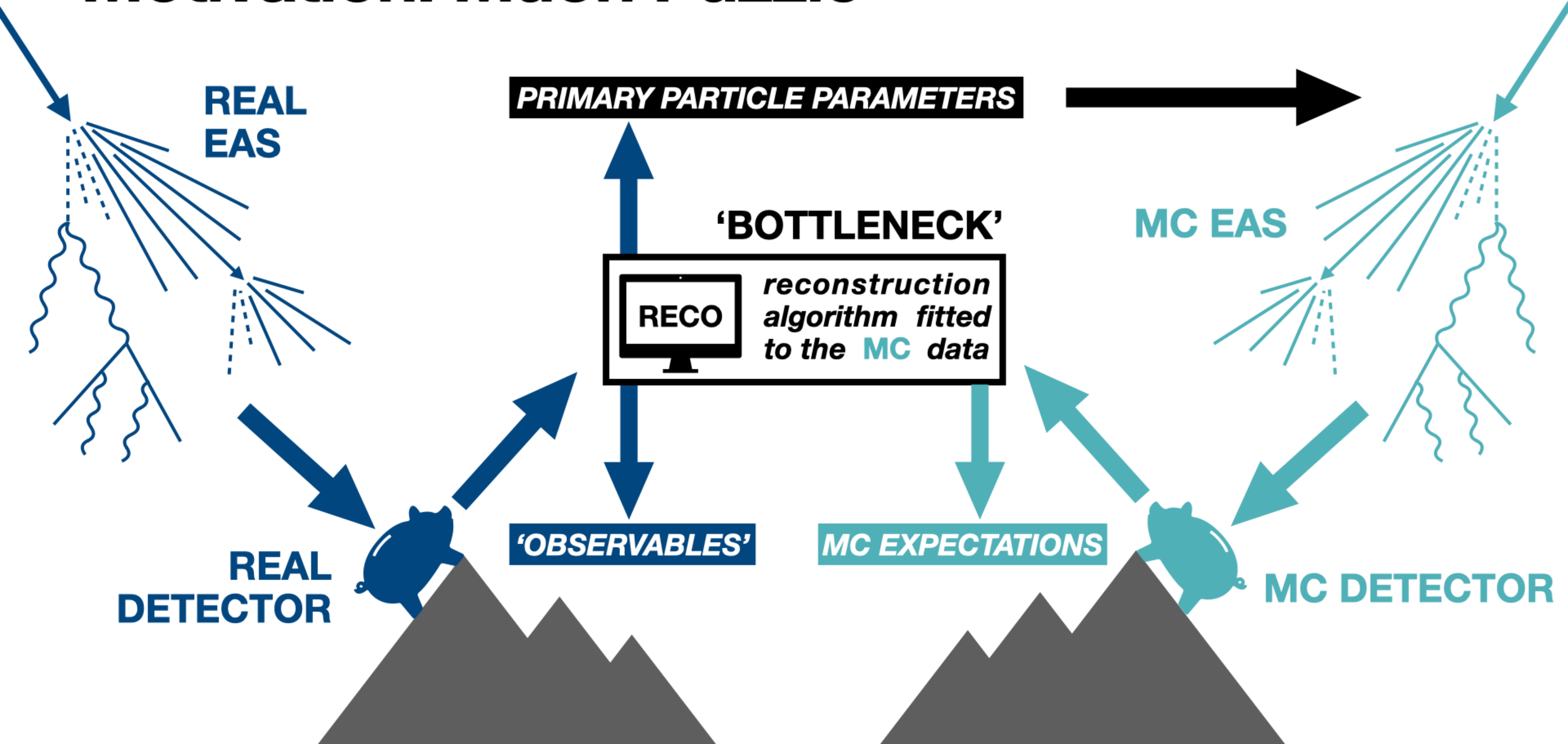

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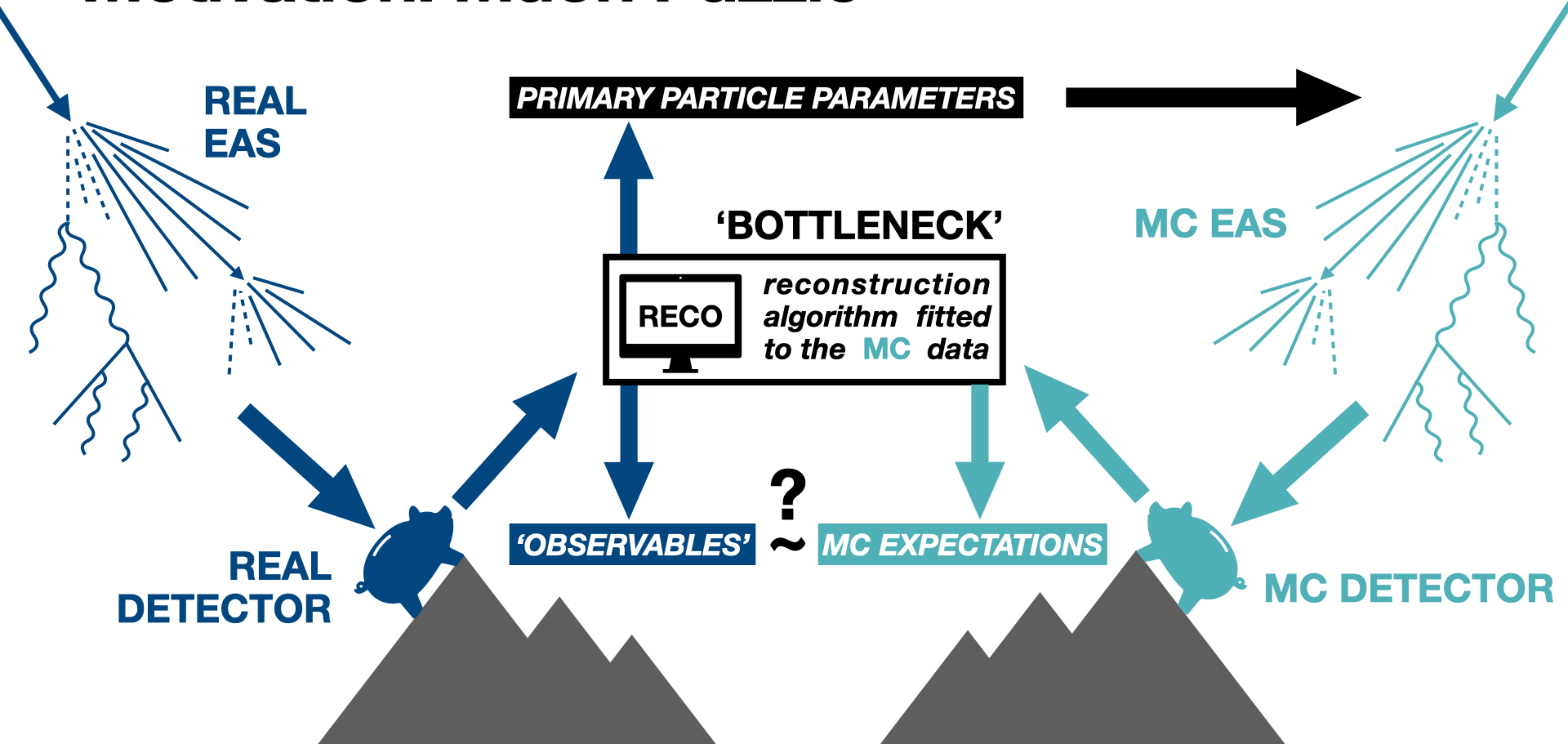

Motivation: Muon Puzzle

'OBSERVABLES' $\overset{?}{\sim}$ *MC EXPECTATIONS*

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'OBSERVABLES' $\overset{?}{\sim}$ **MC EXPECTATIONS**

$N_\mu^{\mathrm{obs}}(\mathrm{primary} = \mathrm{unknown})$

$N_\mu^{\mathrm{MC}}(\mathrm{primary} = p, \ldots, {}^{56}\mathrm{Fe})$

Motivation: Muon Puzzle

'OBSERVABLES' $\overset{?}{\sim}$ **MC EXPECTATIONS**

$N_\mu^{\rm obs}(\text{primary} = \text{unknown})$

$N_\mu^{\rm MC}(\text{primary} = p, \ldots, {}^{56}\text{Fe})$

z-measure:

$$z \equiv \frac{\ln[N_\mu^{\rm obs}] - \ln[N_\mu^{\rm MC}(p)]}{\ln[N_\mu^{\rm MC}({}^{56}\text{Fe})] - \ln[N_\mu^{\rm MC}(p)]}$$

Motivation: Muon Puzzle

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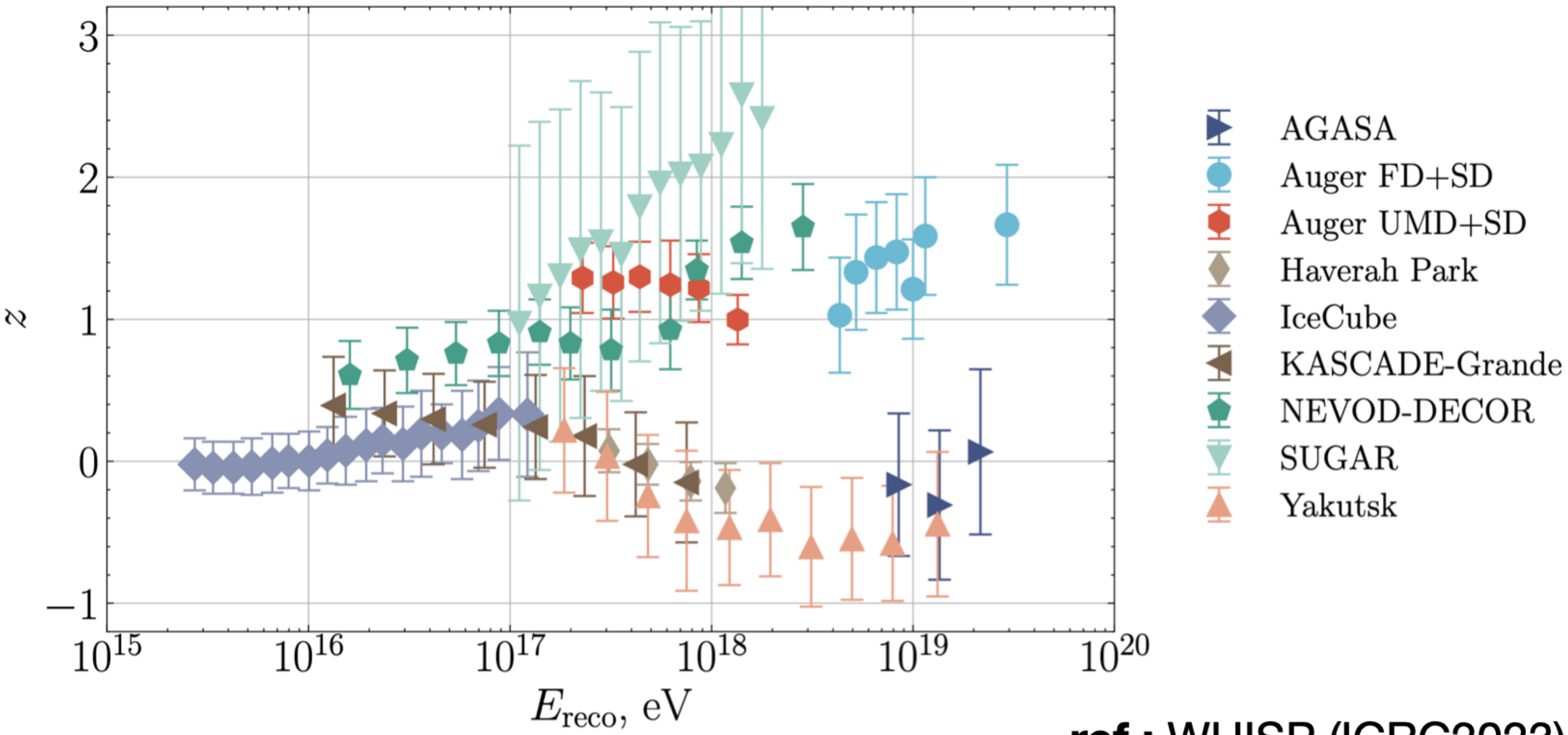
$\forall$ ***reasonable chemical composition*** $0 \leq z \leq 1$

Motivation: Muon Puzzle



ref.: WHISP (ICRC2023)

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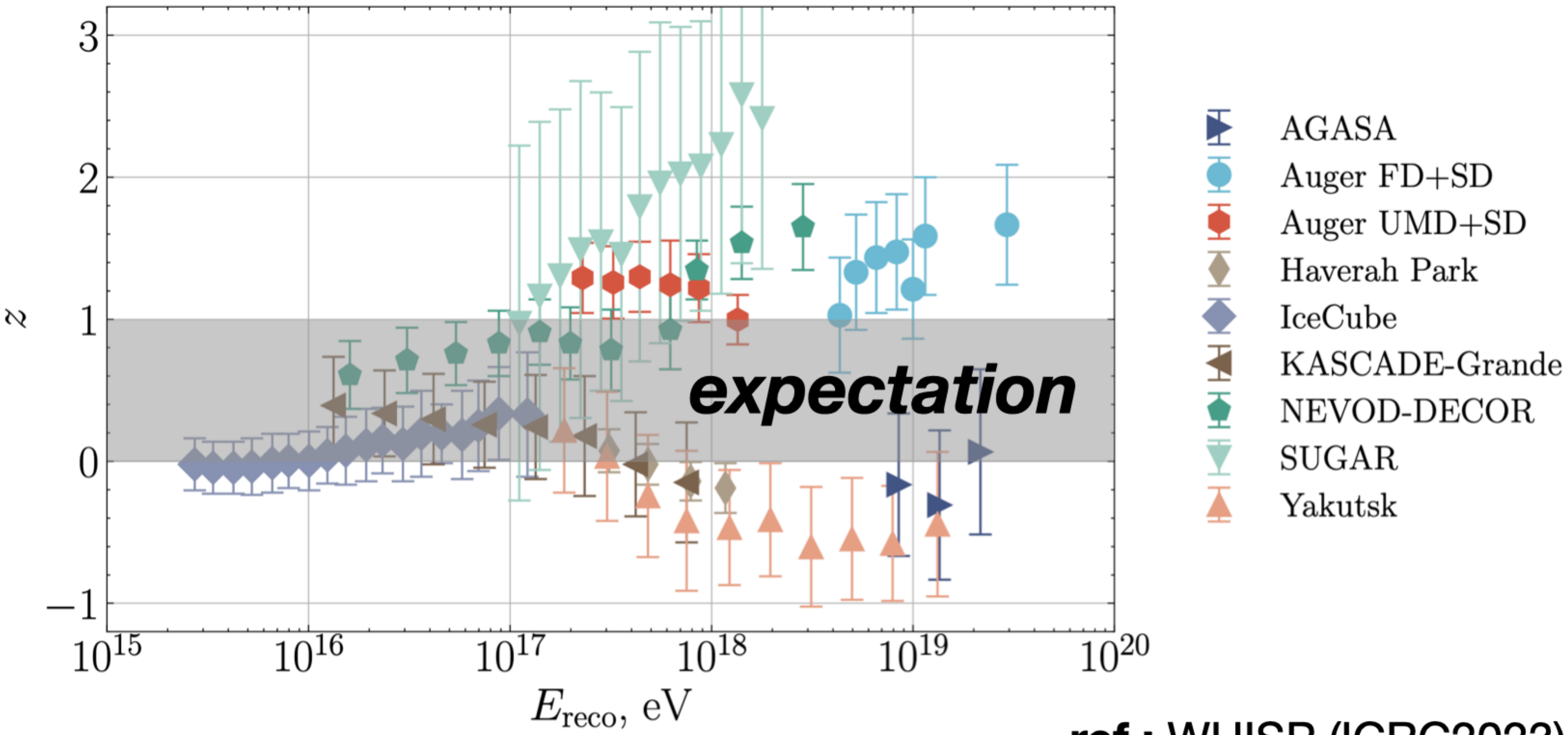

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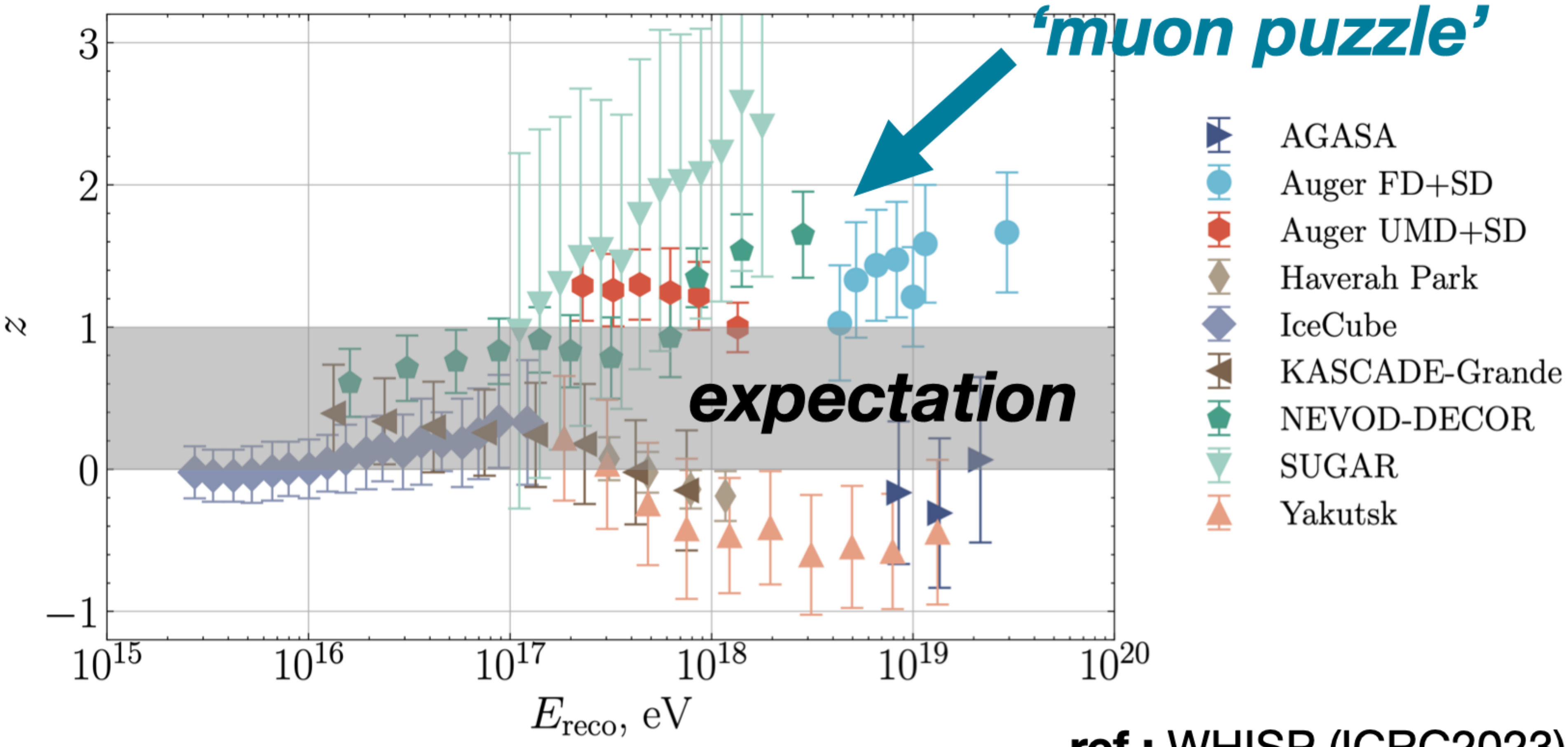

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Motivation: Muon Puzzle

- **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:**

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

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

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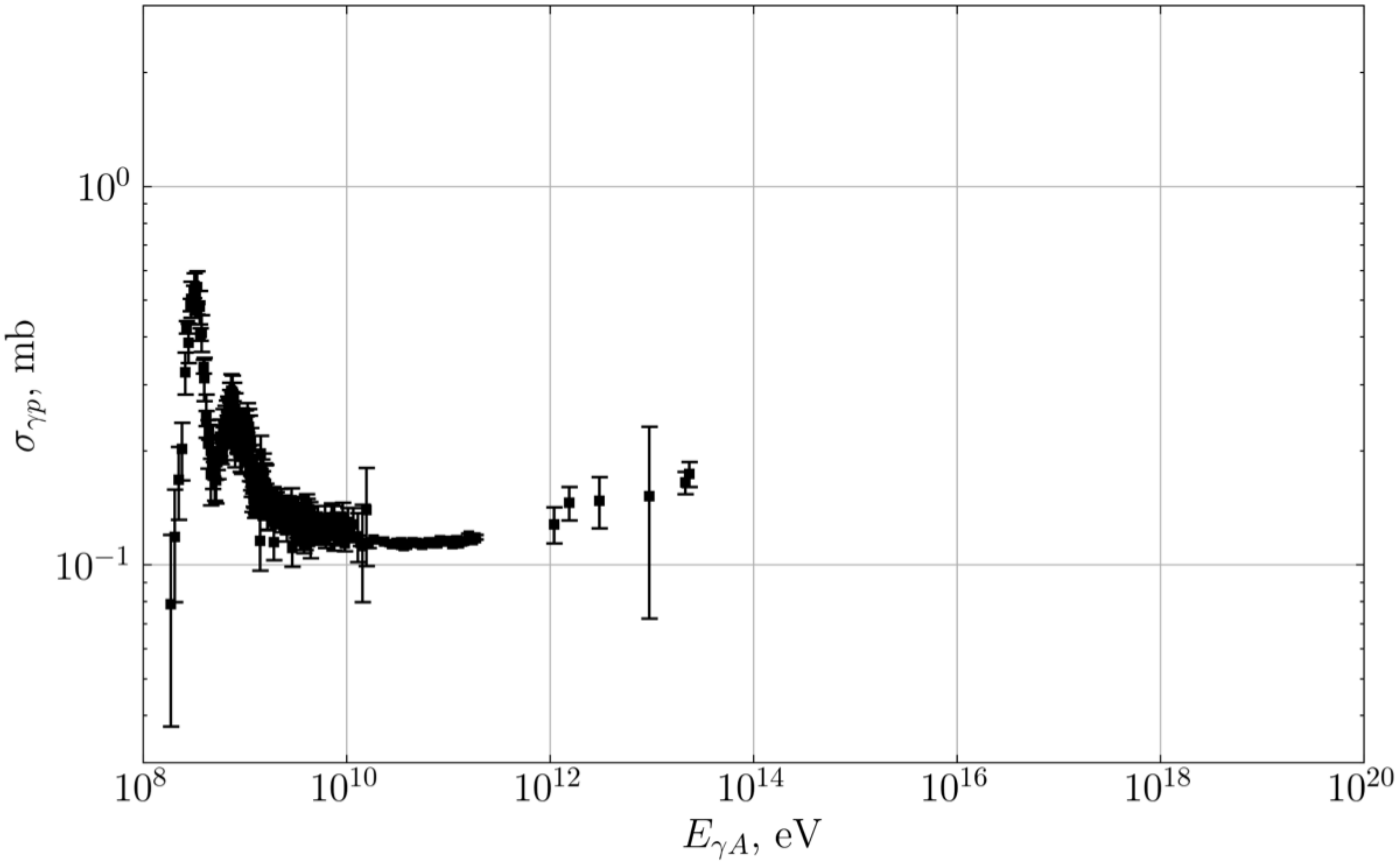
Photonuclear Reaction Cross-section



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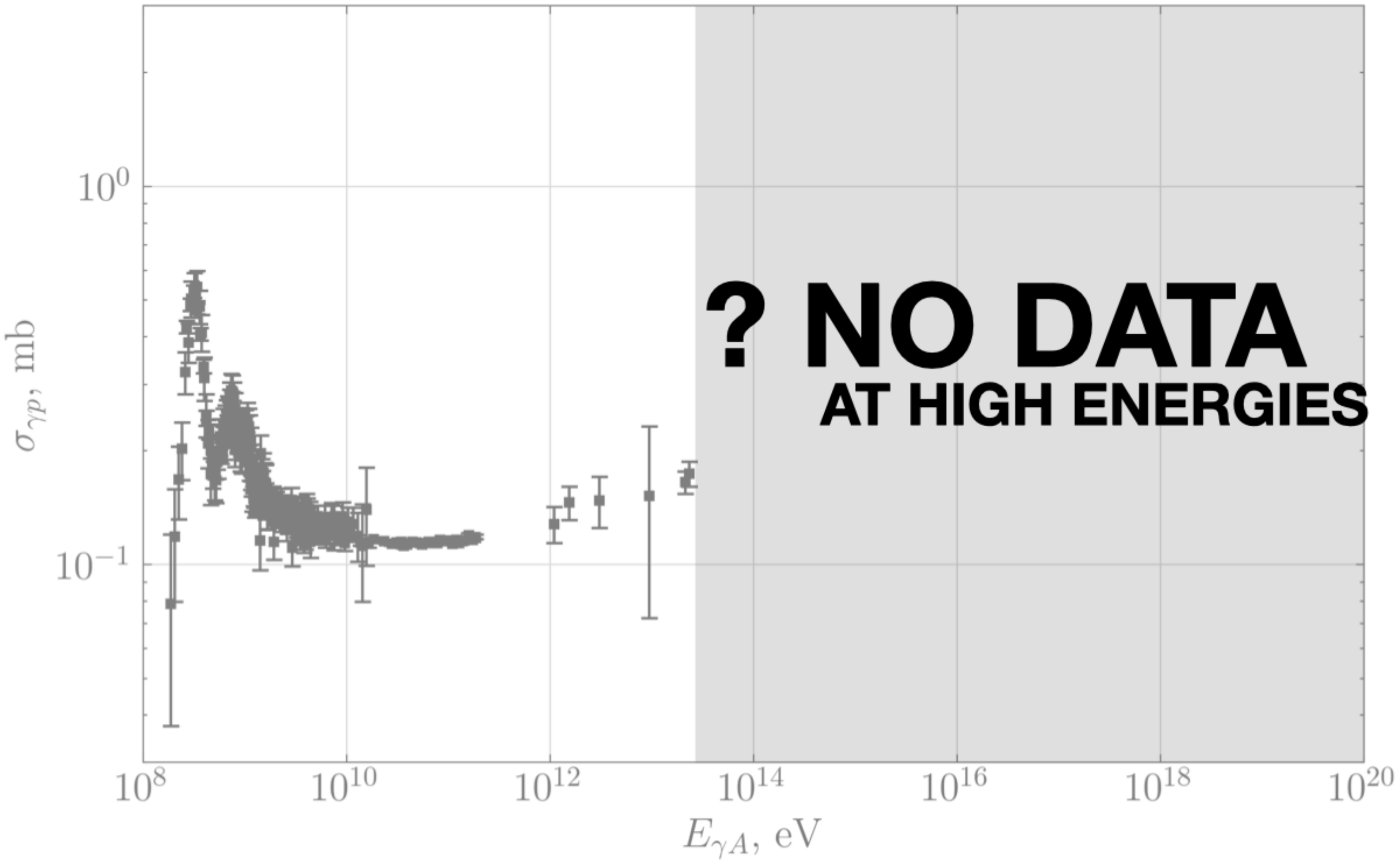
Photonuclear Reaction Cross-section



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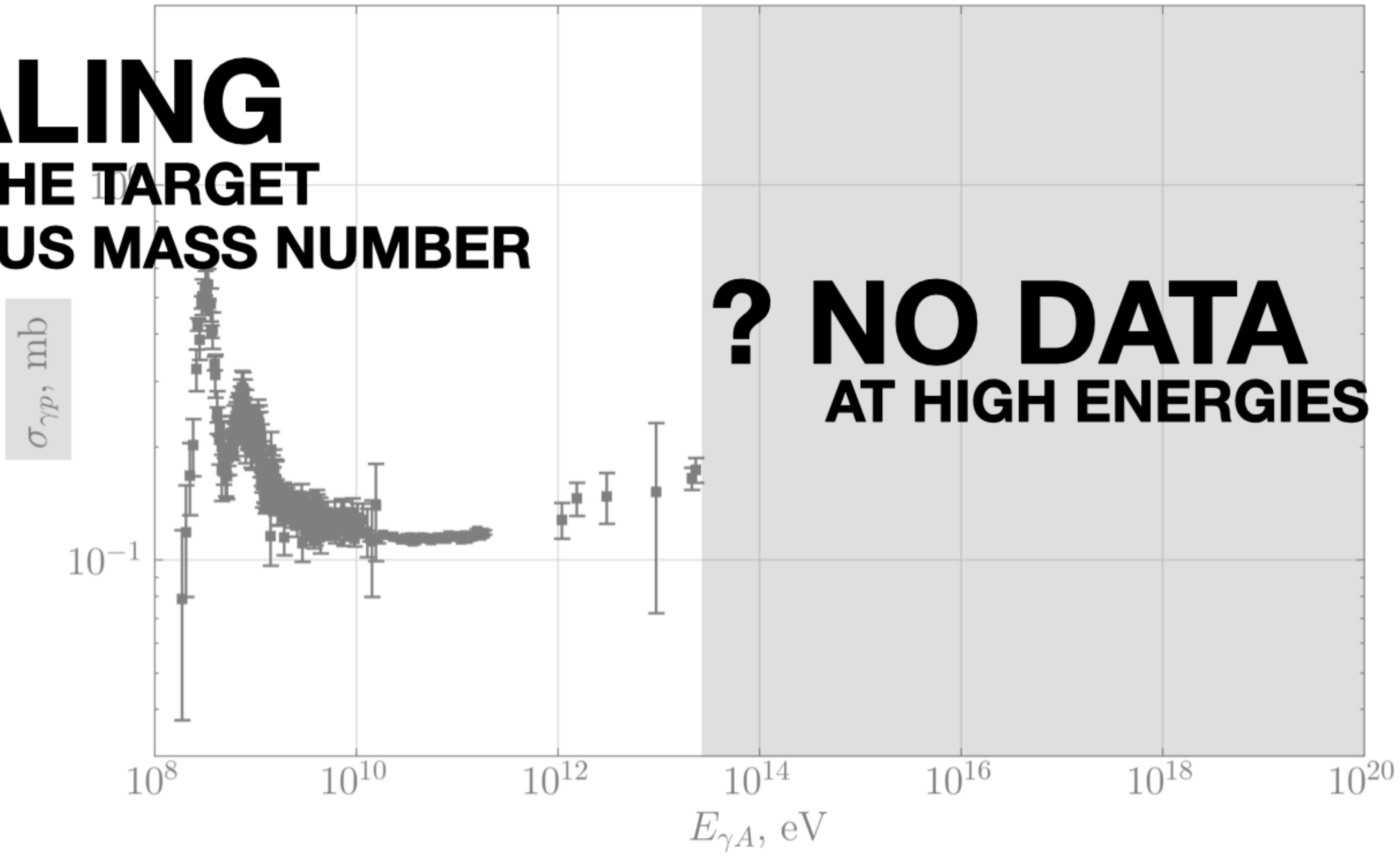
Photonuclear Reaction Cross-section



? SCALING

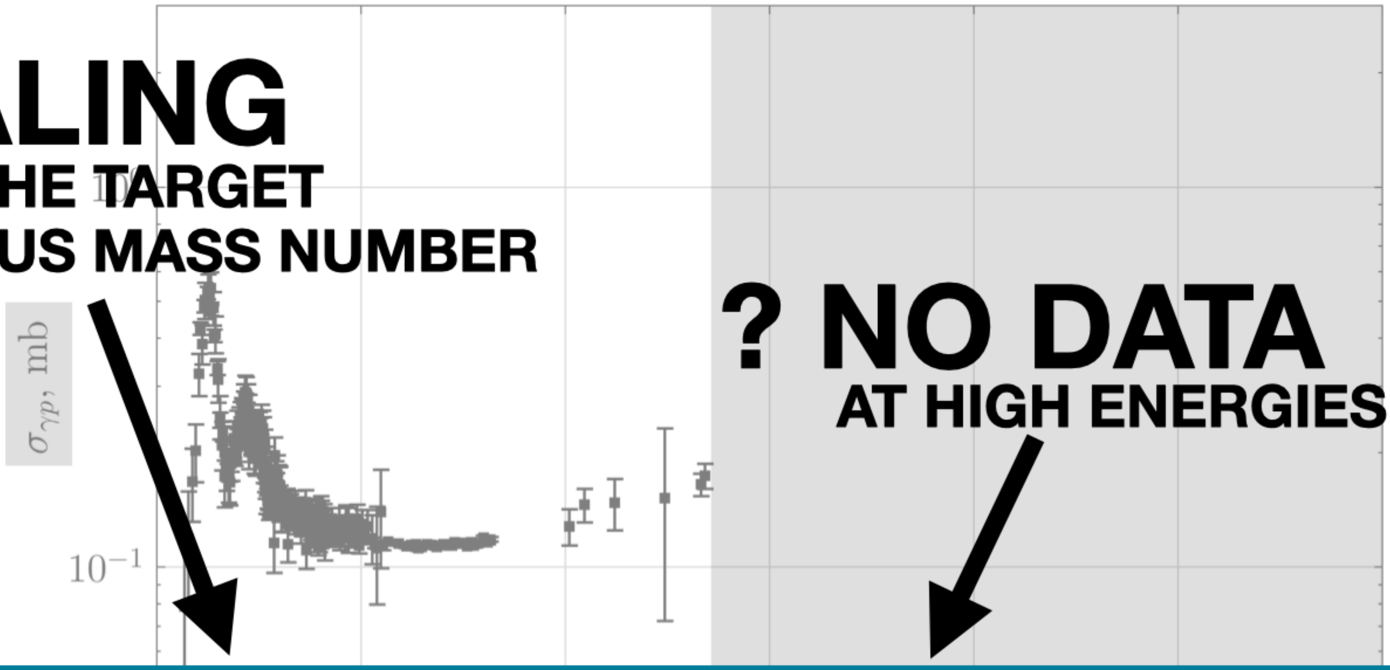
WITH THE TARGET NUCLEUS MASS NUMBER

? NO DATA

AT HIGH ENERGIES

ref.: Particle Data Group (2025)

Photonuclear Reaction Cross-section



? SCALING
WITH THE TARGET NUCLEUS MASS NUMBER

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AT HIGH ENERGIES

! SYSTEMATIC UNCERTAINTY
IN MUON CONTENT PREDICTED BY MC SIMULTATIONS

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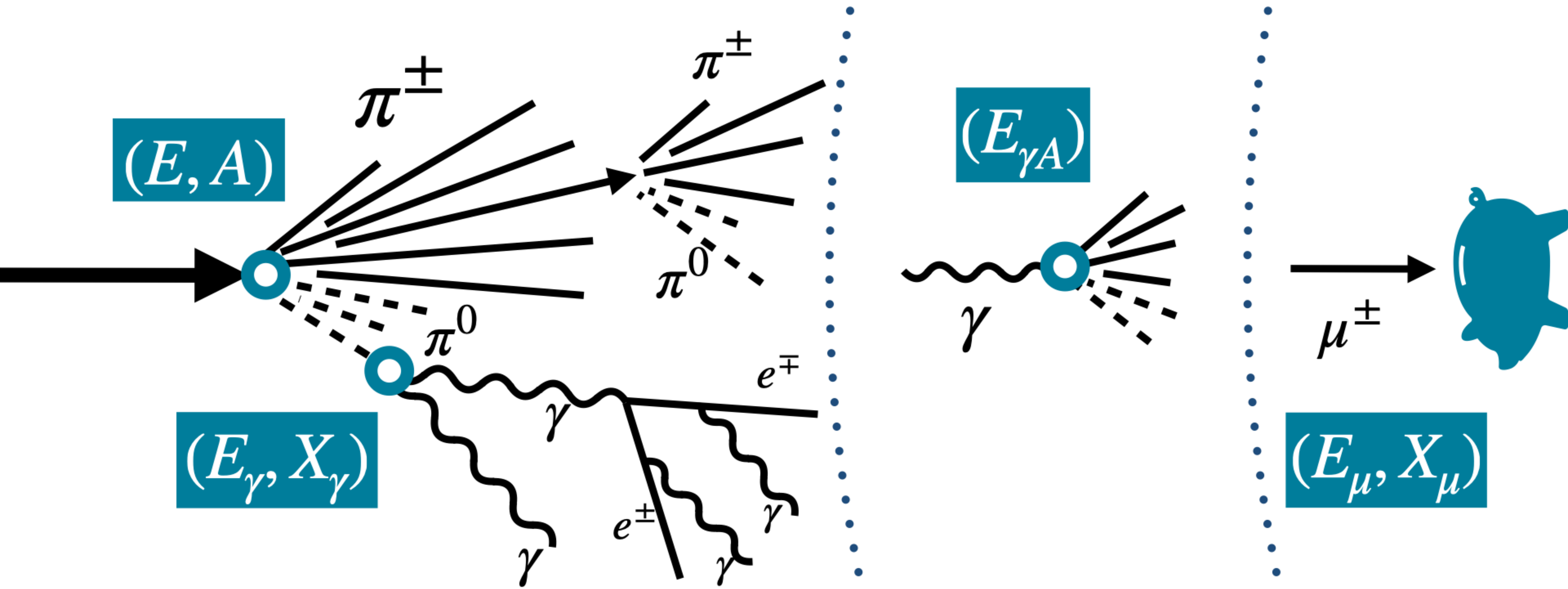
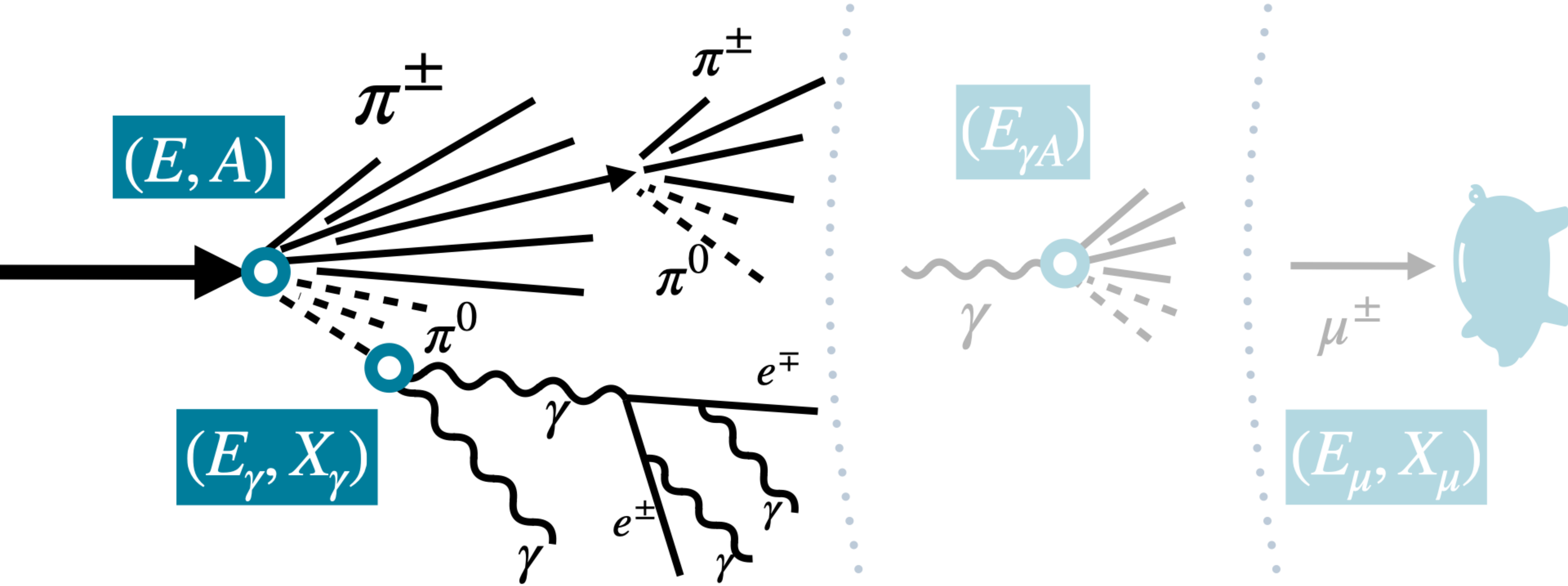
Muon Profiles Systematic Uncertainty



Muon Profiles Systematic Uncertainty

stage I: hadr. interactions→high-energy photons→el.-mag. cascades



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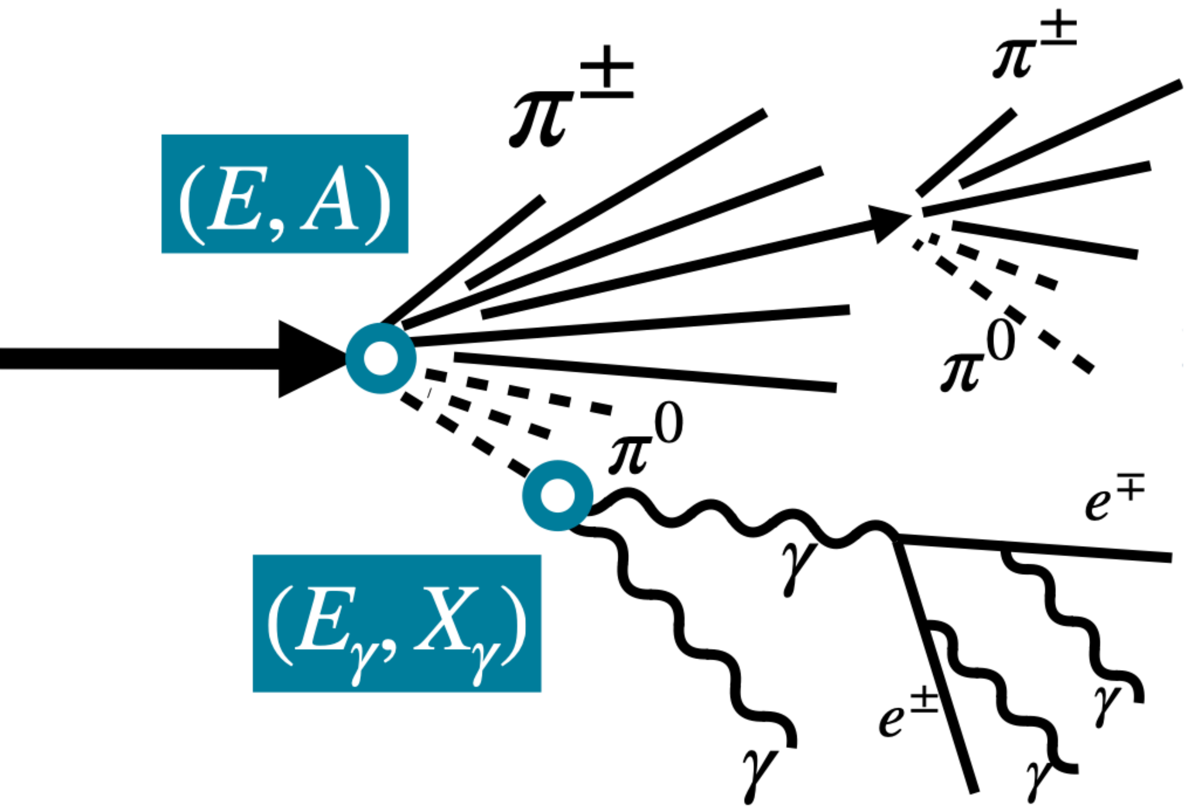

- We assume the Superposition model and thus study only the proton-induced EASs
- We utilize CONEX v7.80, incorporating EPOS LHC-R + UrQMD v1.3 + EGS4
- We model the longitudinal development of the Leading Interactions Tree for the vertical EASs. We consider the primary proton energy range of (10^{15}…10^{19}) eV
- We stop simulations at min{depth of the leading particle reaches 2000 g cm^{-2}, 10 leading interactions are recorded}

Muon Profiles Systematic Uncertainty

stage I: hadr. interactions→high-energy photons→el.-mag. cascades

Key Result: analytical formula for the high-energy photons distribution, $\mathrm{d}N_\gamma \big/ (\mathrm{d}\ln E_\gamma\, \mathrm{d}X_\gamma)$

Fit quality on the validation dataset: $\mathrm{median}\big[\,|\mathrm{pred} - \mathrm{true}\,| \div \mathrm{true}\big] \simeq 9.3\,\%$

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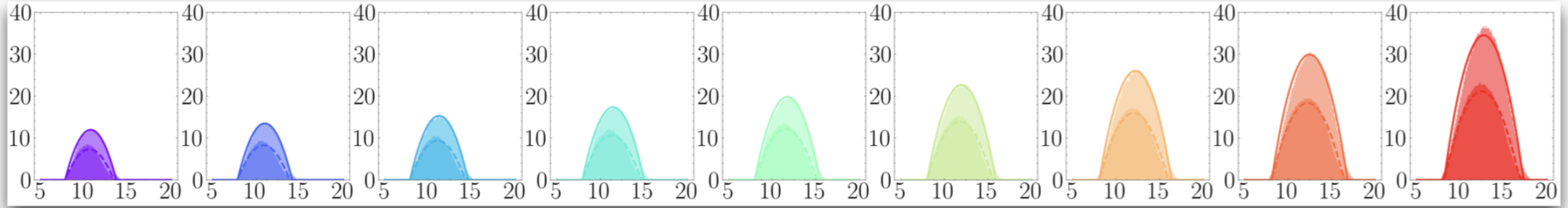
Plot: marginal distribution $\mathrm{d}N_\gamma \big/ \mathrm{d}\ln E_\gamma$ vs $\log_{10}[E_\gamma/\mathrm{eV}]$ for the 'deep' $X_\gamma > \langle X_\gamma \rangle$ and the 'high-altitude' $X_\gamma \leq \langle X_\gamma \rangle$ layers in the EAS energy range of $(10^{15}\ldots10^{19})$ eV, step = 0.5 dex



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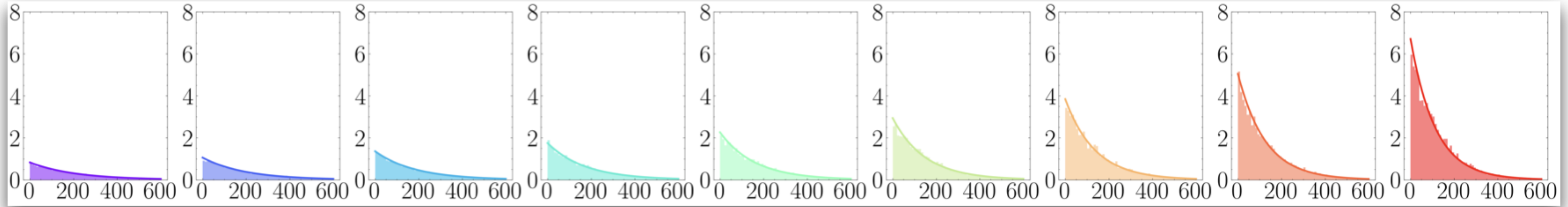
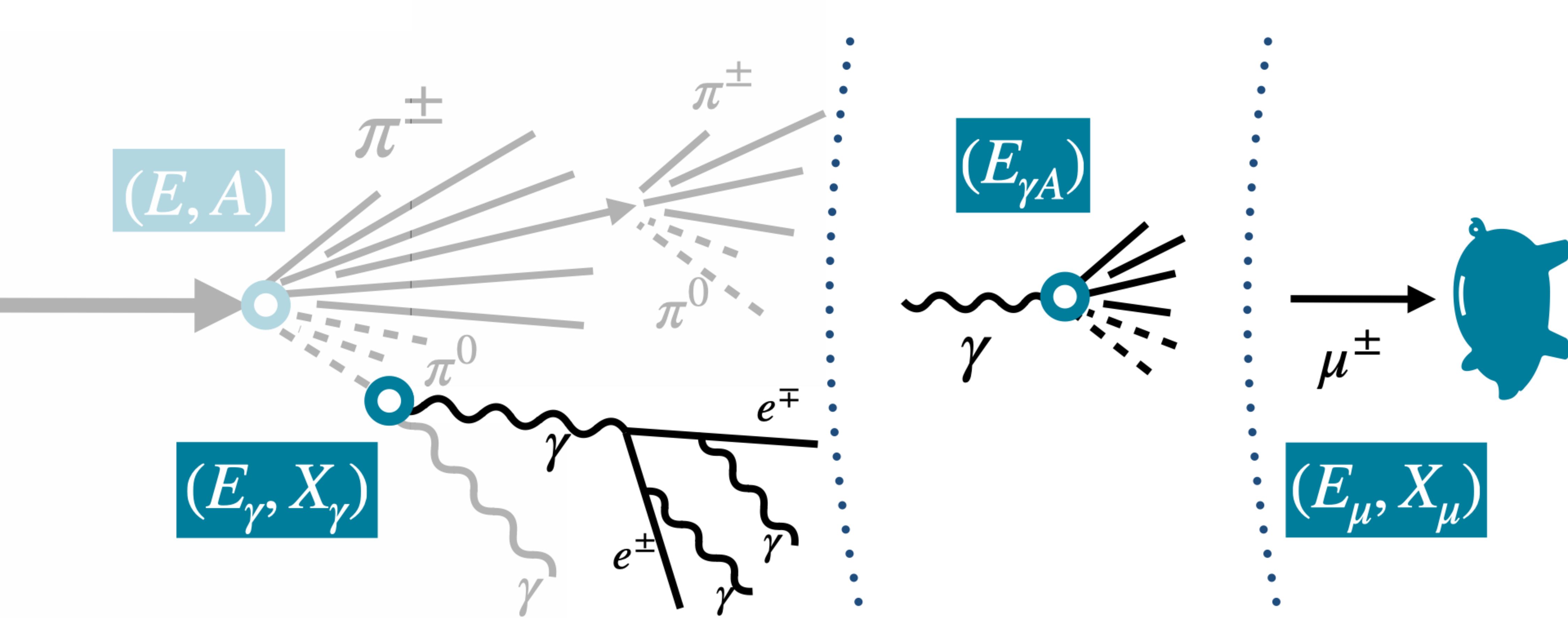
Plot: marginal distribution $\mathrm{d}N_\gamma / \mathrm{d}\ln X_\gamma$ vs atmospheric slant depth $[X_\gamma \cdot \mathrm{g}^{-1}\ \mathrm{cm}^2]$
in the EAS energy range of (10^{15}…10^{19}) eV, step = 0.5 dex



Muon Profiles Systematic Uncertainty

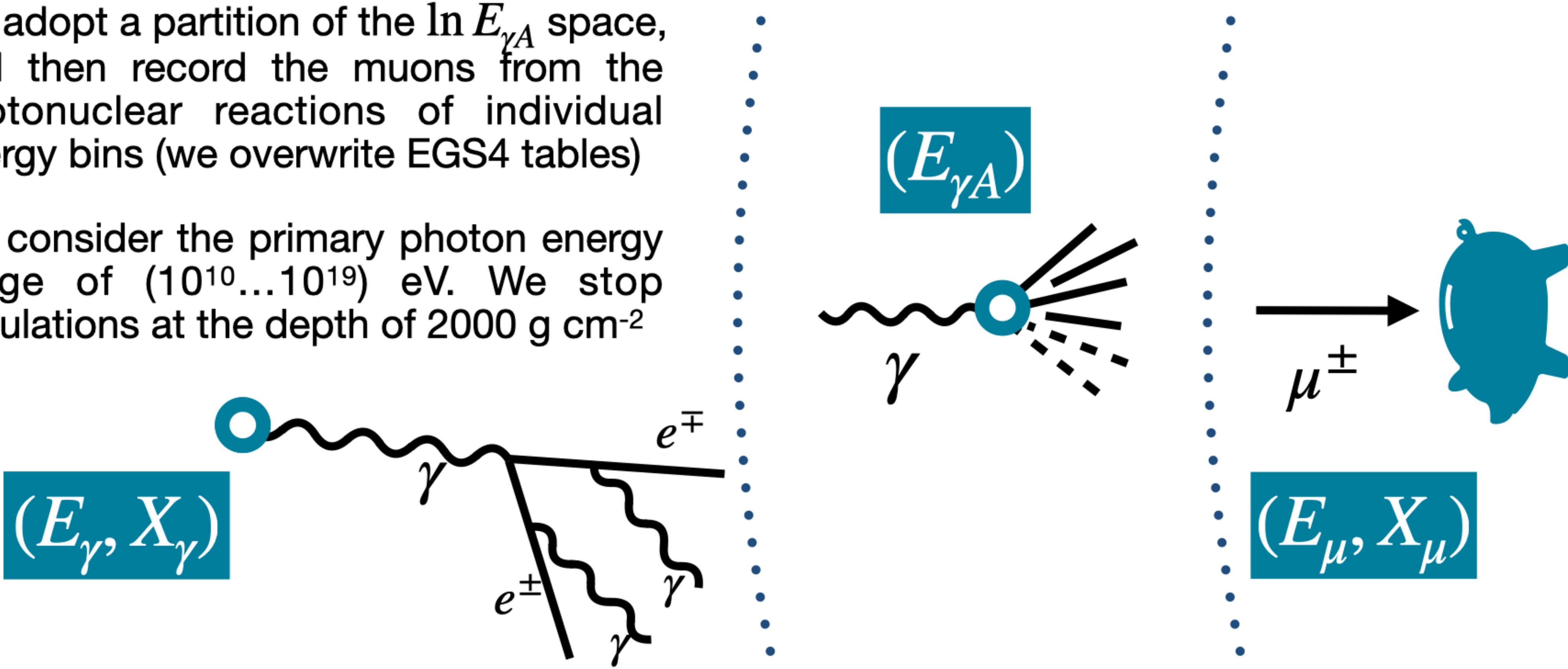
stage II: photonuclear reactions in el.-mag. cascade→hadr. sub-cascades→muons



Muon Profiles Systematic Uncertainty

stage II: photonuclear reactions in el.-mag. cascade→hadr. sub-cascades→muons

- We adopt a partition of the $\ln E_{\gamma A}$ space, and then record the muons from the photonuclear reactions of individual energy bins (we overwrite EGS4 tables)
- We consider the primary photon energy range of $(10^{10}...10^{19})$ eV. We stop simulations at the depth of 2000 g cm^{-2}



Muon Profiles Systematic Uncertainty

stage II: photonuclear reactions in el.-mag. cascade→hadr. sub-cascades→muons

Key Result: analytical formula for the high-energy muons distribution, $\mathrm{d}N_\mu / \mathrm{d}\ln E_{\gamma A}$

Fit quality on the validation dataset: $\mathrm{median}\left[\,|\,\mathrm{pred} - \mathrm{true}\,| \div \mathrm{true}\right] \simeq 6.2\,\%$

Important feature: linear with the photonuclear cross-section!

Muon Profiles Systematic Uncertainty

stage II: photonuclear reactions in el.-mag. cascade→hadr. sub-cascades→muons

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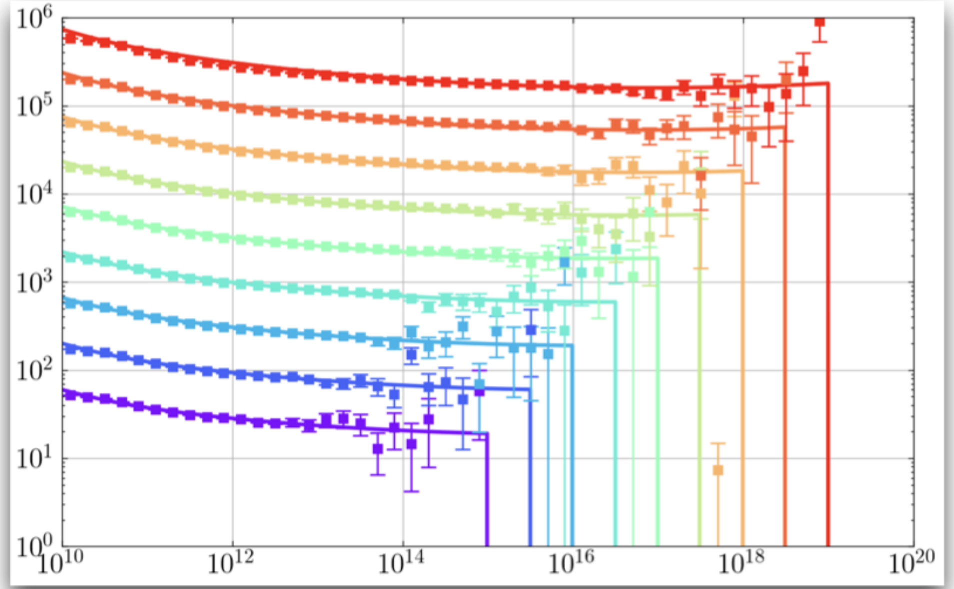
Fit quality on the validation dataset: $\mathrm{median}\big[\,|\,\mathrm{pred} - \mathrm{true}\,| \div \mathrm{true}\big] \simeq 6.2\,\%$

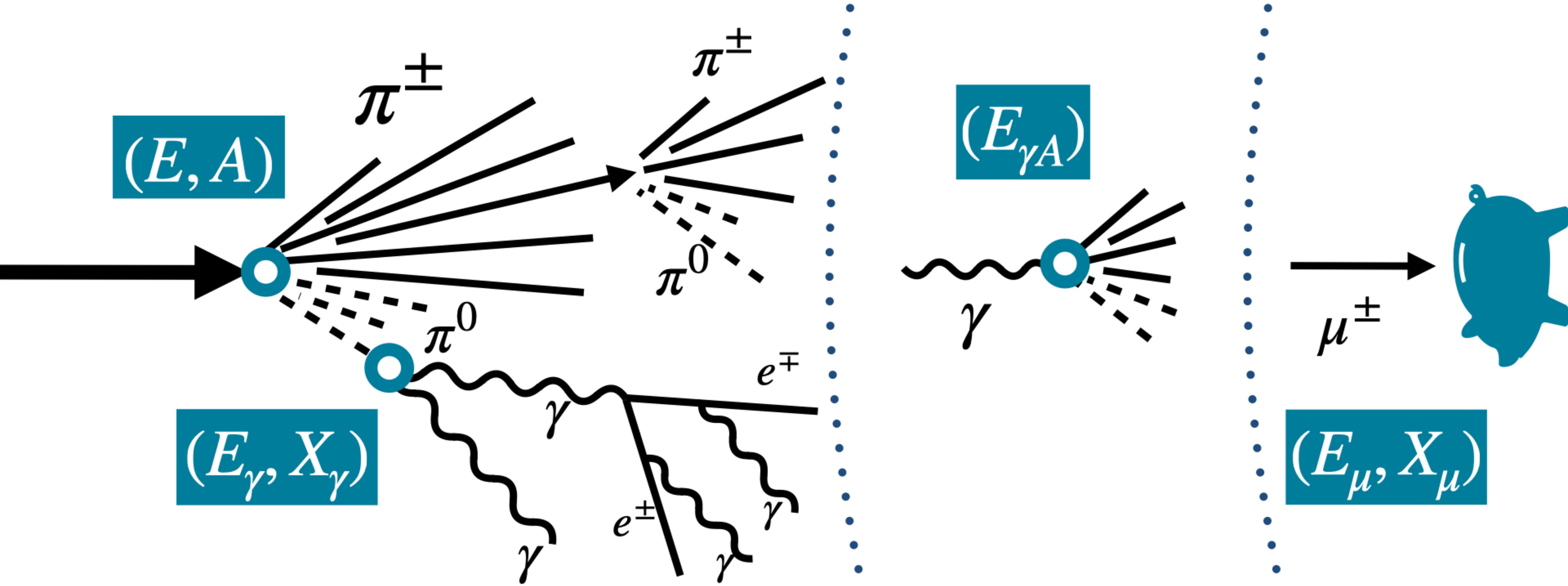
Important feature: linear with the photonuclear cross-section!

Plot: average muon number density $\mathrm{d}N'_\mu / \mathrm{d}\ln E_{\gamma A}$ vs $E_{\gamma A}$ [eV] in the primary proton energy range of ($10^{15}\ldots10^{19}$) eV, step = 0.5 dex, and assuming the detection at the sea level ~1033 g cm^{-2}



Muon Profiles Systematic Uncertainty

stage III: stage I + stage II = powerful analytical instrument



Muon Profiles Systematic Uncertainty

stage III: stage I + stage II = powerful analytical instrument!

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}\ln E_{\gamma A}} = \int\limits_{\ln E_{\gamma A}}^{\ln E} \mathrm{d}\ln E_\gamma \int\limits_0^{X_\mu} \mathrm{d}X_\gamma \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}\ln E_\gamma\,\mathrm{d}X_\gamma} \times \left.\frac{\mathrm{d}N'_\mu}{\mathrm{d}\ln E_{\gamma A}}\right|_{X_\mu - X_\gamma} \right]$$

ΔN_μ (systematic uncertainty) is the linear functional of $\Delta\sigma_{\gamma A}$

Muon Profiles Systematic Uncertainty

stage III: stage I + stage II = powerful analytical instrument!

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ΔN_μ (systematic uncertainty) is the linear functional of $\Delta\sigma_{\gamma A}$

No more need in time & memory-consuming MC simulations — we can analyze a wide class of cross-section models just using the analytical 'Green Function'!

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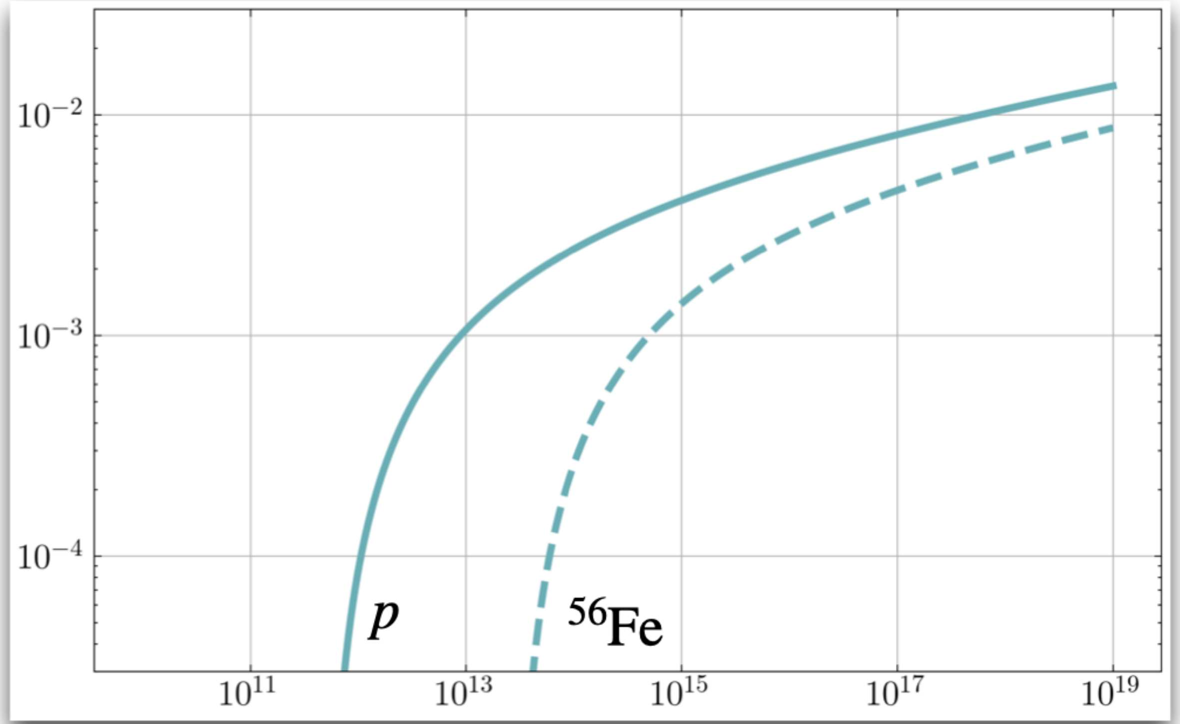
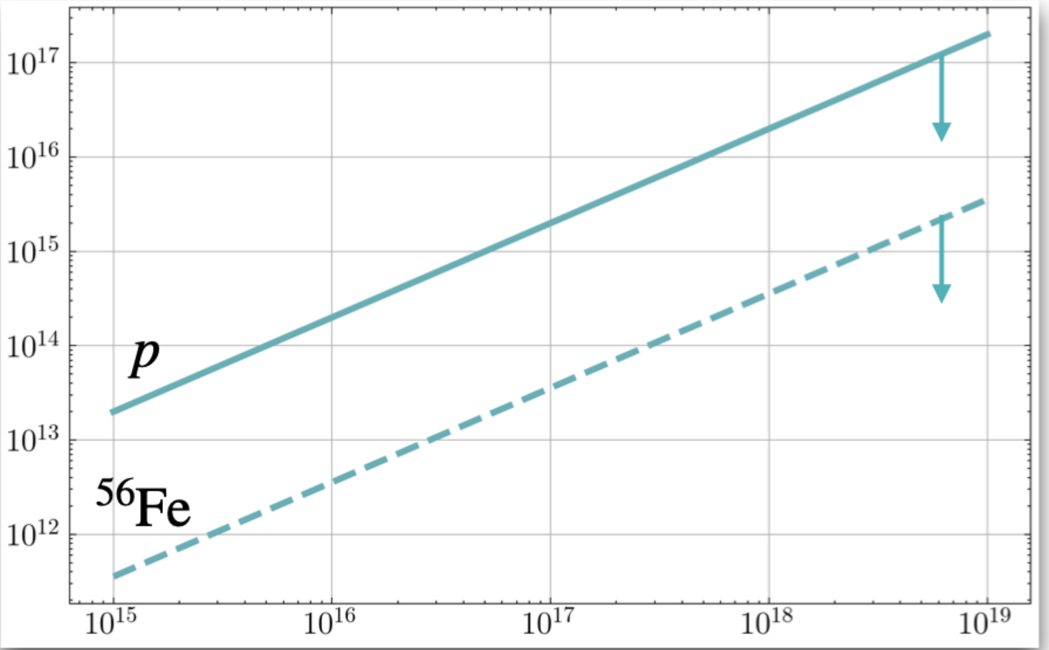
Limitations & Interesting Physical Implications



Plot: muon number—to—photonuclear cross-section relative error ratio vs the primary cosmic-ray particle energy (in eV) at the sea level ~1033 g cm^{-2}. Solid line corresponds to the proton primary, dashed line — to iron-56 primary. The 'high-energy' photonuclear reactions energy threshold is fixed to 10^{10} eV

The systematic error of $\gtrsim 1000\,\%$ for the photonuclear cross-section would induce additional $\gtrsim 10\,\%$ systematic error in the muon number at high energies and thus **could vanish** the significance of **the muon puzzle!**

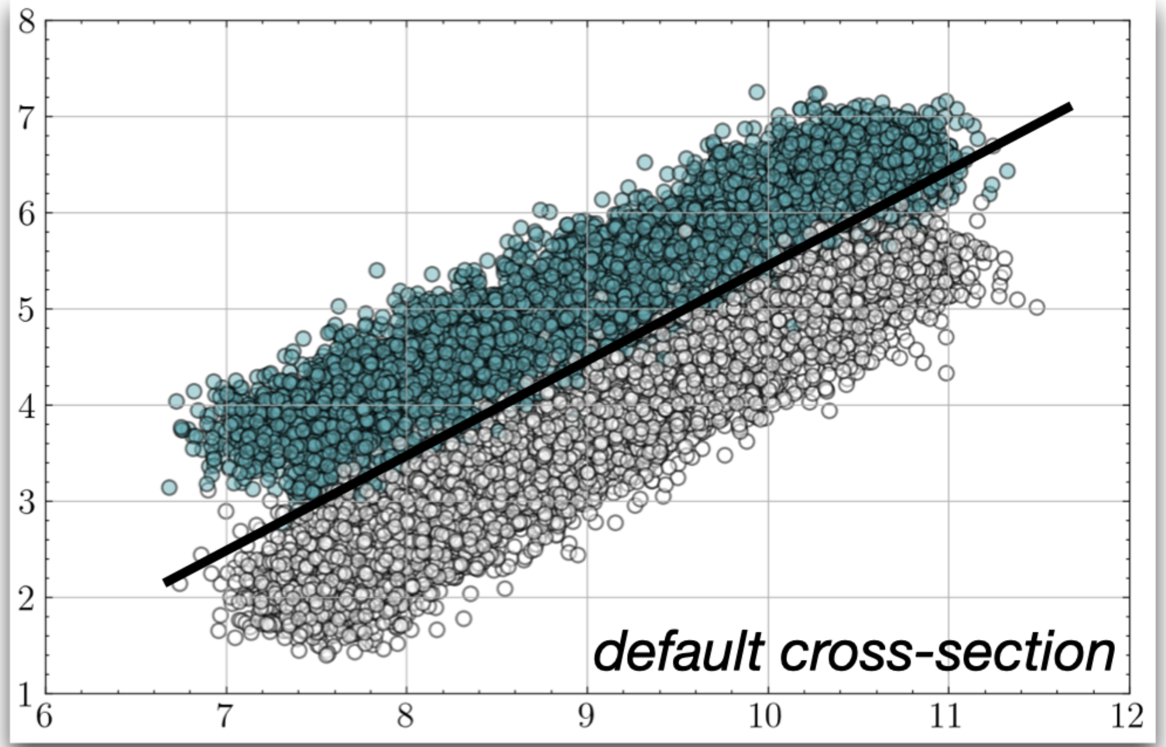
Limitations & Interesting Physical Implications



Plot: the upper limit for the photonuclear reaction energy probed (eV) vs the EAS primary particle energy (eV). Solid line corresponds to the proton primary, dashed line — to iron-56 primary

Even in the highest-energy region of the EASs, one can hardly probe the photonuclear reactions above the energy about **several hundreds PeV** (due to a lack of the corresponding photons)

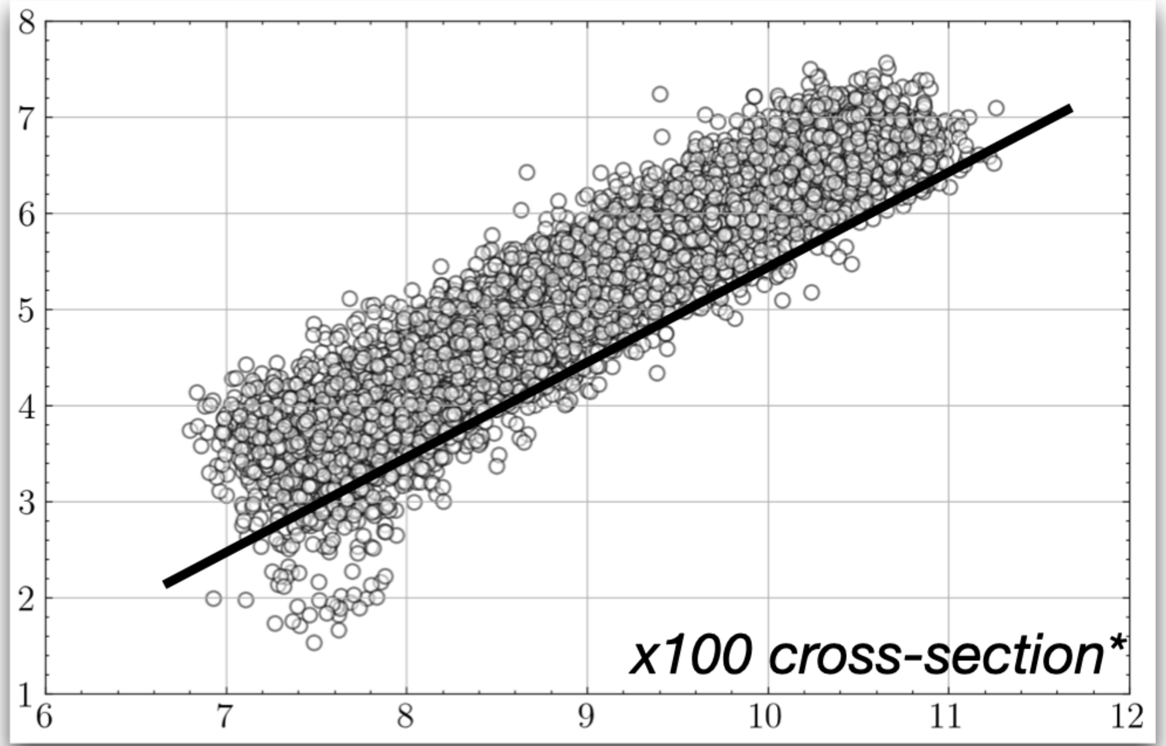
Limitations & Interesting Physical Implications



Plot: logarithm of the electron atmospheric profile integral (arbitrary units) vs the logarithm of the ground-level muon content (arbitrary units) for protons (shown in teal) and photons (shown in white) + manually added gaussian fluctuations

Assuming default photonuclear cross-section, we can distinguish between proton and photon primaries just using a linear criterion (shown in black).

Limitations & Interesting Physical Implications



Plot: logarithm of the electron atmospheric profile integral (arbitrary units) vs the logarithm of the ground-level muon content (arbitrary units) for photons (shown in white) + manually added gaussian fluctuations

The photonuclear cross-section was manually enlarged by a factor of 100. The linear criterion (shown in black) which was trained on the standard MC now is completely broken.

**only within the experimentally allowed high-energy region*

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Conclusions

- The developed 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, $\sigma_{\gamma A}(10^{13}\ \mathrm{eV} < E_{\gamma A} < 10^{18}\ \mathrm{eV}) \sim (10\ldots100)\ \mathrm{mb}$, could lead to a number of additional muons large enough to explain $z \sim (1\ldots2)$. However, a proper calculation of the systematic uncertainty associated with the photonuclear cross-section could reduce the statistical significance of the muon puzzle

- $\sigma_{\gamma A}(10^{13}\ \mathrm{eV} < E_{\gamma A} < 10^{18}\ \mathrm{eV}) \gtrsim 100\ \mathrm{mb}$ is excluded by observations (direct constraints on the photonuclear cross-section from the EASs' muon content!)

- $\sigma_{\gamma A}(10^{13}\ \mathrm{eV} < E_{\gamma A} < 10^{18}\ \mathrm{eV}) \sim (10\ldots100)\ \mathrm{mb}$ imply muon-rich gamma-ray EASs which may be easily confused with that induced by protons