
Simulating UHECR sources with CRPropa using updated Interaction Models

Leonel Morejon

CRPropa meeting

RUB 25.09.2023



BERGISCHE
UNIVERSITÄT
WUPPERTAL

Multi-messenger probe of Cosmic Ray Origins

Goal

Multi-messenger study of bursting sources and their contribution to UHECRs.

Approach

Modelling in-source production, interactions and propagation of UHECRs from bursting sources to compute expected values of observables.

Participating institutions



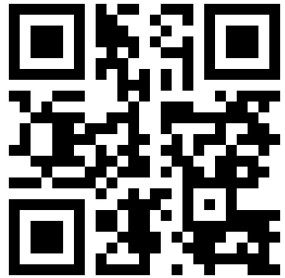
Funded by:



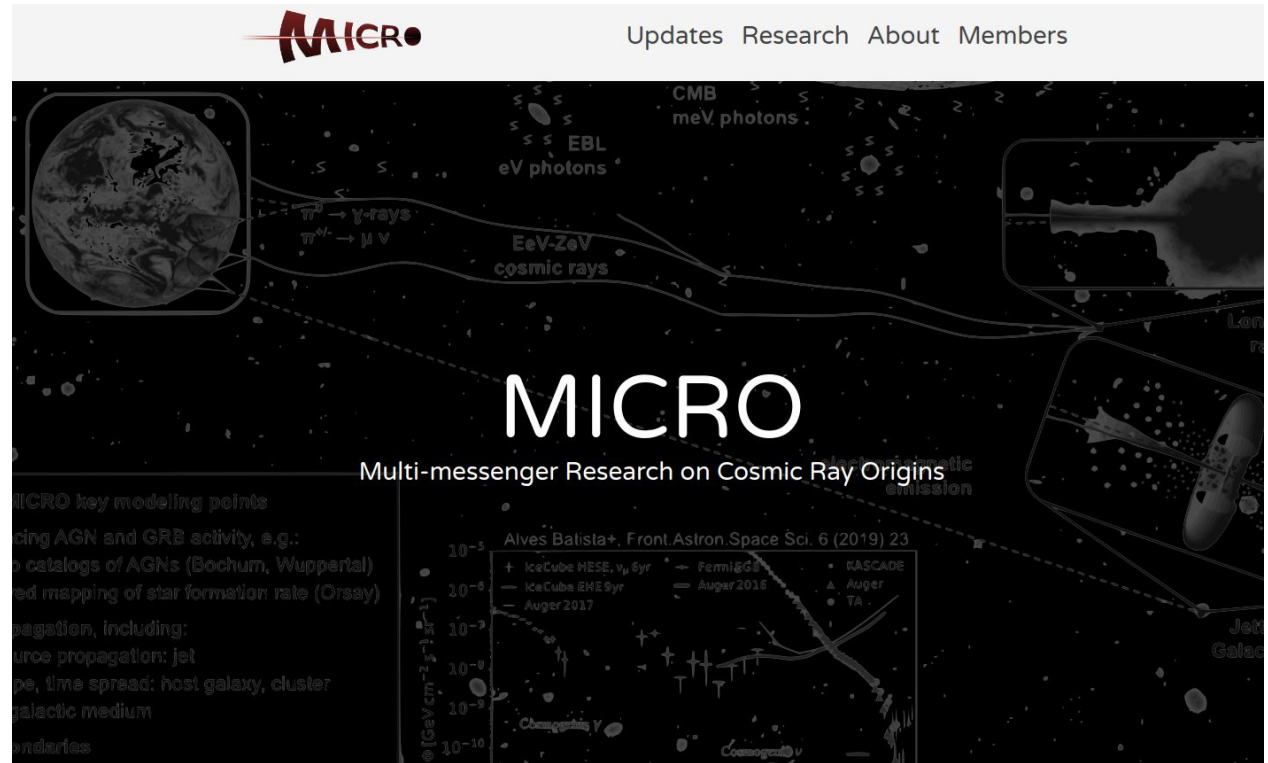
Check the website for updates



<https://micro-uhedr.github.io/>



<https://github.com/micro-uhedr>

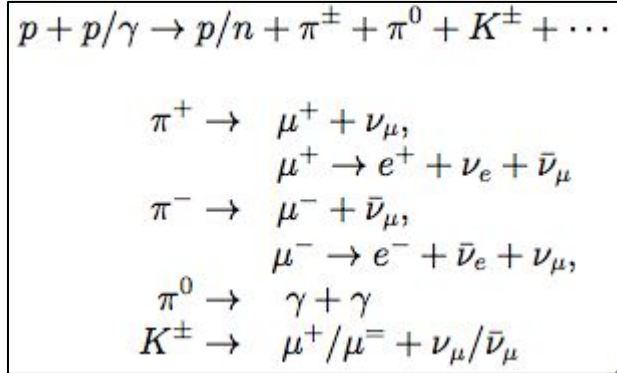
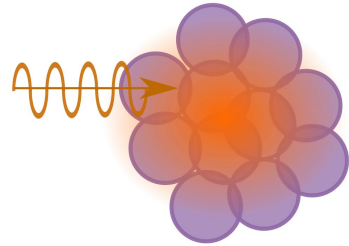


The screenshot shows the MICRO website interface. At the top, there is a navigation bar with the MICRO logo and links for "Updates", "Research", "About", and "Members". The main content area features a dark background with a central "MICRO" title and the subtitle "Multi-messenger Research on Cosmic Ray Origins". To the left, there is a diagram showing the Earth and various cosmic ray components: $\pi^0 \rightarrow \gamma$ -rays, $\pi^\pm \rightarrow \mu \nu$, EBL eV photons, EeV-ZeV cosmic rays, and CMB meV photons. To the right, there are images of a galaxy jet and a satellite. At the bottom left, there is a section titled "MICRO key modeling points" with text: "Including AGN and GRB activity, e.g.:", "AGN catalogs of AGNs (Bochum, Wuppertal)", "Detailed mapping of star formation rate (Orsay)", "Propagation, including:", "Source propagation: jet", "Age, time spread: host galaxy, cluster", "Galactic medium", and "Boundaries". At the bottom right, there is a plot titled "Alves Batista+, Front.Astron.Space Sci. 6 (2019) 23" showing a log-log plot of flux Φ [GeV cm⁻² s⁻¹ sr⁻¹] versus energy. The plot includes data points from IceCube HESE, Fermi GB, RASCADe, Auger 2016, Auger, TA, and Auger 2017, along with theoretical curves for Cosmogenic γ and Cosmogenic ν .

Which interaction models??

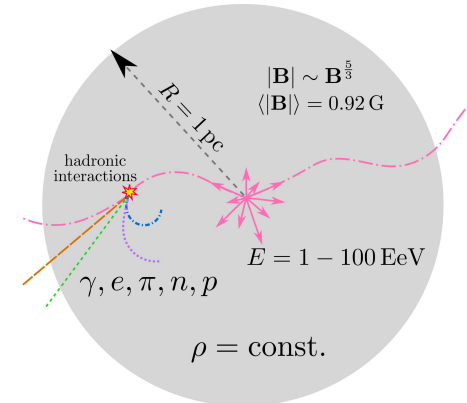
Interactions discussed

Photohadronic
(photomeson)



[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

Hadronic (p+p, p+A)



[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

Workflow in CRPropa

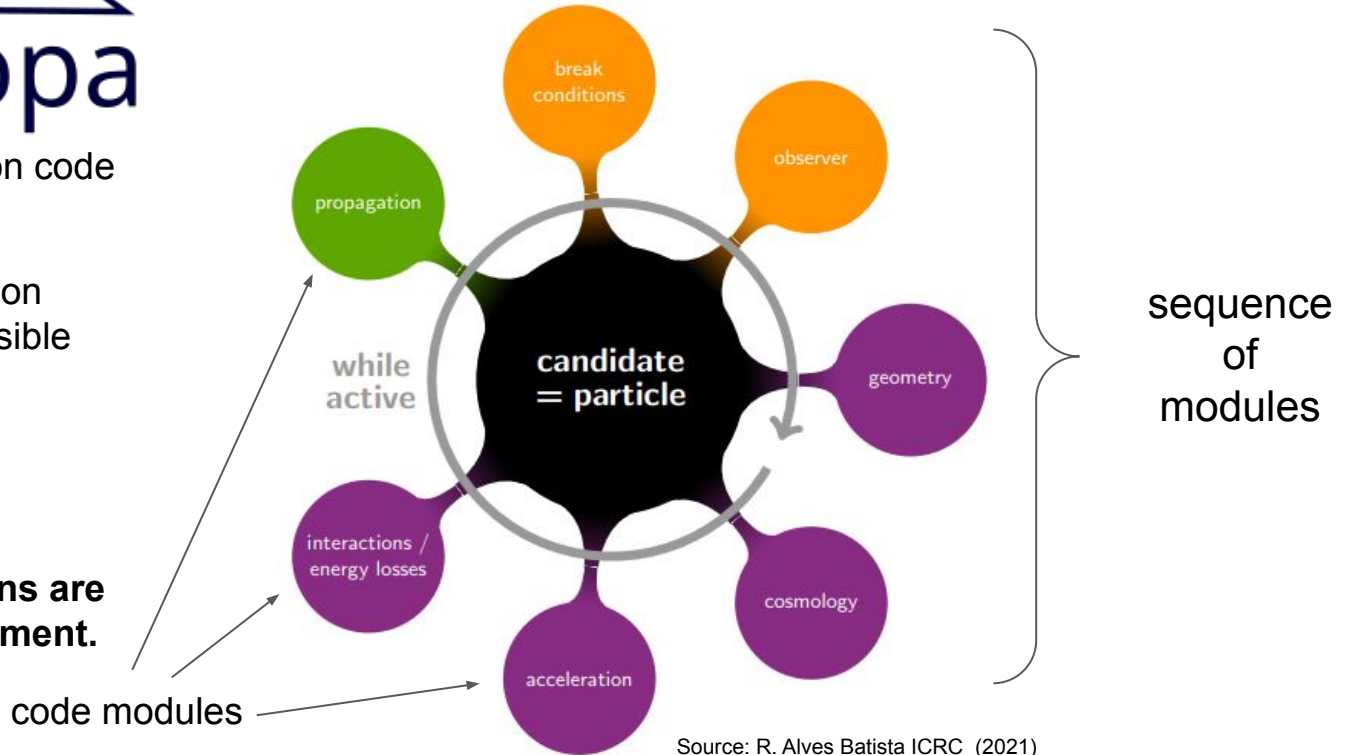
CRPropa

Cosmic Ray Propagation code

- Modular structure
- Interactive simulation
- Flexible and extensible
- **Python interface**

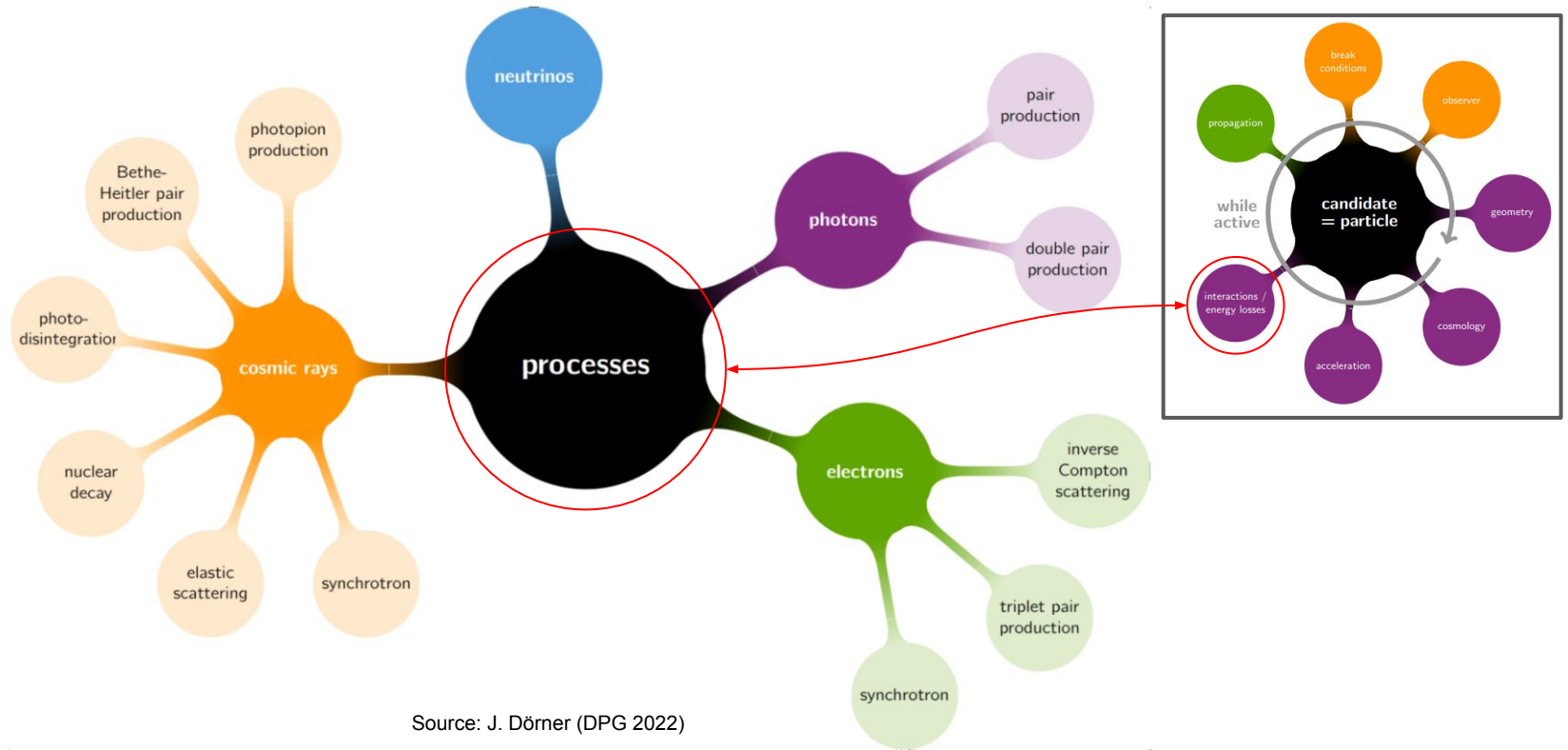


Extensions and plugins are under active development.



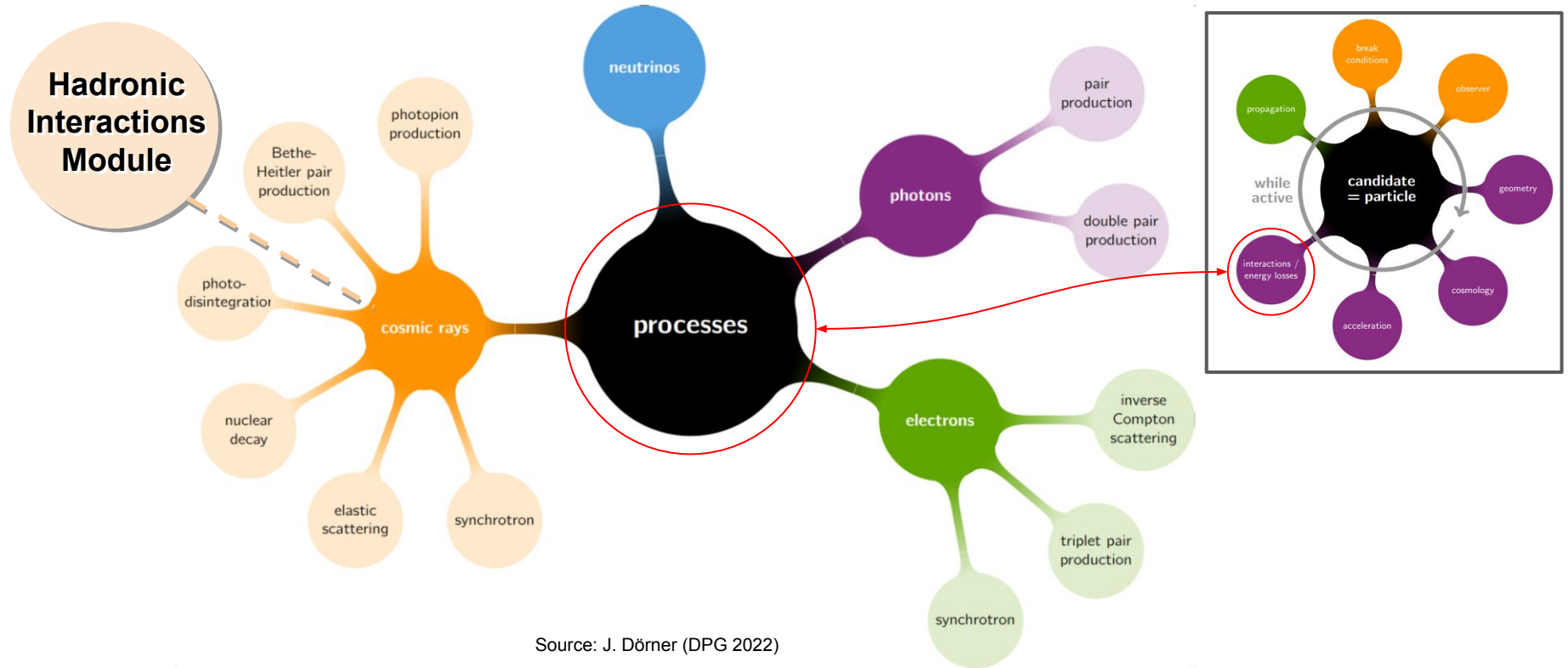
Source: R. Alves Batista ICRC (2021)

Interactions in CRPropa



Source: J. Dörner (DPG 2022)

Interactions in CRPropa

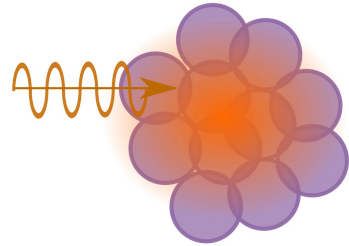


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Which interaction models??

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(photopion)

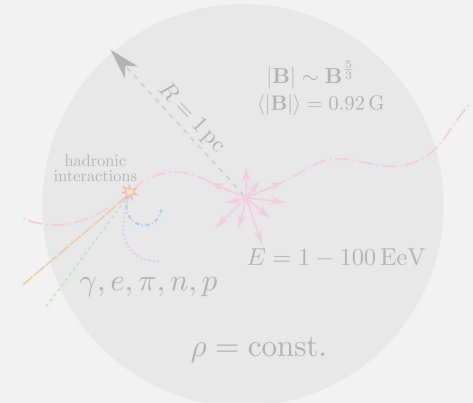


$$p + p/\gamma \rightarrow p/n + \pi^\pm + \pi^0 + K^\pm + \dots$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu, \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu, \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu, \\ \pi^0 &\rightarrow \gamma + \gamma \\ K^\pm &\rightarrow \mu^\pm/\bar{\mu}^\pm + \nu_\mu/\bar{\nu}_\mu \end{aligned}$$

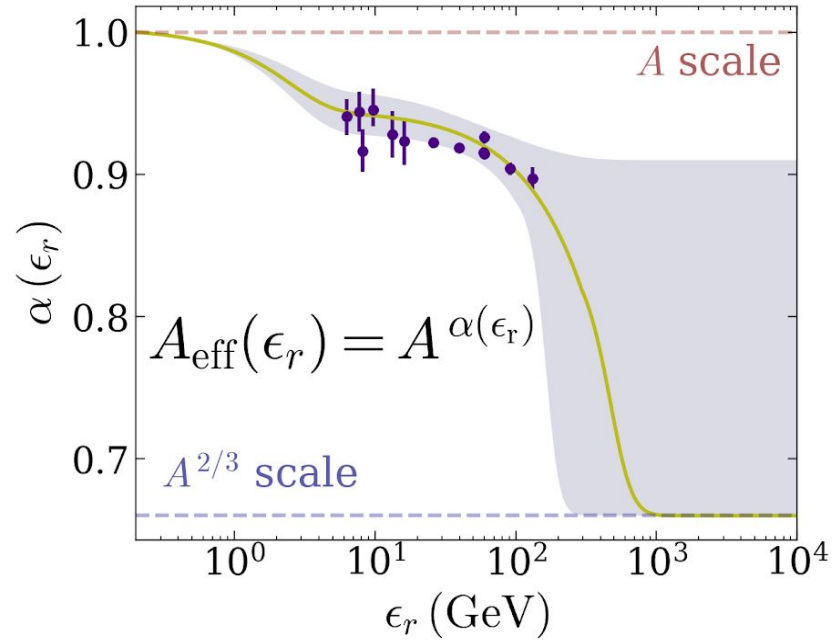
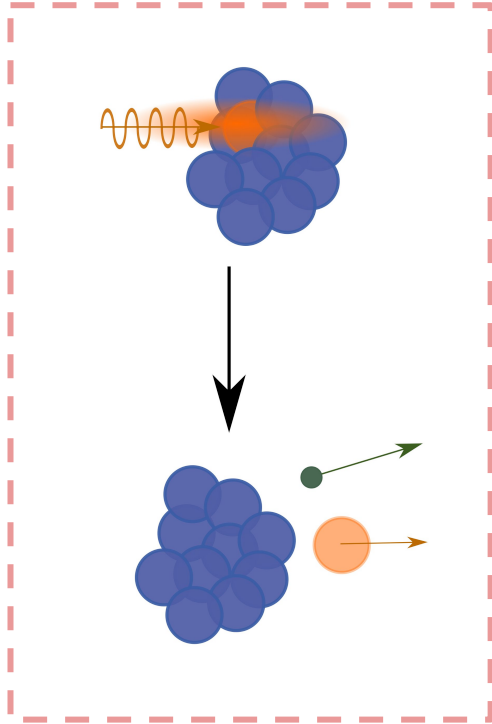
[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

Hadronic (p+p, p+A)



[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

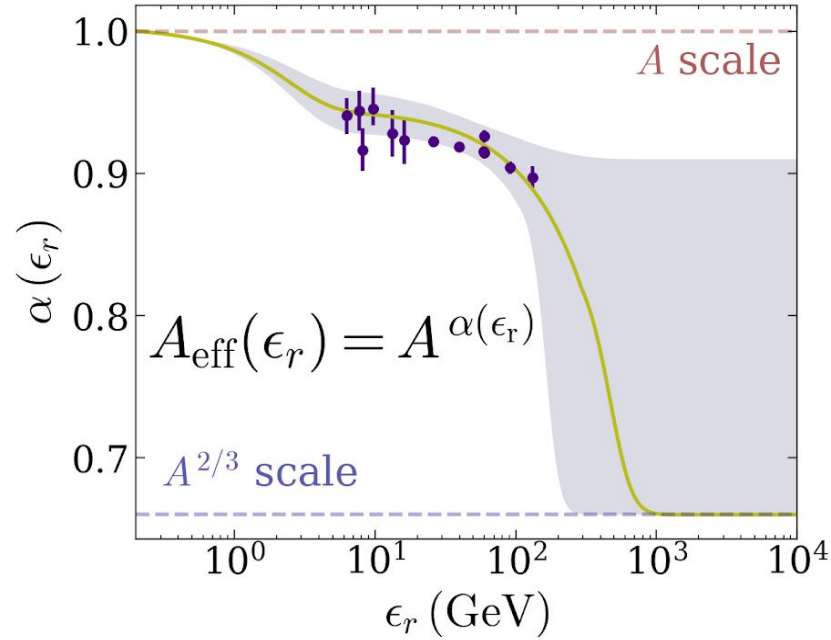
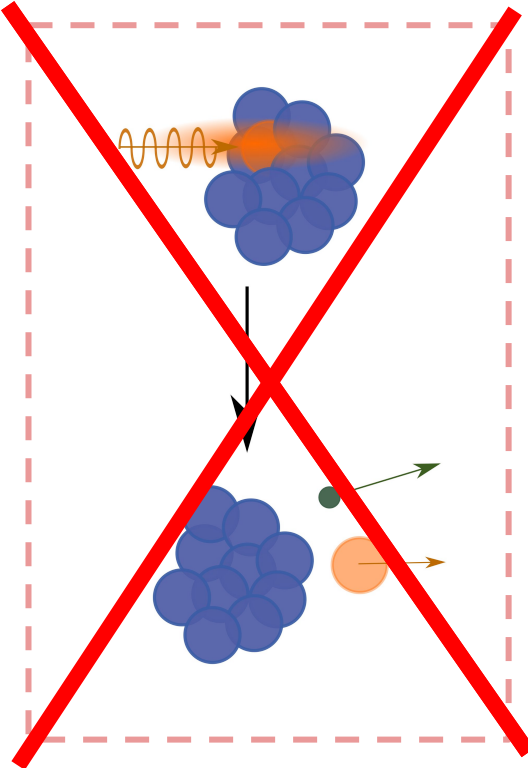
Single nucleon vs Collective interactions



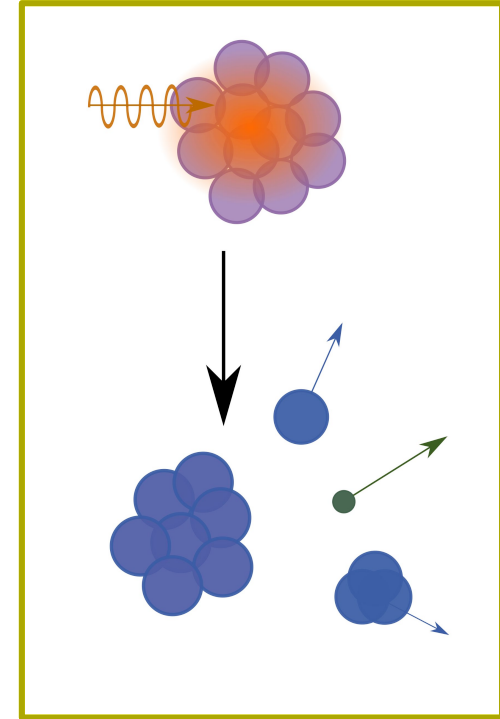
Ref: [L. Morejon, et al. JCAP 11 \(2019\) 007](#)

Photohadronic interactions

Single nucleon vs Collective interactions



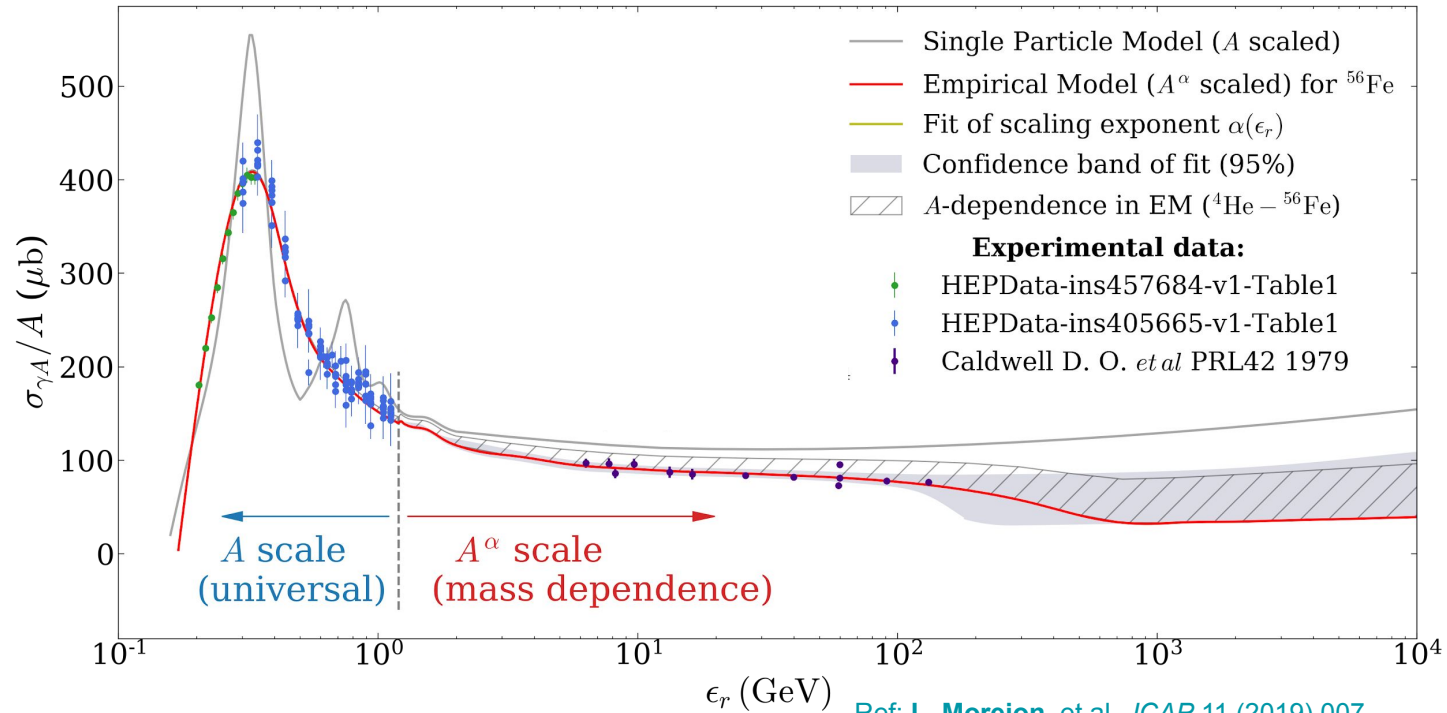
Ref: [L. Morejon, et al. JCAP 11 \(2019\) 007](#)



Total photonuclear cross section

Properties:

- Universal curve for all masses
- Smeared resonances
- Mass scaling is energy dependent

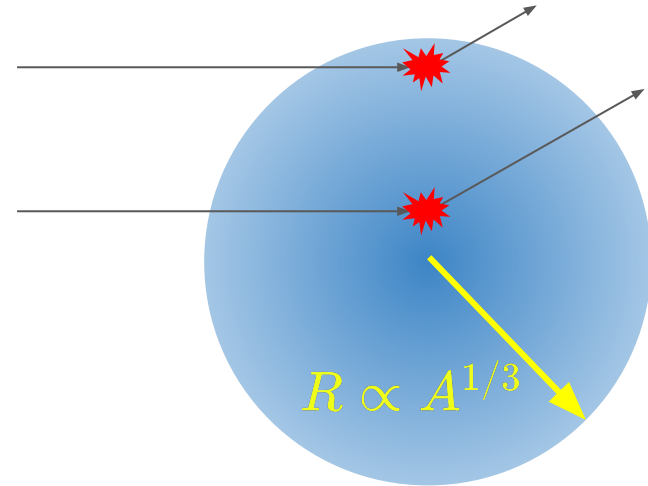


Ref: [L. Morejon, et al. JCAP 11 \(2019\) 007](#)

Photohadronic interactions

Photopion suppression

Energy dependent escape, decrease of production



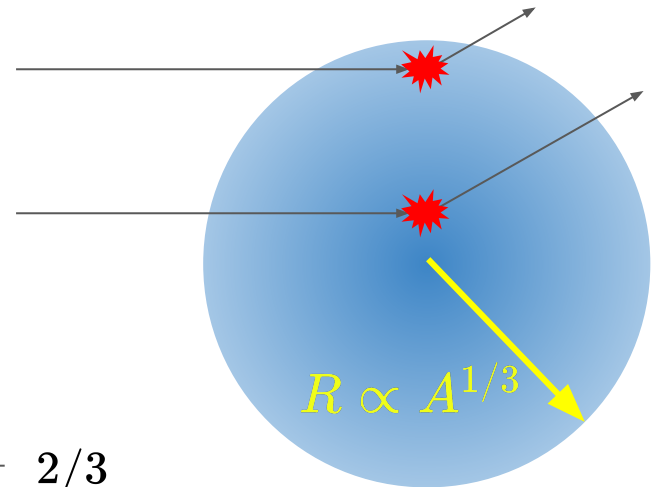
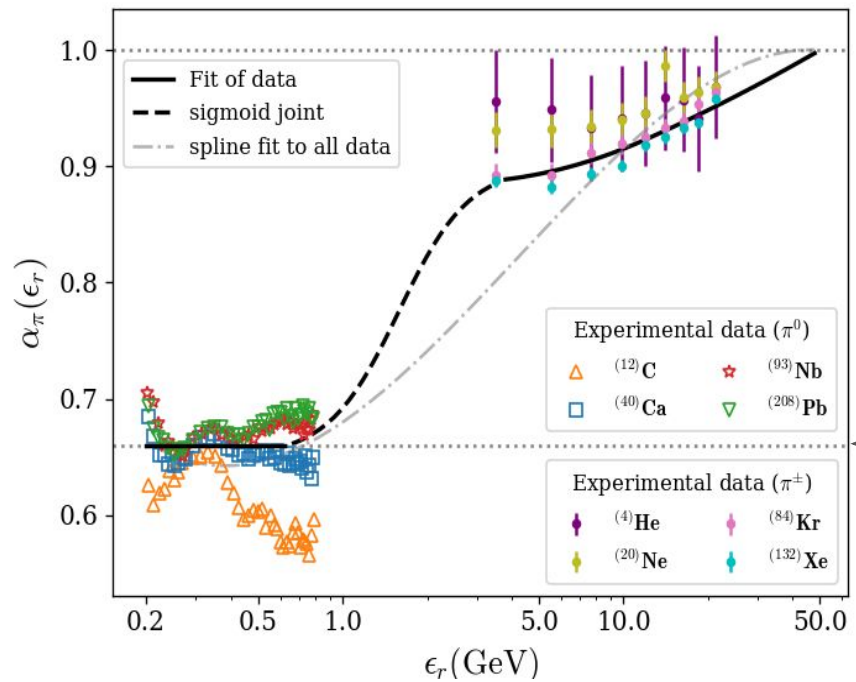
$$\sigma \propto A^\alpha$$

Ref: [L. Morejon, et al, JCAP 11 \(2019\) 007](#)

Photohadronic interactions

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Energy dependent escape, decrease of production



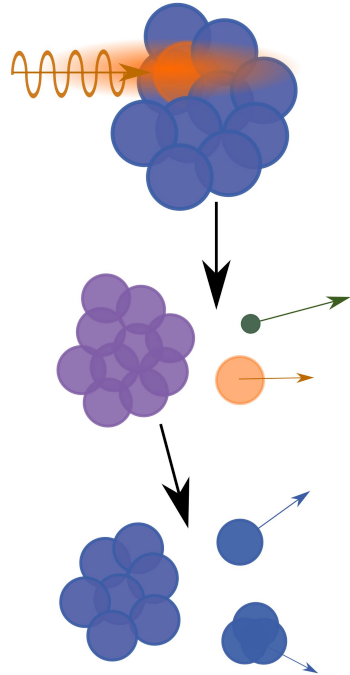
2/3

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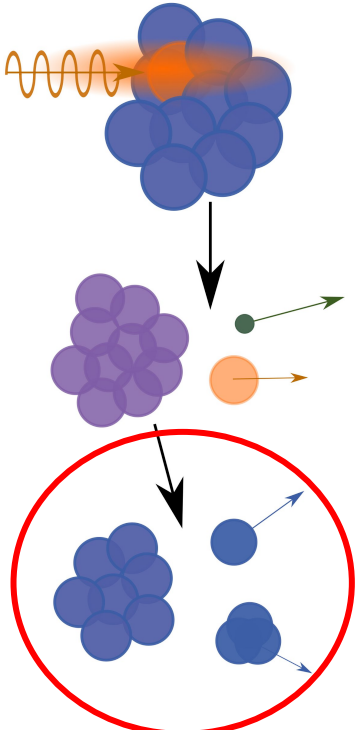
Photohadronic interactions

Cascade Enhancement

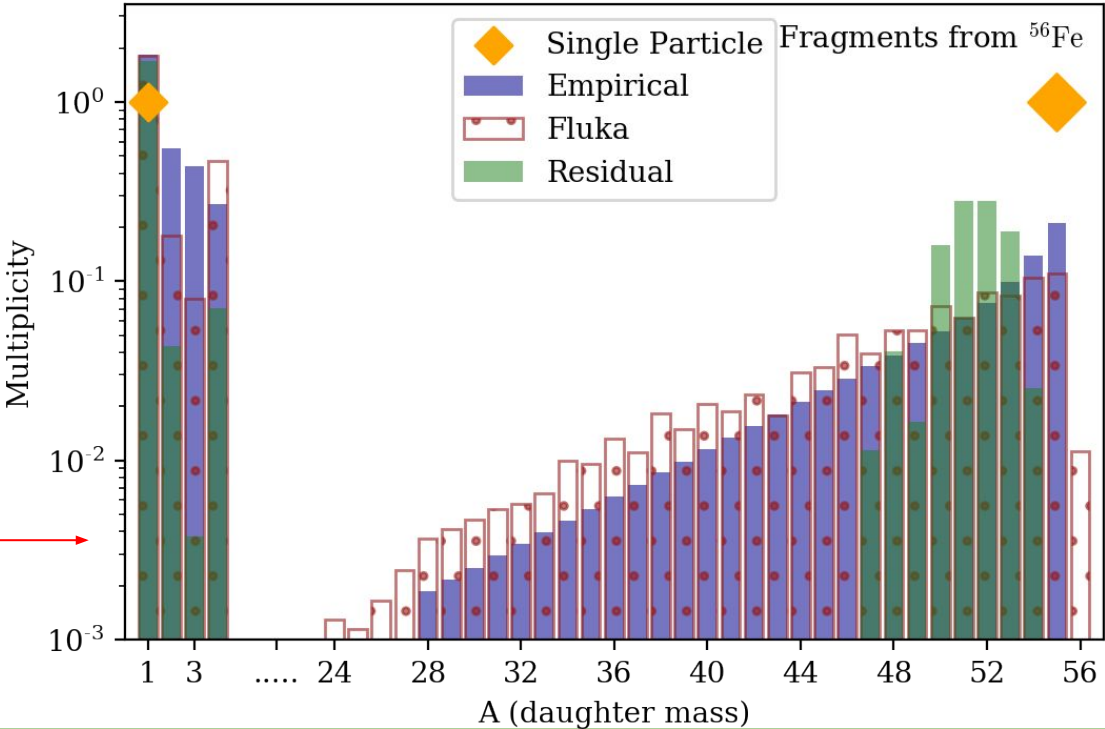


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Cascade Enhancement



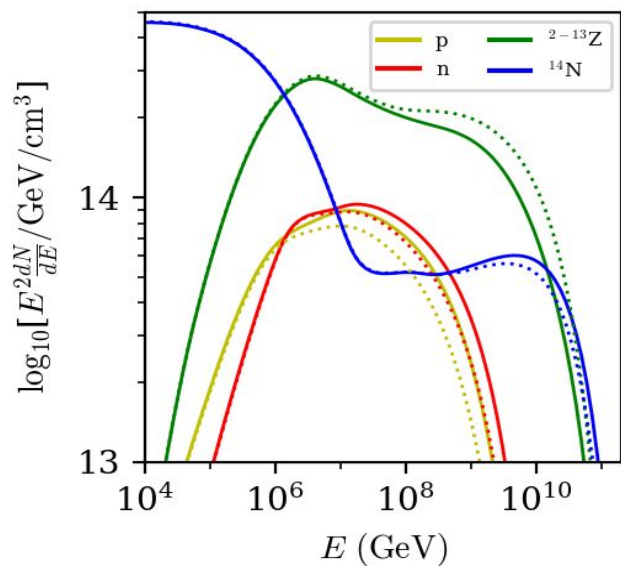
Photopion production with cascade



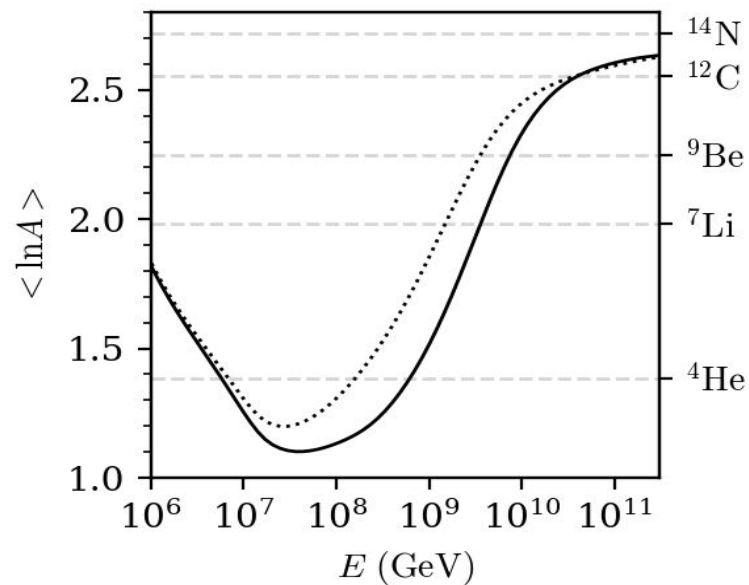
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Impact on source simulation: Tidal Disruption

⋯ Single Particle Model cross section extrapolation
— Empirical Model

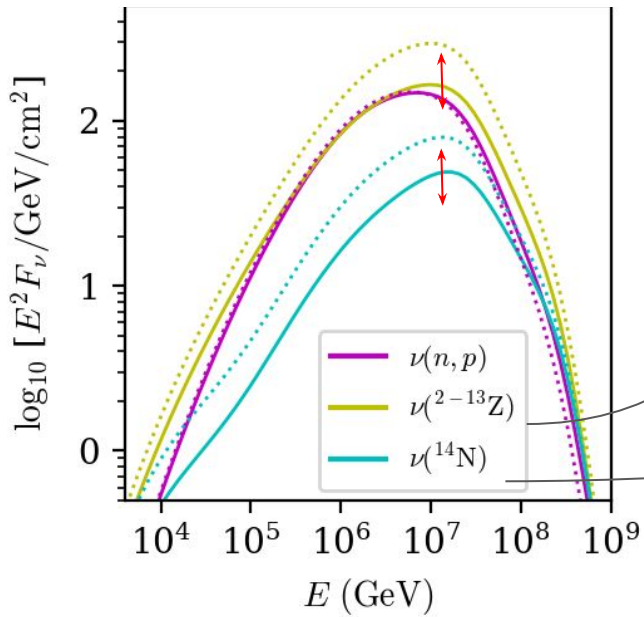


Marked differences in cascade composition!

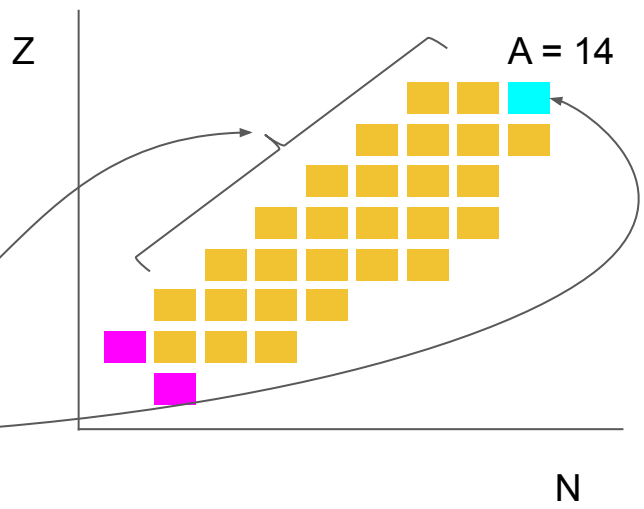


Impact on source simulation: Tidal Disruption

..... Single Particle Model ▒ cross section extrapolation
 — Empirical Model



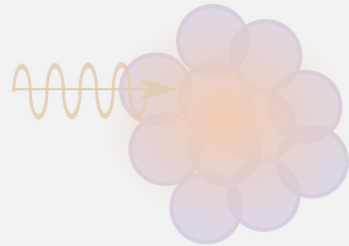
Nuclear contribution is not the dominant!



Which interaction models??

Interactions discussed

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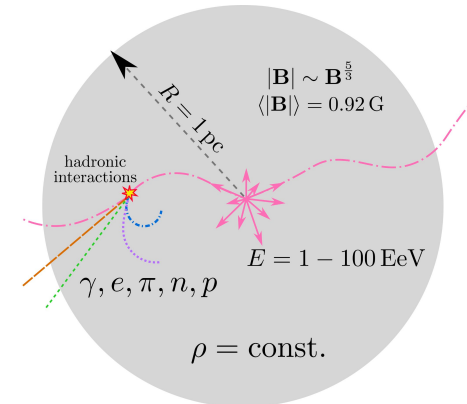


[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

$$p + p/\gamma \rightarrow p/n + \pi^\pm + \pi^0 + K^\pm + \dots$$

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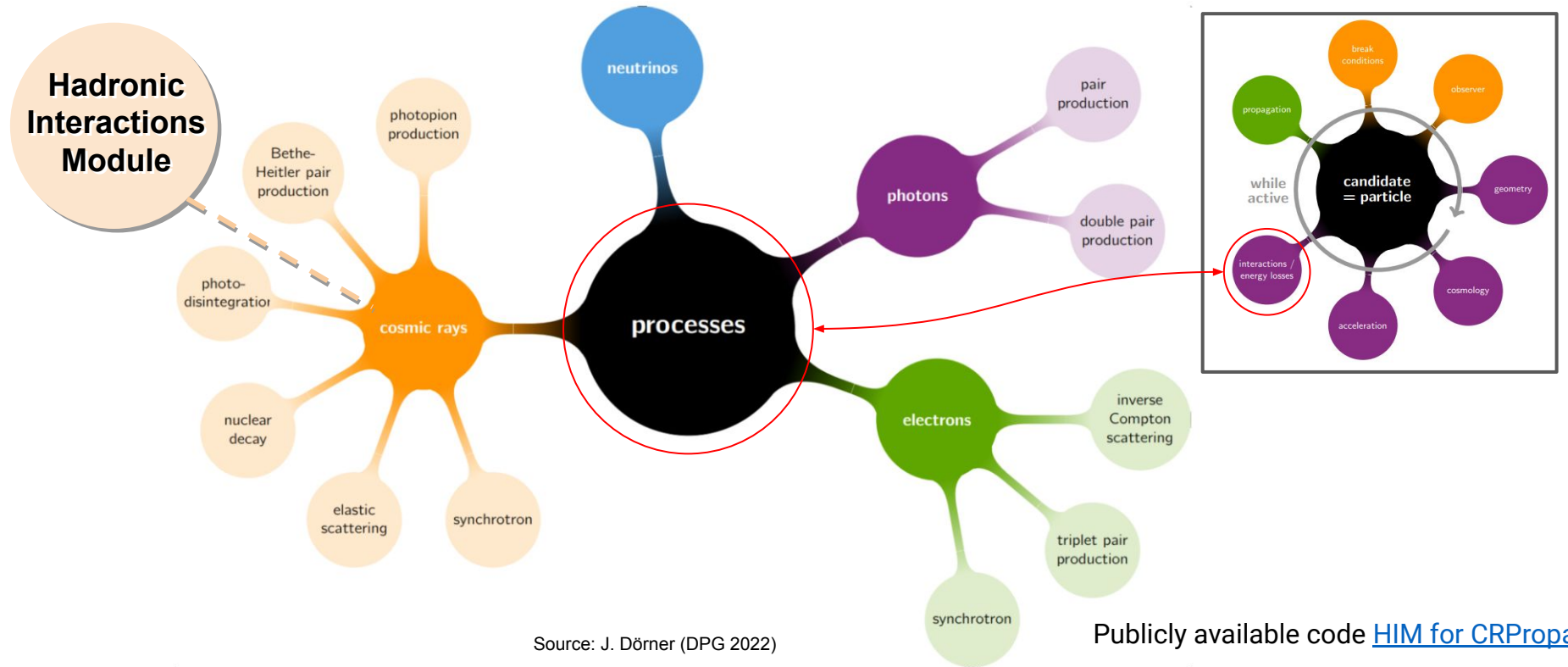
Hadronic (p+p, p+A)



[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

Hadronic interactions

Hadronic Interactions Module (HIM)



Hadronic interactions

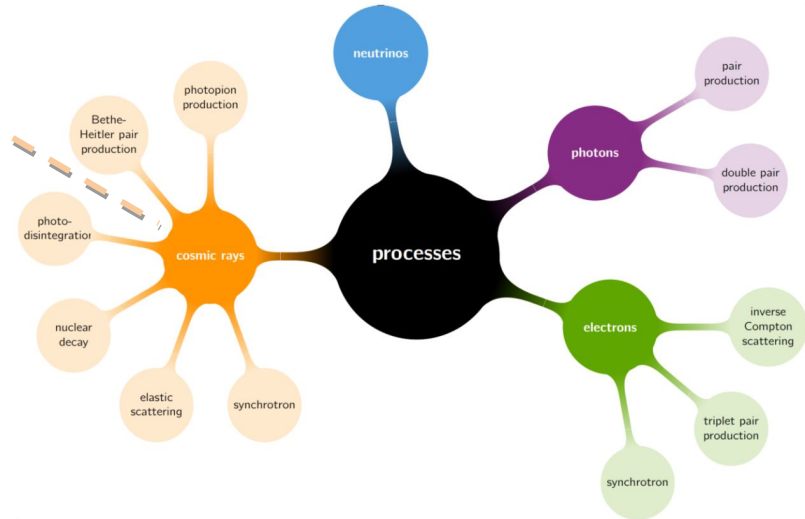
Elements of the HIM

- Sample hadr. interaction
- Produce input params.
- Call to external codes:
 - EPOS-LHC, SIBYLL, QGSJet, DPMJET, etc.
- Collect secondaries
- Transform btw. frames

Hadronic Interactions Module

Module written in python. Available on Github (installation separate from CRPropa)

Publicly available code [HIM for CRPropa](#)



Hadronic interactions

New interface: CHROMO

- Sample hadr. interaction
- Produce input params.
- **Call to external codes:**
 - EPOS-LHC, SIBYLL, QGSJet, DPMJET, etc.
- Collect secondaries
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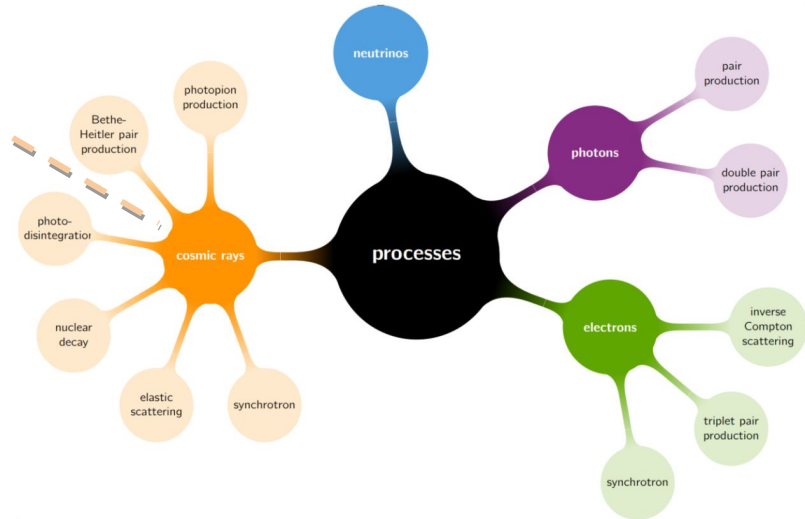
Hadronic Interactions Module

Module written in python. Available on Github (installation separate from CRPropa)

Publicly available code [HIM for CRPropa](#)

<https://github.com/impy-project/chromo>

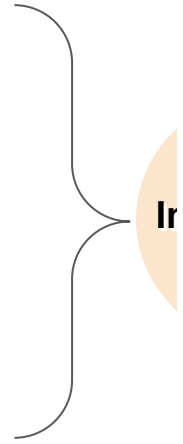
Cosmic ray and HadRONic interactiON MONte-carlo frontend



Hadronic interactions

CHROMO

- Sample hadr. interaction
- Produce input params.
- **Call to external codes:**
 - EPOS-LHC, SIBYLL, QGSJet, DPMJET, etc.
- Collect secondaries
- Transform btw. frames



Interaction model	Supported proj/targ
DPMJET-III 3.0.6 & PHOJET 1.12-35	<i>hN, γγ, γN, hA, γA, AA</i>
DPMJET-III & PHOJET 19.1 and 19.3 (repo on GitHub)	<i>hN, γγ, γN, hA, γA, AA</i>
EPOS-LHC	<i>hN, hA, AA</i>
PYTHIA 6.4	<i>hN, ee, γγ, γN</i>
PYTHIA 8.3 (https://pythia.org/)	<i>hN, ee, γγ, γN & hA, AA (Argantyr)</i>
QGSJet-01	<i>hN, hA, AA</i>
QGSJet-II-03	<i>hN, hA, AA</i>
QGSJet-II-04	<i>hN, hA, AA</i>
SIBYLL-2.1	<i>hN, hA (A<=20)</i>
SIBYLL-2.3d	<i>hN, hA (A<=20)</i>
SOPHIA 2.0	<i>γN</i>
UrQMD 3.4 + second citation	<i>hN, hA, AA*</i>

<https://github.com/impj-proj>



Cosmic ray and HadRONic interactiOn MOnTe-carlo frontend

Interaction rate and step sampling

[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

The interaction step is sampled as

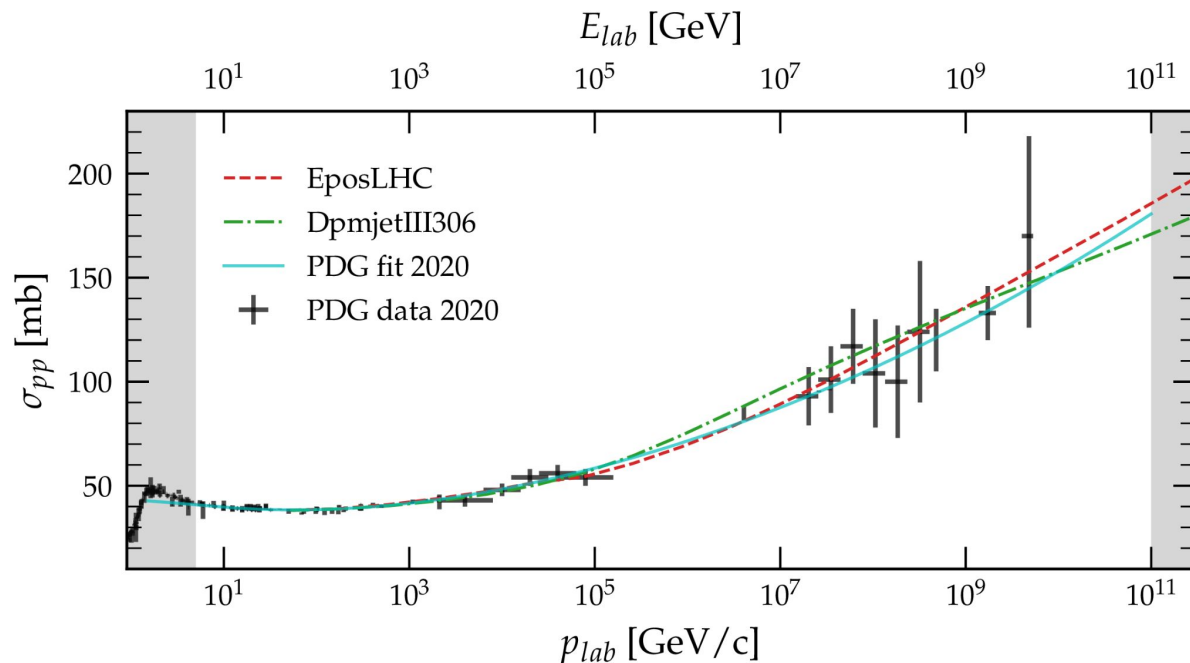
$$d = - \frac{\log p}{\sigma \rho}$$

where p is a random number sampled using CRPropa functions.

The **density** is handled by the Density class available in CRPropa.

The cross section can be chosen:

- from hadronic code (inefficient)
- from DPG recommended fit



* C. Patrignani 2016 Chinese Phys. C 40 100001

* P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

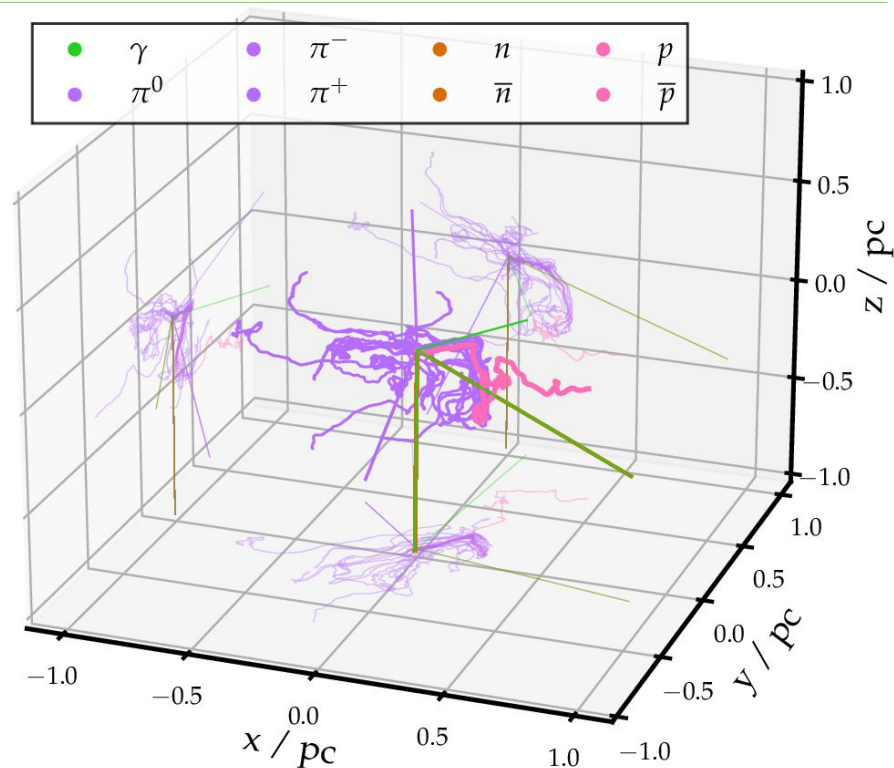
Additional random-seed settings

Seeds available for control:

1. Step-sampling seed
2. Hadronic engine's seed
3. Interaction-plane angle seed

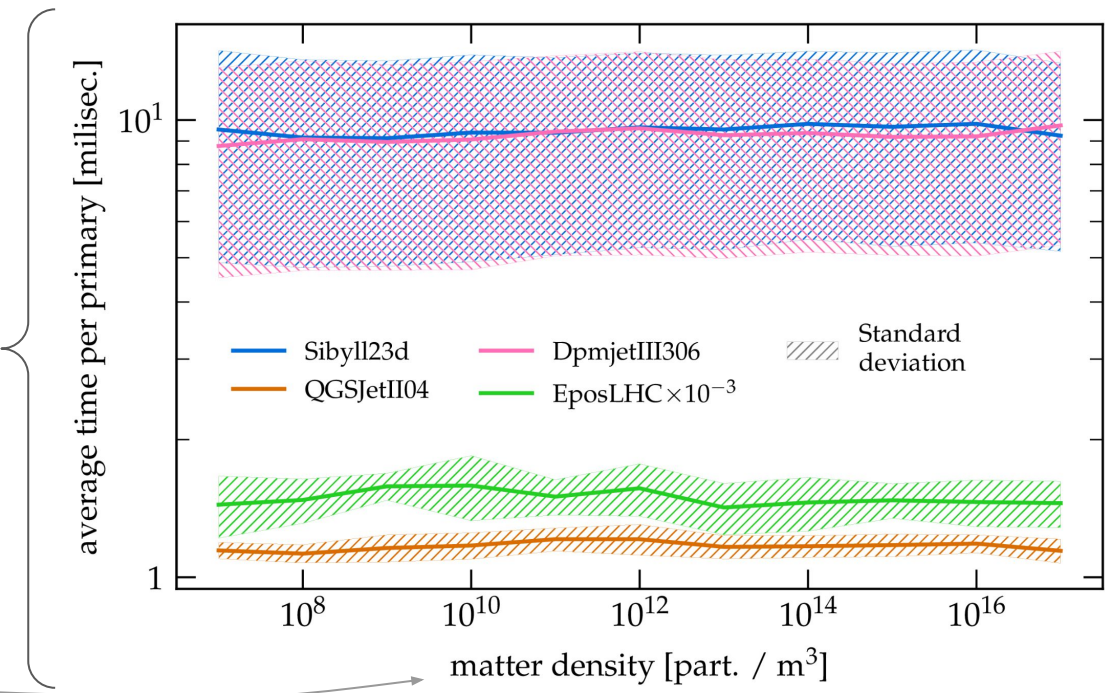
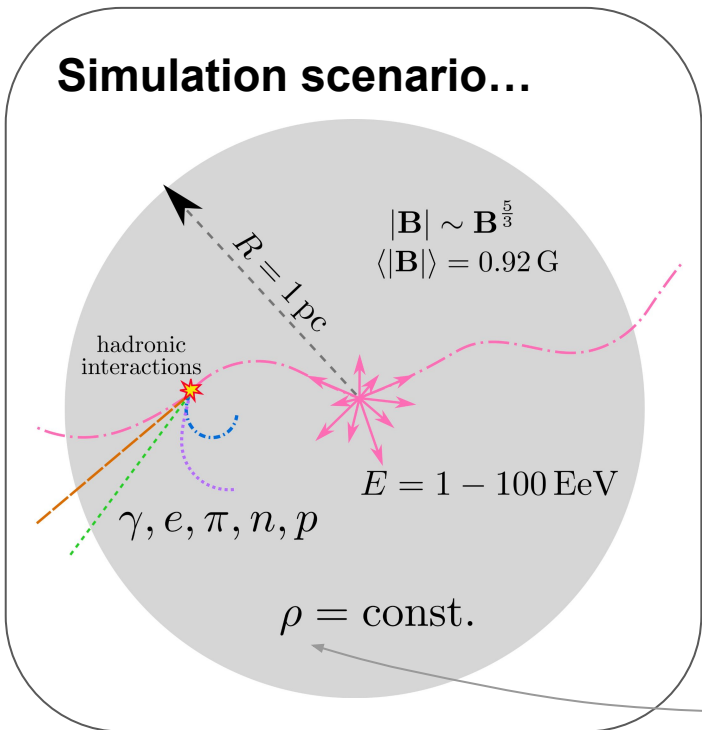
Example figure...

- Injecting a proton 1EeV
- Interaction step controlled by **seed 1**
- Secondaries' species, energy, momenta and distribution controlled by **seed 2**
- Transversal plane momenta controlled by **seed 3**

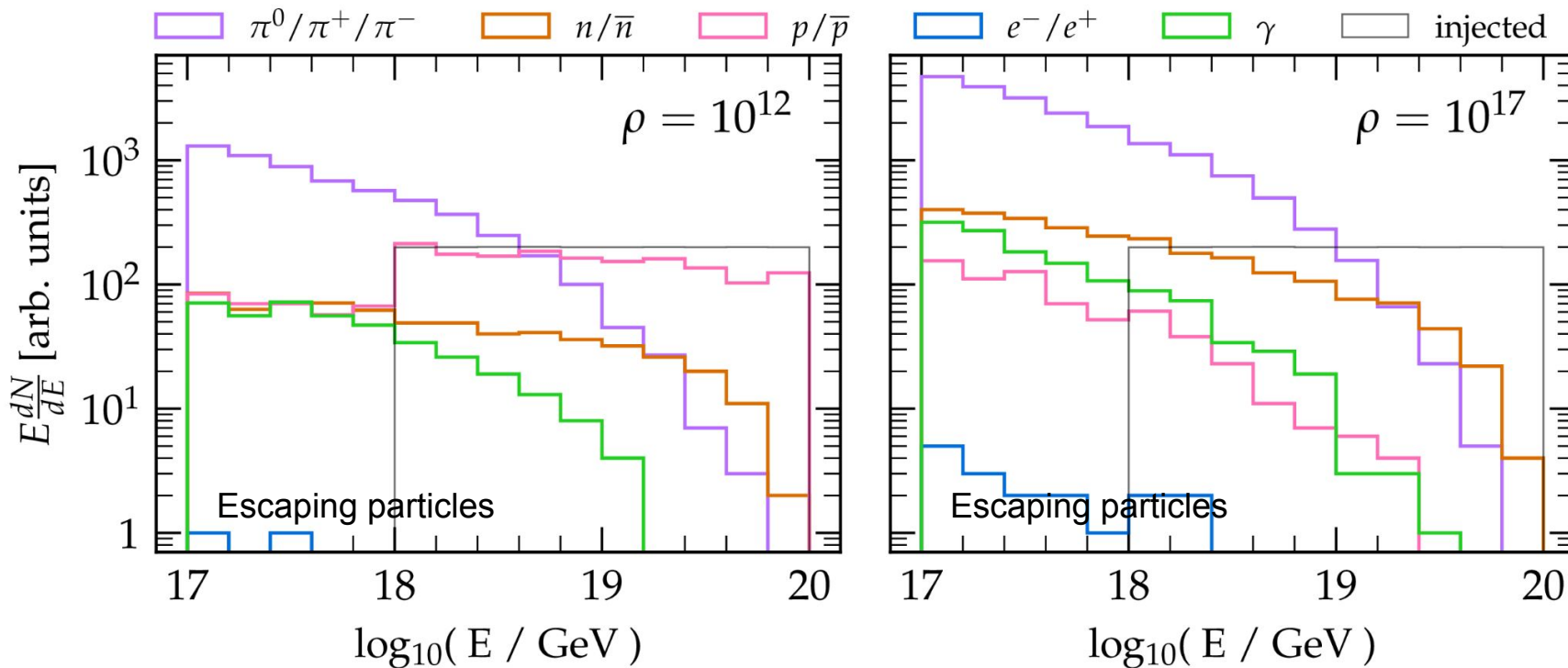


Hadronic interactions

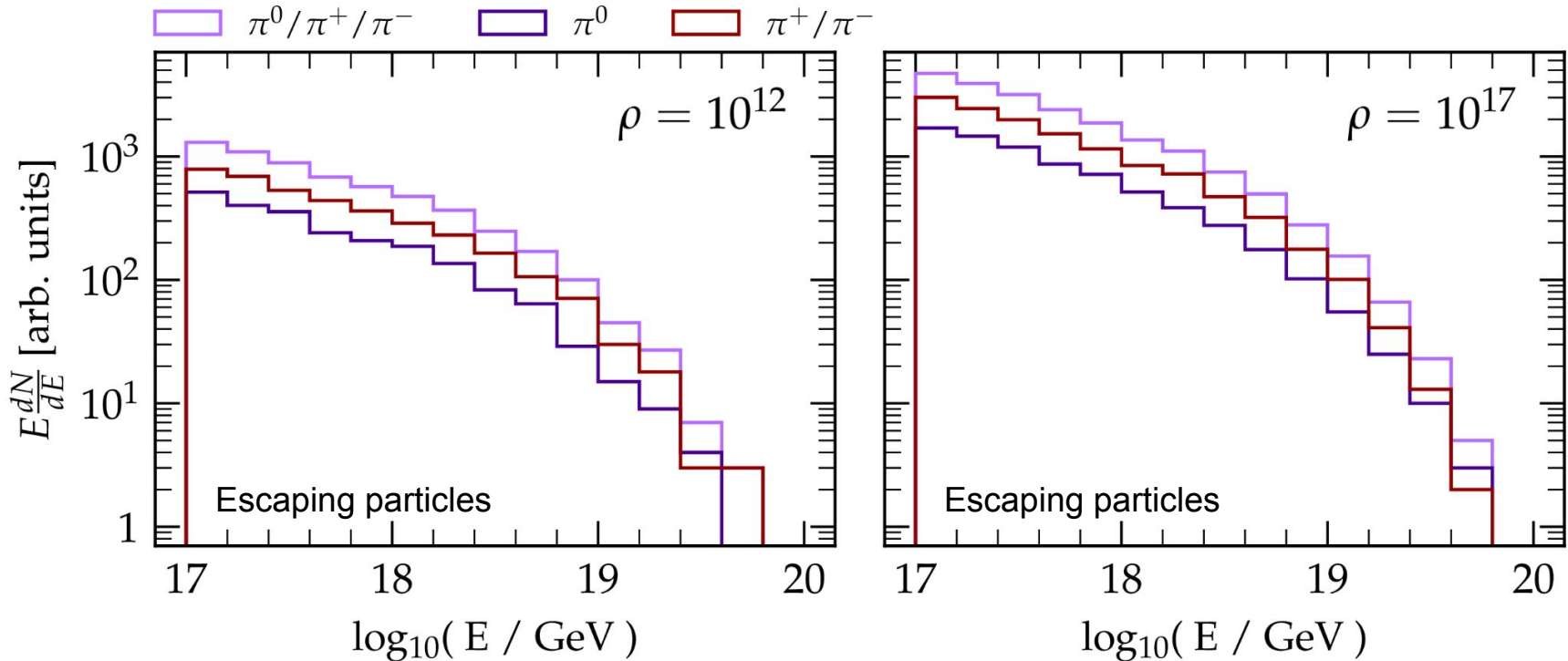
Simulation time versus matter density



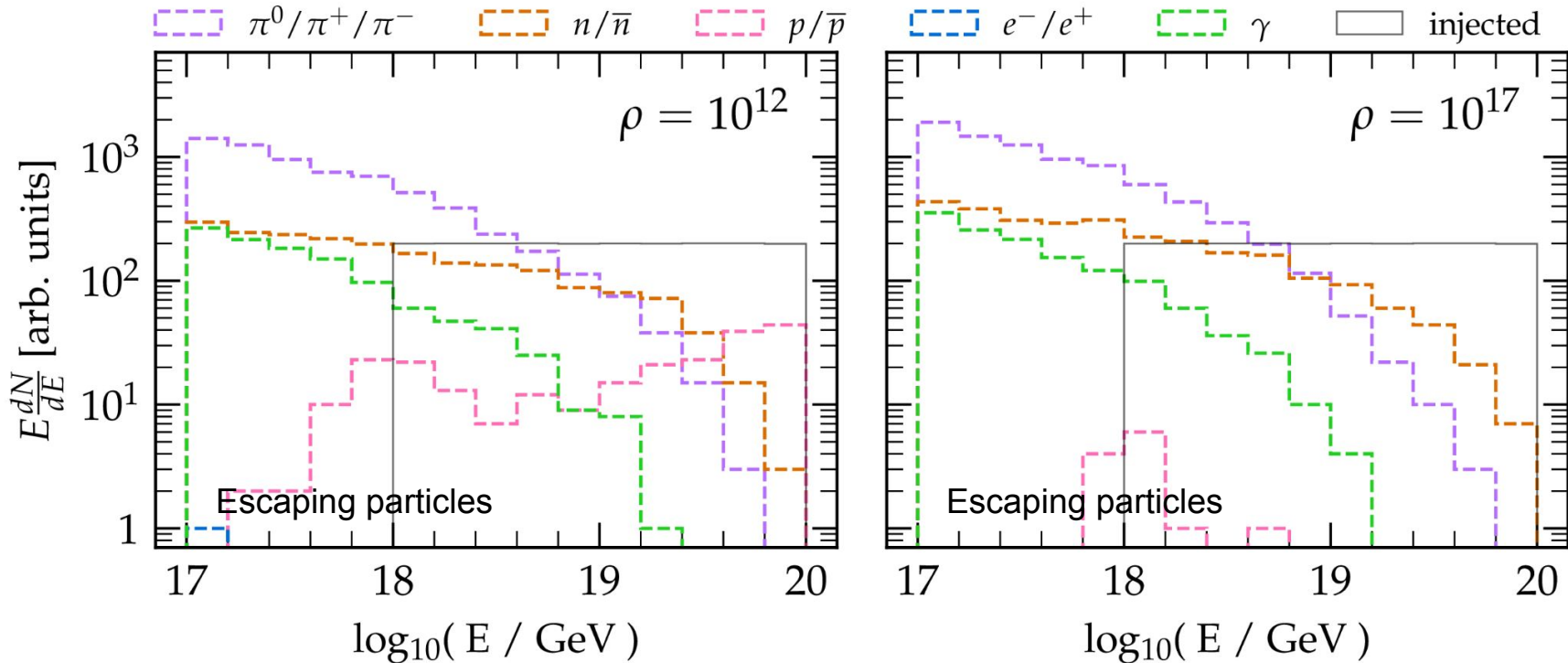
Example simulation (Magn. Field OFF)



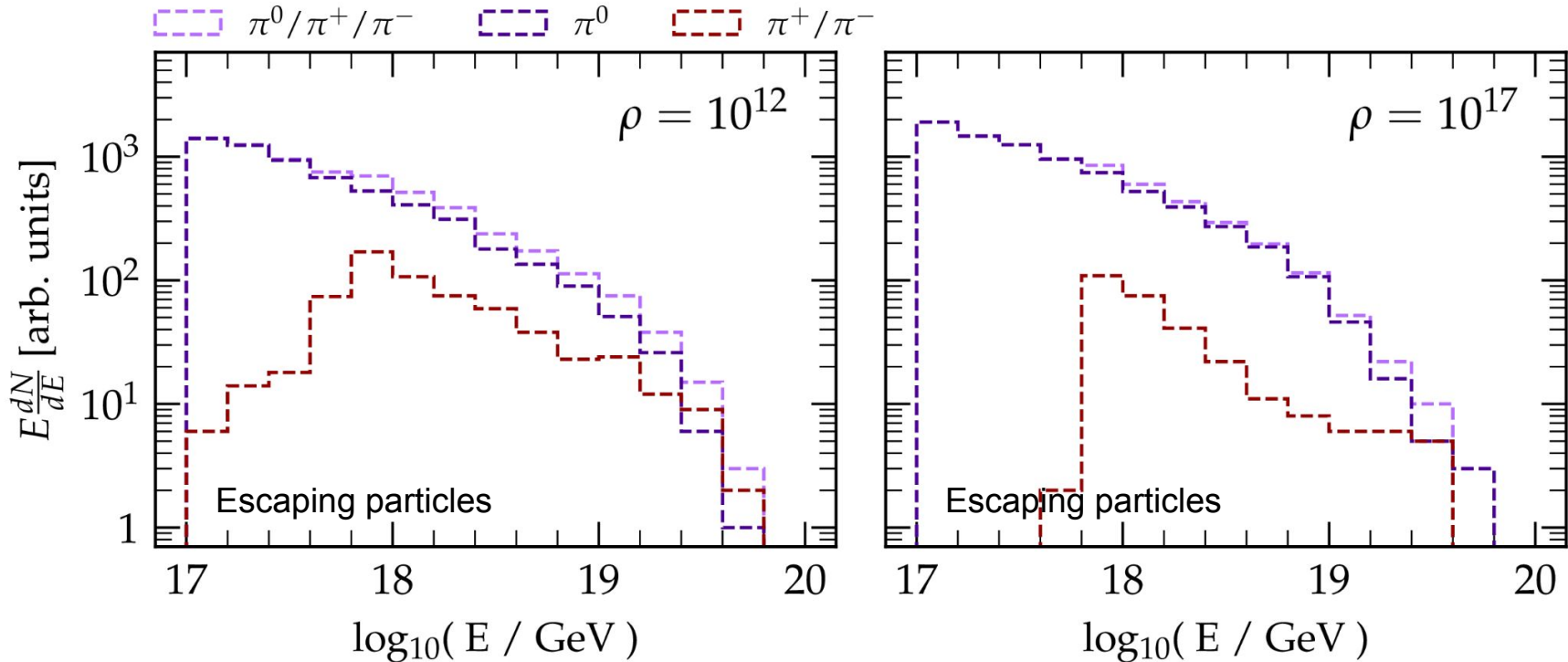
Example simulation (Magn. Field OFF)



Example simulation (Magn. Field ON)

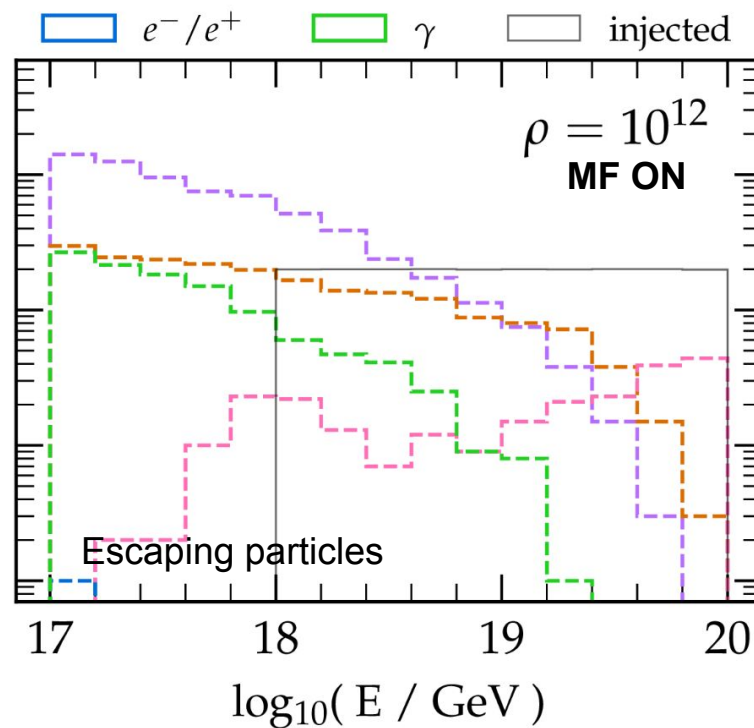
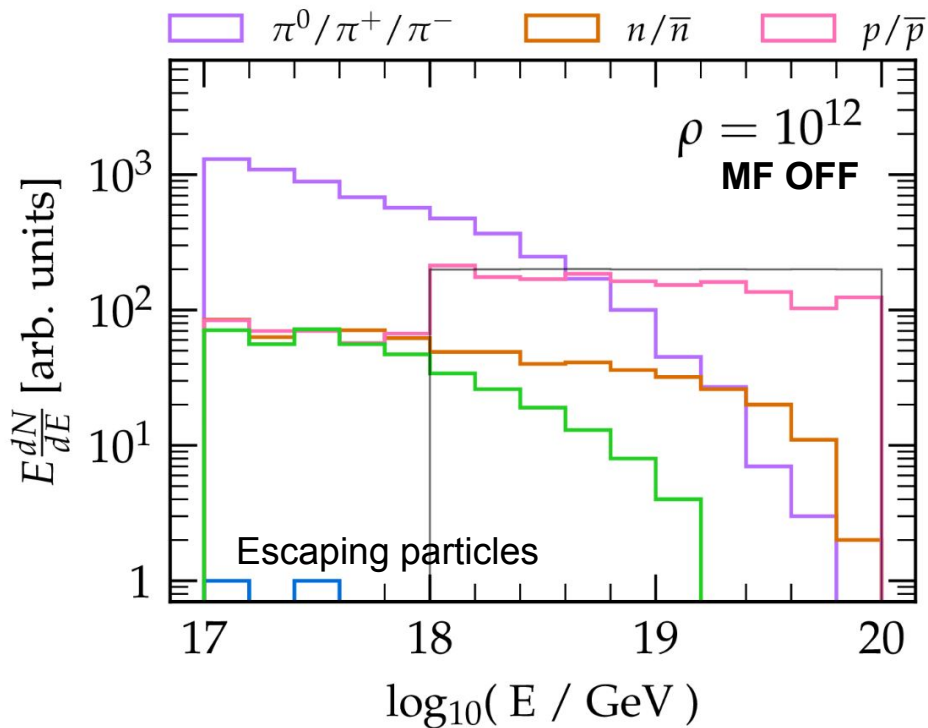


Example simulation (Magn. Field ON)



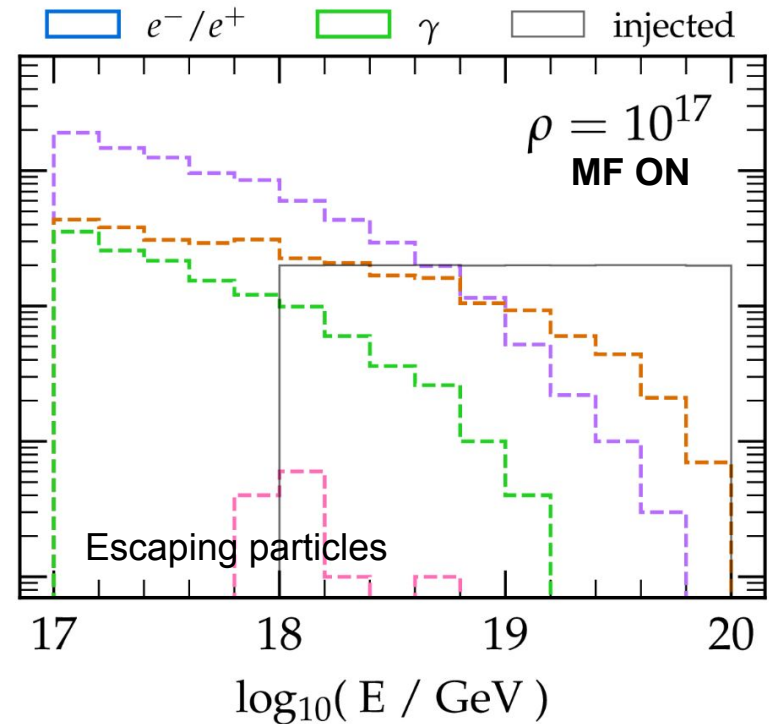
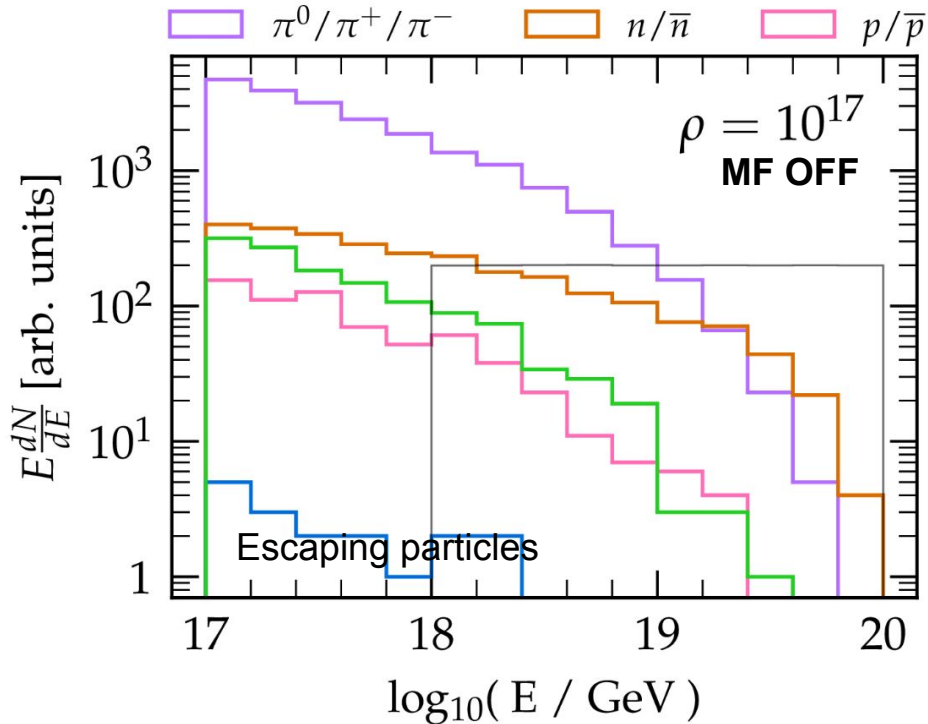
Hadronic interactions

Magn. Field ON versus OFF



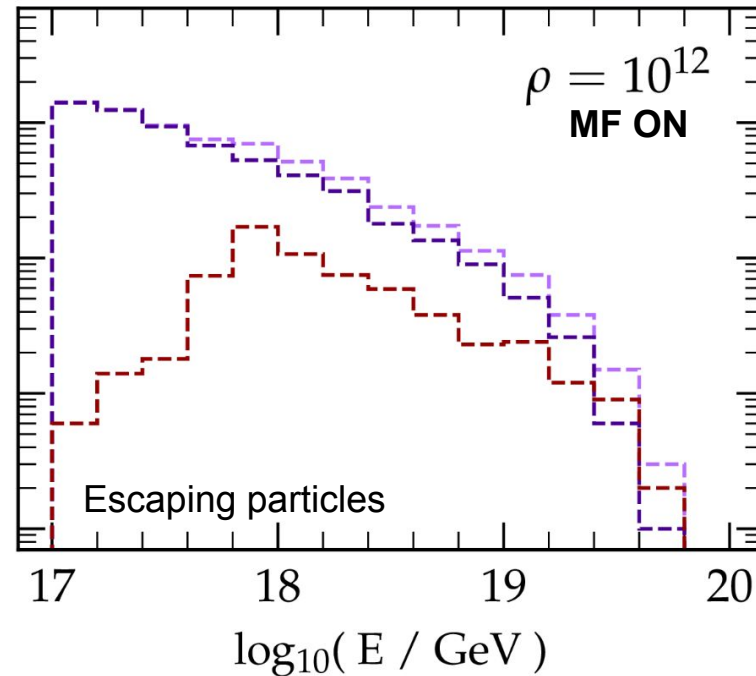
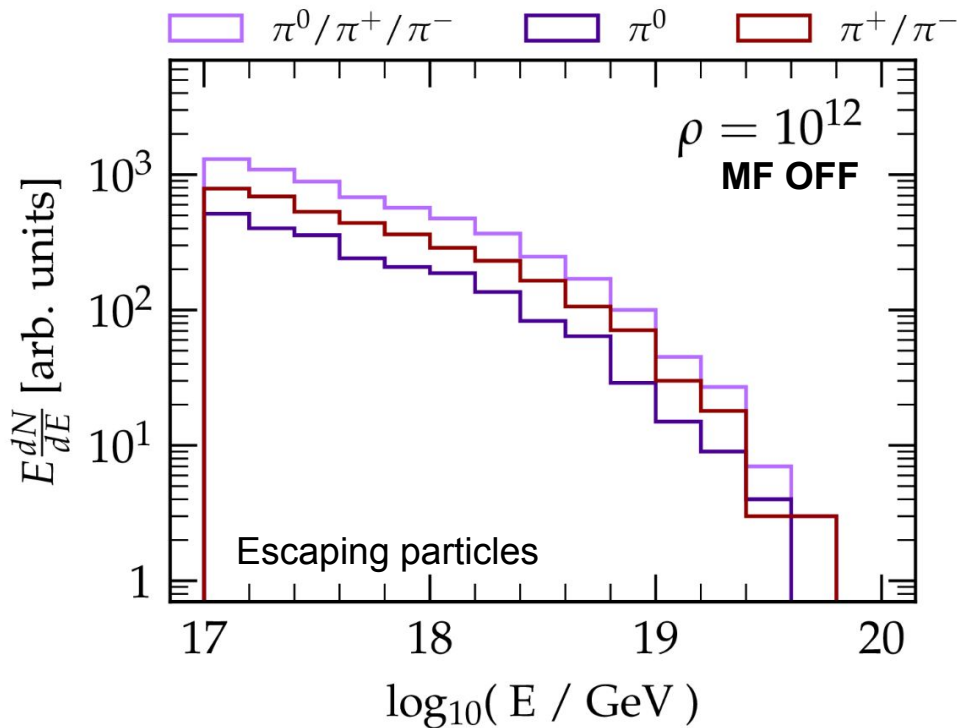
Hadronic interactions

Magn. Field ON versus OFF



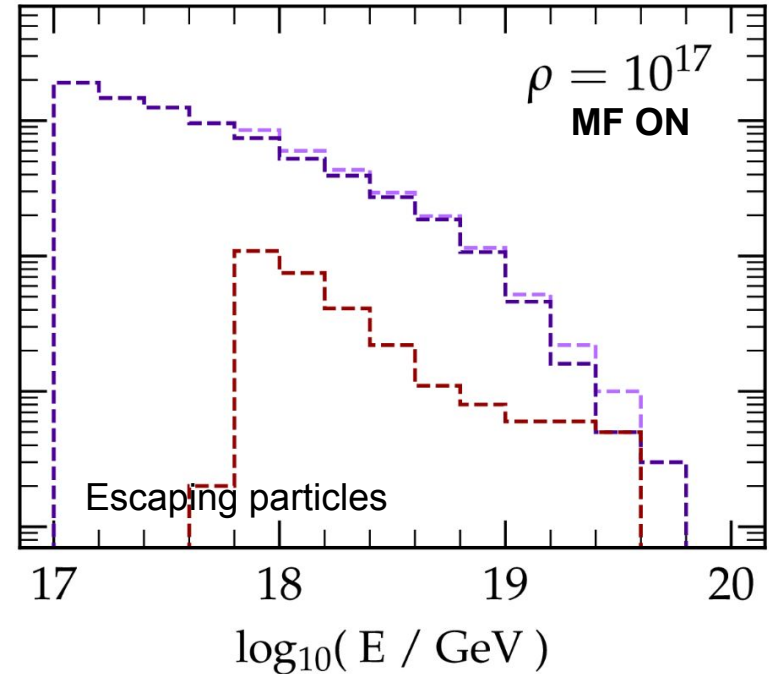
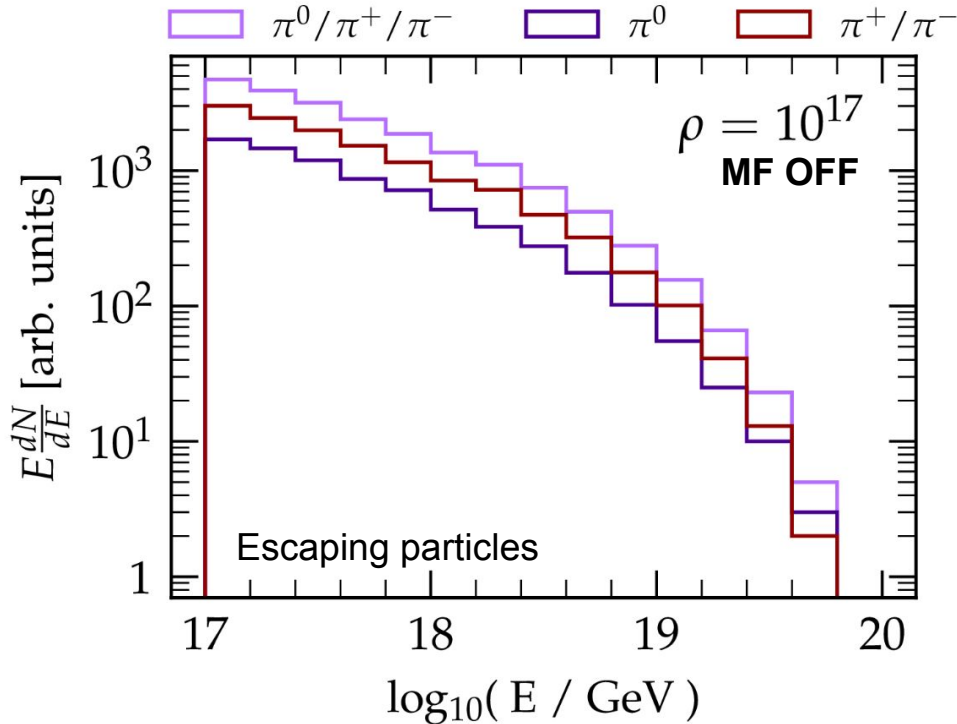
Hadronic interactions

Magn. Field ON versus OFF



Hadronic interactions

Magn. Field ON versus OFF





MICRO website



MICRO@github



Photopion @ github



HIM @ github

Thanks!



[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

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