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Modeling Hadronic Interactions in Ultra-High-Energy Cosmic Rays within Astrophysical Environments: A Parametric Approach

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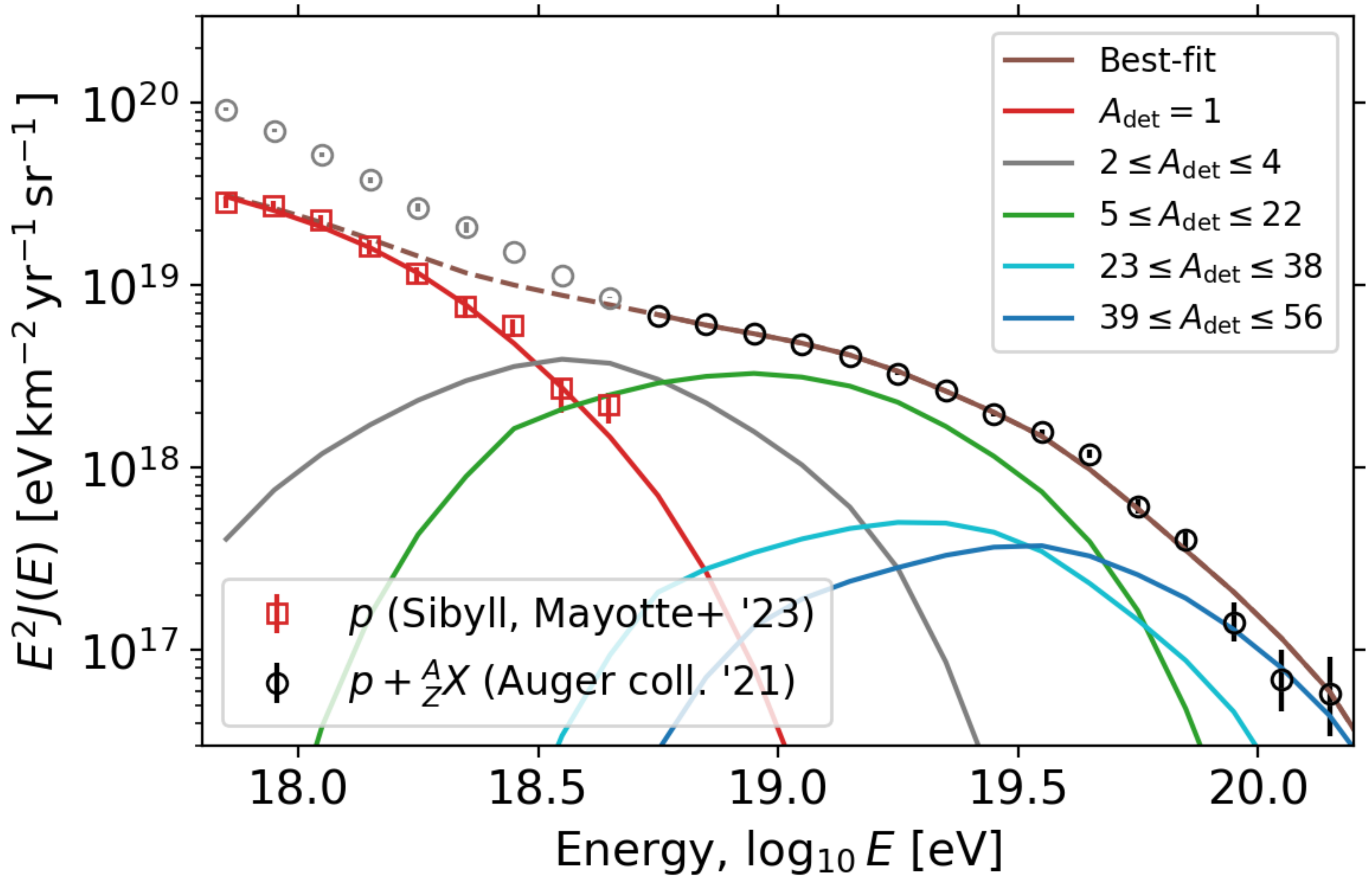
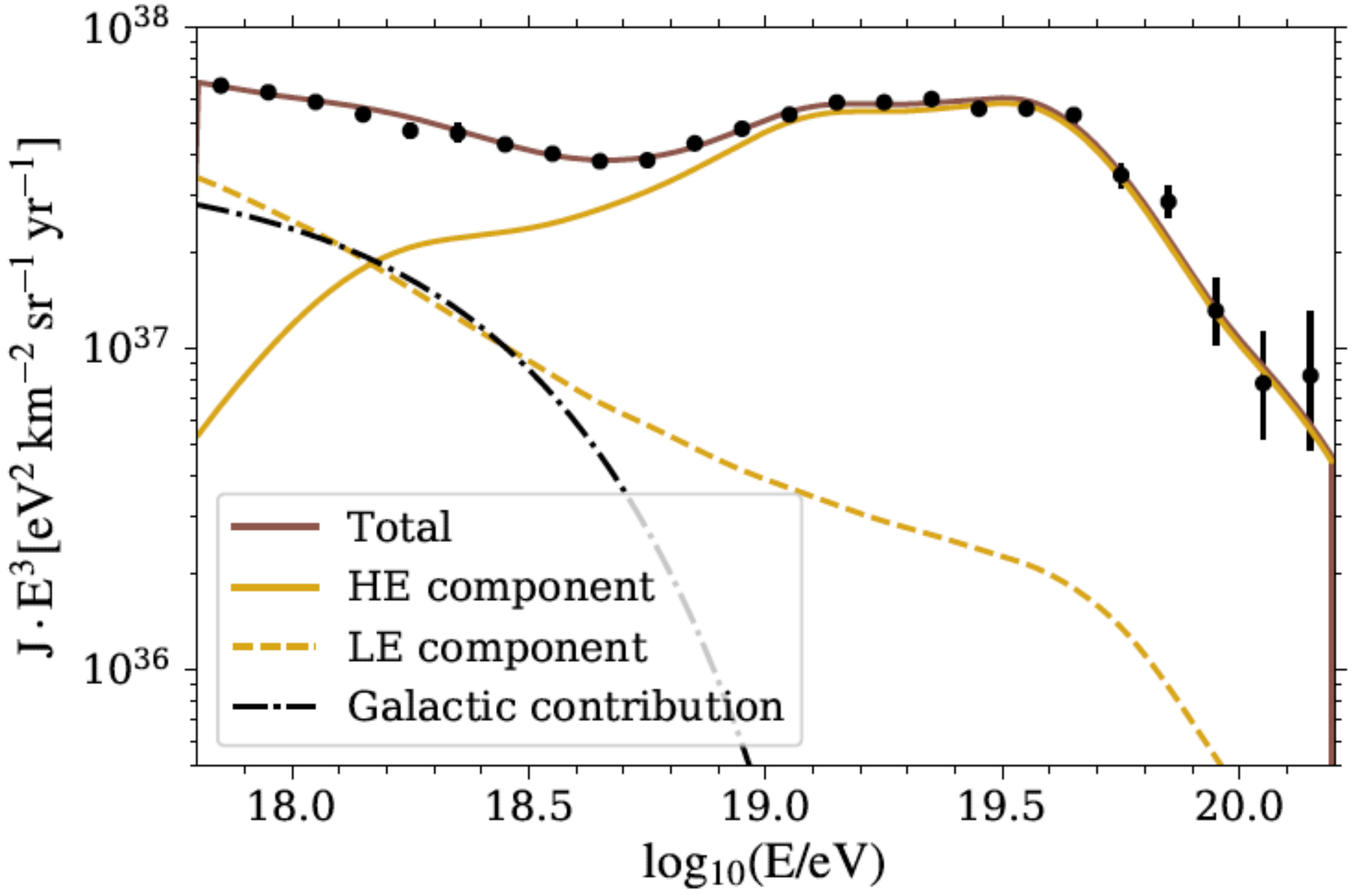
arXiv:2405.02658v1

SimProp meeting, 14/06/2024

Motivation

Understanding propagation in source environment –> key to interpret UHECR data.

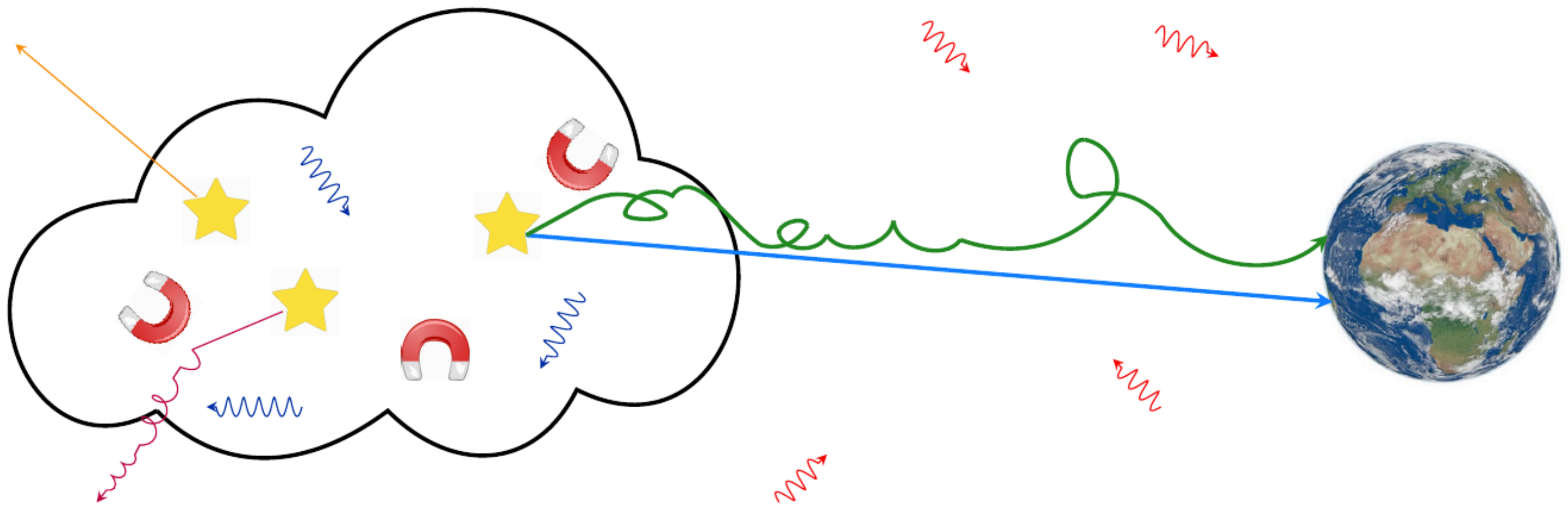




Q. Luce et al., 2022 ApJ 936 62
The Pierre Auger Collaboration, JCAP05(2023)02

Interactions at the source

- Accelerated particles confined in the environment surrounding the source;
- Presence of photon and gas density;
- High energy particles–> escape with no interaction;
- Low energy particles –> Pile-up of nucleons at lower energies.

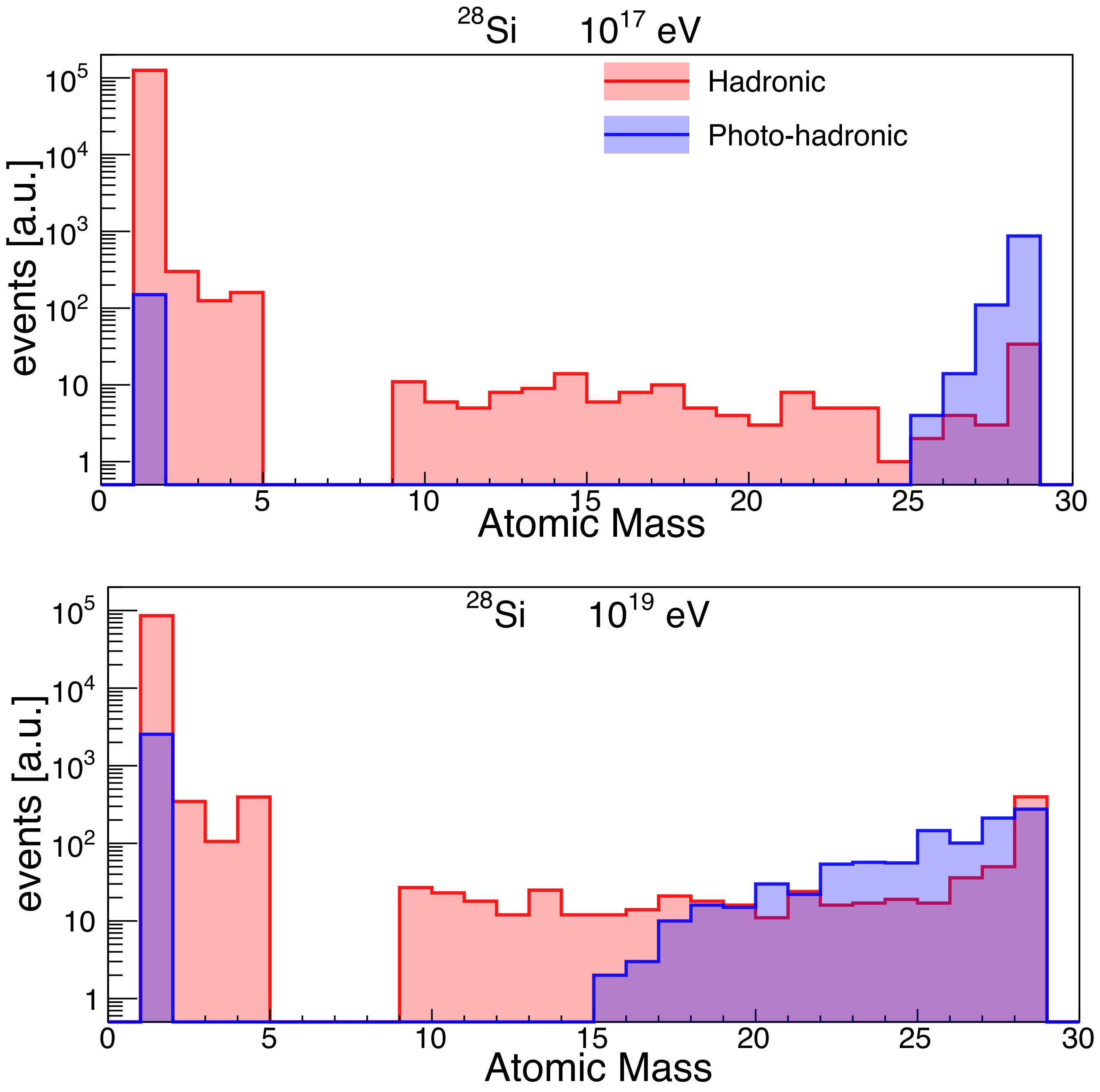


Interactions at the source already discussed in:

- ✓Unger, M., Farrar, G. R., & Anchordoqui, L. A. 2015, PhRvD, 92, 123001
- ✓Globus, N., Allard, D., & Parizot, E. 2015, PhRvD, 92, 021302
- ✓Biehl, D., Boncioli, D., Fedynitch, A., & Winter, W. 2018, A&A, 611, A101
- ✓Zhang, B. T., Murase, K., Kimura, S. S. Et al., P. 2018, PhRvD, 97, 083010
- ✓Fang, K., & Murase, K. 2018, Nature Phys., 14, 396
- ✓Supanitsky, A. D., Cobos, A., & Etchegoyen, A. 2018, PhRvD, 98, 103016
- ✓Boncioli, D., Biehl, D., & Winter, W. 2019, ApJ, 872, 110
- ✓Condorelli, A., Boncioli, D., Peretti., E., & Petrera, Phys. Rev. D 107, 083009

Hadronic interactions in source environment

- HI normally neglected in the extra-galactic propagation due to the low density $\simeq 1\ cm^{-3}$;
- They can play a fundamental role in shaping the UHECR escaping fluxes;
- Leading pion approximation –> do not take into account the energy pion distribution;
- More accurate parametrizations exists (Kelner, Aharonian, Phys. Rev. D 74, 034018) but focused on lower energies;



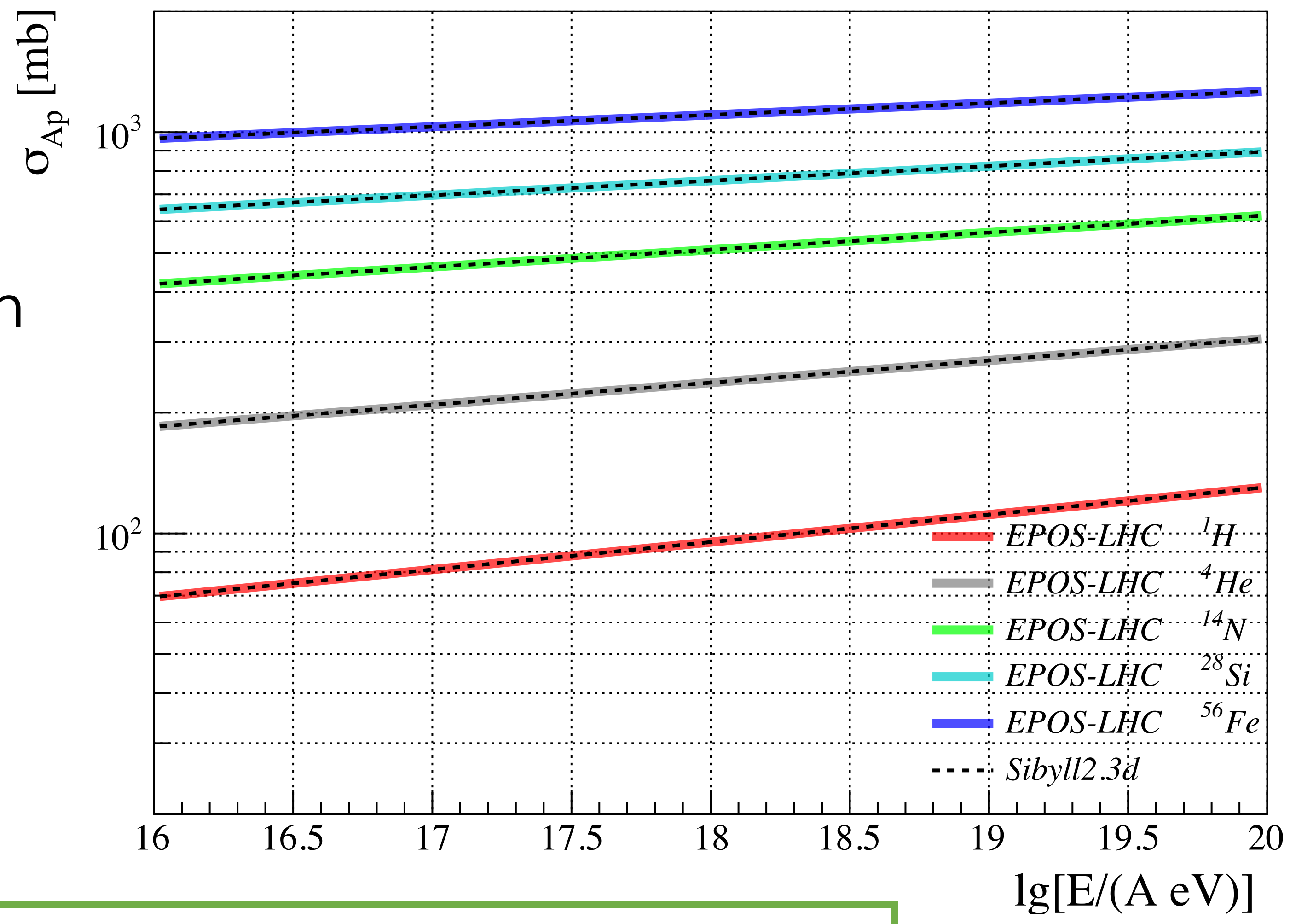
HIMs

- p-p and p-N interactions can be taken into account using Hadronic Interaction Models (HIMs).
- Written in fortran, slow, hard to attach to a Montecarlo code;
- In the UHECRs atmospheric propagation –> forward hadrons play the primary role (decay vs interaction);
- In astrophysical environment –> nuclei and nucleons are important!
- –> **timely problem: simple parametrization capable to provide multi-messenger secondaries in an astrophysical environment with the accuracy of the HIMs and without their complexity.**

My strategy

Quantity to be parametrized

- Use of CRMC (Cosmic Ray Monte Carlo) for EPOS-LHC and Sibyll2.3d;
- Quantity to be parametrized: cross section, secondary production and fragmentation;
- Cross section: important to compute the timescale;
- They are easily fitted assuming logarithmic energy and mass dependence –> perfectly superimposed!



Database for parameterizations

Nucleus(proj) + p (@rest) generated from Sibyll2.3d (program interface/sib_pN.cc)

6 nuclei: p, He, N, Si, Ca, Fe

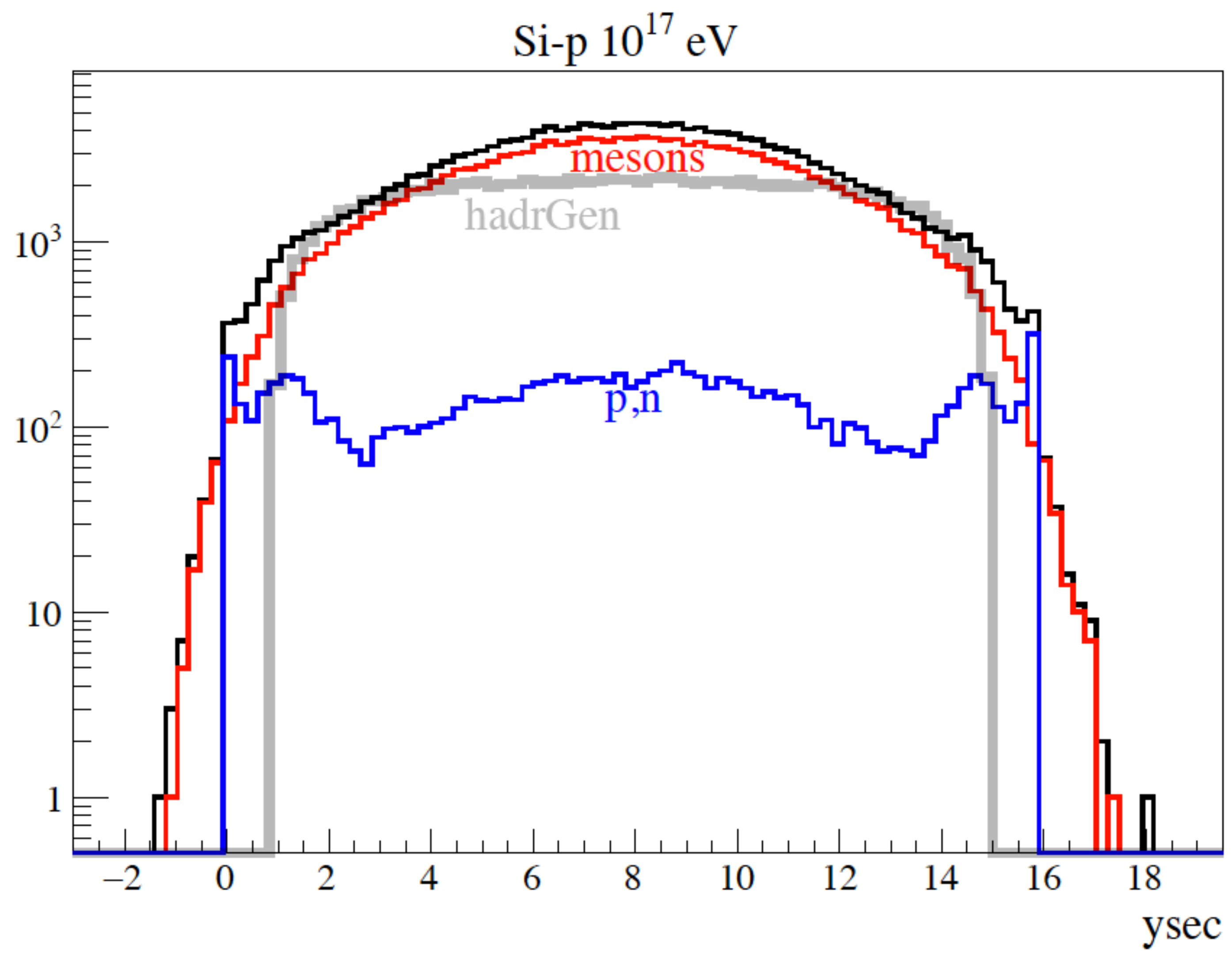
5 energy-per-nucleon bins: 10^{16}, 10^{17}, 10^{18}, 10^{19}, 10^{20} eV

1000 evts/sample

Secondary production

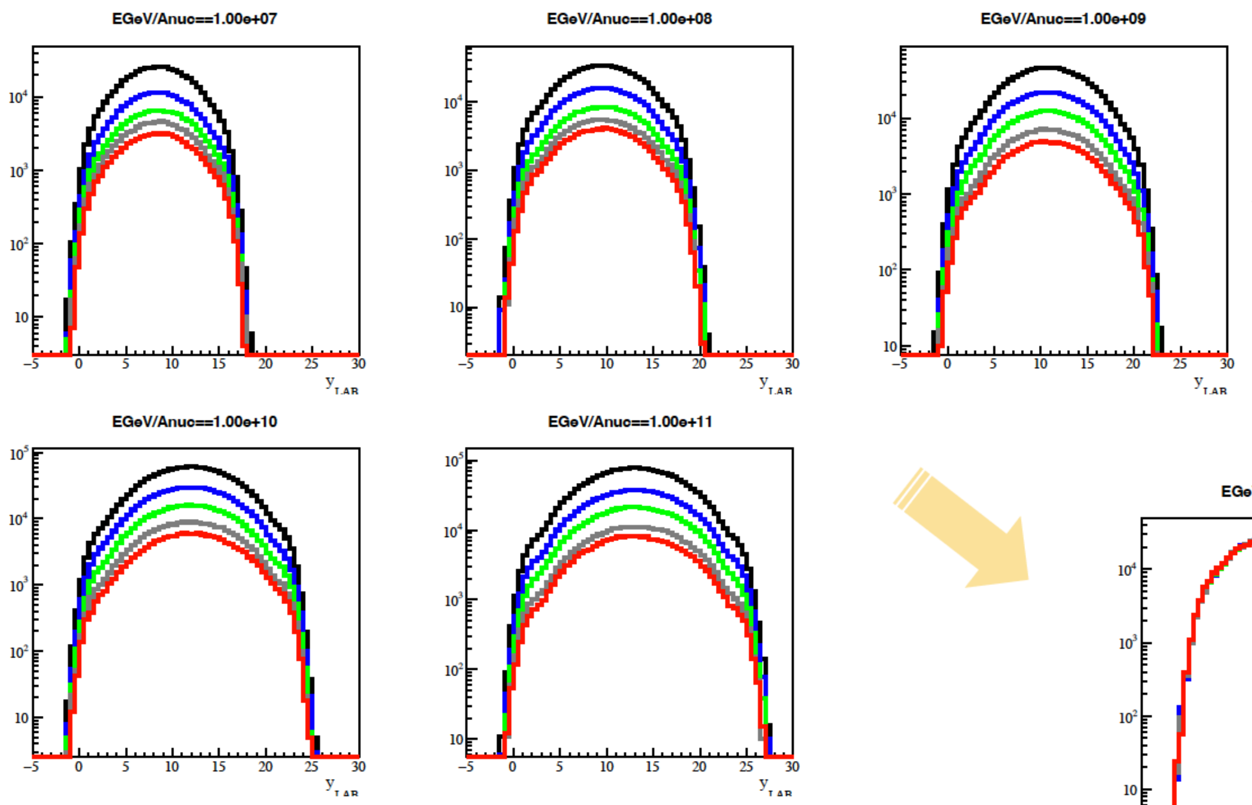
Hypothesis: the secondaries produced are only pions and nucleons (lighest hadron approximation):

- Pions actively contribute to the production of electrons and neutrinos through charged pion-muon decays, as well as photons through neutral pion decays.
- All baryons (antibaryons) heavier than nucleons (antinucleons) undergo successive decays until only nucleons (antinucleons) remain.

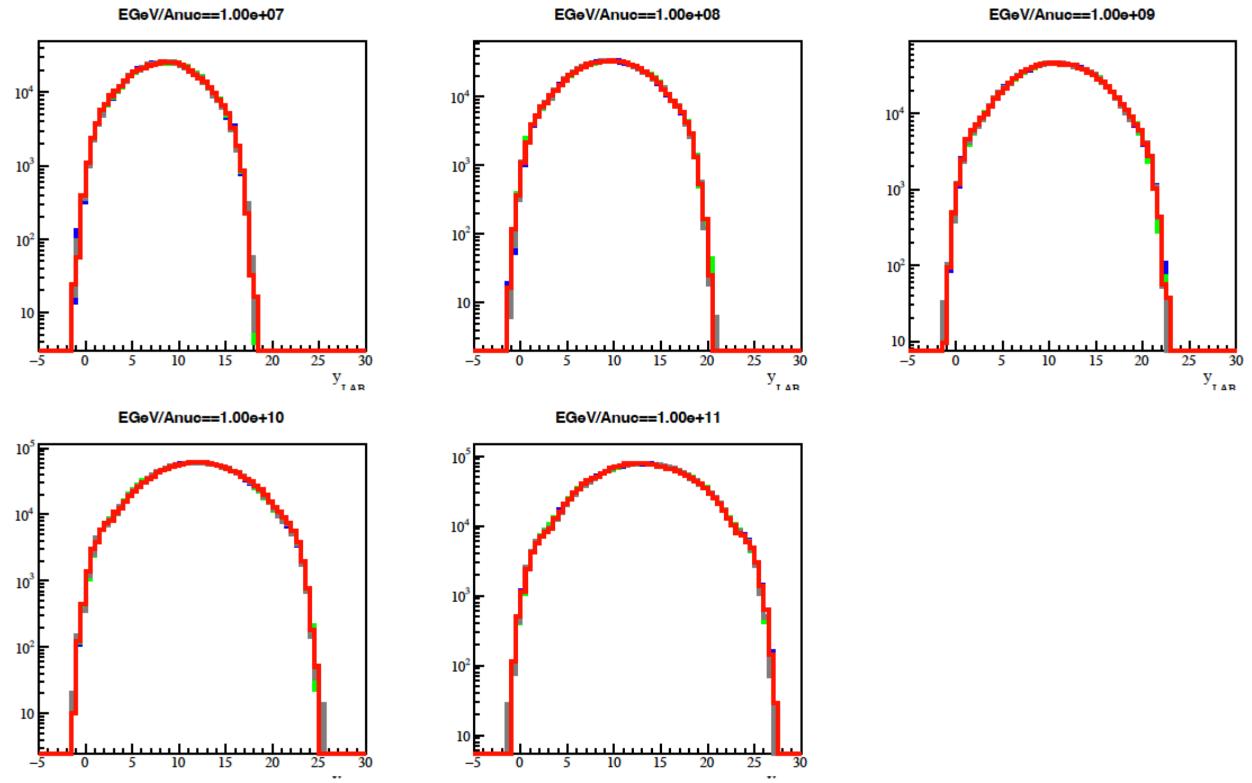


Secondary production (in Sibyll)

- Sibyll –> One single parametrisation as a function of E/A;
- EPOS –> parameterization as a function of Energy-per-nucleon and A.
- Different number of free parameters, bilinear interpolation needed for EPOS.



Rapidity distributions at fixed energy-per-nucleon (GeV/n)

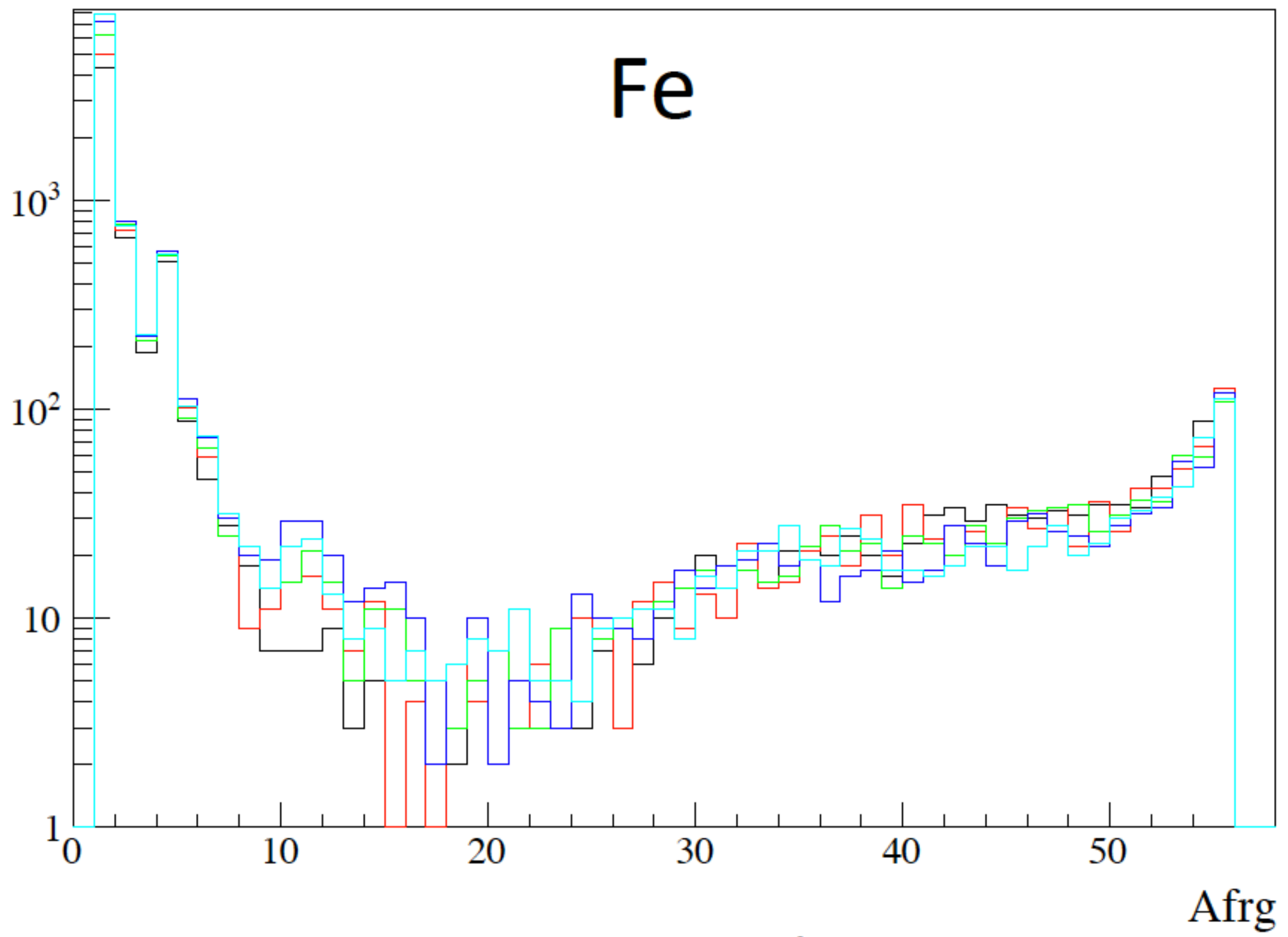


Scaled distributions are independent of A. Scale as nsec(A)

⇒ one single parameterization as a function of Energy-per-nucleon

Nuclear fragmentation

- Nuclear fragmentation is a slow process with respect to hadronic times, predominantly originated by the evaporation of a nucleus excited by HIs:
- Cosmic-ray collisions are predominantly peripheral –> HIs preserve Lorentz factor ;
- Two different HIMs present very different fragmentations;
- First order approximation: energy independent.
- Iterative way –> no analytical expression provided in the paper.



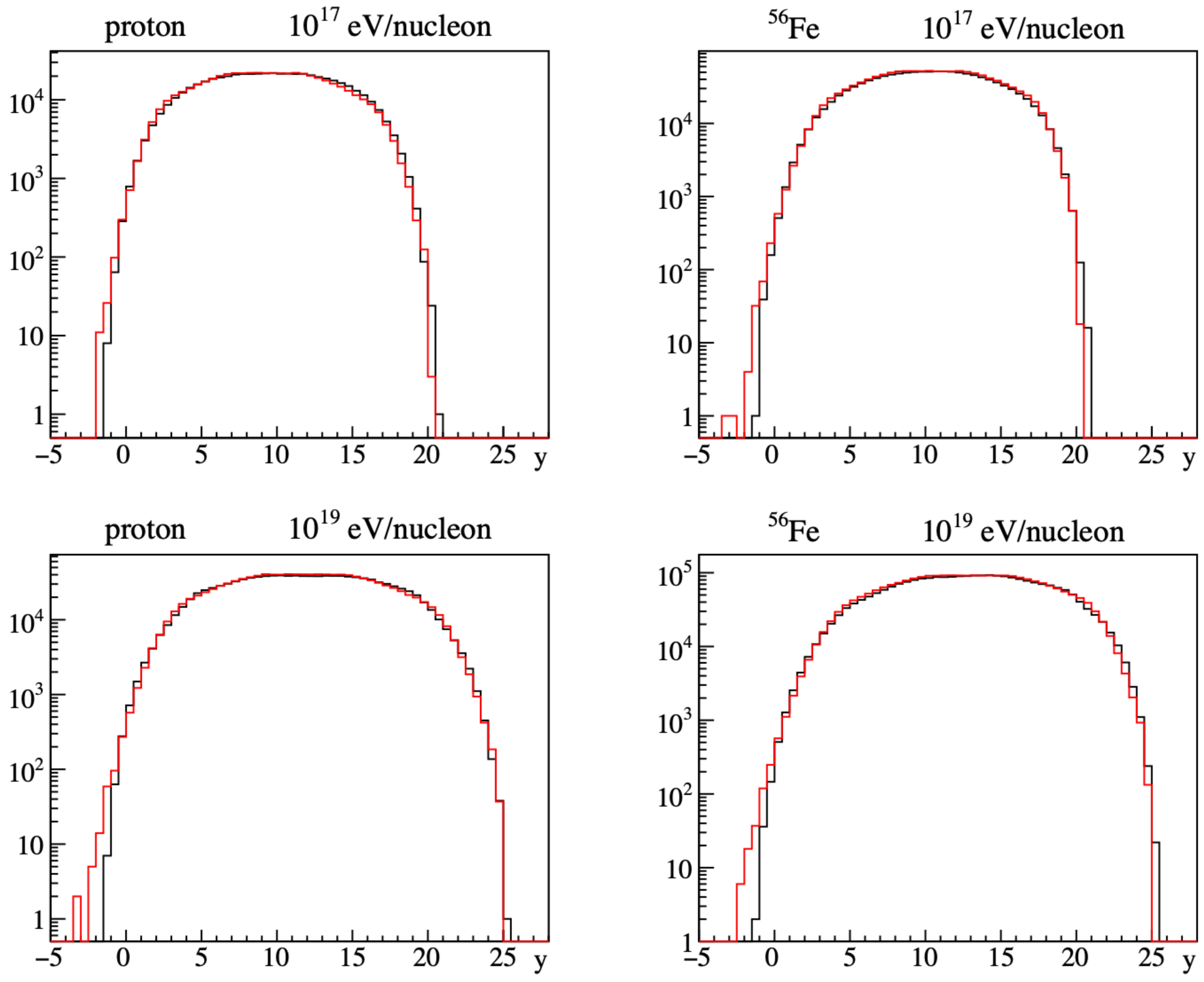
Comparison

Comparison

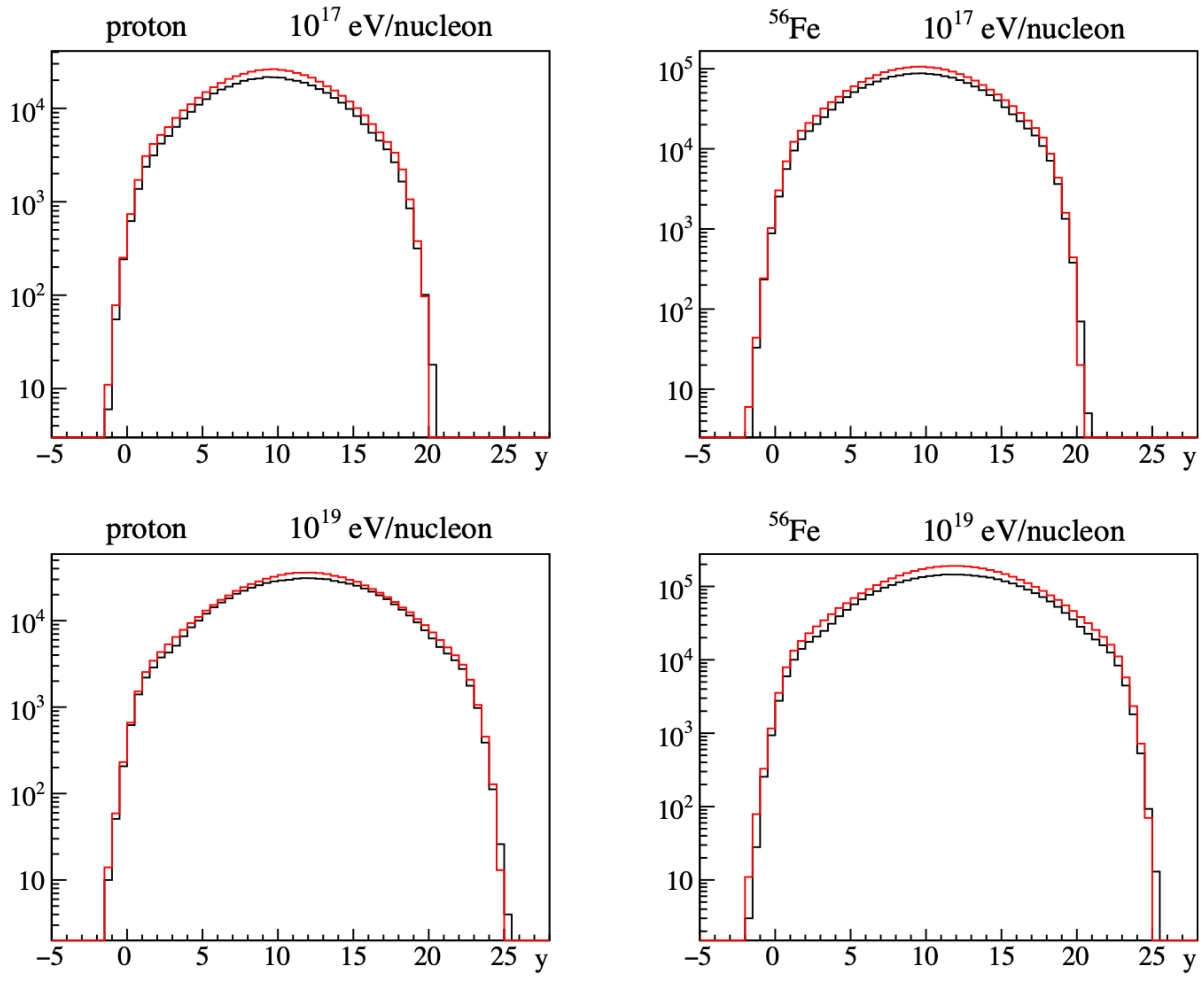
- Important to reproduce the shape –> normalization is fixed a posteriori due to the lightest hadron approximation;
- The nucleons produced in HIs are also taken into account (but now shown here);
- In the following: black line = source code; red line = my parametrization.

Secondaries: rapidity distribution

EPOS-LHC

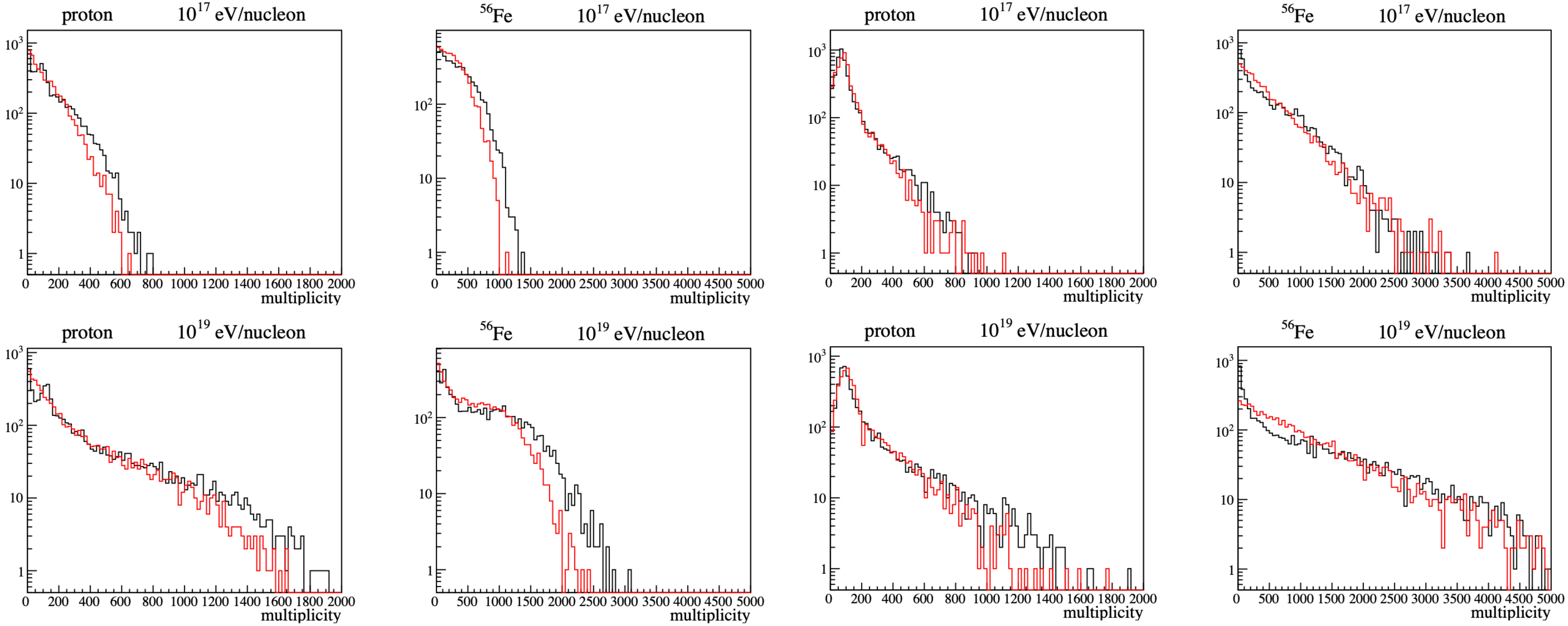


Sibyll2.3d



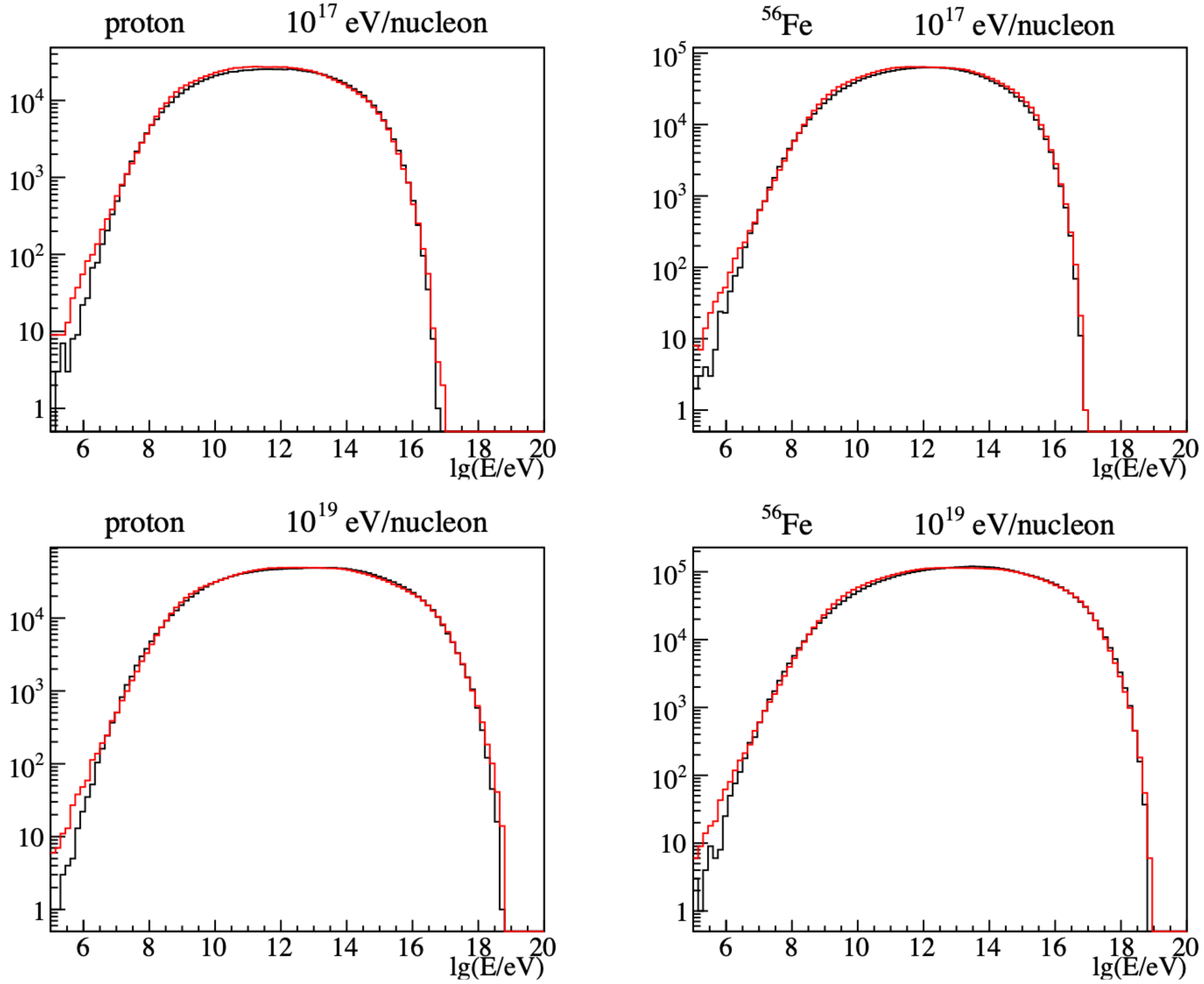
Secondaries:multiplicity

EPOS-LHC **Sibyll2.3d**

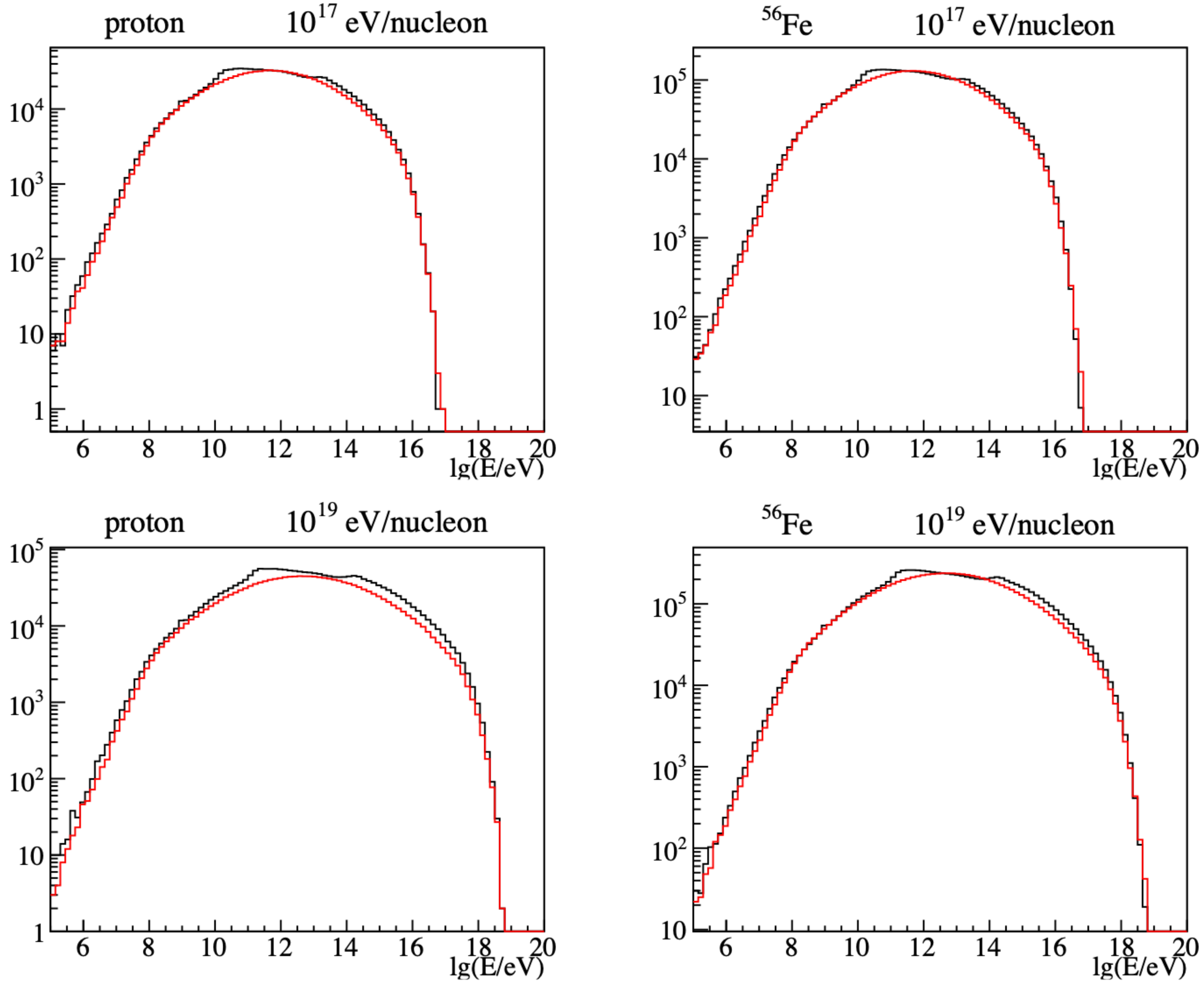


Secondaries: neutrinos

EPOS-LHC



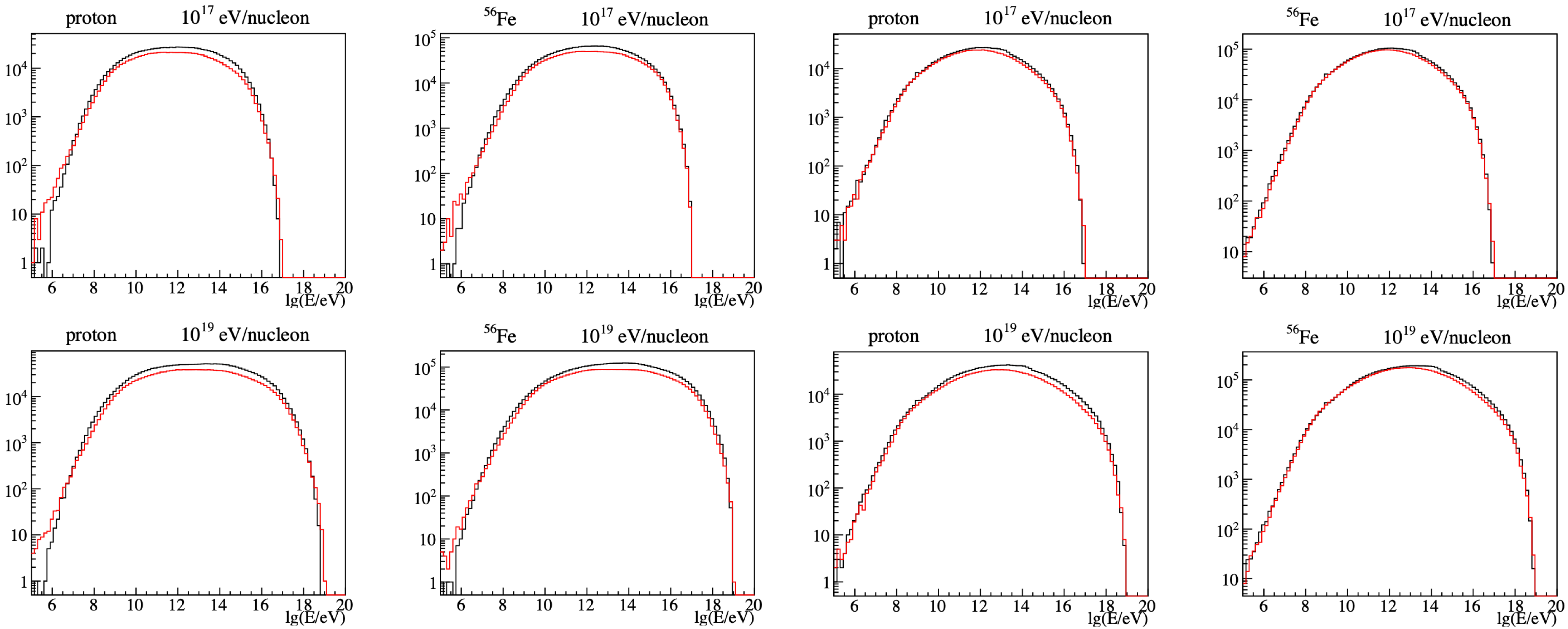
Sibyll2.3d



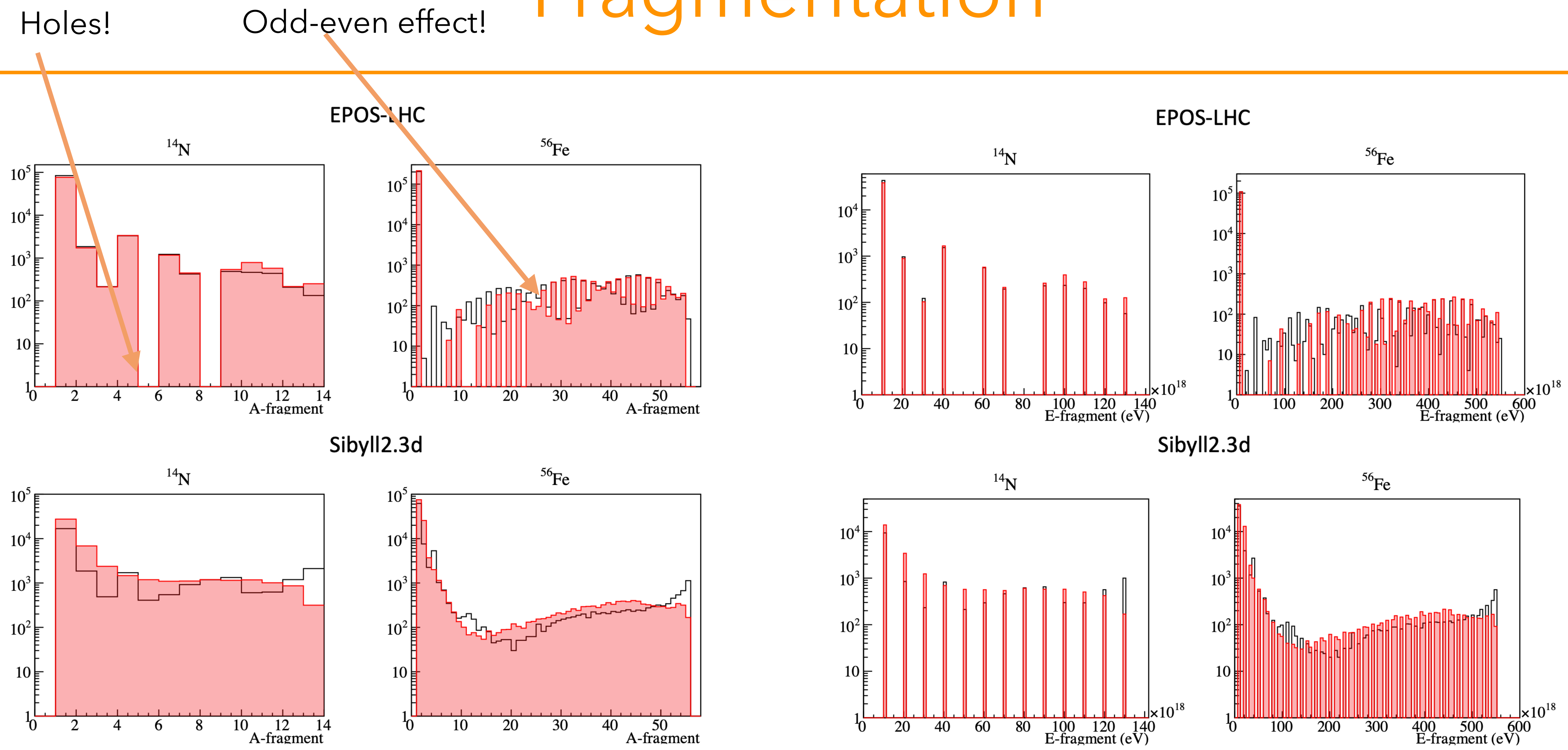
Secondaries: photon

EPOS-LHC

Sibyll2.3d



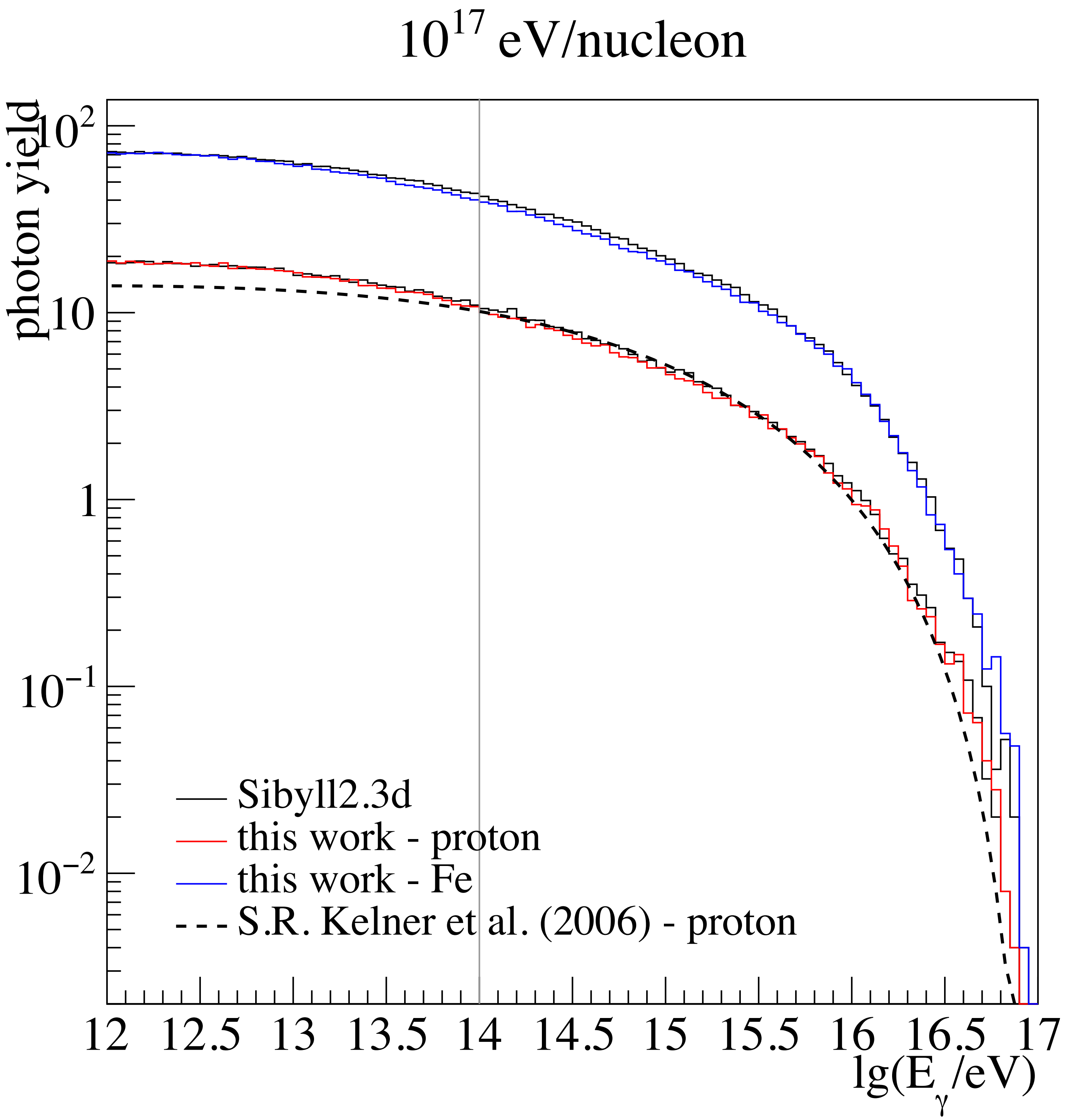
Fragmentation



Recently we added the possibility of hybrid HIMs.

Usage & performance

- PARISH (PARametric simulation of In-Source Hadronic interactions) is a open software;
- 1500 lines, as opposed to the original extensive source codes (approximately 25,000 and 82,000 lines for Sibyll and EPOS, respectively).
- The PARISH execution time per collision consistently remains below 6 ms (from 0.9 to 5 ms for Sibyll2.3d, 6 ms in all cases for EPOS-LHC).



https://doi.org/10.5281/zenodo.11057114

Intel(R) Core(TM) i7-7700 CPU @3.60GHz, 7.7GB of total memory. The system is running Ubuntu 18.04.6 LTS and the installed C++ compiler is g++ (Ubuntu 7.5.0-3ubuntu1~18.04) 7.5.0

A physical case

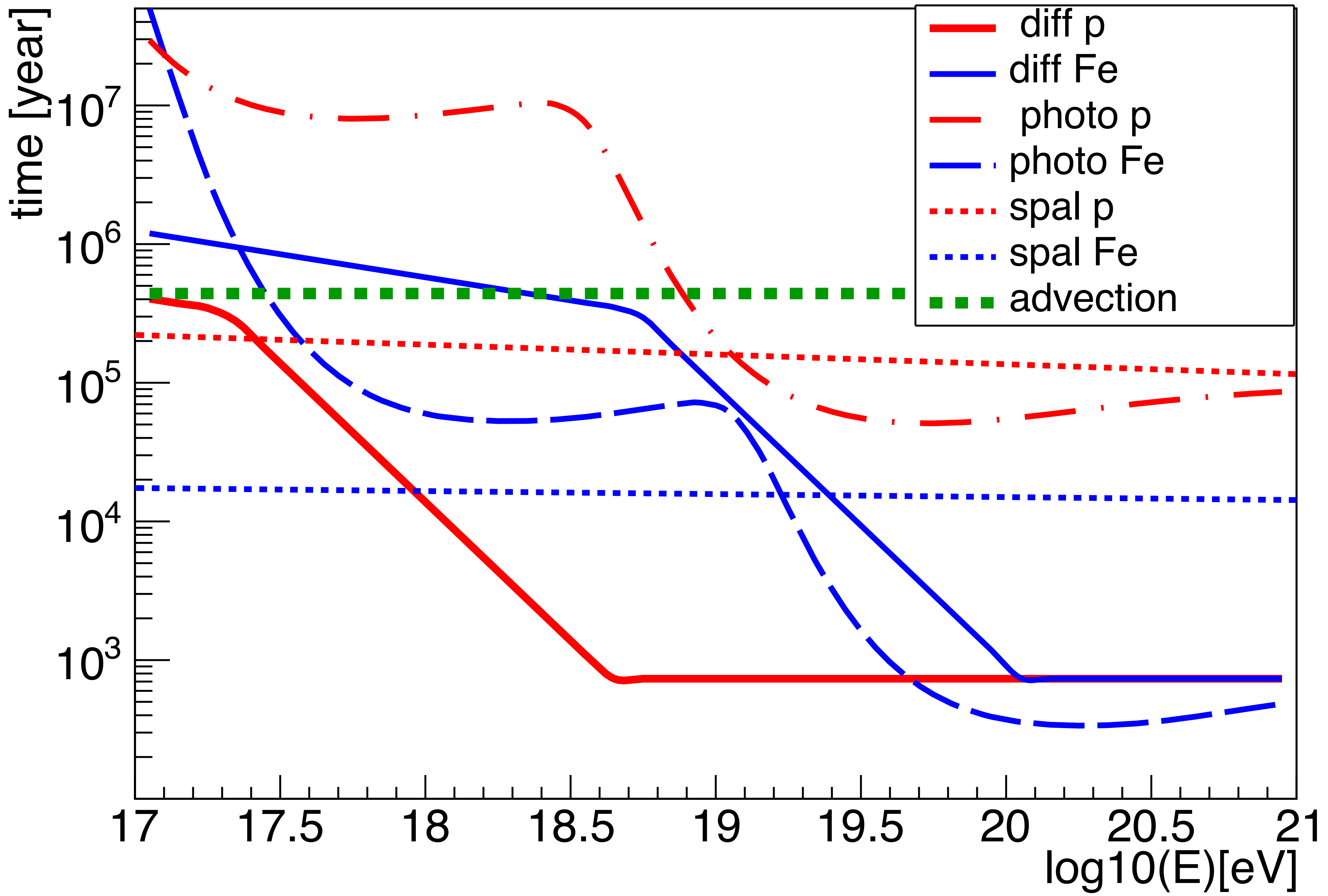
Arp220

- ✳ UHECR acceleration & high gas density –> the core of ultra-luminous infrared galaxies (ULIRGs);
- ✳ Arp220 –> the closest ULIRG to us, very dense in gas $\simeq 10^3\ cm^{-3}$ in the nucleus;
- ✳ Just a test scenario, no hypothesis about the acceleration.
- ✳ Comparison between Sibyll source and Sibyl param (since I don't have EPOS source in SimProp).

Parameter	Value
R (pc)	250
B (μG)	500
$n_{\rm ISM}$ (cm^{-3})	3500
$U^{\rm FIR}_{\rm eV\ cm^{-3}}\left[\frac{kT}{\rm meV}\right]$	31312 [3.5]
$U^{\rm OPT}_{\rm eV\ cm^{-3}}\left[\frac{kT}{\rm meV}\right]$	1566 [350]

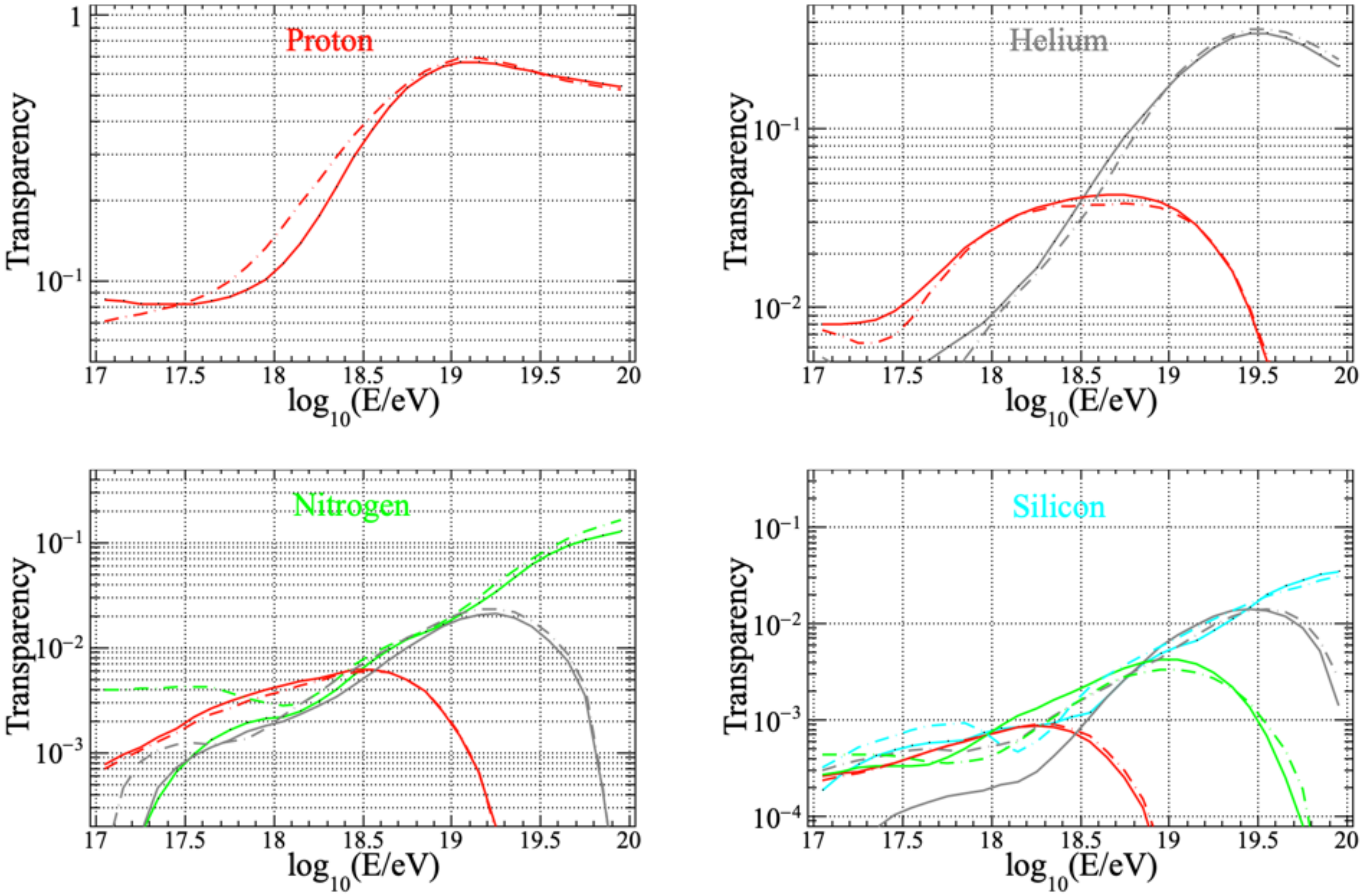
Table 1. Parameters used to compute UHECRs propagation in the Arp220 environment (from (Peretti et al. 2019)). The same notations of (Condorelli et al. 2023) are used.

M82



A. Condorelli et al., Phys. Rev. D **107**, 083009,

Nuclei


Proton
Transparency
1
10^{-1}
17 17.5 18 18.5 19 19.5 20
$\log_{10}(E/eV)$
Helium
Transparency
10^{-1}
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17 17.5 18 18.5 19 19.5 20
$\log_{10}(E/eV)$
Nitrogen
Transparency
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10^{-3}
17 17.5 18 18.5 19 19.5 20
$\log_{10}(E/eV)$
Silicon
Transparency
10^{-1}
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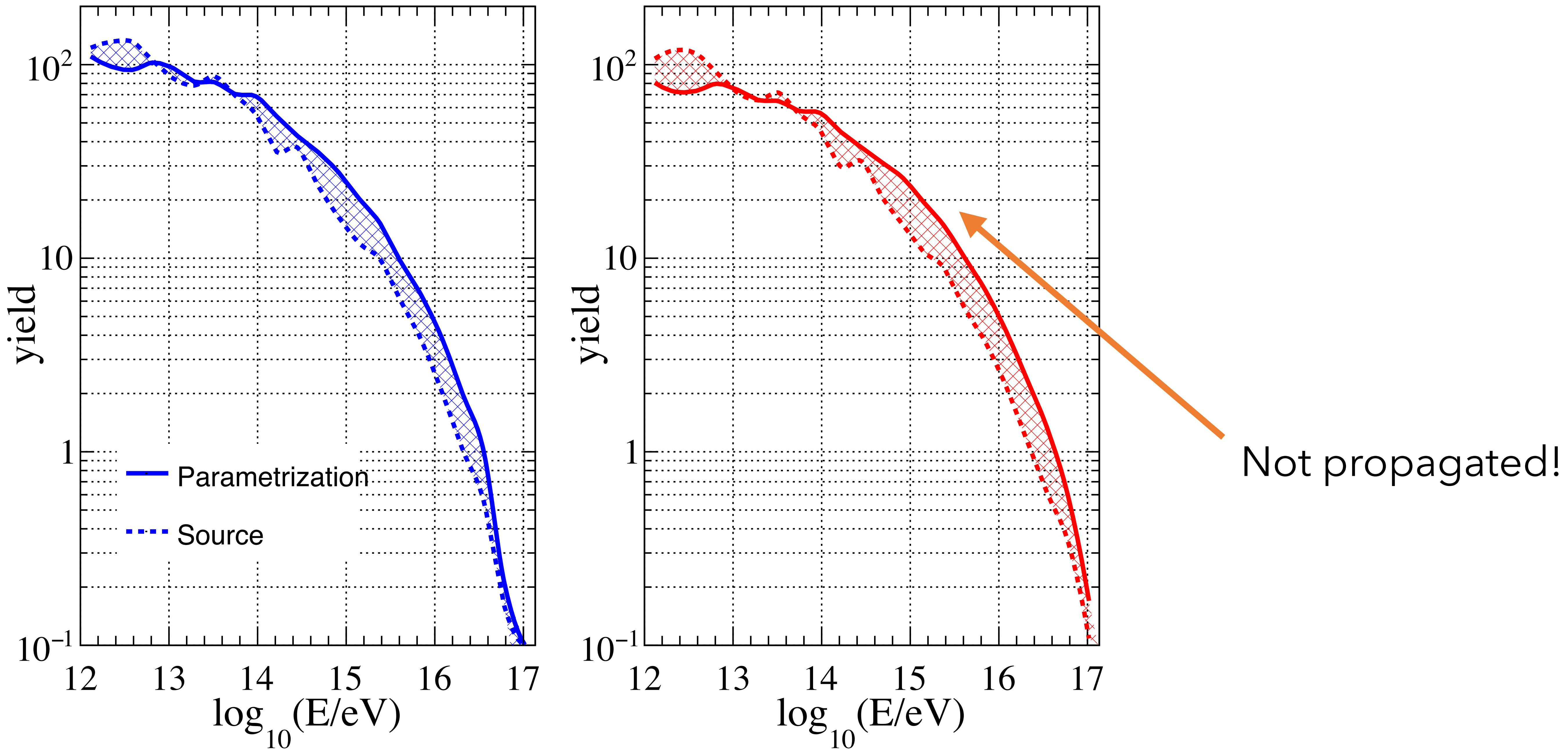
10^{-3}
10^{-4}
17 17.5 18 18.5 19 19.5 20
$\log_{10}(E/eV)$

Neutrinos & EM



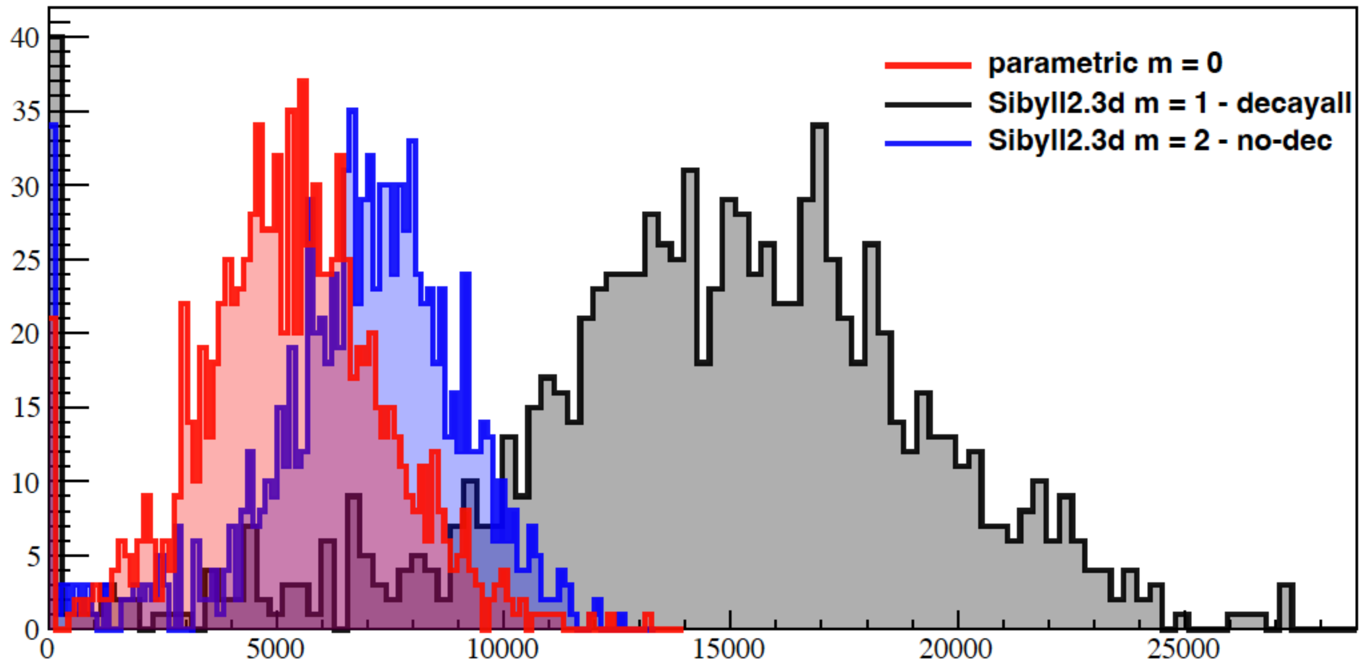
Summary

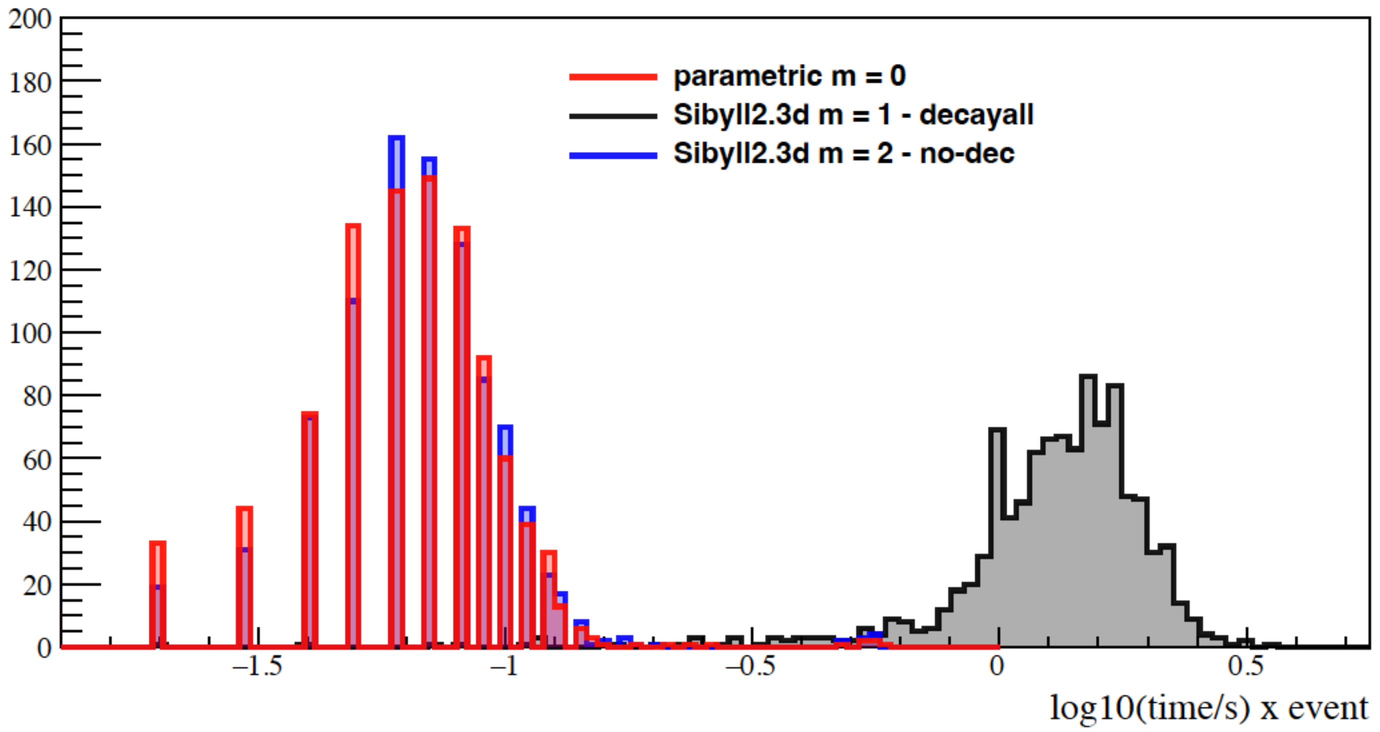
- ✴Parameterization capable of describing the most important features of two different HIMs with good agreement, with distinct advantages in terms of usability and computational efficiency;
- ✴Software is public accessible, it can be used to improve source modelling;
- ✴Potential for extending our parameterizations to lower energies, providing a versatile framework applicable to galactic cosmic rays as well.


BEER...
NOW THERE'S A TEMPORARY SOLUTION
Thanks for your attention!

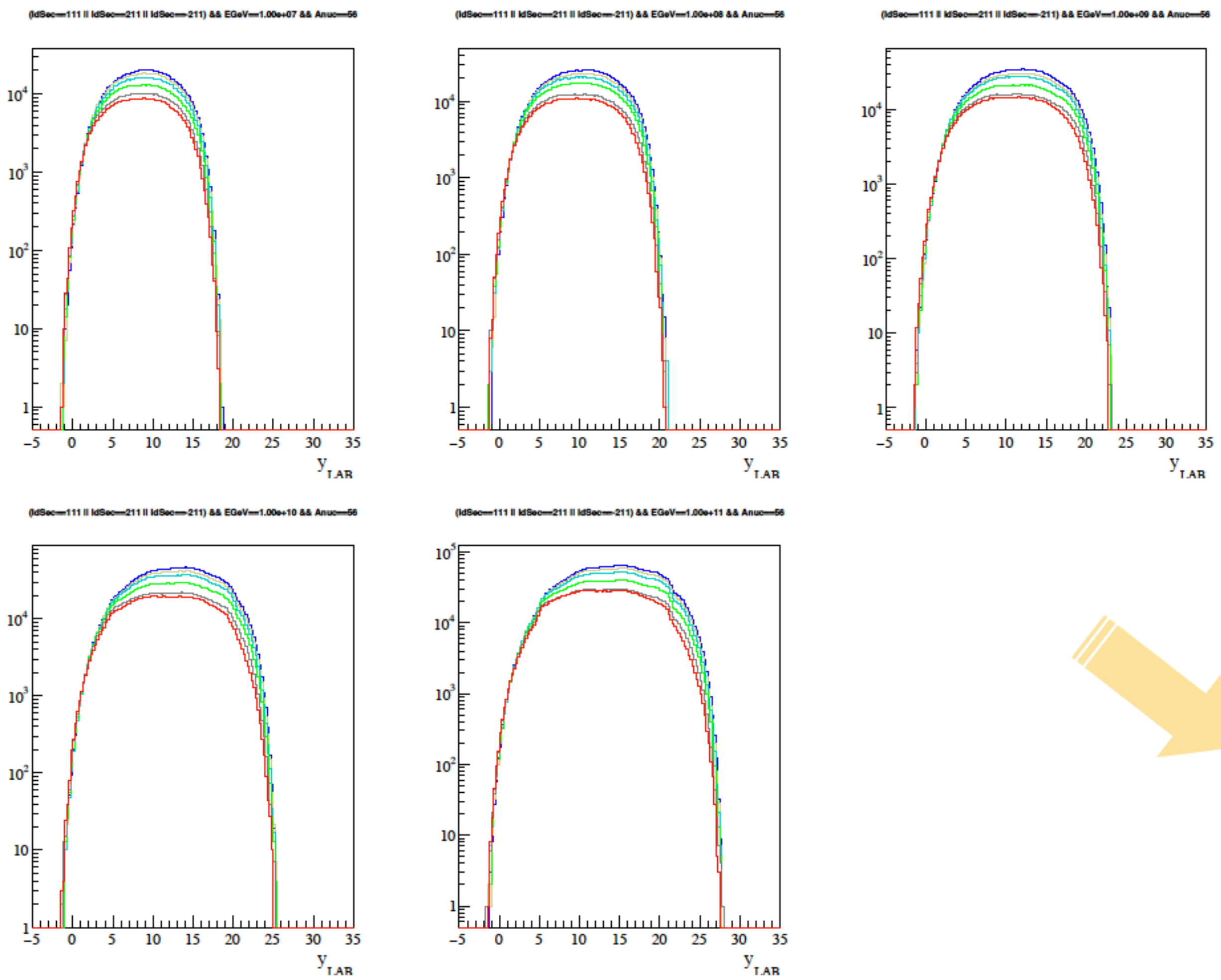
Back-up

Future steps



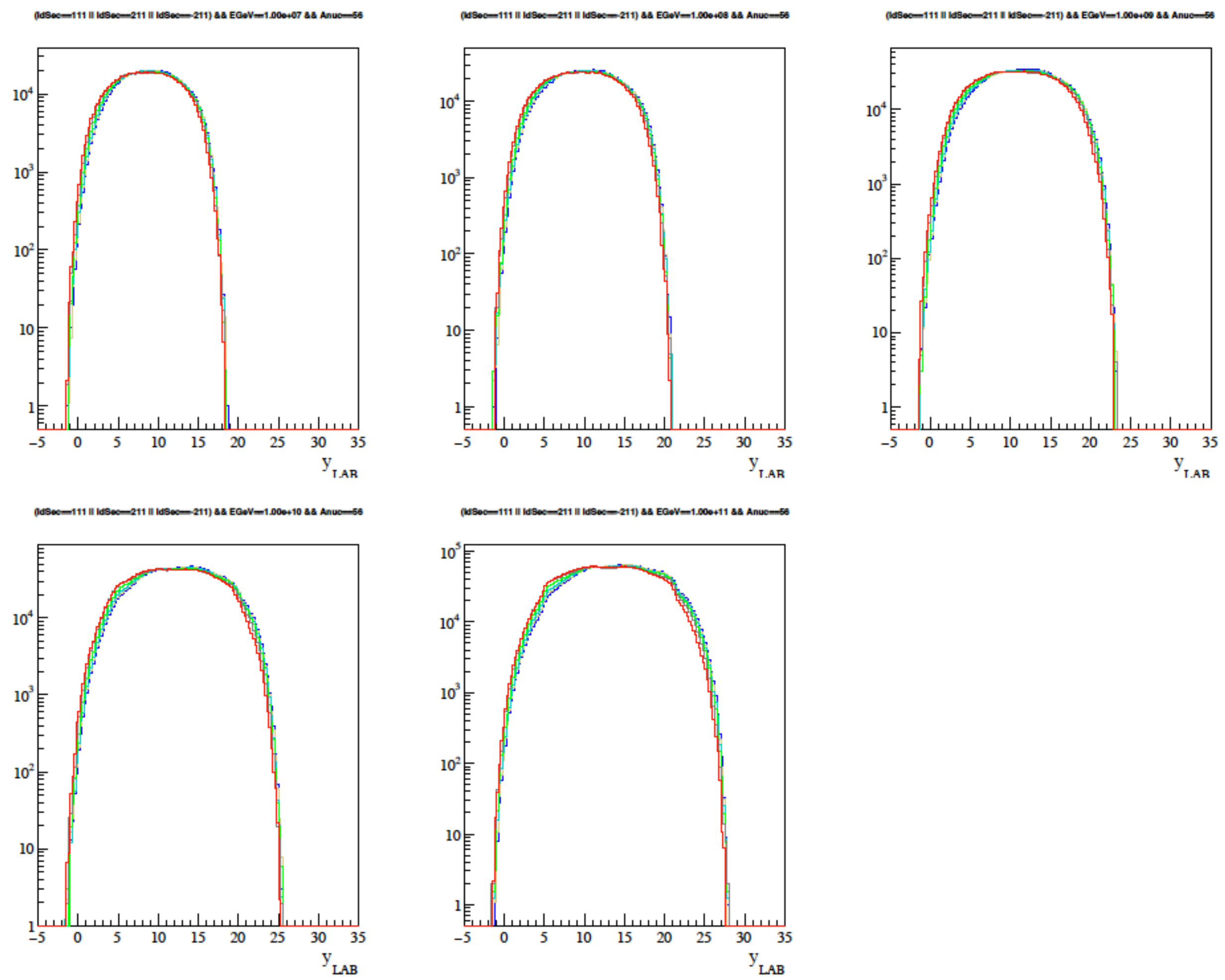


Multiplicity Parametrization-EPOS



EPOS-LHC

Rapidity distributions at fixed energy-per-nucleon (GeV/n)



Scaled distributions are **not** independent of A.

⇒ parameterization as a function of Energy-per-nucleon **and** A

Multiplicity Parametrization-Sibyll

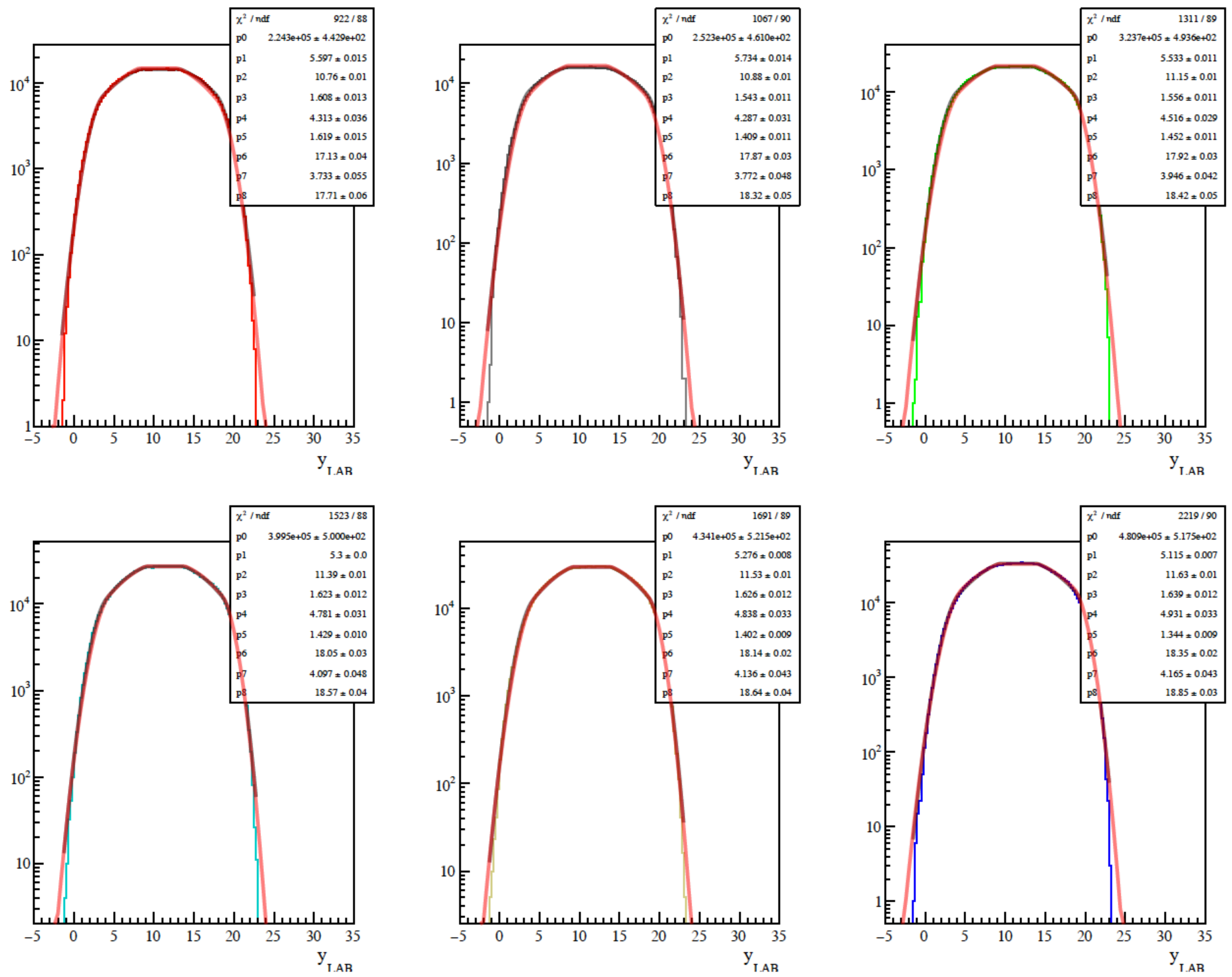
Parametric function at fixed E/A and A

- gaussian centered at the mean rapidity
- + two edge gaussian distributions (Backward and Forward)
- Continuity imposed
- Flat top at 90% of maximum

In total 9 free parameters:
3 means + 3 sigmas + 2 break-points + 1 normalization

Parameters depend ~ linearly on lgE and lnA
Global model (24 parameters):

$$p_i = a_i + b_i\, lg(E/A) + c_i\, lnA$$



Multiplicity Parametrization-EPOS

E/A = 10^{18} eV

EPOS-LHC

Multiplicity distributions

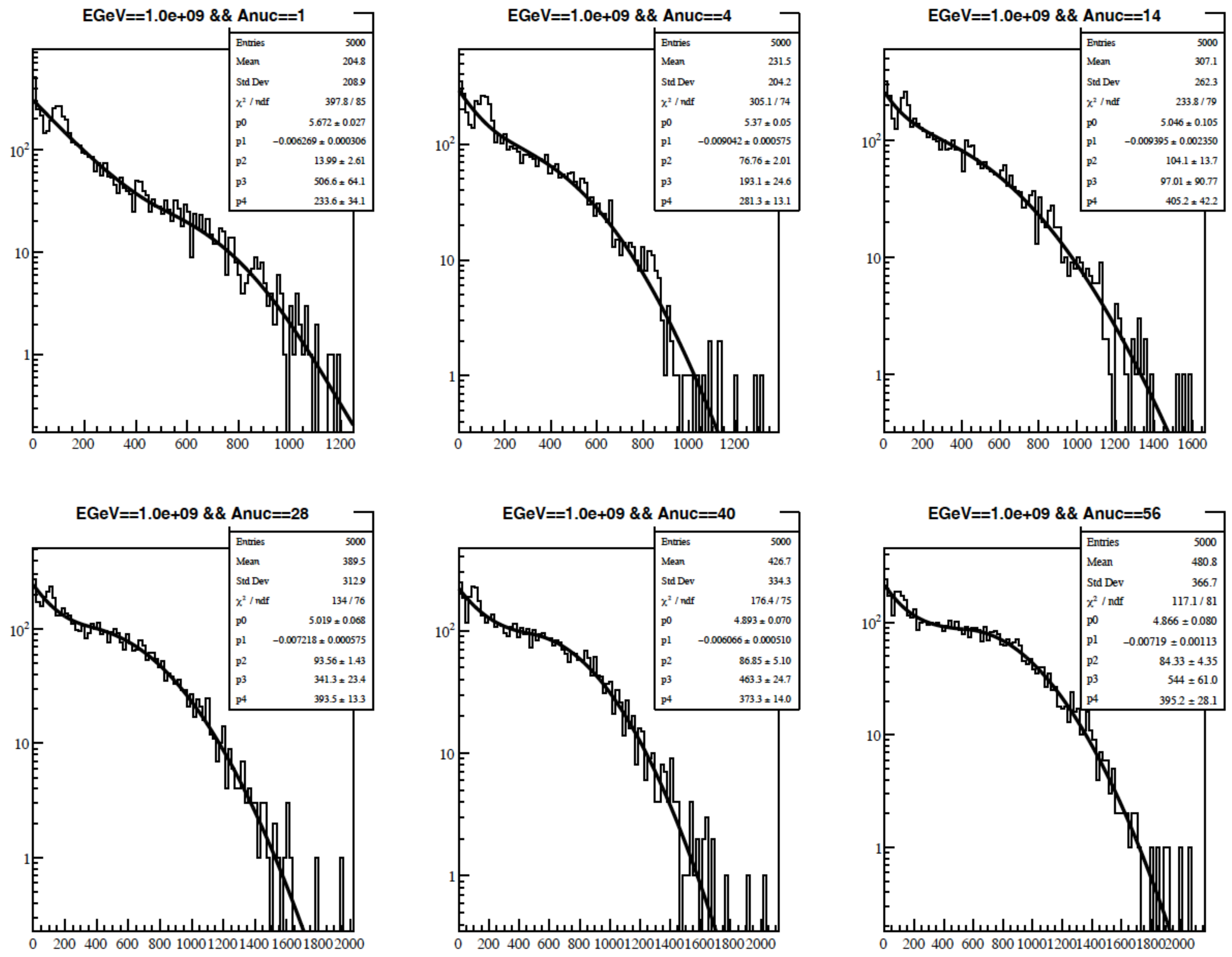
nsec = number of particle secondaries
= all EPOS-LHC secondaries
– nuclear fragments (nucleus & nucleons)
– beam

Distributions depend on *lg(E/A)* and *lnA*

Fit functions: exponential + gaussian
5 parameters: exp0, exp1
norm, mean, sigma

No easy evolution with *lg(E/A)* and *lnA* found

⇒ bilinear interpolation



Fragmentation Parametrization-Sibyll

Fragmentation model

Afrg distribution fit:

a) the overall shape is the superposition of two gaussians, with the high-mass $\sigma_{highA} = 0.55\ \sigma_{lowA}$ (3 pars: norm, A_{brk}, σ_{lowA});
b) the shape distribution is modulated by a sin function with different parameters for odd- and even-Afrg fragments;

} 9<Afrg<A

c) low-mass fragments (3<Afrg<10) fitted as linear in lnAfrg;

d) Afrg = 2 and Afrg = 3 linearly interpolated.