Implementing Pythia 8 for EAS Studies: Another Piece to the Muon Puzzle

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Poster ID

Motivation

To gain insights into the 'Muon puzzle' – a persistent muon deficit observed in air shower simulations compared to measurements, e.g. from the Pierre Auger Observatory – several studies took place: from ad hoc modification of cross-section, multiplicity, and elasticity of hadronic interactions model, or by altering directly particle, to perform a multi-parameter fit of model predictions against Auger data.
This works introduces another hadronic interaction model, Pythia 8, into the landscape of air showers, for which all above-mentioned studies can be applied to.

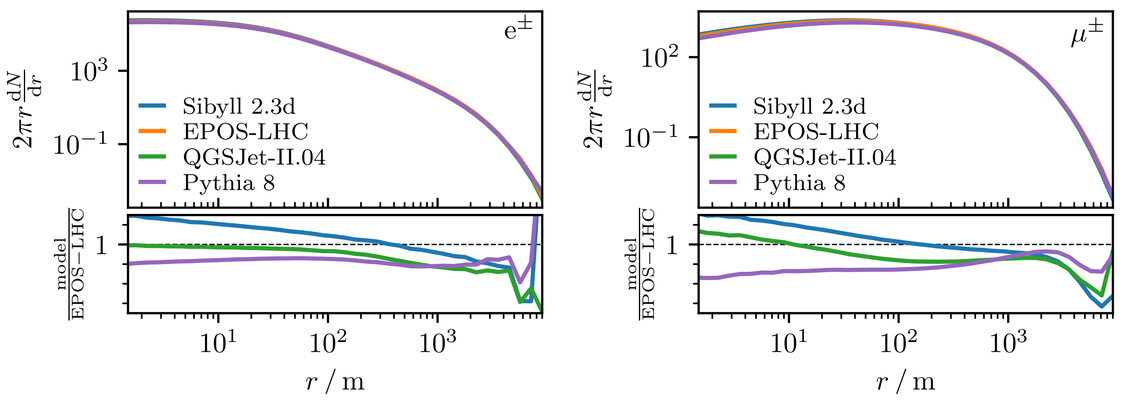
CORSIKA 8

- new C++ based particle shower simulation code, successor of CORSIKA 7
- wide range of state-of-the-art hadronic interaction models available:
  - high energies: Sibyll 2.3d, EPOS-LHC, QGSJet-II.04, **Pythia 8 (preliminary)**, low energies: FLUKA
  - decays handled by Sibyll 2.3d and Pythia 8
  - hadronic interaction results agree at the $\sim$10% level with CORSIKA 7
- new features: enhanced thinning, shower genealogy, cross-media showers
- code can be considered "physics-complete"

Pythia 8

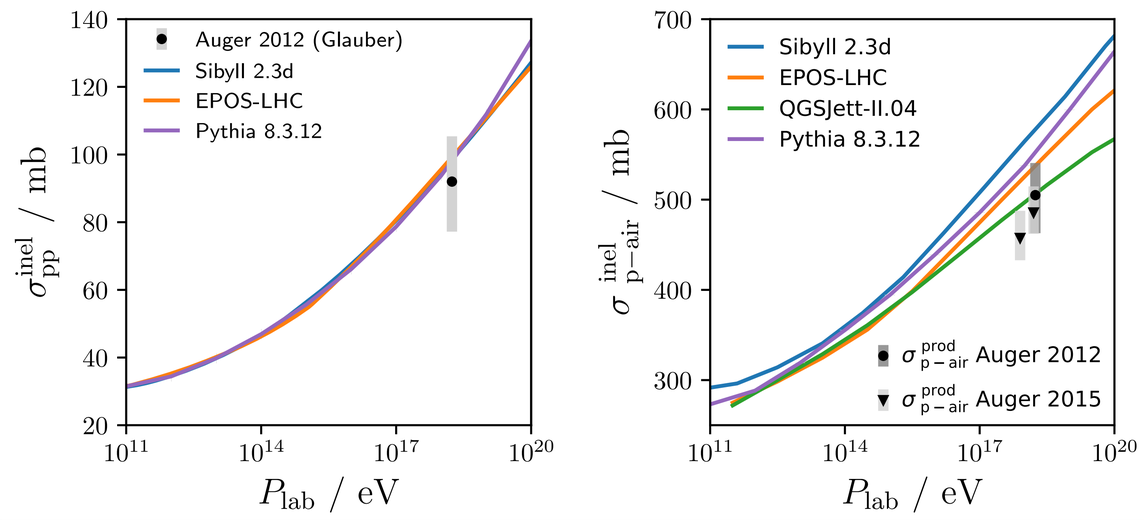
- general purpose hadronic interaction model
- well-tailored for LHC experiments: e^+e^-, pp, $\overline{p}$p, pPb, PbPb interactions
- Angantyr model
  - nuclear geometry given by Glauber model
  - stack individual nucleon-nucleon subcollisions and hadronize them
- new feature in 8.3.12: variable energy and beam on an event-by-event basis

Lateral profile*

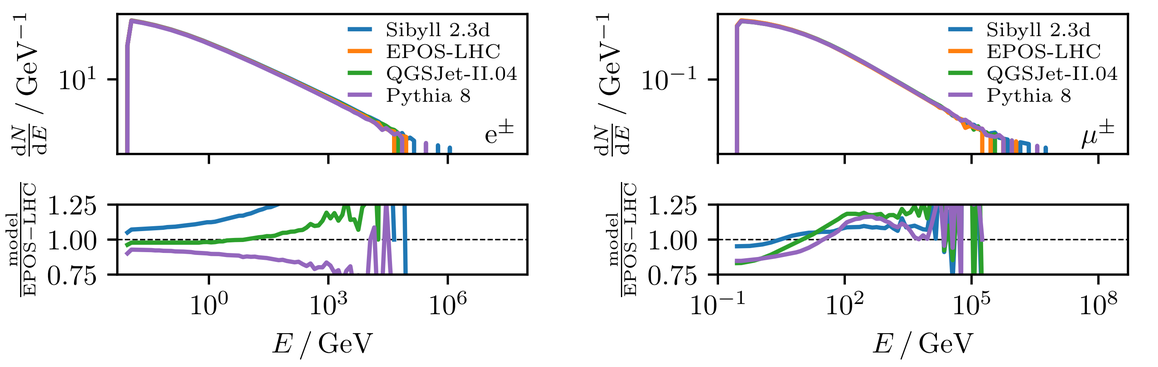


Cross-sections

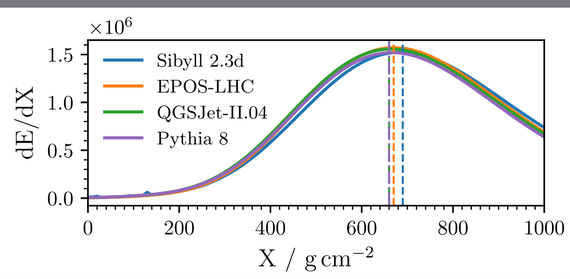
- tabulate total and partial σ, including σ^{inel} for several (projectile, target, $P_{lab} \leftrightarrow s_{\text{NN}}$) with Pythia 8.3.12, using Angantyr for nuclear interactions



Energy spectrum*

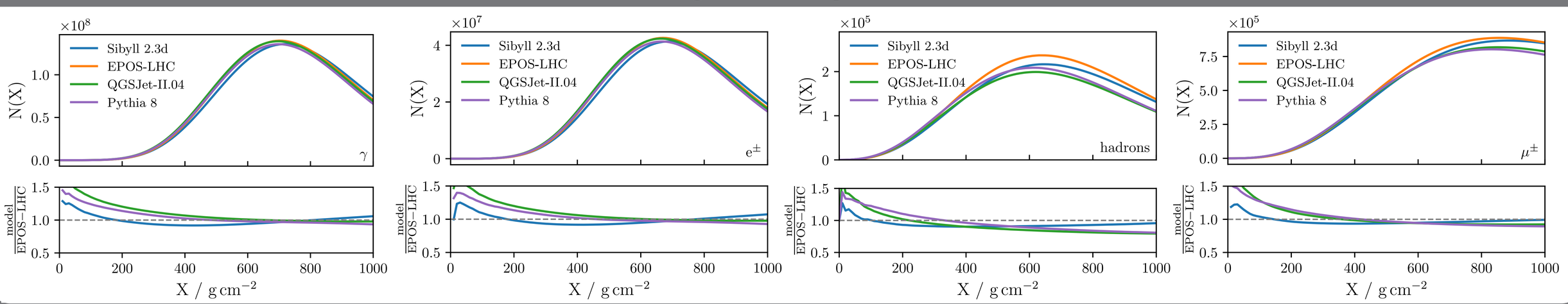


Energy loss*



- X_{max} shift between models
- Pythia 8/QGSJet-II.04: $\sim$ 660 g cm^2
- EPOS-LHC: $\sim$ 670 g cm^2
- Sibyll 2.3d: $\sim$ 690 g cm^2

Longitudinal profile*



Conclusion

- successful CORSIKA 8 implementation of Pythia 8 for proton primaries
  - comparable outputs with state-of-the-art models
  - fewer muons observed at ground
- interesting tuning playground available for Pythia 8
- need for σ^{prod} computation from Pythia 8 for CORSIKA 8 showers
- obstacles for nuclear shower primaries
  - long Angantyr initialization to be reduced thanks to reuse file feature
  - missing data in σ tables for AA interactions to be filled using semi-superposition model (as done with Sibyll 2.3d)
  - target fragments reaching ground to be handled

KEY REFERENCES

[1] C. Gaudu, "Pythia 8 and Air Shower Simulations: A Tuning Perspective," arXiv:2411.00111 [astro-ph.HE].

[2] M. Reininghaus (for the CORSIKA 8 Collaboration), T. Sjöstrand, M. Utheim, "Pythia 8 as hadronic interaction model in air shower simulations," EPJ Web Conf. **283** (2023), 05010 DOI: https://doi.org/10.1051/epjconf/202328305010, arXiv:2303.02792 [astro-ph.HE].

[3] J. Albrecht *et al.*, "The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider," Astrophys. Space Sci. **367** (2022) no.3, 27 DOI: https://doi.org/10.1007/s10509-022-04054-5 arXiv:2105.06148 [astro-ph.HE].

* 300 vertical proton-induced 10^{17} eV air showers: $e^{\pm}/\gamma$ particles cut at 10 MeV, hadron/muon cuts at 300 MeV, thinning at the 10^{-6} level.

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Join the effort!

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