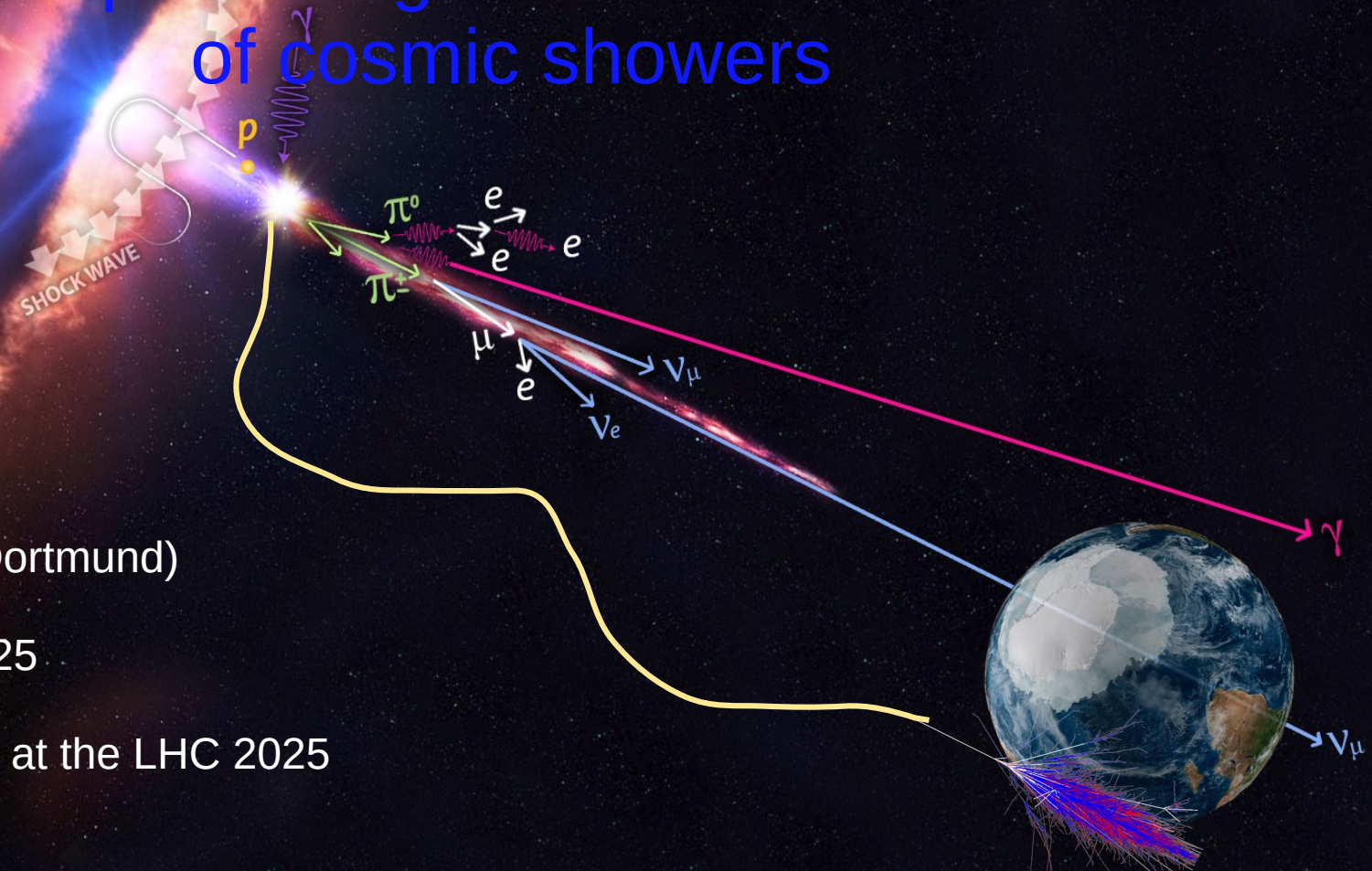
Expected impact of light-ion collisions on models of cosmic showers

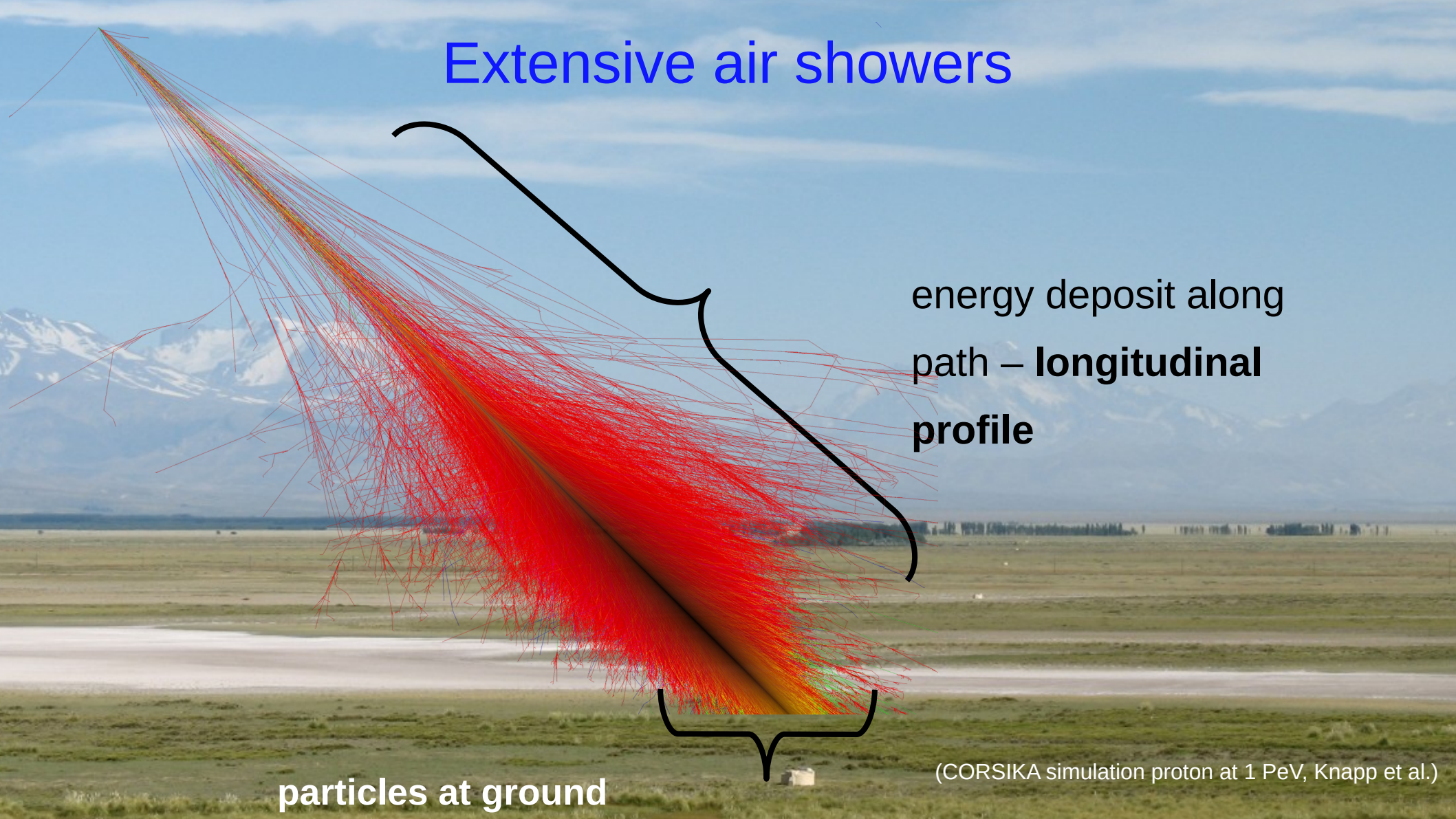


Felix Riehn (TU Dortmund)

December 2nd 2025

Light-ion collisions at the LHC 2025

Extensive air showers

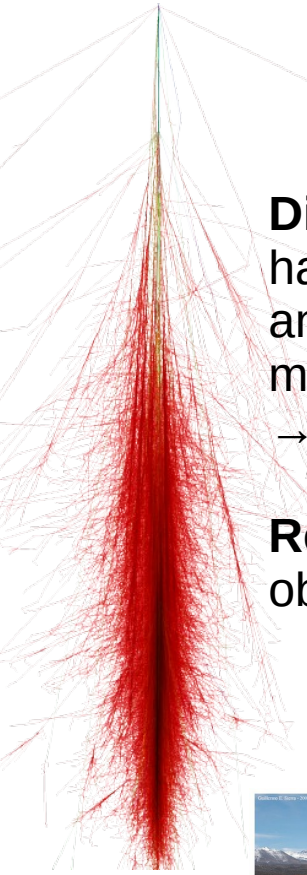


energy deposit along path – **longitudinal profile**

particles at ground

(CORSIKA simulation proton at 1 PeV, Knapp et al.)

The problem: air showers not correctly modeled

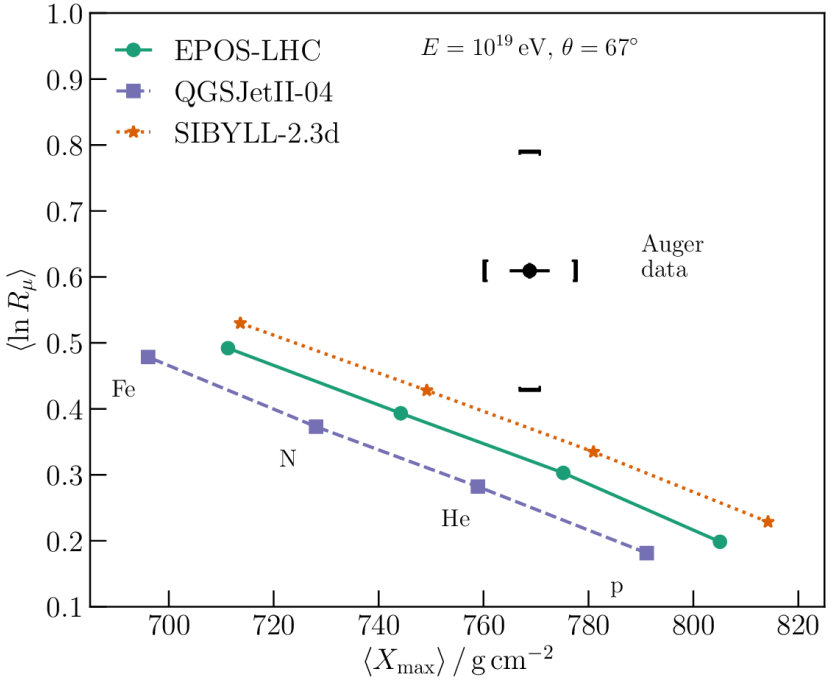


Problem I: modeling individual air showers

Difficulty: Need a fully inclusive model of hadronic interactions of pions, kaons, protons and nuclei with nuclei over 10 orders of magnitude in energy !
→ non-perturbative QCD

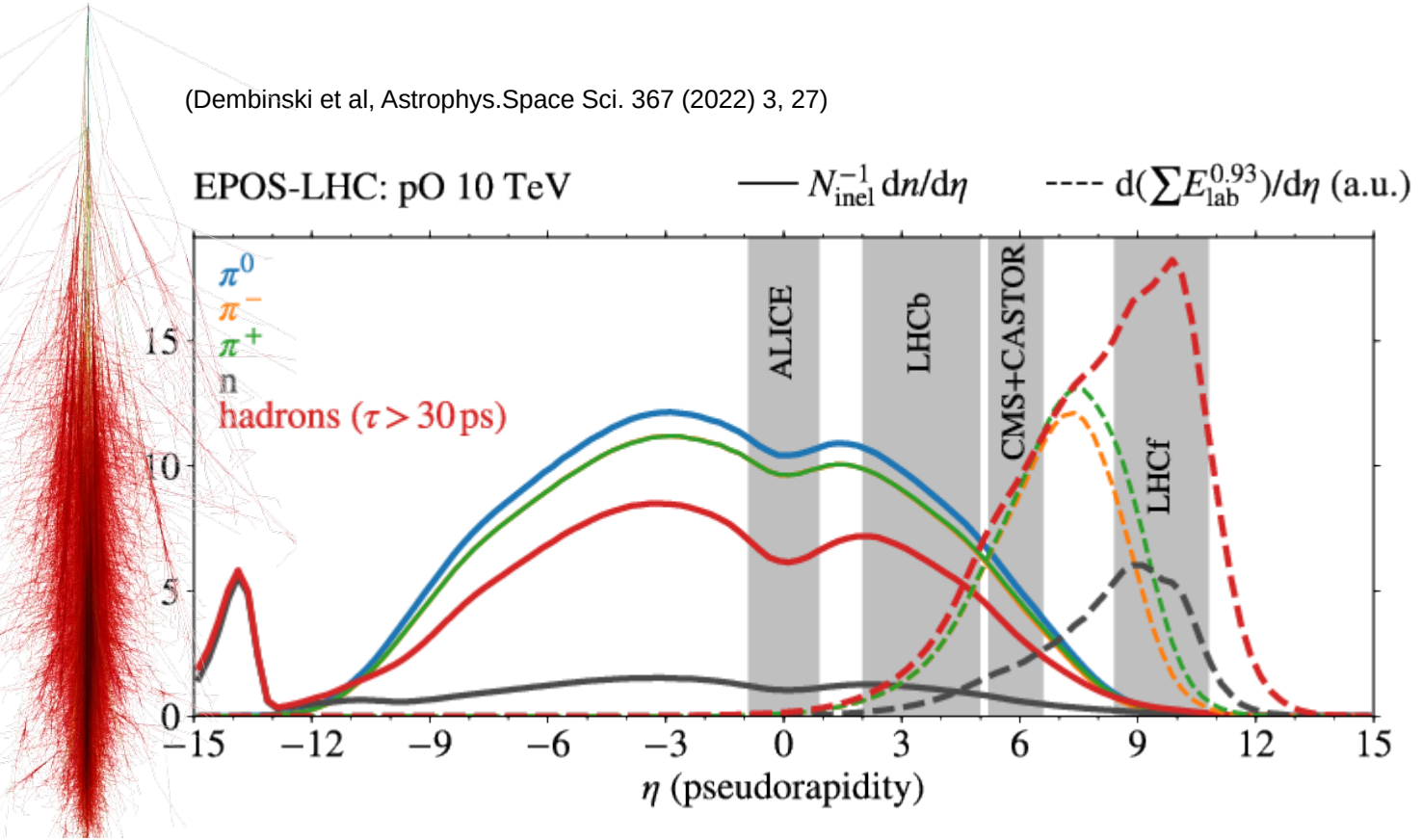
Result: inconsistent results between observables, in-particular ground based

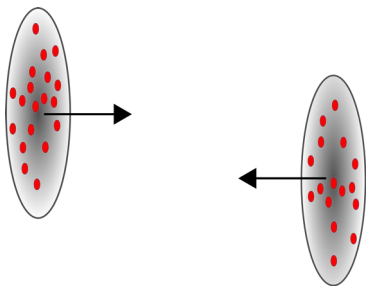
(Auger, PRL 126, 152002 (2021))



Phase space considerations

(Dembinski et al, Astrophys.Space Sci. 367 (2022) 3, 27)





$$\Delta x \Delta p_x \sim 1$$

$$R' = R/\Gamma = R\,m_p/E_p$$

$$p_\perp \sim \Delta p_\perp \sim \frac{1}{R} \sim 200\,\text{MeV}$$

$$p_{||} \sim \Delta p_{||} \sim \frac{1}{R'} \sim \frac{1}{5}E_p$$

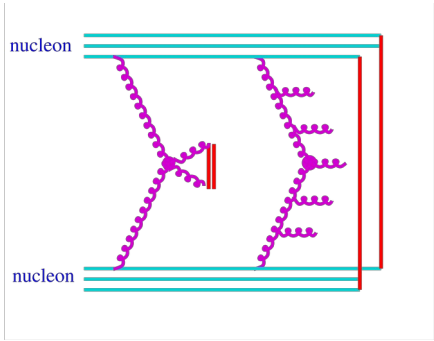
Air shower == chaining average interactions, weighted by energy
==> pT is negligible, **forward particle production**

CR models

SIBYLL (R. Engel, A. Fedynitch, T.K Gaisser, FR, T. Stanev)

- DPM based (related to DPMJET)
- factorization between hard&soft MPI
- charm production
- phenomenologic
- light ions only (A<18)

"bare bones of QCD"



QGSJET II/III (S. Ostapchenko)

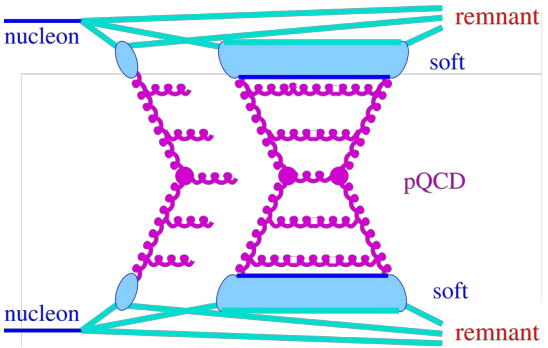
- Gribov-Regge
- non-linear effects
- higher twist

"rigorous model"

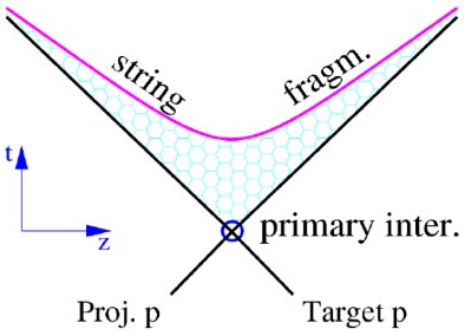
EPOS LHC (T. Pierog, K. Werner)

- Gribov-Regge
- energy sharing at amplitude level
- effective collective effects

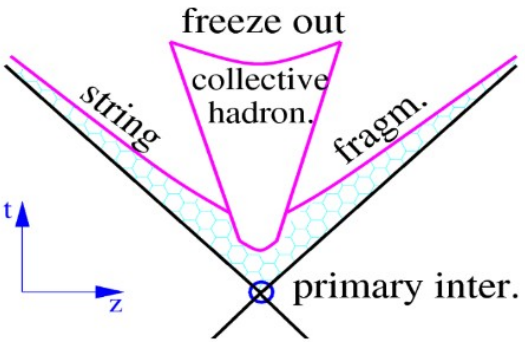
"heavy-ion model"



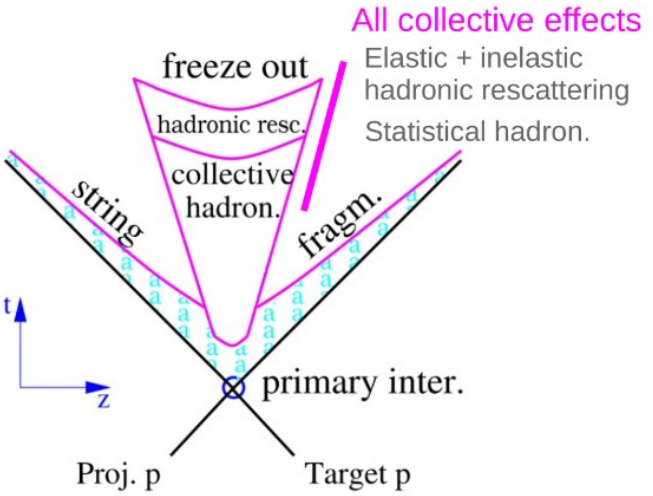
CR models space-time picture



Sibyll, QGSJET



EPOS LHC
(no rescattering)



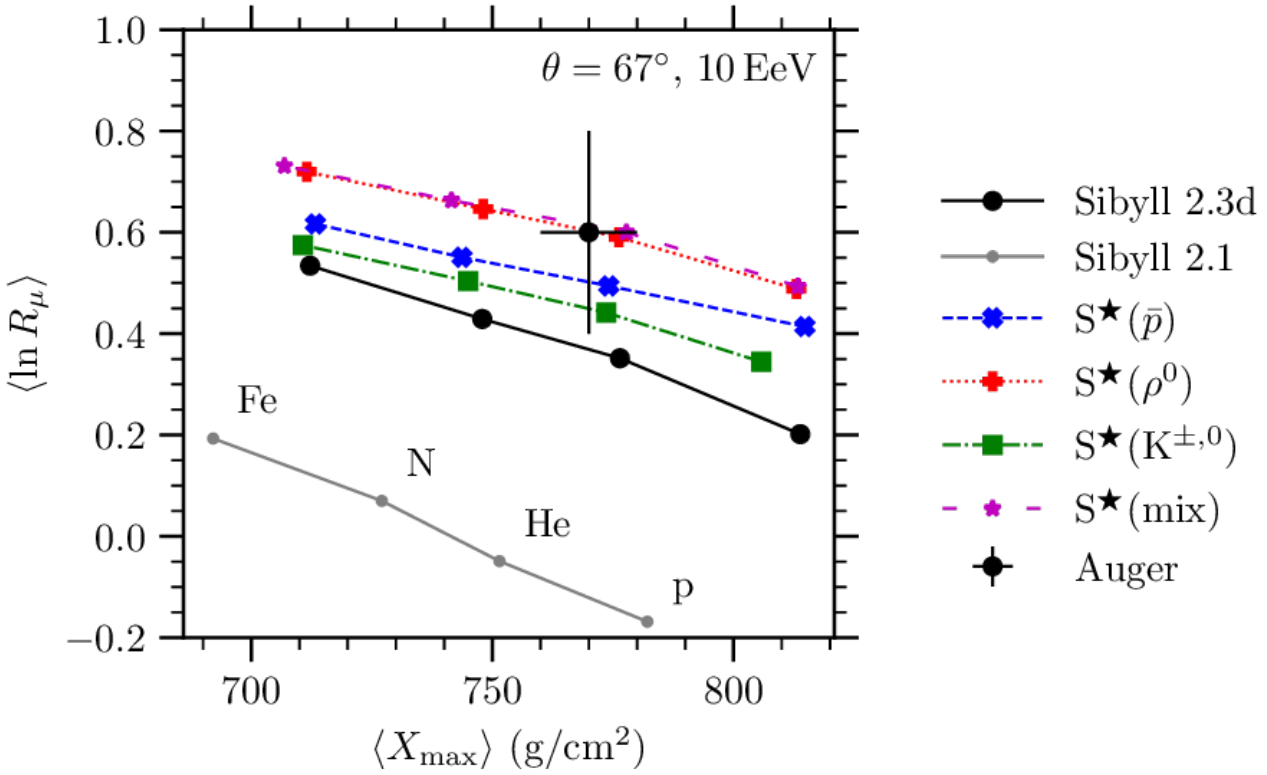
EPOS.LHC-R
(with hadronic rescattering)

(See T.Pierog ICRC2025)

Possible solutions

* more strangeness
* more baryons
* more resonances in pion interactions

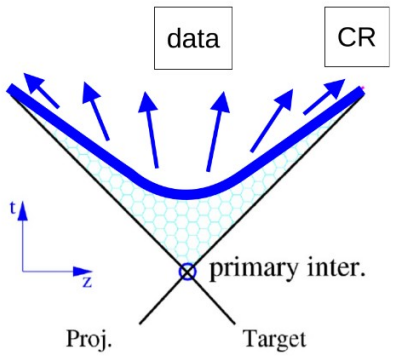
(Astropart.Phys. 160 (2024) 102964)



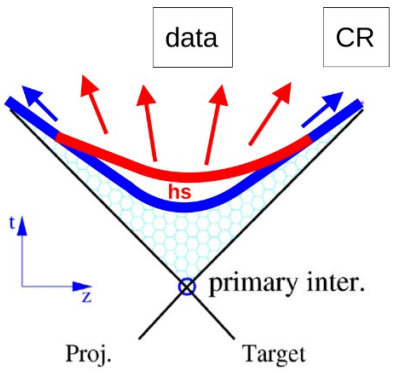
The EPOS LHC R solution

* increased **baryon** and **strangeness** production from collective hadronisation
* change ratio between pi and rho

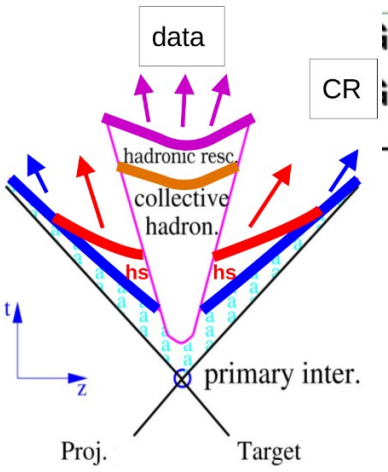
Changes arise from re-tuning with all effects (QGP, had. rescatter) included when tuning (e+e-,hp,pp,pA,AA)



No collective effects



Hadronic reScattering (hs)

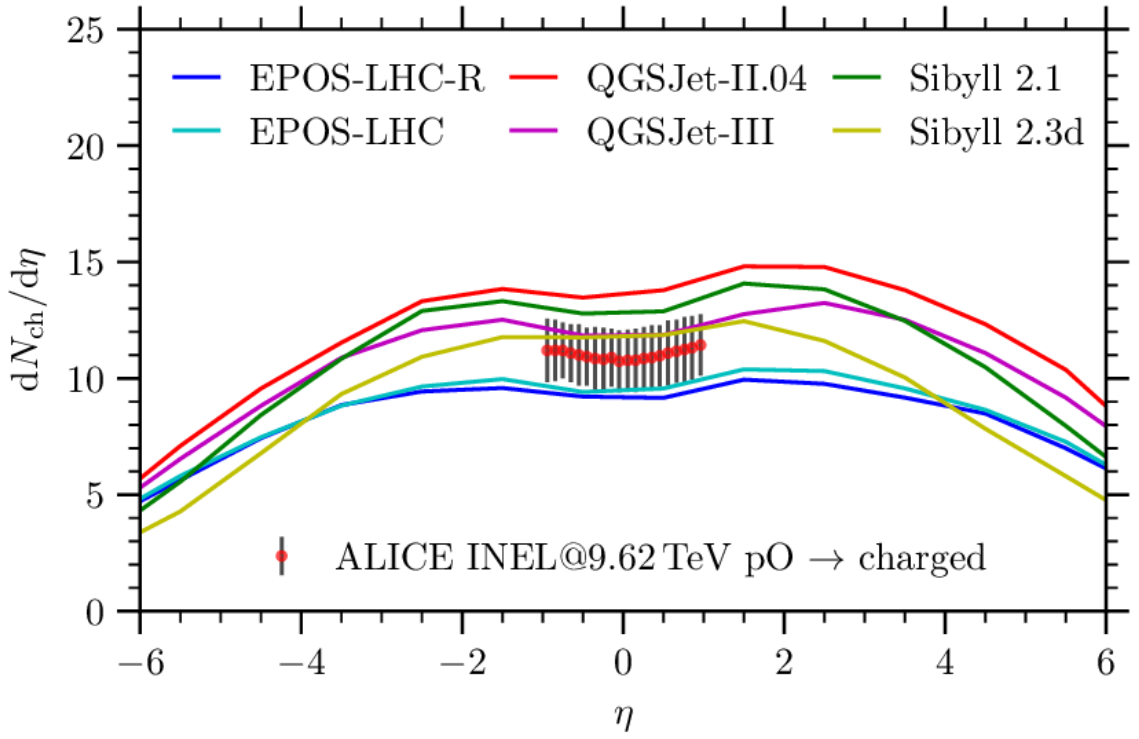


(T. Pierog ICRC 2025)

Expected impact of light-ion collisions at the LHC on models of cosmic showers:

Insights on which model approach is correct

First pO results



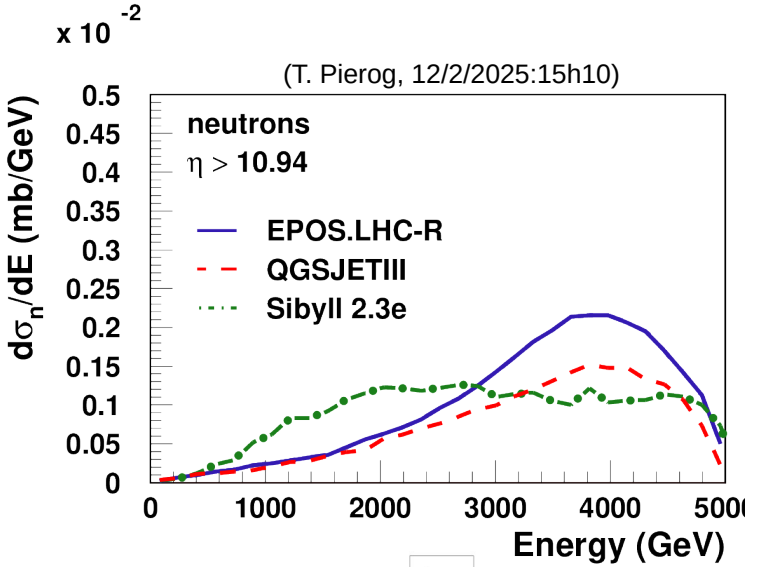
(ALICE, initial stages 2025)

* **all** models make reasonable predictions for central particle production

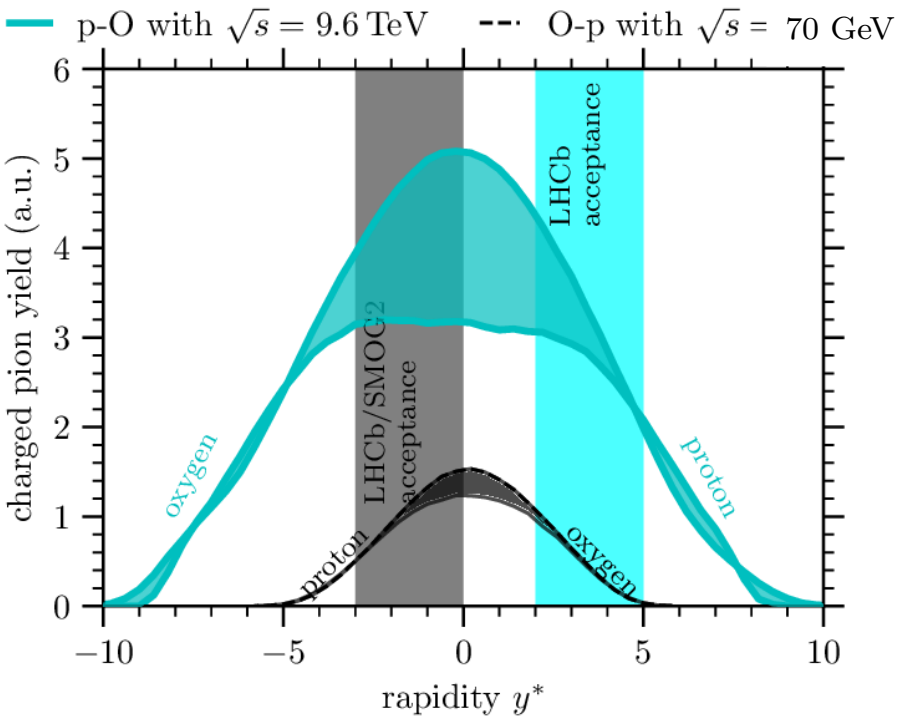
Measurement wish-list for light-ion

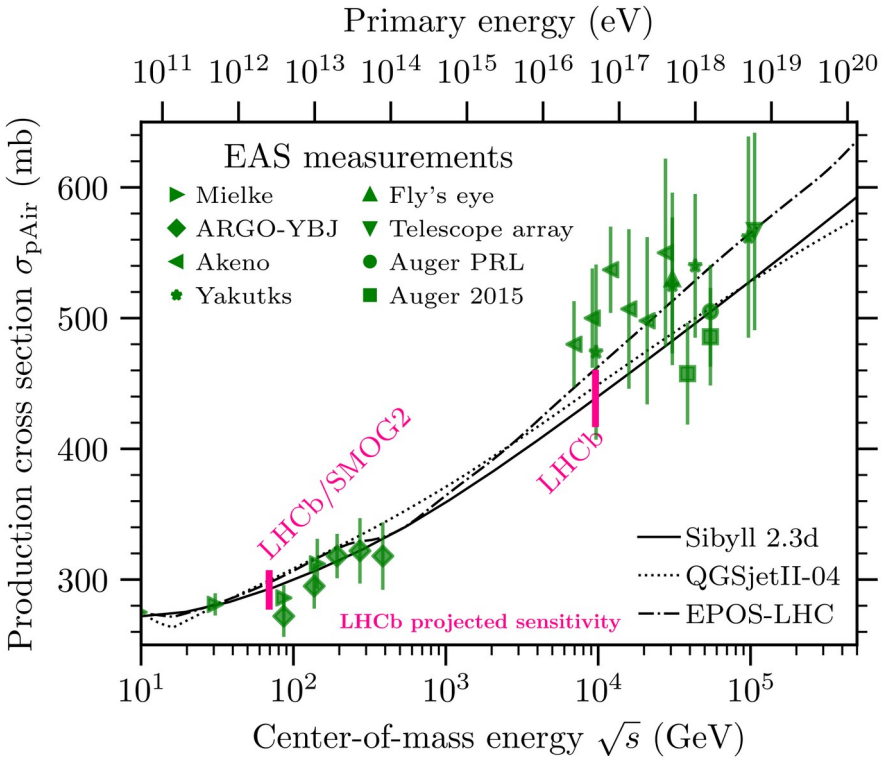
In absence of identified particle spectra at eta>7

- LHCf neutrons in pO
  → constrain elasticity
- central baryon & strangeness production
- measurements of central activity vs forward energy (ATLAS+LHCf, ALICE w ZDC?, CMS?)



Future measurements with LHCb





+ scan A dependence for light-ions w SMOG2!

Summary

* cosmic showers sensitive to very forward particle production

* first pO results of dNch/deta in central region indicate all CR models close to the measurements

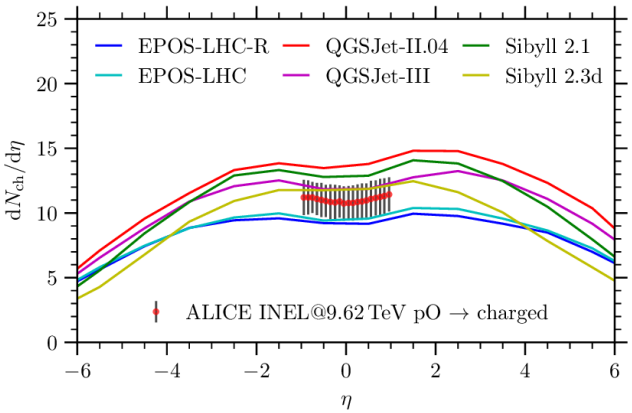
* QGP and HS have indirect effect on the cosmic shower predictions

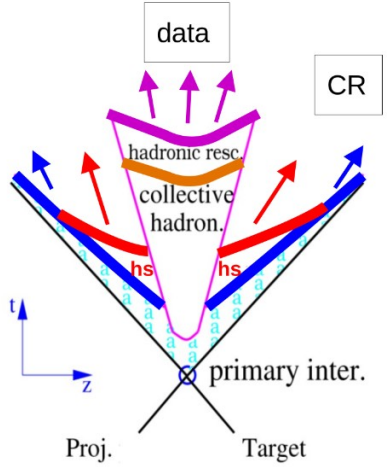
* awaiting decisive measurements

  - LHCf neutrons

  - baryon & strangeness production

  - central & forward correlation

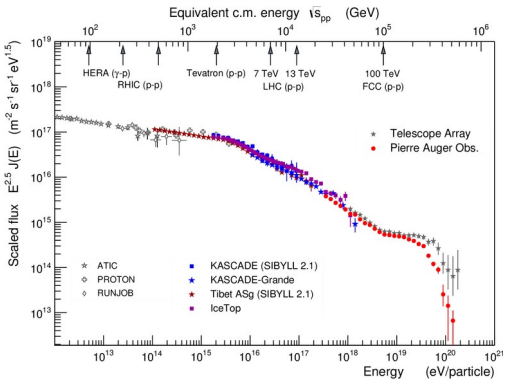




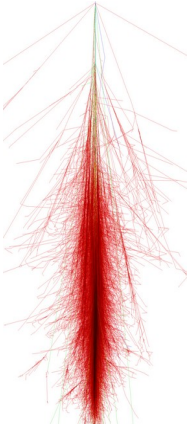
The problem: air showers not correctly modeled

Problem II: modeling all air showers

$$\Phi_\mu = \int$$



$\times$



$\mathrm{d}E$

Flux of muons and neutrinos in atmosphere due to meson decay

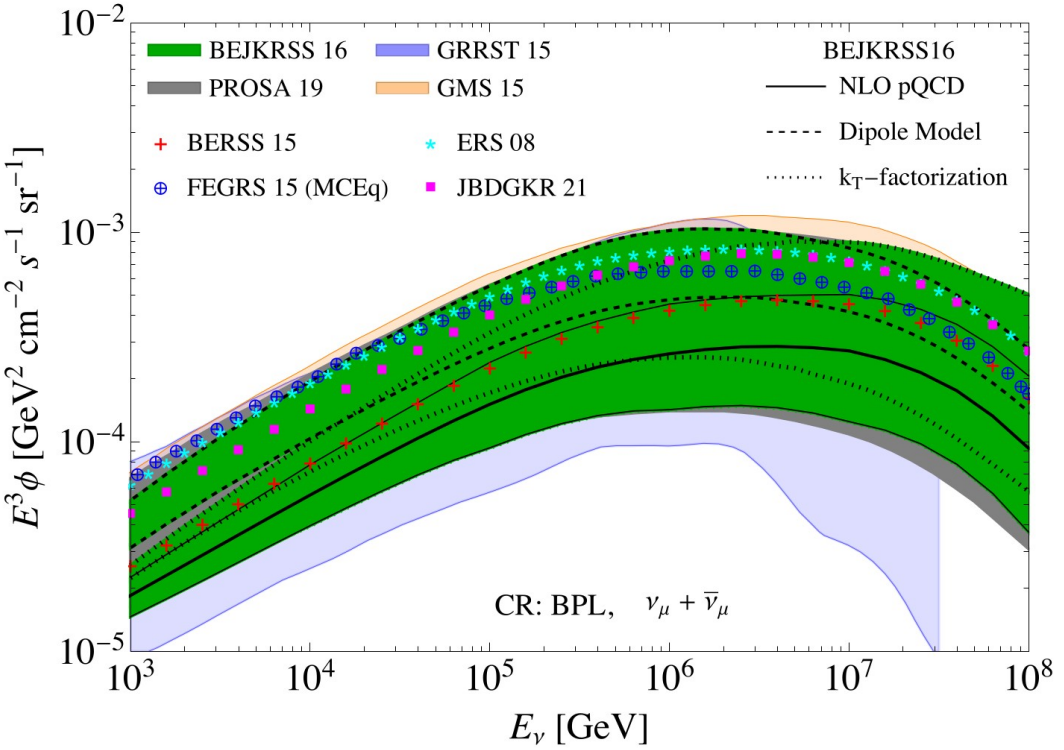
==> compounded problem. Particle production spectra in EAS are weighted by primary spectrum E**2...3
+ sensitive to rare particles

The problem: air showers not correctly modeled

Problem II: modeling all air showers

Broad range of predictions.

Large uncertainty of atmospheric flux at high energies



CR models

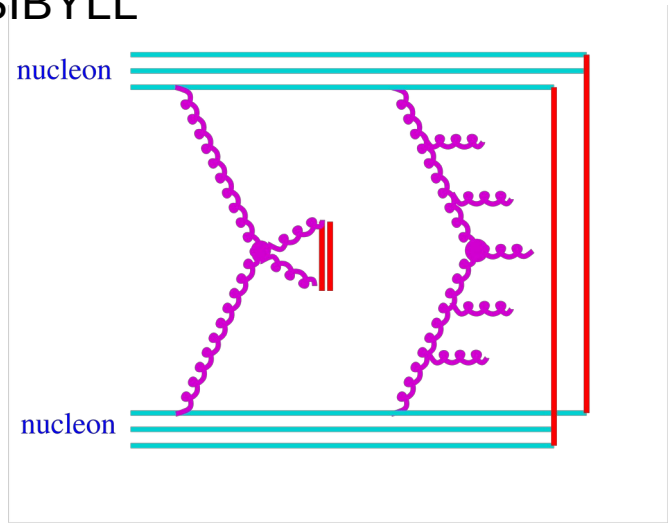
SIBYLL
h+A(<18)

QGSJET II (h+A,A+A)

EPOS (e+e-, h+A, A+A)

Complexity, runtime, #parameters, #data

SIBYLL



EPOS, QGSJET II