

Synergies with the Cosmic-Ray Community

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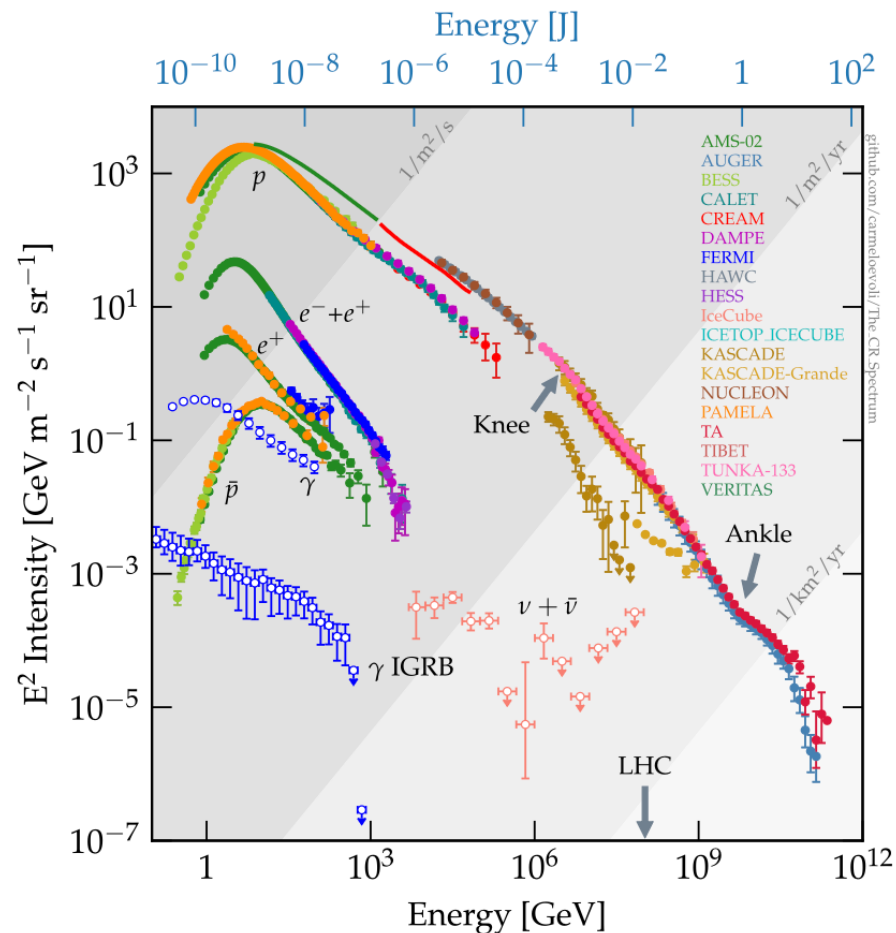
EMMI Workshop: Light-ion collisions 2026, Heidelberg

Current reviews: [Physics Reports 1161 \(2026\) 1–81](#) , [Nature Rev. Phys. Vol. 8, p. 98–114 \(2026\)](#)

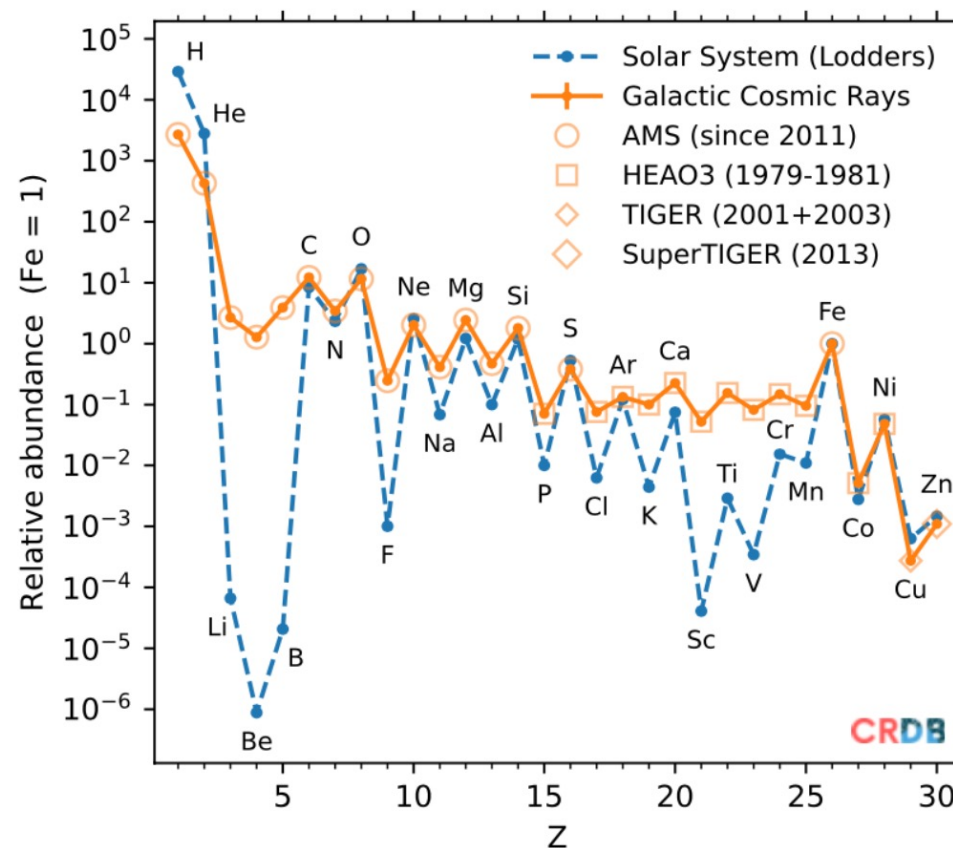


Cosmic-Rays: Cosmic probes spanning orders-of-magnitude

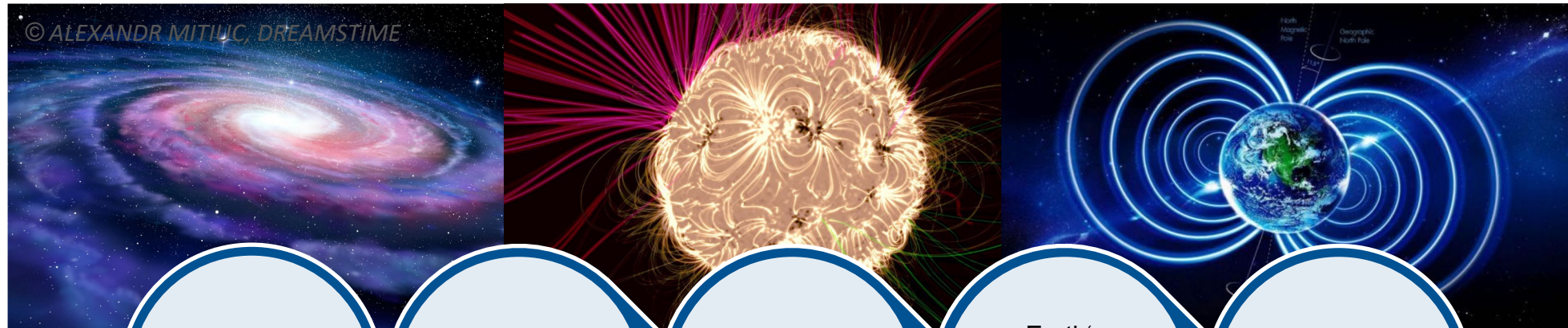
... in energy



... particle-species abundance



Understanding Cosmic-Rays: What we need to know



**Injection spectra
(particles)**

Propagation in
the Galaxy

Solar magnetic
field

Earth's
magnetic field
and
atmosphere

**Cosmic rays
at Earth**

Source hypotheses

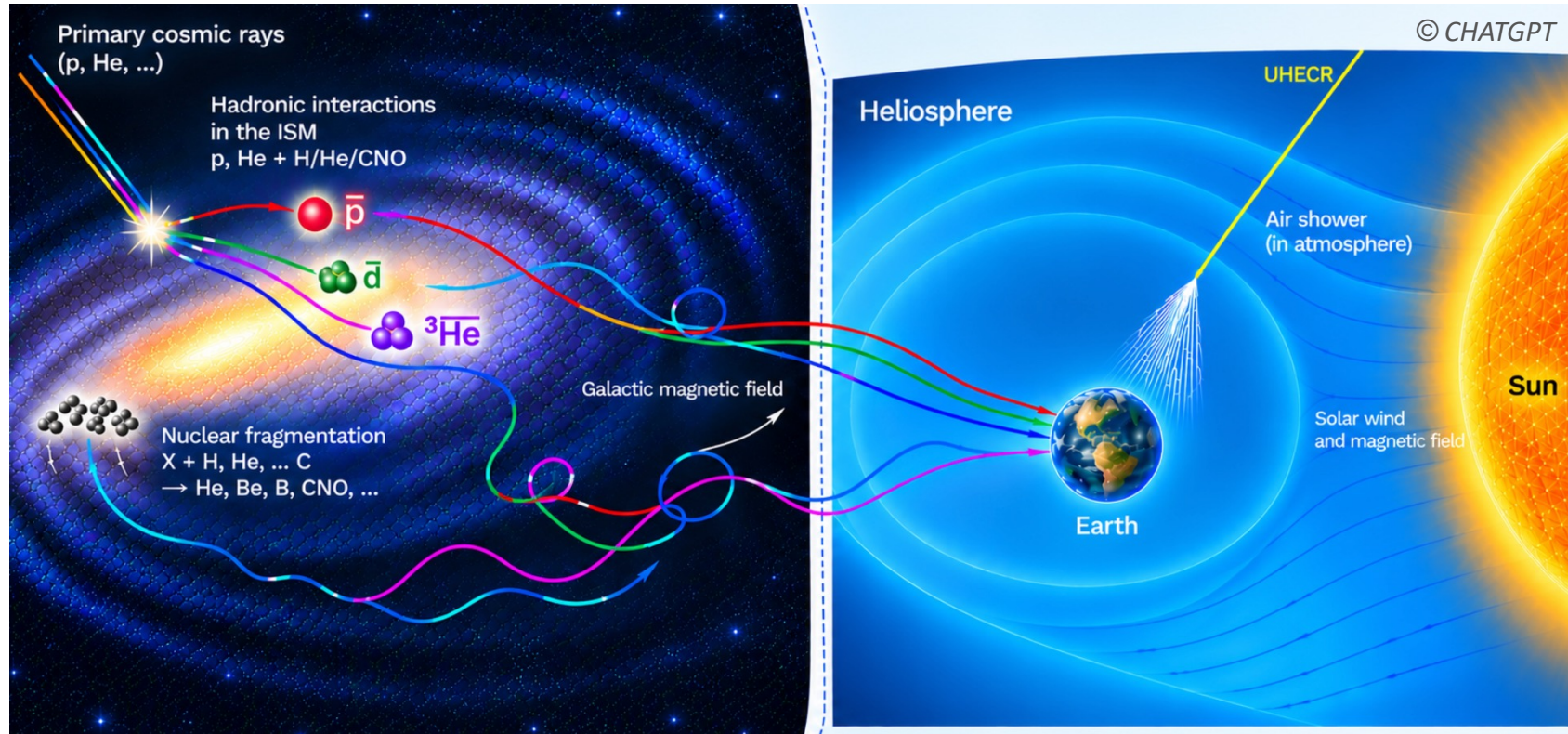
- Primary / secondary
- Injection spectra
- Abundance
- Spatial distribution

Transport models

- (Extra-) galactic propagation
- Heliospheric propagation
- Near-Earth models

Comparison with measurements

Cross-sections for Cosmic-Ray Physics



Antinuclei cross sections

- Production CS for $\bar{p}$, $\bar{D}$, ${}^3\bar{\text{He}}$
- Absorption CS for $\bar{p}$, $\bar{D}$, ${}^3\bar{\text{He}}$

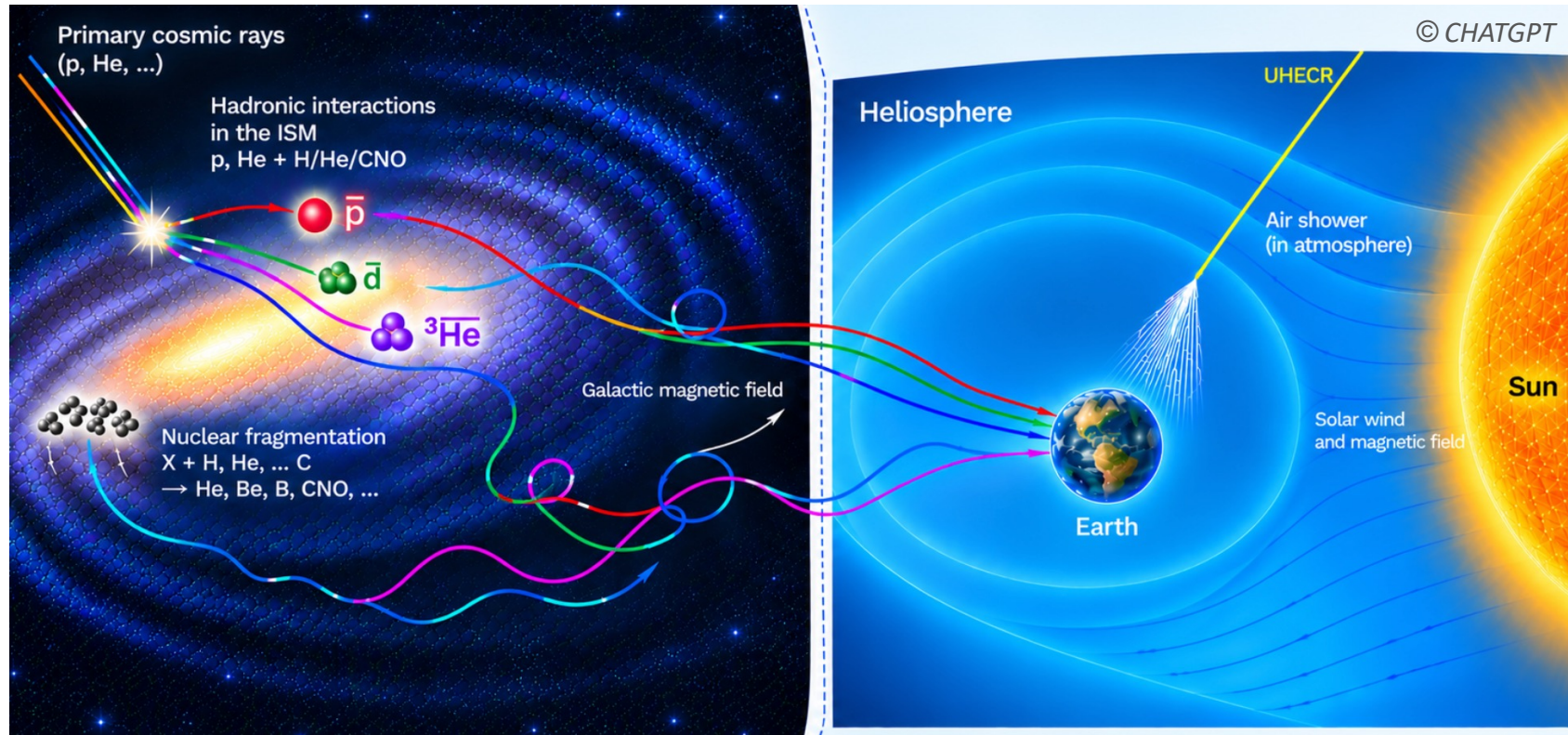
Fragmentation cross sections

- Fragmentation of CRs and creation of stable and unstable nuclei

Hadronic cross sections on air

- Creation and evolution of air showers in the atmosphere

Cross-sections for Cosmic-Ray Physics



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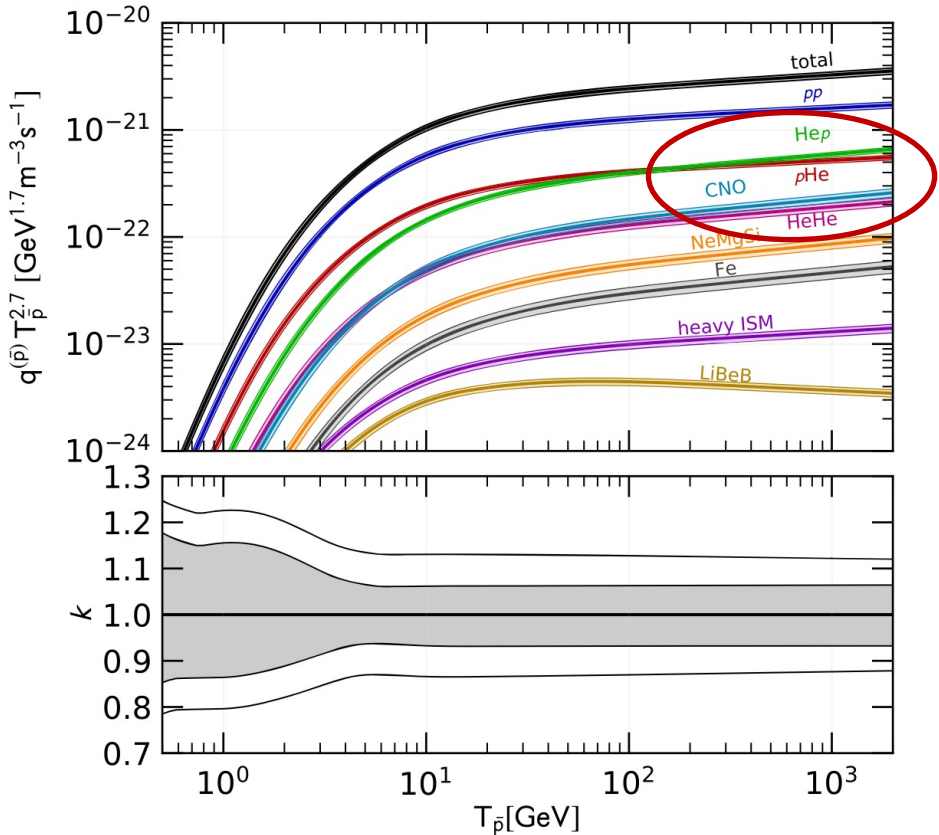
- Creation and evolution of air showers in the atmosphere

Antiproton-production cross sections: The precision era

Measurements of cosmic antiprotons have reached percent-level precision...

... but we miss precision cross-section measurements

Measurements of $\bar{p}$ production in collisions involving light ions

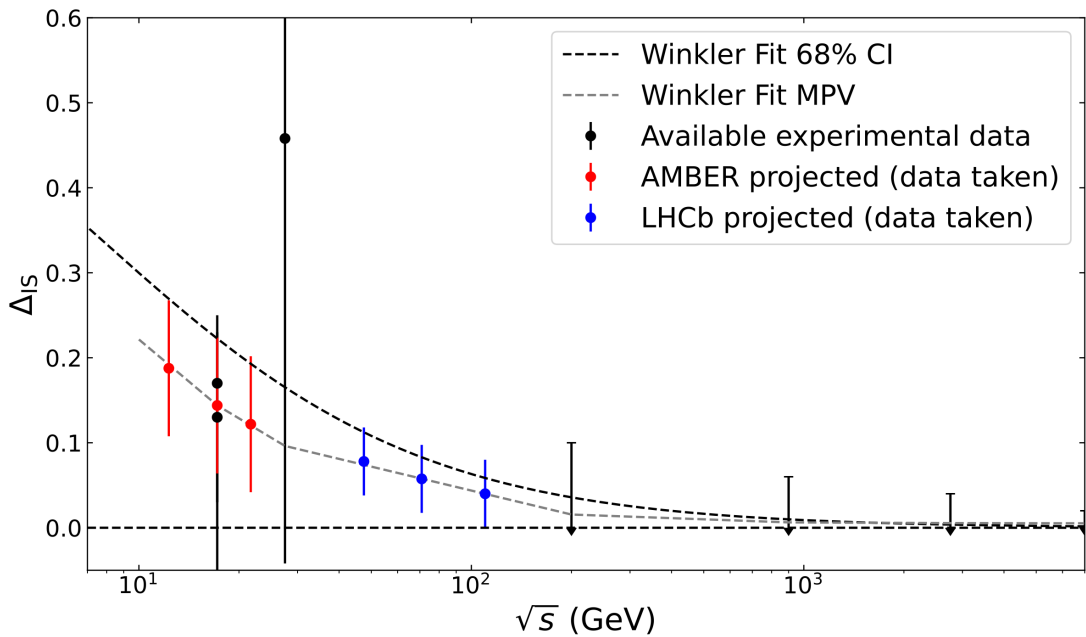


Di Mauro et al. Phys. Rev. D, Vol 97, 103019 (2018)

Thomas Pöschl (Univ. Freiburg)

Difference of antiproton and antineutron production in CR collisions

Assess the isospin-asymmetric antinuclei production by comparison of flipped reactions $p + p \rightarrow \bar{p}X$ $p + n \rightarrow \bar{p}X$
Via comparison of $p - H_2$ and $p - D_2$ collision data



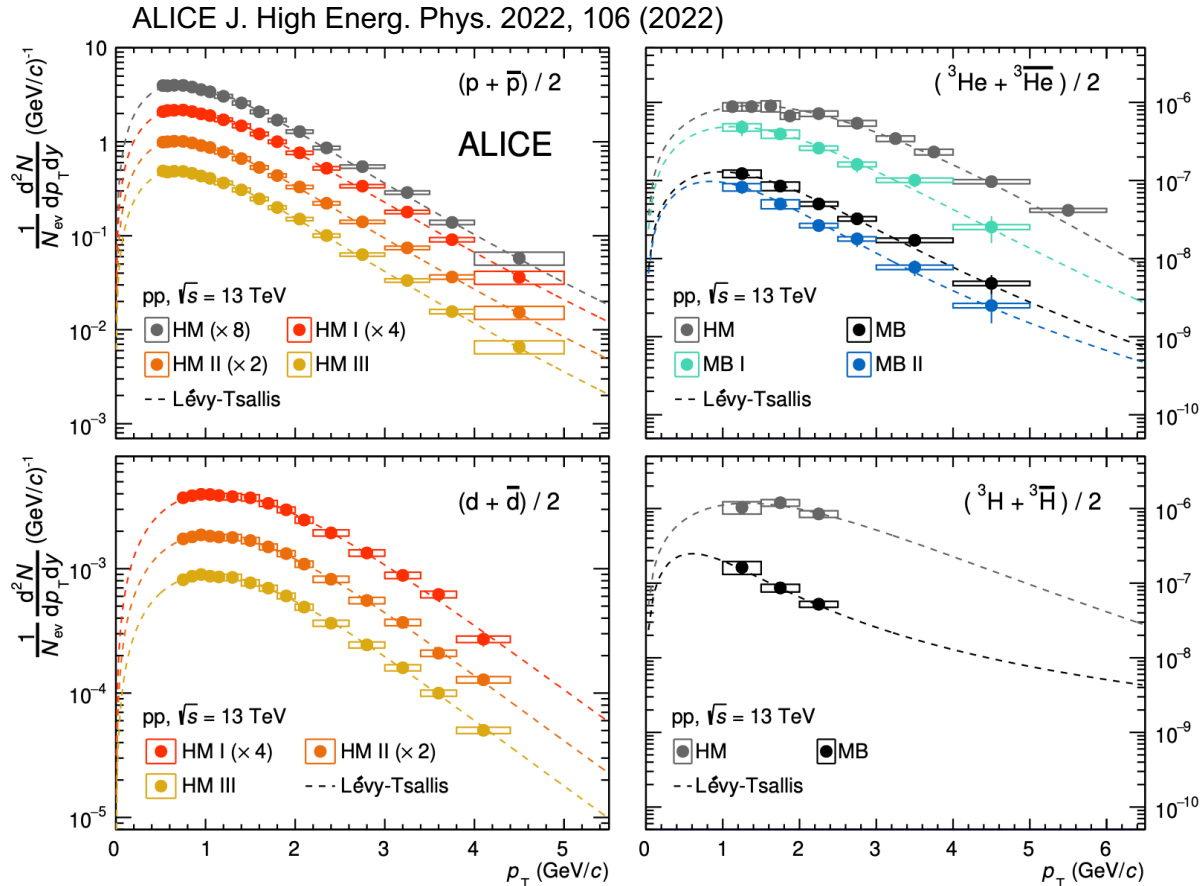
Maurin et al. Physics Reports 1161 (2026) 1–81 (updated)

Antinuclei cross sections: Production and Interactions

Measurements of cosmic antideuteron and antihelium are in reach...

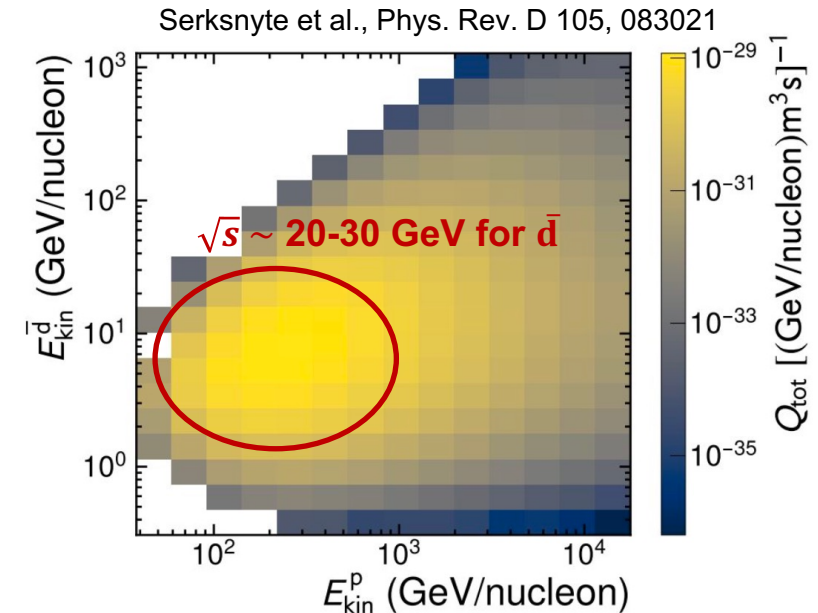
... interpretation requires accurate modelling of involved processes (production, absorption, detector interactions)

Production-measurements of antinuclei



Thomas Pöschl (Univ. Freiburg)

Precise measurements of antinuclei production in pp collisions by ALICE **but**
For CR, production at lower-collision energy relevant
→ model extrapolation of formation process



Antinuclei cross sections: Production and Interactions

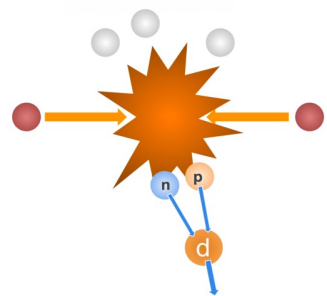
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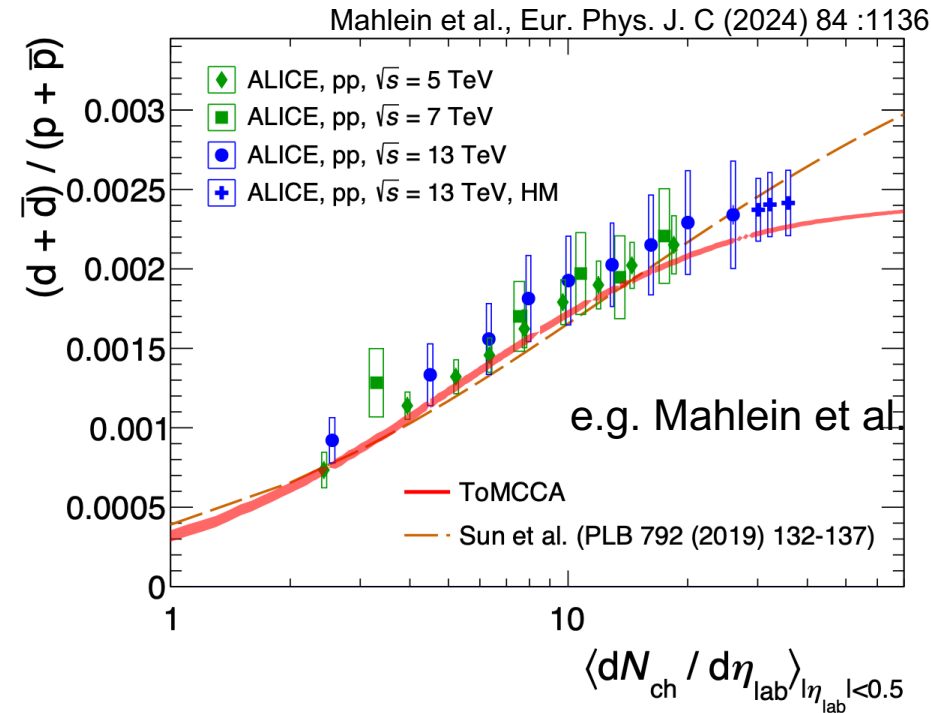
Production-measurements of antinuclei

Approach: Use multiplicity-dependence of the source-size for extrapolation
→ measurements of source-sizes and dependences crucial for antinuclei-production modelling

© M. MAHLEIN



Coalescence mechanism



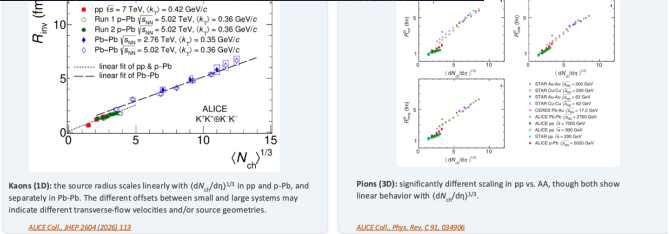
ALICE

LIGHT-ION WORKSHOP (21-25 Sept, 2026) · HEIDELBERG UNIVERSITY

Proton Femtosopic Source in Light-Ion Collisions with the ALICE Experiment

OO and Ne-Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV · ALICE, LHC Run 3

Neelima Agrawal, on behalf of the ALICE Collaboration
University & INFN Bologna, Italy
21 - 09 - 2026



Light-ion collisions add valuable insights to the particle-emitting source

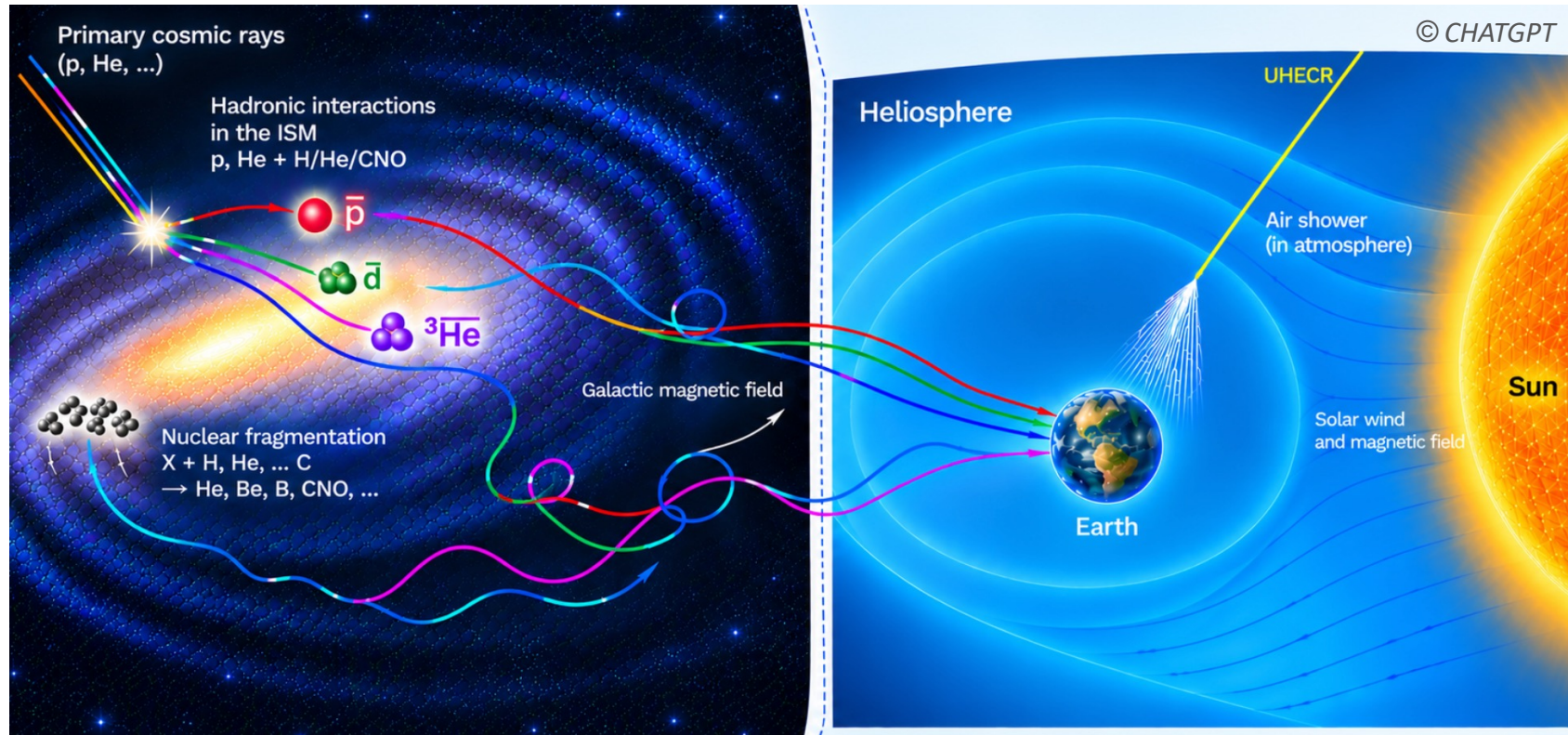
Antinuclei cross sections: Wishlist for the next decade(s) from light ion collisions

Driven by indirect DM search, including $e^\pm, \gamma$

[Physics Reports 1161 \(2026\) 1–81](#)

Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\bar{p}$	$p + p \rightarrow \bar{p} + X$	σ_{inv}	5 to 100 GeV	< 3%
	$p + \text{He} \rightarrow \bar{p} + X$			< 5%
	$p + p \rightarrow \bar{\Lambda} + X$			< 10%
	$p + \text{He} \rightarrow \bar{\Lambda} + X$			< 10%
	$p + p \rightarrow n + X$			< 5%
	$p + n \rightarrow \bar{p} + X$			< 5%
$\bar{d}$	$p + p \rightarrow \bar{d} + X$	$\sigma_{\text{inv}}/n_{\text{tot}}$	5 to 100 GeV	(any data)
	$p + \text{He} \rightarrow \bar{d} + X$	$\sigma_{\text{inv}}/n_{\text{tot}}$	5 to 100 GeV	(any data)
	$p + p \rightarrow \bar{d} + X$	σ_{inv}	2 to 10 GeV	(any data)
$\overline{\text{He}}$	$p + p \rightarrow \overline{\text{He}} + X$	$\sigma_{\text{inv}}/n_{\text{tot}}$	5 to 100 GeV	(any data)
$e^\pm$	$p + \text{He} \rightarrow \pi^\pm + X$	σ_{inv}	5 to 100 GeV	< 5%
	$p + \text{He} \rightarrow K^\pm + X$			< 5%
γ	$p + p \rightarrow \pi^0 + X$	σ_{inv}	5 to 1000 GeV	< 5%
	$p + \text{He} \rightarrow \pi^0 + X$			< 5%

Cross-sections for Cosmic-Ray Physics



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Fragmentation cross sections

- Fragmentation of CRs and creation of stable and unstable nuclei

Hadronic cross sections on air

- Creation and evolution of air showers in the atmosphere

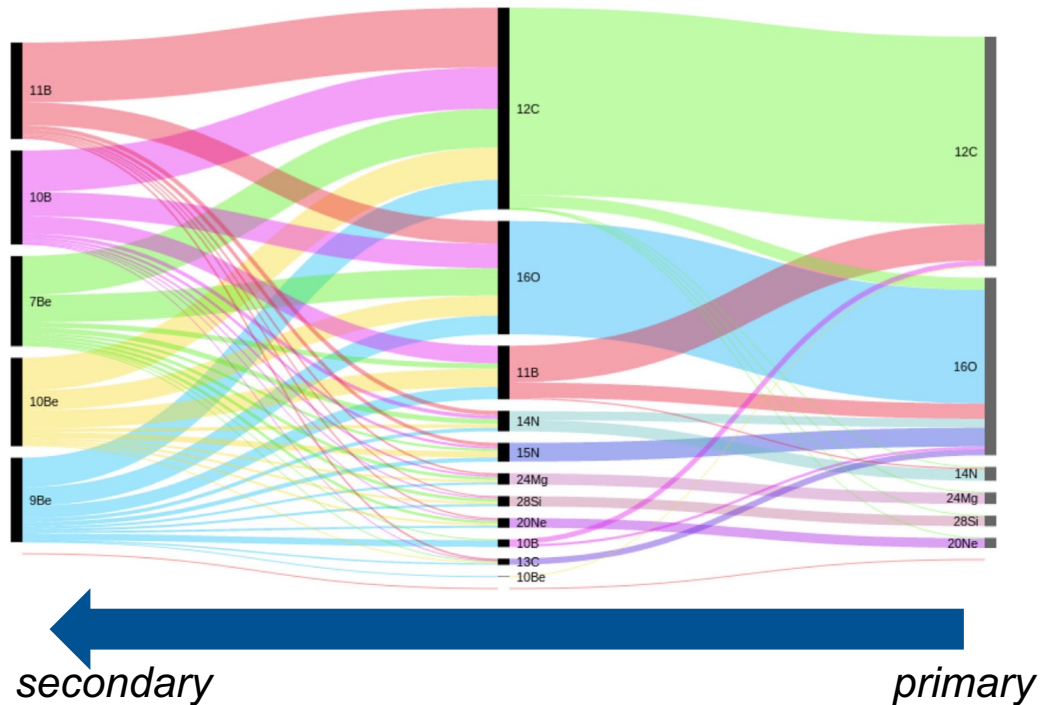
Fragmentation cross sections: A fully-connected particle network

Constrain propagation parameters of Galactic transport of CR by comparing fluxes of different CR types

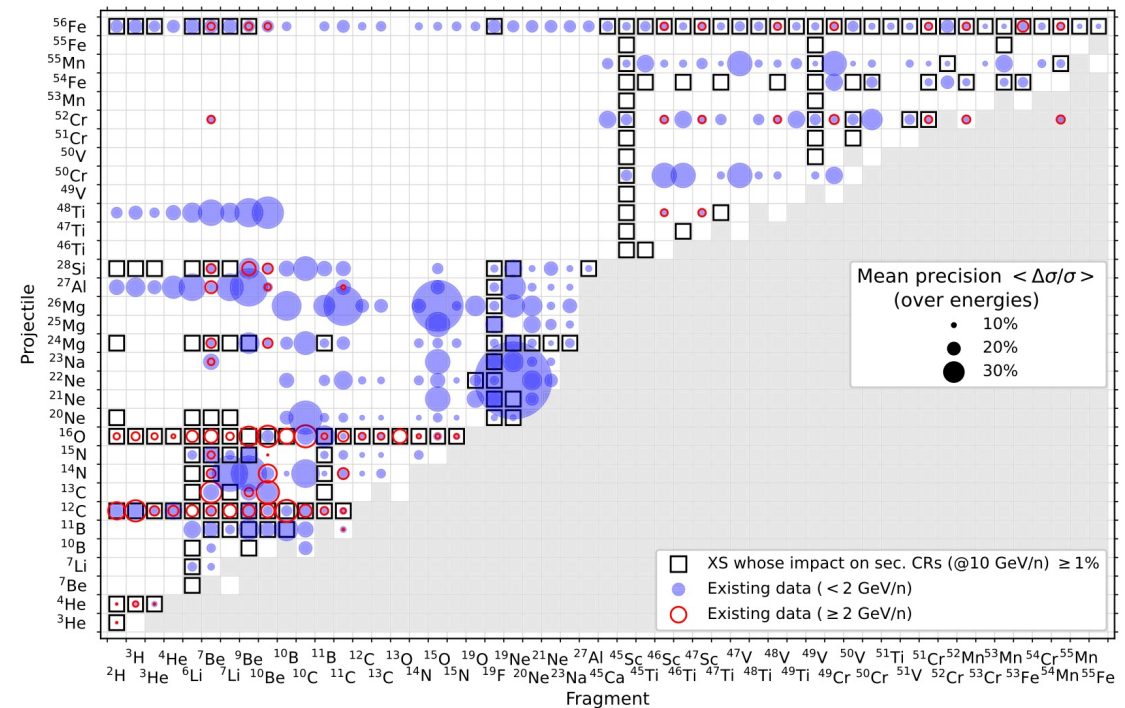
- Fraction of primary-to-secondary cosmic rays constrain the amount of material
- Thickness of galaxy from unstable isotopes

→ Modeling must include all significant production channels for nuclei of interest (e.g. Li, B, Be-9, Be-10, ...)

Tomassetti, Phys. Rev. D 96, 103005 (2017)



Maurin et al. Physics Reports 1161 (2026) 1–81



Overview of existing and required data on XS

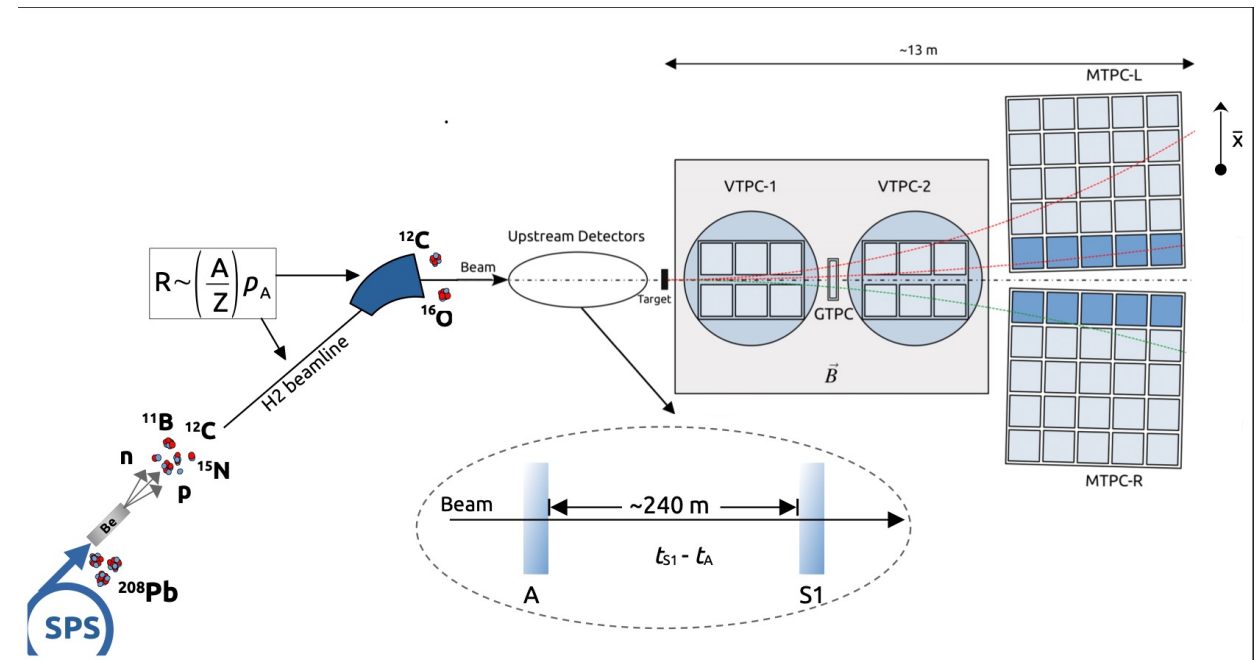
Fragmentation cross sections: Light-Ion Channels

- Most relevant energy region $E_{kin} \sim \sigma(0.1) - \sigma(10)$ GeV/n
- Most relevant collision systems: GCRs/projectile (H, 4-He, 12-C, 16-O, 20-Ne, 24-Mg, 28-Si, 56-Fe, ...) ISM/target: (H, He)

[Physics Reports 1161 \(2026\) 1–81](#)

Facilities: CNAO, NSRL, FAIR, HIAF, SPS

Example: NA61/SHINE



Reaction	N_{int}
$^7\text{Li}+\text{H}$	5k
$^{10}\text{B}+\text{H}$	5k
$^{11}\text{B}+\text{H}$	10k
$^{12}\text{C}+\text{H}$	50k
$^{12}\text{C}+\text{He}$	10k
$^{13}\text{C}+\text{H}$	5k
$^{14}\text{N}+\text{H}$	10k
$^{15}\text{N}+\text{H}$	10k
$^{16}\text{O}+\text{H}$	60k
$^{16}\text{O}+\text{He}$	20k

Reaction	N_{int}
$^{20}\text{Ne}+\text{H}$	50k
$^{20}\text{Ne}+\text{He}$	10k
$^{21}\text{Ne}+\text{H}$	10k
$^{22}\text{Ne}+\text{H}$	20k
$^{22}\text{Ne}+\text{He}$	5k
$^{23}\text{Na}+\text{H}$	10k
$^{24}\text{Mg}+\text{H}$	50k
$^{24}\text{Mg}+\text{He}$	10k
$^{25}\text{Mg}+\text{H}$	10k
$^{26}\text{Mg}+\text{H}$	10k
$^{27}\text{Al}+\text{H}$	10k

Reaction	N_{int}
$^{28}\text{Si}+\text{H}$	50k
$^{28}\text{Si}+\text{He}$	10k
$^{29}\text{Si}+\text{H}$	5k
$^{32}\text{S}+\text{H}$	5k
$^{56}\text{Fe}+\text{H}$	30k
$^{56}\text{Fe}+\text{He}$	10k

Examples of required reactions needed for reaching 1%-precision in CR modeling

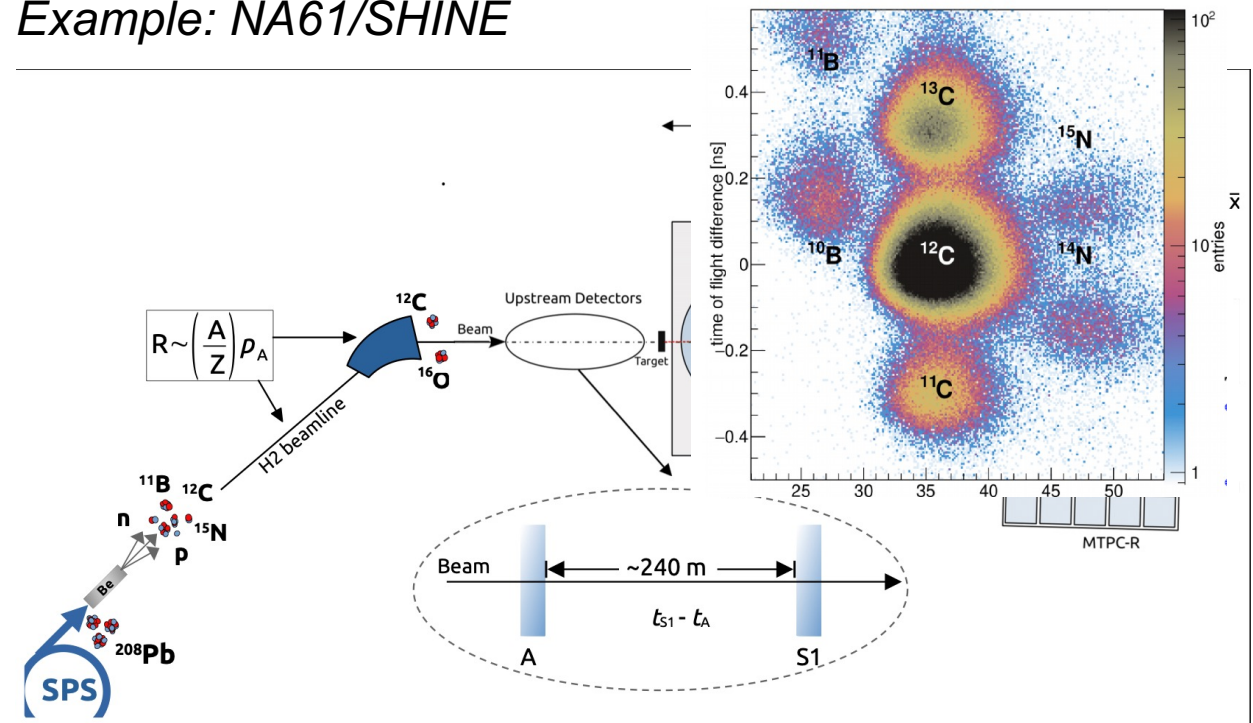
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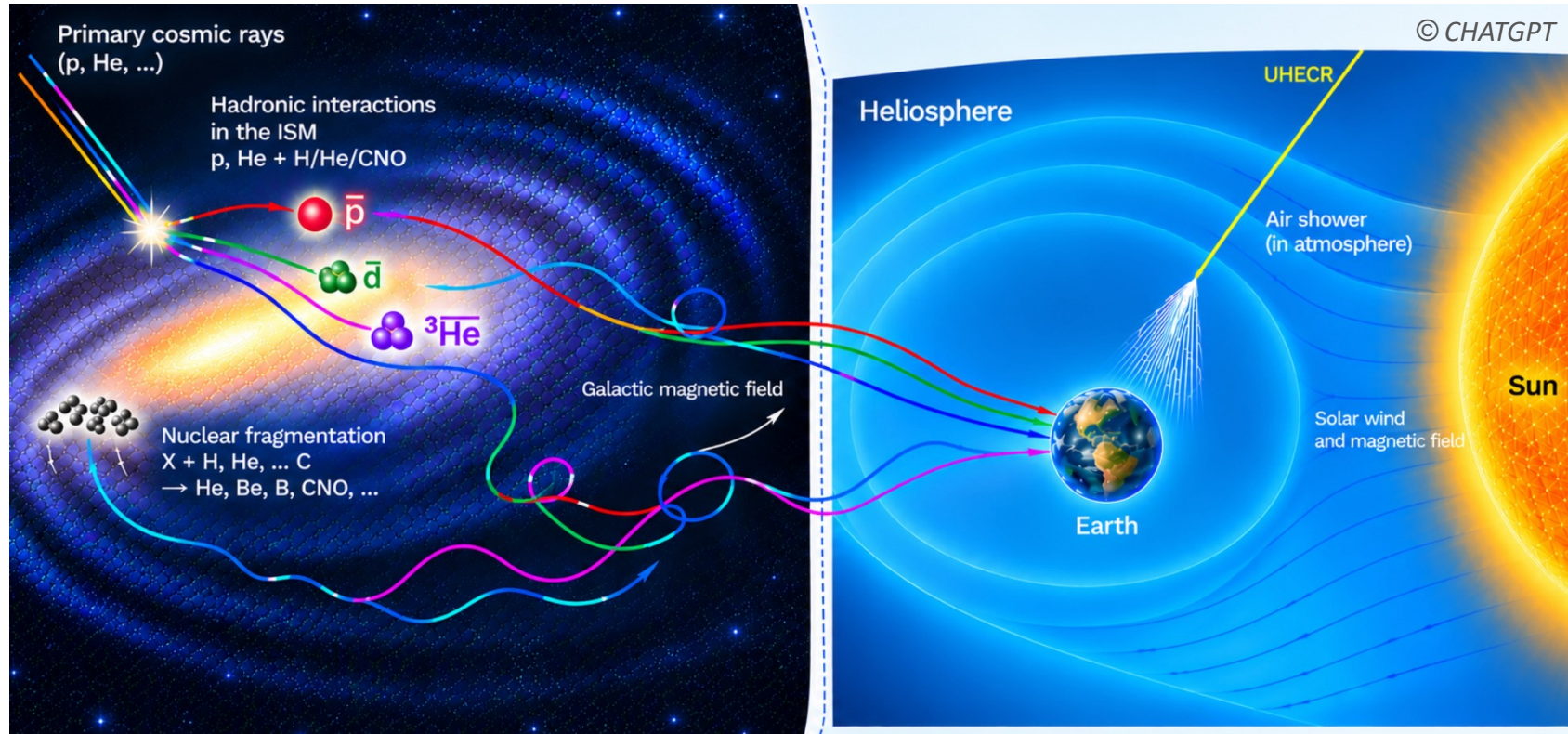
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Reaction	N_{int}	Reaction	N_{int}	Reaction	N_{int}
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$^{10}\text{B}+\text{H}$	5k	$^{20}\text{Ne}+\text{He}$	10k	$^{28}\text{Si}+\text{He}$	10k
$^{11}\text{B}+\text{H}$	10k	$^{21}\text{Ne}+\text{H}$	10k	$^{29}\text{Si}+\text{H}$	5k
$^{12}\text{C}+\text{H}$	50k	$^{22}\text{Ne}+\text{H}$	20k	$^{32}\text{S}+\text{H}$	5k
$^{12}\text{C}+\text{He}$	10k	$^{22}\text{Ne}+\text{He}$	5k	$^{56}\text{Fe}+\text{H}$	30k
$^{13}\text{C}+\text{H}$	5k	$^{23}\text{Na}+\text{H}$	10k	$^{56}\text{Fe}+\text{He}$	10k
$^{14}\text{N}+\text{H}$	10k	$^{24}\text{Mg}+\text{H}$	50k		
$^{15}\text{N}+\text{H}$	10k	$^{24}\text{Mg}+\text{He}$	10k		
$^{16}\text{O}+\text{H}$	60k	$^{25}\text{Mg}+\text{H}$	10k		
$^{16}\text{O}+\text{He}$	20k	$^{26}\text{Mg}+\text{H}$	10k		
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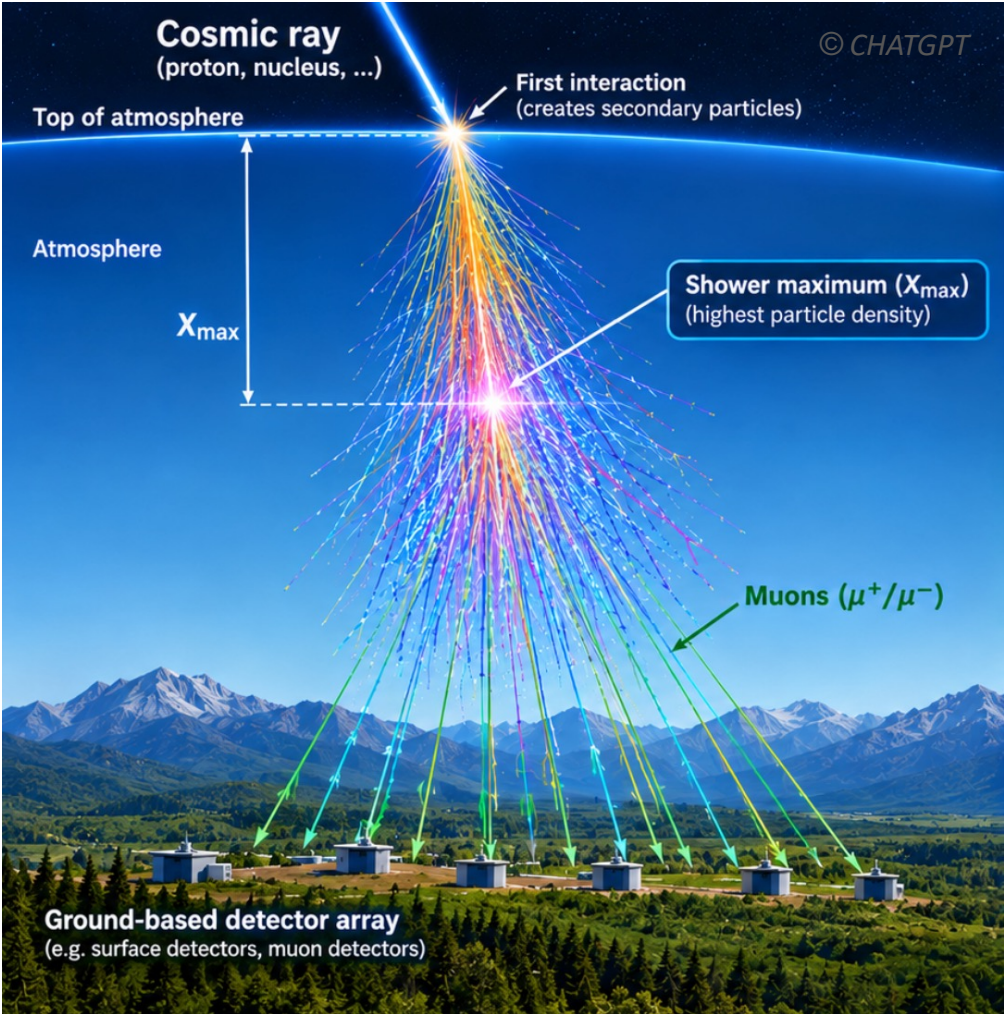
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Understanding cosmic-ray induced air showers



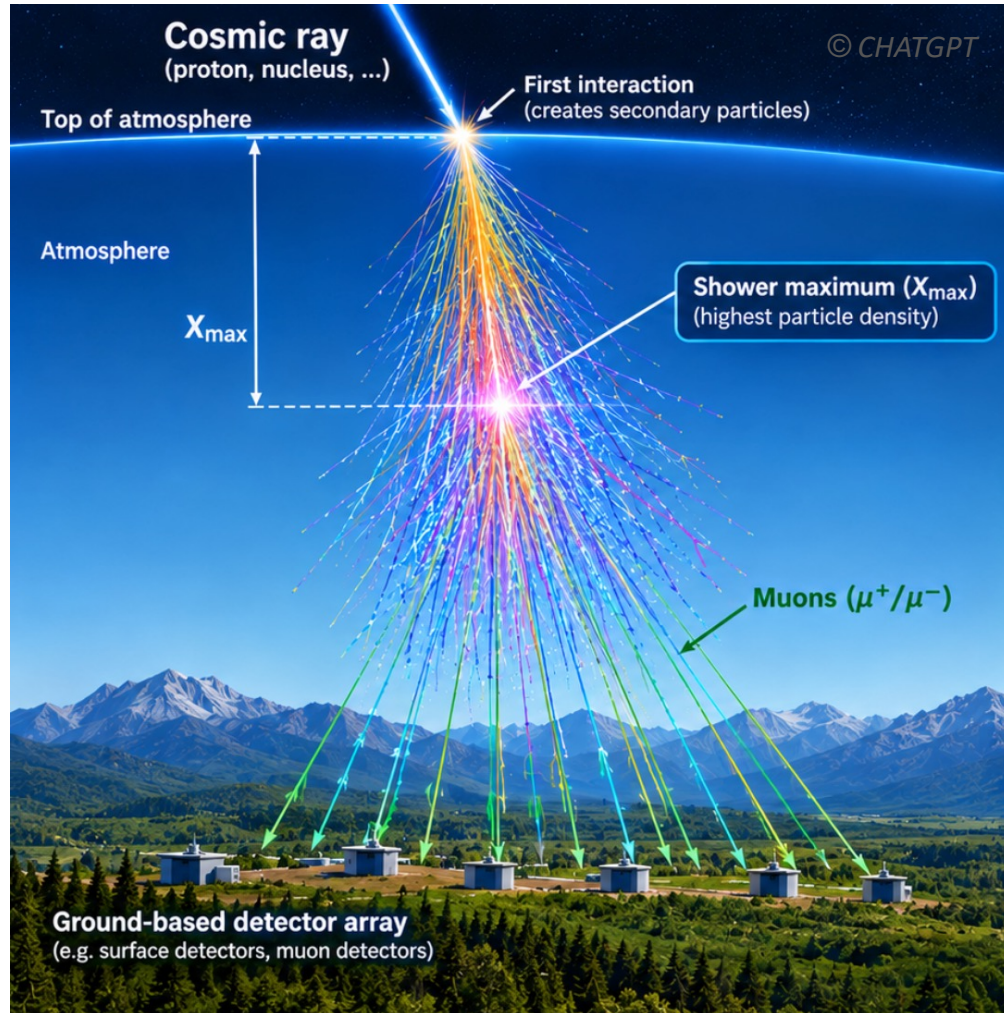
- Air-showers from UHECR contain information on the initial particle type (p , ..., Fe , γ)
- Accurate modeling of observables needed to correctly interpret the CR measurements based on air-shower identification
- Large discrepancies between different hadronic models and also CR data
- So far: Interpolation of LHC data from pp and heavy ion used

Table 4 | Observables in extensive air shower experiments and their sensitivity to quantum chromodynamics features and properties of the cosmic rays⁶¹

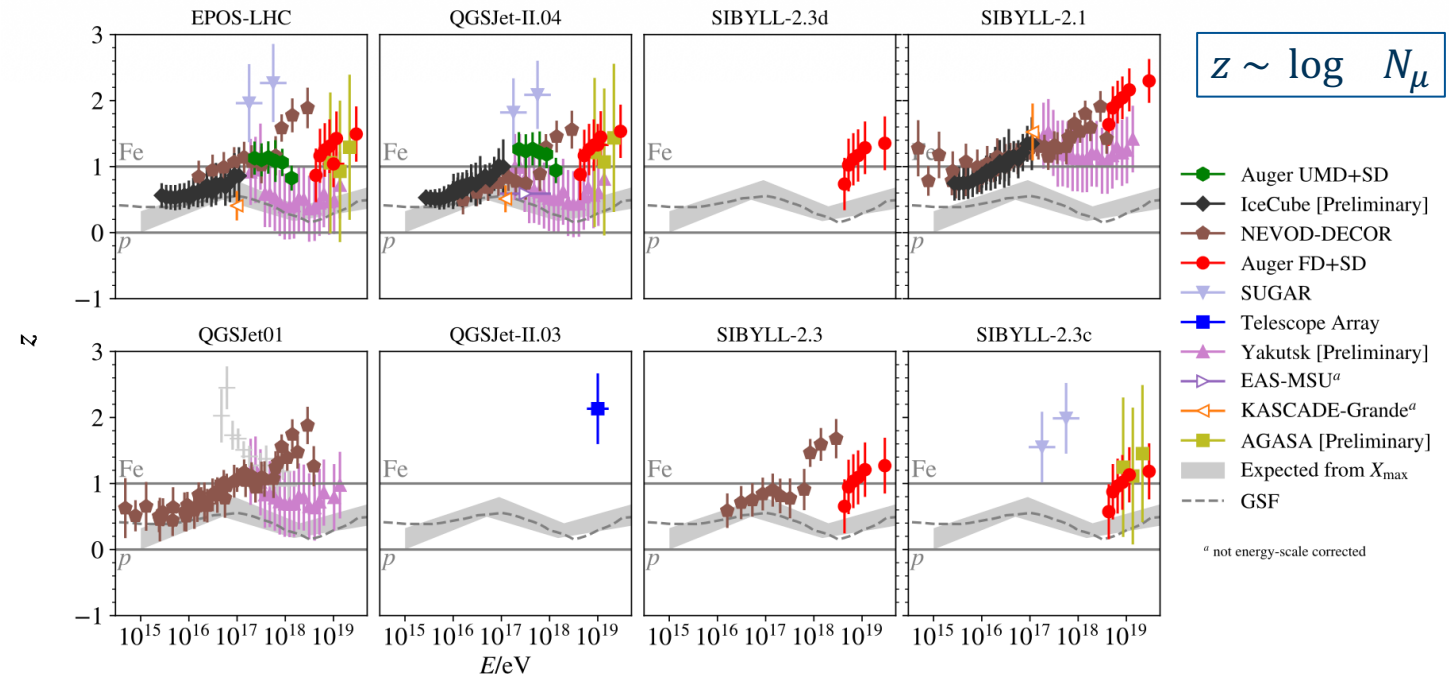
Observable	Sensitivity to QCD feature					Sensitivity to cosmic-ray feature			
	σ_{inel}	N_{mult}	$\frac{E_{\text{max}}}{E}$	$\frac{E_{\pi^0}}{E}$	$\sigma_{D,B}$	C_1	E	$\langle \ln A \rangle$	$\sigma(\ln A)$
$\int (dE/dx) dx$							✓		
$\langle X_{\text{max}} \rangle$	✓	✓	✓			✓	✓	✓	
$\sigma(X_{\text{max}})$	✓		✓			✓	✓	✓	✓
$\langle X_{\mu, \text{max}} \rangle$	✓	✓	✓			✓	✓	✓	
$\sigma(X_{\mu, \text{max}})$	✓		✓			✓	✓	✓	✓
$\langle N_{\mu} \rangle$		✓		✓			✓	✓	
$\sigma(N_{\mu})/N_{\mu}$			✓	✓		✓	✓	✓	✓
$\Phi_{(\nu, \mu), \text{conv}}$	✓	✓	✓	✓		✓	✓	✓	
$\Phi_{(\nu, \mu), \text{prompt}}$			✓		✓	✓	✓	✓	

C_1 , mean free path to first collision; E , primary energy; E_{max}/E , elasticity (energy fraction carried by the most energetic product); E_{π^0}/E , energy fraction carried by neutral pions; N_{mult} , average number of secondary hadrons; QCD, quantum chromodynamics; σ_{inel} , inelastic (p, π)-air cross-section; $\sigma_{D,B}$, production cross-section for D and B mesons; $\langle \ln A \rangle$, mean logarithmic mass; $\sigma(\ln A)$, standard deviation of logarithmic mass.

Understanding cosmic-ray induced air showers



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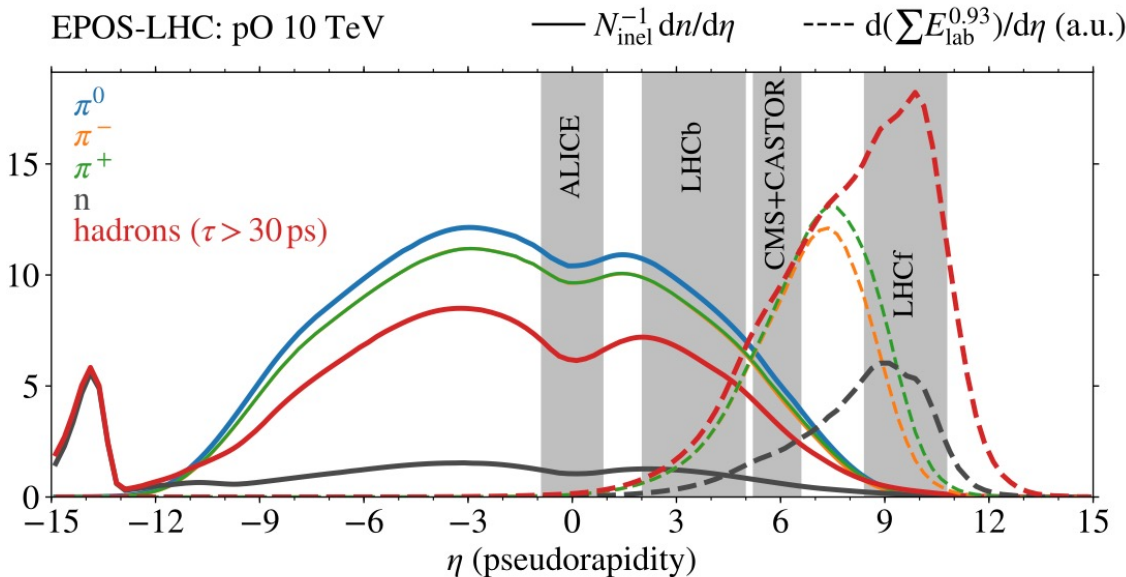
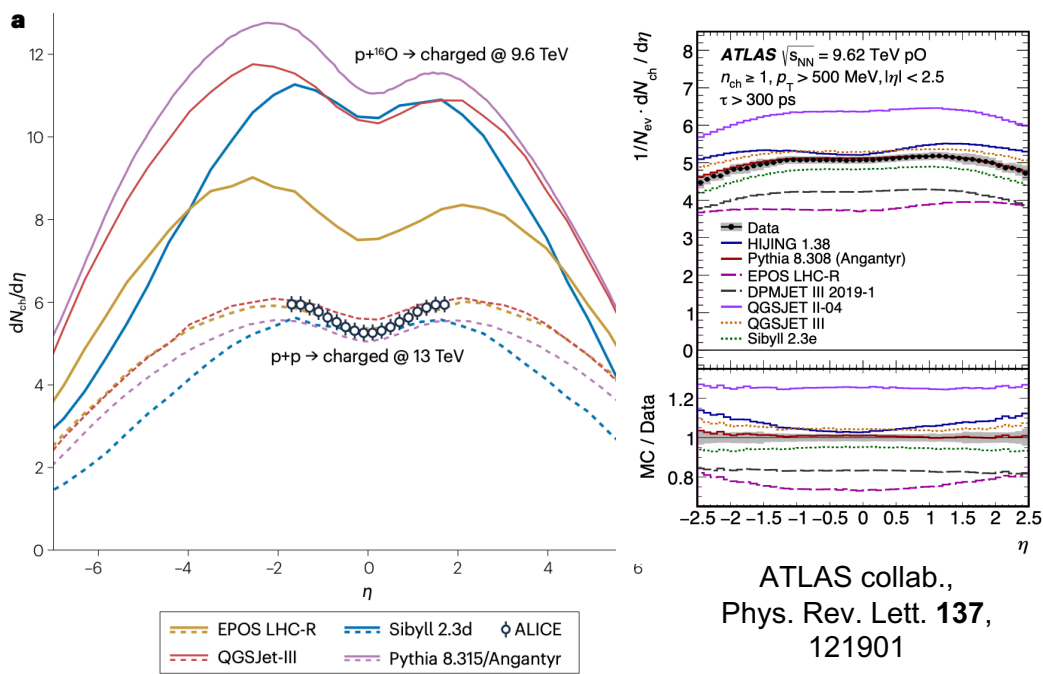
Understanding cosmic-ray induced air showers

New data recorded by LHC on p-O, O-O, Ne-Ne will change the picture

Required input for improving our models

- p-air inelastic cross section (from p-O)
- Abundance of
 - hadron multiplicity
 - Composition and spectra of light hadrons
 - Strangeness production
 - ρ meson production
 - heavy-flavor production
 - Forward energy flow $dE/d\eta$

Covering the largest possible phase space



Summary and Outlook for Cosmic-ray physics from light-ion collisions

CR physics requires precision cross sections from accelerator-based experiments!

Examples for input from light-ion collisions:

Antinuclei production:

- Production of antinuclei in p-He, He-p, He-He, p-C,N,O
- Studies of source-size evaluation across collisions
- Isospin-studies at SPS energies requiring datasets in p-H, p-D or p-He-3, p-He-4

Fragmentation Cross Sections:

- Most relevant are measurements at $\sqrt{s}(0.1) - \sqrt{s}(10)$ GeV/n for many different reactions
- Highest priorities H⁺ion and He⁺ions

Hadronic Cross Sections for Air-shower measurements:

- Analysis of recent p-O measurements
- Extraction of key collision parameters like cross section and particle multiplicities

More details on input for CR: [Physics Reports 1161 \(2026\) 1–81](#), [Nature Rev. Phys. Vol. 8, p. 98–114 \(2026\)](#)

Advertisement: Next edition of the [XSCRC at CERN](#) upcoming (13.-15.01.27)

Thank you for your attention!

