Proton-oxygen cross sections, the muon puzzle, and possibilities to solve it

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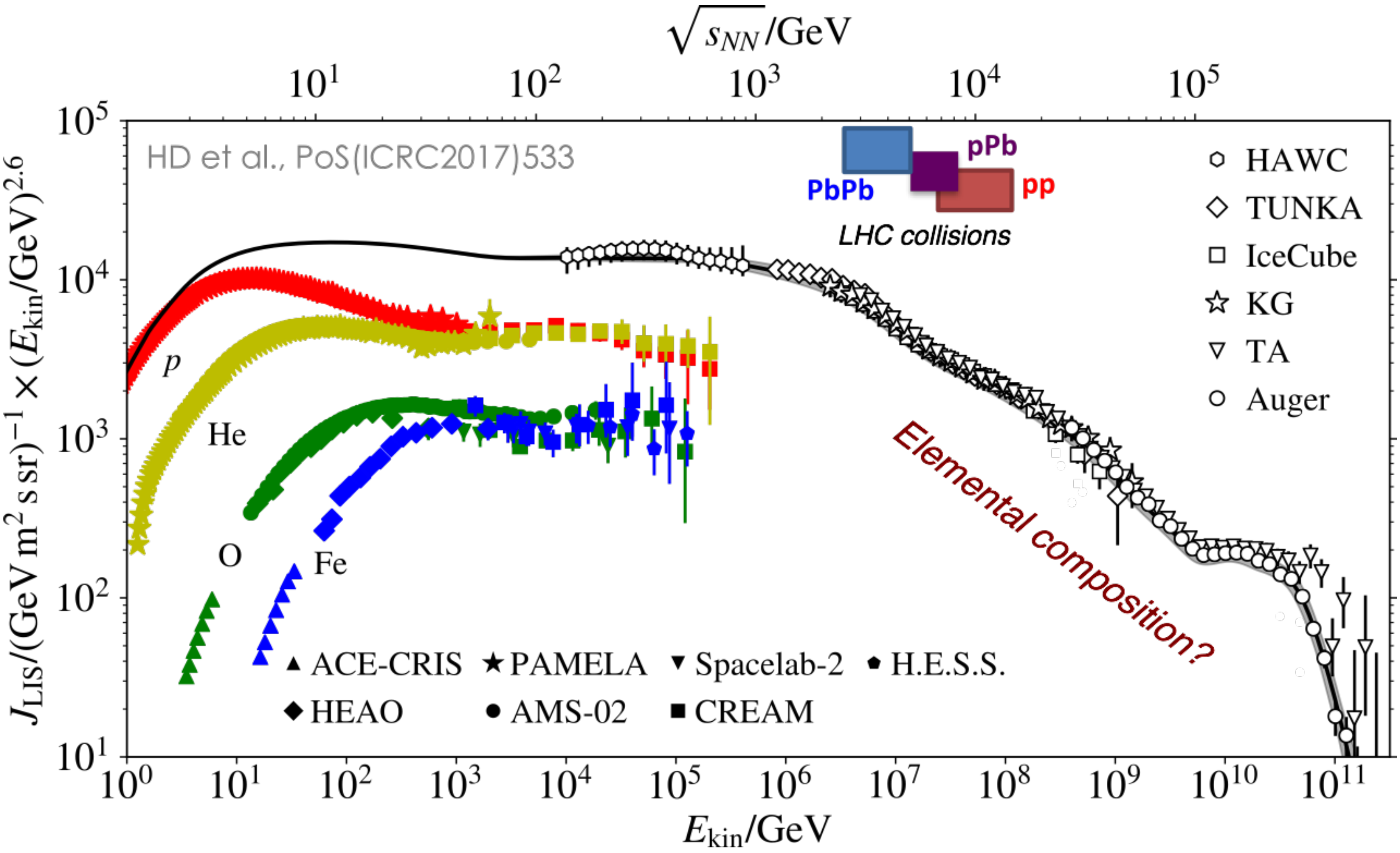
XSCRC Workshop 2019

Take-home message

- High-energy cosmic rays initiate air showers
  - Cosmic rays isotropic, do not point back to sources, but...
  - Cosmic-ray **mass composition** can tell us about sources
  - Requires **accurate simulation** of air showers (hadronic cascades)
  - Background for IceCube and future neutrino observatories
  - QCD at sqrt(s) = 300 TeV!
- Muon Puzzle
  - **Data/MC mismatch** in muon density in air showers, new QCD physics?
  - **Eight experiments** combined **muon density** measurements from **0.5 PeV to 10 EeV** and established mismatch at **8σ**
- Potential solution from the LHC
  - Smoking gun: Energy fraction carried by neutral pions too high?
  - **proton-oxygen** collisions to clarify **nuclear effects**, planned for 2023
  - Also needed: high precision forward measurements in *pp* and *p*-Pb

Part 1: High-energy cosmic rays and the Muon Puzzle

High-energy cosmic rays



Regime of air shower detection

High-energy cosmic ray detection

Artist impression of air shower

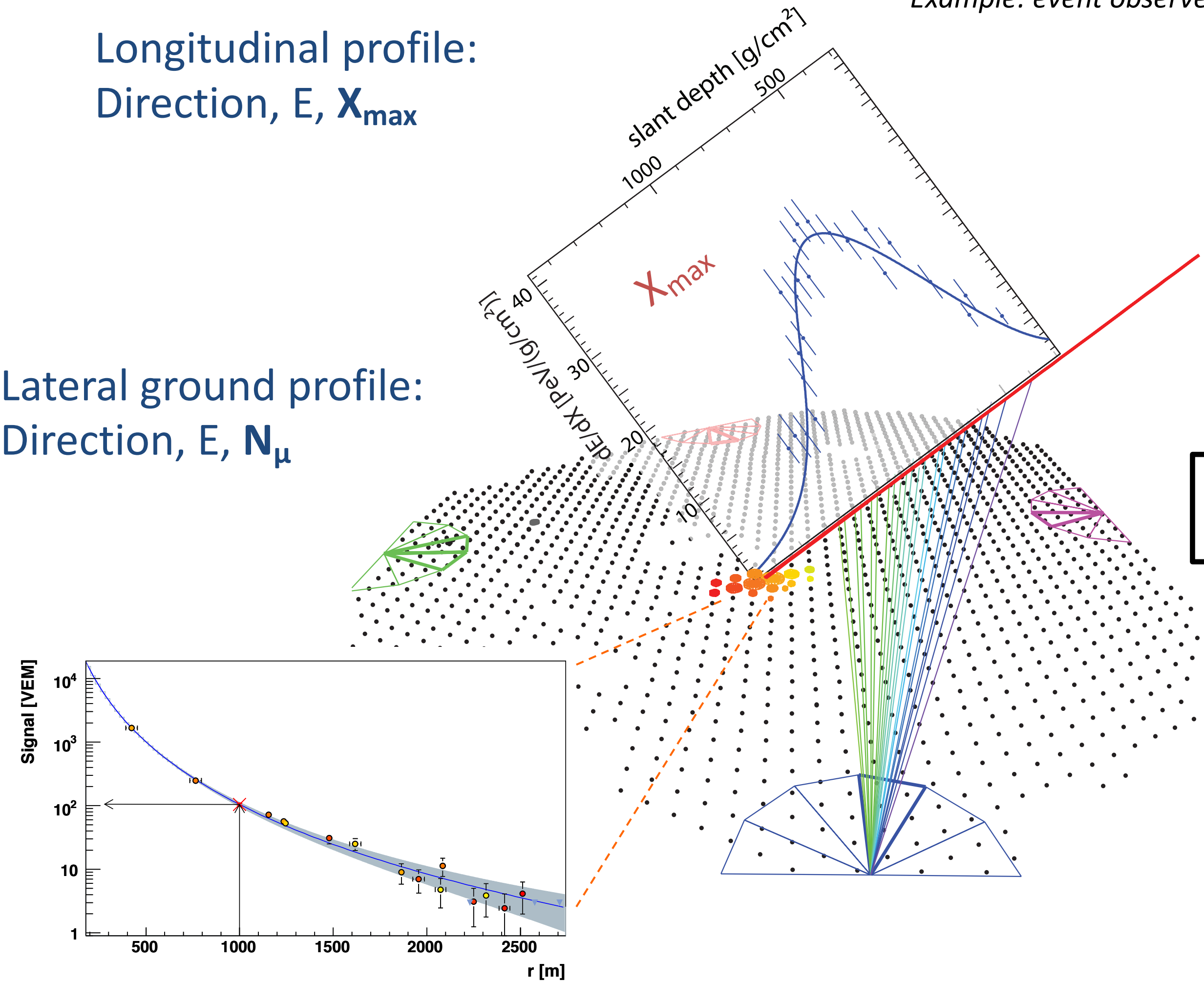
Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0

High-energy cosmic ray detection

Example: event observed with Pierre Auger Observatory

Longitudinal profile:
Direction, E, **X_{max}**

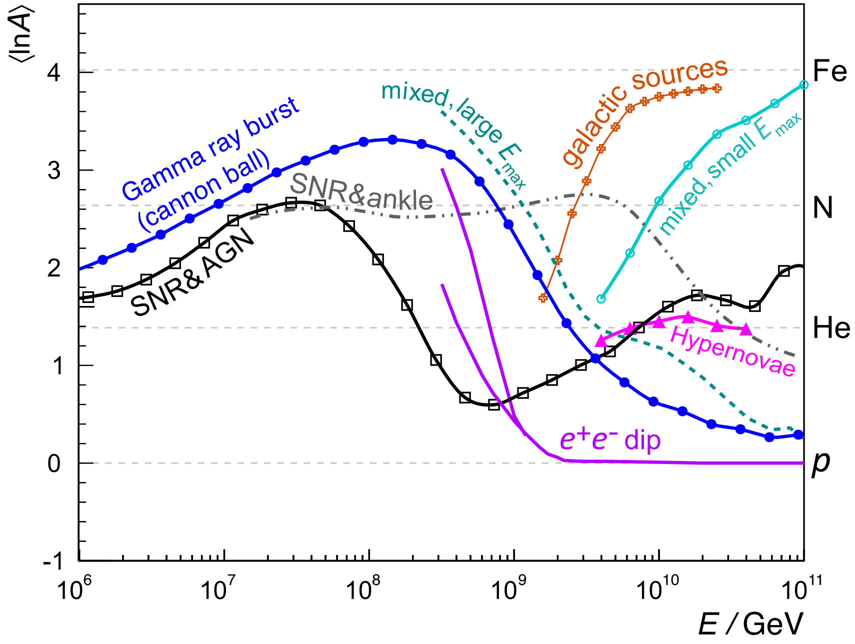
Lateral ground profile:
Direction, E, **N_μ**



Direction from particle arrival times
Energy from size of **eγ component**

Mass from **depth of shower maximum**
and size of **muon component**

Cosmic ray mass composition

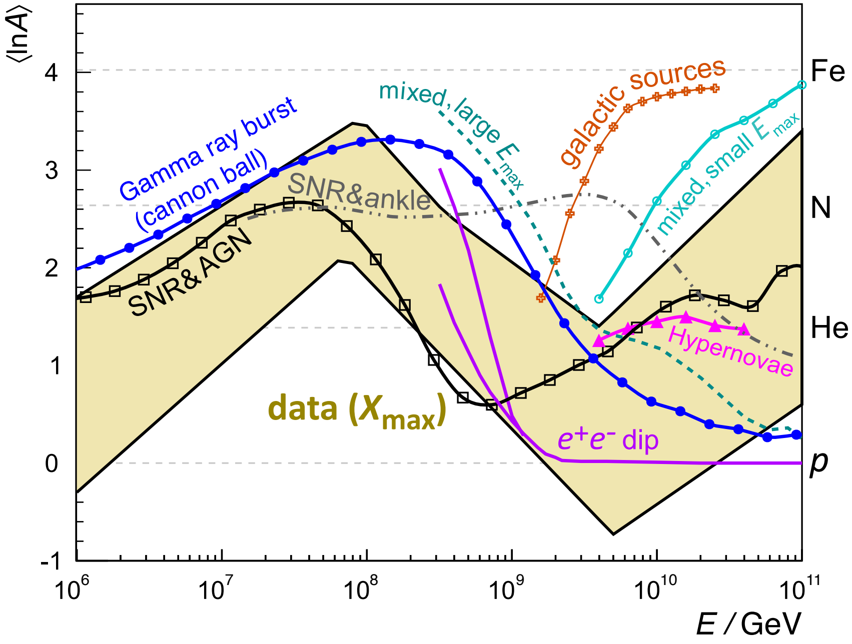


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation

Cosmic ray mass composition

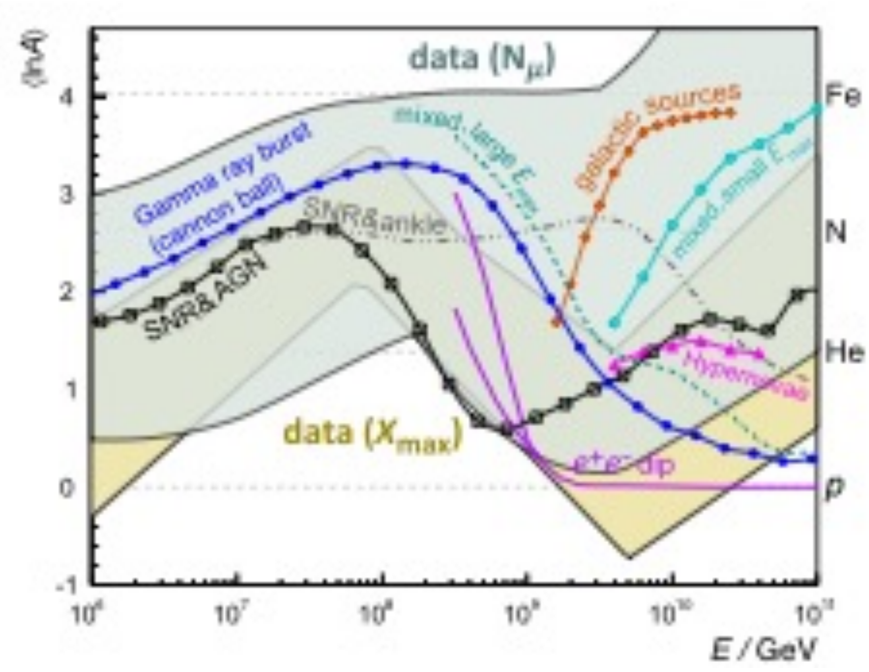


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
- Uncertainties of <lnA> limited by uncertainty in description of hadronic interactions

Cosmic ray mass composition

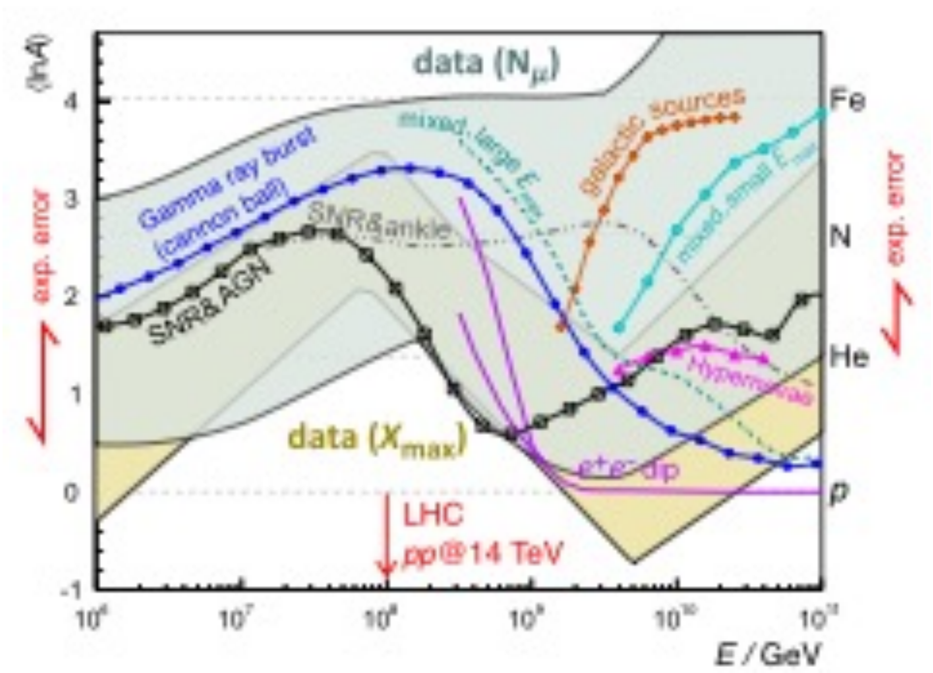


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
- Uncertainties of <lnA> limited by uncertainty in description of hadronic interactions
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with X_{max}

Cosmic ray mass composition



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
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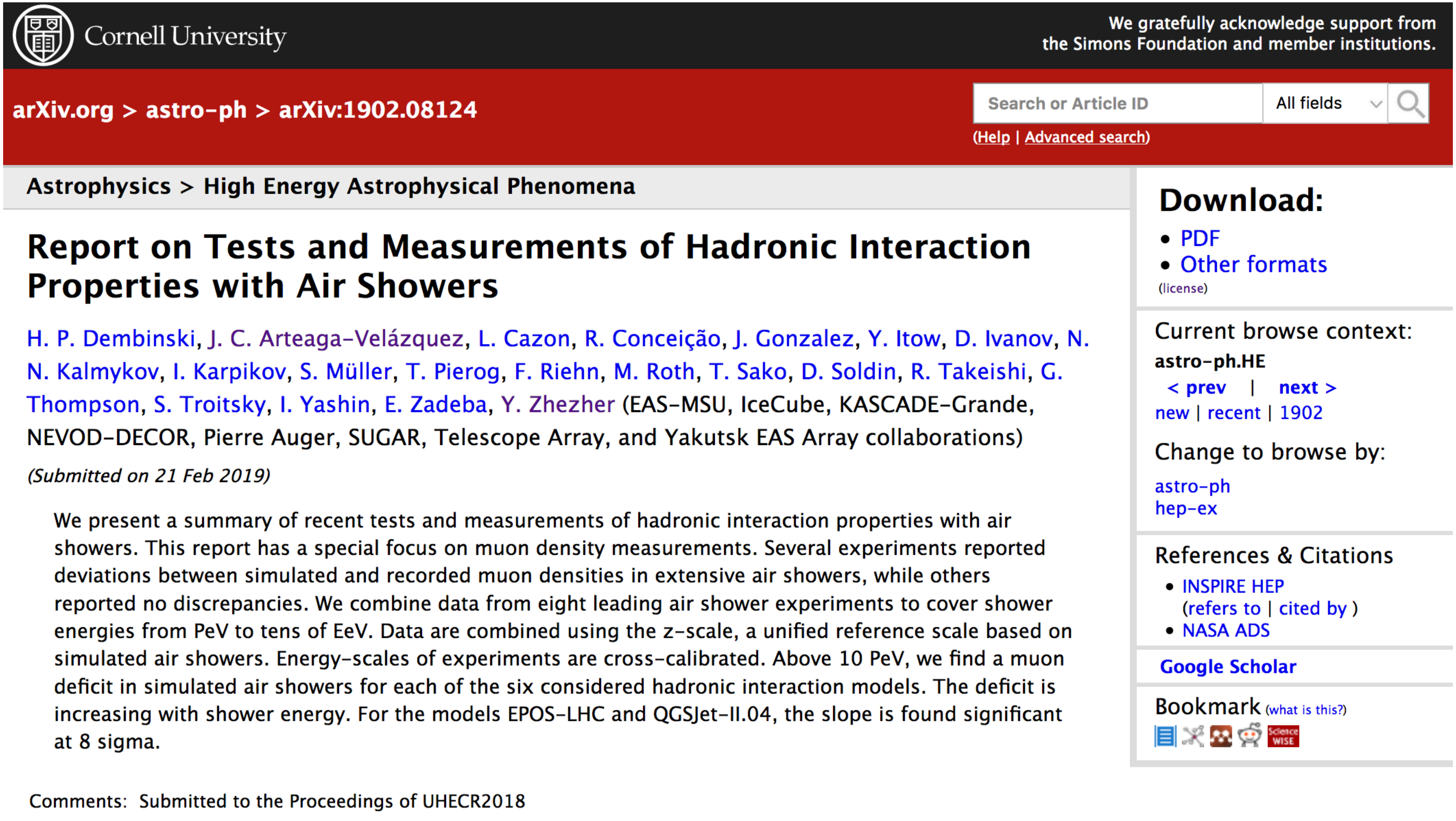
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with X_{max}

How to resolve this?

- Cosmic ray community probes air showers and finds **model inconsistencies**
- Air shower experts connect inconsistencies to **hadronic interaction properties**
- Collider community provides **dedicated reference measurements**

UHECR 2018 Report on Muons



Astrophysics > High Energy Astrophysical Phenomena

Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers

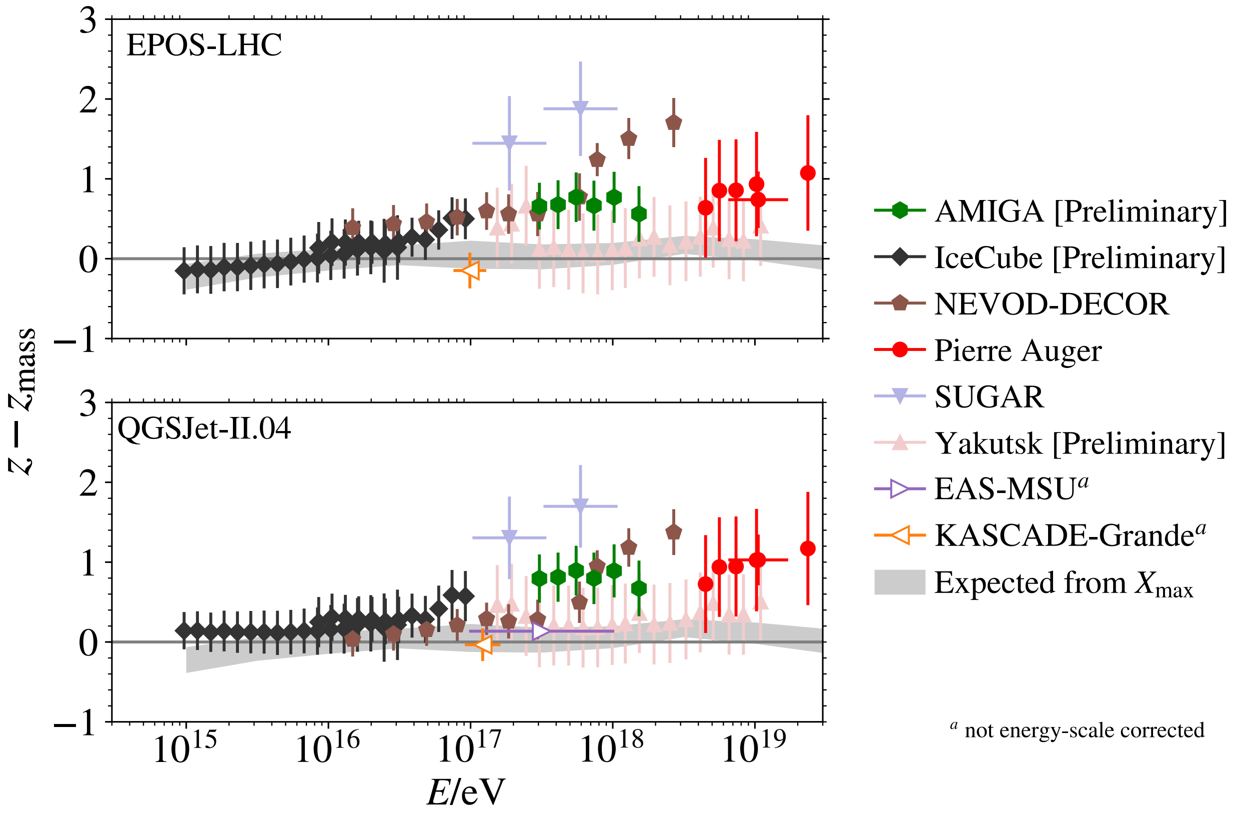
H. P. Dembinski, J. C. Arteaga-Velázquez, L. Cazon, R. Conceição, J. Gonzalez, Y. Itow, D. Ivanov, N. N. Kalmykov, I. Karpikov, S. Müller, T. Pierog, F. Riehn, M. Roth, T. Sako, D. Soldin, R. Takeishi, G. Thompson, S. Troitsky, I. Yashin, E. Zadeba, Y. Zhezher (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array collaborations)

(Submitted on 21 Feb 2019)

We present a summary of recent tests and measurements of hadronic interaction properties with air showers. This report has a special focus on muon density measurements. Several experiments reported deviations between simulated and recorded muon densities in extensive air showers, while others reported no discrepancies. We combine data from eight leading air shower experiments to cover shower energies from PeV to tens of EeV. Data are combined using the z-scale, a unified reference scale based on simulated air showers. Energy-scales of experiments are cross-calibrated. Above 10 PeV, we find a muon deficit in simulated air showers for each of the six considered hadronic interaction models. The deficit is increasing with shower energy. For the models EPOS-LHC and QGSJet-II.04, the slope is found significant at 8 sigma.

Comments: Submitted to the Proceedings of UHECR2018

Energy-dependent discrepancy



- Solved challenges
  - Converted very different muon measurements to universal **z-scale**
  - Cross-calibrated energy scales of experiments by matching all-particle fluxes
- Muon number **rises faster with energy** than any model predicts
  - Non-zero positive slope at **8σ** significance

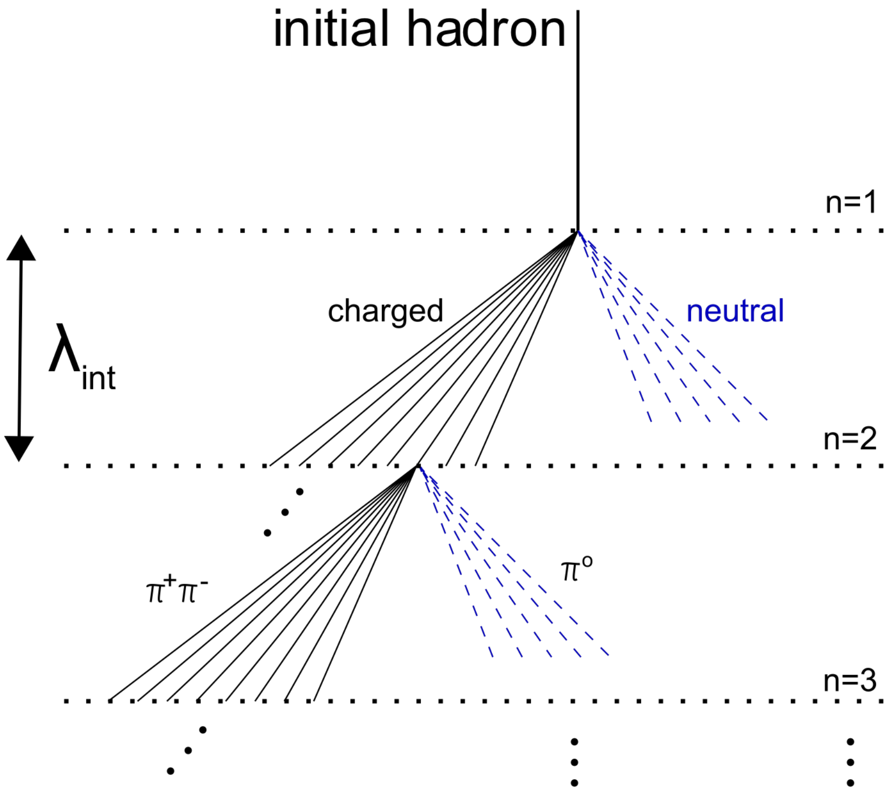
Part 2: How to solve the Muon Puzzle?

Air shower cascade

10 GeV proton in cloud chamber with lead absorbers at 3027 m altitude

K.-H. Kampert and A.A. Watson, Eur.Phys.J. H37 (2012) 359-412

Heitler-Matthews model of air shower



Cascade stops after O(10) steps (energy-dependent)
Pions decay into GeV **muons** at the end of cascade

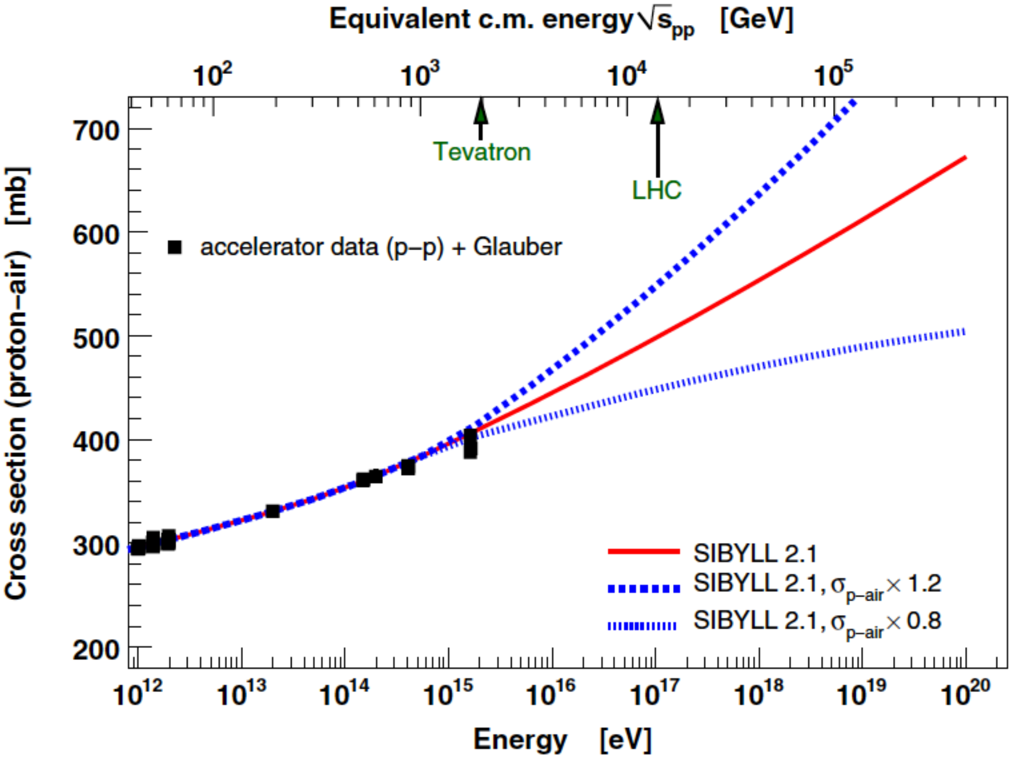
Modify hadronic interaction features

R. Ulrich et al PRD 83 (2011) 054026

Ad-hoc modify features at LHC energy scale with factor $\boldsymbol{f_{LHC\text{-}pO}}$
and extrapolate up to 10^{19} *eV proton shower*

Modified features

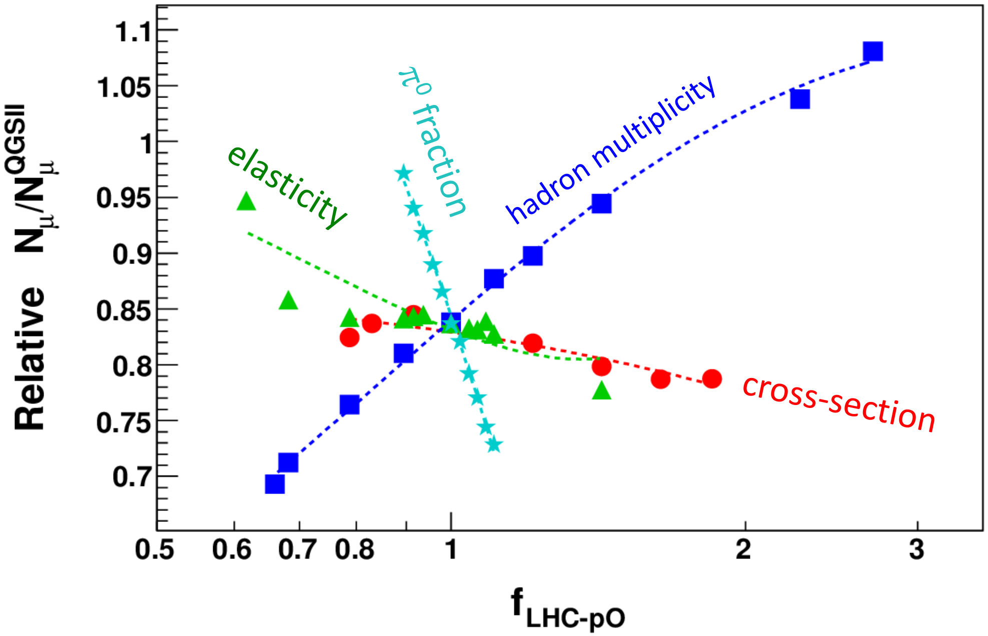
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- $\boldsymbol{\pi^0}$ **fraction**: (no. of π^0) / (all pions)

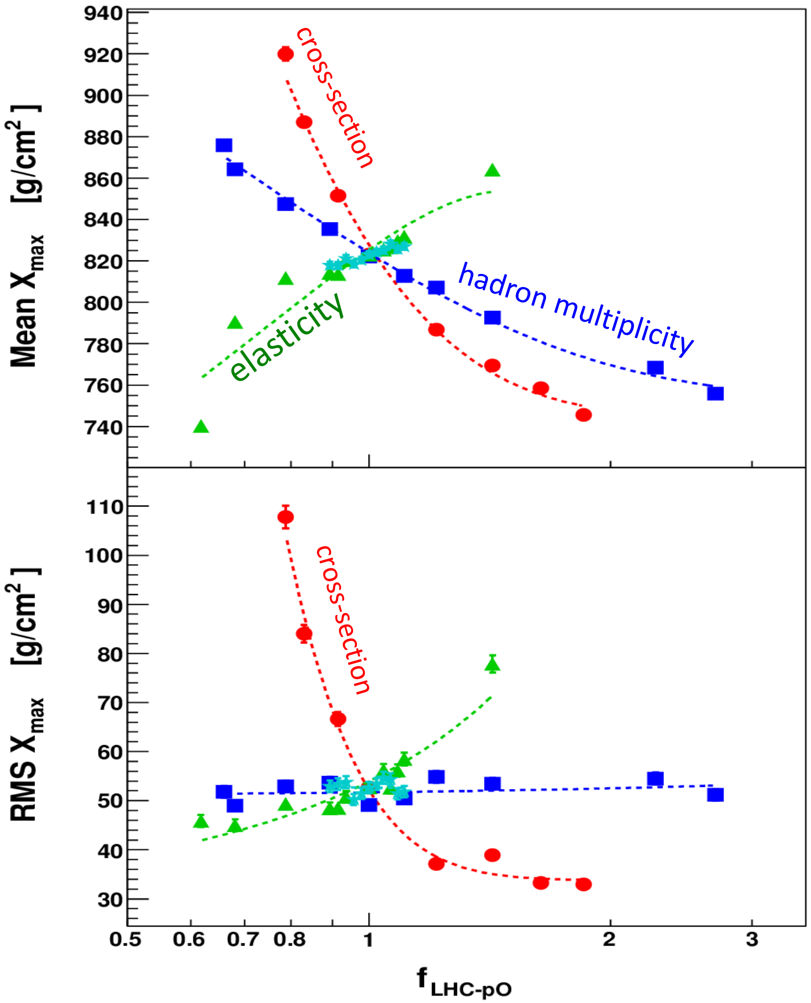


Importance of interaction features

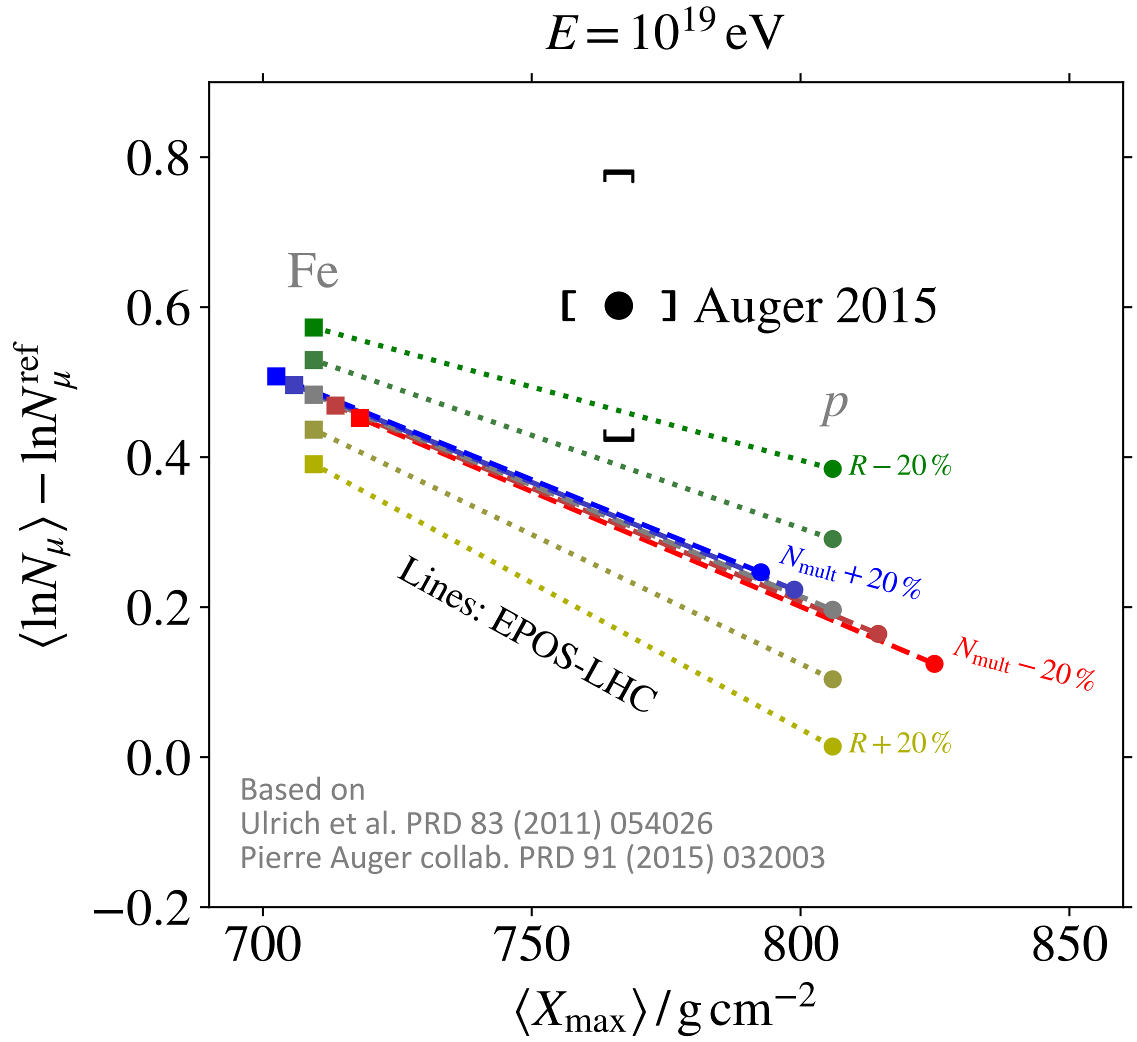
Large impact on muon number

- Neutral pion fraction
- Hadron multiplicity





Projected impact of changes



Based on
Ulrich et al. PRD 83 (2011) 054026
Pierre Auger collab. PRD 91 (2015) 032003

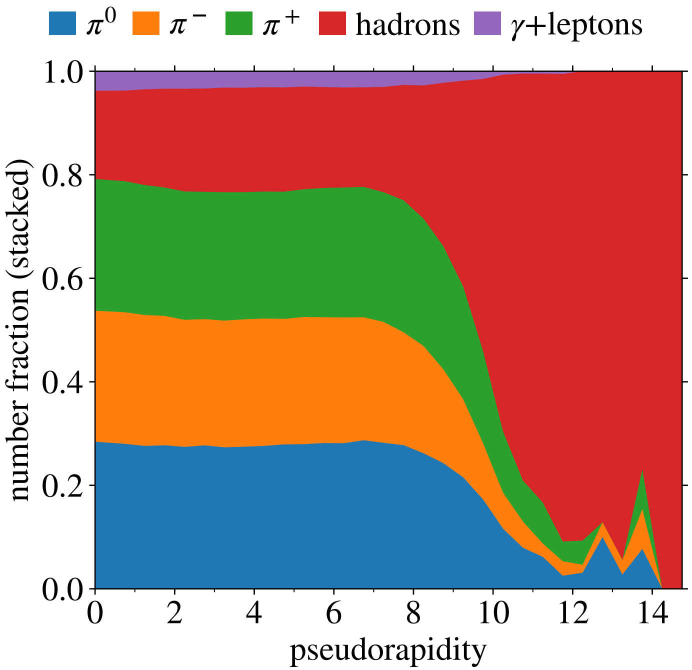
- Changing hadron multiplicity does not solve muon puzzle
- Need to change energy fraction R of neutral pions

$$R = \frac{\sum E_{\pi^0}}{\sum E_\text{long-lived hadron}}$$

Possibilities to reduce *R*

- Nuclear effects are very important for air shower phenomology
  D'Enterria, T. Pierog, G. Sun, Astrophys.J. 874 (2019) 152
- Are collective nuclear effects in π-N or π-O collisions reducing R?

pp 13 TeV ,EPOS-LHC



Collective effects may reduce pion fraction, EPOS-LHC predicts drop in *R* at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

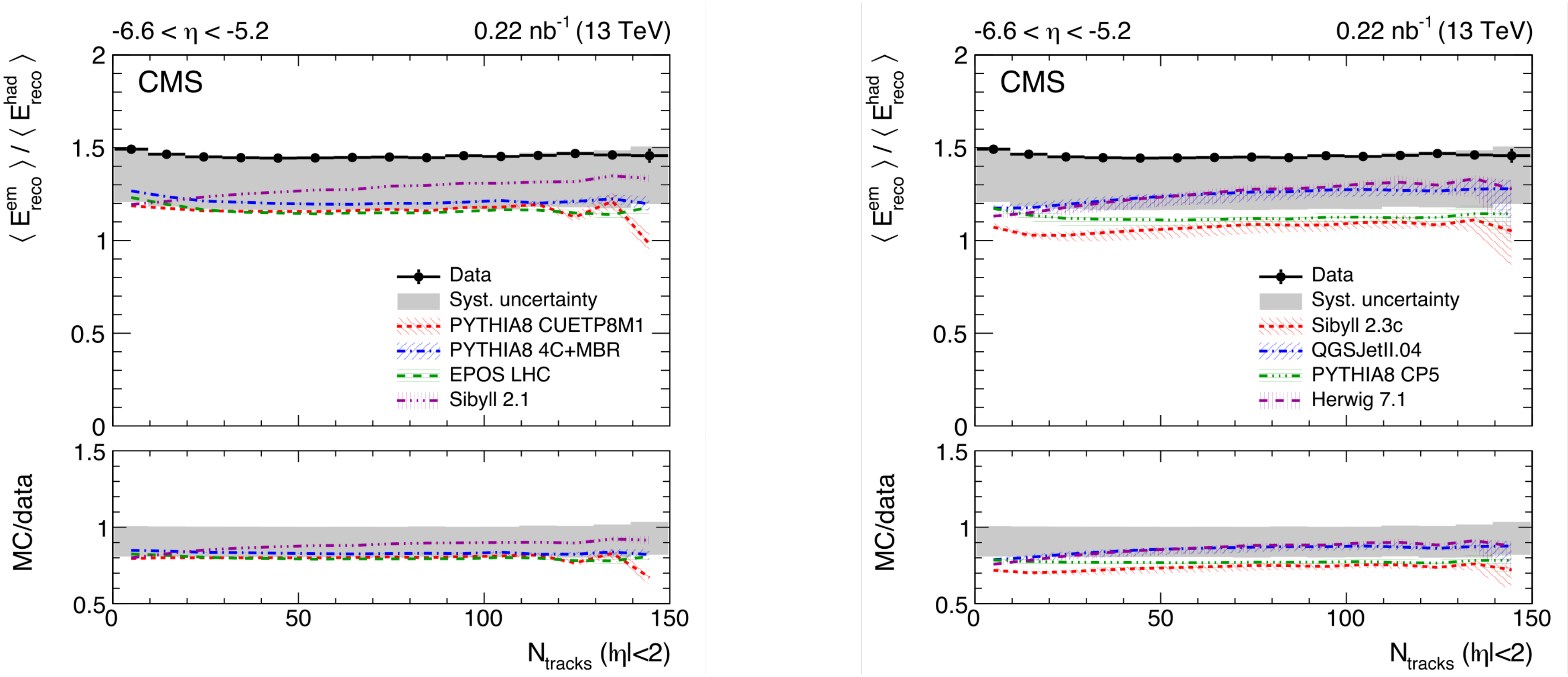
QGP in air showers could enhance strangeness production, reducing pion fraction
https://arxiv.org/pdf/1612.07328.pdf

Unexpected enhancement of strangeness observed in central collisions in *pp*, *p*+Pb
ALICE, Nature Phys. 13 (2017) 535

...or is R already too low?

pp @ 13 TeV

CMS collab., Eur.Phys.J. C79 (2019) no.11, 893



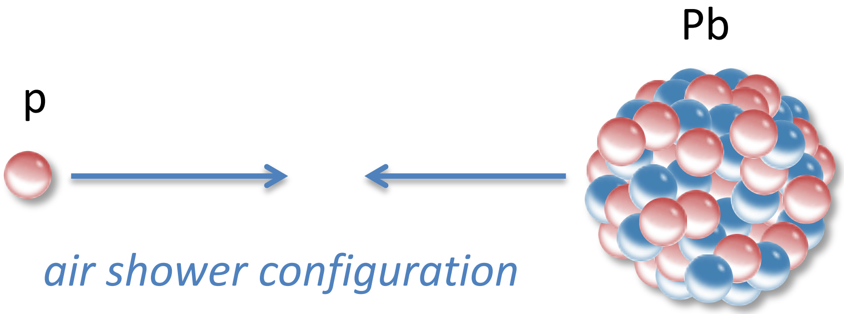
- CMS measurements give higher R than models for 5.2 < |eta| < 6.6
- Models should have higher *R* and then would yield even fewer muons!
- But this is in *pp*, what about ***p*-O**?

Nuclear effects

Nuclear modification factor

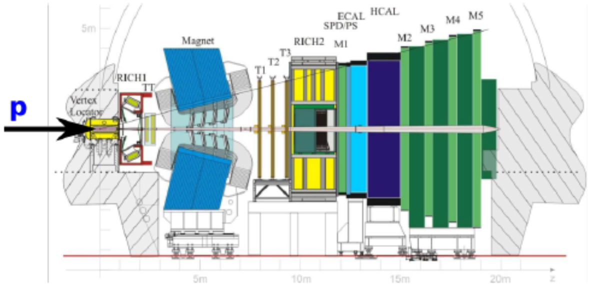
$$R_{pA} = \frac{\text{cross-section for pPb}}{\text{A x cross-section for pp}}$$

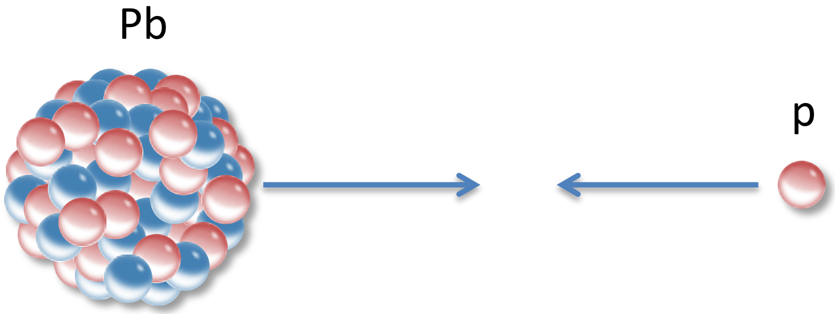
Superposition model: $R_{pA} = 1$



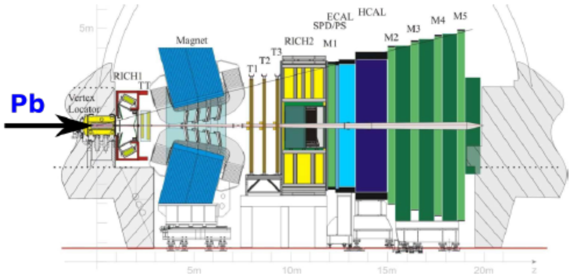
air shower configuration

“forward”



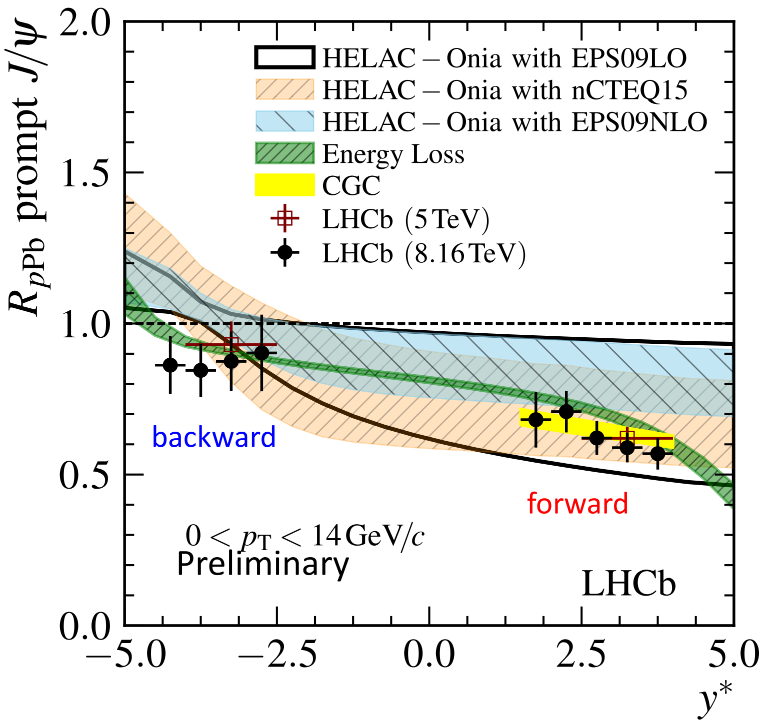


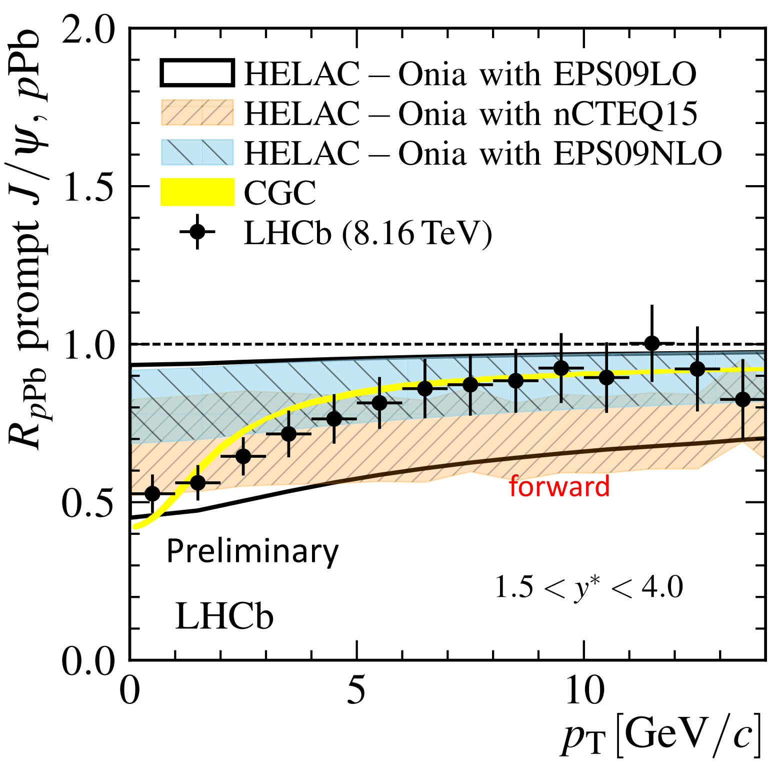
“backward”



Nuclear effects in prompt J/ψ production

LHCb collab., Phys. Lett. B 774 (2017) 159

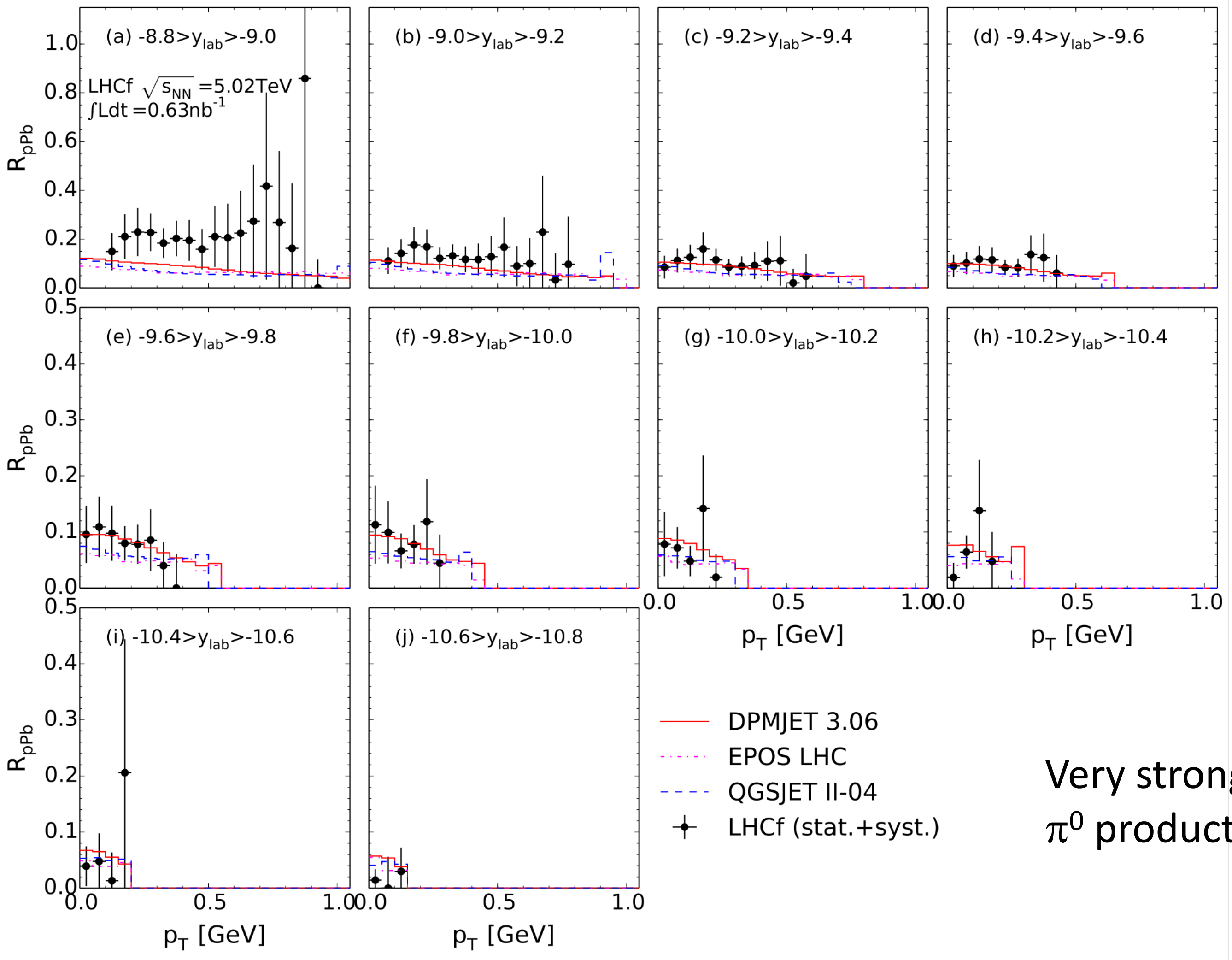




- Up to 50 % suppression in forward direction
- Especially strong where relevant for CR!

Nuclear effects in π^0 production

LHCf collab., Eur. Phys. J. C (2013) 73:2421

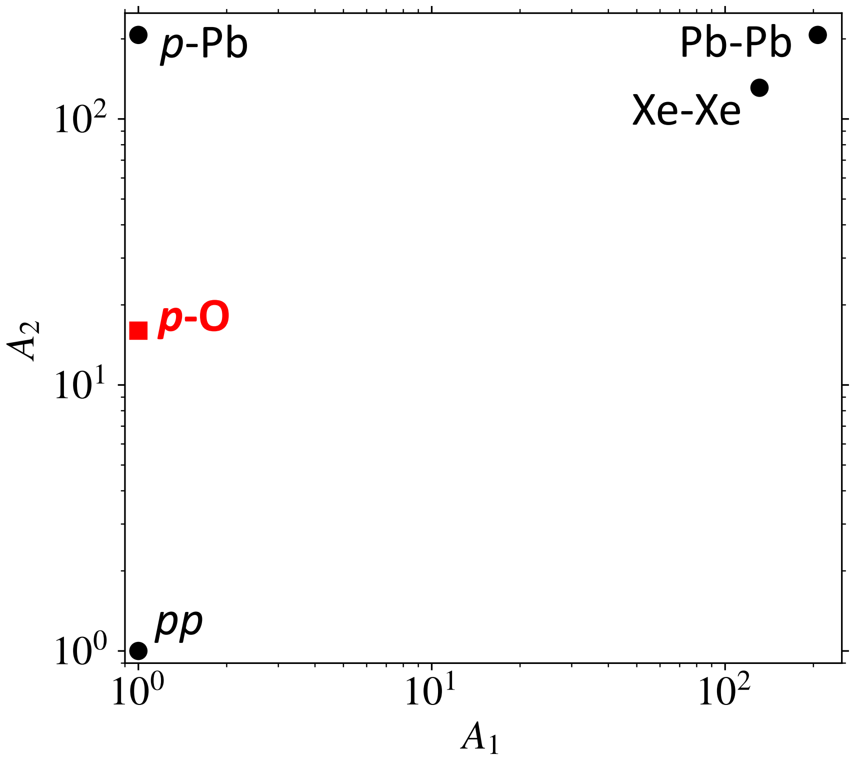


Very strong nuclear effects for π^0 production in far forward

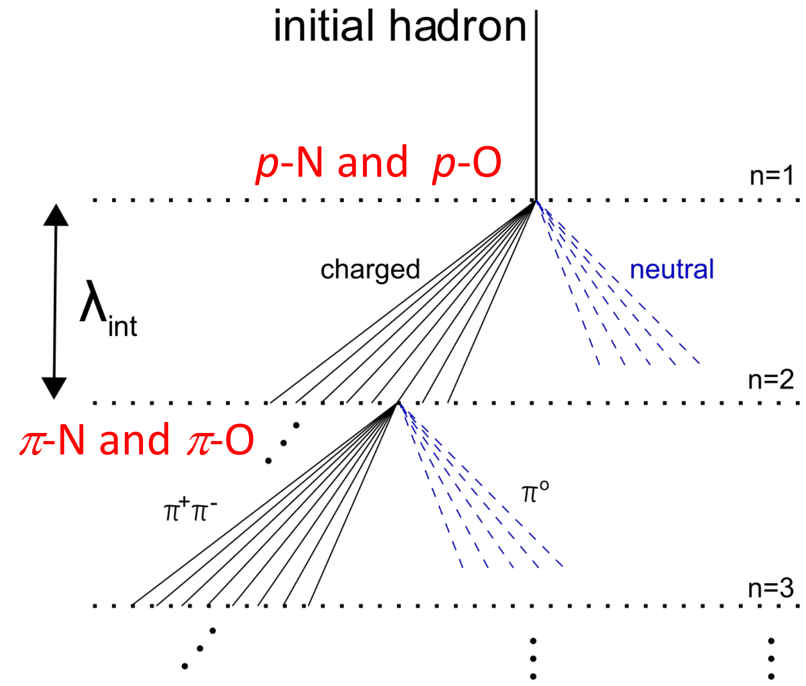
Part 3: proton-oxygen at the LHC

Proton-oxygen collisions at the LHC

Collision systems at the LHC

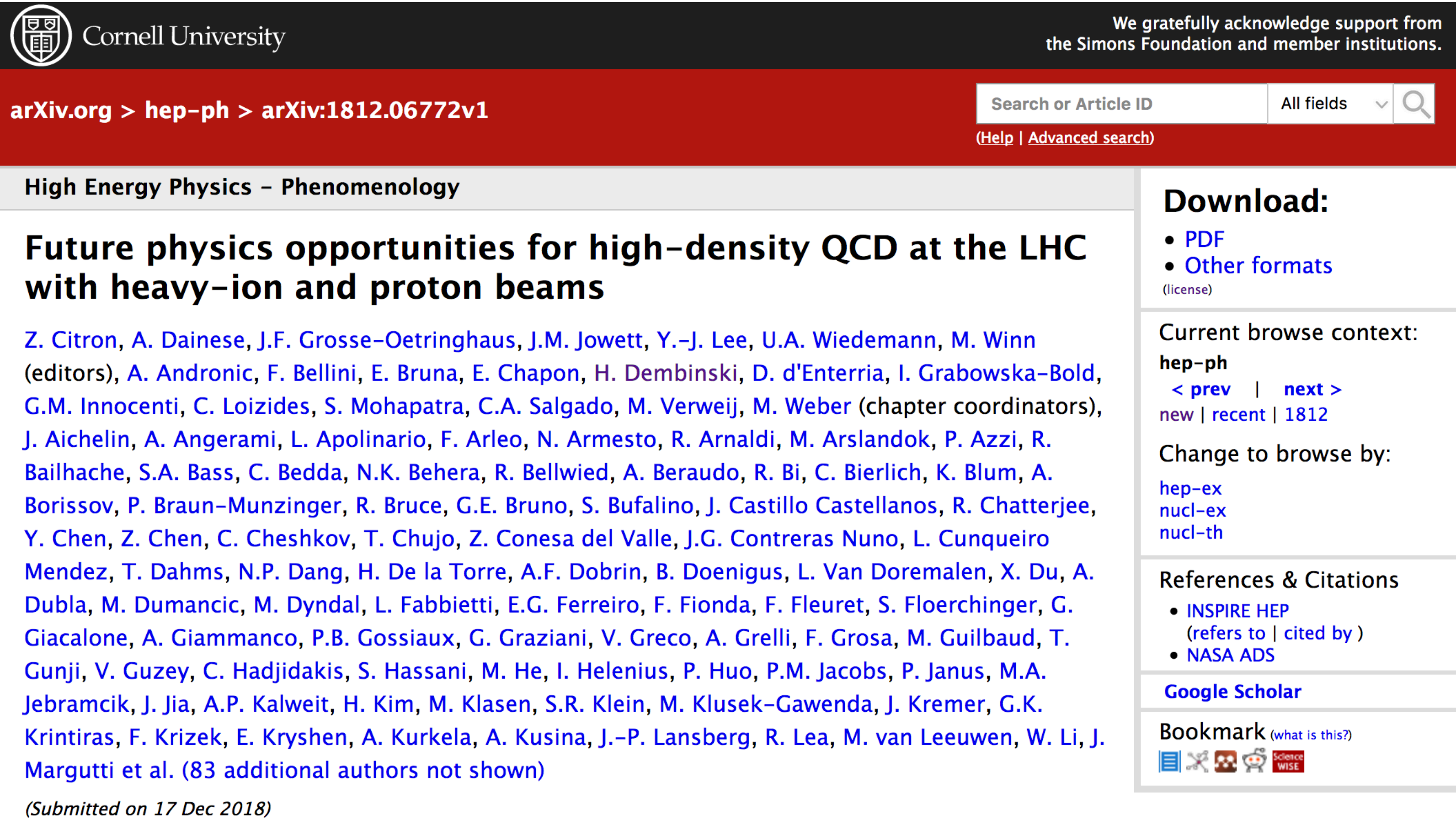


Air shower collision systems



- Only proton-oxygen collisions mimic interactions in air showers
- Need *pp*, *p*-Pb, and ***p*-O** to understand nuclear effects

Proton-oxygen collisions at the LHC



arXiv.org > hep-ph > arXiv:1812.06772v1

High Energy Physics – Phenomenology

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Z. Citron, A. Dainese, J.F. Grosse-Oetringhaus, J.M. Jowett, Y.-J. Lee, U.A. Wiedemann, M. Winn (editors), A. Andronic, F. Bellini, E. Bruna, E. Chapon, H. Dembinski, D. d'Enterria, I. Grabowska-Bold, G.M. Innocenti, C. Loizides, S. Mohapatra, C.A. Salgado, M. Verweij, M. Weber (chapter coordinators), J. Aichelin, A. Angerami, L. Apolinario, F. Arleo, N. Armesto, R. Arnaldi, M. Arslandok, P. Azzi, R. Bailhache, S.A. Bass, C. Bedda, N.K. Behera, R. Bellwied, A. Beraudo, R. Bi, C. Bierlich, K. Blum, A. Borissov, P. Braun-Munzinger, R. Bruce, G.E. Bruno, S. Bufalino, J. Castillo Castellanos, R. Chatterjee, Y. Chen, Z. Chen, C. Cheshkov, T. Chujo, Z. Conesa del Valle, J.G. Contreras Nuno, L. Cunqueiro Mendez, T. Dahms, N.P. Dang, H. De la Torre, A.F. Dobrin, B. Doenigus, L. Van Doremalen, X. Du, A. Dubla, M. Dumancic, M. Dyndal, L. Fabbietti, E.G. Ferreiro, F. Fionda, F. Fleuret, S. Floerchinger, G. Giacalone, A. Giammanco, P.B. Gossiaux, G. Graziani, V. Greco, A. Grelli, F. Grosa, M. Guilbaud, T. Gunji, V. Guzey, C. Hadjidakis, S. Hassani, M. He, I. Helenius, P. Huo, P.M. Jacobs, P. Janus, M.A. Jebramcik, J. Jia, A.P. Kalweit, H. Kim, M. Klasen, S.R. Klein, M. Klusek-Gawenda, J. Kremer, G.K. Krintiras, F. Krizek, E. Kryshen, A. Kurkela, A. Kusina, J.-P. Lansberg, R. Lea, M. van Leeuwen, W. Li, J. Margutti et al. (83 additional authors not shown)

(Submitted on 17 Dec 2018)

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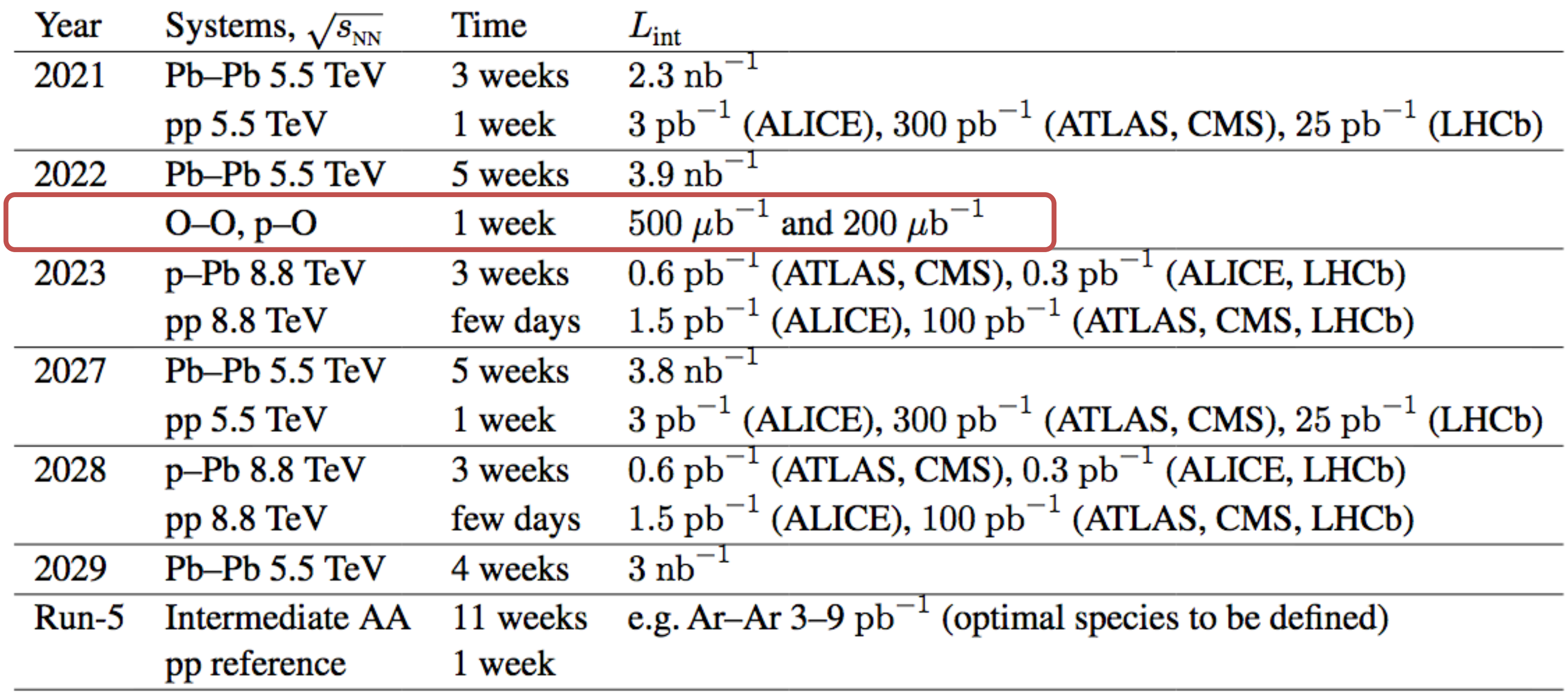
Proposed schedule for Run 3

Z. Citron et al., CERN-LPCC-2018-07



Year	Systems, $\sqrt{s_{\text{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

- 200 μb^{-1} is enough statistics to push statistical error below 5 % in LHCb
- 2 nb^{-1} (10 x minimum) will be requested, also allows to measure charm
- Latest plans moved oxygen-week to **2023**

Summary

- Muon Puzzle in air showers experimentally established
  - Statement by eight leading air shower experiments (8σ)

- Problem not in the data, theory has to change
  - None of the hadronic interaction models reproduces muon data (neither pre- nor post-LHC)
  - Suggests common missing QCD effect, perhaps QGP-related?

- *p*-O and O-O collisions planned for 2023
  - Probably 2 nb^{-1} of *p*-O
  - Data should be analyzed by ALICE, ATLAS, CMS, **LHCb** and **LHCf**

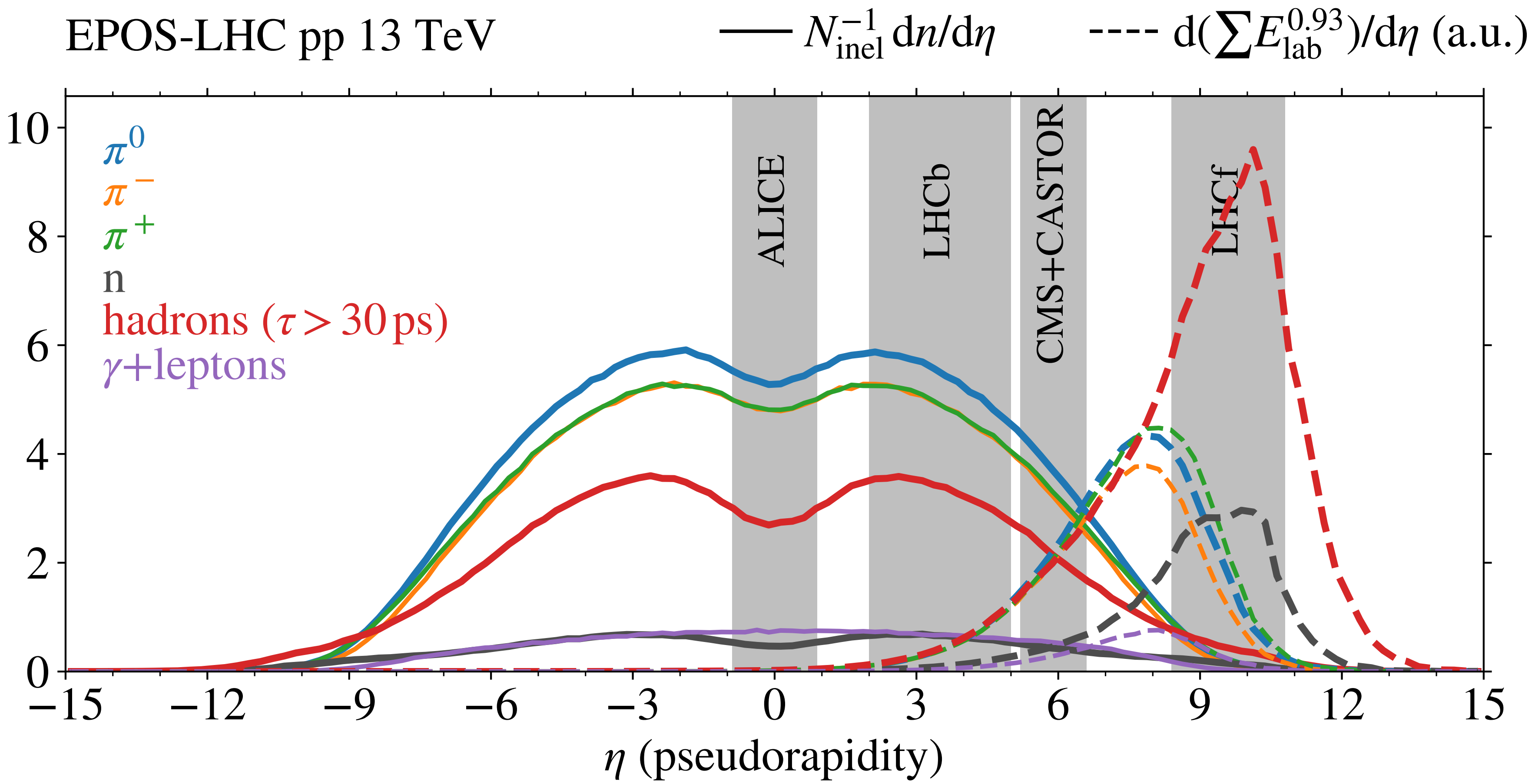
- Key forward measurements to be done at the LHC
  - In *pp*, *p*-Pb, and *p*-O
    - Energy ratio R of π^0 to long-lived hadrons at forward rapidity
    - Production cross-sections for π^0, $\pi^{+/-}$, K, p
  - Precise measurements needed to 5 % or better

Backup

Forward production and nuclear effect

Simulation with CRMC

„Muon weight“

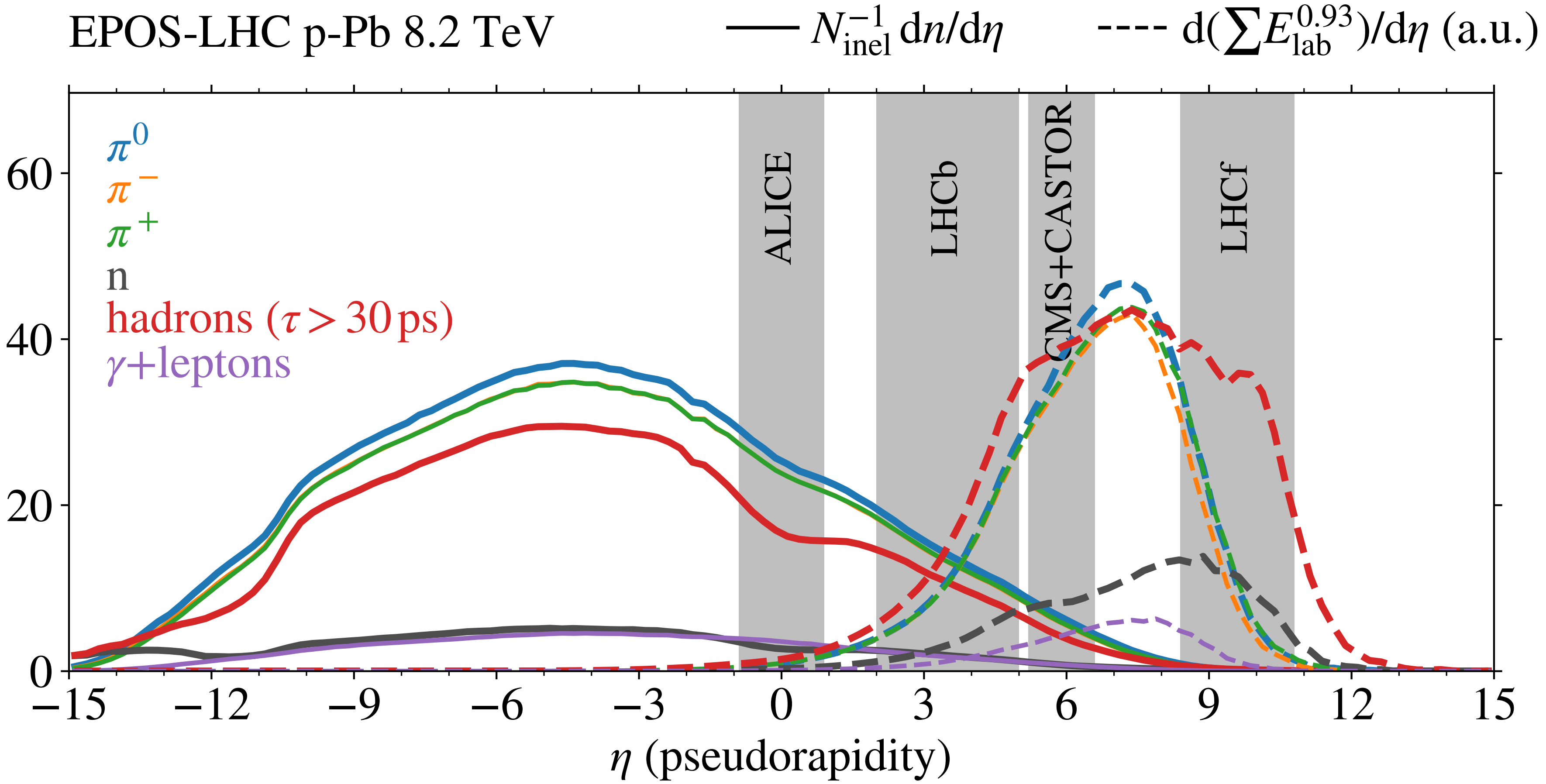


Forward production very important for air showers, LHCb very important because of PID

Forward production and nuclear effect

Simulation with CRMC

„Muon weight“



Forward production very important for air showers, LHCb very important because of PID