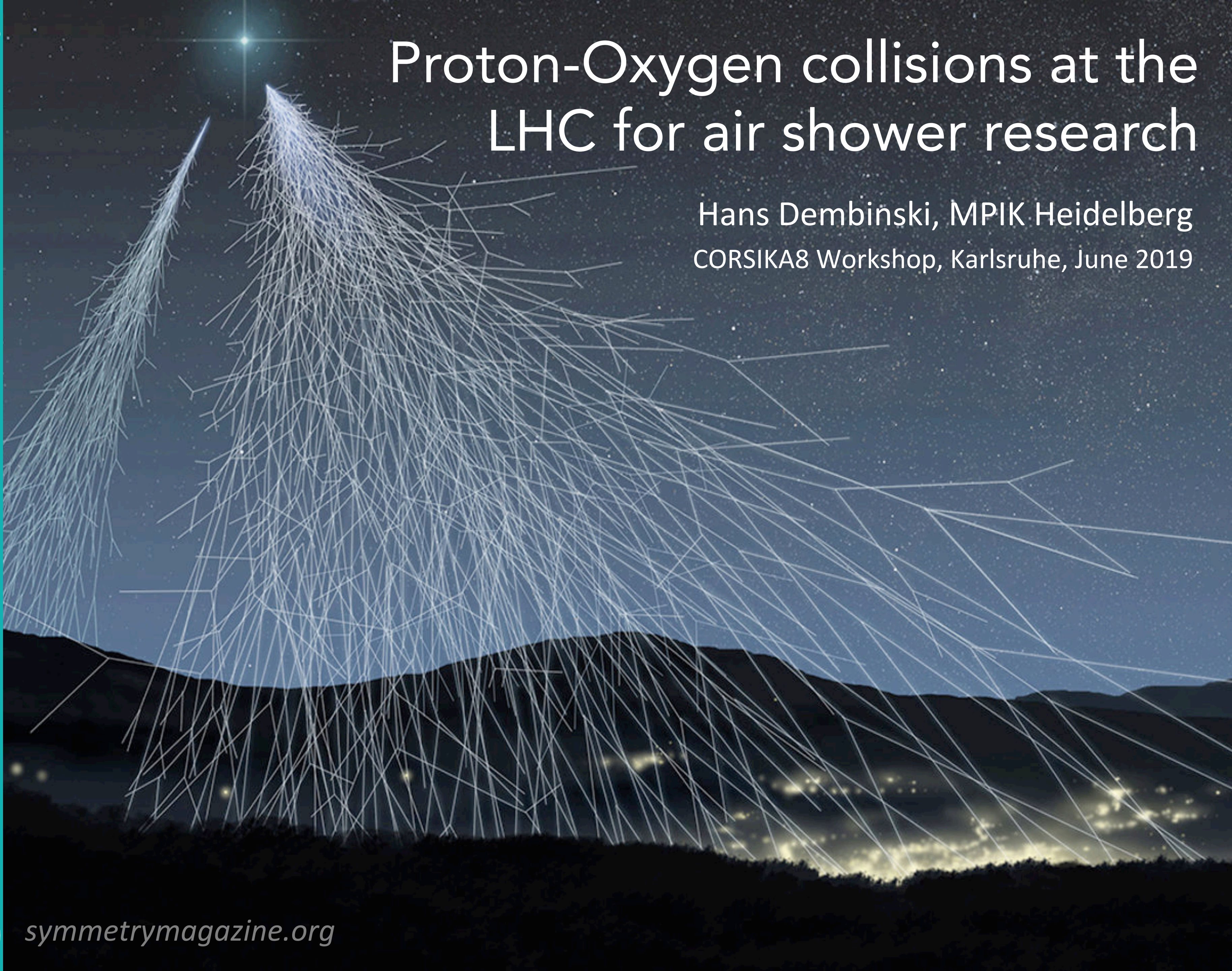
Proton-Oxygen collisions at the LHC for air shower research

Hans Dembinski, MPIK Heidelberg

CORSIKA8 Workshop, Karlsruhe, June 2019



symmetrymagazine.org

Max-Planck-Institut für Kernphysik

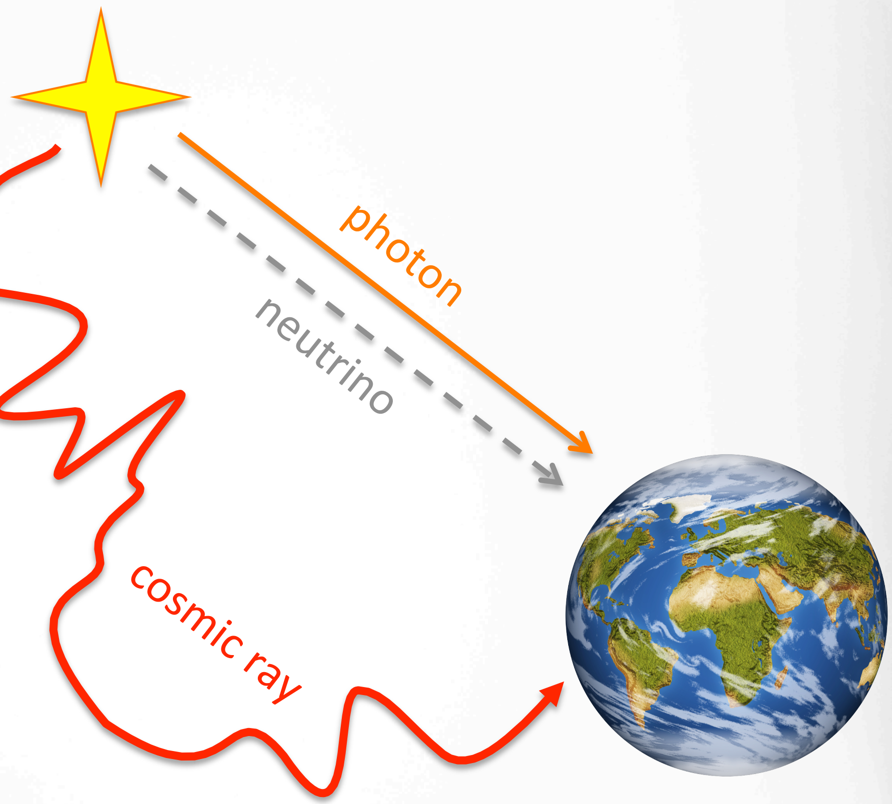
Take-home message

- High-energy cosmic rays initiate air showers
  - Cosmic rays isotropic, do not point back to sources, but...
  - Cosmic-ray **mass composition** tells us about sources
  - Requires **accurate simulation** of air showers
  - Background for IceCube and future neutrino observatories
  - QCD at 100 TeV scale

- **Muon Puzzle**
  - **8σ Data/MC mismatch** in muon density after combining data from **eight leading experiments** from **0.5 PeV to 10 EeV**
  - Potential solution from the LHC
    - Smoking gun: Energy carried by neutral pions too high?
    - **proton+oxygen** collisions to clarify **nuclear effects**, planned for 202(3)

- Bonus issue: Muon lateral density profile in 100 GeV showers
  - Cosmic rays background for γ-ray observatories
  - Energies < 1 TeV well covered by fixed target experiments
  - Still large discrepancies between air shower predictions

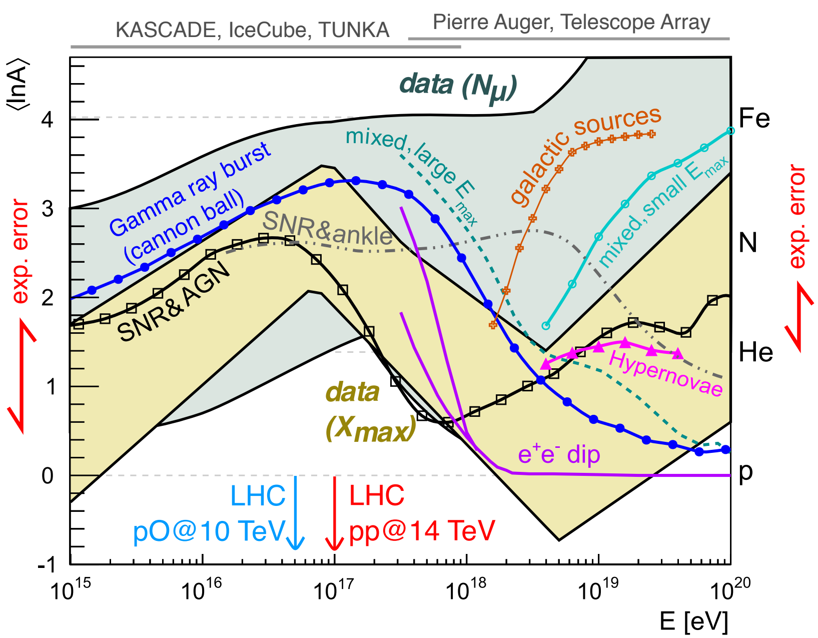
Sources of cosmic rays?



Sources of cosmic rays unresolvable, because cosmic rays scatter on random magnetic fields (like photons on a foggy day)

Photo by Stephen Crowley on Unsplash

Cosmic ray mass



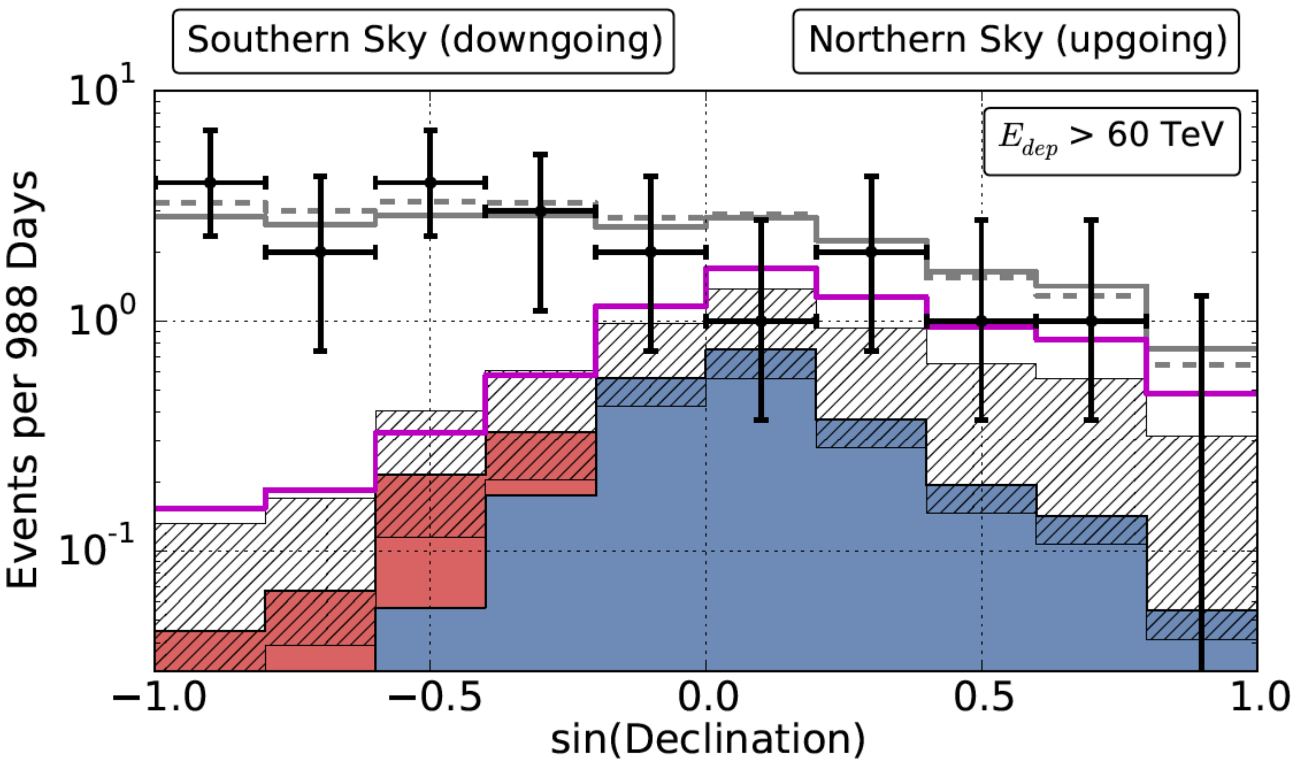
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

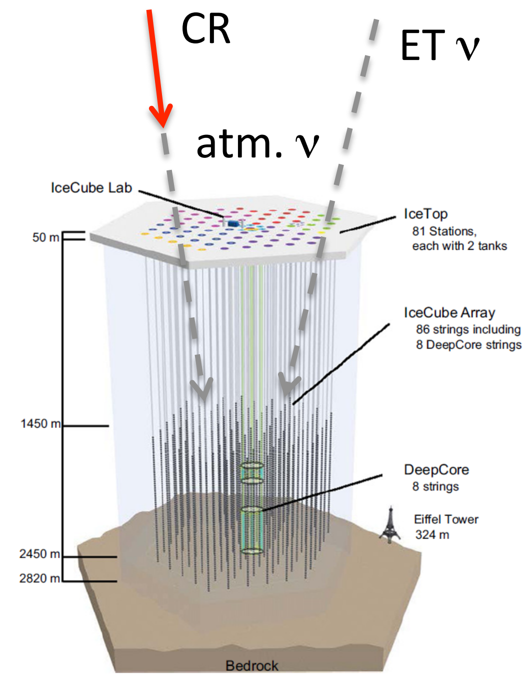
Astrophysical origins of cosmic rays?

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

Background for PeV neutrinos

IceCube collab. Phys.Rev.Lett. 113 (2014) 101101





- Contrary to original design of IceCube, most extra-terrestrial neutrinos come from above
- **50 %** uncertainty in the background: about **30 %** from uncertain CR mass composition

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)

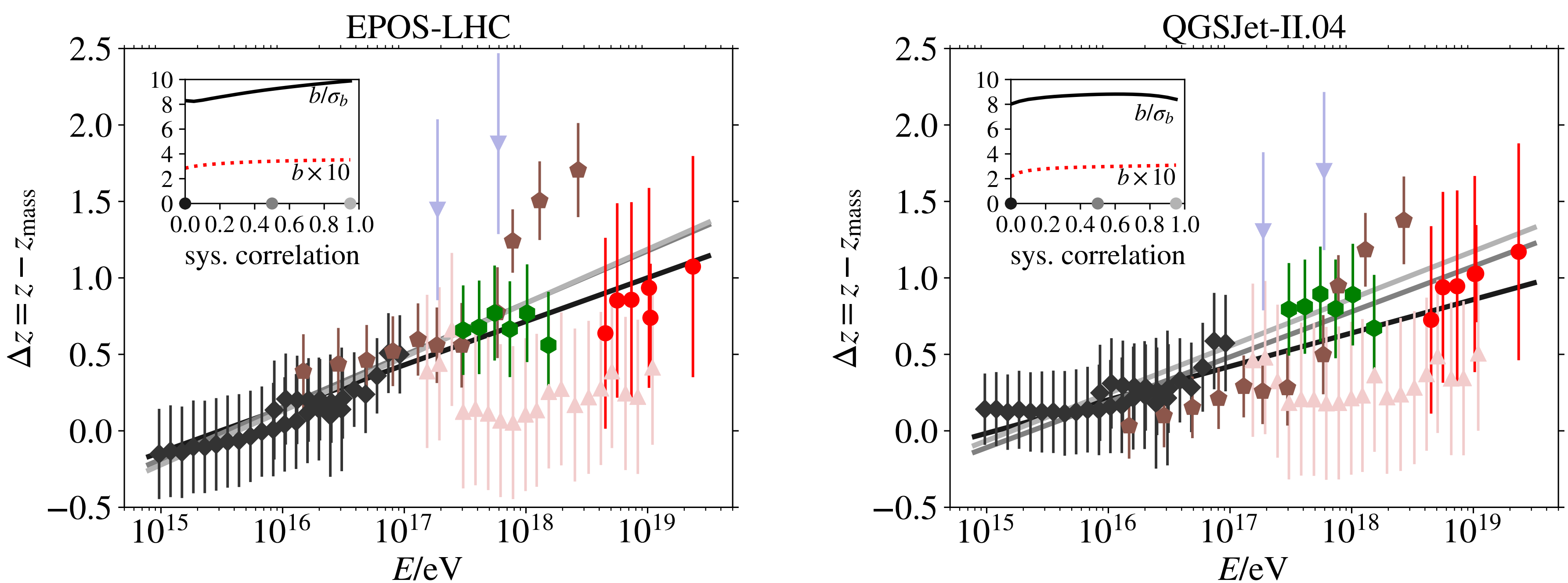
(Submitted on 21 Feb 2019)

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

Significance of Muon Deviation

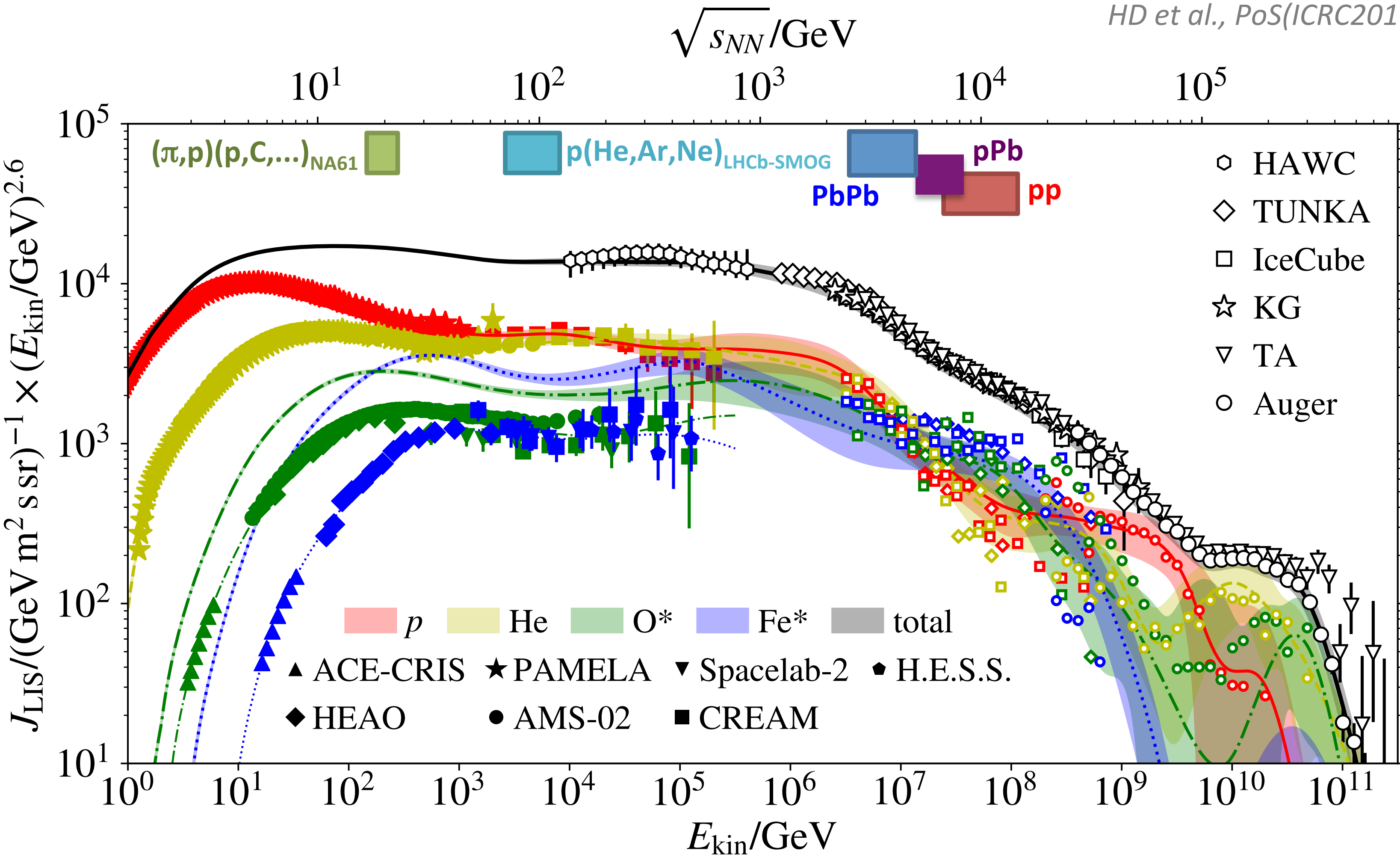
EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array collab.
EPJ Web Conf. 210 (2019) 02004



- Relative energy-scale calibration applied to raw data sets
- Line fit to most complete data for EPOS-LHC and QGSJet-II.04
- Careful treatment of reported errors
- Find deviation of slope from zero **> 8σ**

Collider energies and air showers

HD et al., PoS(ICRC2017)533

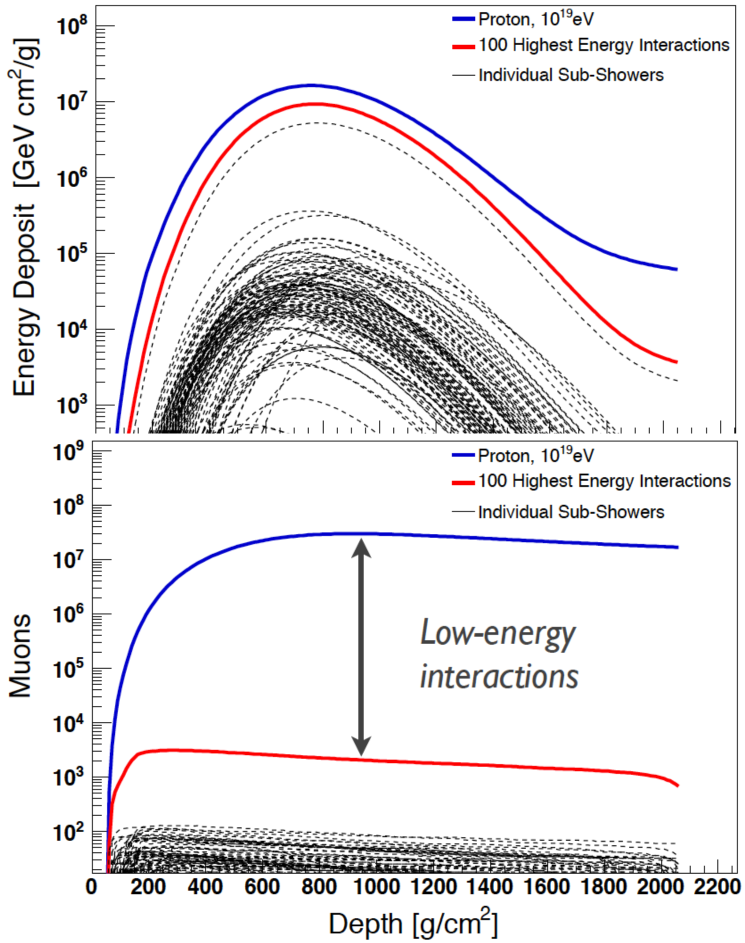


SPS (NA61) and LHC cover **three orders of magnitude** in c.m.s. energy and reach well above the knee

Air shower physics

About 5-7 hadronic interactions, average energy drops by factor 10-100 after each

Plots from R. Ulrich



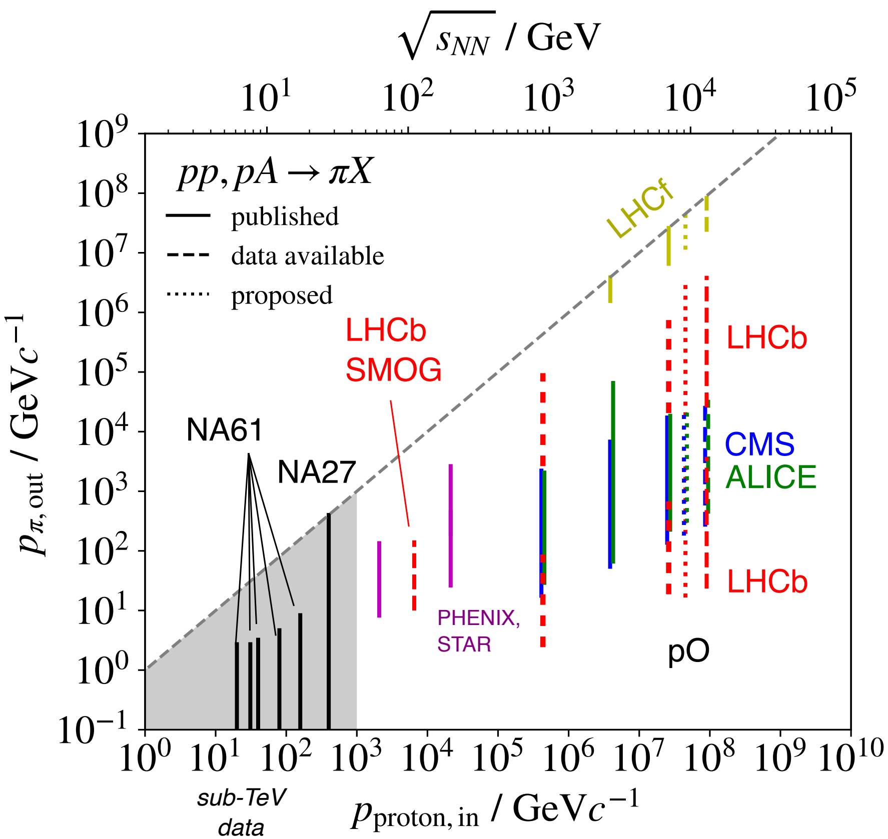
X_{max} is sensitive to high energy interactions

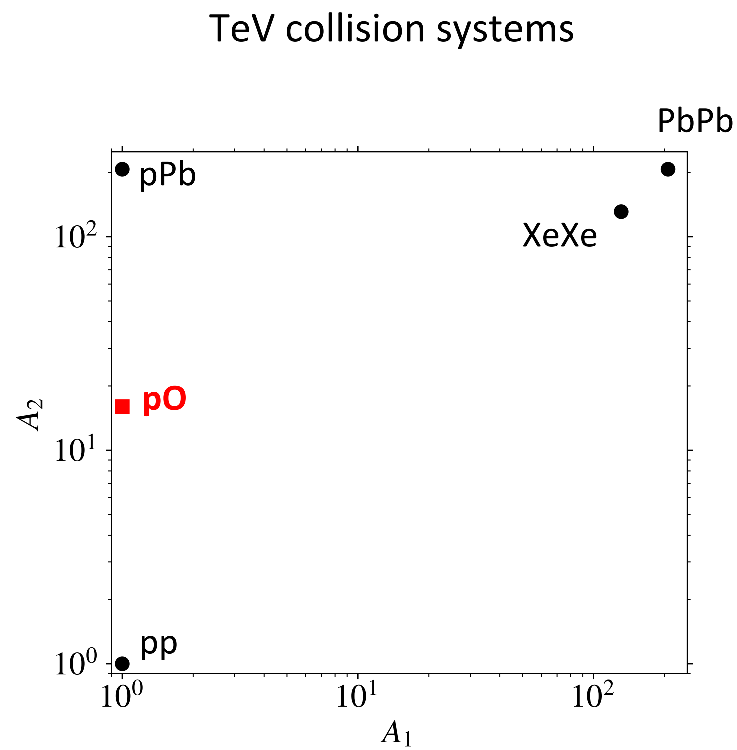
- High-energy sub-showers dominate X_{max}

N_μ is sensitive to high and low energy interactions

- N_μ depends on **energy not lost to EM component** and **energy dispersion** among secondary particles

LHC and data on pion production





- Most common interaction in air shower is **π+N**, use **p+O** as proxy
- Need more data on light hadron production in forward direction
- Do properties scale from **pp** to **pO** to **pPb** or different regimes?

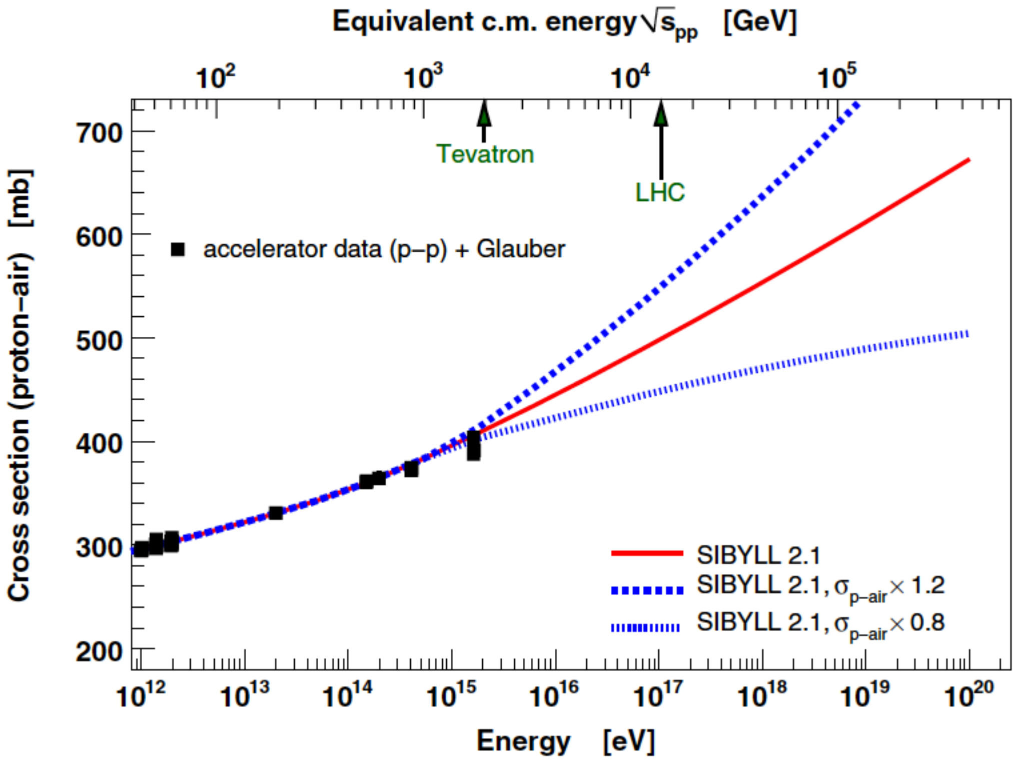
Modify hadronic interaction features

R. Ulrich et al PRD 83 (2011) 054026

Ad-hoc modify features at LHC energy scale with factor $\mathbf{f_{LHC\text{-}pO}}$
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)
- π^0 **fraction**: (no. of π^0) / (all pions)



Importance of interaction features

Modified features

- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
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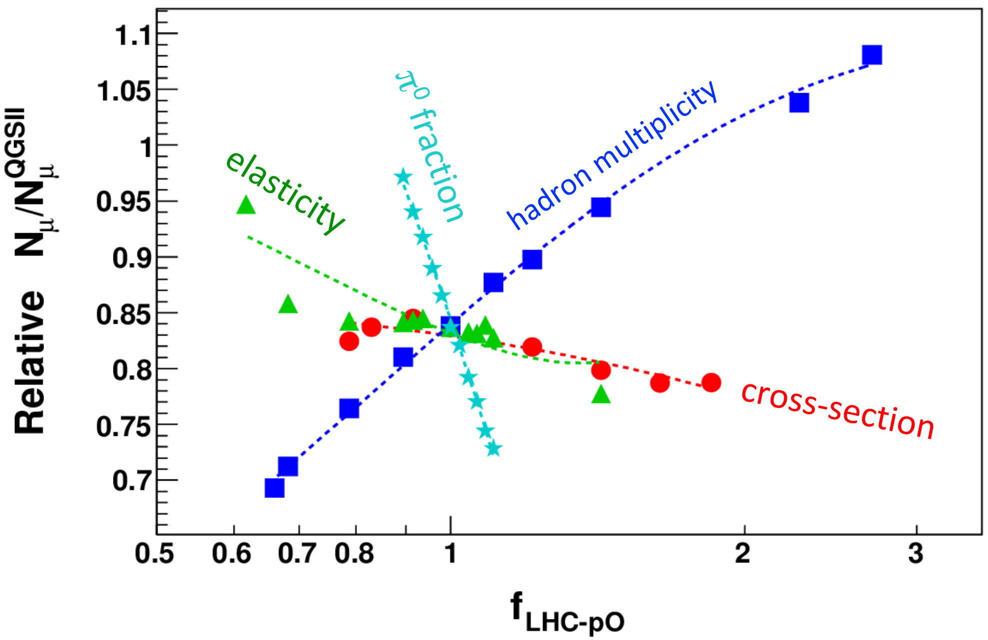
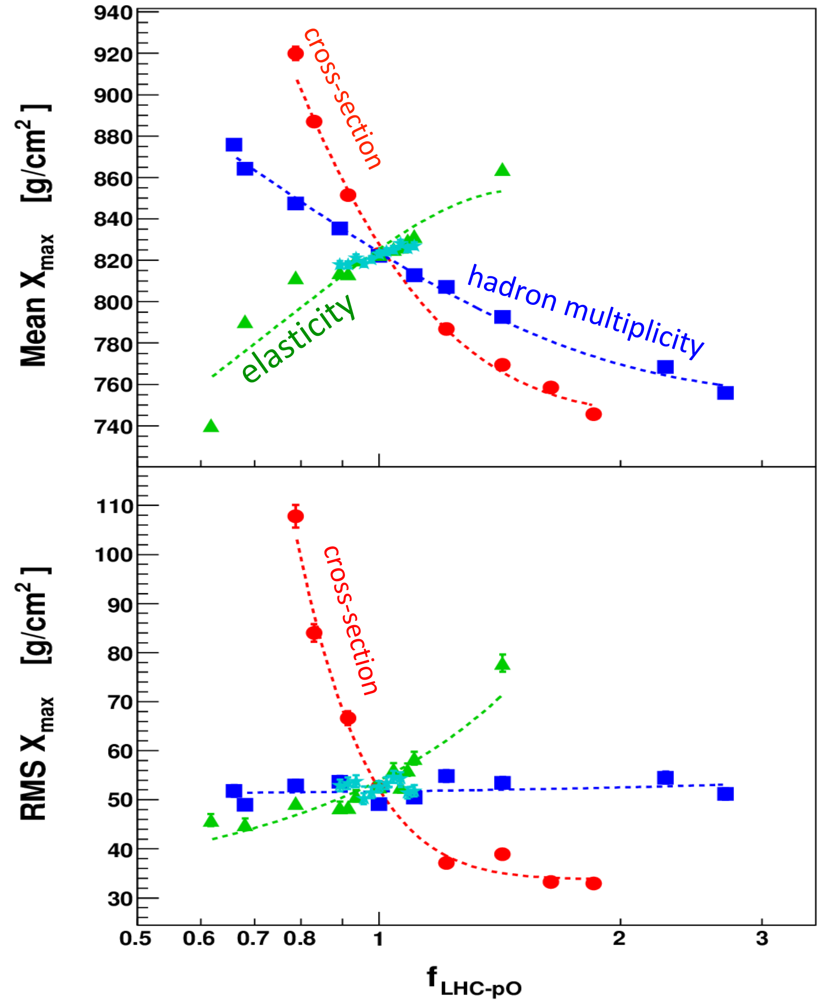
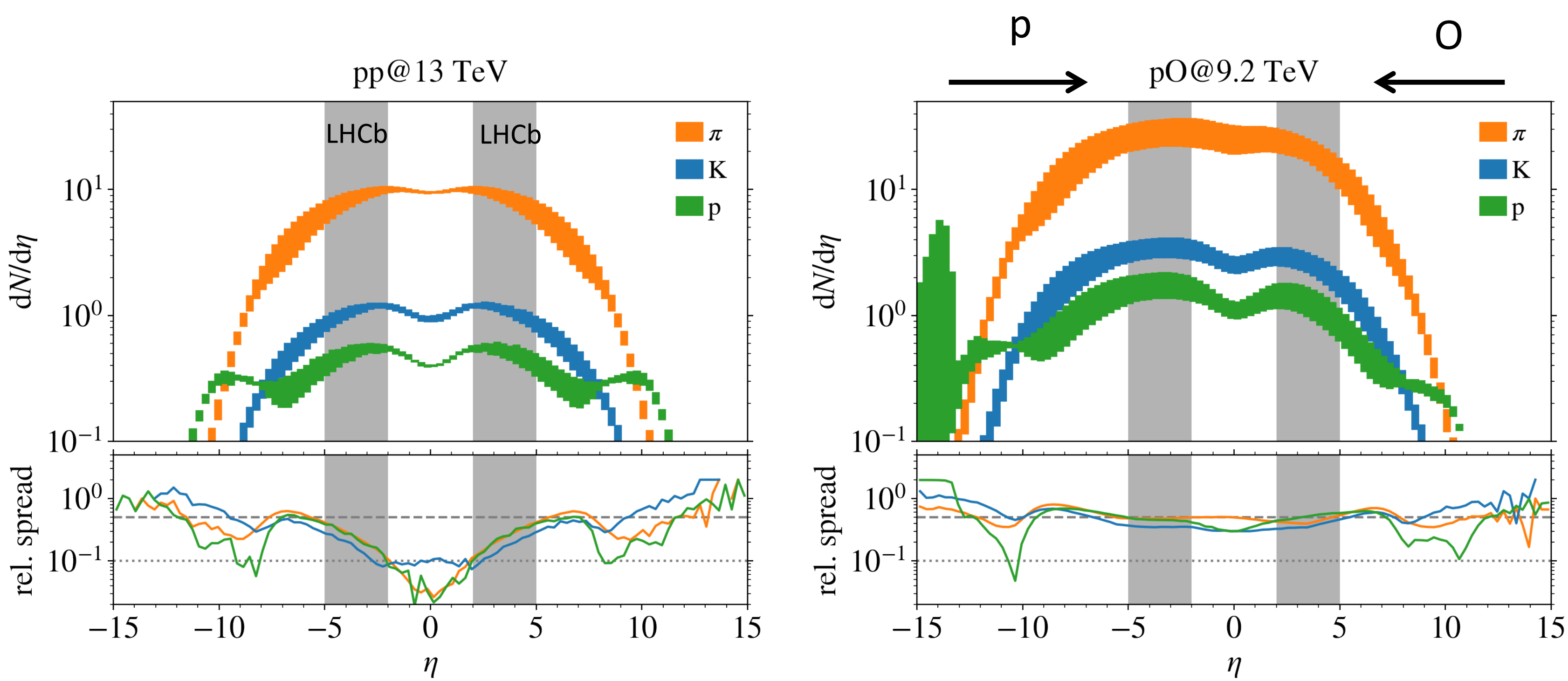




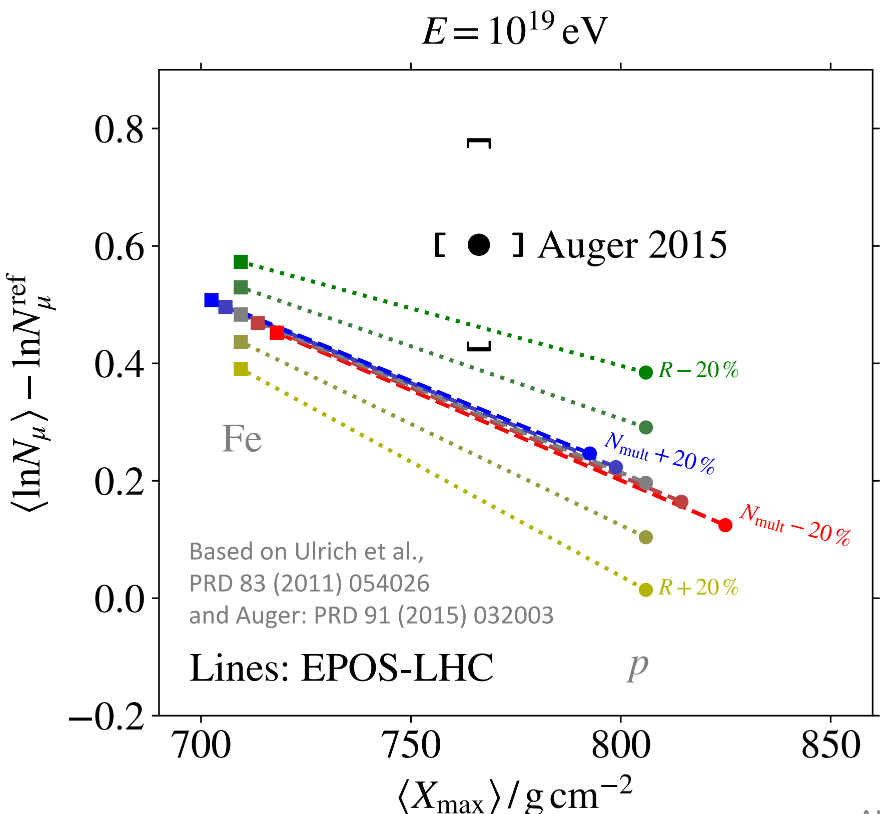
Uncertainty in hadron spectra

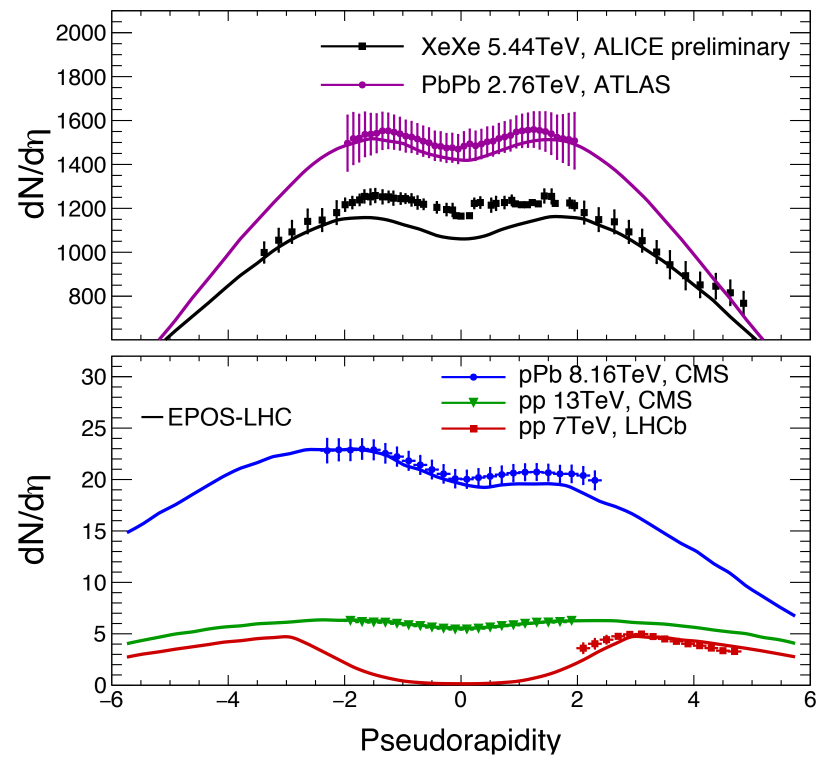
- Simulations done with CRMC
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3



Models mostly tuned to p+p data at |η| < 2: p+p 10 % model spread, **p+O 50 % model spread**

Impact of LHC measurements





ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337; CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2; LHCb p-p arXiv:1402.4430

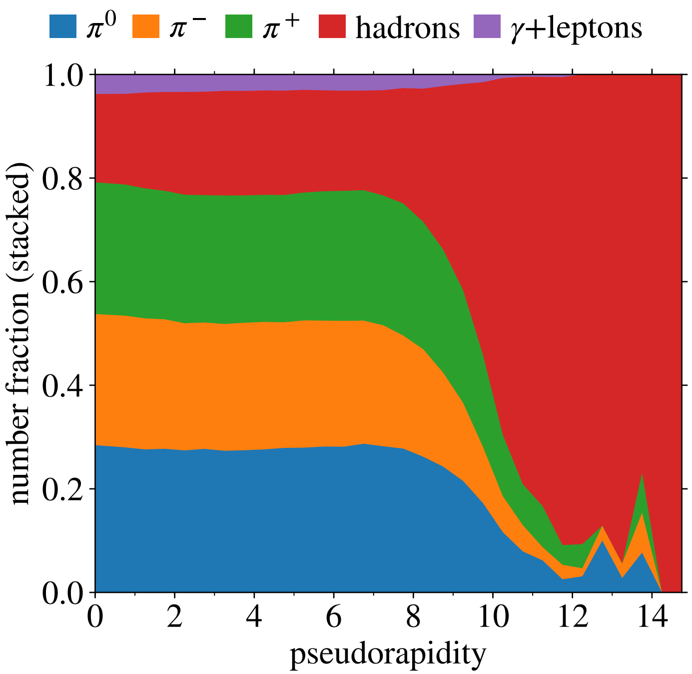
- X_{max} sensitive to: inel. cross-section, hadron multiplicity
- N_μ sensitive to: **energy ratio R**, hadron multiplicity
- Expected: **nuclear modification of forward-produced hadrons**

$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Possibilities to reduce R

Iso-spin symmetry: $N_{\pi+-} = 2N_{\pi0}$, but pion/hadron ratio not fixed

pp 13 TeV, EPOS-LHC



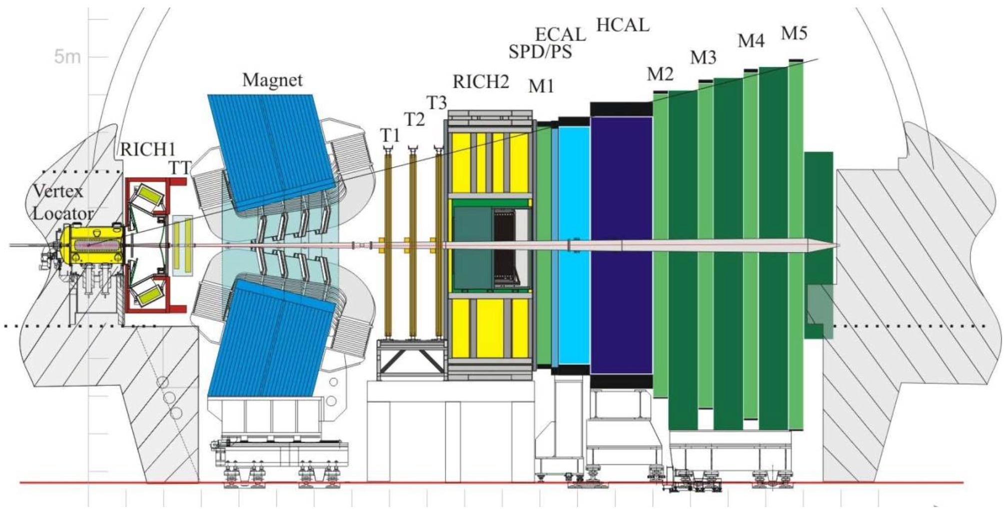
Collective effects may reduce pion fraction, EPOS-LHC predicts drop in R at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

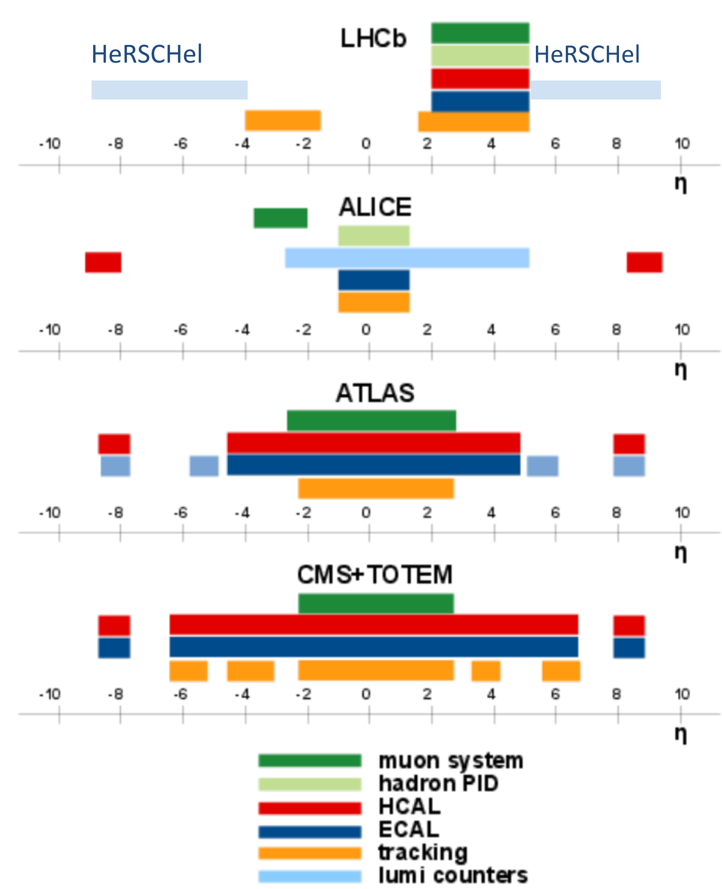
Strangeness production underestimated?
https://arxiv.org/pdf/1612.07328.pdf

Unexpected enhancement of strangeness observed in central collisions in pp, pPb, PbPb
ALICE collab., Nature Phys. 13 (2017) 535

LHCb: a forward spectrometer

JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022





Forward spectrometer

- Fully instrumented at $2 < \eta < 5$
- Very good momentum and vertex resolution
- Good particle identification
- **Optimal**: μ, p, K^{+-}, π^{+-}

Nuclear effects

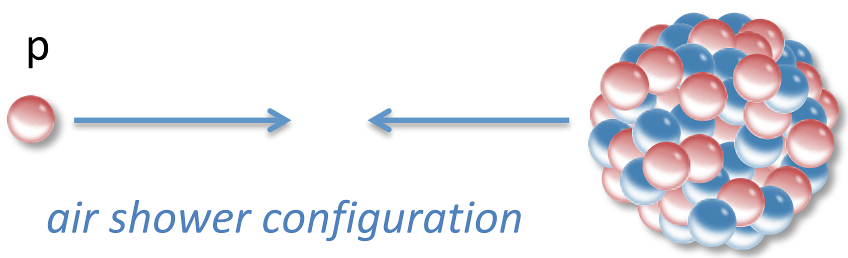
Nuclear modification factor

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

Superposition model: R_{pA} = 1

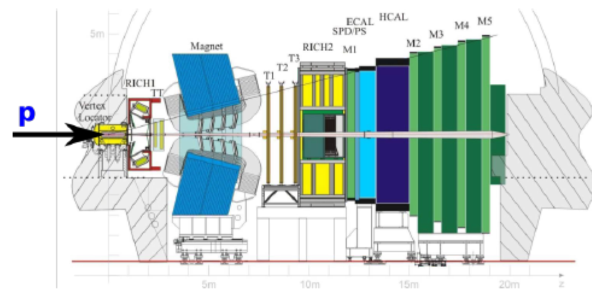
Pb

p



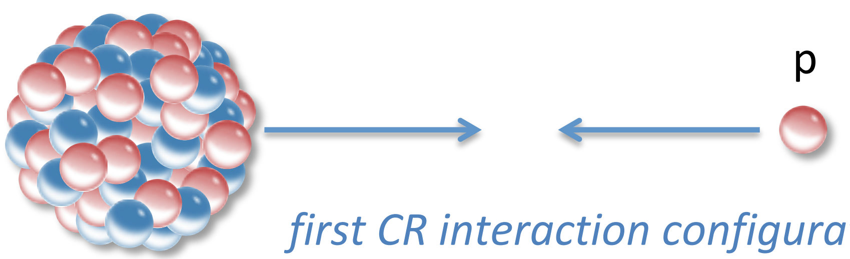
air shower configuration

"forward"



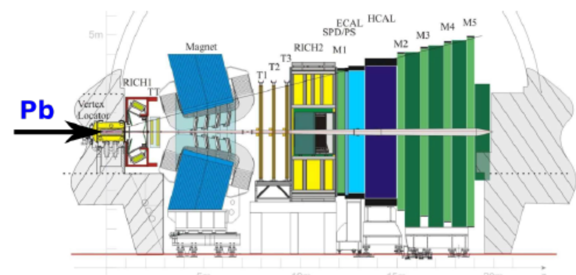
Pb

p

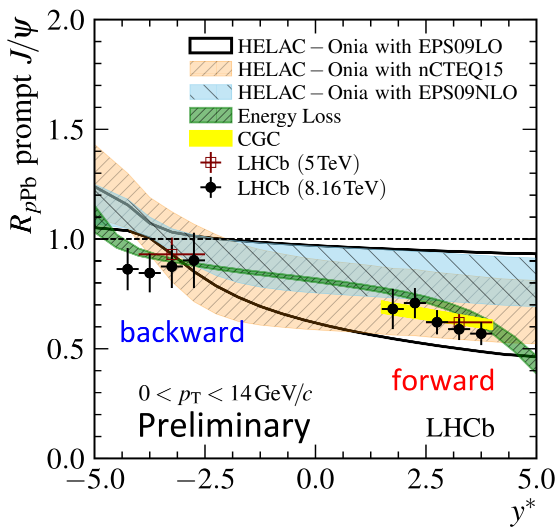


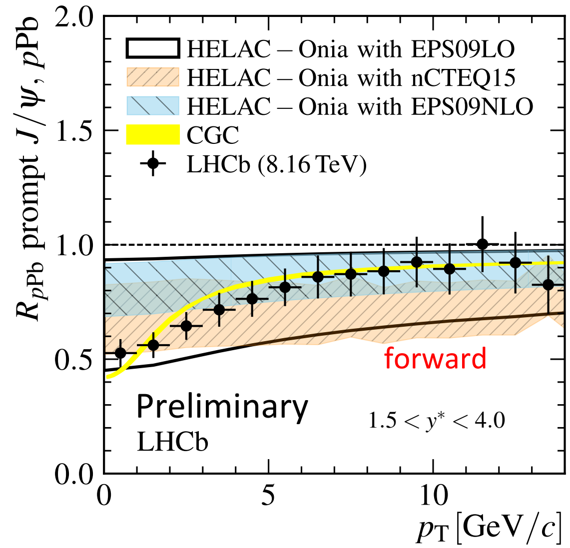
first CR interaction configuration

"backward"



Nuclear effects in prompt J/ψ production



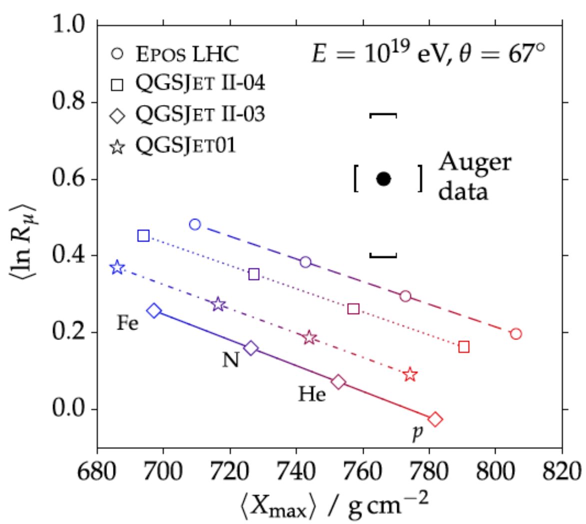


LHCb-PAPER-2017-014

Up to 50 % suppression in forward direction

Especially strong where relevant for CR!

Similar effects *expected* in pion production



- Model lines **parallel**, because of approx. superposition
- Model line **offsets** from nuclear effects (forward effects)

Only need to measure pO, not FeO!

Proton-Oxygen at the LHC

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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

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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 run schedule

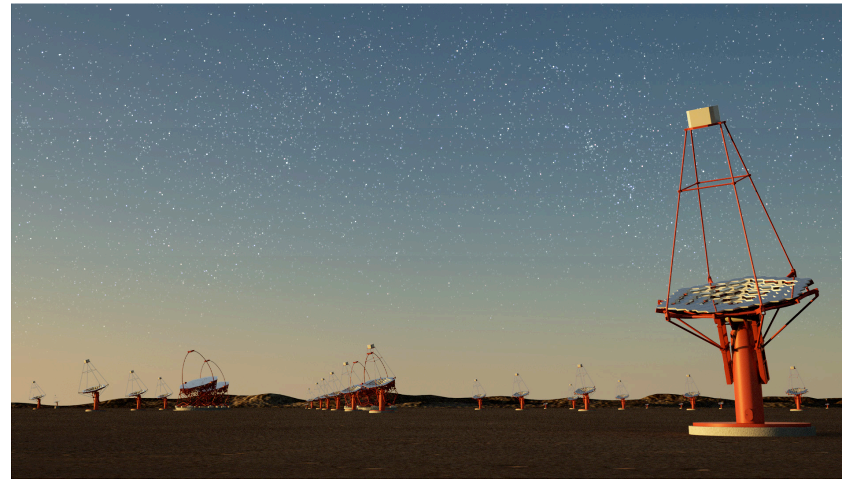
Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	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 $\mu\mathrm{b}^{-1}$ 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

Bonus issue: Muons in < 100 TeV showers

HAWC, 100 GeV to 100 TeV

CTA (artist impression), 10 GeV to 300 TeV

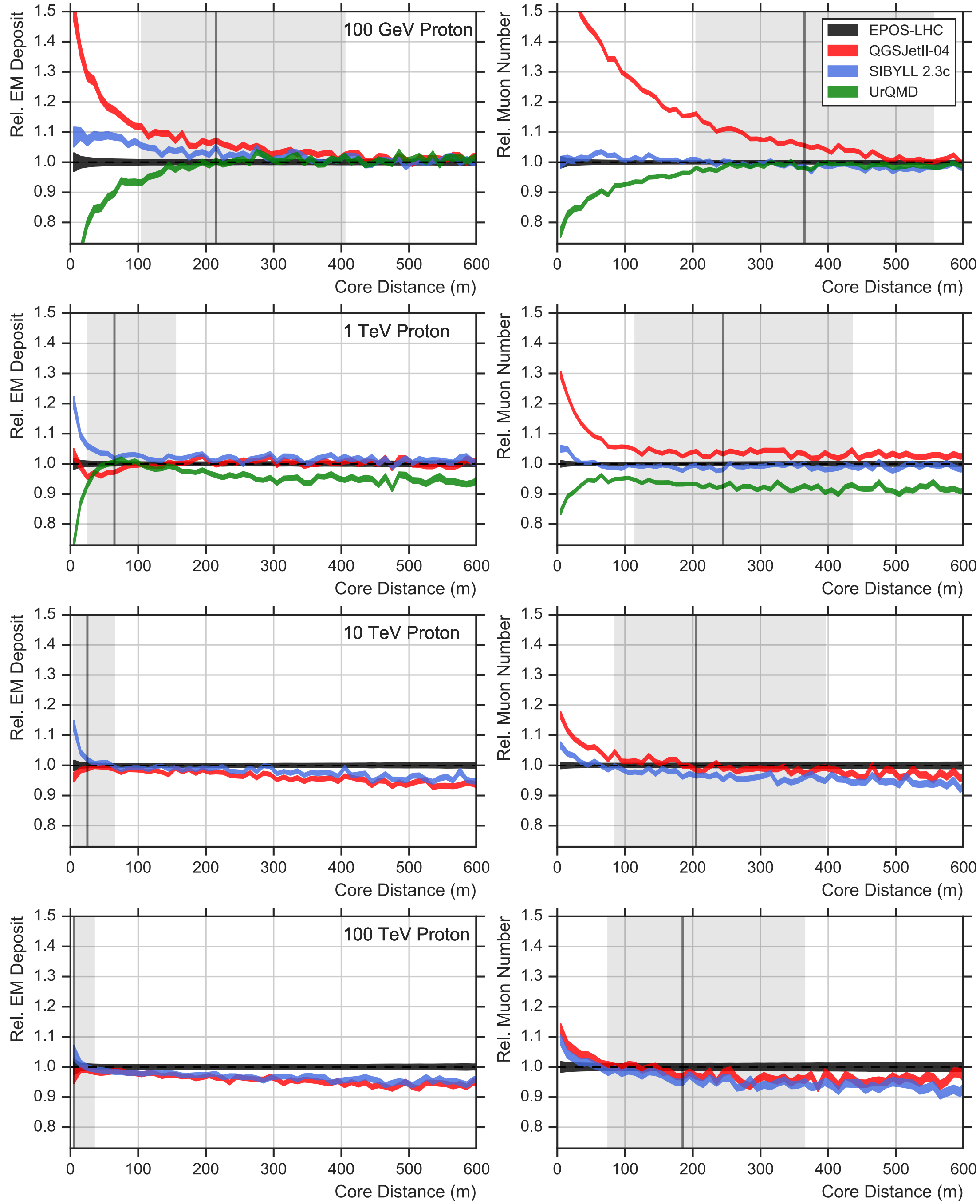


- Cosmic ray showers background for γ-ray observatories: H.E.S.S., HAWC, CTA, SGSO, ...
- γ-ray selection based on poor muon content
- Relies on MC predictions for μ-LDF

LDF spread

R.D. Parsons and H. Schoorlemmer, arXiv:1904.0513, submitted to PRD

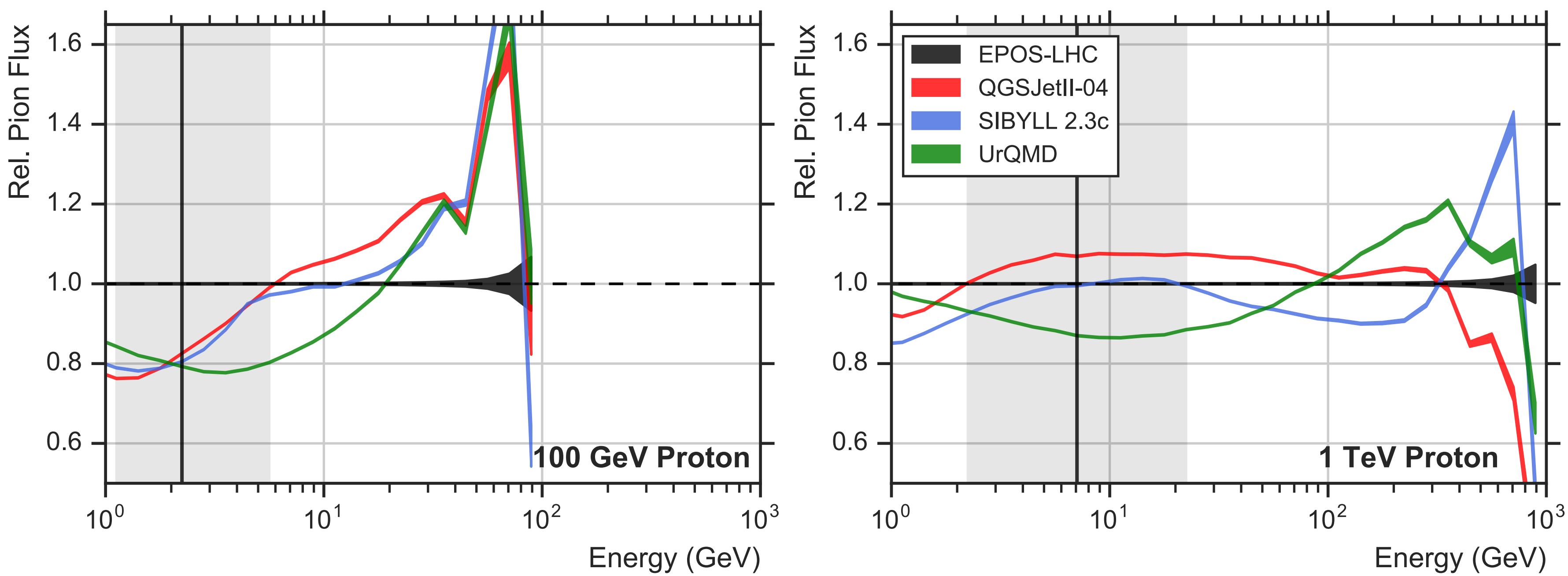
- CORSIKA simulations
  - 100 GeV to 100 TeV
  - UrQMD for E < 80 GeV
  - Varying high-energy model
- Huge discrepancies in eγ-LDF and μ-LDF in 100 GeV showers
- Correlated effects in LDFs
  - QGSJet-II.04 high
  - UrQMD low



Uncertainties from first interaction

R.D. Parsons and H. Schoorlemmer, arXiv:1904.0513, submitted to PRD

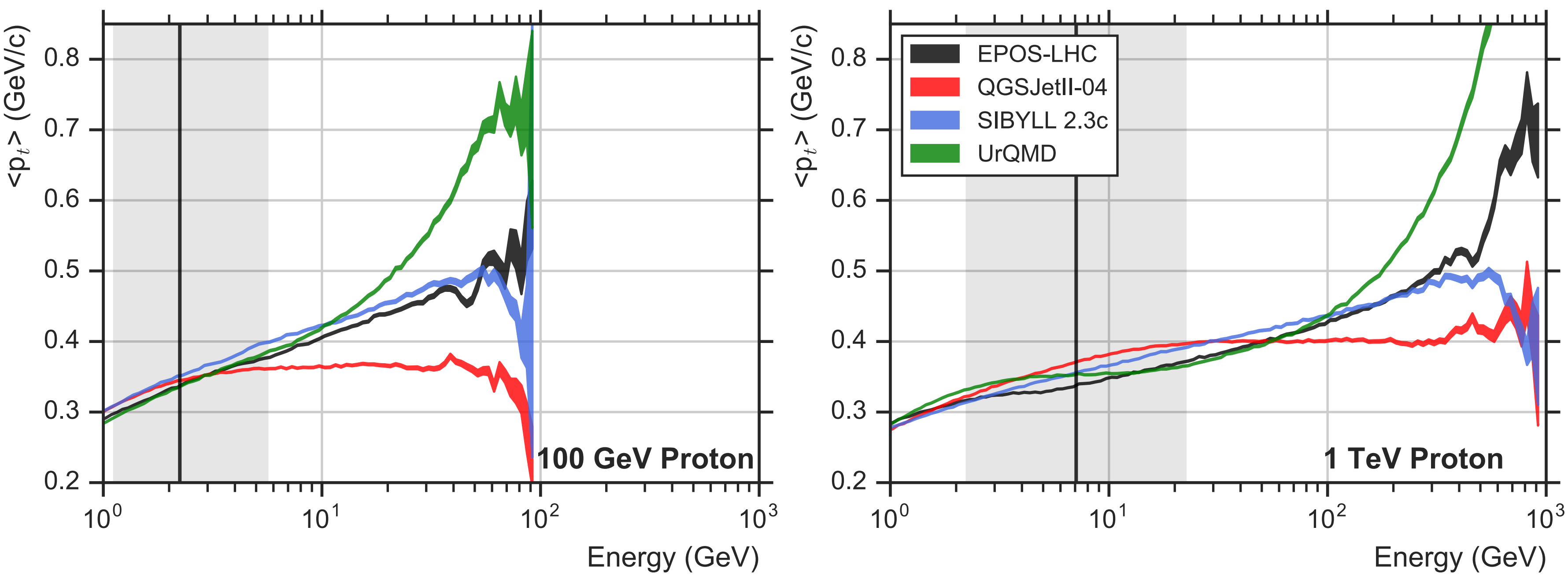
- Same simulation for E<80 GeV
  - Discrepancy must be in first interaction
  - Placed observation level 1 cm below interaction to study pions
- Large spread in pion spectra in first interaction
  - EPOS-LHC produces lowest number of high-energy pions at 100 GeV



Uncertainties from first interaction

R.D. Parsons and H. Schoorlemmer, arXiv:1904.0513, submitted to PRD

- Same simulation for E<80 GeV
  - Discrepancy must be in first interaction
  - Placed observation level 1 cm below interaction to study pions
- Large spread in pion spectra in first interaction
  - QGSJet-II.04 (UrQMD) produces lowest (highest) average p_T



Summary

- Muon Puzzle experimentally established at 8σ
  - Statement by eight leading air shower experiments
  - Problem not in the data, theory has to change
- Key measurements to be done at the LHC
  - Energy ratio R of π^0 to other hadrons at forward rapidity
  - Nuclear modification in forward hadron production
- Proton+oxygen collisions planned for 202(3)
  - Data should be analyzed by ATLAS, CMS, ALICE, LHCb for maximum impact
  - R can be measured with forward calorimeters, no hadron PID!
- Bonus issue: Why air shower simulations differ so much at 100 GeV?
  - Large amount of data on pion production at E < 1 TeV from fixed-target exp.
  - Models should be tuned to this data and agree, but do not
  - Impact of low-energy model? Barely check the low-energy model (FLUKA)
  - CORSIKA8 could generate **automatic validation plots** for all supported models: **Compare predictions with available measurements from accelerators**

Acknowledgments

- Lead nucleus graphic from Inductiveload - Public Domain: https://commons.wikimedia.org/w/index.php?curid=2858666