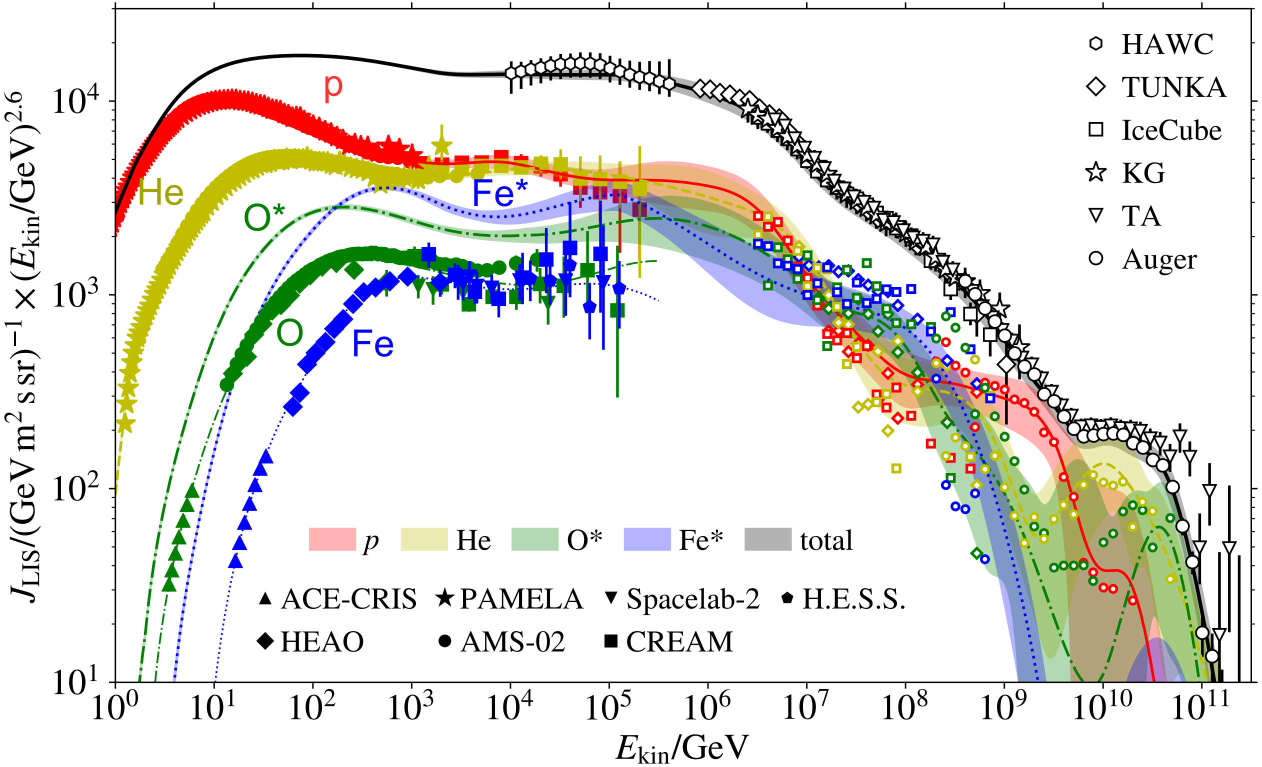
p-O science case: summary

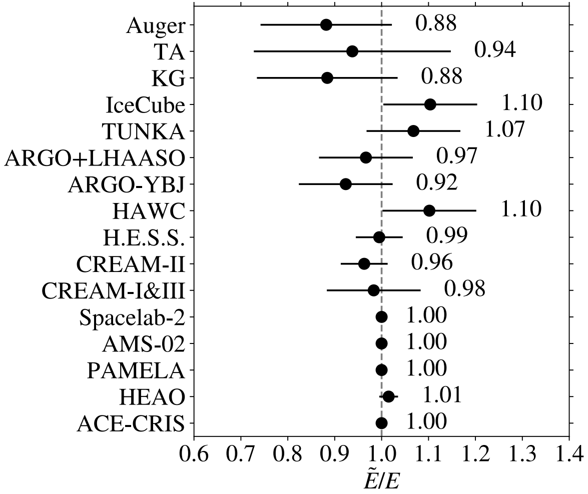
Hans Dembinski, MPIK

Global Spline Fit

HD, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev,
PoS(ICRC 2017)533

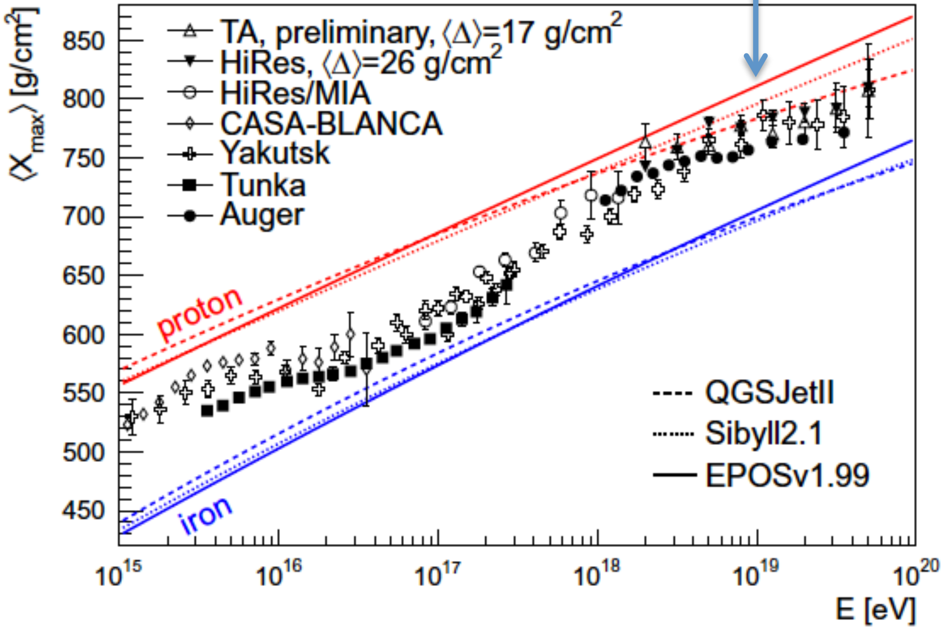


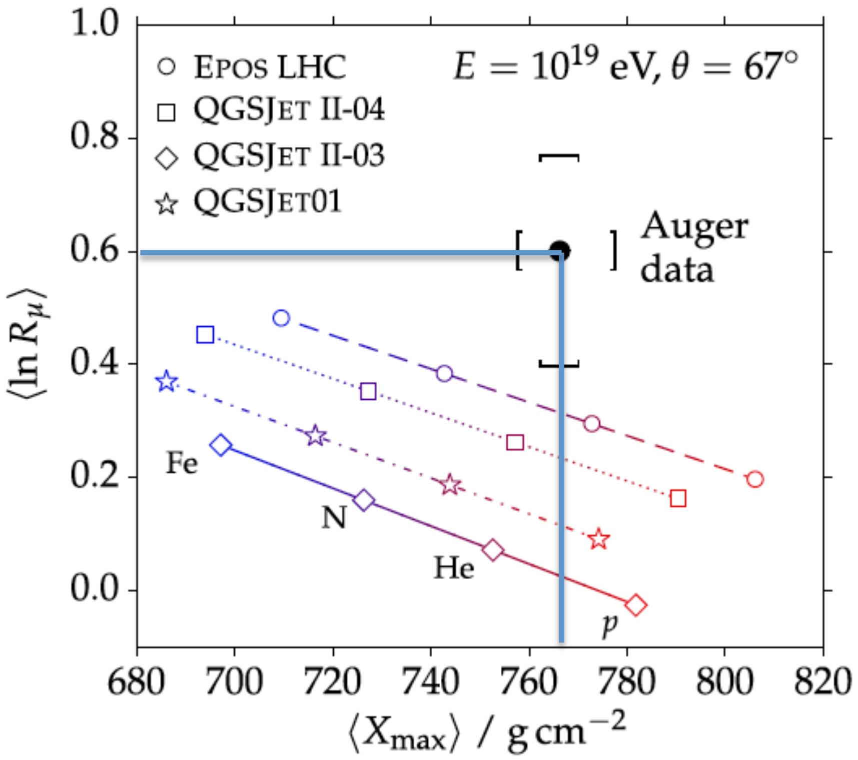
Energy scale adjustment factors (corrections < 12 %)



Uncertainty on all-particle flux about 10 %, good agreement on shape, but mass composition uncertain

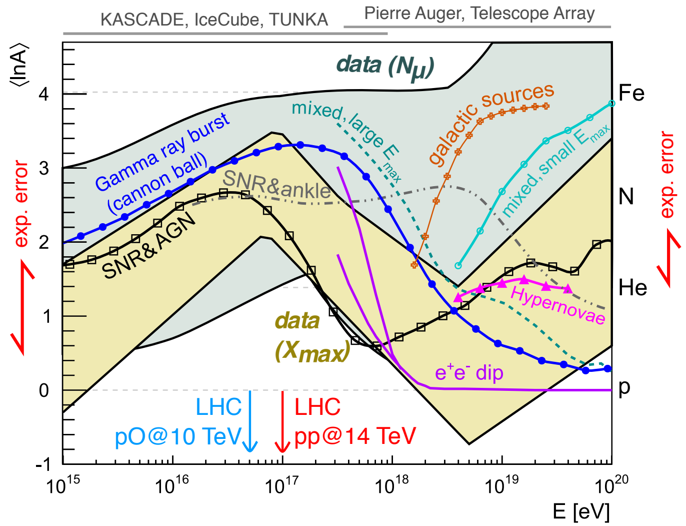
Mass estimation





$\langle \ln A \rangle = \mathbf{a} + \mathbf{b}\, X_{max} = \mathbf{c} + \mathbf{d} \langle \ln N_\mu \rangle$

Motivation: CR mass composition



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

- Precise mass composition could rule out many theories of cosmic ray origin
- Crucial for design of future experiments, if composition is heavy at highest energies...
  - **Strongly reduced flux of GZK neutrinos**
  - **Probably no cosmic ray astronomy**

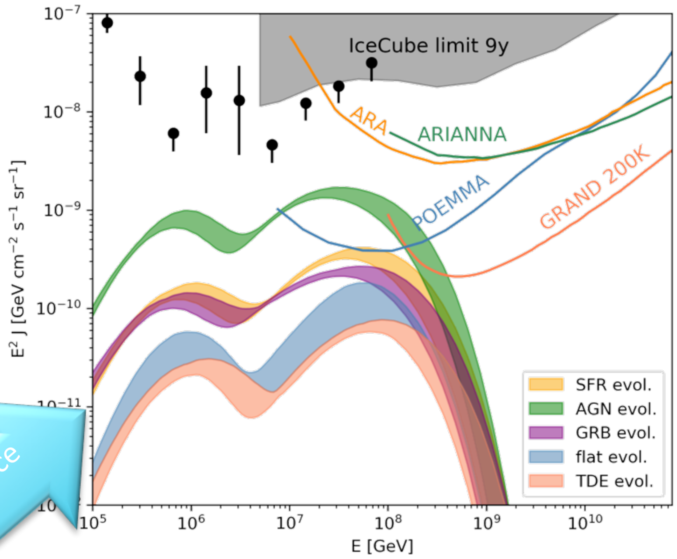
R. Aloisio , V. Berezinsky , A. Gazizov
Ultra High Energy Cosmic Rays: The disappointing model
Astroparticle Physics 34 (2011) 620-626

How to get accurate mass

- **X_{max} is best mass estimator**, but need to also solve **Muon Puzzle** for consistent picture
- Improve accuracy of X_{max} predictions below **10 g cm-2** (current experimental uncertainty)
- **N_μ** must not be as accurate, **only consistent**

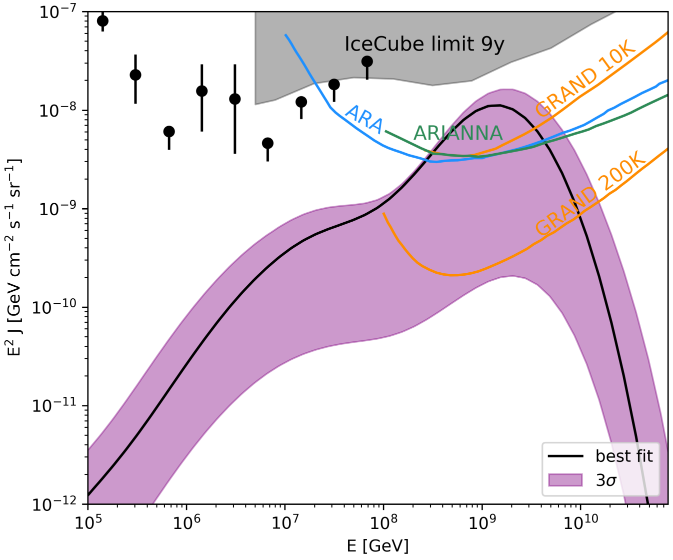
Future neutrino experiments optimized for protons?

Expected neutrino flux from interactions of UHECR nuclei



Different source types

If UHECR were protons…

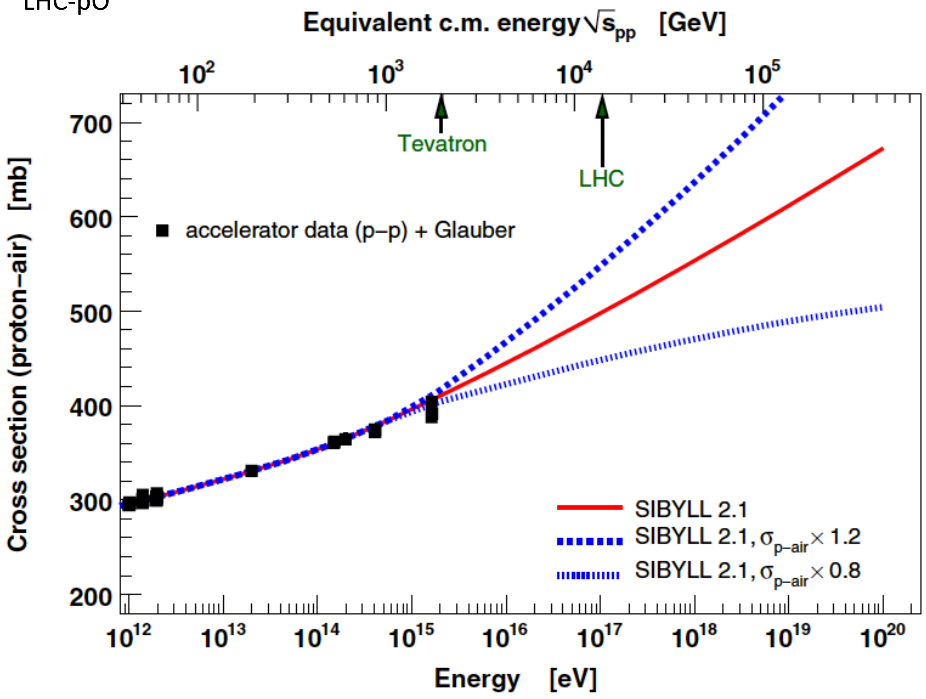


Expensive future experiments)

Future neutrino experiments will all **miss the required sensitivity and energy**, if UHECR are nuclei

Modify hadronic interaction models

Modify features at LHC energy scale with factor $f_{LHC\text{-}pO}$ and extrapolate up to 10^{19} eV proton shower
R. Ulrich et al PRD 83 (2011) 054026



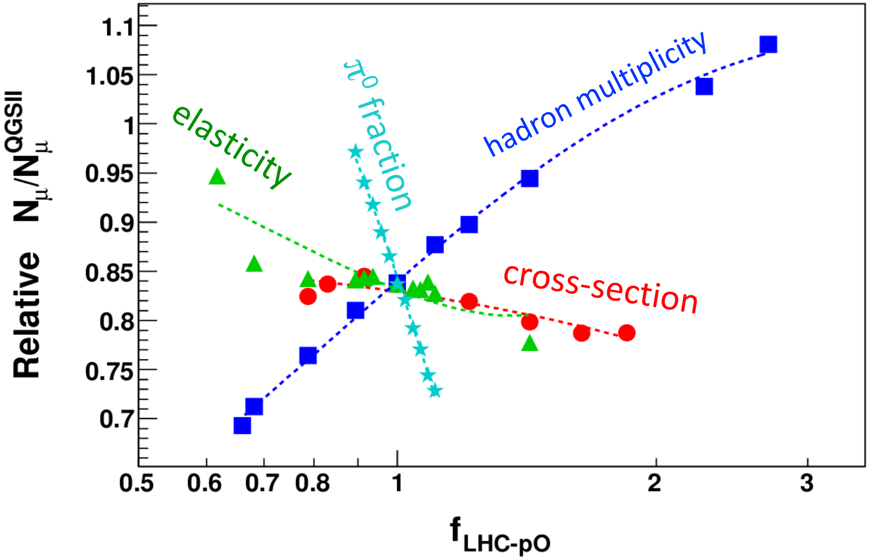
Modified features

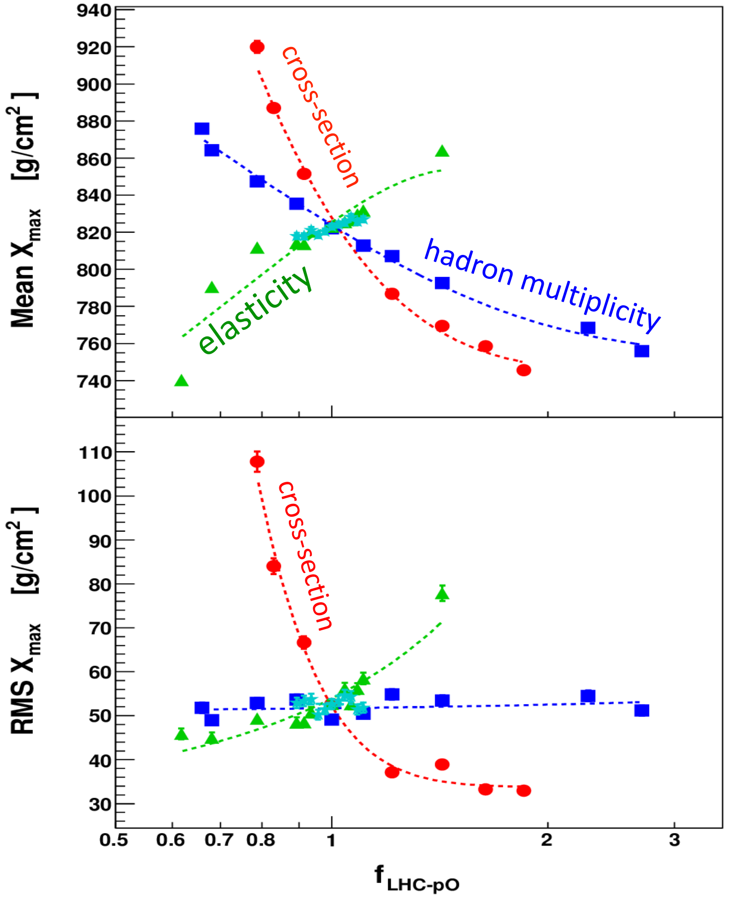
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- π^0 **fraction**: (no. of π^0) / (all pions)

Importance of features

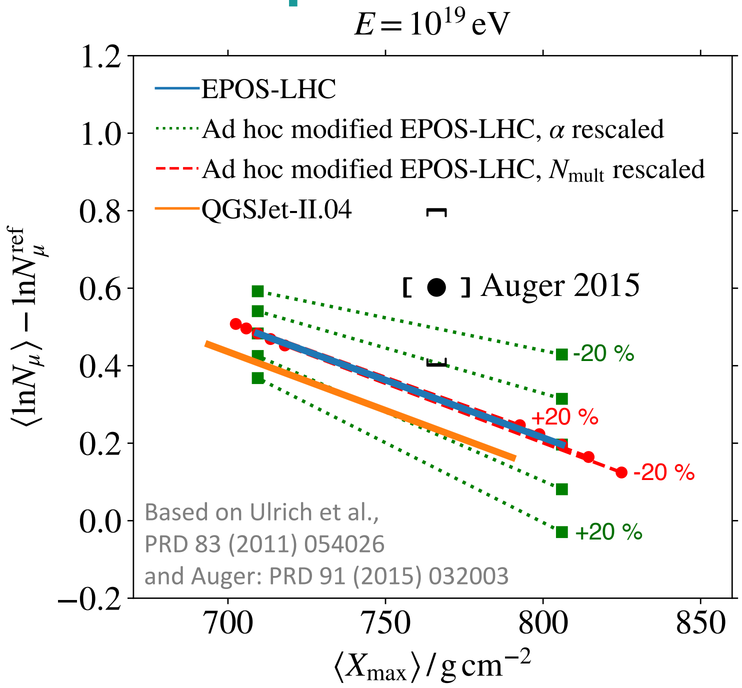
Modify features at LHC energy scale with factor $f_{LHC\text{-}pO}$ and extrapolate up to 10^{19} eV proton shower

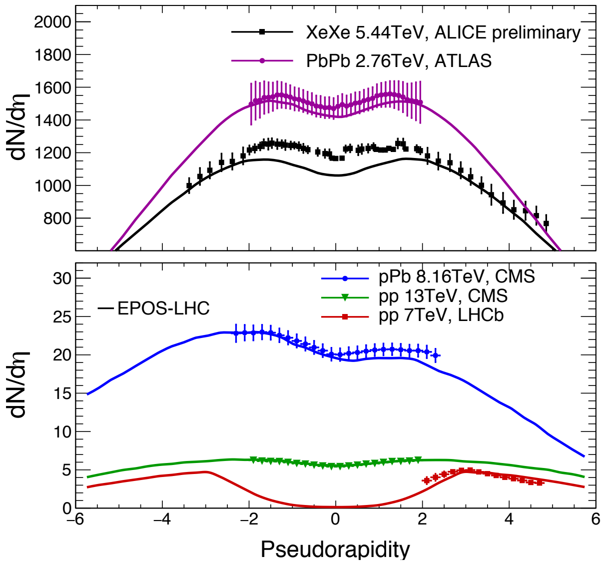
R. Ulrich et al PRD 83 (2011) 054026





Impact of LHC measurements



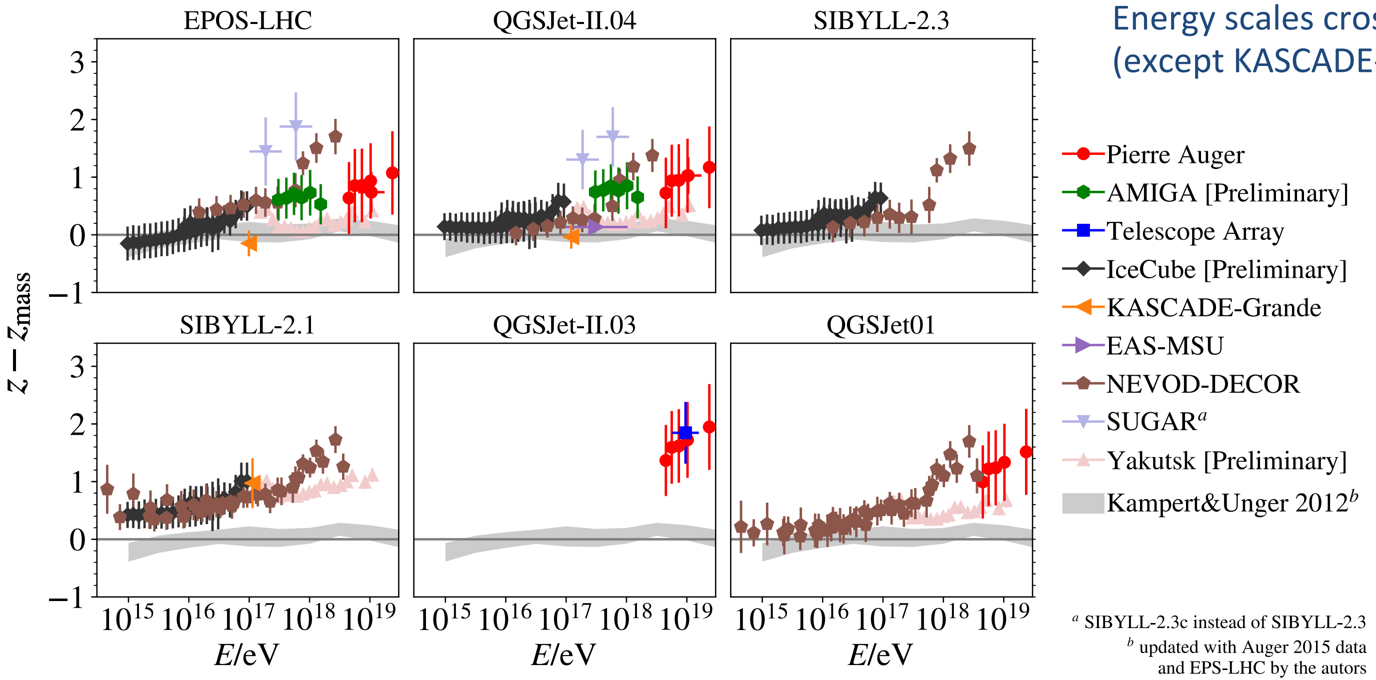


ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337; CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2; LHCb p-p arXiv:1402.4430

- X_{max} sensitive to: **inelastic cross-section**, hadron multiplicity, elasticity
- N_μ sensitive to: **energy fraction lost to π^0**, hadron multiplicity
- **Nuclear modification in forward-produced hadrons** expected and important

Compilation of muon measurements

- WHISP report at UHECR 2018 conference, Oct 8-12 2018
- Comprehensive compilation of muon measurements from air shower experiments



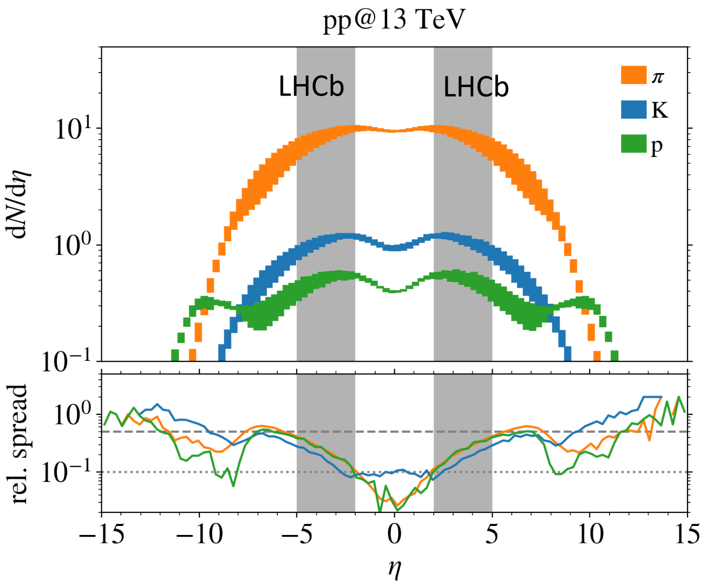
Energy scales cross-calibrated (except KASCADE-Grande, EAS-MSU)

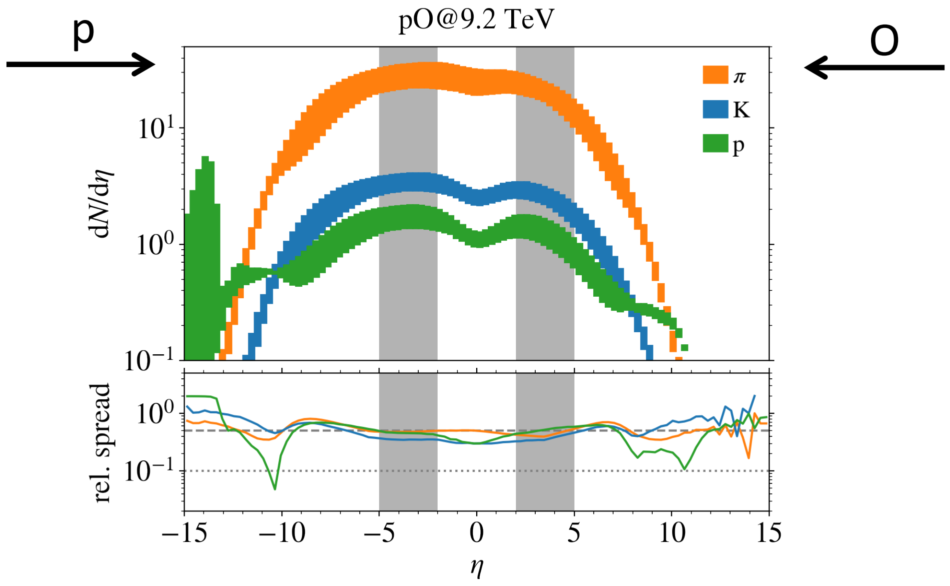
Systematic discrepancies reported by majority of experiments starting around 5×10^{16} eV equiv. to **$s^{1/2}$ = 10 TeV**

Apart from shower energy, possible dependence on shower age, lateral distance, muon energy threshold

Hadron spectra

- Simulations done with CRMC by R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

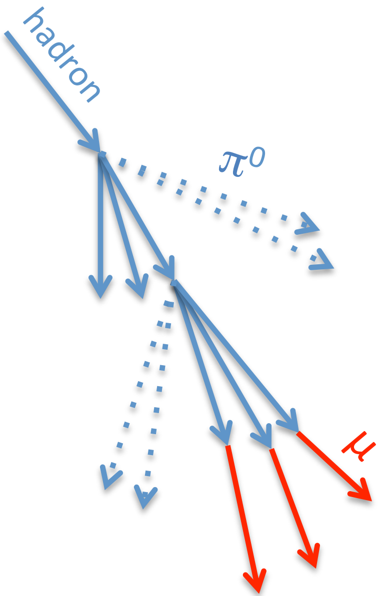


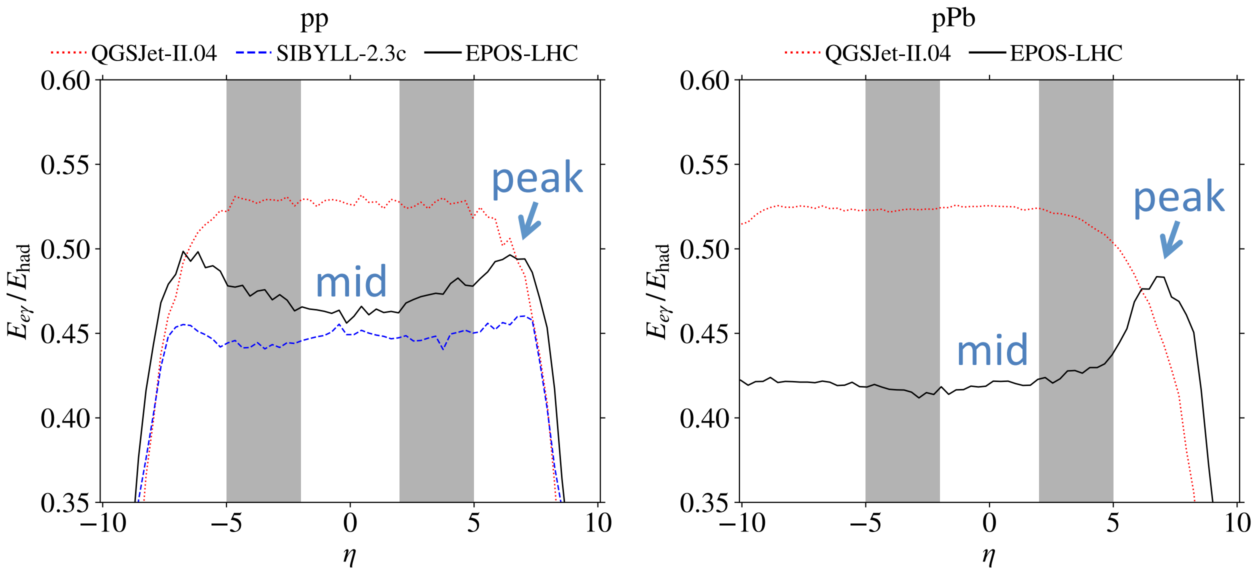


Models mostly tuned to p+p data at |η| < 2: p+p 10 % model spread, **p+O 50 %** model spread

Energy flow ratio

- Hadronic energy “lost” to π^0s cannot produce muons in late shower
- “Energy loss” described by observable $E_{e\gamma}/E_{hadrons}$





- Model predictions differ by **15 %** and in **shape**: only EPOS has forward peaks
- Translates to about **20 % shift in N_μ** **-> high impact on Muon Puzzle**

Measurements in p-O

- Differential cross-section for production of π, K, p
  - Needs hadron PID
  - ALICE: $-2 < \eta < 2$
  - LHCb: $2 < \eta < 5$
- Differential cross-section for charged particles
  - Needs tracking for $-7 < \eta < 7$
  - ATLAS, CMS
- Energy flow separated by hadrons and $e\gamma$
  - Needs good Ecal and Hcal for $-7 < \eta < 7$
  - ATLAS, CMS & CASTOR
- LHCf: π^0, n in very forward range for elasticity
- Inelastic cross-section?
  - Interpolation from pp, pPb probably ok