
IceCube Particle Astrophysics Symposium
IPA
2017
neutrino astronomy · neutrino physics
dark matter and cosmology · multimessenger
astronomy · transient astrophysics
May 8-10, 2017
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Madison, WI
wipac.wisc.edu/IPA2017
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Photo Illustration; original photo Jeff Miller, neutron star collision illustration Dana Berry


THE
SIX MILLION
DOLLAR MAN


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SIX BILLION
DOLLAR MAN

VOLUME 48, NUMBER 11 PHYSICAL REVIEW LETTERS 15 MARCH 1982

Comprehensive Explanation of Cosmic-Ray "Anomalies": Quark Matter Formation by Heavy Nuclear Primaries

F. Halzen and H. C. Liu[a]
Physics Department, University of Wisconsin–Madison, Madison, Wisconsin 53706
(Received 21 December 1981)

It is proposed that the 100-TeV threshold for the appearance of anomalies in cosmic-ray interactions is associated with the critical energy of about 60 GeV/nucleon center-of-mass energy for phase transition to quark matter in nucleus-nucleus interactions. This proposal implies that the high-energy primary spectrum contains a significant heavy nuclear component (e.g., Fe).

PACS numbers: 94.40.Rc, 12.35.Ht, 13.85.Tp, 21.65.+f

COMPREHENSIVE EXPLANATION OF UHECR ANOMALIES: QUARK MATTER FORMATION BY HEAVY NUCLEAR PRIMARIES

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Work done in collaboration with Haim Goldberg and Tom Weiler
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It is proposed that the $10-\mathrm{EeV}$ threshold for the appearance of anomalies in cosmic-ray interactions is associated with the critical energy of about $10^{4.6}$ GeV/nucleon center-of-mass energy for phase transition to quark matter in nucleus-nucleus interactions. This proposal implies that the high-energy primary spectrum contains a significant heavy nuclear component (e.g., Fe).

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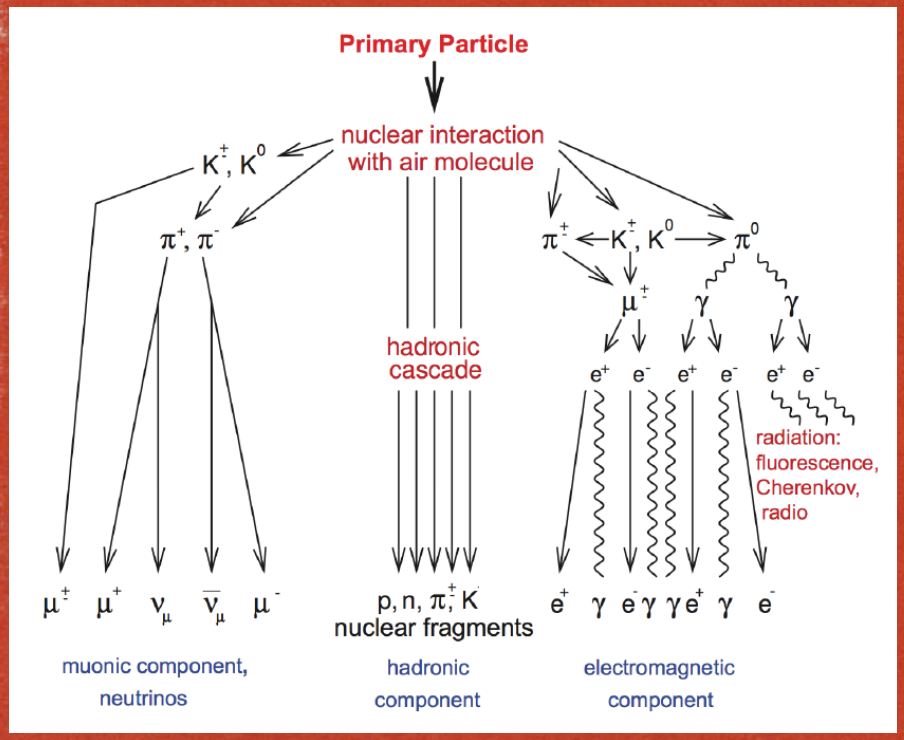
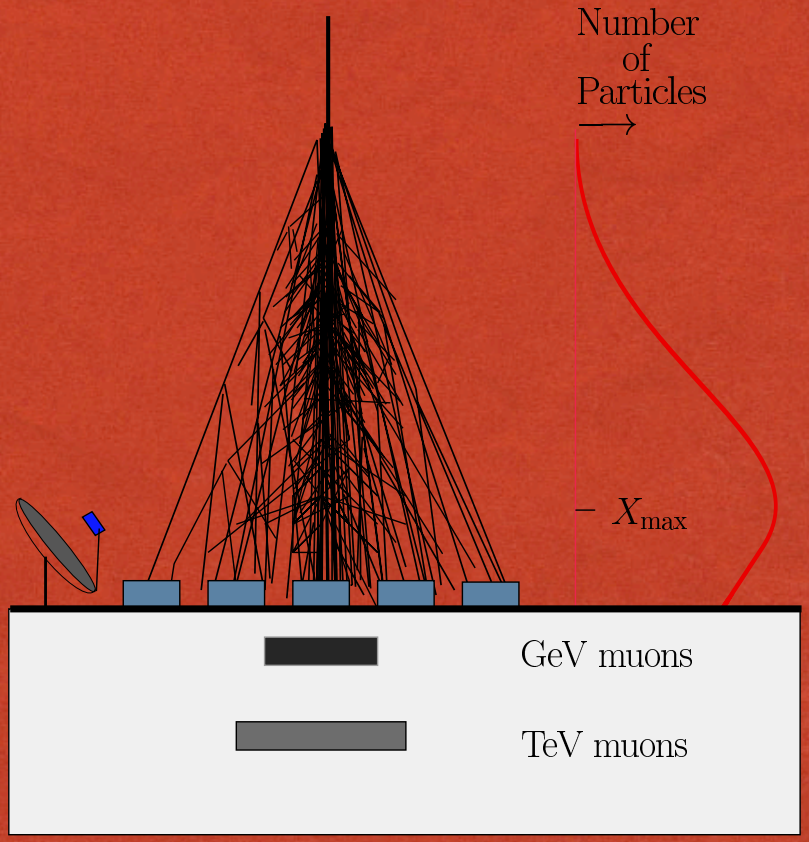
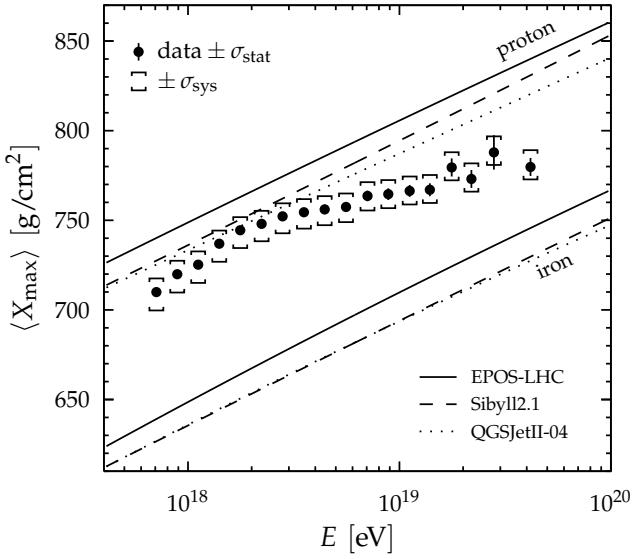
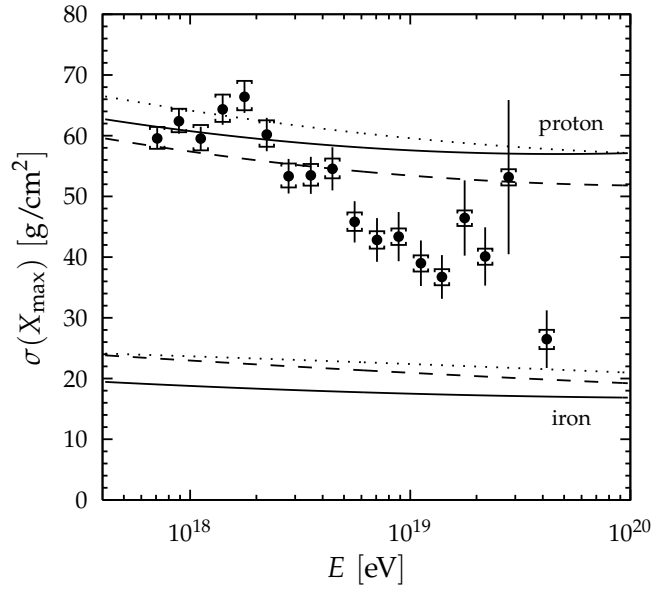
SHOWER PROPERTIES

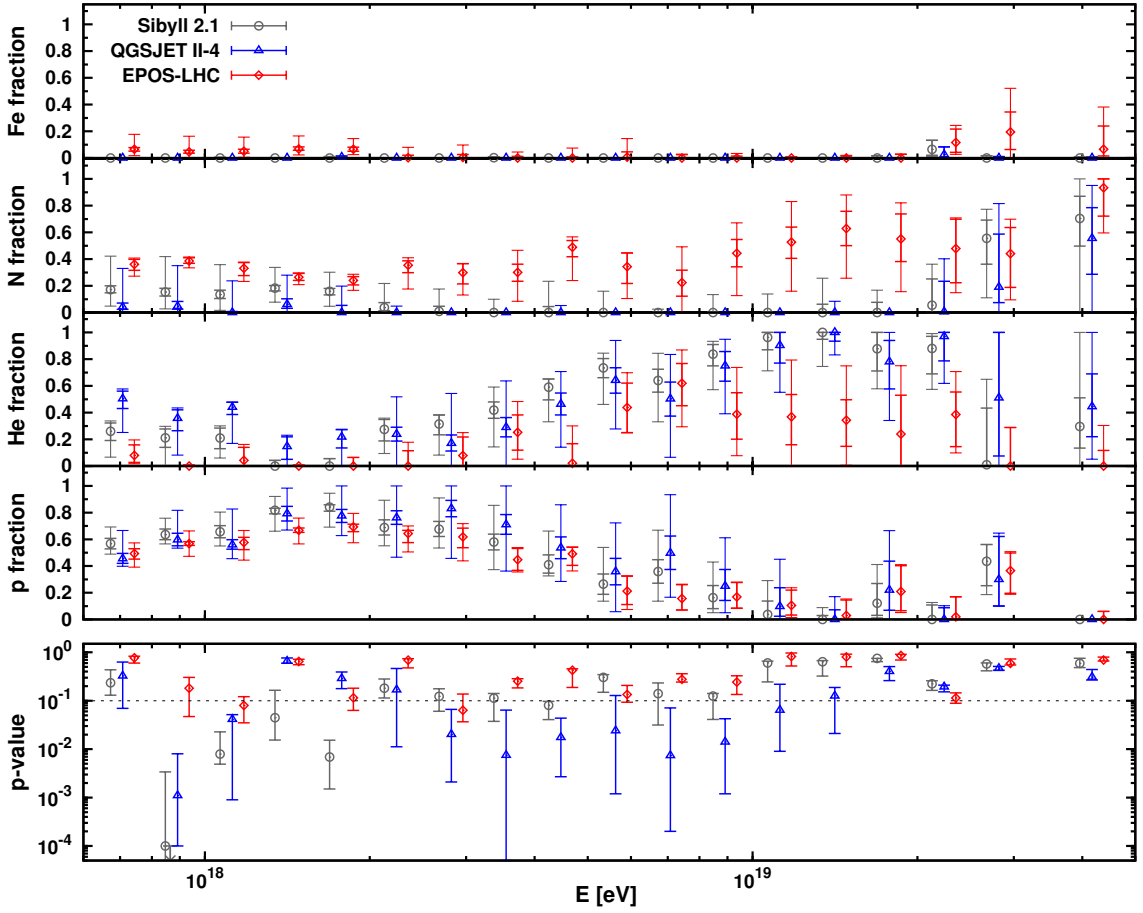




DEPTH OF SHOWER MAXIMUM



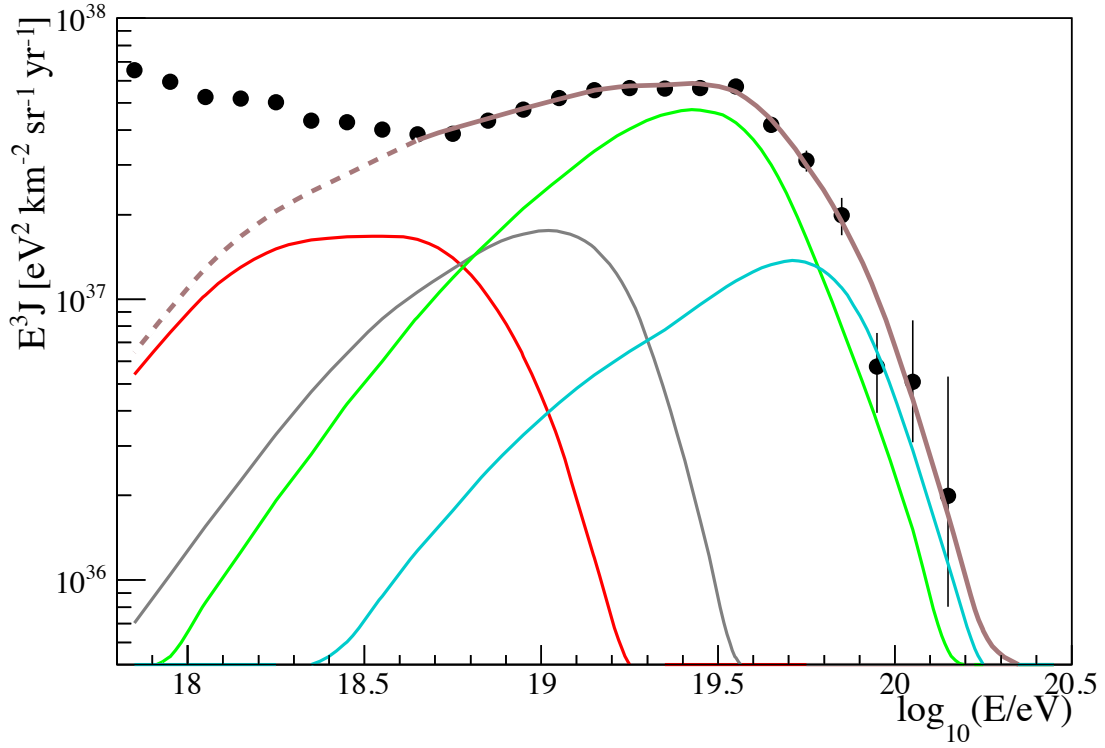


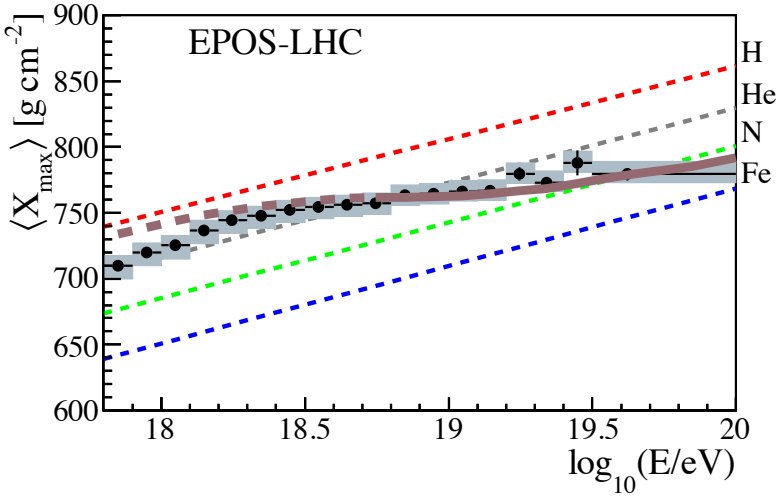


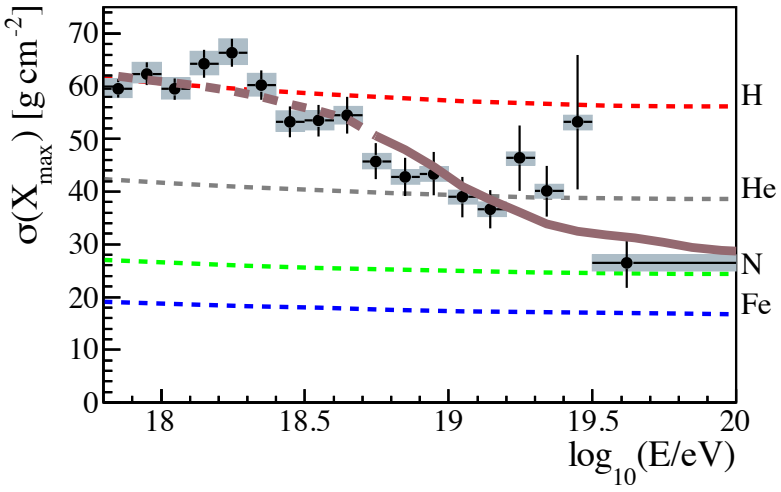
➢ **Fitted fraction and quality for mixed nuclear composition**

Auger Collaboration PRD **90** (2014) 122005; PRD **90** (2014) 122006

COMBINED FIT OF SPECTRUM AND NUCLEAR COMPOSITION



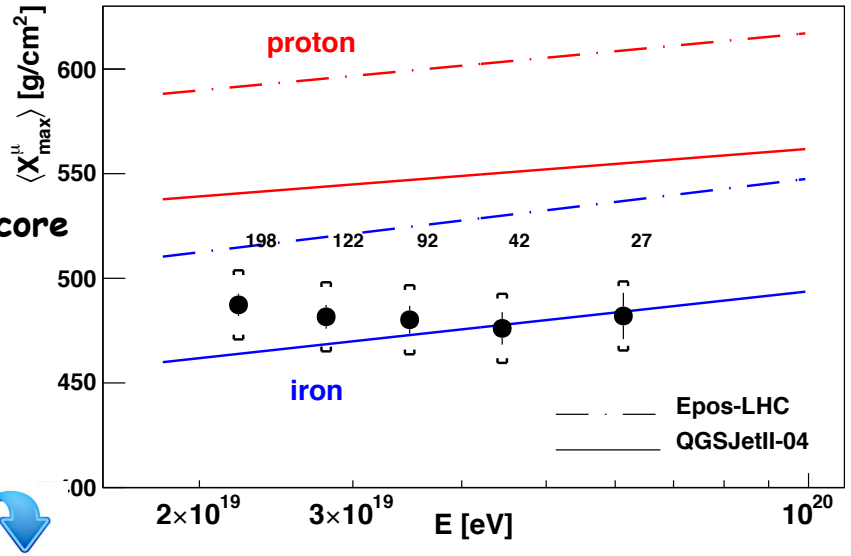




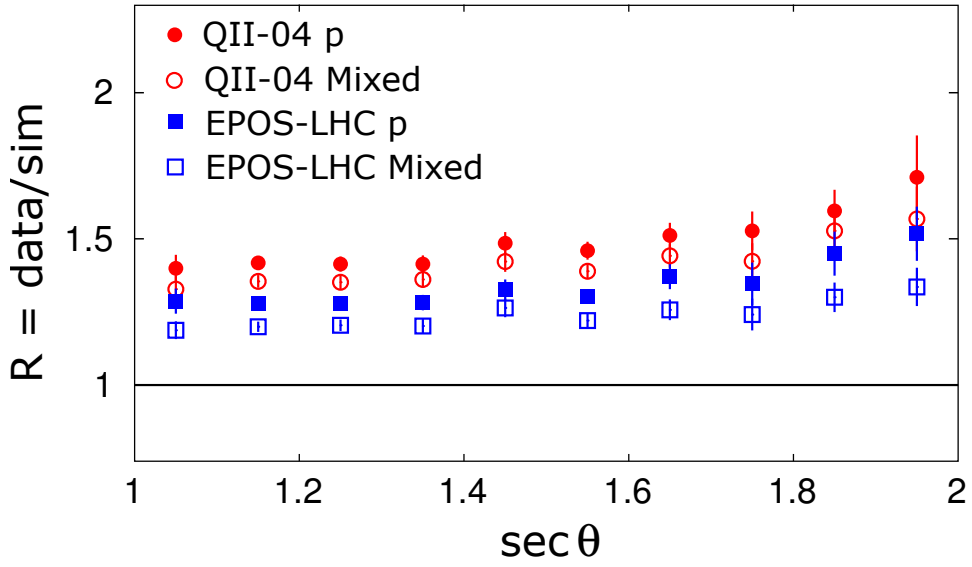
Auger Collaboration JCAP **1704** (2017) 038

DEPTH OF MUON MAXIMUM AND AVERAGE MUON CONTENT

- Using timing information from SD far from shower core we reconstruct muon production depth distribution



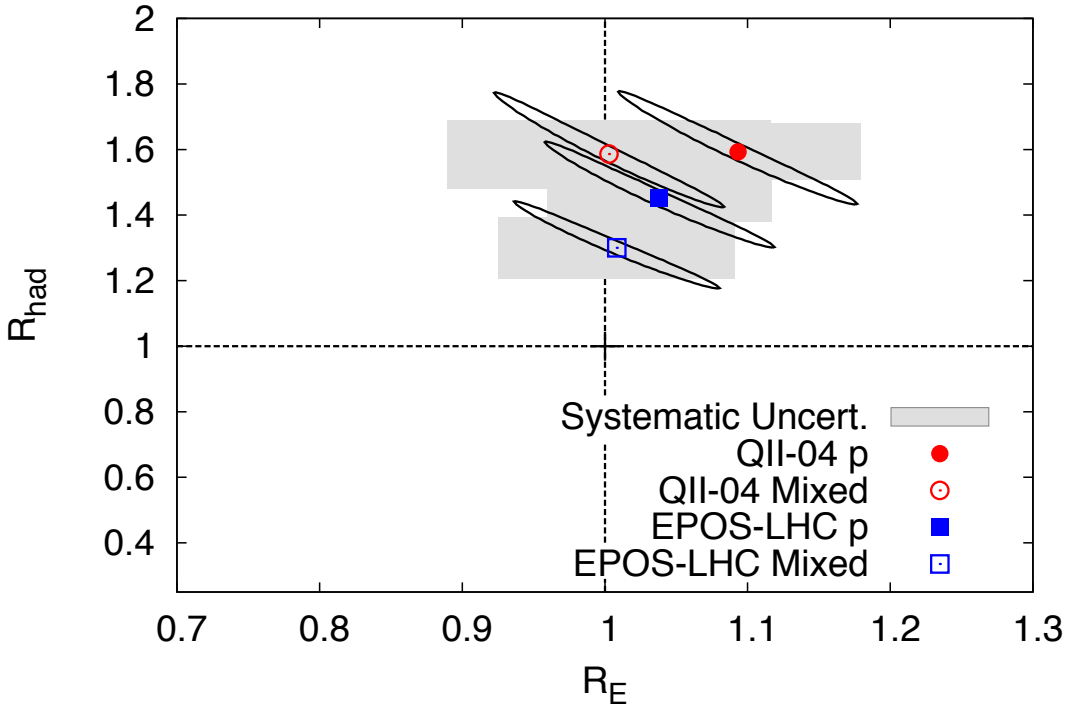
- Average muon number at 1000 m from shower core



Auger Collaboration PRD **90** (2014) 012012; PRL **117** (2016) 192001

MUON EXCESS

➢ Introduce energy rescaling parameter to allow for possible shift in FD energy calibration and multiplicative rescaling of shower hadronic component



➢ $R_{\rm E}$ ☛ rescales total ground signal of event approximately uniformly

➢ $R_{\rm had}$ ☛ rescales only contribution to ground signal of inherently hadronic origin which consists mostly of muons

➢ Hadronic component of showers contains about 30% to 60% more muons than expected

➢ Significance of discrepancy between data and model prediction is somewhat above 2.1σ

Auger Collaboration PRL **117** (2016) 192001

PION SUPPRESSION ➡ FIREBALL MODEL: PLASMA OF MASSIVE QUARKS AND GLUONS

- Fermi-Dirac statistics applied to u, d, s

  with high baryochemical potential ☛ $\mu_B \equiv 3\mu_q \sim 2$ GeV

$$\frac{n_{\bar{s}}}{n_{\bar{q}}} \approx \frac{1}{2}\left(\frac{m_s}{T}\right) K_2(m_s/T) e^{\mu_q/T} \sim 3$$

$T \sim \langle p_T \rangle \sim 580$ MeV $\qquad\qquad$ $m_s \simeq 175$ GeV

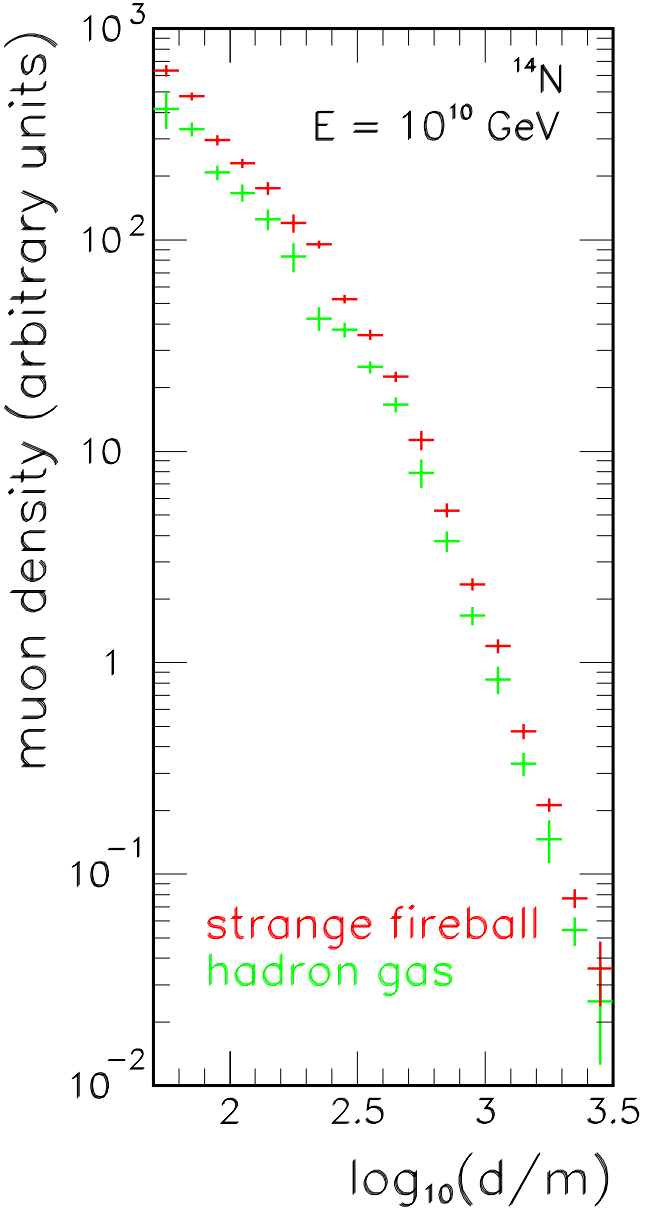
- Number density ratios favor formation of strange mesons $K^+ = u\bar{s}$ and $K^0 = d\bar{s}$ rather than pions $q\bar{q}$
- Multiplicity ratio of first interaction

$$\pi : K : N = 0.15 : 0.45 : 0.40$$

- Multiplicity ratio of of secondary, tertiary, and subsequent generations of particles

$$\pi : K : N = 0.75 : 0.15 : 0.10$$

MUON LATERAL DISTRIBUTION



STRANGE FIREBALL, MUON EXCESS, AND ALL THAT...

TAKE HOME MESSAGE

- Augmented production of strange hadrons by fireball (over that resulting from hadron gas alone) provides mechanism to increase muon content in atmospheric cascades by about 40% in agreement with Auger data
- We would not expect fireball to be created when nuclei just slide along each other
- Mix of peripheral and fireball collisions would produce large fluctuations in $\#\,\mu$ at ground level
- Critical energy for decay of charged pions and kaons is roughly the same
  elongation rate of muon channel would be almost unaltered
  and so muon shower maximum would have small fluctuations
- If fireball modifies $X_{\rm max}$ ☛ peripheral collisions would tend to increase dispersion of $X_{\rm max}$
  mimicking what is expected for light composition in canonical framework
  where no fireballs are being produced in this energy range
- Only new physics model of muon excess using heavy nuclei as primaries
  predicts cosmogenic neutrino flux out of current experimental reach

PROBING QCD APPROACH TO THERMAL EQUILIBRIUM WITH UHECRs

LOOKING AHEAD

- Establish more precise theoretical frameworks for:
  - * collision and creation of plasma
  - * evolution of number densities of different species
  - * fireball explosion
- Simulations
  - * bring CORSIKA to the game
  - * modify first interaction according to fireball model
  - * explore effect of model parameters on EAS observables
- More data are needed to crosscheck anomalies

Soriano, LAA, Hackebill, Paul, Weiler, ICRC 2017