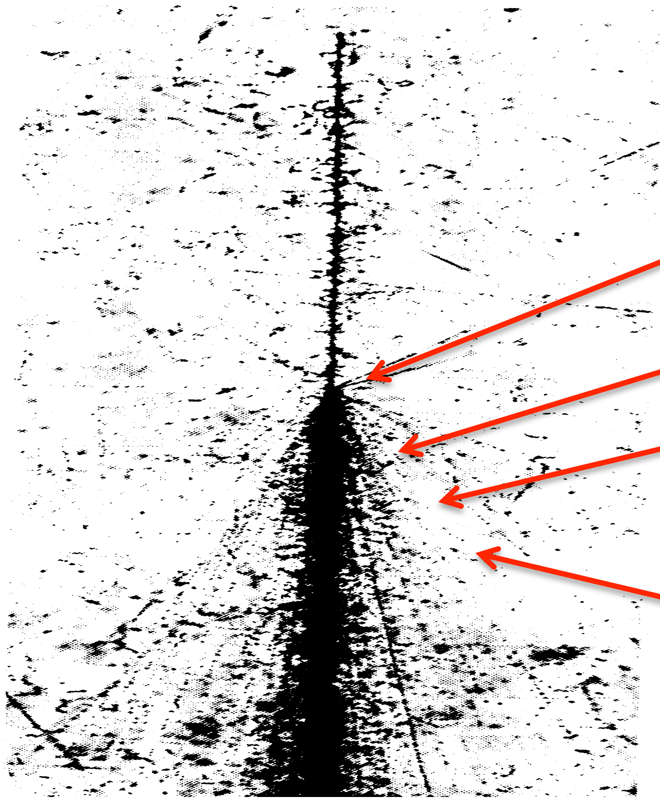
Sphalerons in Air Showers

Charles Timmermans

Nikhef

Radboud University Nijmegen

Air Shower - Observables



Cross section: Altitude of first interaction

Multiplicity: Speed of shower development

High energy photons: EM/hadronic energy

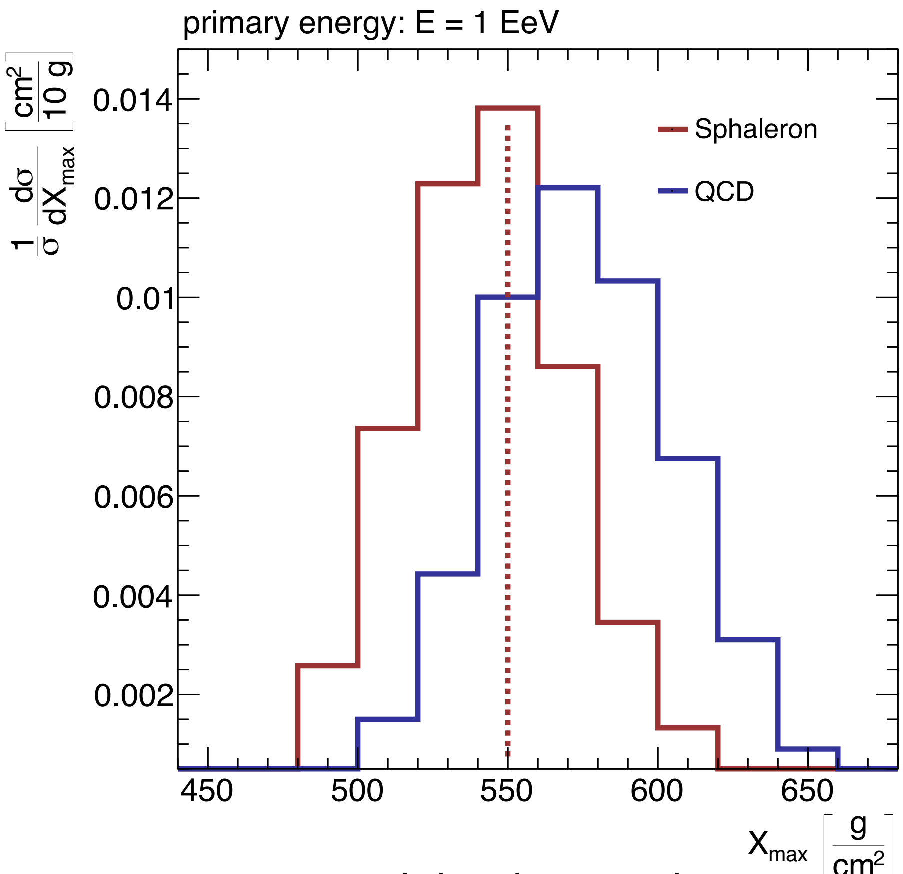
Production of heavy quarks (but also ρ^0):
Muon production height

Altitude of interaction: Lateral distribution of particles at the surface
Heavy quarks, ρ^0 production: Muon/electron ratio at the surface

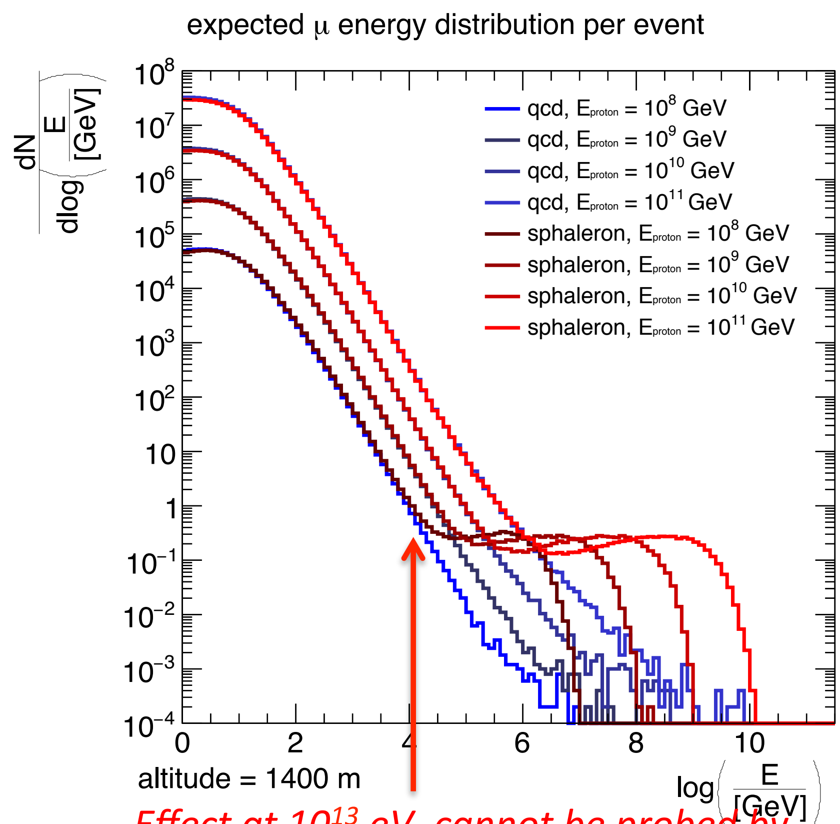
What would the effect of sphaleron production be?

Sphaleron Signature

Increased Cross section → earlier interaction



Note: Vertical depth at 45 degrees, not slant depth!

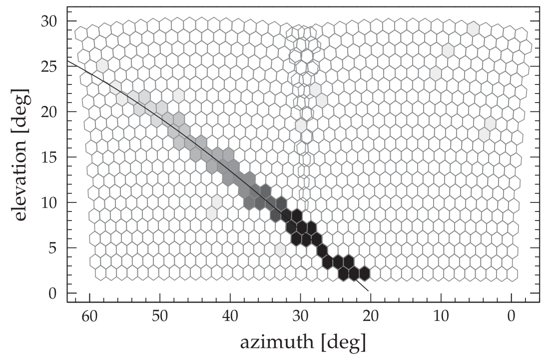


Effect at 10^{13} eV, cannot be probed by underground detectors

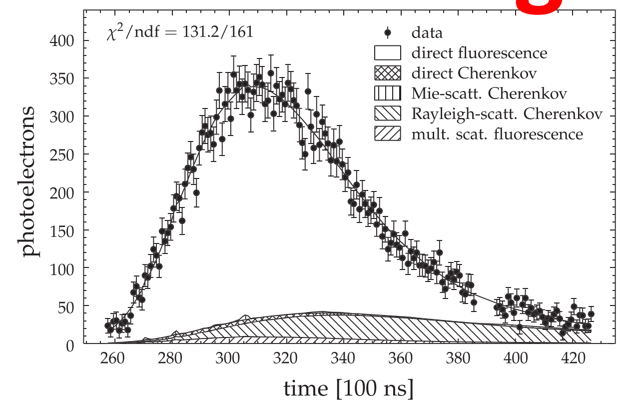
More muons at high energy.
Produced high in the shower.

 Brooijmans, ArXiv 1602.00647

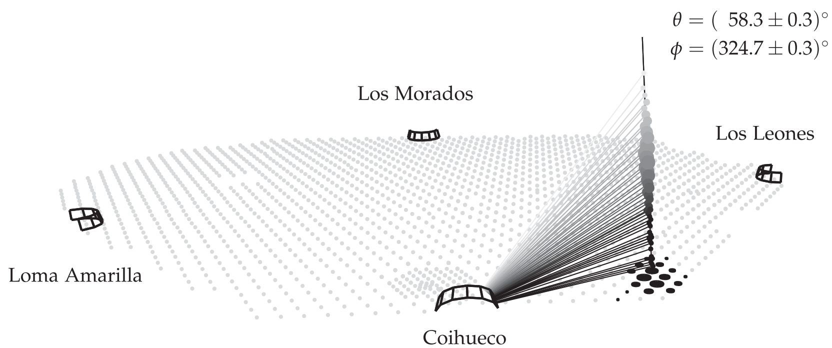
Air shower reconstruction in Auger



(a) Camera view. The timing of the pixel pulses is denoted by shades of gray (early = light, late = dark). The line shows the shower detector plane.

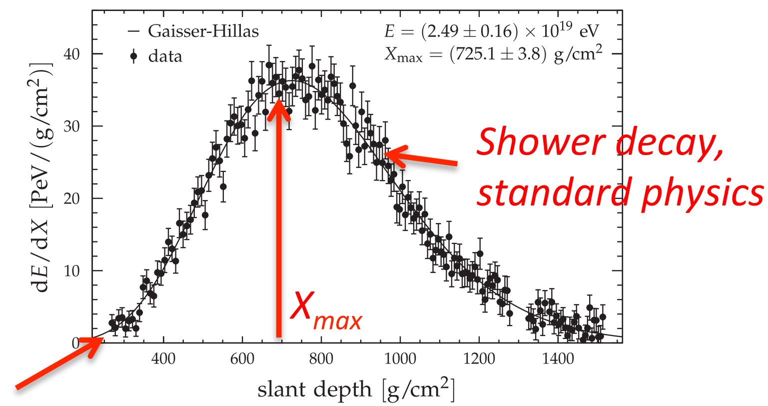


(c) Detected photoelectrons (dots) and the fitted contributions from components of the shower light (open and hatched areas).



(b) Event geometry. Pixel viewing angles are shown as shaded lines and the shower light and surface detector signals are illustrated by markers of different size in logarithmic scale.

EM energy only!



First interaction, difficult to measure accurately

(d) Longitudinal profile (dots) and Gaisser-Hillas function (line).

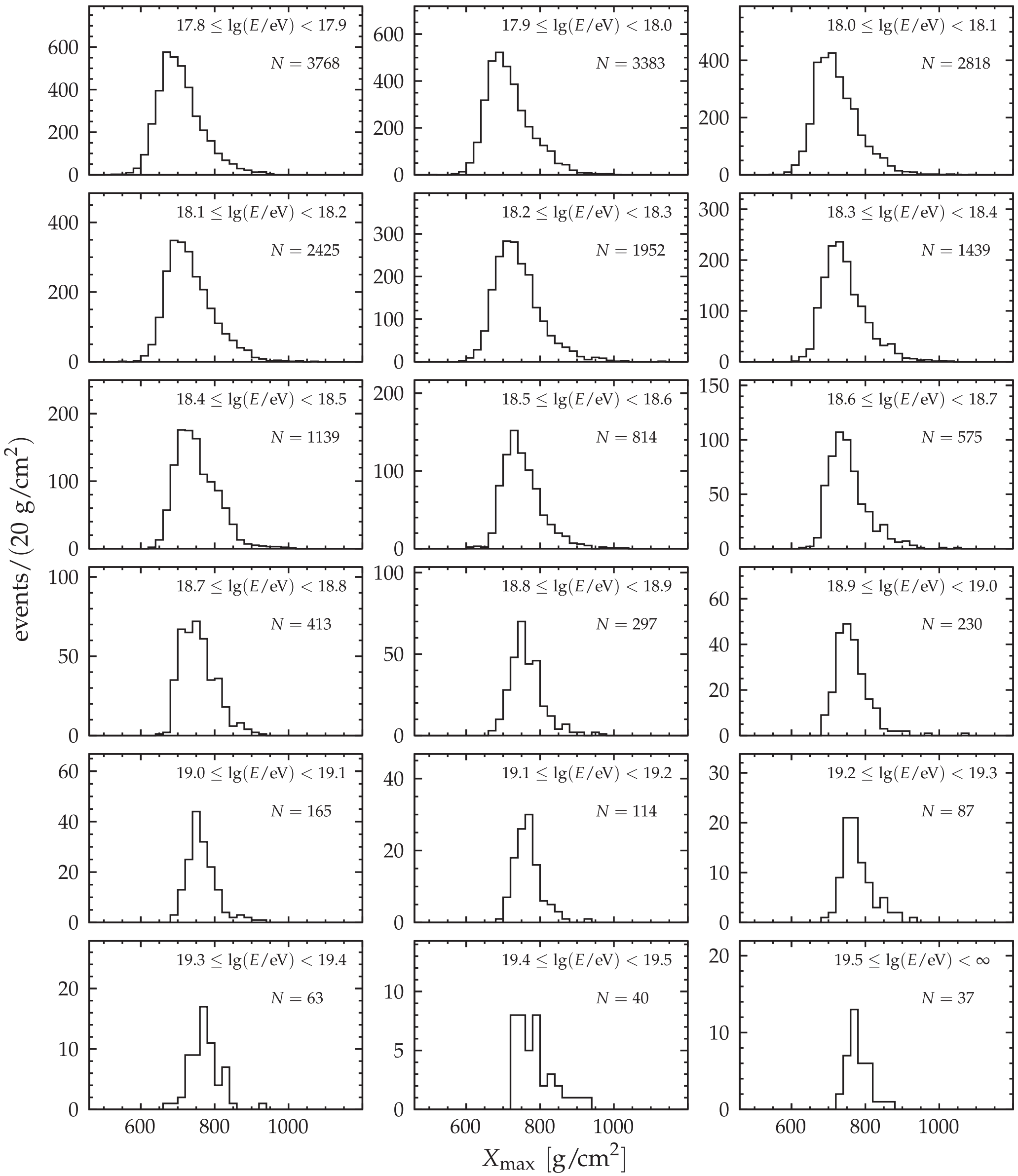
FIG. 1. Reconstruction of event 15346477.

Auger Contribution to the field

Complete X_{max} distributions as a function of energy, to be compared to your favorite model

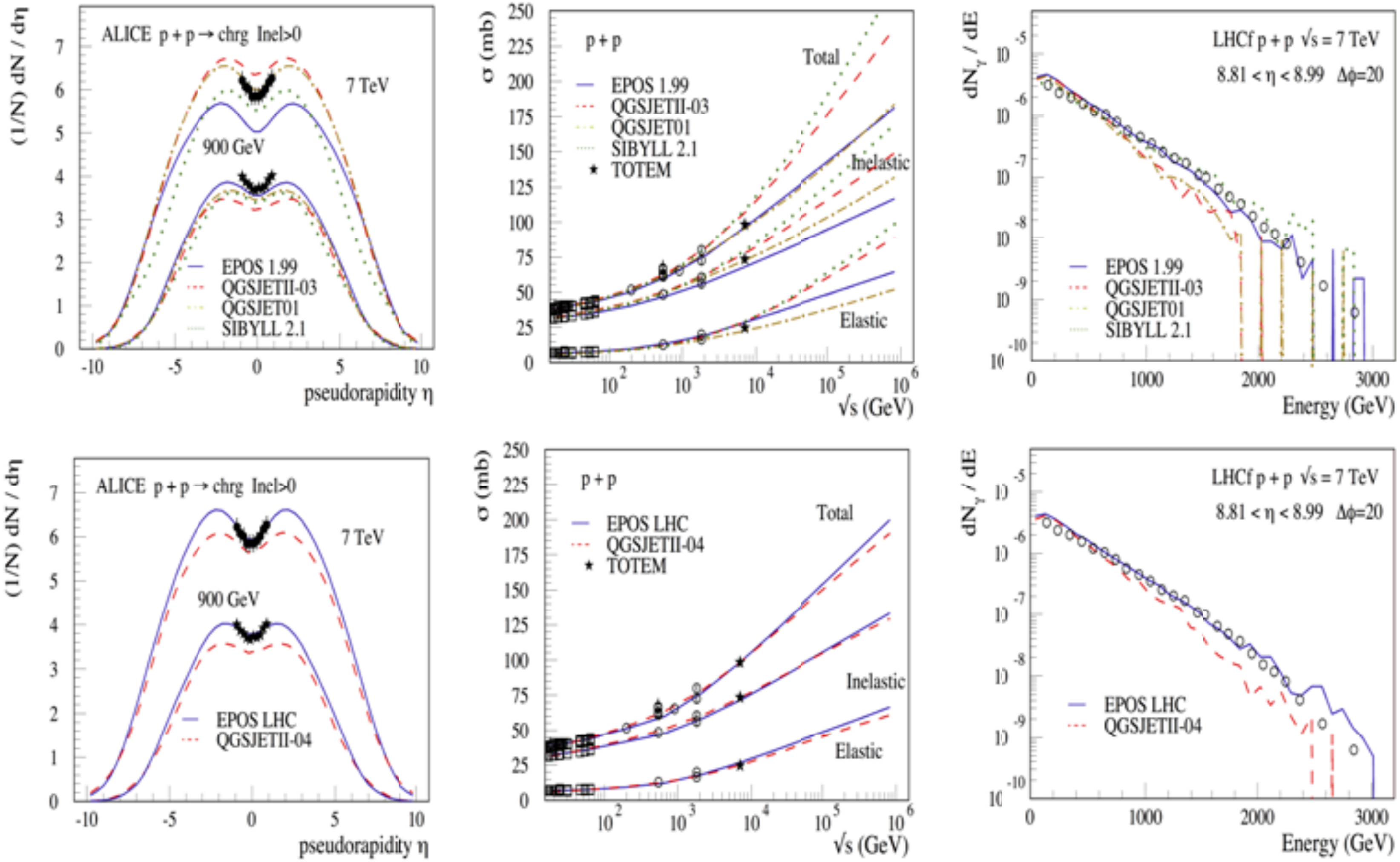
TABLE I. Event selection criteria, number of events after each cut and selection efficiency with respect to the previous cut.

Cut	Events	ε [%]
Pre-selection:		
Air-shower candidates	2573713	. . .
Hardware status	1920584	74.6
Aerosols	1569645	81.7
Hybrid geometry	564324	35.9
Profile reconstruction	539960	95.6
Clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
Quality and fiducial selection:		
P(hybrid)	105749	95.1
X_{max} observed	73361	69.4
Quality cuts	58305	79.5
Fiducial field of view	21125	36.2
Profile cuts	19947	94.4



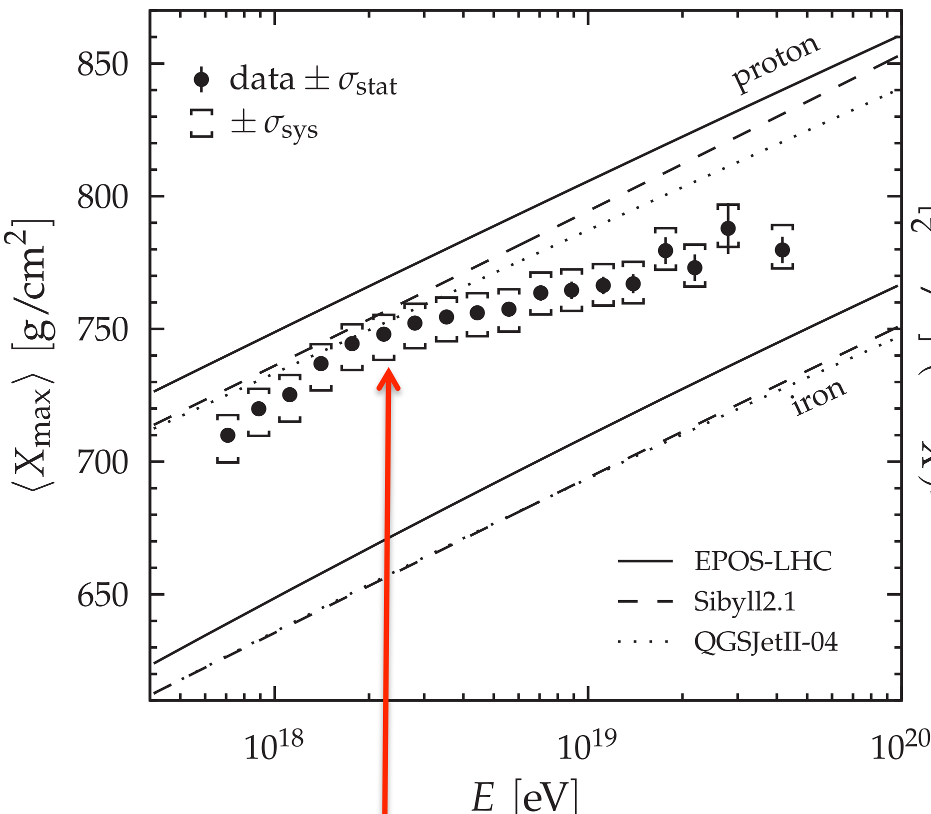
Phys. Rev. D90 (2014)

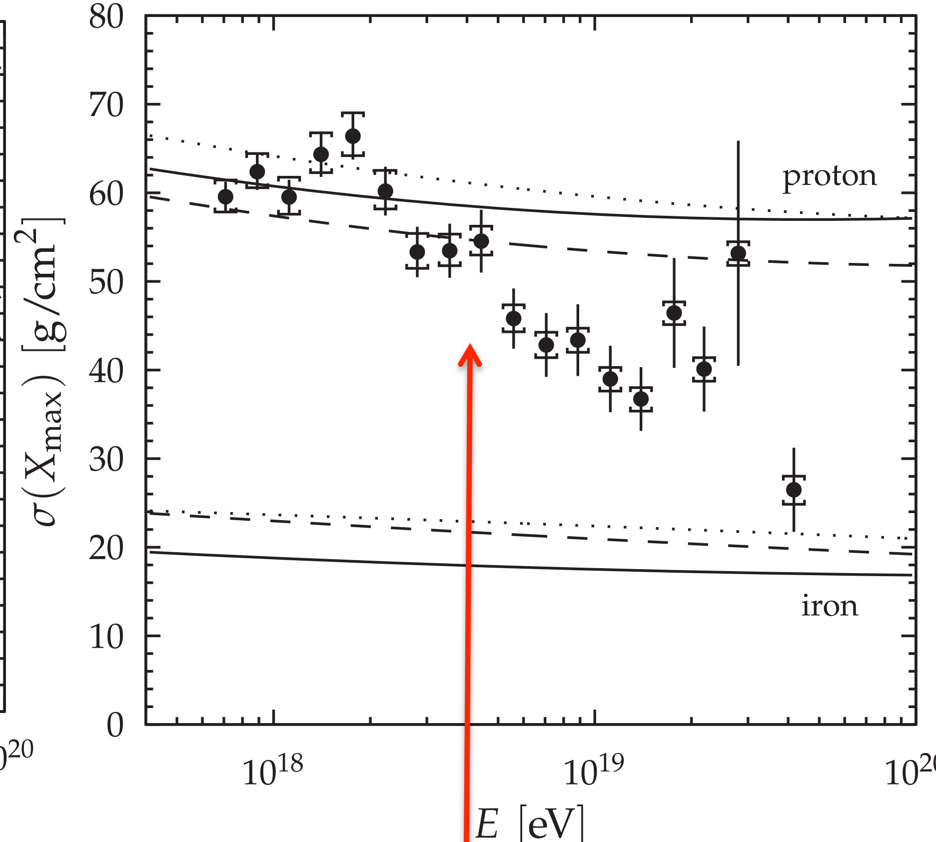
Shower data compared to LHC-tuned simulations



Simulations tuned to LHC measurements

Auger X_{max} summary plots





Cross section increases wrt proton primaries
√(s) = 45 TeV

Width distribution indicates heavier primaries

Sphaleron sensitivity for Auger

Not an Auger result!!

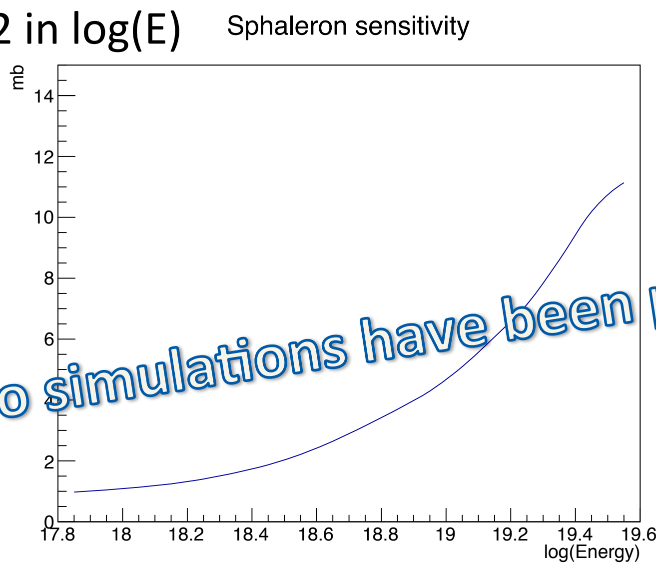
Assuming a sensitivity following

$$f_{\sigma_T} \leq \sqrt{\frac{4\epsilon_{\mathrm{B}}}{\epsilon_{\mathrm{S}}^2 A^2 N}},$$

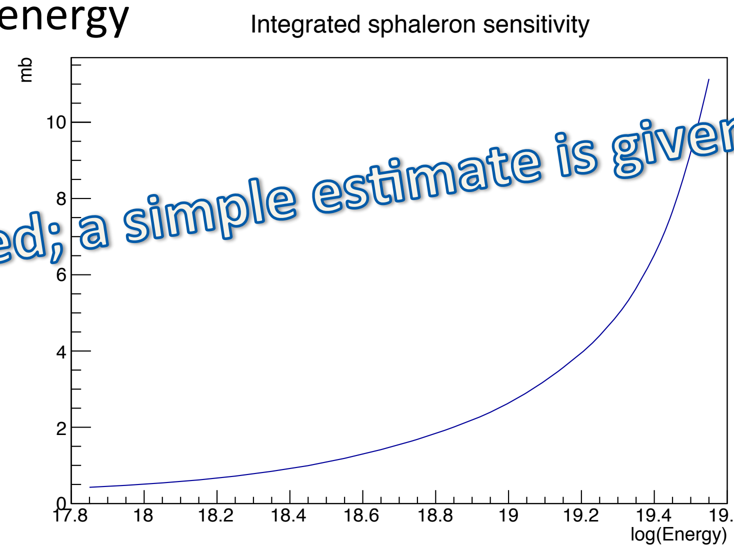
Brooijmans, ArXiv 1602.00647

An efficiency for background acceptance of 20%
An efficiency for signal acceptance of 50%
Assumption protons only, and data in agreement with protons
Event numbers per energy bin as shown before

Sphaleron sensitivity in energy bins of 0.2 in log(E)

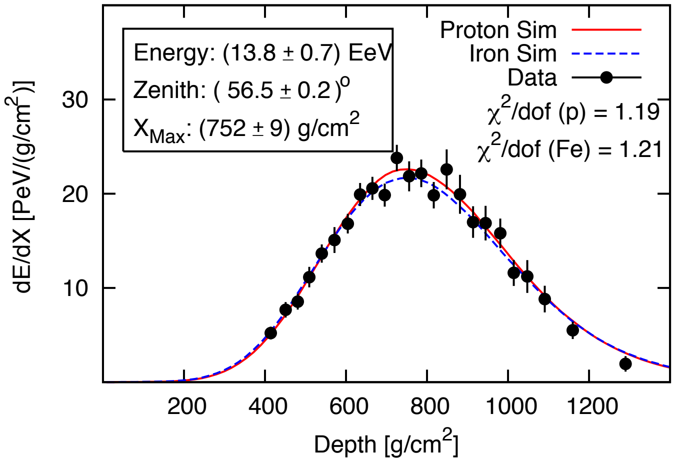


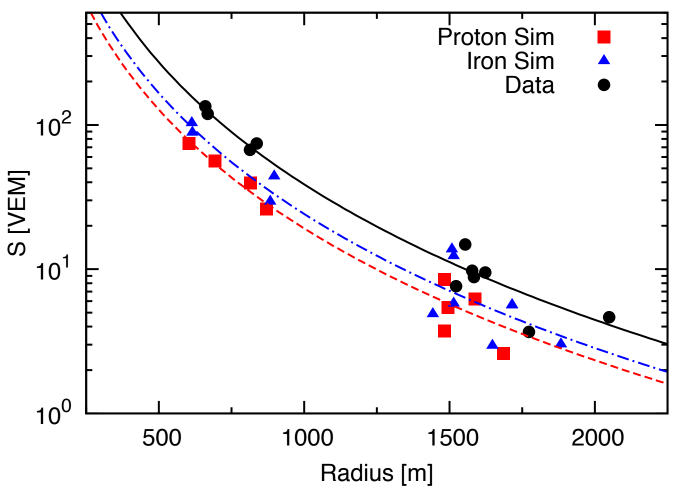
Sphaleron sensitivity above a certain energy



No simulations have been performed; a simple estimate is given

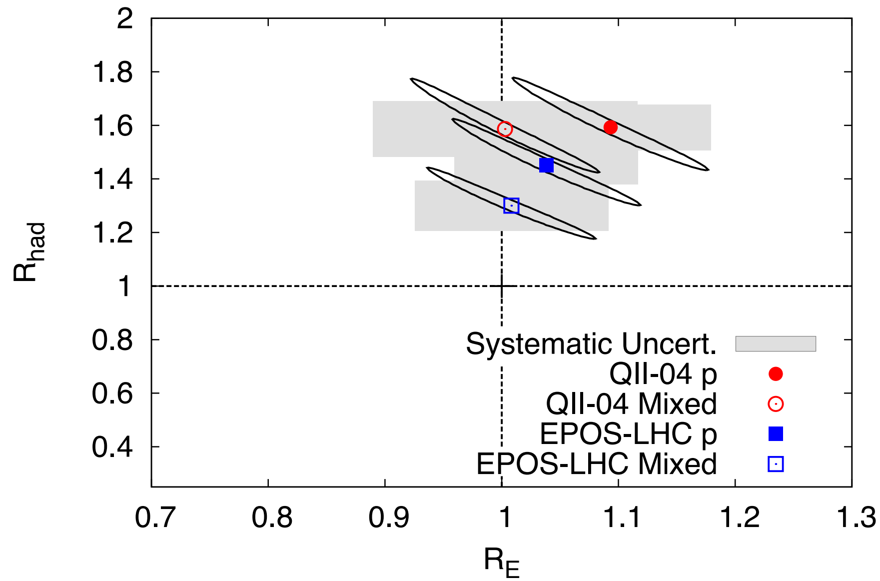
Disentangling new physics from composition of primary: More observables





Combine ground signal and FD

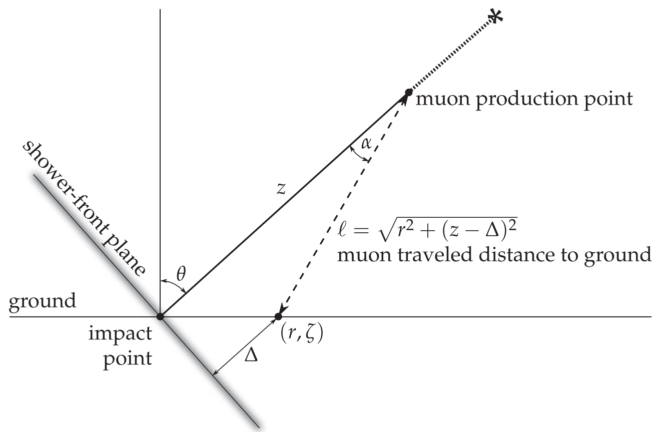
$10^{18.8}$ < Energy < $10^{19.2}$

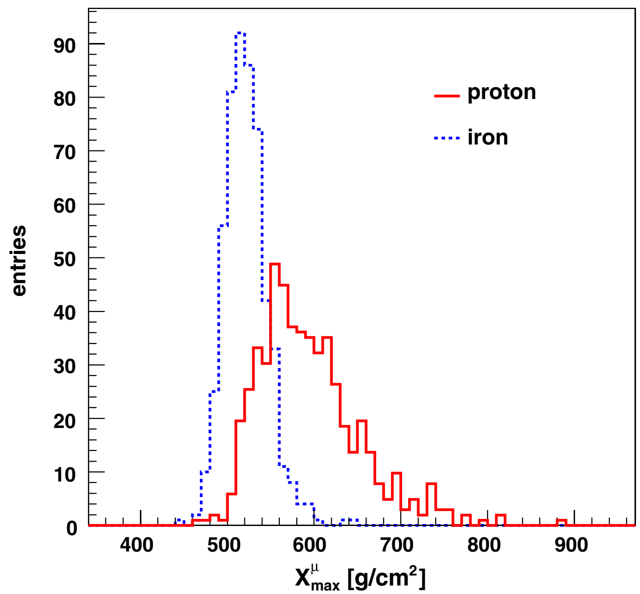


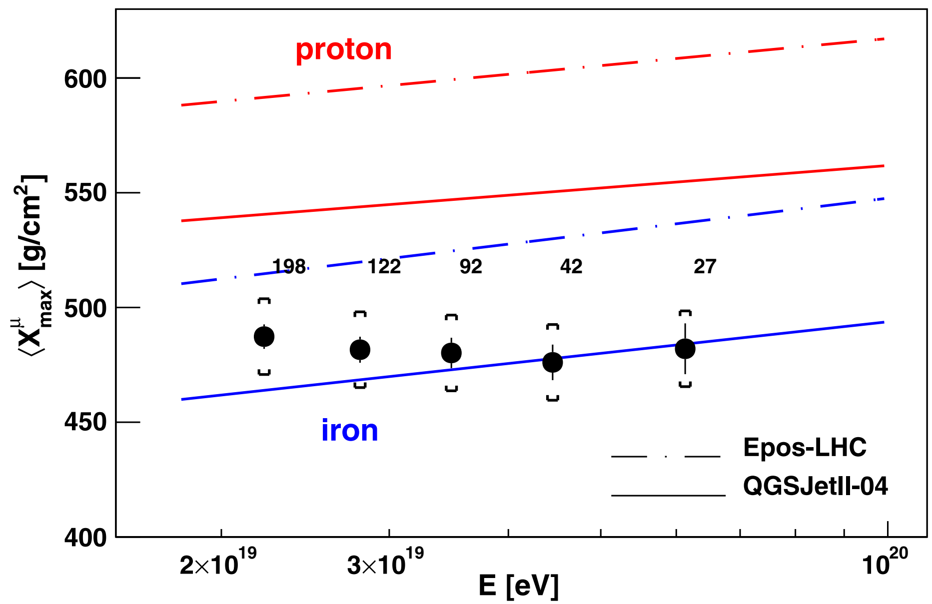
Energy scale can be correct (EM component), but hadronic component much larger in data

PRL August 2016

Muon production depth



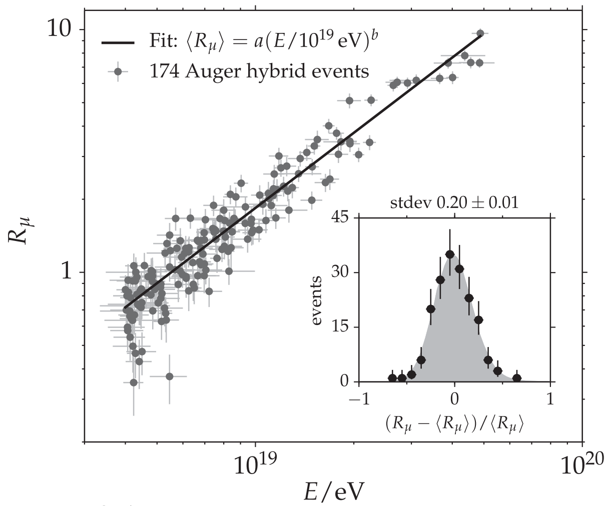




The simulation that best describes the EM production fails to describe the muon production depth. Muons recorded at Earth are generated higher up in the atmosphere

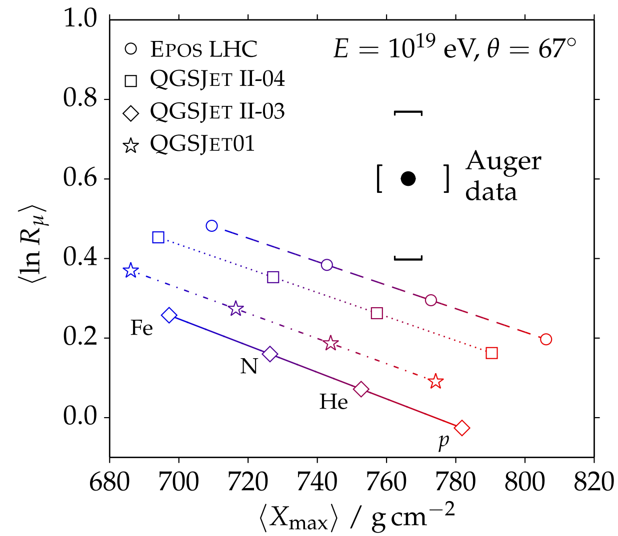
Phys. Rev. D90 (2014), D92 (2015)

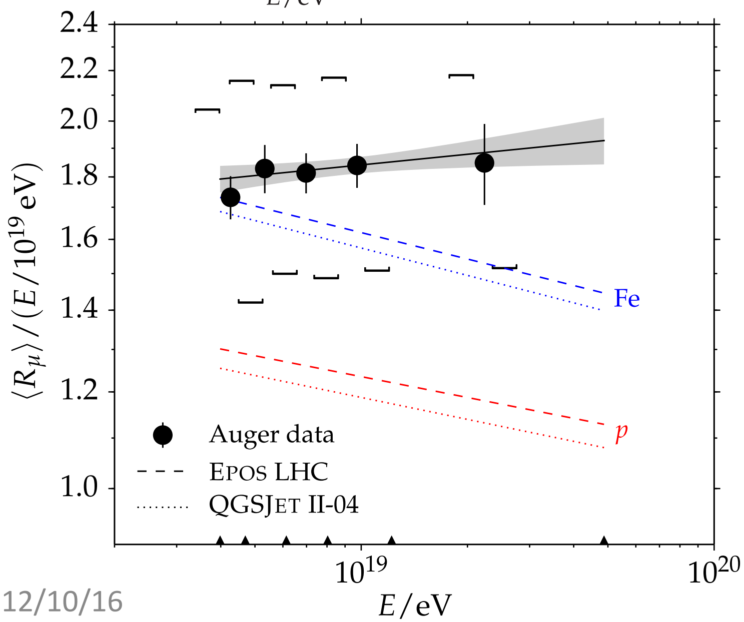
Number of muons in inclined showers



R_μ = 1 means 2.148 10^7 muons with energy above 0.3 GeV at the Auger site.

R_μ is calculated from measured 'muon' distribution

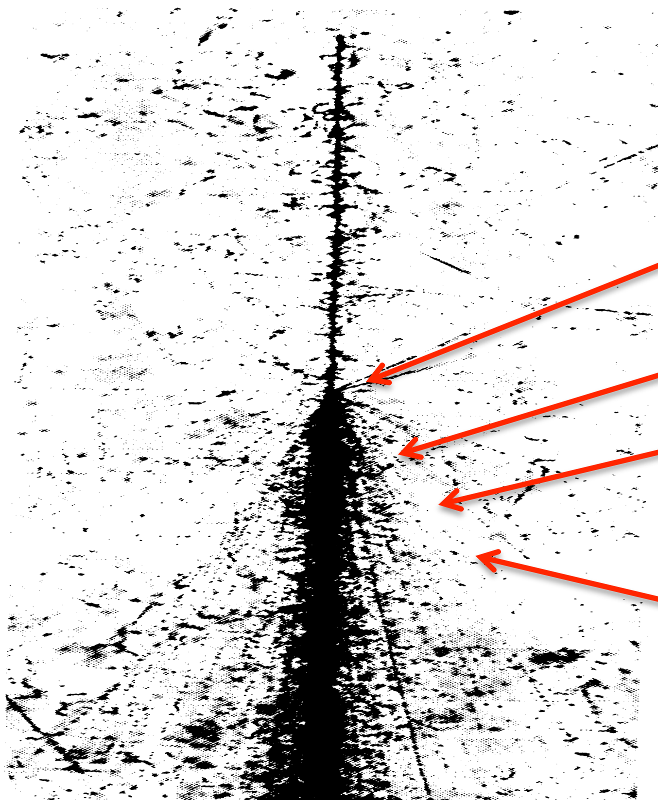




Too many muons are observed in the air shower,
But the uncertainty is large

Phys. Rev. D91 (2015)

AugerPrime improvements



Cross section: Altitude of first interaction

Multiplicity: Speed of shower development

High energy photons: EM/hadronic energy

Production of heavy quarks (but also ρ^0): Muon production height

Altitude of interaction: Lateral distribution of particles at the surface
Heavy quarks, ρ^0 production: Muon/electron ratio at the surface

Conclusions

- At 2 EeV the Auger Xmax measurement is compatible with protons
- This gives a limit on sphaleron production of about 1 mb
- At higher energies, the average shower depth decreases wrt proton primaries, indicating larger cross sections . This is usually attributed to higher mass primaries.
- The surface detector information is incompatible with the models, for all “standard” primary particles.
  - Muon depth: Too high in the atmosphere
  - Muon number: Too many produced
  - Hadronic energy ~ 30% too much
- The upgrade of Auger will decrease the uncertainty on the SD information