Particle physics at the Pierre Auger Observatory

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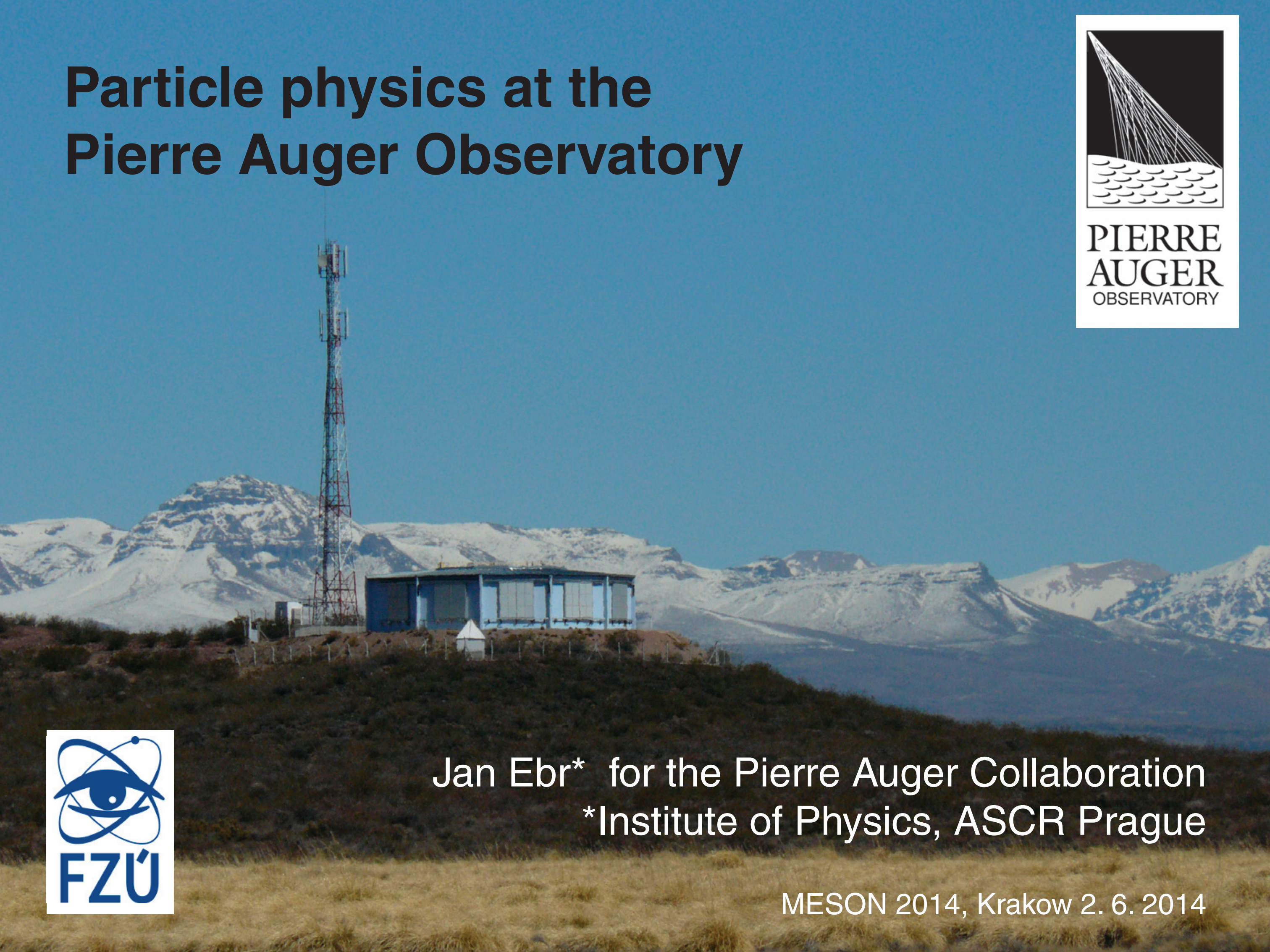
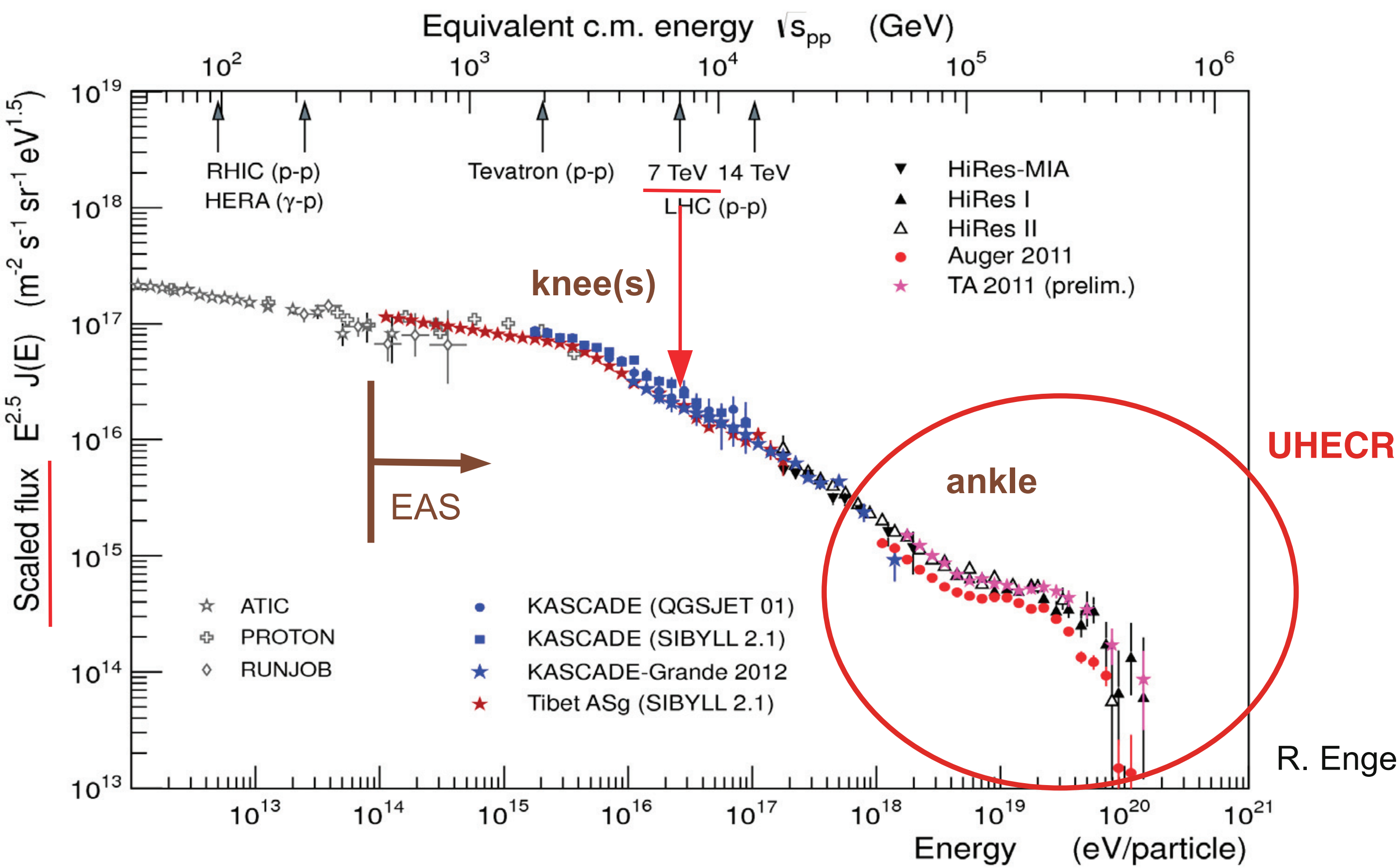
MESON 2014, Krakow 2. 6. 2014



Overview

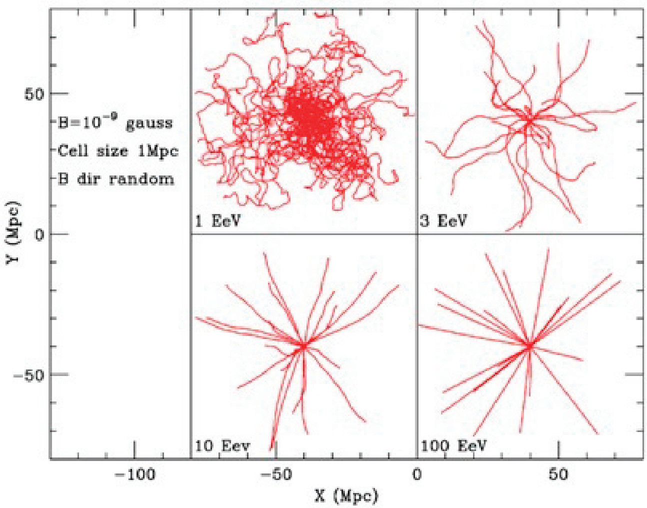
- Ultra-high energy cosmic rays (UHECR) and Extensive air showers (EAS)
- Pierre Auger Observatory
- Longitudinal developement
  - primary beam composition
  - proton-air cross-section
- Muon content at ground level
- Comparison with current hadronic interaction models

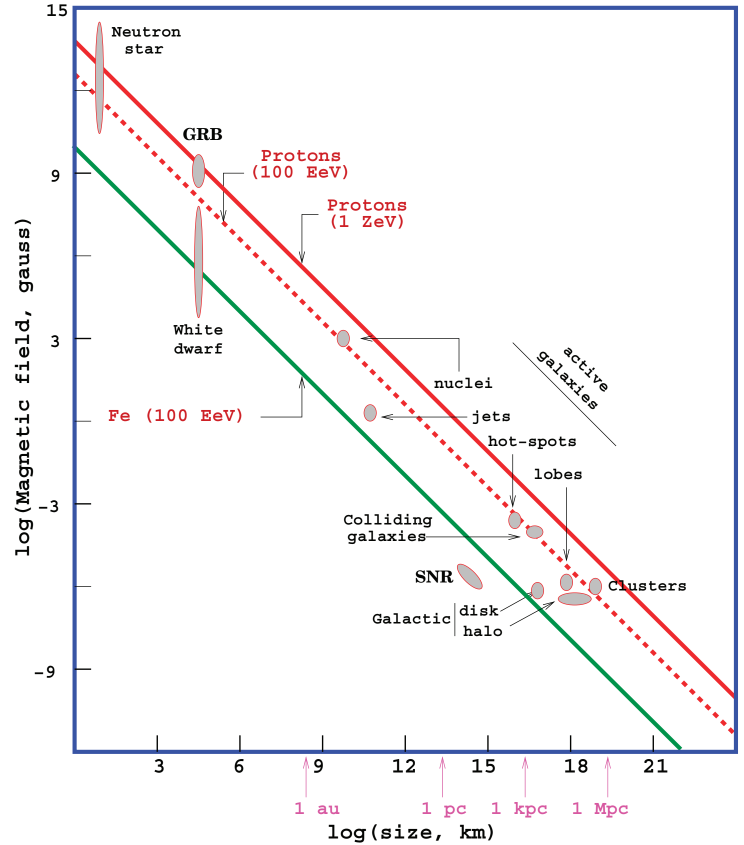


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2011
TA 2011 (prelim.)
knee(s)
EAS
ankle
UHECR
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)
R. Engel

Ultra-high energy CR

- Highest-energy astrophysics
- Exotic sources: AGNs, BHs ...
- Both acceleration and propagation in magnetic fields → particle identification (“mass composition”) essential for interpretation



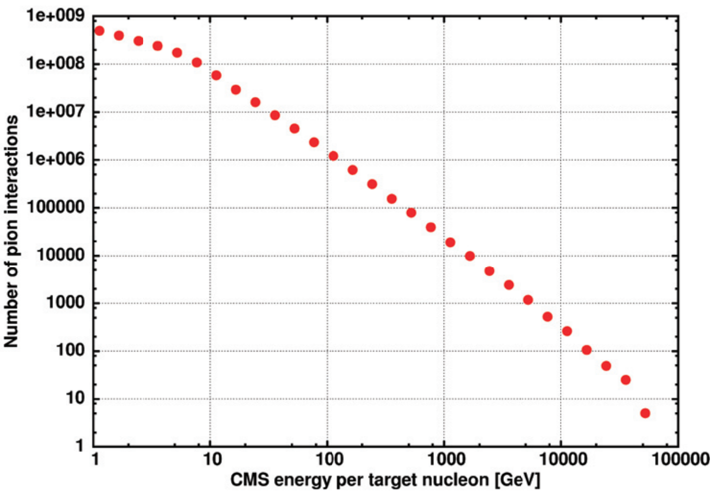


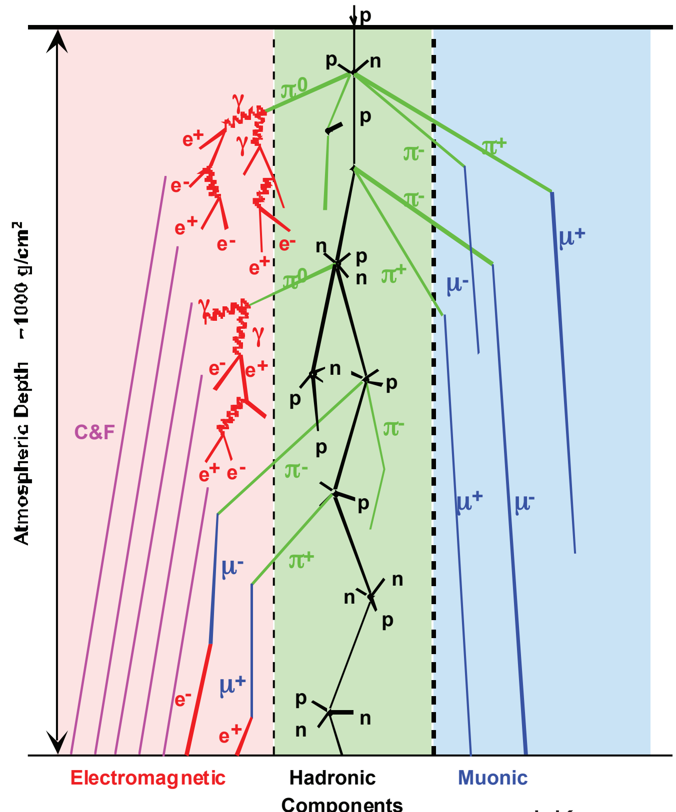
J. Cronin

Extensive Air Showers

- For UHECR: billions of particles
- Secondary hadrons (mostly pions)
- Electromagnetic cascade (π^0 decay)
- Muons ($\pi^{\pm}$, K ... decay)

Below: pion interactions in one simulated 10^{19} eV proton shower → lots of **meson** physics!

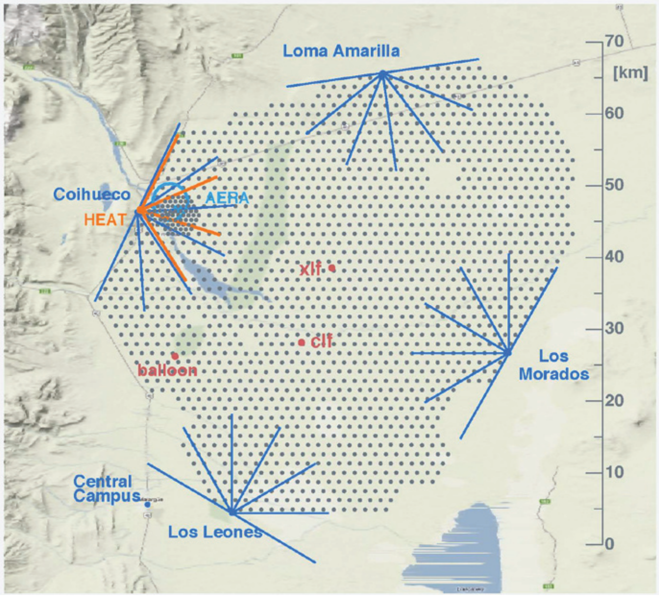


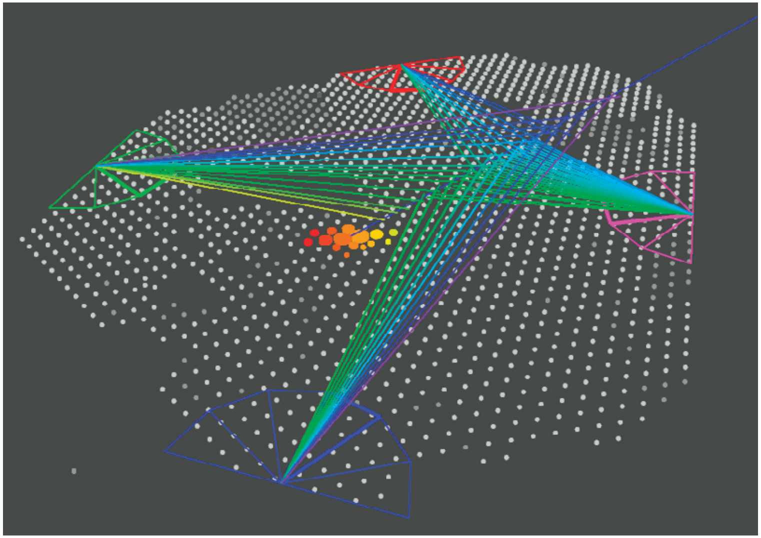


J. Knapp

The Pierre Auger Observatory

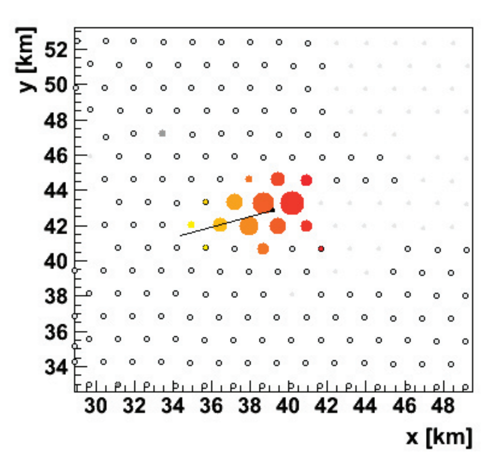
- Surface detector: 1600 water Cherenkov detectors accross 3000 km^2
  - particles arriving at ground level
  - 100 % duty cycle
  - well-known aperture
  - 1500 m spacing → E > $10^{18.5}$ eV
  - AMIGA: 750 m spacing → E > $10^{17.5}$ eV

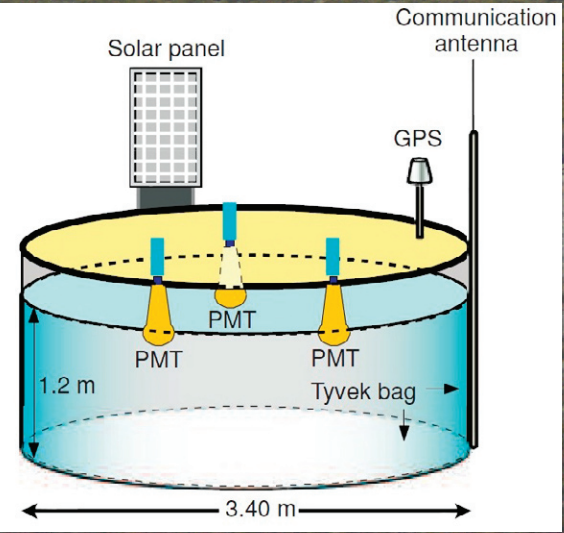


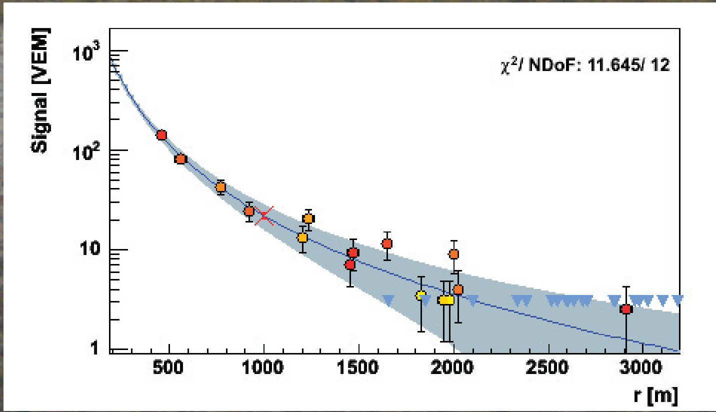


- Fluorescence detector: 24+3 telescopes of 28°×30° FOV
  - UV light from excited N_2
  - 13% duty cycle
  - good energy resolution
- Auxiliary devices
  - atmospheric monitoring
  - detector callibration

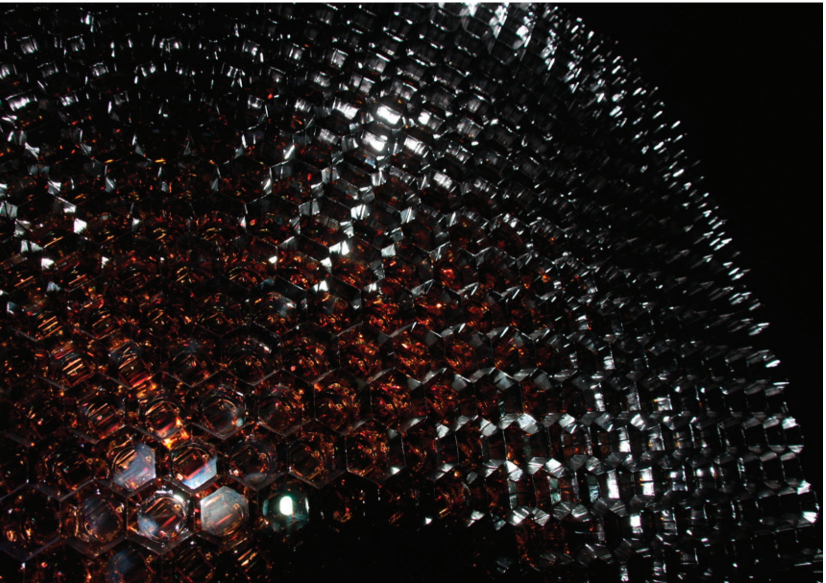
Surface detector

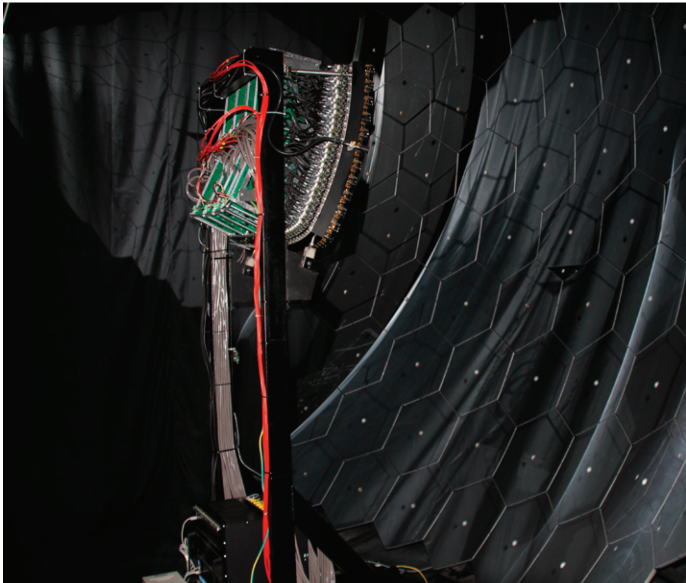






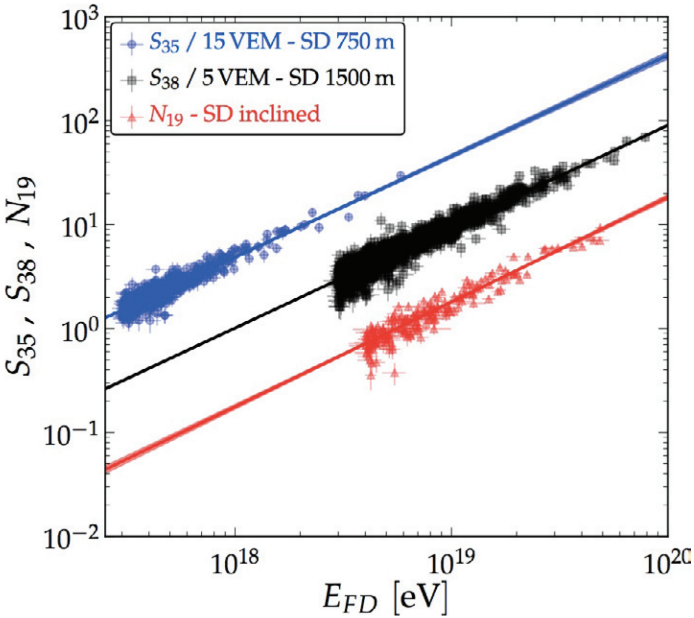
Fluorescence detector

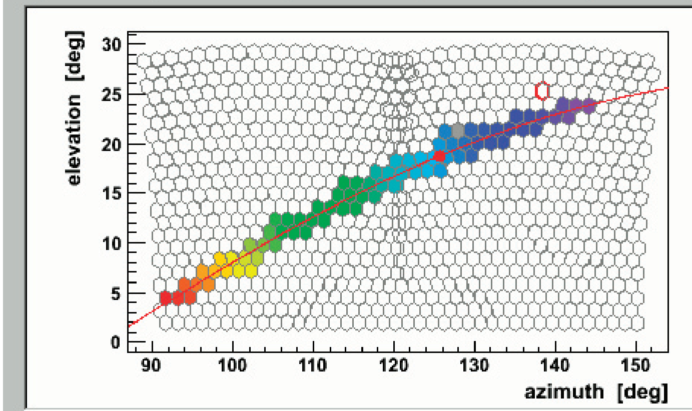


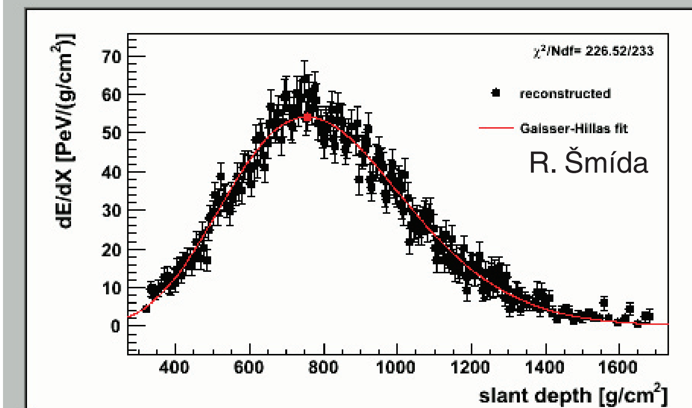


Fluorescence detector

- Calorimetric energy measurement (minus “invisible energy”)
- Calibrate energy estimators of SD
- Systematic uncertainty on the energy scale: 14% (before update 22%)



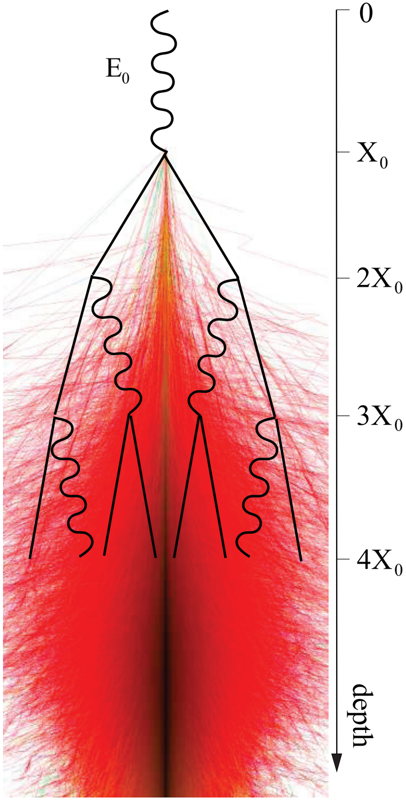




- Energy resolution: 7–8 % (FD), 17–12 % (SD)

Longitudinal shower developement

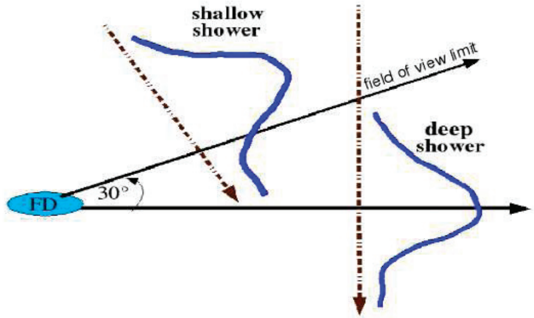
- Electromagnetic cascade (Heitler model)
  - splitting length ≈ radiation length X_0
  - n lengths → 2^n particles, each carries $E = E_0/2^n$
  - when $E < E_{crit}$ (≈ 87 MeV) shower stops growing
  - $X_{max} \approx X_0 \ln(E/E_{crit})$
- Hadronic cascade more complex (Heitler-Matthews)
  - mean free path of 1st interacion λ
  - multiplicity N of interactions
  - ≈ 1/3 of secondaries $\pi^0 \rightarrow$ EM cascades
  - stops with $\pi^\pm$ decay to muons
  - Superposition model for nuclei: A showers with energy E_0/A
- $X_{max} \sim \lambda + \ln(E_0) - \ln(N) - \ln(A)$
  - shallower for heavier nuclei (A lower-energy showers)
  - depends both on composition and interaction
  - simplified model! In pratice: Monte Carlo simulations

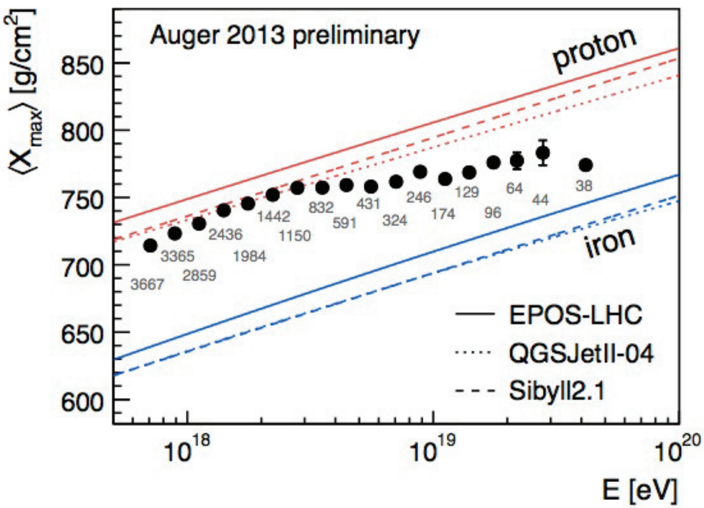


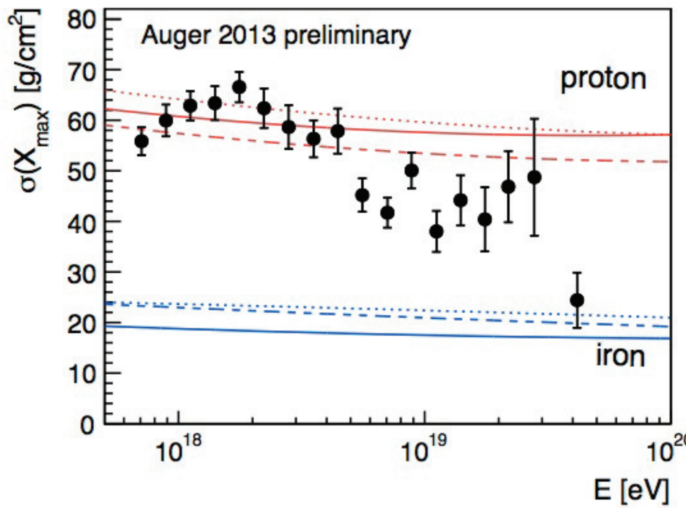
M. Unger

Depths of shower maxima – data

- Unbiased distribution by fiducial volume selection
- Fluctuations corrected for detector resolution
  - heavier nuclei: A showers – less fluctuation
- Suggestive for change of composition (or interaction models) around $10^{18.5}$ eV

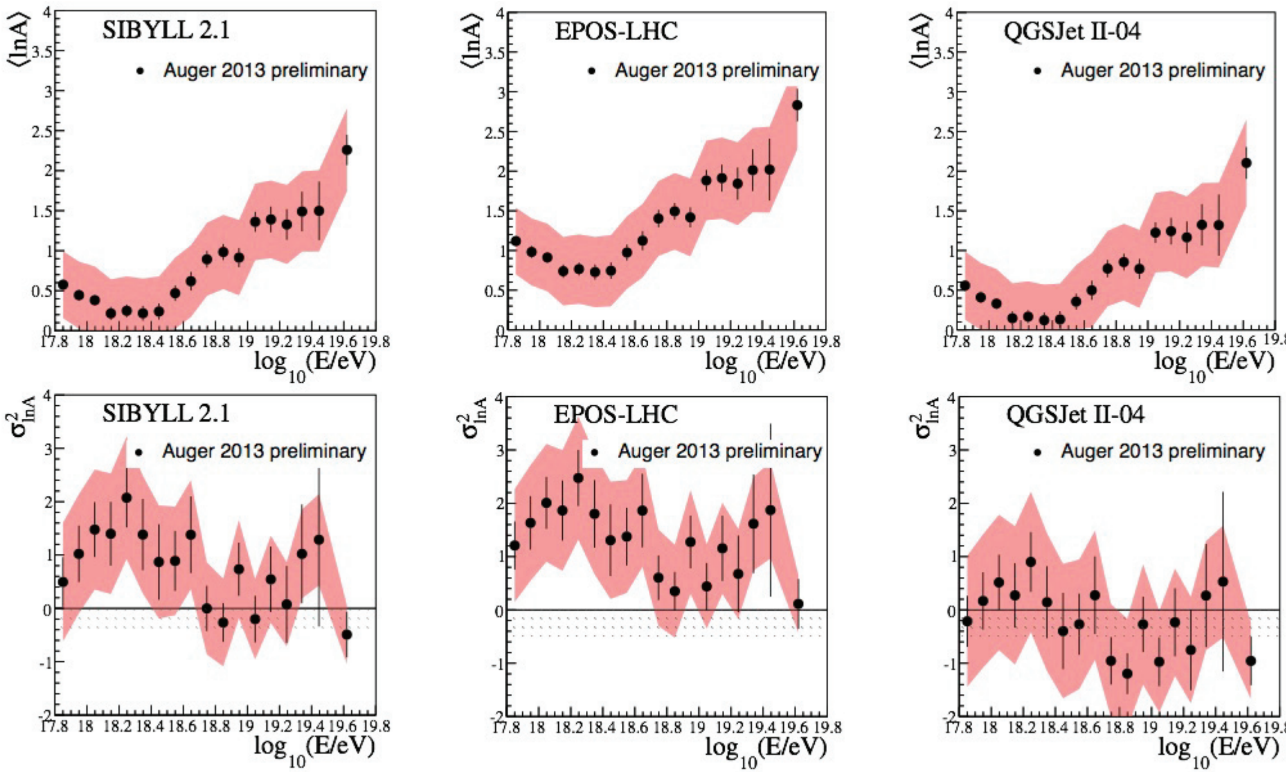






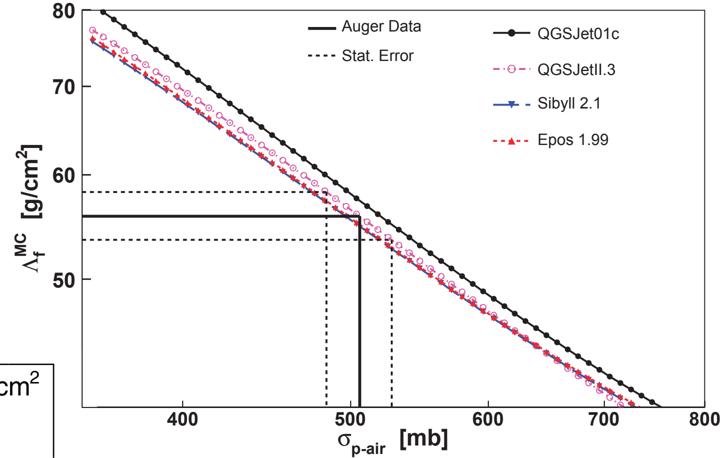
Depths of shower maxima – interpretation

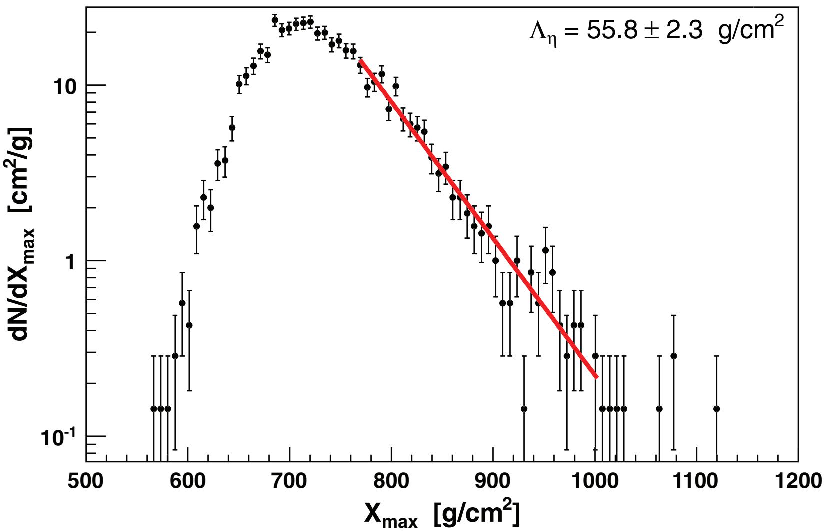
- Not all combinations of mean depth and fluctuations physically possible
  - n.b.: *within erros* still agrees with all models



Particle physics from EAS: p-p cross-section

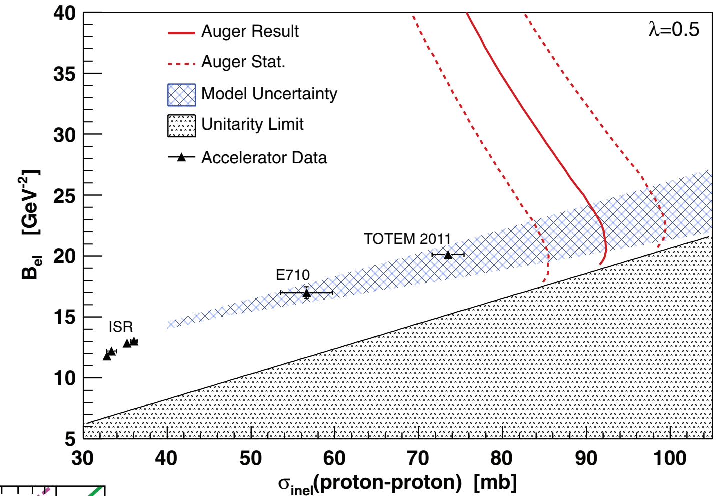
- Fitting the exponential tail of X_{max} distribution
- selects mainly proton-induced showers
  - X_{max} data suggest large proton fraction at least at low energy



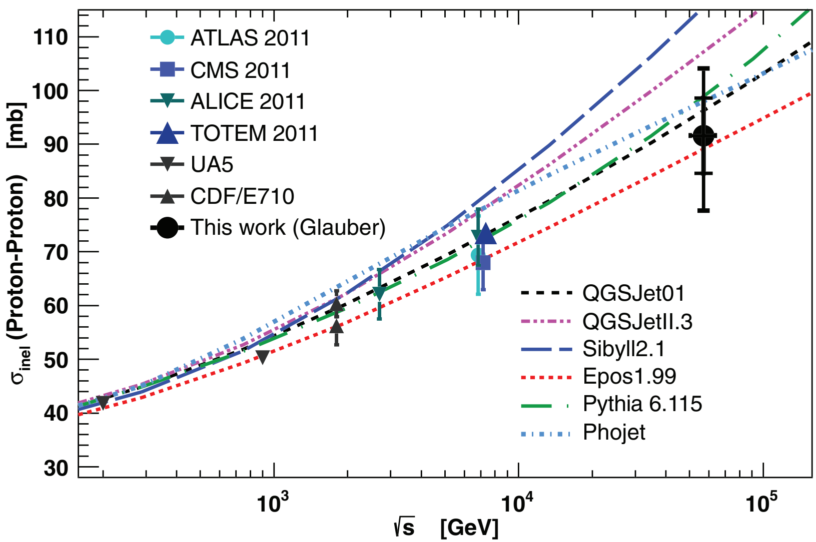


- conversion to cross-section
  - depends on simulations
  - systematics given as differences between models
  - additional systematics from possible He and photon contamination

Particle physics from EAS: p-p cross-section



- Conversion to proton-proton cross--section
  - uncertainities in theoretical assumption (slightly moderated by correlations)

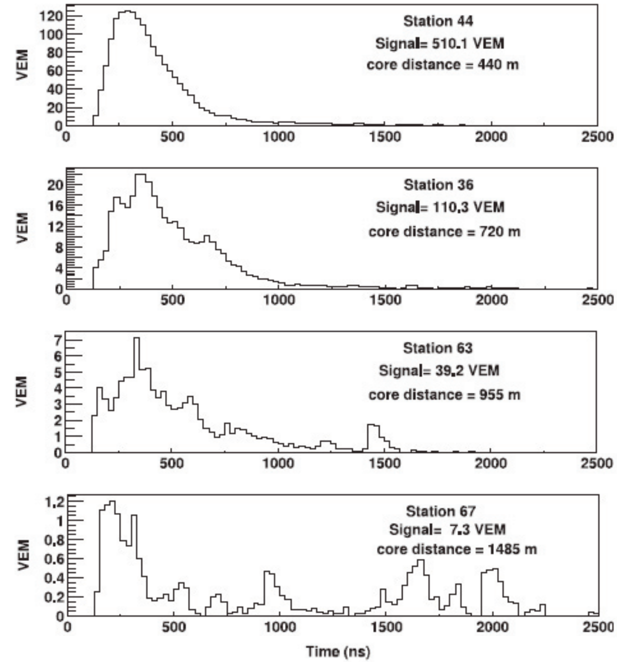


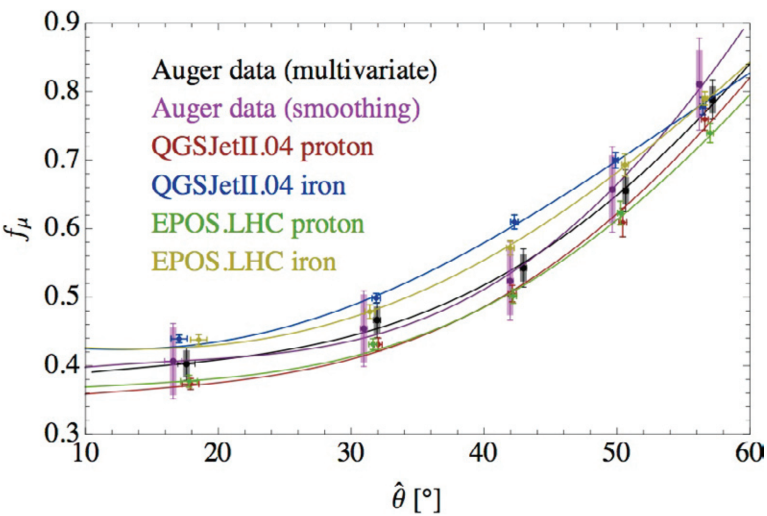
- average c.m.s energy per nucleon 57 TeV

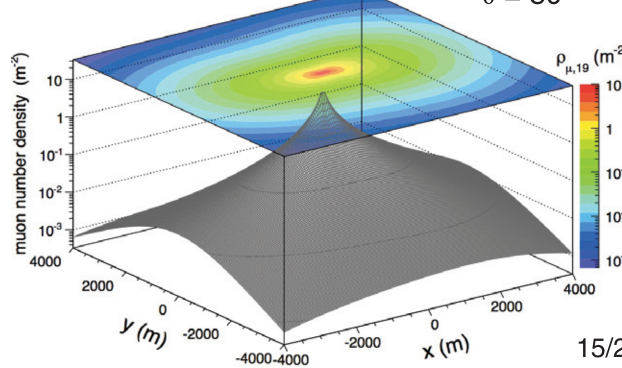
$$\sigma_{pp} = 133 \pm 13(\text{stat})\ ^{+17}_{-20}\ (\text{syst}) \pm 16(\text{Glauber})\ \text{mb}$$

Muon content at ground level

- From superposition model: large nuclei → less generations → less energy converted from hadronic shower to π^0 → more muons
- Water Cherenkov Detectors: combined EM and muon signal
    - analyse time structure for separation
    - use highly inclined showers dominated by muons

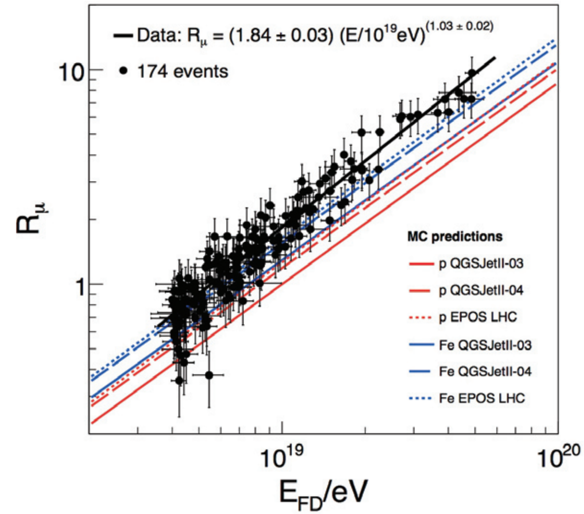


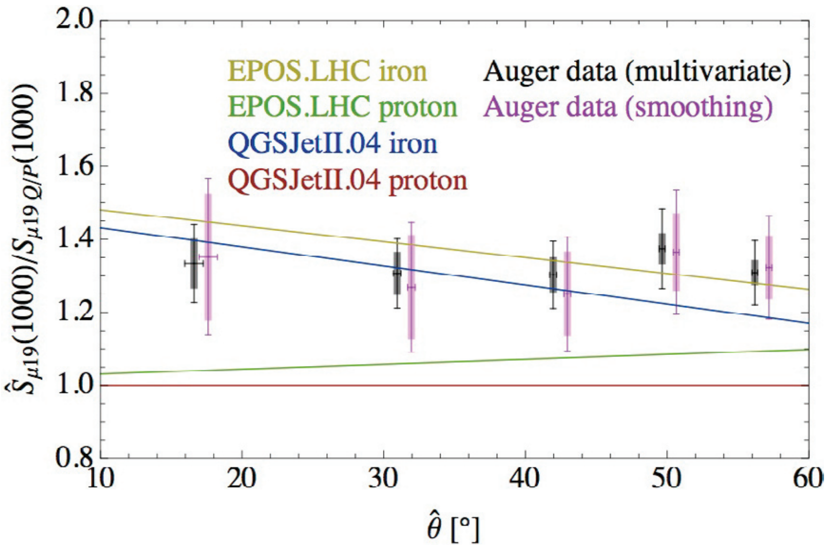


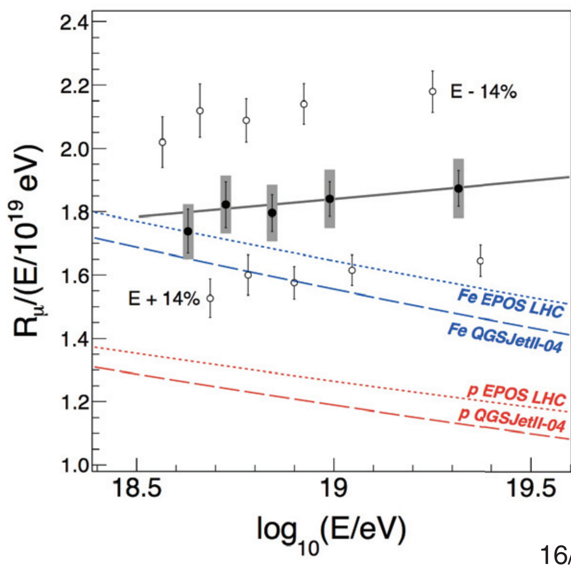


Muon content at ground level

- Both vertical and inclined events indicate muon excess w.r.t. simulations
  - within energy systematics compatible with pure iron
  - however pure iron incompatible with X_{max} data

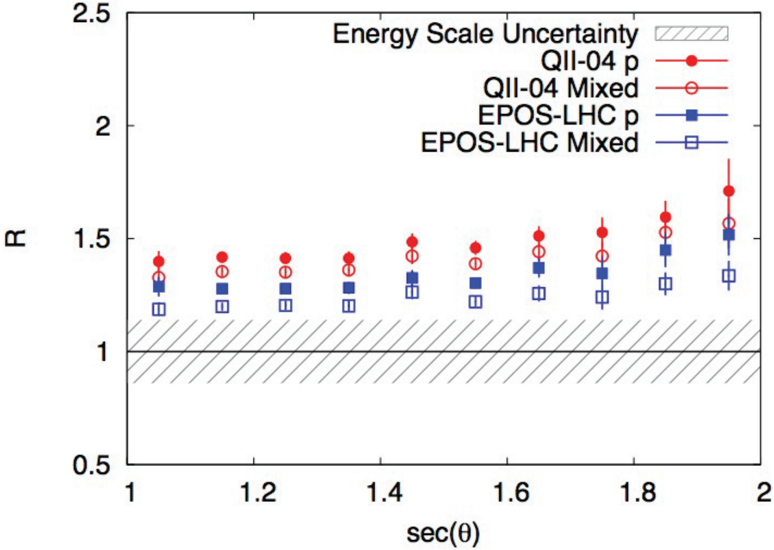


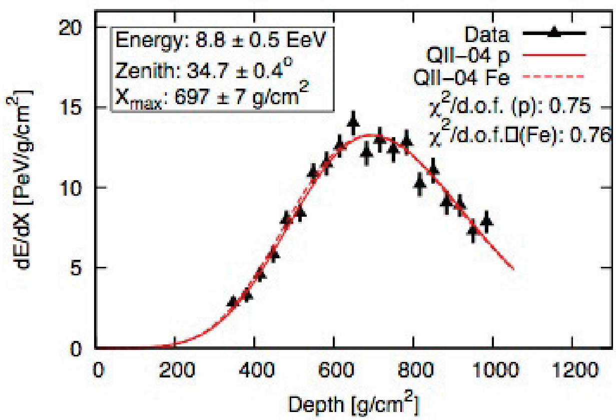


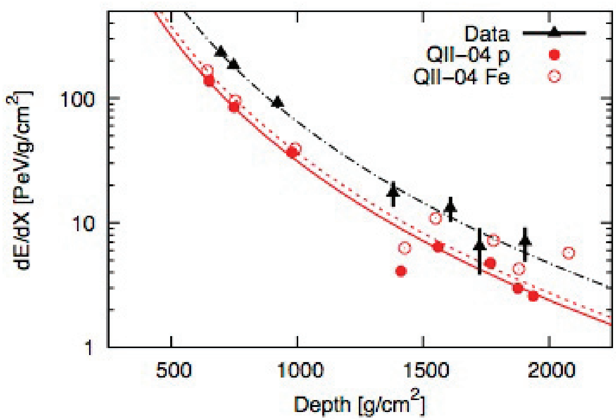


Longitudinal and ground data combined

- For individual well-measured events, pick simulated events with matching profiles.
  - does the ground signal match?

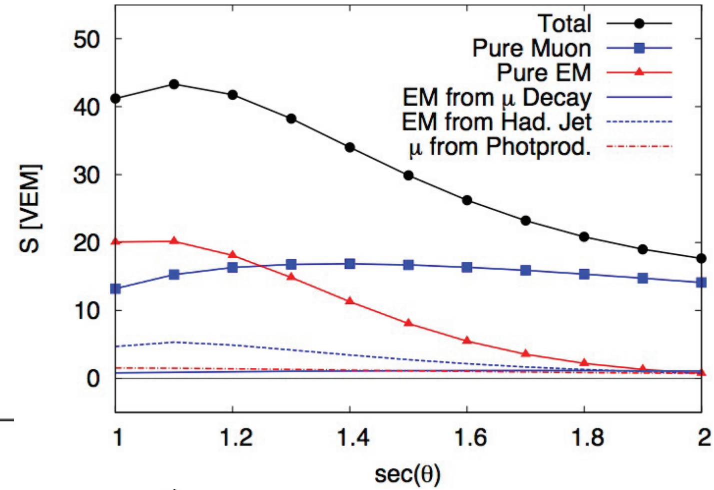


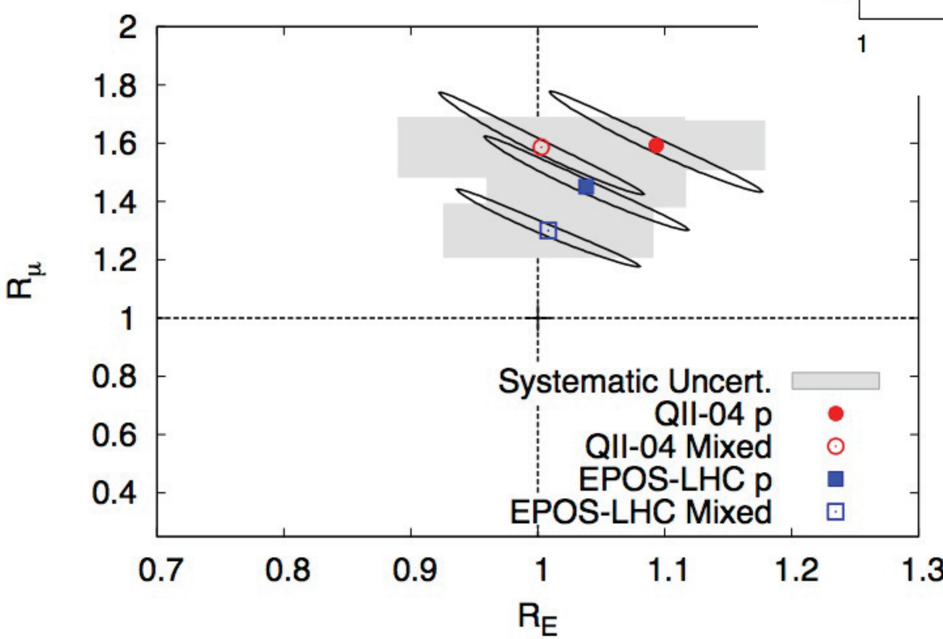




Longitudinal and ground data combined: results

- When it does not, allow EM and muon component to be rescaled independently

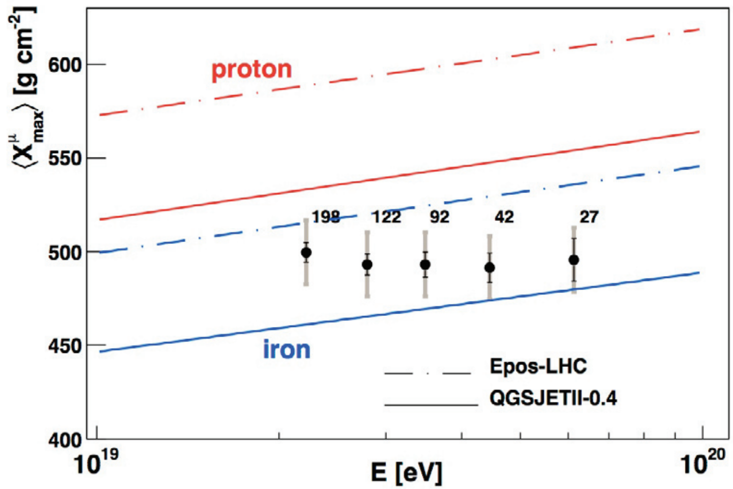


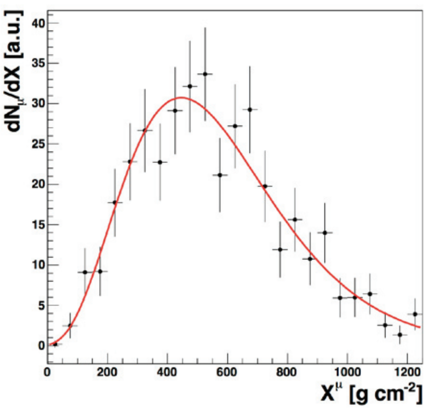


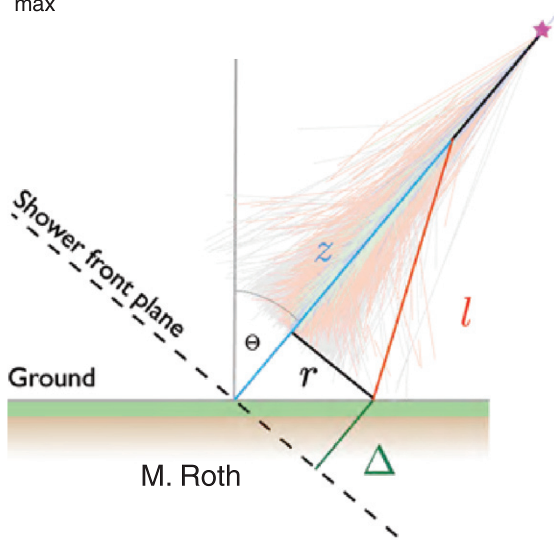
- Different zenith angle dependence allows separation using many events

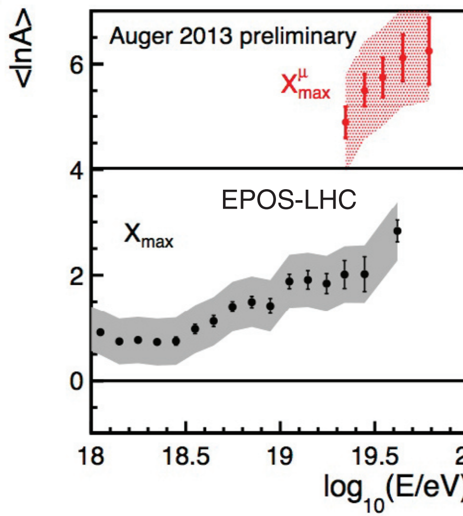
Muon production depth

- Inclined events: identify indiviual muons, measure time delay = reconstruct depth of production
  - 55°– 65° zenith angle to avoid EM contamination
  - distances between 1700–4000 m from shower core
  - incompatible $X_{max} - X^{\mu}_{max}$ for EPOS-LHC









Conclusions

- The Pierre Auger Observatory is sensitive to various observables related to hadronic interactions at extremely high energies
- While most of these observables are also influenced by the (as of yet unknown) composition of the primary beam, useful information for the improvement of interaction models can be extracted, often from interplay between different observables
- A clean and easily interpreted result fo the proton-air cross-section has been shown.
- Further progress is expected with more data, particularly thanks to the currently planned upgrade aimed at a more precise muon measurement.