Ultrahigh Energy Cosmic Rays

What Do We Know and What's Next?

M. Unger (NYU&KIT)

photo by S.J. Saffi, University of Adelaide

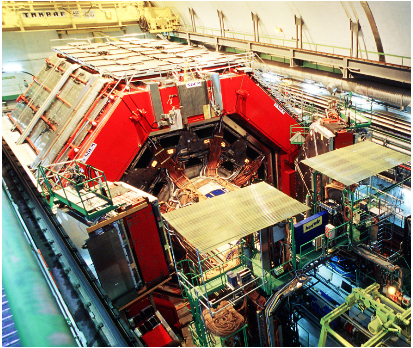
Detour: Astroparticle Physics with Rolf (L3+C)

PRECISION MEASUREMENT OF THE COSMIC RAY MUON MOMENTUM SPECTRUM BETWEEN 20 AND 2000 GeV/c

A letter of intent

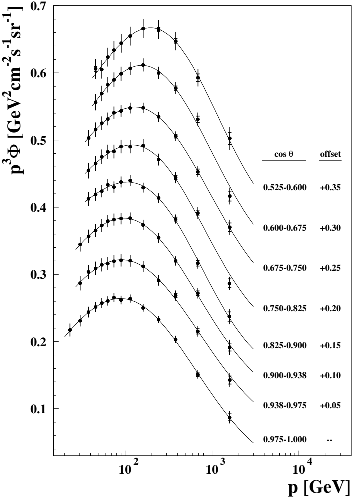
J. Baehr, B. Betev, G. Bobbink, D. Bourilkov, I. Duran, H.S. Chen, H.J. Grabosch, H. Groenstege, T. Hebbeker, H. Hofer, L. Jones, W. Kittel, A. Koenig, J. Kuijpers, P. Le Coultre, H. Leich, R. Leiste, W. Lohmann, B. Monteleoni, R. Nahnhauer, V. Naumov, B. Petersen, B. Schoeneich, H.W. Tang, G. Trowitzsch, U. Uwer, A. van Mil, T. Wijnen.

July 11, 1996

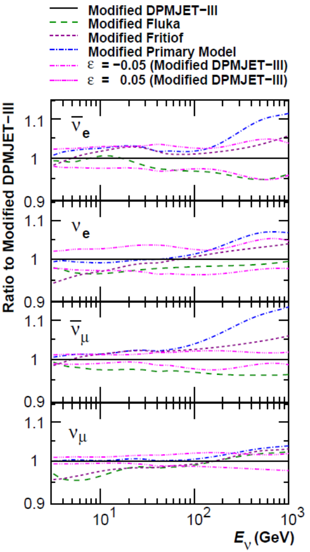


Detour: Astroparticle Physics with Rolf (L3+C)

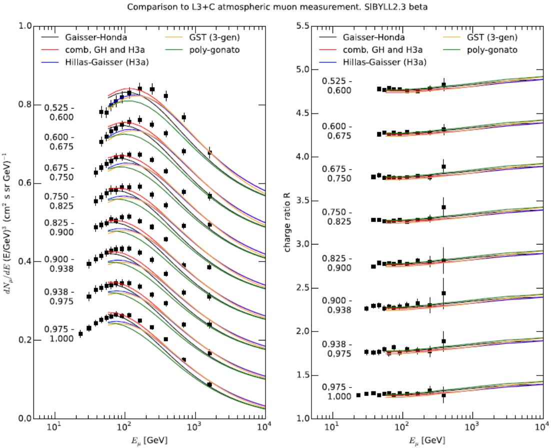
Measurement of the atmospheric muon spectrum from 20-GeV to 3000-GeV
L3 Collaboration (P. Achard *et al.*). Jul 2004. 34 pp.
Published in **Phys.Lett. B598 (2004) 15-32**
CERN-PH-EP-2004-023
DOI: 10.1016/j.physletb.2004.08.003
e-Print: **hep-ex/0408114** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service ; CERN Server
Detailed record - Cited by 163 records 100+



Detour: Astroparticle Physics with Rolf



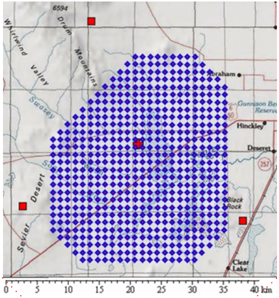
M. Honda et al., Phys.Rev. **D75** (2007) 043006

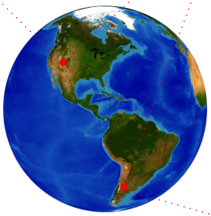


A. Fedynitch et al., IPA 2015

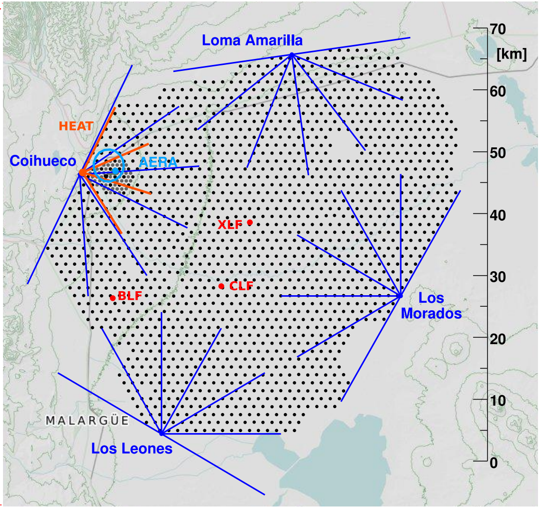
UHECR Observatories

Telescope Array





Pierre Auger Observatory

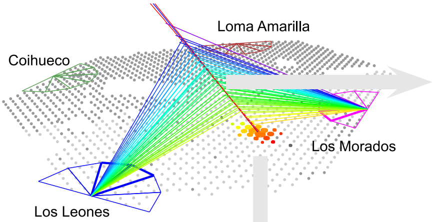


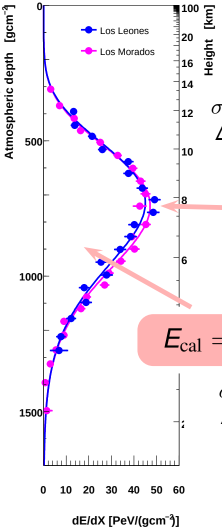
UHECR Observatories

Telescope Array

Pierre Auger Observatory

Hybrid Detection of Air Showers





$\sigma_{X_\text{max}} \leq 20\,\text{g/cm}^2$

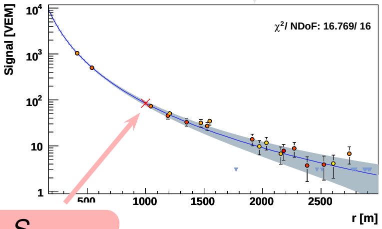
$\Delta_\text{sys} \leq 10\,\text{g/cm}^2$

X_max

$E_\text{cal} = \int \frac{dE}{dX}\,dX$

$\sigma_E/E \sim 8\,\%$

$\Delta_\text{sys} \approx 15\,\%$

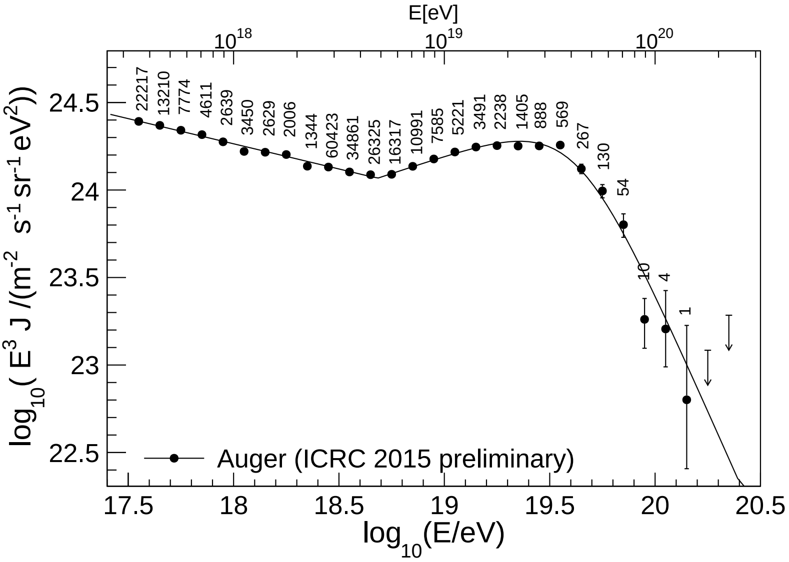


S_{1000}

$E_\text{surface} = f(S_{1000},\ \theta)$

Auger Event Display, Event 3332245

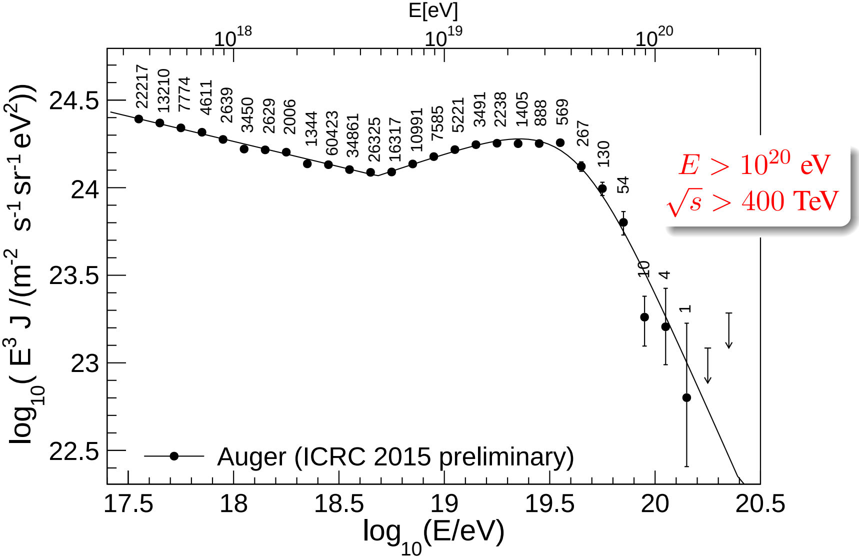
Energy Spectrum of UHECRs



exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Energy Spectrum of UHECRs



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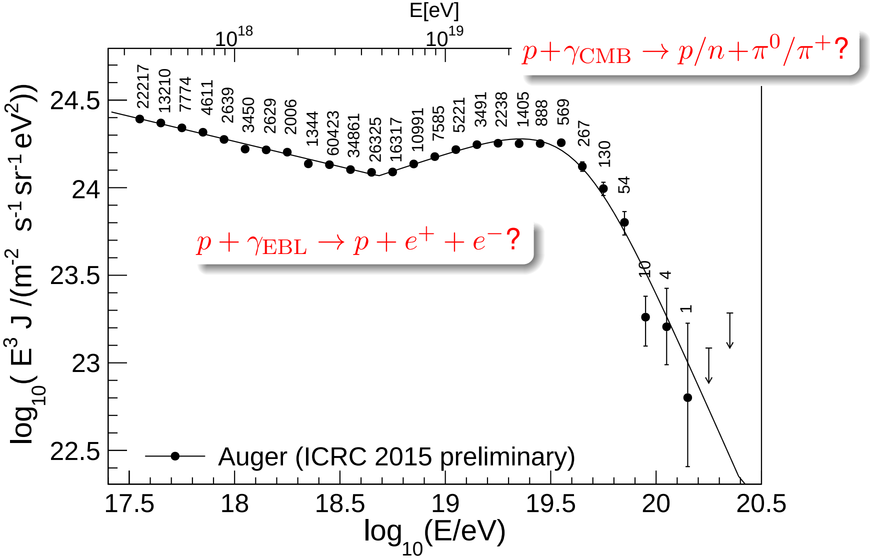
(I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732)

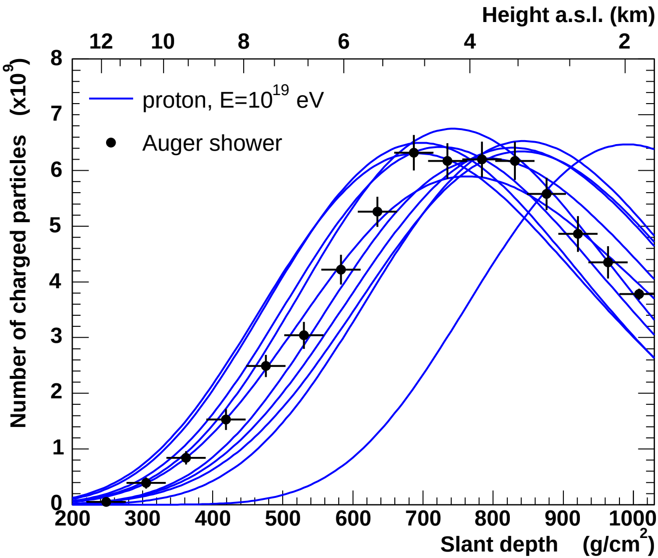
Energy Spectrum of UHECRs



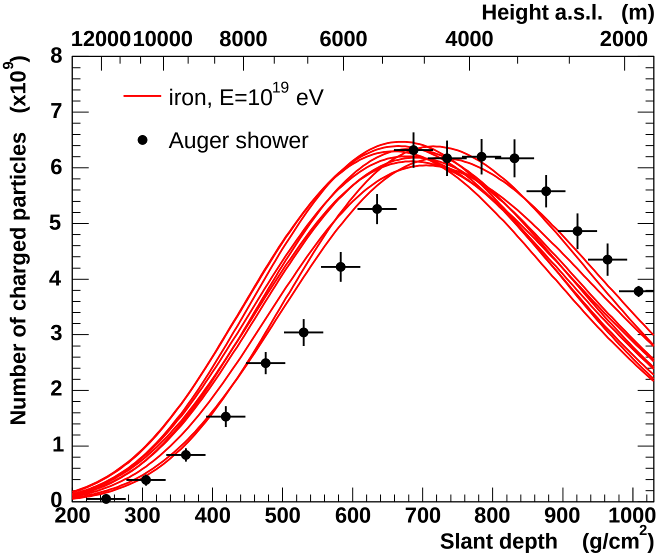
exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

(I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732)

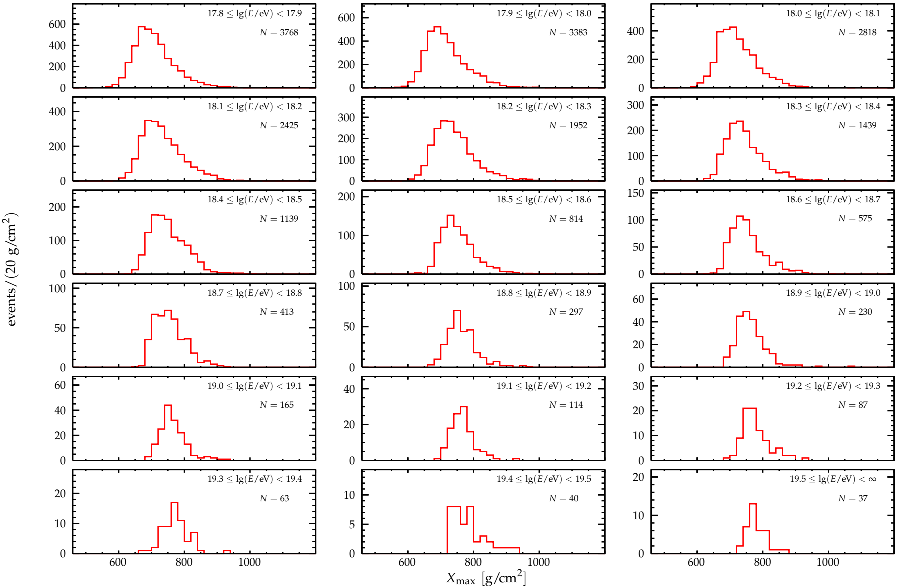
Primary Mass and Longitudinal Shower Profiles



Primary Mass and Longitudinal Shower Profiles

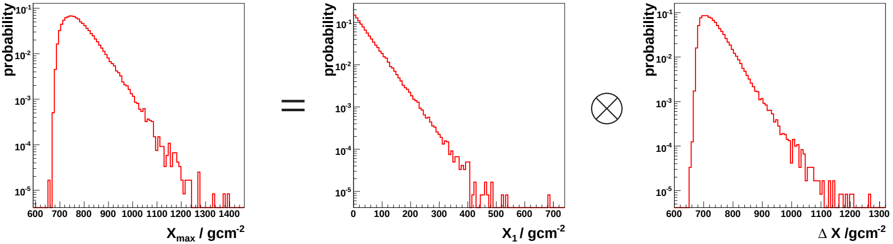


X_{max} Distributions



The Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

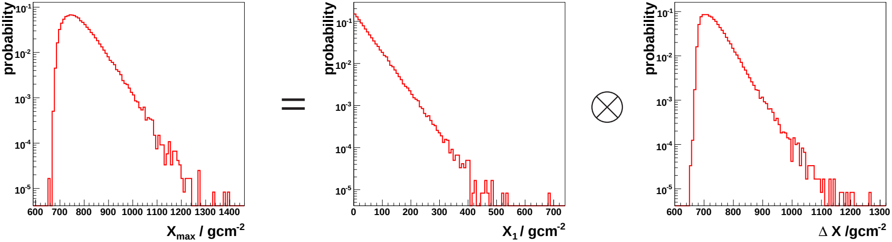
X_{max} Distribution: Mean



- first interaction $\langle X_1 \rangle$: λ_p
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{\mathrm{max}} \rangle_p \sim \lambda_p + D \ln E$

E: primary energy, λ_p: proton interaction length, D: elongation rate, A: mass number

X_{max} Distribution: Mean



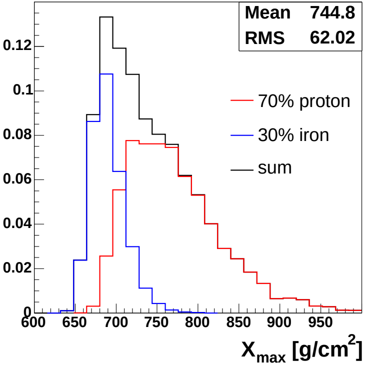
- first interaction $\langle X_1 \rangle$: λ_p
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{\rm max} \rangle_p \sim \lambda_p + D \ln E$

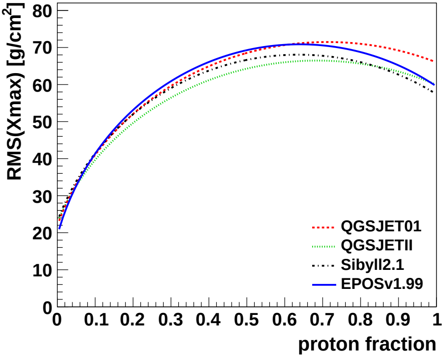
- superposition model: nucleus $(E,\ A) \equiv A$ nucleons $(E/A, 1)$
- $\langle X_{\rm max} \rangle_A \sim \lambda_p + D \ln(E/A)$

E: primary energy, λ_p: proton interaction length, D: elongation rate, A: mass number

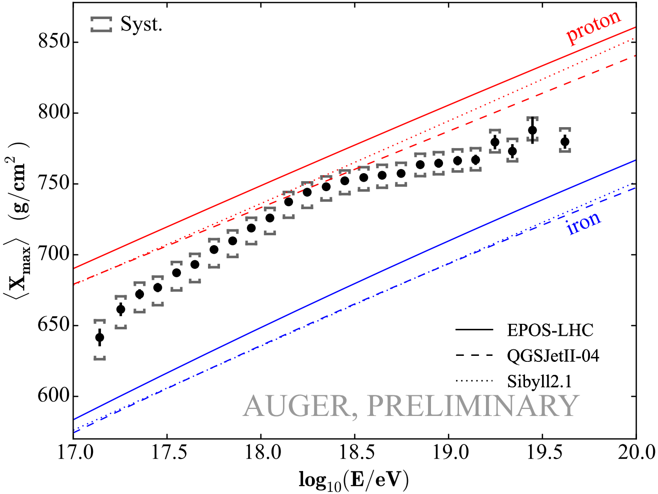
$\mathrm{X_{max}}$ Distribution: Standard Deviation

- $\sigma(X_{\max})_p > \sigma(X_{\max})_A > \sigma(X_{\max})_p/\sqrt{A}$
- mixed composition:



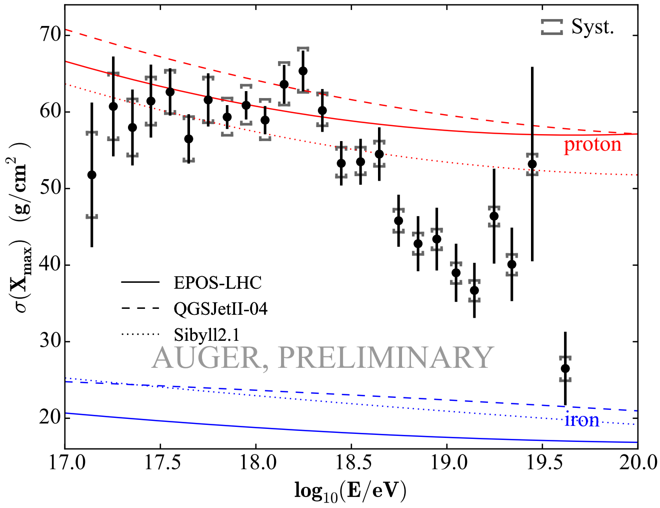


Measured $\langle X_{max} \rangle$



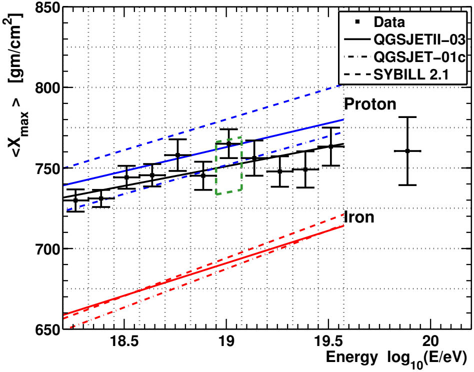
A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Measured $\sigma(X_{max})$

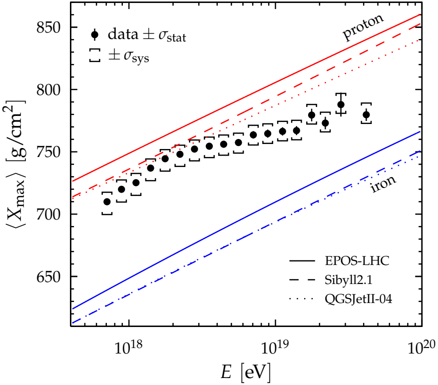


A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Average Shower Maximum: Comparison to TA

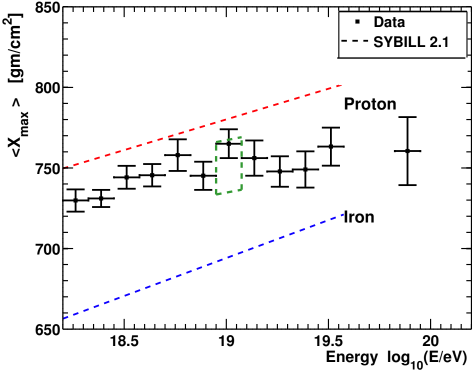


Telescope Array Coll., APP **64** (2014) 49

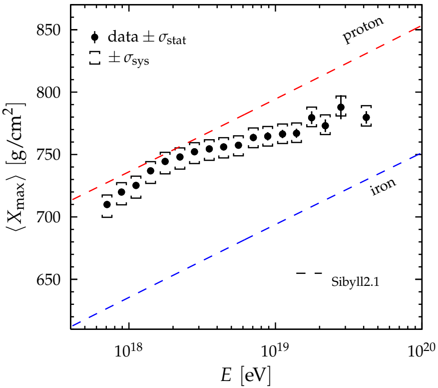


Pierre Auger Coll., PRD **90** (2014) 12, 122005

Average Shower Maximum: Comparison to TA

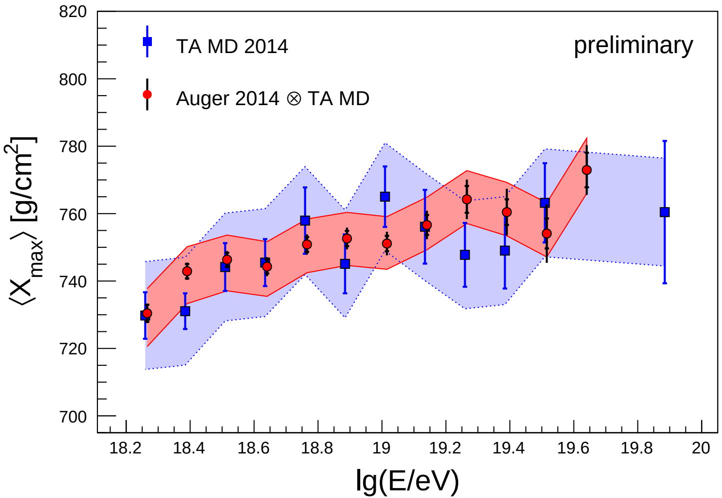


Telescope Array Coll., APP **64** (2014) 49



Pierre Auger Coll., PRD **90** (2014) 12, 122005

Average Shower Maximum: Comparison to TA

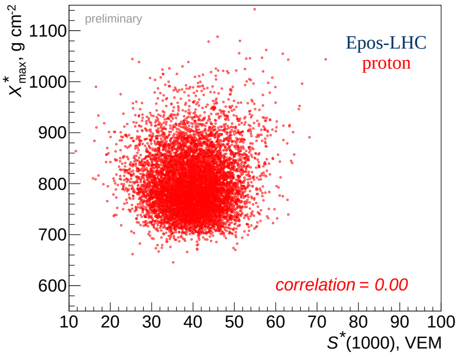


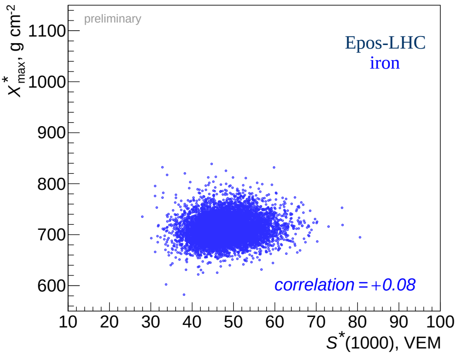
$$\langle\Delta\rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$$

MU for the Pierre Auger and TA Collaborations, Proc. 34th ICRC, arXiv:1511.02103

Correlation between X_{max} and SD Signal

$18.5 < \lg(E/eV) < 19.0$, $X^*_{max}/S^*(1000)$: scaled to 10^{19} eV





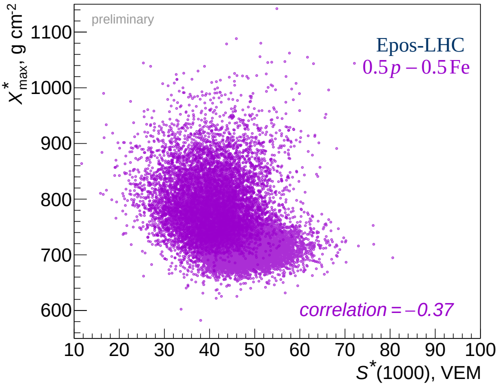
Pure compositions $\Rightarrow$ correlation $\gtrsim 0$

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Correlation between X_{max} and SD Signal

heavier nuclei produce shallower showers with larger signal (more muons)

general characteristics of air showers / minor model dependence

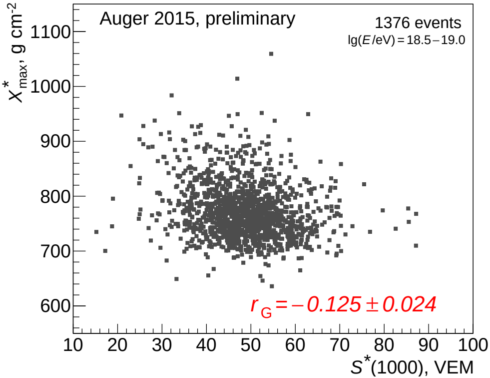


More negative correlation ⇒ more mixed composition

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Correlation between X_{max} and SD Signal

Data:



$r_G(X^*_{max}, S^*(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	**+0.08**	**+0.07**

difference to data

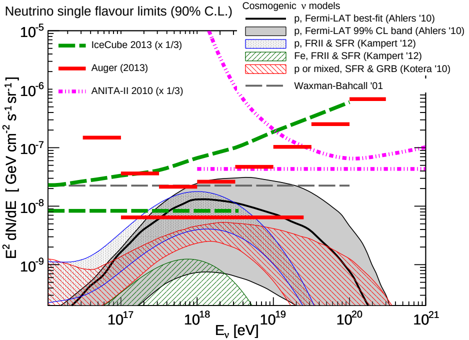
$\approx 5\sigma$	$\approx 8\sigma$	$\approx 7.5\sigma$

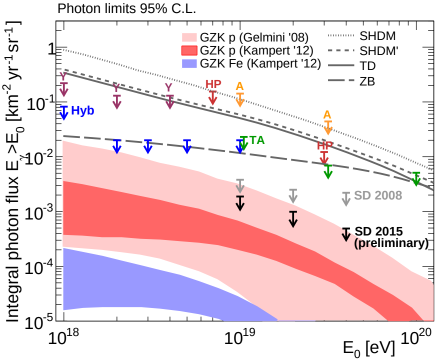
difference is larger for other pure beams

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Neutrino- and Photon-Limits

"guaranteed" flux of cosmogenic photons and neutrinos if CRs are protons

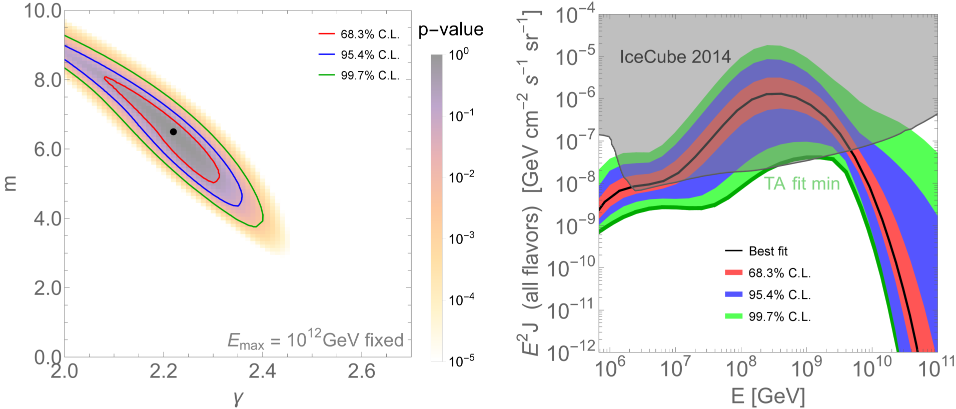




C. Bleve for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Self-Consistent CR+ν Analysis (TA Spectrum)

spectral index at source γ and source evolution $(1+z)^m$

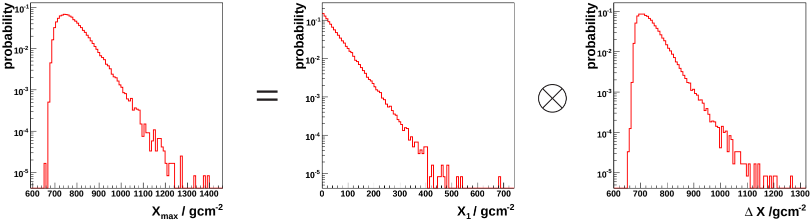


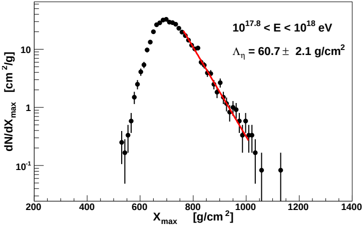
... similar results for three-parameter fit ($m, \gamma, E_{\max}$)

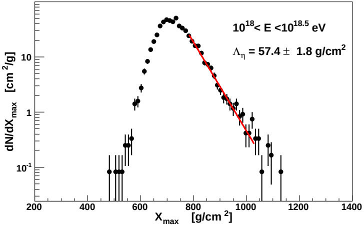
J. Heinze, D. Boncioli, M. Bustamante, W. Winter, arXiv:1512.05988

Measurement of the UHE p+Air Cross Section

tail of $X_{\max}$ distribution:







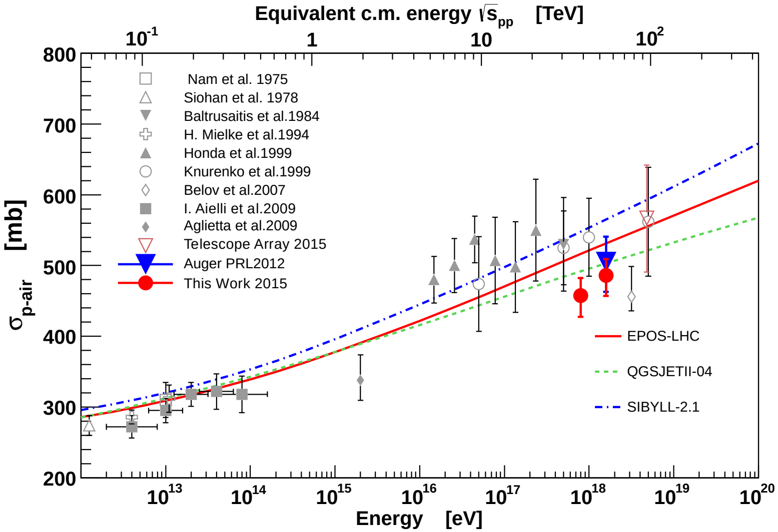
$\langle E \rangle = 10^{17.90}$ eV

$\Lambda_\eta = 60.7 \pm 2.1(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

$\langle E \rangle = 10^{18.22}$ eV

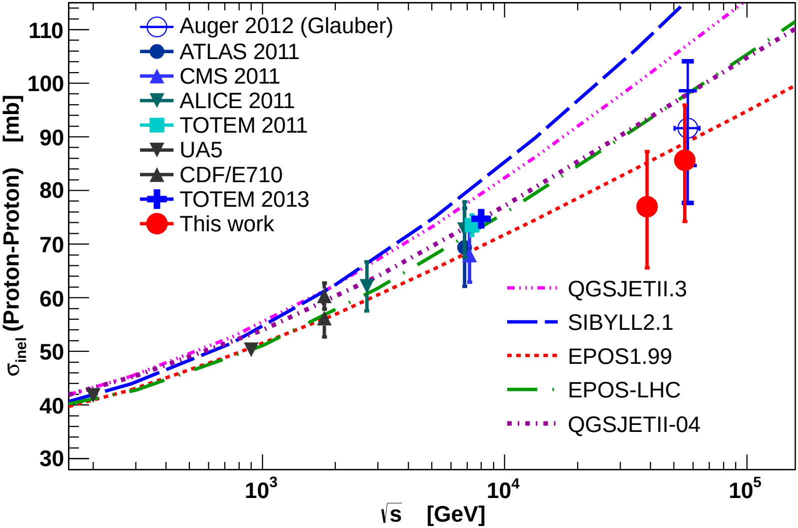
$\Lambda_\eta = 57.4 \pm 1.8(\text{stat}) \pm 1.6(\text{syst})\,\text{g/cm}^2$

Measurement of the UHE p+Air Cross Section



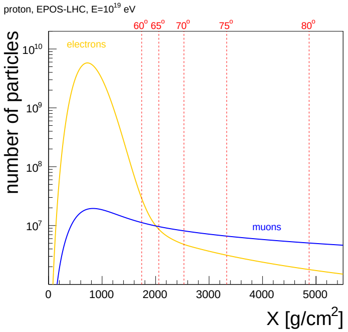
R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

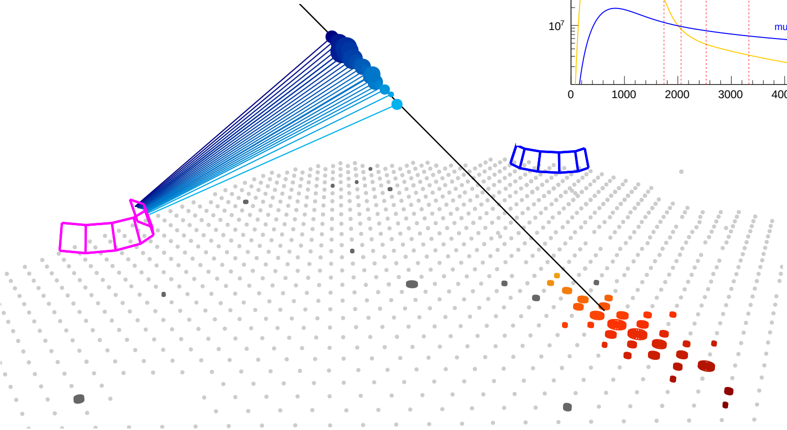
Derived UHE Proton+Proton Cross Section



R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

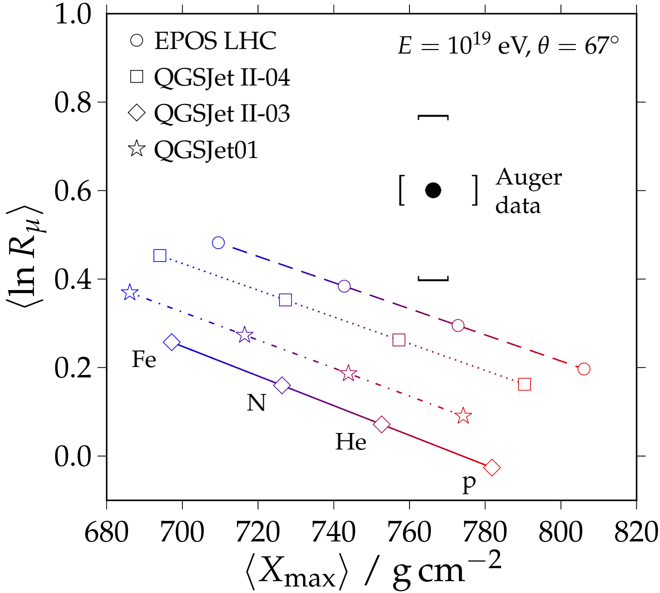
Muon Content of Air Showers





event 201114505353, $\theta = 75.6^\circ$, $E = 15.5\ \mathrm{EeV}$

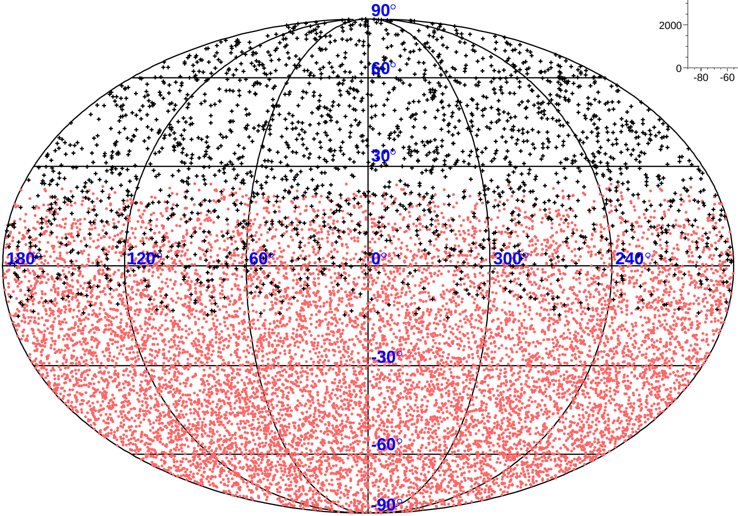
Muon Number vs. X_{max} (FD)

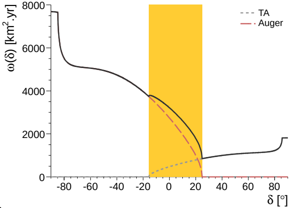


N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

Pierre Auger Coll., PRD **D91** (2015) 3, 032003

The UHECR Sky above 10 EeV

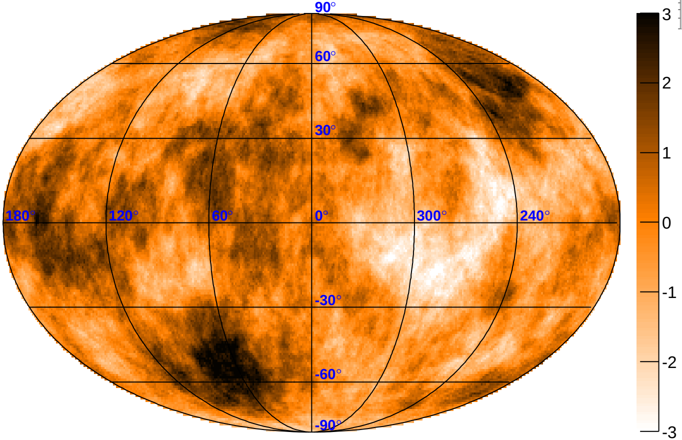


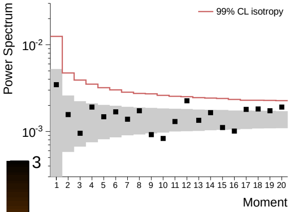


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

The UHECR Sky above 10 EeV

significance map:



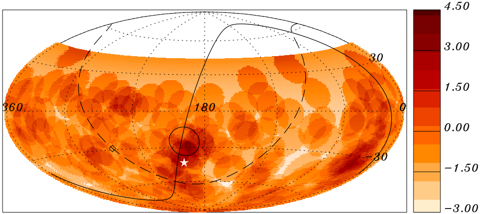


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

Searches for a Localized Excess of UHECRs

Auger:

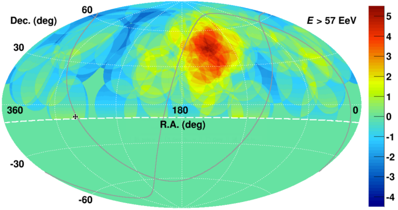
- $r = 1° - 30°$, $\Delta r = 1°$
- $E = 40 - 80$ EeV, $\Delta E = 1$ EeV



- $r = 12°$, $E = 54$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 14/3.23
- pre-trial: 4.3 σ
- post-trial: $P = 69\%$

TA:

- $r = 15° - 35°$, $\Delta r = 5°$
- $E = 57$ EeV



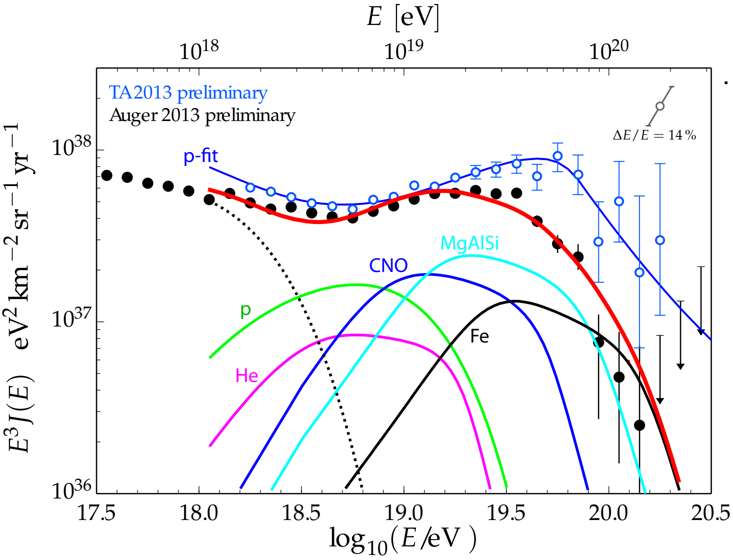
- $r = 20°$, $E = 57$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 24/6.88
- pre-trial: 5.1 σ
- post-trial: 3.4 σ

Auger Coll., APJ **804** (2015) 1, 15; TA Coll., APJ **790** (2014) L21, 7-year update at ICRC15.

Summary of Observations

- spectrum
  $\rightarrow$ flux suppression at $E \gtrsim 5 \times 10^{19}$ eV
- elongation rate, $\langle X_{\max} \rangle$, $\sigma(X_{\max})$, $r_G(X^*_{\max}/S^*(1000))$
  $\rightarrow$ mixed composition around and above the ankle
  (if LHC-inspired extrapolations are ok)
- neutrinos and photons
  $\rightarrow$ start probing cosmogenic fluxes from 100% p
- p+air cross section
  $\rightarrow$ compatible with model extrapolations
- arrival directions
  $\rightarrow$ isotropic in the South, some hints for anisotropy in the North
- muons content of air showers
  $\rightarrow$ at odds with predictions for mixed composition

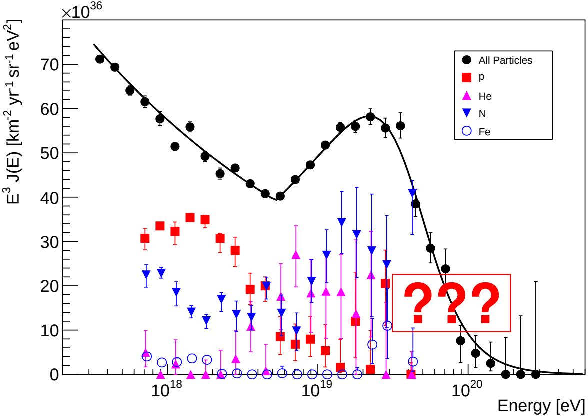
Origin of Ankle and Flux Suppression?



Kampert&Tinyakov, CRP **15** (2014) 318; Aloisio, Berezinsky & Blasi, JCAP 1410 (2014) 10, 02

Upgrade of the Pierre Auger Observatory

- origin of flux suppression?
- proton fraction at UHE?
- hadronic physics above $\sqrt{s} = 140$ TeV



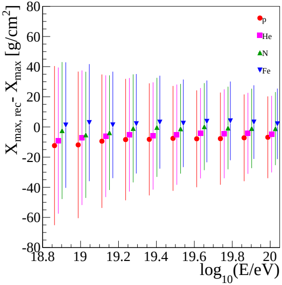
V. de Souza for the Pierre Auger Collaboration, Proc. UHECR14

Upgrade of the Pierre Auger Observatory

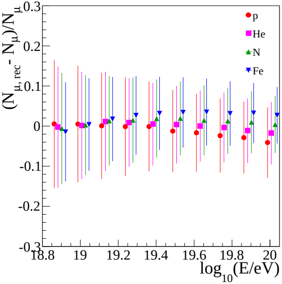
additional scintillators (4 m^2)

$\rightarrow$ event-by-event mass estimate
with 100% duty cycle

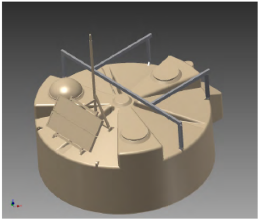
X_{max} determination:

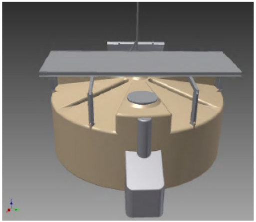


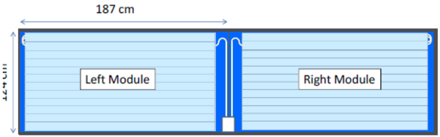
muon determination:



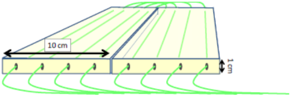
Upgrade of the Pierre Auger Observatory





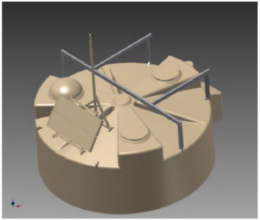


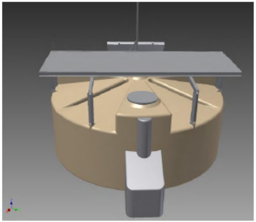
Two modules in one box per station readout by one PMT, area ~4 m^2

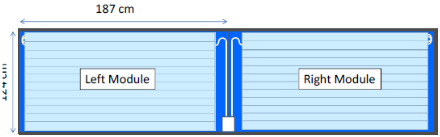


Read-out of scintillators with WLS fibers

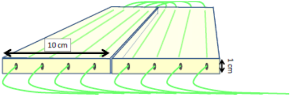
Upgrade of the Pierre Auger Observatory





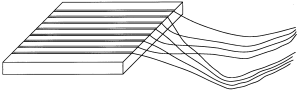


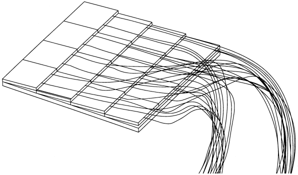
Two modules in one box per station readout by one PMT, area ~4 m^2

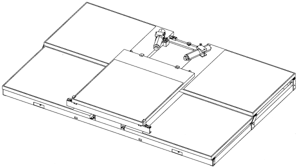


Read-out of scintillators with WLS fibers

... poor man's version of L3+C scintillators





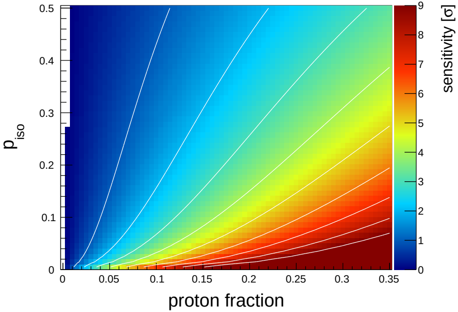


J.Bähr, H.Grabosch, V.Kantserov, H.Leich, R.Leiste, R.Nahnhauer AIP Conf.Proc. **450** (1998) 385

Upgrade of the Pierre Auger Observatory

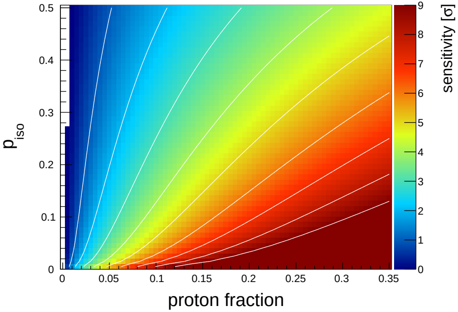
low-Z particle astronomy

no mass determination:



(isotropic background: 25%)

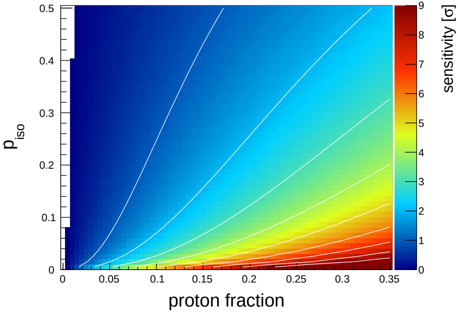
p-Fe separation merit factor: 1.5



Upgrade of the Pierre Auger Observatory

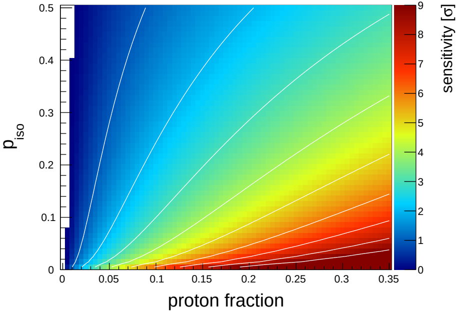
low-Z particle astronomy

no mass determination:

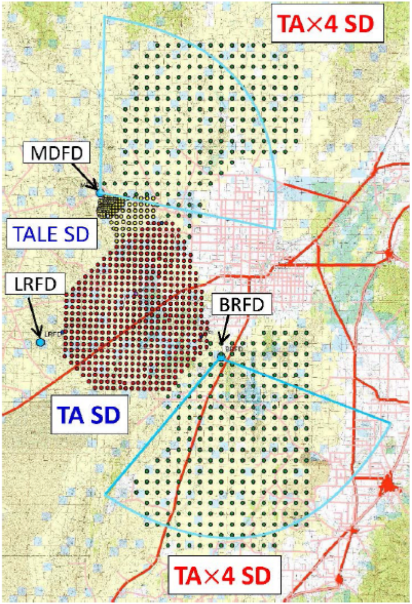


(isotropic background: 50%)

p-Fe separation merit factor: 1.5

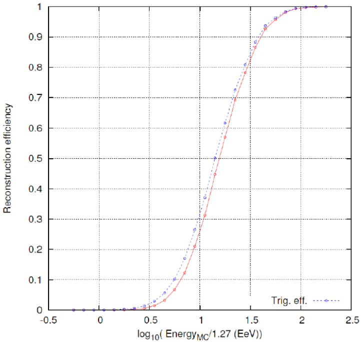


TAx4



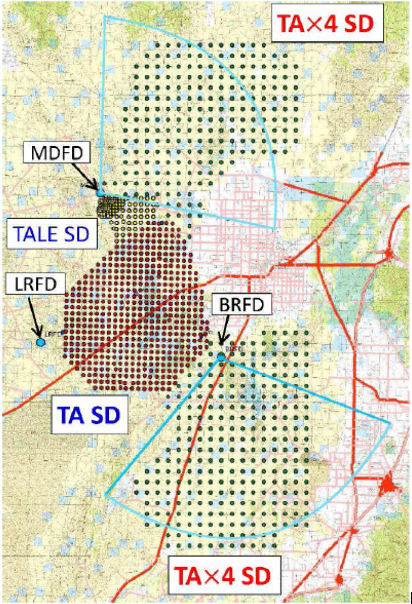
quadruple acceptance:

- 500 add. SDs
- 2.08 km spacing
- 2 add. FD stations

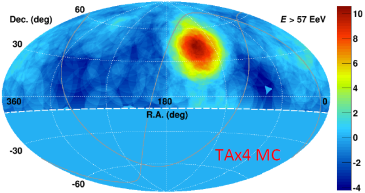


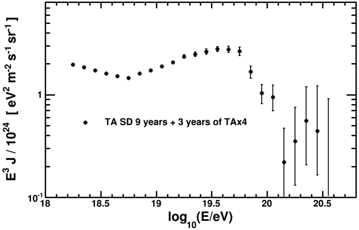
H. Sagawa for TA, UHECR14.

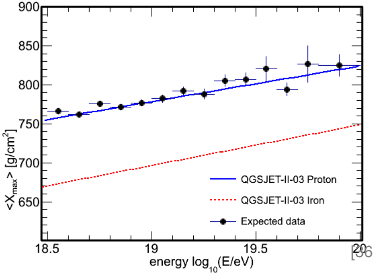
TAx4



H.







Sagawa for TA, UHECR14.

Outlook

- TA & Auger Upgrades:
  - study nature of flux suppression
  - prospects for particle astronomy
  - R&D for Next Generation Observatory
- fluorescence detection from space
  - KLYPVE, Mini-EUSO (K-EUSO), EUSO
- radio detection of air showers
  - ground-based hybrid detectors (radio&surface)
  - high-altitude antennas
- LHC run II
  - $\sqrt{s} = 14\ \text{TeV}$ ($E_{\text{CR}} = 10^{17}$ eV), p+O collisions?