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Evidence for a mixed mass composition at the 'ankle' in the cosmic-ray spectrum

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HAP Workshop Topic 2 | The Non-Thermal Universe (Erlangen)

21.09.2016

PIERRE AUGER OBSERVATORY

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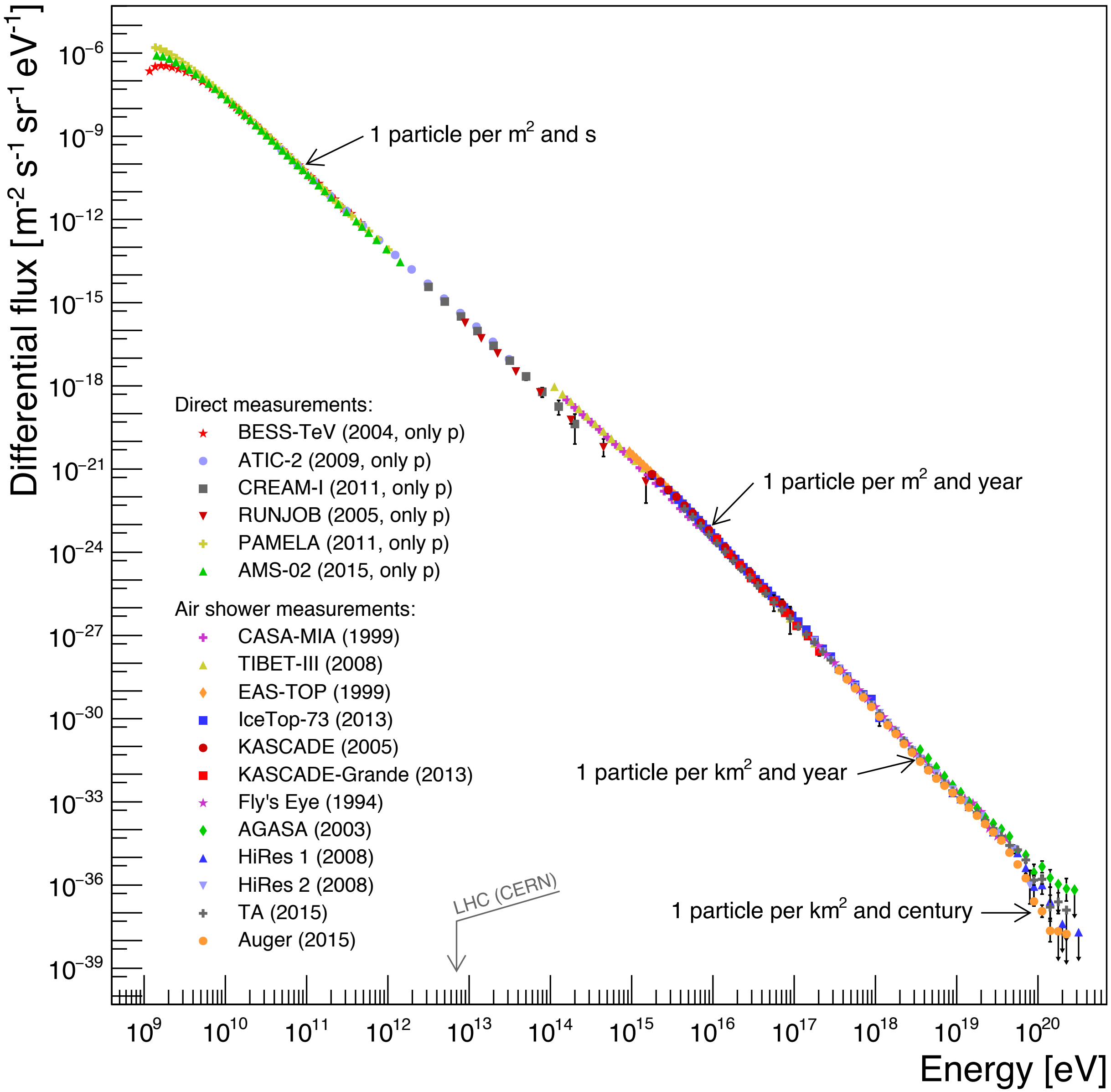
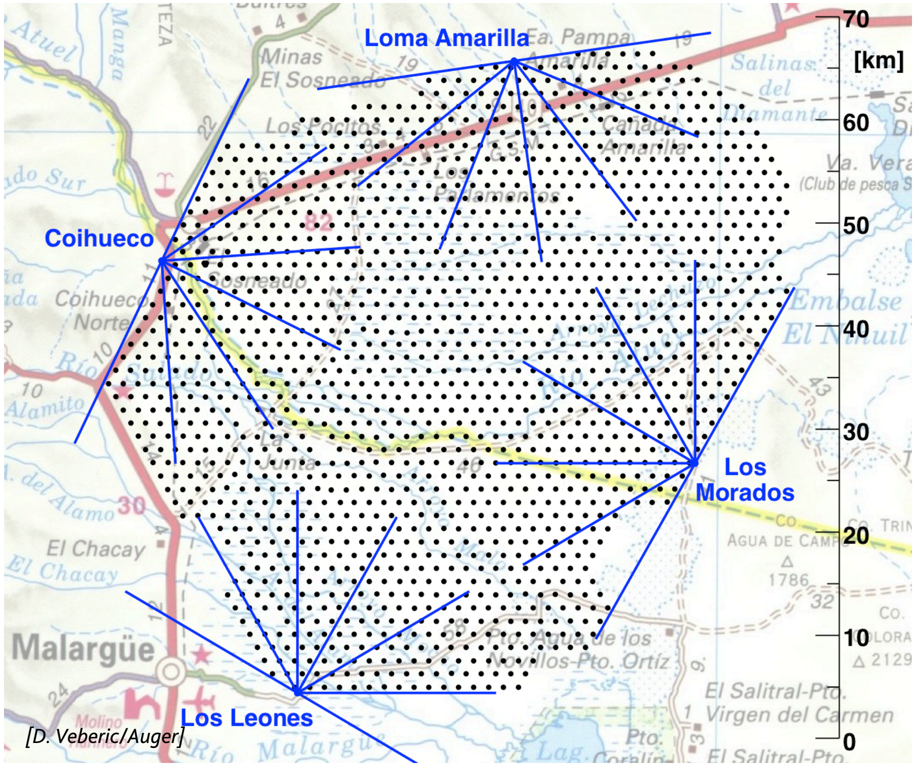
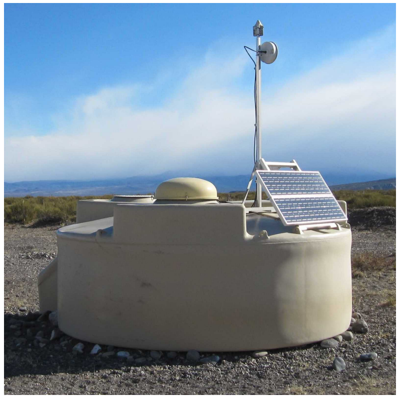
Cosmic rays: energy spectrum

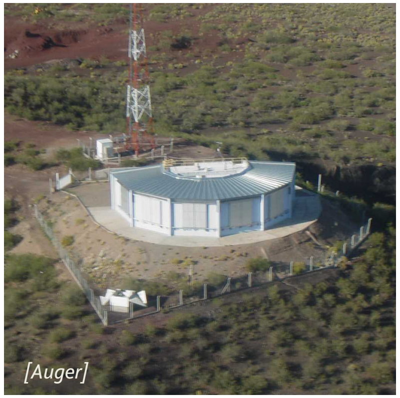


Pierre Auger Observatory

- Located in the Pampa Amarilla near **Malargüe**, Argentina
- **Hybrid concept**: two independent and complementary detector systems
- **Surface detector (SD)**
  - 1660 water-Cherenkov detector stations set up on a hexagonal grid
  - 1.5 km distance between the individual stations
  - Total area covered: more than 3000 km^2
- **Fluorescence detector (FD)**
  - 27 fluorescence telescopes
  - 4 locations at the border of the SD array

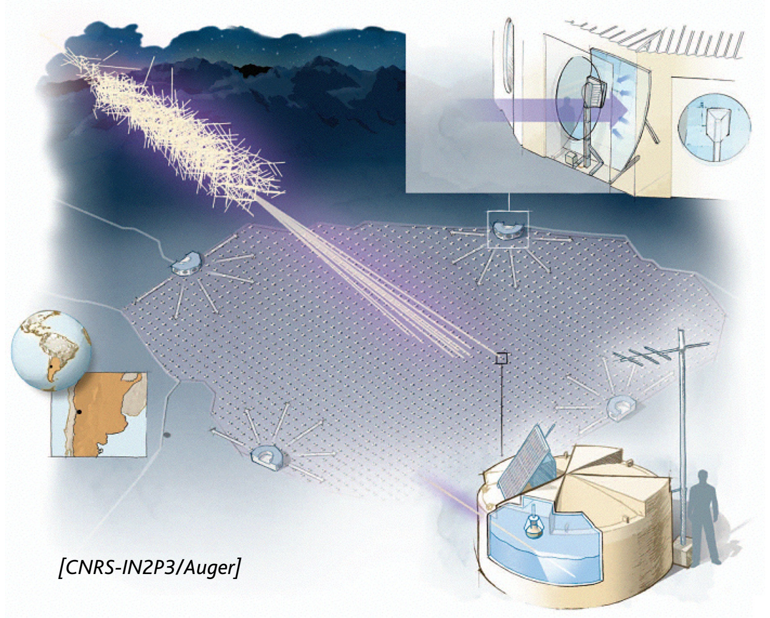






Measurement principle

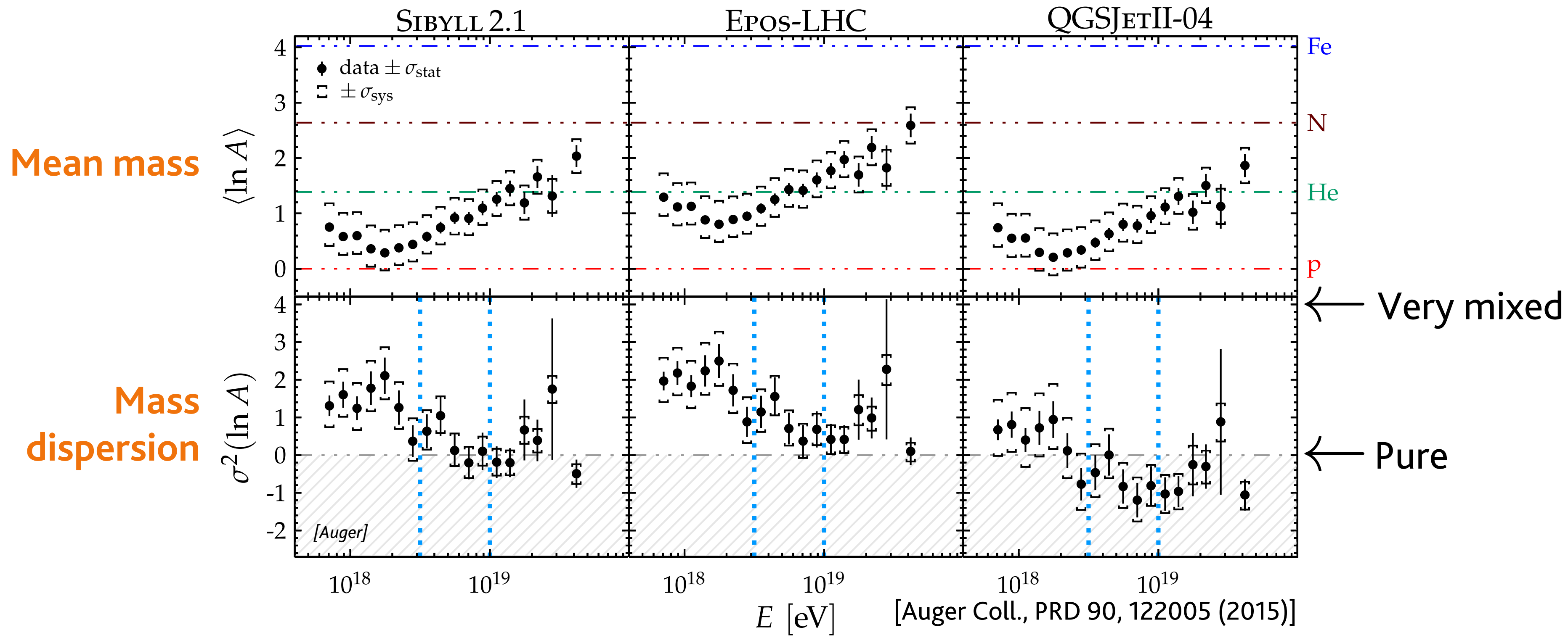
- SD: detect charged particles from an air shower through Cherenkov light in the detector stations
  - Measure the lateral distribution of the particle density at ground level
  - Duty cycle: ~100 %
  - Relevant observable here: S_{1000}, i.e. the interpolated signal in the SD stations at a distance of 1000 m from the shower axis
- FD: detect an air shower through fluorescence light produced in the atmosphere
  - Measure the longitudinal development of the air shower in the atmosphere
  - Measurements only possible in clear, moonless nights: duty cycle ~13 %
  - Relevant observable here: X_{max}, i.e. the atmospheric depth of the shower maximum



[CNRS-IN2P3/Auger]

UHECR composition

- **Mean and variance of ln*A*** derived from the measured X_{max} distributions as a function of energy as published by the Auger collaboration:

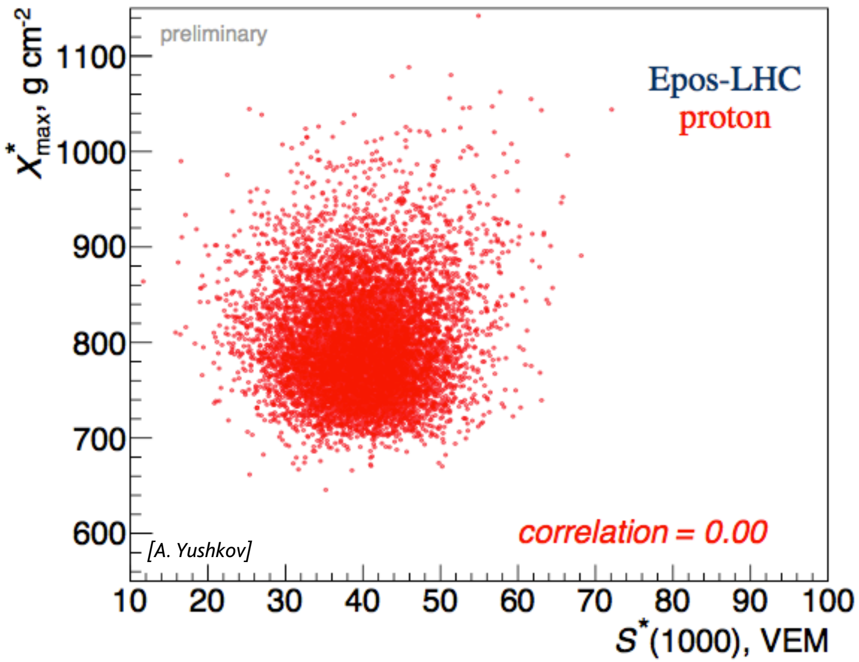


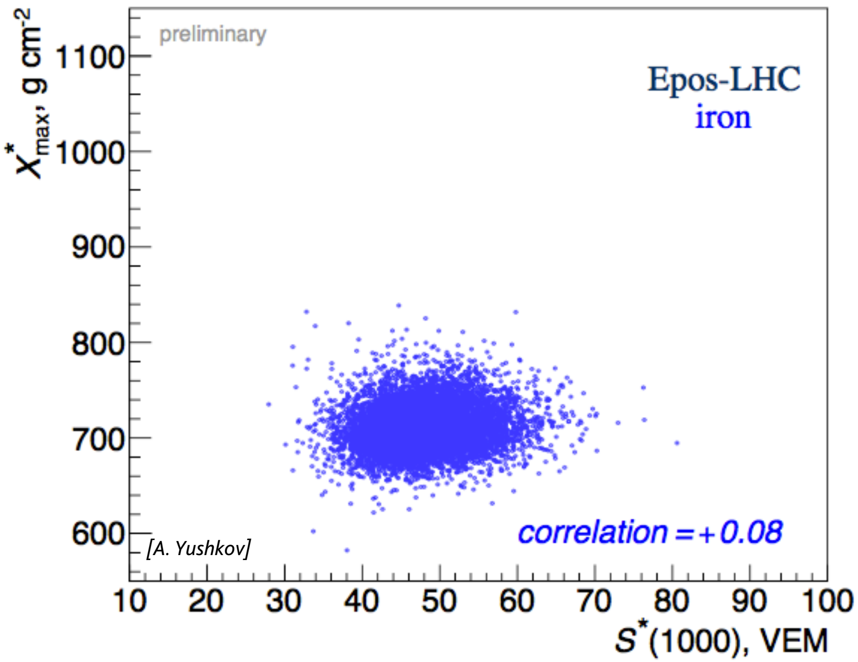
[Auger Coll., PRD 90, 122005 (2015)]

- Results depend on the **hadronic interaction model** used to interpret the measurements
- **Aim of this analysis:** estimate mass dispersion near the ankle (lg(*E* [eV]) ≈ 18.7) in a less model-dependent way

The key idea (I)

- Correlation between the observables X_{max} and S_{1000} depends on the **purity of the primary beam** [P. Younk, M. Risse, ApP 35 (2012), 807]
  - Use **scaled observables** (marked with an asterisk) to remove zenith angle and energy dependencies: X_{max} scaled to 10 EeV, S_{1000} scaled to 10 EeV and 38°

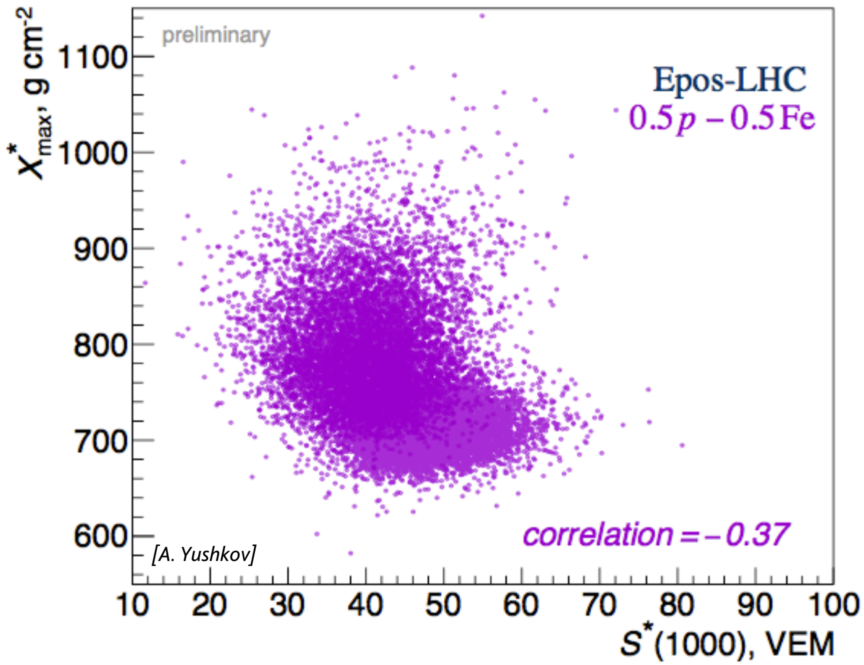




- **Pure composition** $\longrightarrow$ correlation $\gtrsim 0$

The key idea (II)

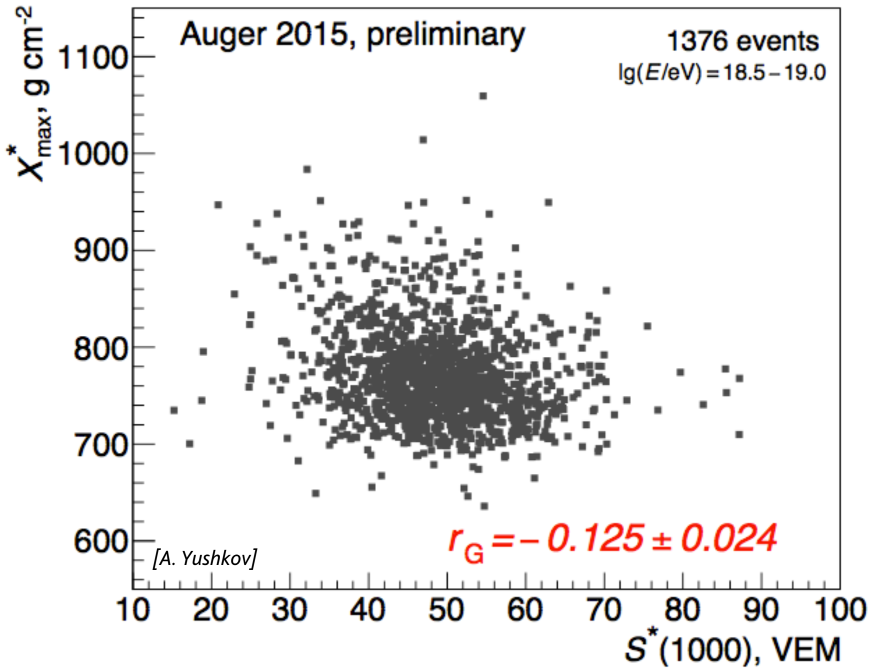
- Correlation between the observables X_{max} and S_{1000} depends on the **purity of the primary beam** [P. Younk, M. Risse, ApP 35 (2012), 807]
  - Use **scaled observables** (marked with an asterisk) to remove zenith angle and energy dependencies: X_{max} scaled to 10 EeV, S_{1000} scaled to 10 EeV and 38°



- **Pure composition** $\longrightarrow$ correlation $\gtrsim 0$
- **More mixed composition** $\longrightarrow$ more negative correlation

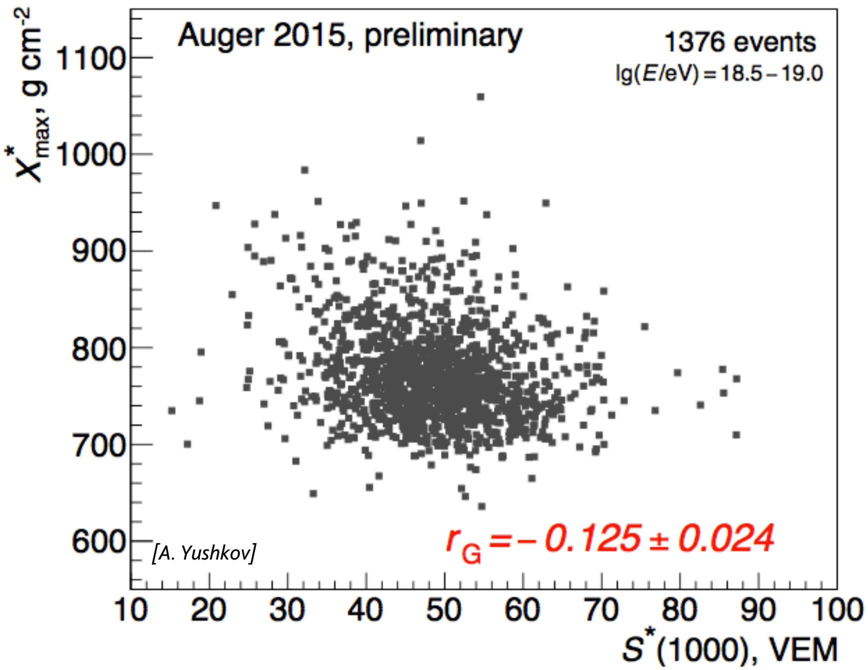
Correlation in data

- Use **8 years of data** (12/2004 – 12/2012)
  - Energy range lg(E [eV]) = 18.5 -19.0, zenith angle range 0 - 65°
  - 1376 high-quality events
- Use **ranking coefficent r_G** to quantify the correlation



- Correlation is **significantly negative**
- **Systematic effects** play only a minor role $\sigma_{syst}(r_G) < 0.01$
  - r_G is invariant to additive and multiplicative scale transformations

Comparison to pure beams



$r_{\mathrm{G}}(X^{*}_{\mathrm{max}},\, S^{*}(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibyll 2.1
$\mathbf{0.00}$	$\mathbf{+0.08}$	$\mathbf{+0.07}$

difference to data

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

difference is larger for other pure beams

- Conclusion: **primary composition around the “ankle” is mixed!**

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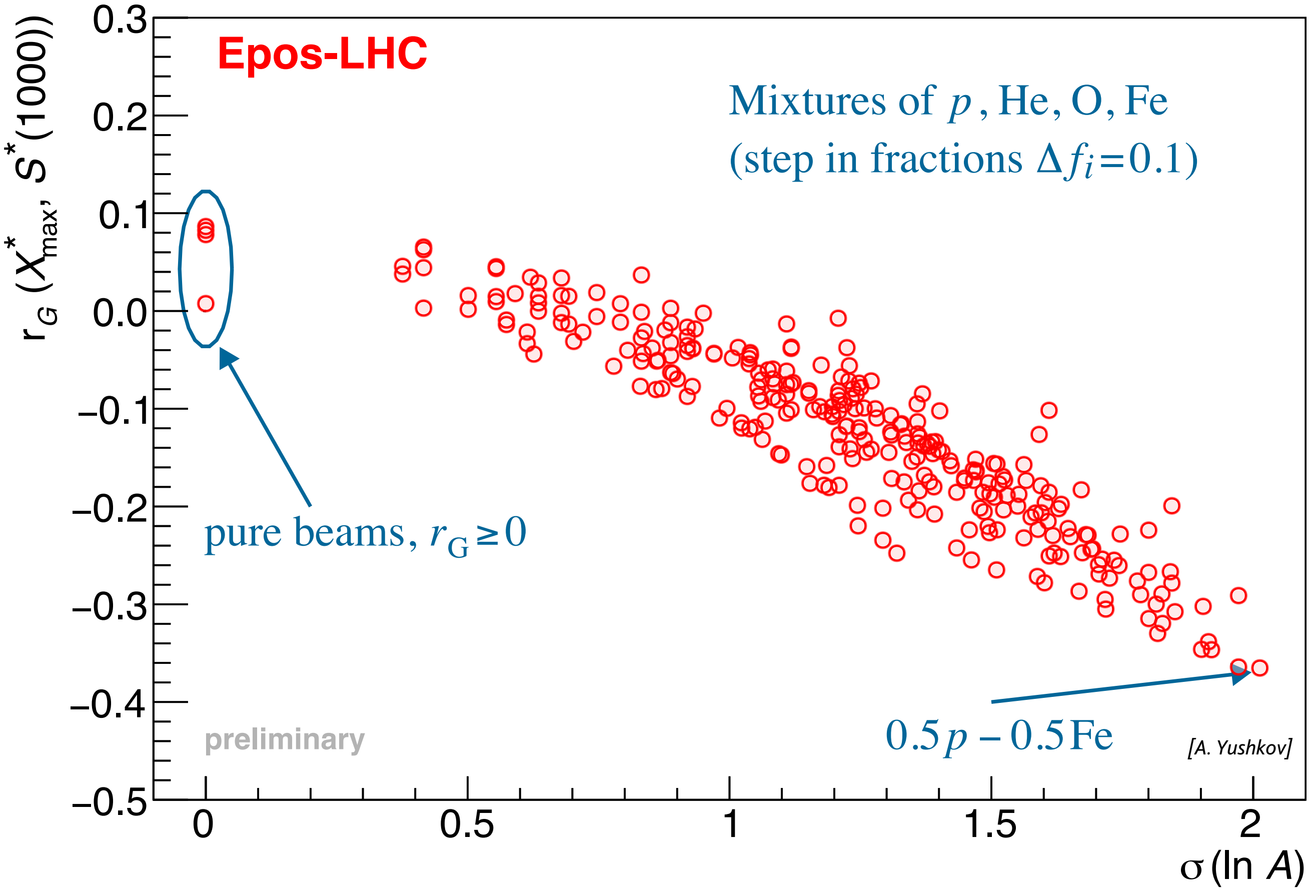
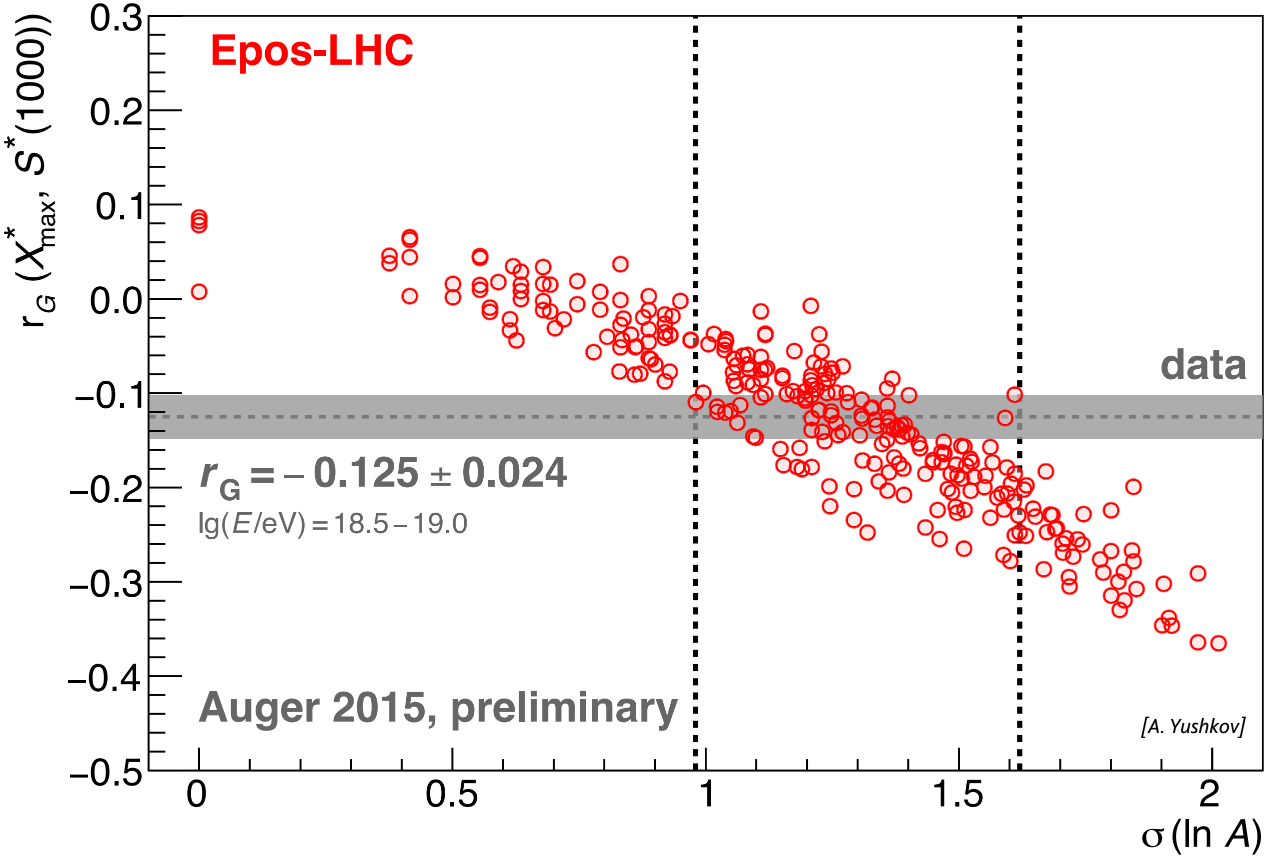
- Simulate **different mixtures** of p, He, O and Fe and determine the expected correlation



- **Comparison** to the value of r_G that was determined from data:



- **Result** (quite independent from the hadronic interaction model):

$$\sigma(\ln A) = 1.35 \pm 0.25$$

Summary

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- The **correlation between X_{max} and S_{1000}** has been studied to provide a less model-dependent estimate of the primary composition around the “ankle” in the cosmic-ray energy spectrum
- **Significantly negative** correlation is found in data:

$$r_{\mathrm{G}}\left(X^*_{\max}, S^*(1000)\right) = -0.125 \pm 0.025$$

$$\text{for } \lg(E\ [\mathrm{eV}]) = 18.5 - 19.0$$

- Difference to the expectation for pure primary beams is larger than 5σ: **the primary composition around the “ankle” is mixed!**
- **Dispersion of masses** in the primary beam compatible with the observed correlation in data (within the interaction models used):

$$\sigma(\ln A) = 1.35 \pm 0.25$$

- **Results are robust** against experimental uncertainties in the observables and moderate modifications of the hadronic interactions

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Uncertainties in hadronic models

Can one get $r_G(X^*_{max}, S^*(1000)) < 0$ for pure protons?

Change proton-air interactions (study with CONEX 3D)

[T. Bergmann et al., ApP 26 (2007) 420, R. Ulrich et al., PRD 83 (2011) 054026]

The modification factor ($f_{19} = 1.5$: increase up to factor 1.5 at 10 EeV)

$$f(E) = 1 + (f_{19} - 1)\frac{\lg(E/1\ \mathrm{PeV})}{\lg(10\ \mathrm{EeV}/1\ \mathrm{PeV})}$$

Modified parameters (for Epos-LHC)

- cross-section
- pion charge ratio
- elasticity
- multiplicity

r_G changes by $\lesssim 0.03$

Possible under-production of muons by hadronic models?

[G. Farrar for the Pierre Auger Collaboration (2013) arXiv:1307.5059, A. Aab et al., PRD 91 (2015) 032003]

re-weighting of muons at ground by factor 1.3: r_G decreases by $\lesssim 0.03$

changes are small compared to difference between data and protons

[A. Yushkov, ICRC 2015]

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Uncertainties

Some of the checks for $r_{\mathrm{G}}(X^*_{\mathrm{max}}, S^*(1000))$

- different FD telescopes
- different time periods
- smaller angular ranges
- smaller energy ranges
- variations in event selection
- changes of energy, X_{max}, $S(1000)$ scales
- ad hoc energy and zenith angle dependent biases in X_{max} (up 10 $\mathrm{g/cm^2}$) and $S(1000)$ (up to 10%)

systematic error on r_{G} estimated to be 0.01

statistical uncertainty $\sigma_{\mathrm{stat}}(r_{\mathrm{G}}) \approx 0.9/\sqrt{N}$ (sample of N events)
(obtained using dedicated MC studies)

for data $\boldsymbol{\sigma_{\mathrm{stat}}(r_{\mathrm{G}}) \approx 0.9/\sqrt{1376} \approx 0.024}$

[A. Yushkov, ICRC 2015]