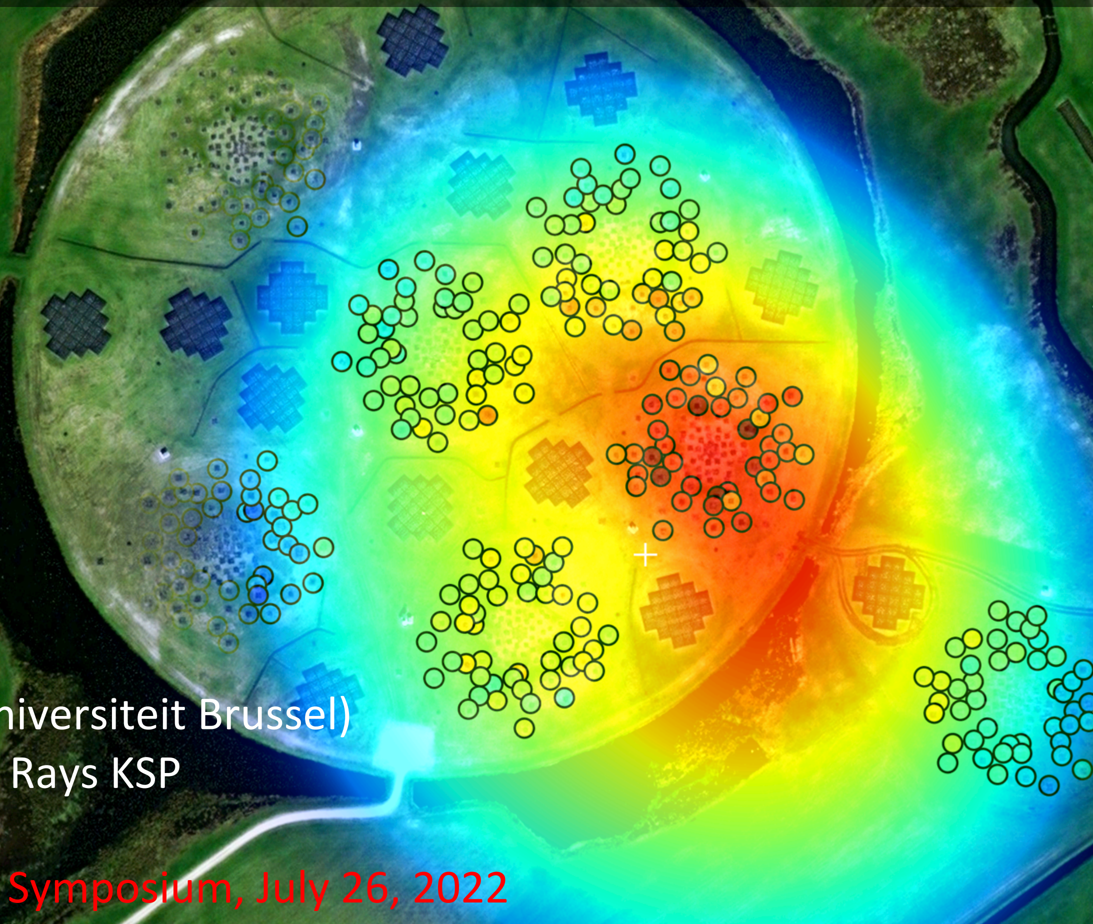
Results from LOFAR on mass composition of cosmic rays



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Publication on mass composition at LOFAR

PHYSICAL REVIEW D **103**, 102006 (2021)

Depth of shower maximum and mass composition of cosmic rays from 50 PeV to 2 EeV measured with the LOFAR radio telescope

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We present an updated cosmic-ray mass composition analysis in the energy range $10^{16.8}$ to $10^{18.3}$ eV from 334 air showers measured with the LOFAR radio telescope and selected for minimal bias. In this energy range, the origin of cosmic rays is expected to shift from galactic to extragalactic sources. The analysis is based on an improved method to infer the depth of the maximum X_{max} of extensive air showers from radio measurements and air shower simulations. We show results of the average and standard deviation of X_{max} versus primary energy and analyze the X_{max} dataset at the distribution level to estimate the cosmic ray mass composition. Our approach uses an unbinned maximum likelihood analysis, making use of existing parametrizations of the X_{max} distributions per element. The analysis has been repeated for three main models of hadronic interactions. Results are consistent with a significant light-mass fraction, at best fit 23% to 39% protons plus helium, depending on the choice of hadronic interaction model. The fraction of the intermediate-mass nuclei dominates. This confirms earlier results from LOFAR, with systematic uncertainties on X_{max} now lowered to 7 to 9 g/cm². We find agreement in mass composition

Results published in May 2021

Corstanje et al.,
Phys Rev D 103, 102006 (2021)

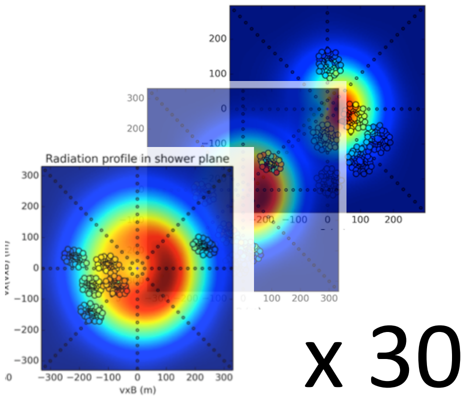
arXiv: **2103.12549**

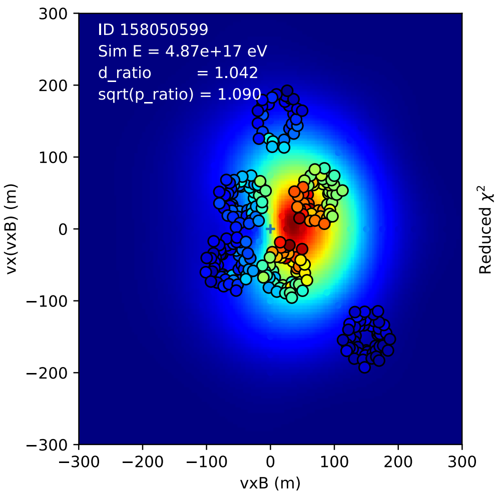
This talk: overview published paper

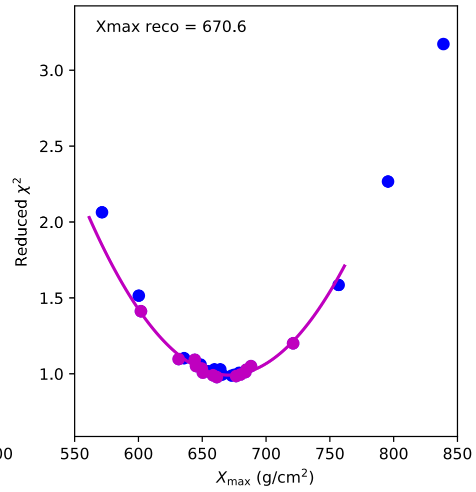
Matching simulated footprints to data

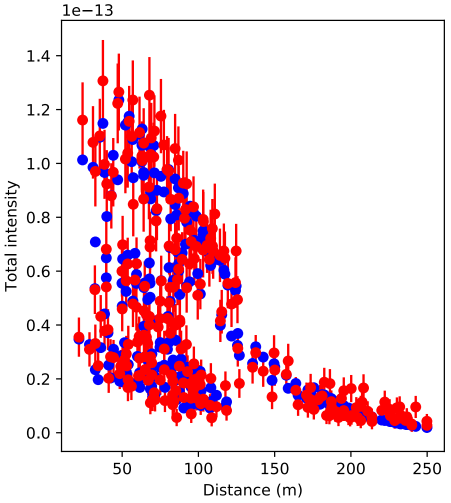
- Simulate about 30 showers per measured shower
- Fit them to data, observe X_{max} of best fit

- X_{max} resolution about **20 g/cm²**
- Energy resolution **9 %**
- Systematic uncertainties < **9 g/cm²** on X_{max}, **14 %** on energy



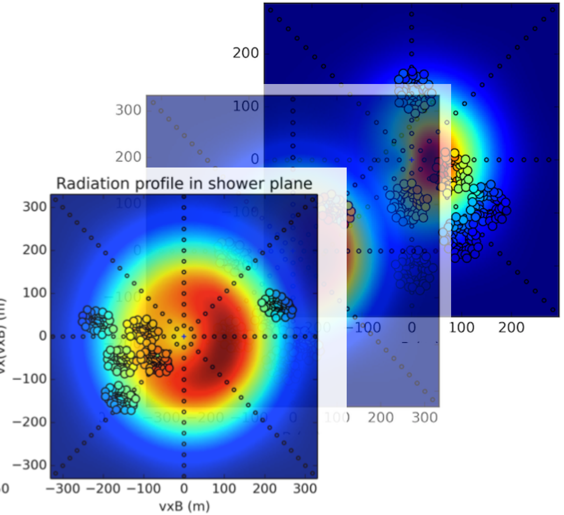






Matching simulated footprints to LOFAR data

- Simulate ~ 30 showers per event, spanning X_{max} range
- Reconstruction uncertainty from Monte Carlo procedure
  - Take one simulated shower, add LOFAR noise levels, reconstruct with other showers from ensemble
- Require core position precision < 7.5 m



Air shower dataset:

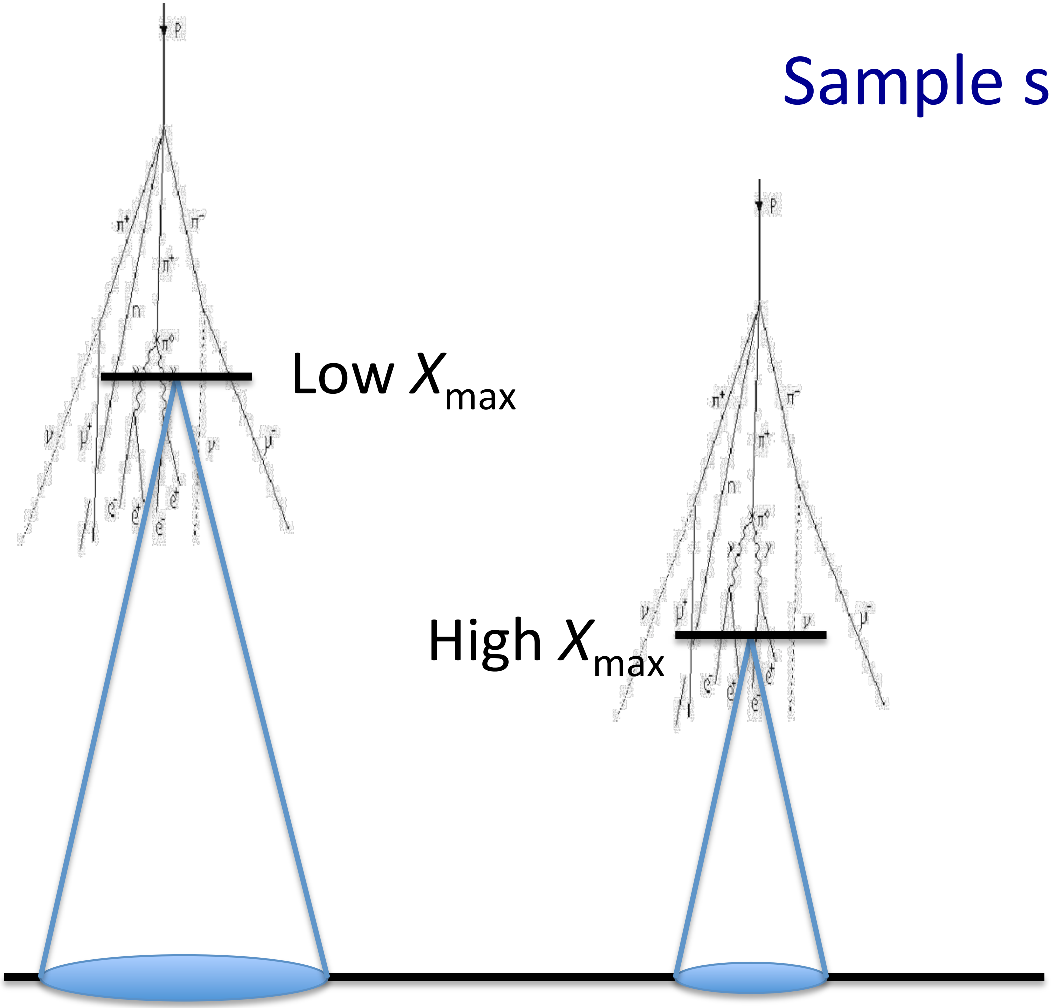
data points

($X_{max} \pm \sigma_X$, log $E \pm \sigma_{\log E}$)

Selected for minimal bias

x N = 334

Sample selection

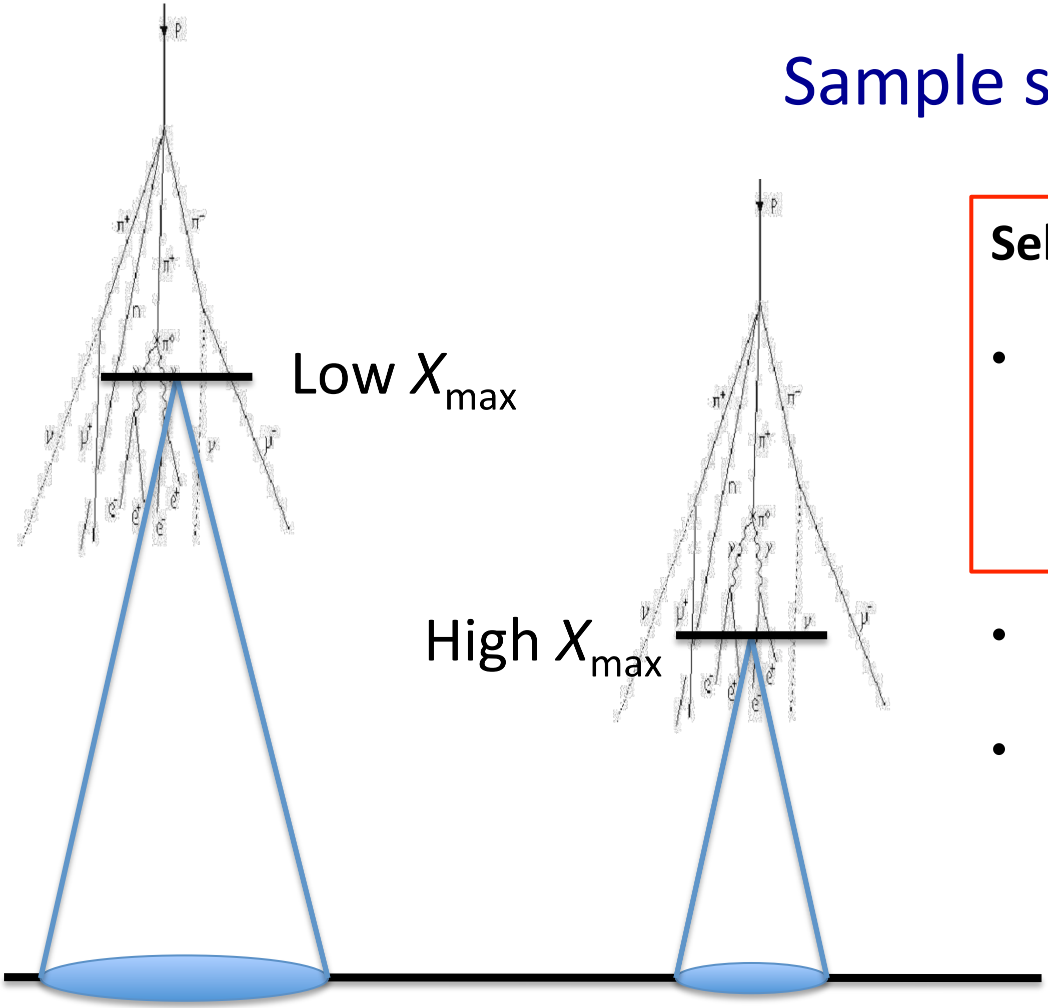


Opposite sources of bias:

- **low X_{max}**:
  fewer particles reach ground,
  may not trigger
- **high X_{max}**:
  radio footprint is smaller,
  harder to trigger 3 LOFAR stations

for a shower at given energy
and core position

Sample selection

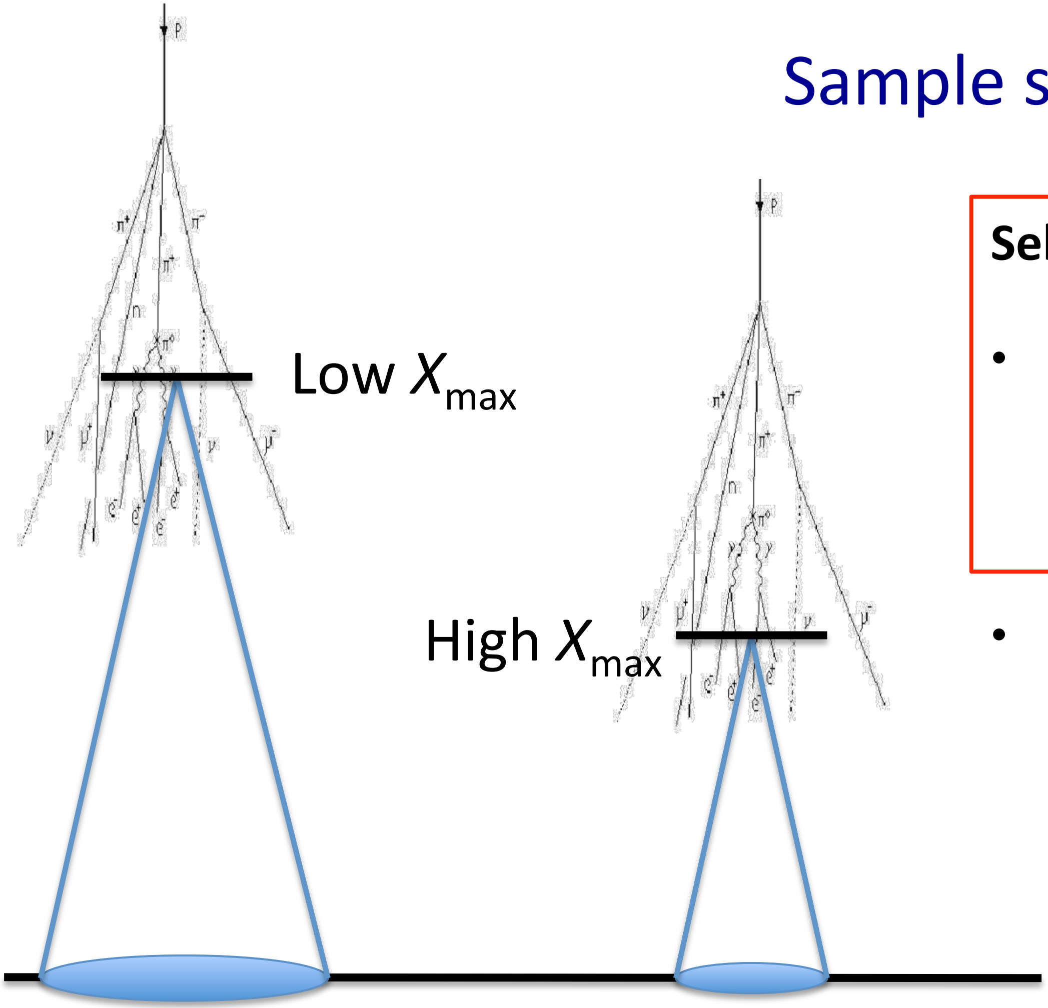


Selection criterion:

- Each measured shower, given energy and core position, must be able to trigger in both particles and radio, would it have any other X_{max} level within natural range

- LOFAR has irregular layout, fiducial volume hard to construct
- Number of showers is modest, allows treatment per shower

Sample selection

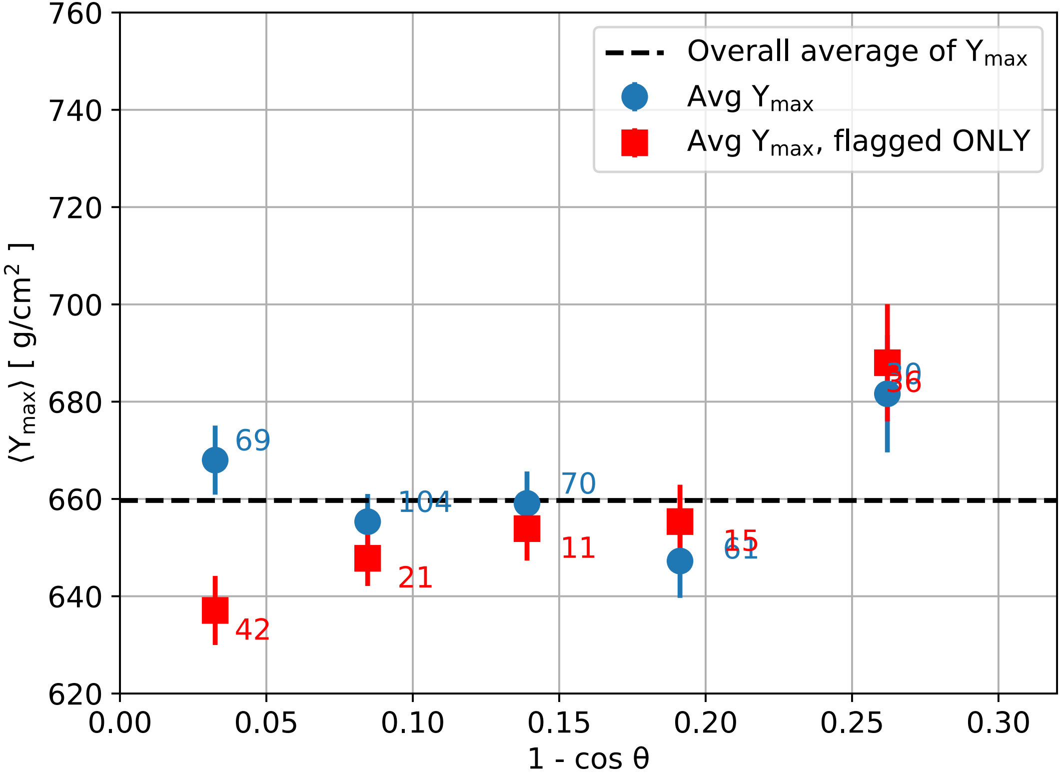


Selection criterion:

- Each measured shower, given energy and core position, must be able to trigger in both particles and radio, would it have any other X_{max} level within natural range

- Use simulated ensemble spanning X_{max} range:
  - Particle content and detector simulation
  - Radio (energy) footprint

Sample selection: result and test for residual bias



Retained 334 out of 459 events (**73 %**)

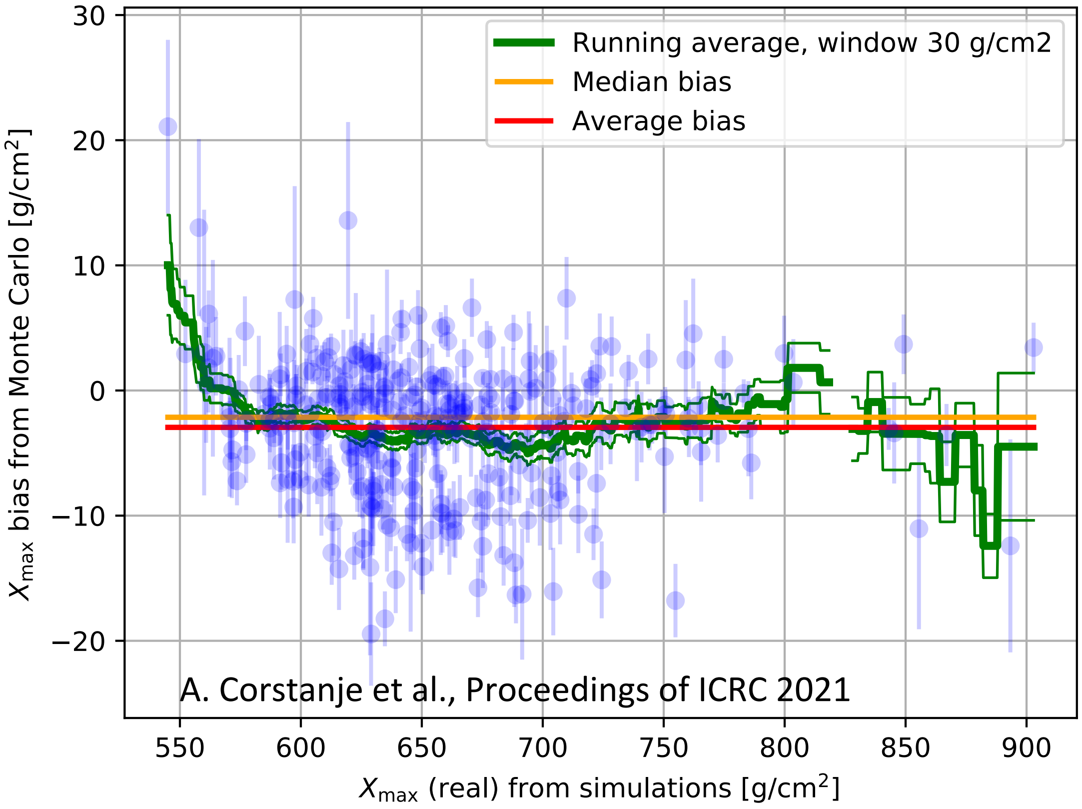
Test Y_{max} , which is X_{max} corrected for average energy (elongation rate)

Versus zenith angle (cos theta)

Final set, blue points: consistent with a constant

Flagged events: positive trend with increasing zenith angle – as expected

Test for bias in the reconstruction process



From reconstructing showers in Monte Carlo ensemble per measured shower

Bias versus (simulated X_{max})

Green line: running average

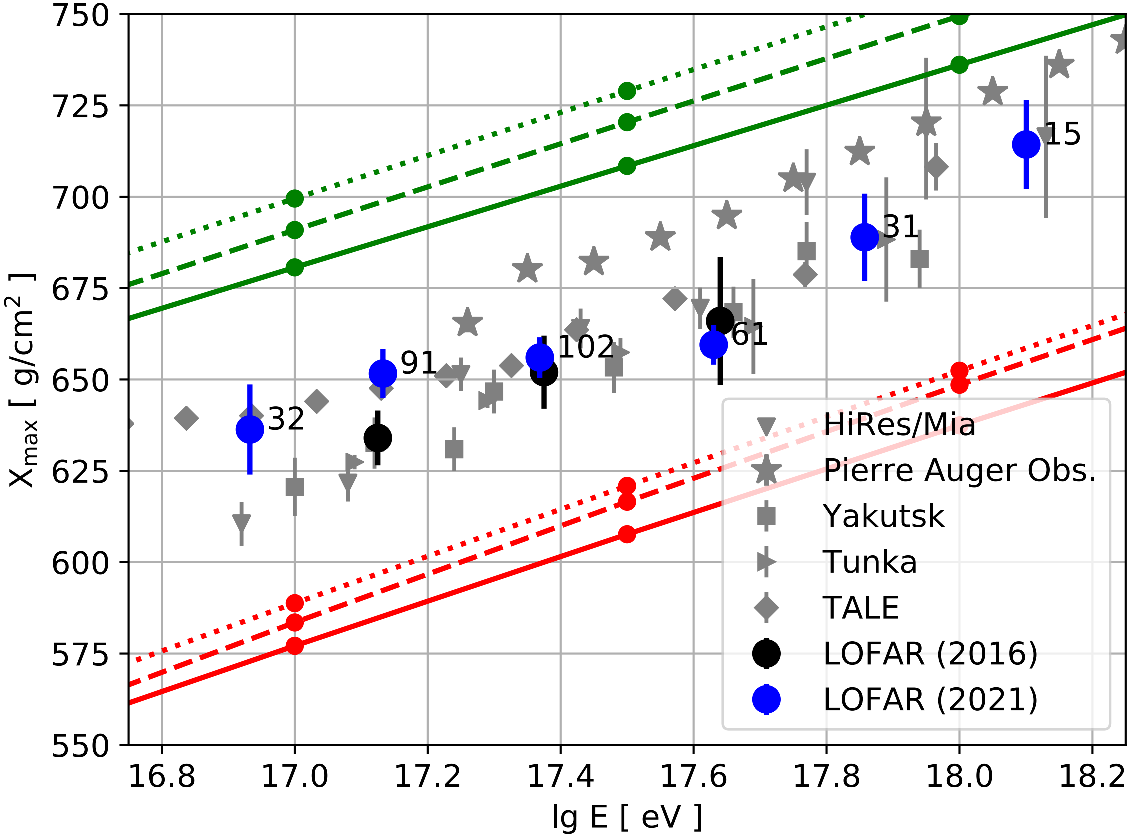
Median -2.1, mean -2.9 g/cm^2
In line with stat. unc. on $\langle X_{max} \rangle$

Edge effects: low number stats

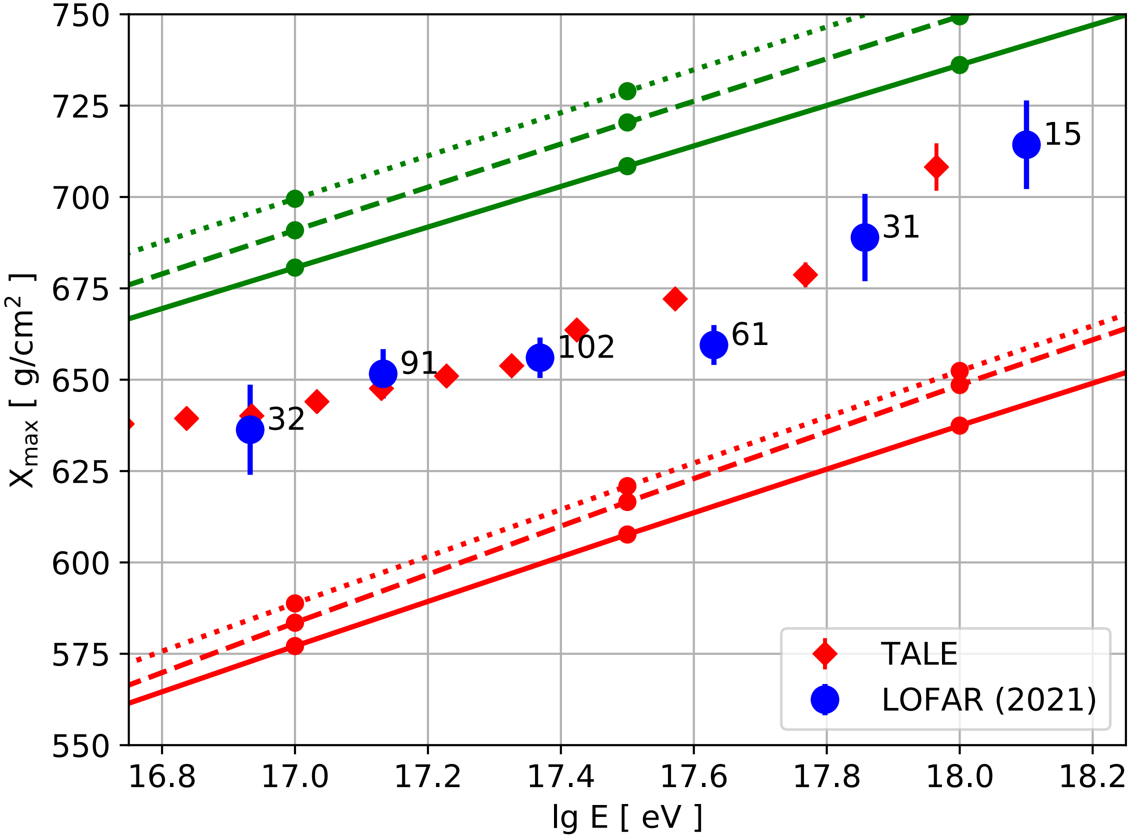
Systematic uncertainties

On X_{max}:	SYST	STAT
Choice of hadronic interaction model: (for X_{max} reconstruction)	5 g/cm^2	
Remaining uncertainty, atmosphere	~ 1 g/cm^2	2 g/cm^2
Atmospheric uncertainty (5-layer Corsika):	2 g/cm^2	4 g/cm^2
Possible bias, from $\langle X_{max} \rangle$ vs zenith:	4 g/cm^2	
Total, added in quadrature:	**7** g/cm^2	
For composition analysis:		
Parametrized X_{max} distributions, Conex:	5 g/cm^2	
Total, added in quadrature:	**9** g/cm^2	**20** g/cm^2
Energy:	**14** %	**10** %

Result: Average X_{max} versus primary energy

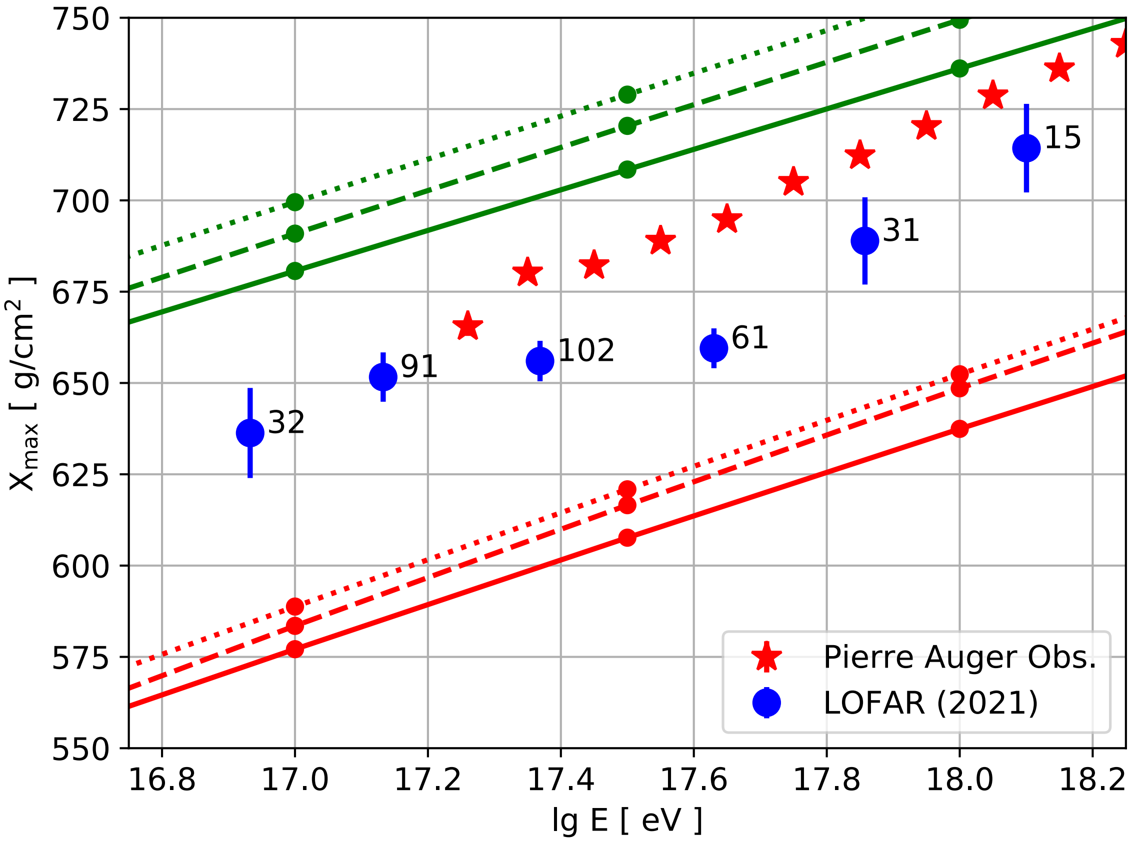


Result: Average X_{max} versus primary energy



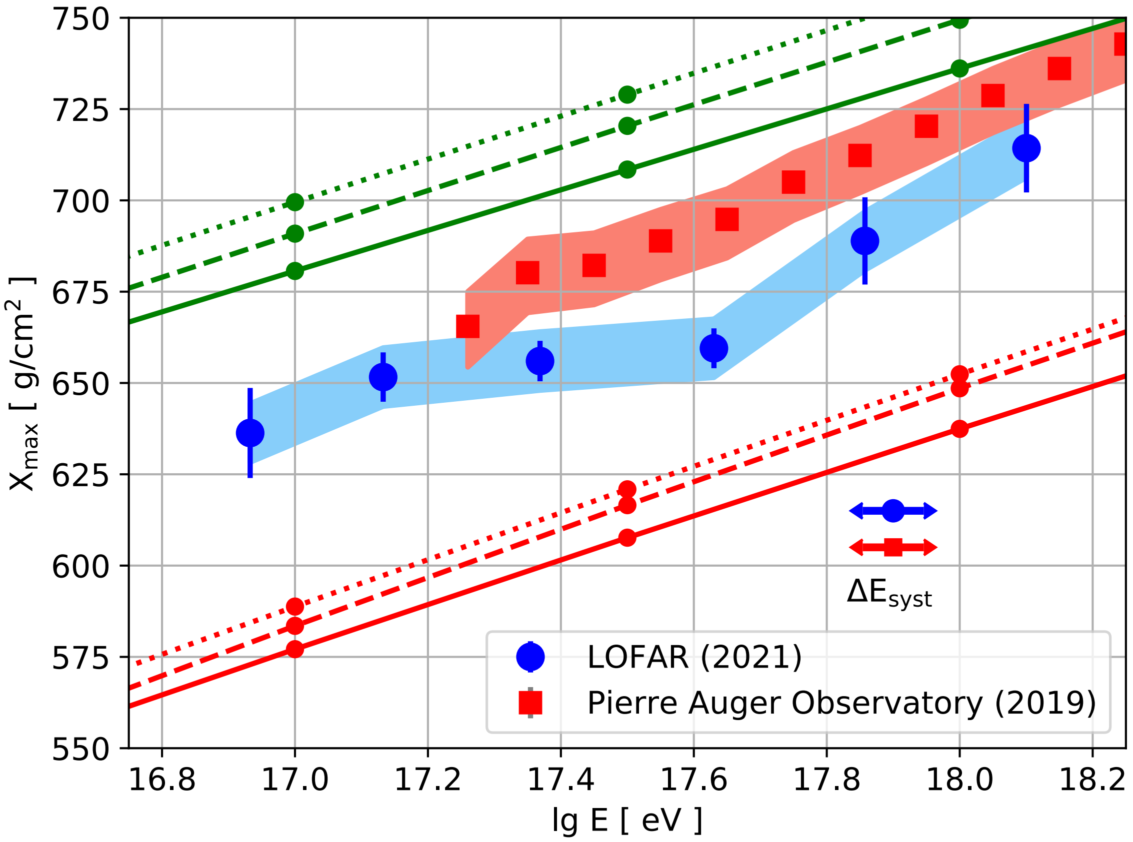
- Consistent with TALE
- Also with Tunka, Yakutsk , for lg E > 17.3, HiRes/Mia , for lg E > 17.2

Result: Average X_{max} versus primary energy



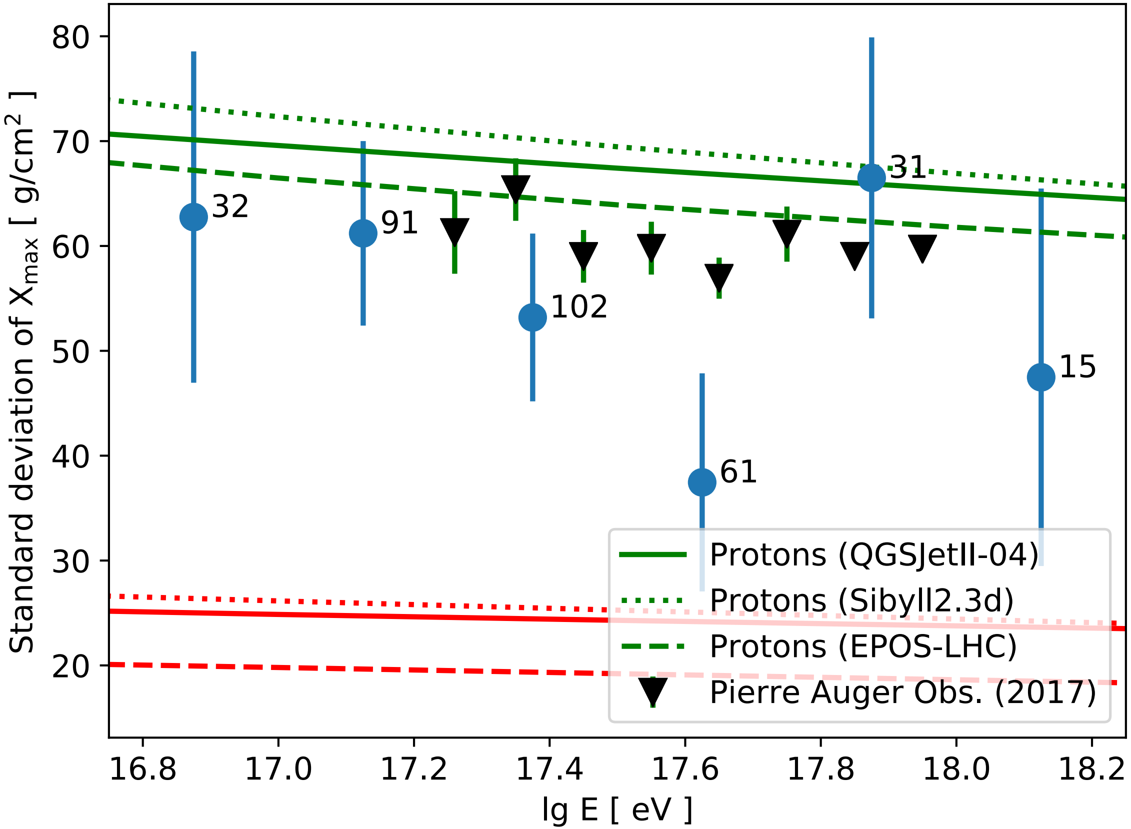
- Discrepancy with Auger, where both have data (lg E > 17.2)
  - Not fully explainable from statistics and systematic uncertainties
  - Unclear if would agree below lgE = 17.25, lack of data

Result: Average X_{max} versus primary energy



- LOFAR and Pierre Auger results, with systematic uncertainties
- Tension as yet unexplained

Result: Standard deviation of X_{max} versus energy



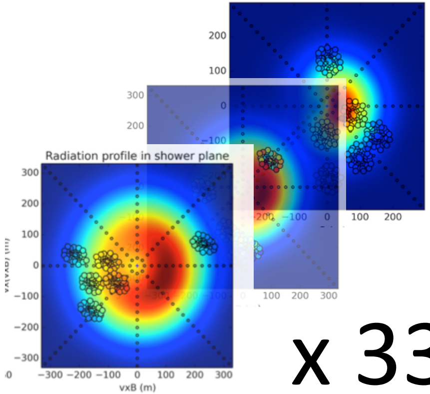
- Mostly consistency between LOFAR and Pierre Auger
- Statistical uncertainties considerable due to size of dataset

Result on mass composition

Intermediate-mass component dominates (C/N/O)

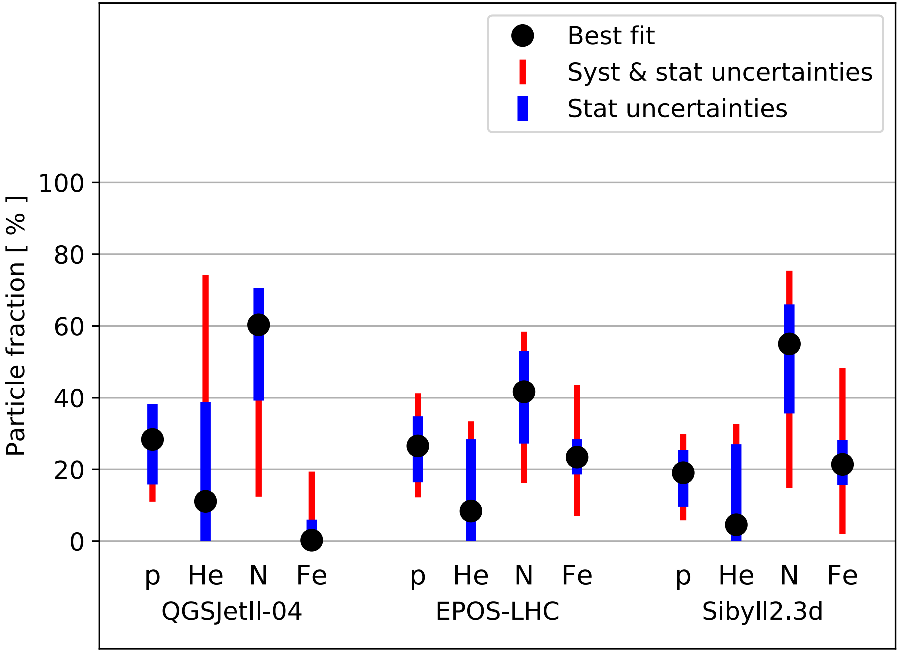
Significant light-mass component (p+He)
Still considerable uncertainties, some inevitable

- overlap of X_{max} distributions
- Hadronic interaction models



x 334

From unbinned analysis:
main coverage in lg E: **17.39 +/- 0.32**



Result on mass composition

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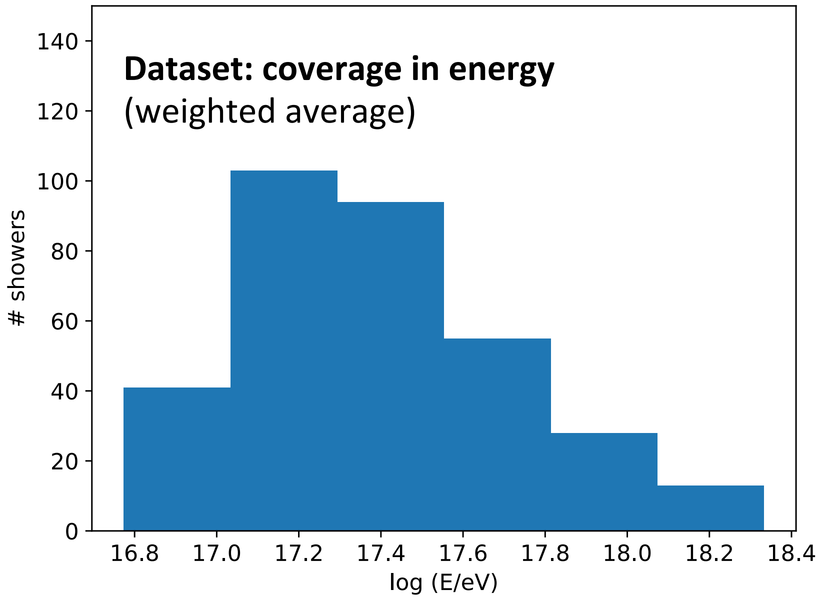

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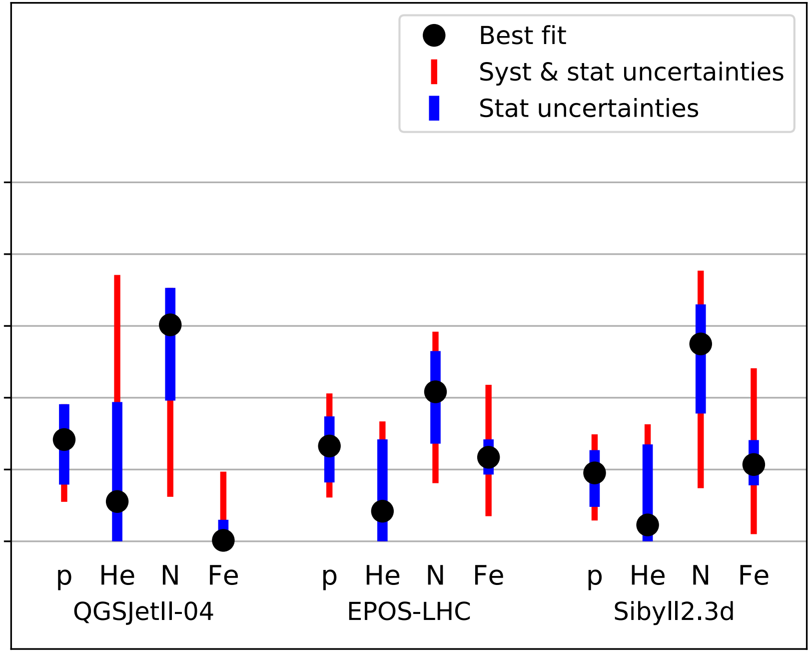
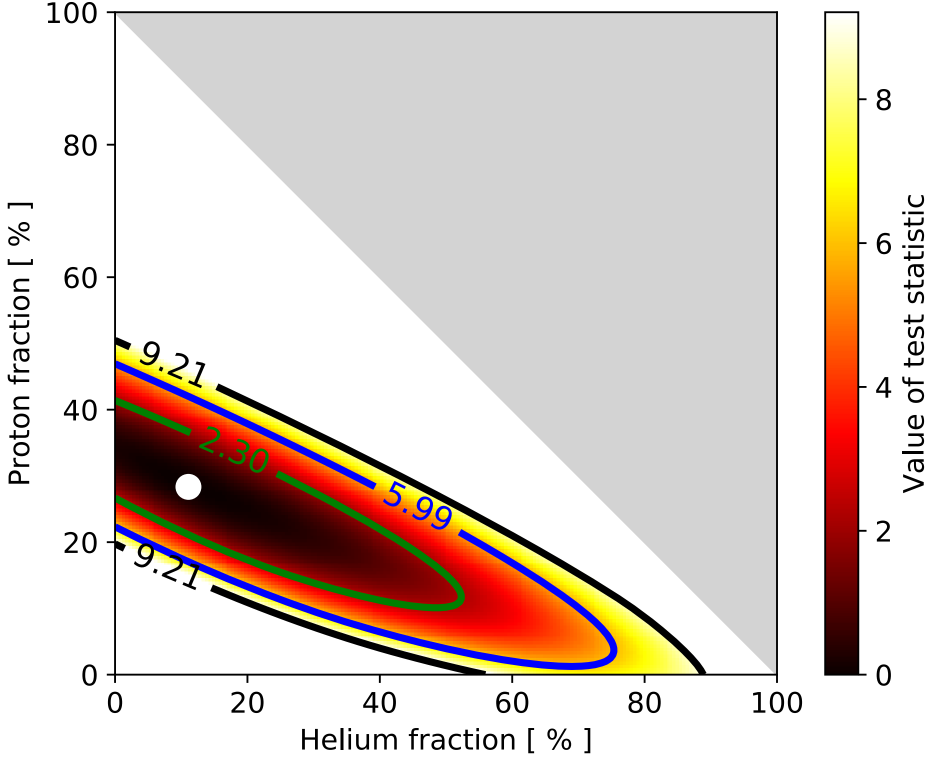


Result on mass composition

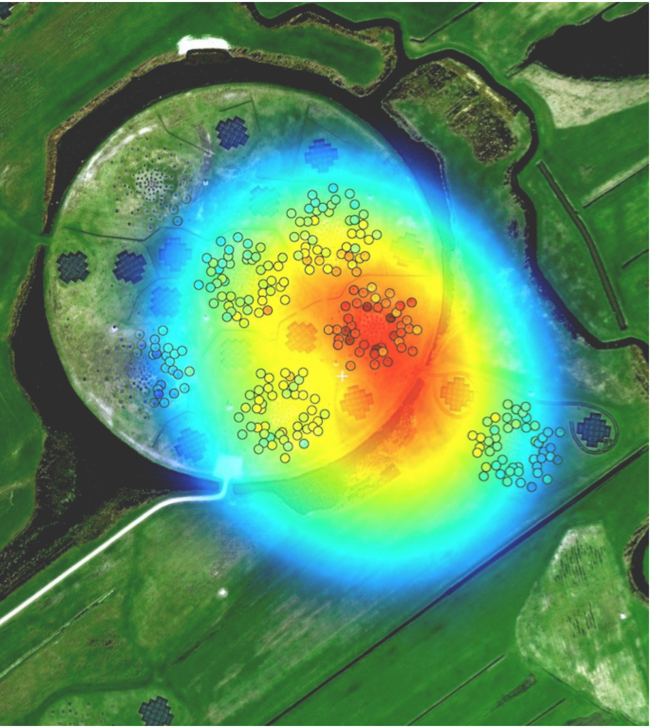


Likelihood when interchanging protons and helium (contours for one-sigma, 95% and 99% C.L.)

Lower proton fraction implies (much) higher helium fraction

Ability to distinguish protons and helium is limited: overlapping X_{max} distributions, dataset size, systematics

Summary



LOFAR has measured the shower maximum X_{max} at a resolution of **19 g/cm²** and systematic uncertainty of **7 to 9 g/cm²**

Average X_{max} versus energy differs from the Auger result, while consistent with TALE and others; tension is currently unexplained

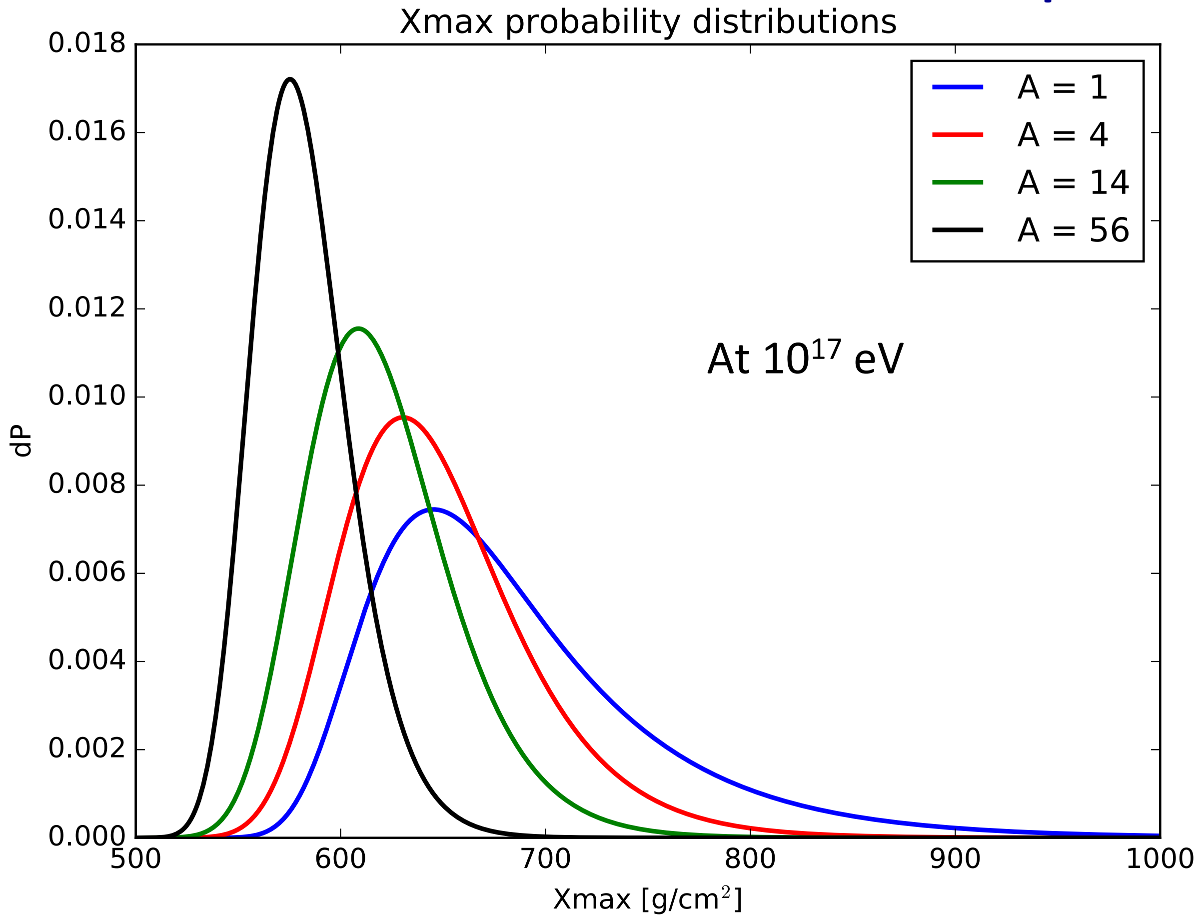
Detailed comparison with AERA procedures is called for

Mass composition analysis confirms significant light-mass component, C/N/O dominant

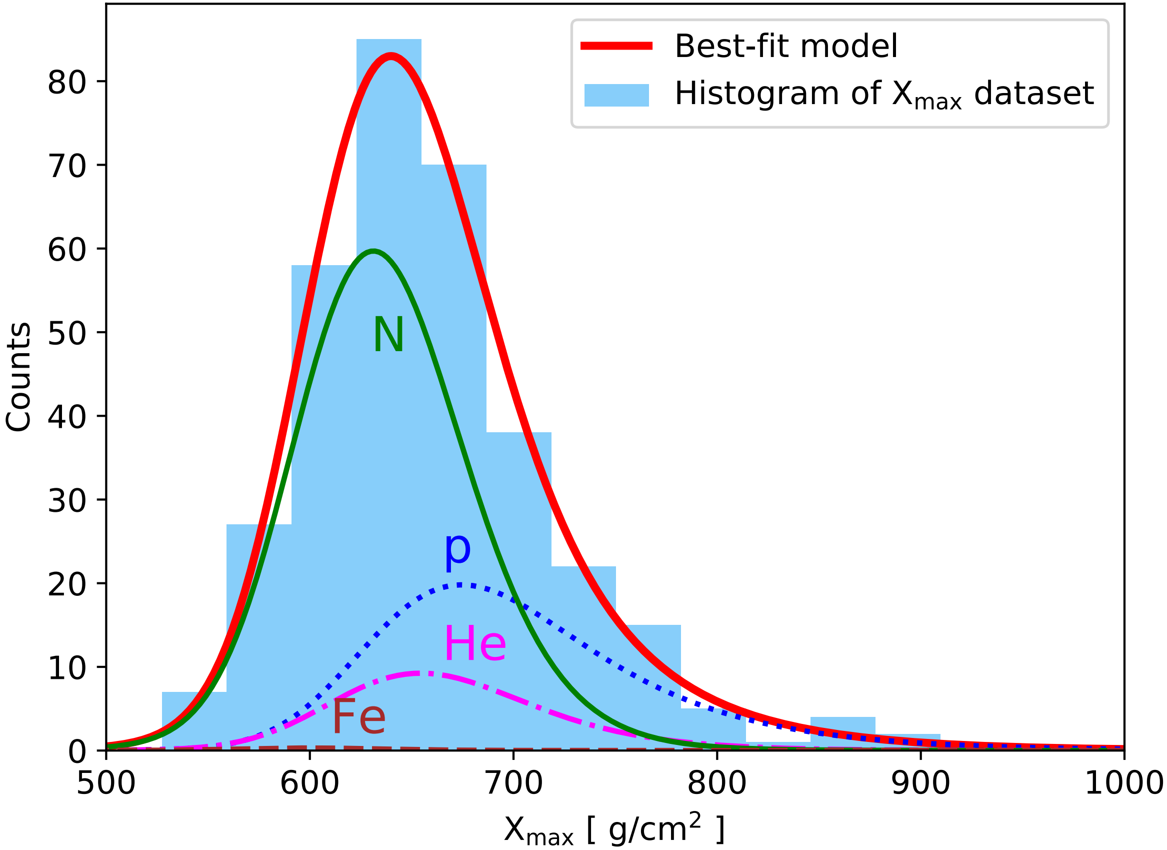
Conclusions about trend with energy require a larger dataset (factor 2 to 3)

Backup

Backup


Xmax probability distributions
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
dP
500
600
700
800
900
1000
Xmax [g/cm²]
A = 1
A = 4
A = 14
A = 56
At 10^{17} eV

Backup



Overall histogram of X_{max}:
Goodness of fit quite reasonable, including the tails

Models were NOT fit to the histogram; result of unbinned likelihood analysis

Shown is best fit for QGSJetII-04
Stat & syst margins, see slide 16