Cosmic ray mass composition with LOFAR

June 9, 2016 - ARENA 2016 Groningen

Stijn Buitink - Vrije Universiteit Brussel

Vrije Universiteit Brussel

KVI university of groningen

LOFAR

erc European Research Council

Radboud Universiteit Nijmegen

for the LOFAR Cosmic Ray KSP

A. Bonardi, A. Corstanje, J.E. Enriquez, H. Falcke, J.R. Hörandel,
P. Mitra, K. Mulrey, A.Nelles, S. Thoudam, J.P. Rachen, L. Rossetto,
P. Schellart, O. Scholten, G. Trinh, S. ter Veen, T. Winchen

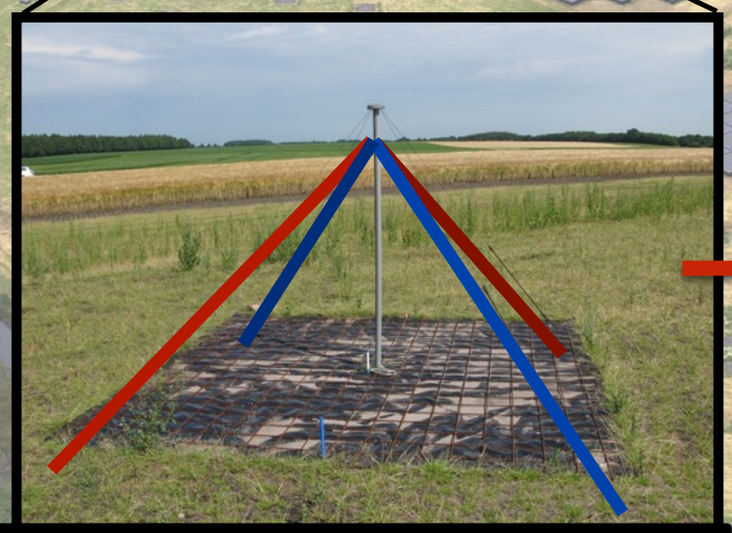
LORA
LOFAR Radboud Array
scintillator detectors

Superterp:
* diameter ~ 300 m
* 20 LORA detectors
* 6 LBA stations
  (= 6 x 48 antennas)

* more LBA stations around superterp

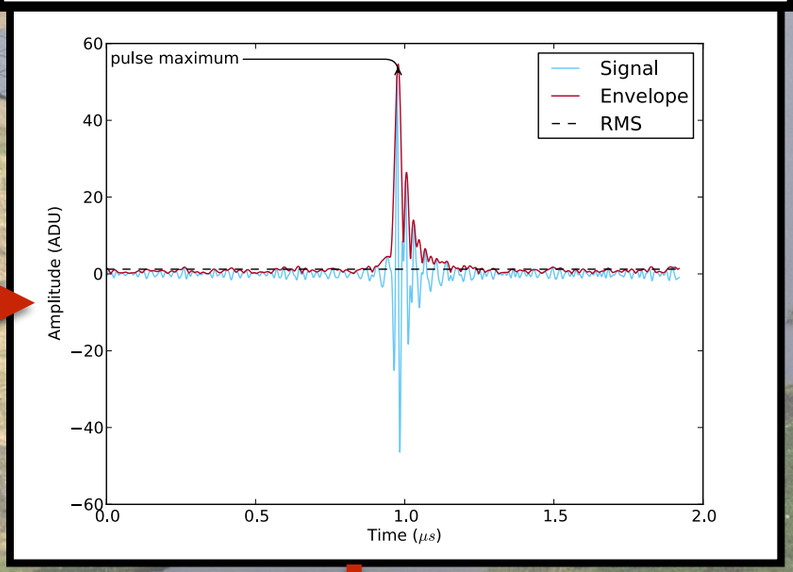
trigger: 16 of 20 detectors

offline analysis
P. Schellart et al., A&A 560, 98 (2013)



Low Band Antennas (LBA)
30 - 80 MHz filtering

buffer
2 ms read-out

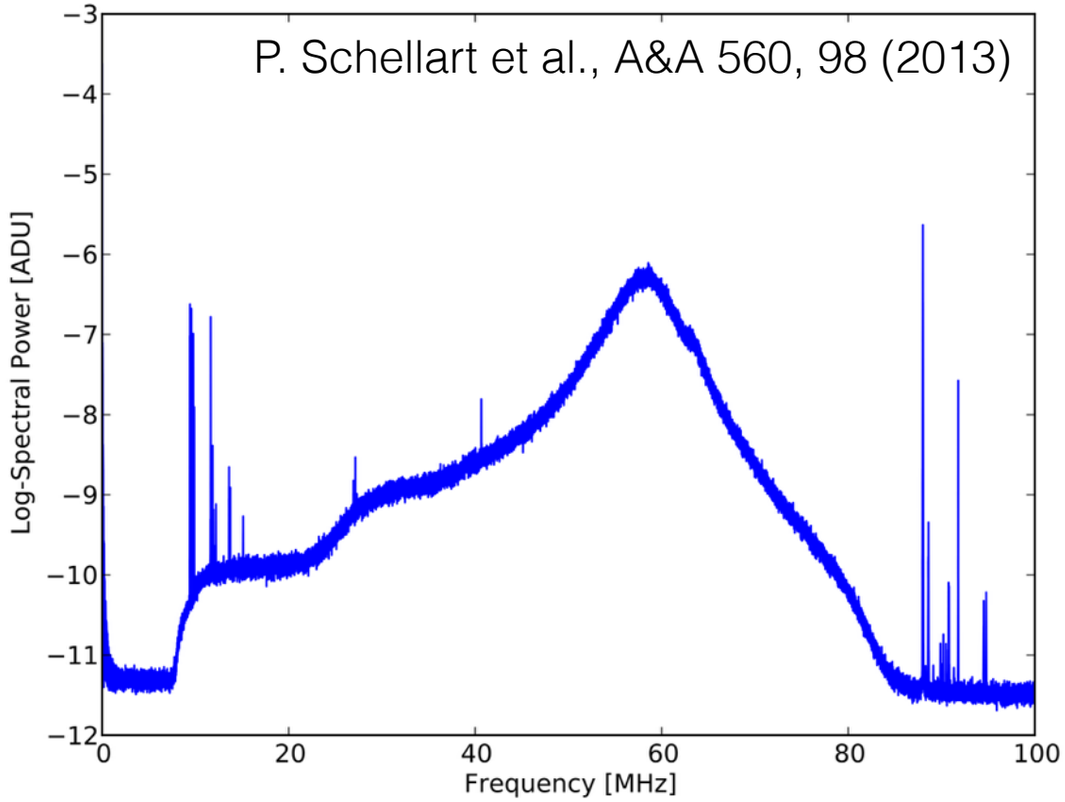


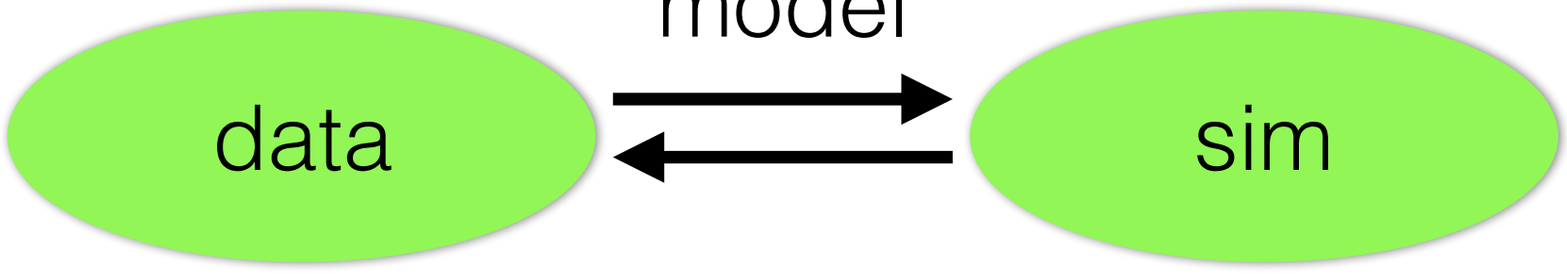
Selection this analysis:
4+ LBA stations

data processing

This analysis:

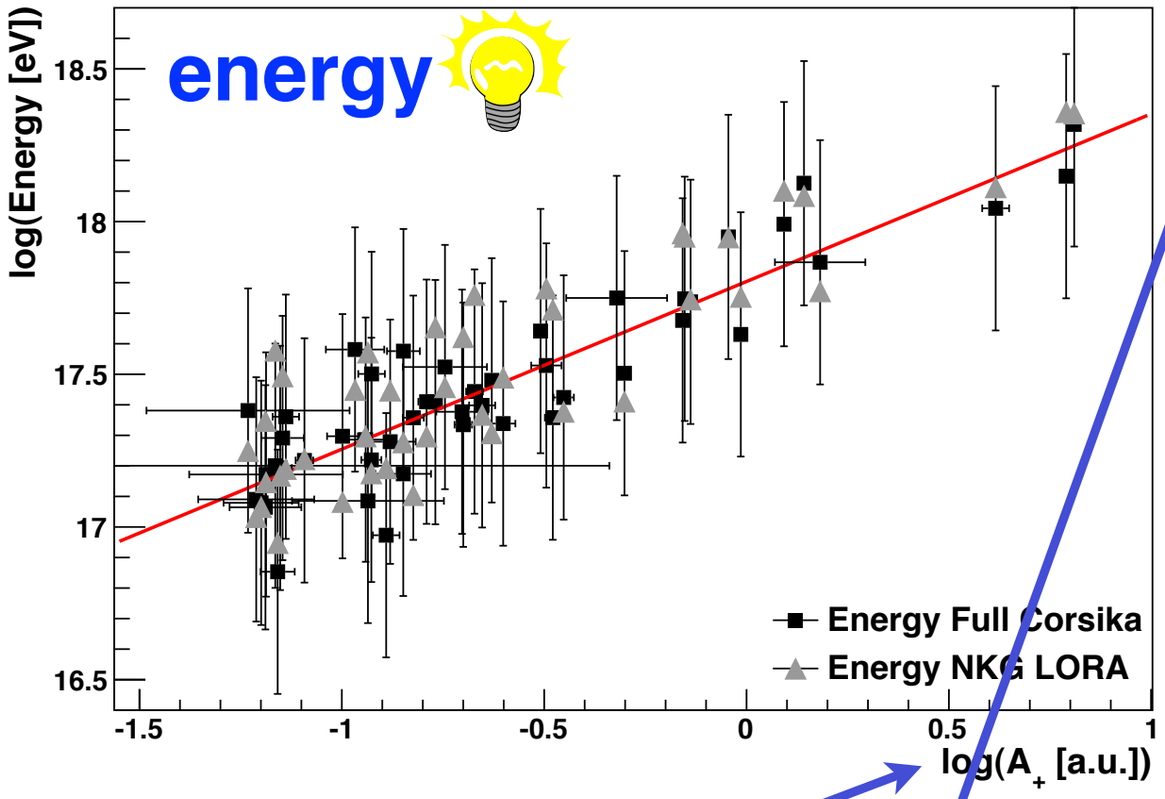
- find peak value
- calculate total power in 11 bins (= 55 ns) around maximum

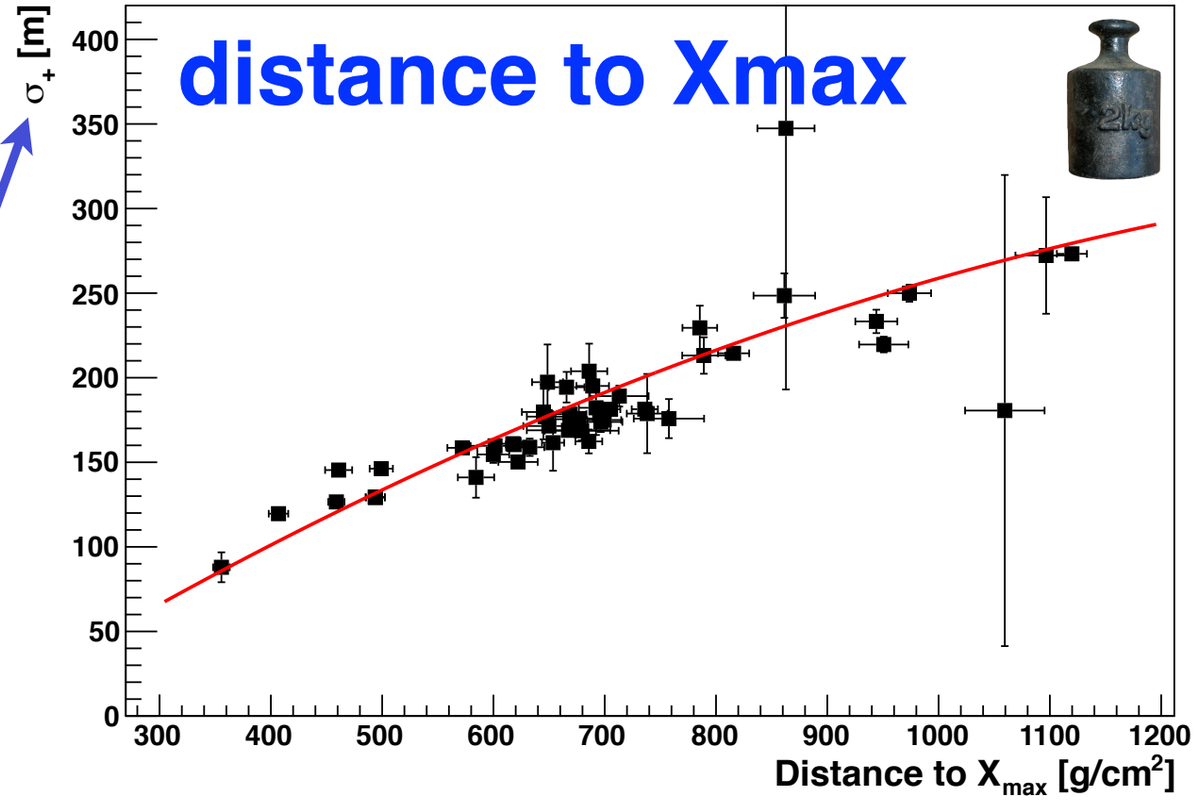




We apply antenna model to simulation
comparison of **measured voltage** [not actual radiation field]
advantages: stability against noise, model uncertainties.

Properties of primary particle





$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

LOFAR

A. Nelles et al., JCAP 05 (2015) 018

double Gaussian fit gives:
- energy resolution 30%
- Xmax resolution 38 g/cm²

→ input for sim

simulation pipeline

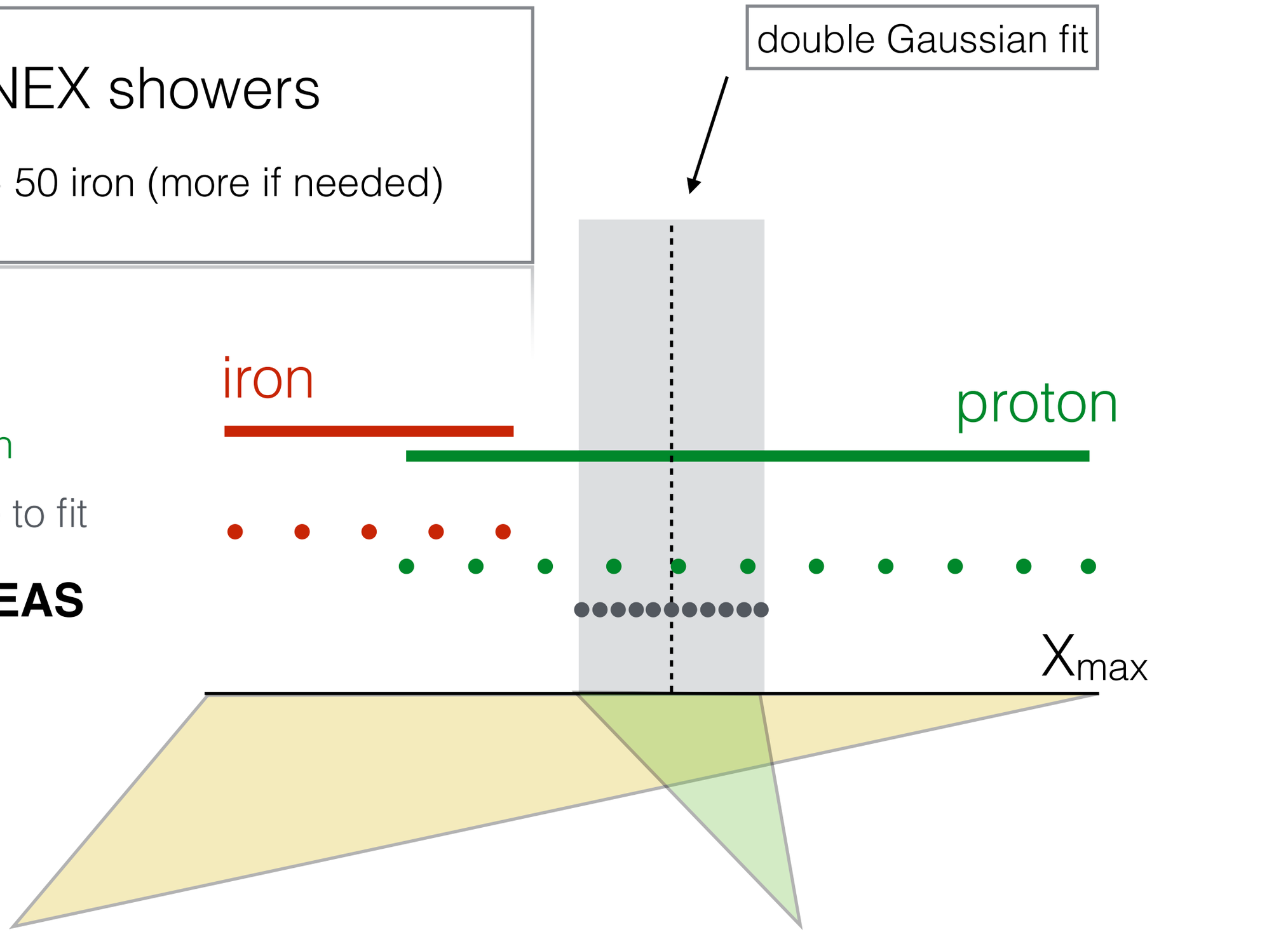
CONEX showers

200 proton + 50 iron (more if needed)

select:

- 5 iron
- 11 proton
- 11 close to fit

for **full CoREAS**

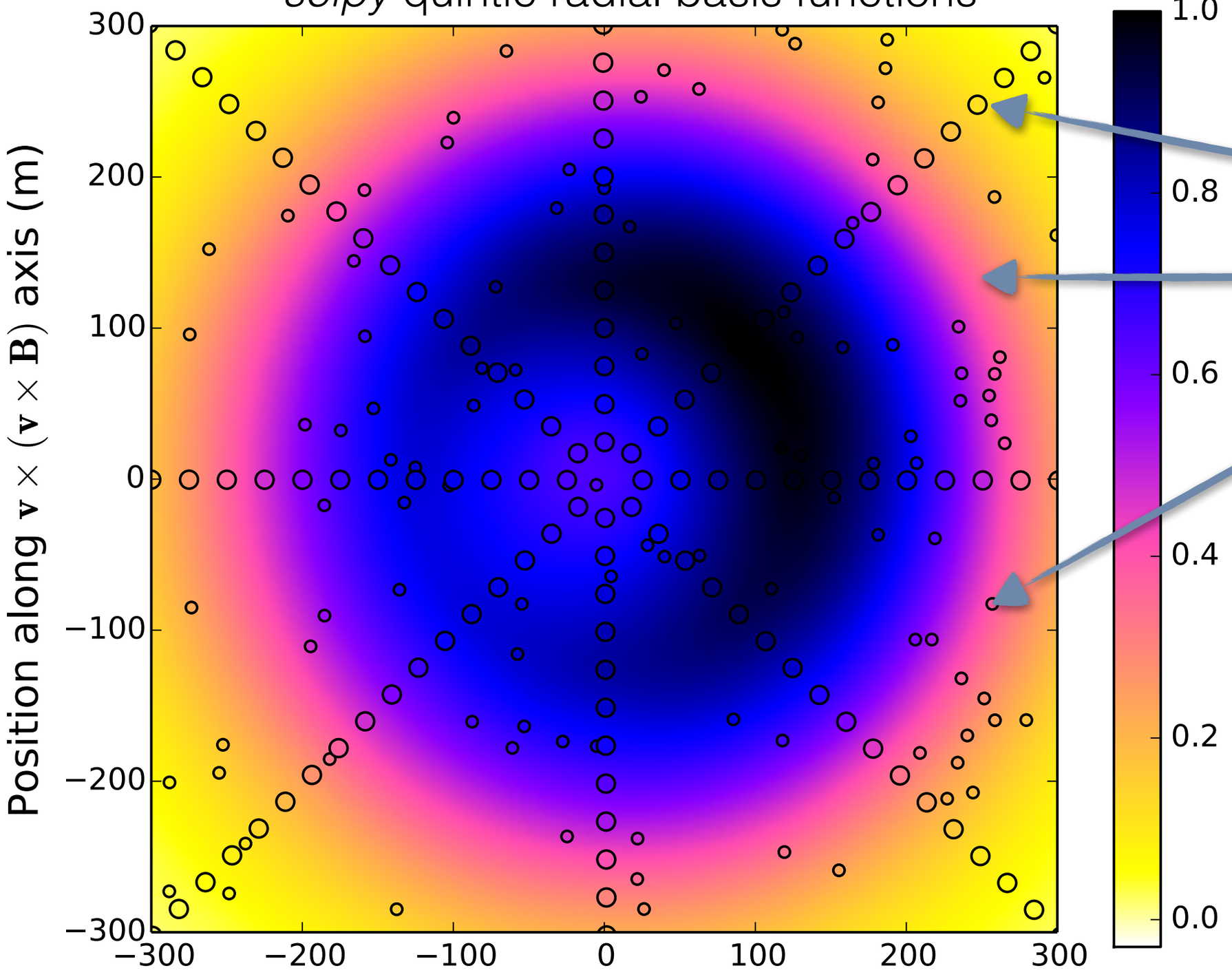


full range:
- anti-bias cut
- consistency check

close-up:
- resolution
- shower-to-shower fluctuations

Construction of 2D map: interpolation from star pattern

scipy quintic radial basis functions



large circles: simulation

background color: interpolation

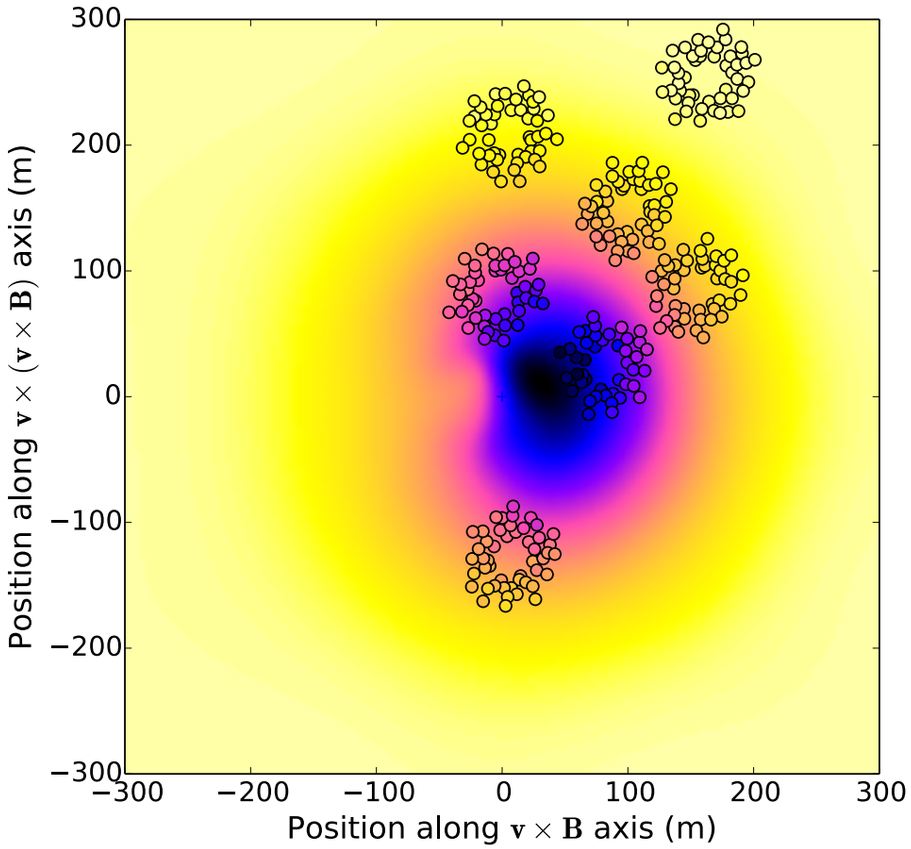
small circles: verification

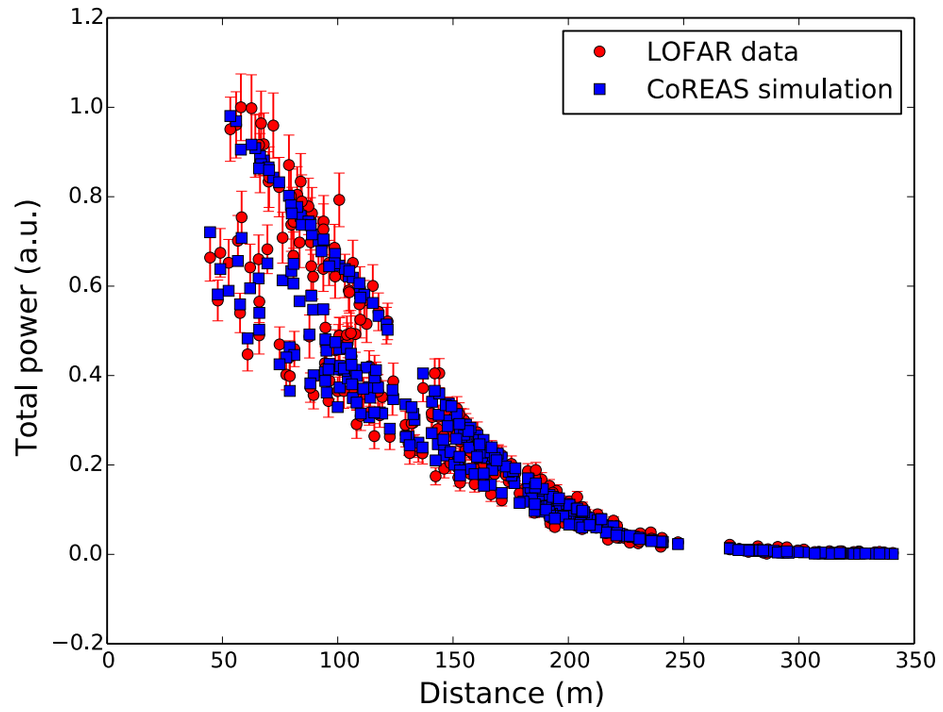
error < 2.5% of P_{max}

S.B et al., PRD 90 082003 (2014)

Reconstruction of Xmax

- based on fitting 2D radio profile *(S.B et al., PRD 90 082003 (2014)*.

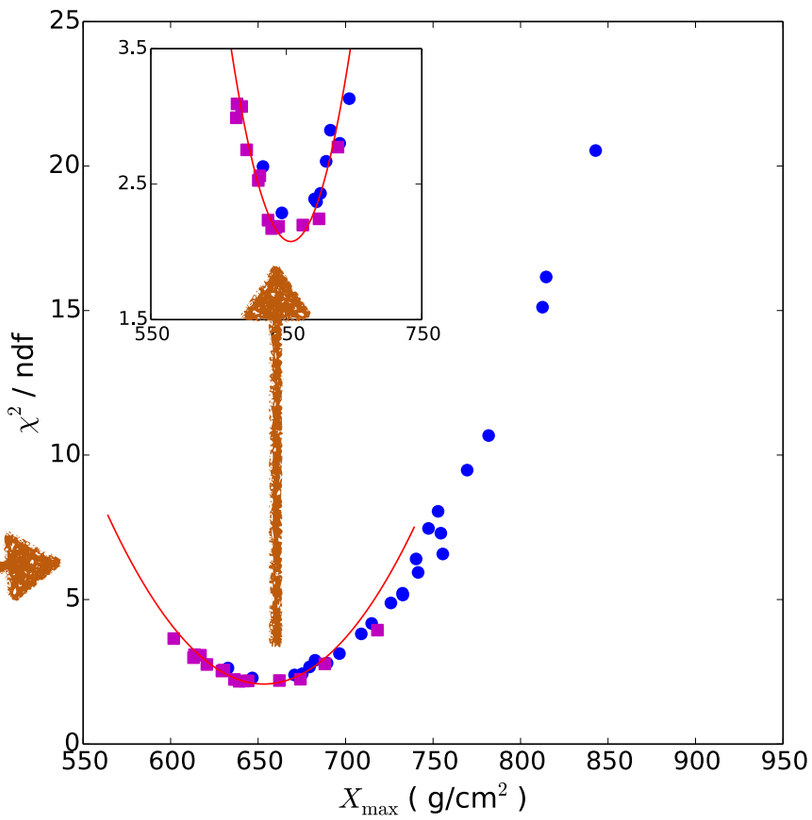




background: CORSIKA / CoREAS
circles: data
fit: 2D radio + 1D particle

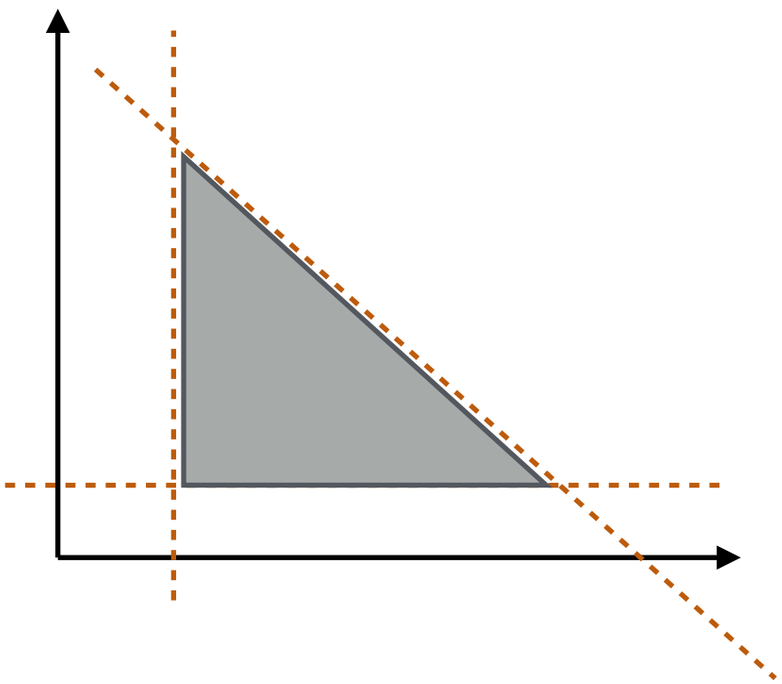
for **each** shower a **dedicated MC set** is produced:
50 p + 25 Fe
Xmax reco: use quality-of-fit
energy reco: from particles

energy mismatch?: repeat cycle



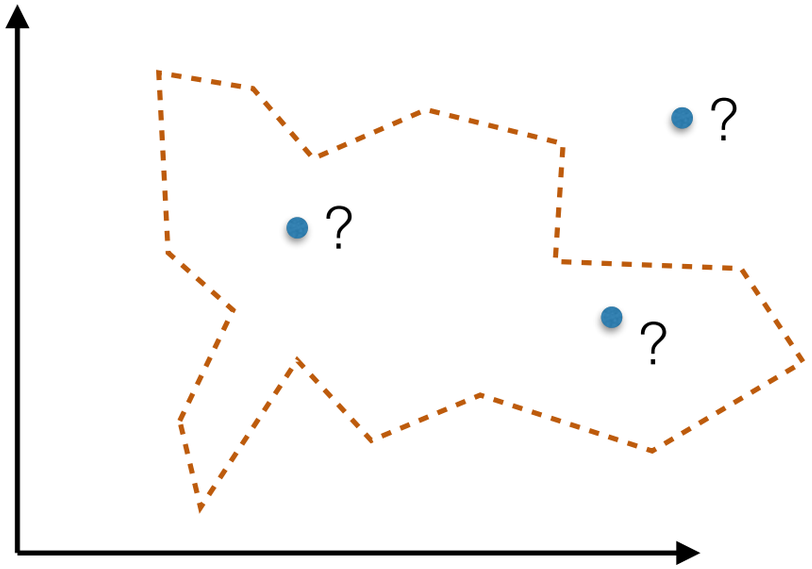
Anti-Bias cut

What parameter space (position, direction, energy) has ~100% detection efficiency?



Straight cuts don't work for LOFAR:

- signal strength depends on zenith and azimuth
- highly irregular antenna grid



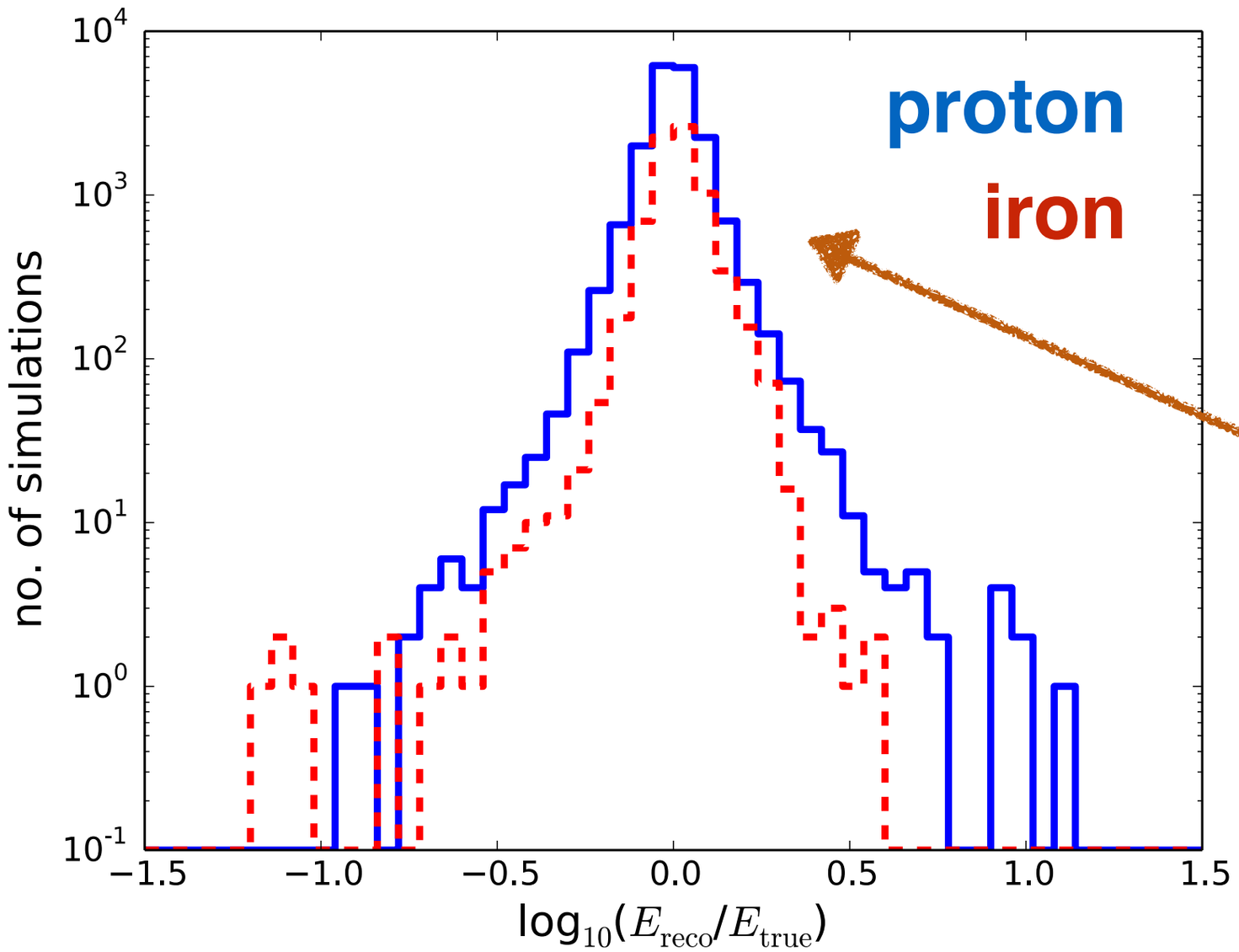
Alternative:
determine efficiency **per shower**

- all showers in **dedicated MC set** have to pass trigger and selection criteria

Energy cut

Anti-bias cut removes:
* 4 of 122 showers **> 10^{17} eV**
* ~half of showers **< 10^{17} eV**

energy cut:
* E_{reco} **> 10^{17} eV**



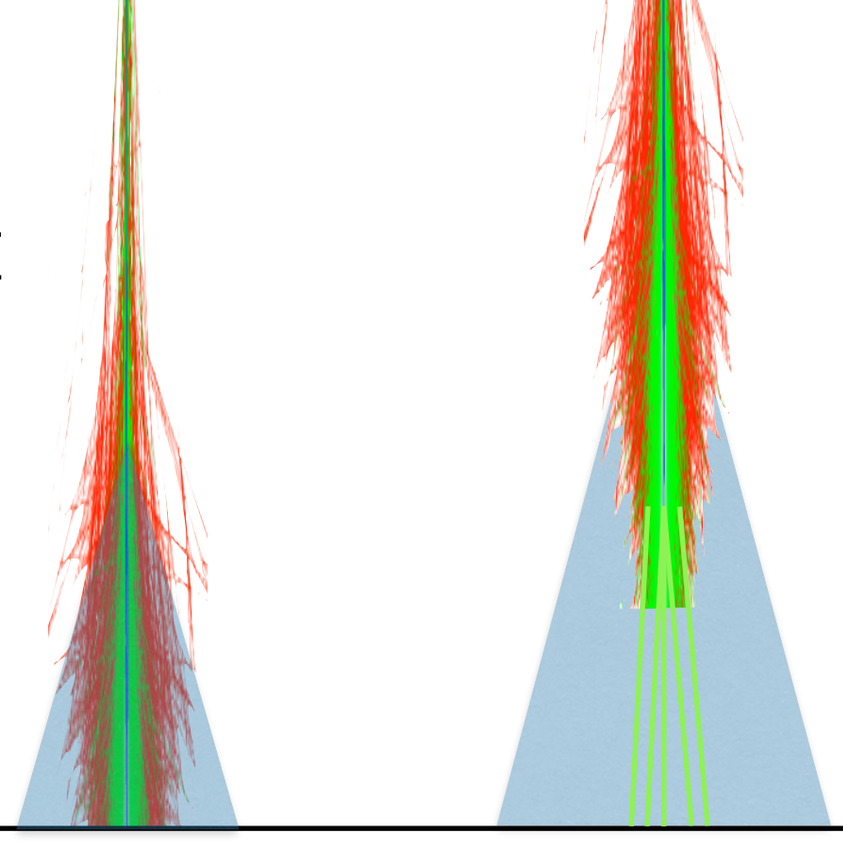
Cuts:
- no thunderstorms
- E_{reco} **> 10^{17} eV**
- anti-bias
- core < 5m

syst. offset between reconstruction error proton vs iron
~ 1%

no bias introduced

deep showers
small radio footprint

shallow showers
low particle density

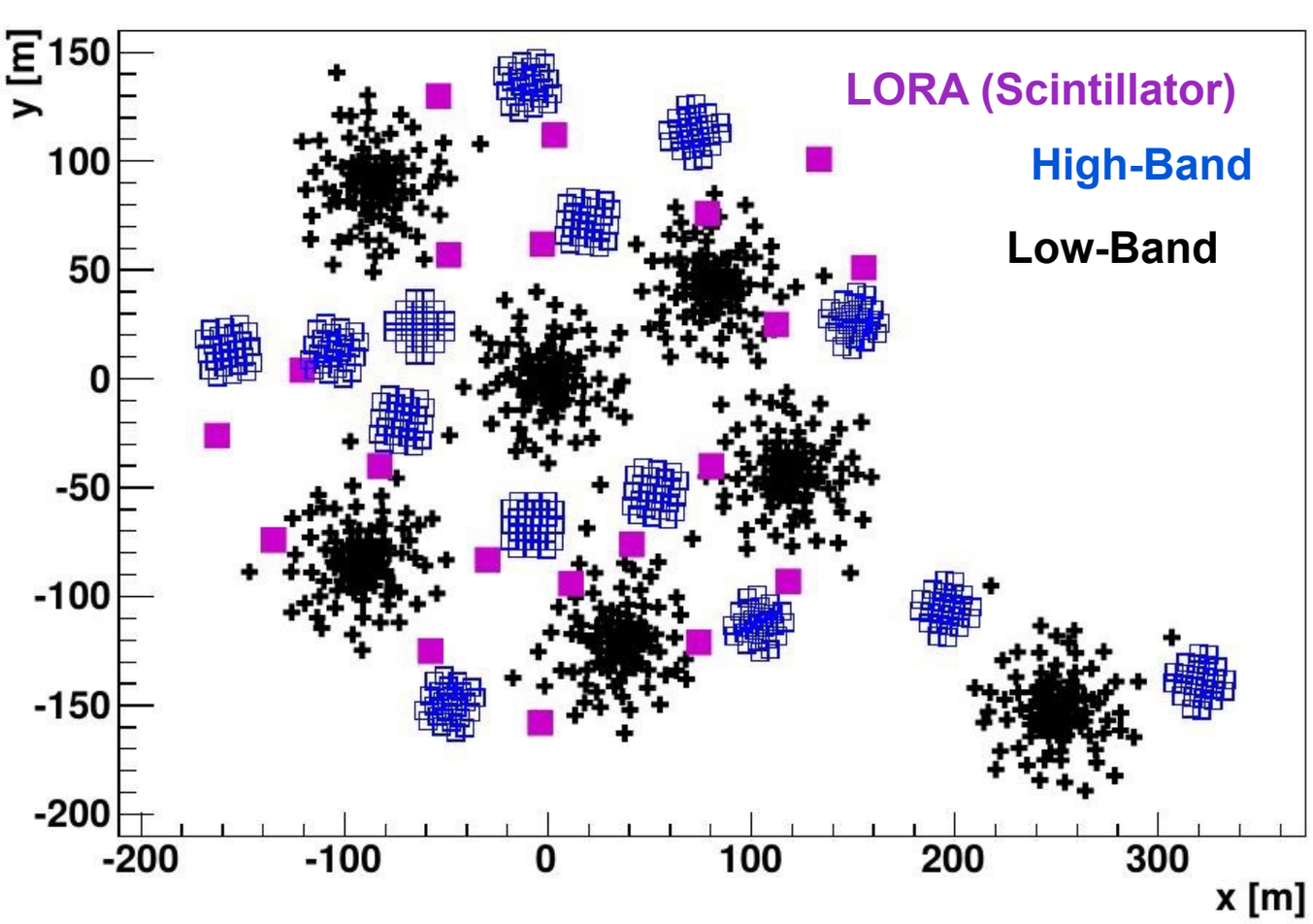


All simulated showers:

triggering 16/20 LORA detectors
selection 4+ antenna stations

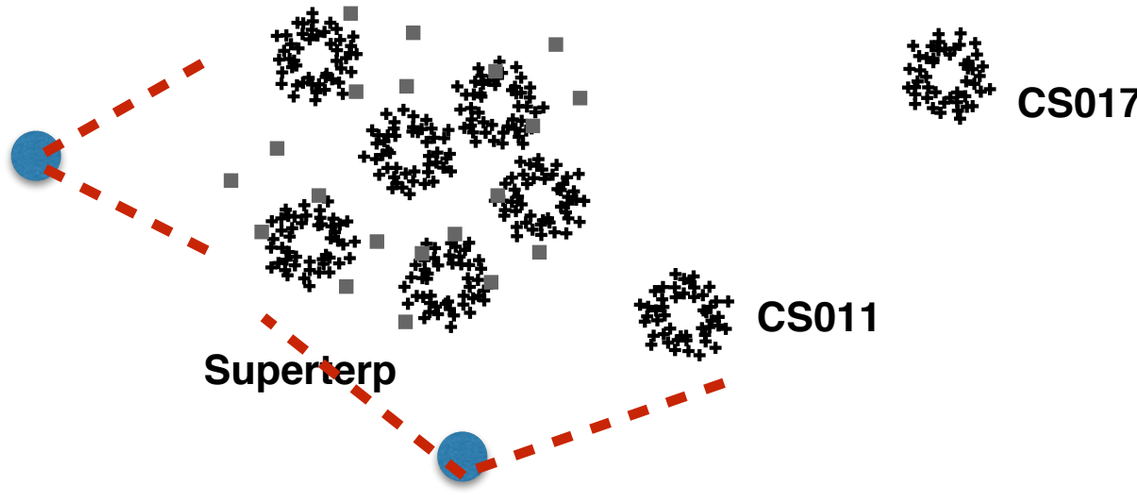
energy < 10^{17} eV:

hybrid trigger
x detectors + *y* antennas
see poster Katie Mulrey



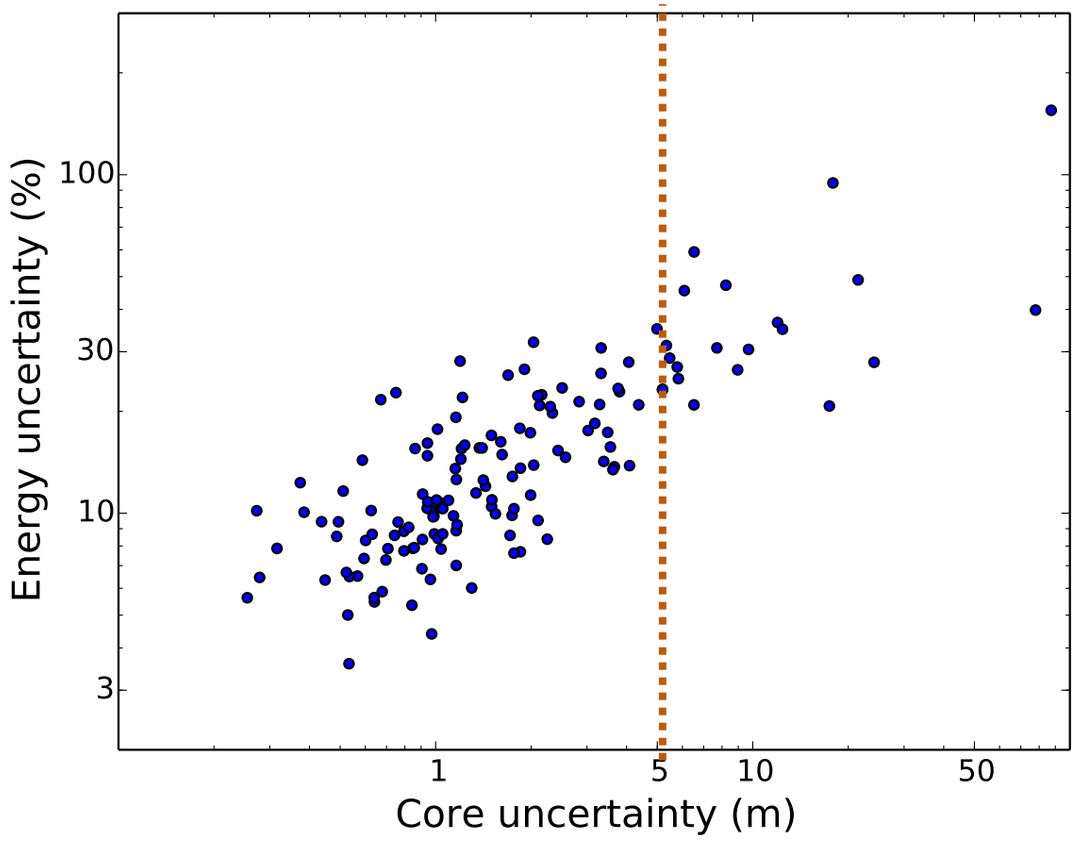
Quality cut

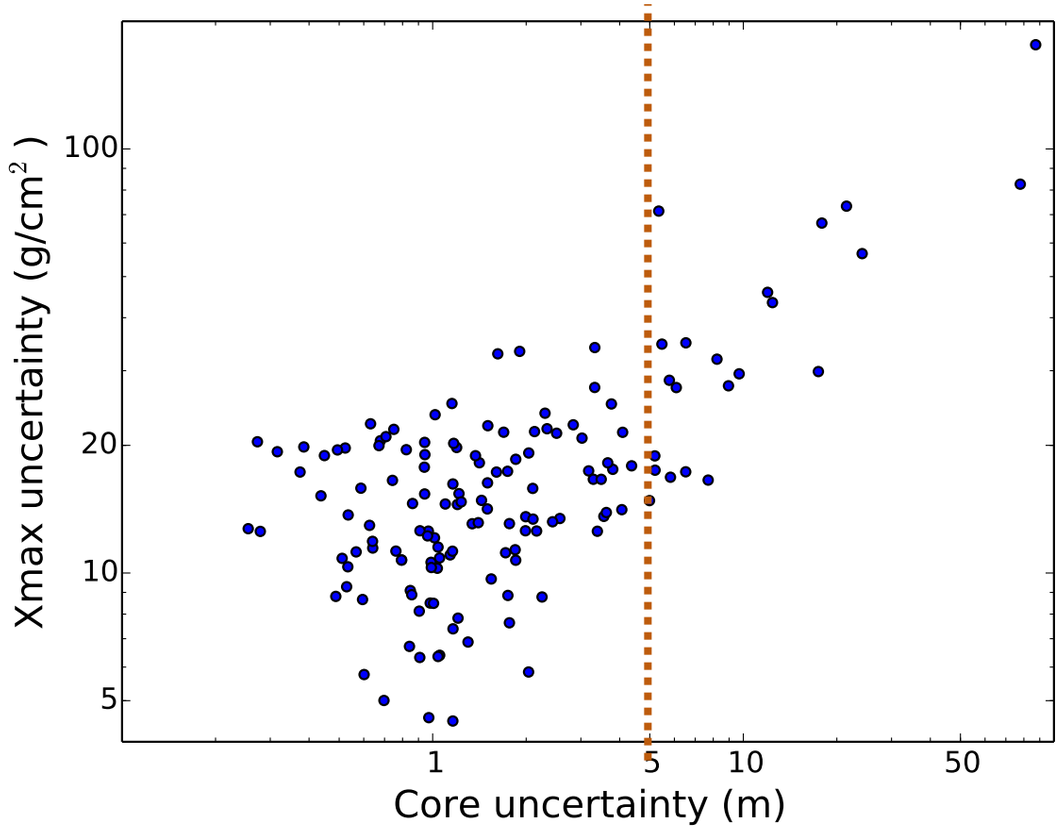
From **dedicated MC sets**:
uncertainty on
- core position σ_{core}
- energy reco σ_E
- Xmax reco σ_X



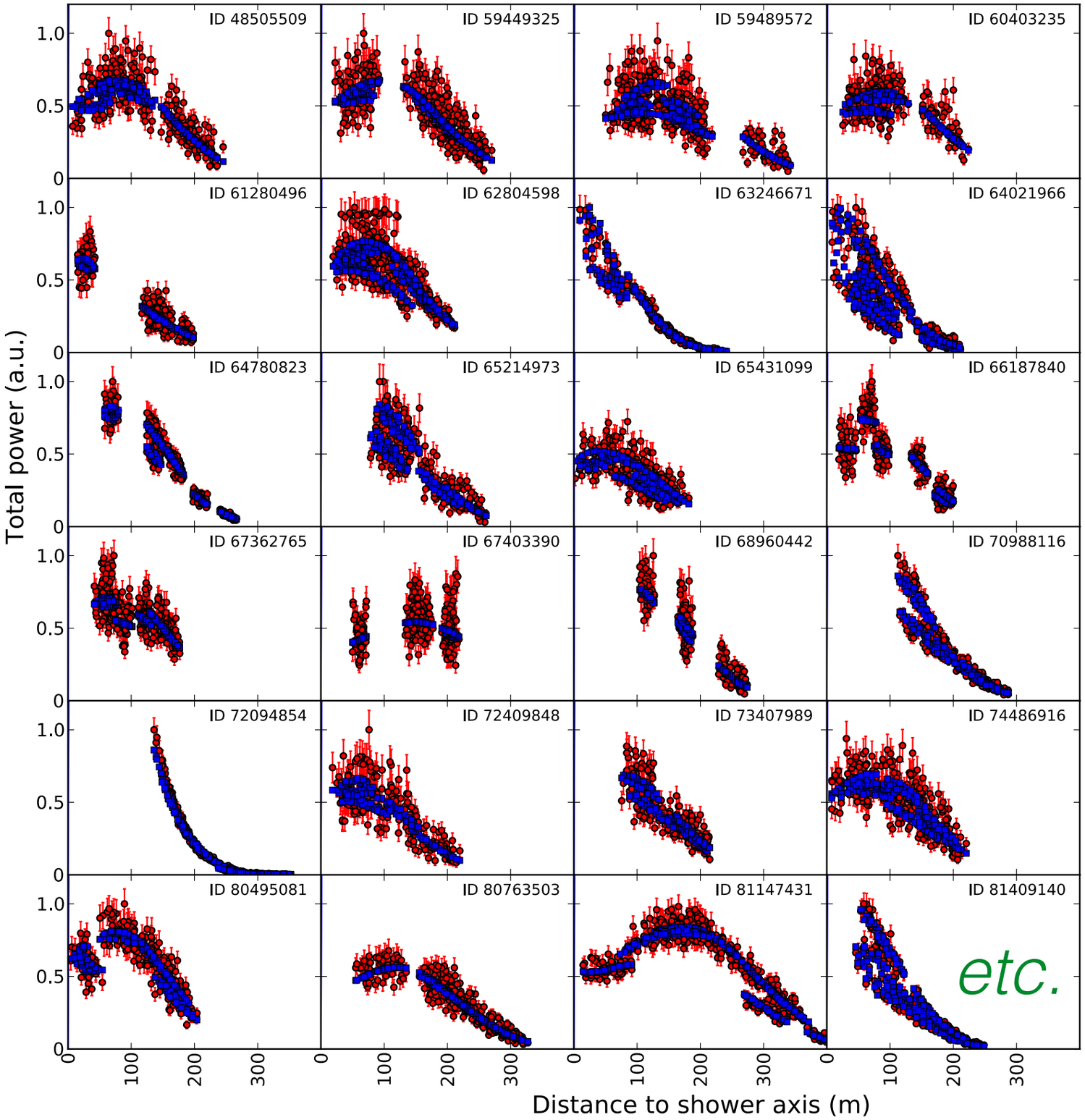
azimuthal coverage of
non-contained showers

cut: $\sigma_{core} < 5m$





Final sample



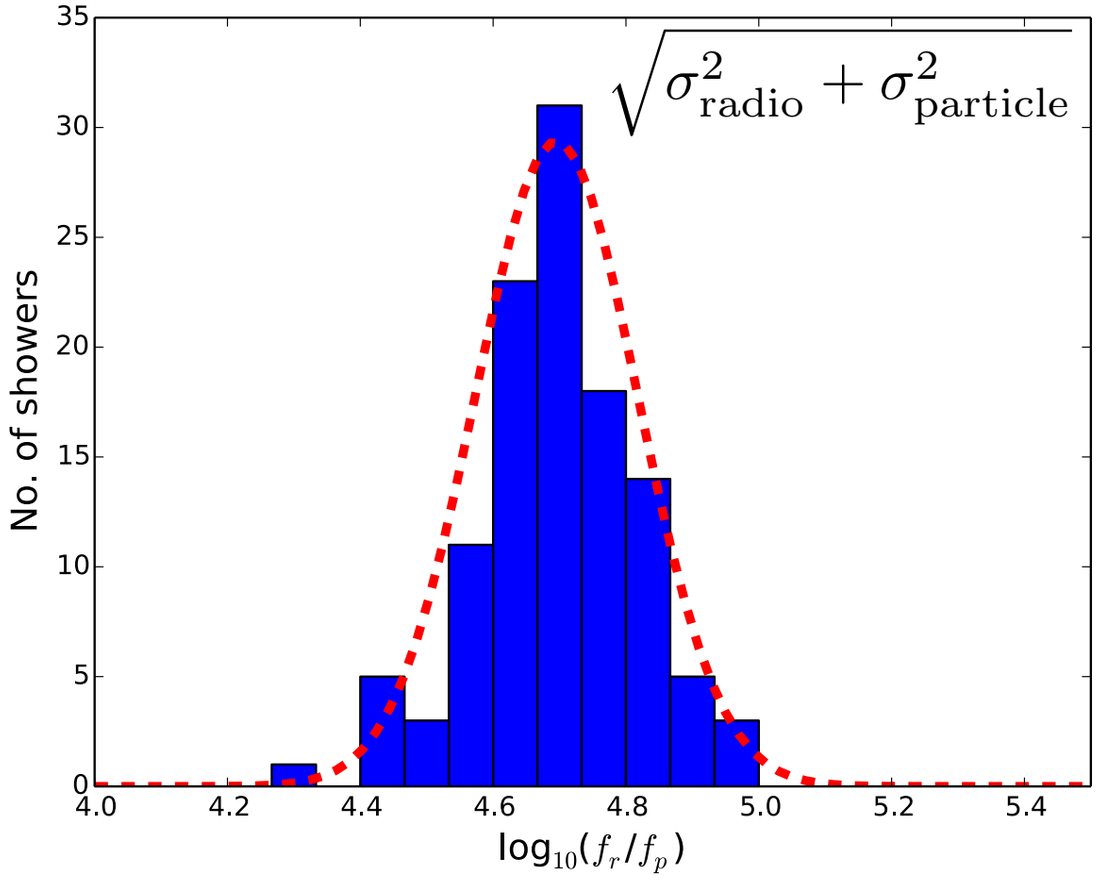
Cuts:

- no thunderstorms
- $E_{reco} > 10^{17}$ eV
- anti-bias
- $\sigma_{core} < 5$m

- **First sample: 114 showers**
- 200 - 450 antennas/event
- Fit
  all features reproduced
- no indications of discrepancy
  CoREAS ↔ data
  (also true for higher freq. and polarisation)

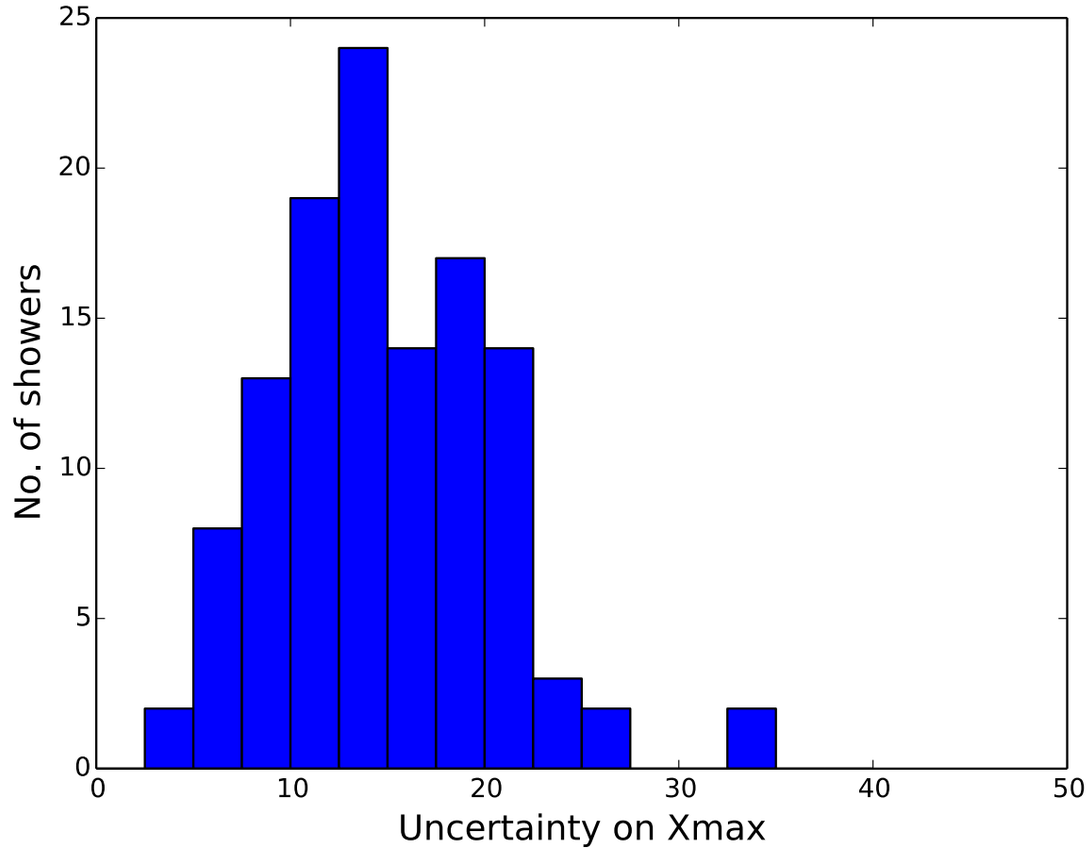
resolution

energy <32%



ratio of scaling factors in the fit for radio profile and particle LDF

Xmax < 20 g/cm²

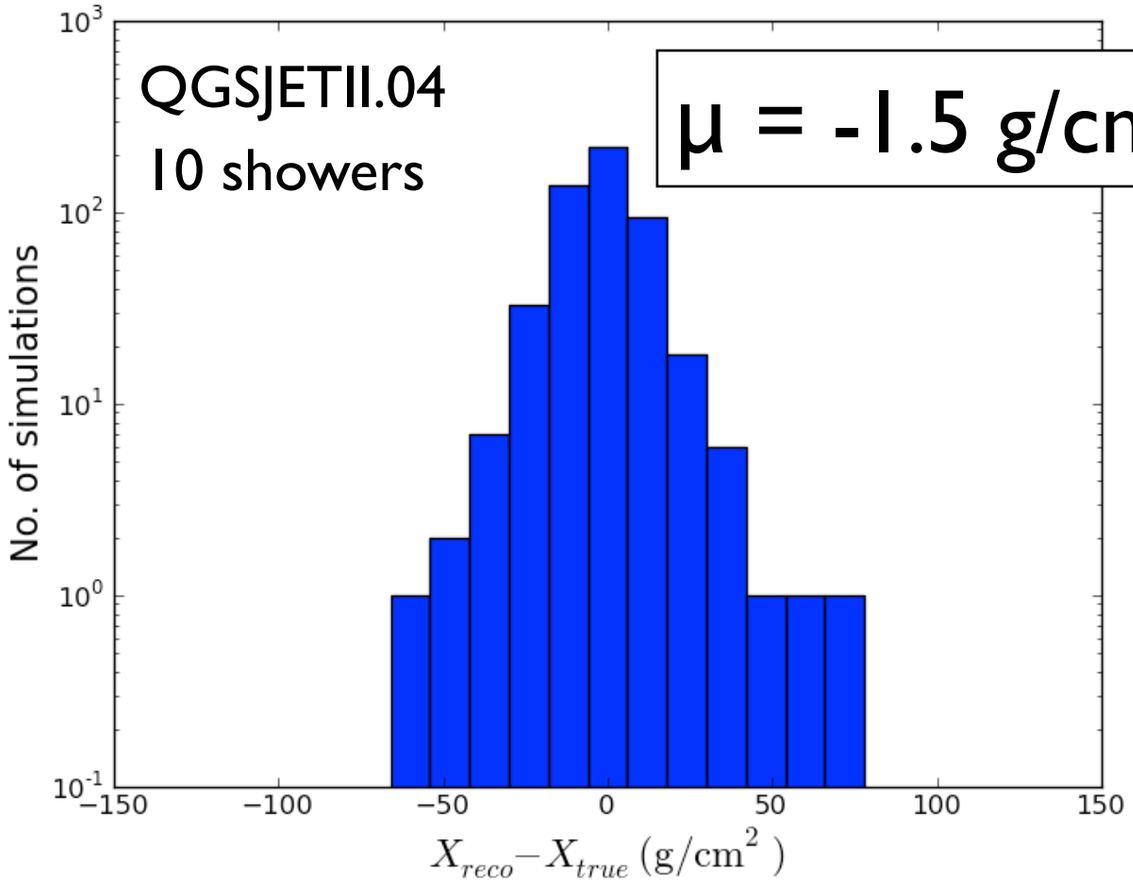


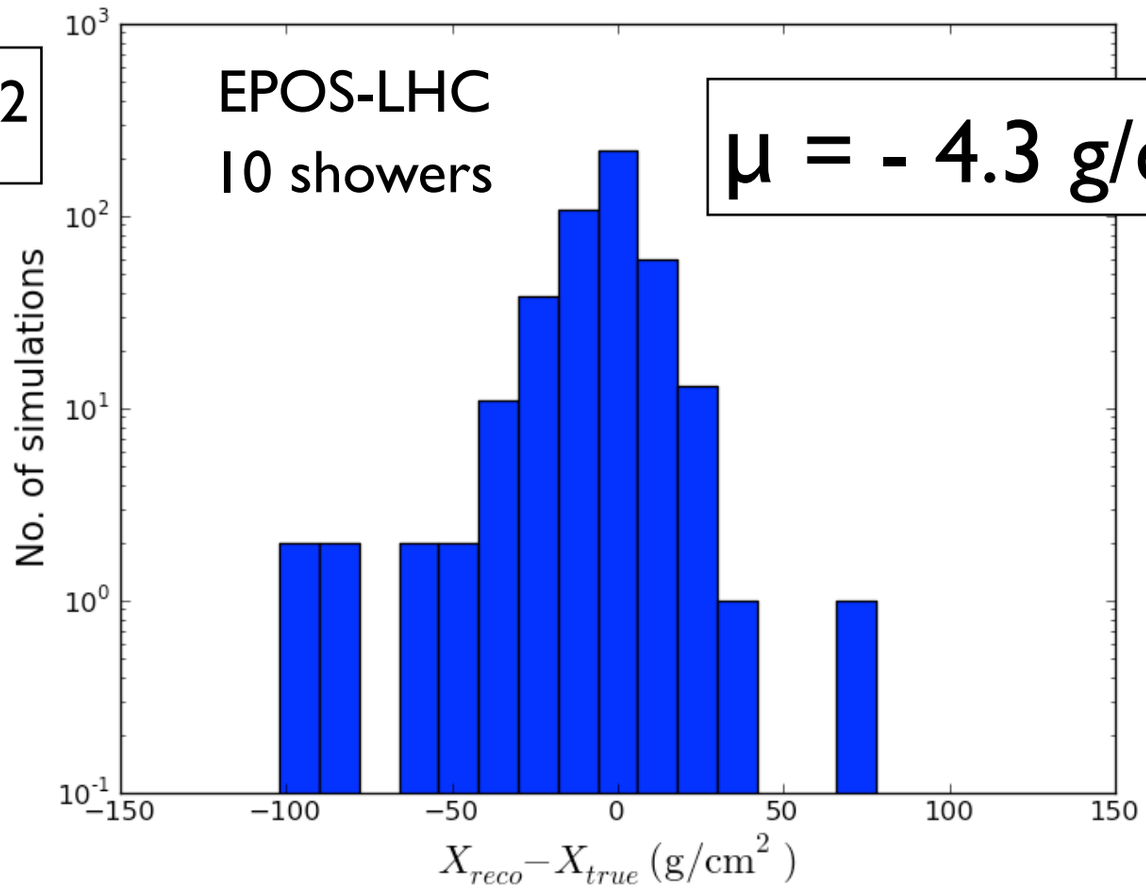
this sample: mean = 17 g/cm²

<u>includes:</u>

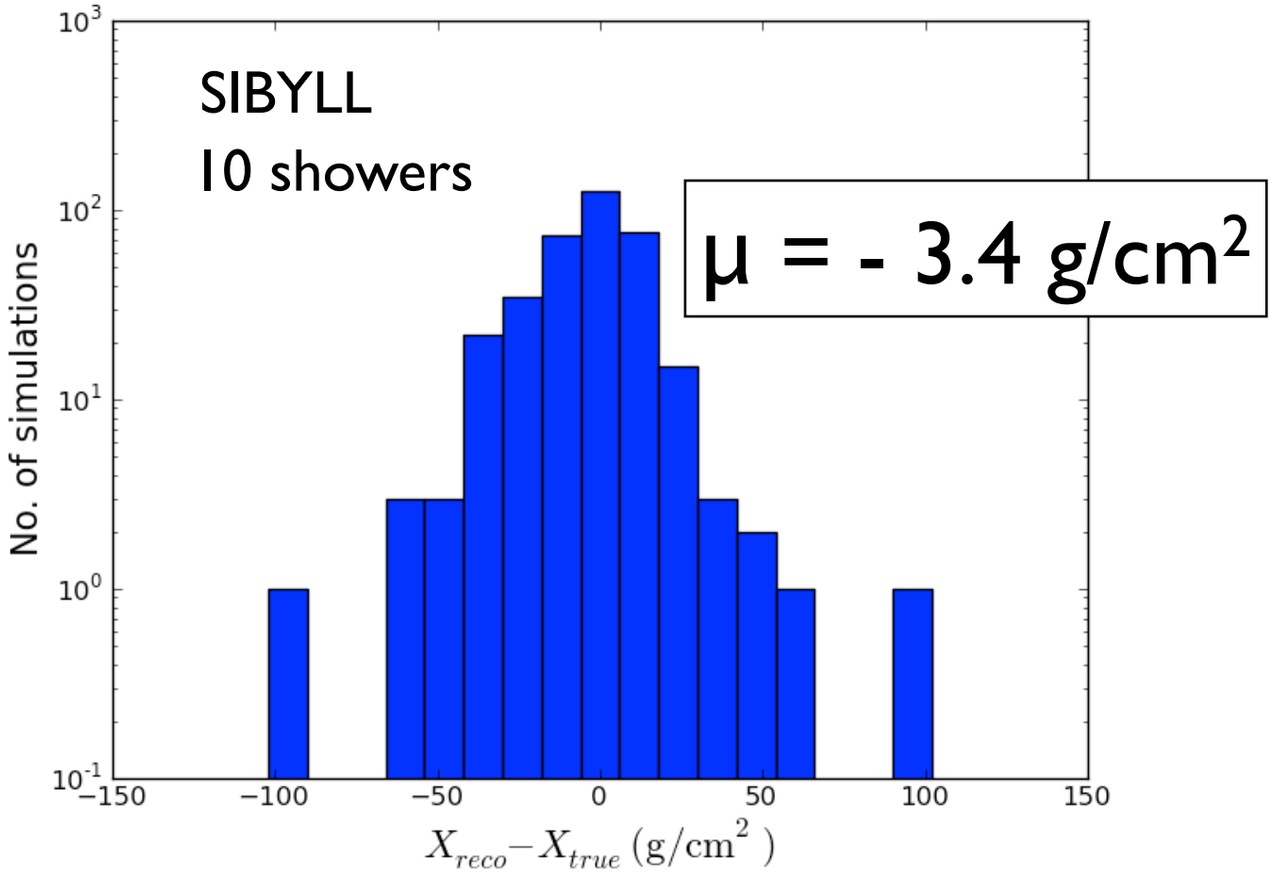
5 g/cm² index-of-refraction

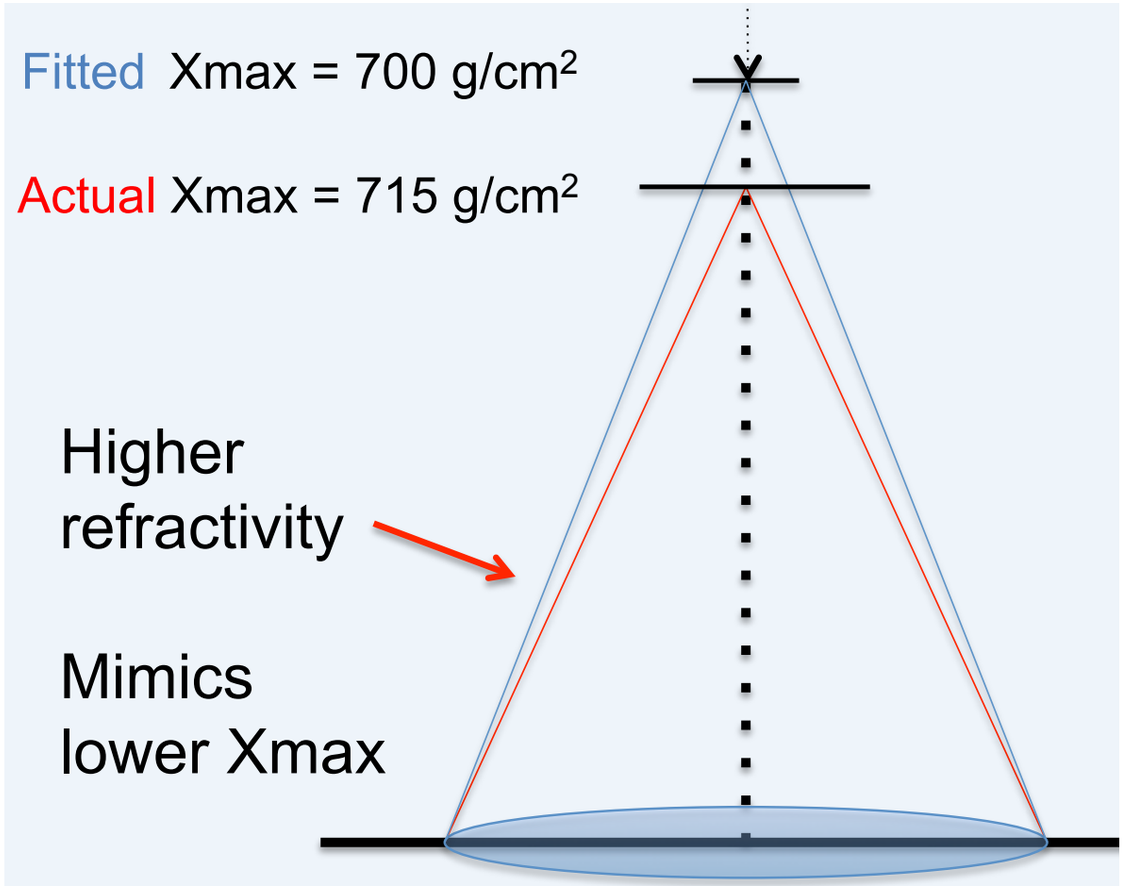
1 g/cm² density profile



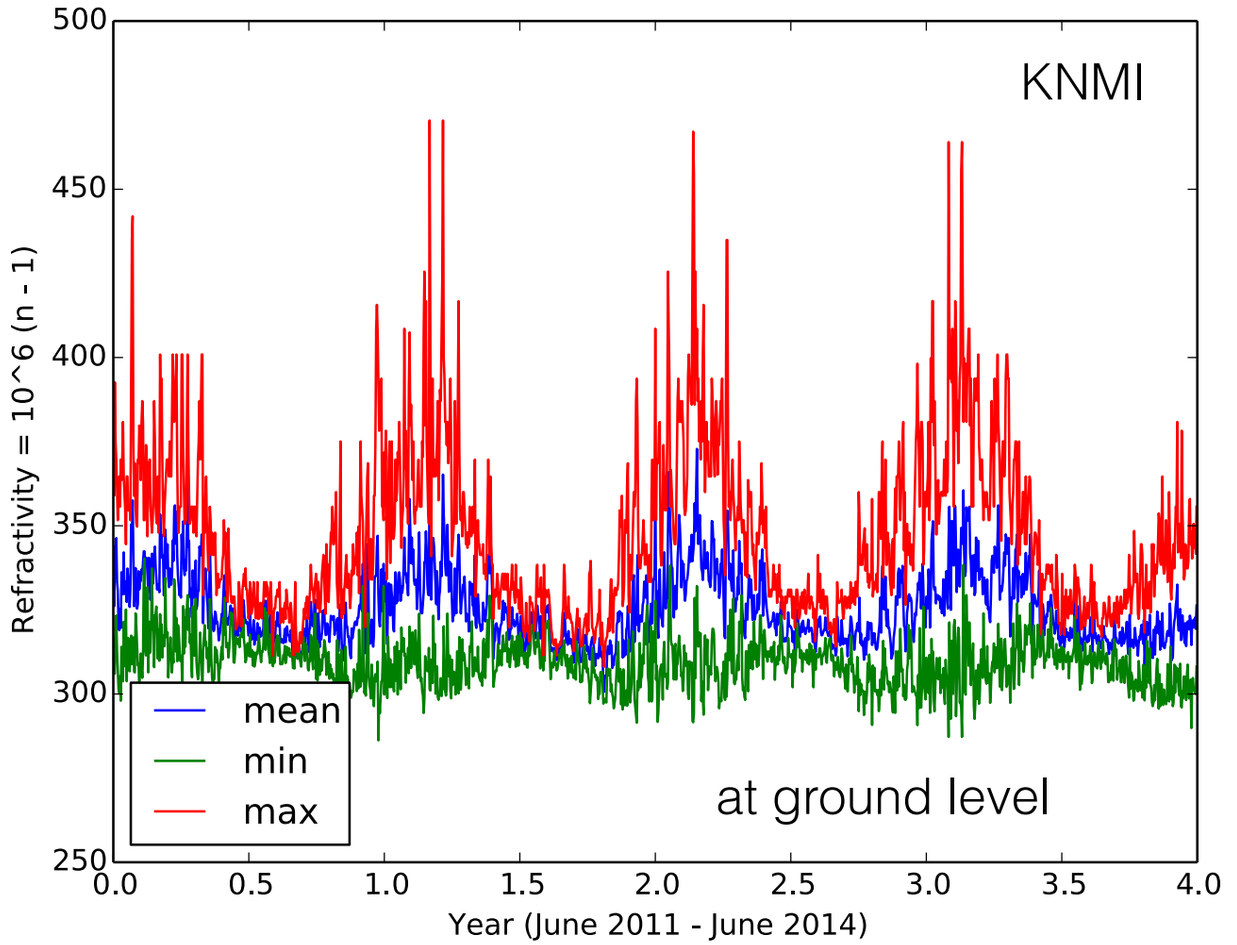


- Shower simulated with QGSJETII EPOS & SIBYLL
- Reconstructed using QGSJETII
- 10 showers; 25 p + 15 Fe each
- Systematic effect on Xmax reconstruction is small *geometrical measurements*



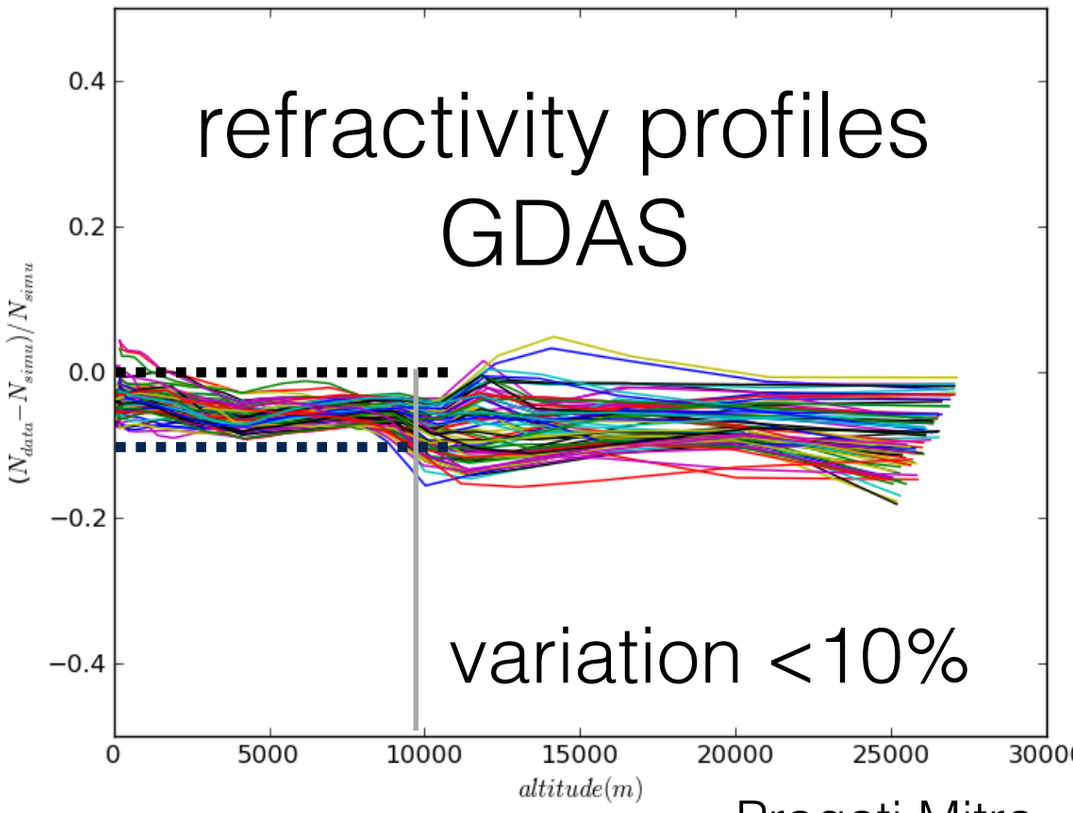


Arthur Corstanje



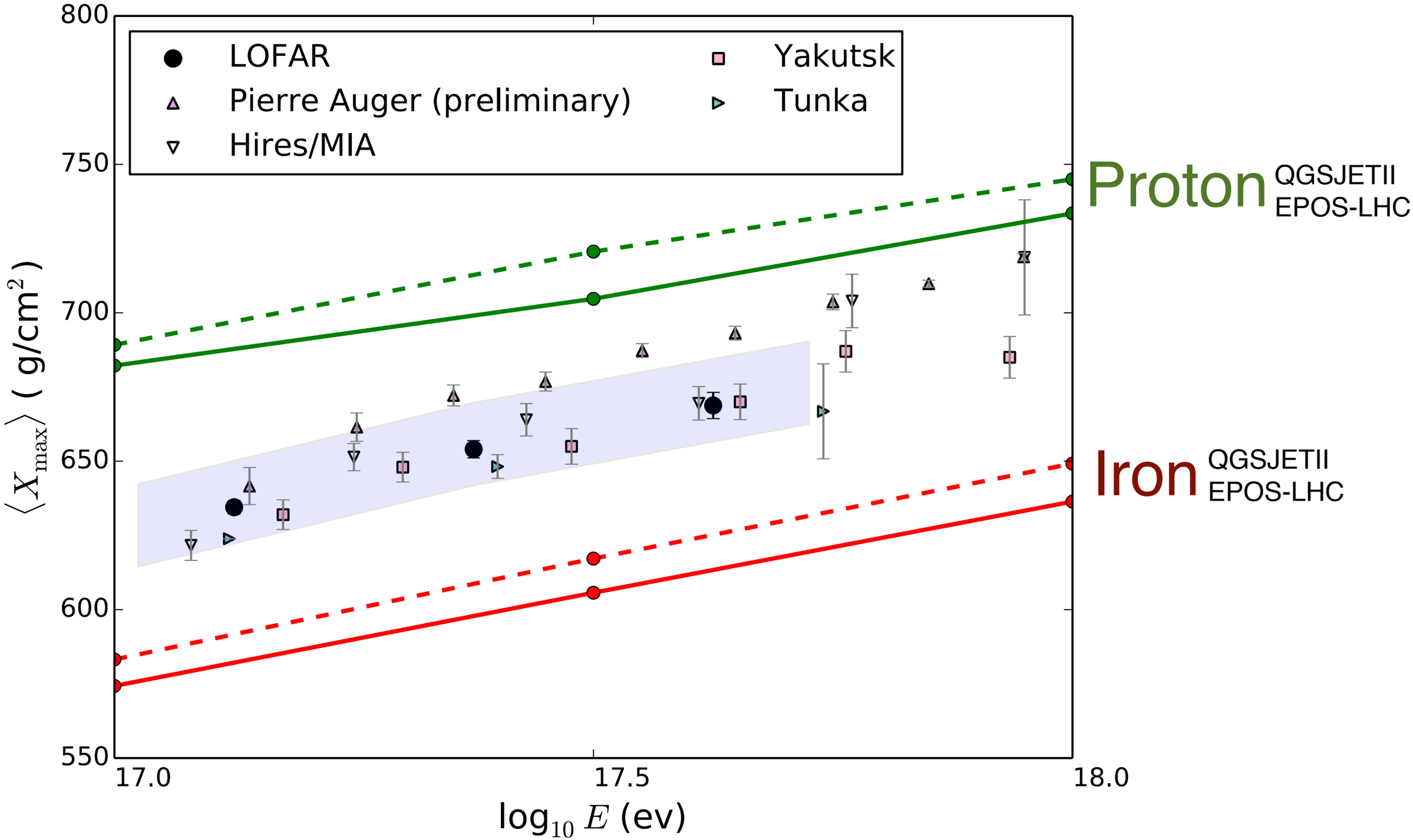
systematic uncertainties

zenith angle	+/- 8 g/cm²
refractive index	+10 g/cm²
hadronic interaction model	+/- 5 g/cm²
total	**+14 / -10 g/cm²**



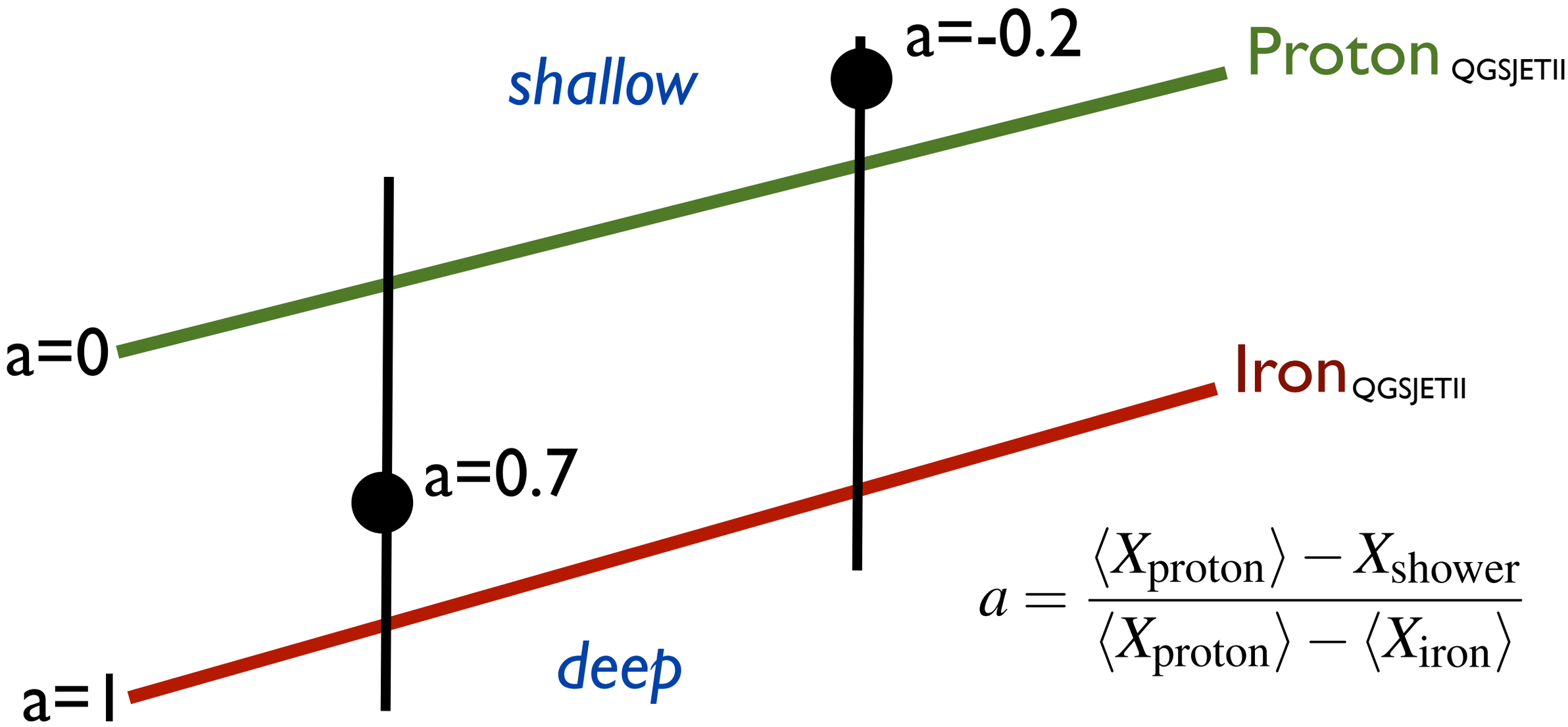
Pragati Mitra

Mean X_{max} for 114 showers



S.B. et al, *Nature* **531**, 70 (2016)

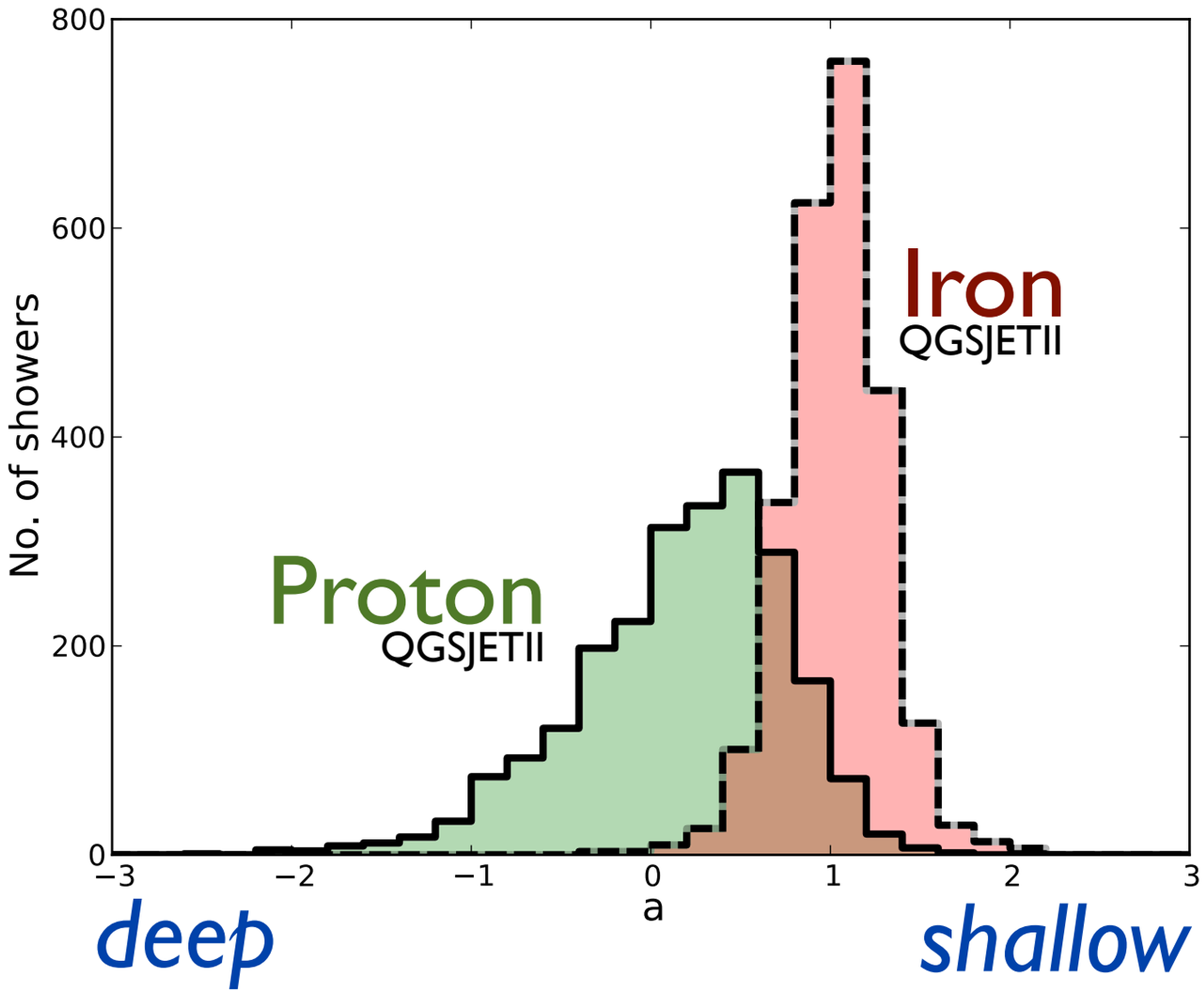
Unbinned analysis



$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$

Calculate *a* for each individual shower

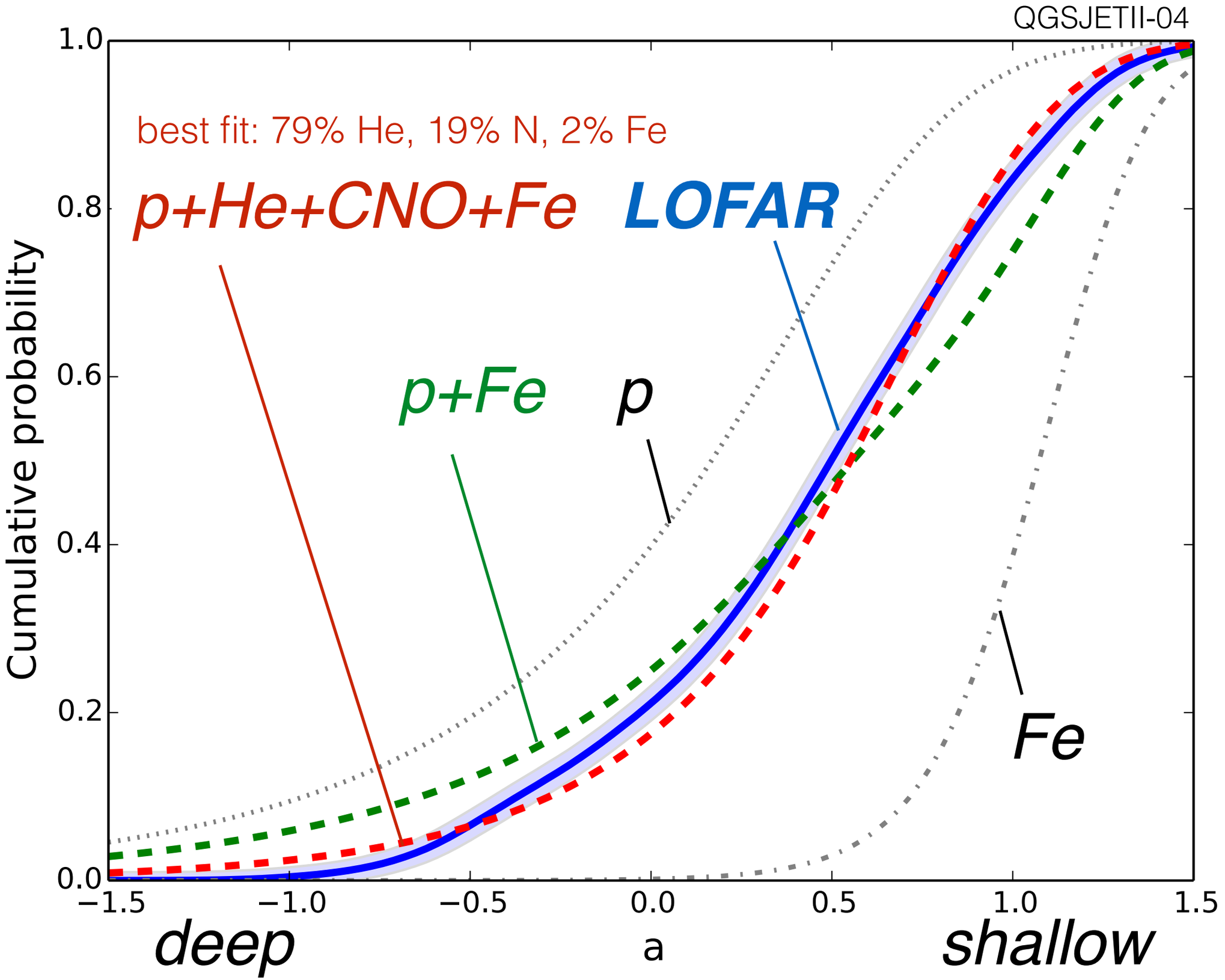
Composition at 10^{17} -10^{18} eV



- Use full distribution of Xmax not only mean value
- First calculate mass parameter a

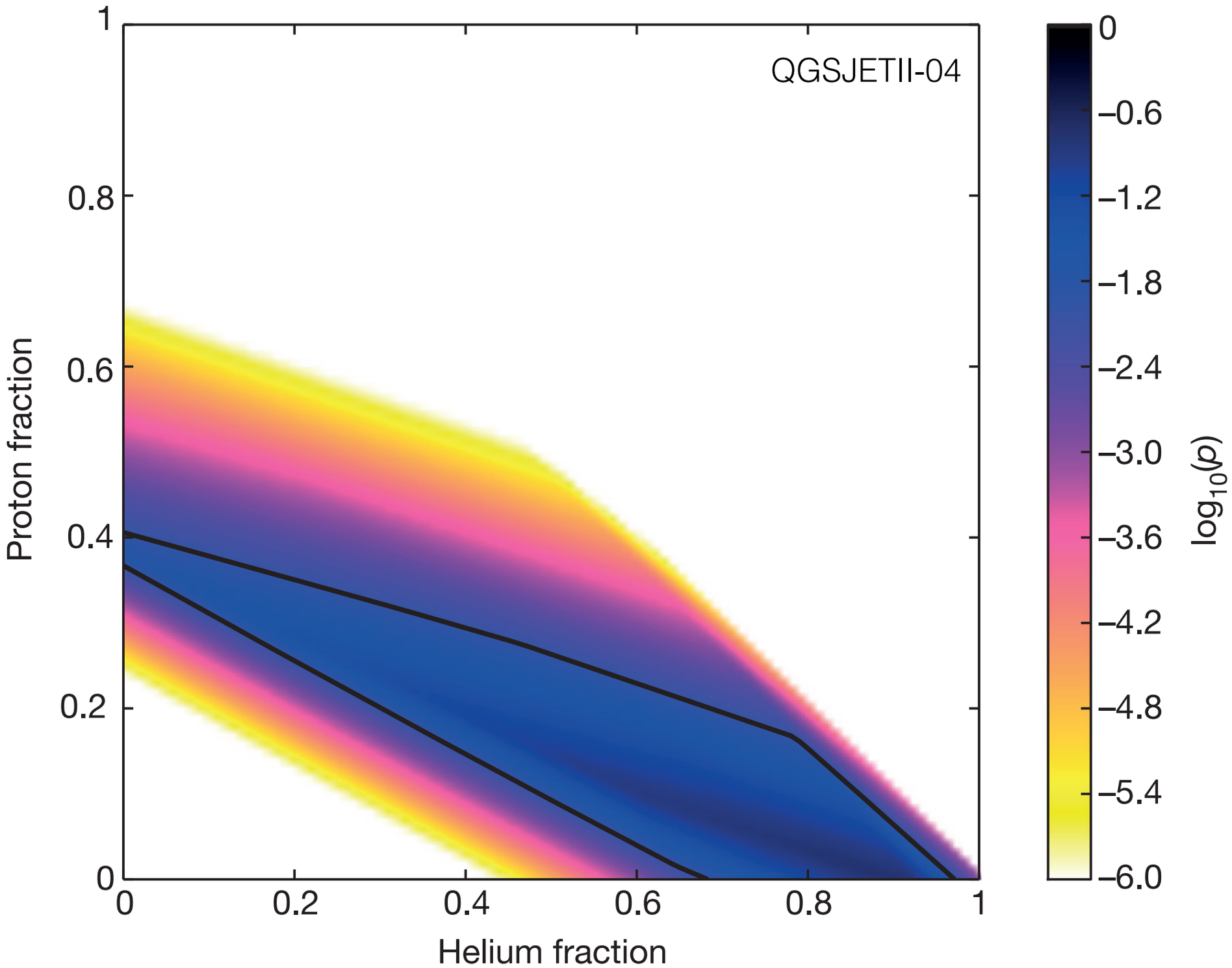
$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$

- Fit model distribution to measured distribution



Best fit: 80% light particles (p+He) at 10^{17} -$10^{17.5}$ eV

Four component model scan

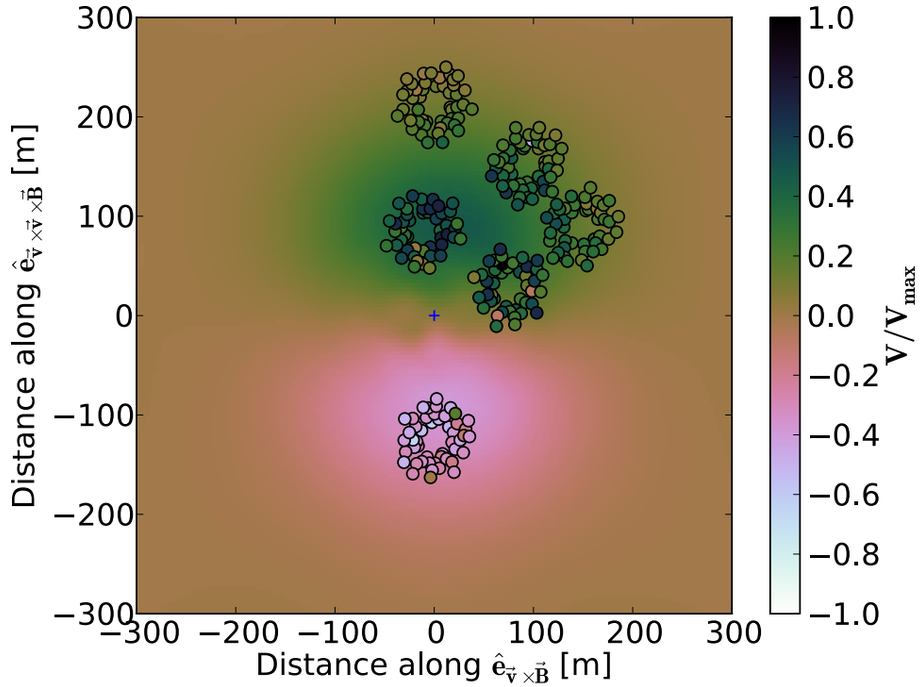


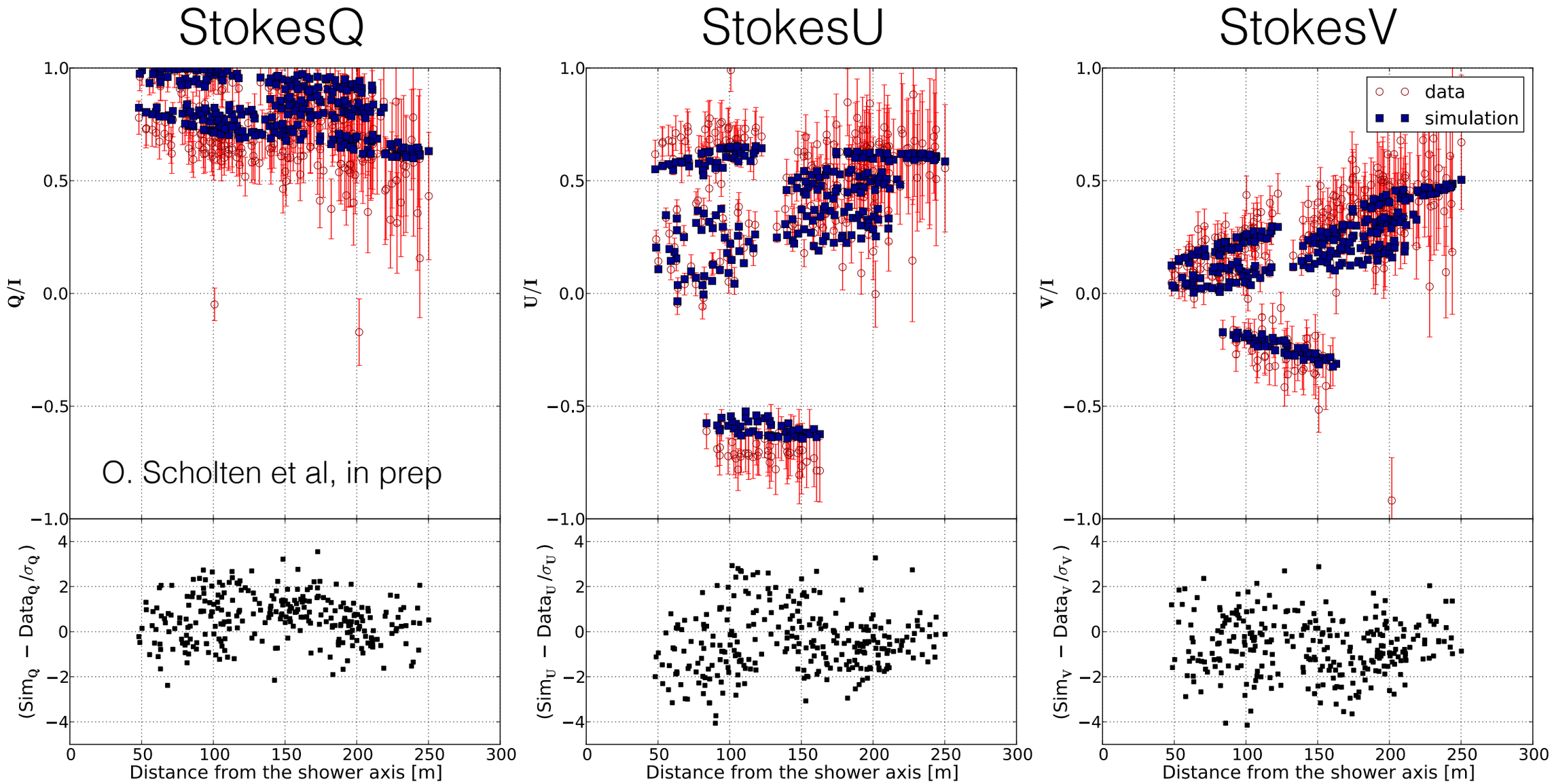
Total fraction of light elements (p+He) in [0.38,0.98] at 99% C.L.

Circular polarization

Full Stokes measurements
2D interpolation maps for I,Q,U,V

at 100m: U/V ~ 1/3
Δt ~ 1 ns





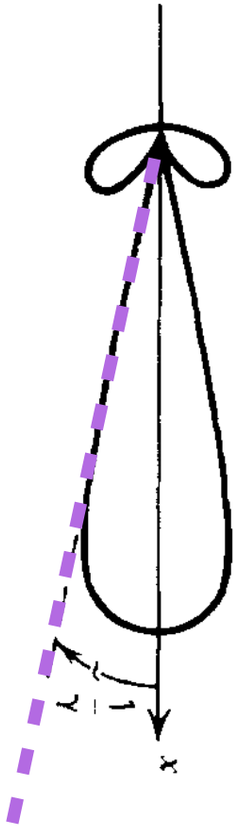
Caution!!

For observer at 100m peak of charge excess emission is delayed by 1 ns

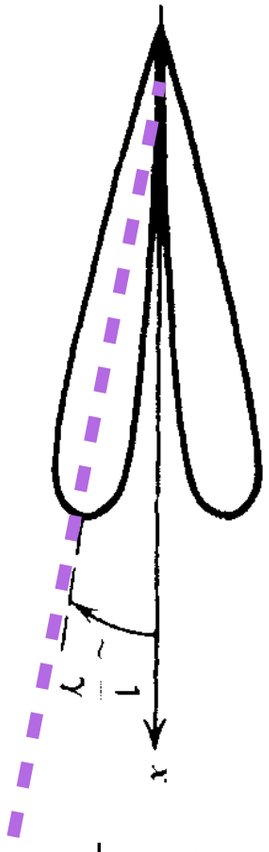
≠

Charge excess emission emitted at later stage in shower development

(actually, it's simultaneous/earlier, see talk C. Glaser)



transverse current



charge excess

emission beam shape different for geomagnetic and charge excess radiation

charge excess has maximum at larger Θ_{obs}

↓

for fixed observer Θ_{obs} increases with time

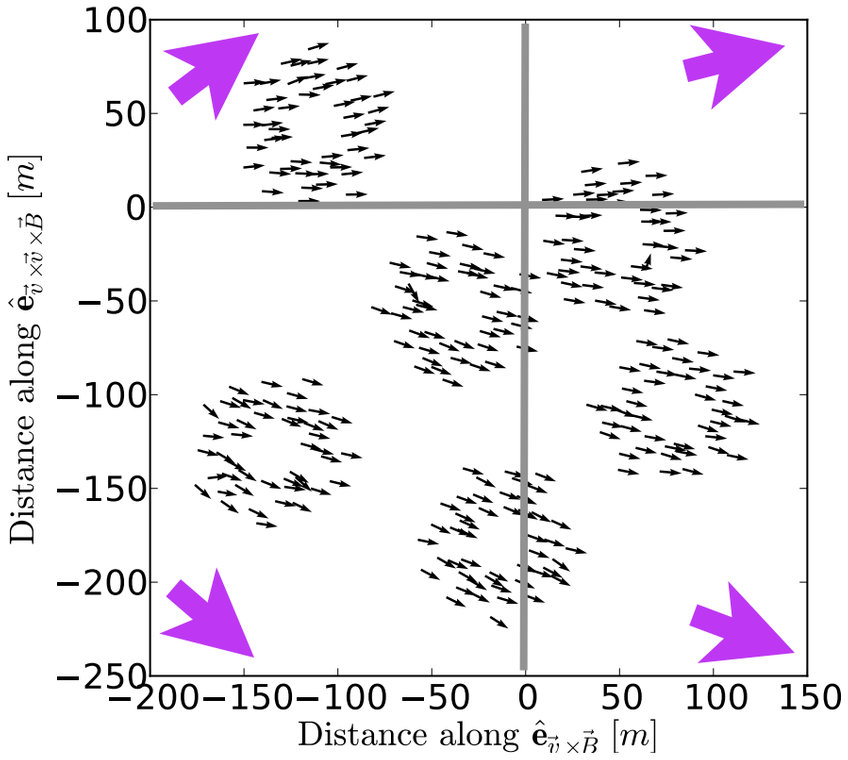
↓

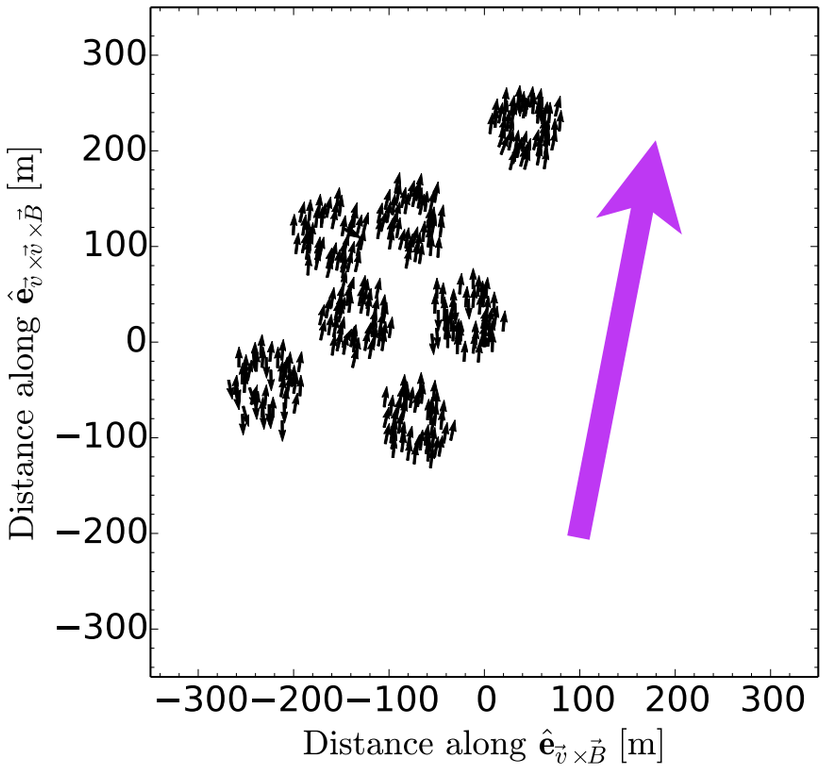
observed shift in peak emission

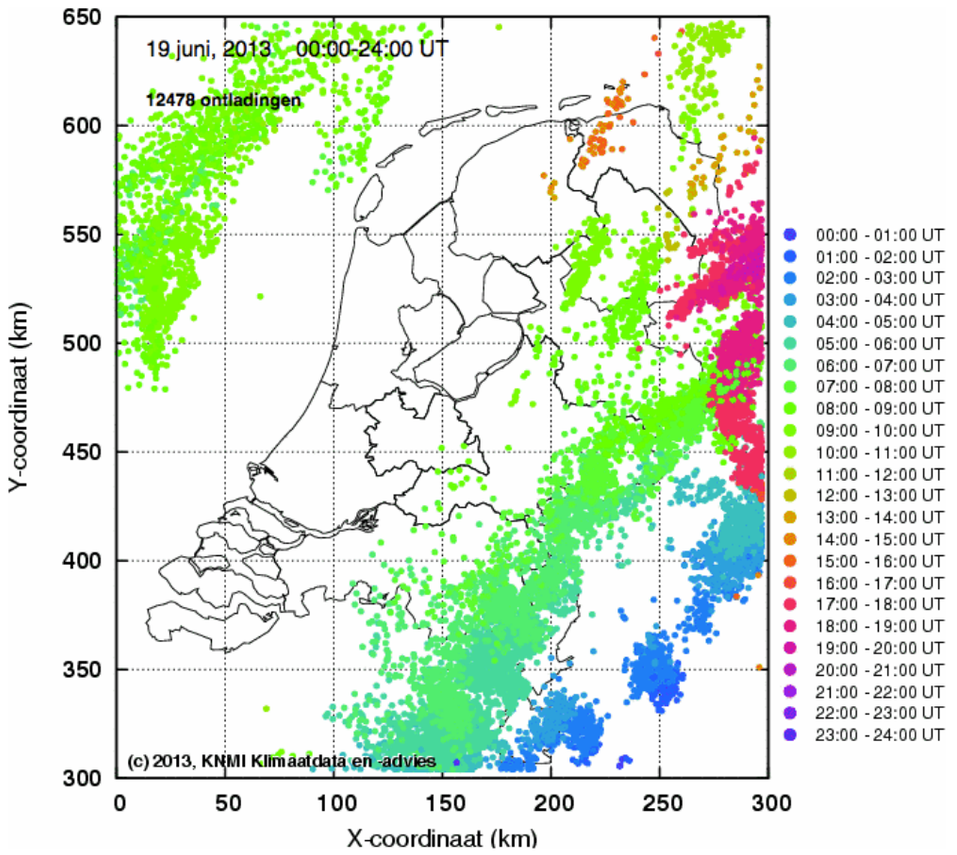
Conclusions

- LOFAR can measure X_{max} with resolution ≲ 20 g/cm^2
- A set of cuts is applied to obtain a bias-free sample of 114 air showers
- First LOFAR composition result in agreement with other experimental techniques.
- Strong light element fraction (p+He) at 10^{17} eV
- Coming up: correction for index-of-refraction, low energies with hybrid triggering

thunderstorm events







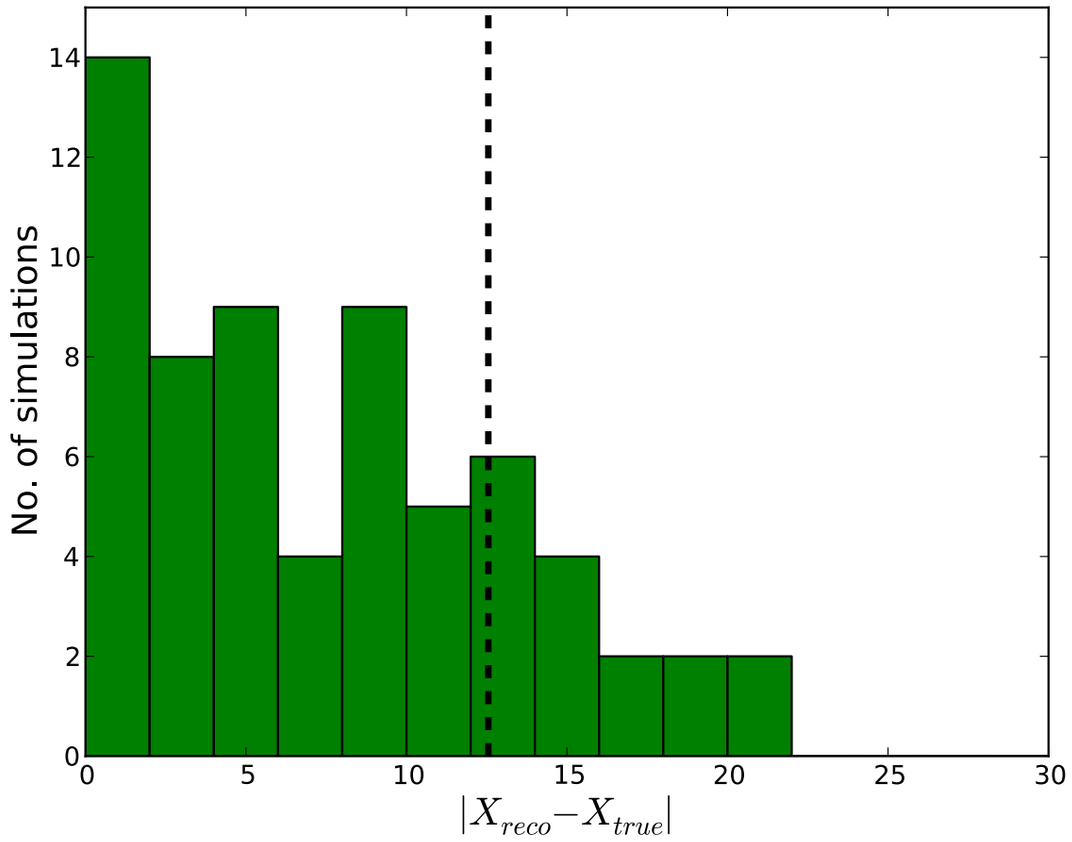
- Identification:
weather service + polarization signature

- removed from sample

- dedicated analysis:
see poster Olaf Scholten

Schellart et al. PRL **114**, 165001 (2105)
Trinh et al. PRD **93**, 023003 (2016)

Uncertainty on Xmax



<u>Monte Carlo vs Monte Carlo method</u>

reconstruct Xmax for many simulations of the same event

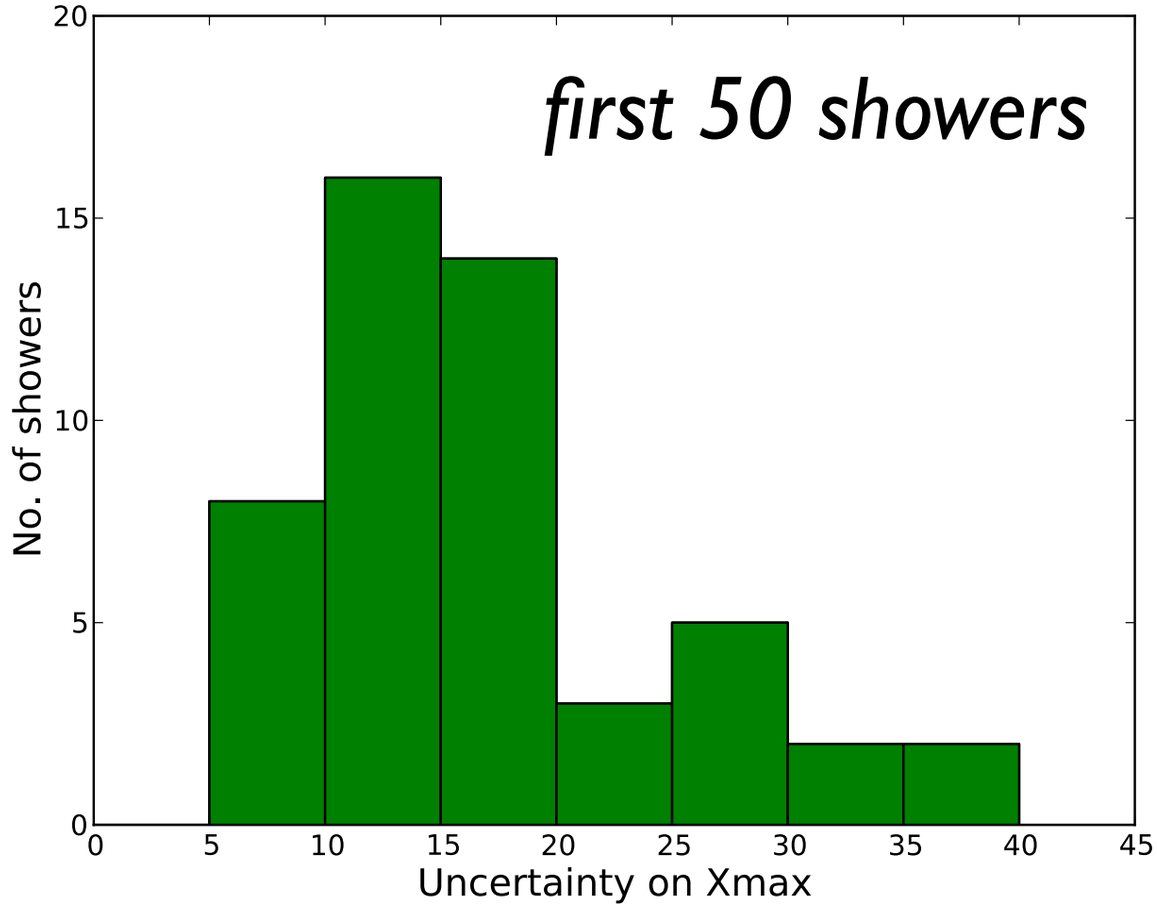
construct region that contains 68% of $|X_{reco} - X_{true}|$

$\sigma_{meth} = 12.7$ g/cm^2
$\sigma_{atm} = 1$ g/cm^2 (after correction)
$\sigma = 13$ g/cm^2

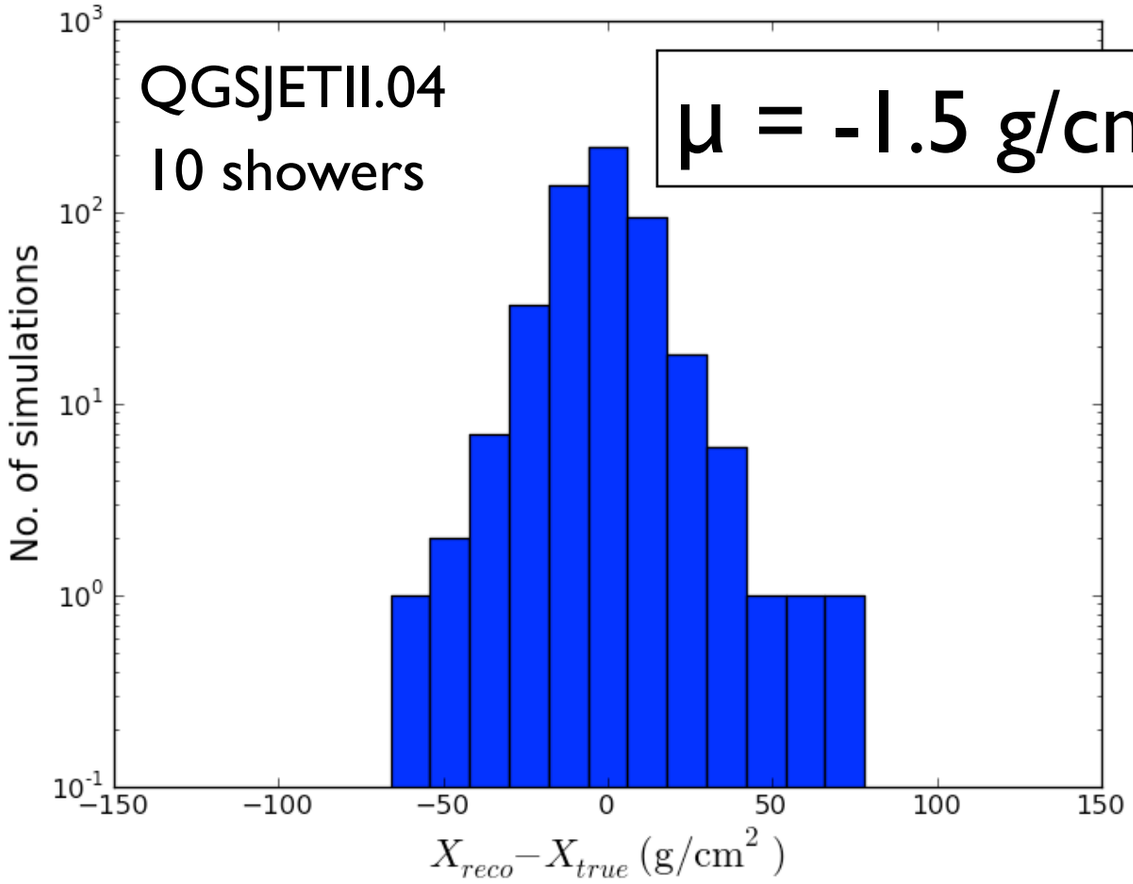
<u>first event sample:</u>

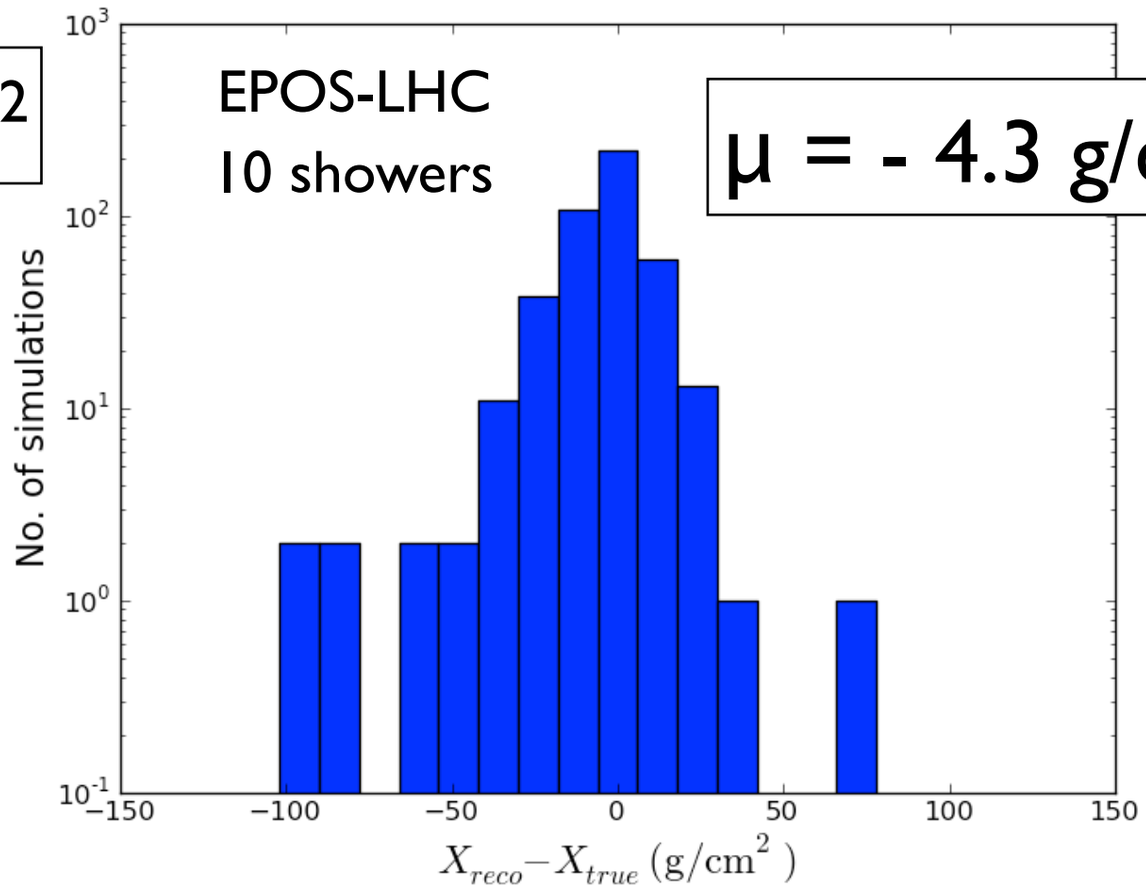
σ ranges from 7.5 to 37 g/cm^2

mean value 17 g/cm^2

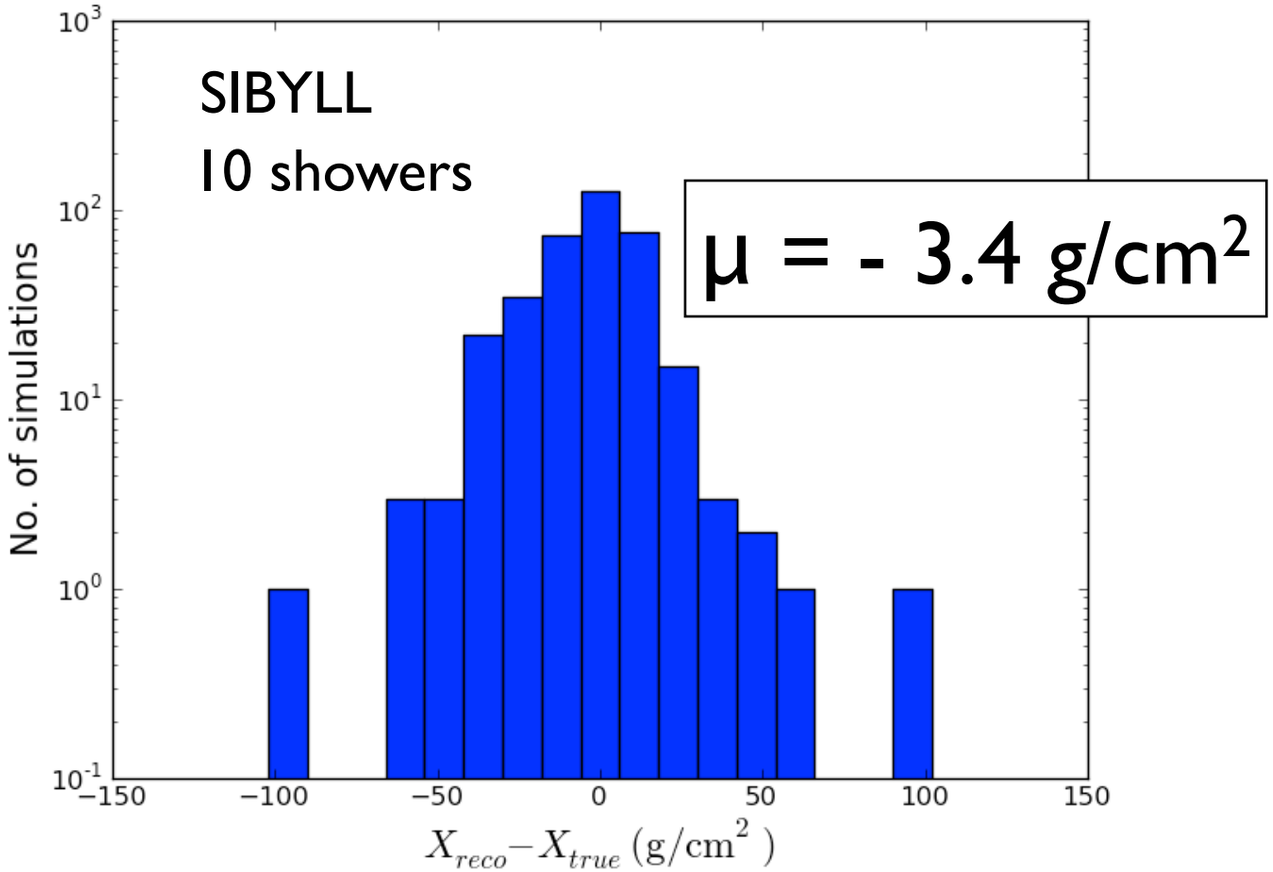


SB *et al.* PRD 90 082003 (2014).

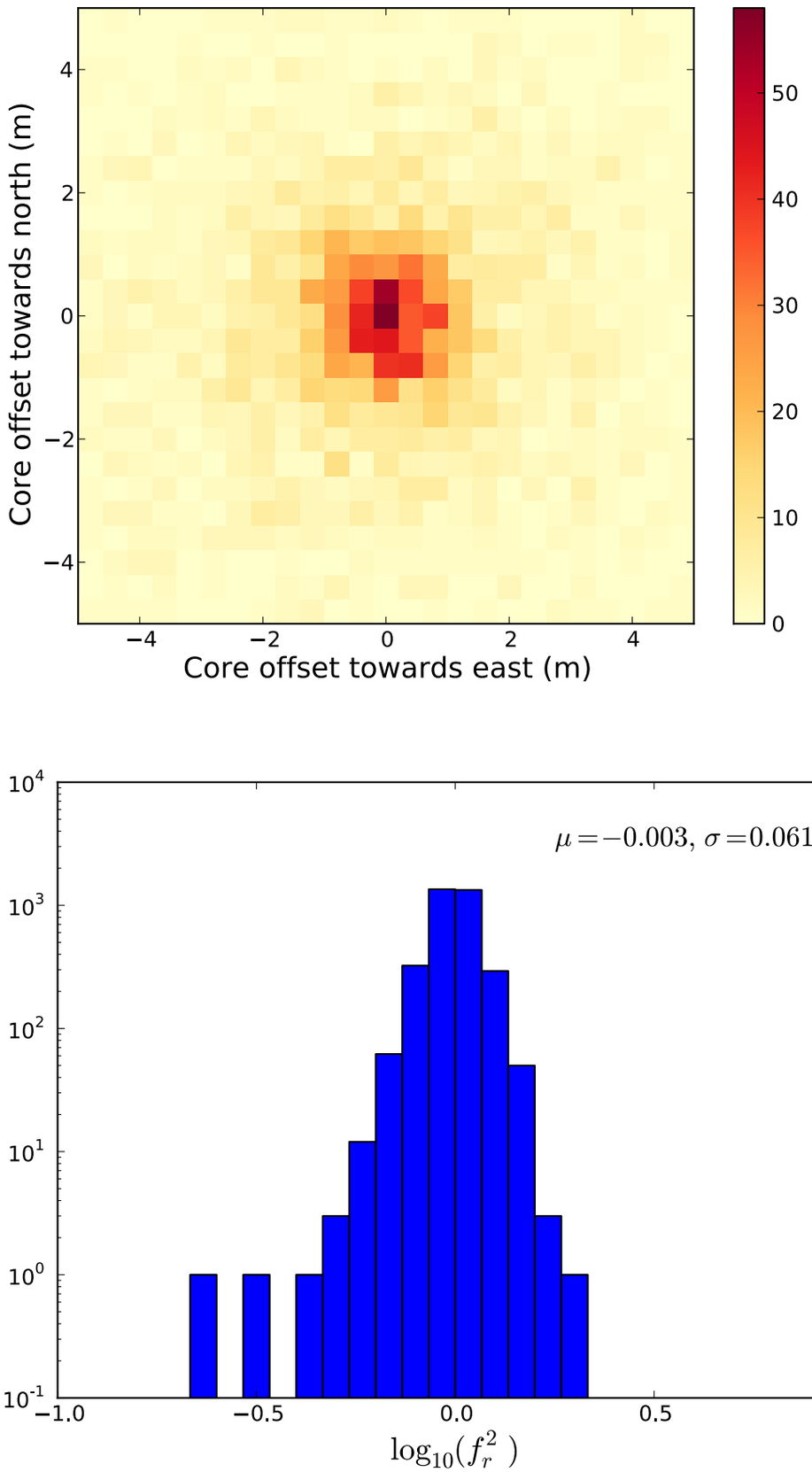


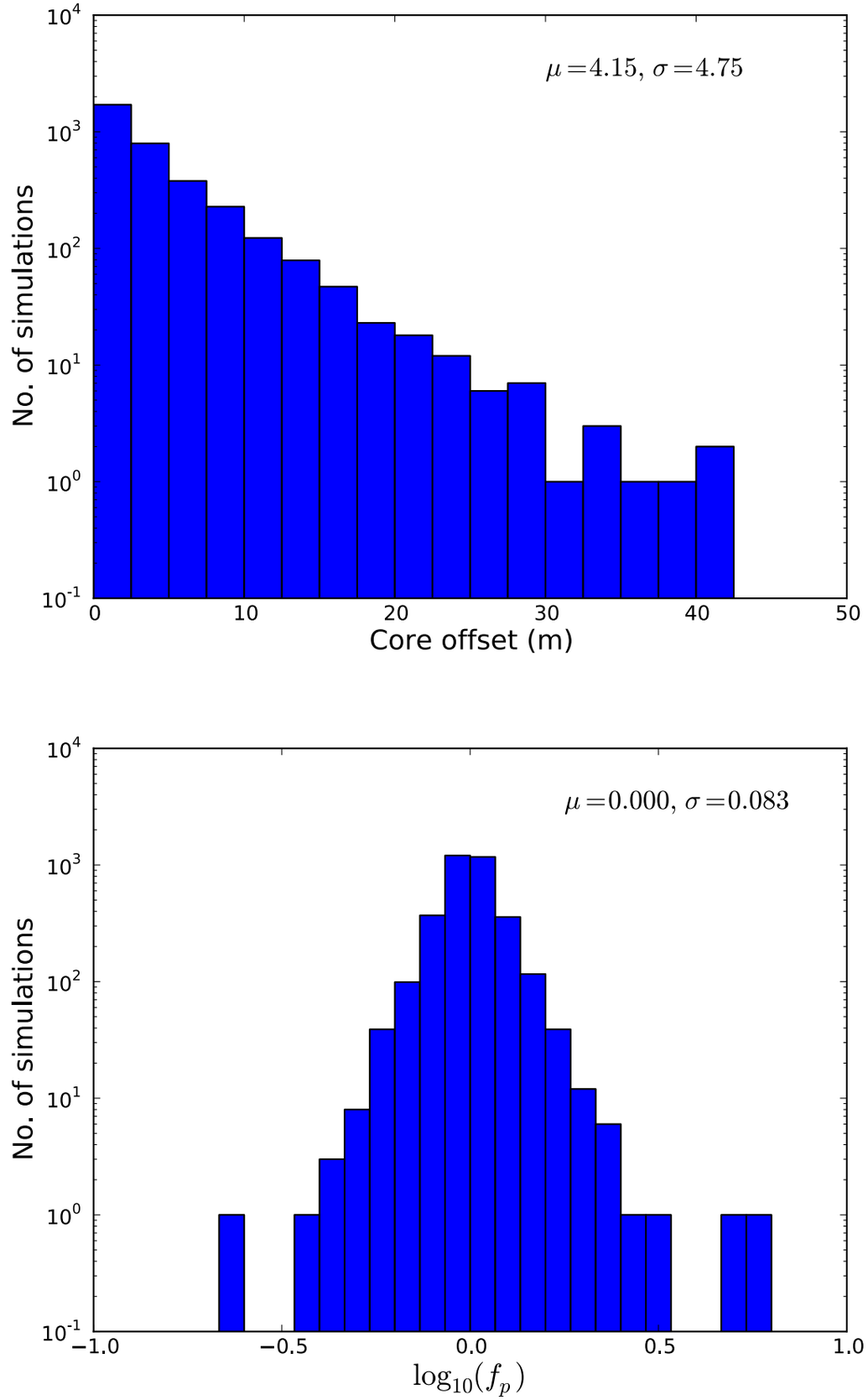


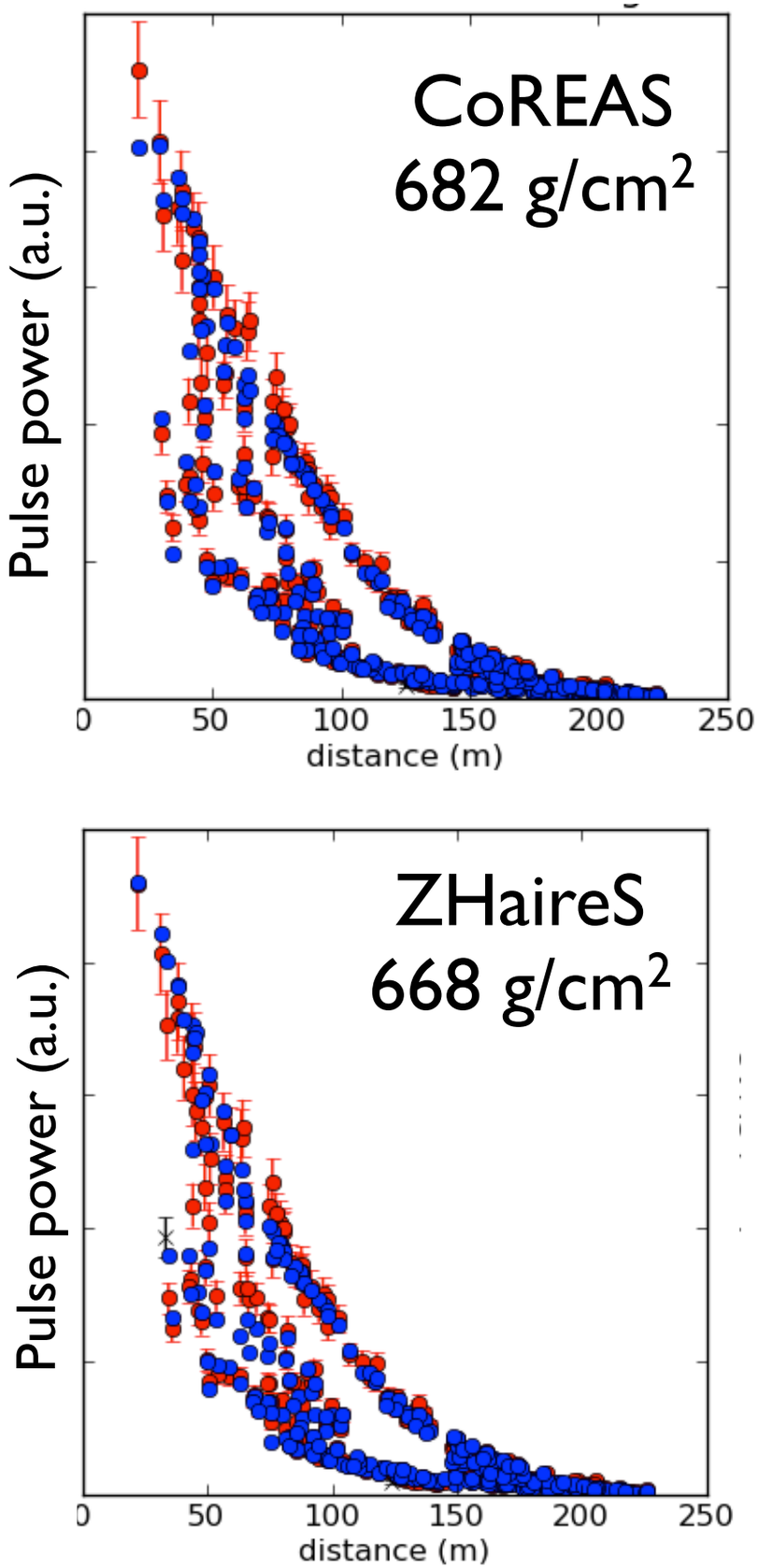
- Shower simulated with QGSJETII EPOS & SIBYLL
- Reconstructed using QGSJETII
- 10 showers; 25 p + 15 Fe each
- Systematic effect on Xmax reconstruction is small *geometrical measurements*



no bias due to multivariate fit







- Simulation workshop Nijmegen (february 2014)

  simulation by all 4 codes for 10 LOFAR events

- Preliminary results:

  Microscopic models (CoREAS & ZHaireS) very similar

  Macroscopic models are close; parametrizations break down near shower axis?