Cosmic-ray energy spectrum above 10^{16} eV measured with LORA

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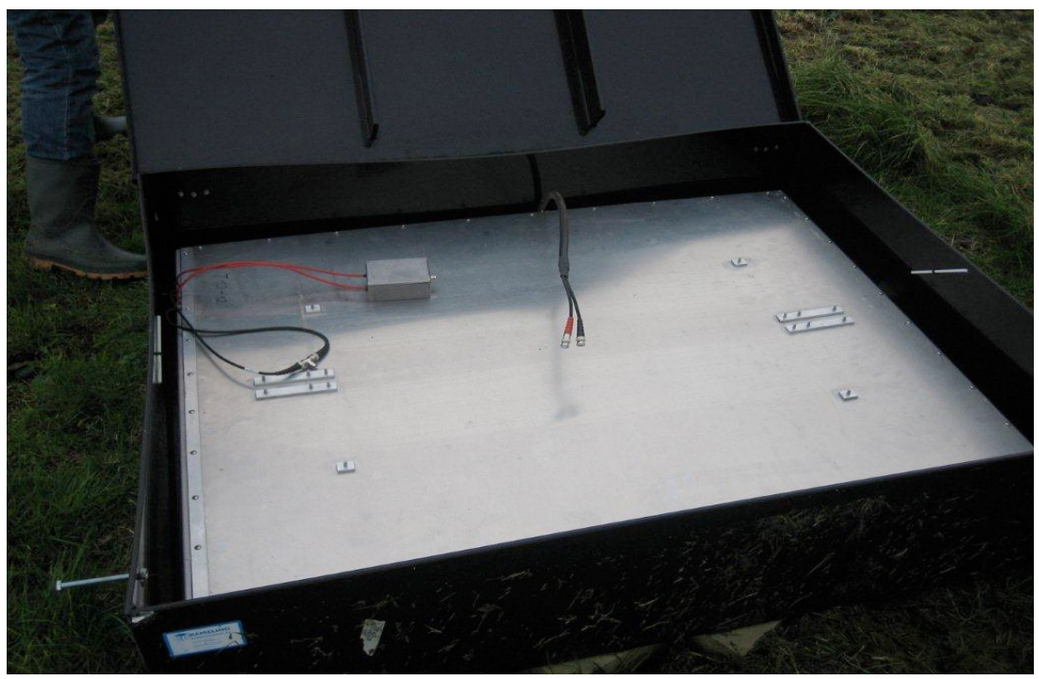
(For the LOFAR key science project cosmic ray)

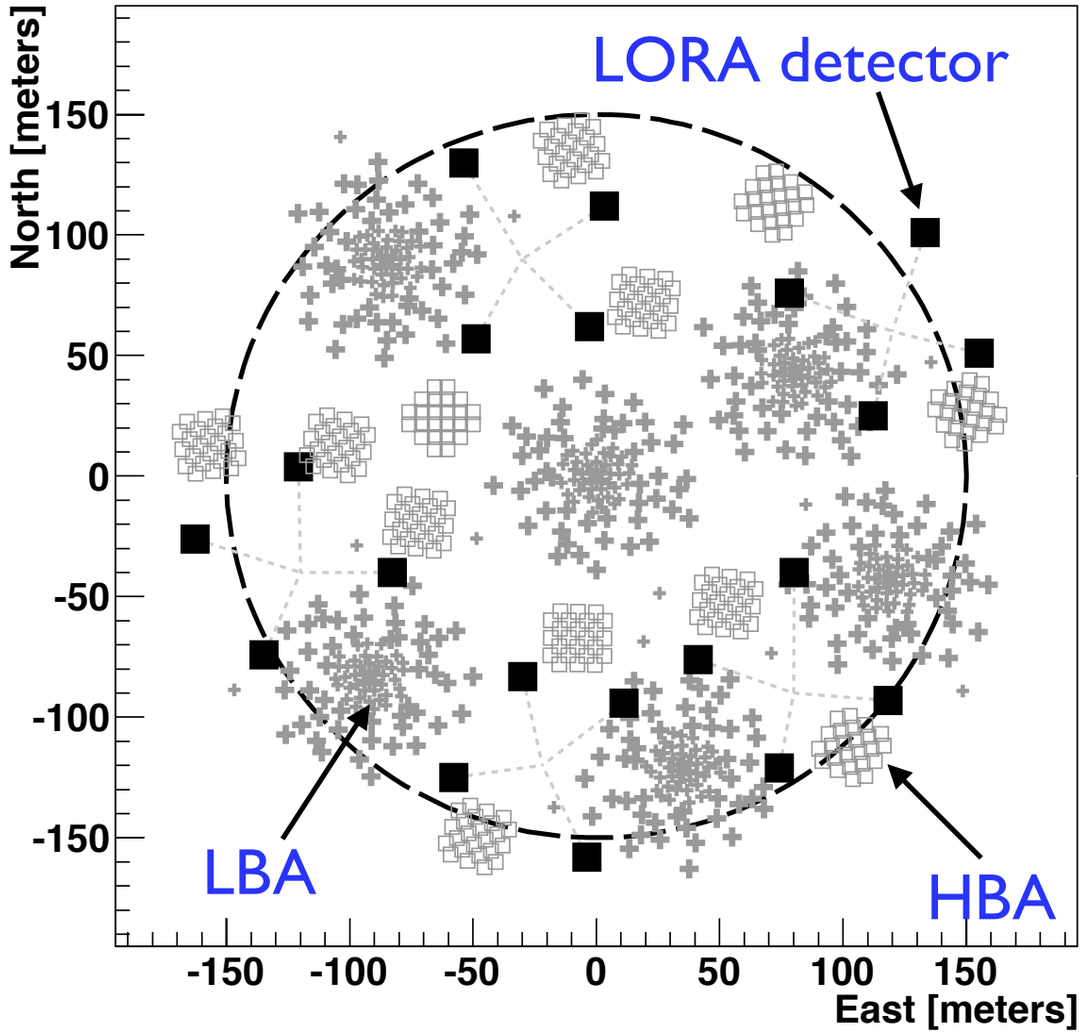
Thoudam et al., *Nuclear Inst. and Methods in Physics Research A*, 2014, 767, 339
Thoudam et al., *Astroparticle Physics*, 2015, Submitted

LORA: LOFAR Radboud Air Shower Array

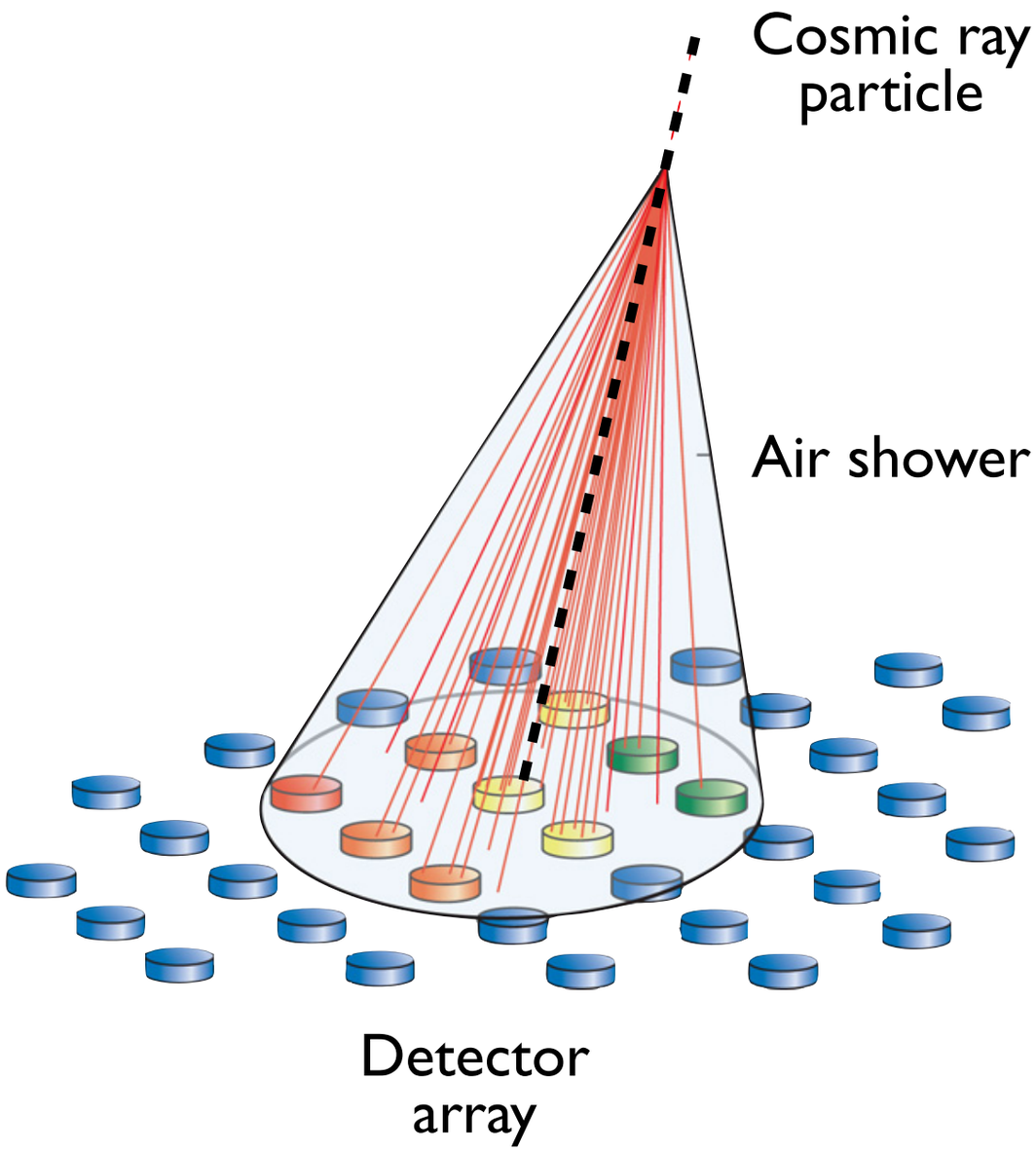
- Array of 20 plastic scintillator detectors
- Location: LOFAR core, Netherlands
- Detector spacings: 50-100 m within 300 m ring
- Detector size~ 1mx1m
- Primary purpose are to provide:
  - Cosmic-ray trigger to LOFAR
  - Basic air-shower parameters
- Measure cosmic rays above ~ 10^{16} eV energy

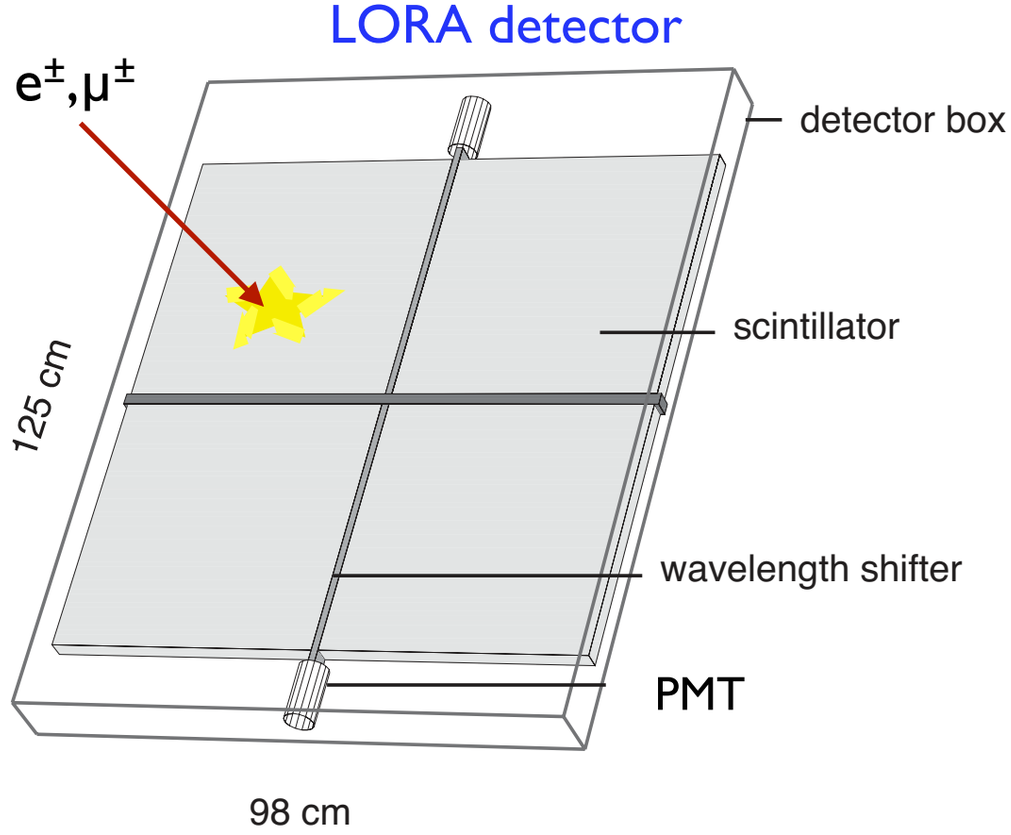
LOFAR superterp

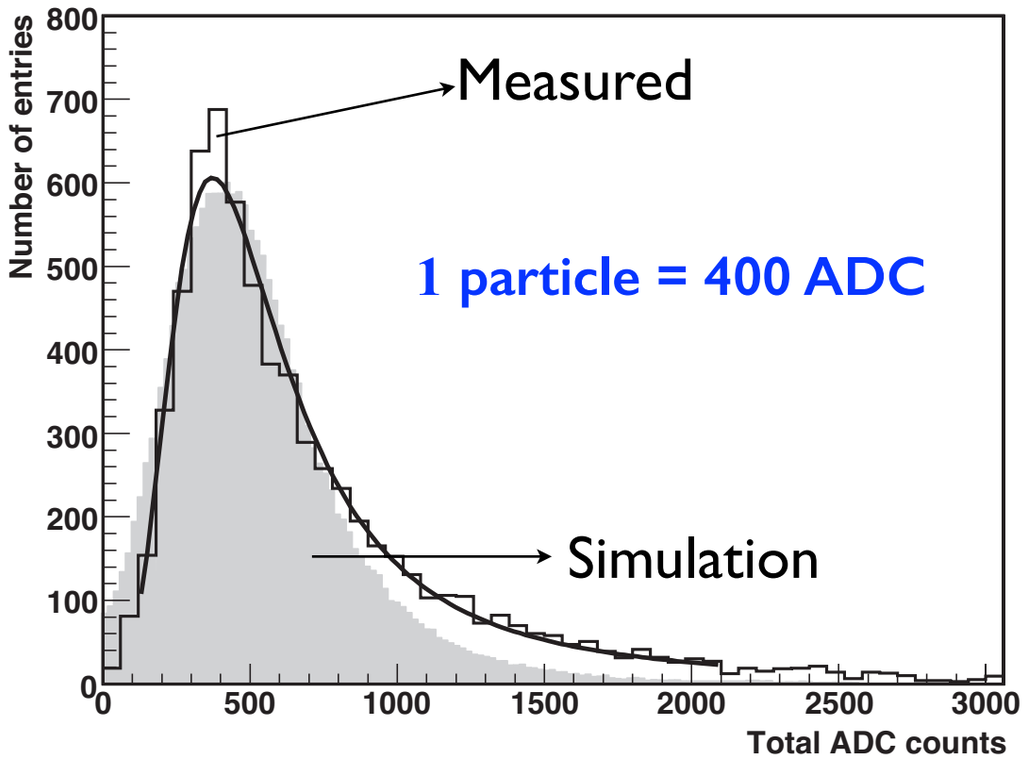




Cosmic-ray Air shower detection with the LORA array



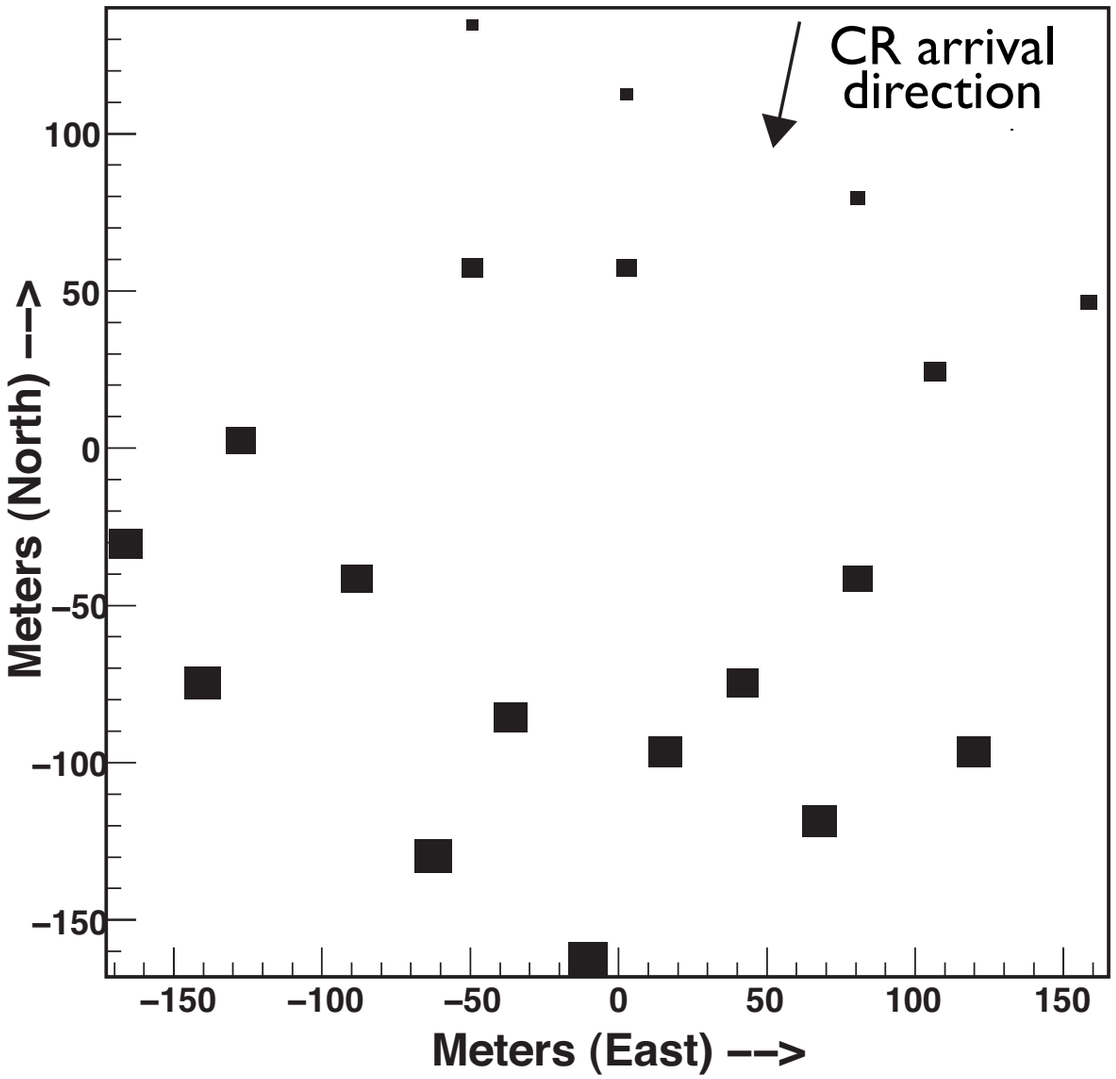




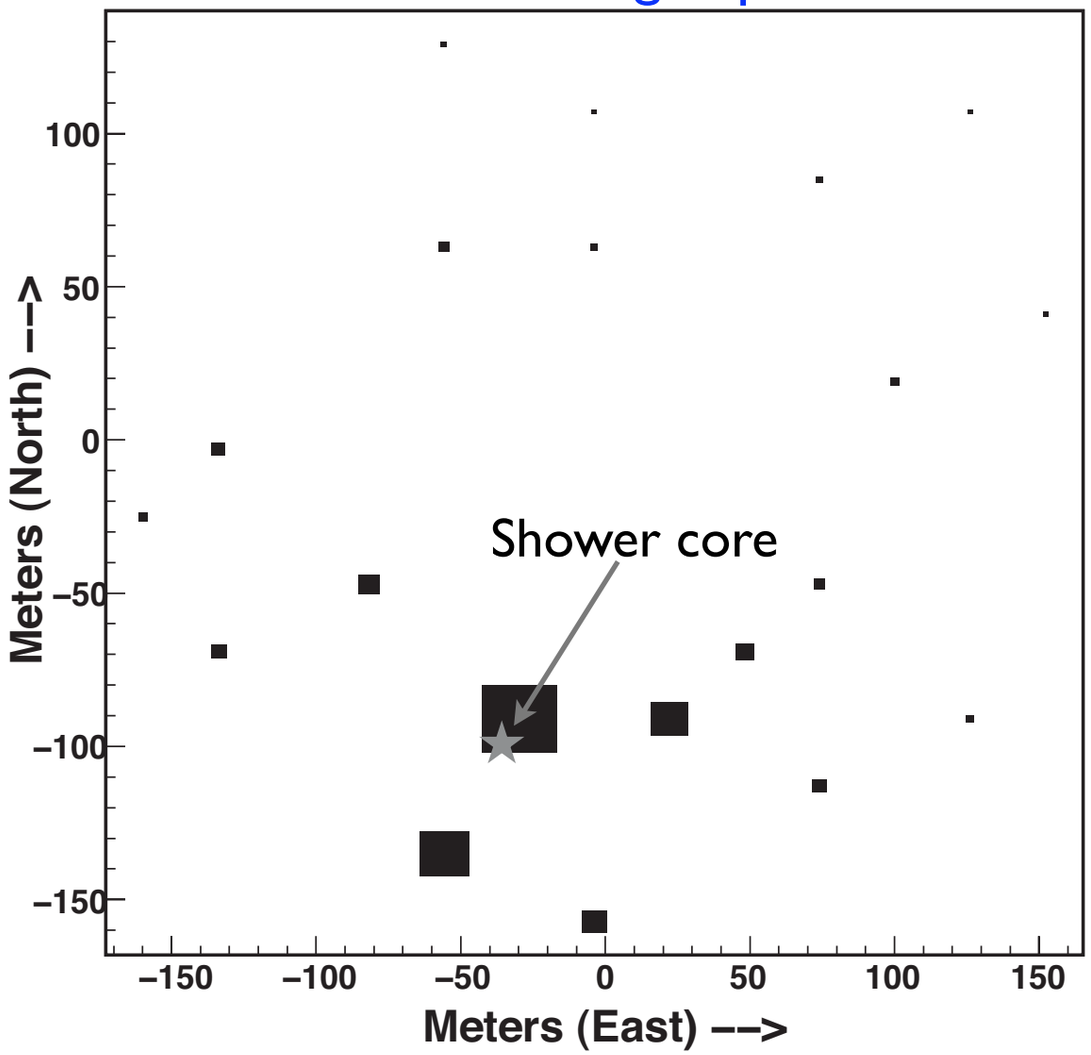
Energy deposit by a single charged particle

A cosmic-ray event measured with LORA

Arrival time



Energy depositions
≡No. of charged particles

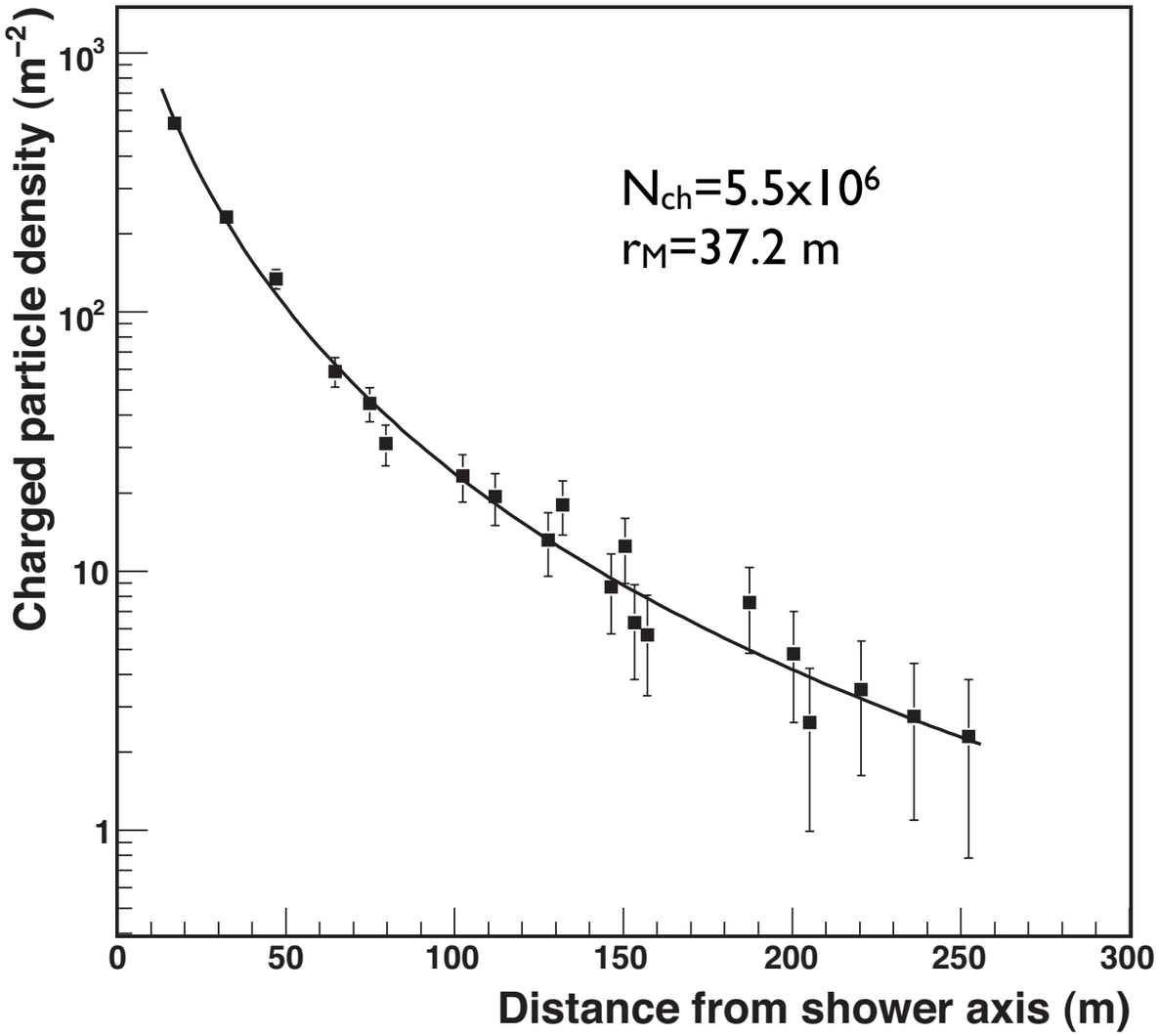


Arrival direction: From the relative arrival time between detectors

Shower core: From multi-parameter minimization using NKG function

A cosmic-ray event measured with LORA

Charged particle lateral distribution



Fit using NKG function:

$$\rho(r) = N_{ch} C(s) \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4.5}$$

ρ : Charged particle density

$r(x,y)$: Distance to the shower core

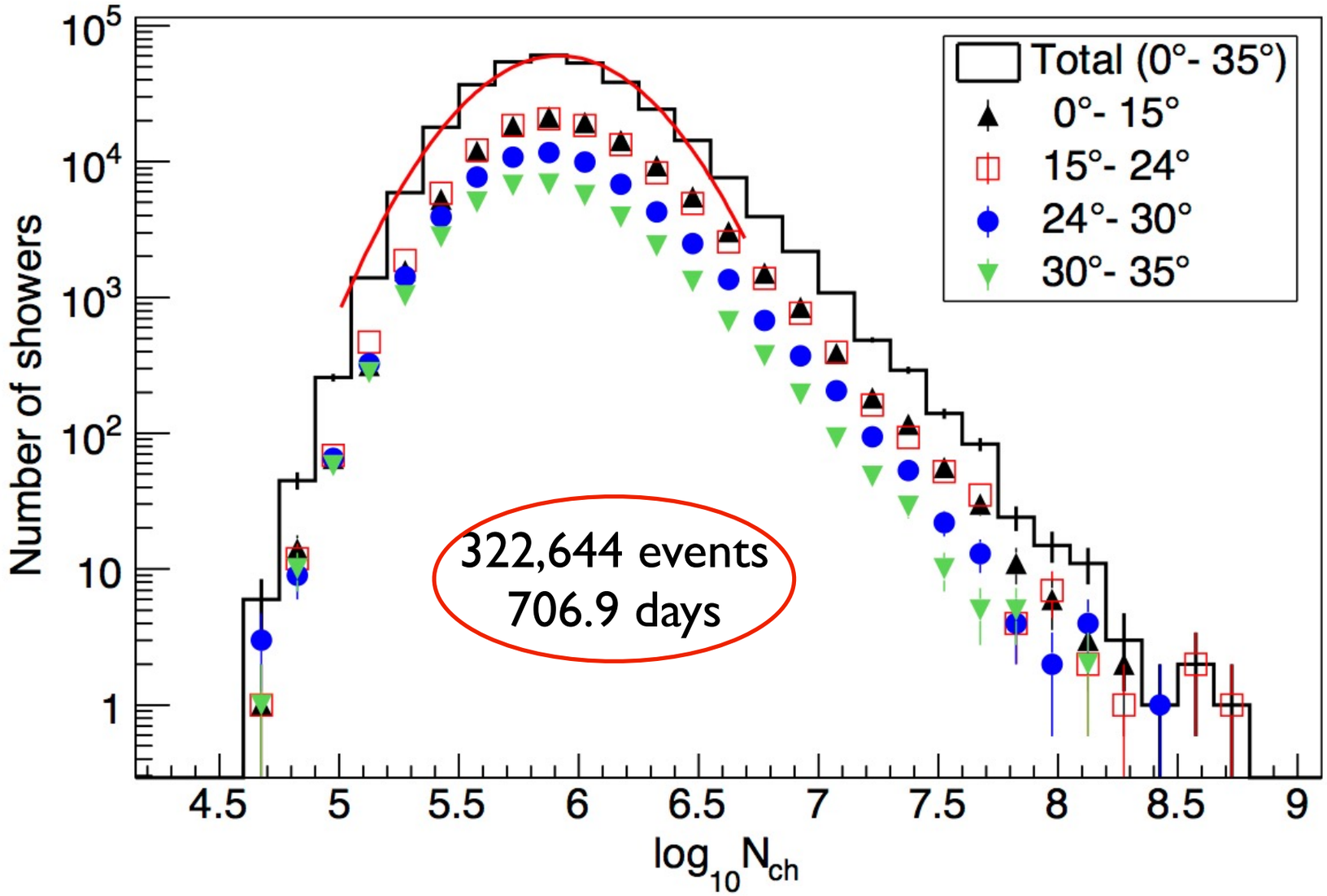
N_{ch} : No. of charged particles (shower size)

$\propto$ Primary cosmic-ray energy

r_M : Moliere radius

s : Age (shape) parameter

Size distribution of air showers measured with LORA



Trigger condition:	
Single unit trigger:	3/4 detectors
Analysis:	5 detectors with ≥ 1 particle m^{-2}
Number of leftover showers:	$1,861,045$
Quality cuts:	
Zenith angle:	$\theta < 35°$
Position of the shower axis:	< 150 m from array center
Radius parameter:	$10 \text{ m} < r_{\mathrm{M}} < 200$ m
Number of leftover showers:	$322,664$

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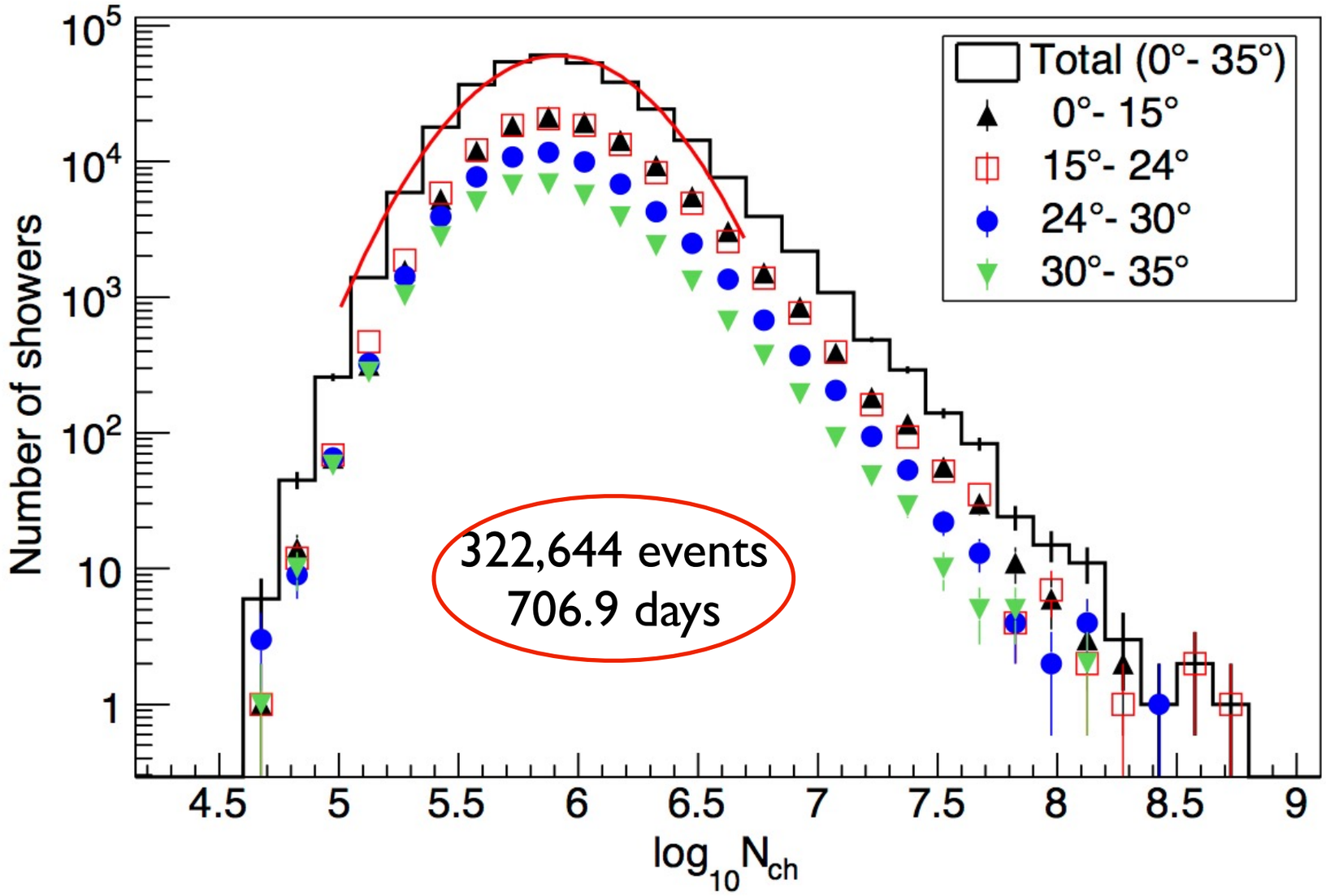
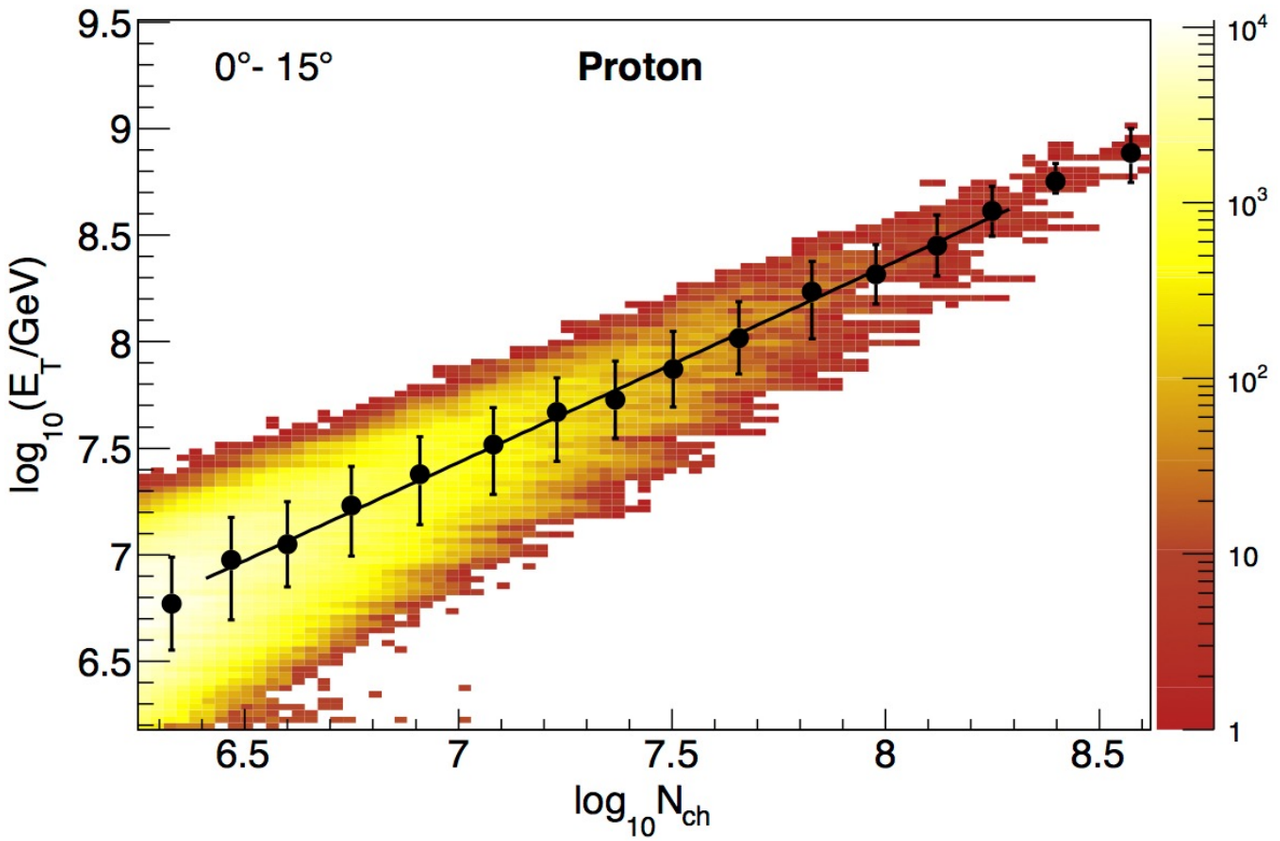


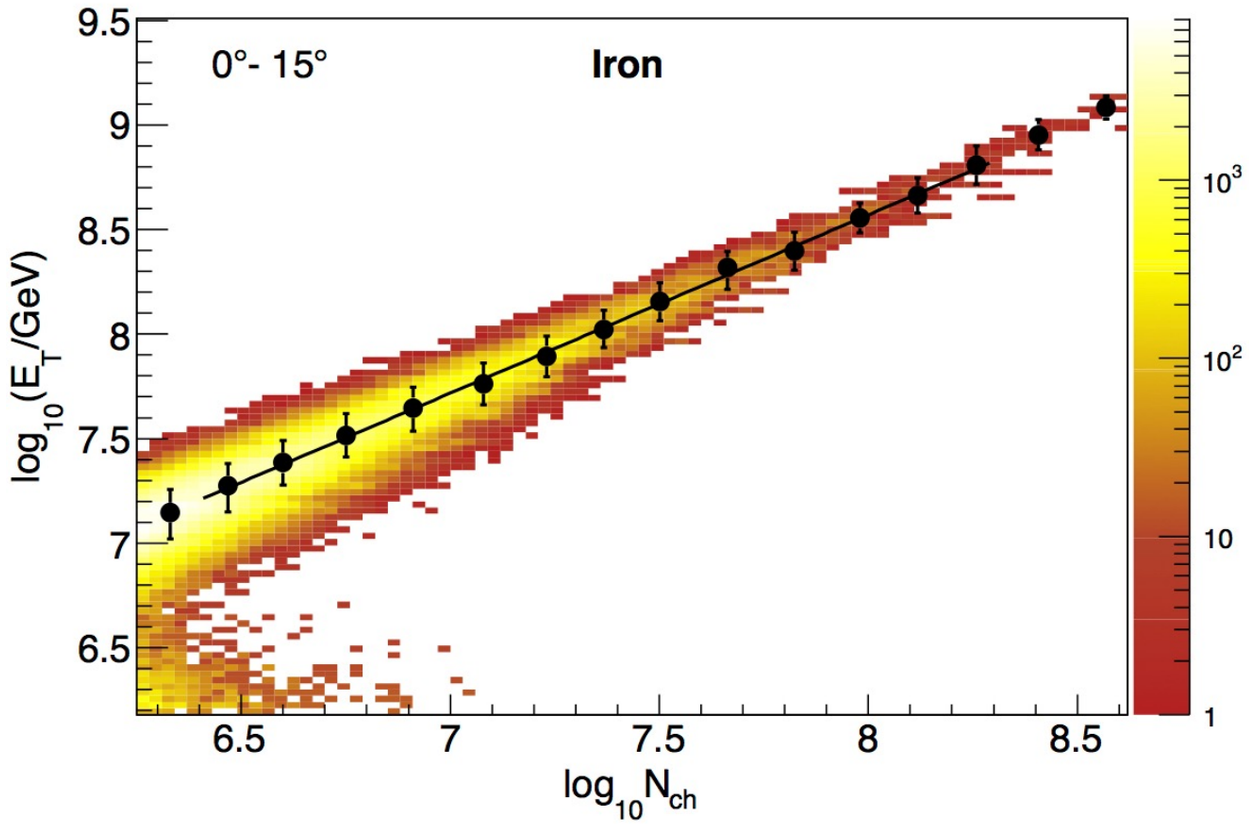
Covert Size=> Cosmic-ray energy

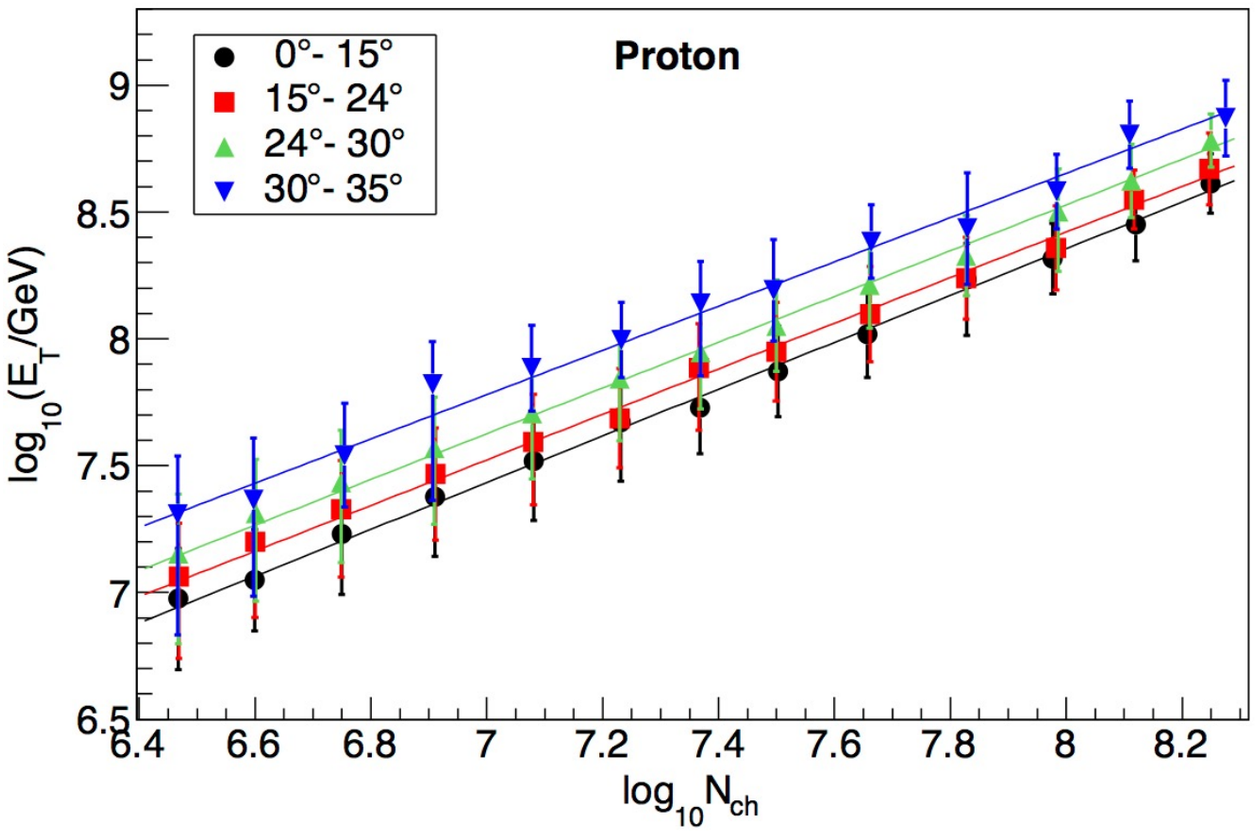
Simulation studies for the LORA array

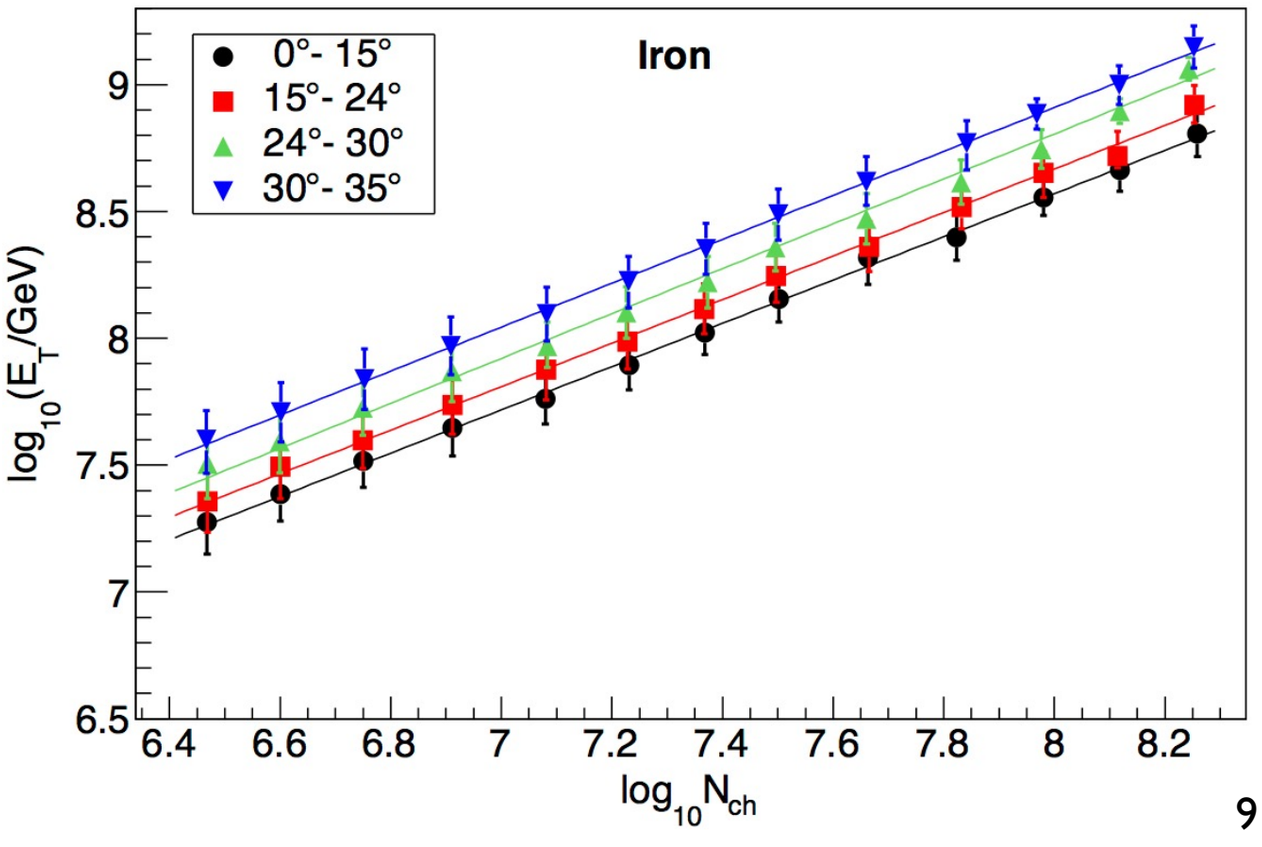
- Air-shower simulation using CORSIKA (proton & iron nuclei)
- Detector simulation using GEANT4
- Reconstruction of shower parameters (shower size, arrival direction, …)
- Determine relation between shower size and cosmic-ray energy
- Obtain trigger+reconstruction efficiencies and effective area (required for the reconstruction of cosmic-ray energy spectrum)

Energy calibration (Shower Size <=> Cosmic-ray energy)

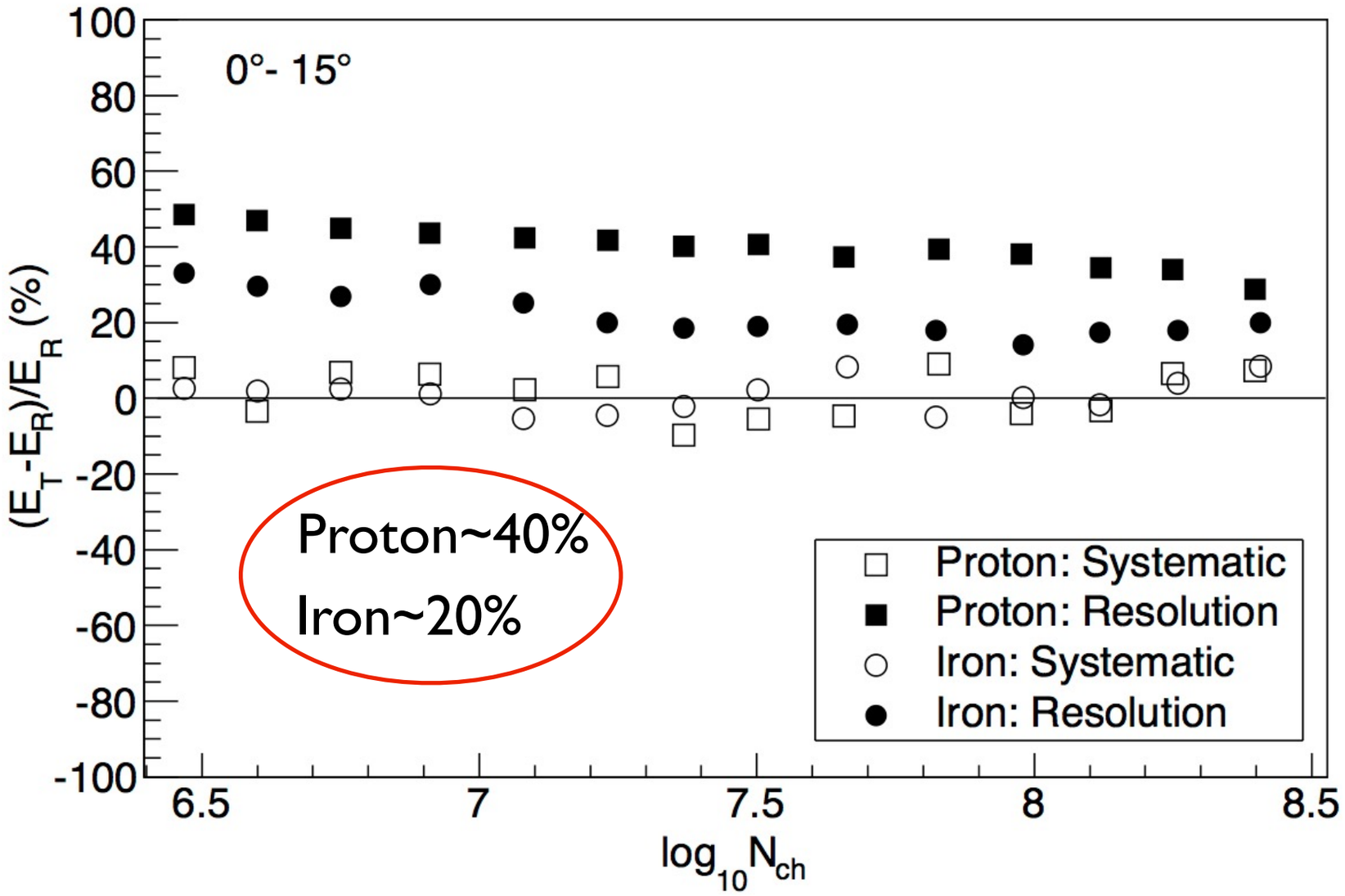








Energy resolution: Reconstructed energy accuracy



Systematic uncertainty in the reconstructed energy

- **Energy calibration: Shower size <=> Cosmic-ray**
- Spectral slope of the cosmic-ray spectrum in the simulation
- VEM: Calibration of energy deposit of single particle on the detector
- Type of the cosmic-ray particle: Proton OR Iron nuclei
- Hadronic Interaction model used in air shower simulation

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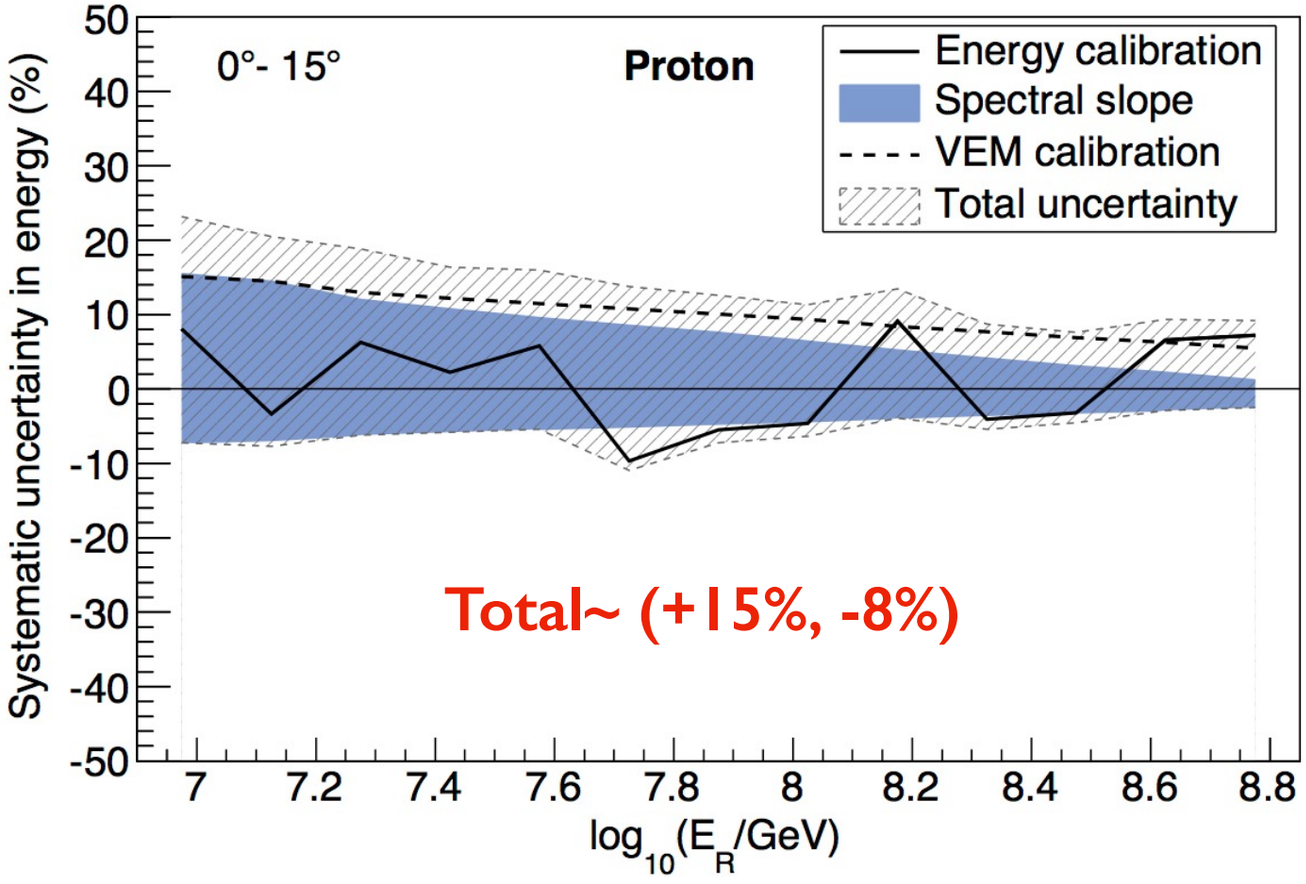
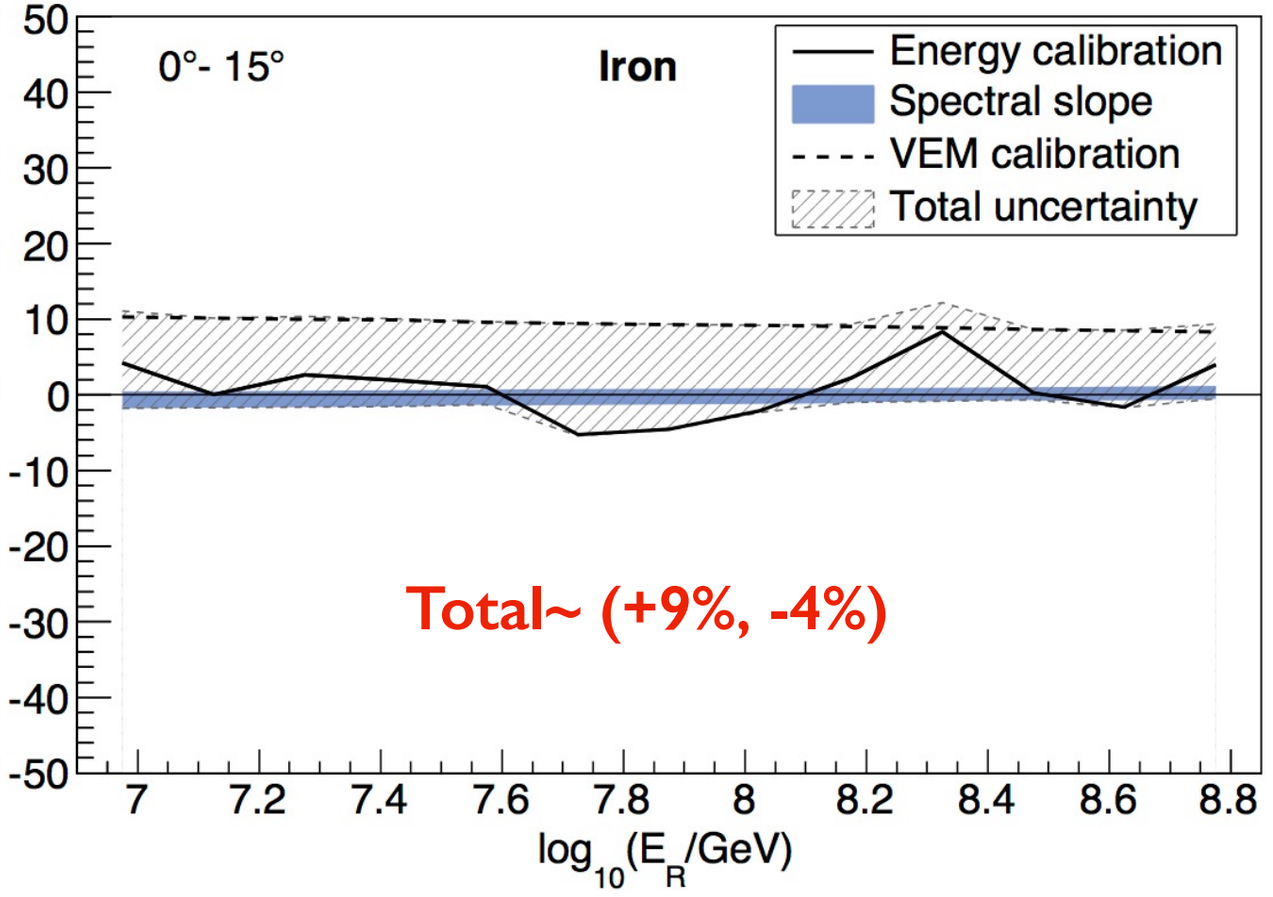
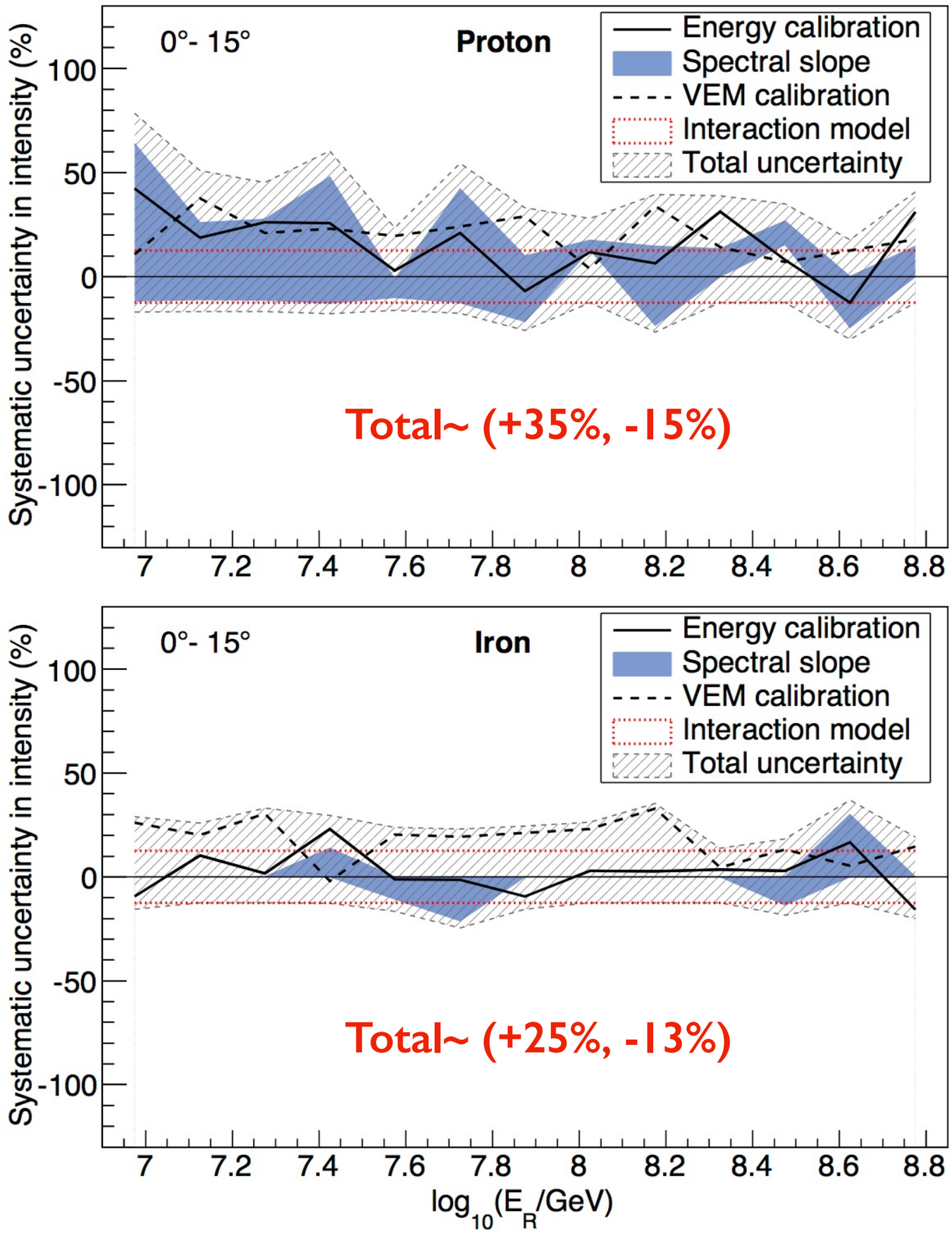
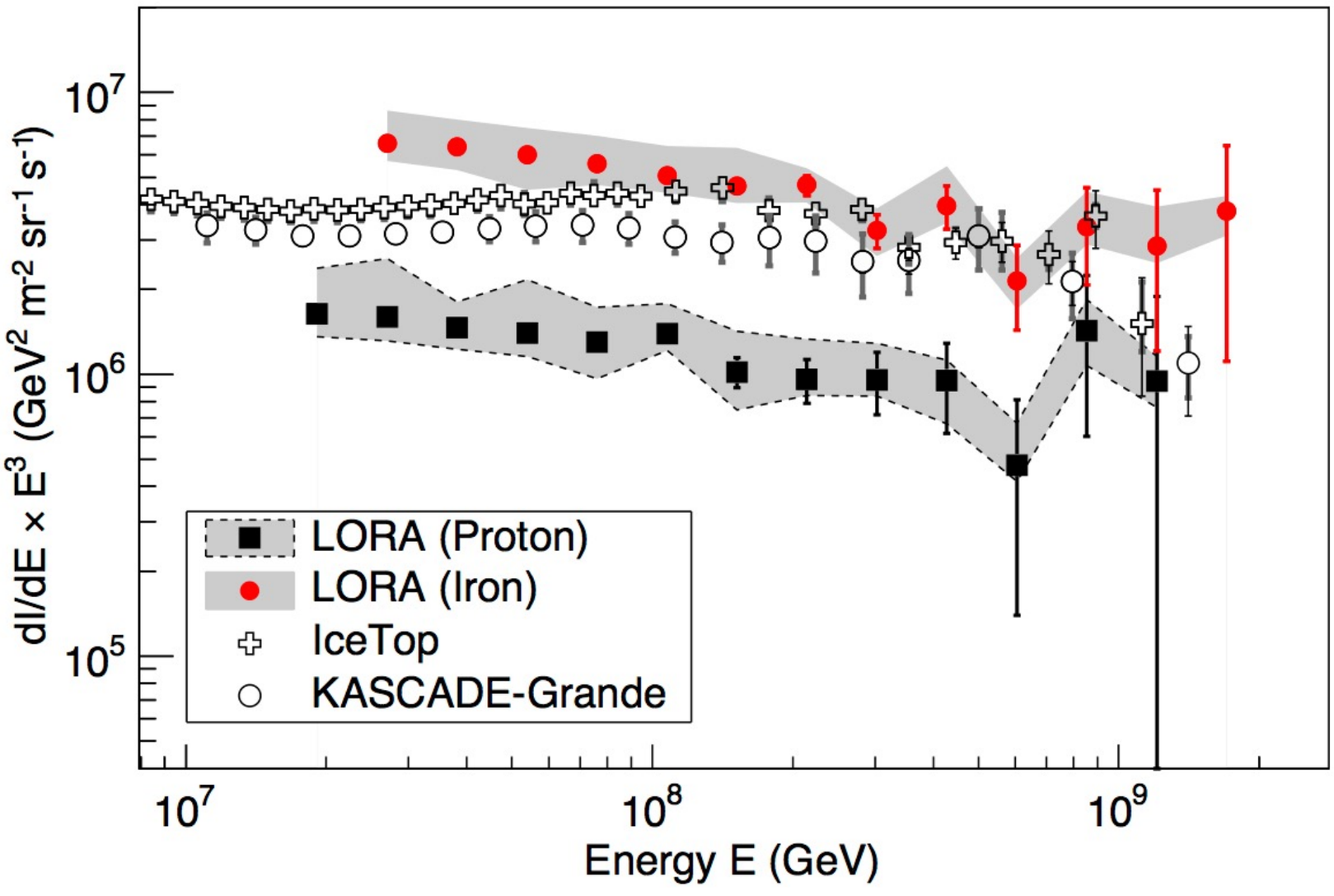




Systematic uncertainty in the reconstructed energy Spectrum



Reconstructed all-particle cosmic-ray energy spectrum



Summary and outlook

- Performed detailed energy calibration for air showers measured with the LORA array.
- Energy resolution: ~40% for protons; ~20% for iron nuclei.
- Systematic uncertainty in energy: ~(+15%,-8%) for protons; (+9%,-4%) for iron nuclei.
- Systematic uncertainty in intensity: ~(+35%,-15%) for protons; (+25%,-13%) for iron nuclei.
- All particle cosmic-ray energy spectrum above 10^{16} eV has been reconstructed assuming a pure proton and a pure iron composition.
- Future effort will be to incorporate the composition measurement from LOFAR to determine the cosmic-ray energy spectrum

Thank you!!