Measurement of the All-Particle Cosmic Ray Energy Spectrum with IceTop

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for the IceCube Collaboration

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DESY

IceCube

Outline

IceCube and IceTop

Snow

Air Shower Reconstruction

Determination of the Primary Energy

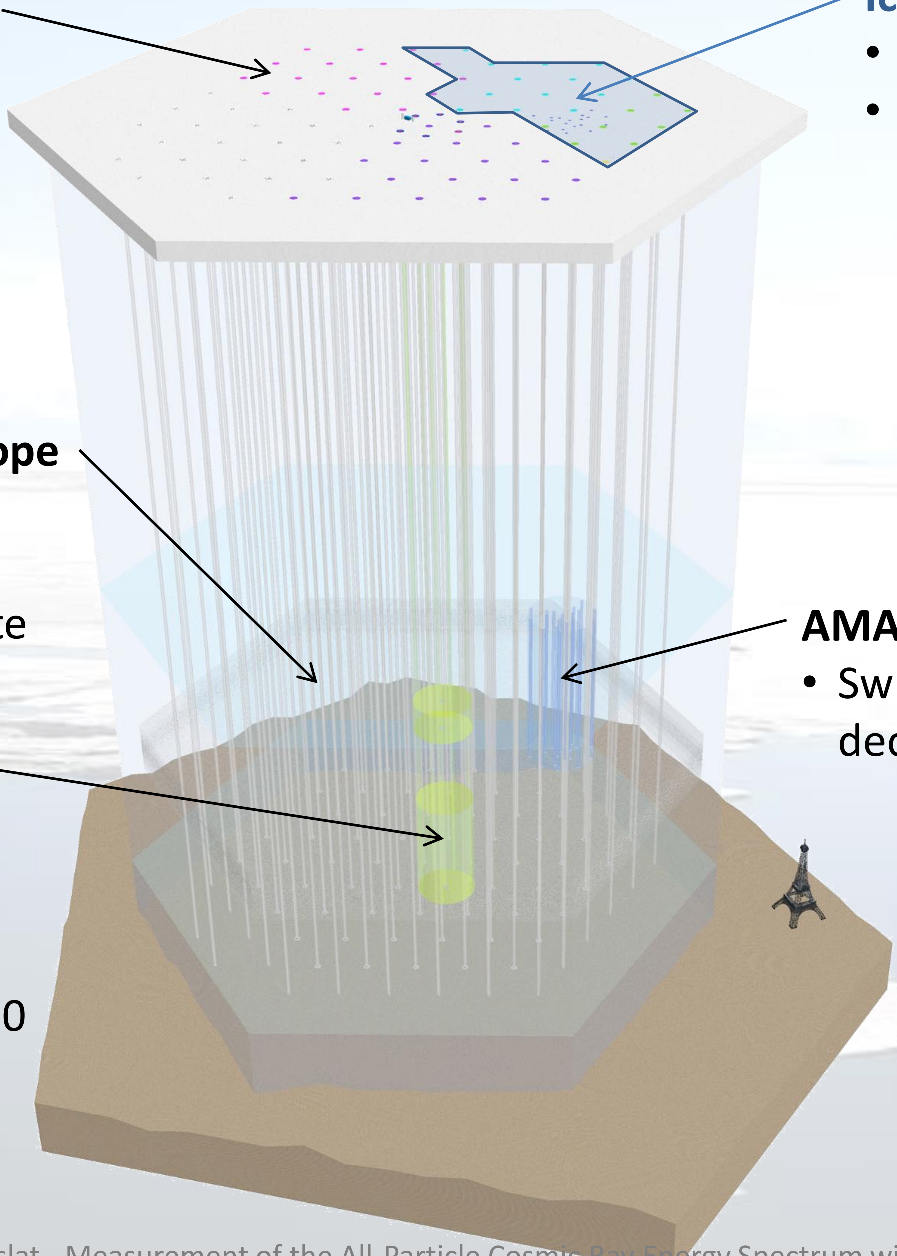
The Energy Spectrum

Outlook

IceCube and IceTop

IceTop Air Shower Array
- Currently 73 stations
- 125m triangular grid
  → Threshold 300 TeV

IceTop in 2007
- This analysis
- 26 stations



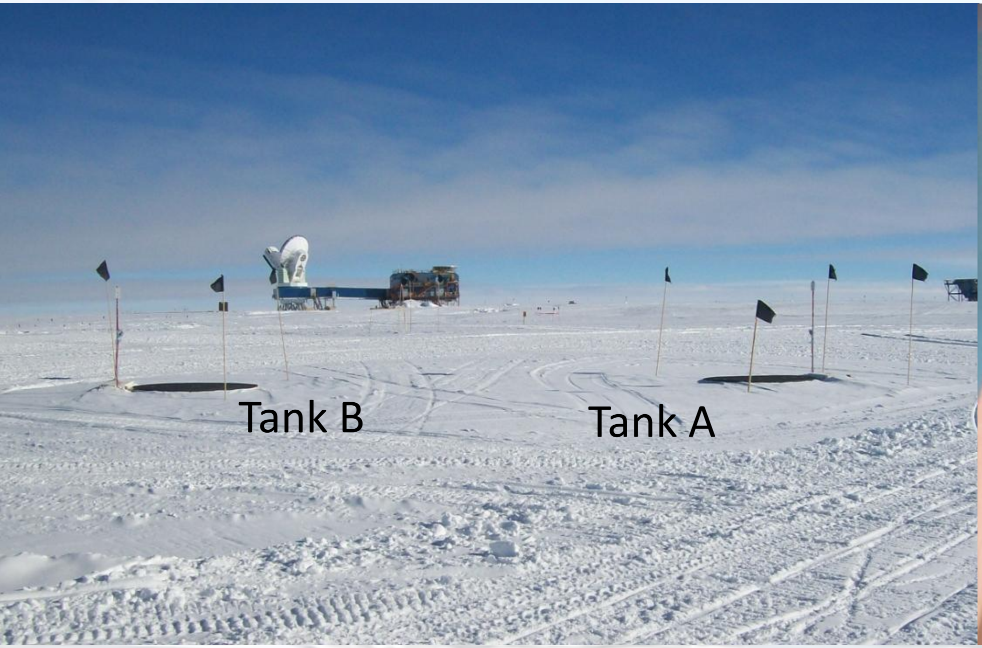
IceCube Neutrino Telescope
- Currently 79 string
- 60 DOMs per string
- DeepCore now complete

AMANDA
- Switched off and decomissioned in 2009

DeepCore
- IceCube Low-Energy Extension
- 6 strings
- Integrated in IceCube
- Complete since Jan 2010

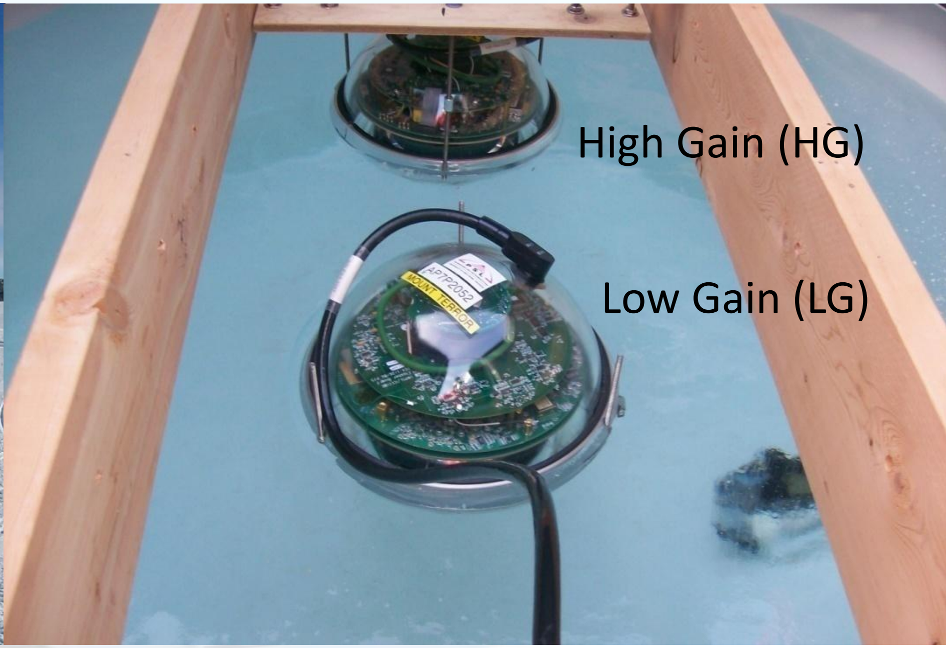
IceCube and IceTop

IceTop Station



- 2 Tanks
- 10m spacing
- Connected by Local Coincidence
  $\rightarrow$ Reduce noise rate

IceTop Tank

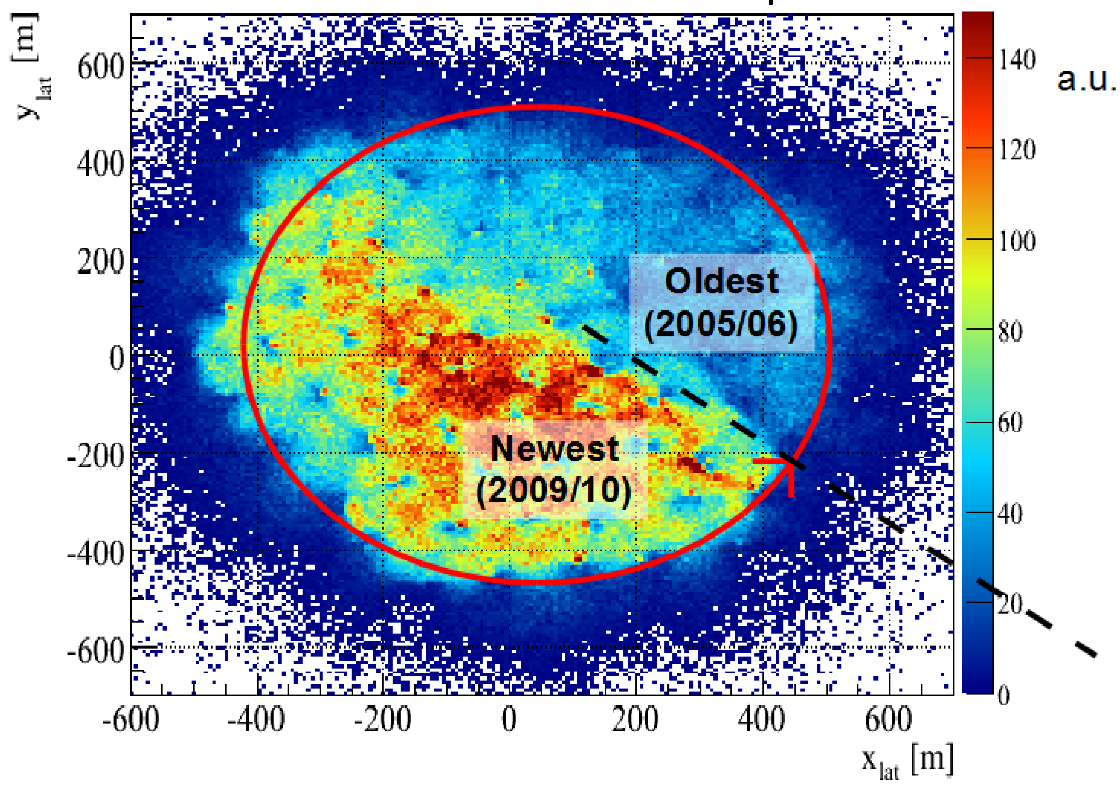


- Filled with Ice
  $\rightarrow$ Cherenkov light
- 2 Digital Optical Modules (DOMs)
- Different gains
  $\rightarrow$ Increase dynamic range

Snow

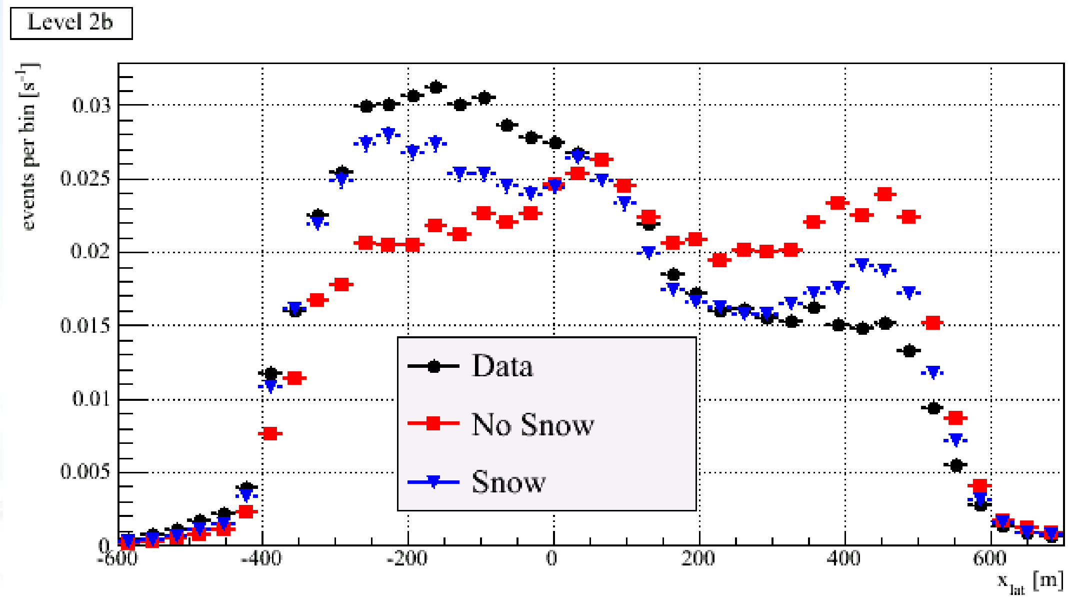
- Amount of snow on top of tanks changes
- Non-uniform distribution of snow
  - Accumulation due to drifting
  - Array installation during several years
- Parameterized in simulation for $e^{\pm}$, γ, μ

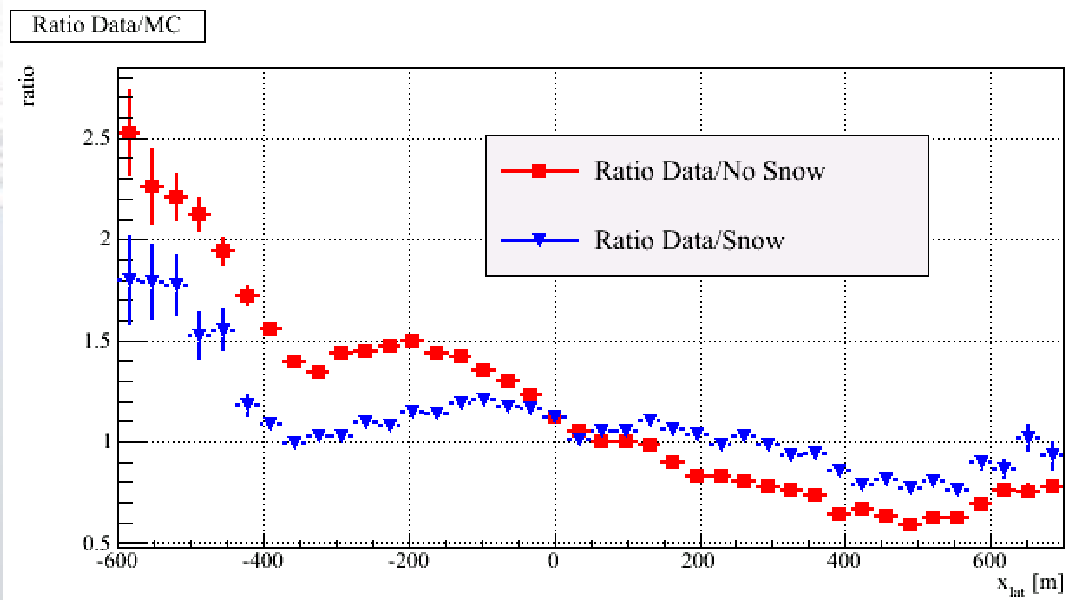
Core distribution in IceTop 73



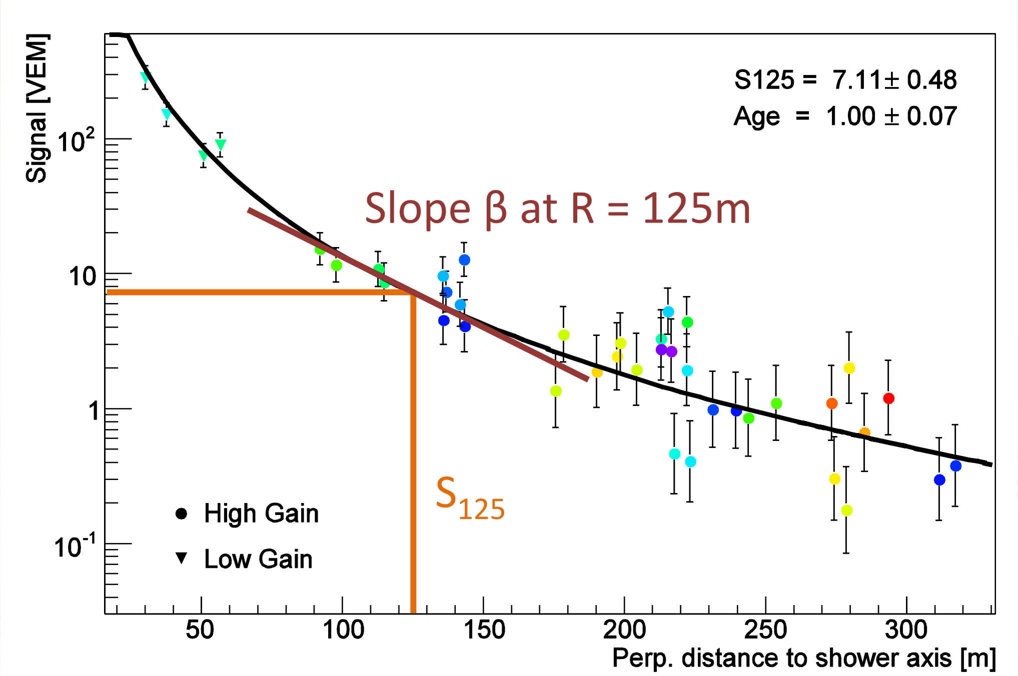
Snow

- **Projection** of core distribution on x-axis (IceTop 40, 2008)
- **First attempt** to fix this in a parametrized simulation
- New **Geant4** based simulation in development
- **IceTop 26** (2007) data used in this analysis less affected





Air Shower Reconstruction



$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125\mathrm{m})}$$

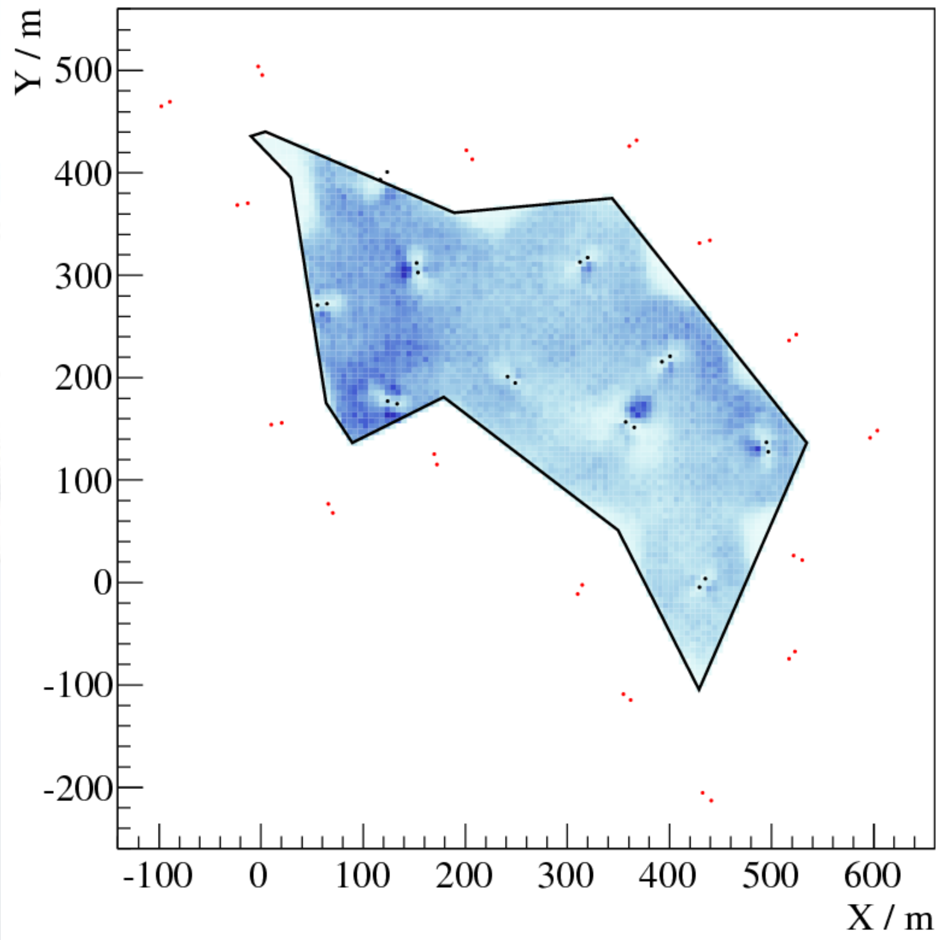
$\kappa = 0.303 = \text{const}$

$\rightarrow$ **4** free parameters: S_{125}, β, x_{core}, y_{core}

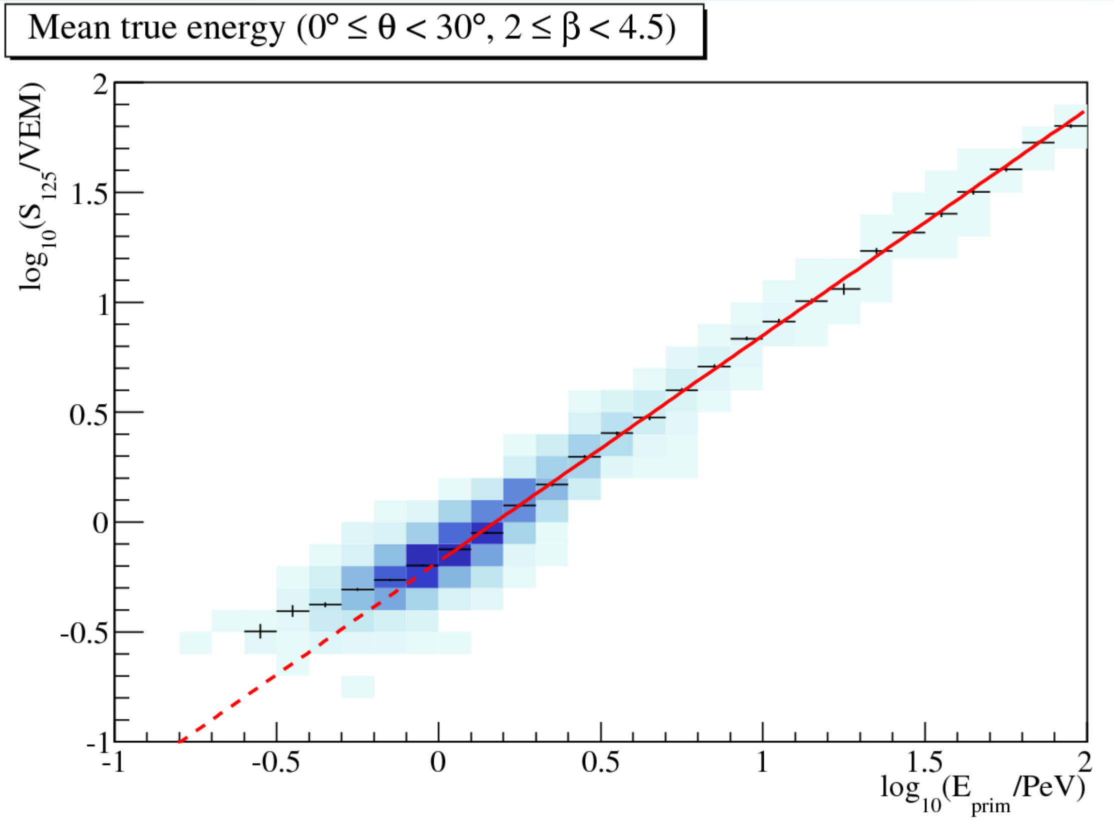
- Seeded with centre-of-gravity and plane fit
- Likelihood fit with $\mathbf{P_{nohit}}$ term
- **Log-normal** fluctuations of charges measured in tank-to-tank comparison

Dataset and Quality Cuts

- Data taken June 2007 – October 2007
- Total number of events: 9′984′826
- Quality Cuts:
  - #Stations ≥ 5
  - $2.0 \leq \beta < 4.5$
  - Core **position uncertainty** less than 20m
  - Reconstructed **core contained**
  - Station with **largest signal contained**



Determination of the Primary Energy



Based on **MC simulations** of **different primaries**

- Pure Proton
- Pure Iron
- 2-Component Composition (Glasstetter, 26th ICRC 1999)

Data divided into **zenith bands**:

- 0° – 30°
- 30° – 40°
- 40° – 46°

- Linear fit of energy vs shower size S_{125} relation

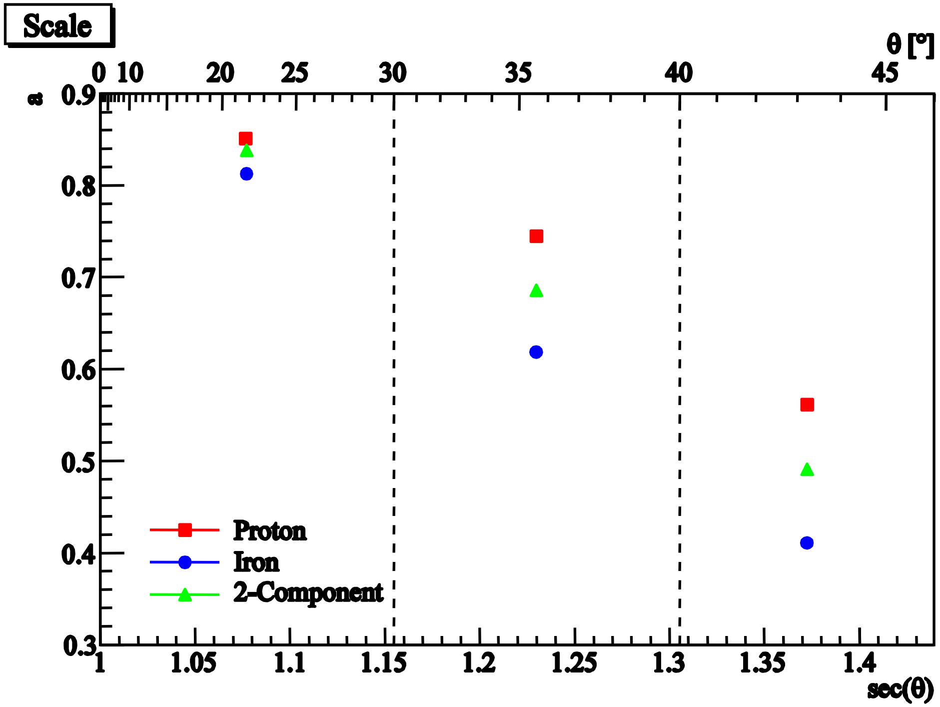
$$\log(S_{125}) = a + b\,(\log(E/\mathrm{PeV}) - 1)$$

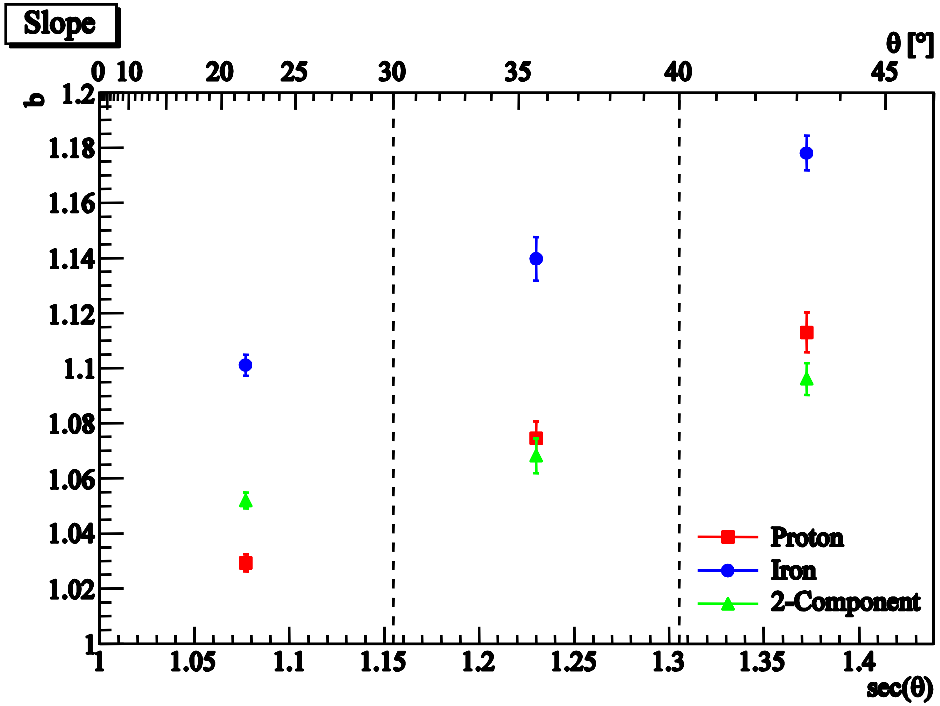
  – For each zenith band and for each primary composition

Determination of the Primary Energy

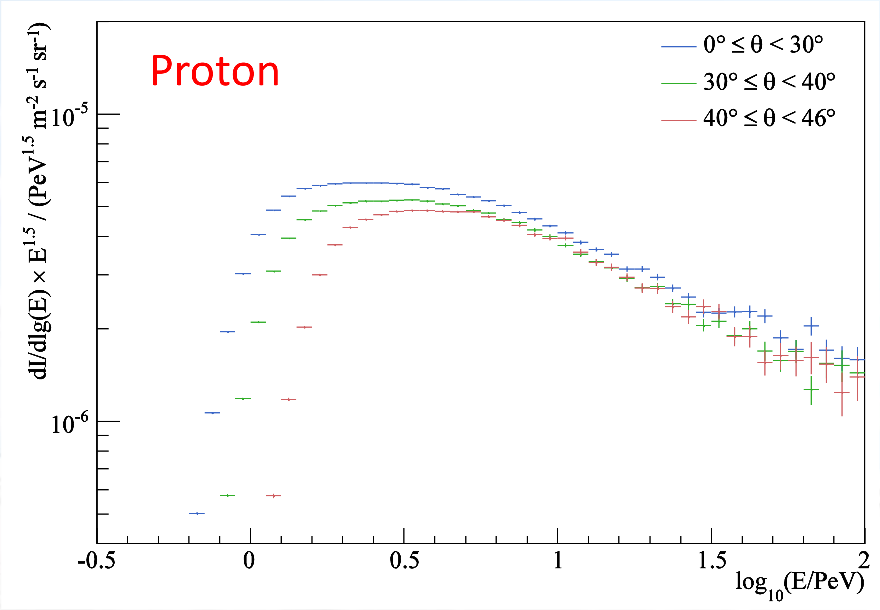
- All parameters used in the energy calculation

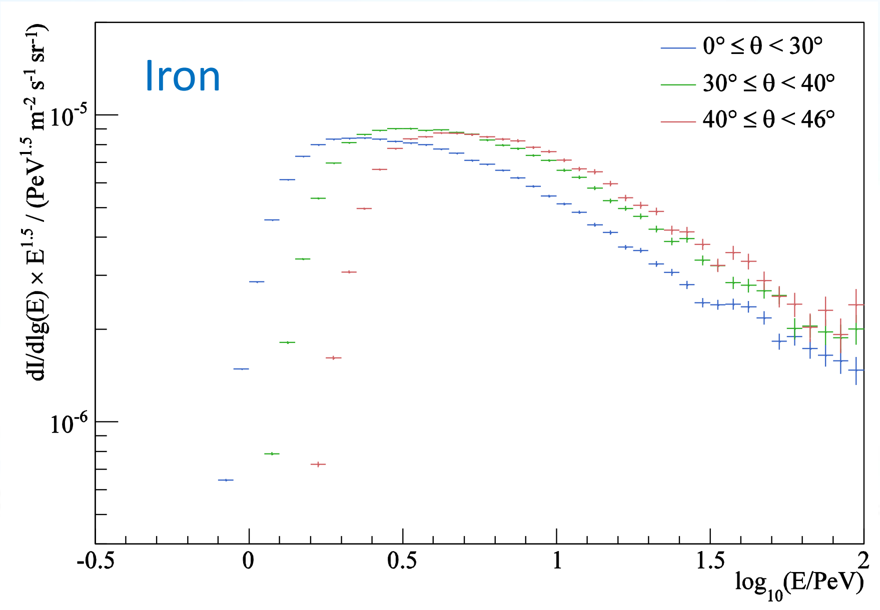
$$\log(S_{125}) = a + b\,(\log(E/\mathrm{PeV}) - 1)$$

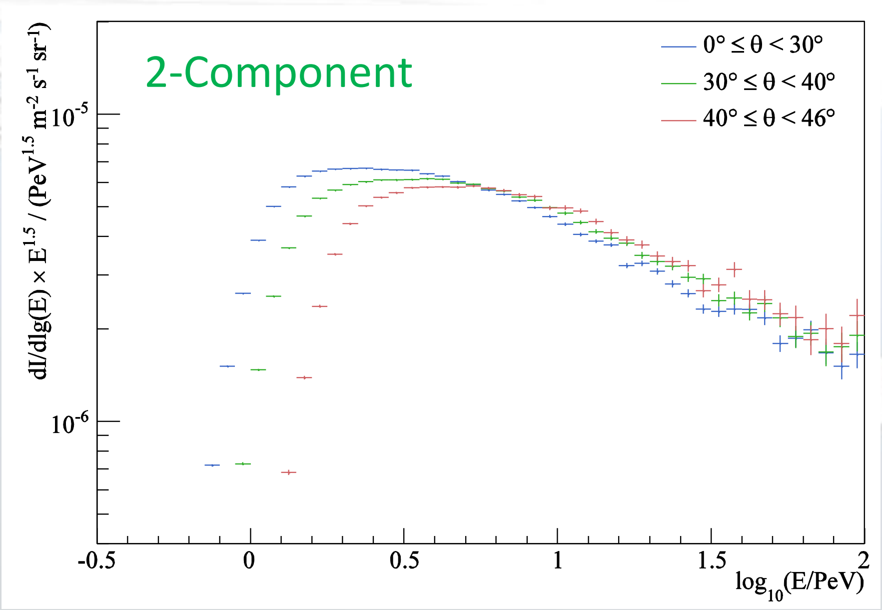




Raw Energy Spectra

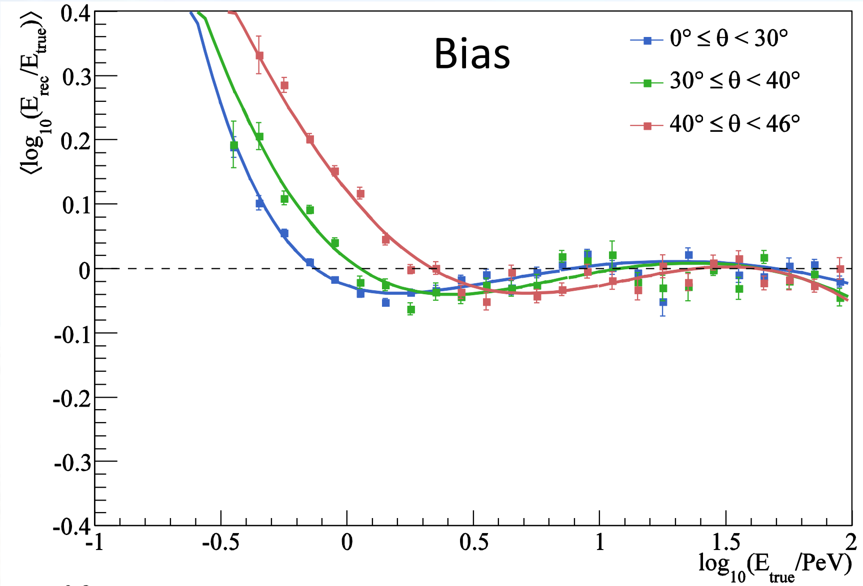


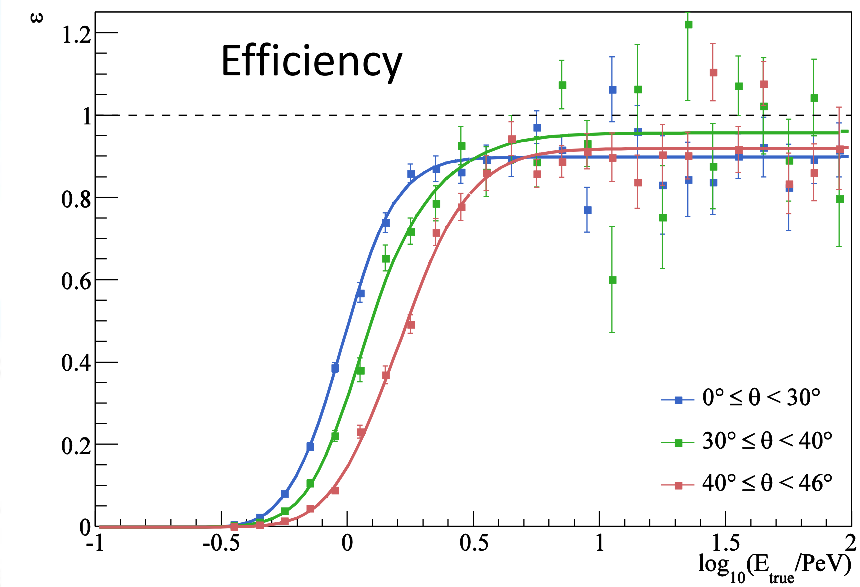


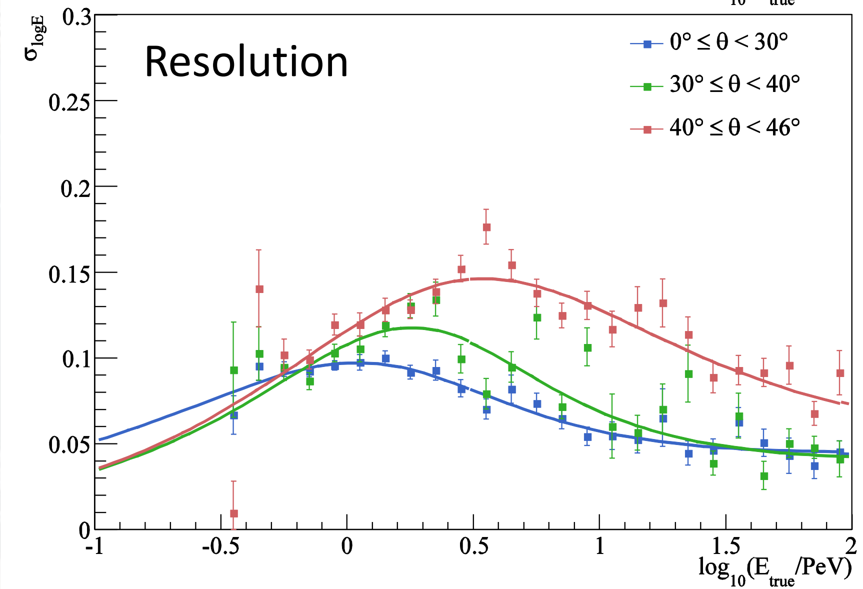


Detector Response

- Raw Spectra influenced by **detector response** → **unfold**
- Response for **protons**:

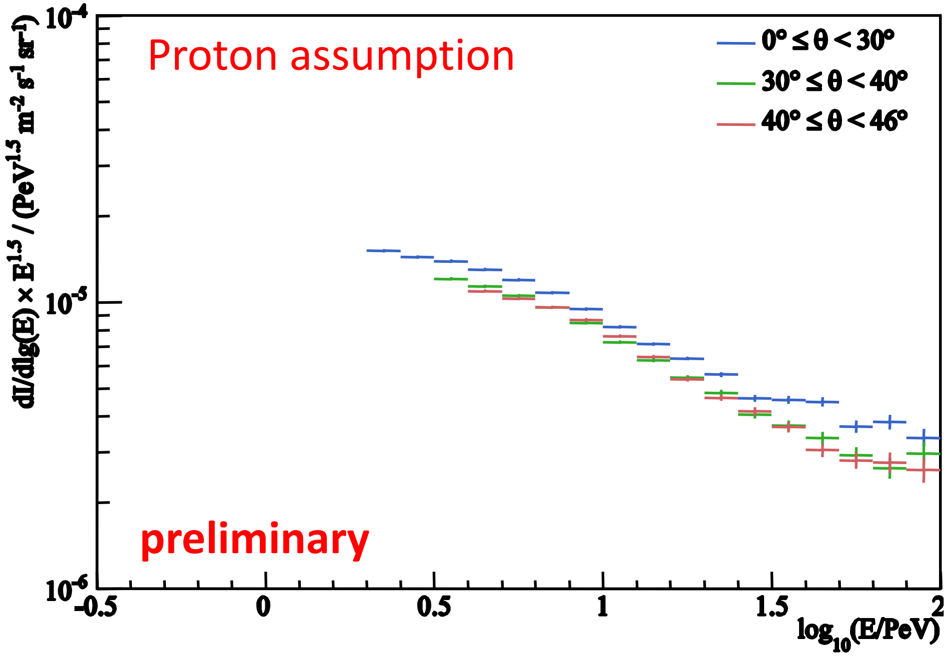


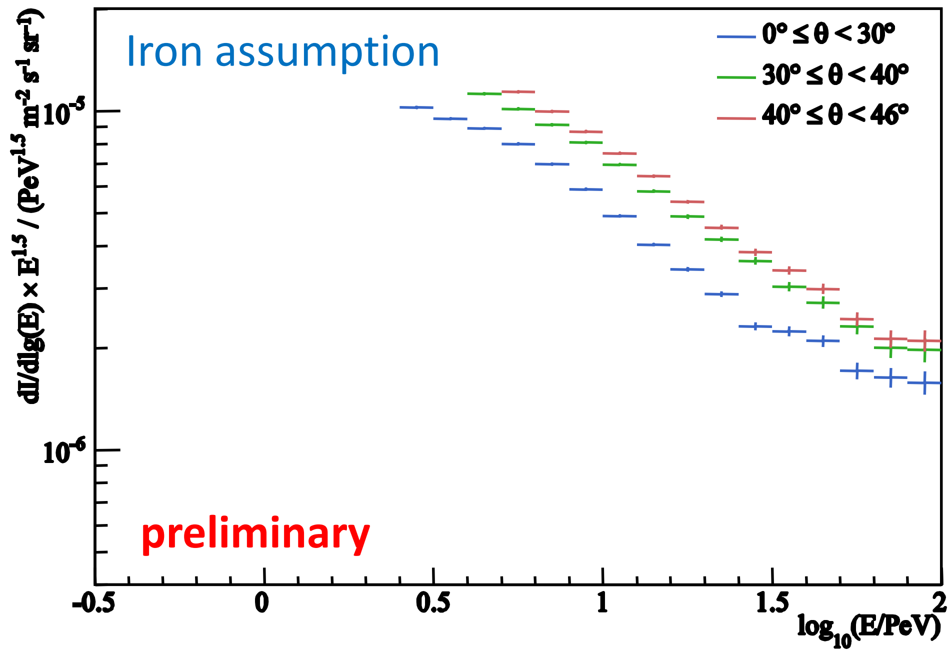


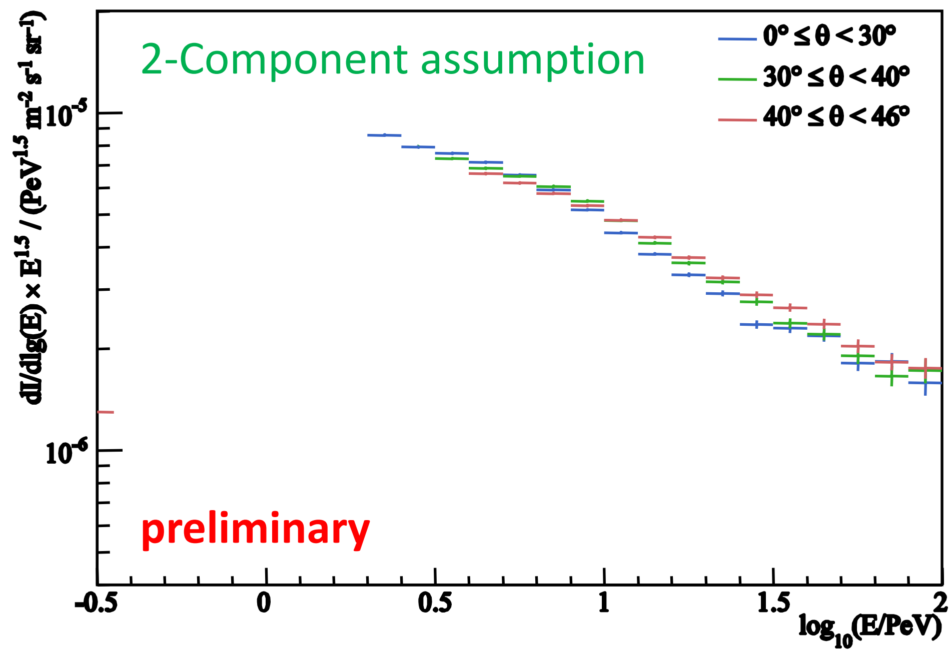


- **Small bias** at full efficiency
- **~90% efficiency** for cores in fiducial area
- **Resolution** 0.05 – 0.15 in log(E)

Unfolded energy spectra







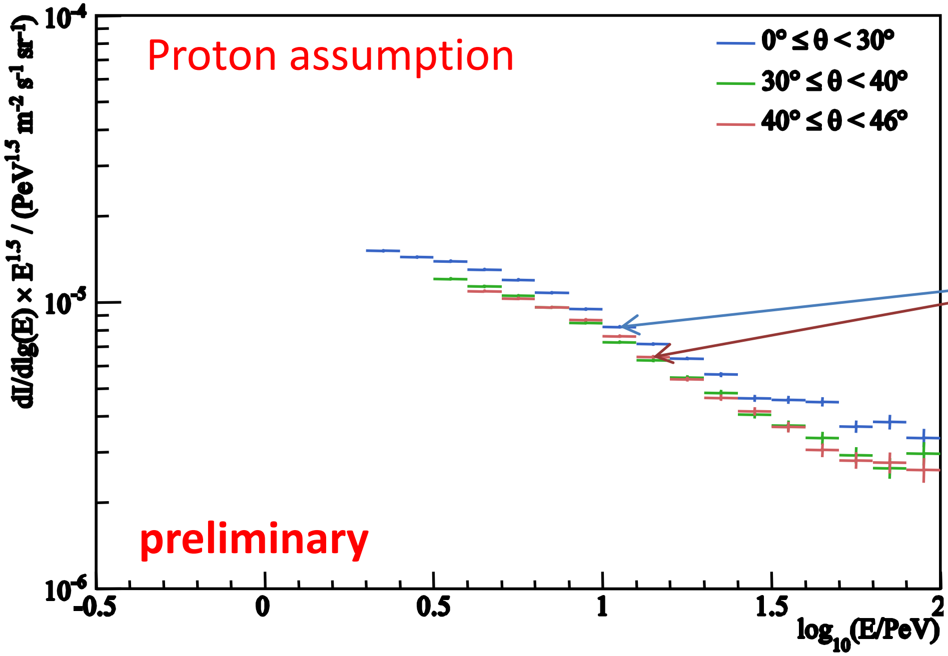
Isotropy

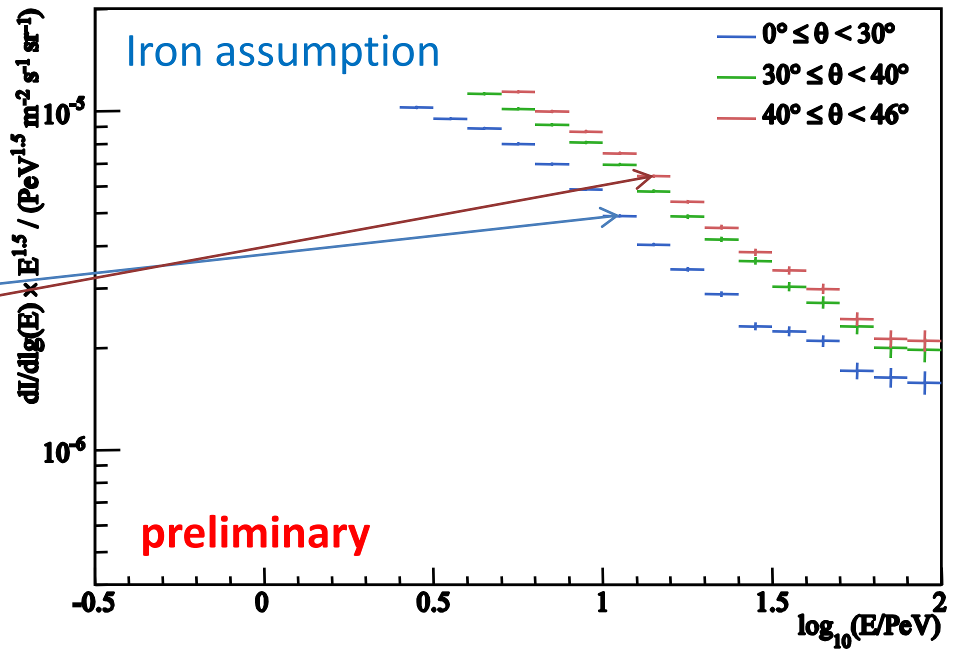
→ Spectra from different zenith bands should agree

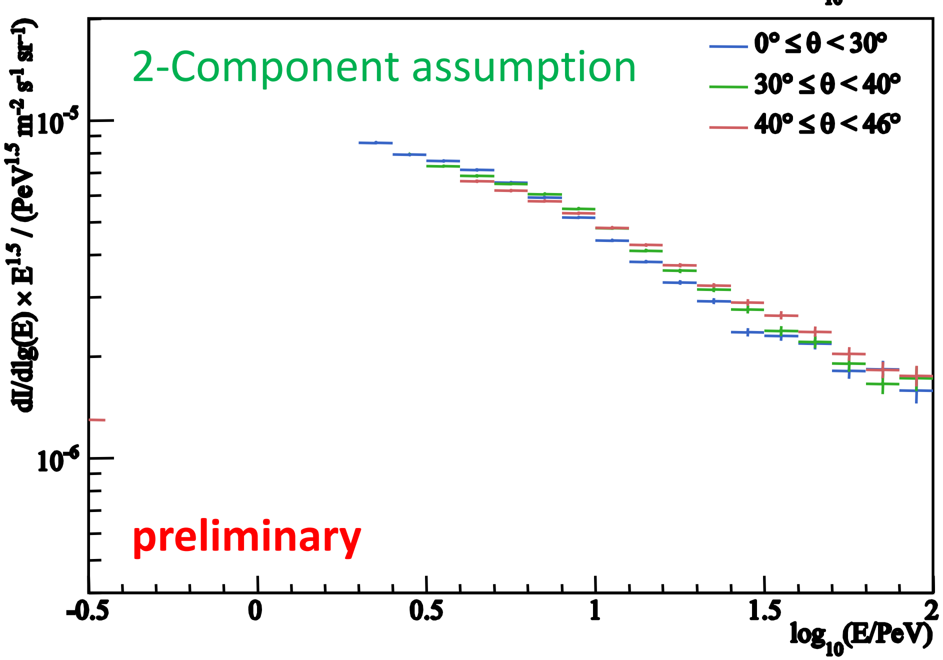
→ Best agreement for **mixed composition**

→ Pure iron not compatible with isotropy

Unfolded energy spectra







Isotropy

→ Spectra from different zenith bands should agree

→ Best agreement for **mixed composition**

→ Pure iron not compatible with isotropy

Summary

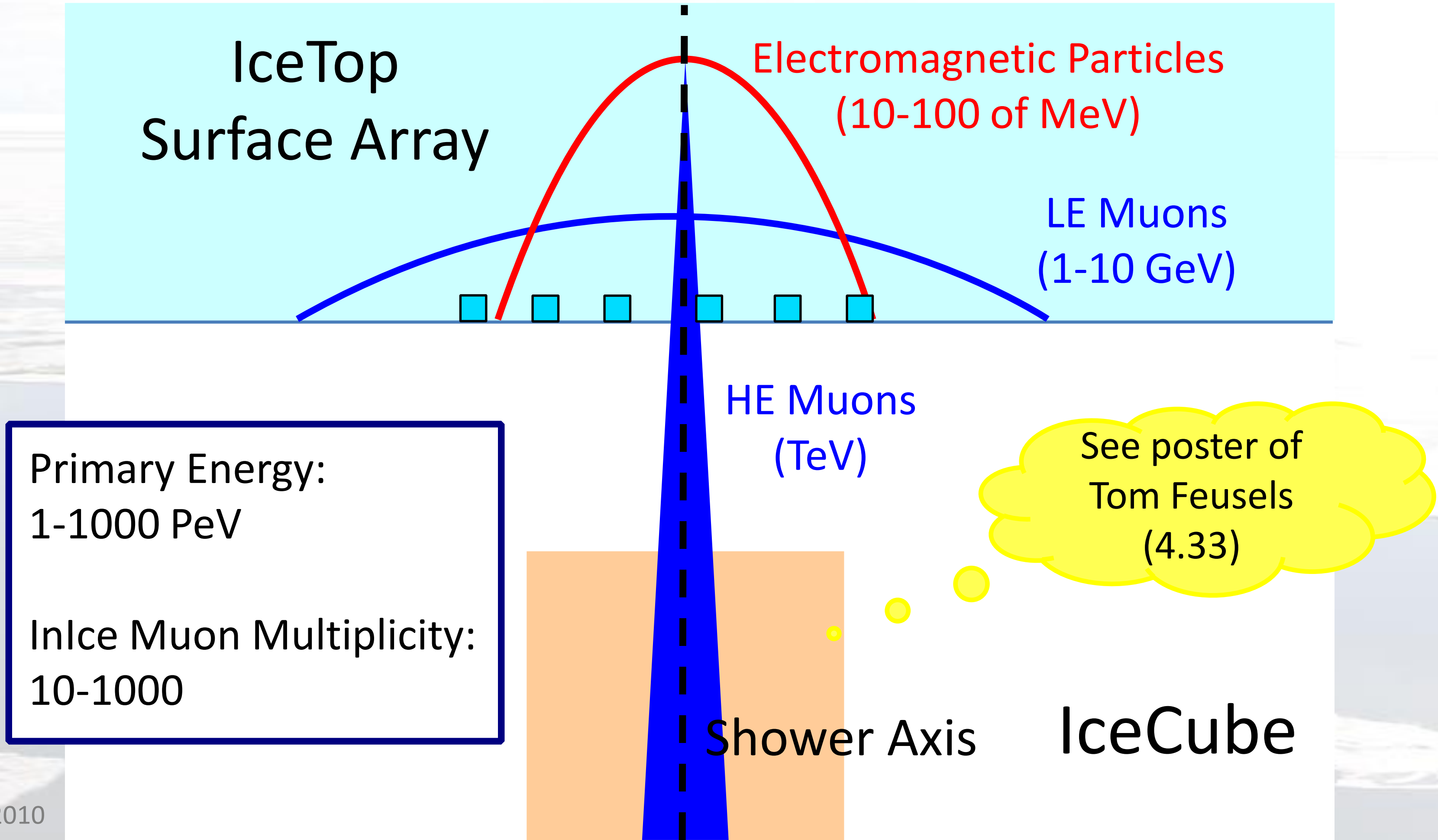
- A method to reconstruct the primary energy of air showers with IceTop has been developed
- Energies can be reconstructed with a resolution up to 0.05 in log(E) $\leftrightarrow$ ~10%
- A mixed composition yields the best agreement with isotropy (pure iron excluded)

Outlook

- Investigate systematic uncertainties
- Check absolute energy scale

Future IceTop developments

- Completion during next season → 81 stations
- Small infill array → extend energy range down to 100 TeV
- 3 Ways to measure composition




Thank you for your attention!

Backup

Air Shower Reconstruction

- Combined likelihood fit of charges and times
- Assuming lognormal charge fluctuations
- Likelihood function with P_{nohit} term:

$$L = L_q + L_0 + L_t$$

  - L_q = **Charge likelihood**: log-normal distribution of charges

$$L_q = -\sum_i \frac{\left(\log(S_i) - \log(S_{\text{fit}}^{(i)})\right)^2}{2\sigma_q(S_{\text{fit}}^{(i)})^2} - \sum_i \log\left(\sigma_q(S_{\text{fit}}^{(i)})\right)$$

  - L_0 = **No-hit likelihood**: Probability that a station (2 tanks!) does not trigger for a given expectation value

$$L_0 = \sum_j \log\left(1 - P_{\text{hit}}^{(j)\,2}\right)$$

$$P_{\text{hit}}^{(j)} = 1 - \frac{1}{\sqrt{2\pi}\sigma_0} \int_{-\infty}^{S_{thr}} \exp\left(\frac{\left(\log(S_j) - \log(S_{\text{fit}}^{(j)})\right)^2}{2\sigma_q(S_{\text{fit}}^{(j)})^2}\right) \mathrm{d}\log S_j$$

  - L_t = **Time likelihood**: Fit a curved shower front

Effects of the Quality Cuts