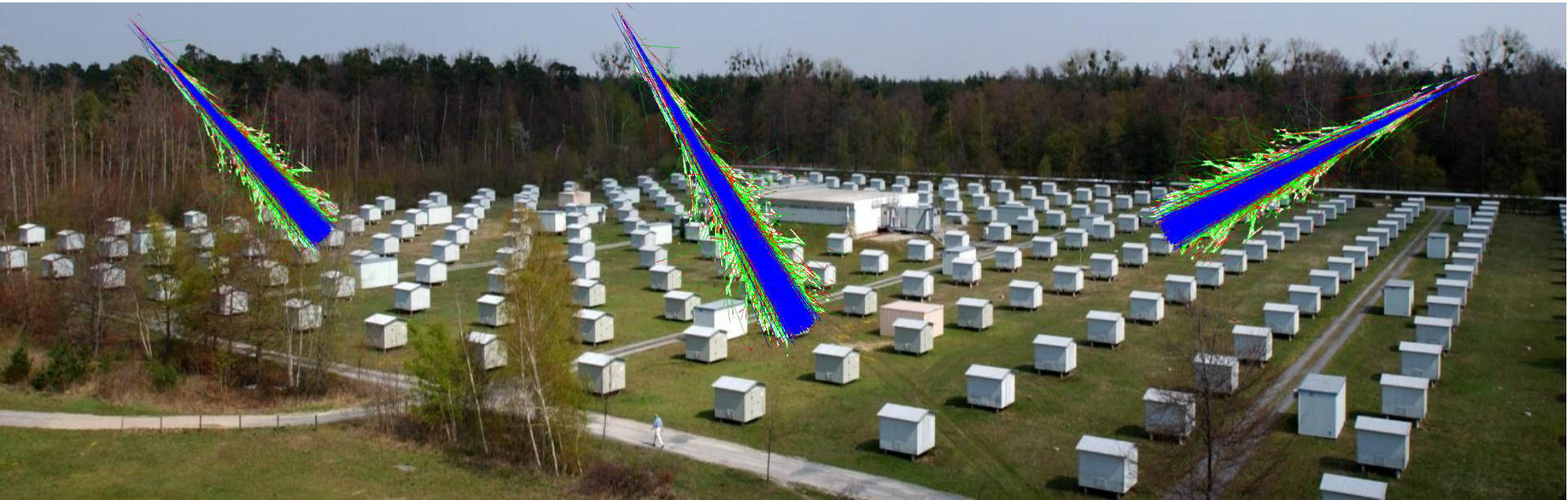
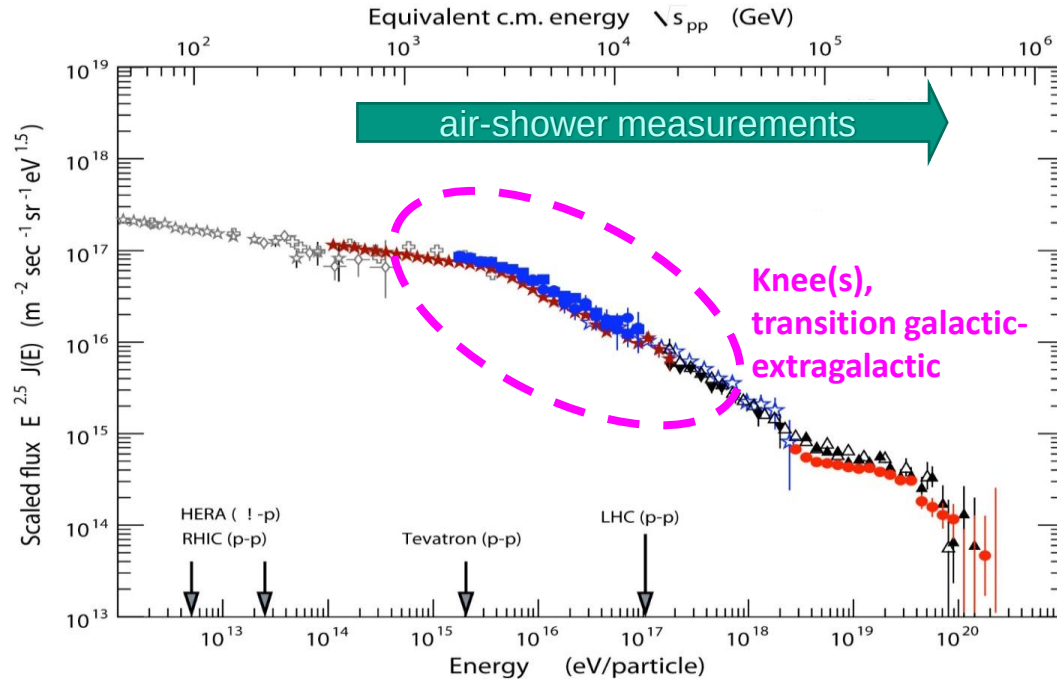


37 years of KASCADE ... and still new results

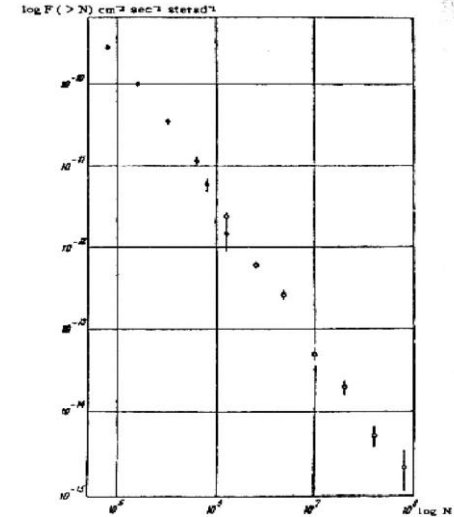
IPA 2026, Madison, October 14-16, 2026

Andreas Haungs, Donghwa Kang -- Institute for Astroparticle Physics





The “first knee”



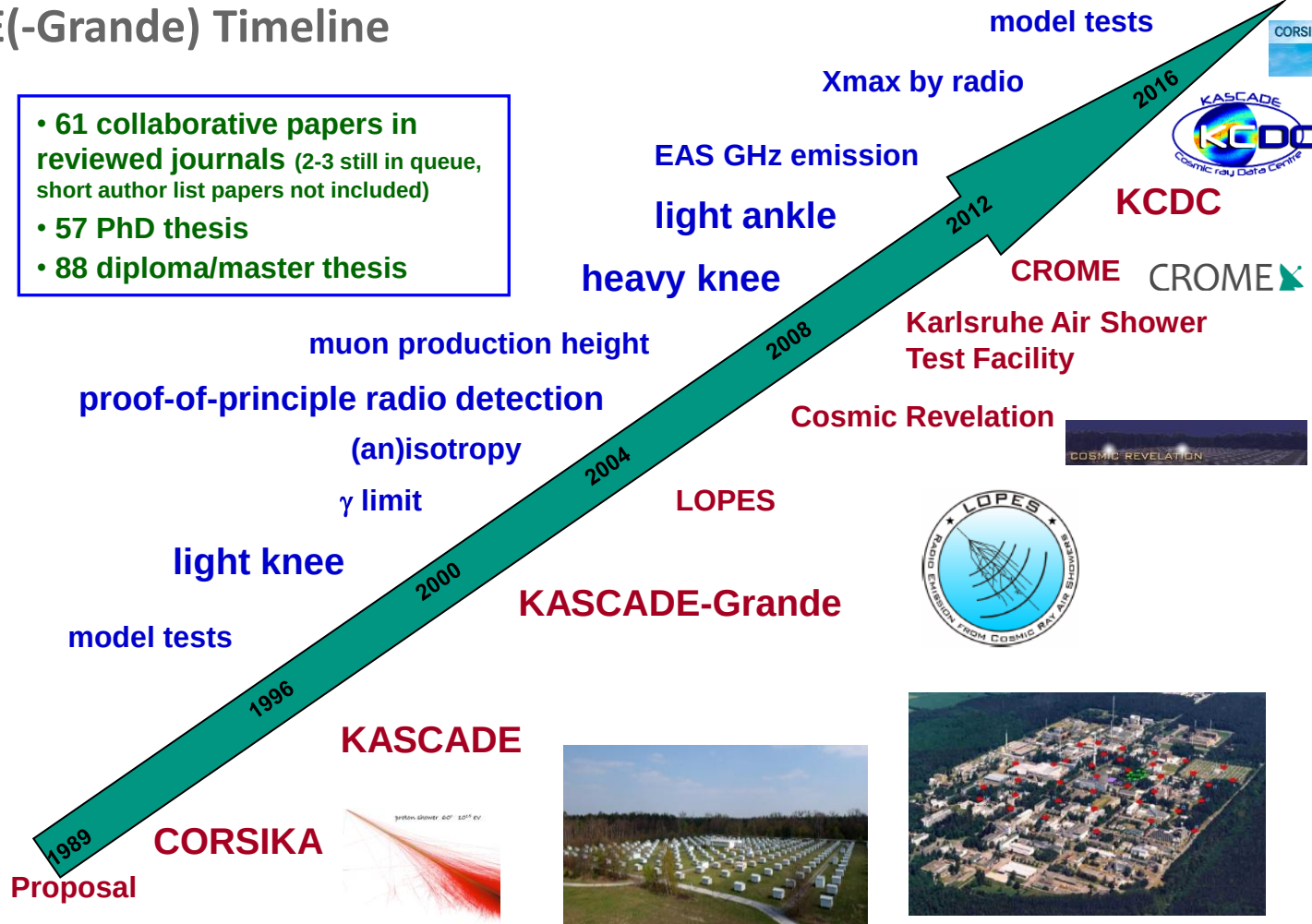
G.V.Kulikov & G.B.Khristiansen, *Soviet Physics JETP*, Volume 35(8), No 3, March 1959

measured N_{ch} spectra, hodoscope counters in a 20x20 m² array

„the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin“

KASCADE(-Grande) Timeline

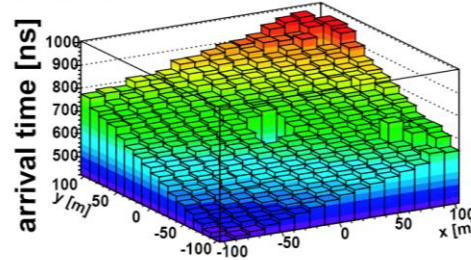
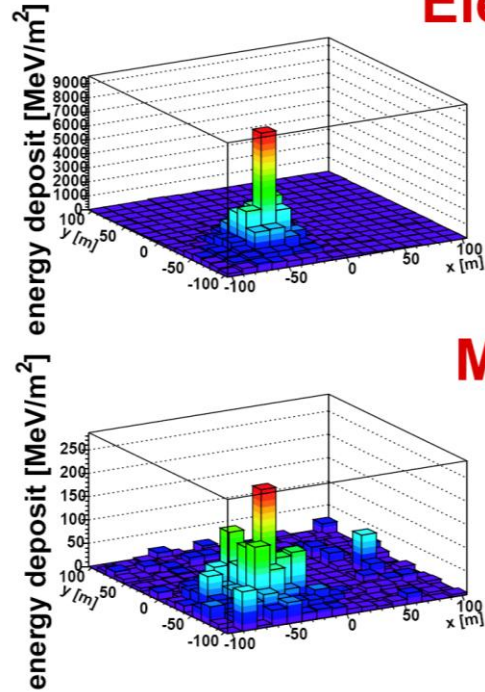
- 61 collaborative papers in reviewed journals (2-3 still in queue, short author list papers not included)
- 57 PhD thesis
- 88 diploma/master thesis



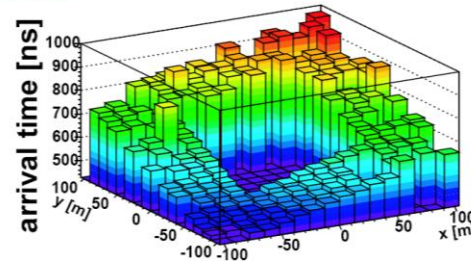
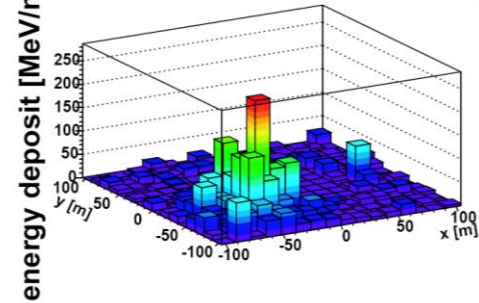
KASCADE measured air shower

Array

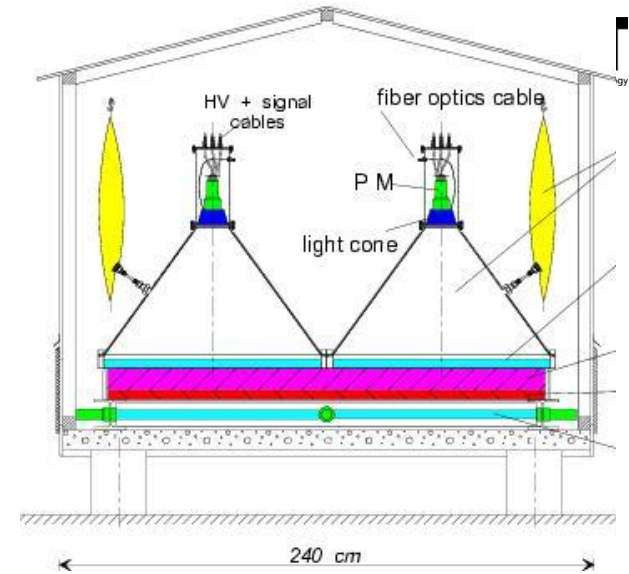
Electrons



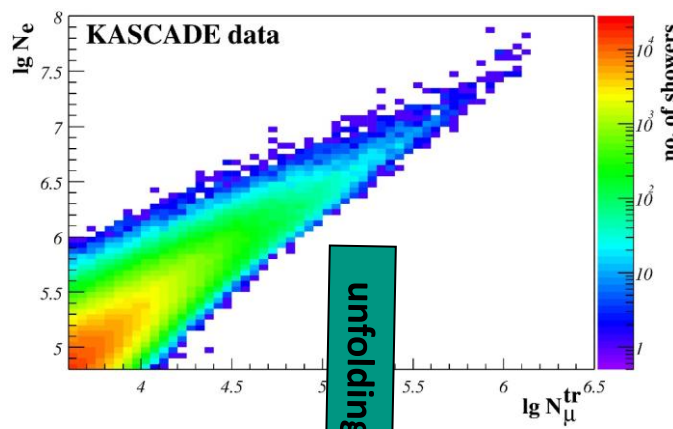
Muons



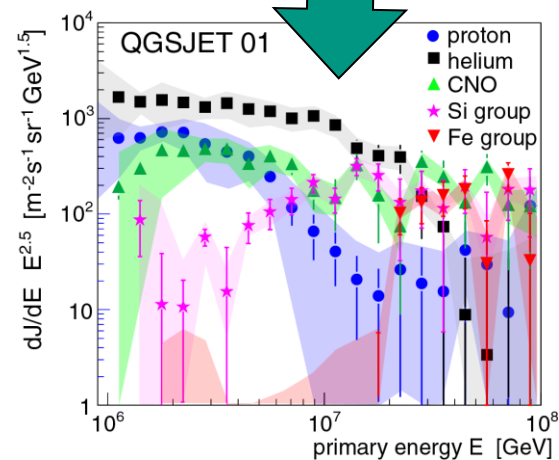
Run 3226, File 2, leve 65041, Ymd 10215, Hms 225810, Neds 250, Npds 138
 (Xc,Yc) = (-45.4,-51.0), (Ze,Phi) = (36.7,228.6), log10(Ne)=6.14, log10(Lmuo)=4.66



KASCADE: energy spectra of single mass groups



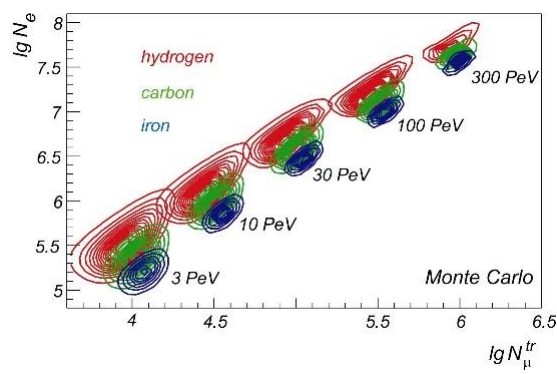
unfolding



Searched: **E** and **A** of the Cosmic Ray Particles

Given: N_e and N_μ for each single event

→ solve the inverse problem



- kernel function obtained by Monte Carlo simulations (CORSIKA)

- contains: shower fluctuations, efficiencies, reconstruction resolution

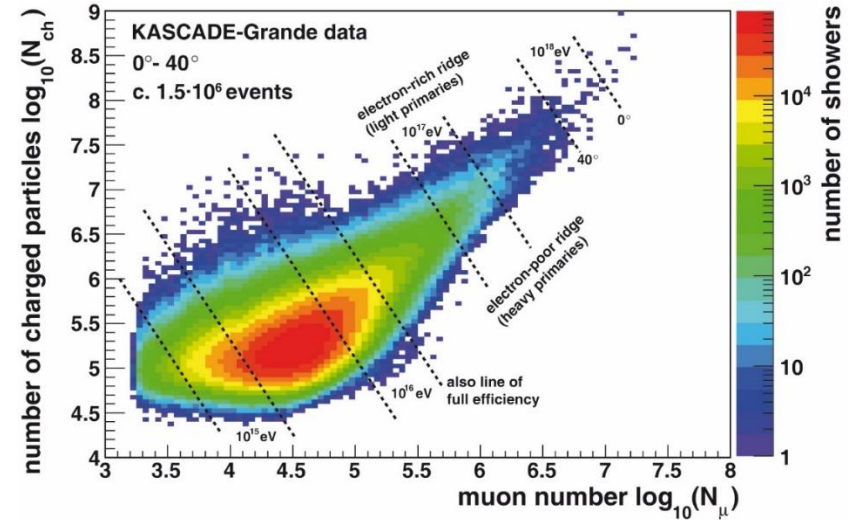
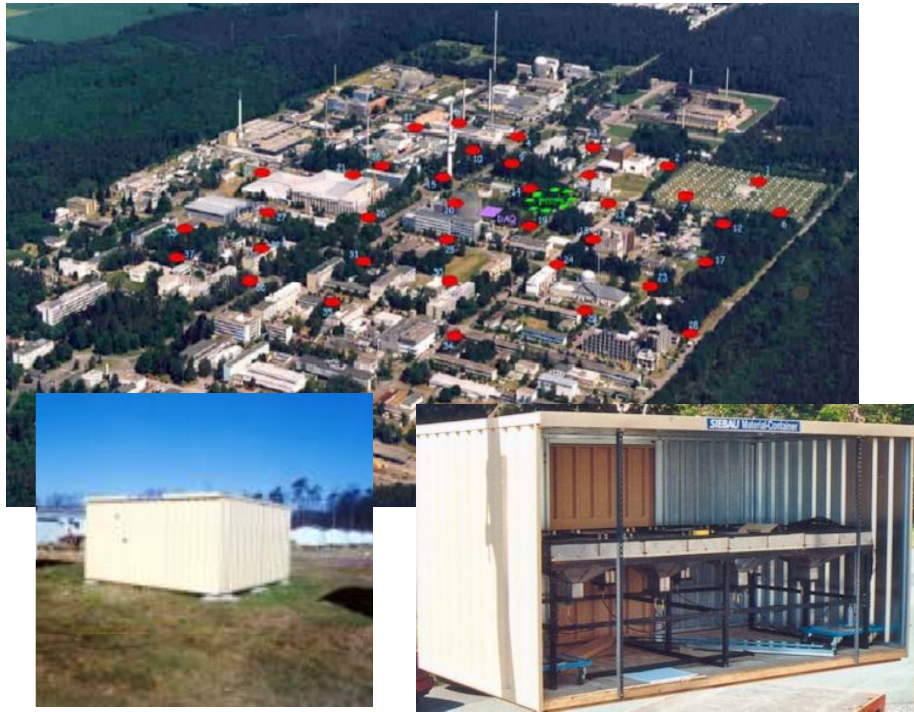
$$\frac{dJ}{d \lg N_e d \lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d \lg E} p_A(\lg N_e, \lg N_\mu^{tr} | \lg E) d \lg E$$

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25

- IUPAC Particle Dispersions Symposium
IPA 2026
 From the Upgrade to IUPAC-Gen2
 OCTOBER 5-7 • 3rd, 2026 • [iupac.org](https://www.iupac.org)
 #IUPAC2026

- Energy range: 100TeV – 1EeV
- Area: 0.5 km²
- Grande: 37×10 m² plastic scintillation detectors
- N_{ch} + total muon number

- ➔ determination of primary energy
- ➔ separation in “electron-rich” and “electron-poor” event

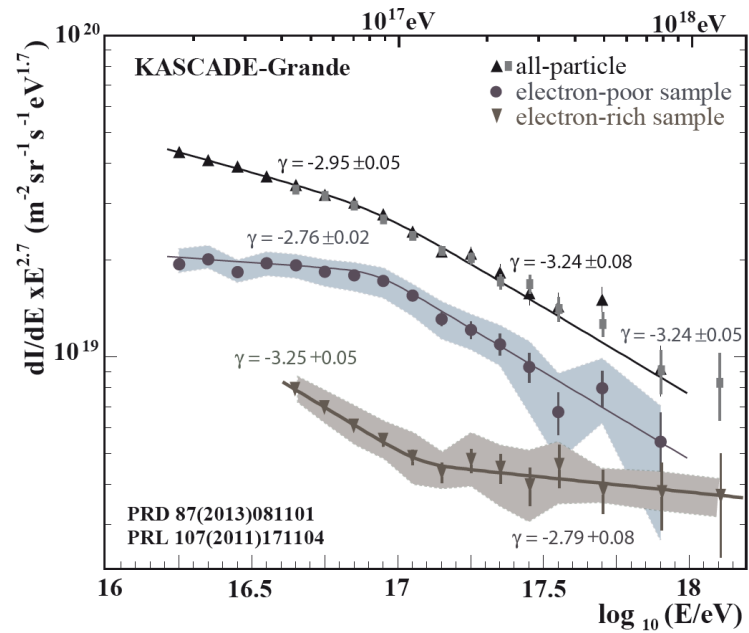


$$\log_{10}(E) = [a_p + (a_{Fe} - a_p) \cdot k] \cdot \log_{10}(N_{ch}) + b_p + (b_{Fe} - b_p) \cdot k$$

$$k = (\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_p) / (\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_p)$$

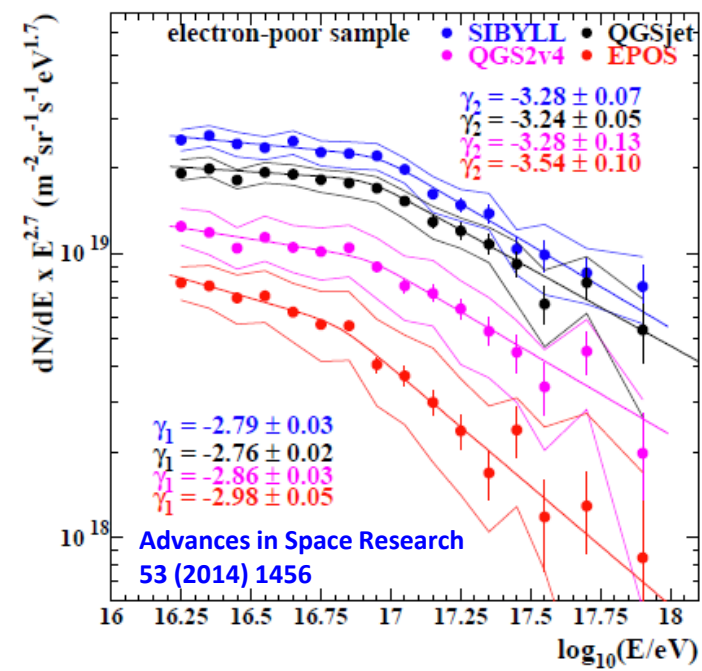
W.D.Apel et al, Nucl.Instr. and Meth. A620 (2010) 202

KASCADE-Grande: results



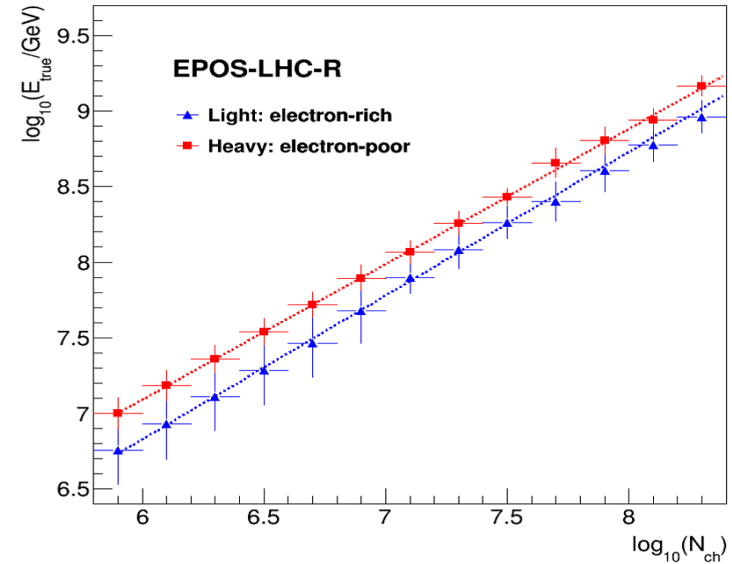
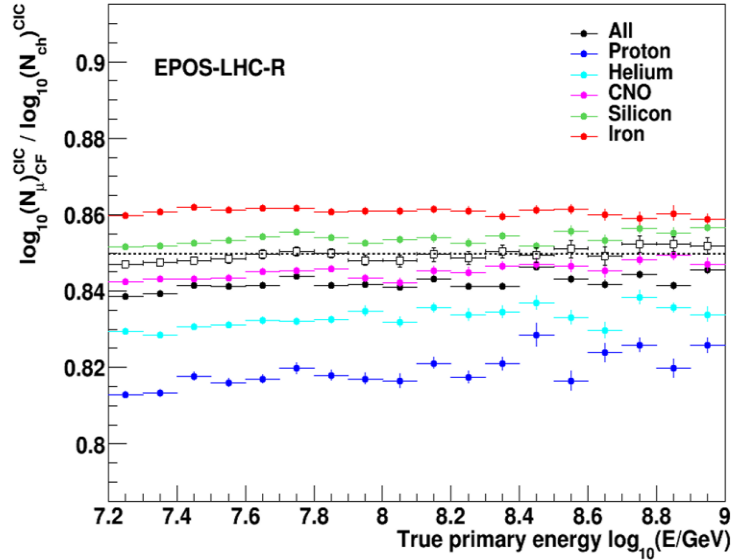
- steepening due to heavy primaries (3.5 σ)
- hardening at $10^{17.08}$ eV (5.8 σ) in light spectrum
- slope change from $\gamma = -3.25$ to $\gamma = -2.79$!

KASCADE-Grande: model dependence



- Spectra of heavy primary induced events
 - ➔ knee structure at the heavy component
 - ➔ relative abundances different for different high-energy hadronic interaction models

KASCADE-Grande: analysis method

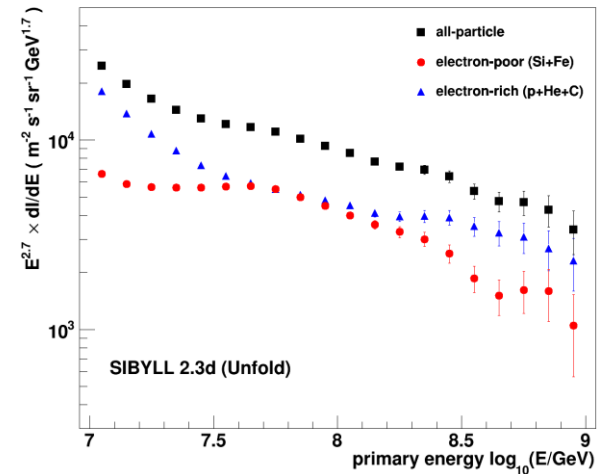
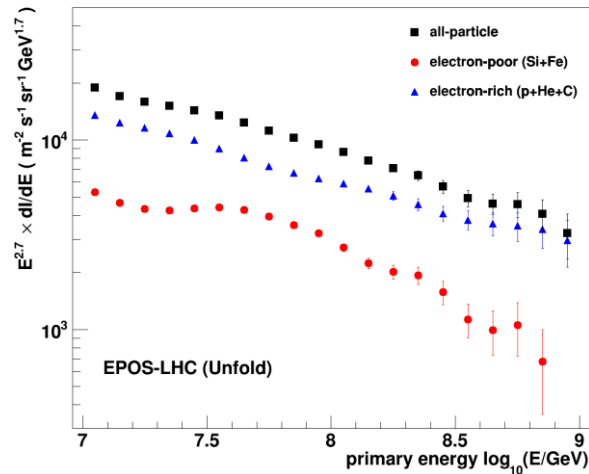
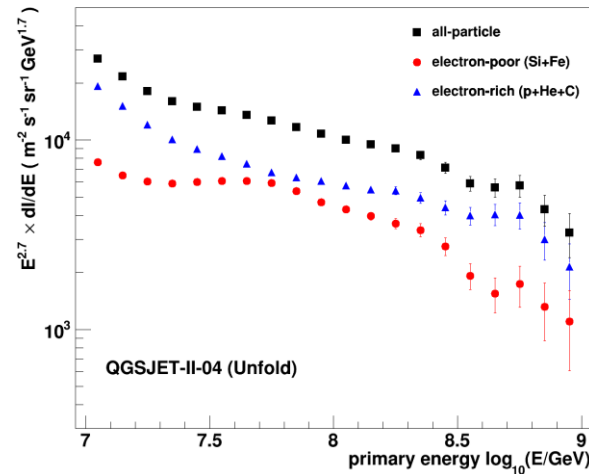


- Selection criteria separating heavy and light mass groups by attenuation correction shower size ratio:
- $y_{CIC} = \log_{10}(N_{\mu})^{CIC} / \log_{10}(N_{ch})^{CIC}$
- The y_{CIC} values are model-dependent Not corrected for shower fluctuation yet

- Energy calibration by linear fits in log-log scale for heavy (red) and light (blue) primary groups:
- $\log_{10}(E_{\text{true}}/\text{GeV}) = a \cdot \log_{10}(N_{ch}) + b$
- Unfolding as a next step

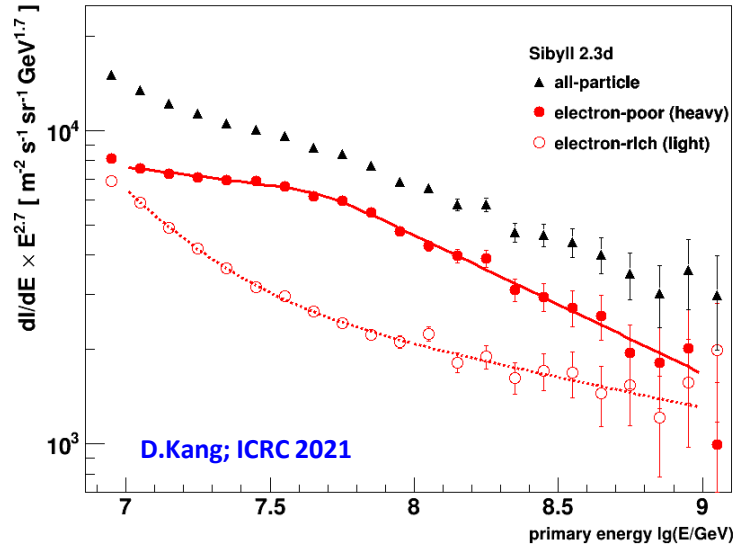
D.Kang;

Andreas Haungs
Donghua Kang



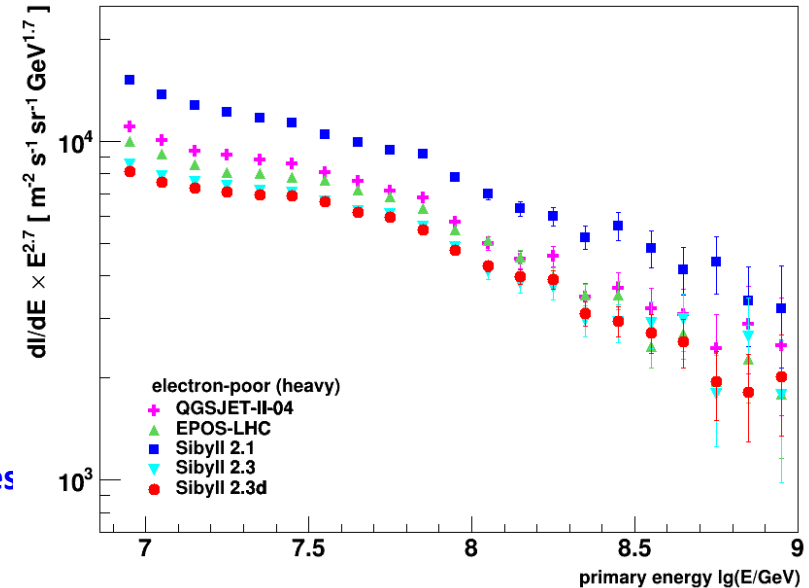
- Reconstructed energy spectra for heavy (Si+Fe) and light (p+He+CNO) primary mass groups
- Data selection by attenuation corrected shower size ratio N_{ch}/N_{μ}
- Accounted shower-to-shower fluctuation based on the Bayesian unfolding algorithm
- Knee-like structure of heavy primaries below 10^{17} eV, hardening of light primaries is significant
- Only statistical uncertainties are shown, for a discussion on systematics see PoS(ICRC2023)307

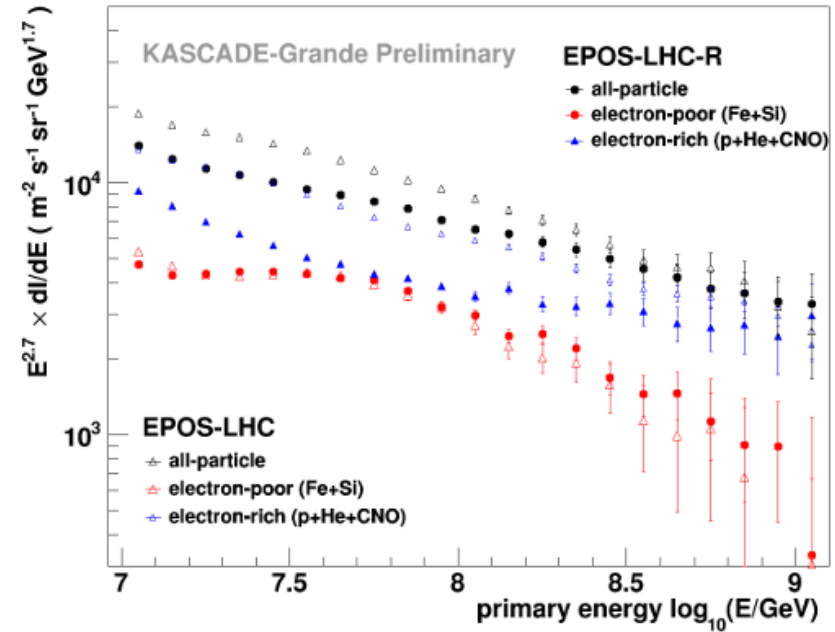
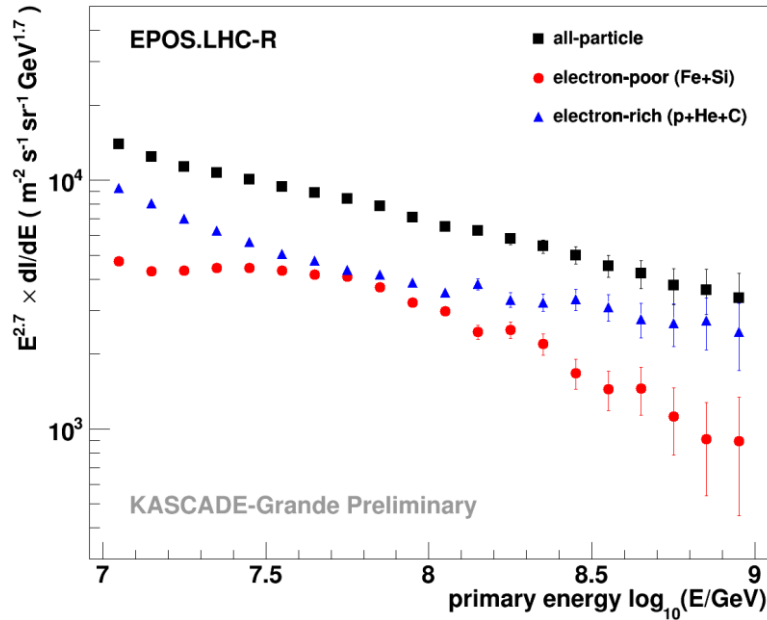
D.Kang; ICRC 2023



- SIBYLL 2.3d gives the lowest flux of heavy primaries
- The spectral slope of light primaries for SIBYLL 2.3d changes smoothly below 10^{17} eV
- Not corrected for shower fluctuation yet

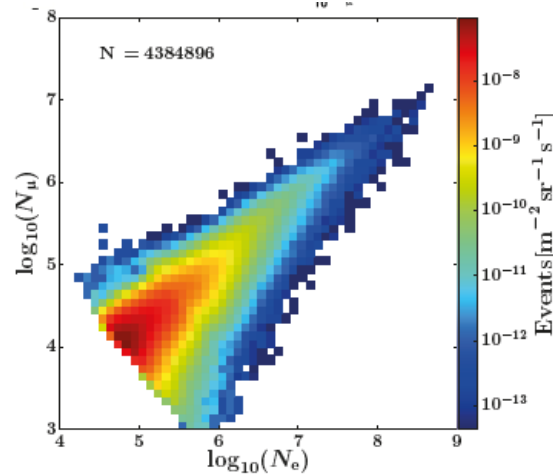
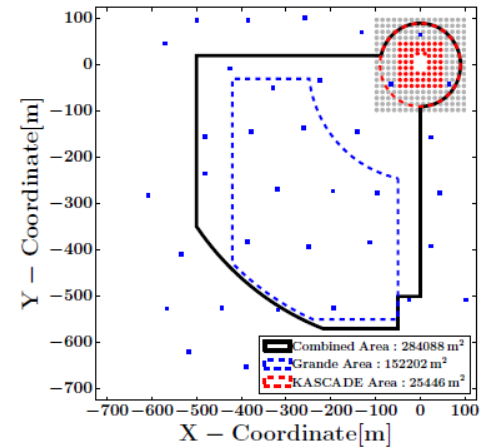
KASCADE-Grande: heavy primaries



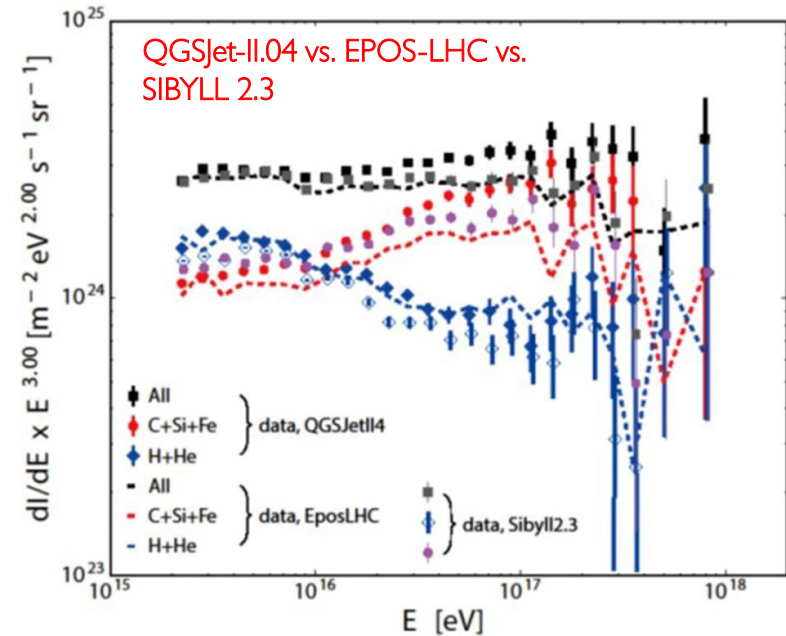


- Reconstructed energy spectra for all-particle (black), heavy (red), and light (blue) primaries, based on EPOS.LHC-R
- Shower fluctuations have not yet been corrected
- For light primaries, EPOS.LHC-R is less dominant compared to EPOS-LHC, resulting in a slightly lower all-particle spectrum for EPOS.LHC-R

KASCADE-Grande, combined analysis 2016

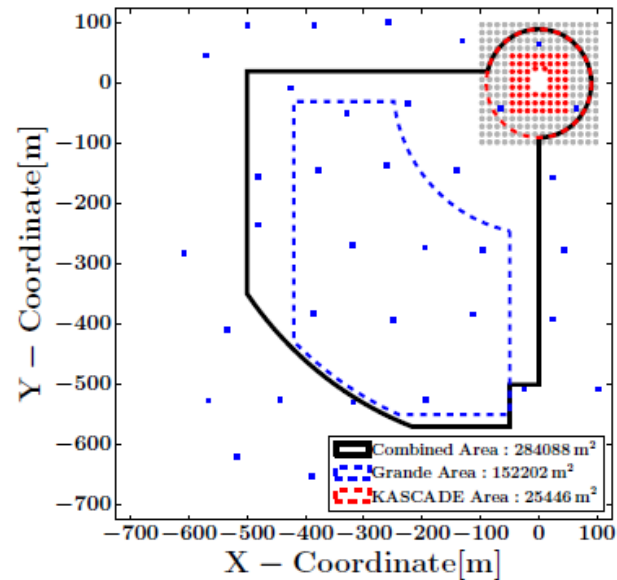
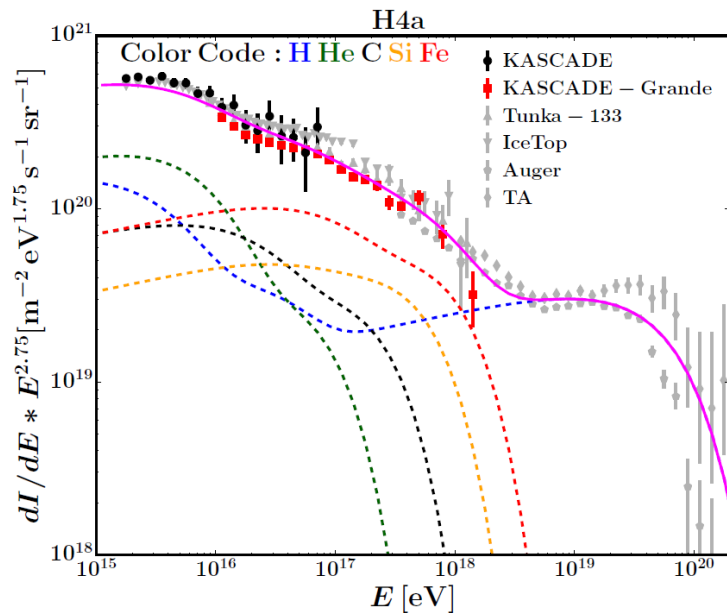


- for KASCADE: additional stations at larger distances
→ higher energies
- for Grande: additional 252 stations
→ higher accuracy

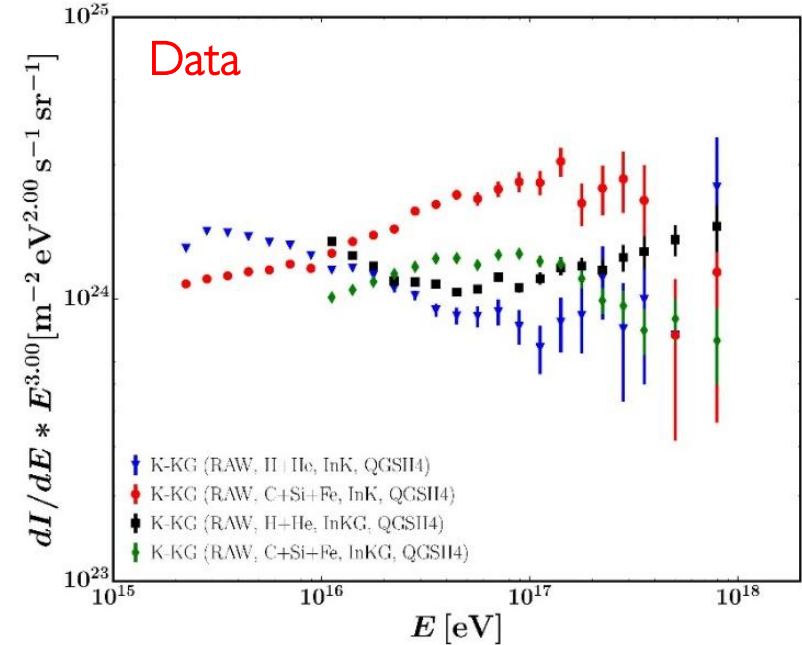
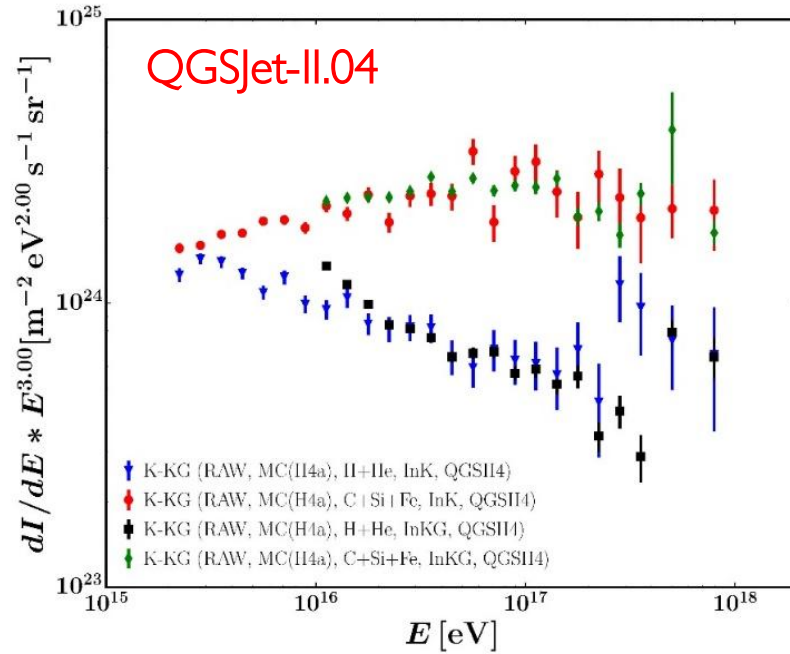


Post LHC models:
light primary interactions okay?
heavy primary interactions show differences

Sven Schoo, KIT, PhD 2016



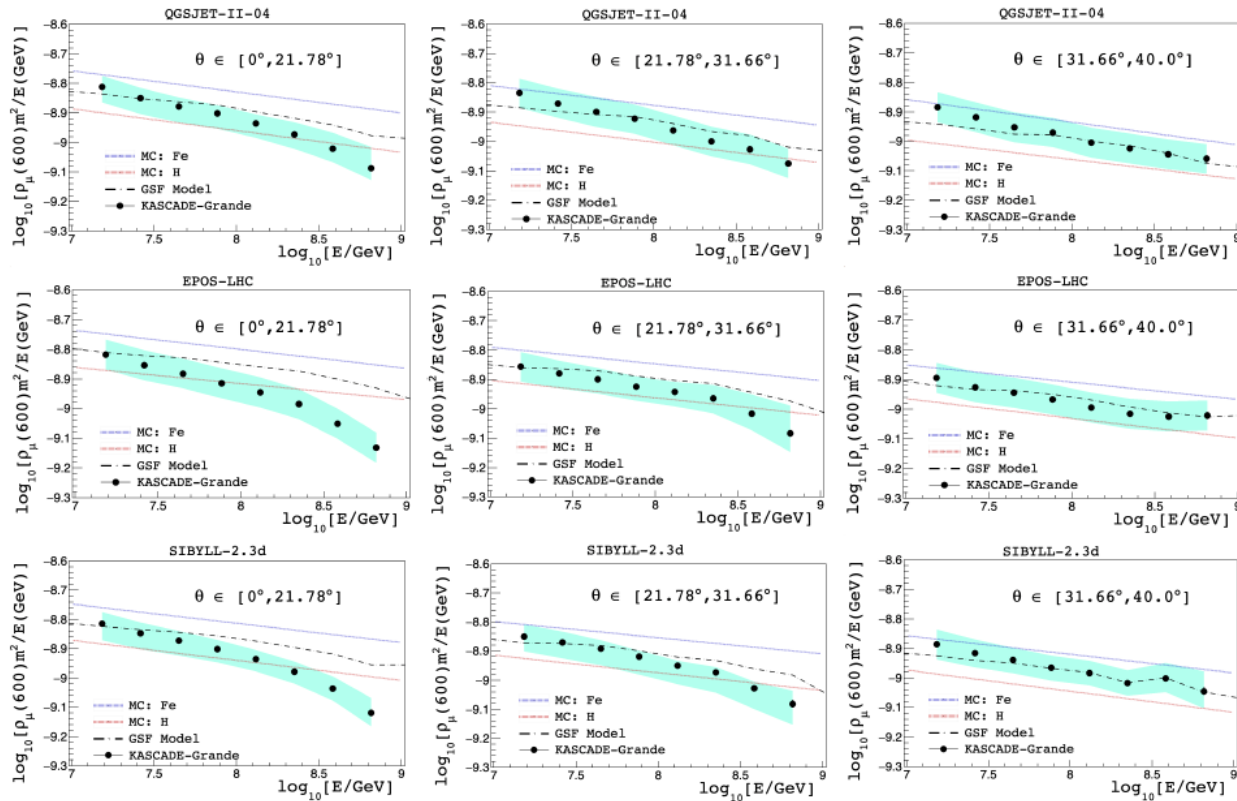
- assume a composition model: H4a by Tom Gaisser
 - two selections: core located in KASCADE, core located in Grande
- ➔ we measure “different” muons



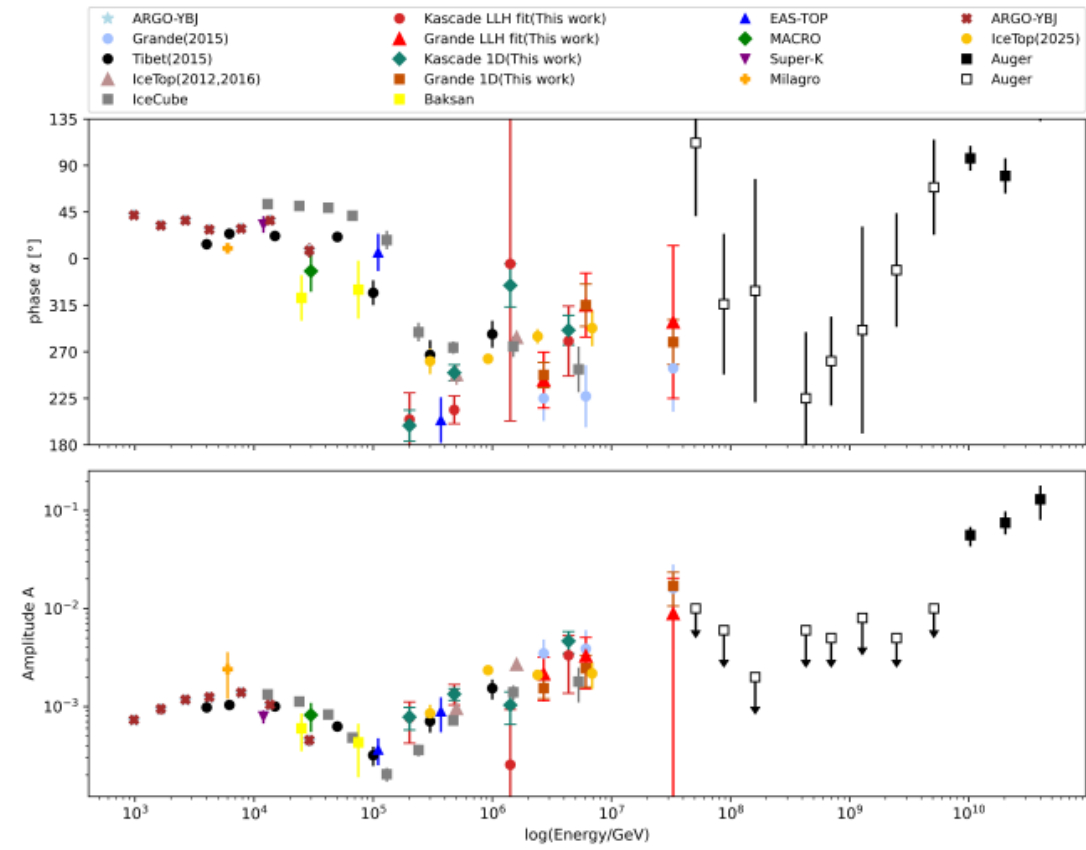
- One model, but two selections:
Simulations okay, but strong differences in data
(similar result for **QGSJet-II.04**, **EPOS-LHC**, **SIBYLL 2.3**)
➔ Muon component not sufficiently described

KASCADE-Grande and the Muon Puzzle

Data – MC – 3 models – 3 zenith ranges



- Studies the local muon density $\rho_\mu(r)$ at 600 m shower core distance
- At $10^{16} - 10^{17}$ eV, the measured muon densities are more or less compatible with the model predictions
- At higher energies, near-vertical showers show a deficit of muons in the data relative to MC
- The discrepancy becomes smaller for more inclined showers (at least at larger distances)
- ➔ Muon component not sufficiently described



- Dipole amplitude gradually increases with energy from 0.2 PeV to ~ 33 PeV
- Dipole phase evolves with energy, consistent with the phase transition near $10^{14} - 10^{15}$ eV
- Results are consistent with previous measurements
- Further work: combine KASCADE and IceTop for a full-sky analysis to better constrain systematic effects



Open Data $\neq$ Outreach

- as open data serves for community and the research field and the society
- outreach profits from open data
- KCDC is a platform for both, open data and outreach



<https://arxiv.org/pdf/1909.09222.pdf>

DRAFT VERSION SEPTEMBER 23, 2019

Preprint typeset using L^AT_EX style emulatejg v. 12/16/11

LARGE- AND MEDIUM-SCALE ANISOTROPIES IN THE ARRIVAL DIRECTIONS OF COSMIC RAYS OBSERVED WITH KASCADE-GRANDE

MARKUS AHLERS

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University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
Draft version September 23, 2019

ABSTRACT

We search for anisotropies in the arrival directions of cosmic rays observed by the KASCADE-Grande air shower experiment. The analysis is based on public data of about 23.7 million events with reconstructed primary energies above 1 PeV. We apply a novel maximum-likelihood reconstruction method for the cosmic ray anisotropy, that compensates for spurious anisotropies induced by local detector effects. We find no evidence for a large-scale dipole anisotropy in the data, consistent with official results based on the conventional East-West derivative method. On the other hand, a subset of cosmic rays with median energy of 33 PeV shows strong evidence for a medium-scale feature with an angular diameter of 40 degrees. After accounting for the look-elsewhere effect, the post-trial significance of this medium-scale feature is at the level of 4σ .

Subject headings: cosmic rays — methods: data analysis

1. INTRODUCTION

Cosmic rays (CRs) experience deflections by Galactic and extragalactic magnetic fields before their arrival on Earth. The spatial variation of these magnetic fields in strength and orientation scrambles the particles' arrival direction and time. Combined with the limited energy resolution and lifetime of CR observatories, these effects can explain the continuity of the flux of CRs and the mostly isotropic distribution of their arrival directions. However, some CR experiments have achieved the necessary level of statistics to be able to infer weak anisotropies in the arrival directions that reach per-

range from 2 PeV to 8 EeV. This observation would provide valuable data to decipher the transition between Galactic and extragalactic CR sources.

In this paper we search for anisotropies in the arrival directions of CRs observed with the KASCADE-Grande air shower experiment. The analysis is based on public data provided by the KASCADE Cosmic Ray Data Center (KCDC) (Haungs et al. 2018) and uses a novel maximum-likelihood reconstruction method introduced in Ahlers et al. (2016), that we outline in the following section. We then first study the presence of a dipole anisotropy in the data and compare our re-

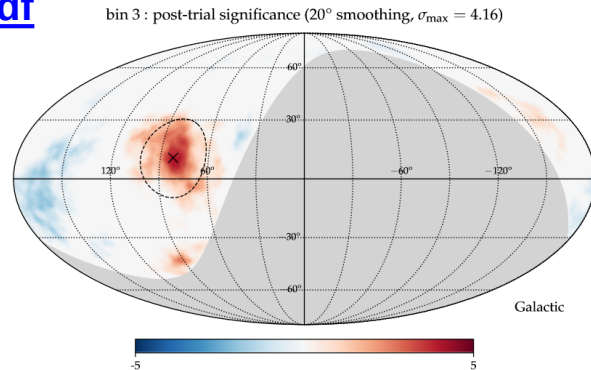


FIG. 3.— Mollweide projection in Galactic coordinates of the post-trial significance of 20° smoothed anisotropies at 33 PeV (bin 3). We use a trial factor $N_{\text{trials}} \simeq 14$ in Eq. (12) and show units of Gaussian standard deviations. We indicate the location of the maximum significance by the symbol $\times$ and the 20° smoothing radius by a dashed line.

ACKNOWLEDGEMENTS

I would like to thank the KASCADE-Grande Collaboration for sharing their data via KCDC. In particular, I would like to thank Andrea Chiavassa, Ralph Engel, Andreas Haungs, Donghwa Kang, Dmitriy Kostunin, Markus Roth and Jürgen Wochele for their feedback on KASCADE-Grande data and previous anisotropy analyses. This work was supported by VILLUM FONDEN under project no. 18994.

Conclusions – open points

- **Light and heavy knee established**
- **Light ankle most probably there**
- **Difficult to compare experiments due to different observables (help by radio experiments?)**
- **Yet no conclusive result due to insufficient hadronic interaction models**
- **Continuation in improving hadronic interaction models required**
- **Still problem: absolute mass scale**
- **Confrontation of the data with astrophysical models still challenging**
- **Future: (mass dependent) Anisotropy studies**
- **Future: Galactic Multi-Messenger Analyses (cosmic rays, g-rays, neutrinos)**
- **IceCube(-Gen2), TAIGA, LHAASO, GRAPES, TALE, Auger, NEVOD, HAWC, SWGO**
- **Global Data Centre for Astroparticle Physics**
- **Cross-experimental co-operation needed for Cosmic-Ray Physics in the Transition Region**



The Experiment Ended. The Science Continues. Thank you!



AI-generated; prompted by Donghwa