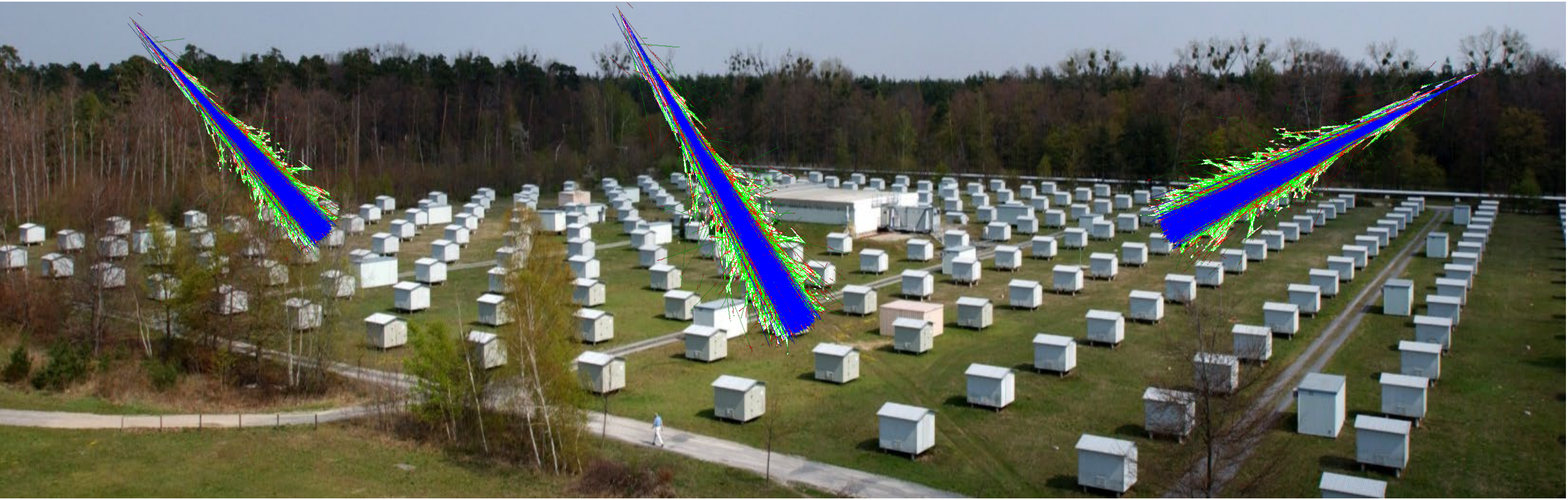
KASCADE-Grande results and its connection to the validity of hadronic interaction models

Workshop on tuning of hadronic interaction models

22-25 January 2024, Andreas Haungs, Institute for Astroparticle Physics

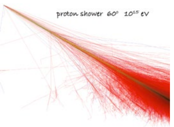


KASCADE-Grande Timeline

- 60 collaborative papers in reviewed journals (2-3 still in queue, short author list papers not included)
- 56 PhD thesis
- 86 diploma/master thesis

1989 Proposal

CORSIKA



1996

KASCADE

model tests

light knee

2000

KASCADE-Grande

γ limit

(an)isotropy

2004

LOPES

proof-of-principle radio detection

muon production height

Cosmic Revelation

2008

Karlsruhe Air Shower Test Facility

heavy knee

light ankle

CROME

2012

EAS GHz emission

KCDC

Xmax by radio

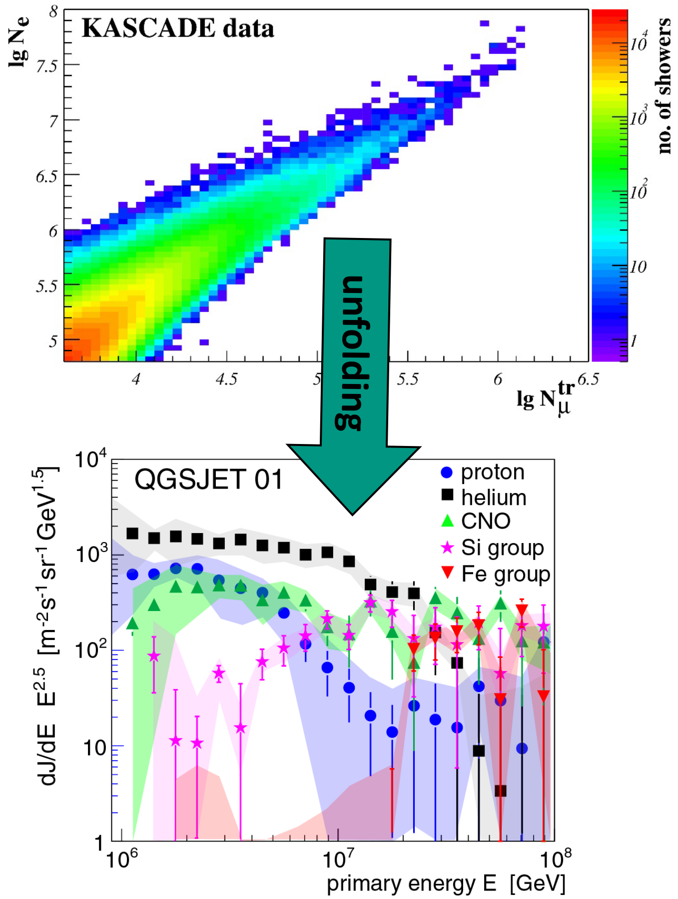
2016

KArlsruhe Shower Core and Array DEtector

- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables: electrons, muons@4 thresholds, hadrons

T.Antoni et al.
NIM A513
(2003) 490

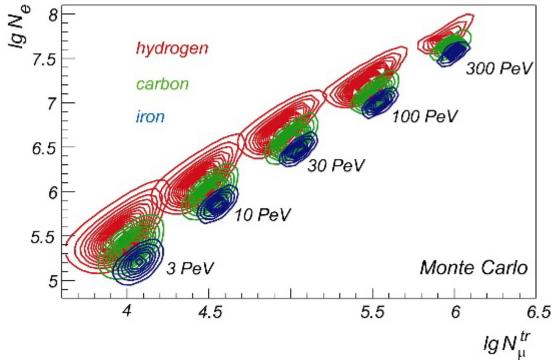
KASCADE: energy spectra of single mass groups



Searched: E and A of the Cosmic Ray Particles

Given: N_e and N_μ for each single event

➔ solve the inverse problem



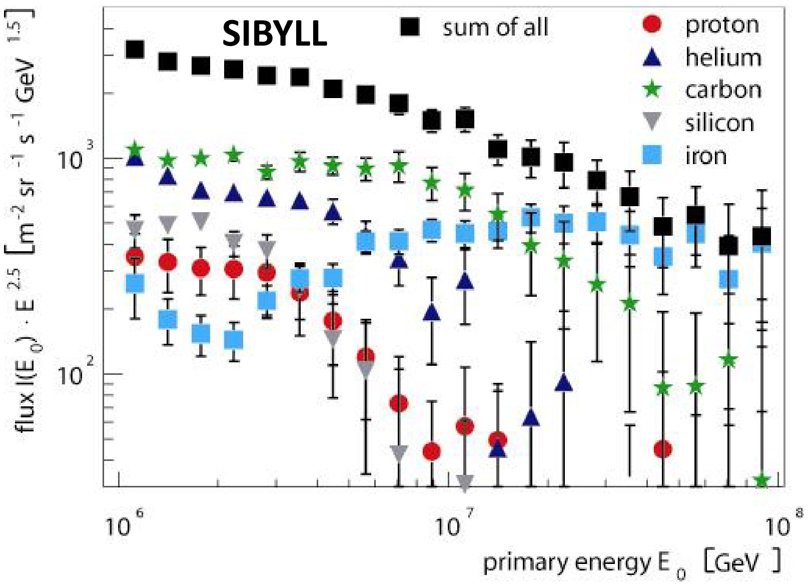
- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

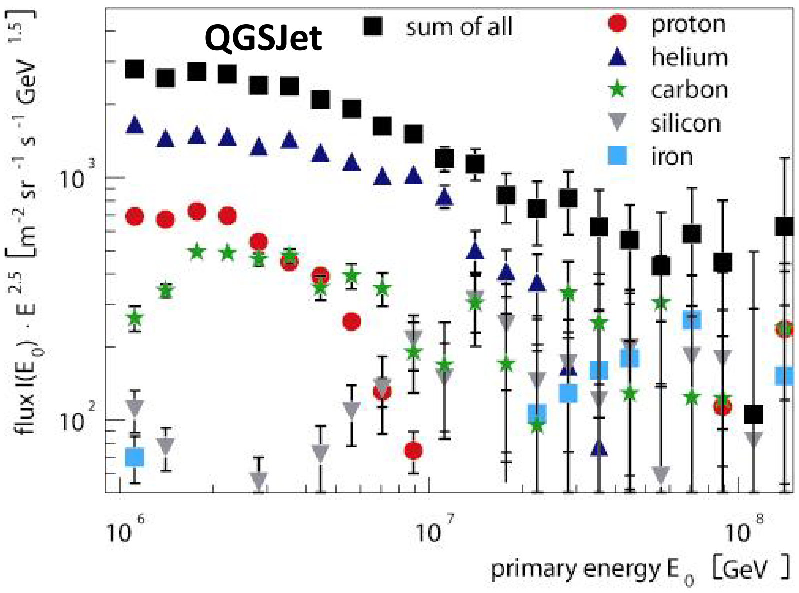
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

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

KASCADE: the rigidity knee

- same unfolding but based on different hadronic interaction models embedded in CORSIKA



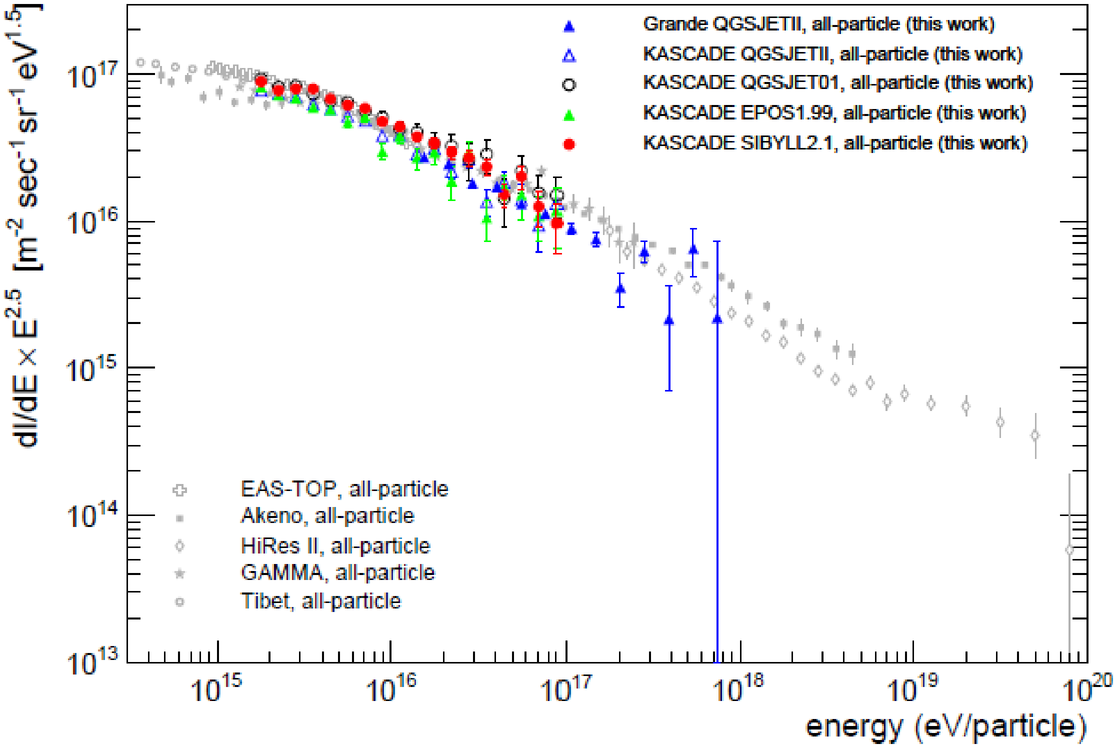


- all-particle spectrum similar
- general structure similar: knee by light component
-relative abundances very different for different high-energy hadronic interaction models

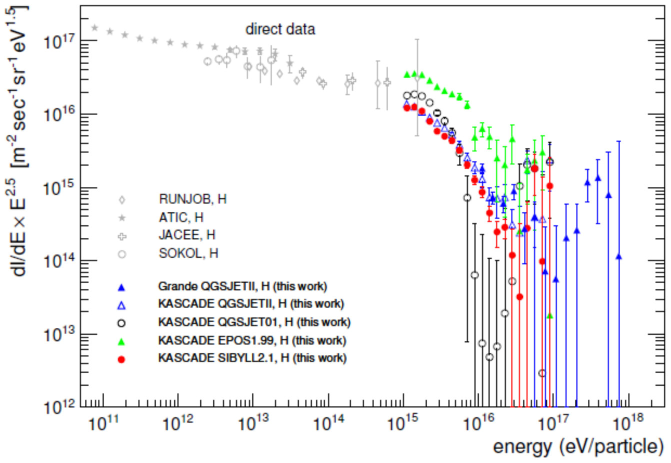
but for many models: proton not the most dominant component!

KASCADE collaboration, Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

…spectrum, composition, and test of hadronic interaction models



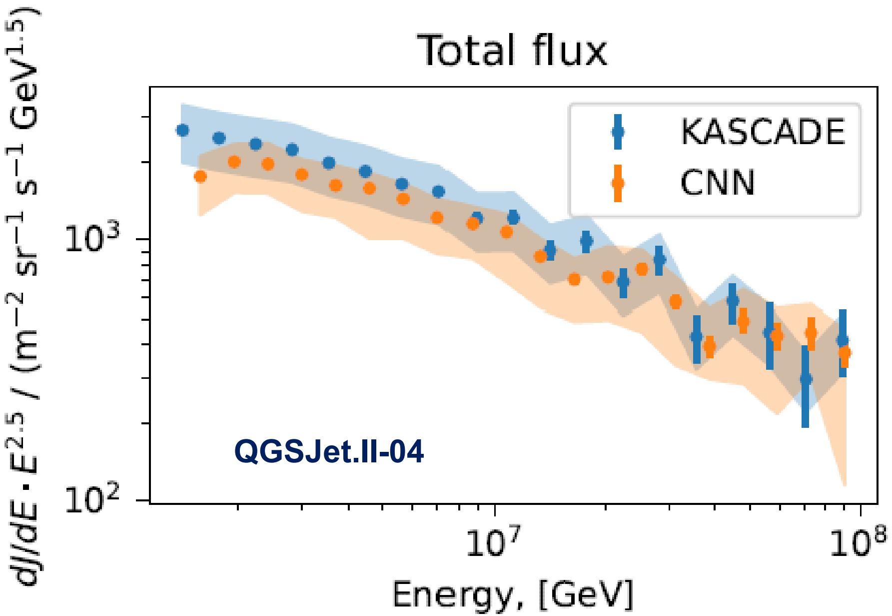
- Differences in (post-LHC?) hadronic interaction models down to PeV

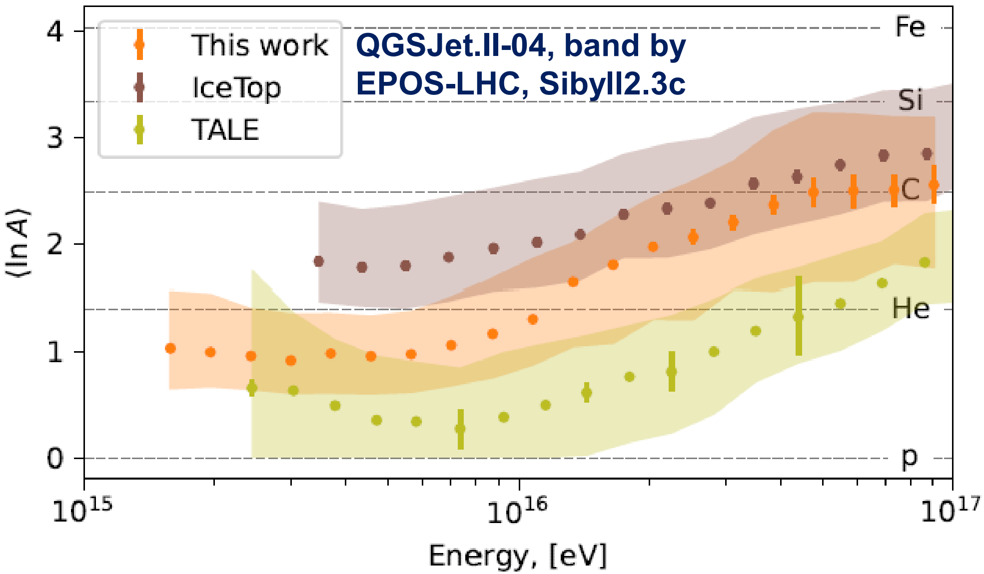


Marcel Finger (2011) , PhD Thesis KIT, thesis

KASCADE: further studies

…use of public data (KCDC)



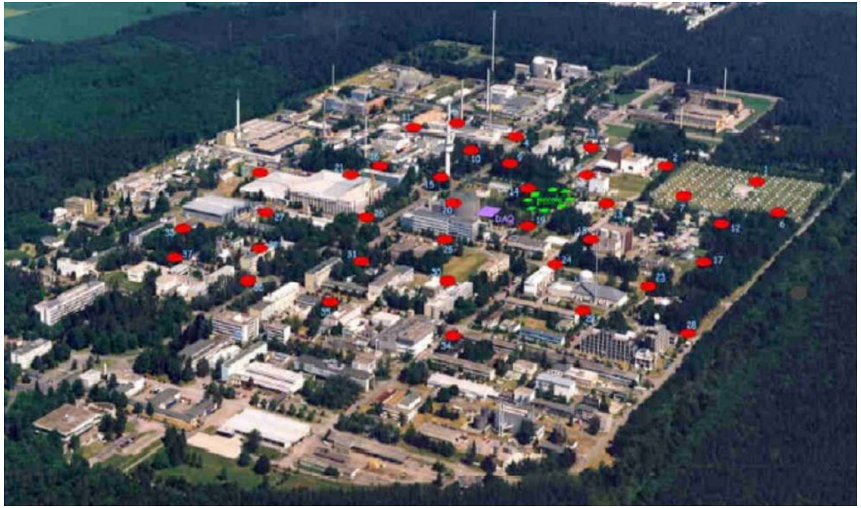


- Used CNN applied to public KASCADE data (KCDC) to obtain spectrum and composition

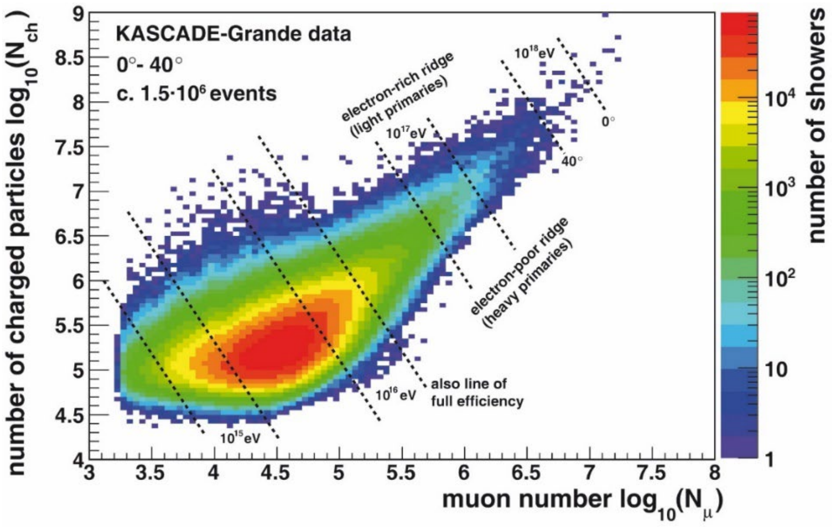
M.Yu. Kuznetsov et al, arXiv 2311.06893 & 2312.08279

KASCADE-Grande

- Energy range: 100TeV – 1EeV
- Area: 0.5 km^2
- Grande: 37×10 m^2 plastic scintillation detectors
- Nch + total muon number



→ determination of primary energy
→ separation in "electron-rich" and "electron-poor" event



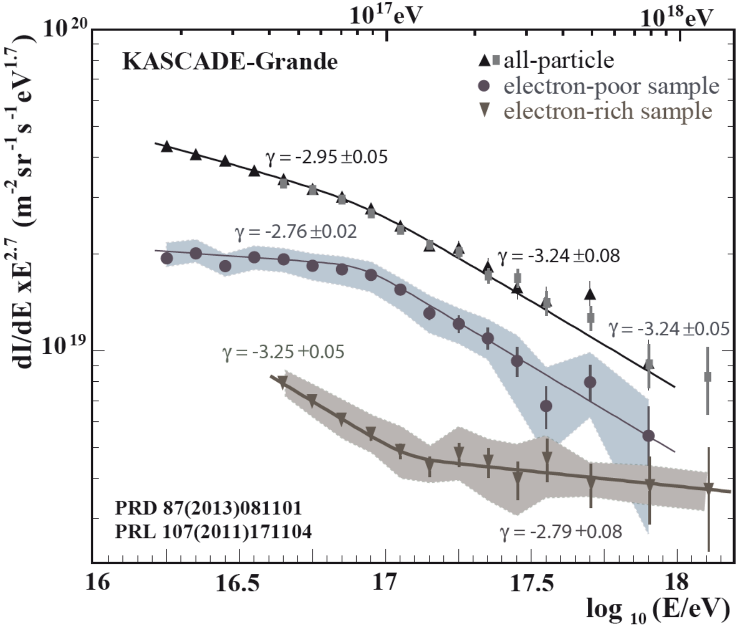
$$\log_{10}(E) = [a_p + (a_{Fe}-a_p)\cdot k] \cdot\log_{10}(N_{ch}) + b_p + (b_{Fe}-b_p)\cdot k$$

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$

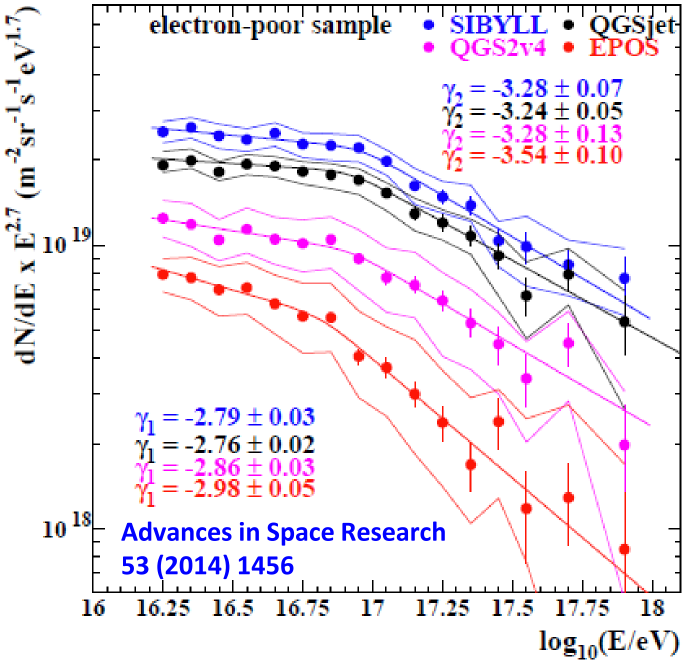
W.D.Apel et al, Nucl.Instr. and Meth. A620 (2010) 202

KASCADE-Grande Results

KASCADE-Grande: results



KASCADE-Grande: model dependence



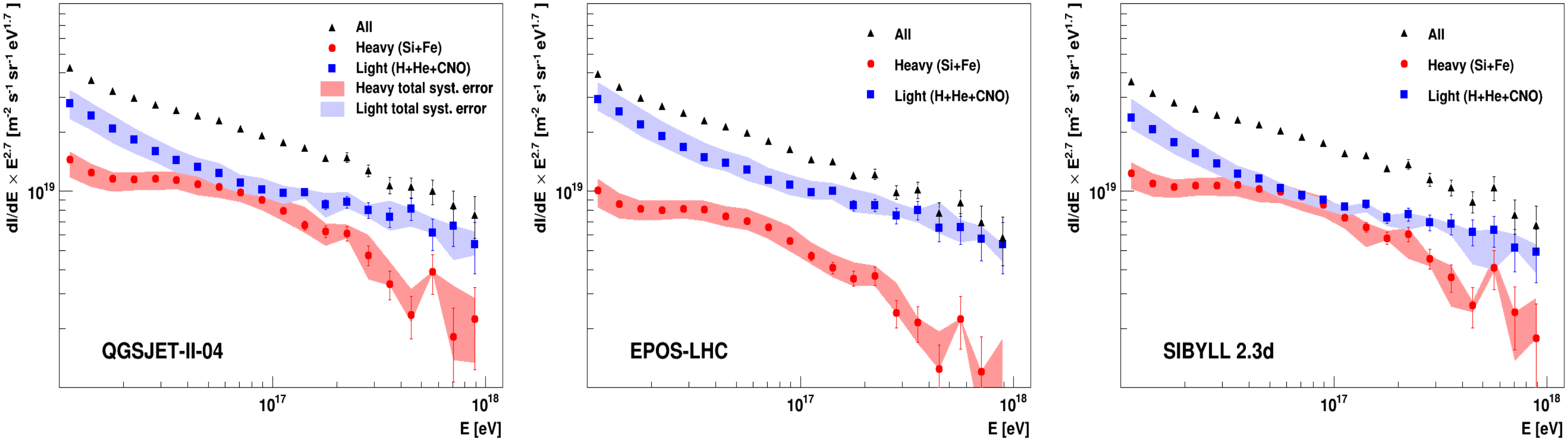
- steepening due to heavy primaries (3.5σ)
- hardening at $10^{17.08}$ eV (5.8σ) in light spectrum
- slope change from γ = -3.25 to γ = -2.79!

- Spectra of heavy primary induced events

➔ knee structure at the heavy component

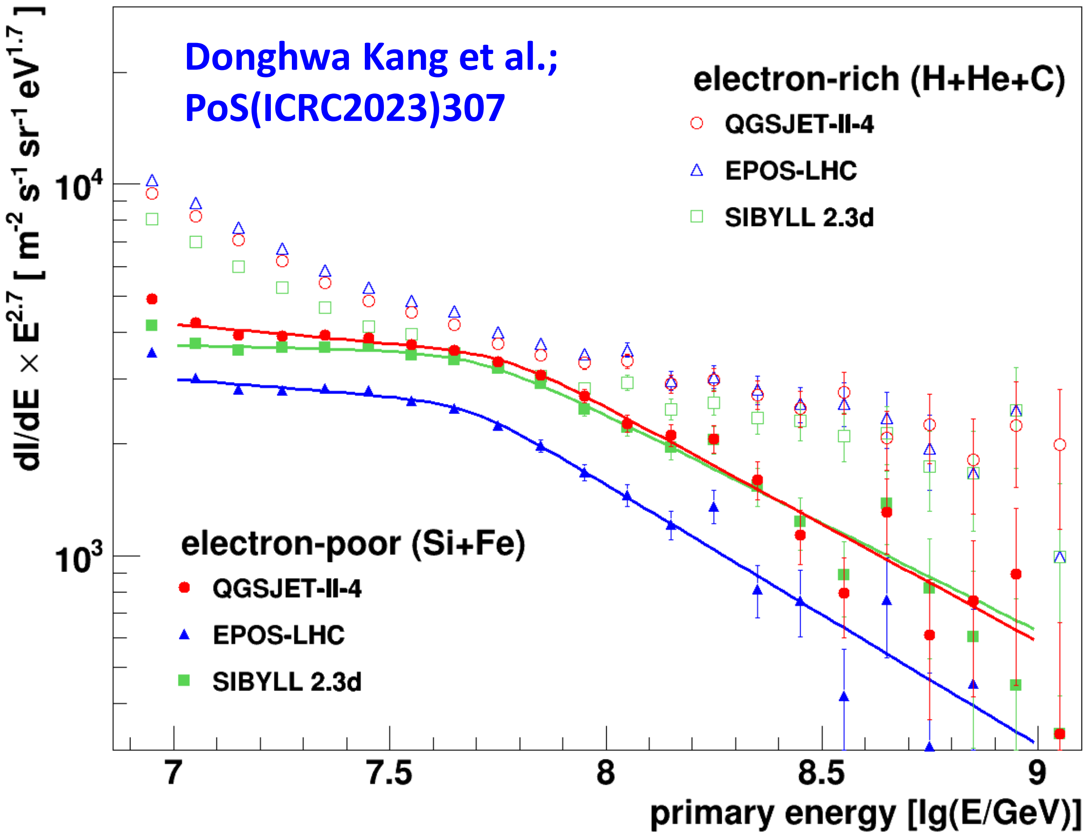
➔ relative abundances different for different high-energy hadronic interaction models

KASCADE-Grande Results: new model versions



Donghwa Kang; ICRC 2021, ISVHECRI 2022, COSPAR 2022, ICRC 2023

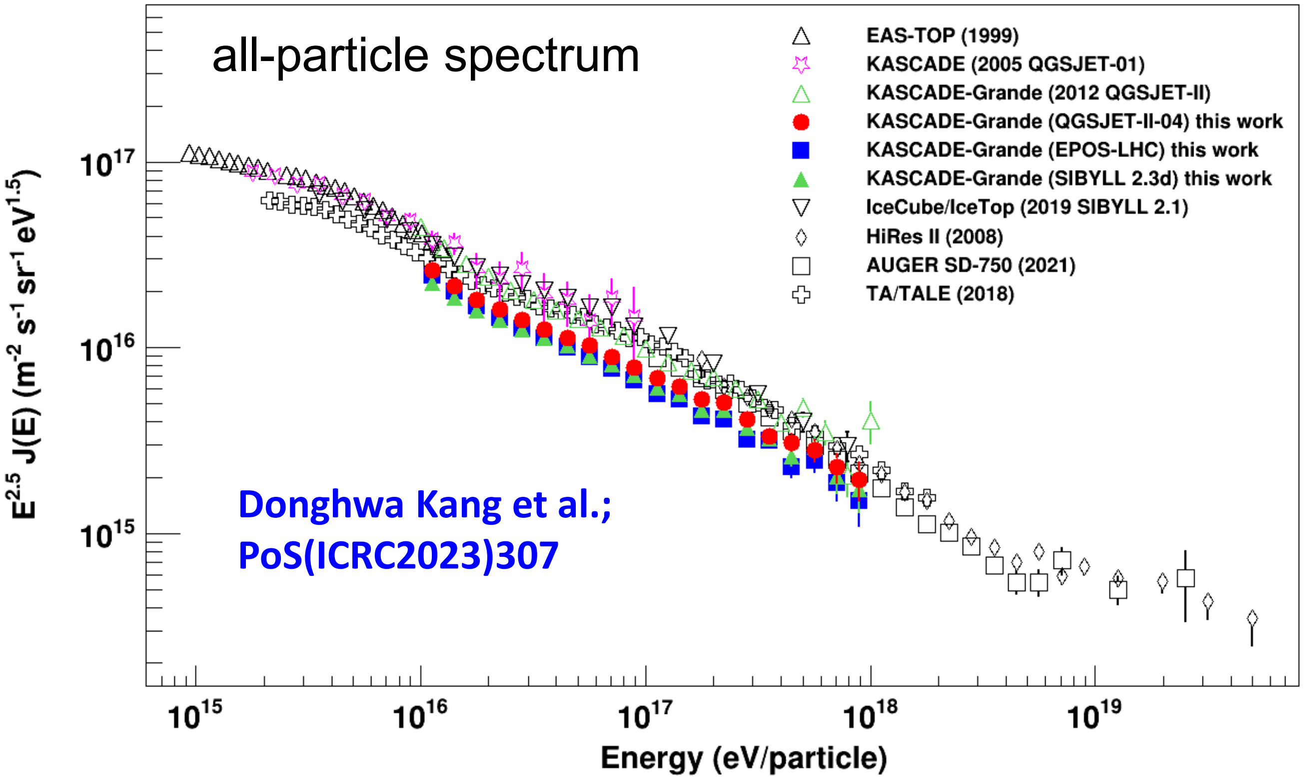
KASCADE-Grande Results: new model versions



- Knee-like structure of heavy primaries are similar
- EPOS-LHC gives the lowest flux of heavy primaries of all models due to the different ratio of N_{ch}/N_{μ}
- The light sample is always more abundant due to the separation around the CNO mass group
- Hardening of light primaries are similar for all models

*EPOS-LHC model predicts more muons than the other post-LHC models ➔ the data interpretation leads to a more light composition

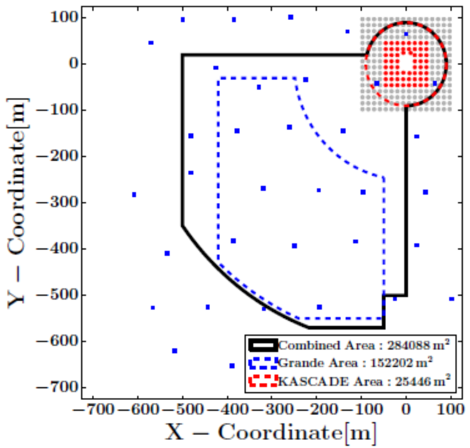
KASCADE-Grande Results: new model versions

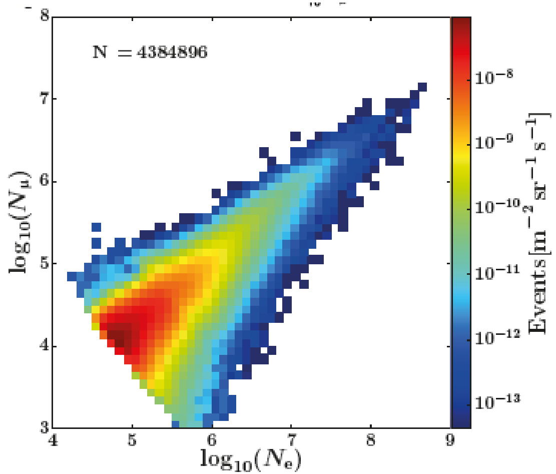


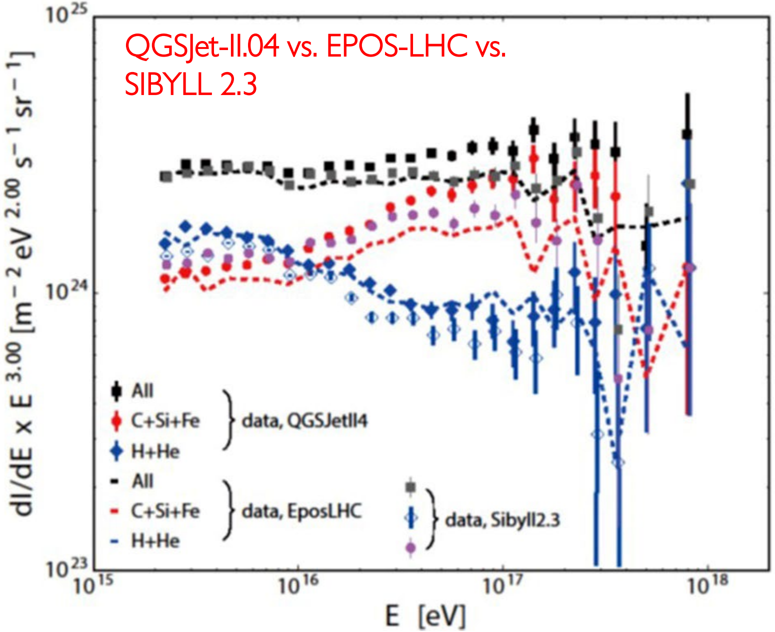
Donghwa Kang et al.; PoS(ICRC2023)307

- Small difference among the post-LHC models for KASCADE-Grande
- In terms of the absolute flux, there is an up to 20% lower flux compared to the other measurements
- Due to the measurements close to sea level?

KASCADE-Grande, combined analysis





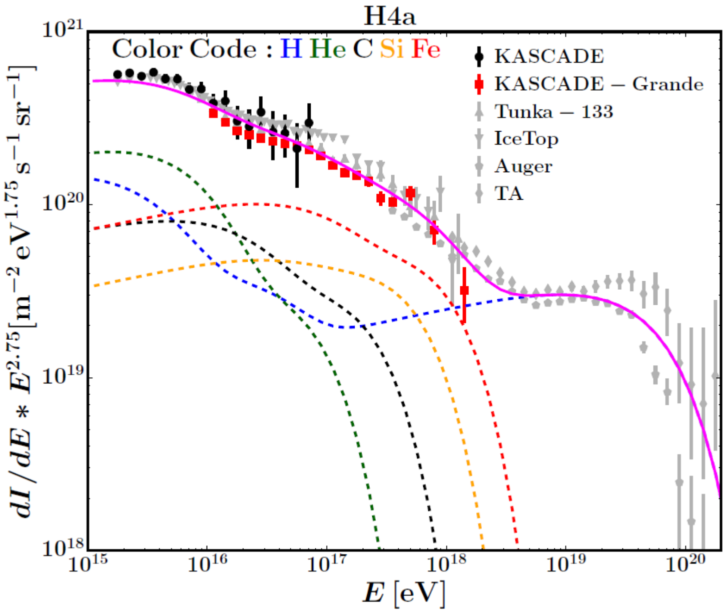


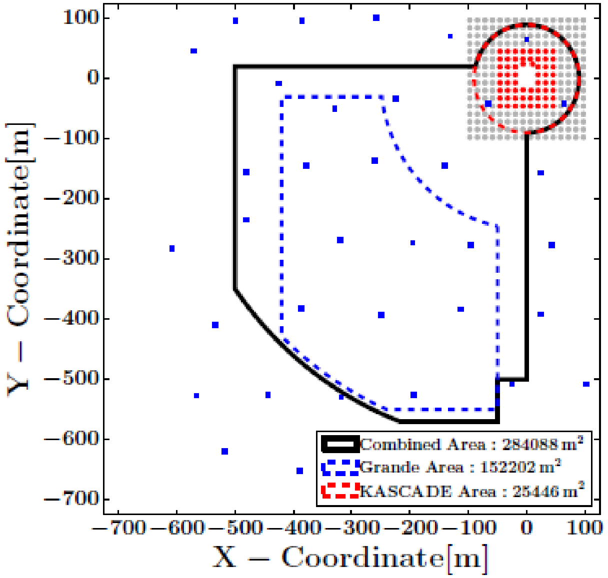
- **for KASCADE: additional stations at larger distances**
  ➔ **higher energies**
- **for Grande: additional 252 stations**
  ➔ **higher accuracy**

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

Sven Schoo, KIT, PhD 2016

KASCADE-Grande, hadronic interaction model test

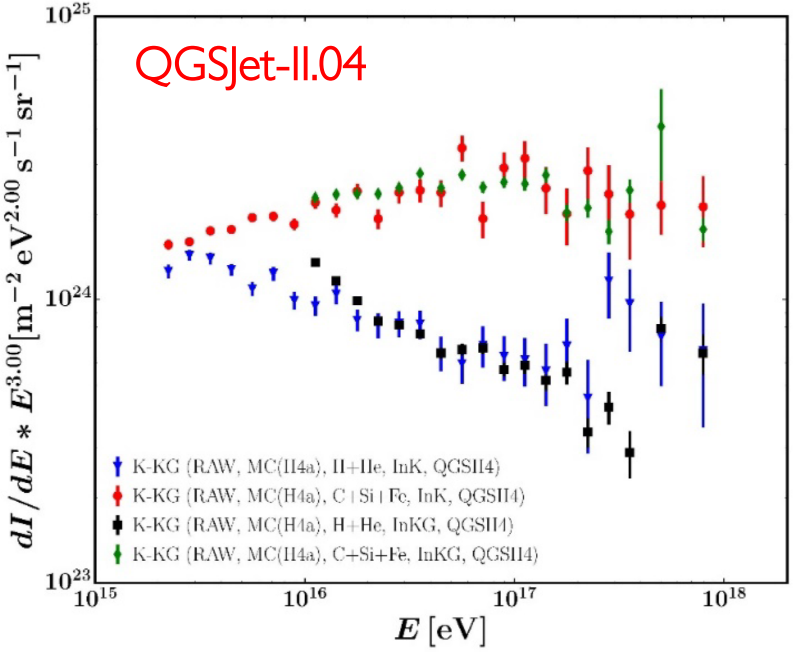


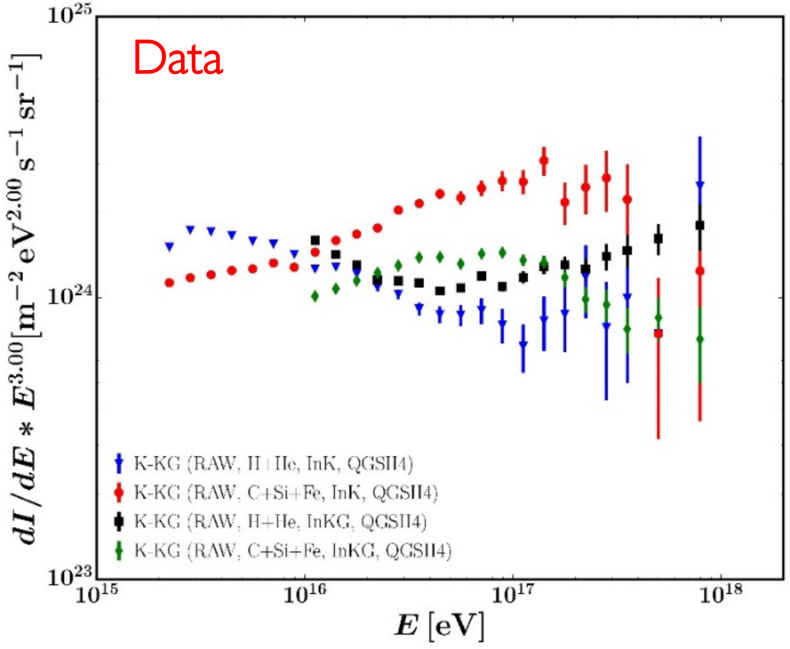


- assume a composition model: H4a by Tom Gaisser
- two selections: core located in KASCADE, core located in Grande
  ➔ we measure "different" muons

Sven Schoo, KIT, PhD 2016

KASCADE-Grande, hadronic interaction model test



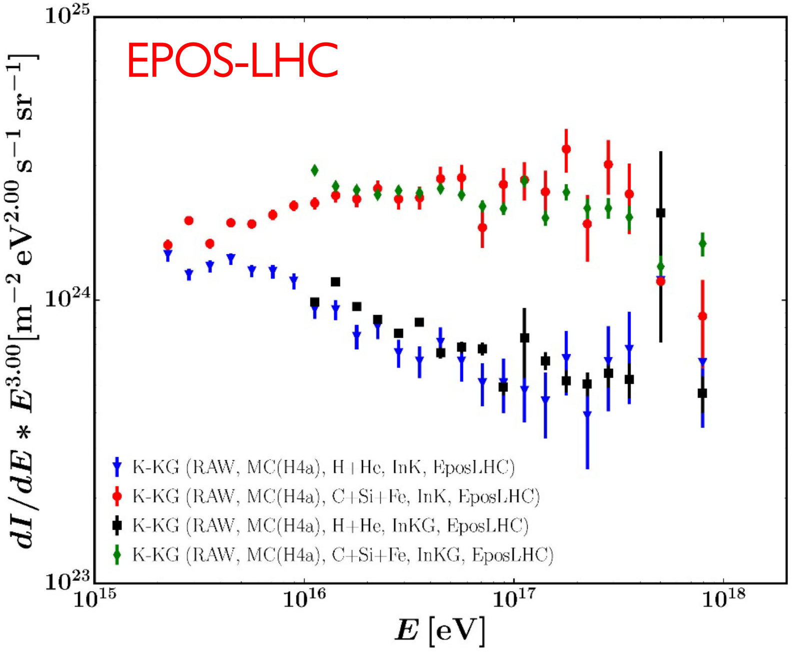


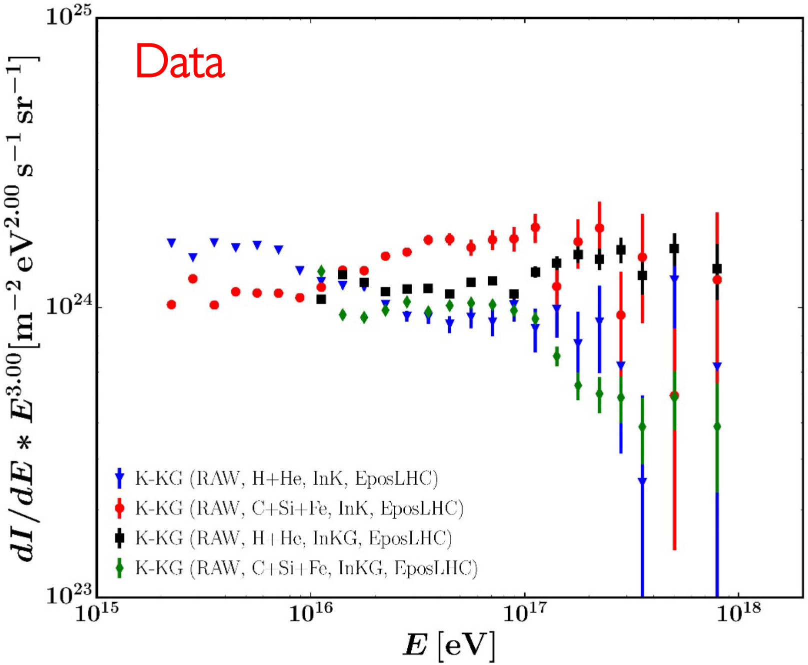
- **One model, but two selections:**
  Simulations okay, but strong differences in data
  (similar result for QGSJet-II.04, EPOS-LHC, SIBYLL 2.3)

➔ Muon component not sufficiently described

Sven Schoo, KIT, PhD 2016

KASCADE-Grande, hadronic interaction model test



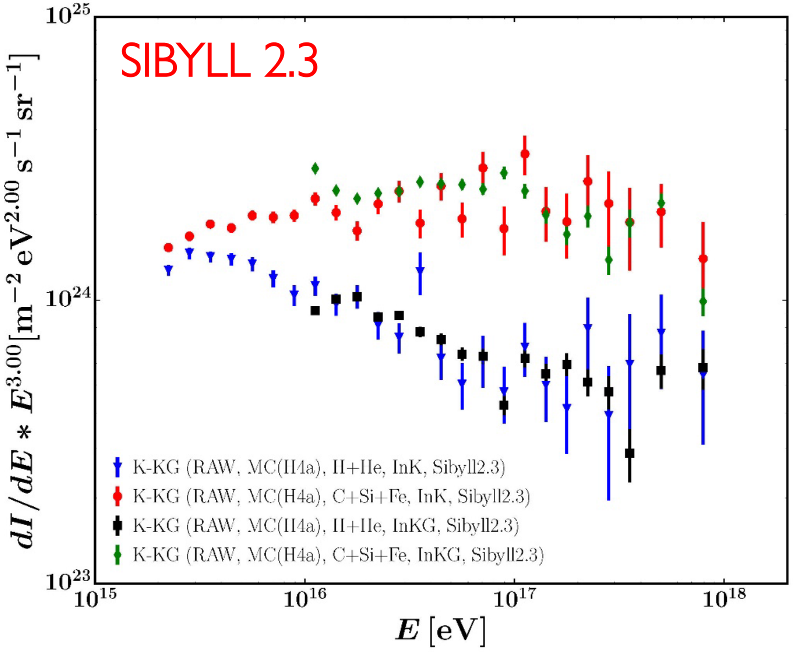


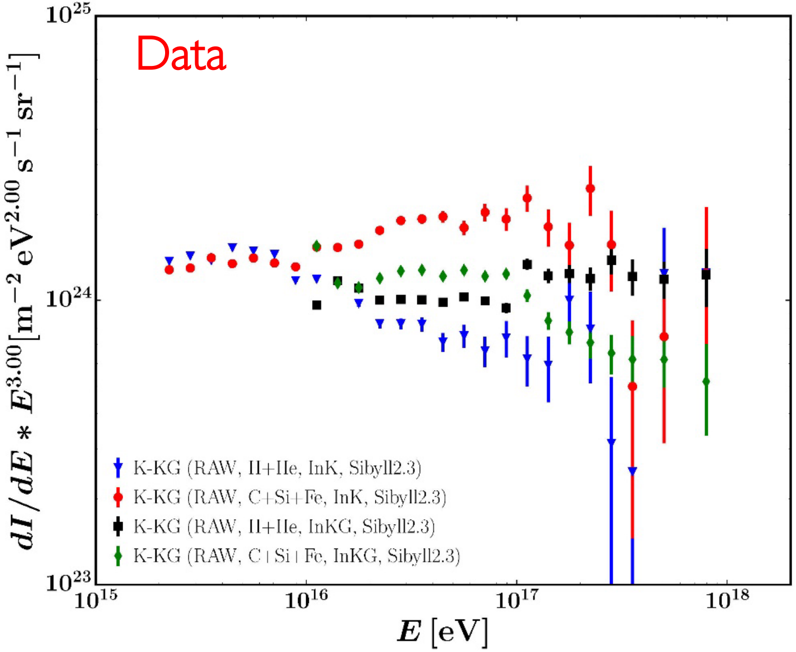
- **One model, but two selections:**
  Simulations okay, but strong differences in data
  (similar result for QGSJet-II.04, EPOS-LHC, SIBYLL 2.3)

➔ Muon component not sufficiently described

Sven Schoo, KIT, PhD 2016

KASCADE-Grande, hadronic interaction model test





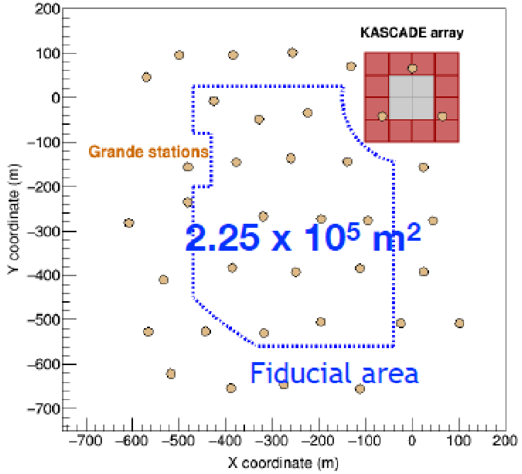
- **One model, but two selections:**
  Simulations okay, but strong differences in data
  (similar result for QGSJet-II.04, EPOS-LHC, SIBYLL 2.3)

➔ **Muon component not sufficiently described**

Sven Schoo, KIT, PhD 2016

KASCADE-Grande and the Muon Puzzle (also for WHISP)

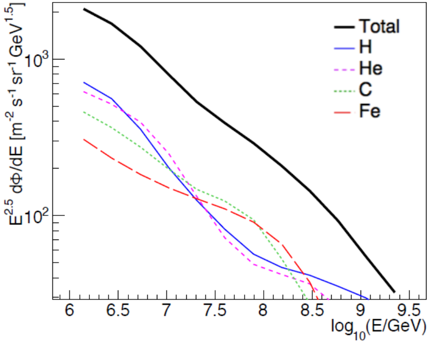
J.C. Arteaga; ICRC 2021. ICRC 2023



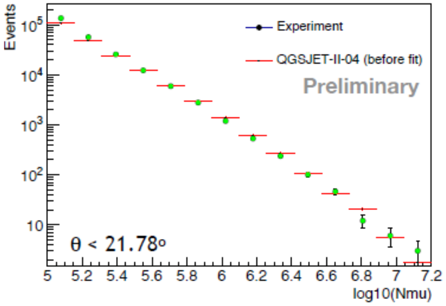
Reference cosmic ray composition model:

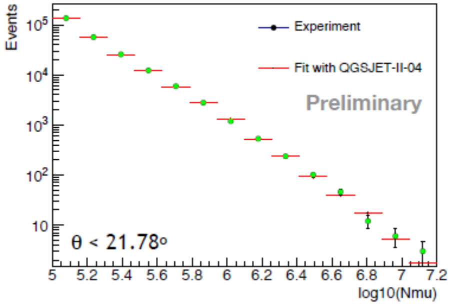
- Obtained by re-weighting all MC simulations.
- All-particle energy spectrum and composition adopted from GSF model [Dembinski et al., PoS (ICRC2017) 533].
- Primary mass groups: H, He, C and Fe.
- GSF model using Auger energy scale

$E^{Auger}/E^{GSF} = 0.87$

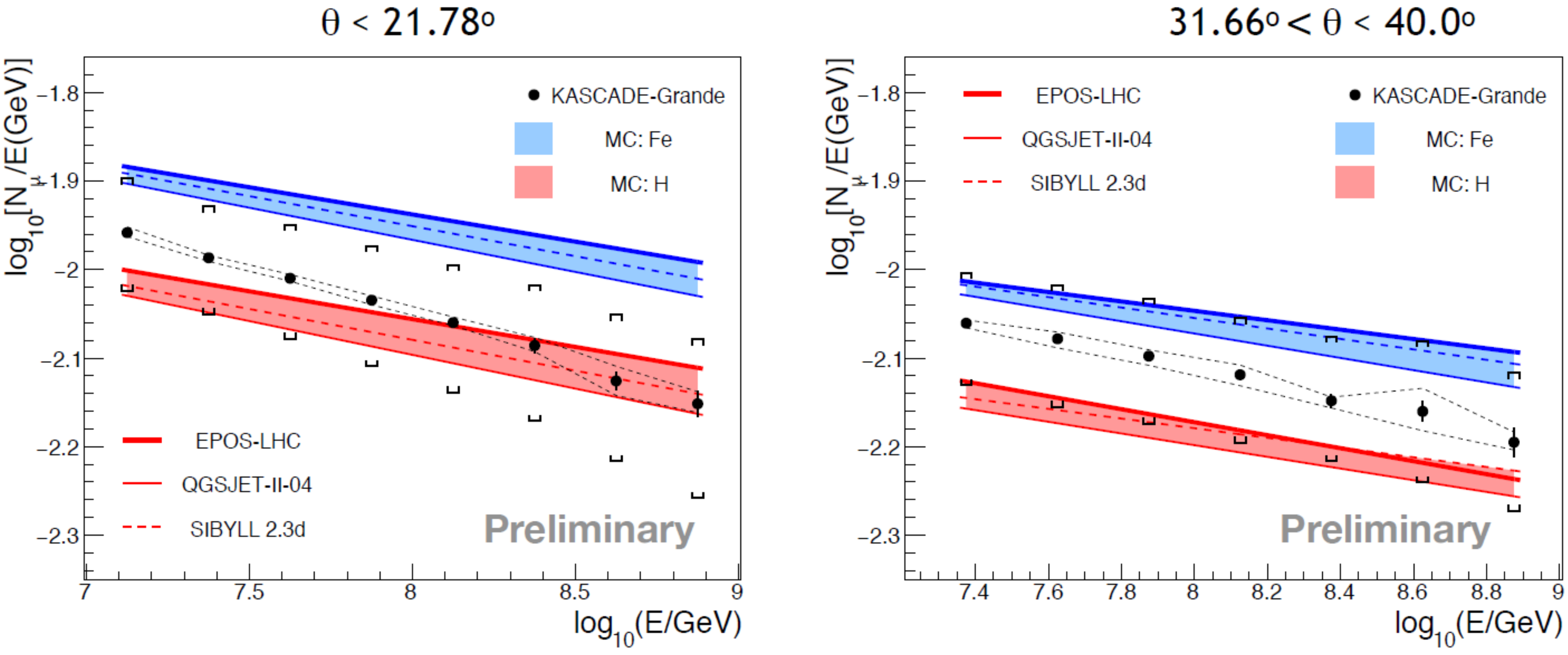


- **Measure $N_\mu(E)$ from 10 PeV to 1 EeV for zenith angles θ < 40º**
- **Re-weight MC simulations to the GSF composition model (shift δ_μ)**
- **Use for GSF model the Pierre Auger energy scale**
- **Determine systematic uncertainties (δ_μ, composition, ldf of muons, energy scaling, muon correction function)**





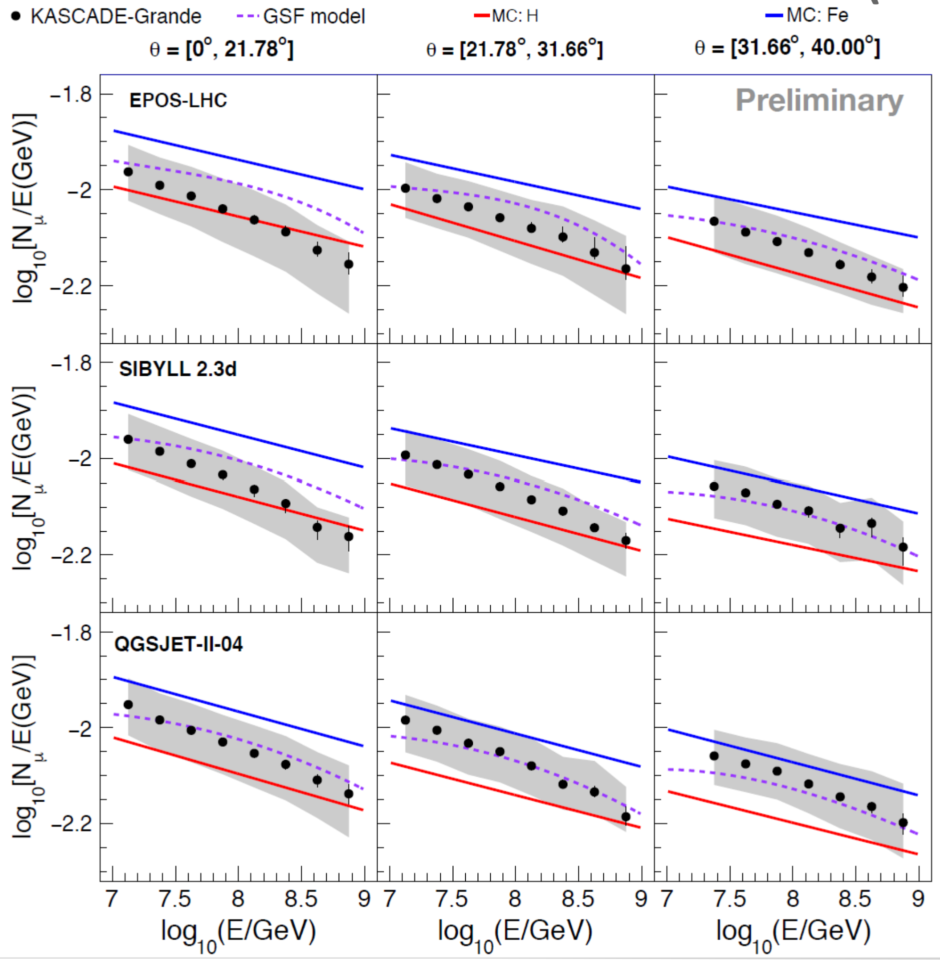
KASCADE-Grande and the Muon Puzzle (WHISP)



Hadronic models

J.C. Arteaga; ICRC 2021

KASCADE-Grande and the Muon Puzzle (WHISP)

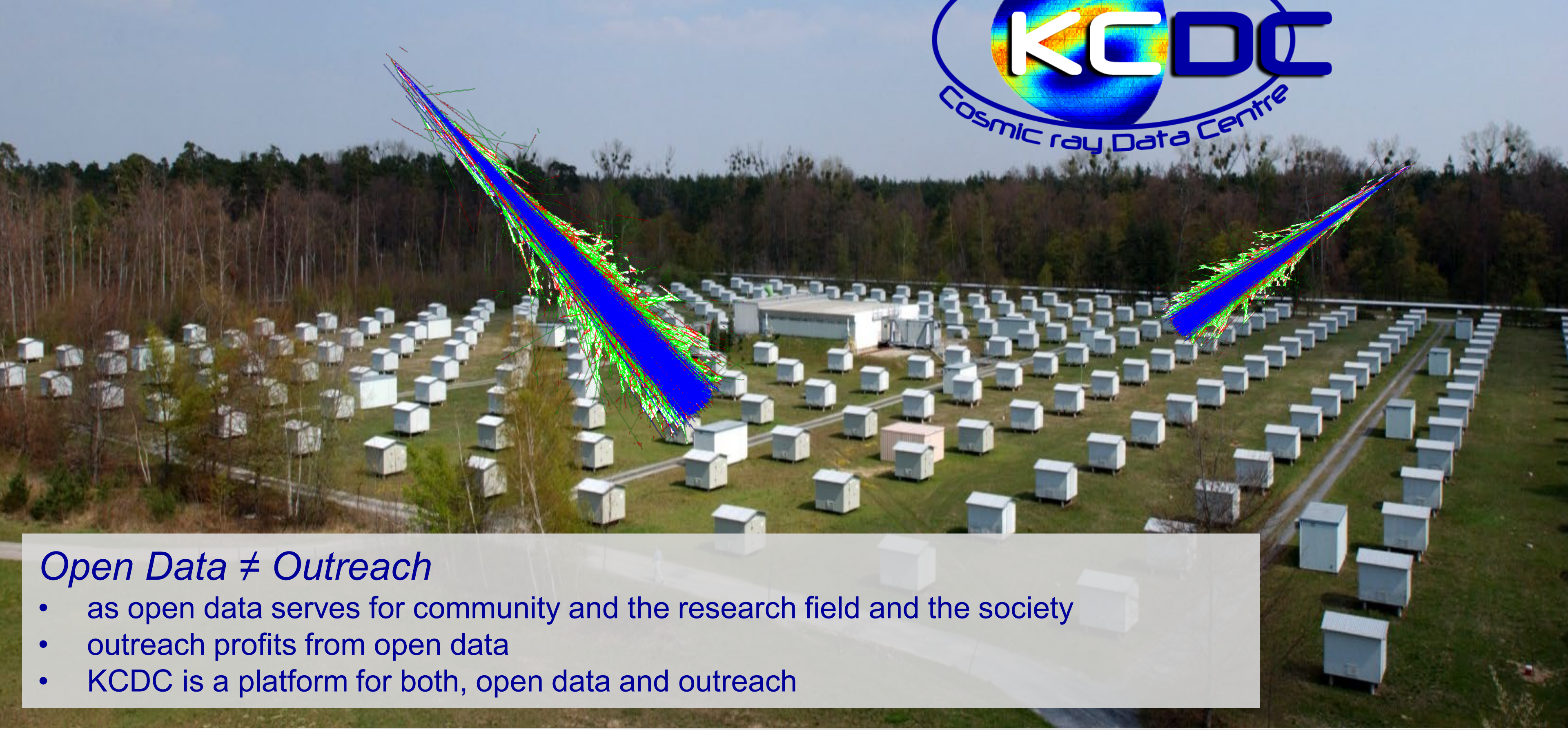


- None of the high-energy hadronic interaction models studied here is able to describe consistently the KASCADE-Grande EAS data on Nμ for all zenith angles and energies
- KASCADE-Grande data (calibrated with Pierre Auger energy scale) is (out of this 3 models) in best agreement with QGSJET-II-04. Predictions of EPOS-LHC and SIBYLL 2.3d are above the KASCADE-Grande data for vertical EAS.
- Attenuation of Nμ with zenith angle is smaller in data than in MC simulations, which is in agreement with previous results on the muon attenuation length (App 95 (2017) 25).
- Measurements and expectations seem to be in better agreement for inclined EAS
- Observations could imply that the energy spectrum of muons from real EAS at production site for a given primary energy is harder than the respective model predictions.

A.Haungs; ICRC 2023

KASCADE Cosmic-ray Data Centre KCDC

https://kcdc.iap.kit.edu



Open Data ≠ 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

Status of KCDC

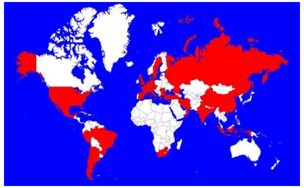
What's KCDC?

- ➢KCDC is a web-based platform to provide scientific data for the general public
- ➢KCDC is to archive original research data such as from KASCADE-Grande (and other experiments)
- ➢KCDC is to offer long-term scientific data for the community as well as for students and the interested public
- ➢KCDC is load on a sophisticated web portal
- ➢KCDC has in all aspects a FAIR (Findable – Accessible – Interoperable – Reusable) data management

What's new?

- ➢Independent Data Shops: Allows for Multi-Experimental Analysis
- ➢Jupyterhub https://jupyter.iap.kit.edu, supports online, in-KCDC analyses
- ➢KCDC accessible via Helmholtz Authentication and Authorisation Infrastructure (AAI)
- ➢KCDC is now running on the operating system UBUNTU 20.04 LTS.
- ➢The outdated ftp-download procedure is switched to a direct https-download
- ➢KCDC provides extended simulations and published spectra
- ➢KCDC provides online event displays
- ➢KCDC masterclass for students and extended Tutorials via Jupyterhub PoS (ICRC2021) 1378
- ➢KCDC has close partnership with the Cosmic-Ray DataBase (CRDB: https://lpsc.in2p3.fr/crdb)

https://kcdc.iap.kit.edu


KCDC user map

A.Haungs; ICRC 2023

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
- Largest problem: absolute mass scale
- Confrontation of the data with astrophysical models still challenging
- IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, Auger, NEVOD, HAWC, SWGO
- Cross-experimental co-operation needed for Cosmic-Ray Physics in the Transition Region