

Latest Analysis Results from the KASCADE-Grande Data

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for the KASCADE-Grande Collaboration



KArlsruhe Shower Core and Array DEtector + Grande

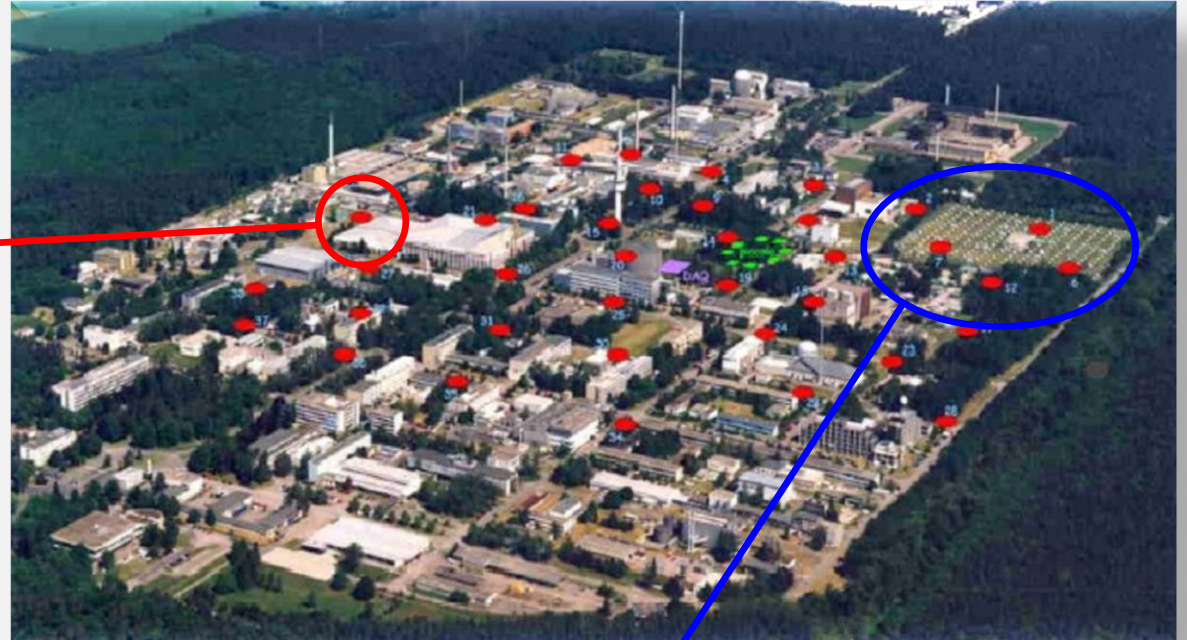
[Nucl. Instr. and Meth. A620 (2010) 202]



- 10 PeV – 1 EeV
- 0.5 km²
- 37 stations (each 10 m²)

Successfully completed data acquisition at the end of 2013

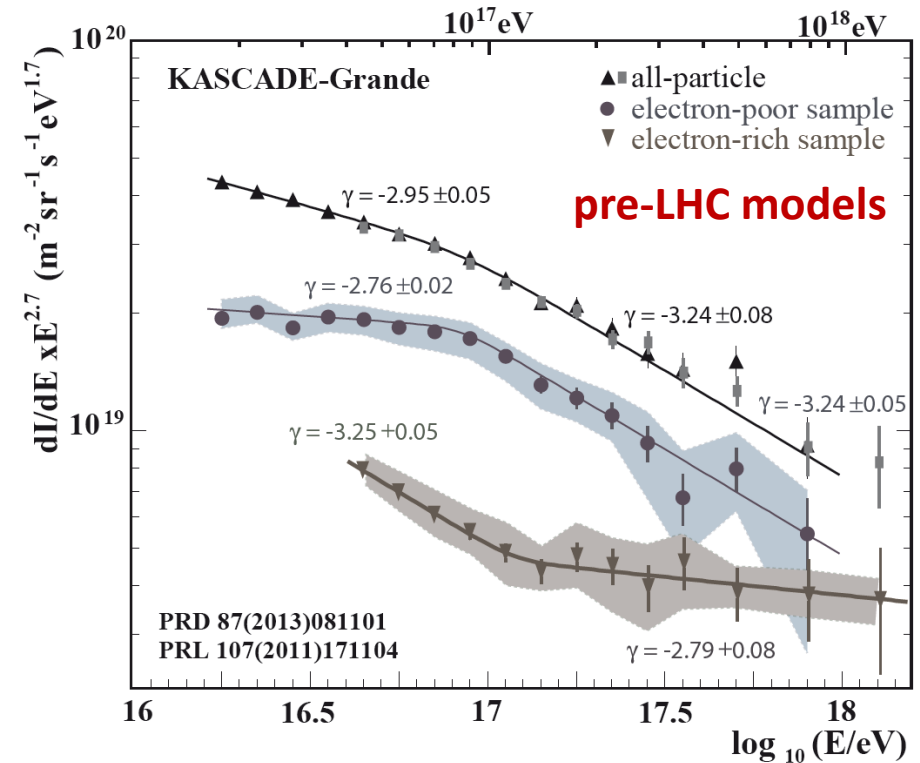
Data from more than 20 years of measurements are now available for public usage



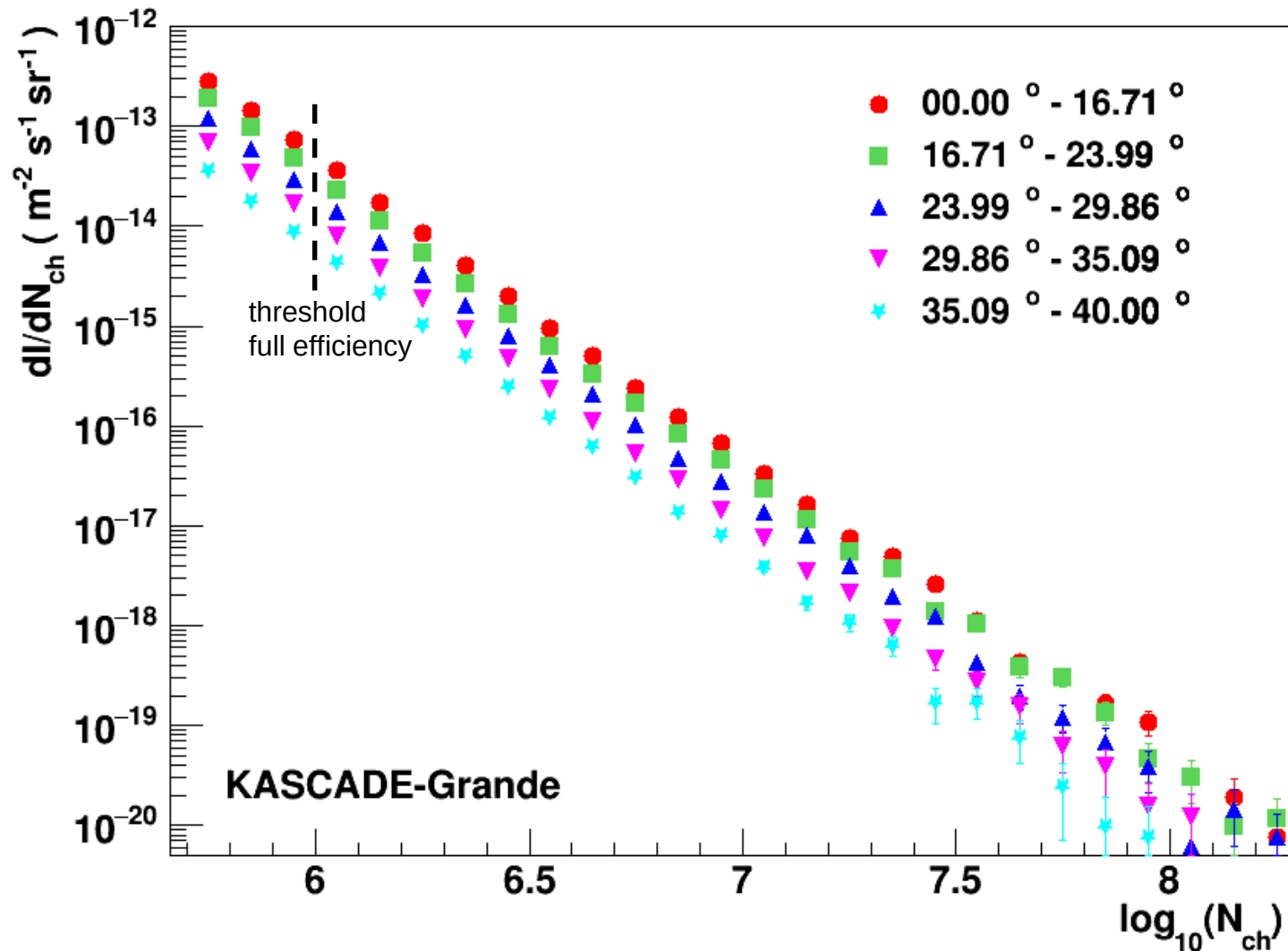
- 100TeV – 80PeV
- 252 scintillation detector stations
- Large number of observables

Features of Energy Spectra Observed by KASCADE and KASCADE-Grande

- KASCADE: knee by light primaries at $\sim 3 \cdot 10^{15}$ eV (He dominant)
[*Astropart. Phys.* 24 (2005) 1-25]
- KASCADE-Grande: knee of heavy primaries at $\sim 9 \cdot 10^{16}$ eV (3.5σ)
[*Astropart. Phys.* 36 (2012) 183, *PRL* 107 (2011) 171104]
- Heavy knee less distinct compared to light knee
[*PRD* 87 (2013) 081101]
- Hardening of the light component at $10^{17.08}$ eV (5.8σ)
- Mixed composition for 10^{15} to $\sim 10^{18}$ eV
- Relative abundancies (composition) depend strongly on hadronic interaction model



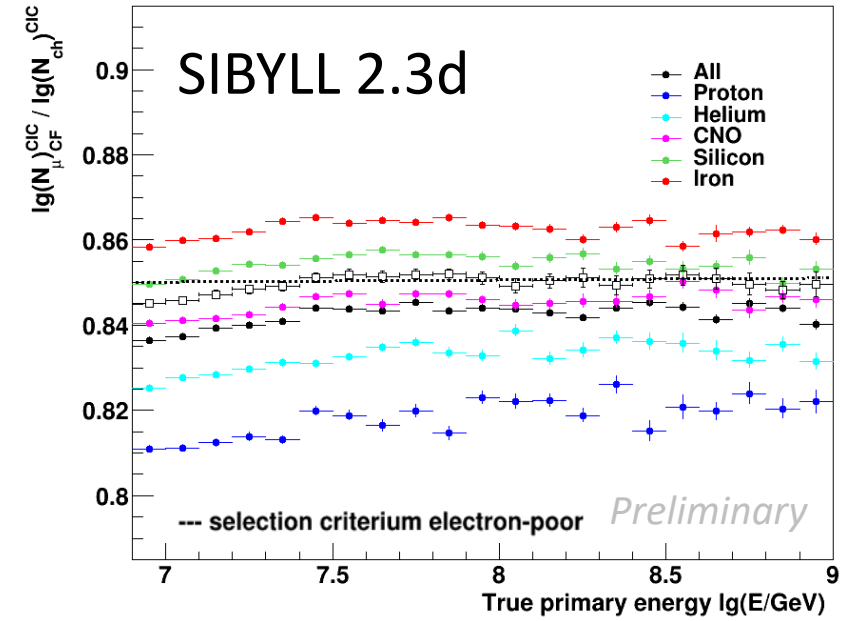
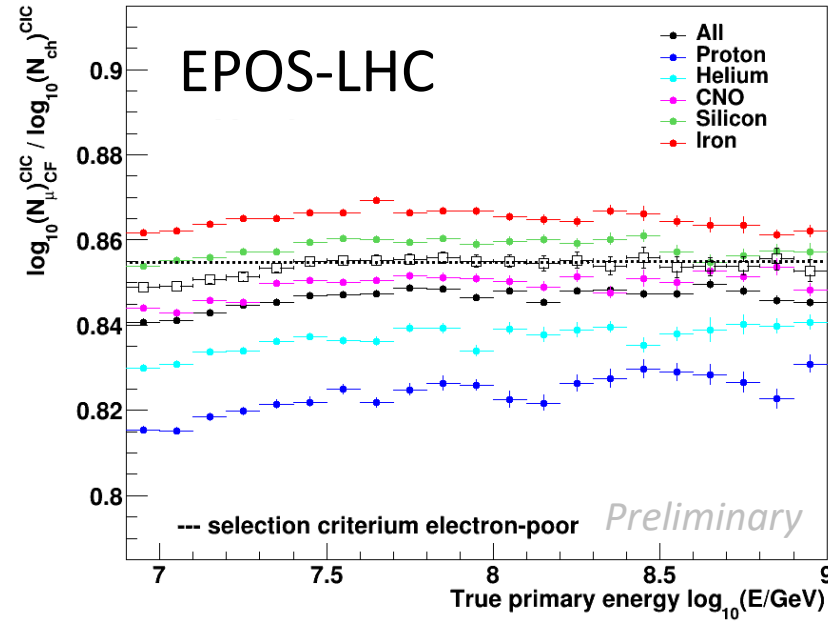
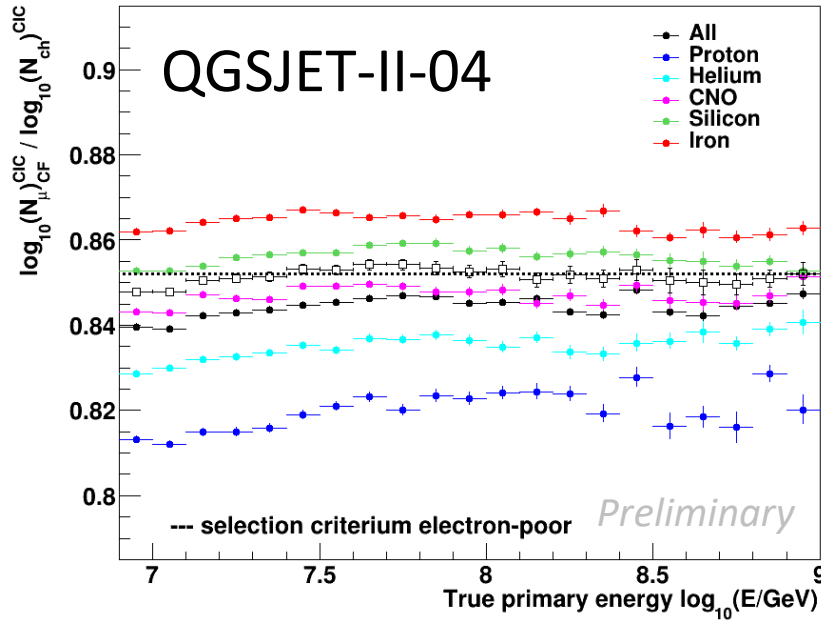
Measured Shower Size Spectrum



- Full statistics: $8.8 \cdot 10^7$ events for 1865.62 days ($1.7 \cdot 10^7$ after quality cuts)
- Measured shower size spectra for different zenith angle bins
- Attenuation effects corrected by the Constant Intensity Cut Method (CIC)
- Energy reconstruction based on the shower size (N_{ch})

*The number of muons is obtained from muon densities measured by KASCADE muon detectors

Selecting Primary Mass Group



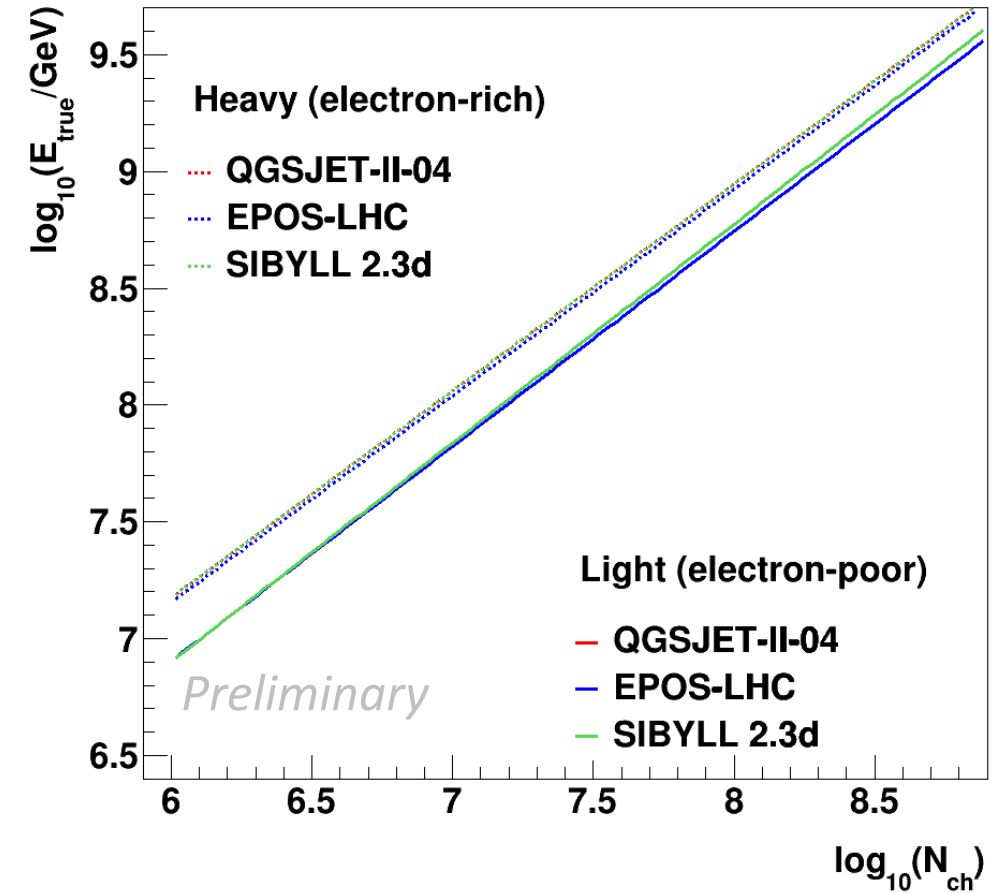
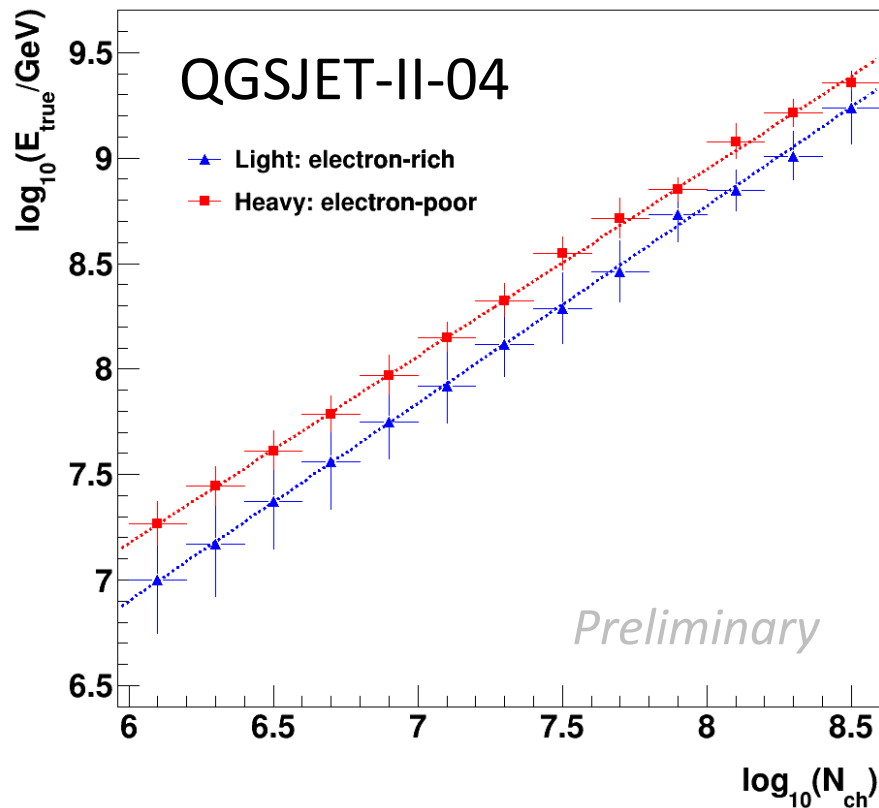
Heavy (Si+Fe) and light (H+He+C) mass group
by attenuation corrected shower size ratio:

$$Y_{CIC} = \lg(N_{\mu,CF})^{CIC} / \lg(N_{ch})^{CIC}$$

*Selection between CNO and silicon distribution

Models	Y_{CIC} at 10^{17} eV
QGSJET-II-04	0.8520
EPOS-LHC	0.8548
SIBYLL 2.3d	0.8501

Energy Calibration

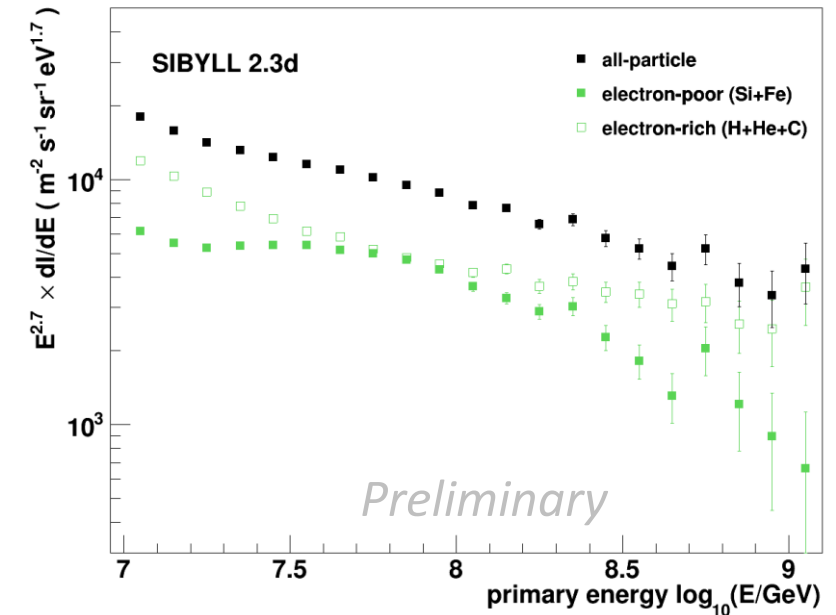
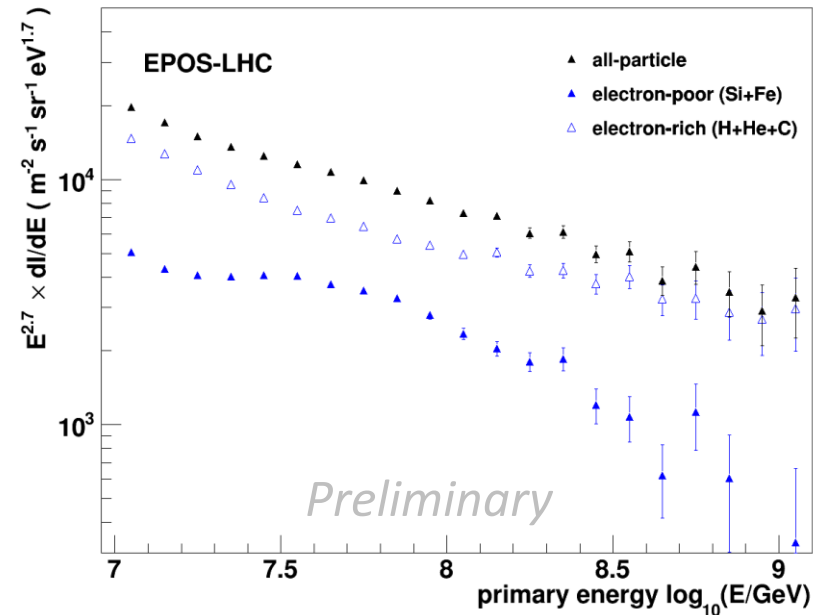
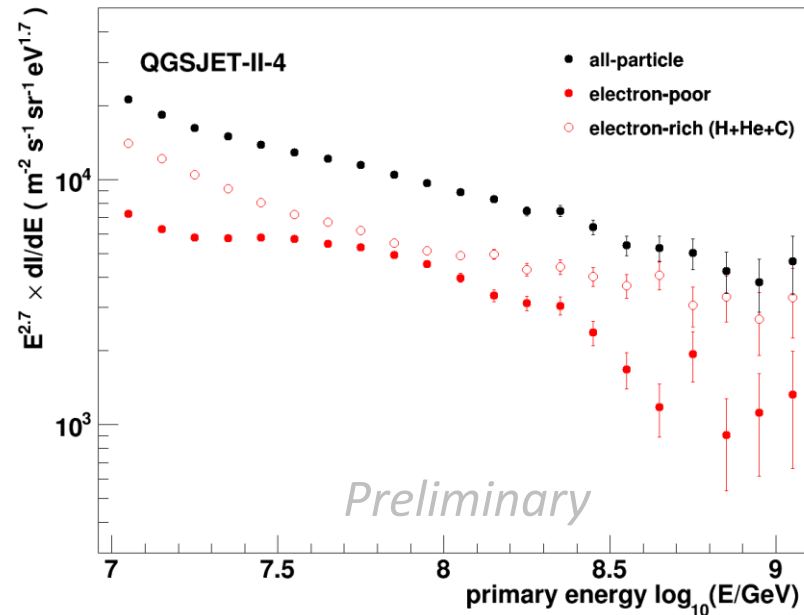


For electron-poor (heavy) and electron-rich (light) mass groups

Fit: $\log_{10}(E_{\text{true}}) = p0 \cdot \log_{10}(N_{\text{ch}}) + p1$

Models	HEAVY		LIGHT	
	p0	p1	p0	p1
QGSJET-II-04	0.885 ± 0.003	1.863 ± 0.023	0.936 ± 0.006	1.285 ± 0.039
EPOS-LHC	0.885 ± 0.004	1.847 ± 0.023	0.919 ± 0.005	1.388 ± 0.035
SIBYLL 2.3d	0.892 ± 0.004	1.795 ± 0.023	0.939 ± 0.005	1.239 ± 0.035

Spectra of Individual Mass Groups



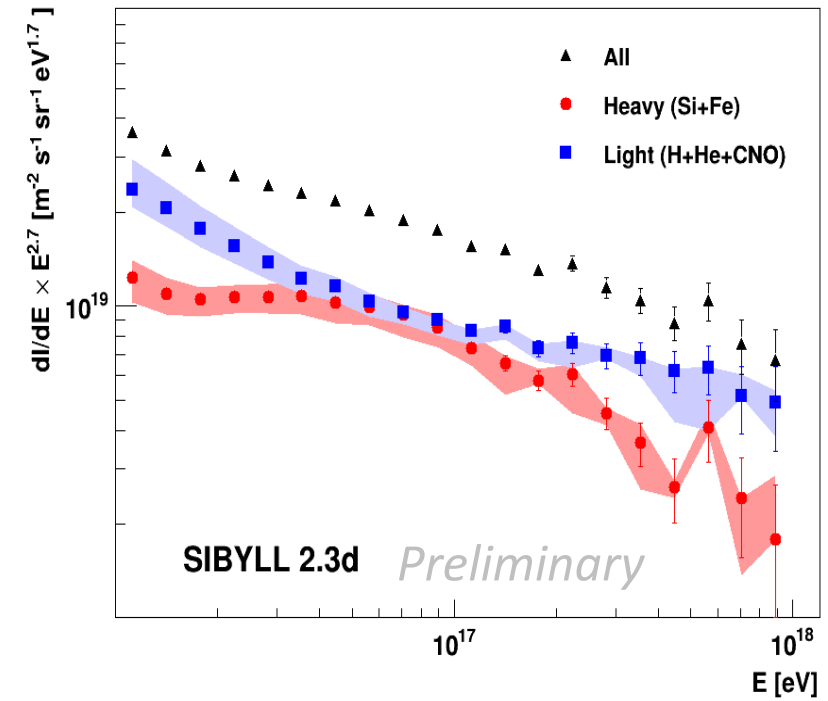
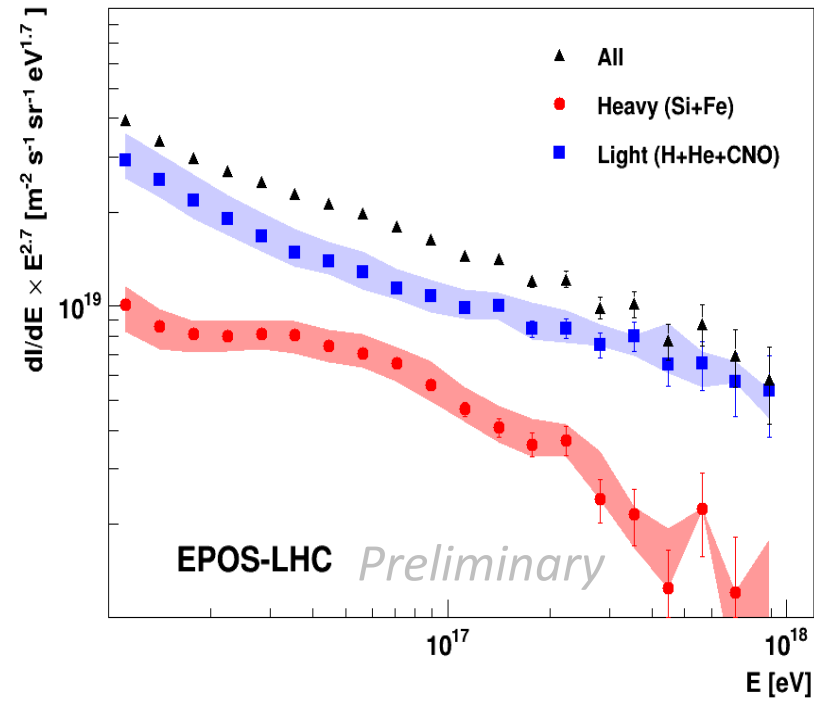
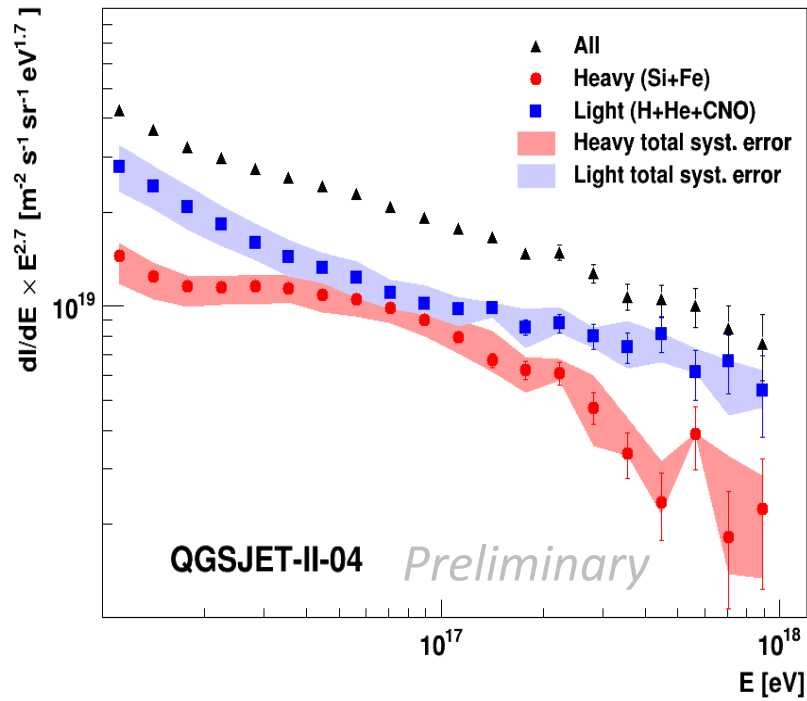
- Spectral index changes from $\gamma \sim 2.7$ to $\gamma \sim 3.3$ for all models
- Knee-like structure of heavy primaries below 10^{17} eV
- Concave feature at around 10^{16} eV is visible in heavy primaries
- Hardening of light primaries is significant

Systematic Uncertainties

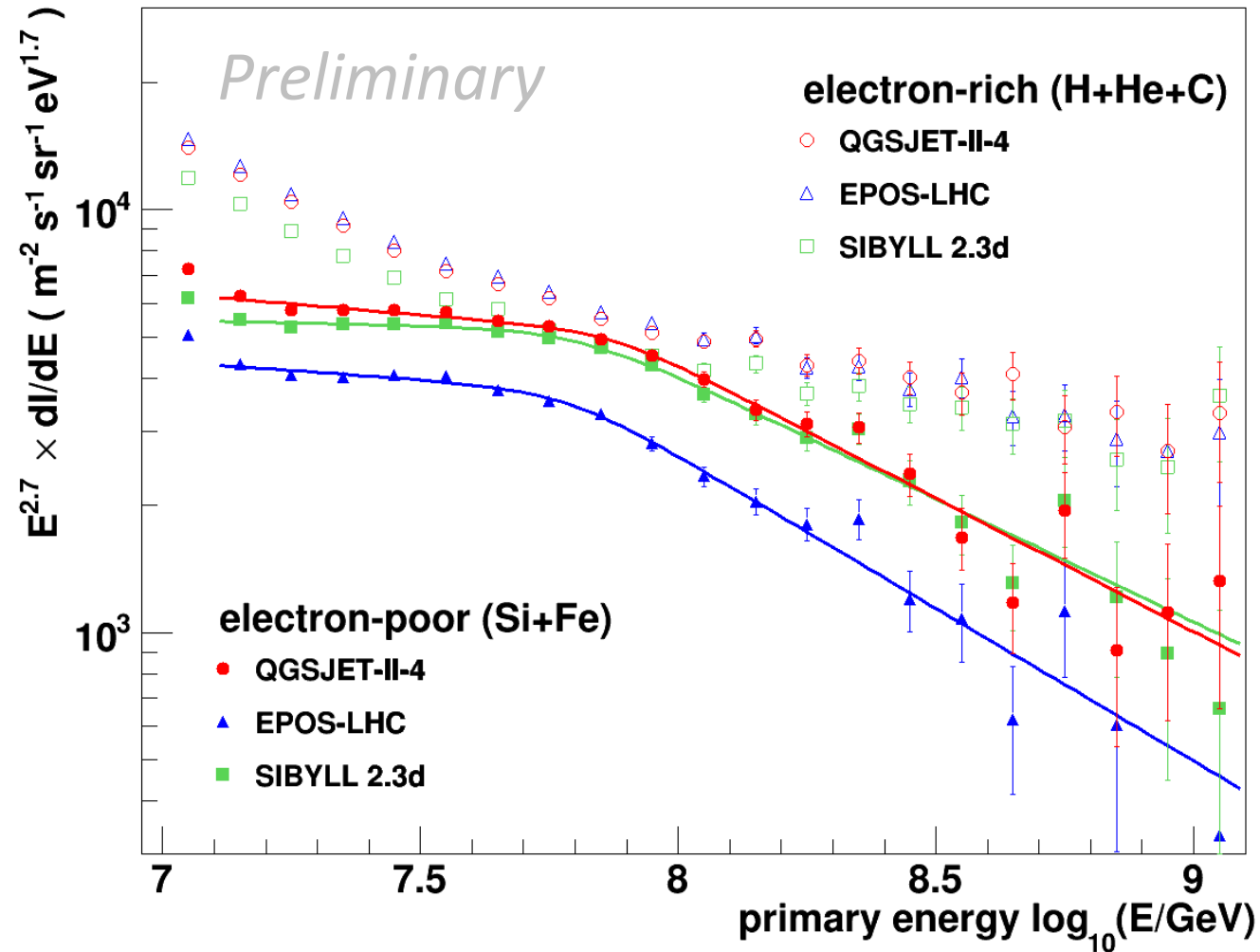
Syst. Error at 10^{17} eV	QGSJET-II-04		EPOS-LHC		SIBYLL 2.3d	
	Light(%)	Heavy(%)	Light(%)	Heavy(%)	Light(%)	Heavy(%)
Spectral index:						
gamma = -2.8	2.66	1.78	2.54	3.21	3.96	0.63
gamma = -3.2	5.32	9.32	0.28	2.67	5.41	7.13
CIC method:						
Attenuation curve fit	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$\theta_{ref} = 10$ deg	9.80	7.03	9.29	7.22	9.91	6.34
$\theta_{ref} = 30$ deg	14.1	10.0	17.5	14.2	11.4	0.48
Energy conversion fit	0.79	0.51	0.58	0.51	0.23	1.35
Total	+14.1/ -11.5	+10.1/ -11.8	+17.7/ -9.32	+14.5/ -7.71	+9.89/ -13.9	+1.43/ -9.66

*Uncertainties from Muon Correction Function and unfolding are not taken into account yet (<2-3%)

Spectra of Individual Mass Groups



Spectra of Heavy Primaries



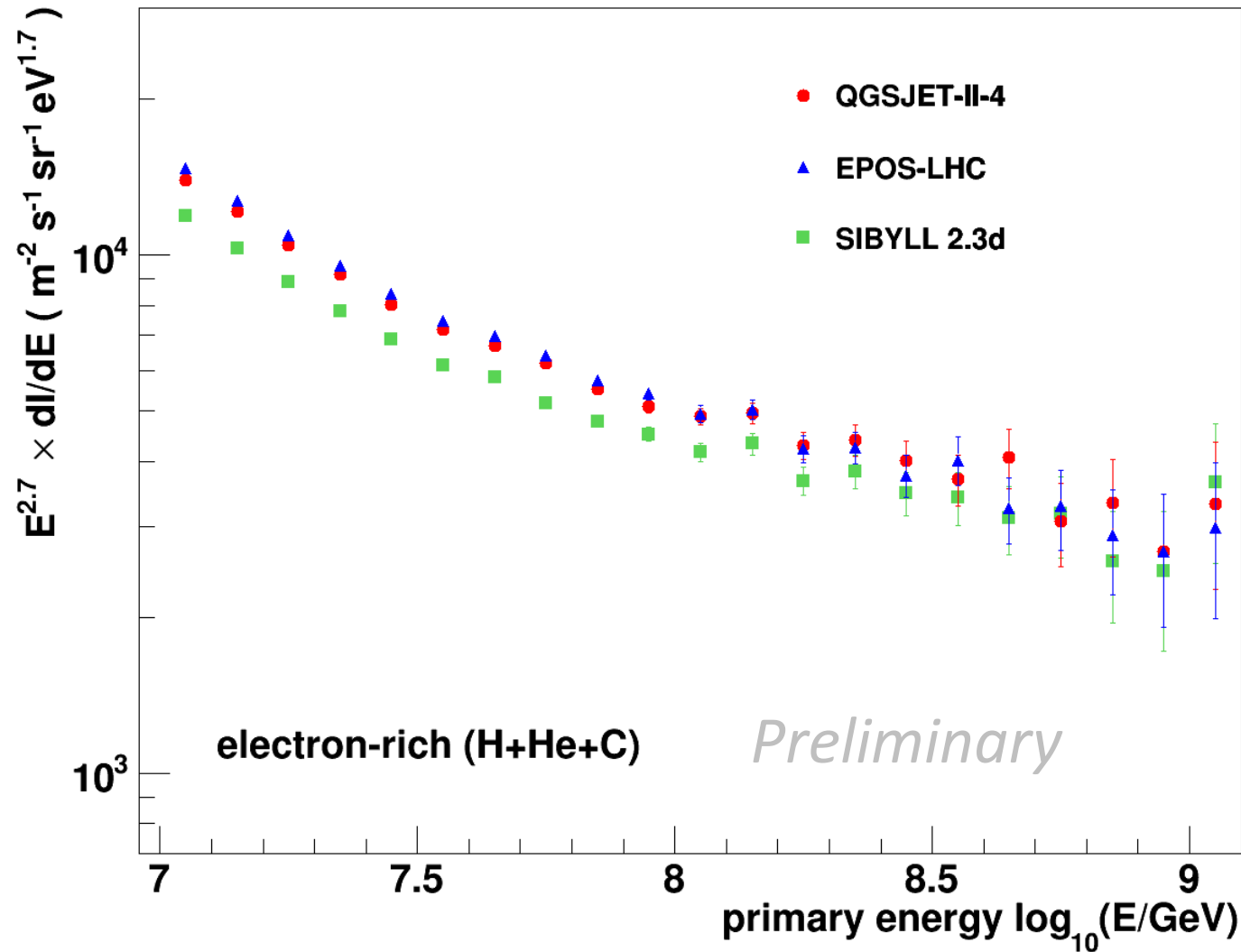
- Knee-like structure of heavy primaries are similar
- EPOS-LHC gives the lowest flux of heavy primaries of all models due to the different ratio of N_{ch}/N_{μ}

■ Fit:
$$\Phi(E) = K \cdot E^{\gamma_1} \left[1 + \left(\frac{E}{E_K} \right)^\varepsilon \right]^{\frac{\gamma_2 - \gamma_1}{\varepsilon}}$$

electron-poor	$\lg(E_K/\text{GeV})$	γ_1	γ_2	$\Delta\gamma$	χ^2/ndf
QGSJET-II-04	7.87 ± 0.05	2.80 ± 0.01	3.33 ± 0.06	0.53	3.96
EPOS-LHC	7.79 ± 0.04	2.79 ± 0.01	3.42 ± 0.06	0.63	2.38
SIBYLL 2.3d	7.81 ± 0.04	2.73 ± 0.01	3.28 ± 0.06	0.55	1.97

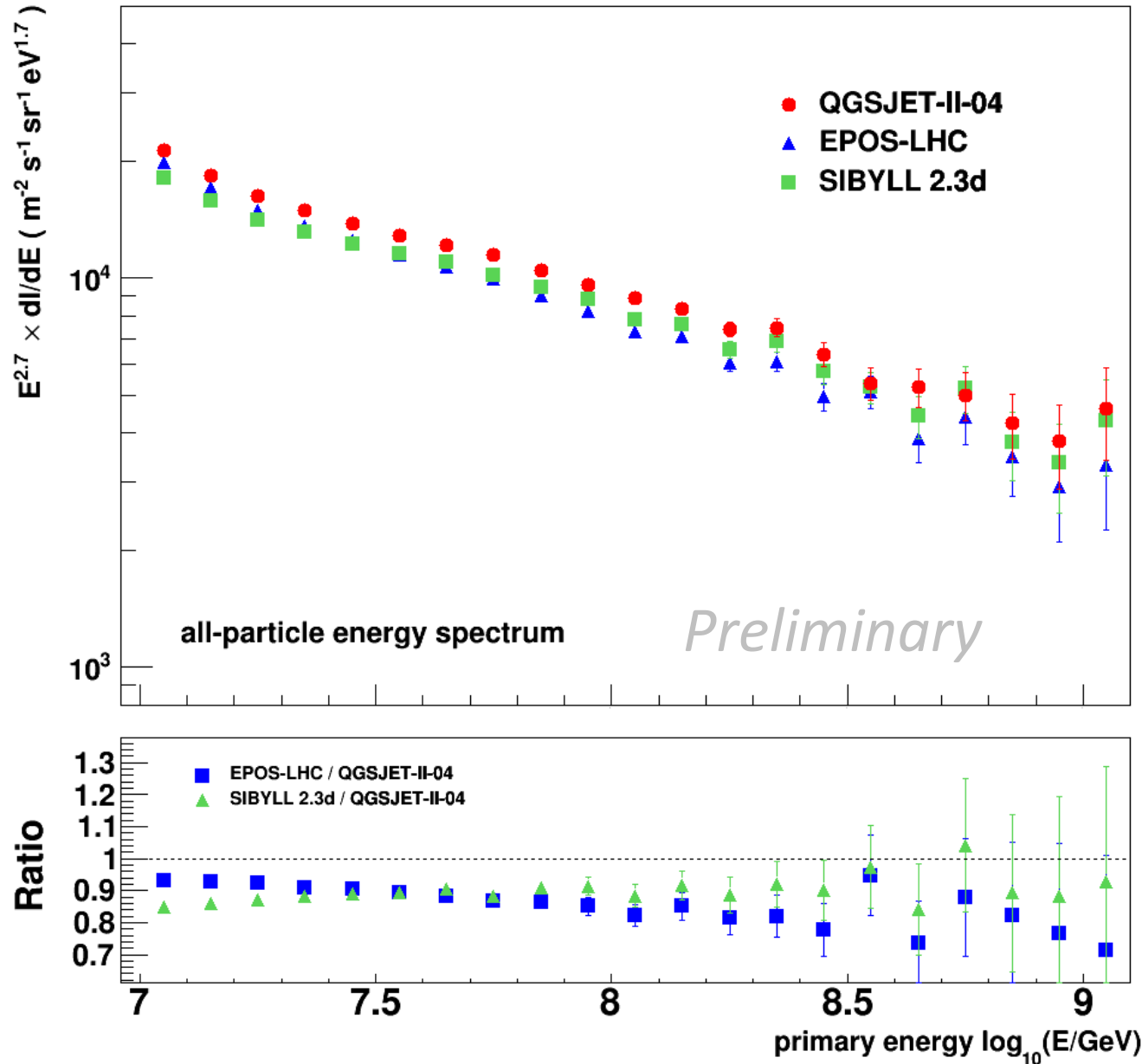
*EPOS-LHC model predicts more muons than the other post-LHC models → the data interpretation leads to a more light composition

Spectra of Light Primaries



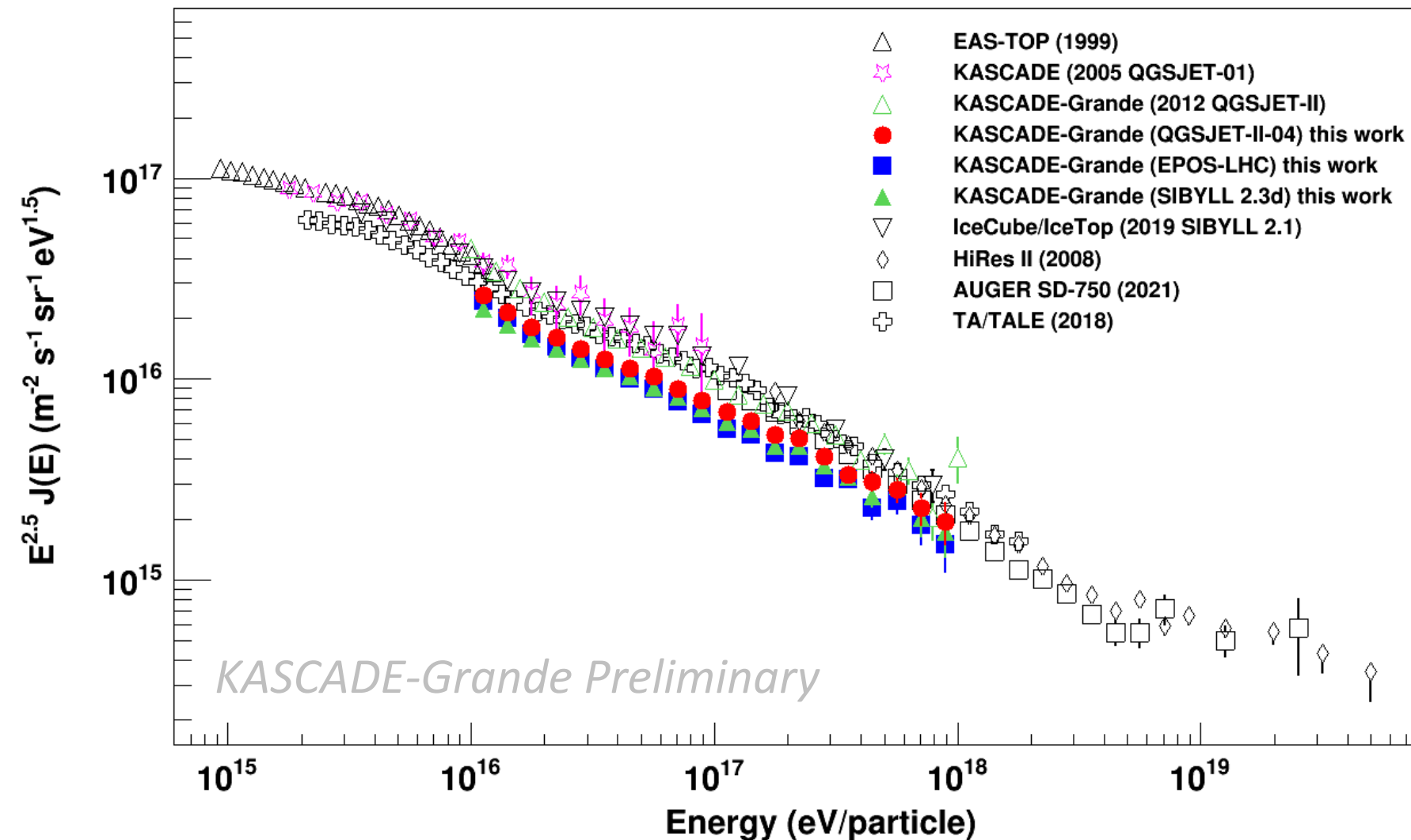
- The electron-rich sample is always more abundant due to the separation around the CNO mass group
- Hardening of light primaries are similar for all models
- Slope changes smoothly at around 10^{17} eV

All-Particle Energy Spectrum



- All-particle energy spectrum is obtained from the sum of the individual heavy and light spectra
- Ratio of EPOS-LHC and SIBYLL 2.3d spectra with respect to QGSJET-II-04
- Small difference among the post-LHC models over the whole energy range

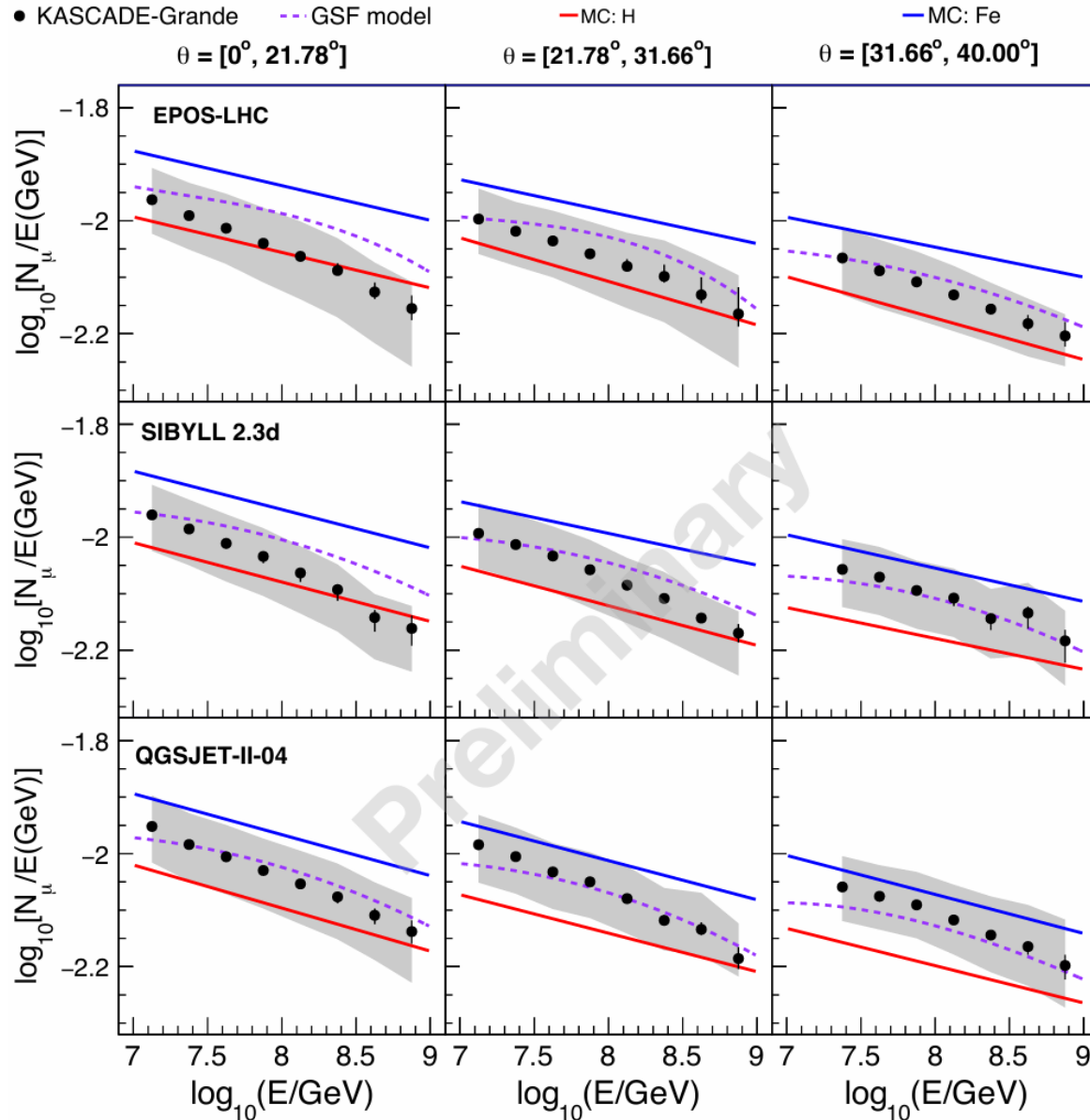
All-Particle Energy Spectrum



- Relatively small dependencies among the hadronic interaction models in use
- Though, in terms of the absolute flux, there is for KASCADE-Grande an up to 20% lower flux compared to the other measurements
- Due to the measurements close to sea level. Moreover, differences of N_{ch} and N_{μ} are related to the absolute normalization of the energy scale by the various models

[[PoS\(ICRC2023\)307](#)]

Muon Content of EAS in KASCADE-Grande



- The muon number measured by KASCADE-Grande is investigated in the primary energy between 10^{16} and 10^{18} eV for three zenith angle intervals
- No excess of EAS muon data with respect to the models
- A deficit is observed in data for vertical EAS close to 1 EeV
- Reasonable agreement between experiment and data for inclined showers
- Smaller atmospheric attenuation of actual EAS muon data

[J.C.Arteaga-Velazquez, ISVHECRI2024]

KASCADE Cosmic ray Data Centre (KCDC)

<https://kcdc.iap.kit.edu>



KCDC is a web-based platform, in which scientific data of the completed KASCADE and KASCADE-Grande experiments are made available for the astroparticle community and interested general public

In the latest release (QUALOR 2.0) at the end of 2022:

- Independent data shops: allow for multi-experimental analysis
- Now running on the operating system Ubuntu 20.04 LTS
- JupyterHub (<https://jupyter.iap.kit.edu>) for online, in-KCDC analyses
- KCDC masterclass for students and extended tutorials via Jupyterhub
- Provides extended simulation and more published spectra of various experiments
- Provides online event displays
- Close partnership with the Cosmic-Ray DataBase (CRDB)

[*A.Haungs, PoS(ICRC2023)1614*]

Summary

- By means of the shower size measured by KASCADE-Grande, the energy spectra of heavy and light mass groups were reconstructed based on the post-LHC models QGSJET-II-04, EPOS-LHC, and SIBYLL 2.3d:
 - All features of the energy spectrum are confirmed, but total energy flux is shifted
 - Flattening of the light component below 10^{17} eV
 - Relatively small dependencies among the post-LHC hadronic interaction models in use
 - In terms of the absolute flux, the result shows lower flux compared to the other measurements, however, a considering agreement among different experiments within systematic uncertainties
- The muon content measured by KASCADE-Grande shows slightly zenith angle dependence, however, the data shows a reasonable agreement with the MC expectation
- Over the past few years, KASCADE Cosmic ray Data Center (KCDC) is continuously updated
- Preparation of papers on composition studies with post-LHC models