Karlsruhe Institute of Technology

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Results from KASCADE-Grande

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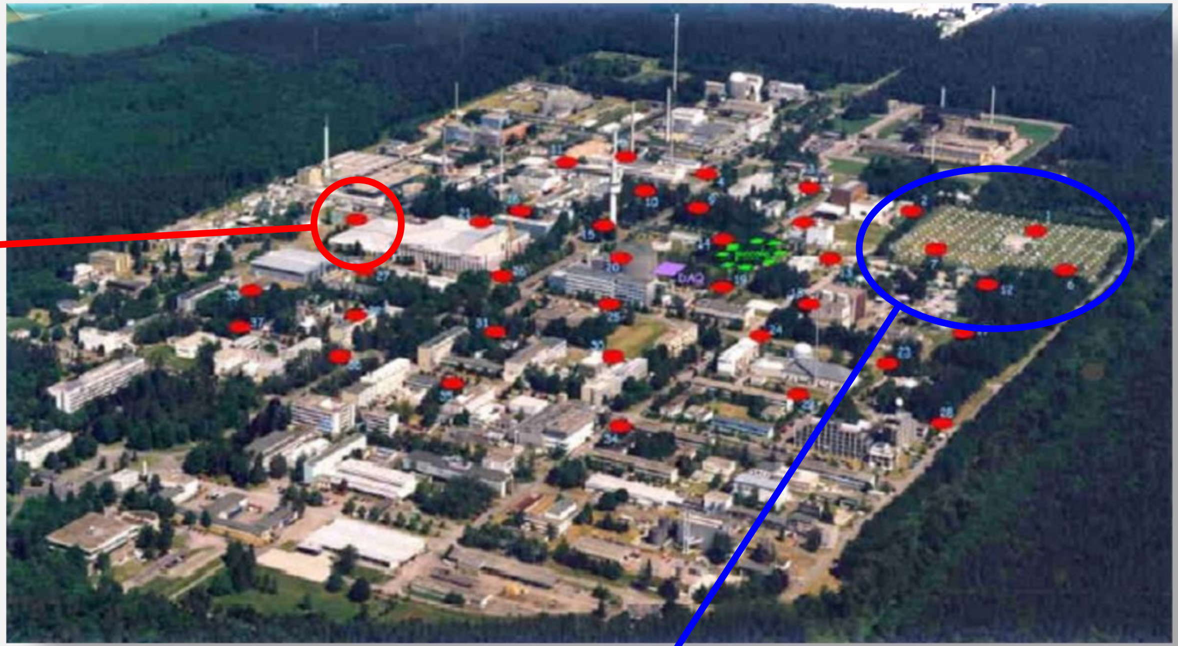
KArlsruhe Shower Core and Array DEtector + Grande

- 10 PeV – 1 EeV
- 0.5 km^2
- 37 stations (each 10 m^2)



Successfully completed data acquisition at the end of 2013

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

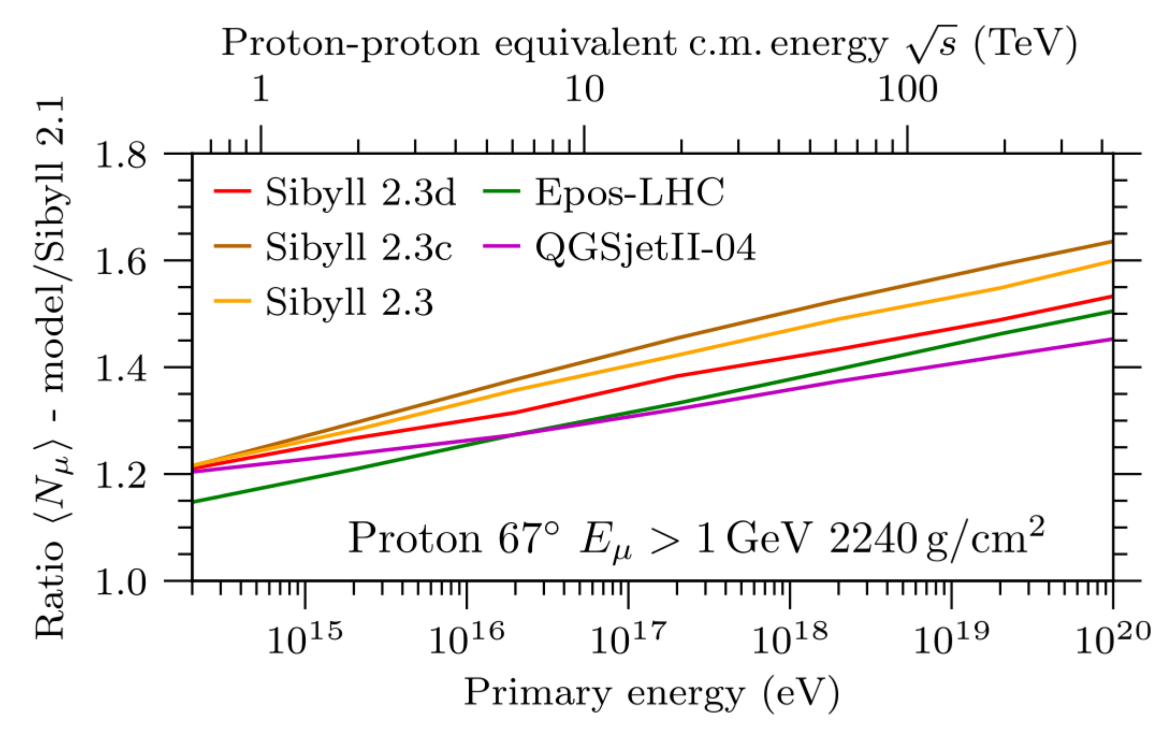
- 100TeV – 80PeV
- 252 scintillation detector stations
- Large number of observables

Features of Energy Spectra
Observed by KASCADE and KASCADE-Grande

- KASCADE: knee by light primaries at ~$3 \cdot 10^{15}$ eV (He dominant)
  [Astropart. Phys. 24 (2005) 1-25]
- Hardening at 10^{16} eV due to knee of medium primaries
- KASCADE-Grande: knee of heavy primaries at ~ $9 \cdot 10^{16}$ eV
  [Astropart. Phys. 36 (2012) 183, PRL 107 (2011) 171104]
- Heavy knee less distinct compared to light knee
  [PRD 87 (2013) 081101]
- Flattening of the light component around 10^{17}eV
- Mixed composition for 10^{15} to ~10^{18} eV
- Relative abundancies (composition) depend strongly on hadronic interaction model

SIBYLL 2.3d

- Previous composition studies with post-LHC models (QGSjet-II-04, EPOS-LHC, Sibyll 2.3, Sibyll 2.3c)
  [*EPJ Web Conf. 208 (2019) 04005*]
- A new version of Sibyll is developed by improving the behavior of the $\pi^{\pm}$ to π^{0} ratio in different mechanisms of hadronization



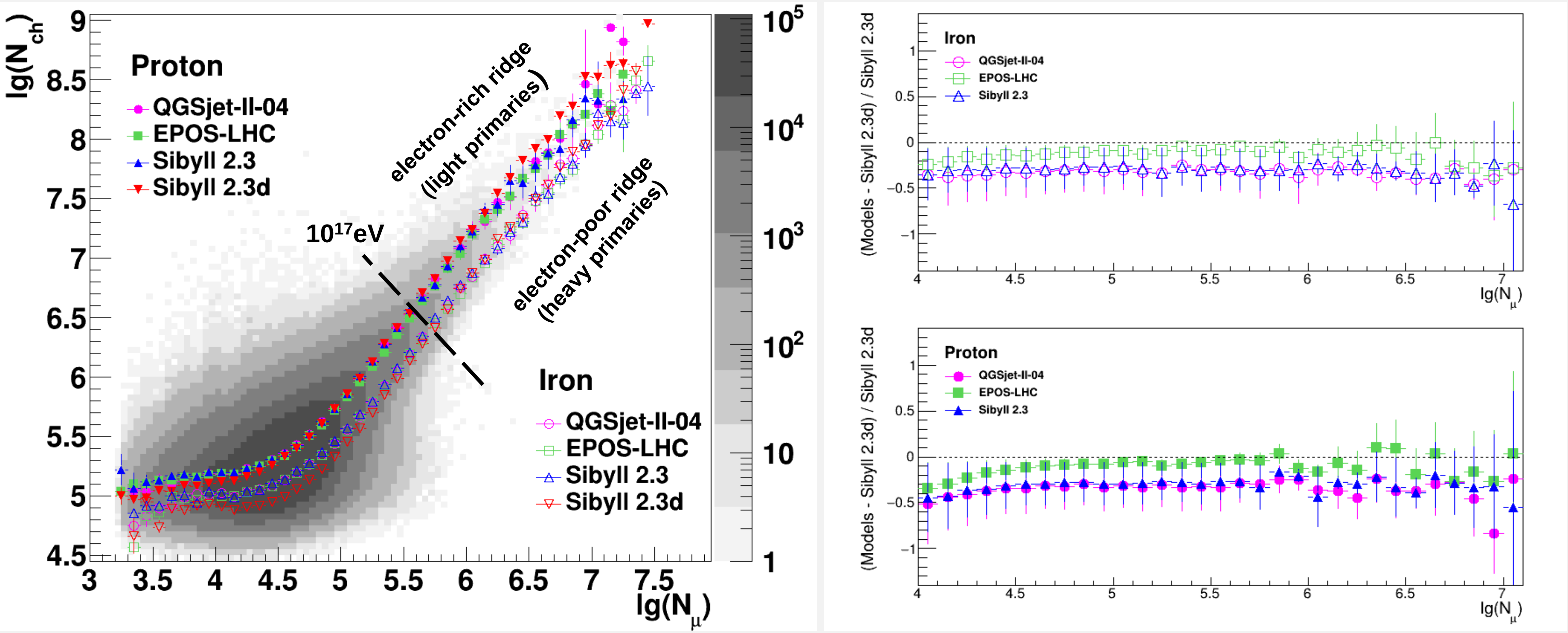
- Predictions for extensive air showers:

- The muon number in Sibyll 2.3d increased by 20–50% relative to Sibyll 2.1

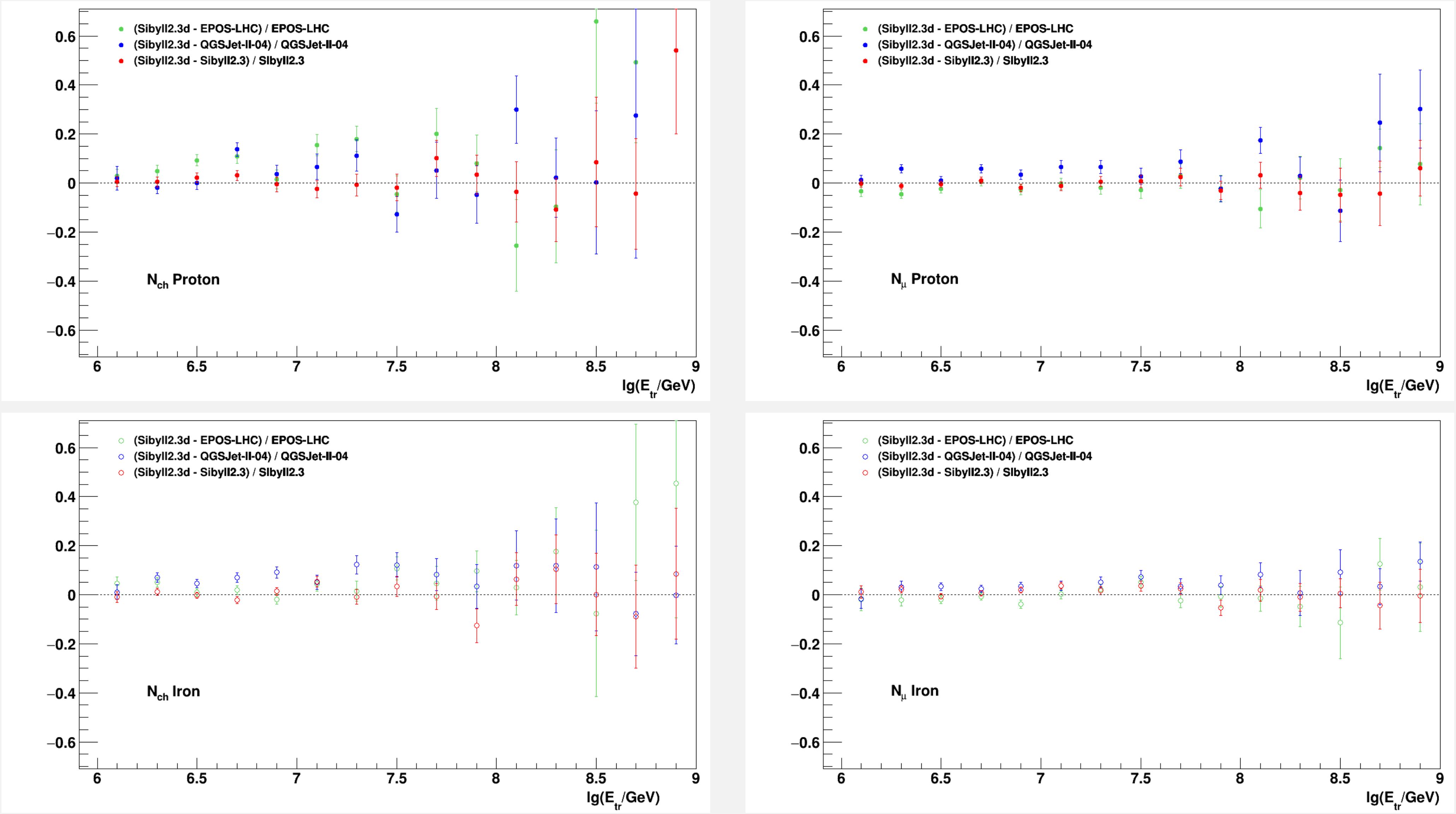
- Exceeding the number of muons by 1–5%, compared to QGSjet-II-04 and EPOS-LHC

[*F. Riehn et al., Phys. Rev. D 102 (2020) 063002*]

Shower Size

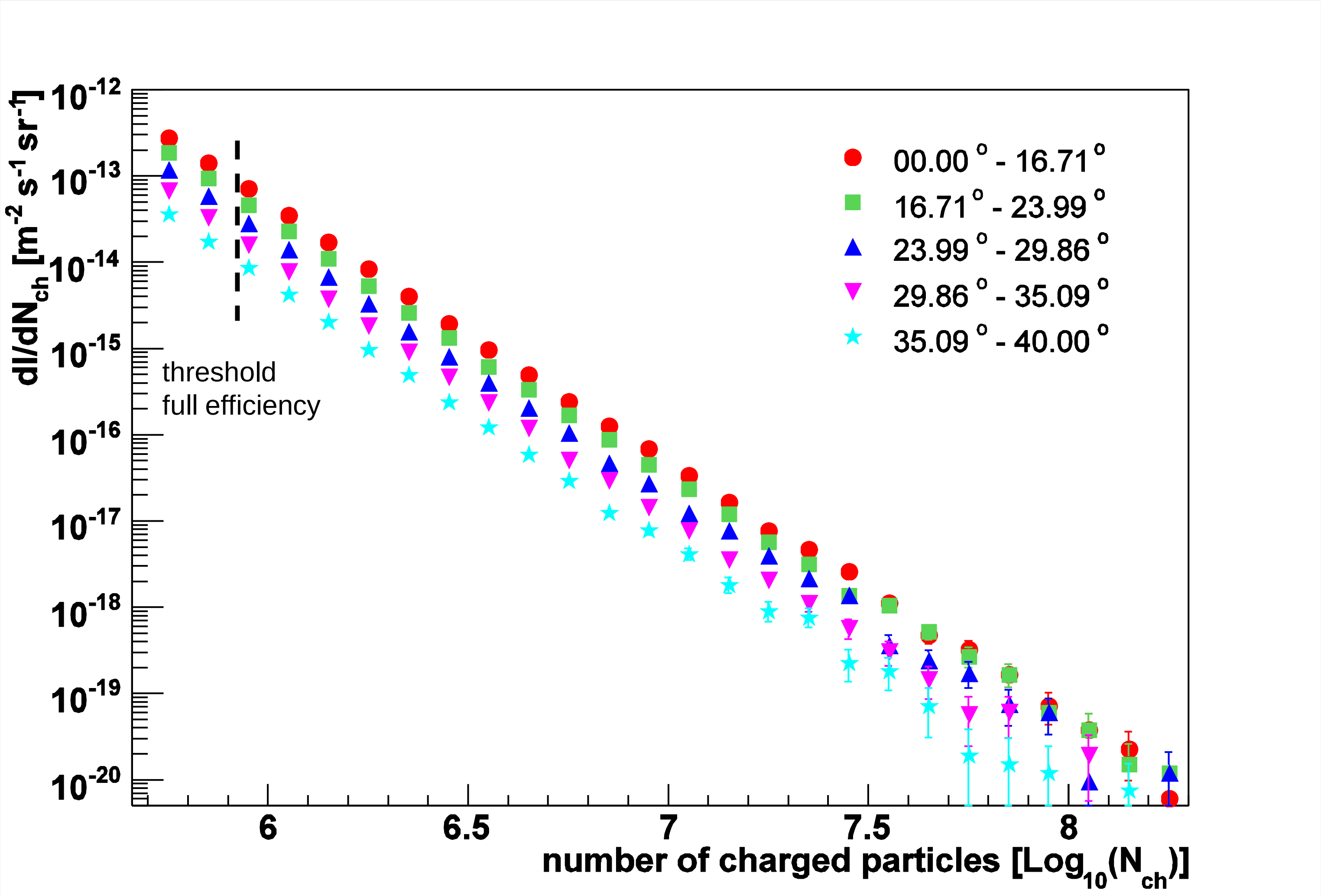


- 2-dim. Shower size spectrum, along with proton and iron induced showers for different post-LHC models
- Residual plots: Sibyll 2.3d has about 30% and 10% more muons relative to QGSjet-II-04 and EPOS-LHC, respectively



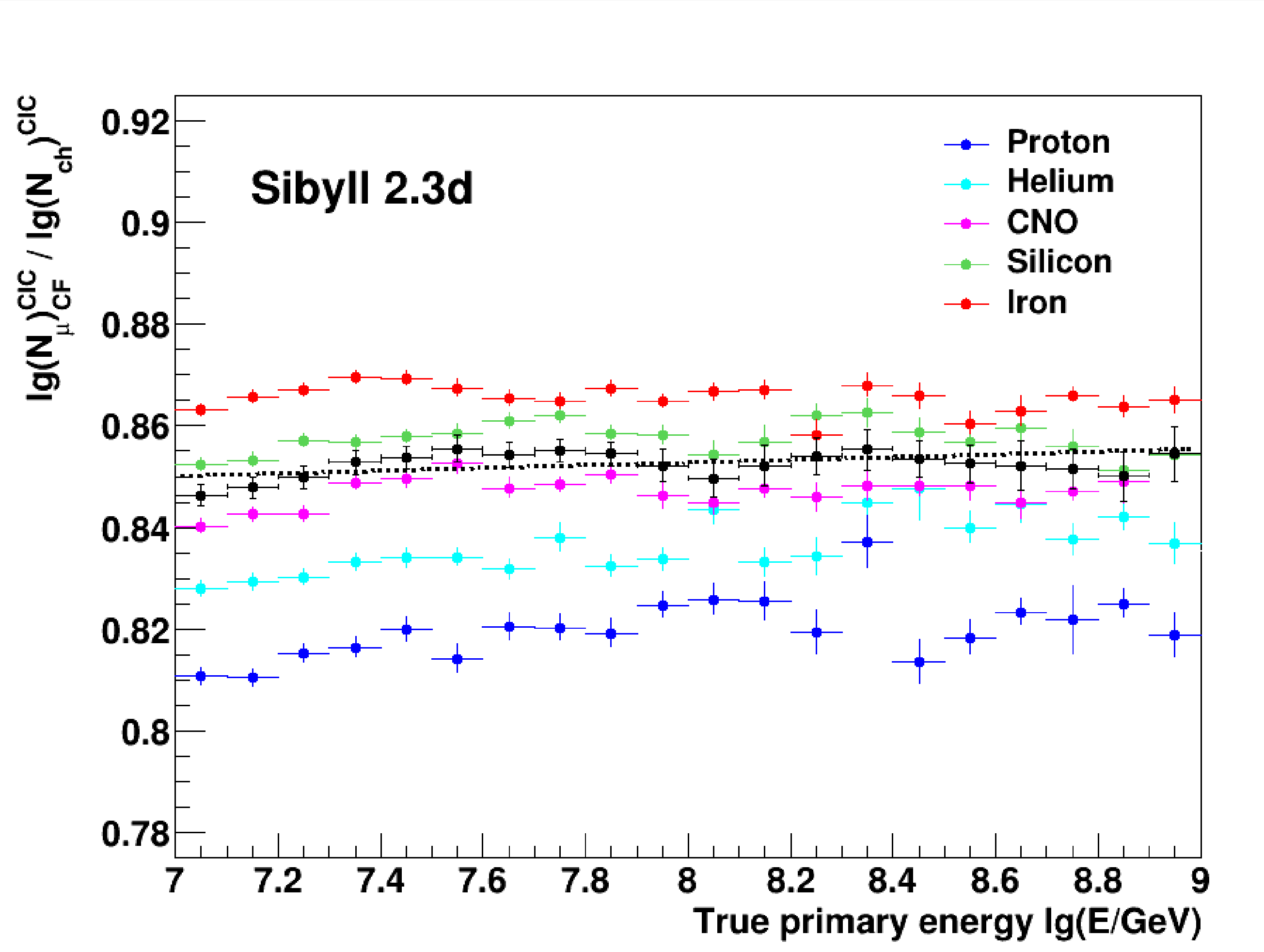
- Deviation of Sibyll 2.3d relative to other models shows about 10% for Nch and 5% for Nμ

Measured Shower Size Spectrum



- Measured shower size spectra for different zenith angle bins
- Attenuation effects are corrected by the Constant Intensity Method
- Energy spectrum based on the shower size

Selecting Primary Mass Group



- Individual spectra by attenuation corrected shower size ratio:

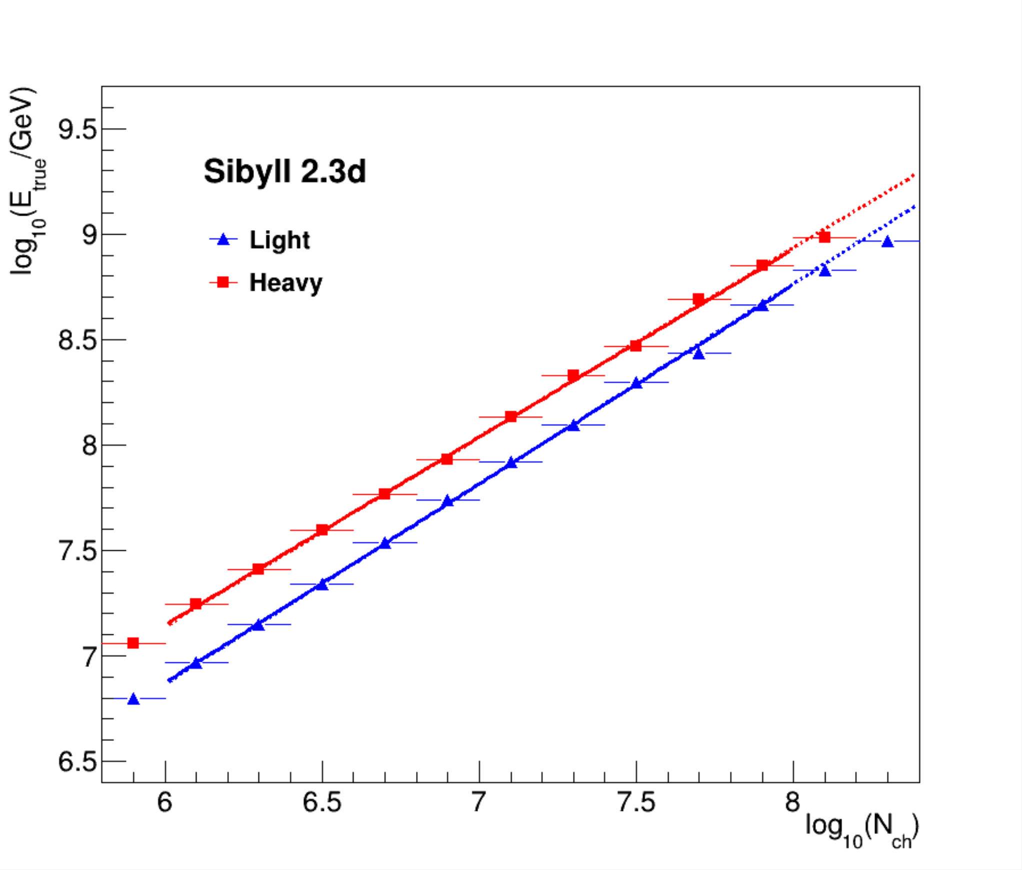
  $$Y_{CIC} = \lg(N_{\mu,CF})^{CIC} / \lg(N_{ch})^{CIC}$$

- For the same true energy Sibyll 2.3d reconstructs a lighter mass

	Y_{CIC} at 10^{17}eV
Sibyll 2.3d	0.853
Sibyll 2.3c	0.845
Sibyll 2.3	0.852
Sibyll 2.1	0.840

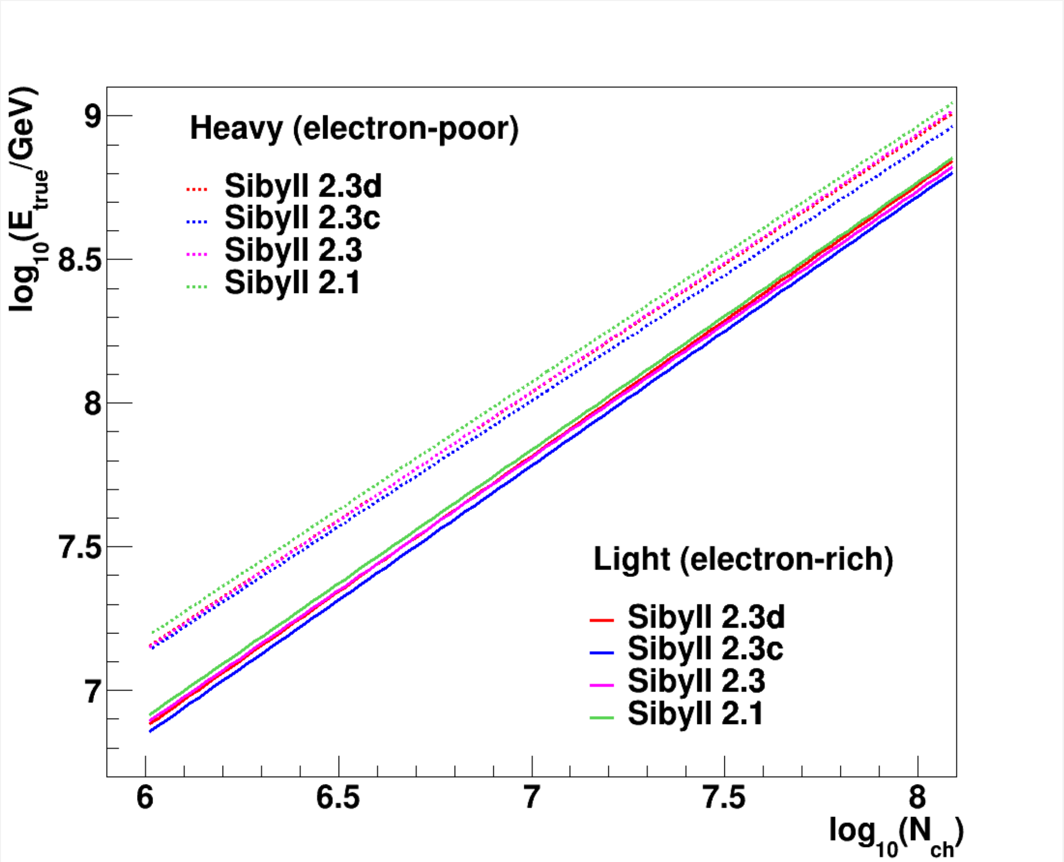
Energy Calibration

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



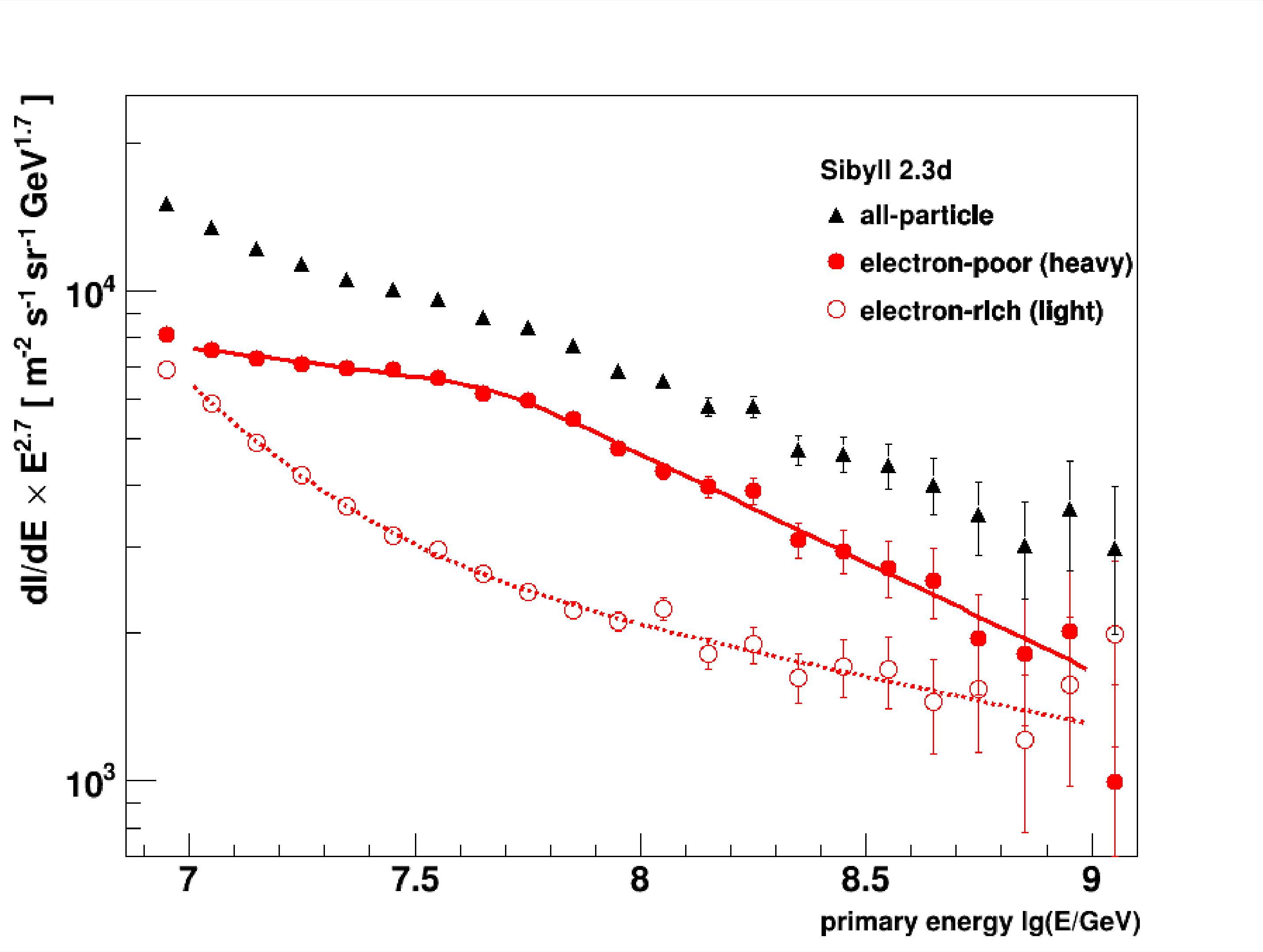
Fit: $\log_{10}E_{true} = p0 \cdot \log_{10}N_{ch} + p1$

For same shower size Sibyll 2.3d predicts slightly lower energy



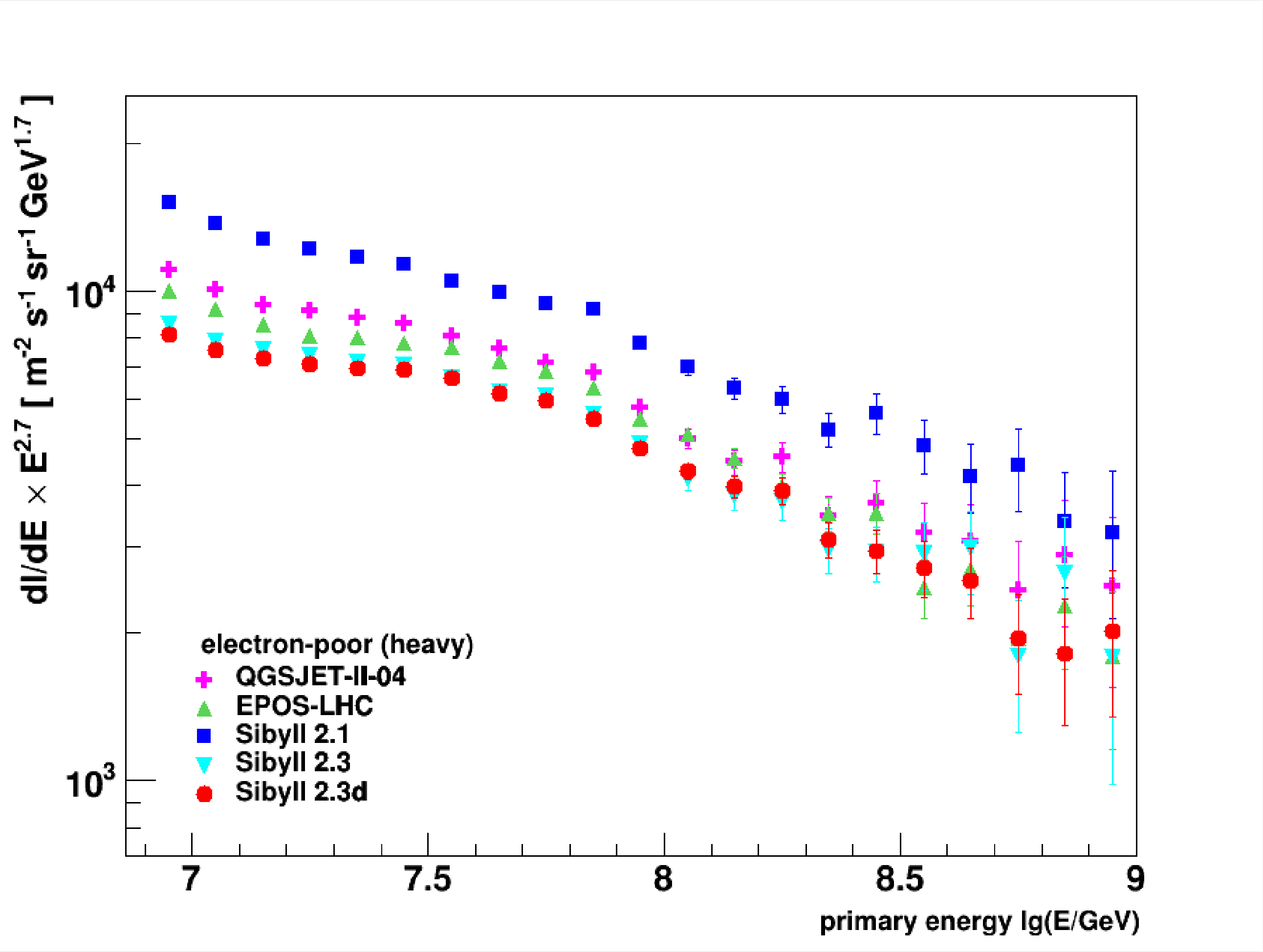
	HEAVY		LIGHT	
	p0	p1	p0	p1
Sibyll 2.3d	0.891	1.802	0.943	1.216
Sibyll 2.3c	0.875	1.883	0.936	1.229
Sibyll 2.3	0.897	1.764	0.927	1.321
Sibyll 2.1	0.890	1.847	0.931	1.321

Spectra of Individual Mass Groups



- Knee-like structure of heavy primaries below 10^{17} eV
- Hardening of light primaries is significant
- Not corrected for shower fluctuation yet
- Estimation of systematic uncertainties is in progress (expected to be about the order of 20%)

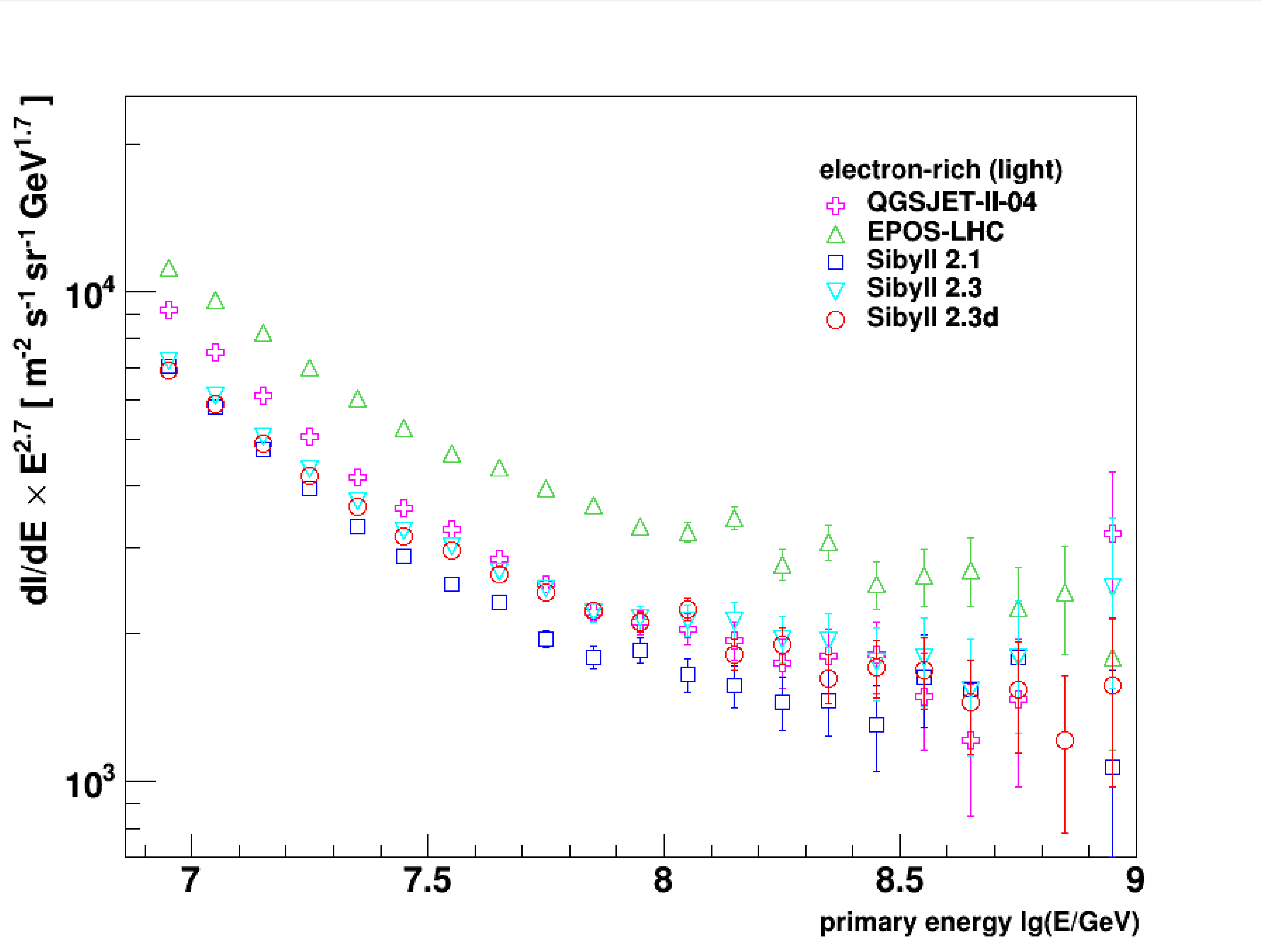
Spectra of Heavy Primaries



- **Knee-like structure of heavy primaries are similar**
- **Sibyll 2.3d gives the lowest flux of heavy primaries of all models**
- **Concave structure is shown clearly**
- **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	$\lg(E_k/\mathrm{GeV})$	γ_1	γ_2	$\Delta\gamma$	χ^2/ndf
QGSjet-II-04	7.73 ± 0.05	2.89 ± 0.01	3.18 ± 0.04	0.29	2.16
EPOS-LHC	7.79 ± 0.03	2.87 ± 0.01	3.20 ± 0.03	0.33	4.72
Sibyll 2.1	7.75 ± 0.09	2.87 ± 0.03	3.15 ± 0.05	0.28	1.28
Sibyll 2.3	7.71 ± 0.05	2.83 ± 0.01	3.18 ± 0.05	0.35	0.96
Sibyll 2.3d	7.69 ± 0.05	2.82 ± 0.01	3.14 ± 0.03	0.32	1.47

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
- The spectral slope of Sibyll 2.3d changes smoothly below 10^{17} eV

Conclusion

- Validity test of the new hadronic interaction model Sibyll 2.3d:
- All features of the energy spectrum are confirmed, but total energy flux is shifted
- The lowest flux of all models, i.e. dominant light mass composition due to more muons
- Flattening of the light component below 10^{17}eV
- Models still do not agree to each other and to data
- Problem probably in the muons
- Muon content studies [J.C. Arteaga-Velazquez, PoS(ICRC2021)376]
- Full datasets and simulations including detector responses can be found in KASCADE Cosmic ray Data Center (KCDC) [A.Haungs, PoS(ICRC2021)422]
- Preparation of a paper on composition studies with post-LHC models