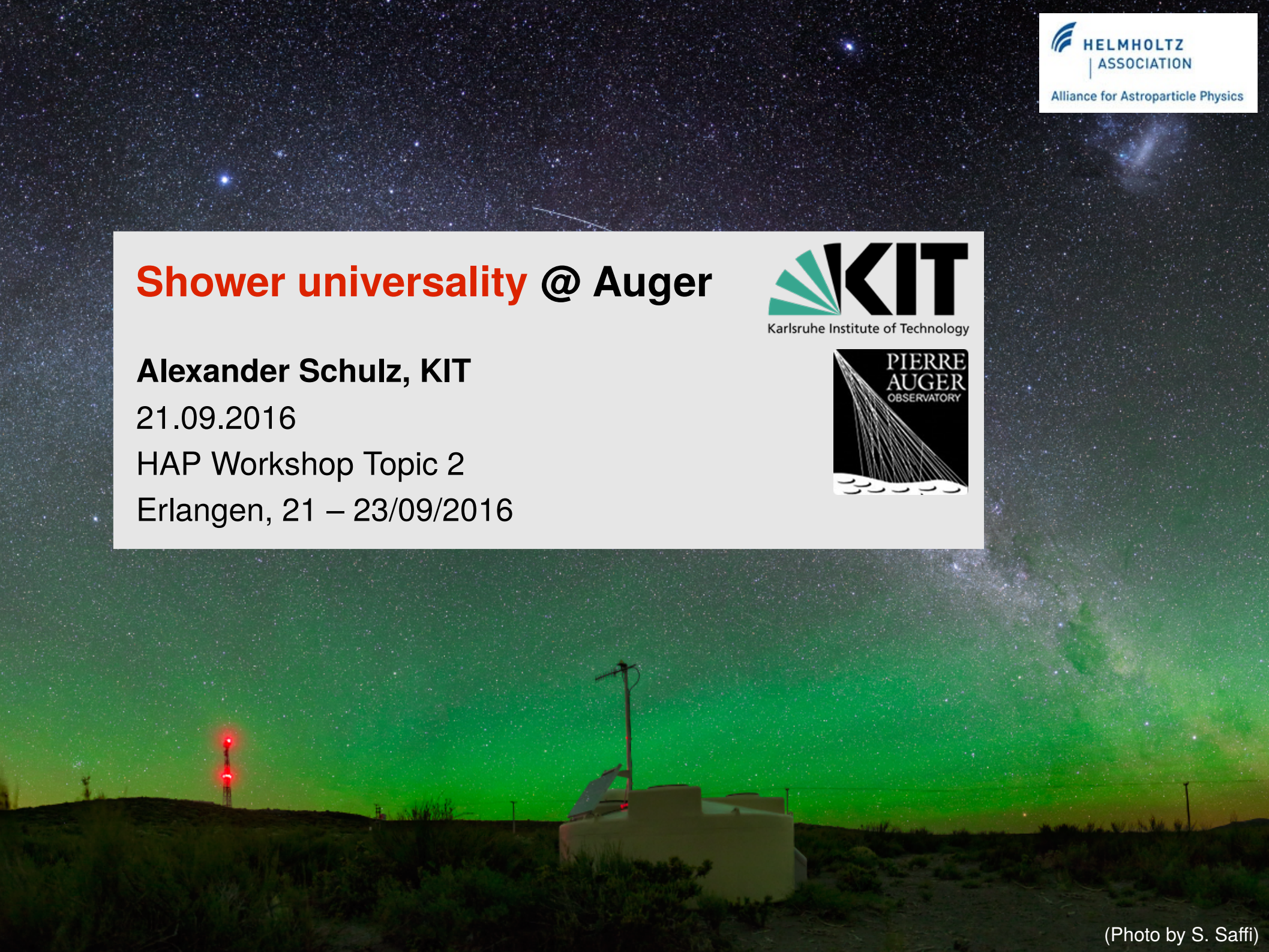


Shower universality @ Auger

Alexander Schulz, KIT

21.09.2016

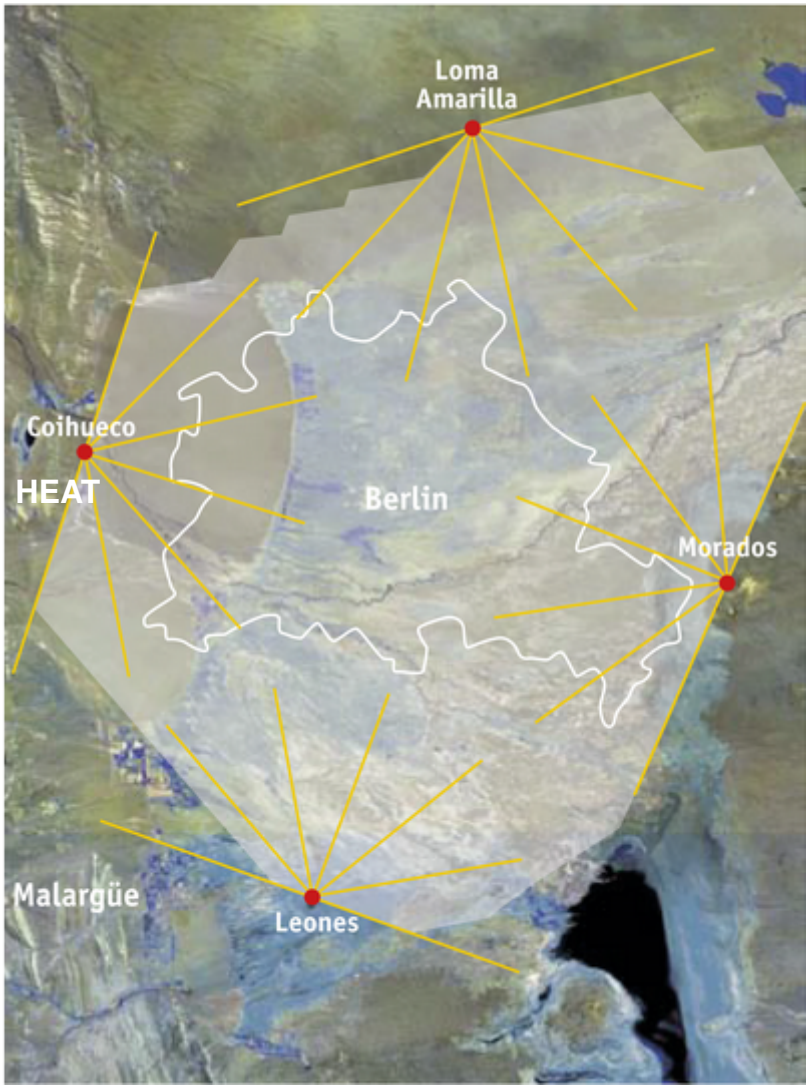
HAP Workshop Topic 2

Erlangen, 21 – 23/09/2016

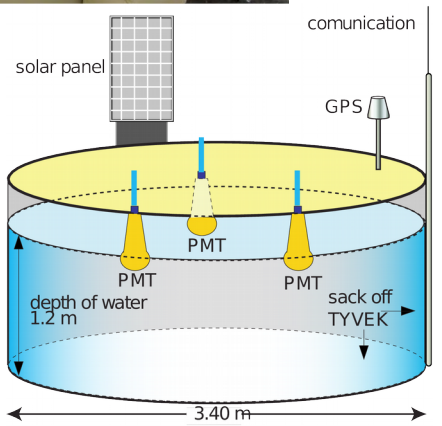
(Photo by S. Saffi)

The Pierre Auger Observatory

Measurement of UHECRs using a *hybrid approach* with **5 FD buildings** and **~1700 SD WCDs**

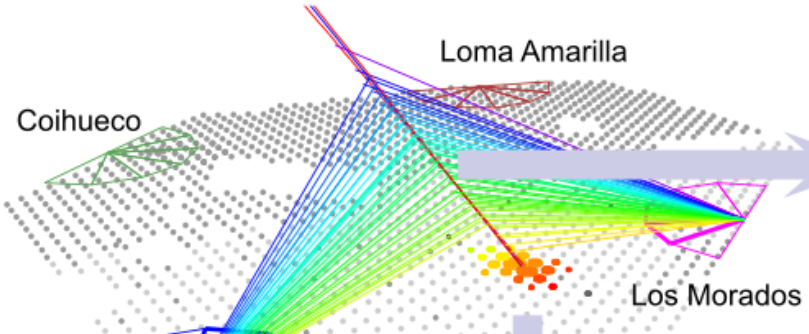


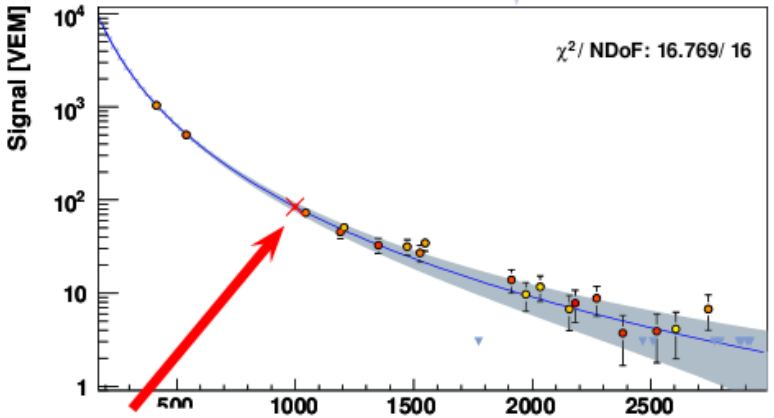
SD with upgrade prototype



Standard air shower reconstruction

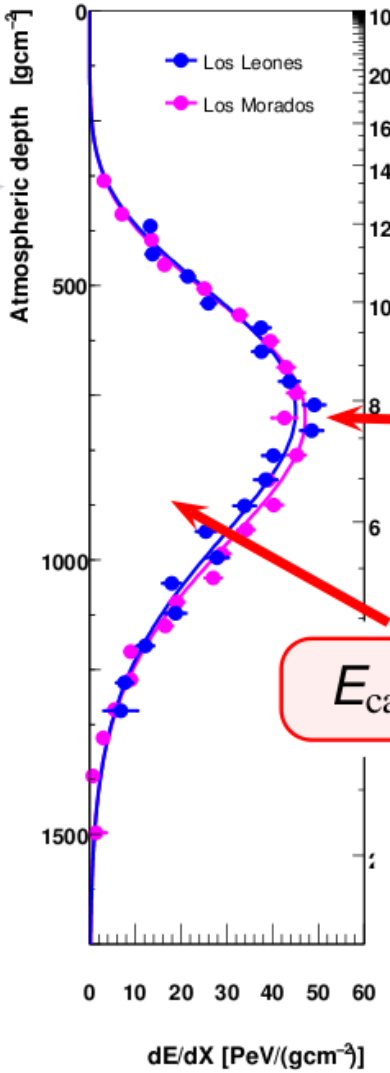
- Standard SD air shower reconstruction: based on an empirical description of the lateral distribution





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



$\sigma X_{\mathrm{max}} < 20\ \mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\ \mathrm{g/cm^2}$

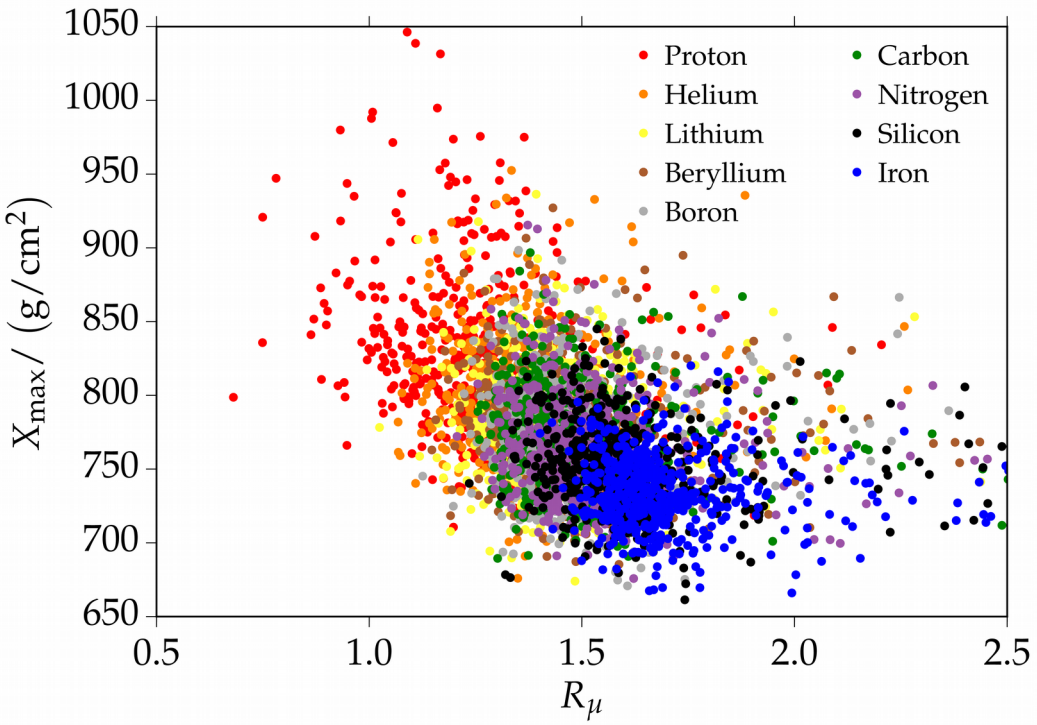
X_{max}

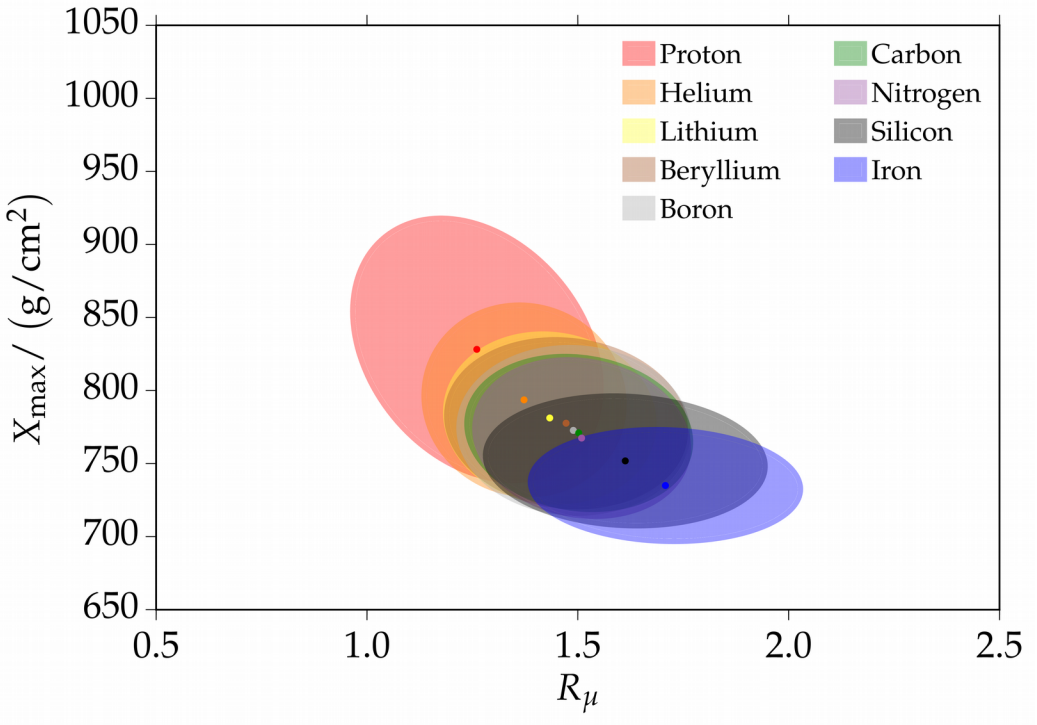
$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

Event discrimination of different elements

- Seperation of different elements in a plane spanned by X_{max} and R_μ
  - Event-by-event probabilities for a certain primary type can be calculated
  - Large overlap of intermediate elements, but light and heavy can be seperated
- Plots using QGSJet-2.4 simulations; reference model: QGSJet-2.3 proton
- Universality gives us a way to get the information using only the SD

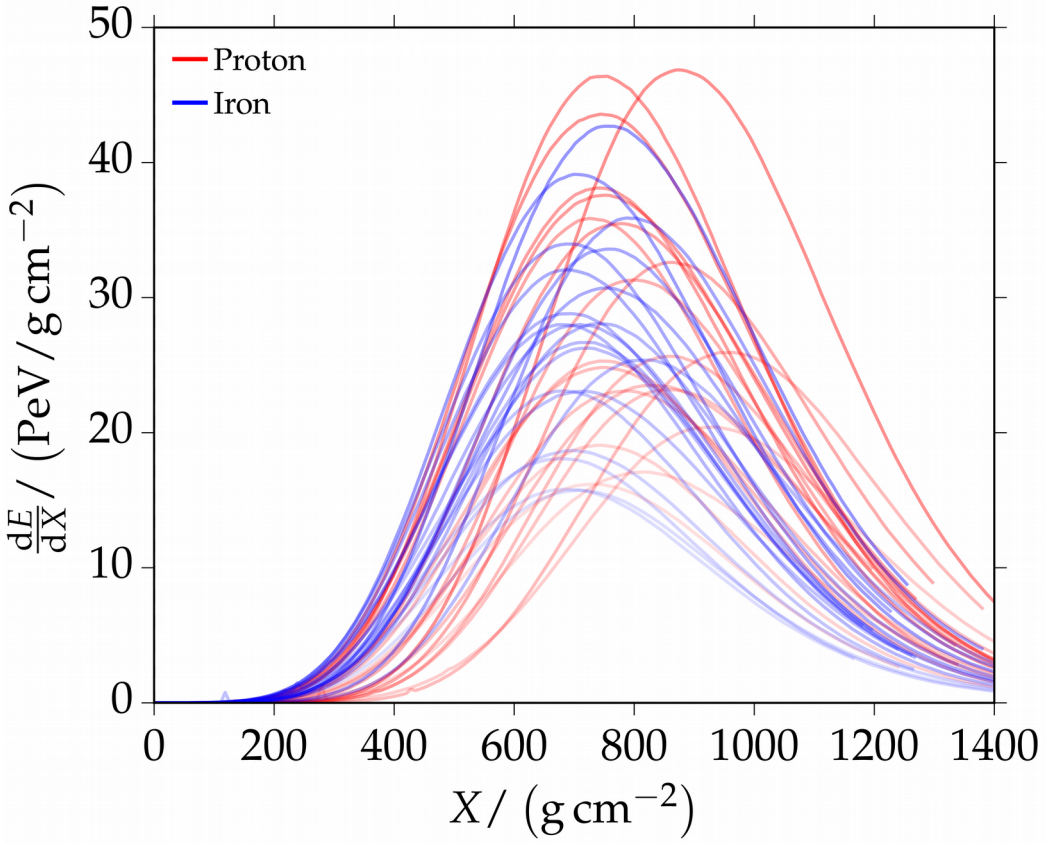


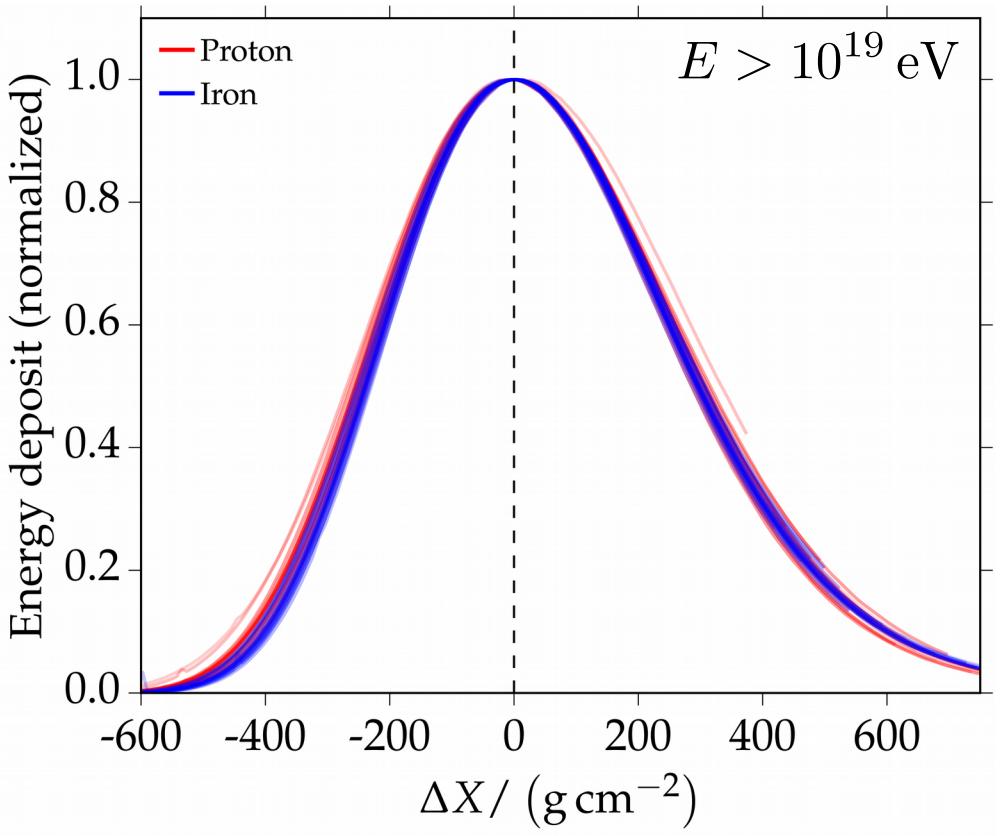


The basic idea of shower universality

- **Fluctuations in the shower development at UHECR energies** are *small enough* to achieve a “universal” shower description

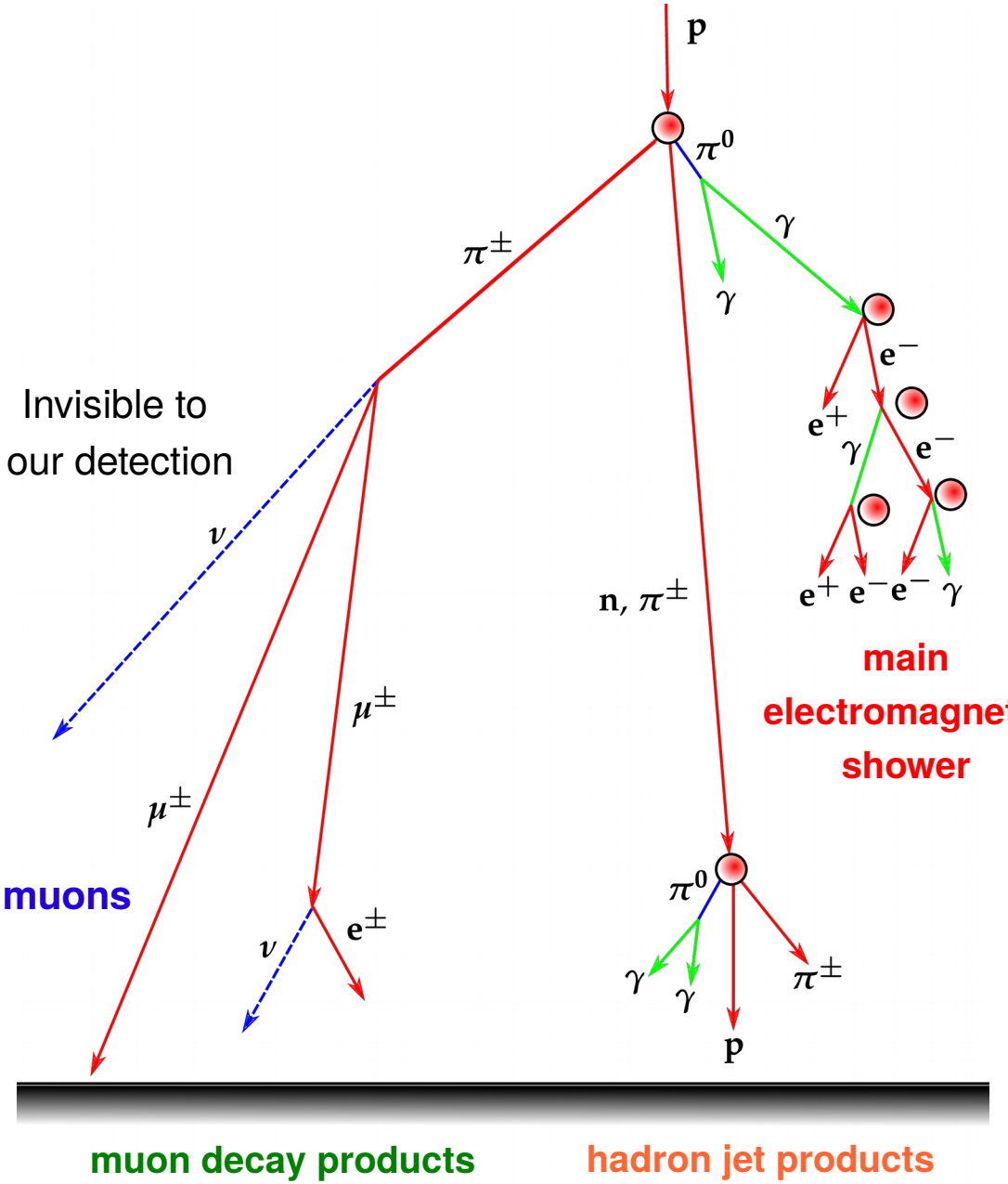
$$N_{\max} \propto E\,, \quad \langle X_{\max} \rangle \propto \ln A\,, \quad \langle X_{\max} \rangle \propto \ln E$$

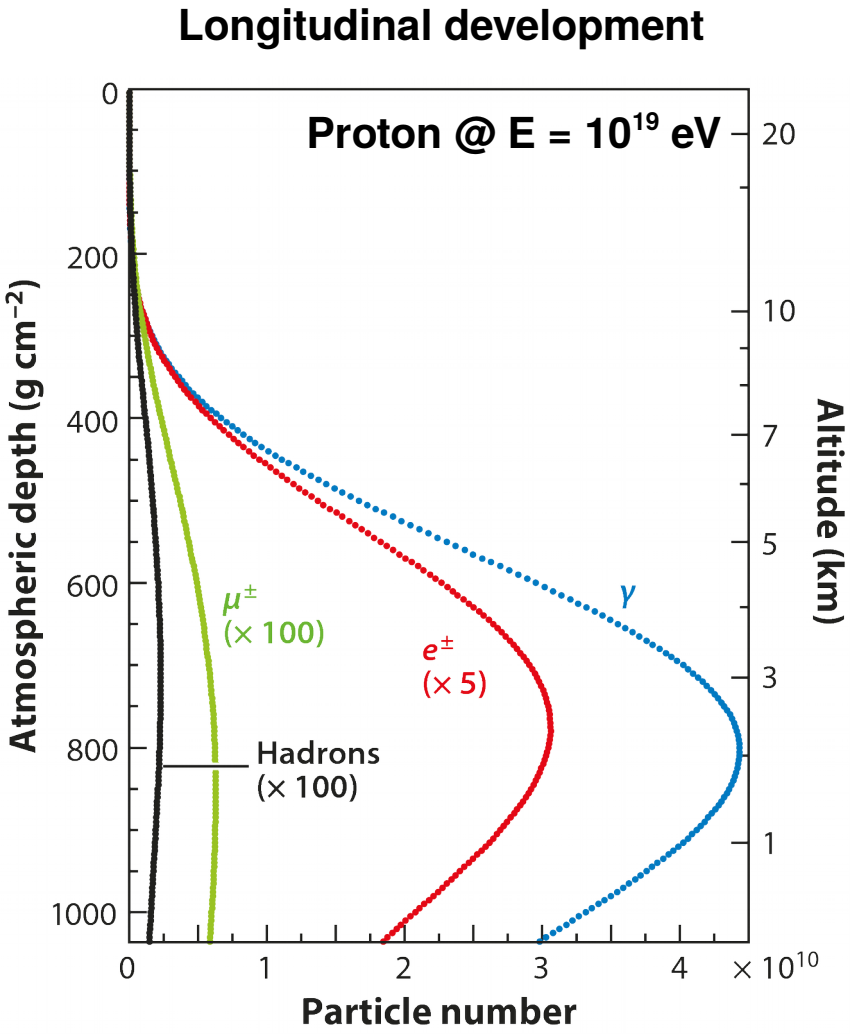




Normalized w.r.t. total energy deposit

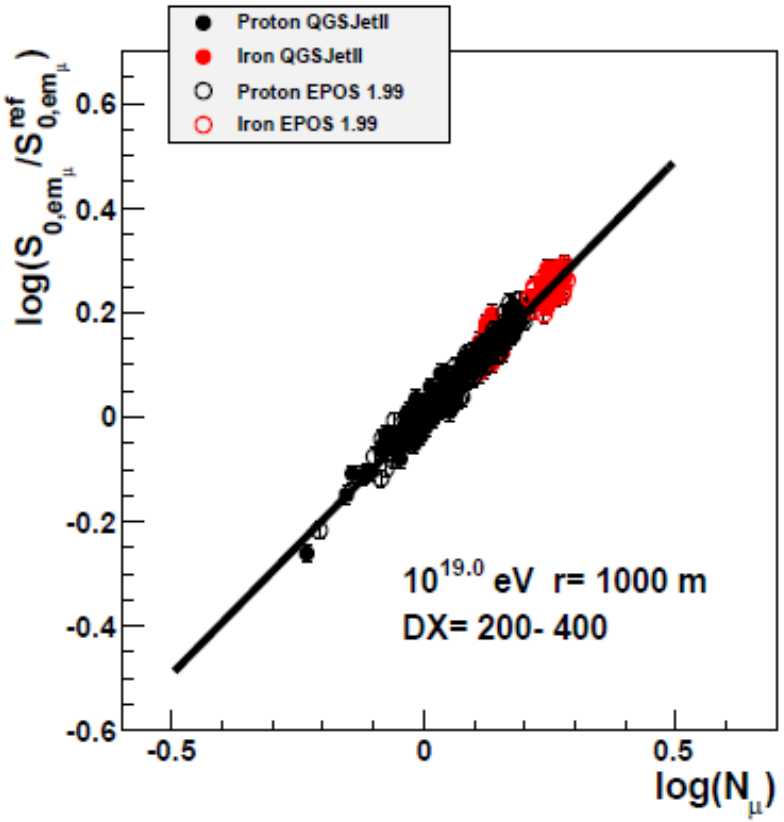
The physics behind shower universality

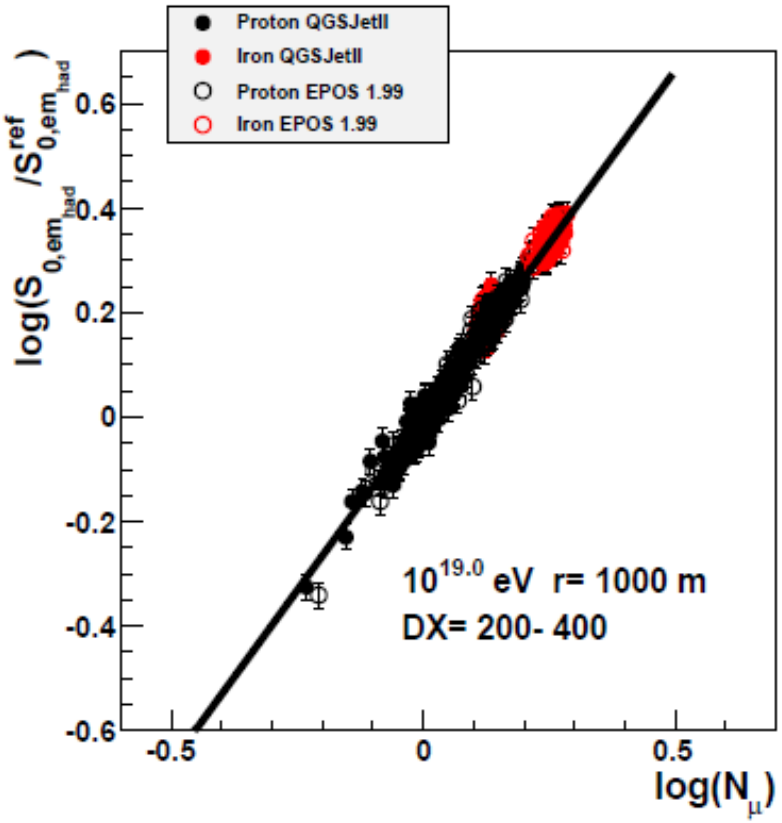




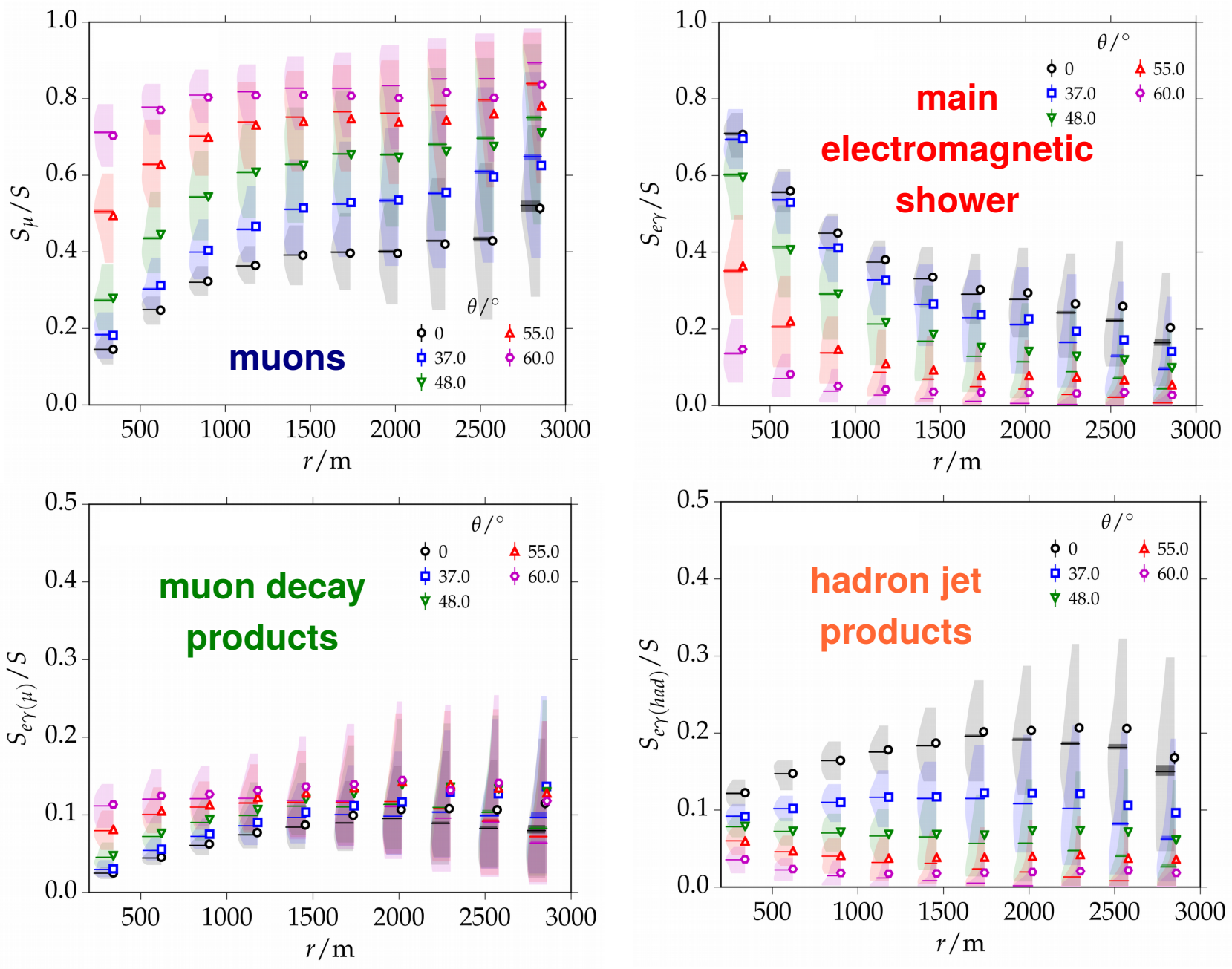
Scaling with the muon content

$$
\begin{aligned}
\text{total signal} \quad & S_{\text{tot}} = \\
\text{pure electromagnetic} \quad & S_{\text{em}}(DX, E) \\
\text{muonic} \quad & + N_{\mu}^{\text{rel}} \cdot S_{\mu}(DX, E) \\
\text{muon decay products} \quad & + N_{\mu}^{\text{rel}} \cdot S_{\mu}^{\text{em}}(DX, E) \\
\text{hadron jets} \quad & + (N_{\mu}^{\text{rel}})^{\alpha} \cdot S_{\text{em}}^{\text{jet}}(DX, E)
\end{aligned}
$$





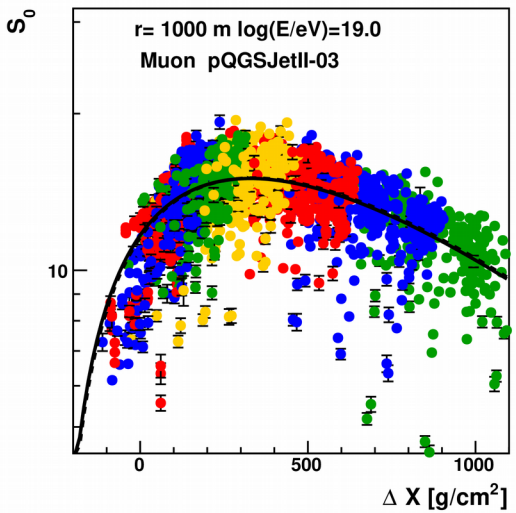
Shower components at Auger observation level

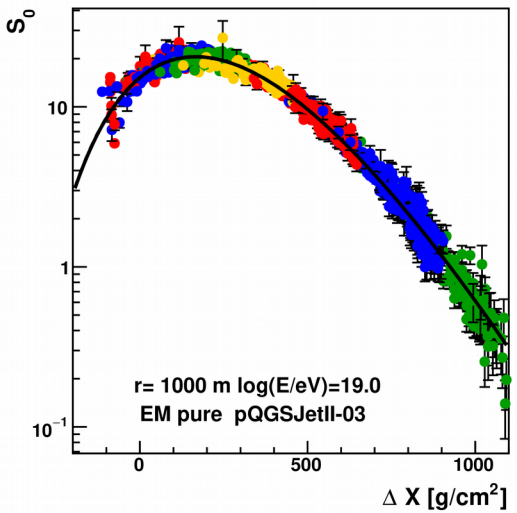


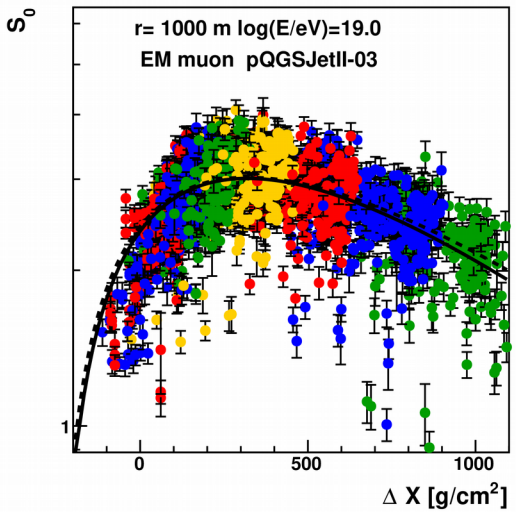
QGSJet-2.3, EPOS-1.9 simulations of proton, carbon, iron at energies > 50 EeV

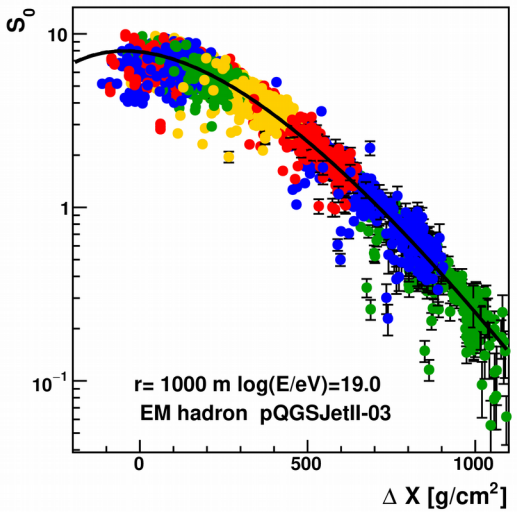
Shower development of the signals

Distance to the shower maximum ΔX has main impact on the signal size

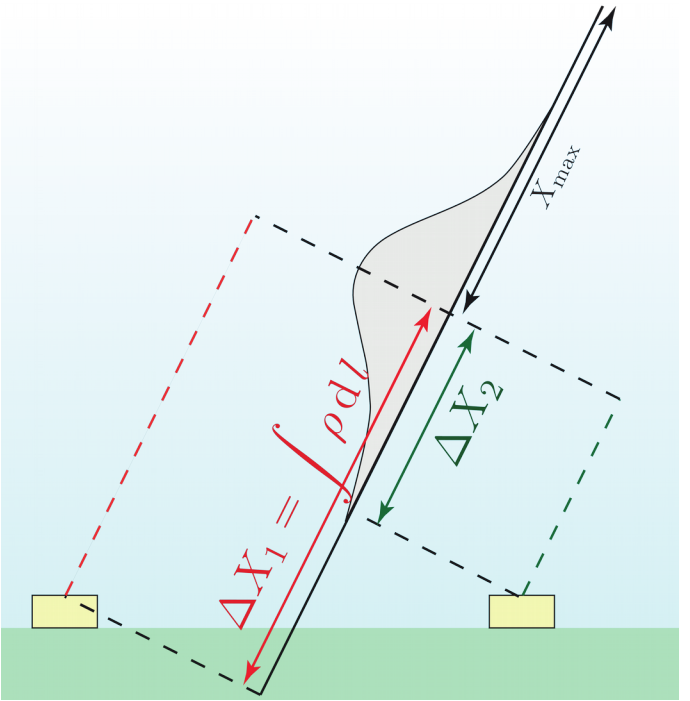








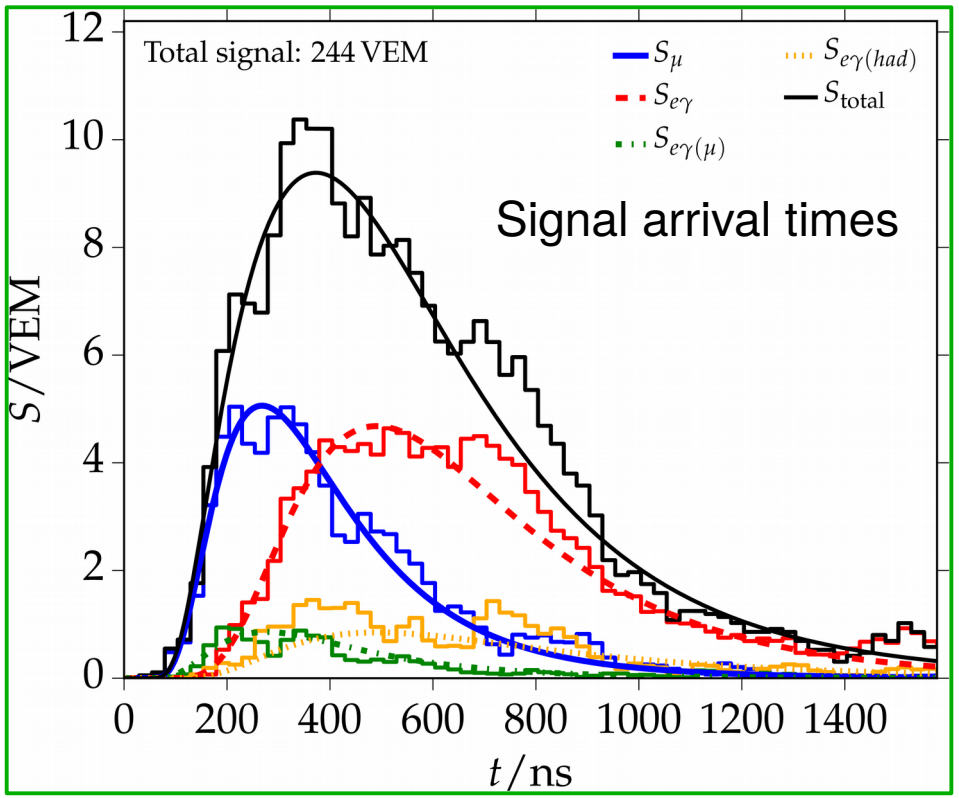
Longitudinal shapes are described with Gaisser-hillas functions

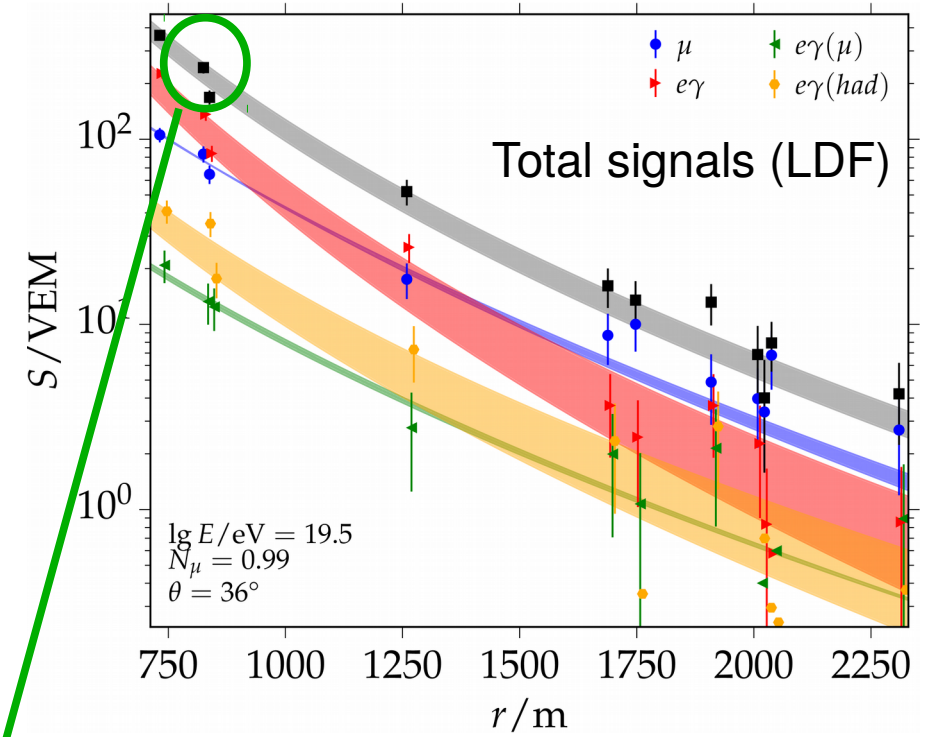


A detailed description of air showers

$$S = S(\Delta X, E, R_\mu, r)$$

- Model of the longitudinal and lateral signal development
- Total signal:
  Sum of the 4 signal components





- Model of particle arrival times for the four components
- First particle arrival times:
  Spherical shower fronts
  (origin depends on particle type)

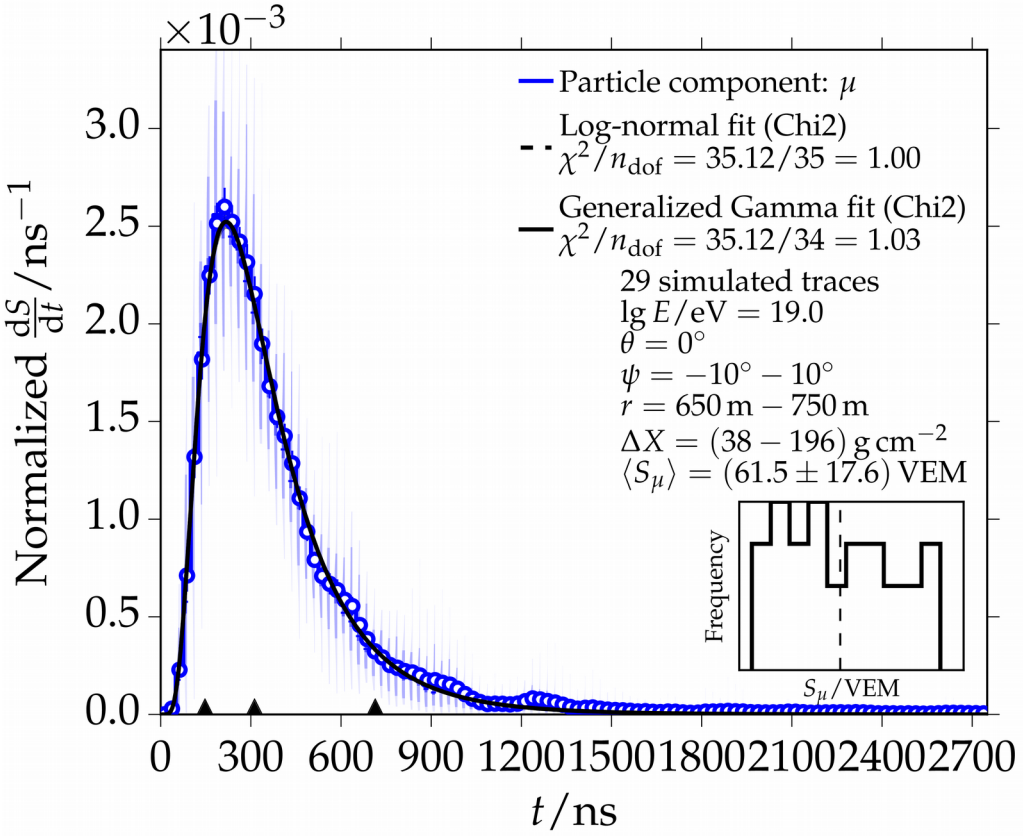
A model of signal arrival times

- Description of average time traces by *log-normal distributions* (mean *m* and width *s*)

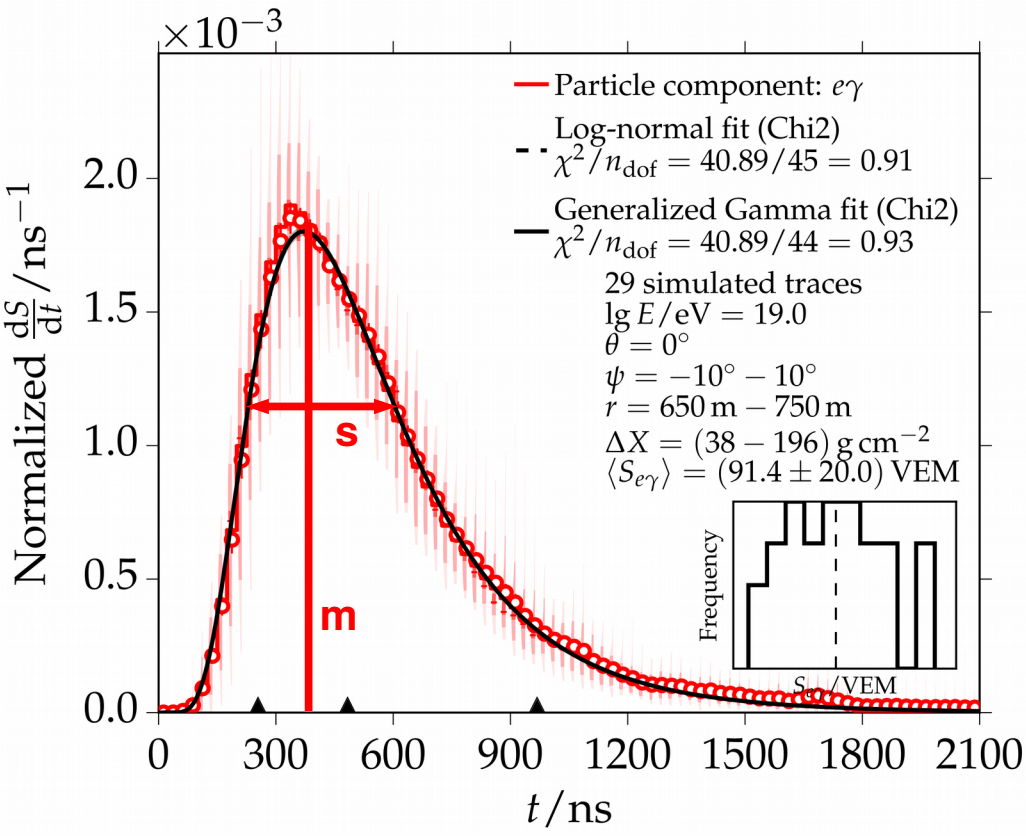
$$f(t|m,s) = \frac{1}{t\,s\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(t/\mathrm{ns})-m}{s}\right)}$$

  - QGSJet-2.3, EPOS-1.9 simulations of proton, carbon, iron, energies 0.1 – 100 EeV

muons



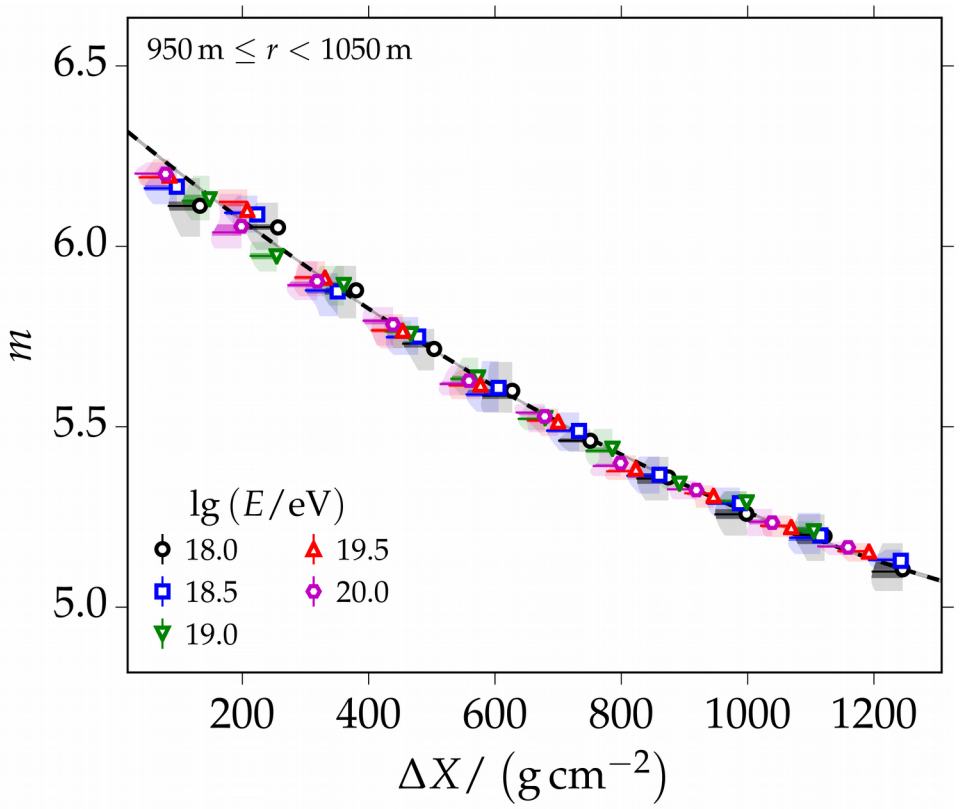
main electromagnetic shower



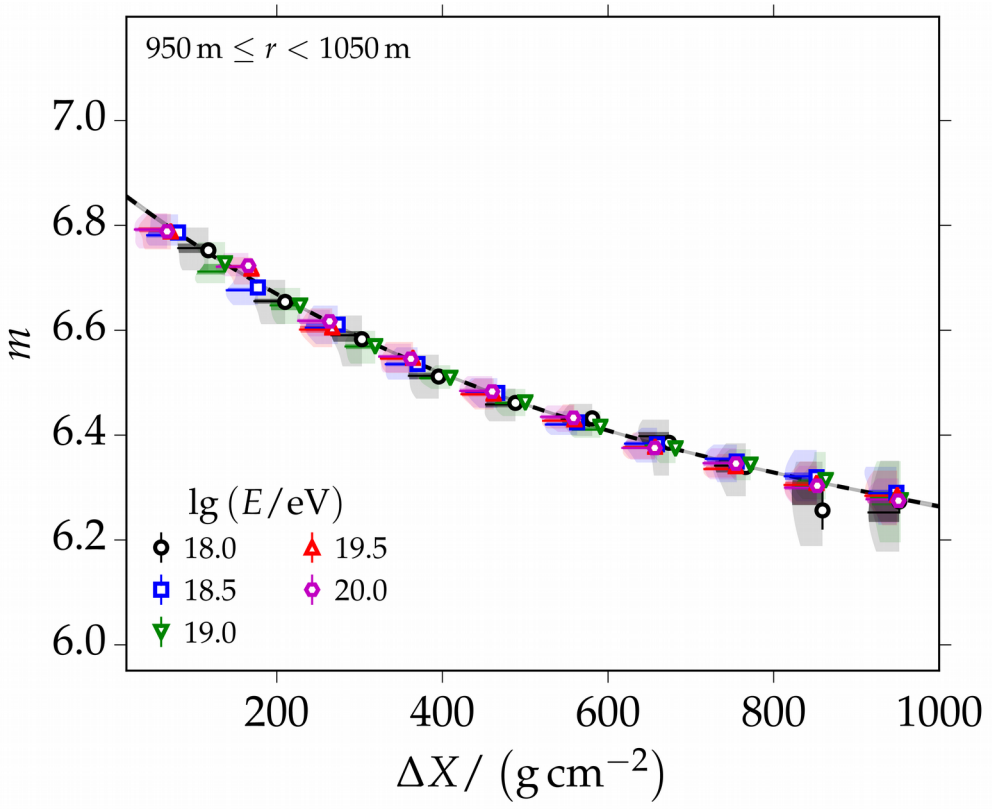
Average time delay

- Similar dependencies of the average time delay of different particle components on the distance to the shower maximum (widths exhibit different behaviors)

muons

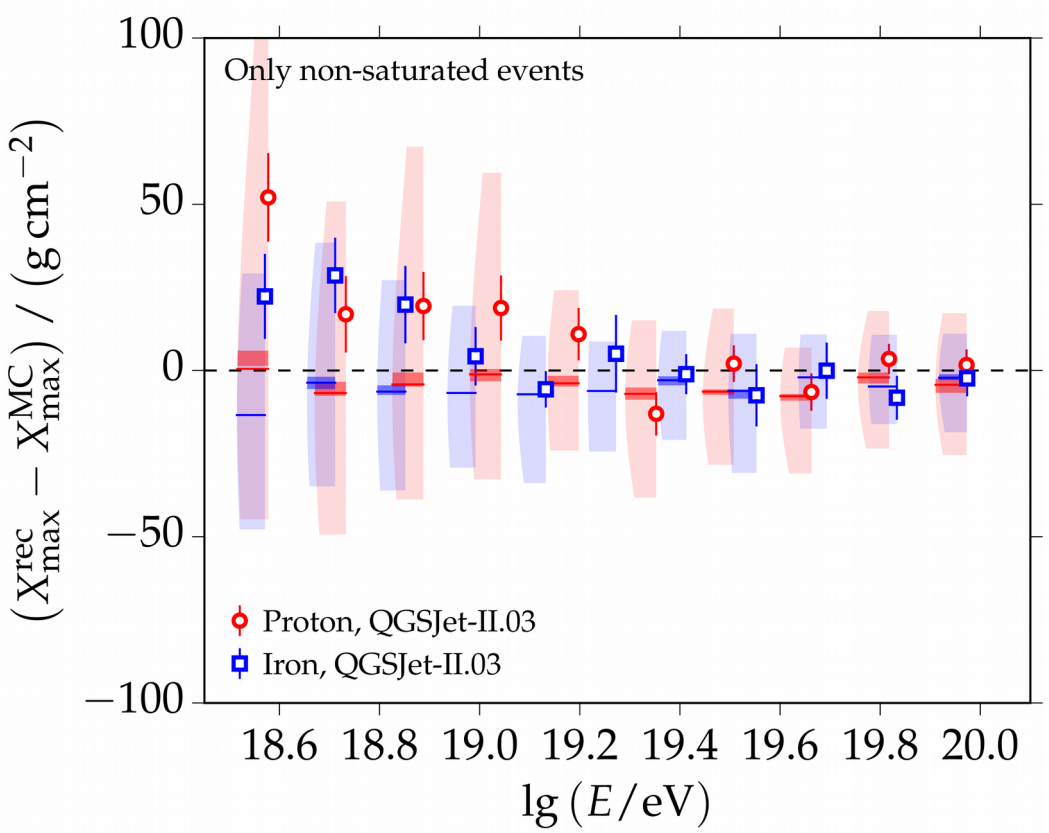


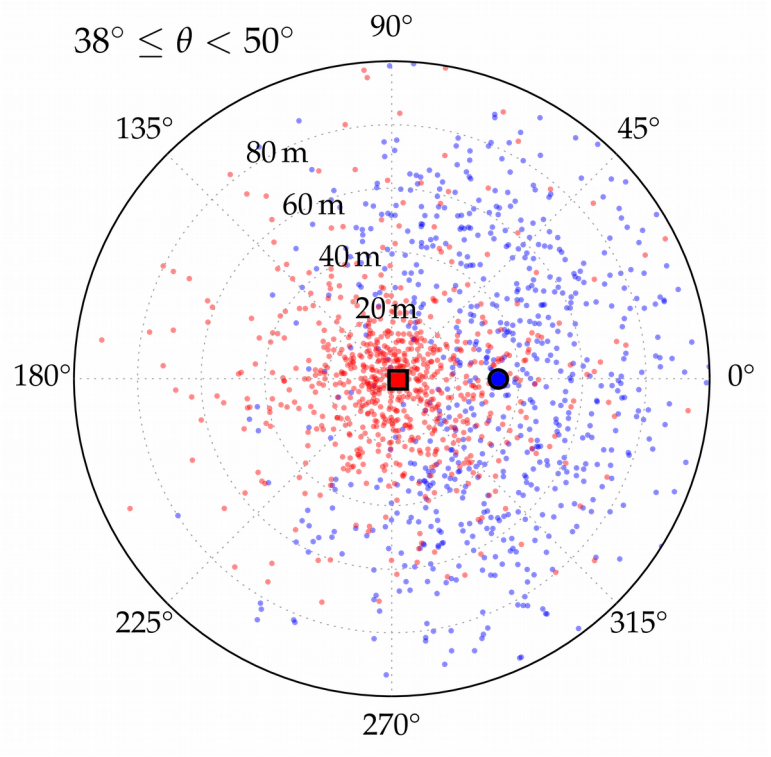
main electromagnetic shower



Air shower reconstruction with SD universality

- **Make use of full SD data to extract mass information**
- **Unbiased reconstruction** of the shower core and arrival direction
  - Asymmetries in the shower development naturally included



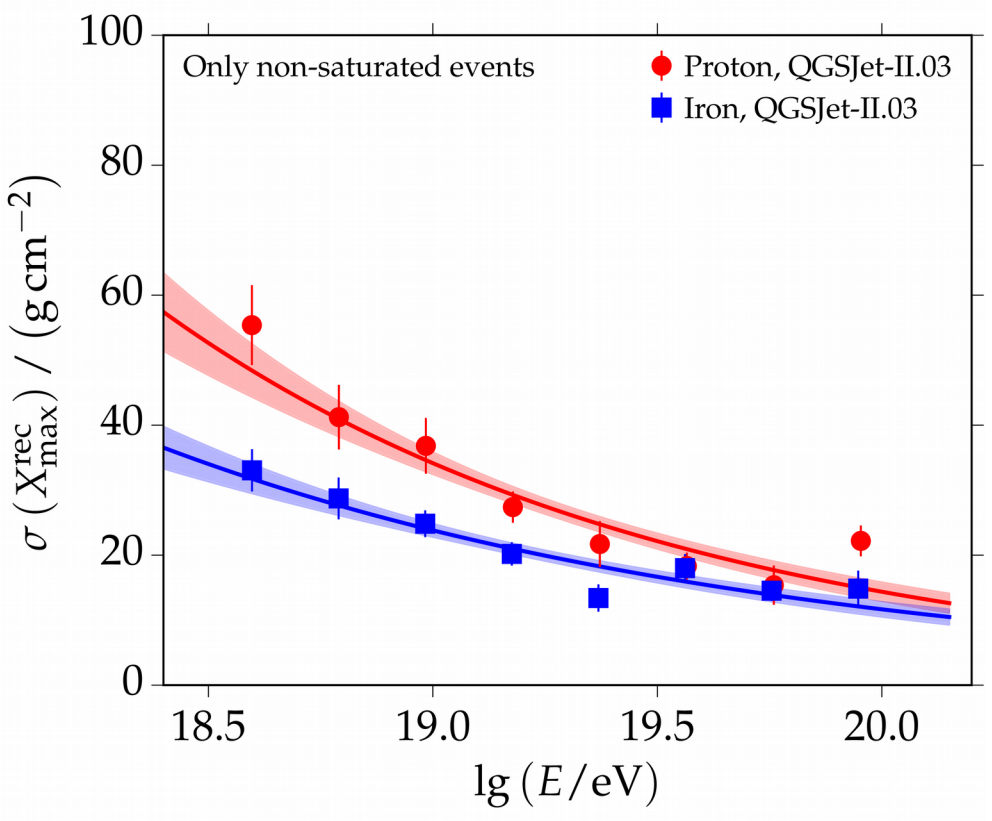


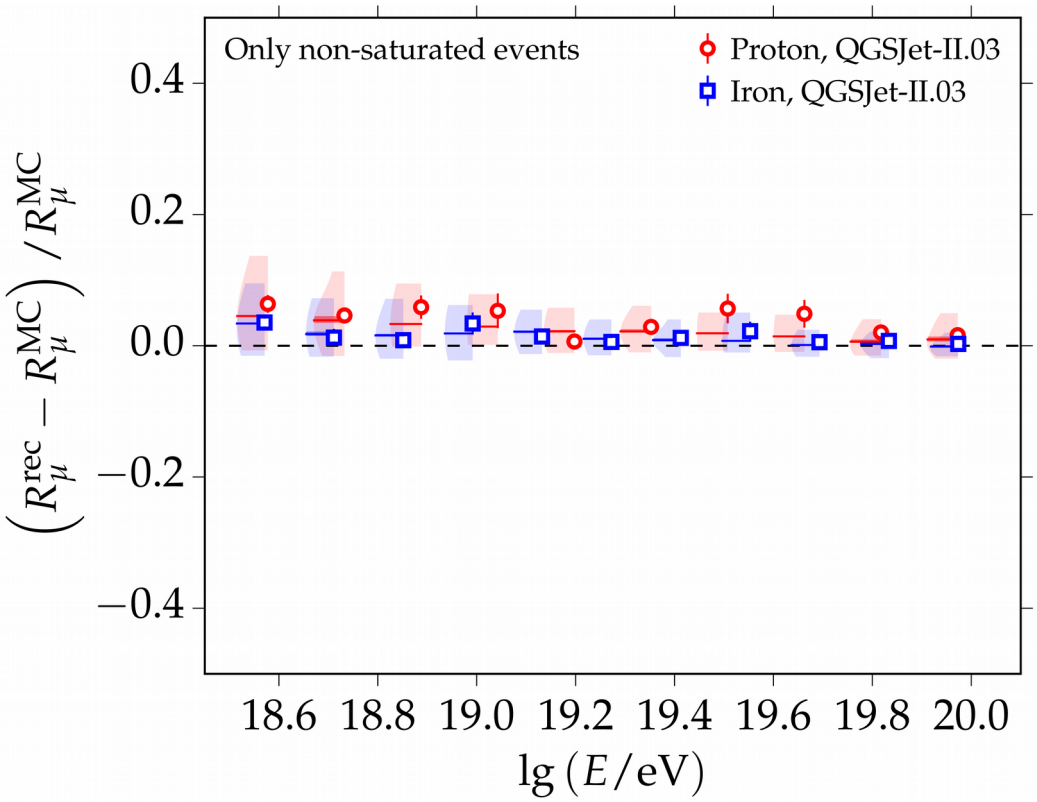
- At energies > 10 EeV: unbiased reconstruction of the depth of shower maximum using only SD information!

  + Relative muon number

Reconstruction quality

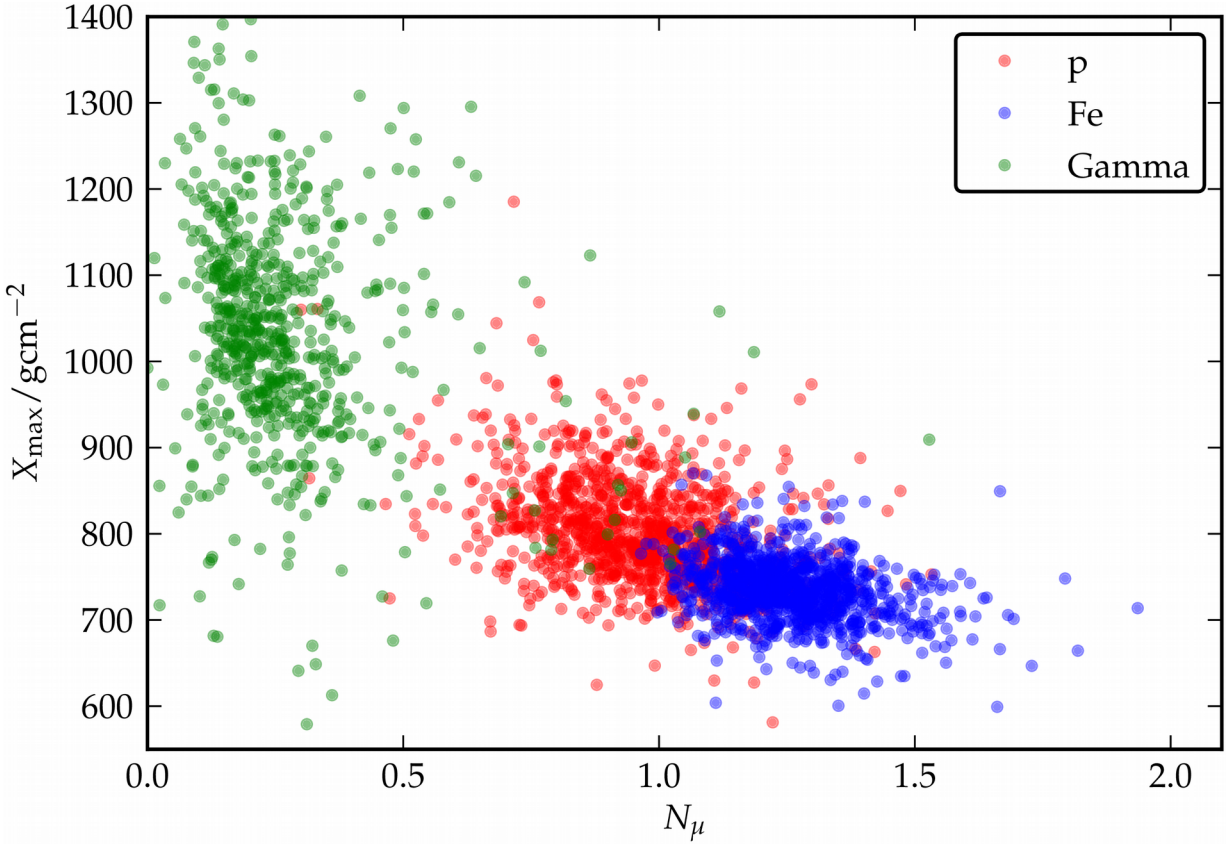
- Resolution in X_{max} on the order of **20 g/cm² achievable at the highest energies**
  - Depends on primary particle due to (mostly) size of muon content
- Unbiased estimation of the relative muon content





Further applications of universality

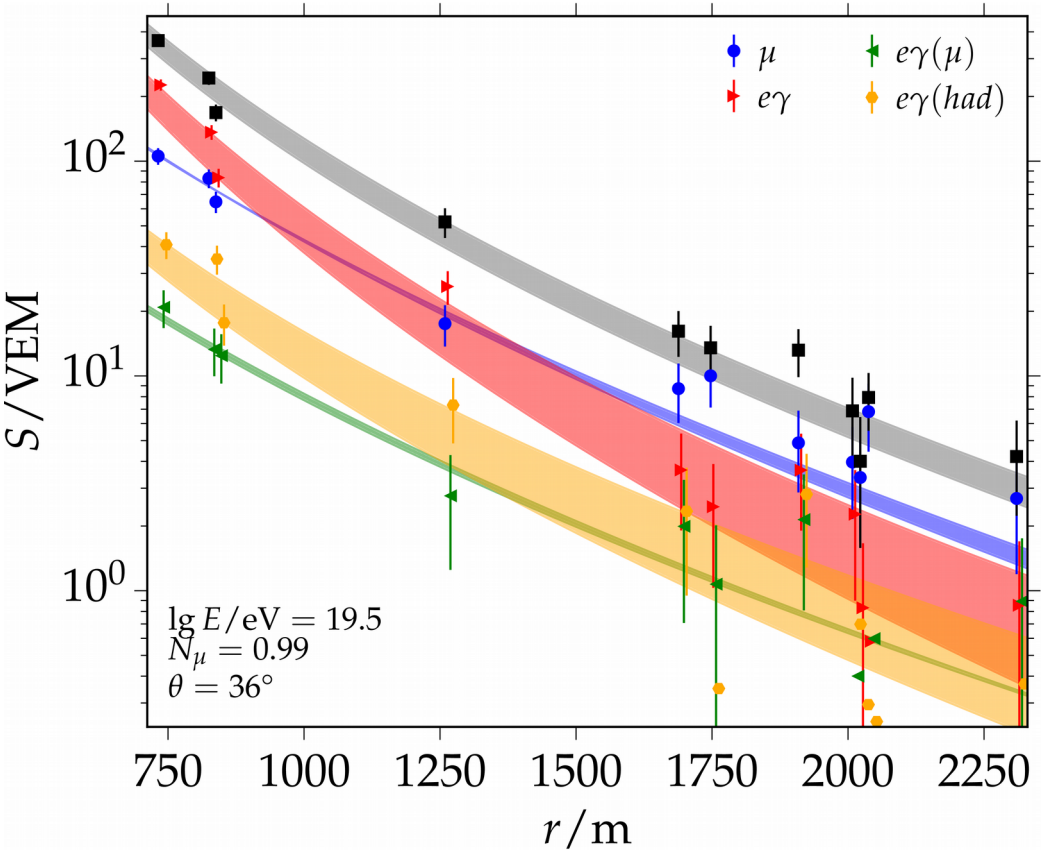
- Determination of the energy spectrum independent of the standard reconstruction
- Search for photons, neutrinos, exotics…
- Compare models to data and learn more about hadronic interactions



AugerPrime

- Measurement of different particle components with the **combination of WCD + SSD**
  - We can constrain and tune universality models with data!

    → More powerful physics-based air shower reconstruction



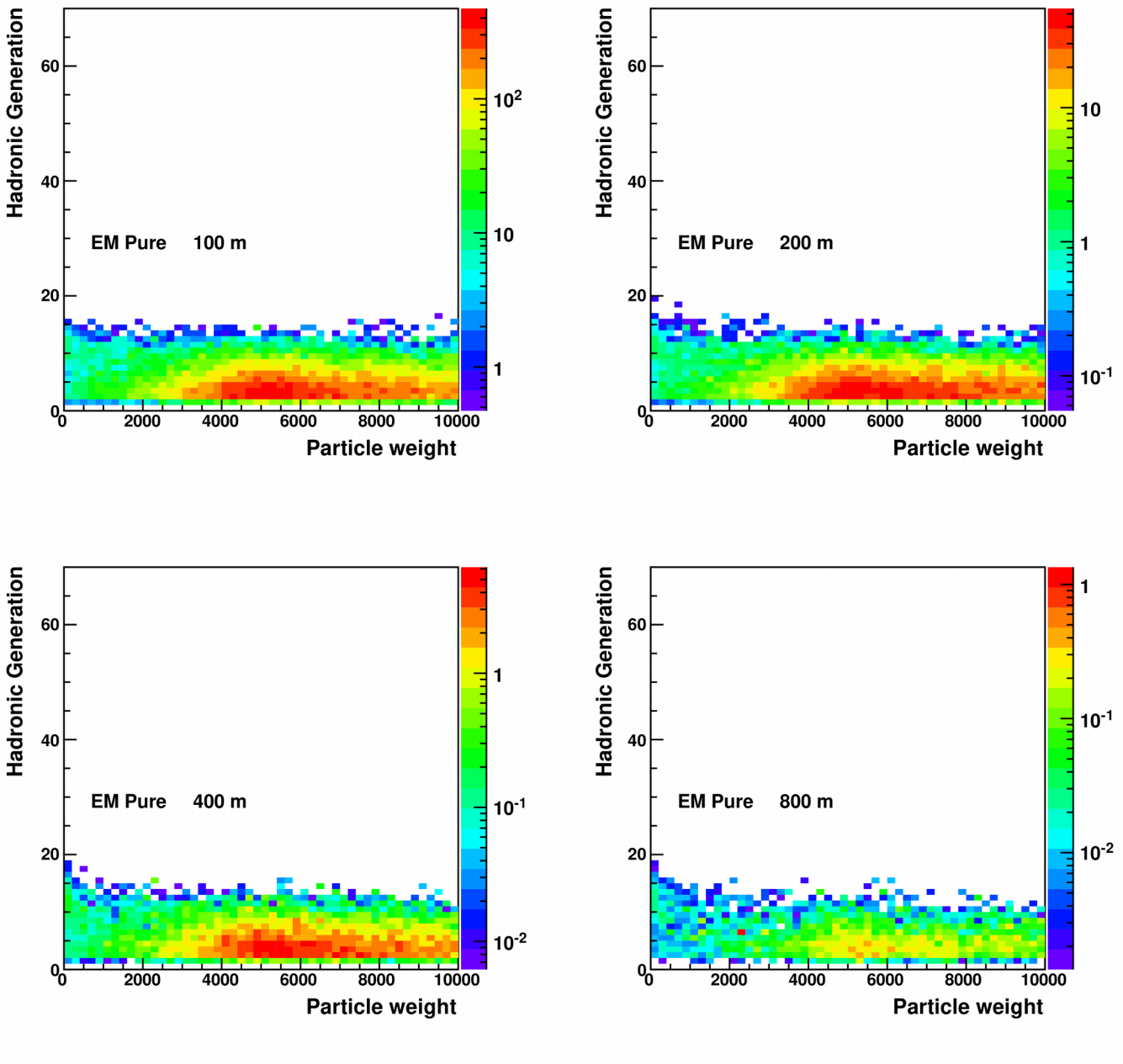
Summary and outlook

- Full description of air shower signals and times following the paradigm of shower universality
- *Independent, physics-based reconstruction* of air showers
  - Accurate estimation of the depth of shower maximum, energy and relative muon content
- Estimation of the primary mass based on statistical averages

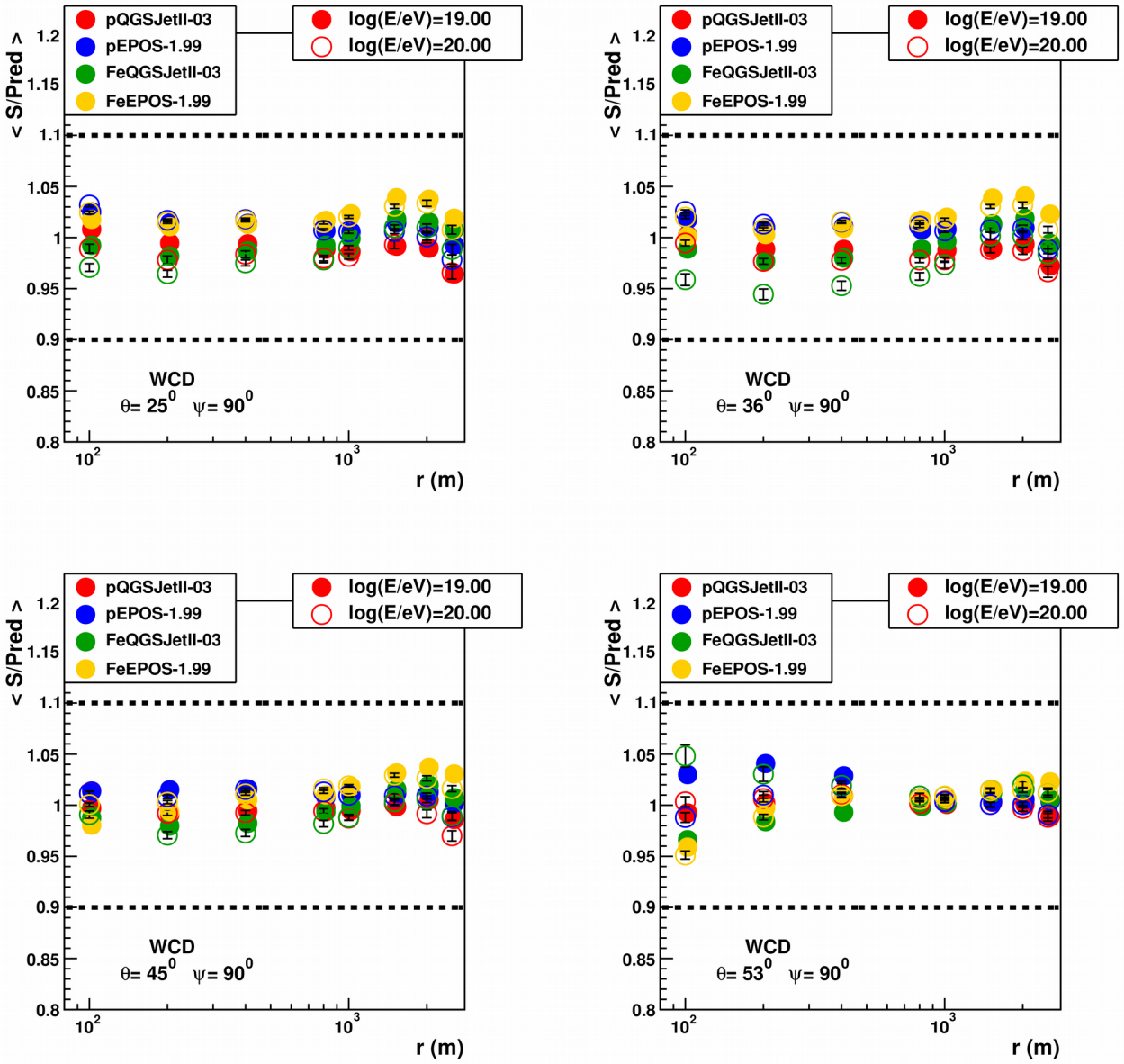
  or using mass discrimination on event-by-event basis (i.e. fisher analyses)
- Reconstruction of the primary flux independent of the standard method
- Universality will be a powerful tool together with the upgraded detectors of AugerPrime
- Further applications to search for photons, neutrinos etc.

Backup

Separation of hadron jets



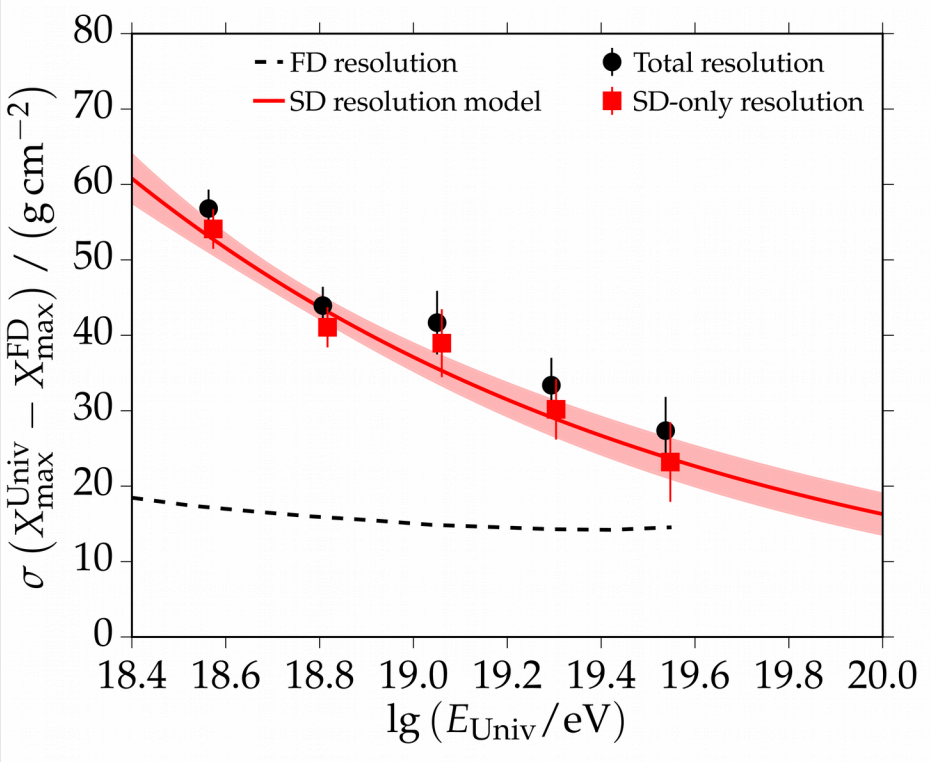
Signal model residuals



Two different reconstruction types

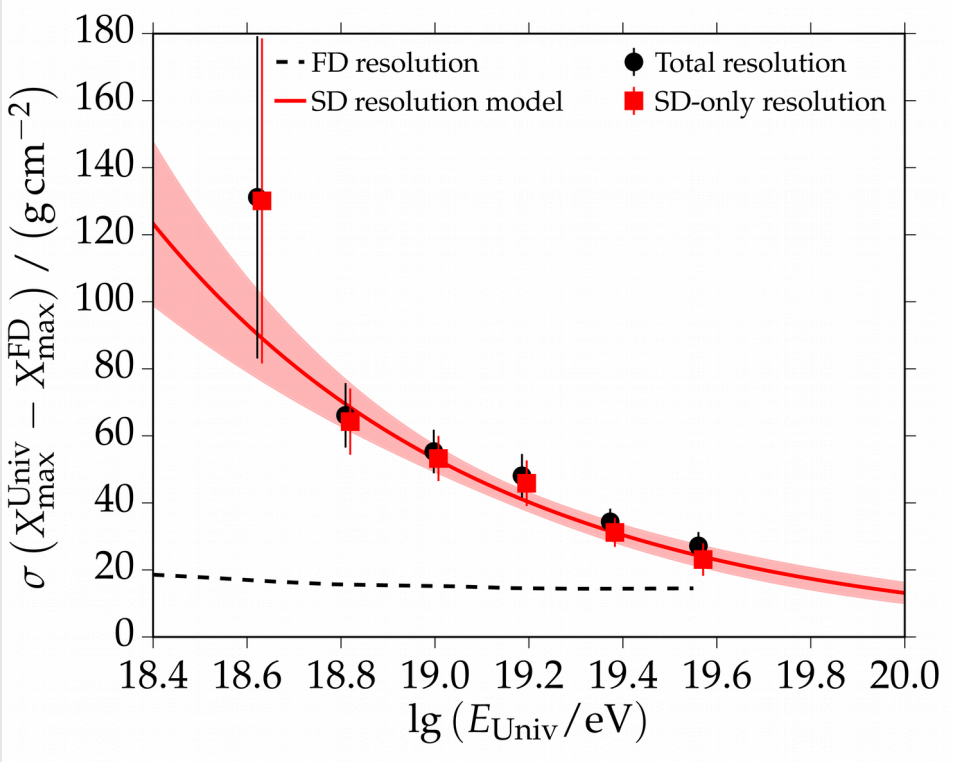
Iterative reconstruction

- *Quantities are fit in separate stages*
  1) energy, core 2) Xmax, timing 3) …
- Makes use of constraints to results of the SD reconstruction and models derived from golden hybrids
- Better resolution of rec. quantities
- Not all correlations are taken into account, outliers



Classic reconstruction

- *Only one reconstruction stage*
  - All quantities except the primary energy are simultaneously fit (energy is fixed to SD result)
- Correlations are taken into account
- Needs large number of candidate stations of >7
- Reconstruction biases below 10 EeV, large resolutions



Auger Infill WCD SD with SSD, Amiga