HEP Seminar May 2000.

How to Measure Cosmic Ray Composition through Air Showers: Interpreting the Data from BLANCA/CASA/MIA.

Talk outline:

- Cosmic Rays — What are they and why do we care? What do we know and what would we like to find out?
- Anatomy of an Extensive Air Shower — How can we measure them and get information about the Primary Cosmic Rays?
- Shower Simulations — The CORSIKA program
- The BLANCA/CASA/MIA experiment:
  - Finding the Primary Energy.
  - Finding the Primary Mass.
- Conclusions

Clem Pryke - University of Chicago

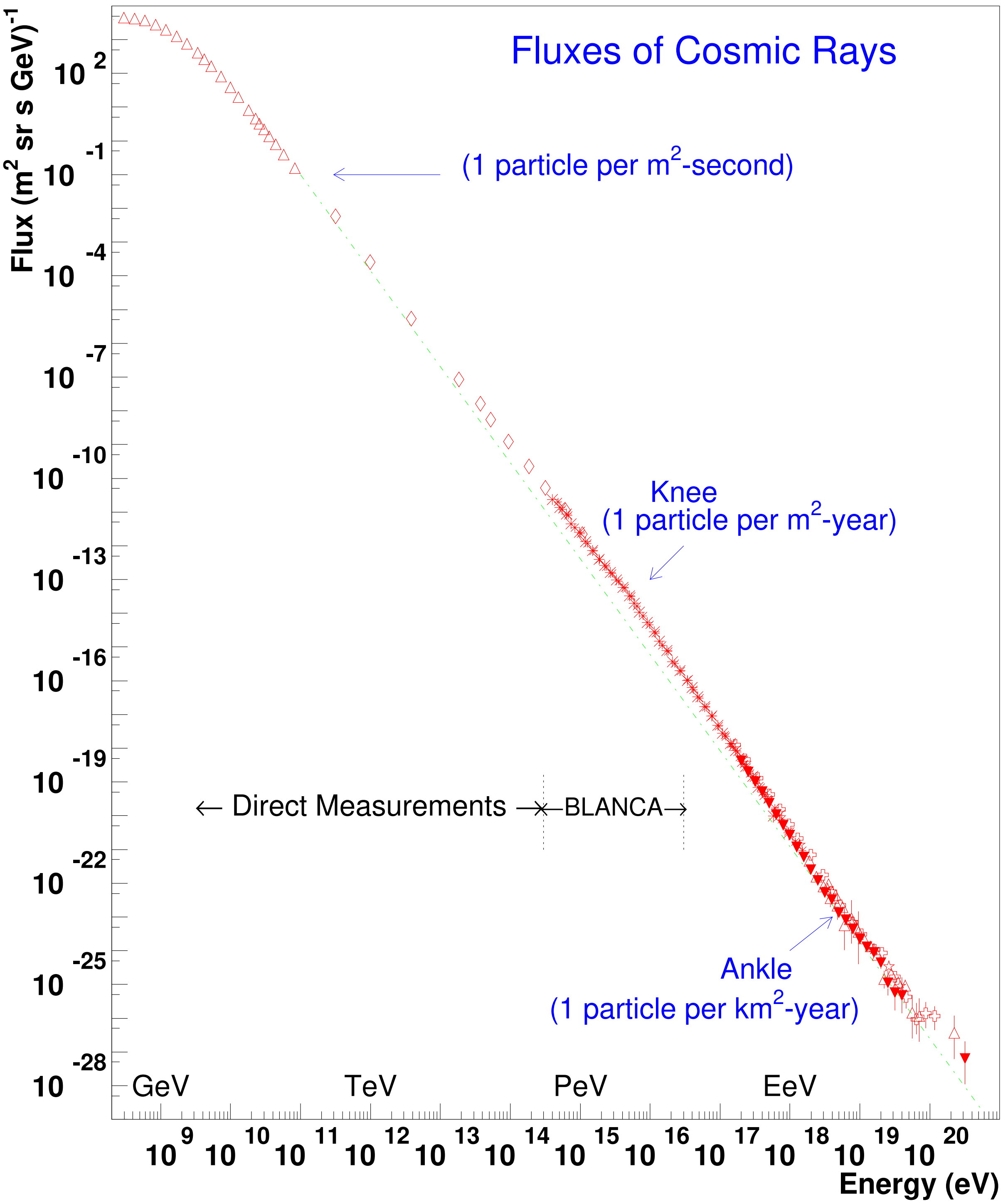
What are they and why do we care?

- A flux of relativistic charged particles apparently filling galactic space.
- Most important observational feature is a power law energy spectrum: $\frac{dN}{dE} \propto E^{-2.5}$
- An important/intriguing fact: Many energy densities are similar (~ 1 MeV m^{-3})

CR $\sim$ B-Field $\sim$ Starlight $\sim$ Gas-motion ($\sim$ CMB)

- However, most of the energy is at the bottom end of the spectrum... Though not as overwhelming as you might think: $\frac{dE}{dlog(E)} \propto E^{-0.5}$.

The Cosmic Ray Energy Spectrum

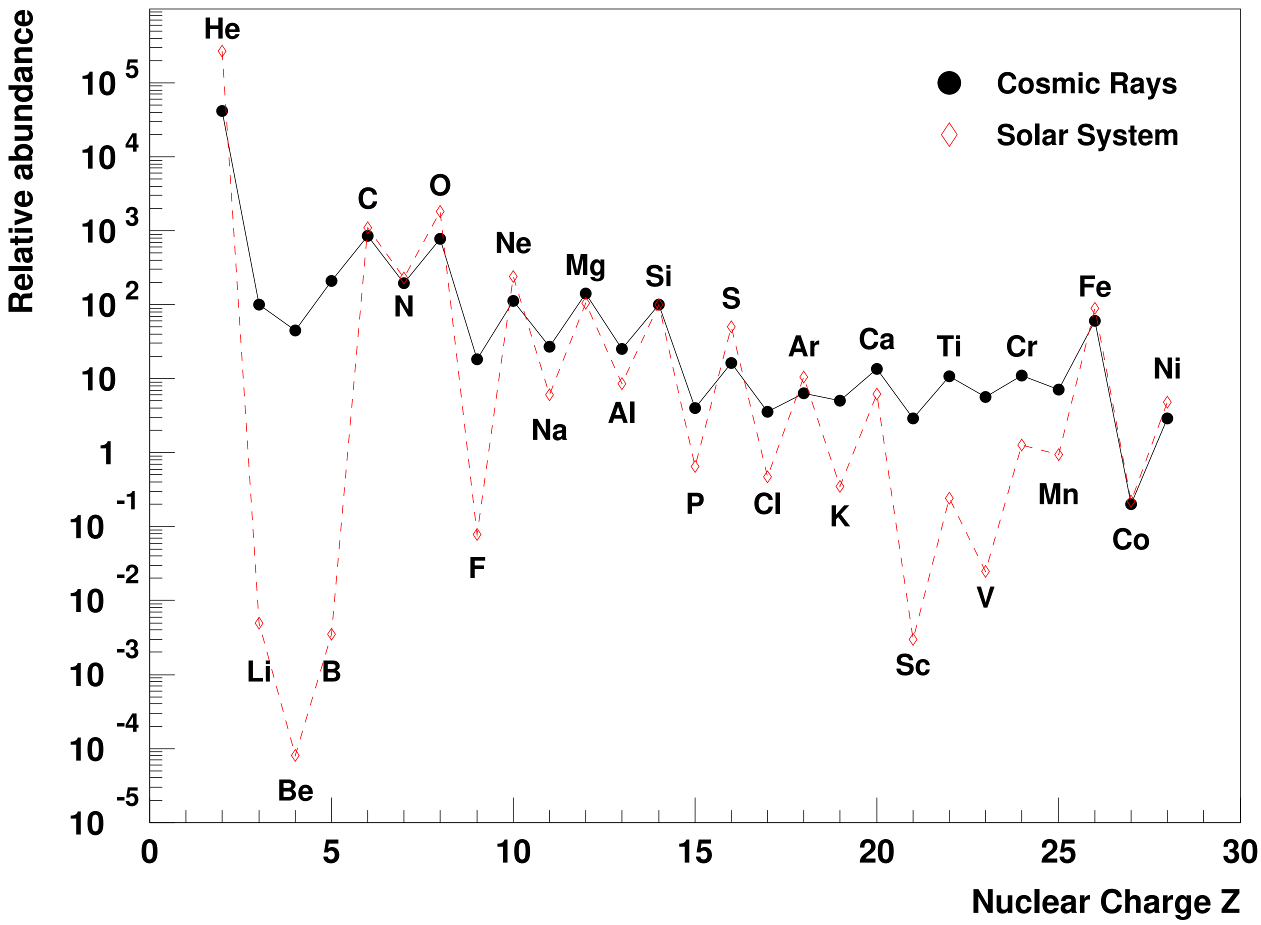


from Swordy, Scientific American

What we know at Lower Energies

- Can directly measure particle type and energy with satellite and balloon experiments.
- Also arrival direction — but tells us nothing due to interstellar magnetic fields...
- Elemental composition tells us many things... Spallation etc...
- High resolution isotopic ratios tell us even more... Radio isotope "clocks" etc...
- Plausible source theory: Supernova shock acceleration.
- All of this is possible because we get to measure the uninteracted primary...

Low Energy Cosmic Ray Composition

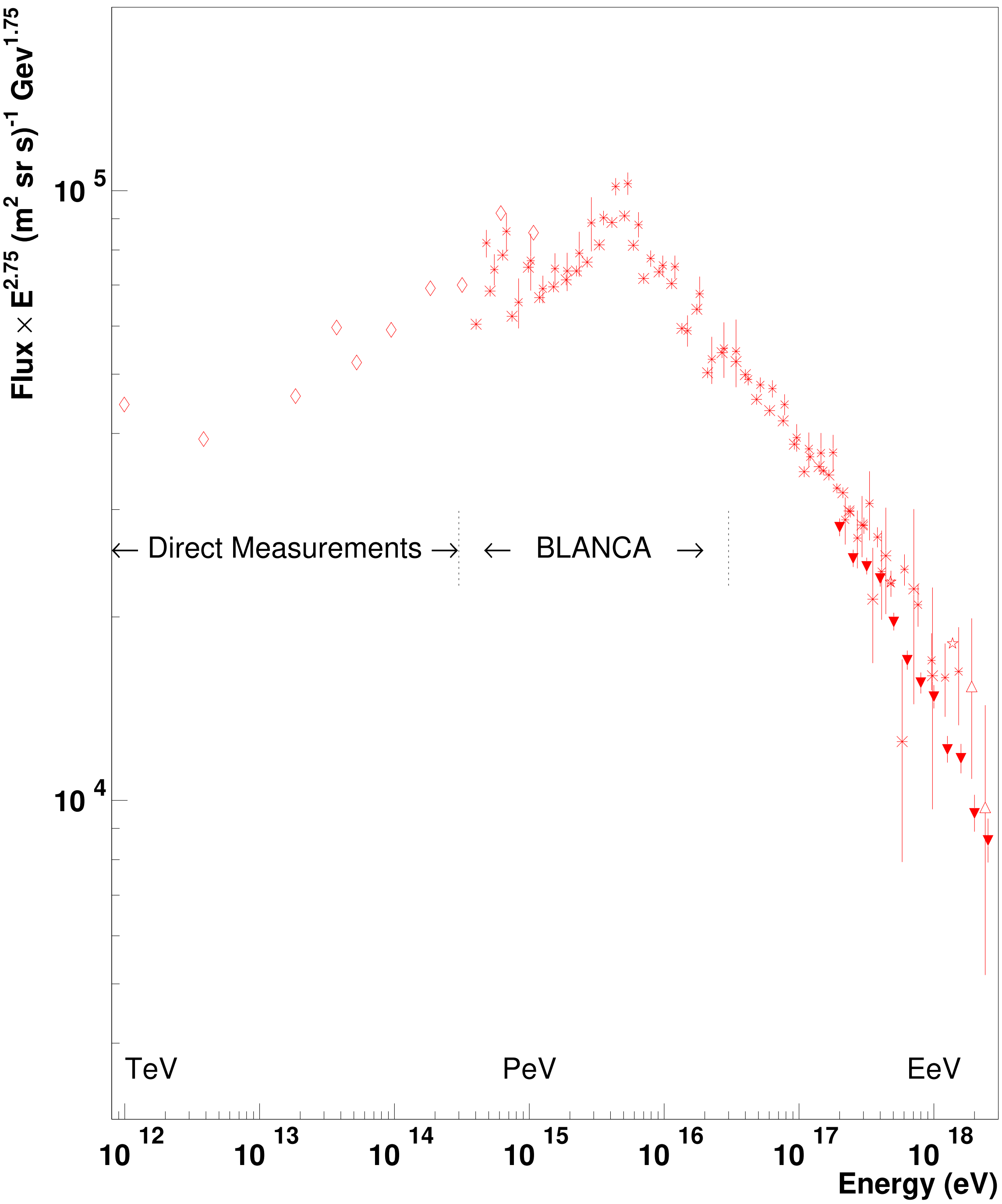


from Simpson Ann. Rev. Nucl. Part. Sci. **33** (1983) 326

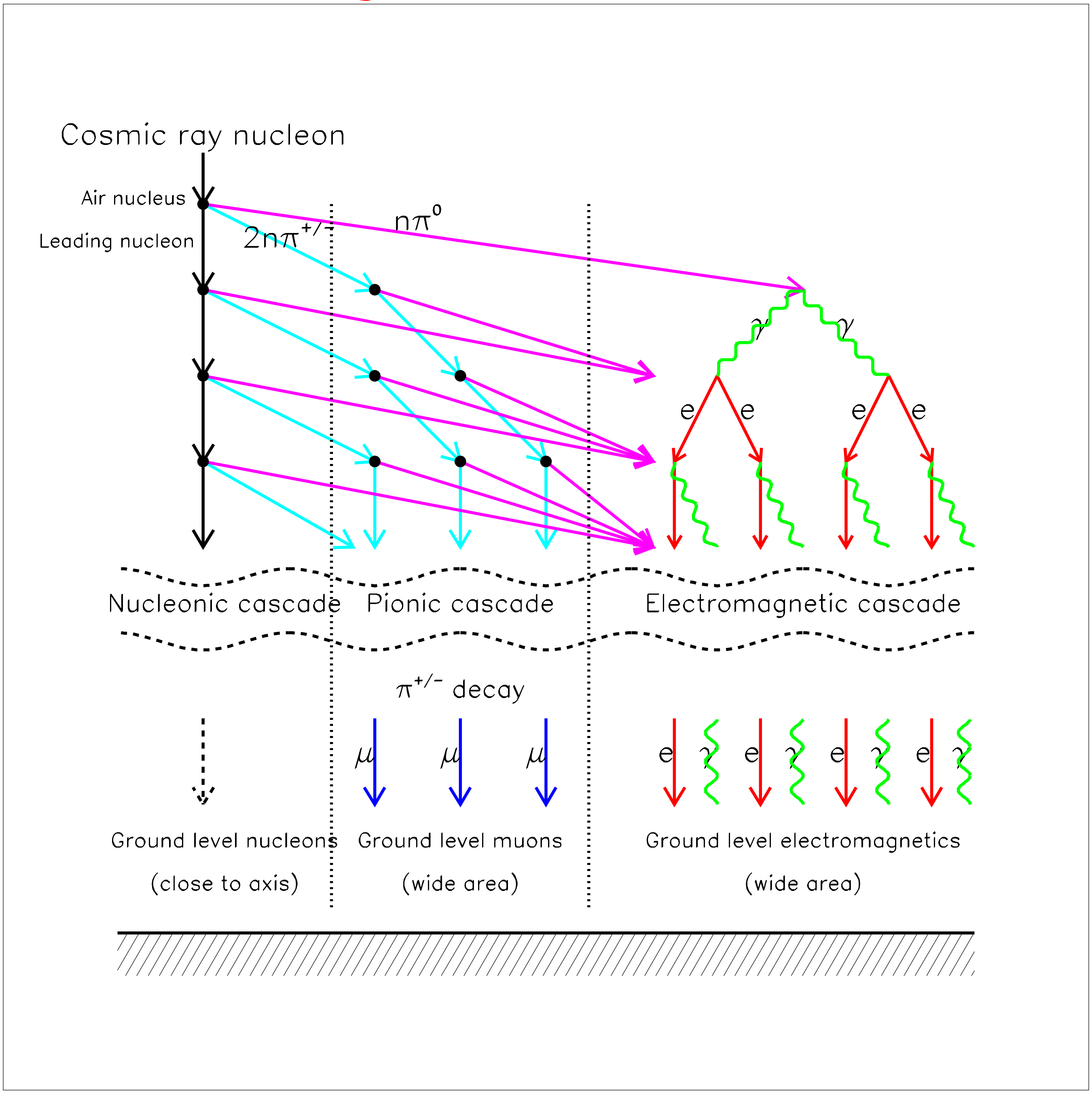
What we know at
Higher Energies

- Must measure cosmic ray primaries through the extensive air showers they produce.
- Can measure total particle energy.
- Very hard to measure particle type (main theme of this talk).
- Supernova acceleration runs out of steam at $\sim 10^{15}$ eV: spectrum from 10^{15} to 10^{18} is a real mystery...

Energy Spectrum in the Knee Region



Anatomy of an air shower



Cascade processes

- At each "generation" $\approx \frac{1}{3}$ of the available pionic energy is transferred to the electromagnetic cascade $(\pi^0 \Rightarrow \gamma + \gamma)$.
- After some number of generations the $\pi^{+/-}$ start to decay before interacting ($\approx$ 20 GeV).
- At this point the remaining energy is dumped into muons which propagate to ground level with little further interaction.
- Electromagnetic cascade diffuses out from the axis through multiple scattering.
- At ground level, and larger core distances, muon energies are typically 10's of GeV, while electromagnetics have 10's of MeV.

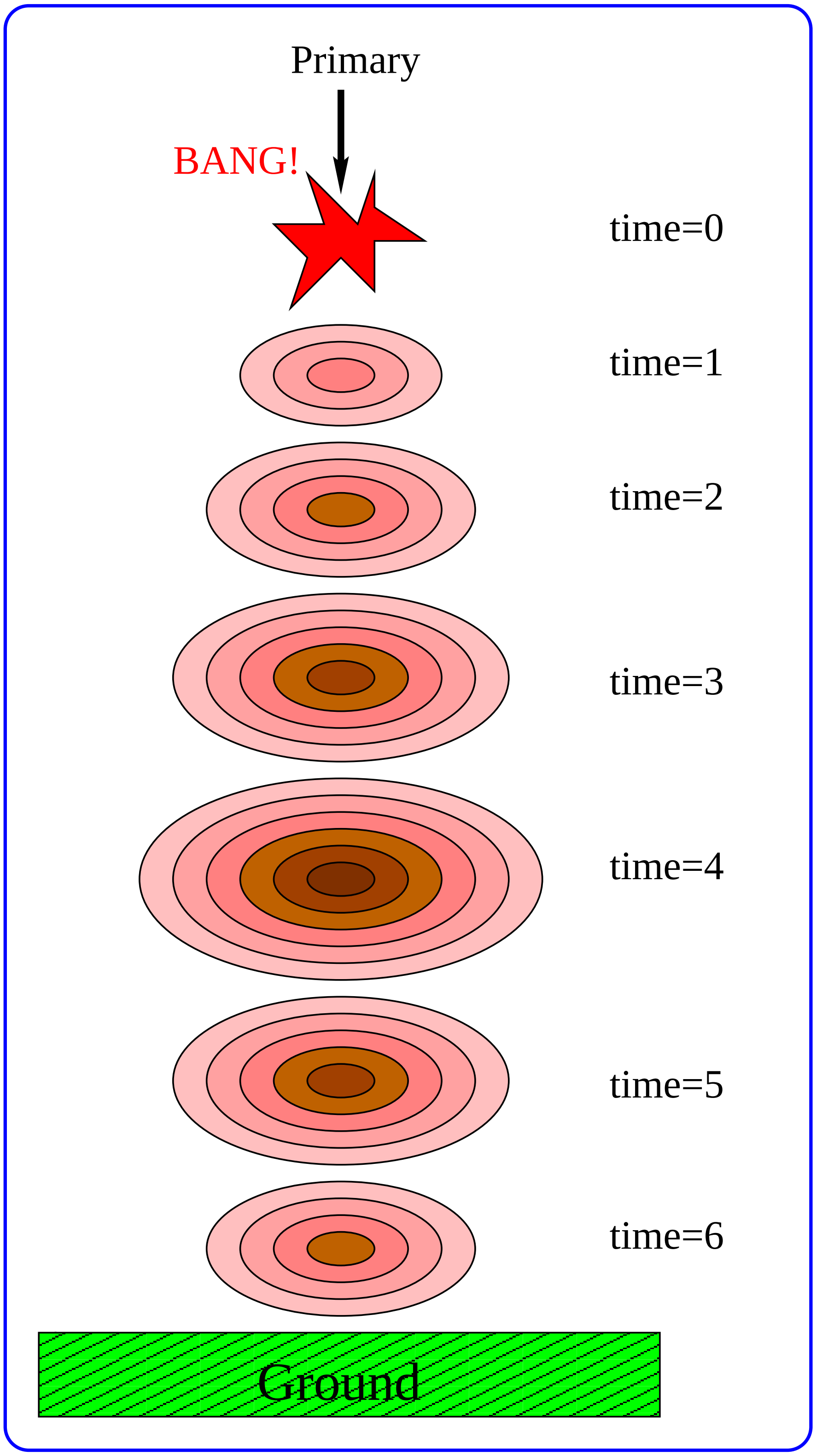
Light Generation

The shower also makes two types of light in the atmosphere:

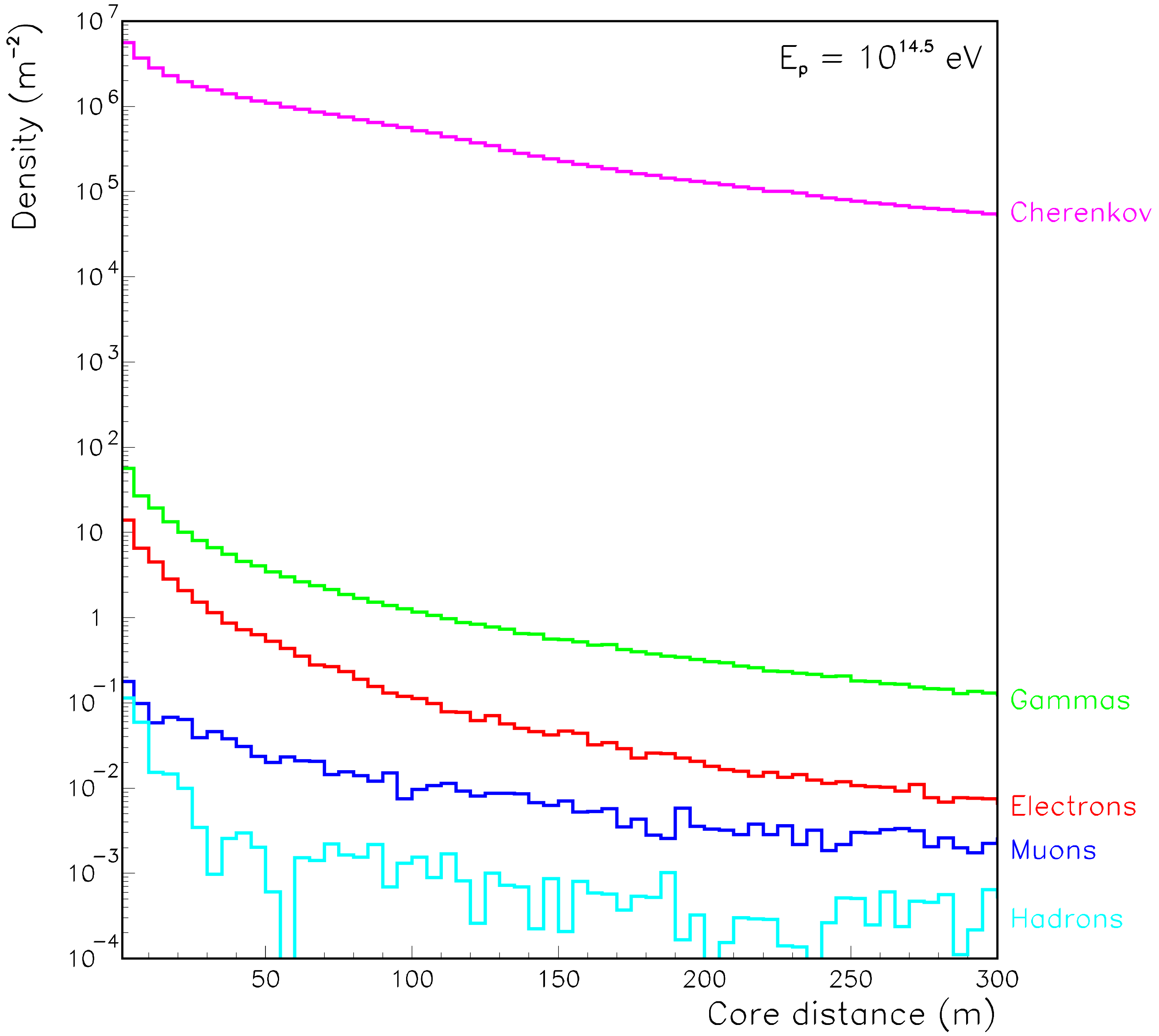
- Intense Čerenkov light emitted in the forward direction. (Nearly parallel to the shower axis.) Continuum emission falling as λ^{-2}.

- Weaker fluorescence (scintillation) light emitted isotropically. Allows remote sensing calorimetry, but too weak to detect over background at $E < 10^{17}$ eV

Air Shower Development



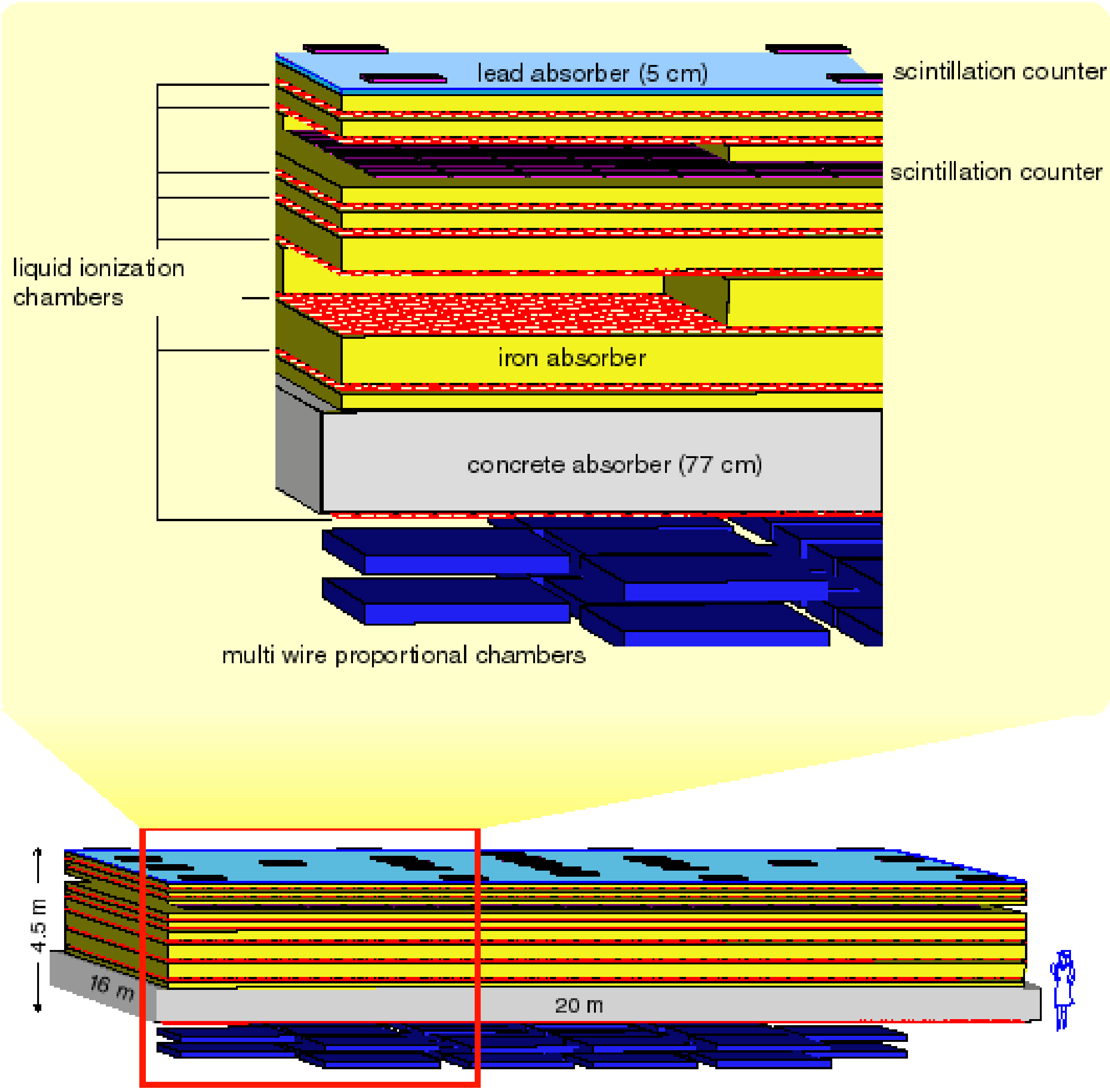
Lateral Distributions



Detection Techniques in Knee Region

- Lateral Distribution style:
  - Measure Electrons using surface thin scintillator arrays.
  - Measure Electrons, Gammas and Muons using deep water Čerenkov detectors.
  - Measure Muons using shielded (buried) scintillators etc.
- Imaging style:
  - Measure Čerenkov angular distribution using telescope and pixellated camera.
  - Measure Muon angles using tracking detector.
- Shower core:
  - Measure high energy Hadrons using deep calorimeter.

Aside: Kascade Complex



Differences between Proton and Heavy Nuclei Showers

- A heavy nucleus entering the atmosphere has a shorter mean free path than a proton - It starts to cascade higher up.

- Heavy nuclei quickly fragment - They behave as A nucleons each of energy E/A....

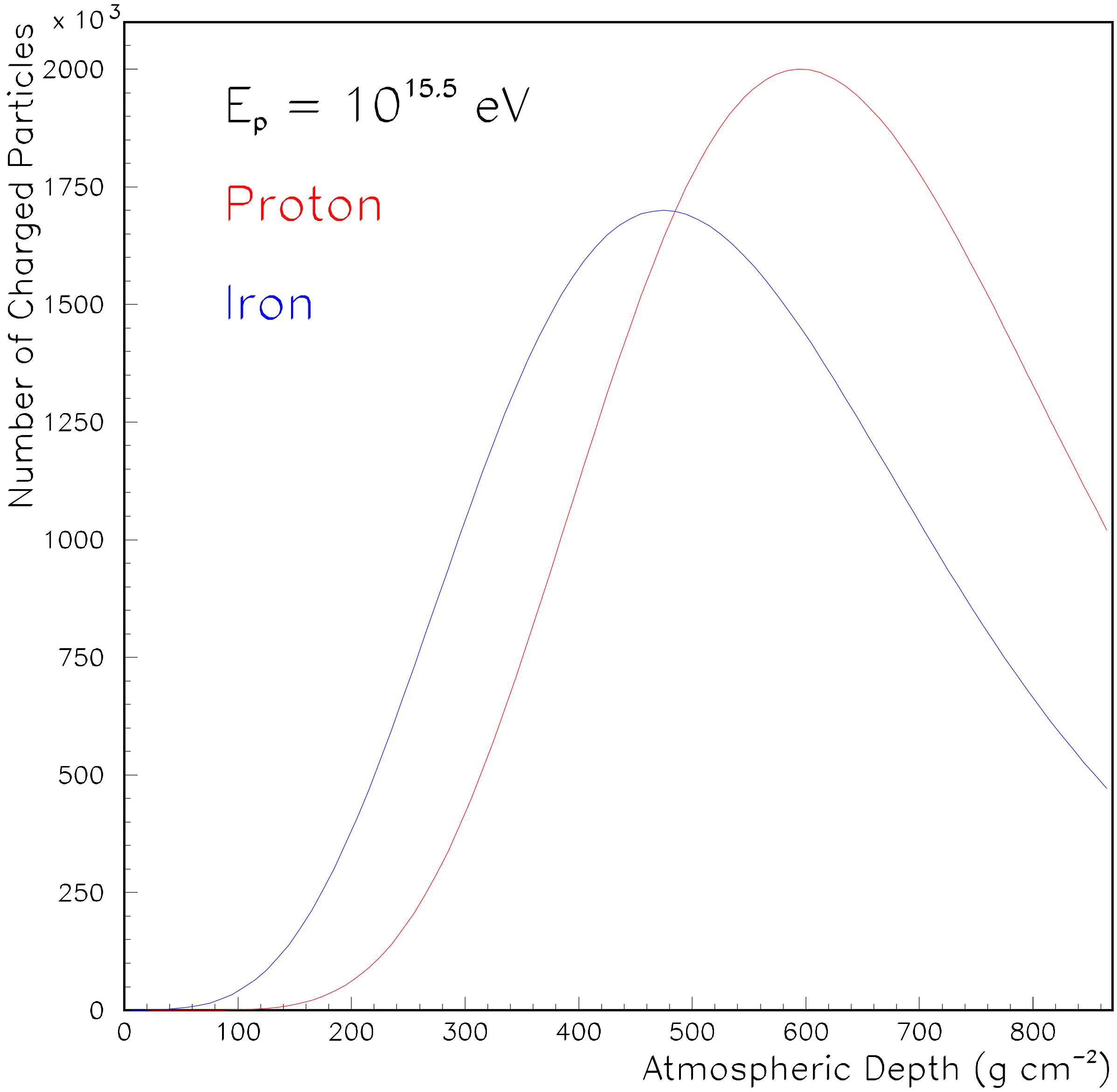
- ....hence the number of generations required to reach the $\pi^{+/-}$ decay energy is reduced.

- The fraction of energy going into muons is $f_\mu \propto E_{nuc}^{-0.18}$, where E_{nuc} is primary energy *per nucleon*....

- ....so there are $\approx$ twice as many muons in an iron initiated shower compared to a proton shower of the *same total energy.*

- The shower is "older" at ground level so the lateral distribution is flatter...

Typical Longitudinal Distributions

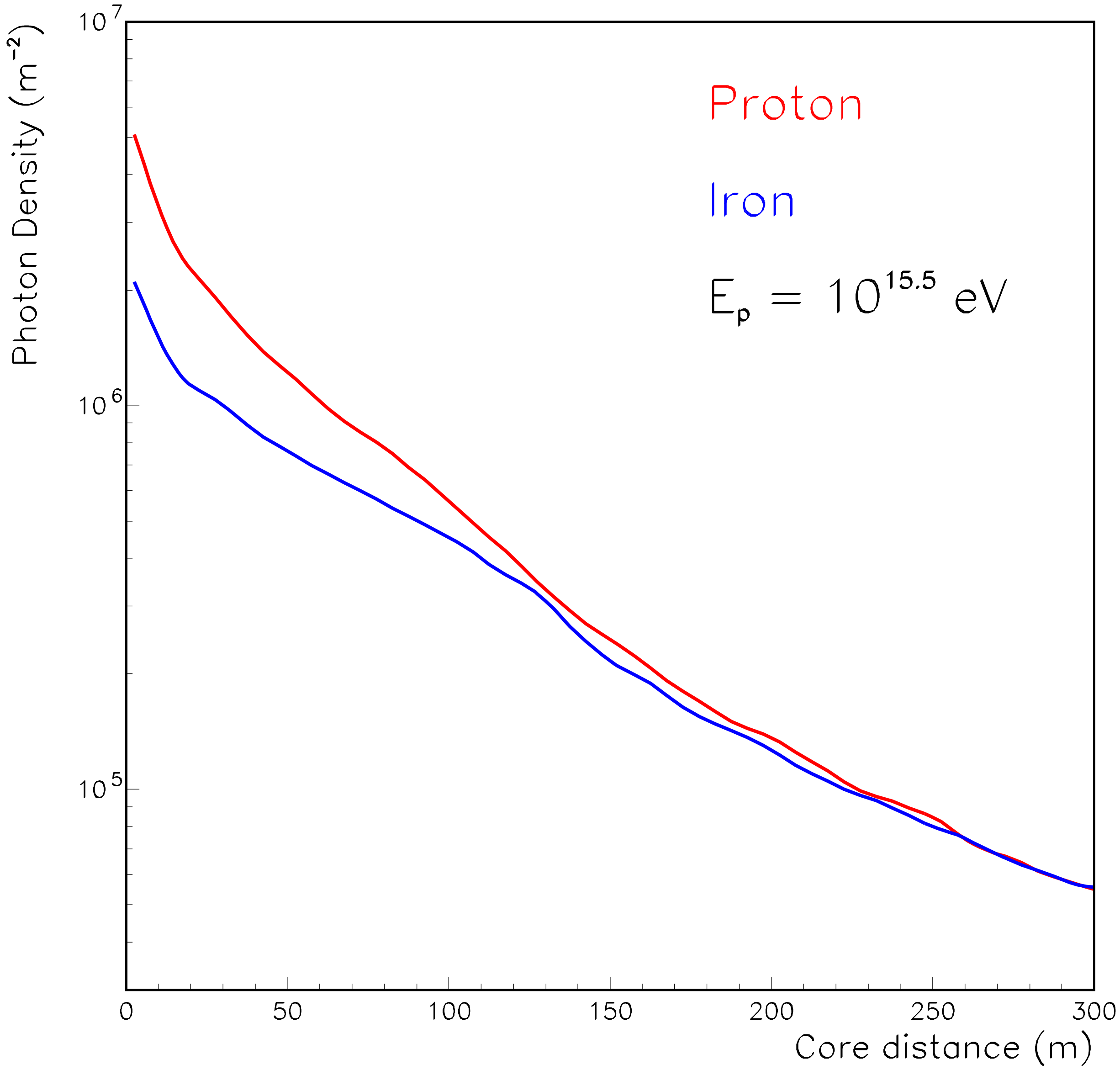


Note very different size at ground.

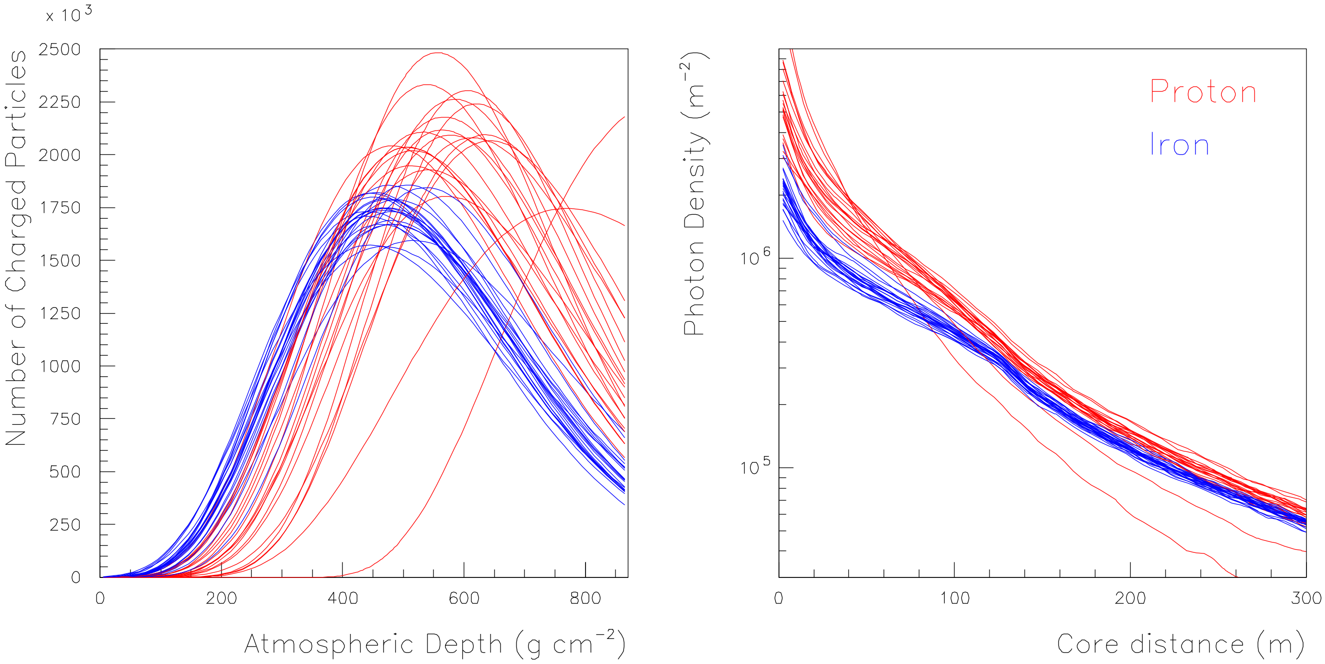
Electron vs. Čerenkov Array

- In principle Electron and Čerenkov lateral distributions carry similar information.
- The Normalization and Slope are related to primary Energy and Mass.
- However Čerenkov light is much easier to measure with high precision:
  - Photons very numerous $\Rightarrow$ Moderate area detector required.
  - Lateral distribution flatter $\Rightarrow$ Moderate dynamic range required.
  - Downside: Background light means run only on moonless (and cloudless) nights.

Čerenkov Lateral Distribution



Fluctations are Severe

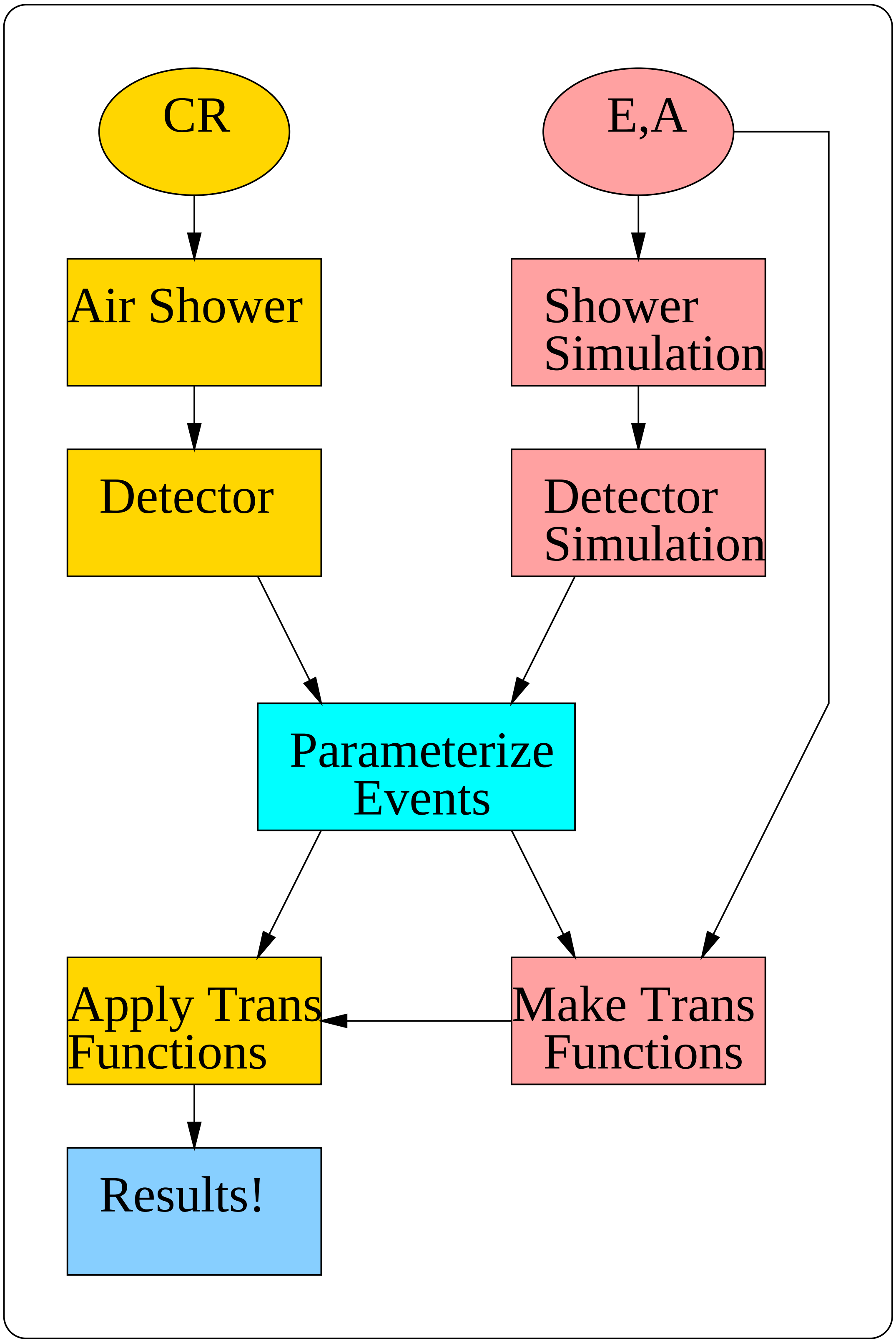


Caused by fluctuations in:

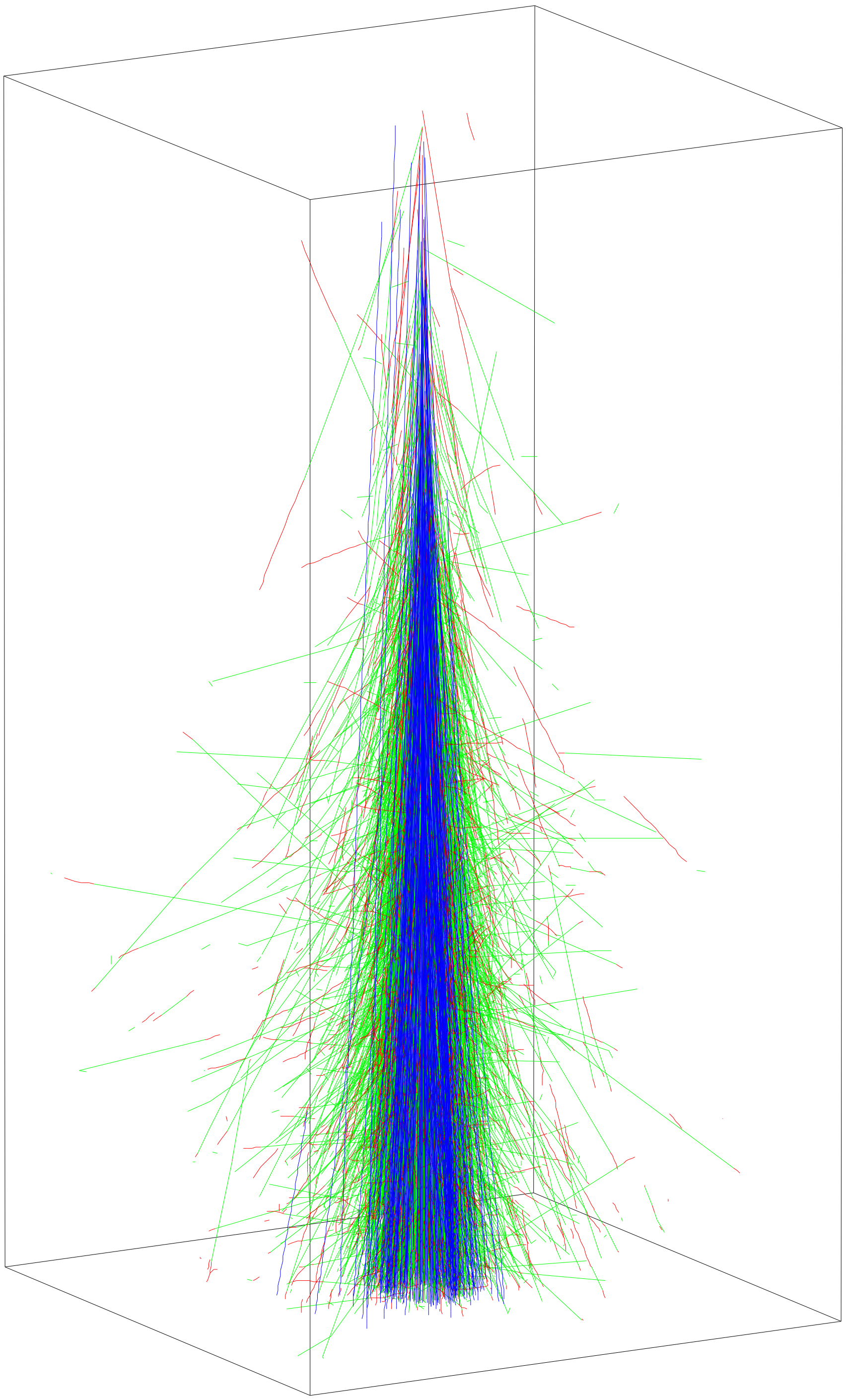
- Depth of first interaction point.
- Elasticity of first interaction.

Nature is very unkind...

Interpreting the Data



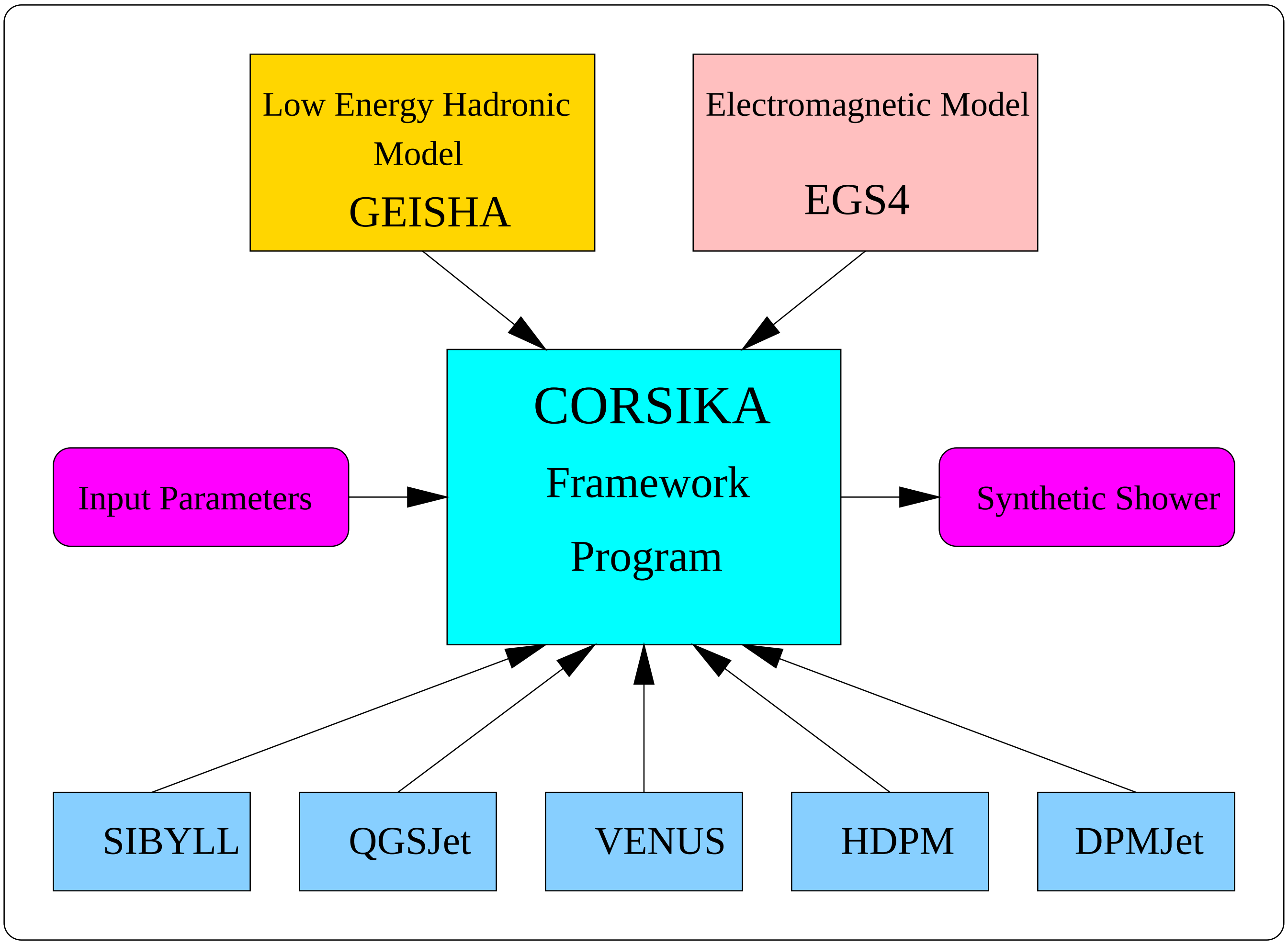
Air Shower Simulation



Frame box: 6 x 6 x 12 km high.

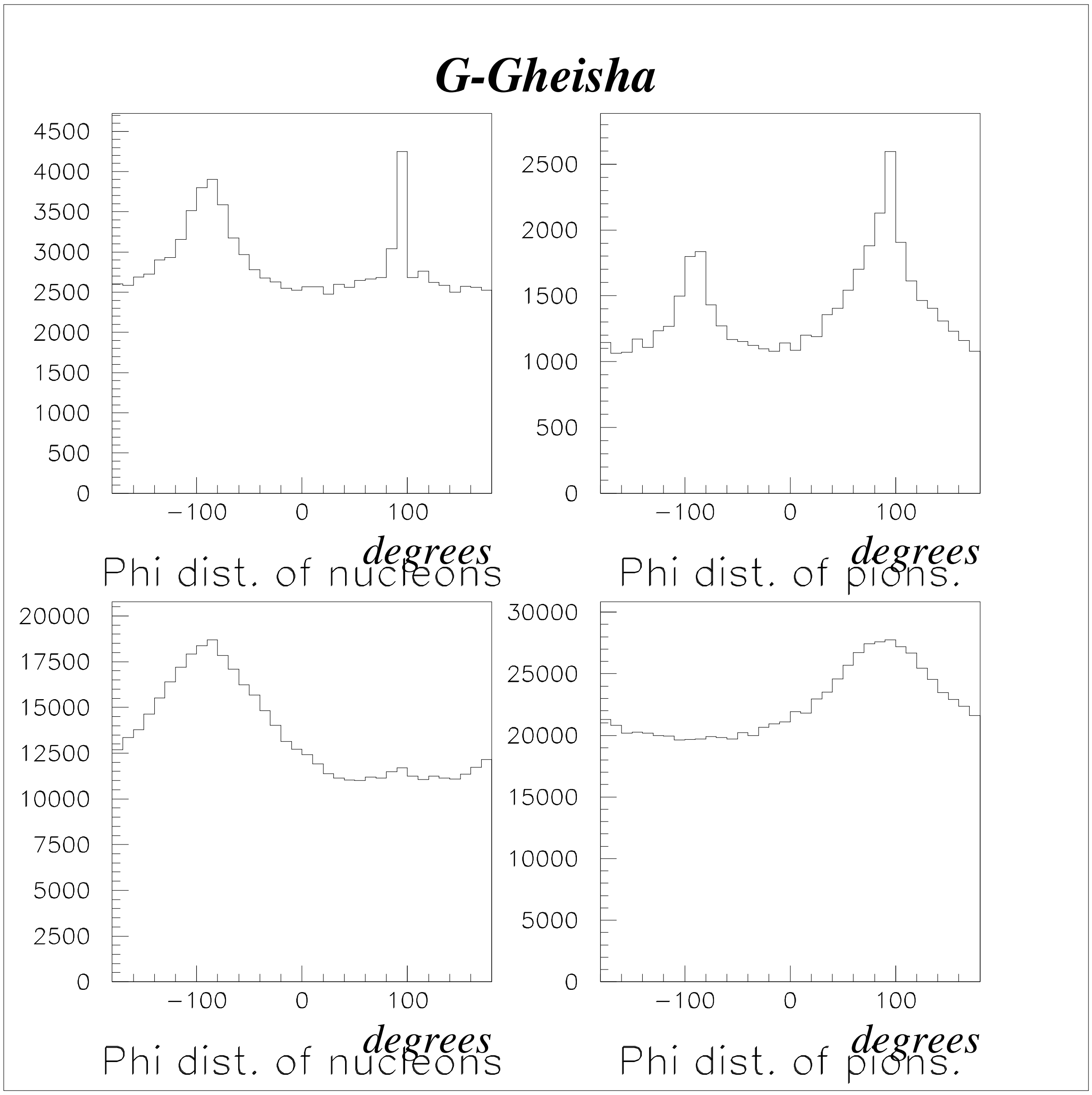
Color code: γ, e, μ.

CORSIKA Air Shower Simulation Program



- Uses highly respected HEP simulation codes for the low energy modeling — GEISHA and EGS4
- Pluggable high energy hadronic models (uncertain).
- Prepared in support of the KASCADE experiment but freely available.
- Philosophy - don't try and reinvent the wheel...

Aside: The Mighty GEISHA?!



Basic physics demands that these plots be flat!

From ATLAS Internal Note PHYS-No-086

BLANCA/CASA/MIA

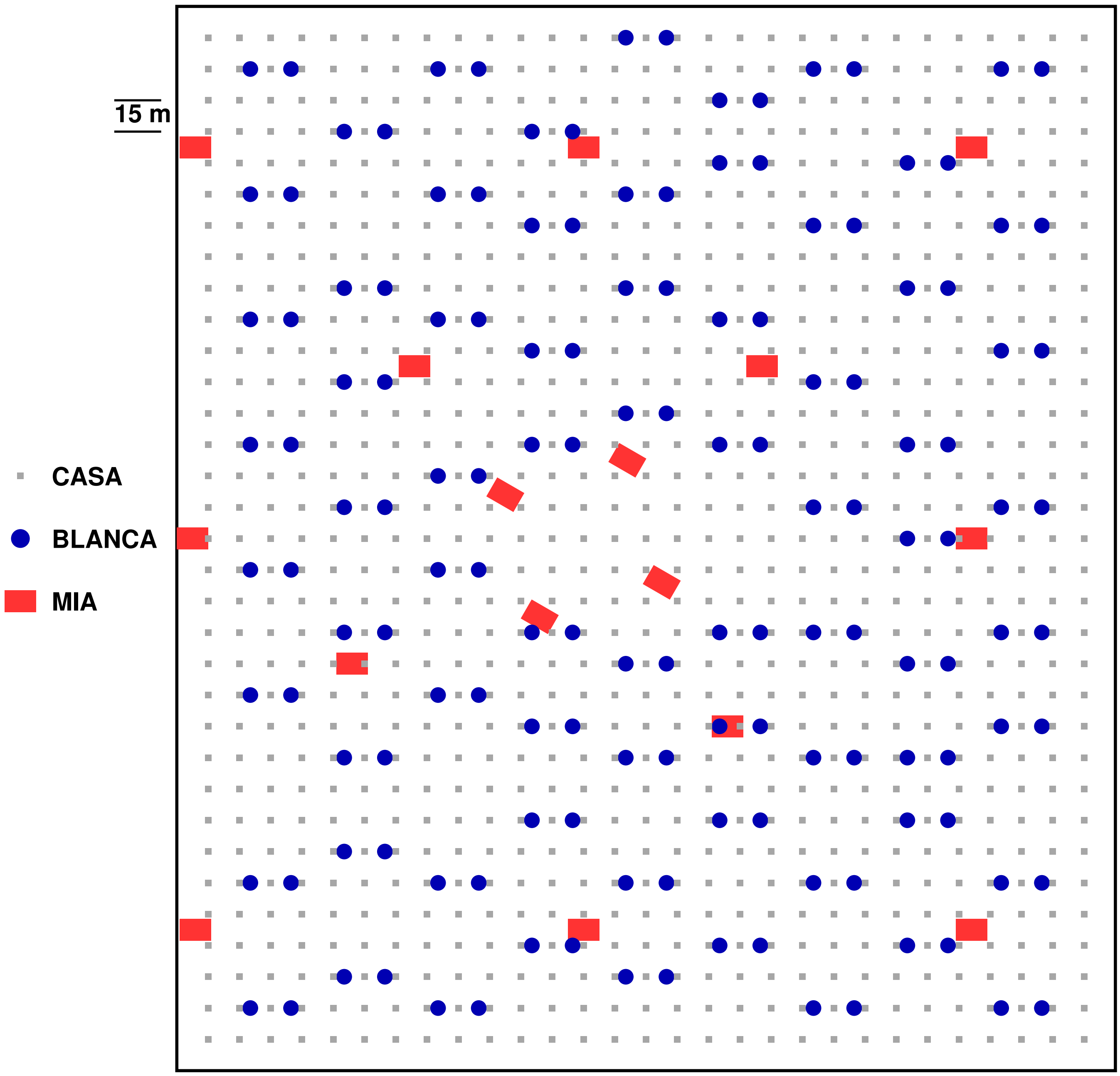
At Dugway Utah:

- Existing large Electron array CASA.
  $\sim$ 1000 units of $\sim$ 2 m^2 in a 500 m $\times$ 500 m grid.

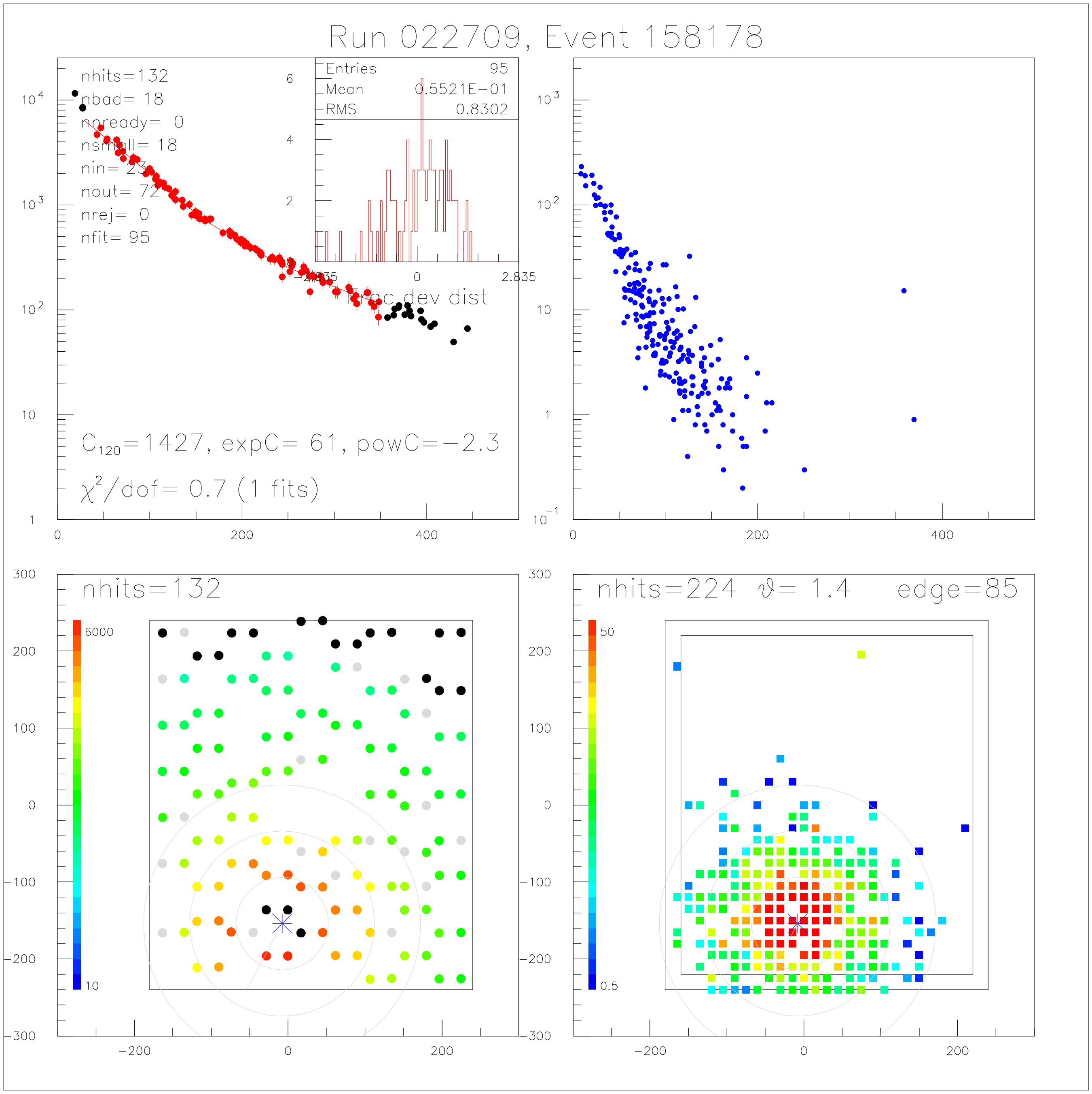
- Existing large Muon array MIA.
  16 patches of buried muon detectors, total $\sim$ 2500 m^2.

- New 144 element angle integrating Čerenkov array BLANCA.
  Built by Joe Fowler, Lucy Fortson etc...

Array Layout



An Example Event



CASA/BLANCA

⇒ Measures both Particles and Čerenkov light.

Parameterizing the Events

- Čerenkov lateral distribution fit to exponential in range 30–120 m $\Rightarrow$ Get normalization at 120 m (C_{120}), and Slope (S).

- Standard CASA analysis provides integral under Electron lateral distribution (N_e).

- Standard MIA analysis provides integral under Muon lateral distribution (N_μ).

Shower Libraries

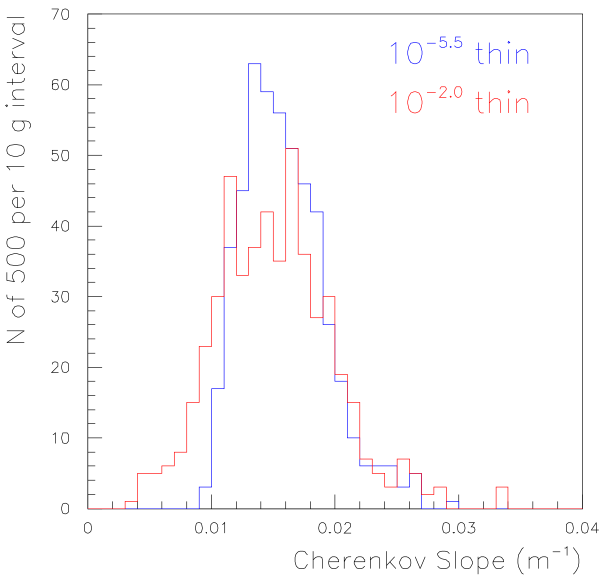
- Simulated 4 primary species — Proton, Helium, Nitrogen, Iron — 10,000 of each type with flat spectrum $14.0 < \log(E) < 16.5$
- High energy hadronic models: QGSjet, VENUS, SIBYLL and HDPM.

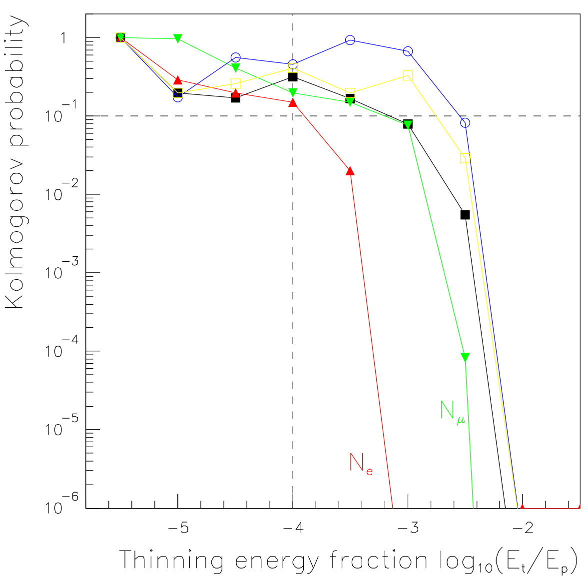
That's $4 \times 10,000 \times 4 = 160,000$ showers.

Need big libraries to characterize Fluctuations...

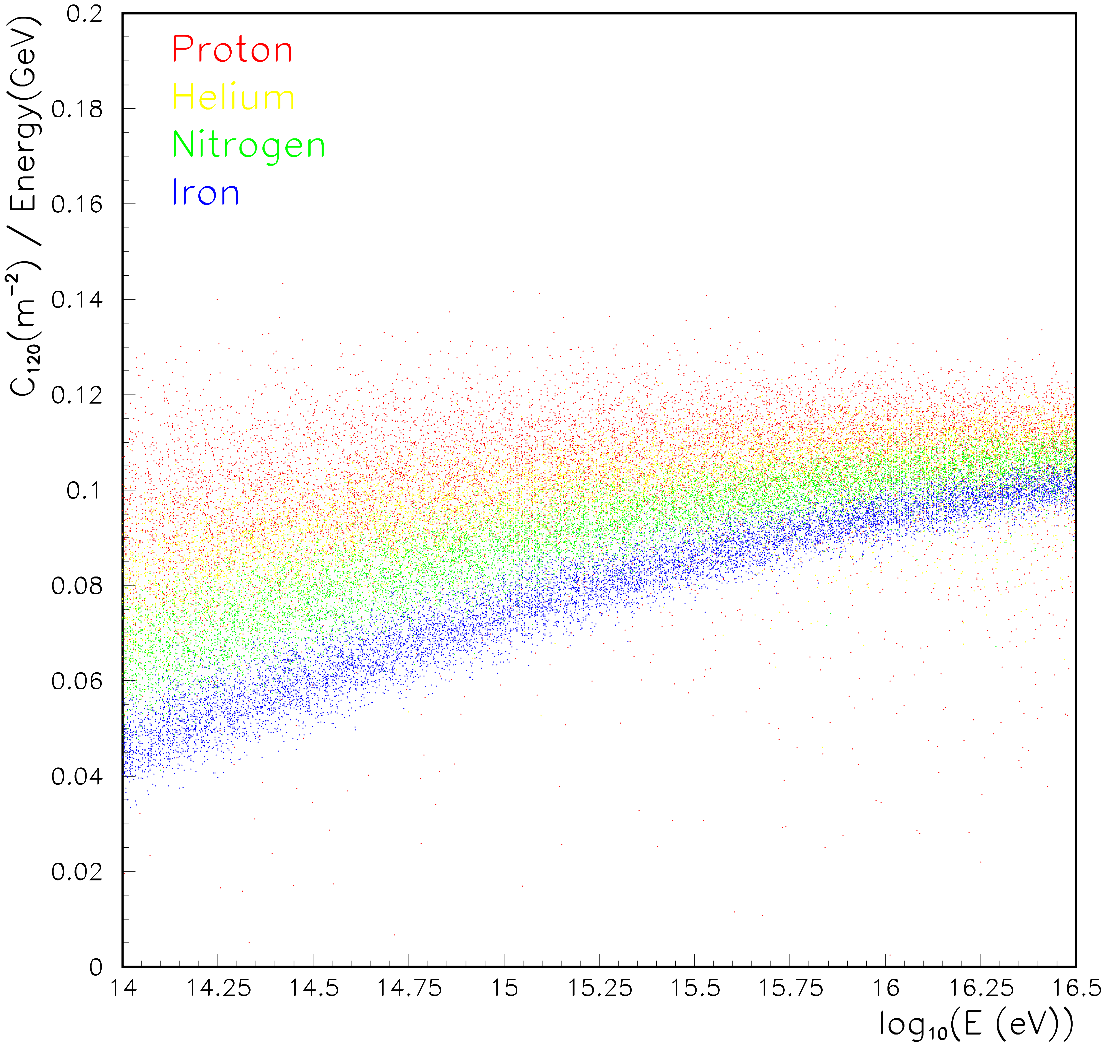
Aside: Thinning

- Necessary to use computational tricks to accelerate shower simulations.
- "Thinning" a popular technique ⇒ Below Threshold Energy only a sample of particles are tracked.
- Threshold normally specified as a fraction of the Primary Energy.
- There is a lot of folklore about what is an appropriate level....





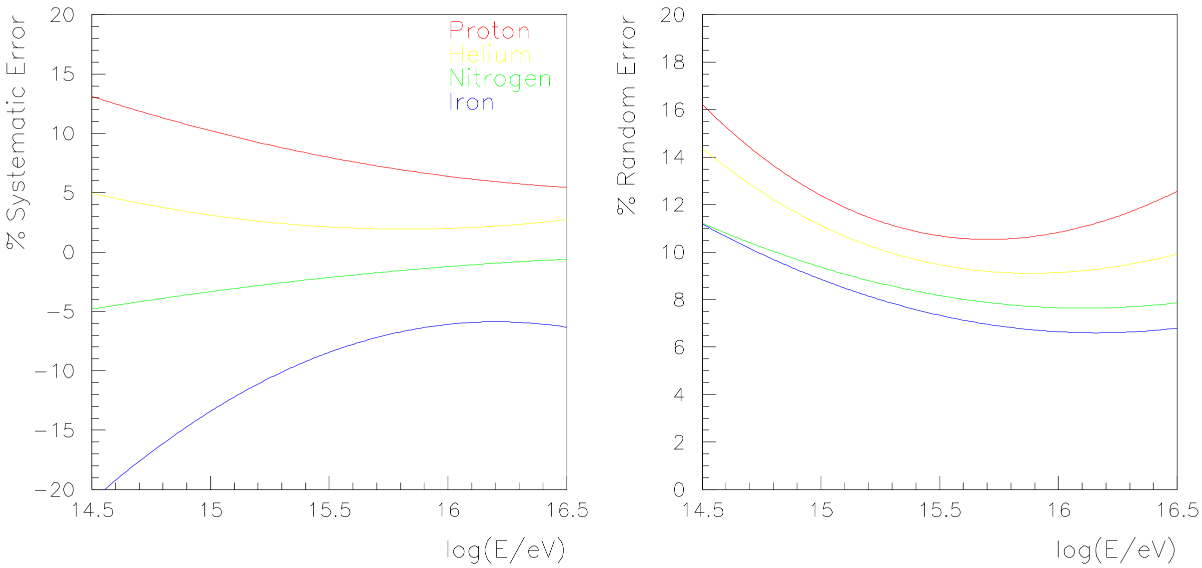
Energy Transfer Function



- Primary Energy is close to linearly related to C_{120}.
- In fact make small corrections for Primary Mass (using Č Slope), and Zenith Angle. $E = f(C_{120}, S, \theta)$

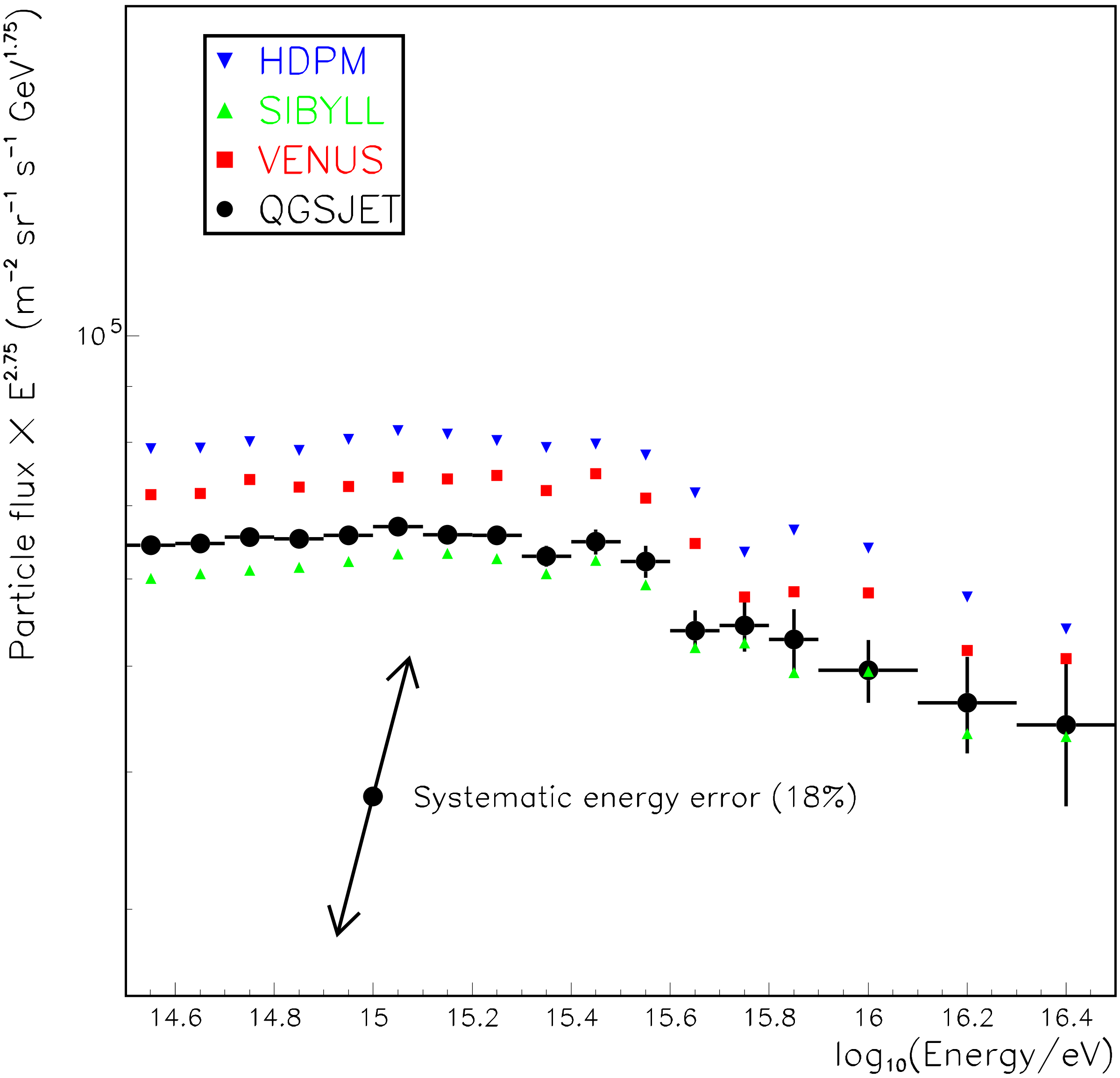
Energy Transfer Errors

- Derive the Transfer Function using an equal composition mix.
- Apply it to each Primary Type in turn:



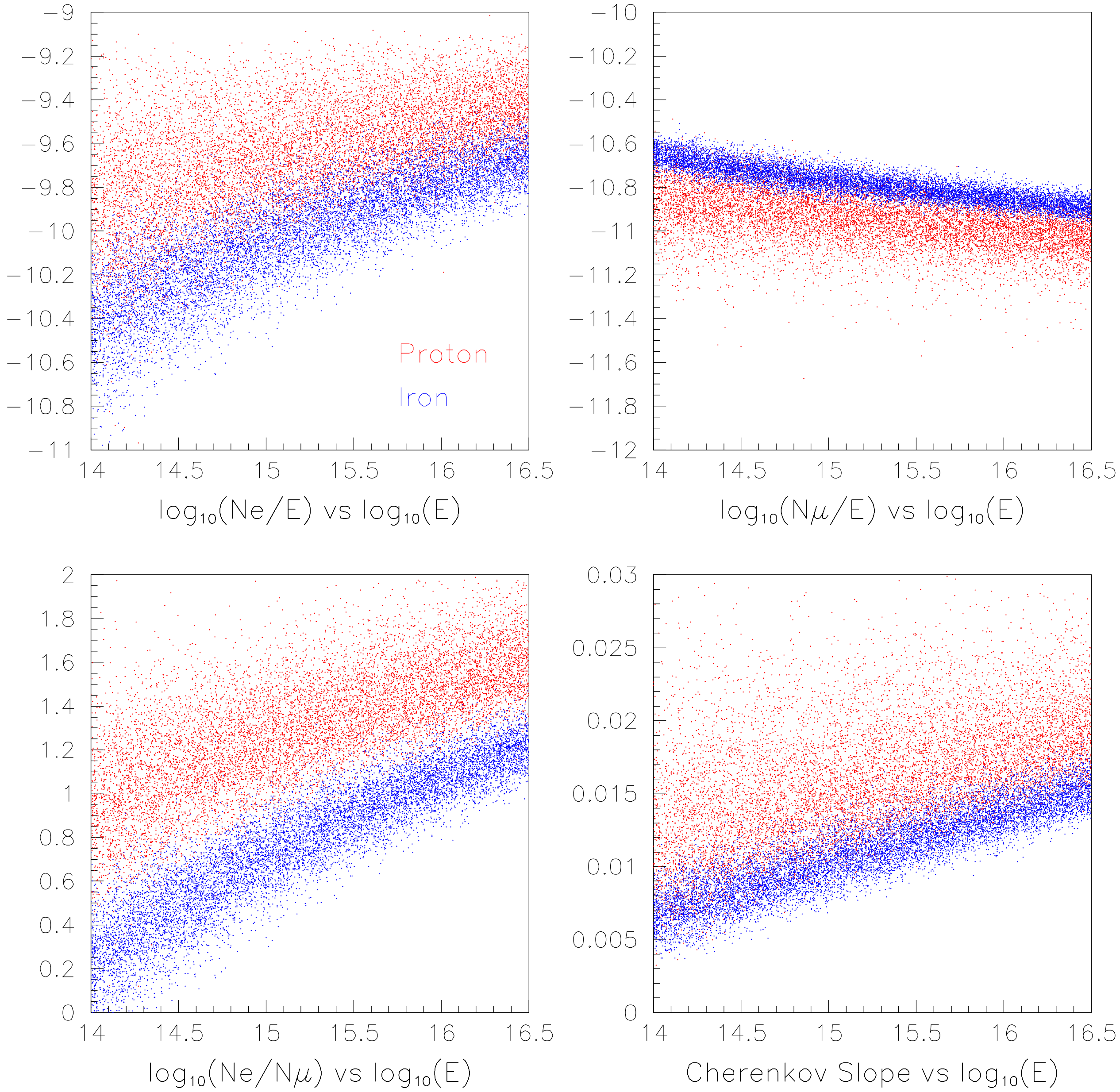
Energy Spectrum

Make Energy Transfer Function for each of the Four Models...



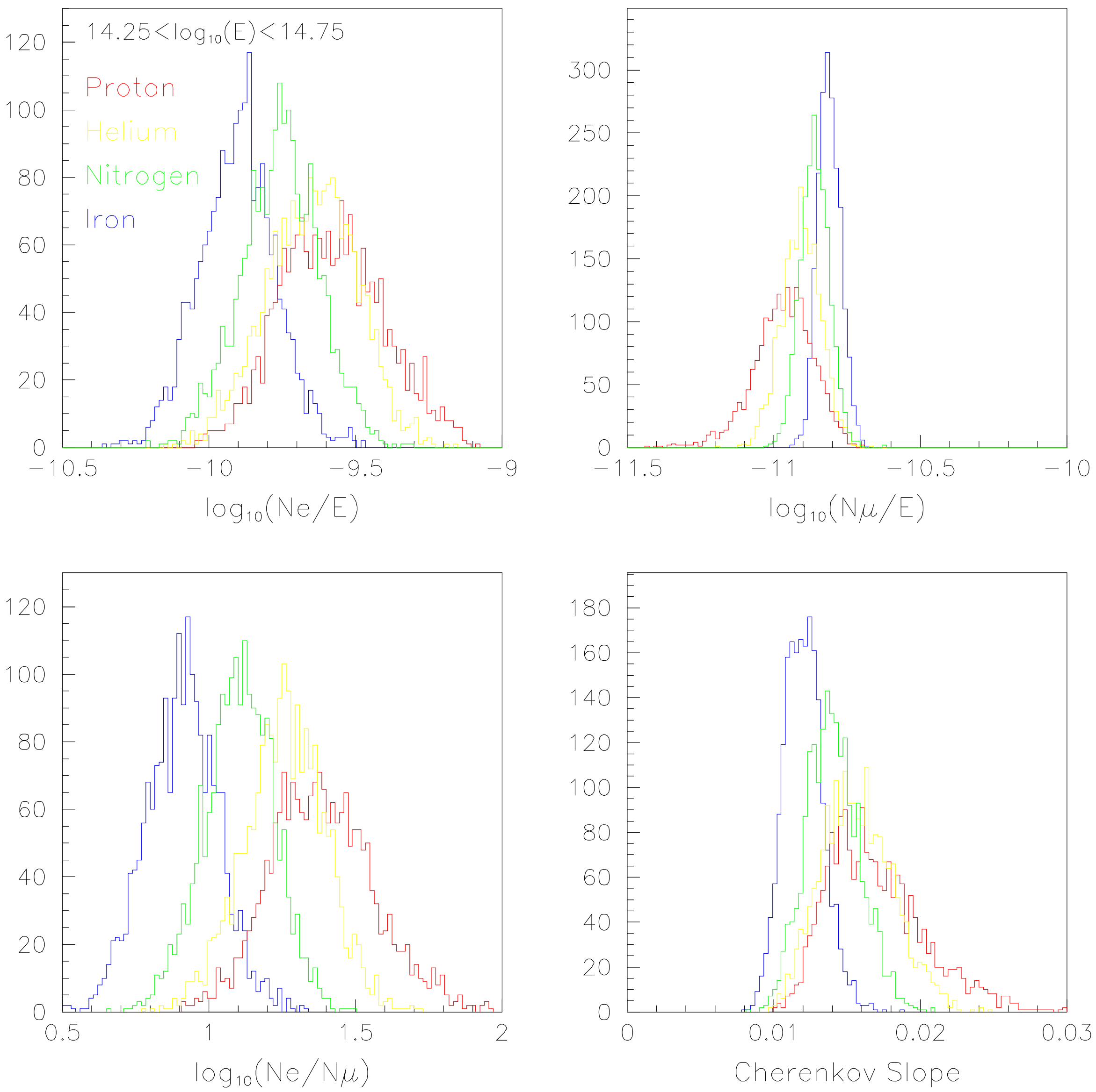
Model Systematic smaller than absolute calibration uncertainty.

Composition Parameters



- All are functions of primary Energy as well as Mass.
- In principle N_e/N_μ is better than Čerenkov Slope.

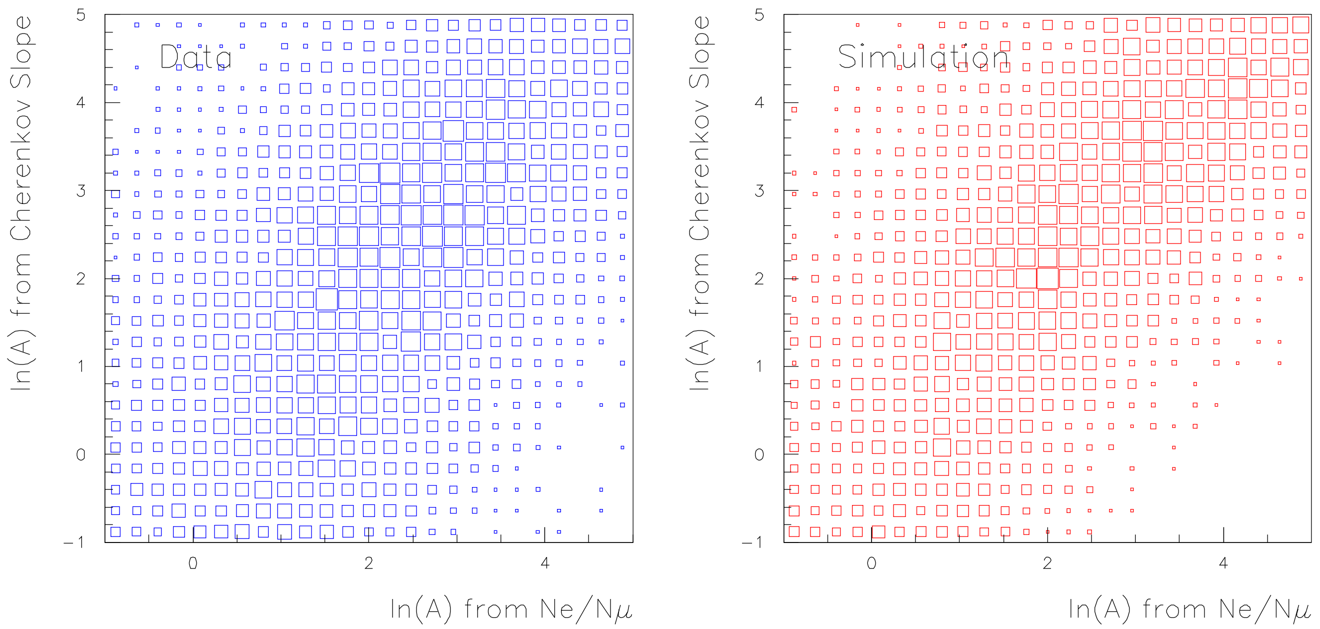
Composition Parameter Distributions



- At given primary Energy both Slope and N_e/N_μ are close to linearly related to the log of primary Mass.

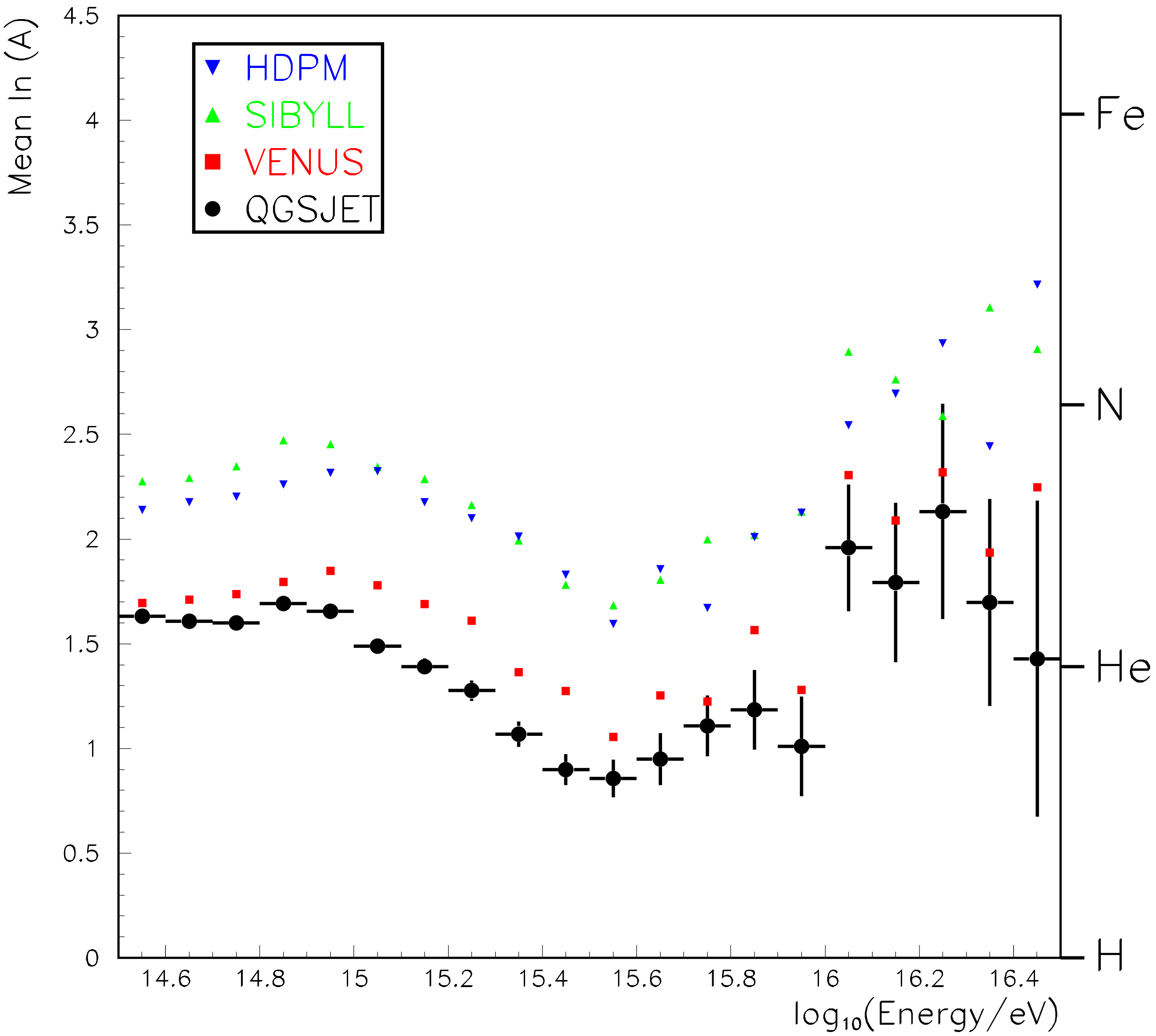
- Compose transfer functions:
  $\ln(A) = f(C_{120}, N_e/N_\mu)$
  $\ln(A) = f(C_{120}, S)$

Mass Estimator Correlation



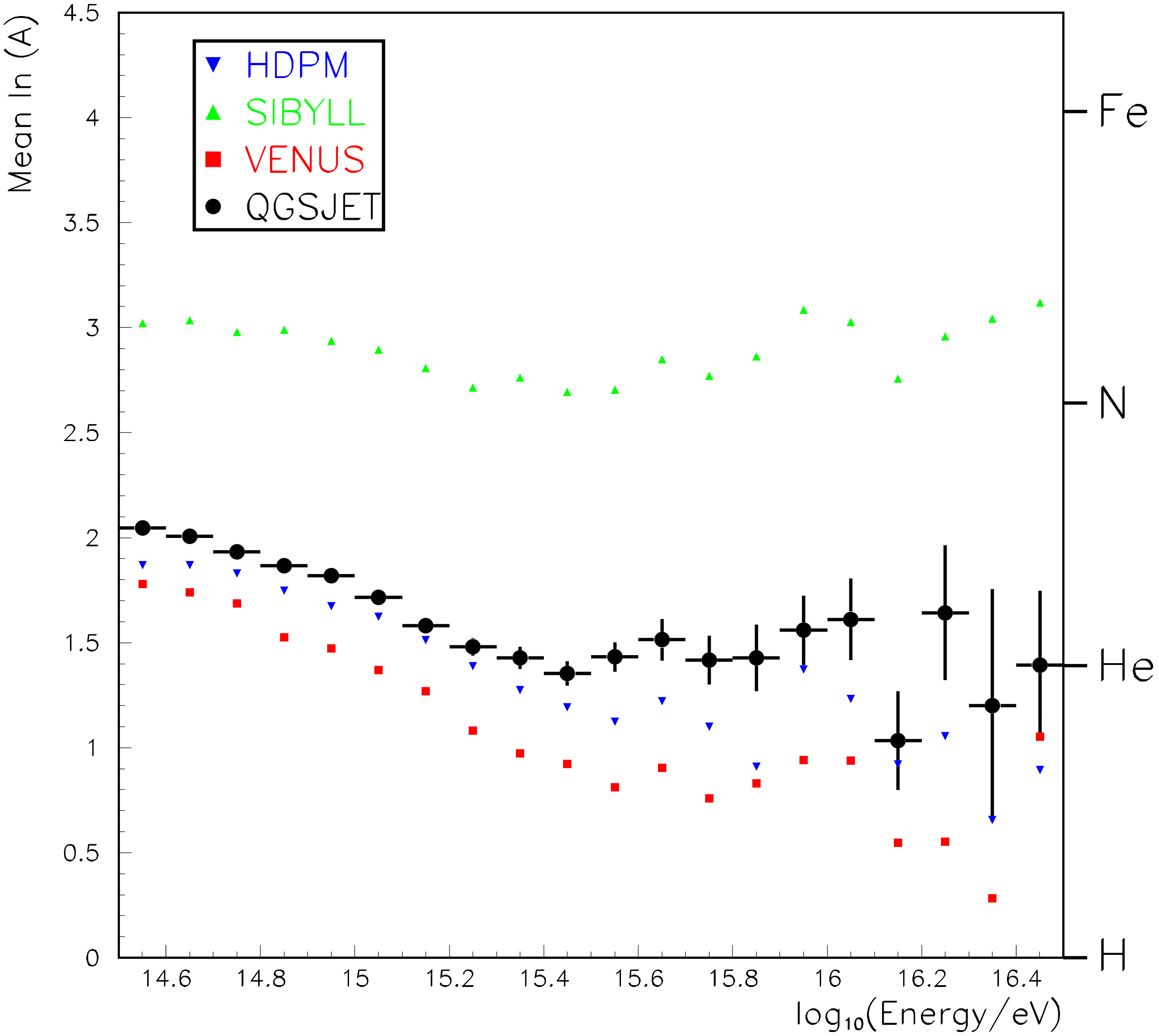
Correlate almost as well as in (incomplete) simulation.

Mean Mass using Čerenkov Slope



- Shows heavy ⇒ light ⇒ heavy trend for all models.
- Absolute normalization model dependent.

Mean Mass using N_e/N_μ

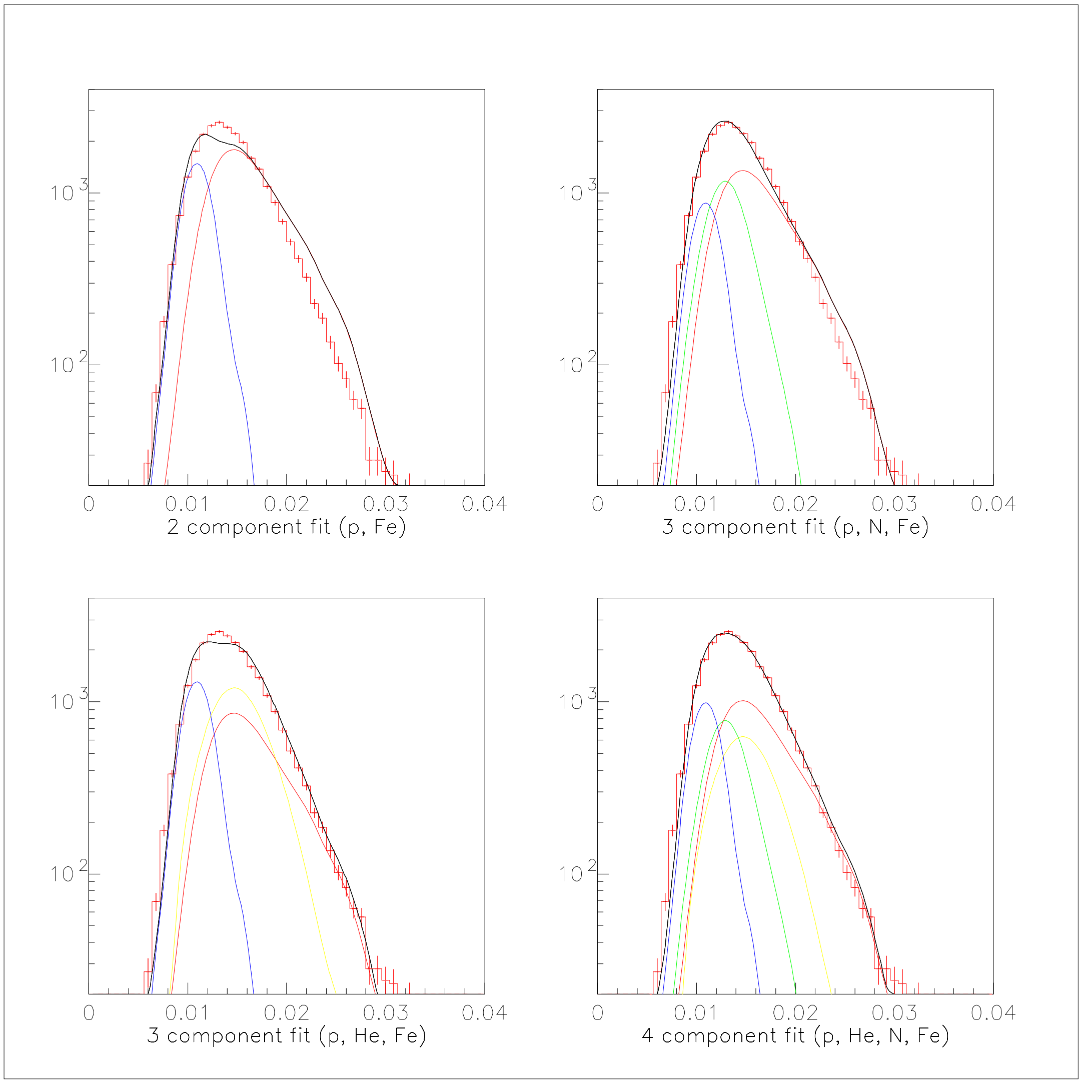


- Shows similar trend to Čerenkov Slope analysis.
- Interesting but suspect due to incomplete simulation...

Multicomponent Model

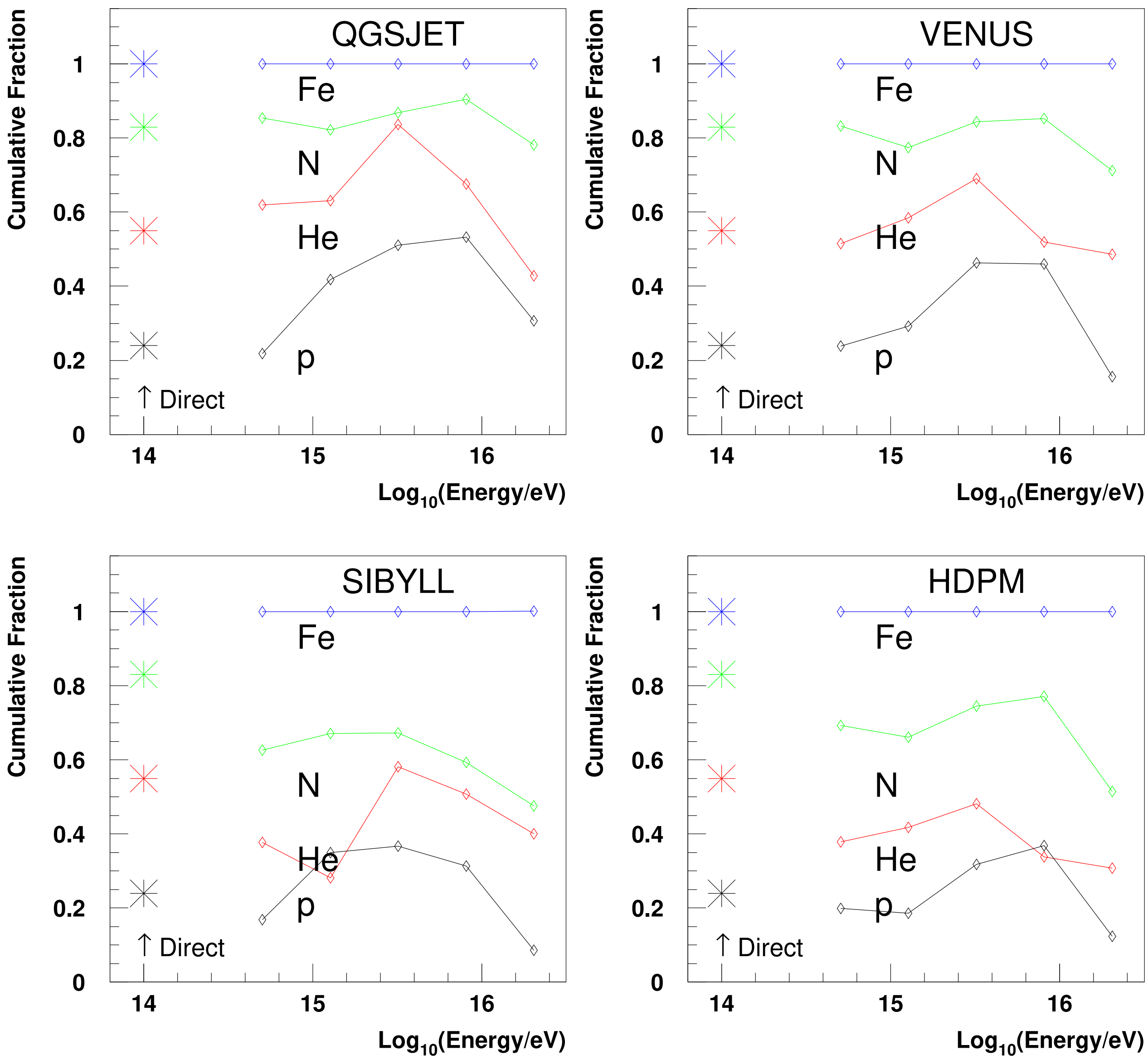
- Mean Mass is all very well but if Detector Simulation works there is much more information in the shape of the composition parameter distributions.

- Try to fit the Čerenkov Slope distribution using combination of simulated distributions.



Multicomponent Results

- Fractions are not constrained to be 0-1.
- Negative numbers indicate inadequate model.



A dream coming true?...

Conclusions

At the moment two things limit our ability to measure cosmic ray composition using air showers:

- Uncertainty in the hadronic interaction models.
  - In principle this could be removed up to $\sim 10^{15}$ eV with the right accelerator experiments...
- Shower Fluctuations
  - No amount of human ingenuity will eliminate them.

Composition experiments are now good enough that they are pushing these limits.