(Some) Properties of Extensive Air Showers

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- no review: **introduction**
- no data: **simulations**
- not complete: **focus**
- nie po polsku: **jeszcze nie**

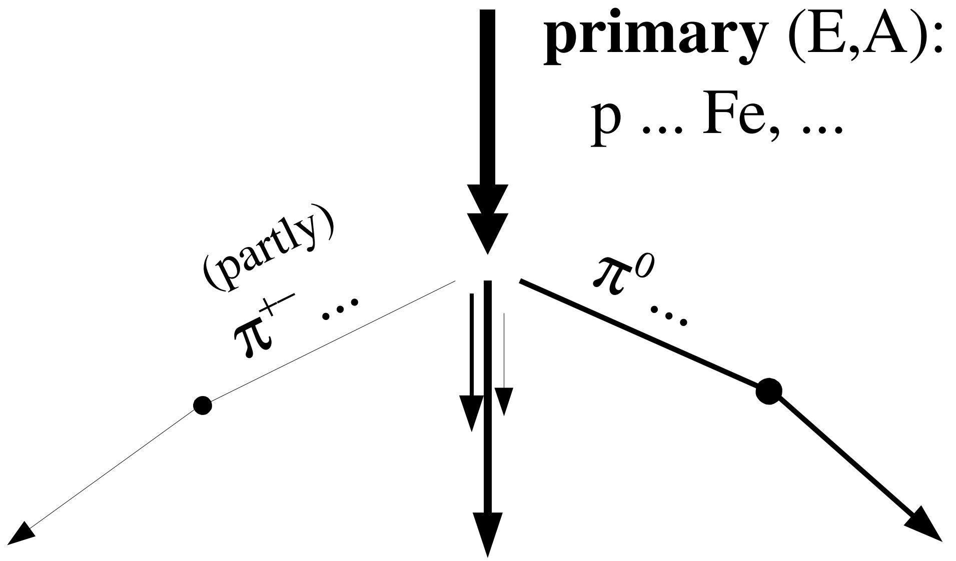
Extensive Air Showers are ...

- **known** for ≈70 years
- **cascades** initiated by cosmic rays in air
- connection to **highest particle energies** in nature
  - steep spectrum -> low flux above 1 PeV
- **tools** for **astrophysics** and **particle physics**
- consisting of **different shower components**

  -> observables & detection techniques => reconstruction
- **fluctuating** (1.: analysis   2.: MC simulation)
  - here: **CORSIKA** EAS-MC

... gratis !

EAS: Schematic View



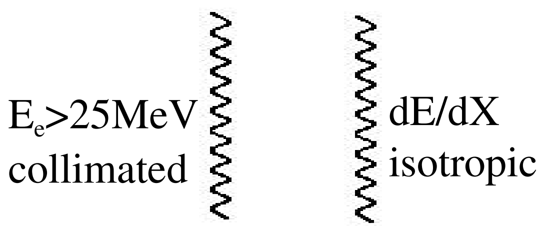
muon, neutrino | **hadron** | **elmagn**

-> *large* λ | -> *feeding* | -> *cascading*

inelasticity k:
energy fraction
into secondaries

-> ≈**1/3 k** into
elmagn channel
per hadr. interact.

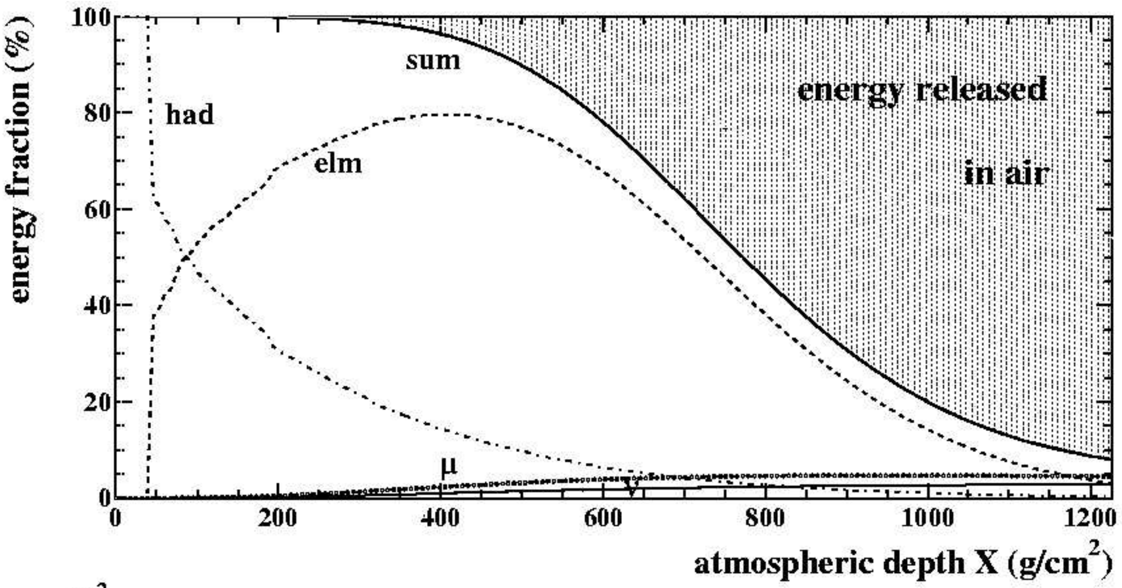
<k> ≈ 0.6 => **20%**

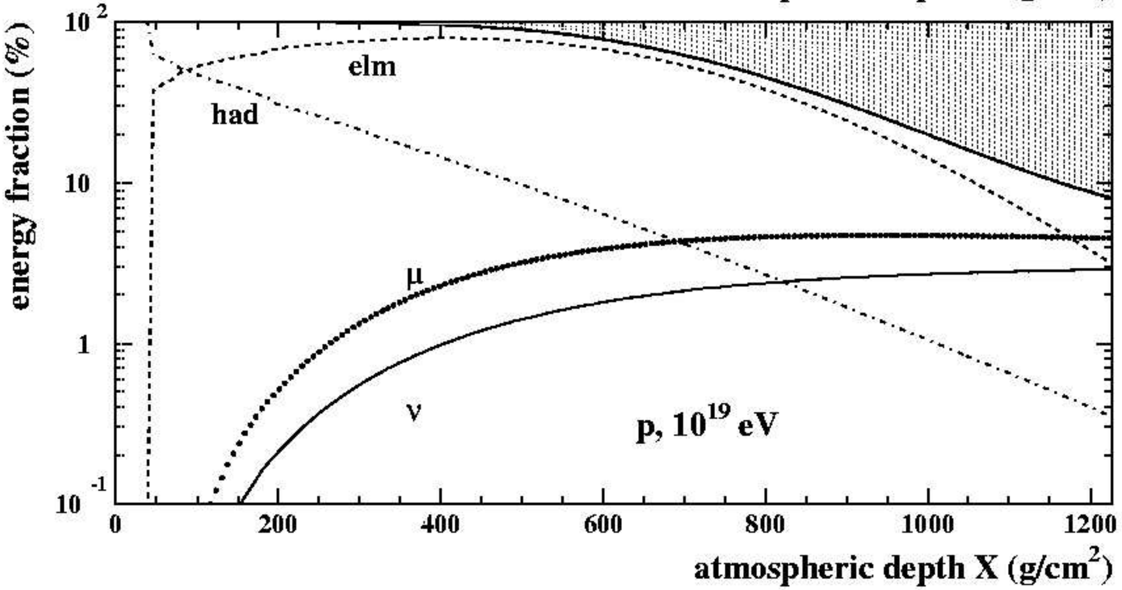


detection: muons - hadrons - elmagn **Č** **fluorescence** **...**

particles on ground *opt --- UV*

Energy Flow in EAS: CORSIKA simulation





CORSIKA: Heck et al., 1998

Hadrons:

each step **1/3 k** in elm channel

➔ $\mathbf{E_{had}/E_0\,(X) \approx (1-1/3\,k)^{X/\lambda_{had}}}$

➔ hadronic scale depth:

$|\lambda_{had}/\ln(1-1/3\ k)| \approx$ 250 g/cm^2

with: $\lambda_{had} \approx$ 60g/cm^2, $k \approx$ 0.6

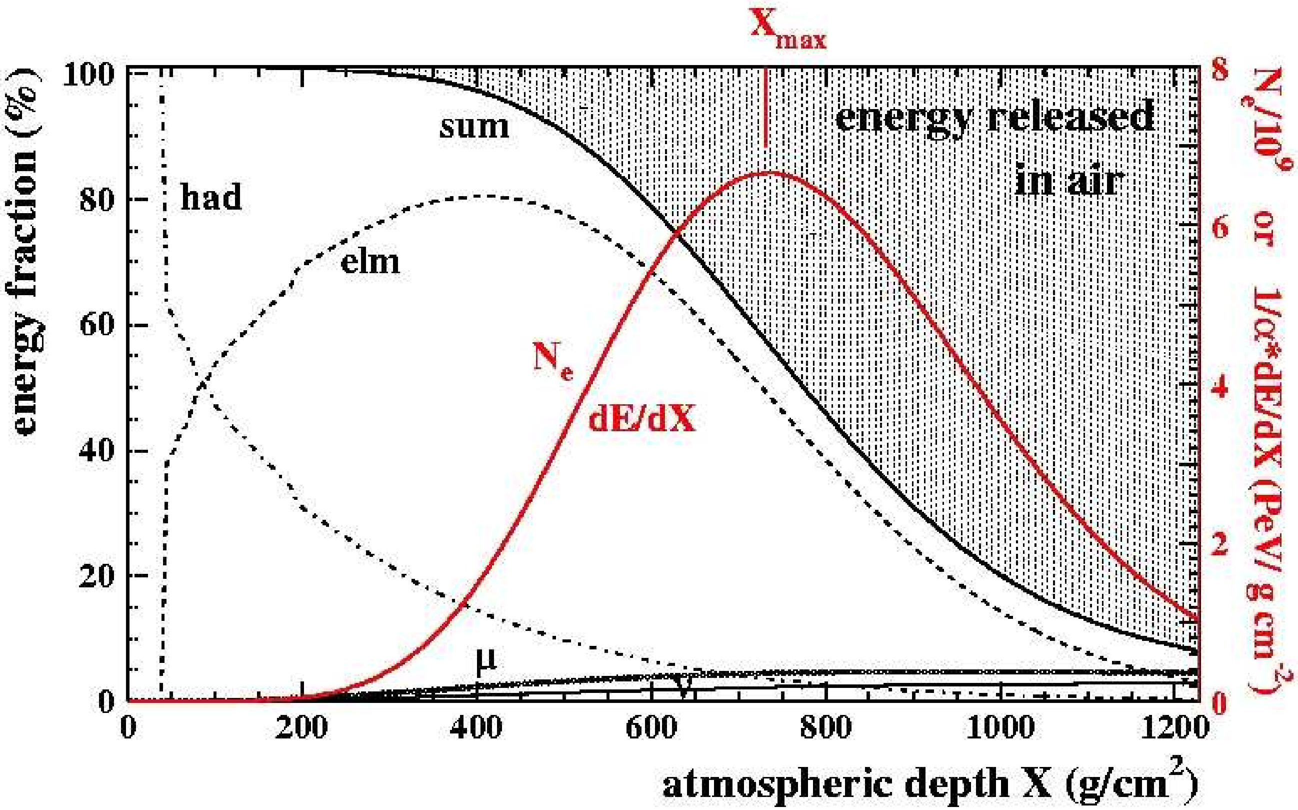
Muons, neutrinos:

≈ few %; **integral** character

Electromagnetic:

feeding by had vs ionization loss

Energy Flow and Ionization Loss



- relativistic particle:
  $dE_i^{(1)}/dX = \alpha \approx \text{const}$
  $\alpha \approx 2\ \text{MeV/gcm}^{-2}$

→ **EAS:**
$dE_i/dX\ (X) \approx \alpha * N_e(X)$

Electromagnetic: feeding by hadrons vs ionization loss

→ dE_i/dX => 70-90% of E_0 in air

→ max. of contained energy <=> **$-dE_{had}/dX = dE_i/dX$** (-> not **X_{max}** !)

→ **observation:** N_e (**ground**) & dE/dX (**fluorescence**) -> particle multiplication

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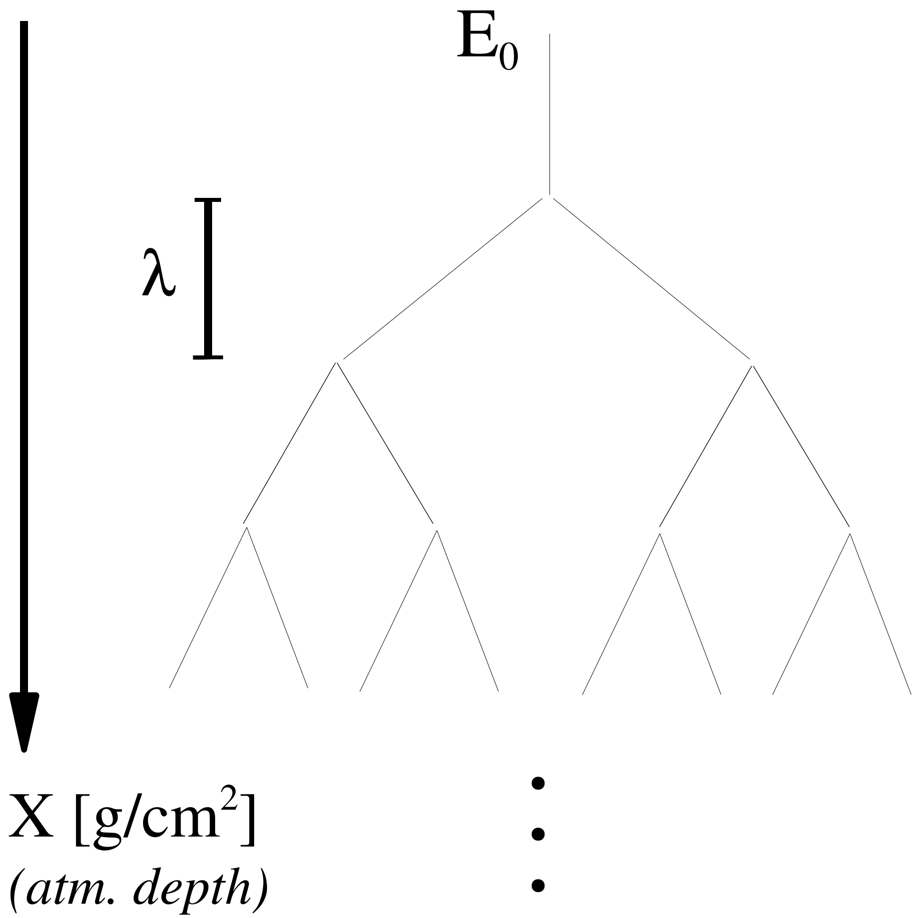
Particle Multiplication: Toy Model



each vertex: equal energy splitting

=> after $n=X/\lambda$ steps: $N(X) = 2^{X/\lambda}$

particles with $E(X) = E_0 / N(X)$

particle multiplication stops at

$E(X) = E_L$ => **shower maximum:**

$N(X_{max}) = E_0 / E_L$

$X_{max} = \lambda/\ln 2 * \ln(E_0 / E_L)$

-> *qualitatively OK:*

$\mathbf{N_{max} \sim E_0}$

(Heitler 44) $\mathbf{X_{max} \sim \ln(E_0/AE_L)}$

with **superposition** model

for nucleus E_0 -> $A*E_0/A$ ...

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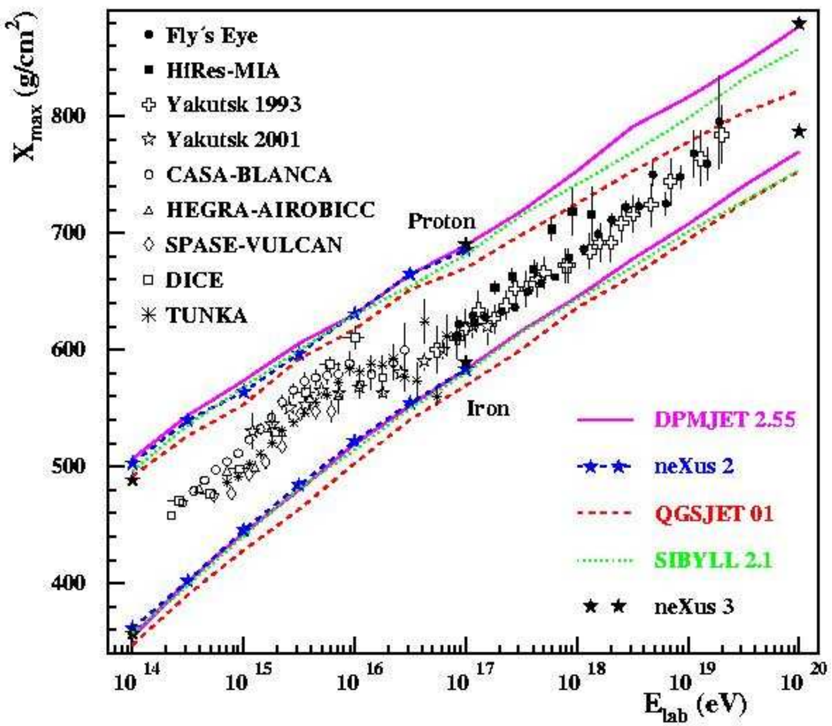
Primary Mass Separation (1): X_{max}

$<X_{max}>$

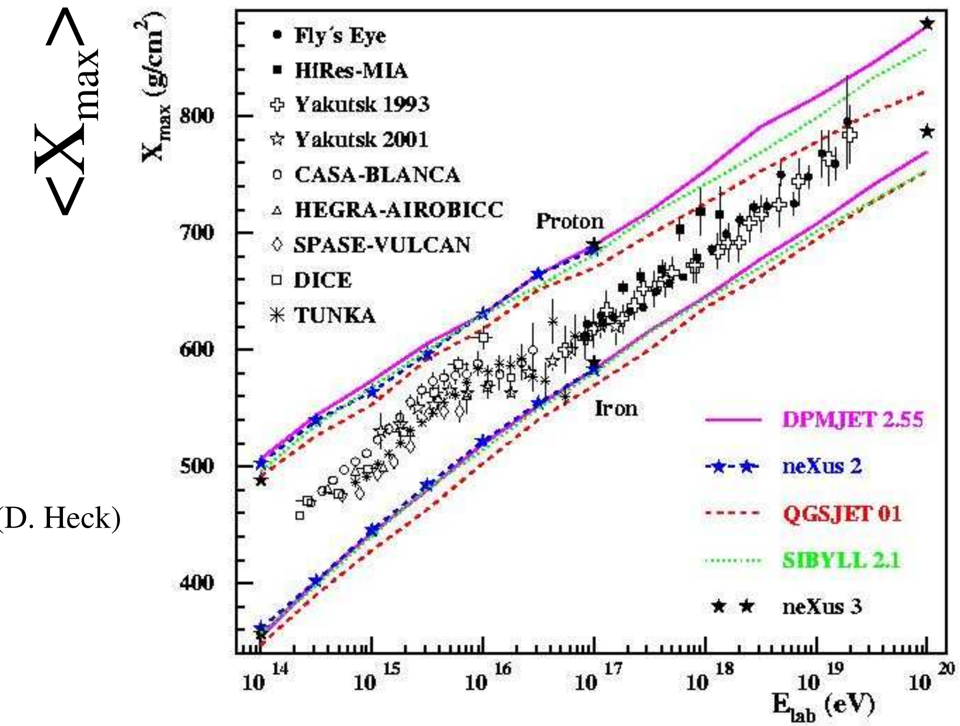


(D. Heck)

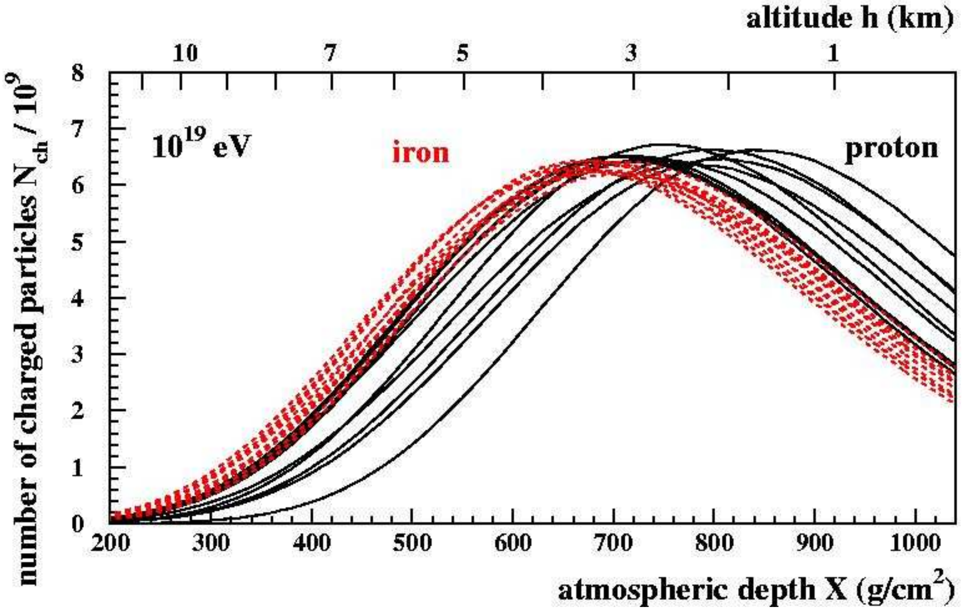
- $<X_{max}> \sim \ln(E_0/AE_L)$
- $X_{max}(Fe) < X_{max}(p)$ ($\approx 80 g/cm^2$)

➔ *sensitivity on primary mass*

Primary Mass Separation (1): X_{max}



(D. Heck)



- ✔ $\langle X_{max}\rangle \sim \ln(E_0/AE_L)$
- ✔ $X_{max}(Fe) < X_{max}(p)$ ($\approx 80 g/cm^2$)
- ➔ *sensitivity on primary mass*

- ✔ N_{max} similar (also area)
- ✔ $N_{ground}(Fe) < N_{ground}(p)$ (X_{max} !)

- but: *X_{max} fluctuations* !
- ➔ ΔX_{max}, $p \approx 60 g/cm^2$, $Fe \approx 20 g/cm^2$
- ➔ event-by-event difficult
- ➔ measure *fluctuations -> mass*

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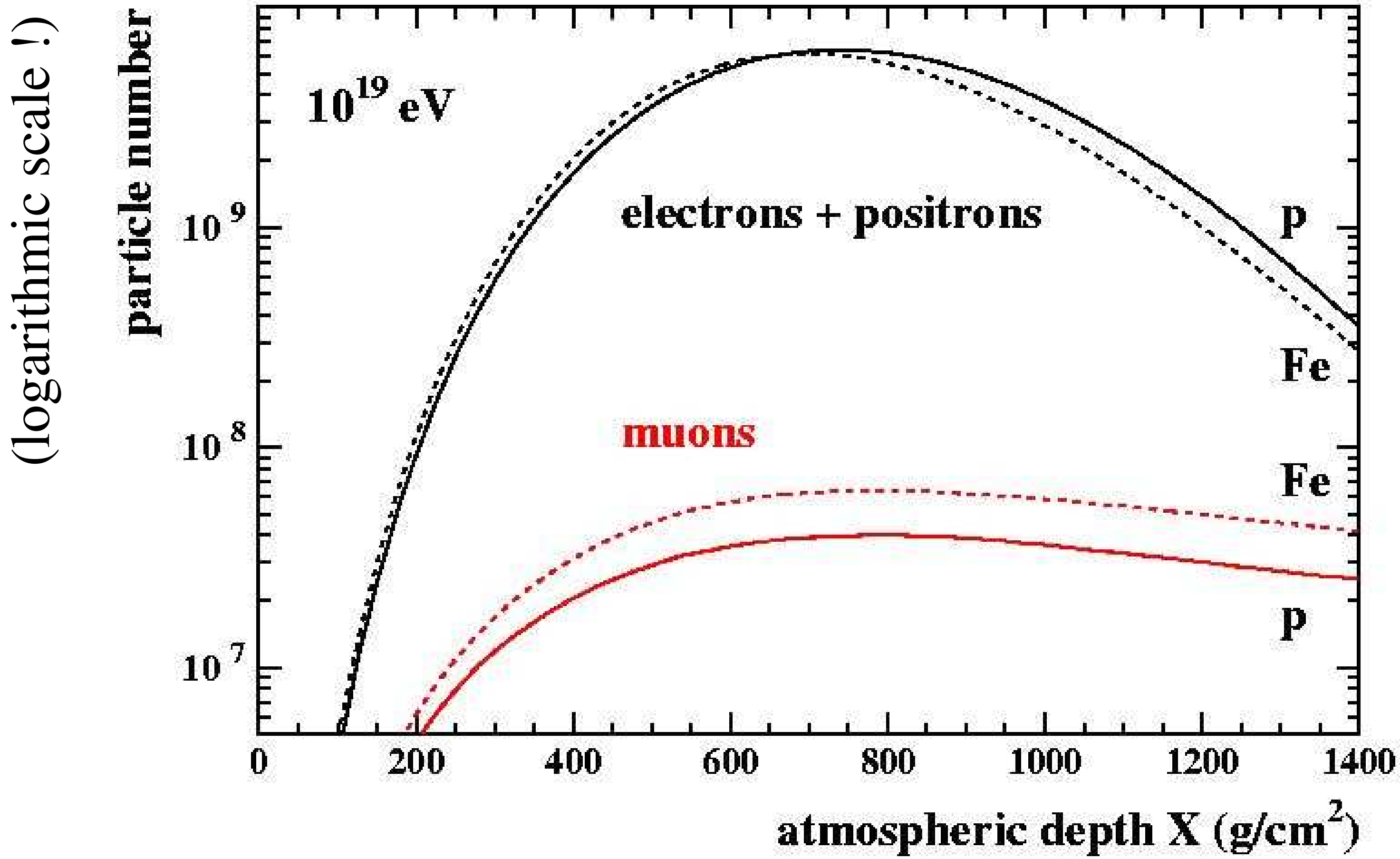
p vs Fe: Muons



note different development of N_e and N_μ

- **Fe: more muons** (total number) *-> primary mass sensitivity*

✓ smaller E_0/A -> π^{+-} less energetic

✓ higher altitude -> smaller ρ

} decay favoured

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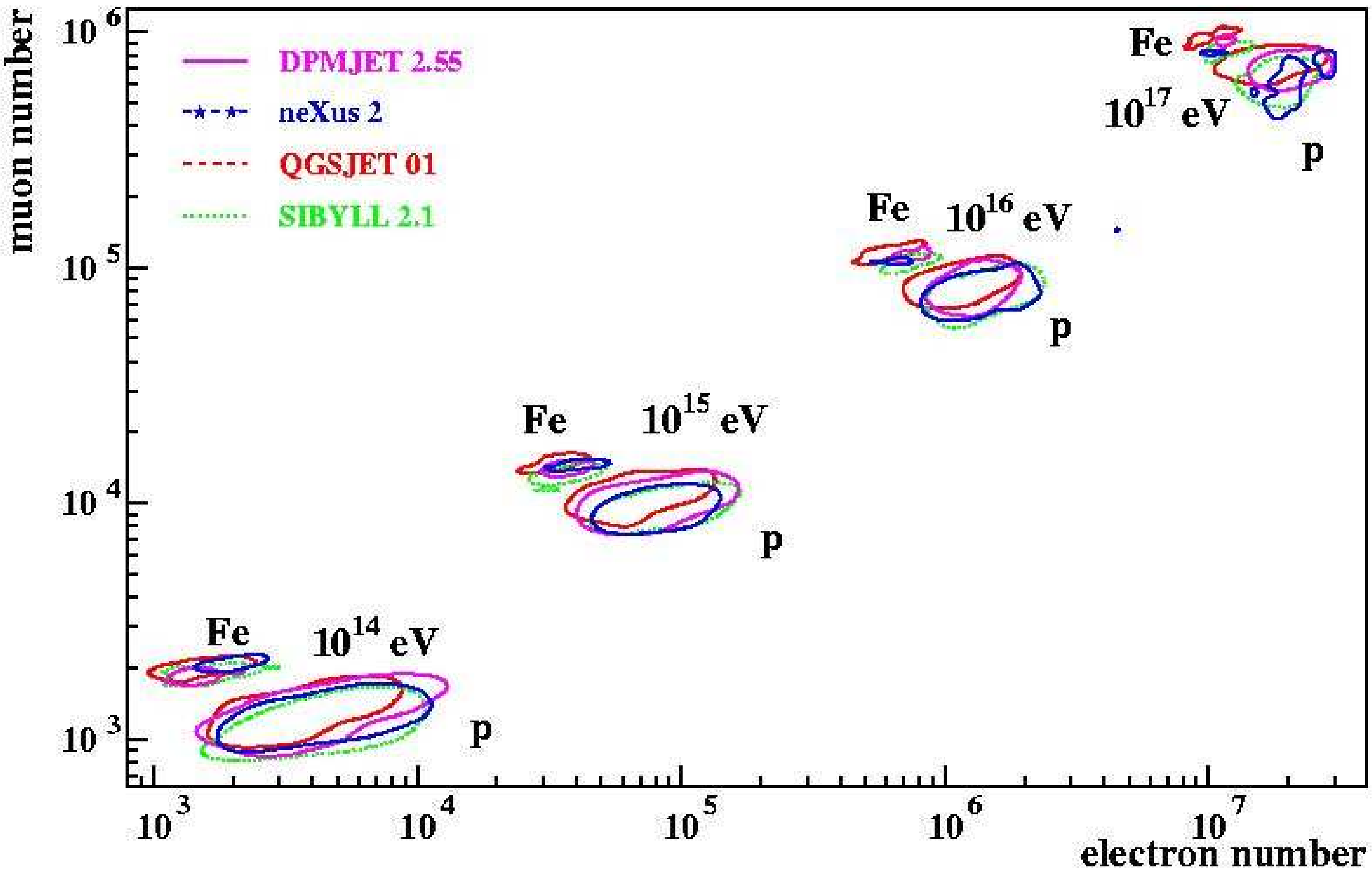
Primary Mass Separation (2): N_e vs N_μ



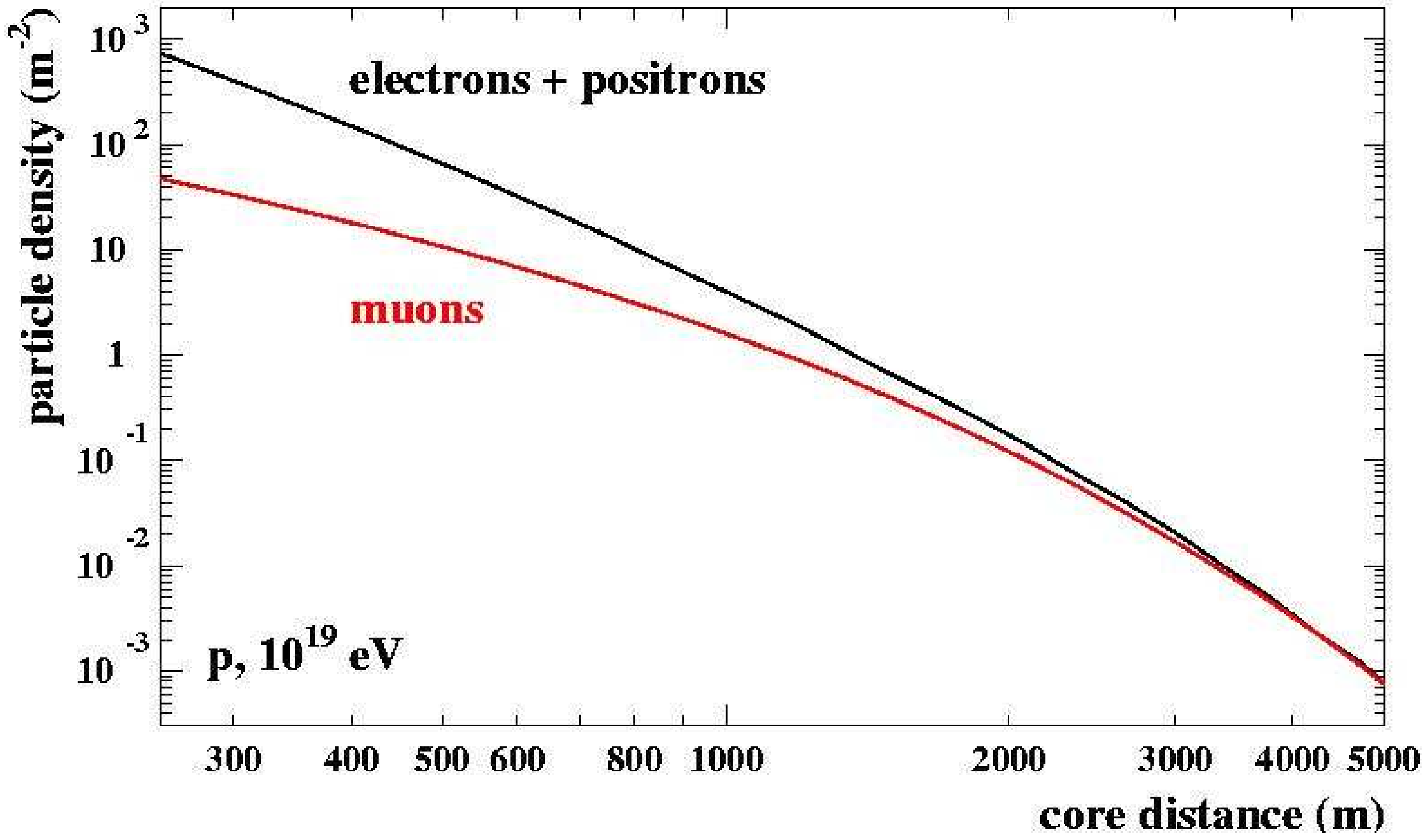
"potato plot"

(D. Heck)

- **correlated** measurement (+ analysis)

➔ *primary energy and mass*

Lateral Distributions on Ground



➔ different characteristics of shower components:

muon lat.dist. flatter (from larger altitudes)

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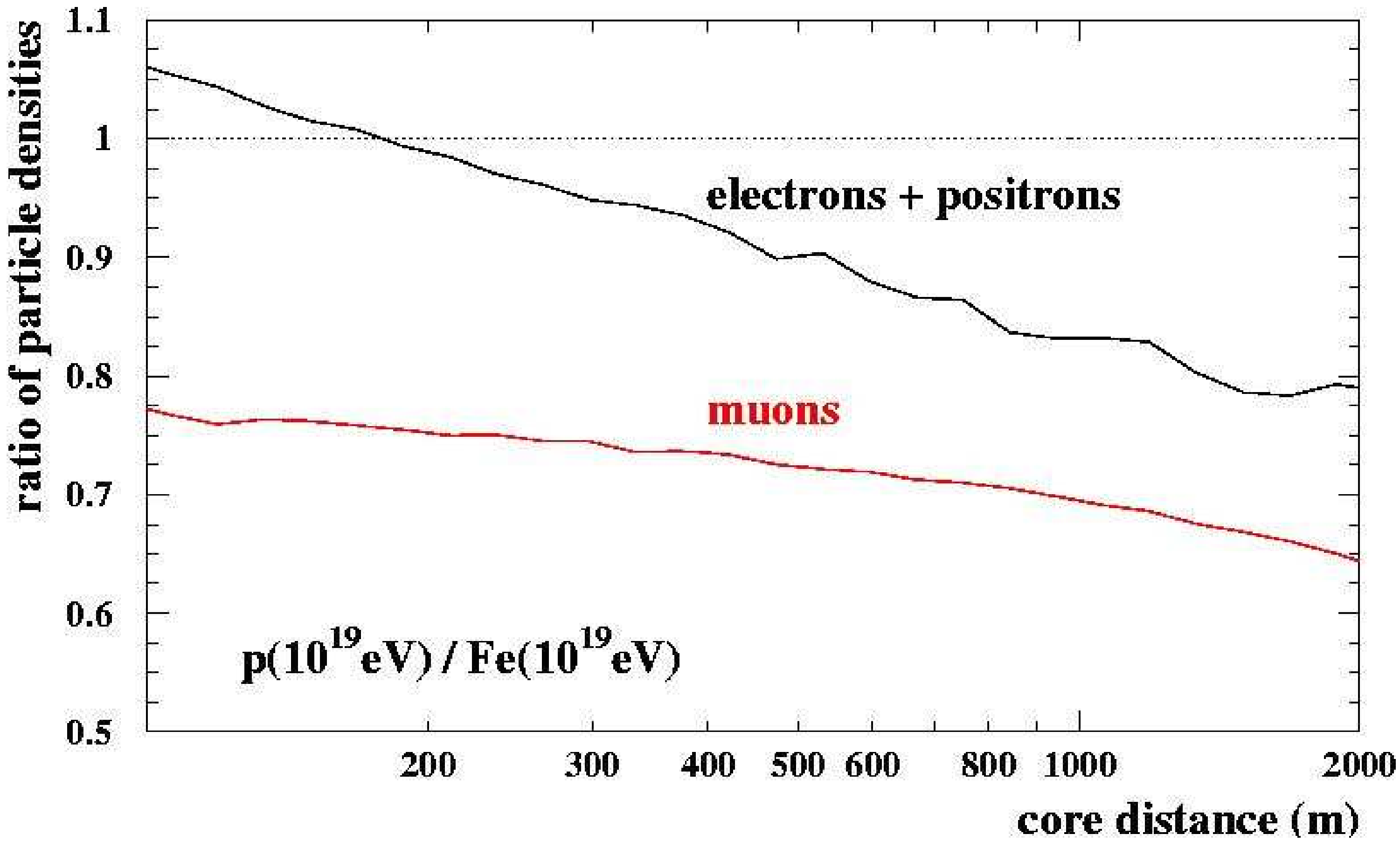
Lateral Distribution and Primary Mass



- **Fe lat.dist.s flatter** (from larger altitudes)

✓ Fe more muons (p more electrons: r < 200 m)

➔ densities vs distance *-> primary mass sensitivity*

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More Properties ... *flashed*

- **S(600-1000m):** smaller ground particle fluctuations
  - ➔ primary energy with large ground arrays
- **time structure** of front (muons vs electrons)
  - ➔ primary mass sensitivity
- **inclined showers** (atmosphere "filters" muons)
  - ➔ primary mass sensitivity
- **EAS hadrons:** also primary mass sensitivity; but ...
  - ➔ **test of interaction models**
- **primary photons** at $E_0 > 10^{19}$ eV (preshower, LPM)
  - ➔ separation of primaries ?

Conclusion: Extensive Air Showers ...

- different **shower components** (w different features)

➔ handle to determine E, A

➔ **astrophysics**

challenge, though !

➔ high-energy interactions, forward direction

➔ **particle physics**

- *even after many decades:*

... fascinating tools for astro & particle physics

DZIĘKUJE BARDZO !

primary interaction

different components

shower detection

(artistic view of an EAS)