Ultra High-Energy Cosmic Rays with Pierre Auger Observatory

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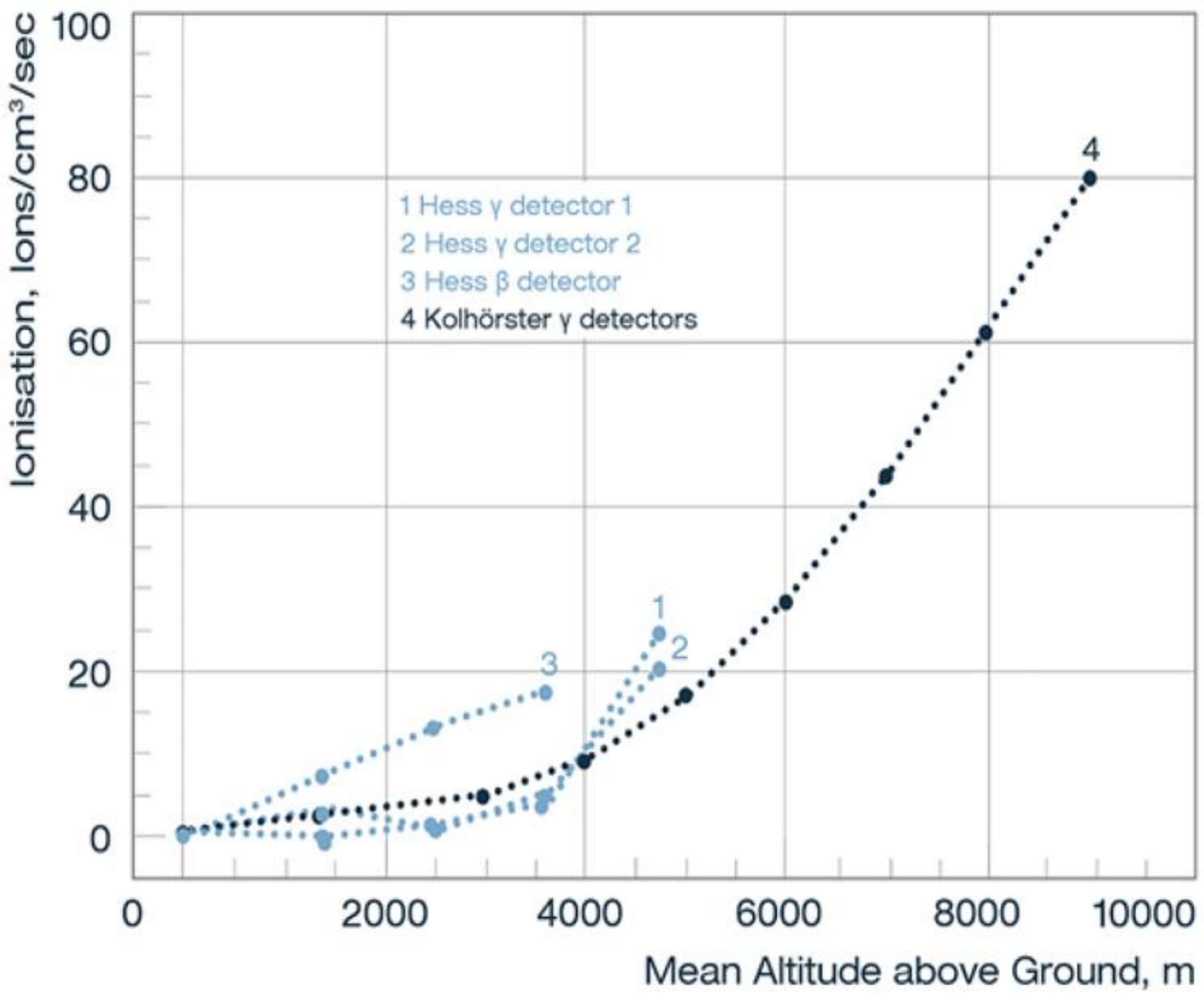
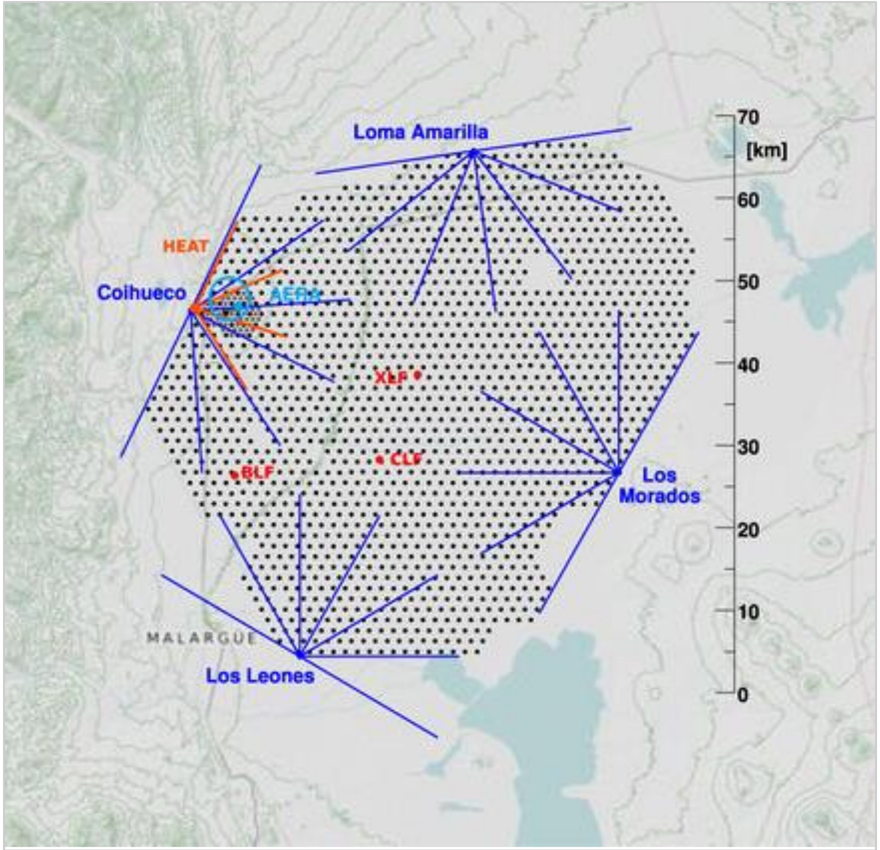
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

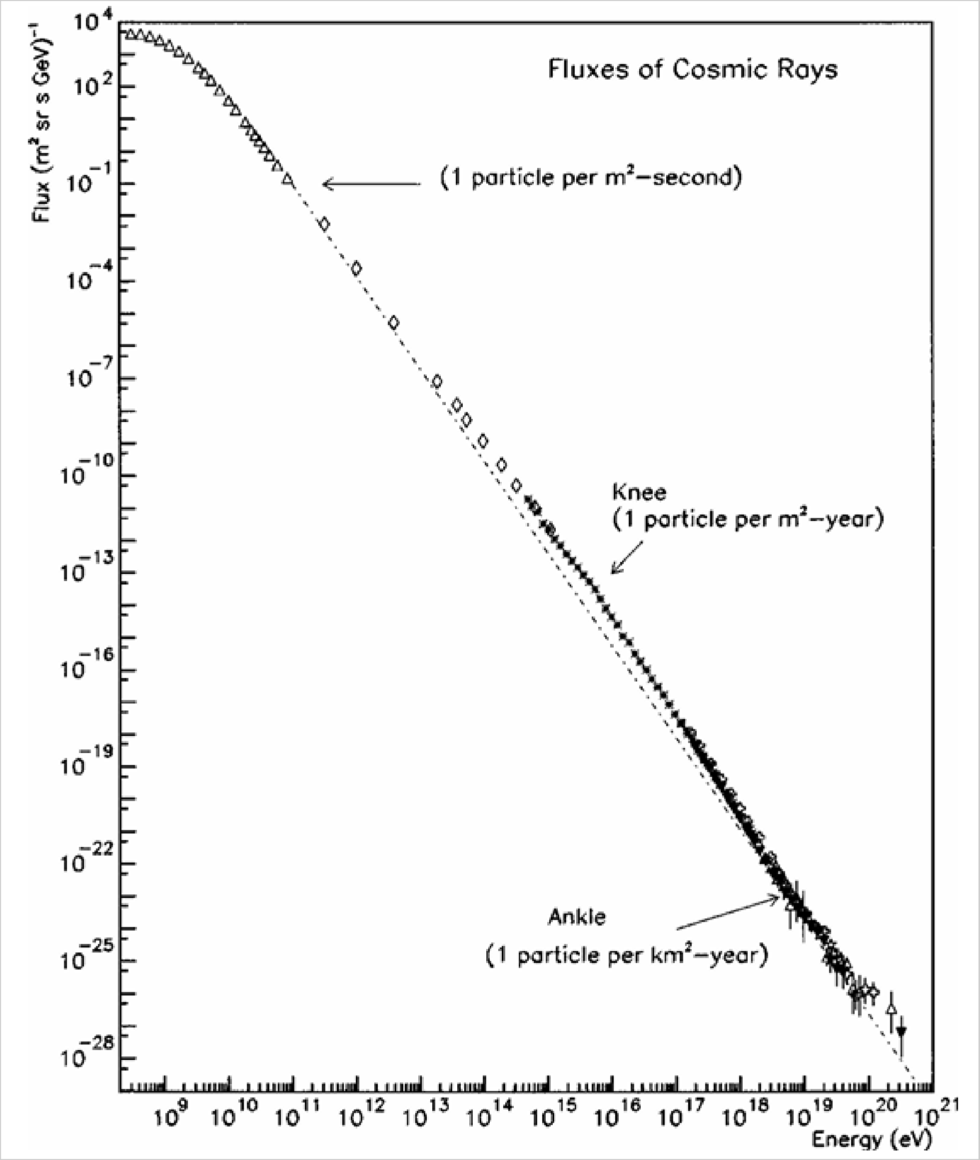
Introduction



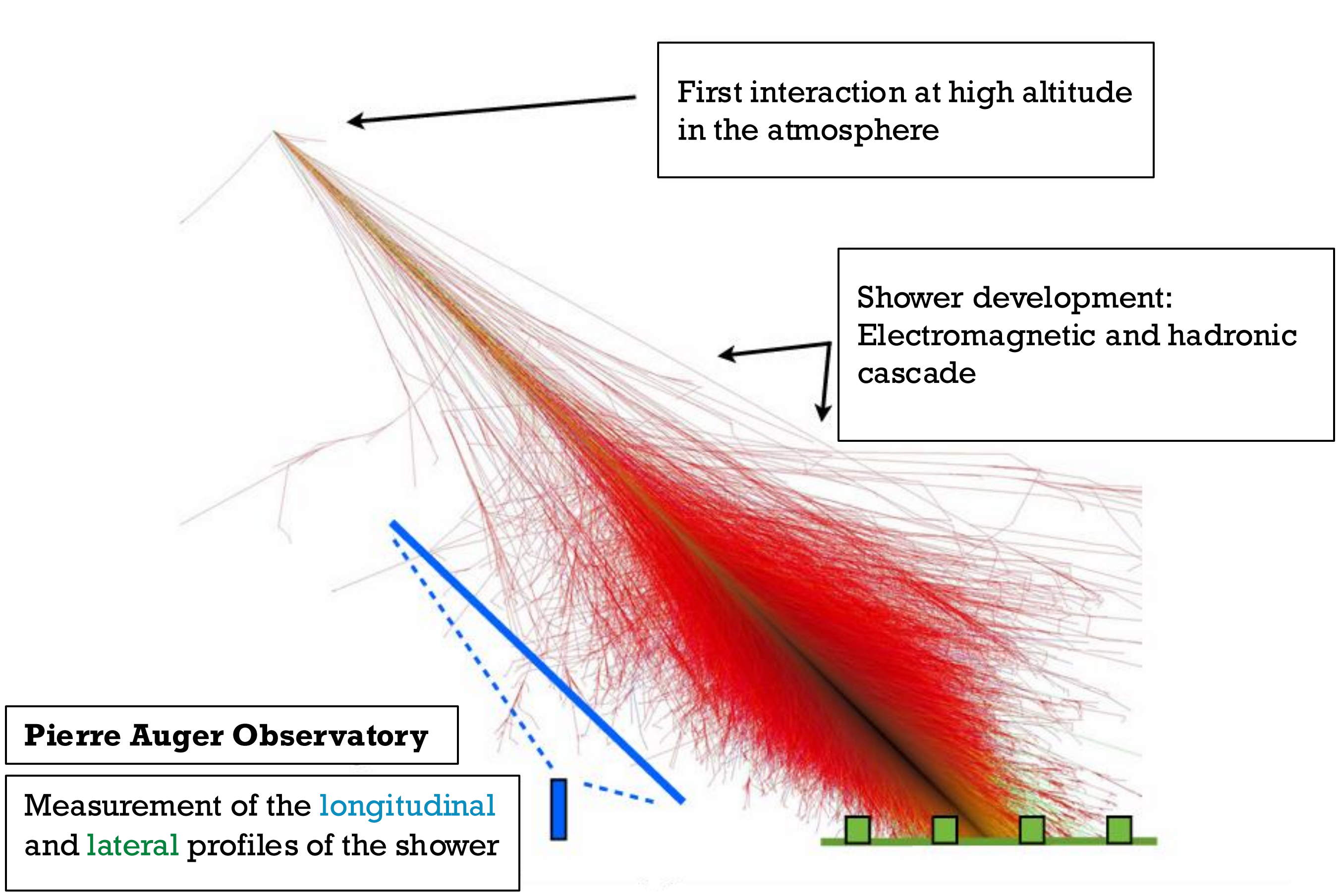
Pierre Auger Observatory

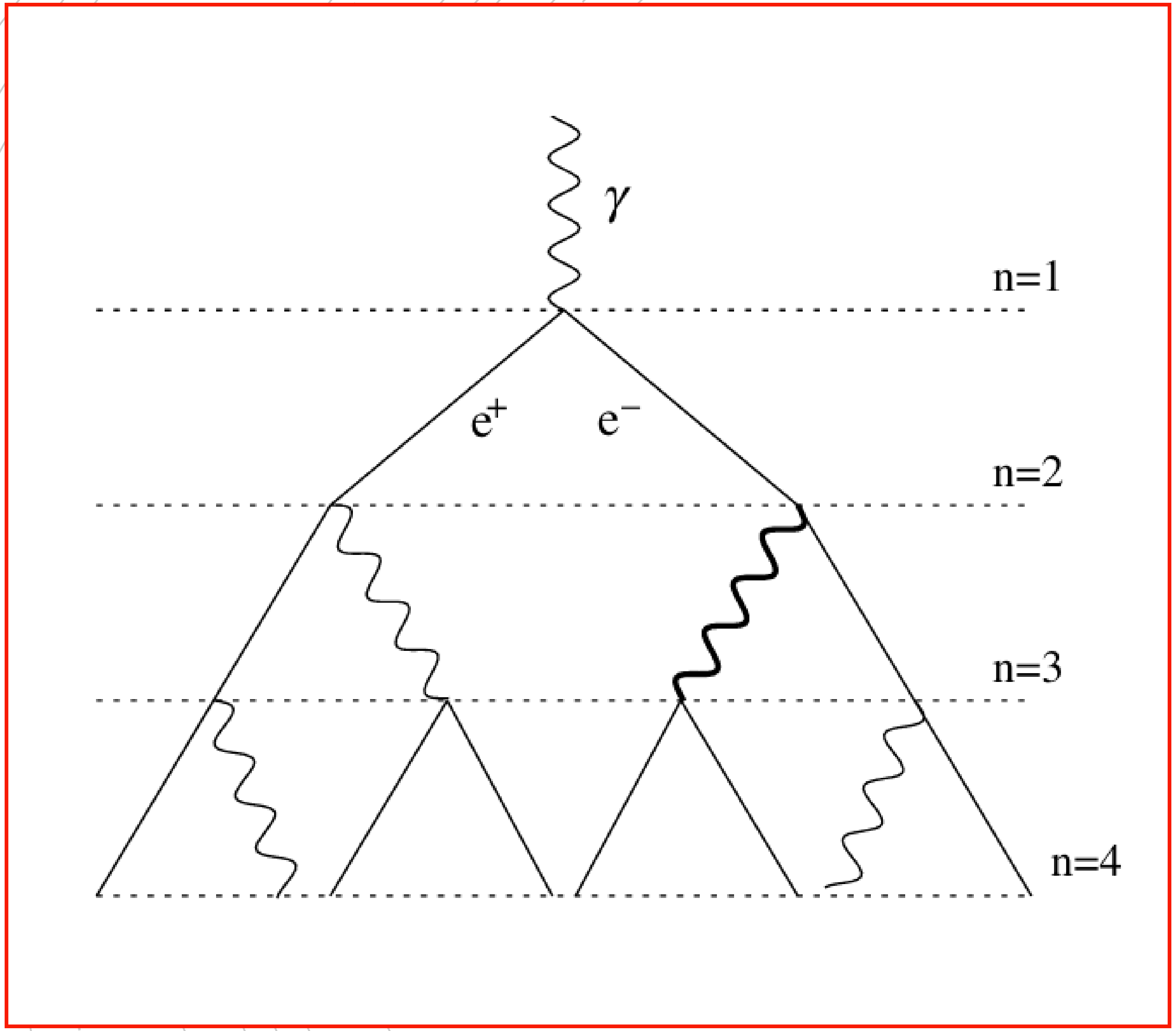
- Low flux of particles;
- Hybrid Detector;





Heitler Model for Air Shower

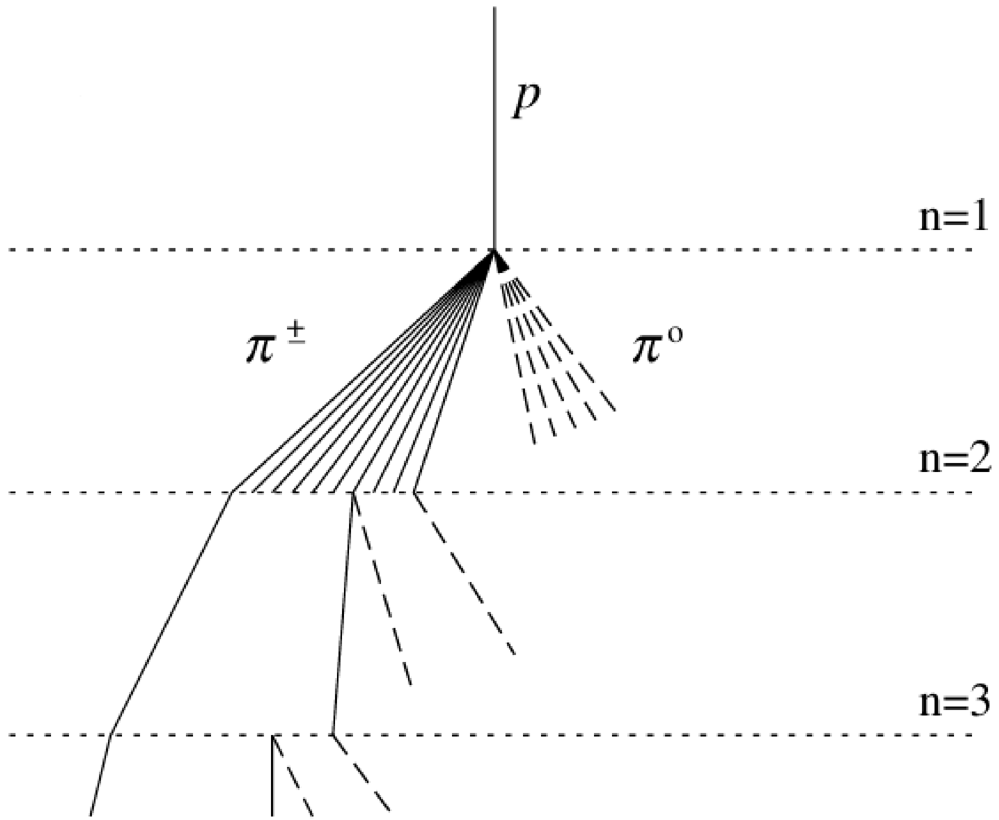




2.1 Electromagnetic Showers

- Primary photon splits into electron-positron pairs;
- Bremsstrahlung after each generation;
- Stops when electron-positron energies drop below critical energy;

$$X_{max}^{\gamma} = n_c \lambda_r \ln 2 = \lambda_r \ln\left(\frac{E_0}{\xi_c^e}\right)$$



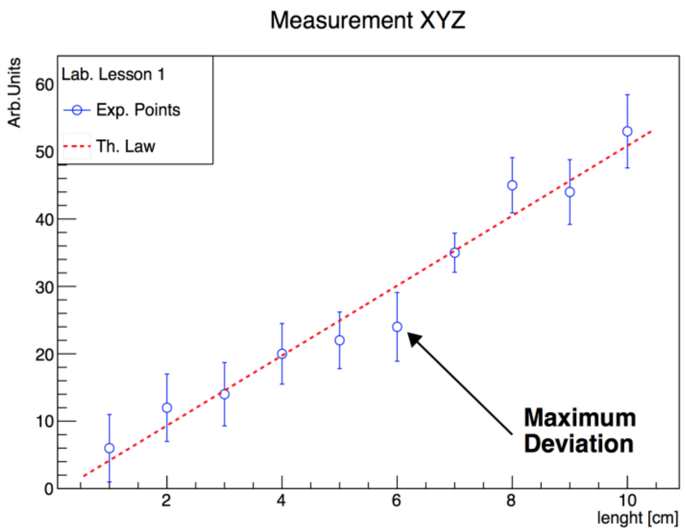
2.1 Hadronic Showers

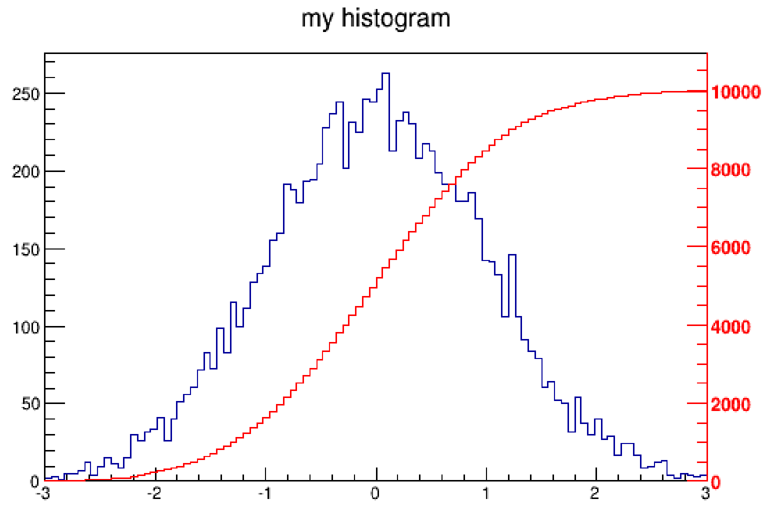
- Primary proton splits into pions;
- Charged pions form new pions;
- Neutral pions decay and form EM showers;
- Stops when pions energies drop below critical energy and decay into muons;
- Nuclei induced showers are treated as the superposition of individual proton showers;

$$X^{p}_{max} = \lambda_I \ln 2 + \lambda_r \ln\left(\frac{E_0}{3N_{ch}\xi^e_c}\right)$$

CORSIKA and ROOT

- ROOT: framework for data analysis;





- COsmic Ray SImulations for KAscade;
- Monte Carlo simulations;

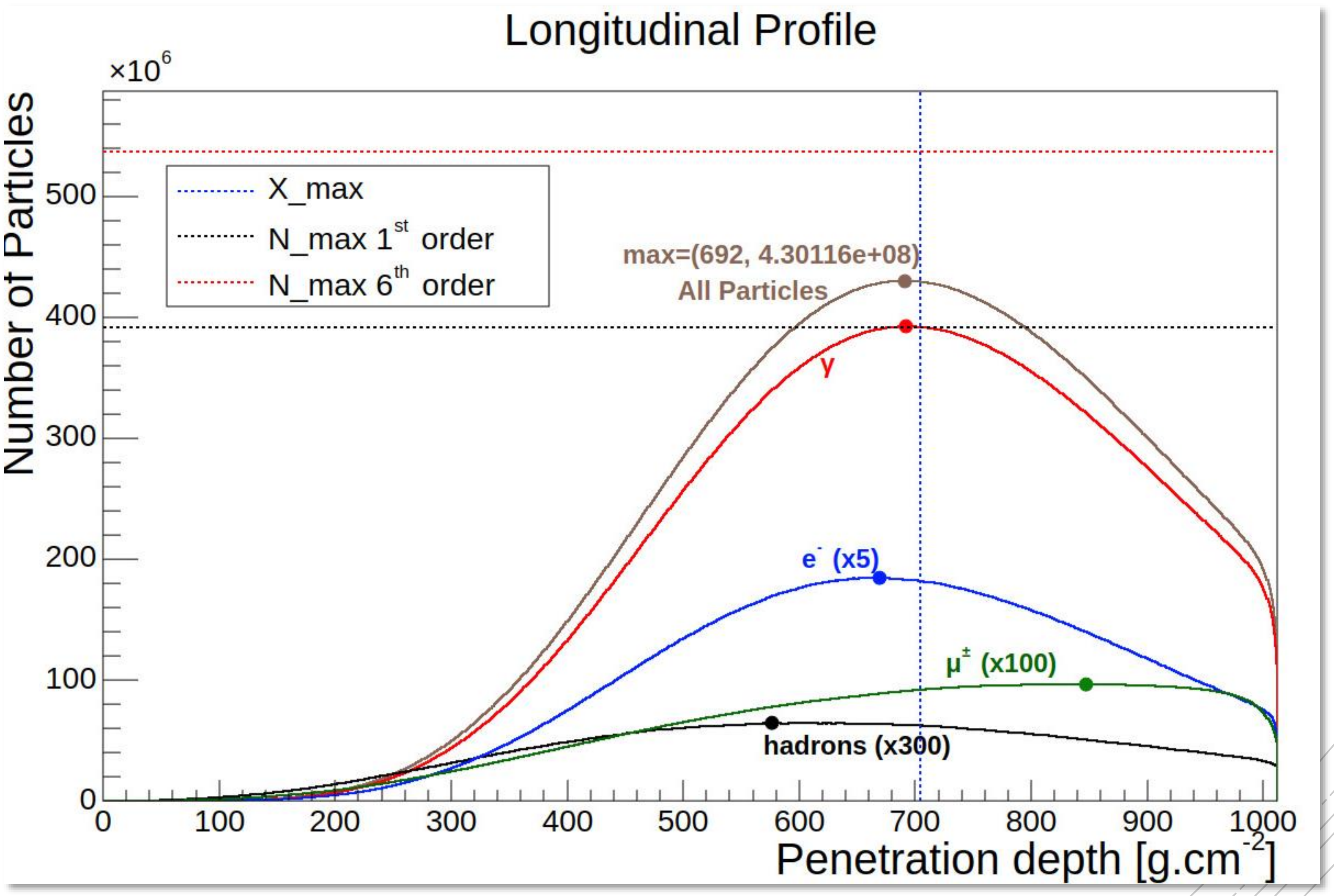
Results and Discussion

Proton shower

- **Energy: 10^{17} eV; θ=30°**

- Longitudinal Profile;
- Model vs simulation;

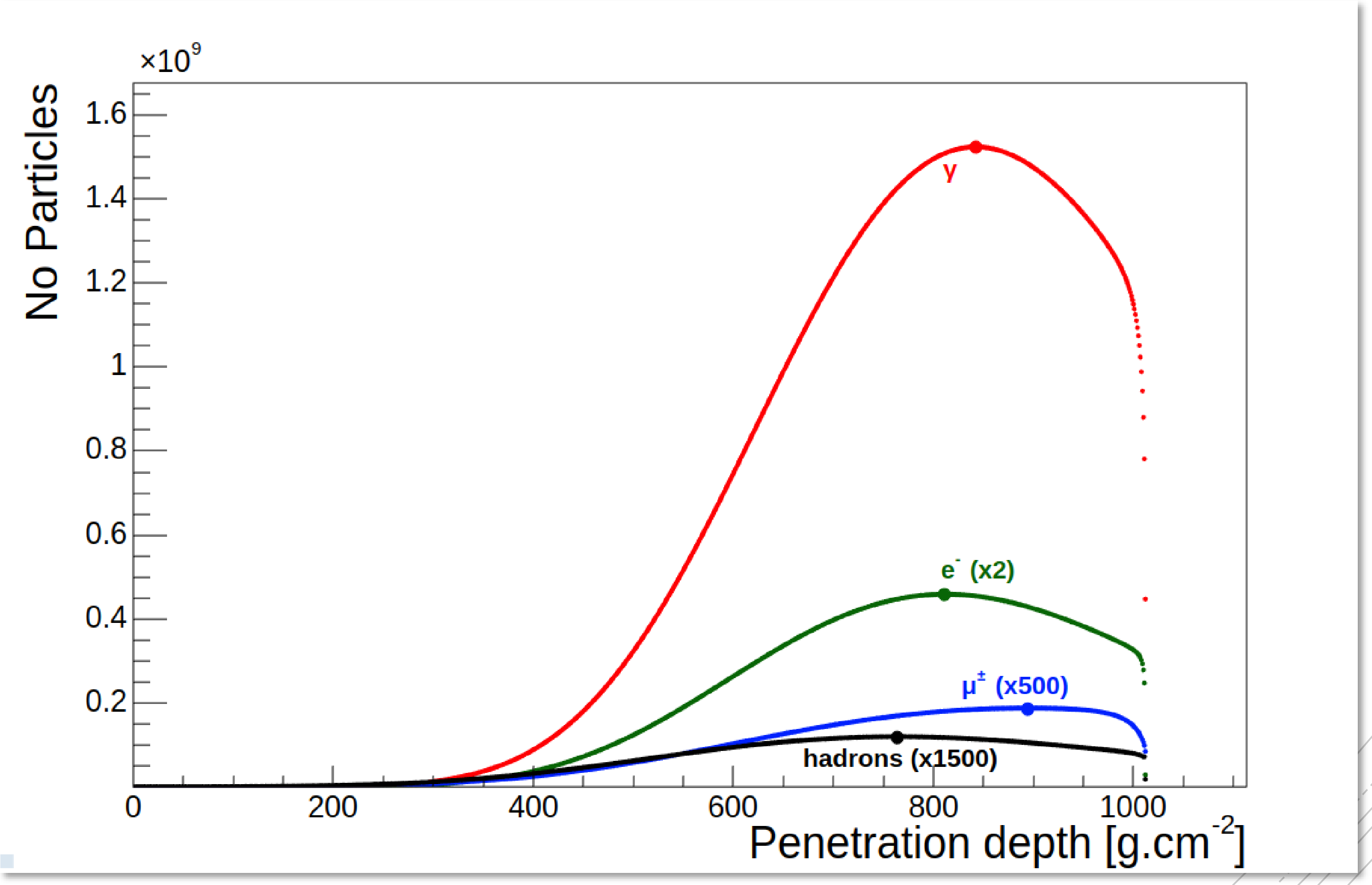
$$N_{max} = \frac{E_0}{\xi_c^e}\left(\sum_{i=1}^{n_c}\frac{1}{2}\cdot\left(\frac{2}{3}\right)^i\right)$$



Gamma shower

- **Energy: 10^{17} eV; θ=30°**

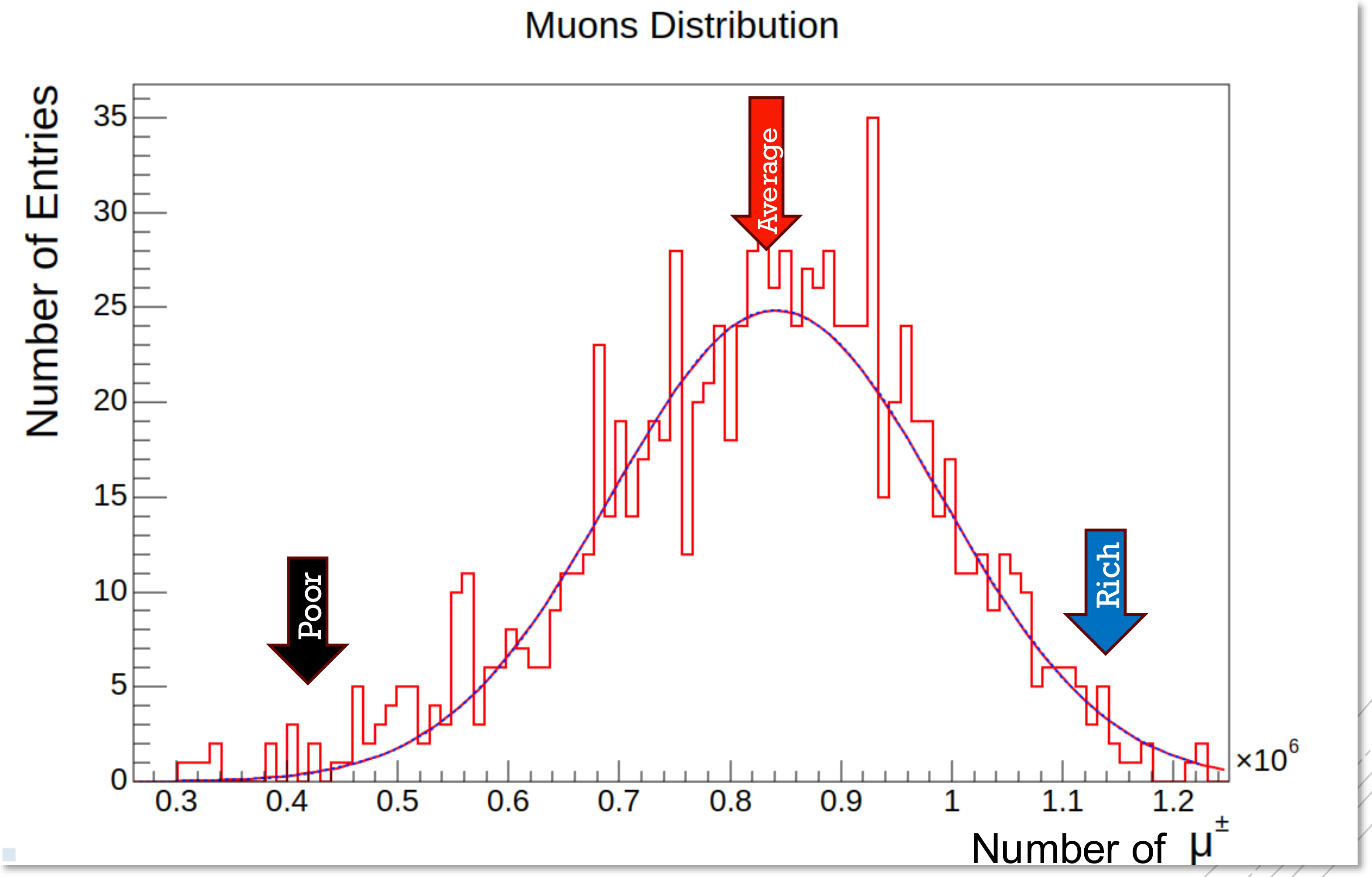
- Longitudinal Profile;
- #Photons > #Electrons;
- Muons on gamma shower;



Proton showers

- **Energy: 10^{17} eV; θ=30°**

- Muon number distribution for 1000 showers;
- Choosing a muon rich, poor and average showers;



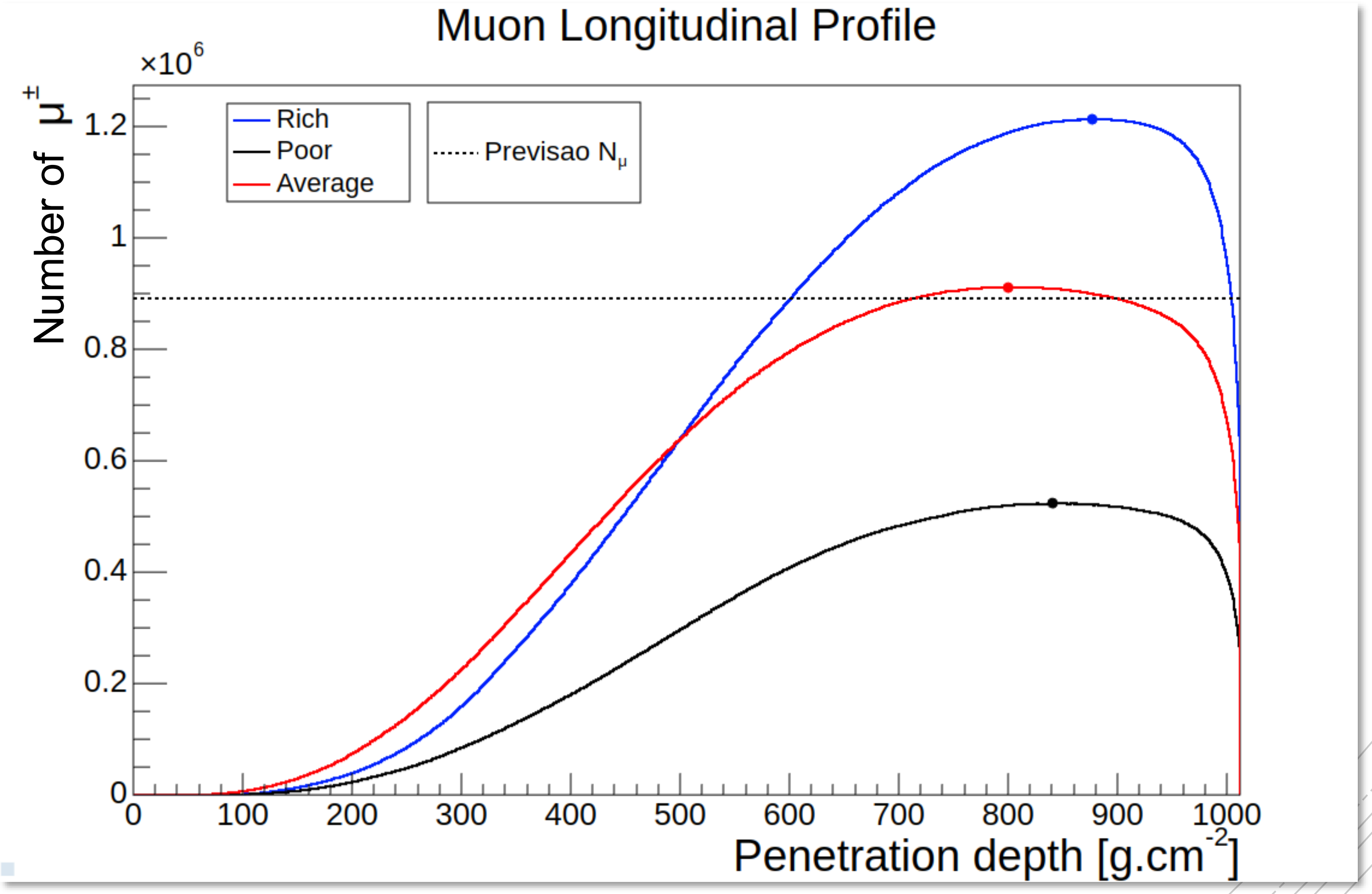
Proton showers

- **Energy: 10^{17} eV; θ=30°**

- Rich, poor and average showers longitudinal profile;
- Prediction of #Muons;

$$N_\mu = N_\mu^p = \left(\frac{E_0}{\xi_c^\pi}\right)^\beta$$

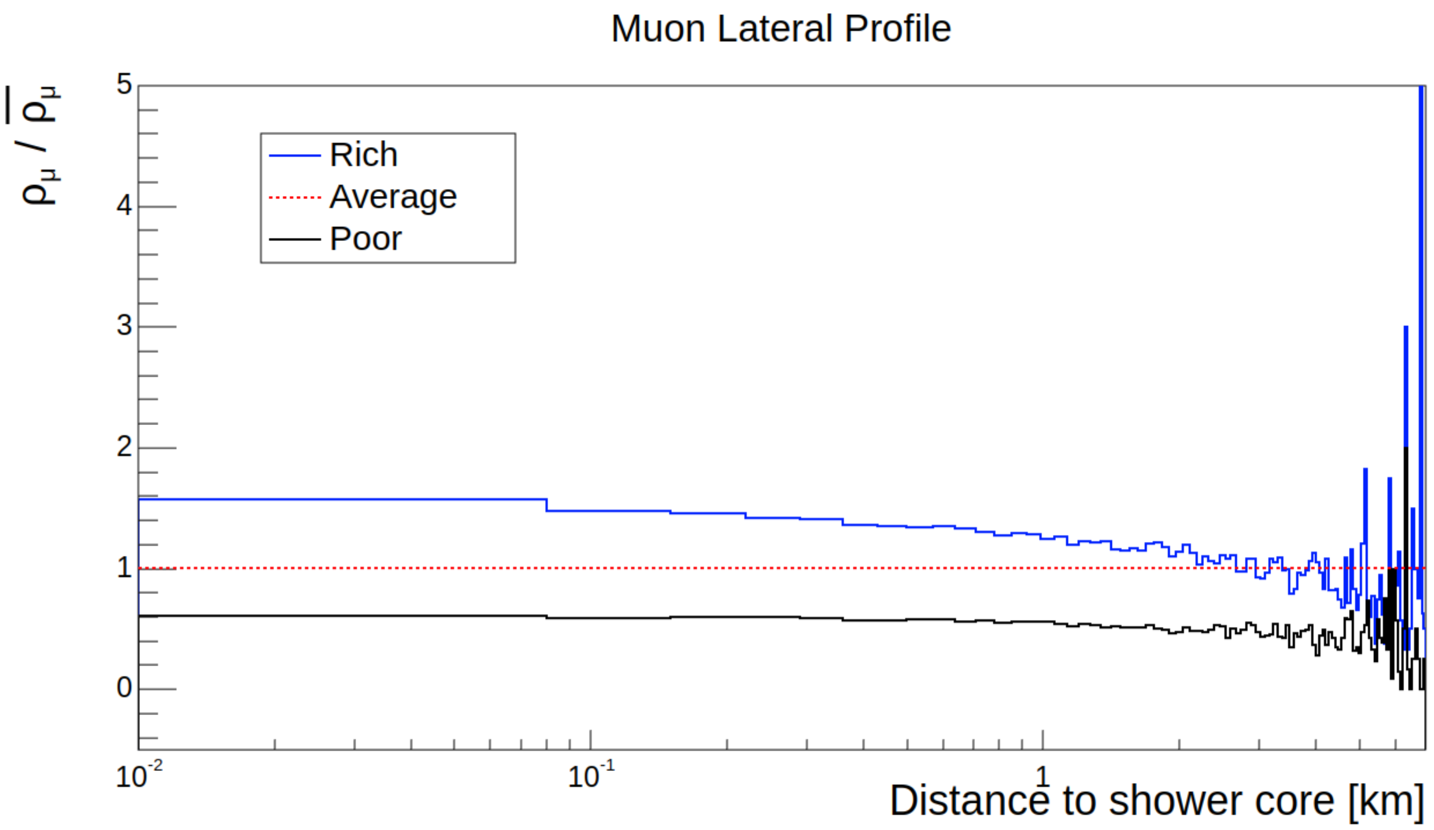
$$\beta = \frac{ln[N_{ch}]}{ln[\frac{3}{2}N_{ch}]} = 0.85$$



Proton showers

- **Energy: 10^{17} eV; θ=30°**

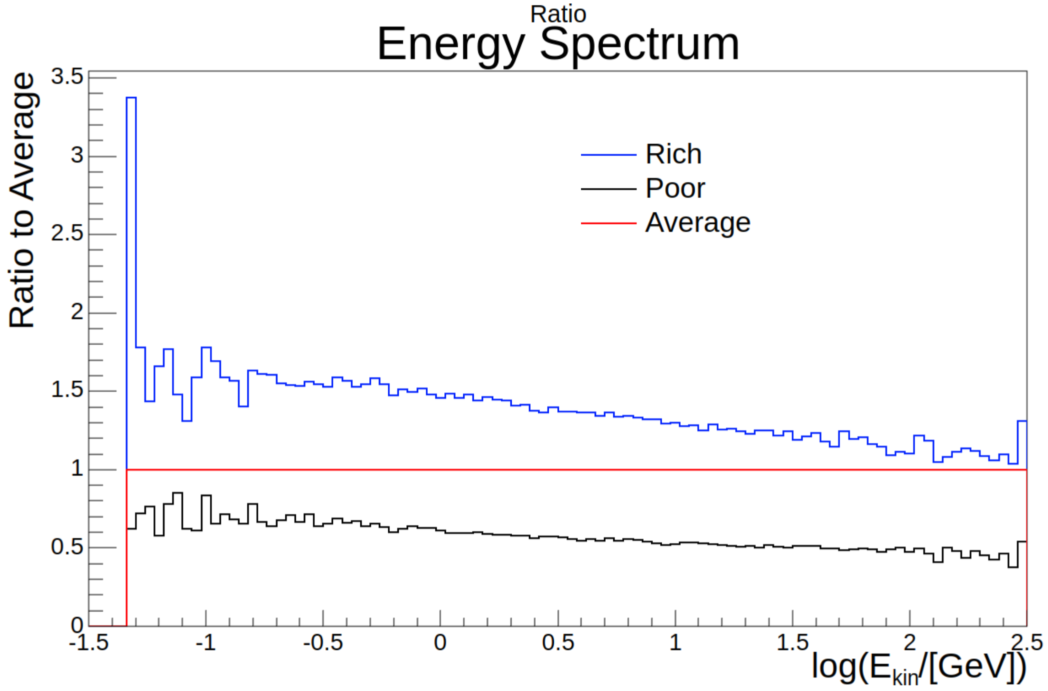
- Lateral profile;
- Rich and poor relative to average;

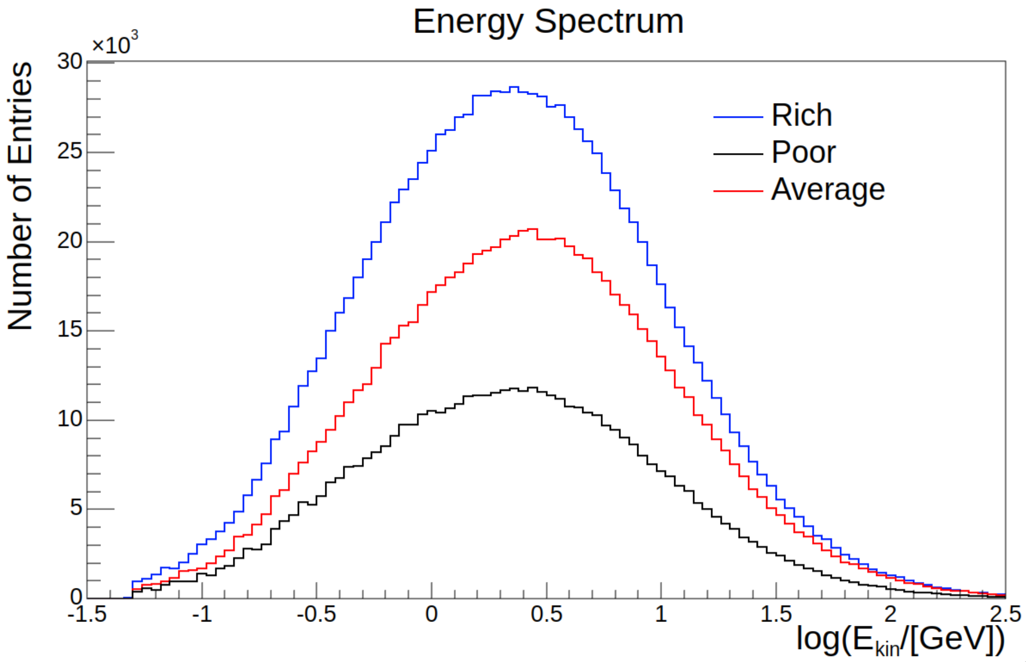


Proton showers

- **Energy: 10^{17} eV; θ=30°**

- Energy Spectrum for each sample chosen;



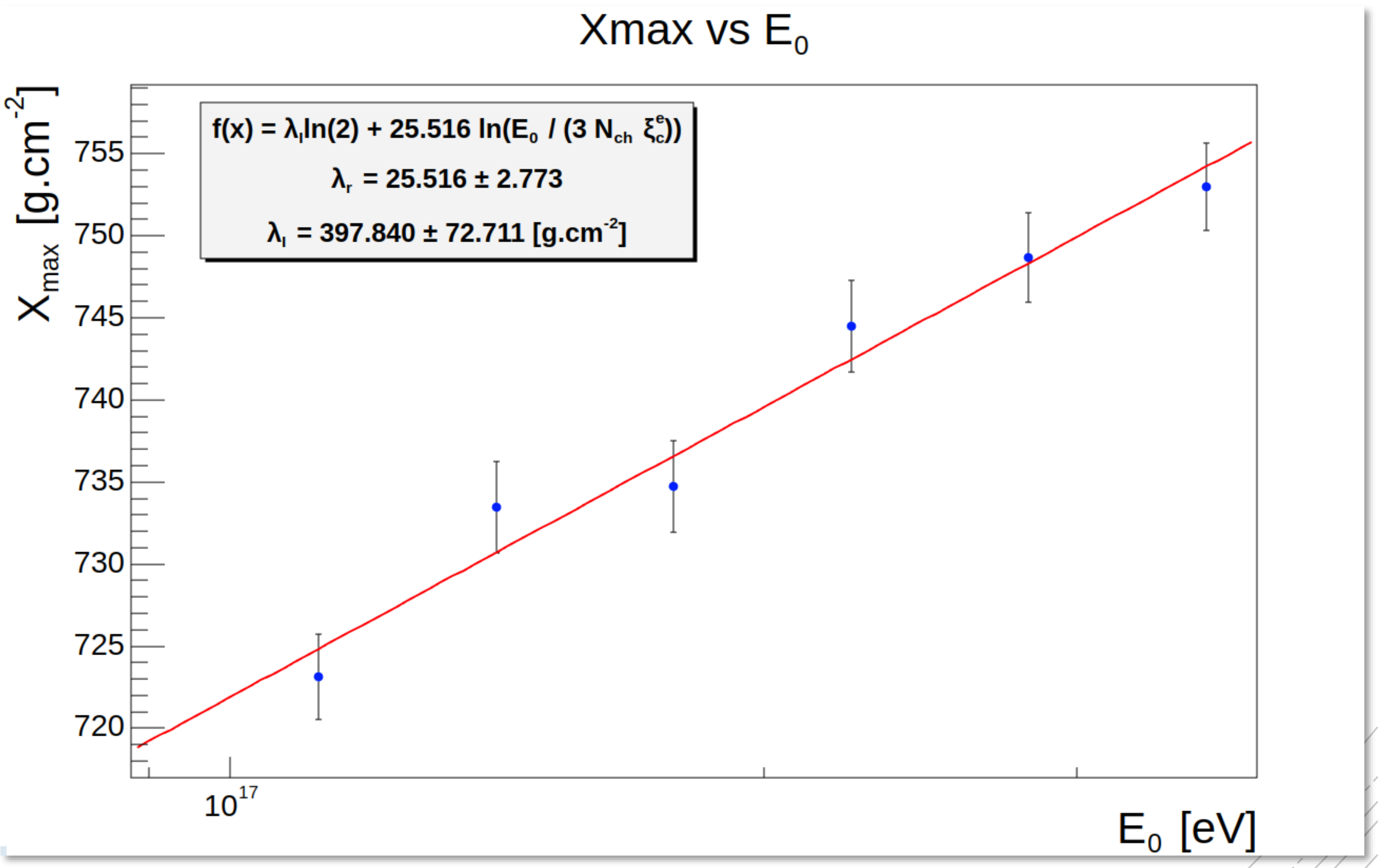


Proton showers

- **Energy: $10^{17\text{-}17.6}$ eV; θ=30°**

- Estimate for λ_r (37 g.cm^{-2}), using λ_I (120g.cm^{-2});

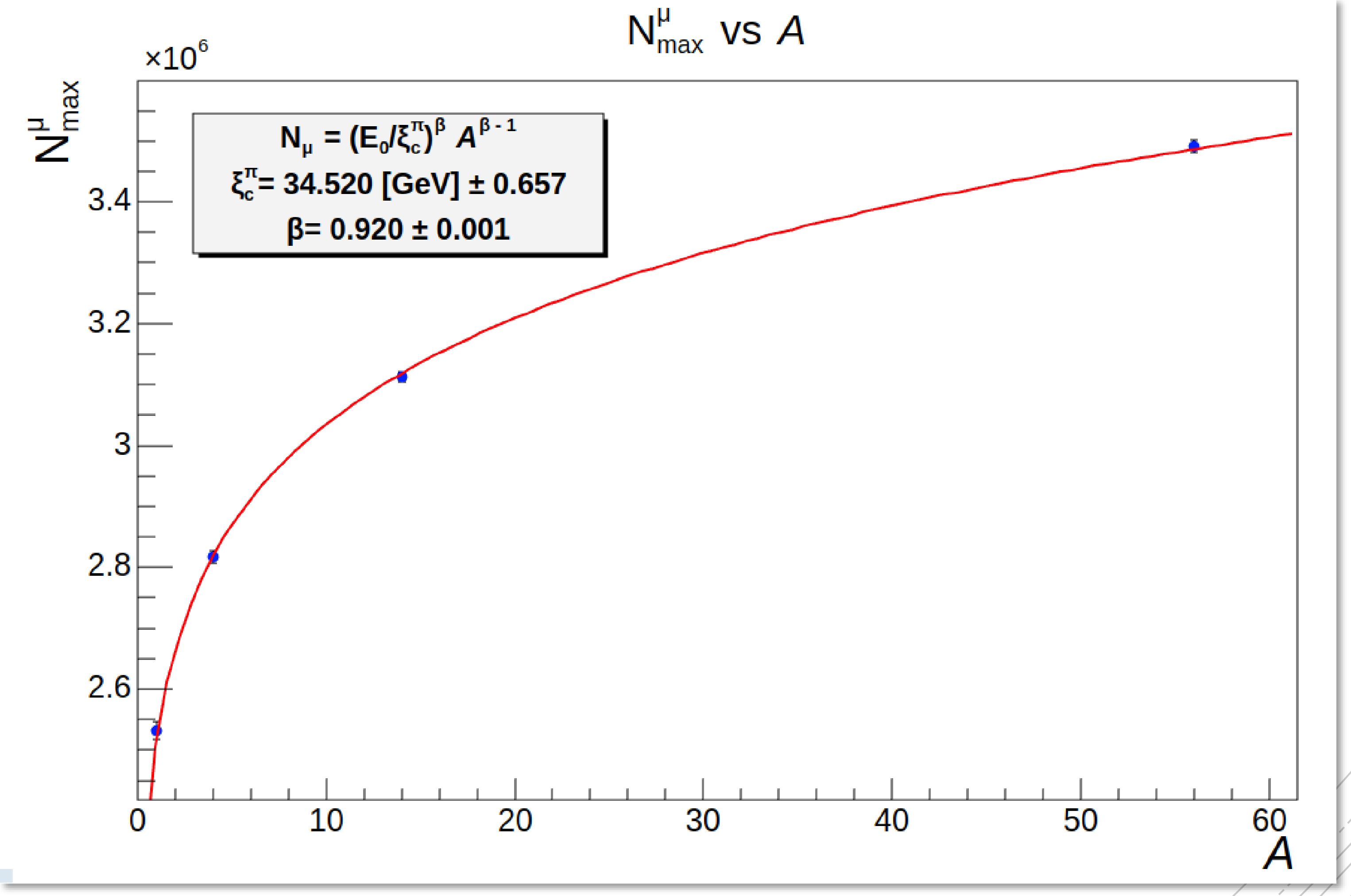
$$X_{max}^{p} = \lambda_I \ln 2 + \lambda_r \ln\left(\frac{E_0}{3N_{ch}\xi_c^e}\right)$$



- **Energy: $10^{17.4\text{-}17.6}$ eV; θ=30°**

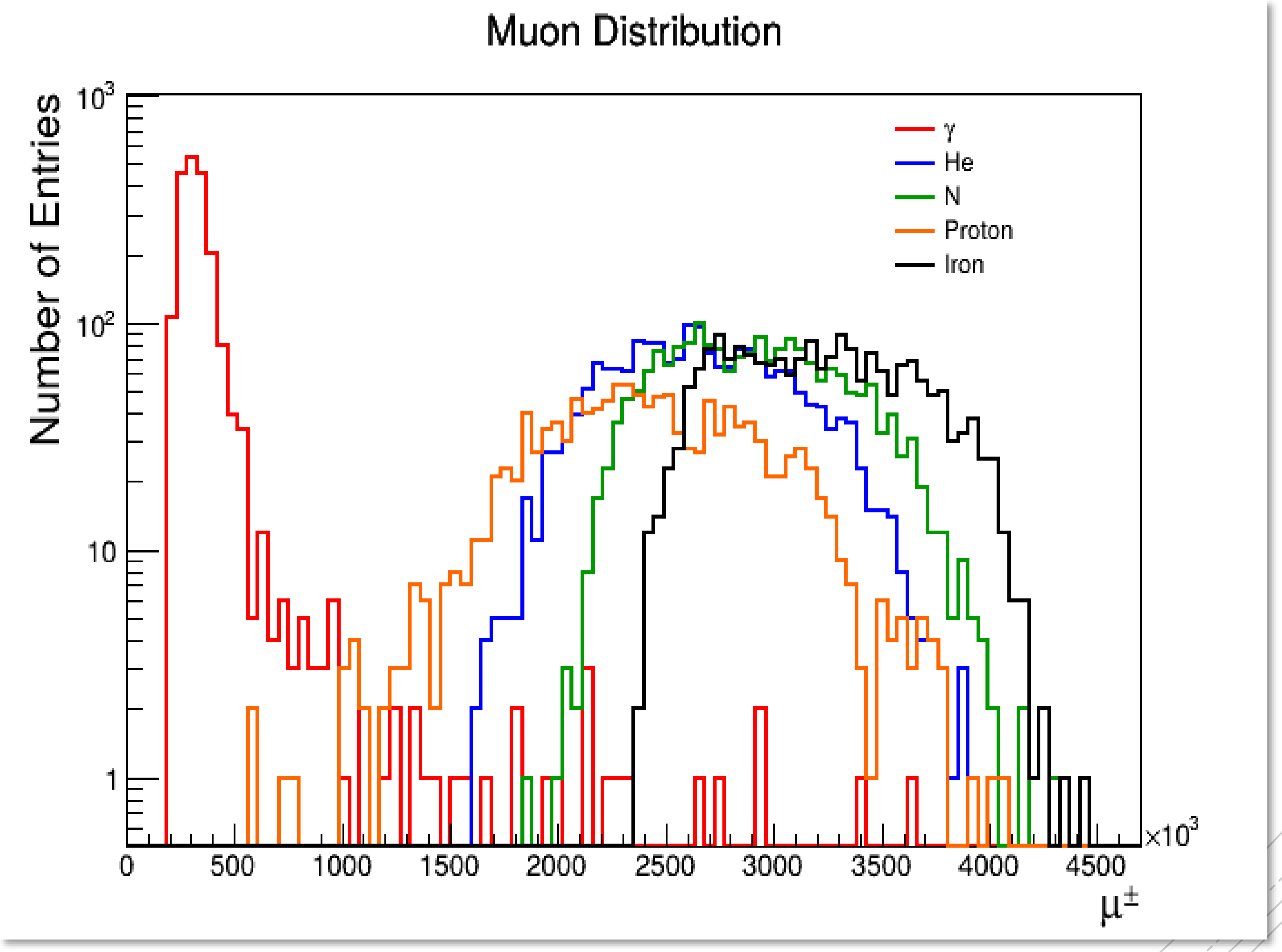
- Proton, Helium-4, Nitrogen-14, Iron-56;
- Estimate for β (0.85 $g.cm^{-2}$) and ξ_c (10 GeV);

$$N_\mu^A = N_\mu^p A^{0.15}$$



- **Energy: $10^{17.4\text{-}17.6}$ eV; θ=30°**

- Comparison of muon distribution for showers with different primaries;
- #Muons (γ) ≈ #Muons (Fe);



Conclusion

- We were able to study EAS and its components;
- Through simulations, we got to probe Heitler's model for EAS;
- Heitler's model, although simple, captures the essence of the physical processes responsible for these showers;
- Heitler's model allows us to make predictions and estimate physical quantities, but fails to take into account the randomness of the real world EAS;

References

- Grupen, Claus, Astroparticle Physics, 2, Springer Cham
- W. Cronin, J. (1999). Cosmic rays: the most energetic particles in the universe, Rev. Mod. Phys.
- Matthews, J. (2005). A Heitler model of extensive air showers, Volume 22, Issues 5–6, 387-397
- Pierre Auger Observatory (March 2024). Open Data. https://opendata.auger.org/
- Slides provided by the professor Raul Sarnento for LIP Internship of 2025