UNIVERSIDAD DE GRANADA

Ultra-peripheral collisions in Extensive Air Showers

MeV2TeV-III (17/02/23)

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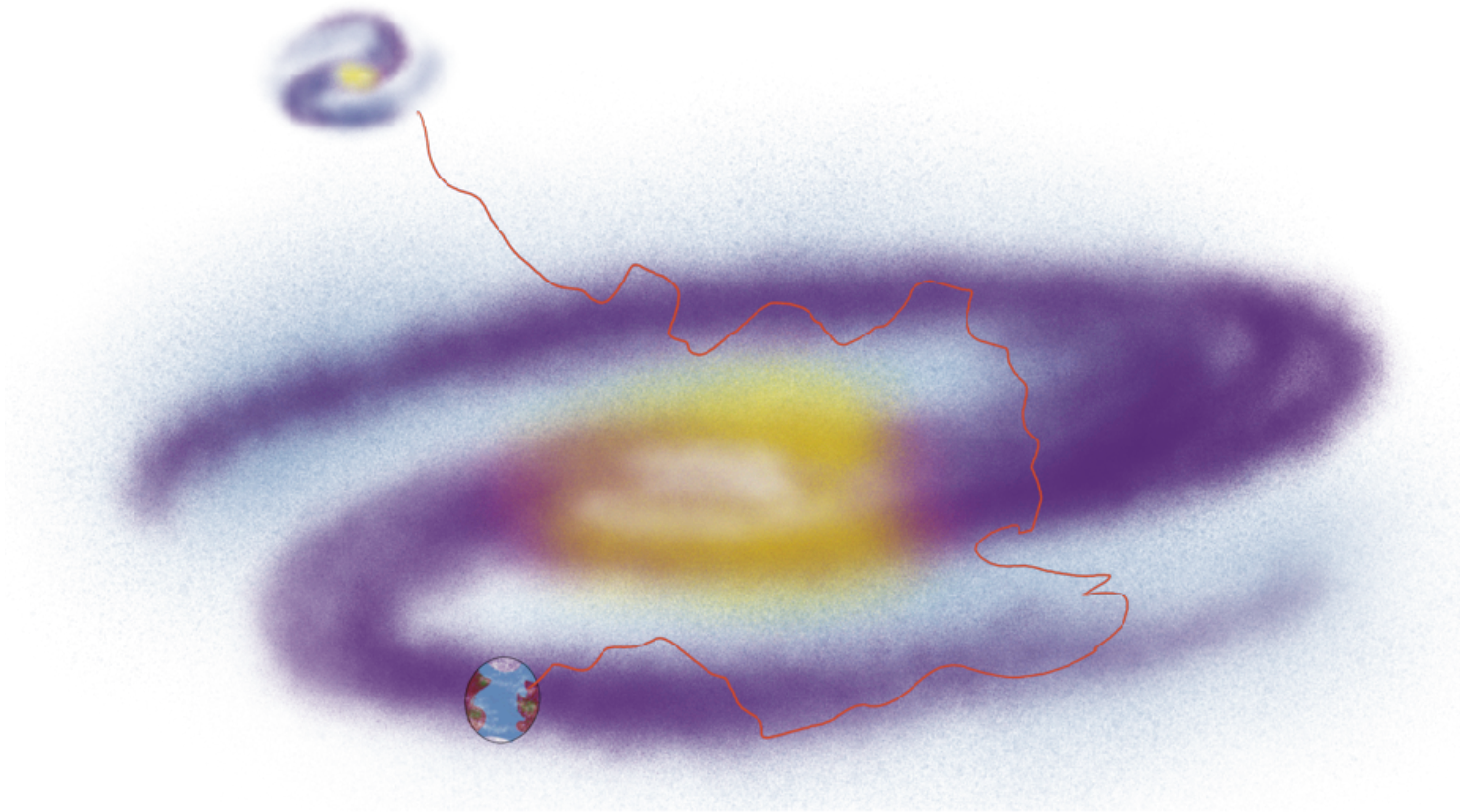
Overview

- Introduction → motivation
- Methodology
- Results
- Conclusion

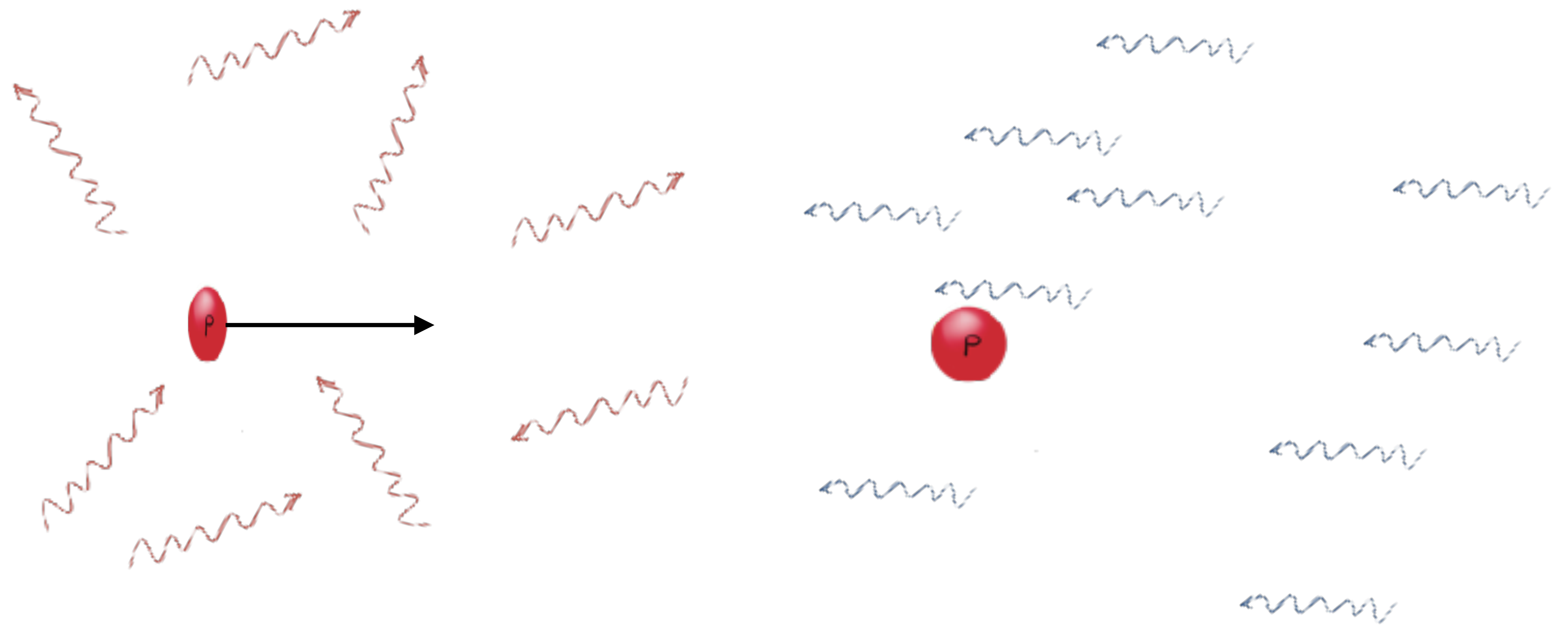
What are cosmic rays?

- **Cosmic rays** are particles that reach the earth
- They can be of **galactic** or **extra-galactic** origin
- During their travel, they are **accelerated** by different sources
- And, they can **decay** during their travel

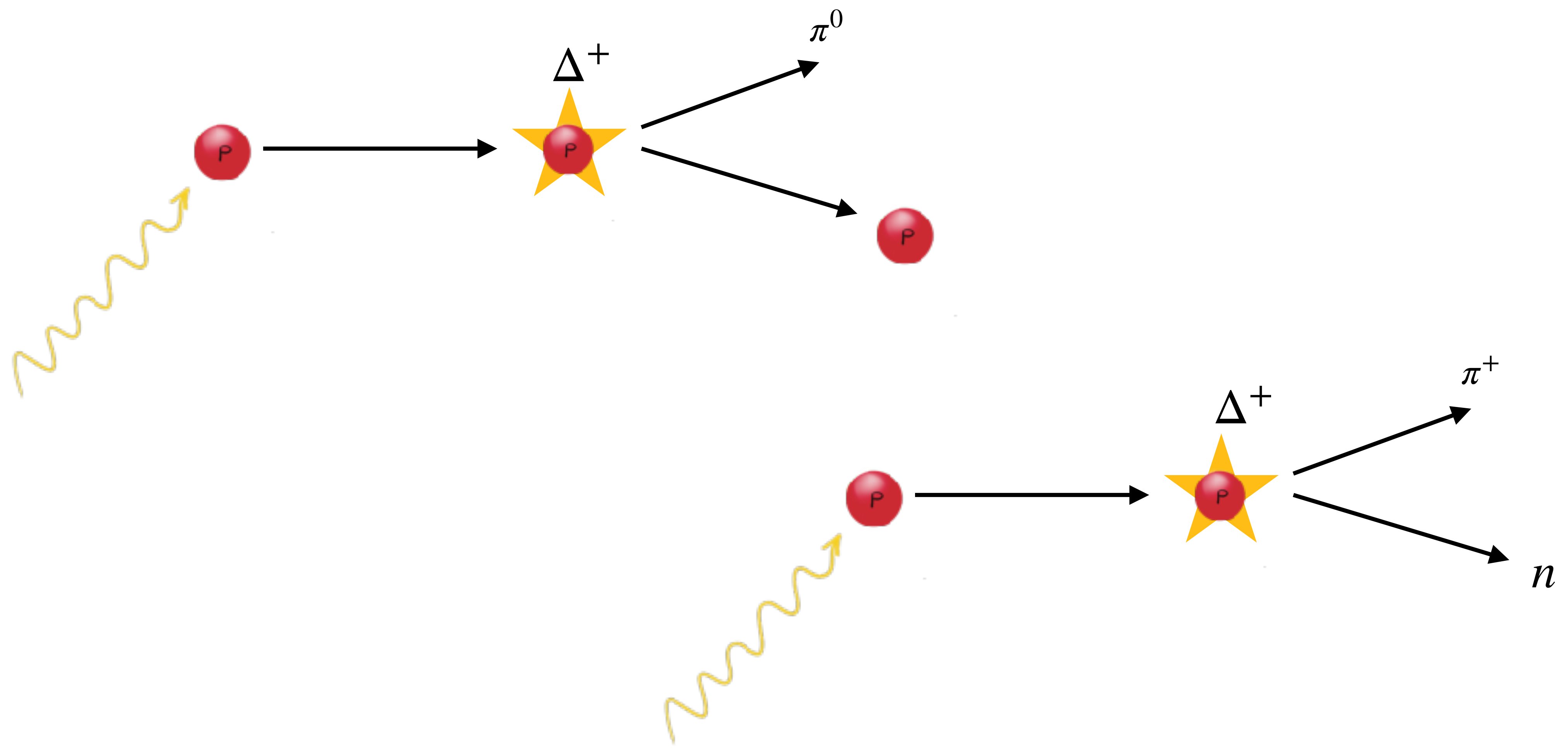


WARNING: Not to scale.

Greisen–Zatsepin–Kuzmin limit

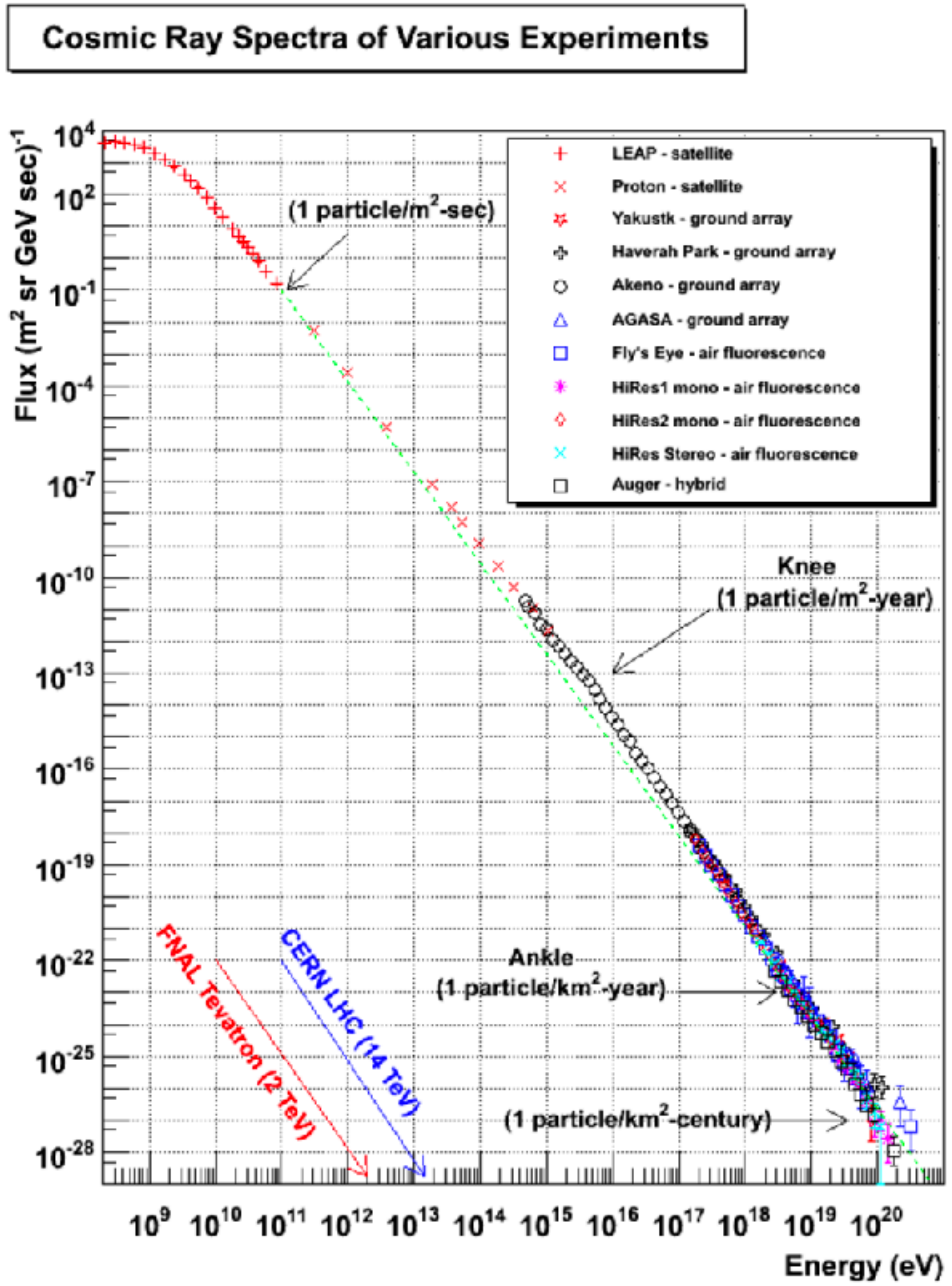


- **Limits the maximum energy** expected for cosmic rays,
- **Energies** $> 5 \cdot 10^{19}$ eV,
- **Pair-production** happens even **earlier** but **takes less energy** from the primary particle



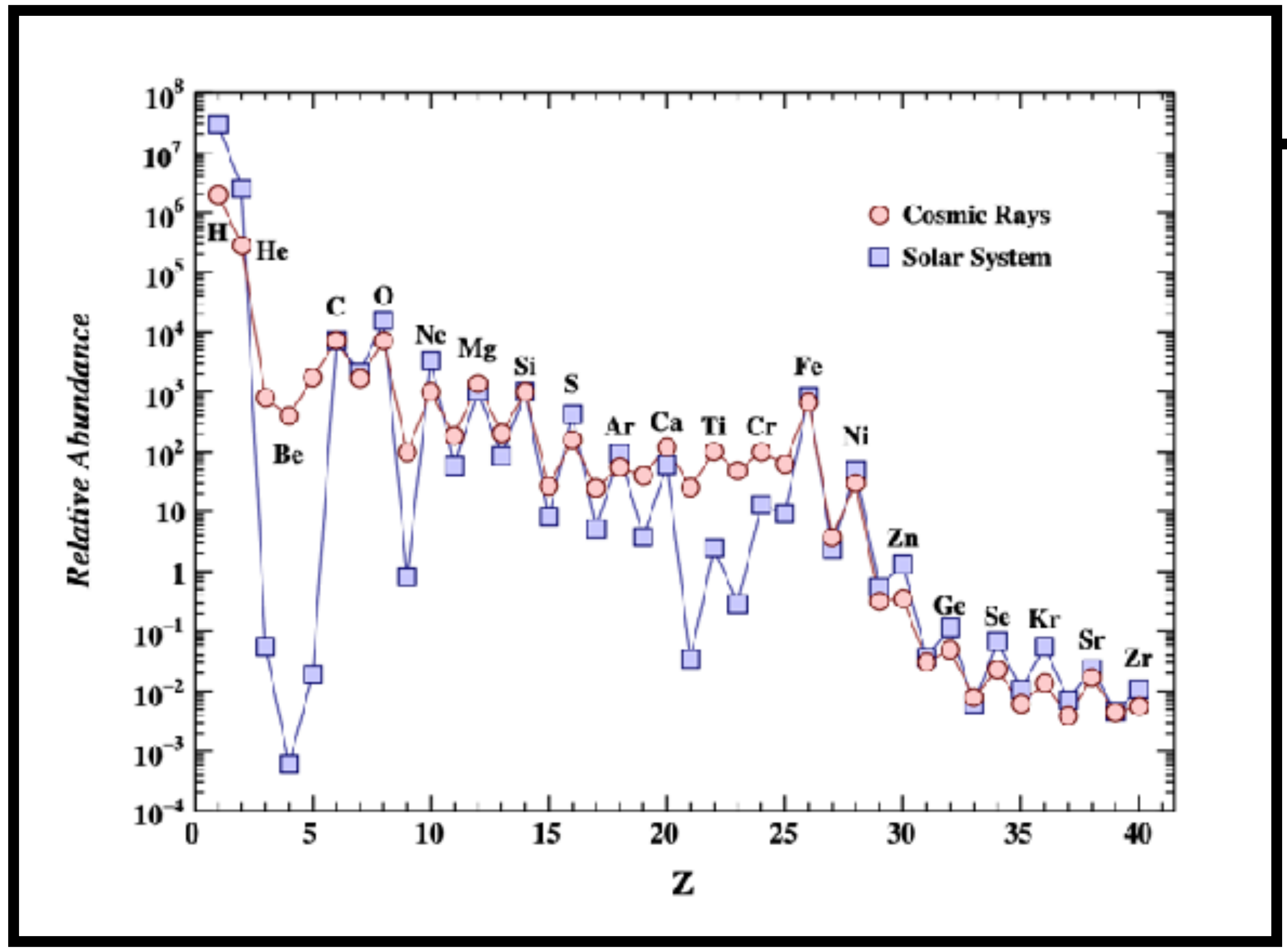
Cosmic rays spectrum

- Low-energy: mainly the Sun
- GeV - 100 TeV: Galactic supernova remnants
- UHECR: AGN, GRB, Intergalactic Shock, …

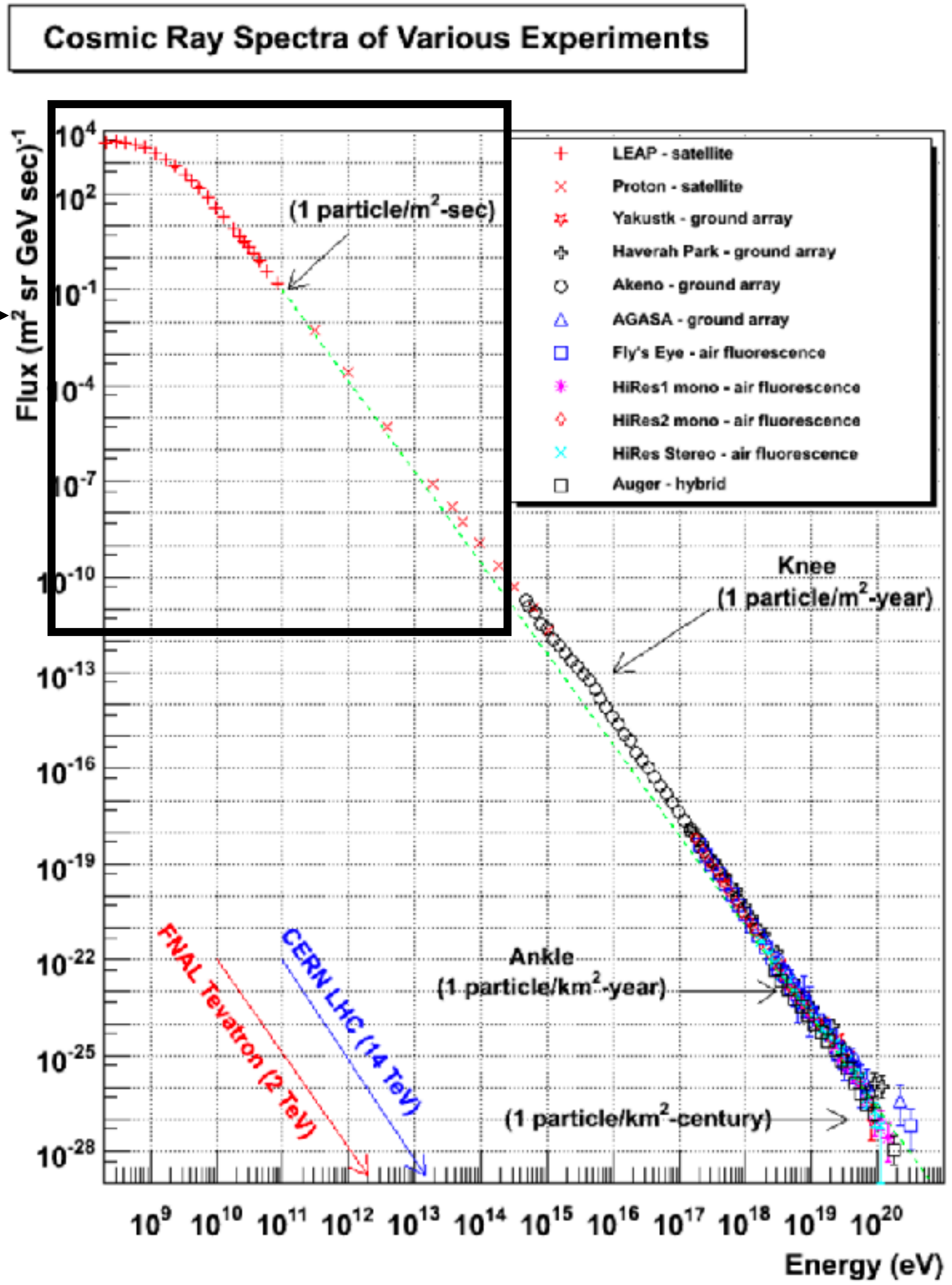


Ref: R Blandford, P Simeon, Y Yuan - Nuclear Physics B-proceedings …, 2014 - Elsevier

Cosmic rays spectrum



Ref: PDG Cosmic rays review

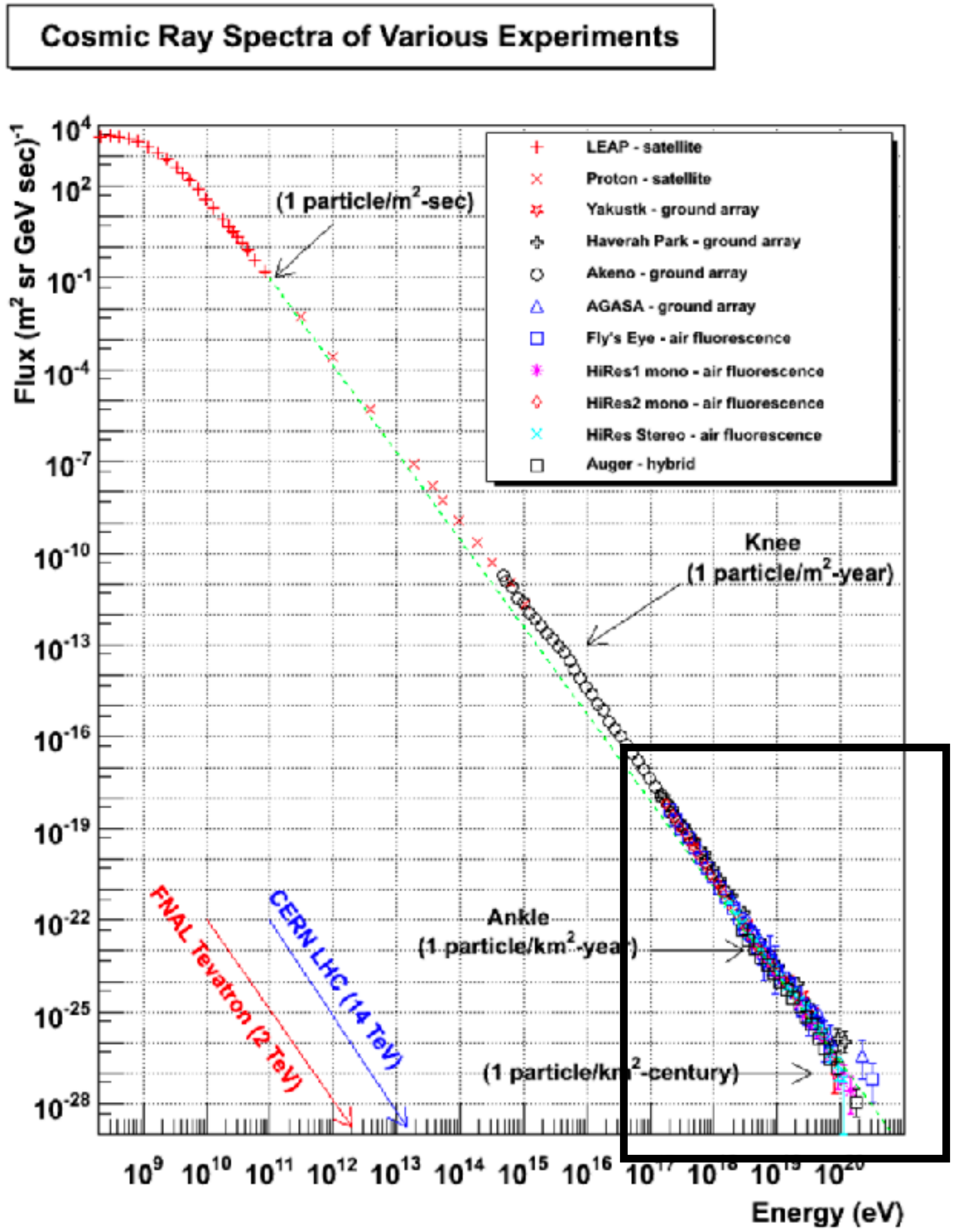


Ref: R Blandford, P Simeon, Y Yuan - Nuclear Physics B-proceedings …, 2014 - Elsevier

- Cosmic ray abundance ≈ Solar System abundance,
- Primary measured directly.

Cosmic rays spectrum

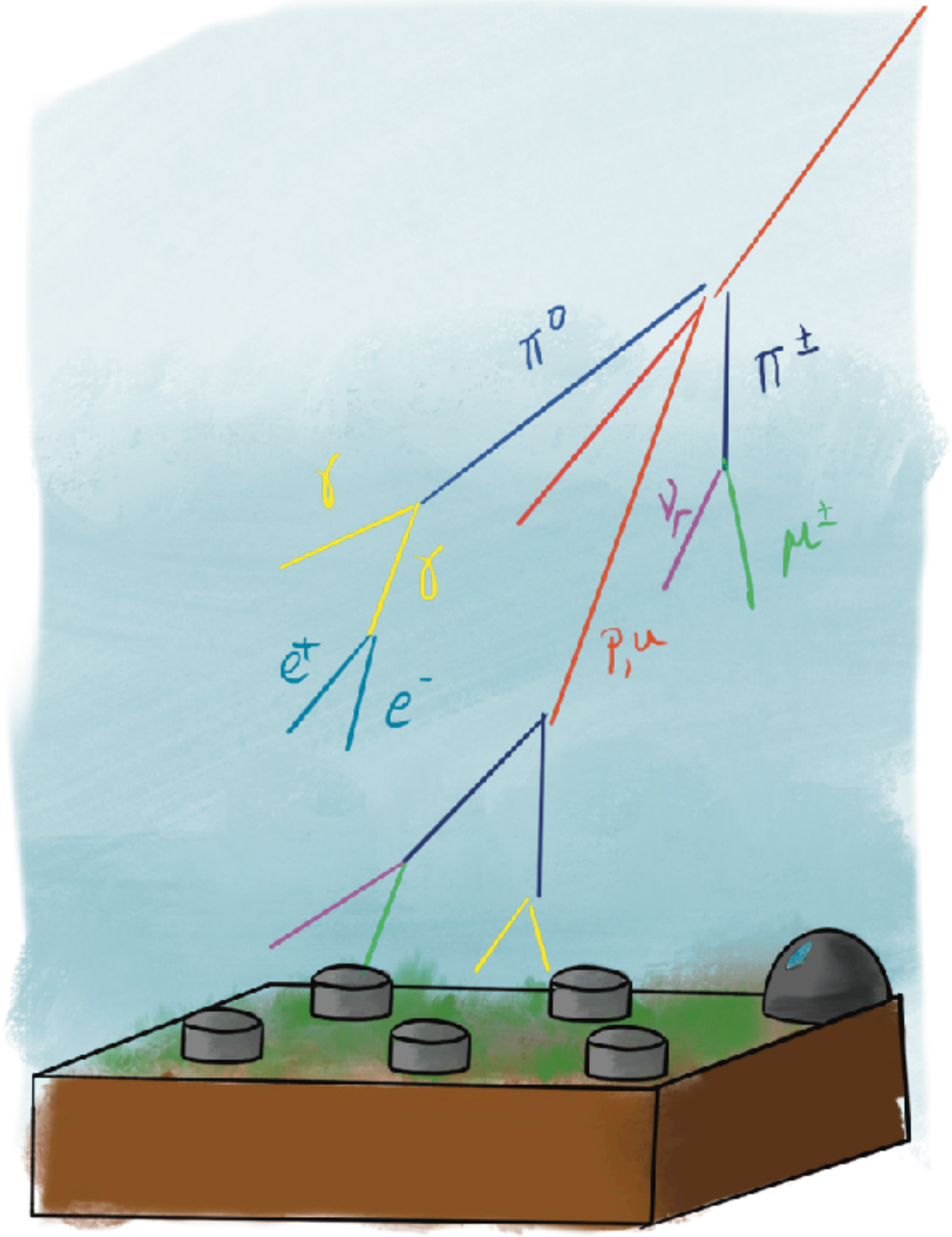
- The **composition** of the UHECR ($E > 10^{18}$ eV) is **still debated,**
- The primaries cannot be directly detected because the **flux is too small**,
- The effects of the interaction between the primary and the atmosphere must be detected at ground → **EAS**.



Ref: R Blandford, P Simeon, Y Yuan - Nuclear Physics B-proceedings …, 2014 - Elsevier

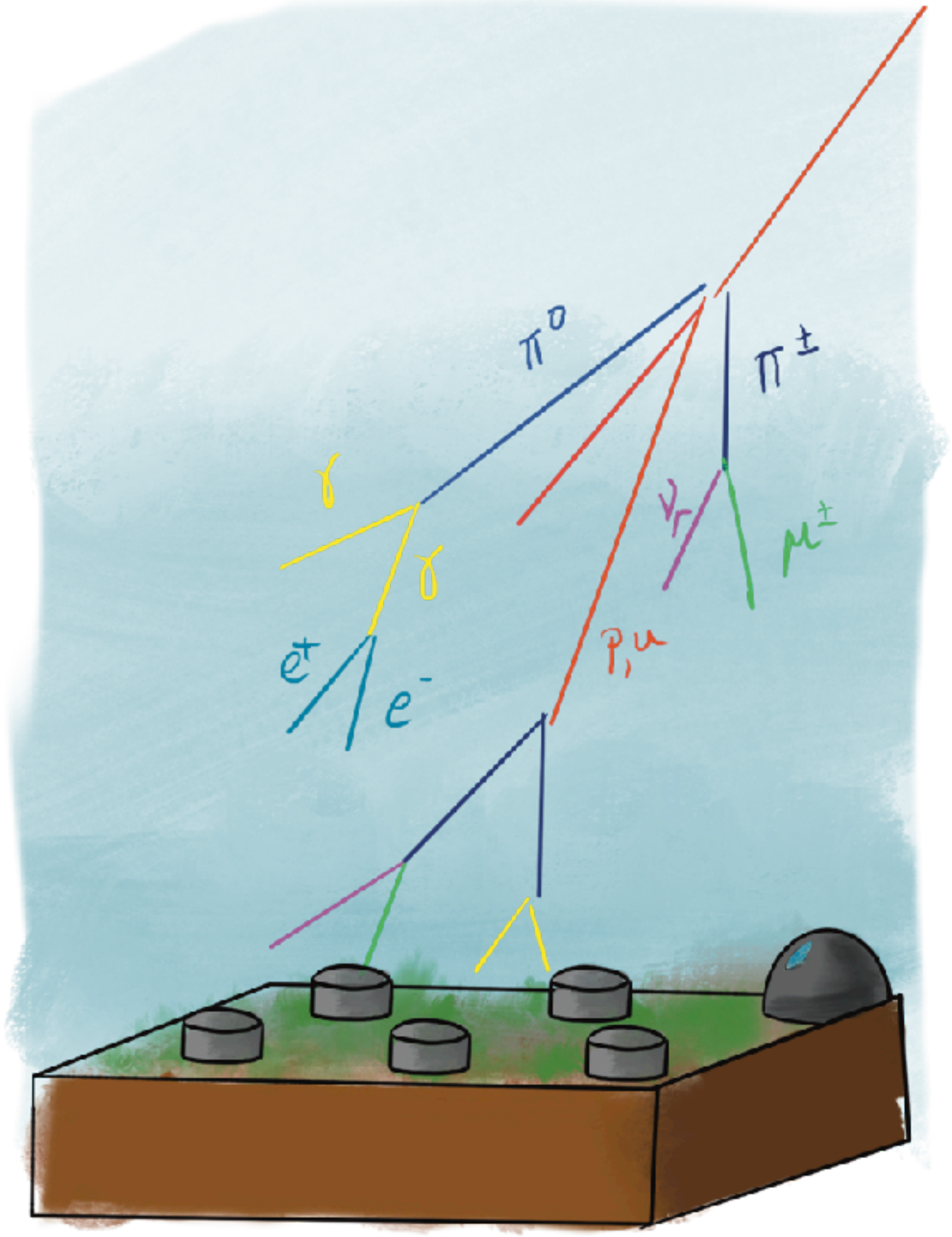
Extensive Air Showers (EAS)

- **Electromagnetic** component
- **Hadronic** component
- Muon + invisible



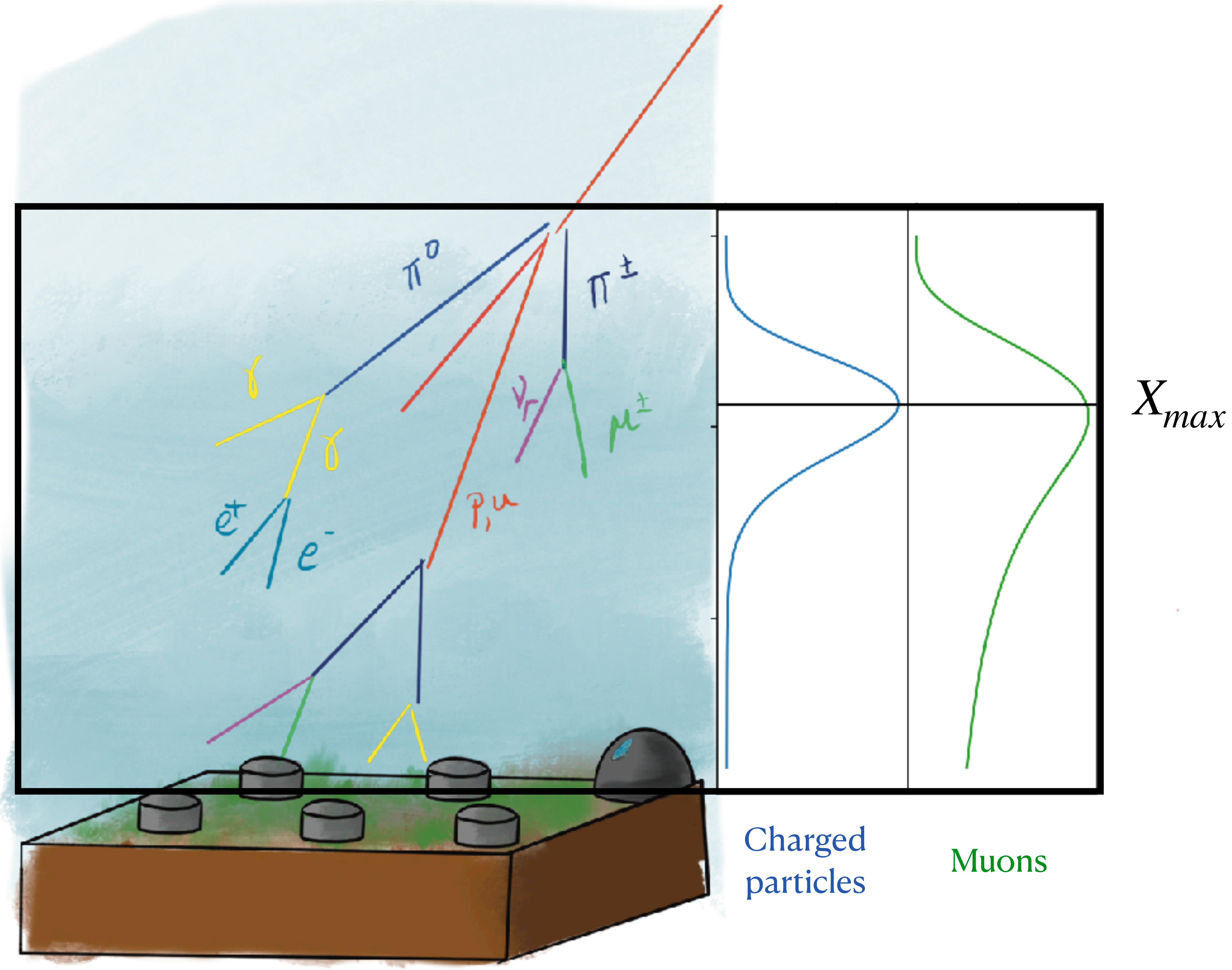
Extensive Air Showers (EAS)

- **Muons** and electromagnetic radiation on the **ground,**
- **Fluorescence** radiation.

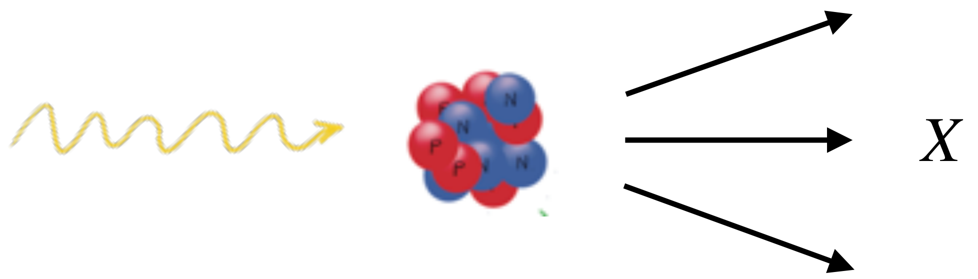


Extensive Air Showers (EAS)

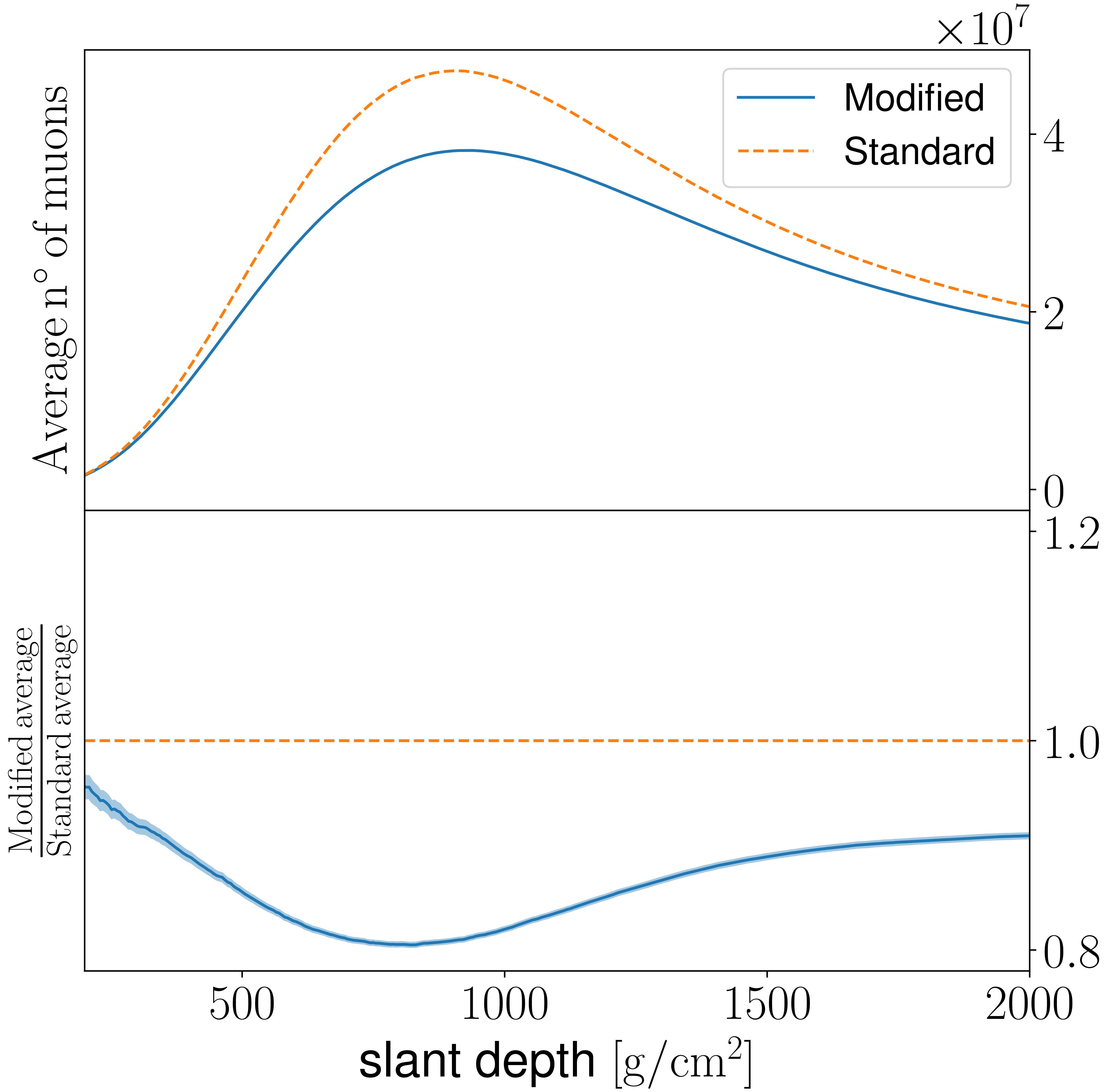
- X_{max} is the depth at which the number of charged particles is maximum,
- The Muon maximum is a little bit after,
- **Muons are long lived** and a good amount of them reach the ground.



Switching off photo-hadronic collisions

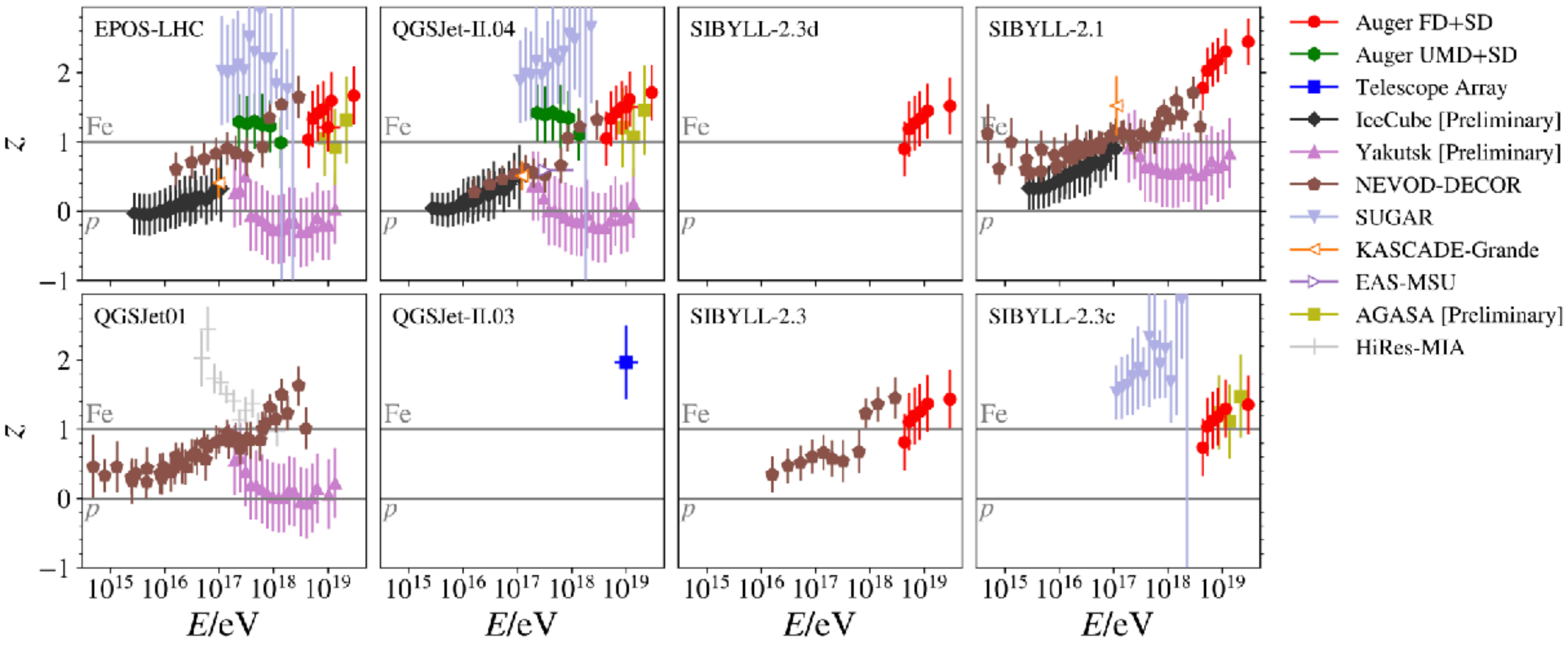


- There is some return to the hadronic component through photo-hadronic collisions,
- The effect is relevant, around 20% at the shower maximum and 8% at ground.



Muon puzzle

Ref: *PoS* ICRC2021 (2021) 349



$$z = \frac{\ln\langle N_{\mu}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

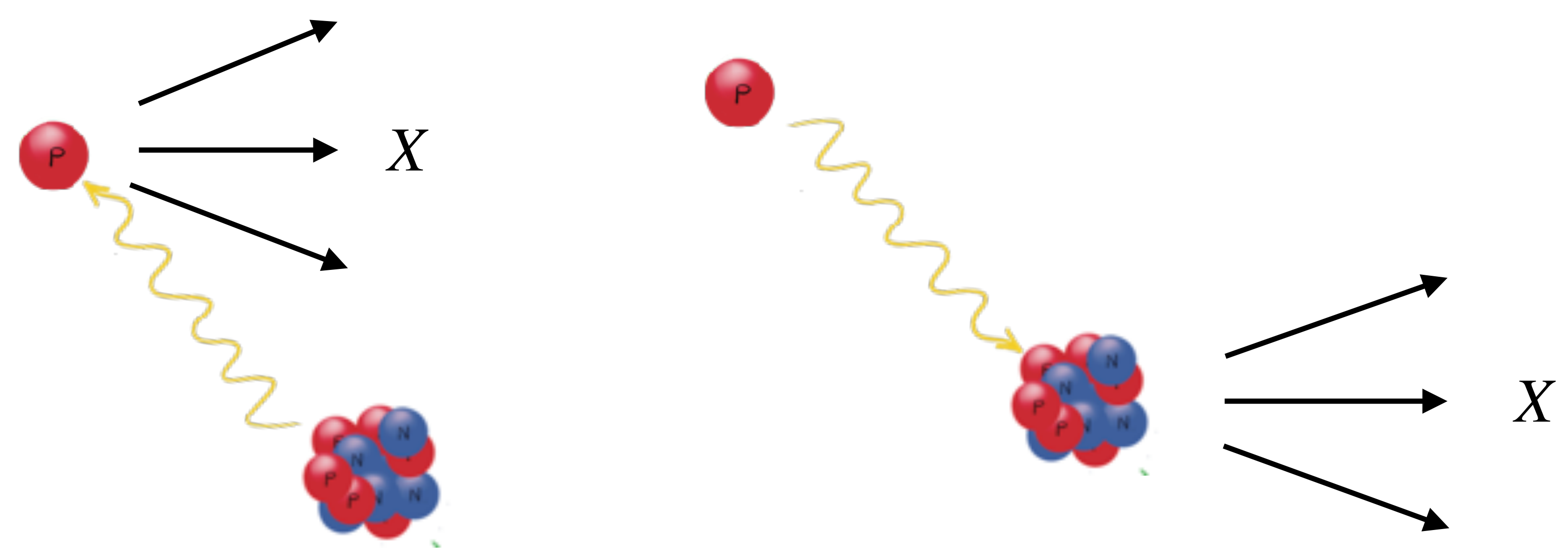
- $\ln\langle N_{\mu}^{det}\rangle$: average muon density estimate as seen in the detector,
- $\ln\langle N_{\mu,p}^{det}\rangle$, $\ln\langle N_{\mu,Fe}^{det}\rangle$: simulated muon densities for proton and iron showers after full detector simulation.

Summary → Motivation

1. For UHECR, the **composition must be inferred**,
2. It requires a precise **simulation of the EAS**,
3. **Photon scattering** can become **non-negligible** at these high energies,
    1. GZK limit,
    2. Photo-hadronic interactions
4. **Excess muons** at ground level measured,
5. Electromagnetic field behaves as **real photons** for large boosts.

→

- Study of the electromagnetic interactions of charged hadrons with air.

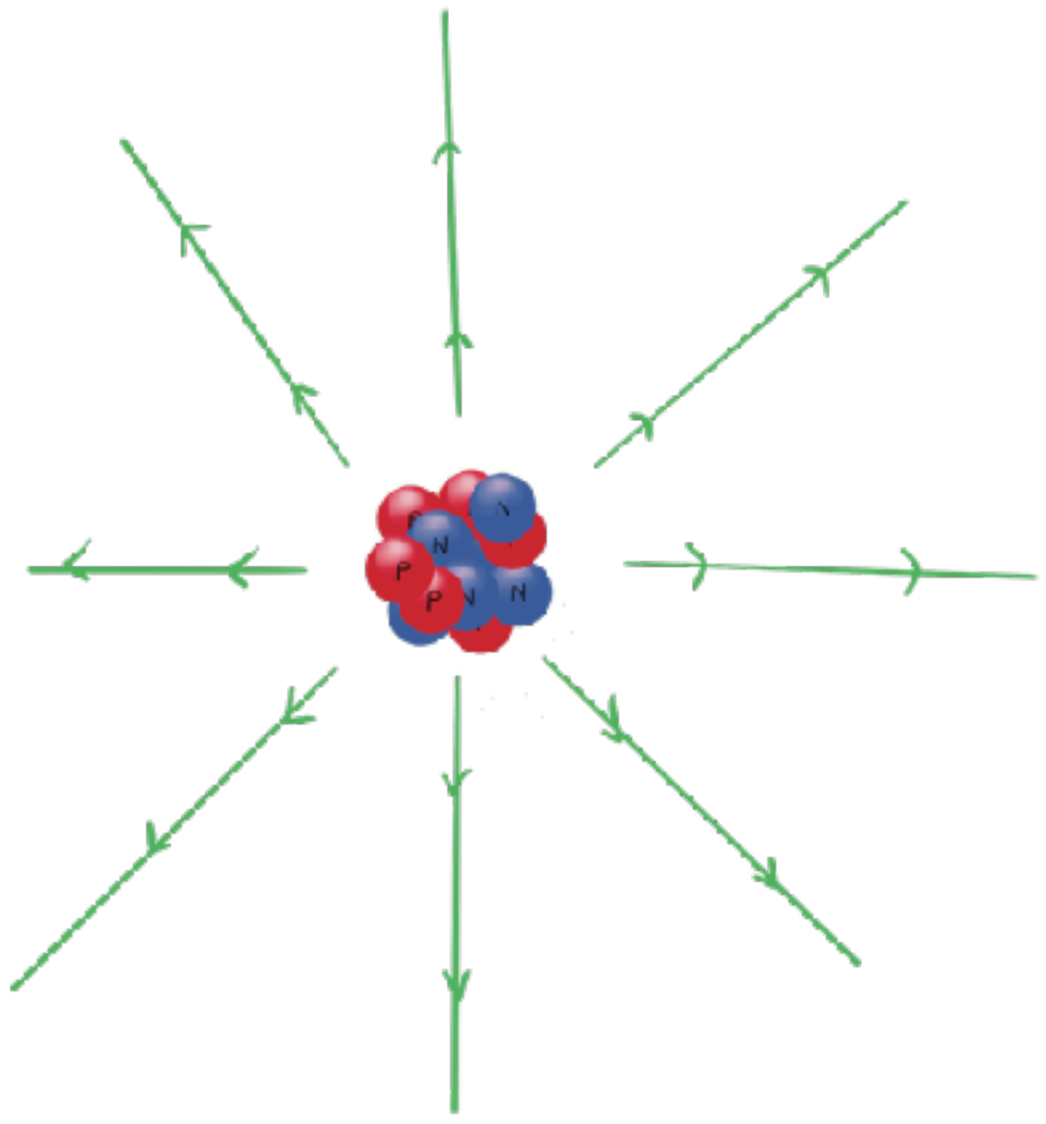


Ref:E Fermi - arXiv preprint hep-th/0205086

EPA

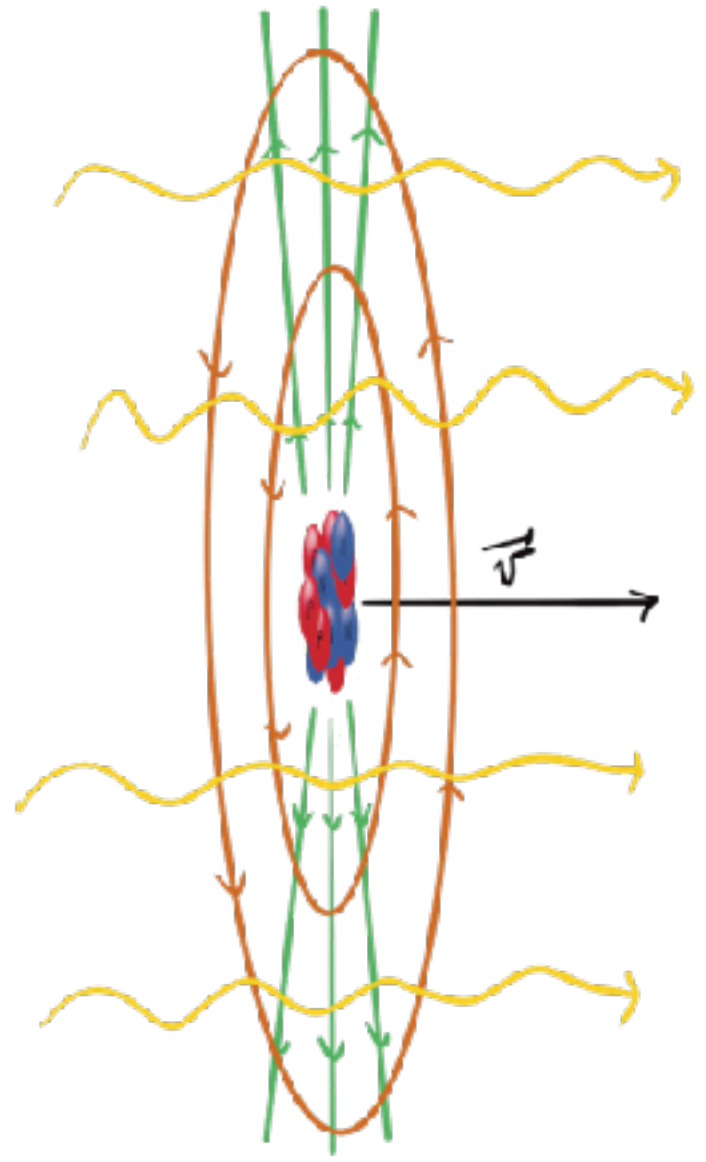
- A nucleus at rest has an inverse square electric field around it,
- Boosted, the electric and magnetic fields form a disc in the transversal plane,
- These fields can be treated as **real photons** with an spectrum given by their Fourier components.

Nucleus at rest



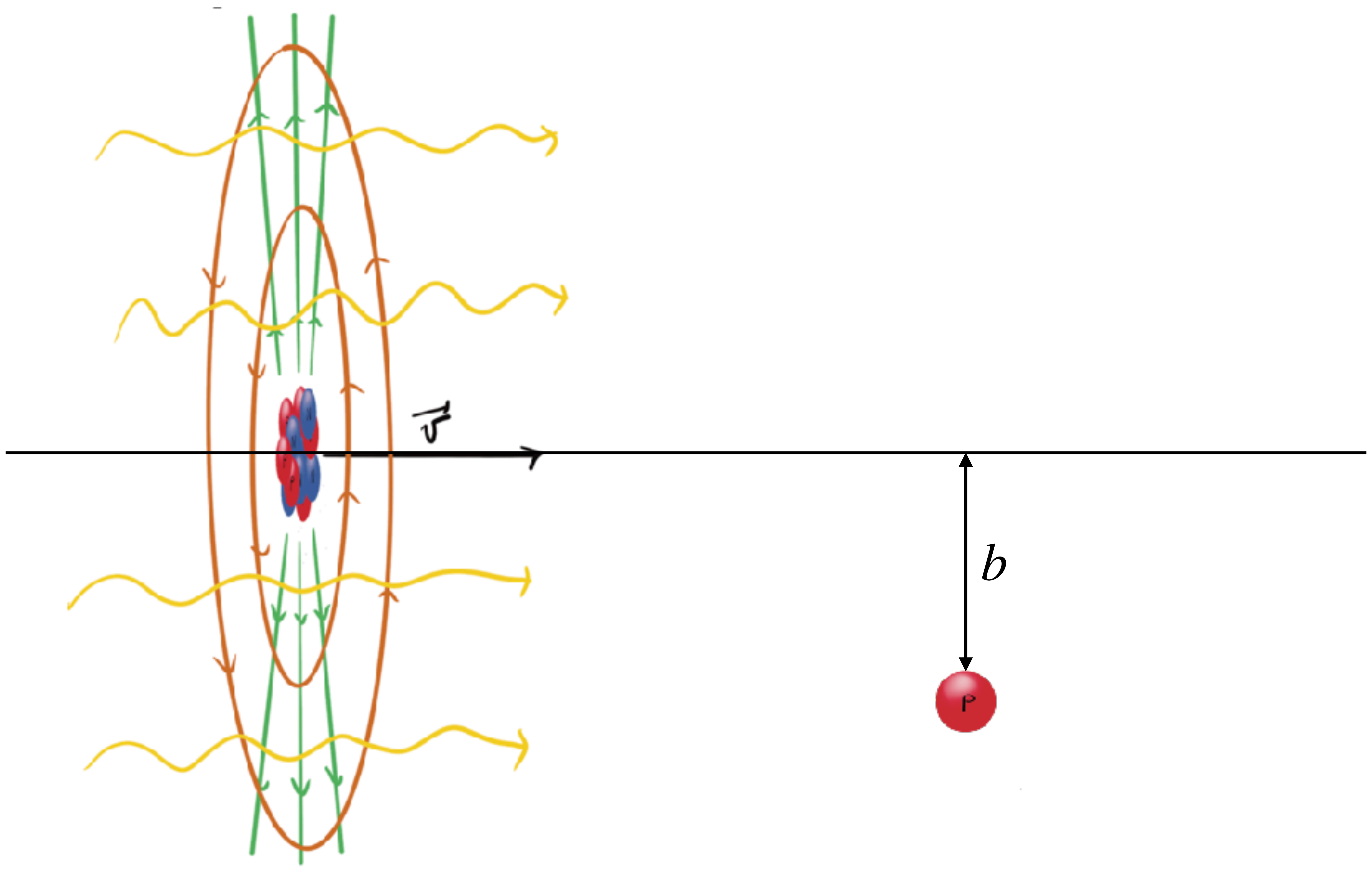
$$E = \frac{Ze}{r^2}$$

Boosted



EPA

$$n(\omega) = \frac{\alpha Z^2}{\pi \gamma^2}\left[\omega b^2 \left(K_0(x)^2 - K_1(x)^2\right) + 2\gamma b K_1(x) K_0(x)\right]\Bigg|_{b_{min}}^{b_{max}}$$



- Reference frame: incident hadron at rest,
- Spectrum of real photons given by $n(\omega)$,
- Only depends on nucleus properties: (Z, γ)
- $b_{min} = R_A, \quad b_{max} \approx 1/\alpha m_e$

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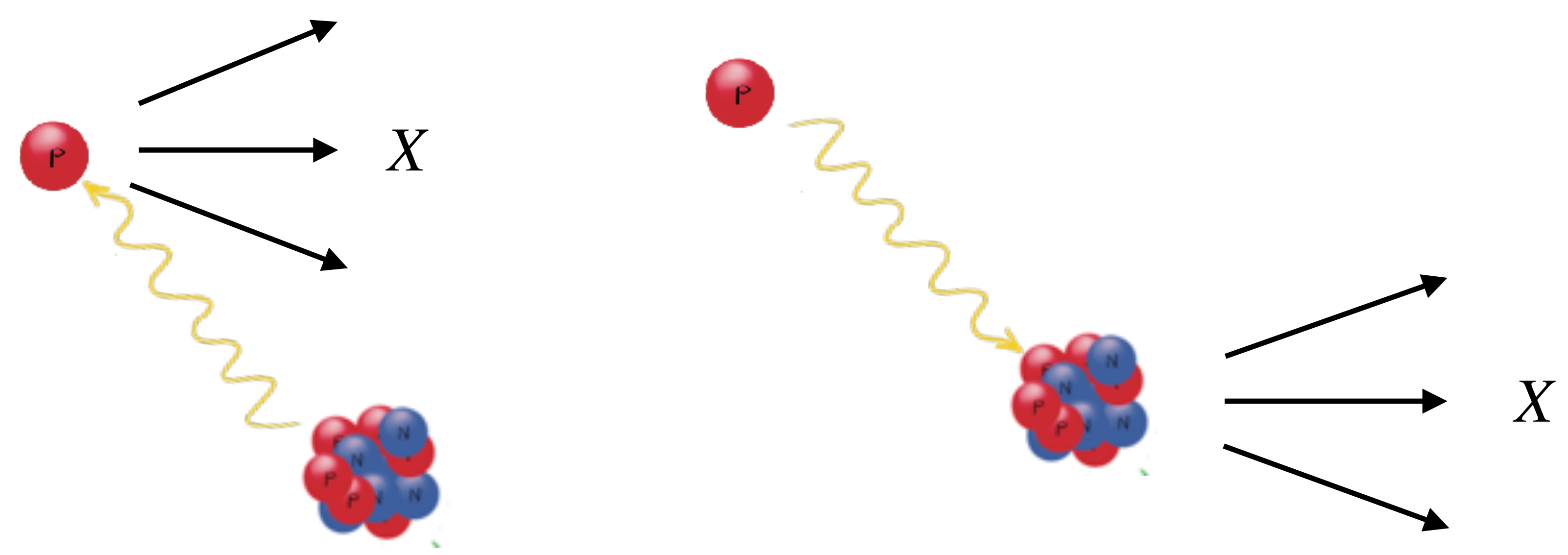
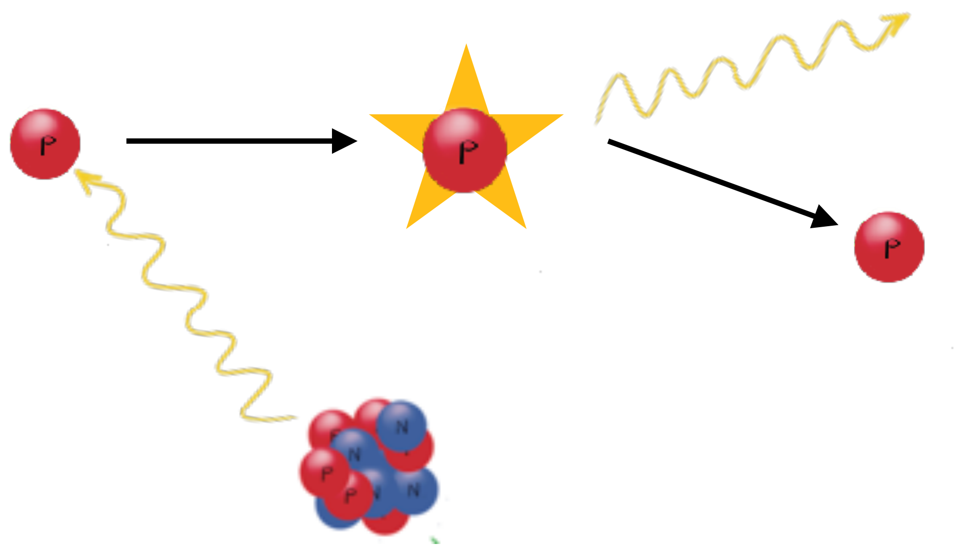
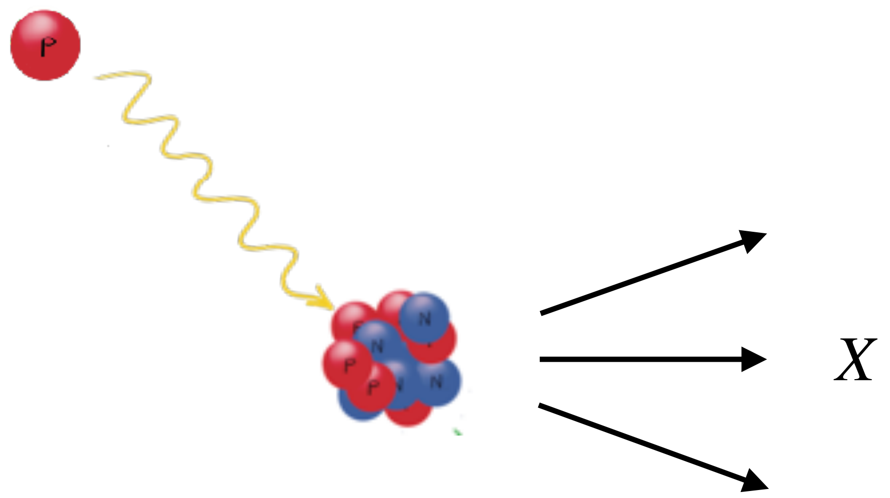


Processes

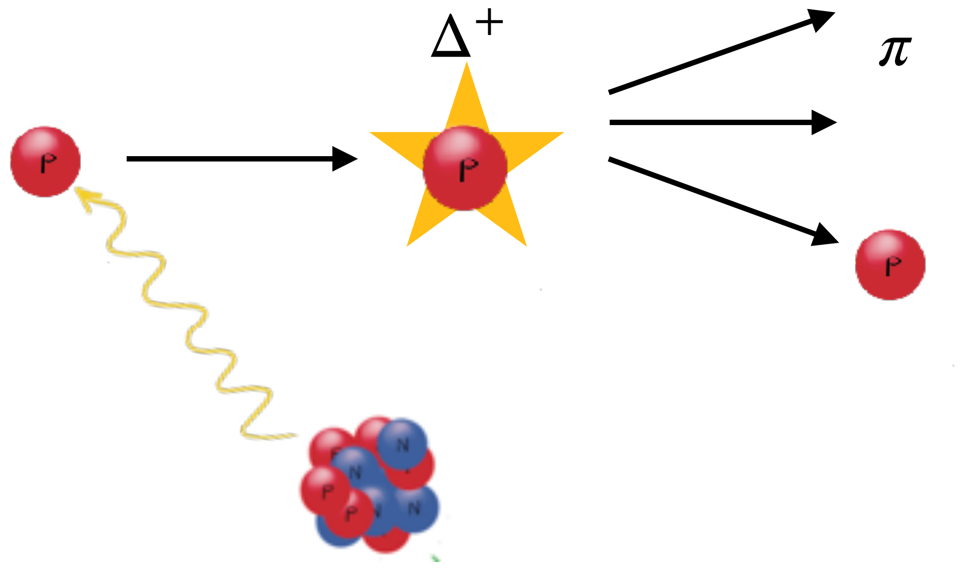
- Bremsstrahlung



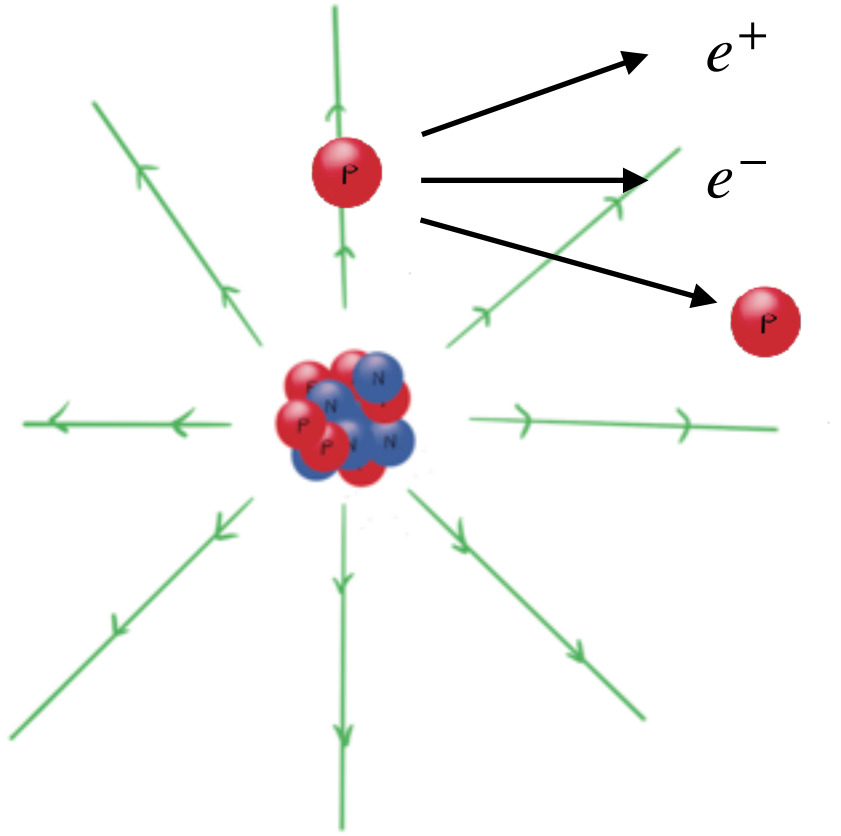
- Photo-nuclear



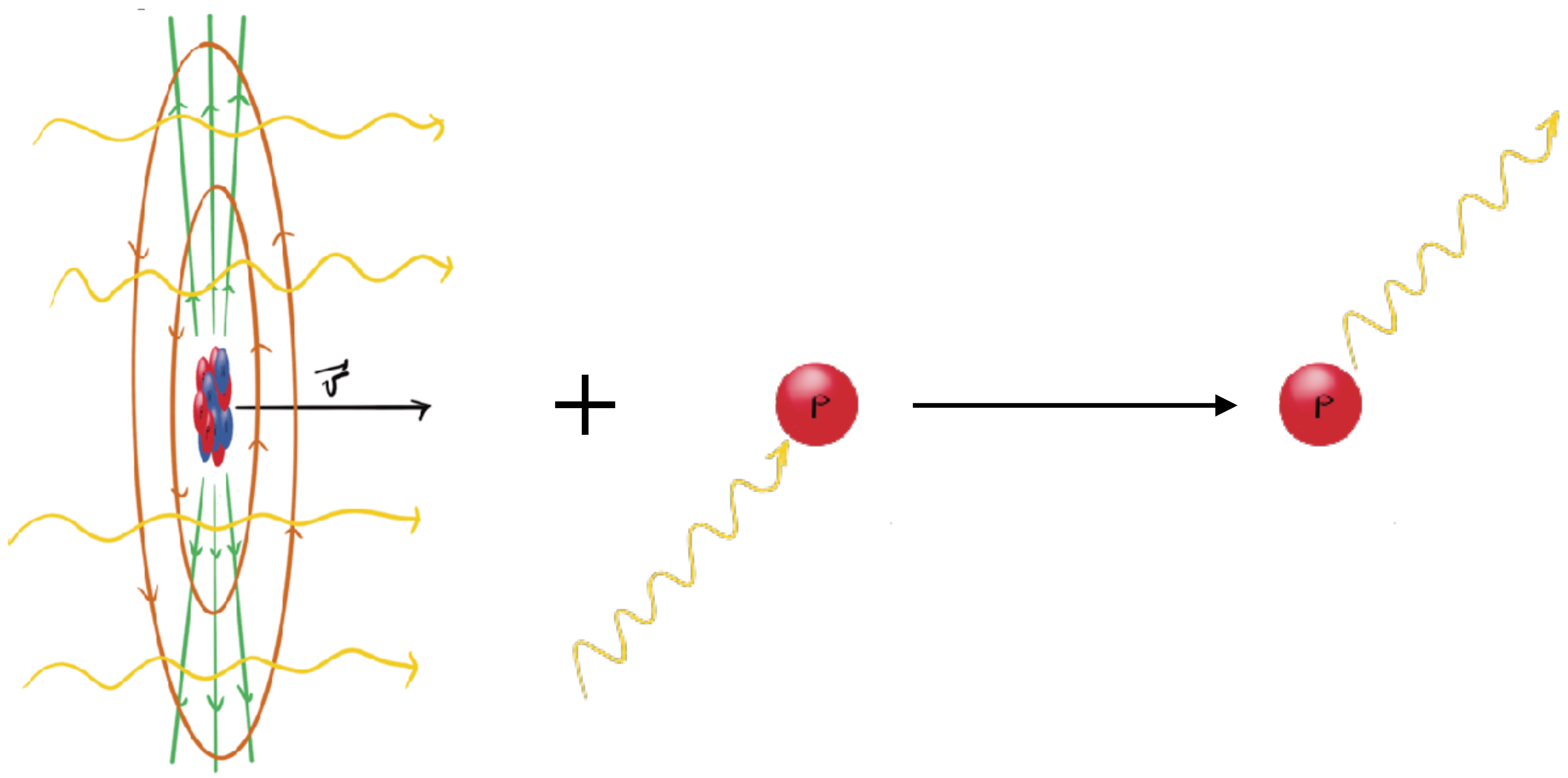
- Diffractive

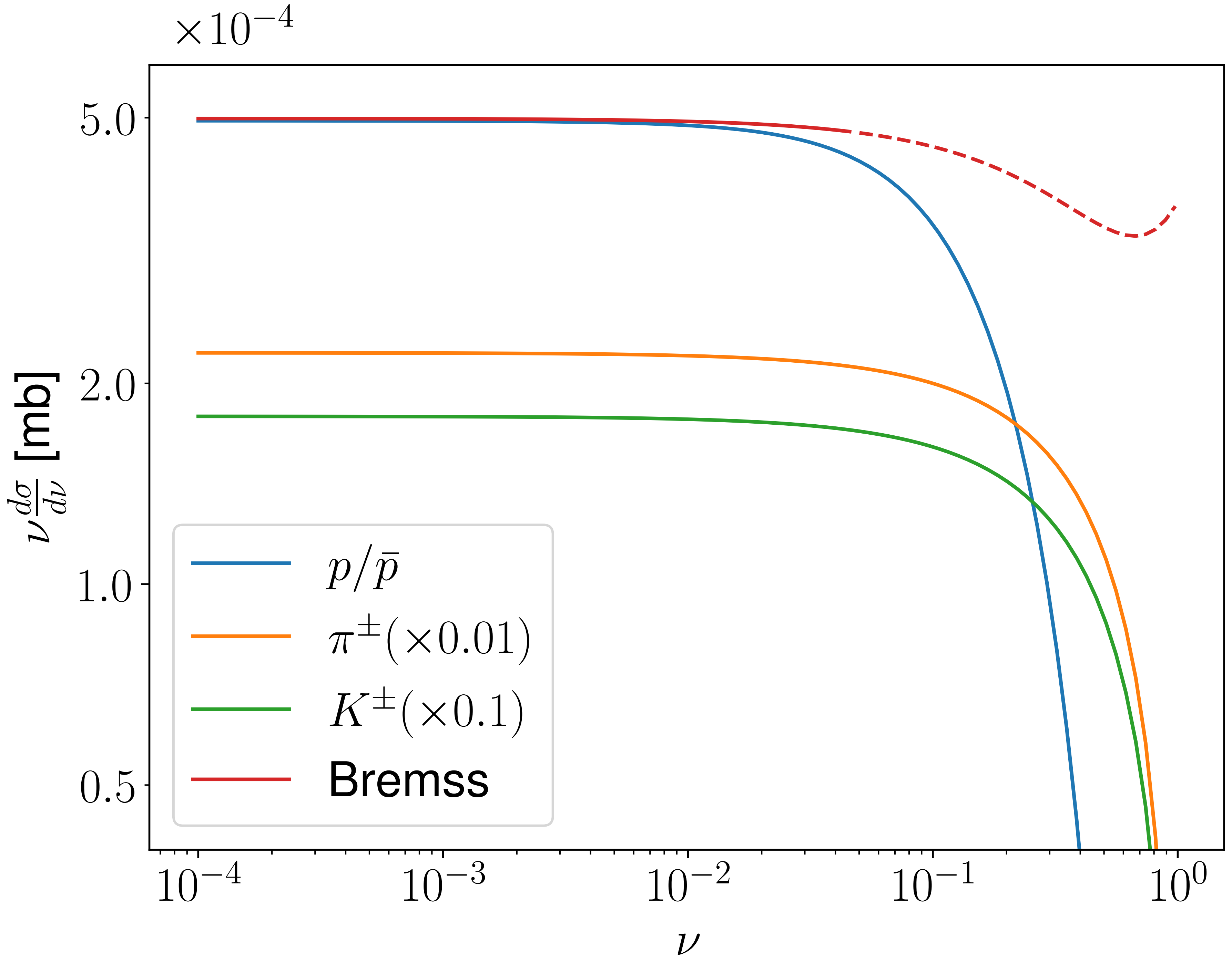


- Pair-production



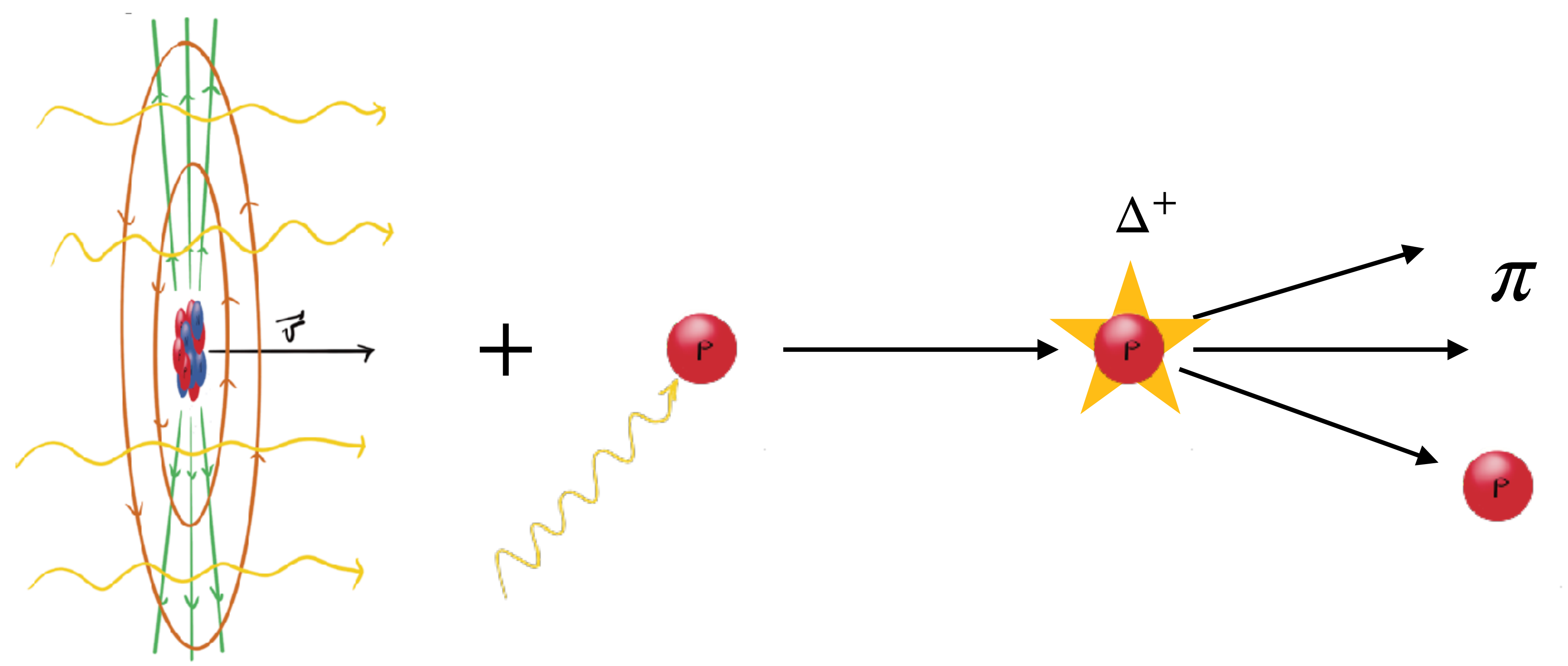
Bremsstrahlung





- EPA + Compton scattering,
- Form factor for the hadrons,
- Good agreement between the Muon formula up to high energy transfers.

Diffractive cross-section



- EPA + photo-hadronic cross-section,
- Form factor for the hadrons.

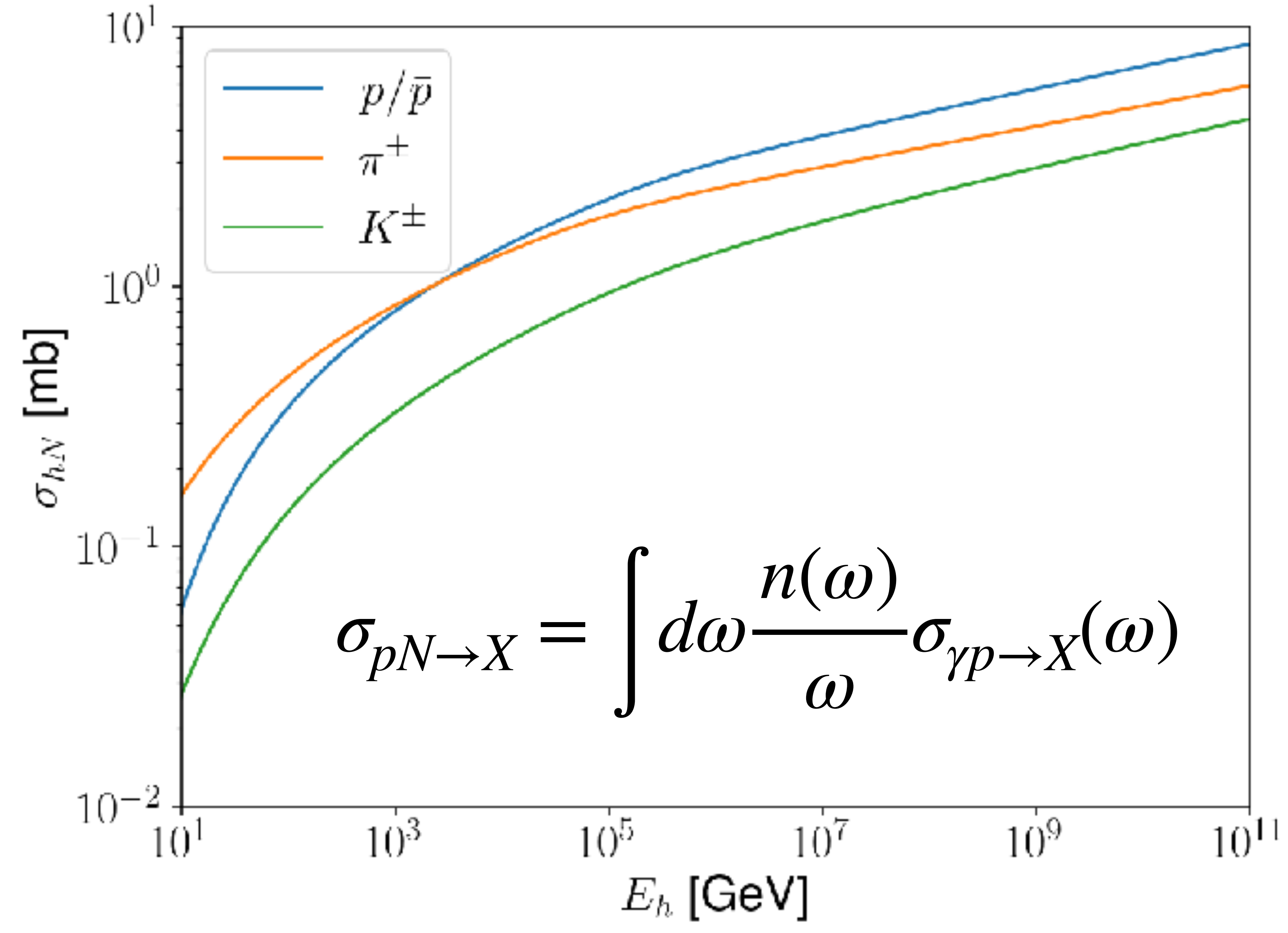
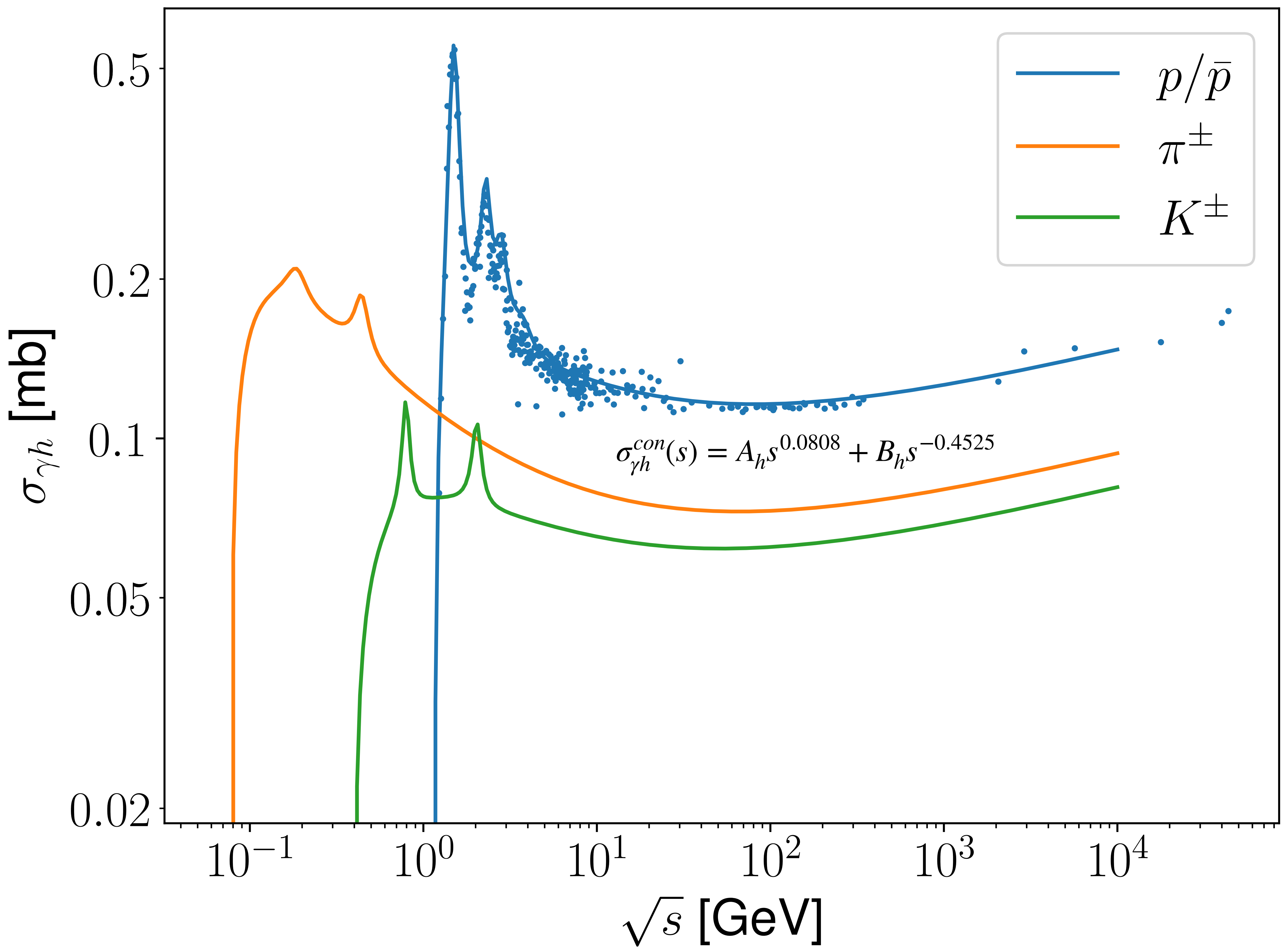


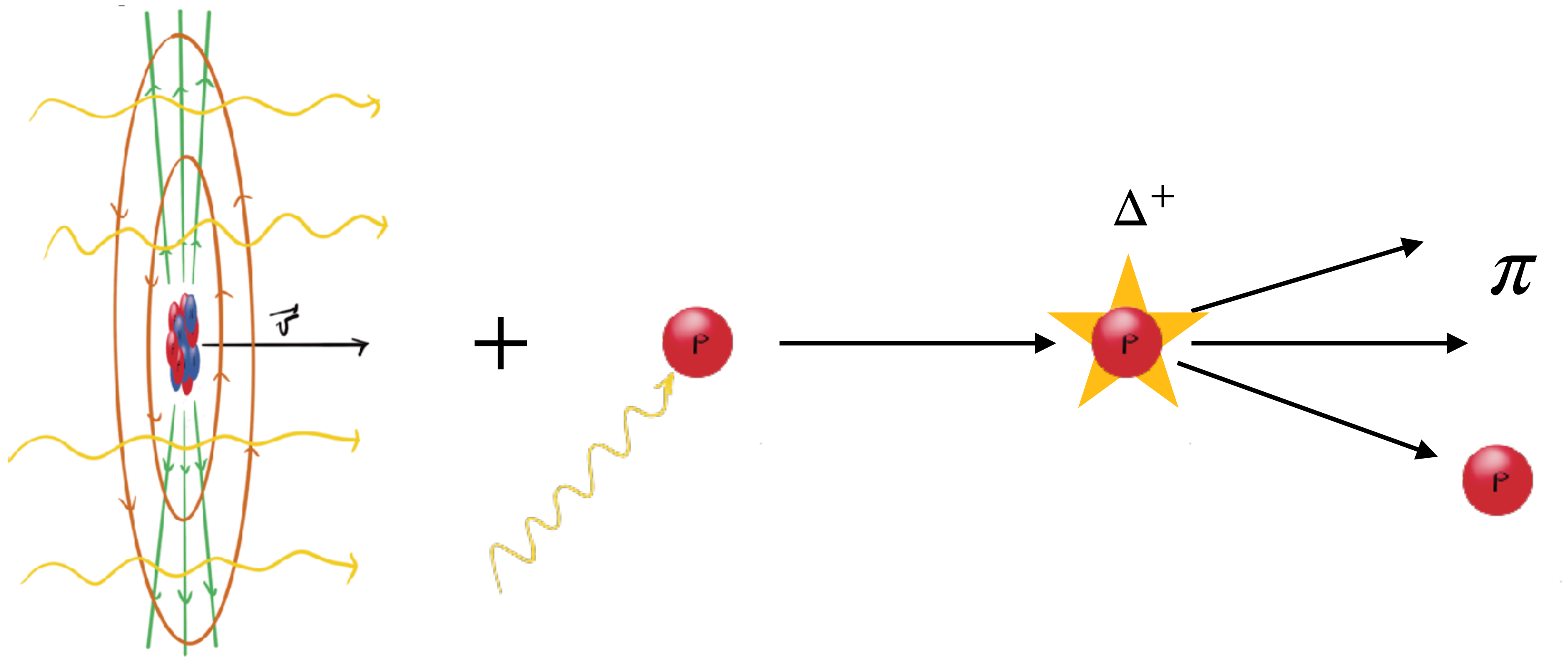
Photo-hadronic cross-section

- Two parts: resonances + continuum

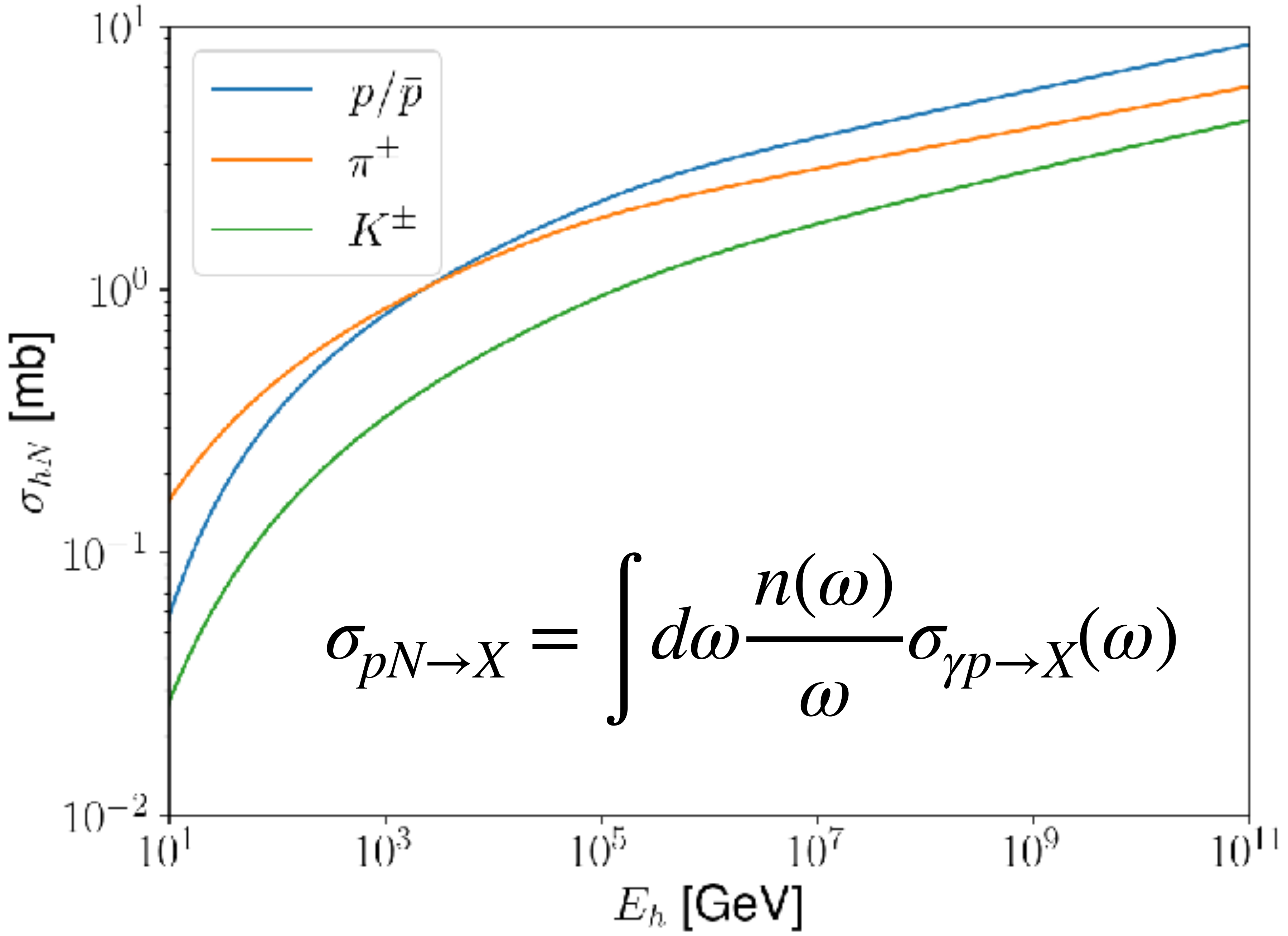
$$\sigma_{res} = \frac{s}{(s-m^2)^2}\frac{4\pi b_\gamma(2j+1)\Gamma^2 s}{(s-M^2)^2+\Gamma^2 s}$$



Diffractive cross-section

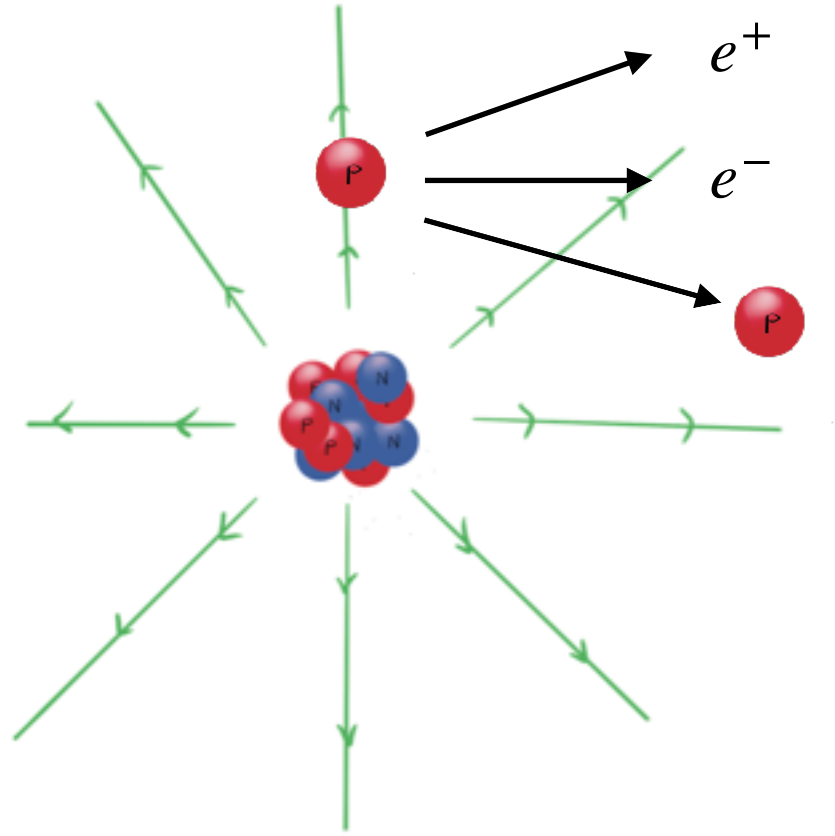


- EPA + photo-hadronic cross-section,
- Form factor for the hadrons.



Electron-positron pair-production

- Large cross-section to emit low-energy electron-positron pairs,
- Results in small energy losses for the incident hadron.



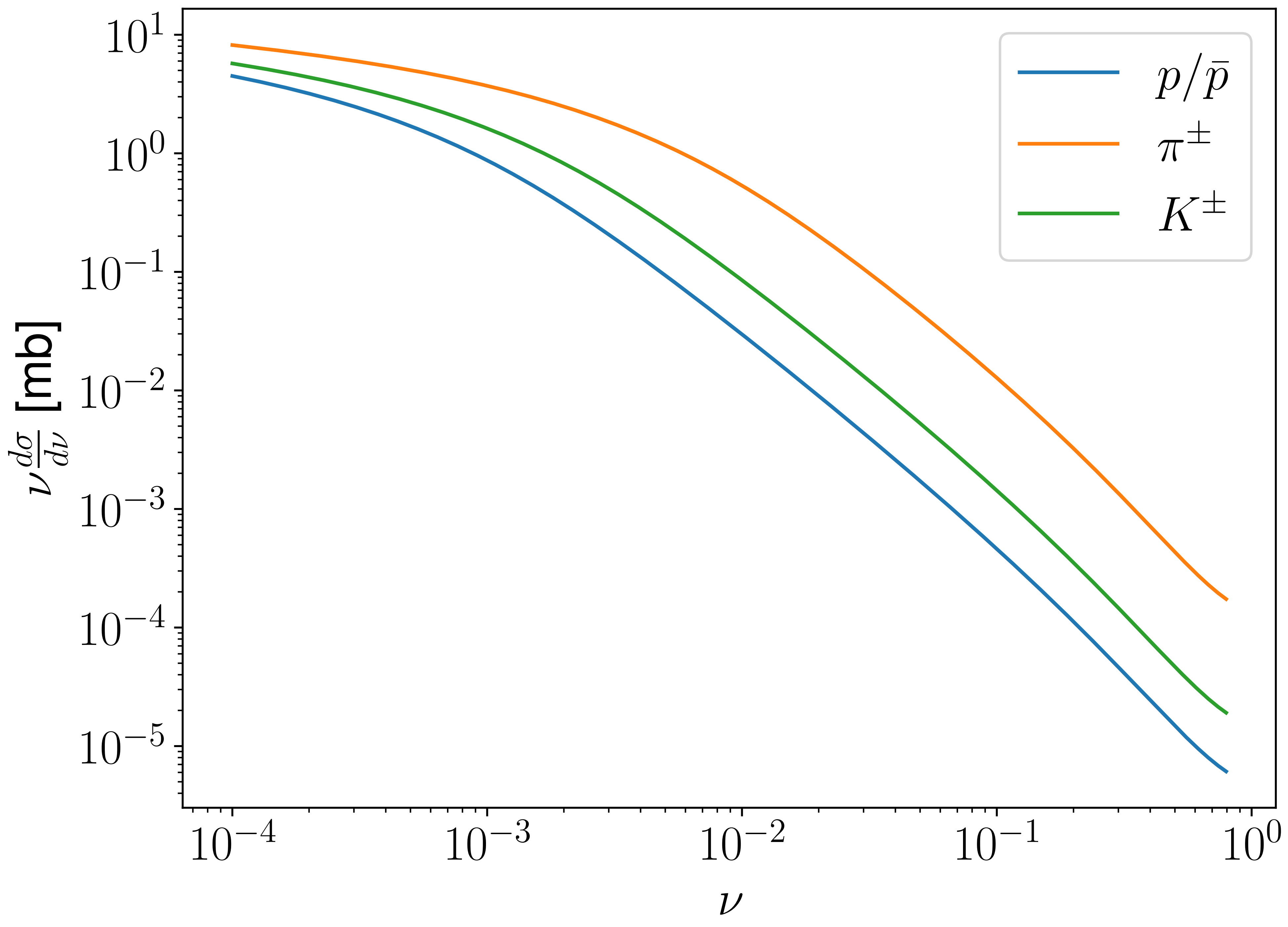
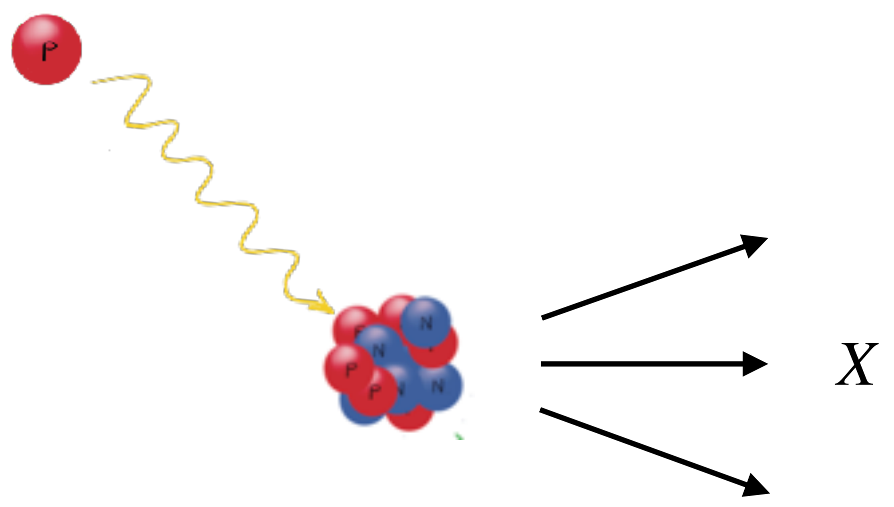
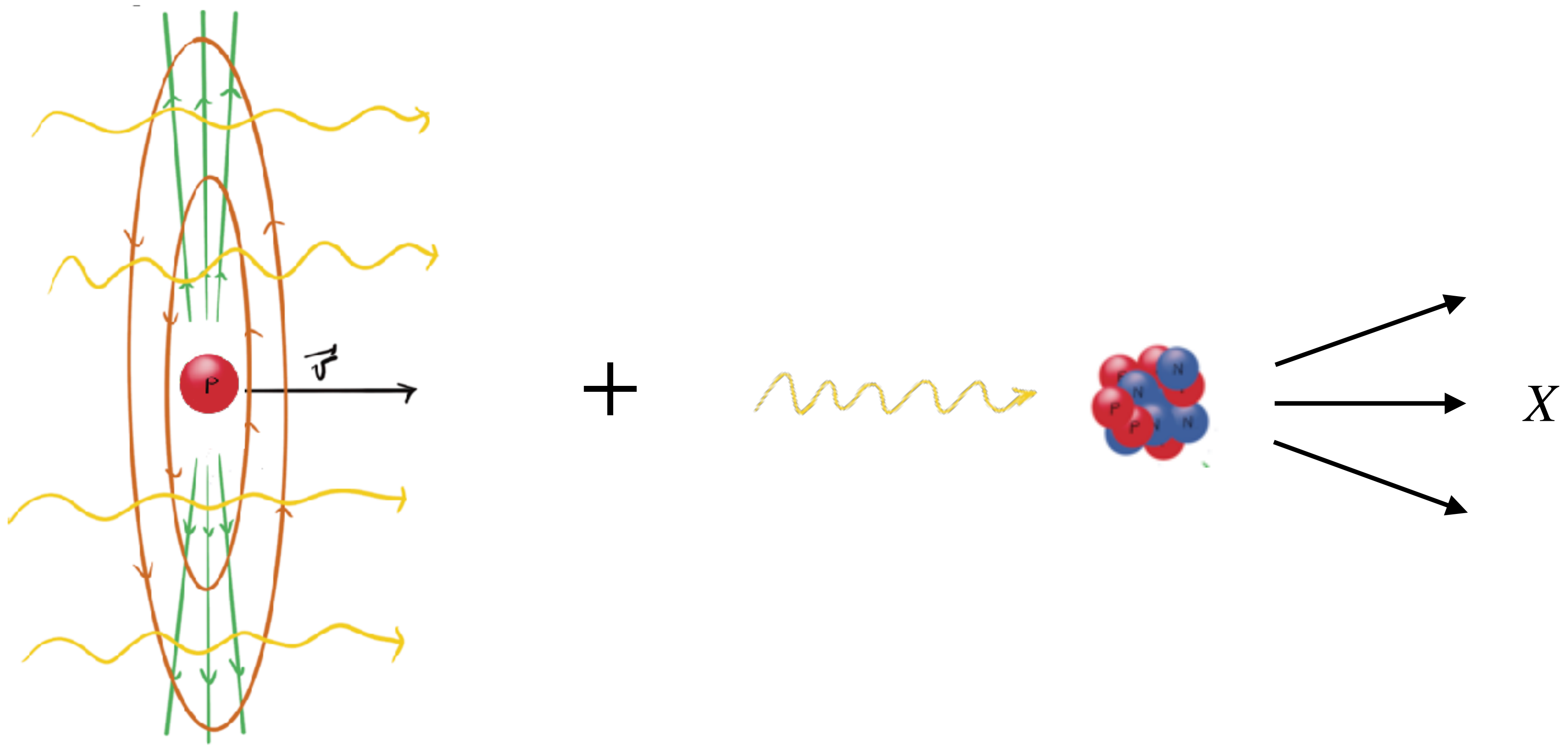


Photo-nuclear collisions



- The photo-nuclear interaction is implemented in AIRES for real photons,
- We sample the equivalent photons and treat the as real.



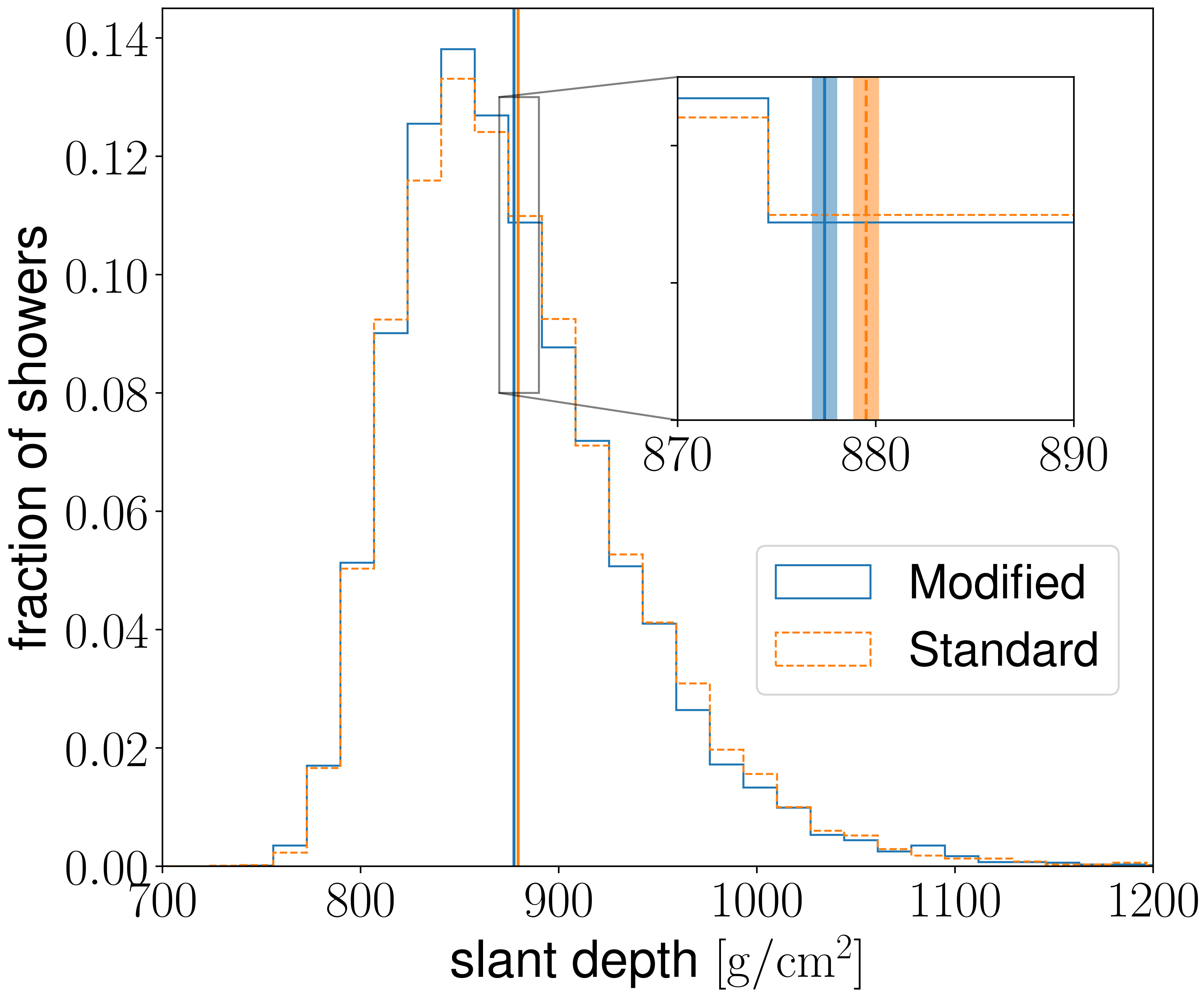
Run input parameters

- Site: Malargue,
- Atmosphere: Marlargue average,
- Zenithal angle: 70 degrees,
- Primary: Proton,
- Primary Energies: 10^{20} eV,
- 10000 showers

Ref: photo from Pierre Auger Observatory

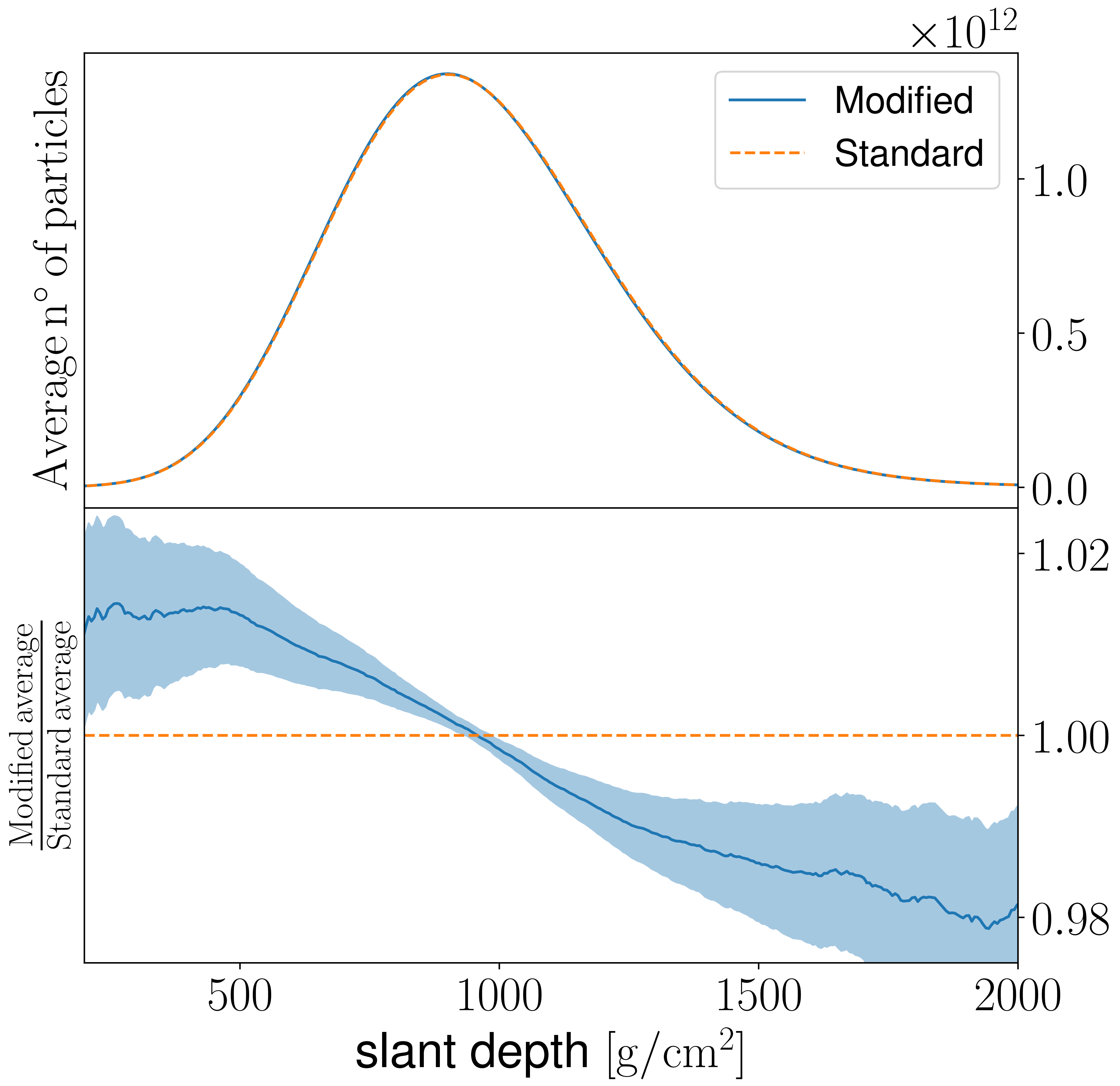
X_{max} modification

- The X_{max} is a bit advanced with respect to the standard AIRES,
- The effect is small, around $0.2 - 0.3\ \%$,
- But consistent for different zenith angles and energies.



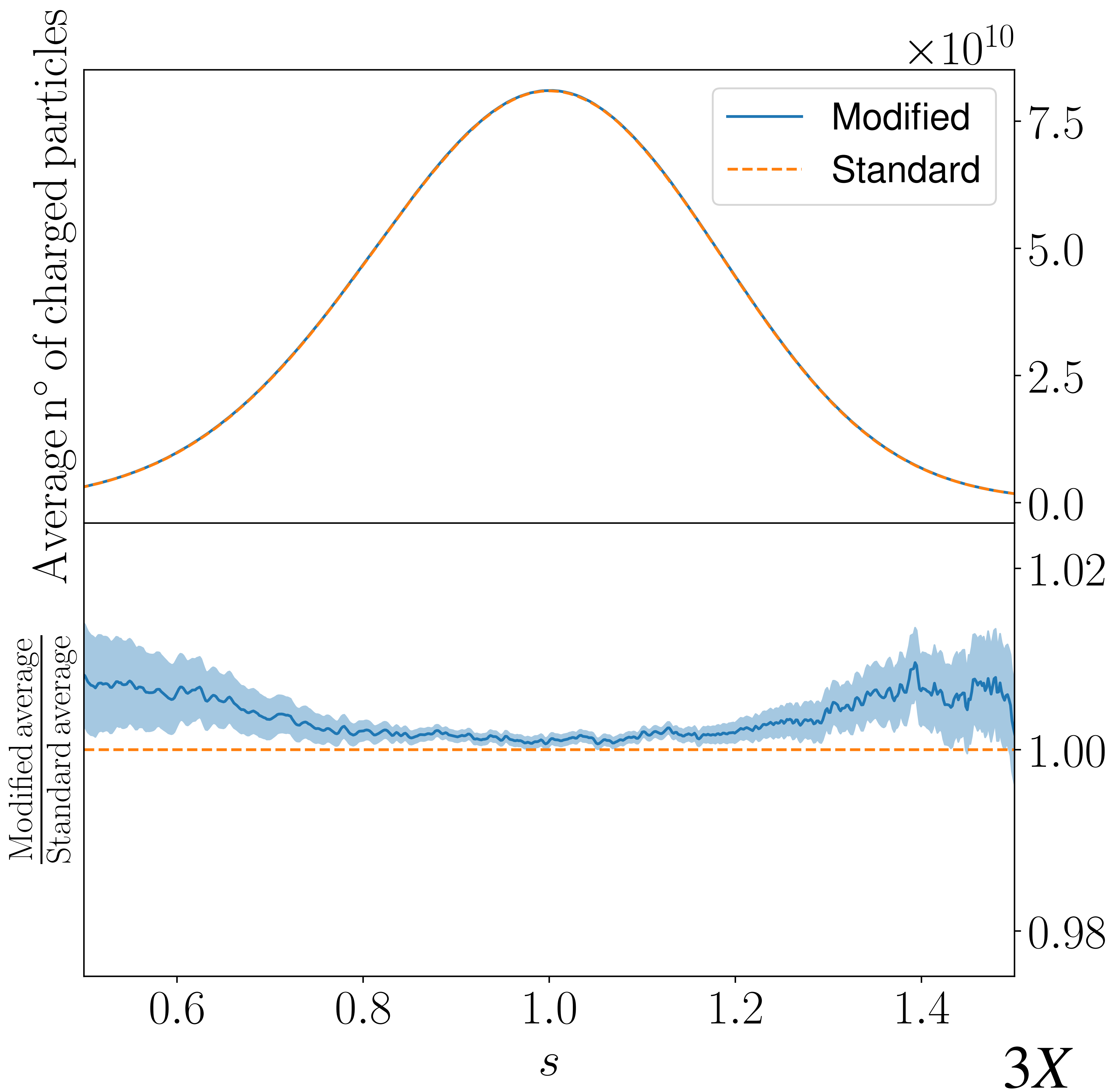
Particle number modification

- There are more particles at small depths ($\backsim 2\,\%$),
- Less particles at high depths ($\backsim 2\,\%$),
- These effect can be explained by the change on the X_{max}, the shower is just developing a little bit earlier.



Change in shower development

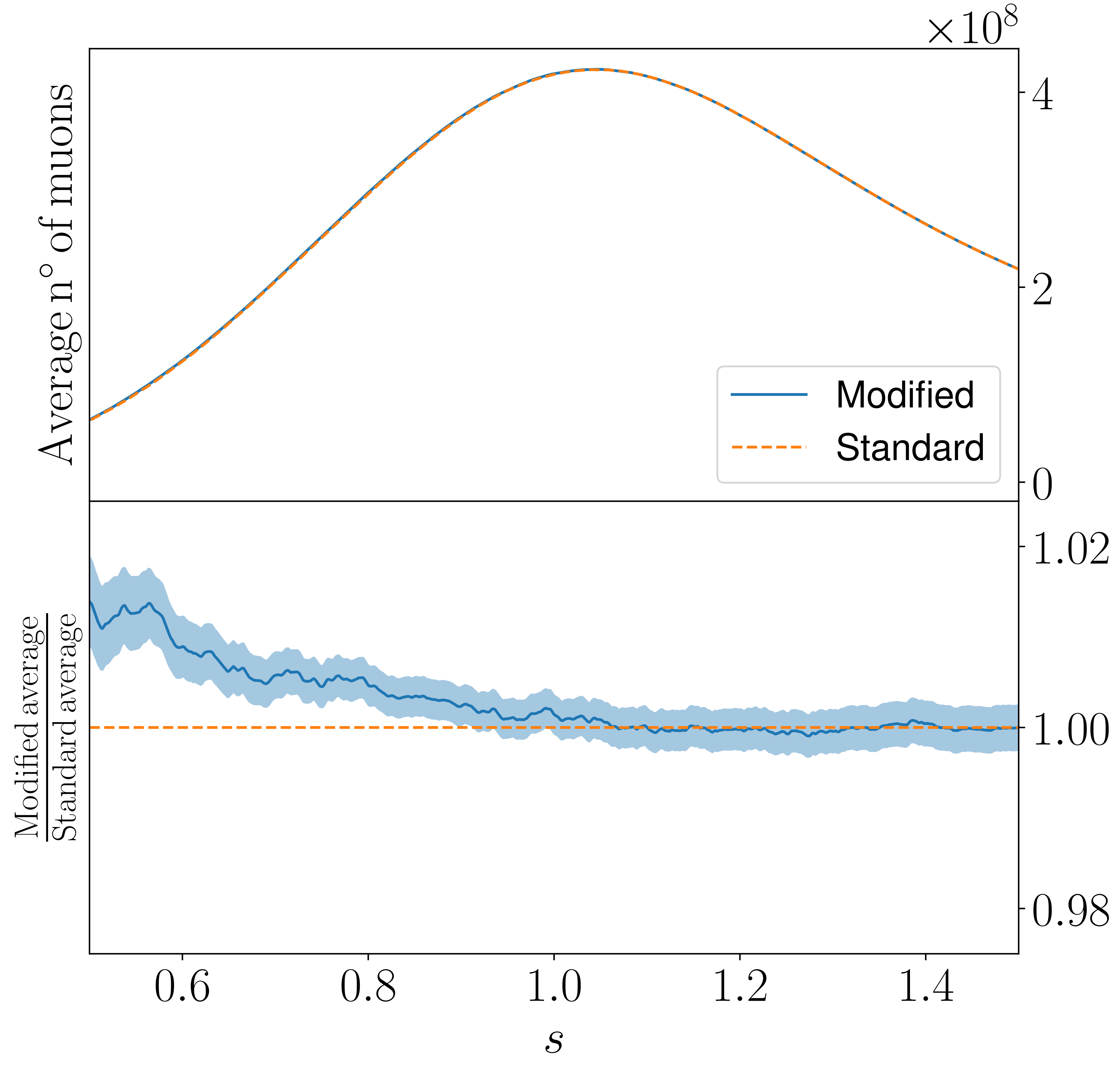
- To remove the effect of the change in X_{max}, we use the age of the shower, s,
- Small increase, $\approx 1\,\%$, when the shower is young and old,
- Smaller effect close to X_{max}.



$$s = \frac{3X}{X + 2X_{max}}$$

Change in shower development

- Small increase, $\approx 1\,\%$, when the shower is young,
- But the effect is zero for old showers.



Conclusions

- Added missing processes to AIRES AES MC,
- They advance the development of the shower by $\approx 0.2 - 0.3\,\%$,
- The number of particles is $> 1\,\%$ greater when the shower is young and old,
- There is a increase on the muon number of $\approx 1\,\%$ when the shower is young, but it is left unchanged when the shower is old.