Energy Scale Calibration of Calorimeters in Space using Moon Shadow

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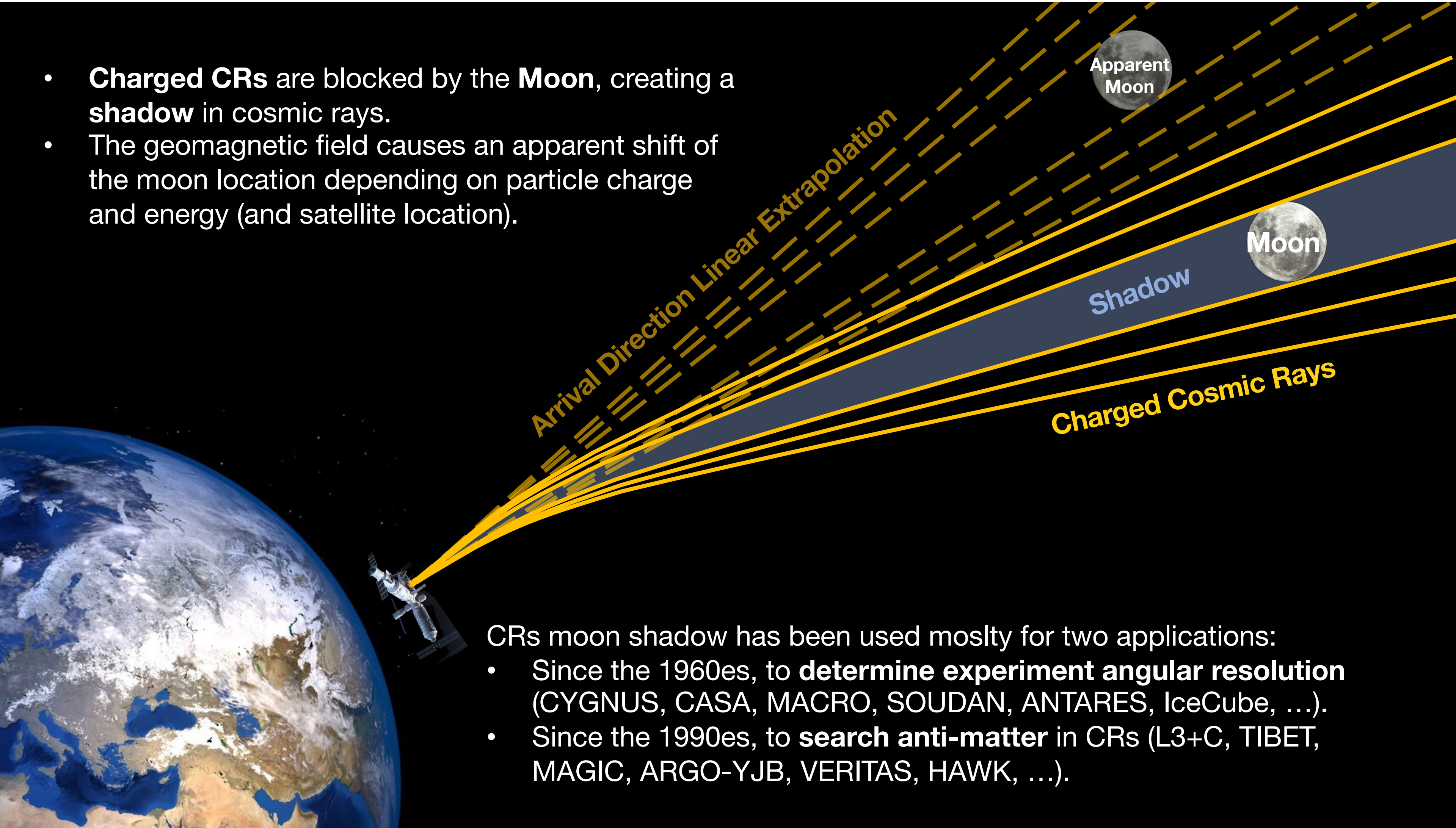
Cosmic Rays Moon Shadow

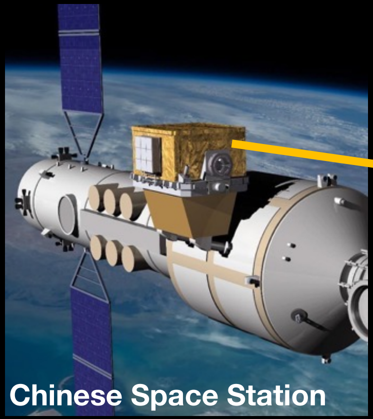
- **Charged CRs** are blocked by the **Moon**, creating a **shadow** in cosmic rays.
- The geomagnetic field causes an apparent shift of the moon location depending on particle charge and energy (and satellite location).

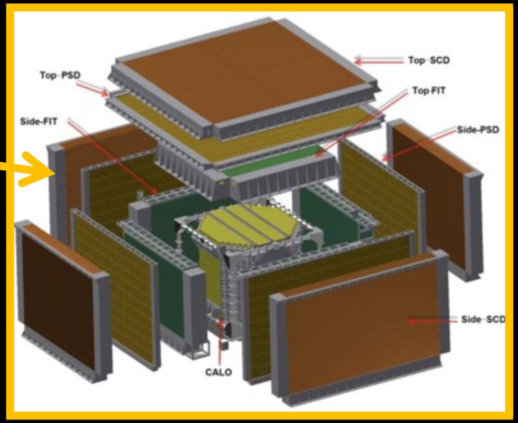


CRs moon shadow has been used moslty for two applications:

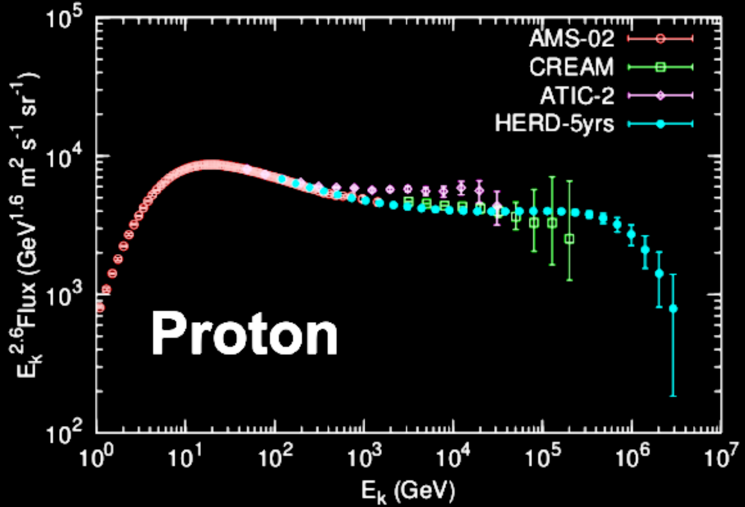
- Since the 1960es, to **determine experiment angular resolution** (CYGNUS, CASA, MACRO, SOUDAN, ANTARES, IceCube, …).
- Since the 1990es, to **search anti-matter** in CRs (L3+C, TIBET, MAGIC, ARGO-YJB, VERITAS, HAWK, …).

Direct Measurement of Cosmic Rays up to Knee





F. Gargano *et al.*, Proc. of 37th ICRC (2021) 26.



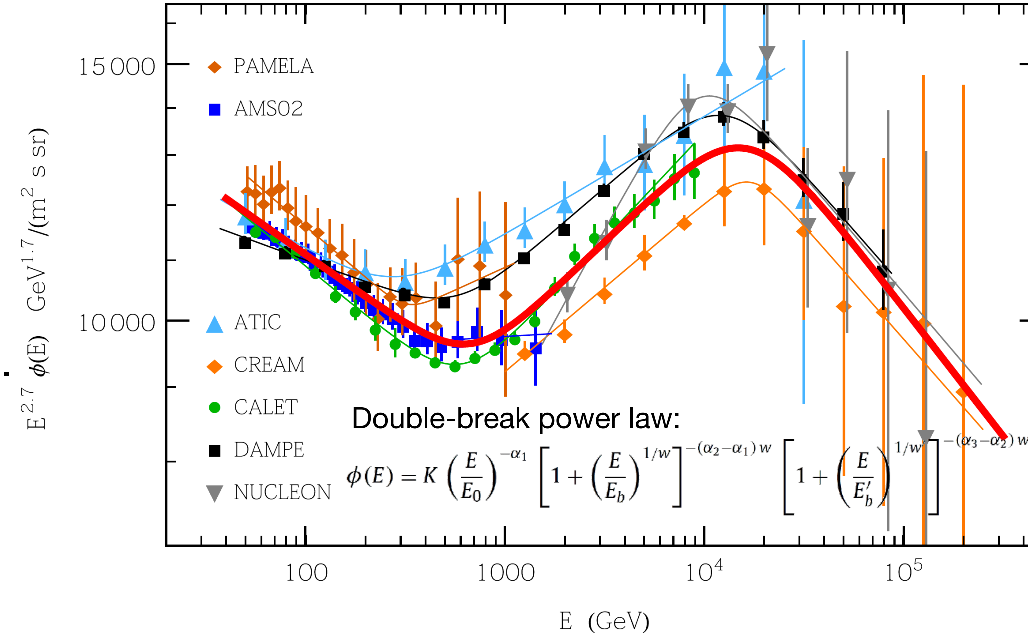
To reach the highest energies in CRs with **direct measurement calorimetric missions,** like HERD or CALET, have been proposed. HERD design is based on a 3D, homogeneous, finely-segmented calorimeter of 55 X_0 with a wide field of view, complemented by other detectors for PID (charge, tracking, …).

An important factor, for the accuracy of calorimetric experiments, is to understand the **hadronic energy scale at the highest energies:**

- At low energy the Earth rigidity cutoff can be used (see P. Marocchesi CALET talk of this morning).
- In HERD is included a TRD in the design, to identify multi-TeV protons.
- …

Expected Proton Flux

P. Lipari et al., ApJ **120** (2020) 102441.



Let's consider a HERD-like instrument with:

- A generous acceptance of 10 m^2 sr.
- Mission lifetime of 5 years.
- A 2π field-of-view (looking to half-of the sky all the time).
- An angular resolution of 0.1° (silicon tracker).
- An energy resolution of 30% (calorimeter).

Since moon has angular diameter is about 0.52°, the shadowed CRs fraction is $4{\cdot}10^{-5}$.

Energy	Proton Integral Flux $(m^2\ sr\ s)^{-1}$	Protons in FOV	Expected missing protons due to the Moon
E > 100 GeV	2.5	1900M	78k
E > 500 GeV	0.15	120M	5k
E > 1 TeV	0.049	0.38M	1.5k
E > 5 TeV	0.0037	3M	120

Small effect

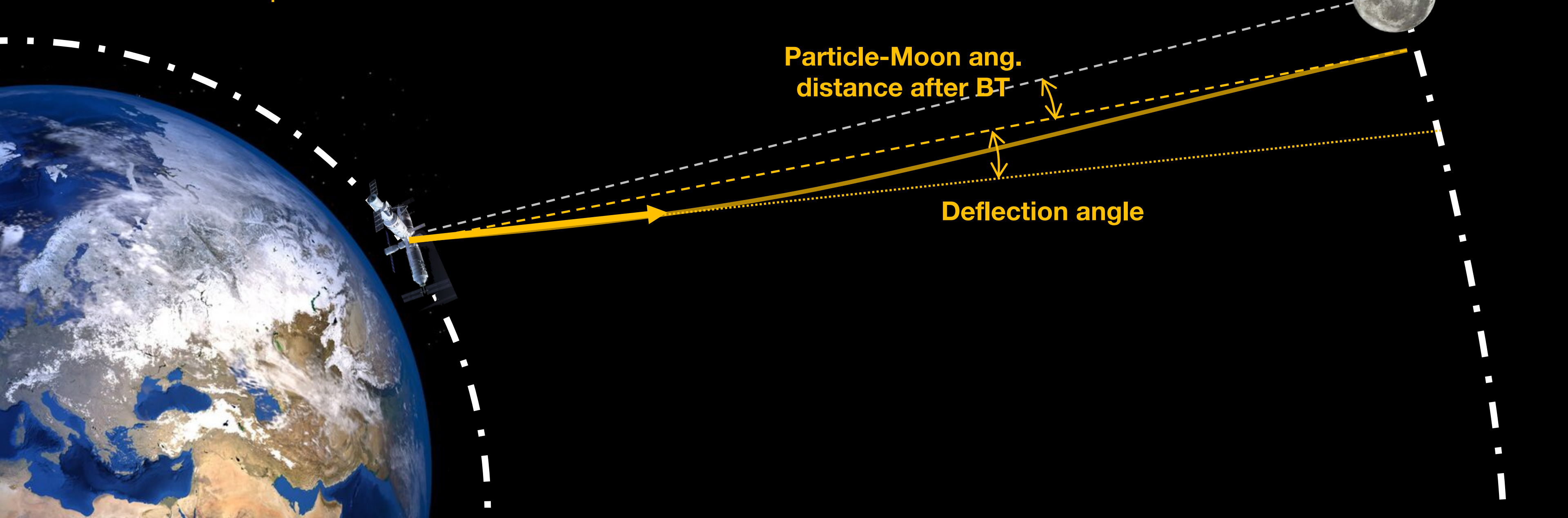
Simulation

Orbit simulation:

- Simulation of satellite orbit using TLE of Chinese Space Station (~400 km).
- Simulation of Moon orbit (J. Meeus, Astronomical Algorithms).

“True”-particle, from the surface of the detector we generate protons:

- Isotropically in the detector field-of-view.
- Energy is sampled from Lipari’s double-break proton spectrum.
- Backtrace protons in the Earth Magnetic Field up to the Moon sphere.
- If the proton falls into the Moon the event is removed.



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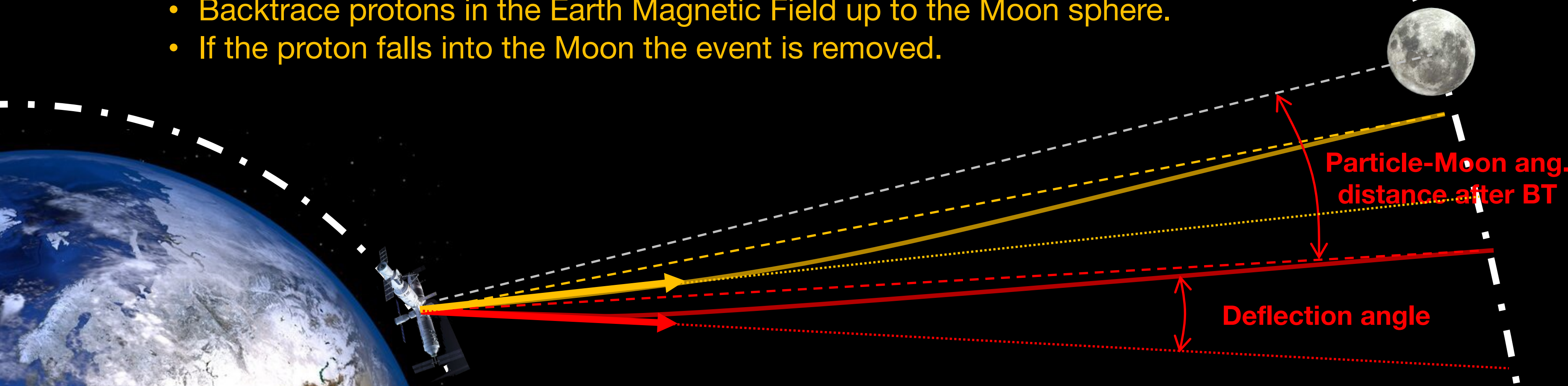
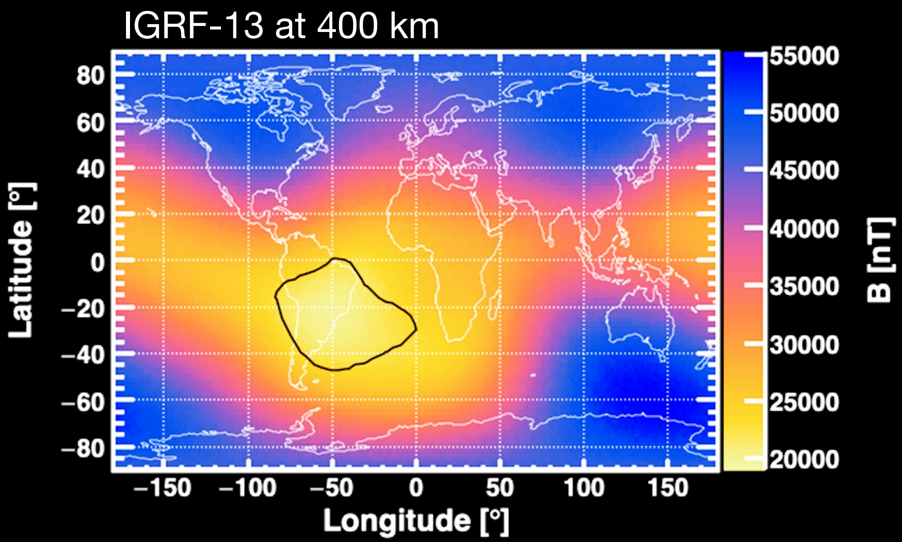
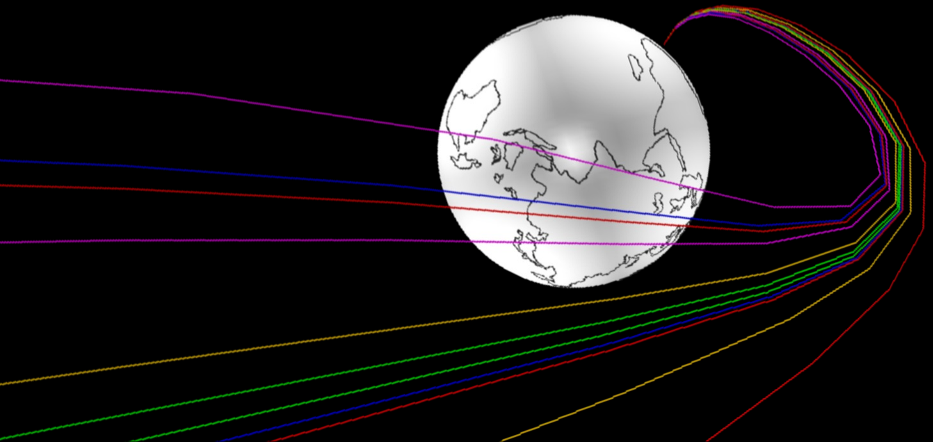


"Measured"-particle, includes detector effects:

- Extract energy and angle smearing to be applied to the particle.
- Backtrace the "measured" particle up to the Moon sphere.
- Evaluate the angle beween Moon and the the "measured" particle.

Particle Tracing





Generated protons to the detector surface are **back-traced** (backwards in time = tracing forward with opposite charge and direction) to the Moon sphere.

Magnetic field model: International Geomagnetic Reference Field model (IGRF-13). We ignore external field components, that should be included in a more realistic scenario.

Equation of motion: relativistic Lorentz EoM, solved with adaptive Runge-Kutta Fehlberg 7(8) method.

$$\begin{cases} \frac{\mathrm{d}\vec{x}}{\mathrm{d}t} = \frac{\vec{p}c}{E} \\ \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \frac{qc^2}{E}\vec{p} \times \vec{B} \end{cases}$$

Relativistic Lorentz equation of motion

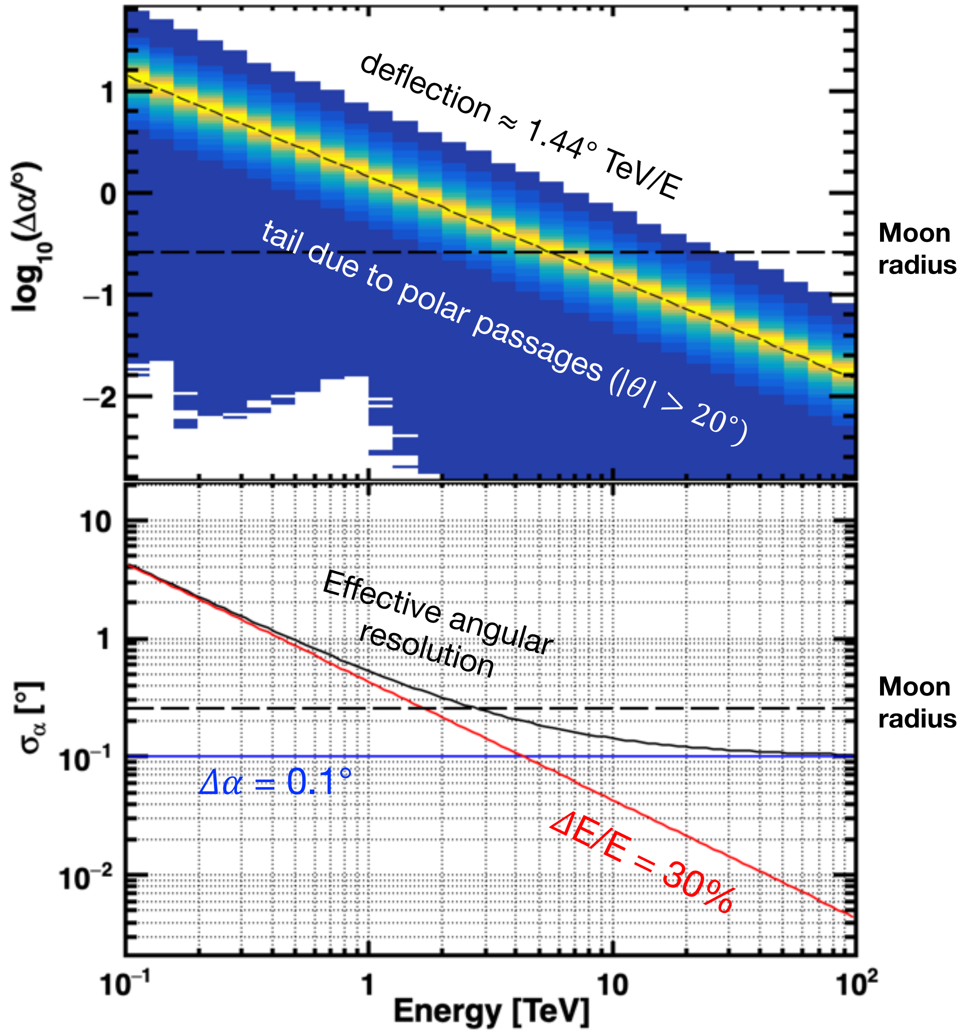
Deflection and Angular Resolution

Two energy-dependent effects should be considered: the particle deflection, and the effective angular resolution.

At low energies (< TeV): the particle deflection due to geomagnetic field is ≫ Moon size, but the effective angular resolution becomes ≫ Moon size because of the uncertainity on the energy measurement. However, the statistics in this region is large, there is sensitivity to energy scale.

At ~ TeV: the particle deflection is larger than effective angular resolution and of the Moon size. There is sensitivity to energy scale.

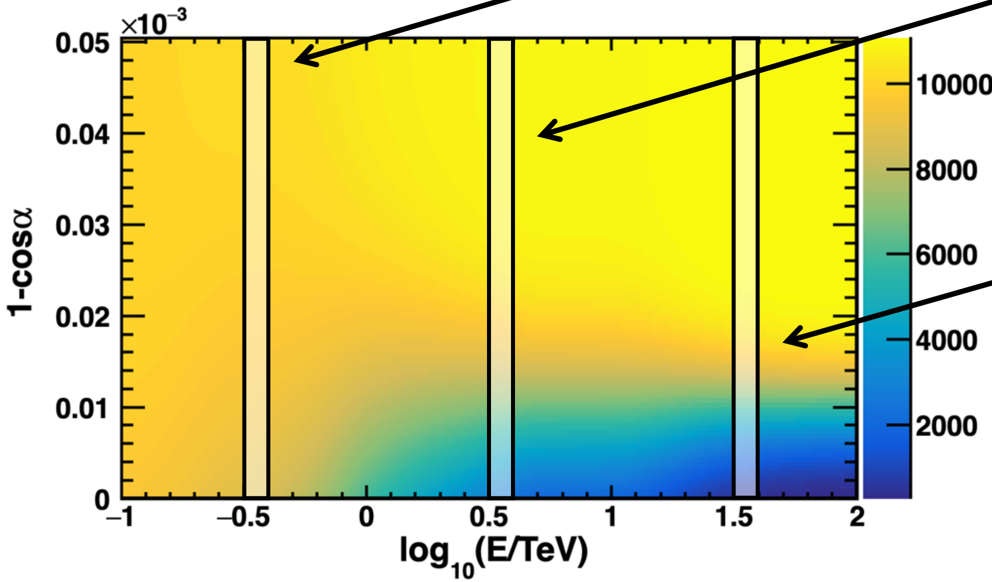
At high-energies (>10 TeV): the particle deflection is ≪ Moon size, and the Moon shadow becomes independent from energy and is only related to the detector angular resolution. No sensitivity to energy scale.

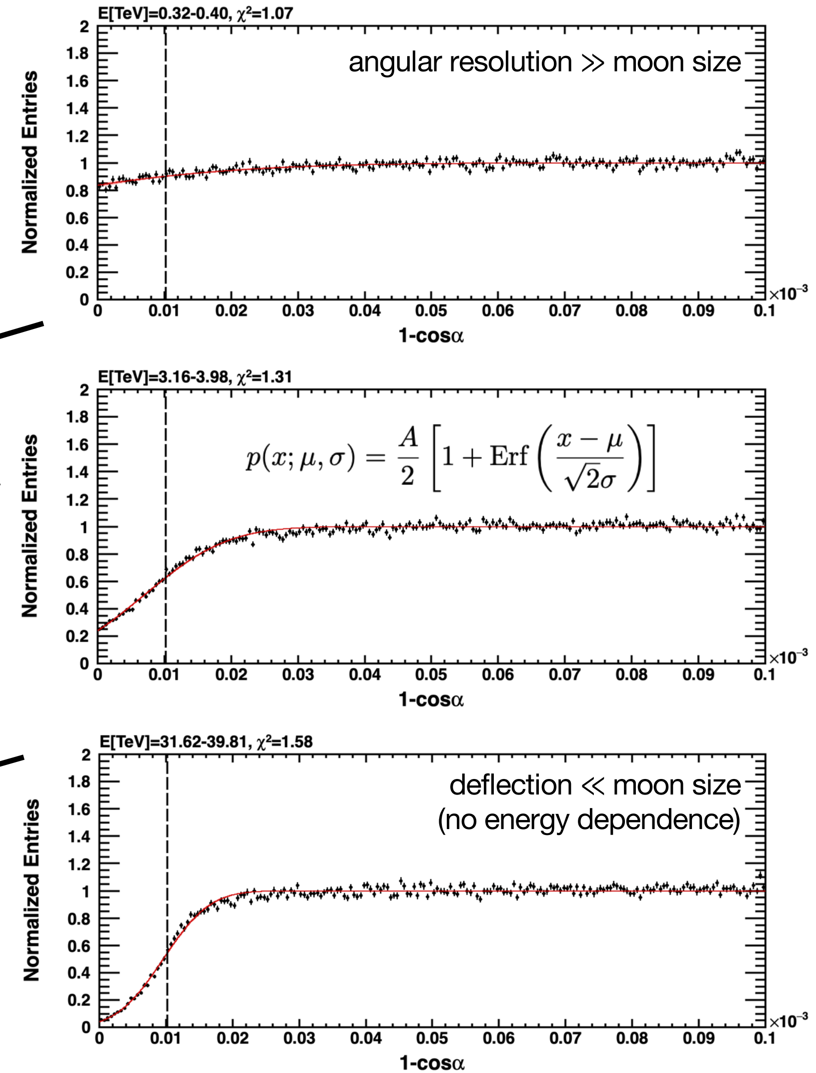


Probability Density Function

Characterisation of the measured Moon angular distance after BT as function of the measured energy.

To have a reasonable PDF large statistics has been produced and reweighted by the expected proton flux (to get the right migrations inside the PDF).





$$p(x;\mu,\sigma) = \frac{A}{2}\left[1 + \mathrm{Erf}\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)\right]$$

Binned Likelihood

Defining a binned likelihood with the created PDFs including a *scale parameter k*, for the energy scale calibration:

$$p(x;k,\mu,\sigma) = \frac{A}{2}\left[1 + \mathrm{Erf}\left(\frac{x/k - \mu}{\sqrt{2}\sigma}\right)\right]$$

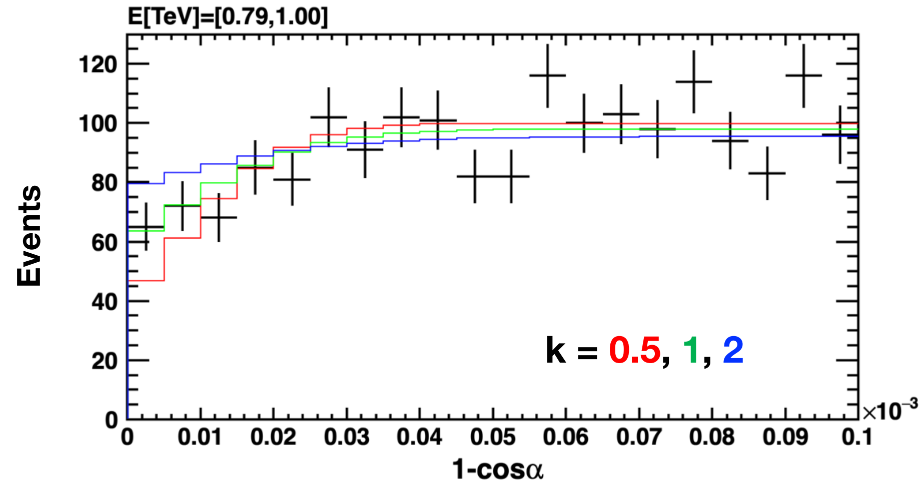
$$N_i^{\mathrm{exp}} = p_i \sum N_j^{\mathrm{obs}}$$

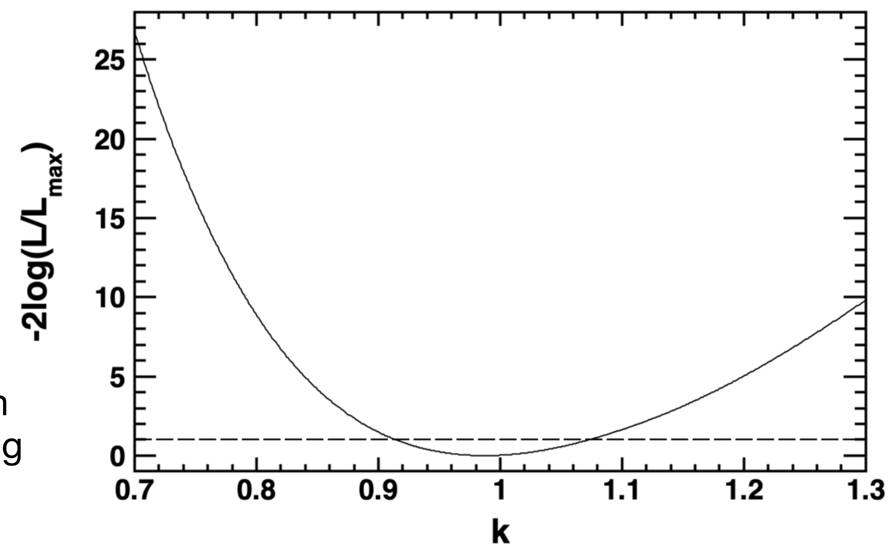
$$-2\log L = -2\sum\left(N_i^{\mathrm{obs}}\log N_i^{\mathrm{exp}} - N_i^{\mathrm{exp}}\right) + \mathrm{const.}$$

We can derive:

$$\hat{k} = 0.99^{+0.08}_{-0.07}$$

Restricting the fit from 0.5 TeV to 2 TeV, $\hat{k} = 0.97^{+0.10}_{-0.09}$. Verifications performed applying shifts in the simulation both for the PDF evaluation and the fitted data, resulting in compatible results.





Conclusion

- The simulation shows that is in principle **possible to evaluate the proton energy scale up to few TeV, for calorimeters in space** (with adequate statistics, angular and energy resolutions) **using the moon shadow.**

- Statistics seems to be the main issue. Sun-shadow can be also employed, roughtly doubling the statistics.