A Modern High-Precision Calculation of Deep Underground Cosmic Ray Muons

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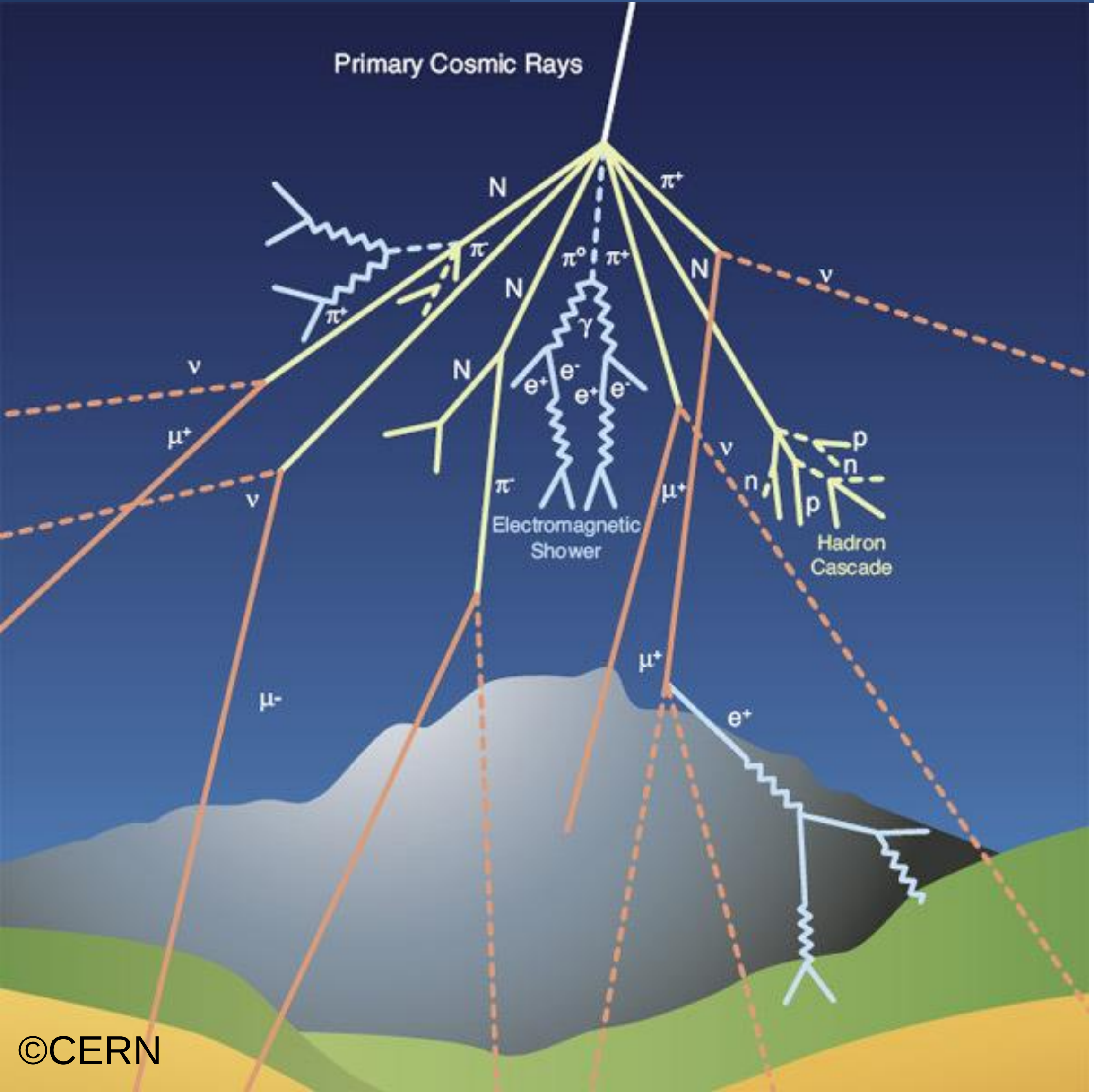
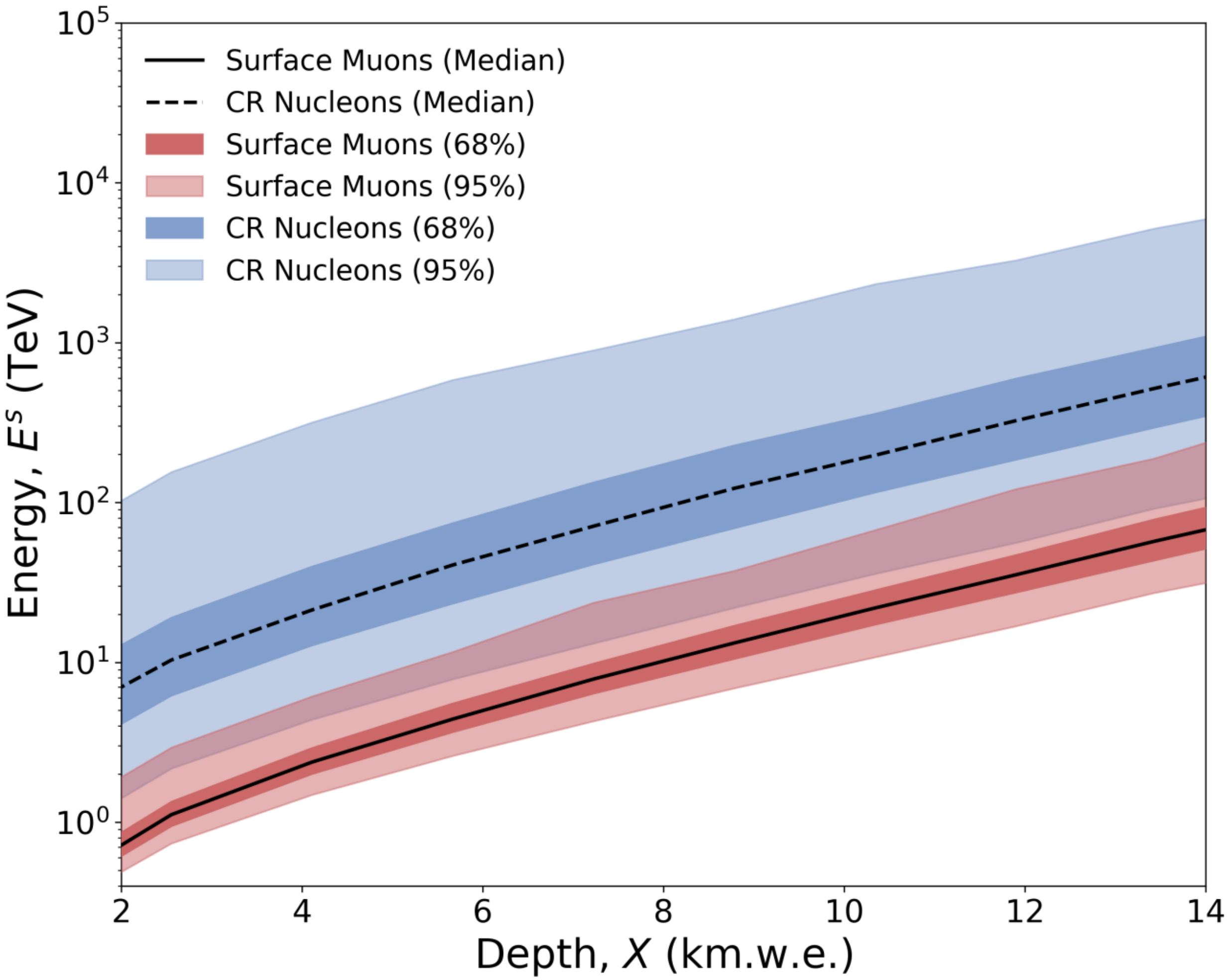
ICRC, July 2021

Introduction



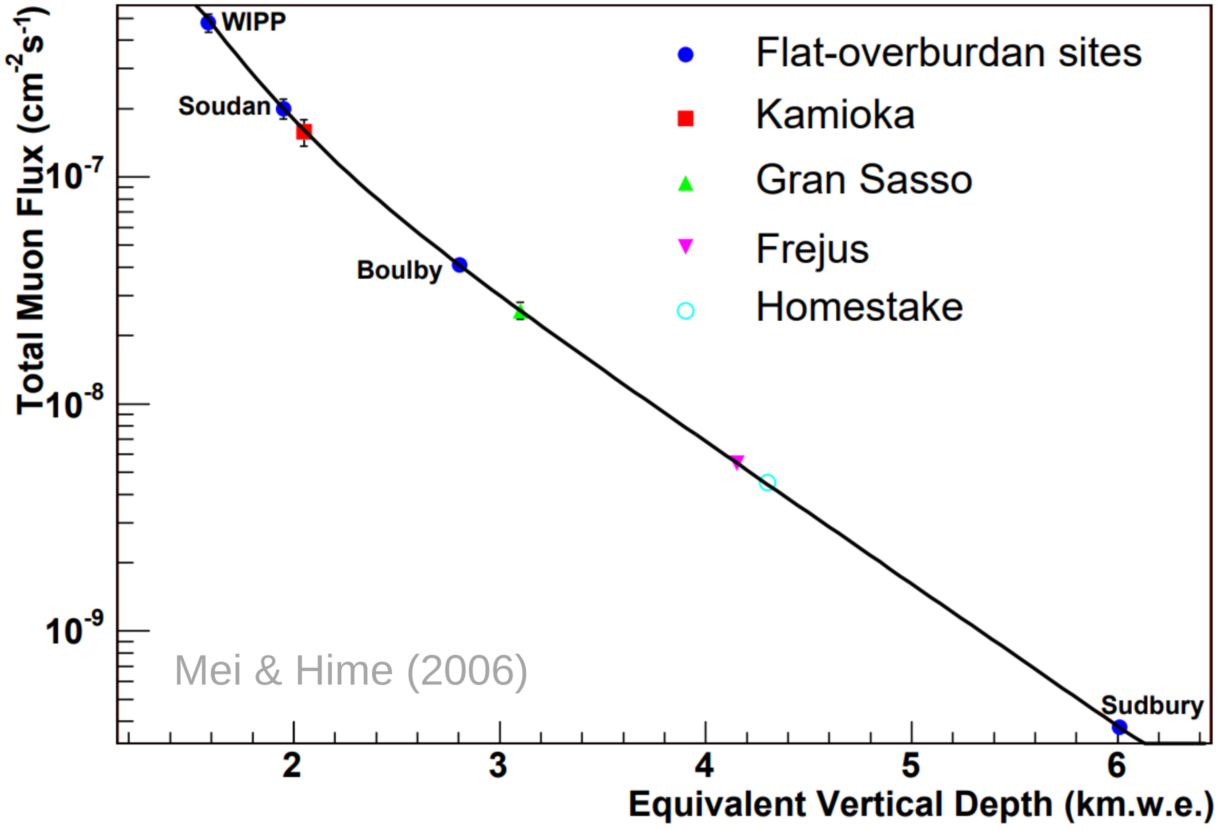


Introduction

- The last complete reference for cosmic ray muons was published in 2000 (Bugaev, [1]).
- Bugaev calculations lack rigorous treatment of uncertainties.
- Mei & Hime (2006) [2] and Crouch (1987) [3] use Depth-Intensity Relations (DIRs):

$$I(h) = I_1 e^{(-h/\lambda_1)} + I_2 e^{(-h/\lambda_2)}$$

- Equivalent vertical depth is the depth under flat earth that a lab under a mountain would be at, given the muon flux the detector sees.



- Phenomenological fits may contain bias induced by systematics.

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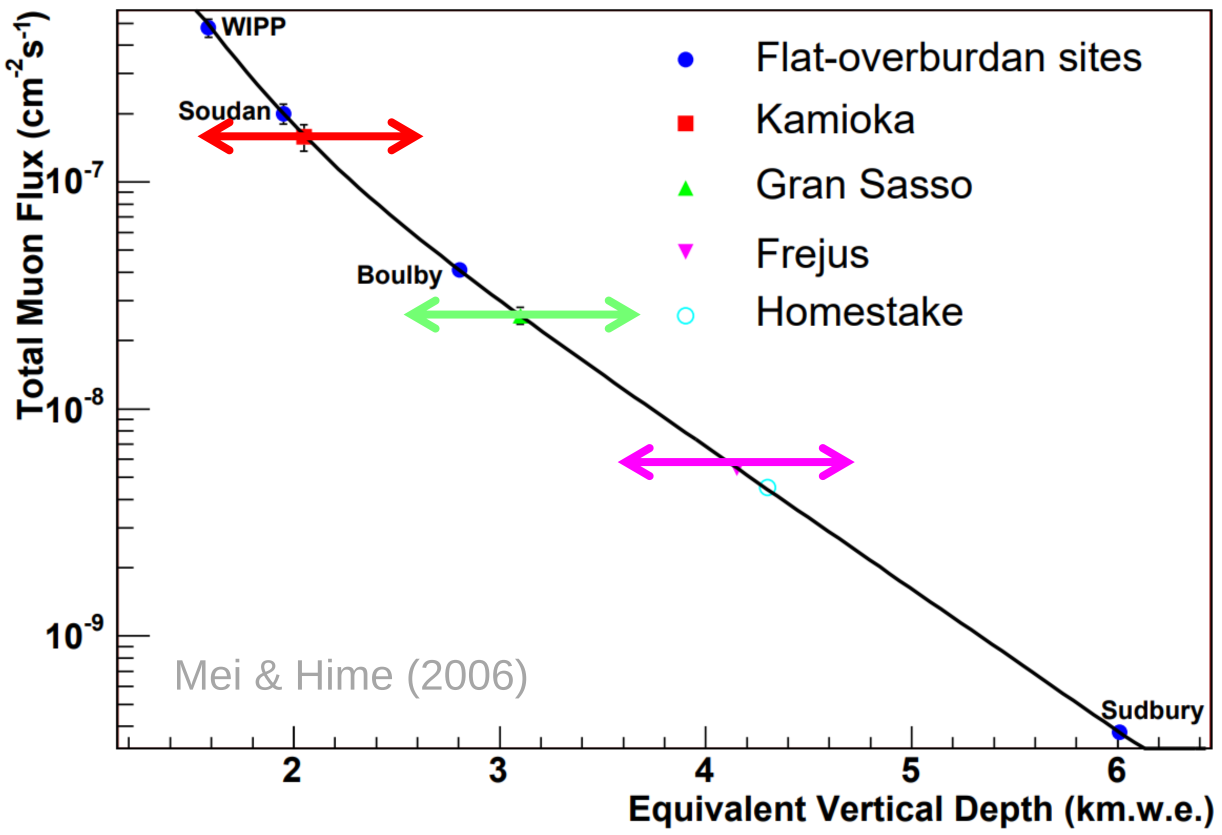


- Phenomenological fits may contain bias induced by systematics.

Issues with Vertical-Equivalent Intensity

- Vertical-equivalent intensity is typically:

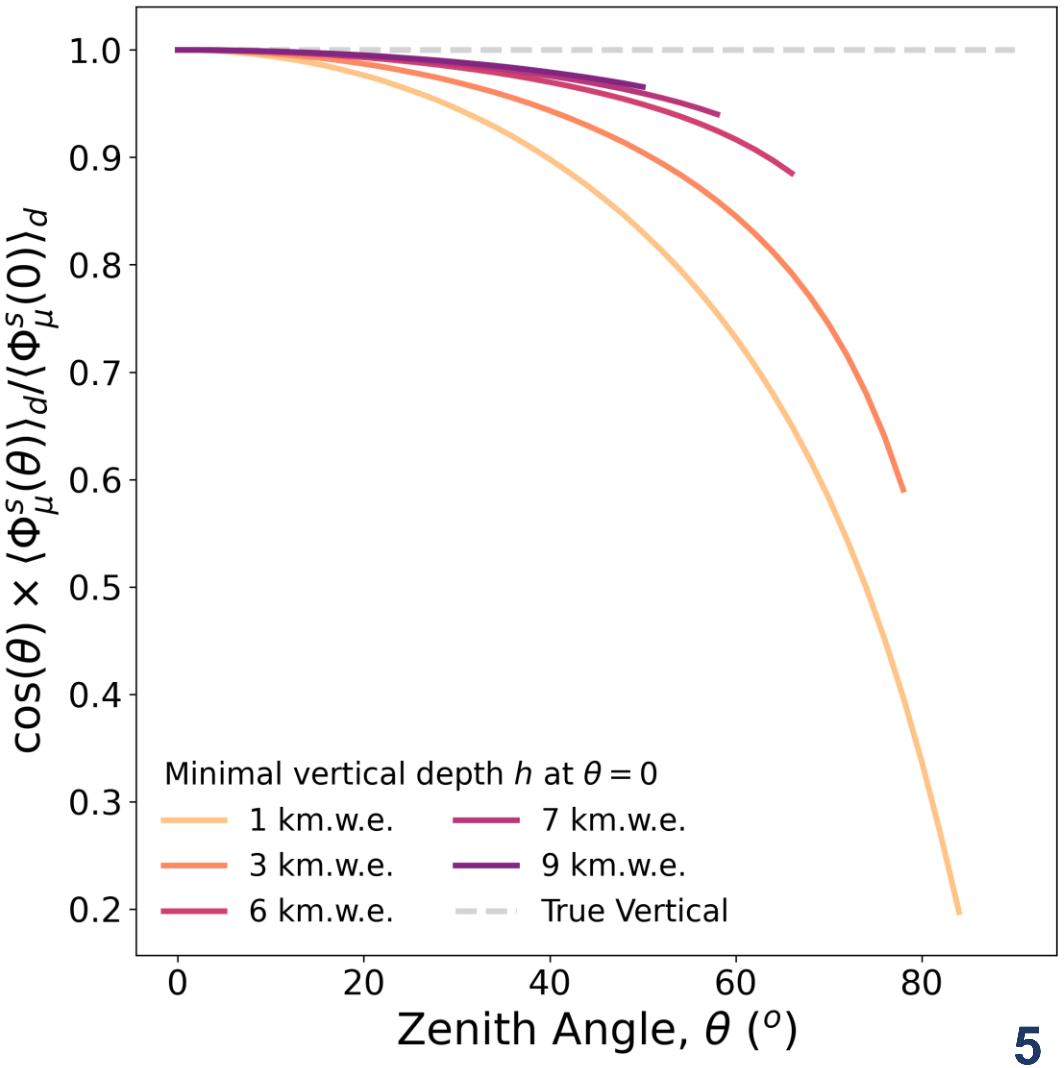
$$I^u_{eq}(X) = I^u(X,\theta)\cos(\theta)$$

- However, the approximation that the muon flux scales with 1/cos(θ) is poor at large θ.

- Instead, calculate a true vertical intensity by calculating the muon intensity for only $\theta = 0$:

$$I^u_{tr}(X) = I^u(X,\theta = 0)$$

- We aim to develop a new, modern, flexible, high-precision method to improve on the Bugaev and Mei & Hime papers.



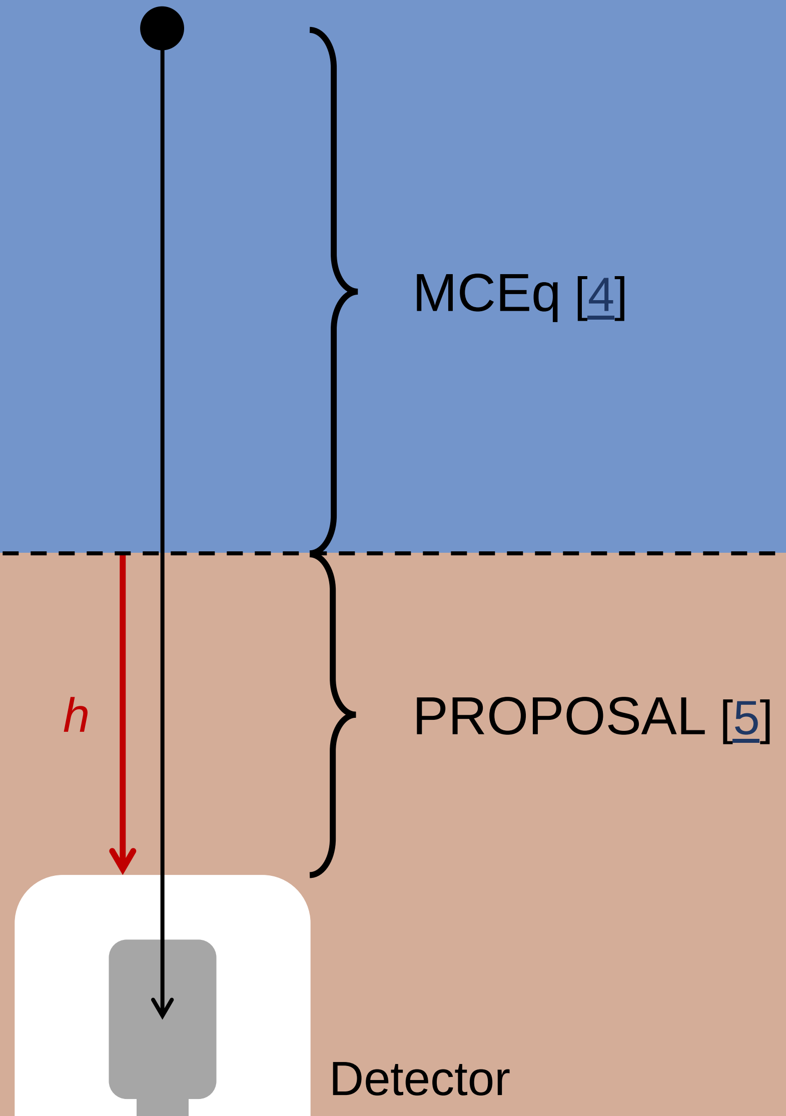
Simulation Method

Surface Muon Spectra:

- Primary cosmic rays
- Atmosphere
- Angular distributions

Transport Underground:

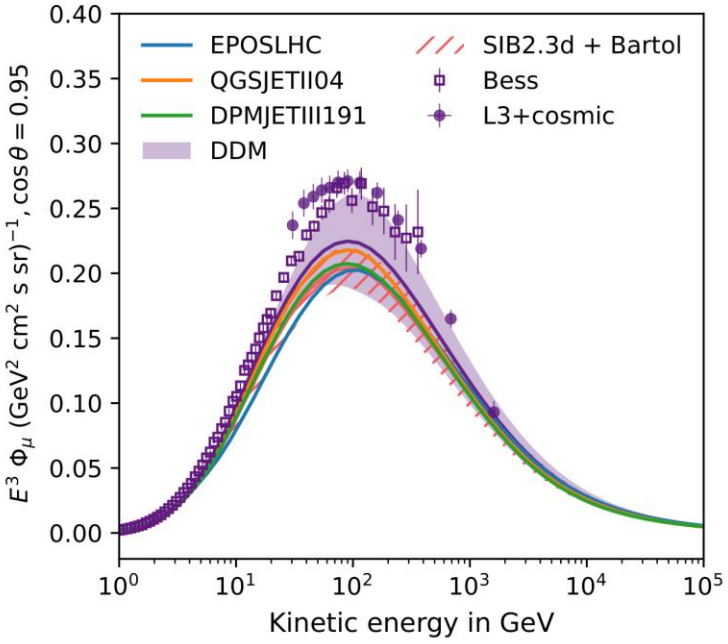
- Discrete losses
- Continuous losses
- Stopping and decay



Simulation Method

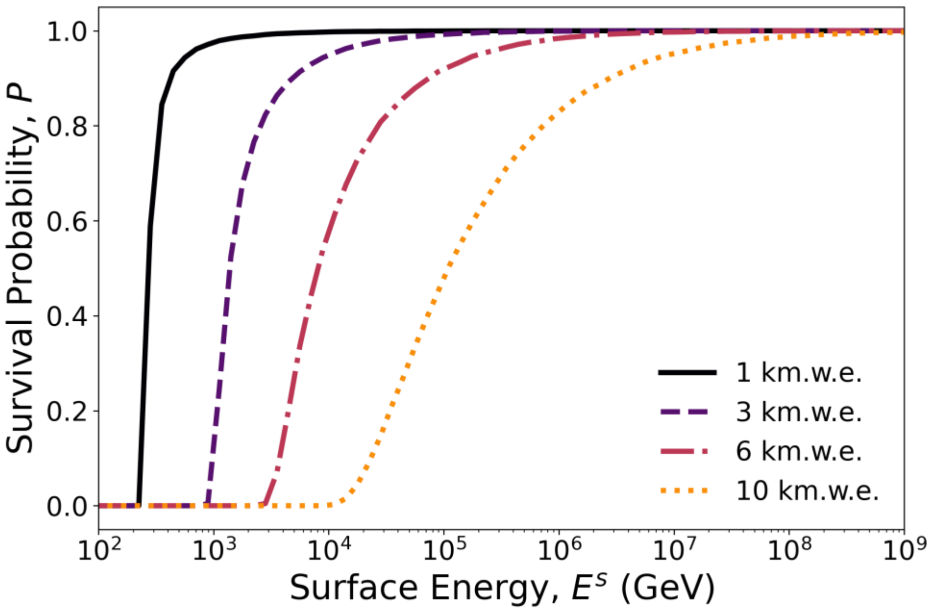
Atmosphere to Surface: MCEq

- One-dimensional fast cascade equation solver.
- Use recent hadronic interaction models DDM [6] and SIBYLL-2.3d [4] + Bartol errors [7].



Surface to Underground: PROPOSAL

- Full Monte Carlo program that simulates the transport of leptons through long ranges of matter quickly and with high precision.
- Used to calculate transfer matrices.

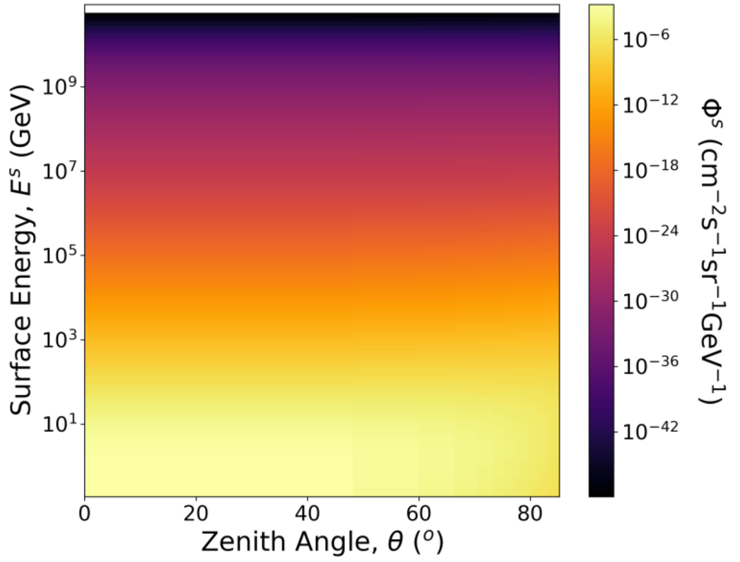


See Anatoli Fedynitch's talk (#1227) for more details.

Calculation of the Underground Flux

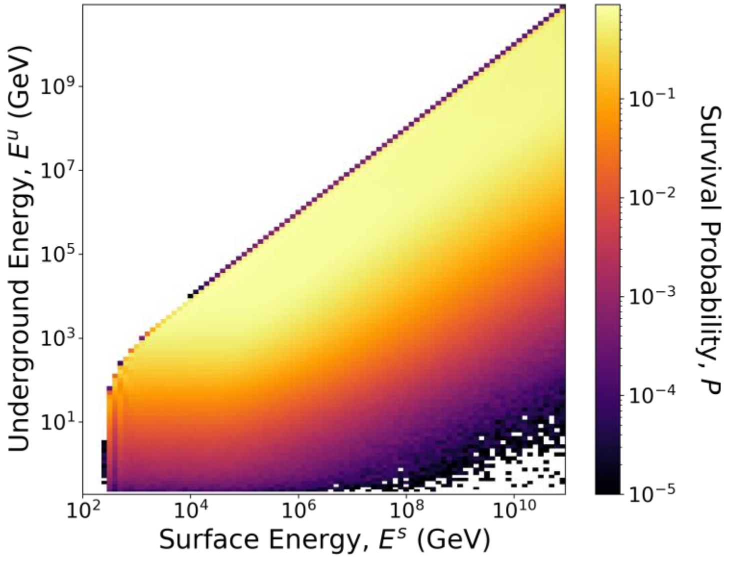
Underground Flux: $\Phi^u(E_j^u, X_k, \theta_k) = \sum_i \Phi^s(E_i^s, \theta_k) P\left(E_i^s, E_j^u, X_k\right)\left(\frac{\Delta E_i^s}{\Delta E_j^u}\right)$

Surface Flux



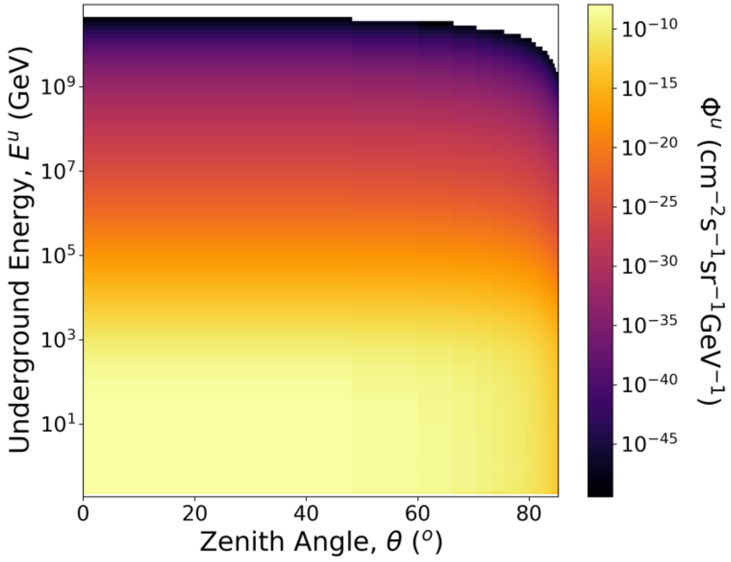
From MCEq

Transfer Matrix

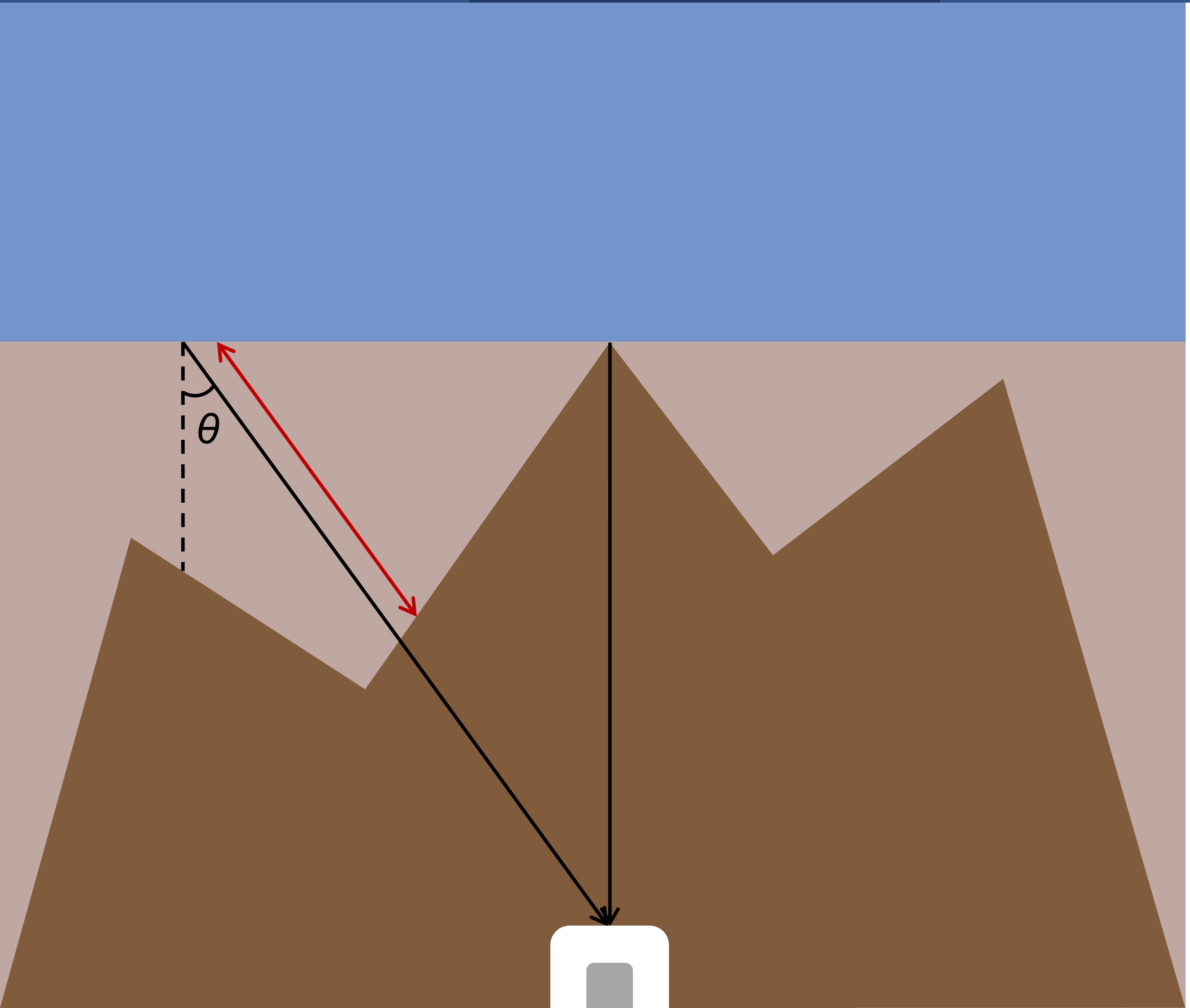


From PROPOSAL

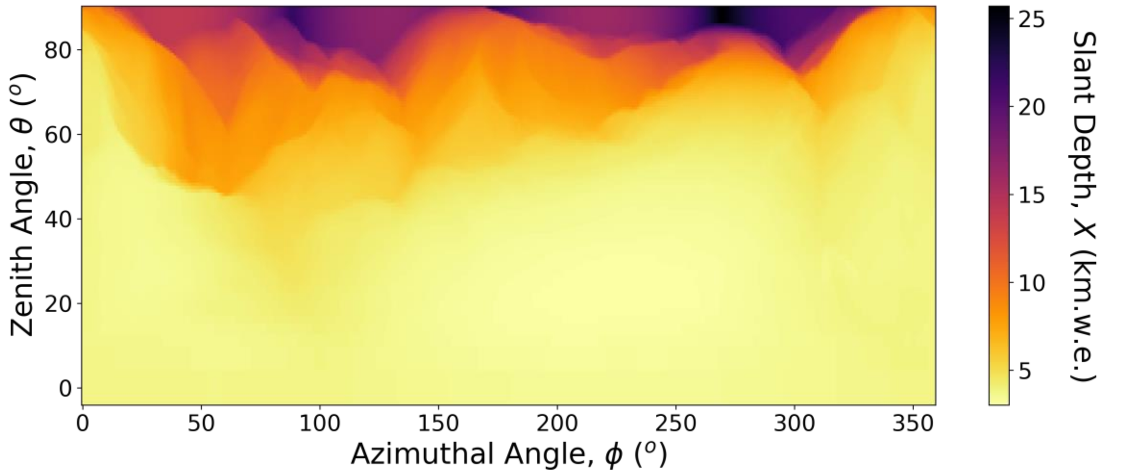
Underground Flux

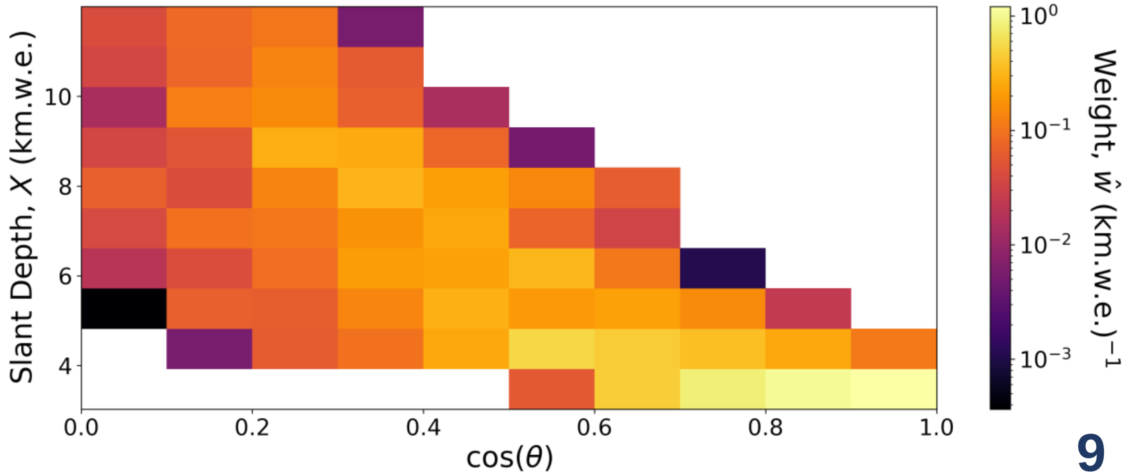


Non-Flat Overburdens



Gran Sasso





Underground Intensity

- Underground intensity:

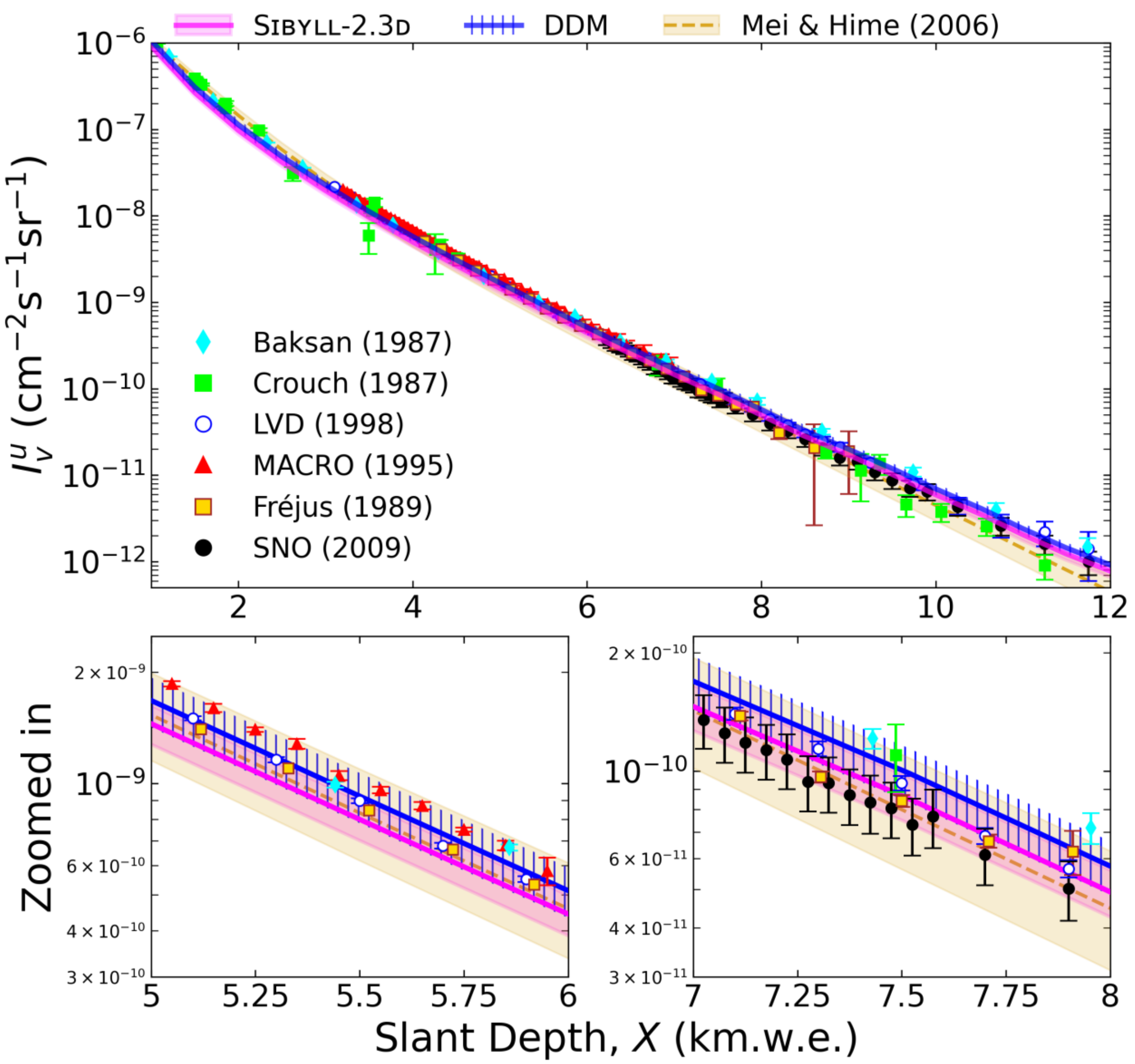
$$I^u(X,\theta) = \int_{E_{\min}}^{E_{\max}} \Phi^u(E^u, X, \theta)\mathrm{d}E^u$$

- There is non-negligible uncertainty that comes from the use of equivalent-vertical intensity (see slides 17 and 18).

- Therefore, we perform our calculation using true vertical intensity:

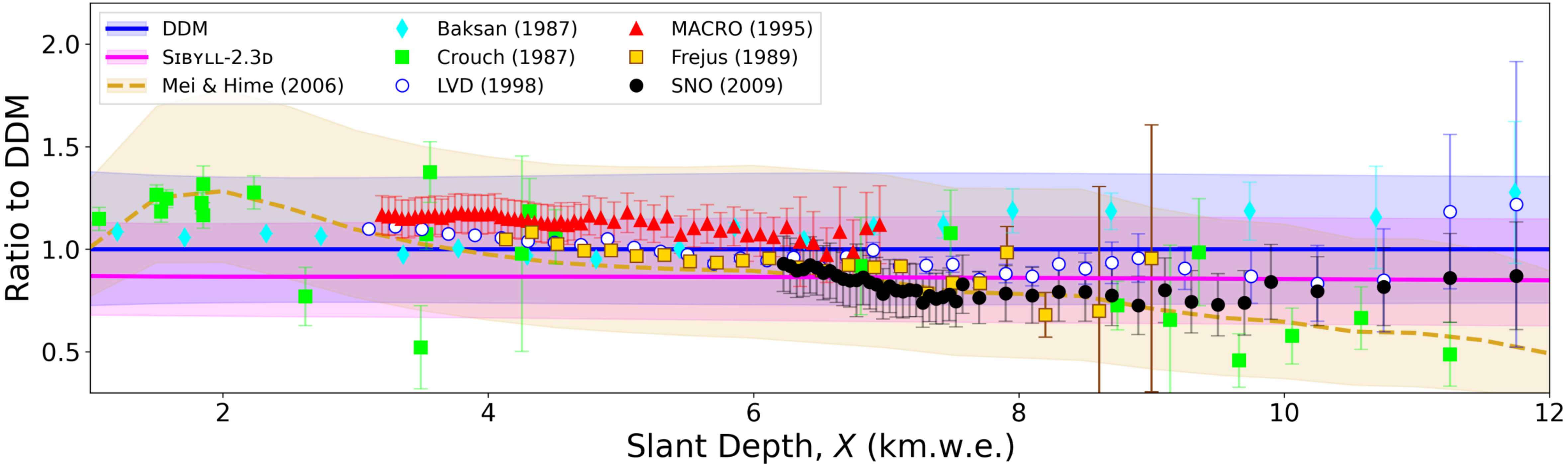
$$I^u_{tr}(X) = I^u(X, \theta = 0)$$

- There is good agreement with the data (from [8]) over the entire depth range.

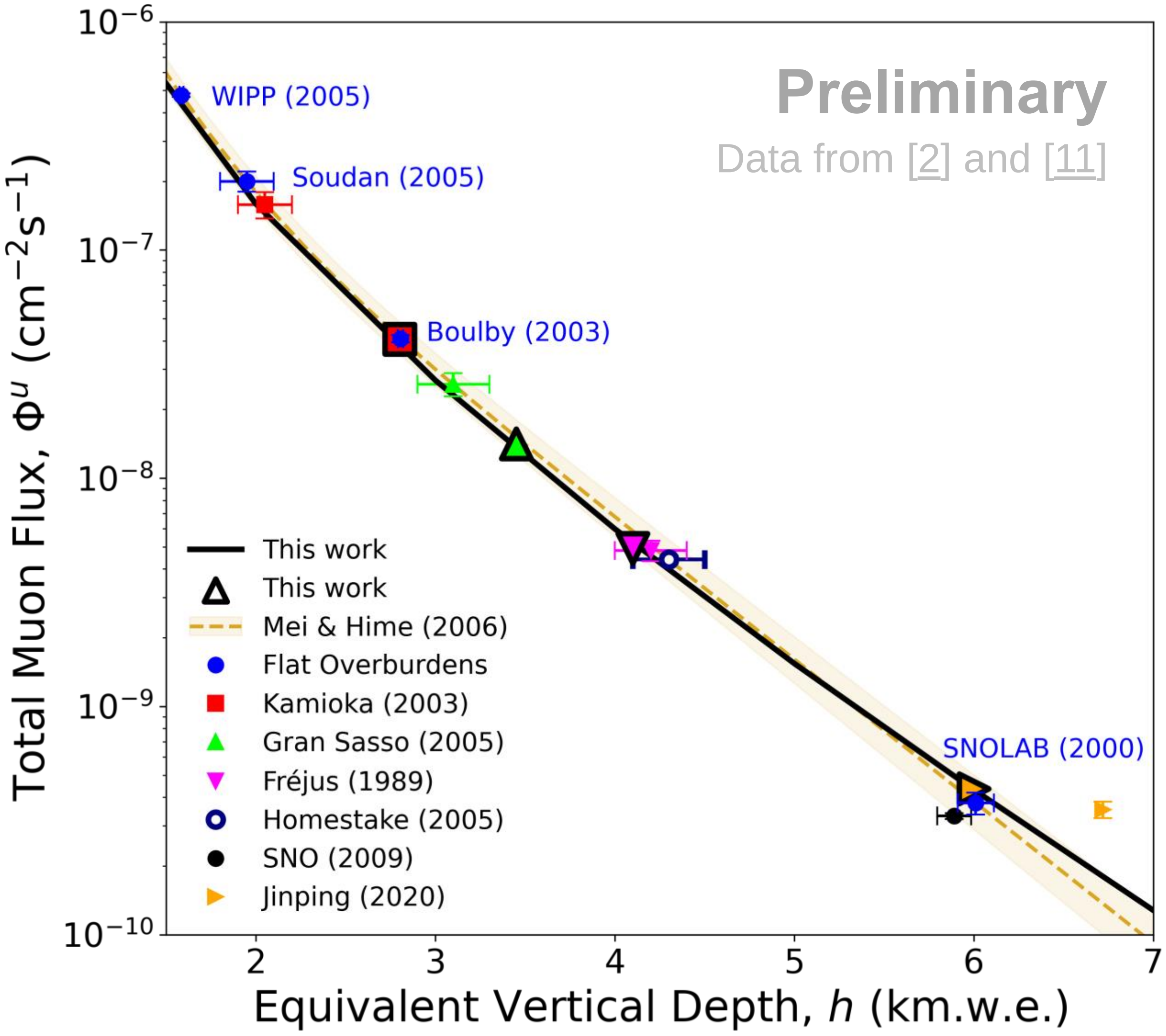


Comparison to Data

- DDM is better at describing shallow slant depths, and SIBYLL is better at deeper slant depths.
- Uncertainties on data are smaller than those on theory.
  ⇒ Using our method, we can constrain hadronic and cosmic ray uncertainties.



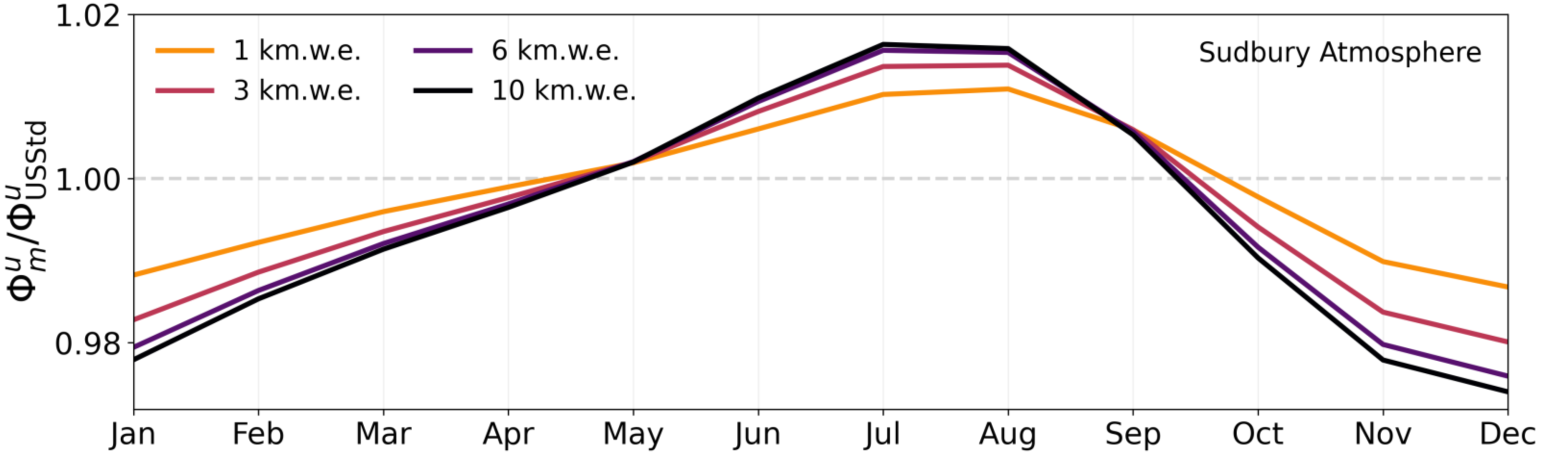
Total Underground Flux

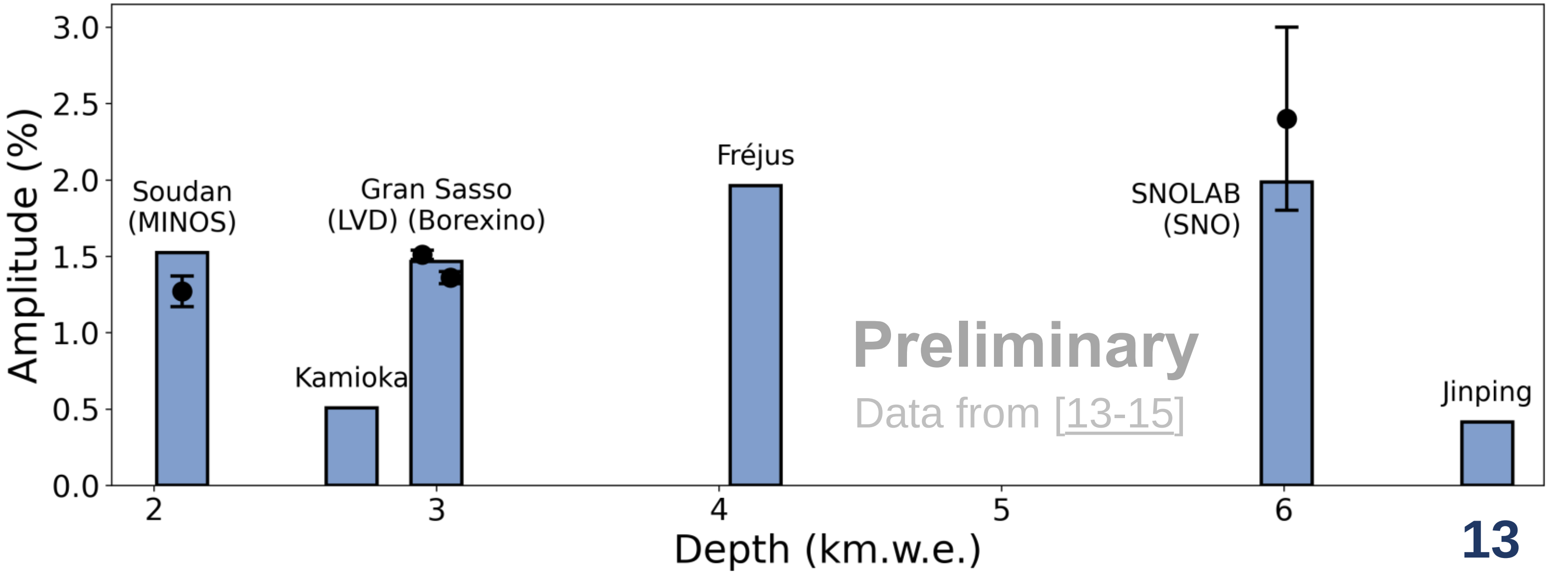


- The total underground flux is integrated over all energies and angles.
- This is the relevant observable for calculations of underground muon-induced backgrounds.
- Equivalent depths for mountain labs determined from computations for flat overburdens (maps from [9] and [10]).
- Our calculation reproduces flat-overburden labs (WIPP, Soudan, Boulby, SNOLAB) excellently.
- The empirical fit of Mei & Hime is reproduced well without doing any fits to data.

Seasonal Variations

- Density and temperature of the atmosphere vary across seasons, so pions and kaons decay into muons more or less often.
- Therefore, there is seasonal variation in the muon flux.
- The NRLMSISE-00 model [12] allows the atmosphere to be changed in MCEq to simulate this.
- Two contributing effects:
  1. The depth of the lab
  2. The location on Earth





Conclusion

- A program has been written to combine modern codes MCEq and PROPOSAL to make predictions for muons deep underground.
- The program is fast, precise, and flexible. The results match experimental data very well.
- It can be used by dark matter and neutrino experiments to calculate muon underground fluxes for labs with flat overburdens or mountains.
- It can simulate the seasonal variations of the muon flux.
- It can be used to constrain hadronic and cosmic ray uncertainties.
- A paper will be ready for publication soon, and the code will be made public. Stay tuned!

Thank you

We acknowledge the help of Marco Selvi, who provided us with a topographic map of the Gran Sasso mountain from LVD data, as well as Shaomin Chen, who provided us with a topographic map of the Jinping mountain from JNE data. We acknowledge, as well, the help of Michel Zampaolo and Luigi Mosca for the data of the Fréjus detector and Shigetaka Moriyama for the map of Kamioka. AF acknowledges the support from the JSPS (KAKENHI 19F19750). MCP acknowledges the support from the McDonald Institute.

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