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

William Woodley

Prof. Marie-Cécile Piro
Dr Anatoli Fedynitch (ICRR, University of Tokyo)
CAP Congress, June 2021

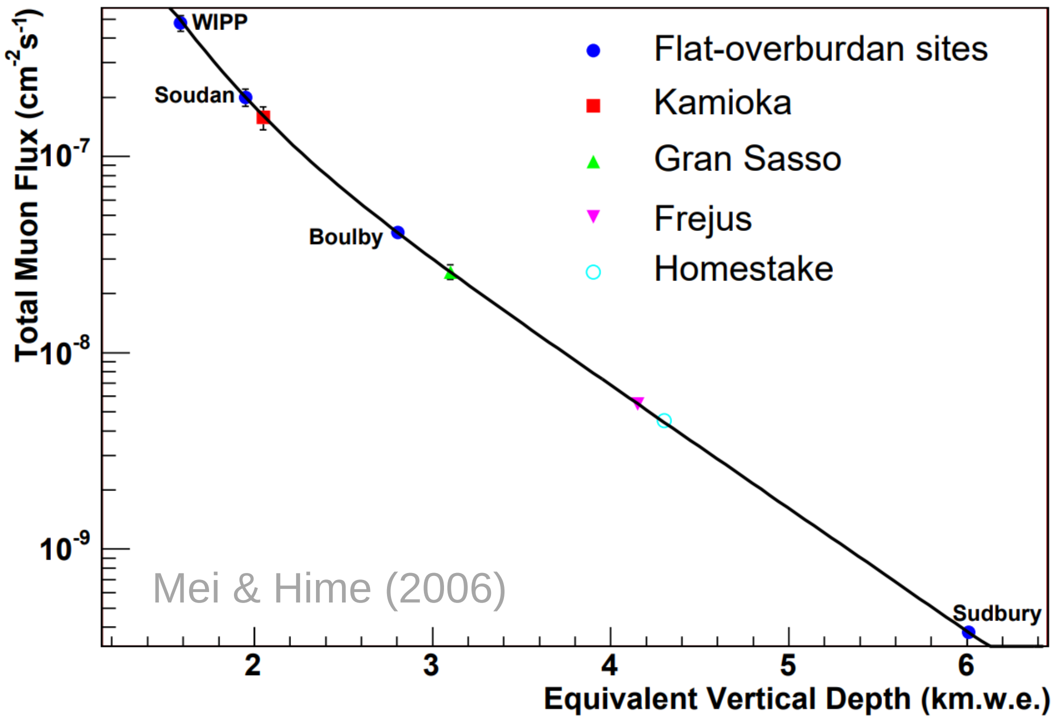
Introduction

- Muon-induced background processes are relevant to dark matter and neutrino searches, as particles like neutrons can mimic signals in dark matter and neutrino detectors.

- In the past, two methods to calculate fluxes:
    1. Parametrisations of data (e.g. Mei & Hime, 2006)
    2. Theoretical calculations (e.g. Bugaev, 2000)

- Two issues:
    1. Empirical fits are oversimplified
    2. No realistic uncertainties from theory

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



- We aim to develop a new, flexible, high-precision method to calculate these muon-induced backgrounds **that will solve both of these issues**.

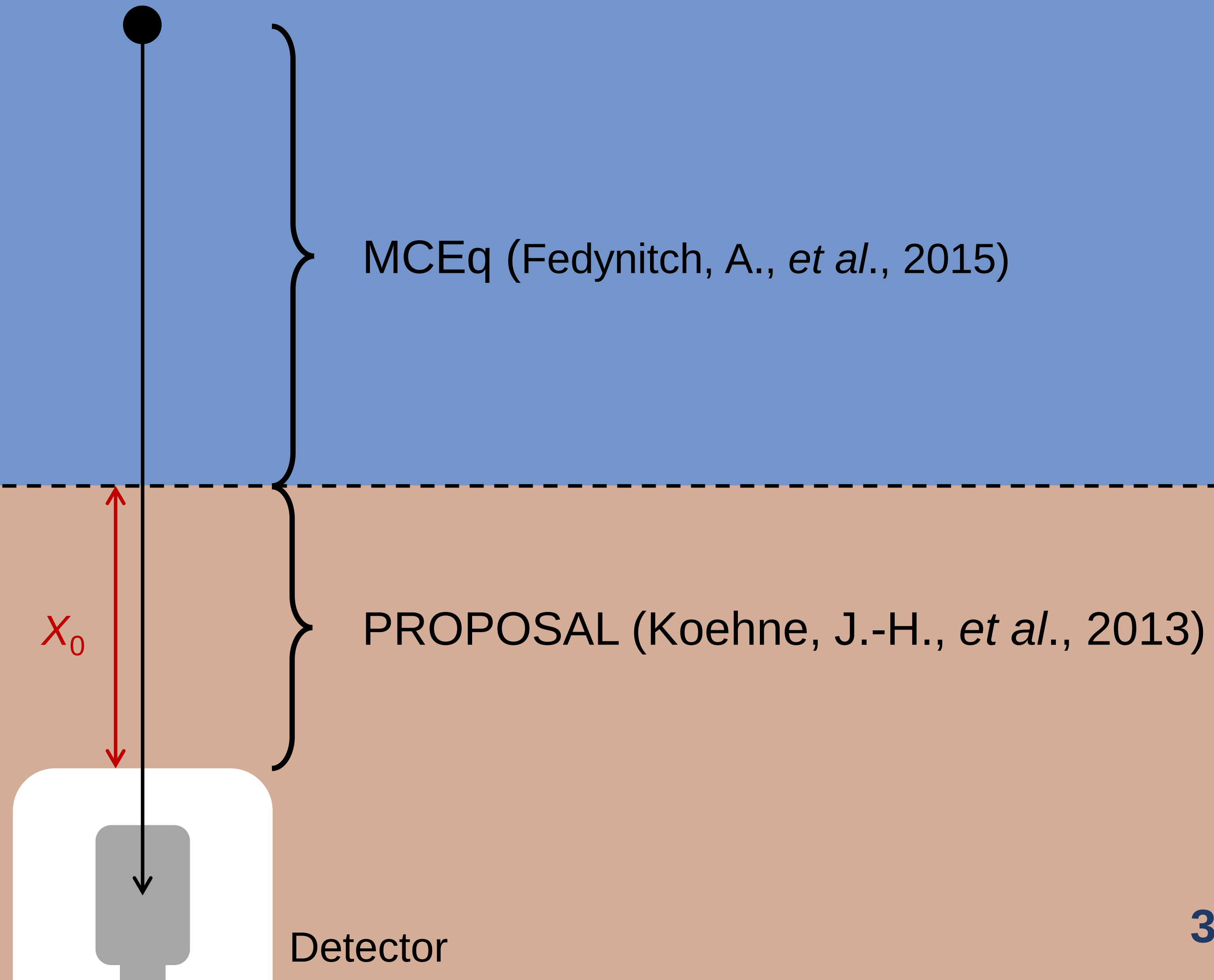
Simulation Method

Surface Muon Spectra:

- Primary cosmic rays
- Atmosphere
- Angular distributions

Transport Underground:

- Ionisation
- Discrete losses
- Decay and stopping

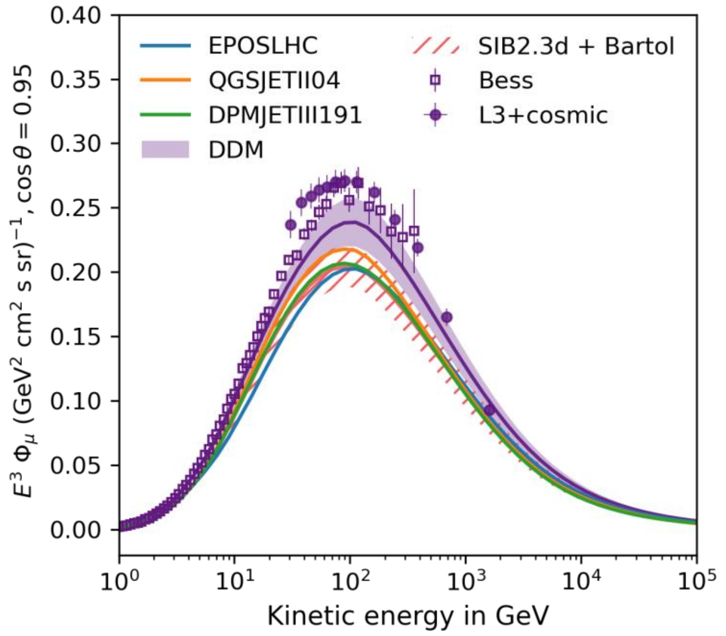


Simulation Method

Atmosphere to Surface: MCEq

- One-dimensional fast cascade equation solver.

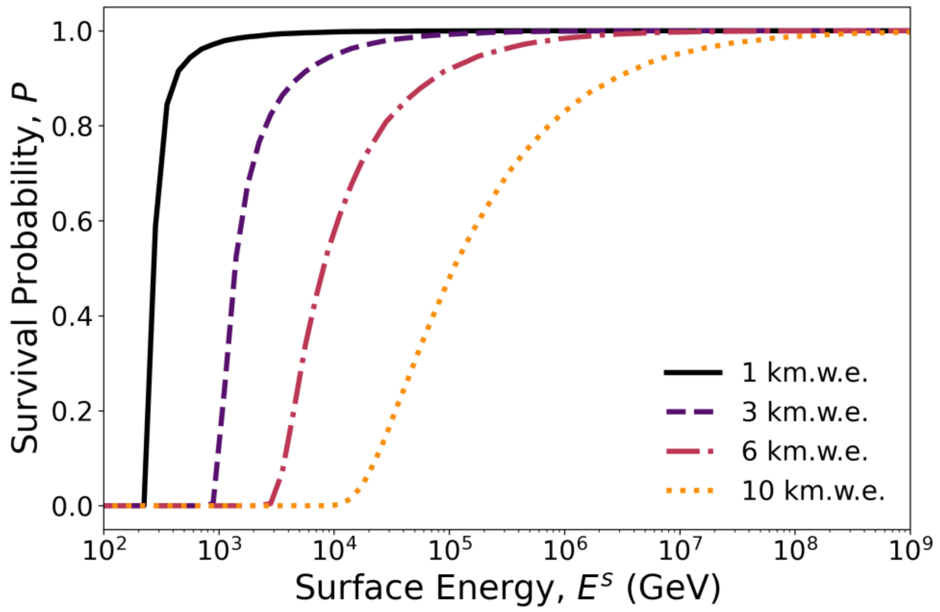
- Use recent hadronic interaction models DDM and SIBYLL-2.3d + Bartol errors.



Surface to Underground: PROPOSAL

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

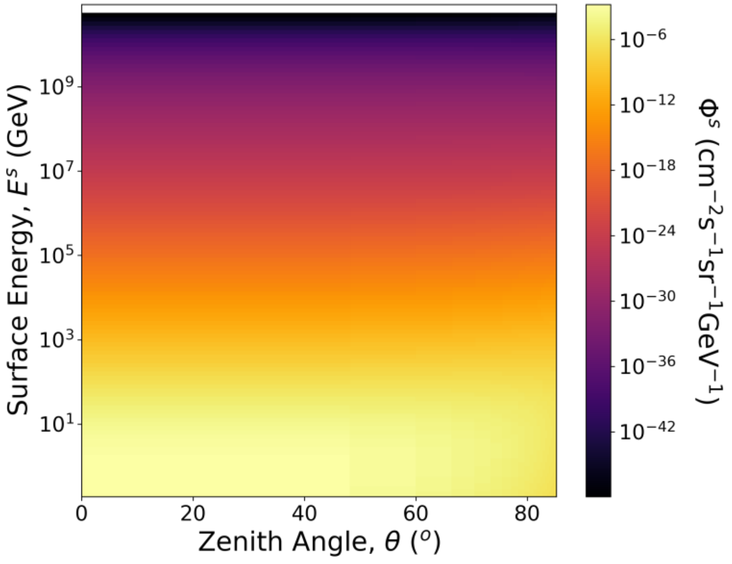
- Used to calculate transfer matrices.



Calculation of the Underground Flux

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

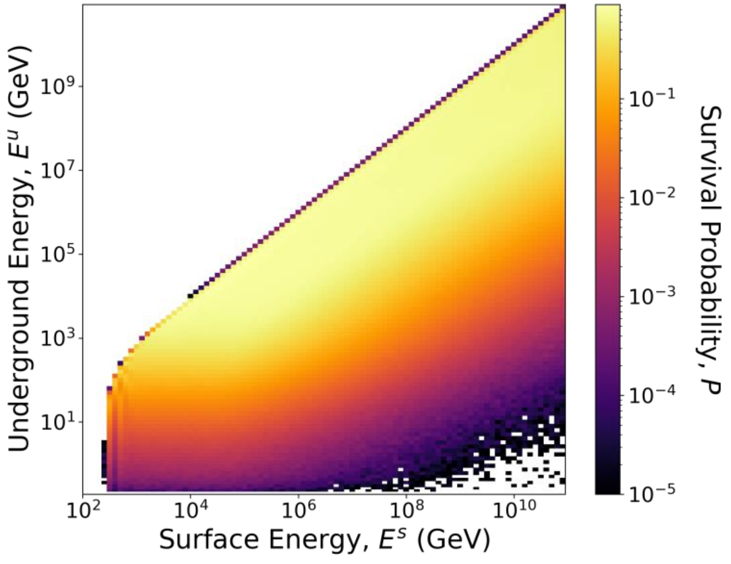
Surface Flux



From MCEq

×

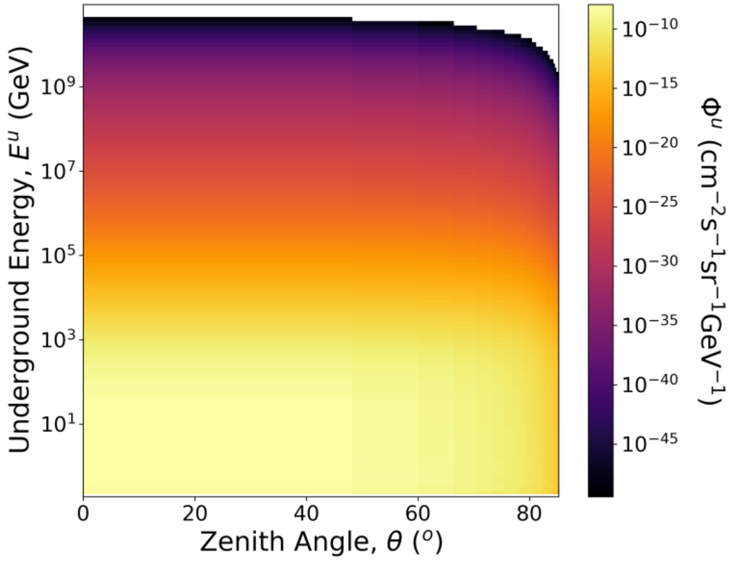
Transfer Matrix



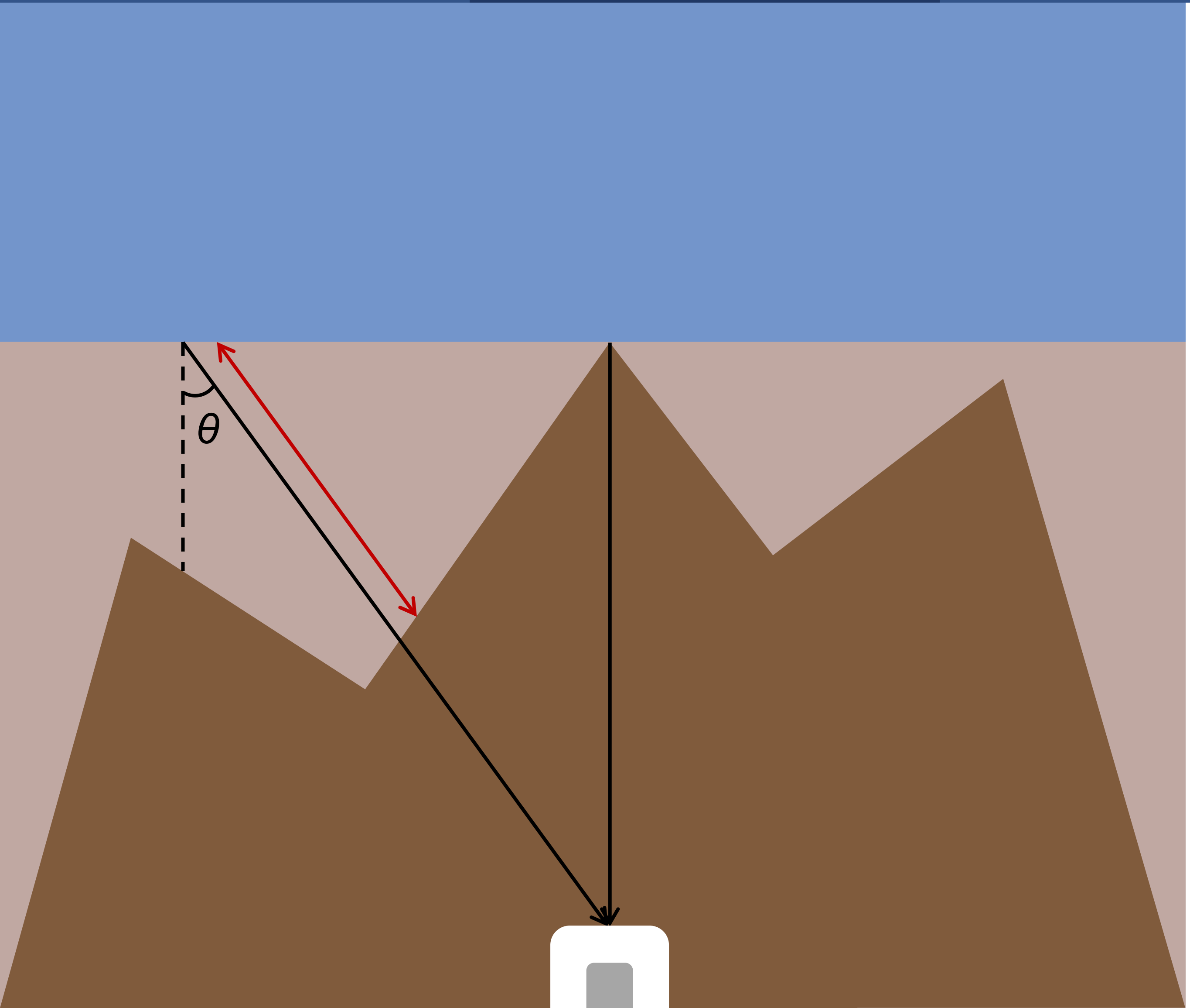
From PROPOSAL

=

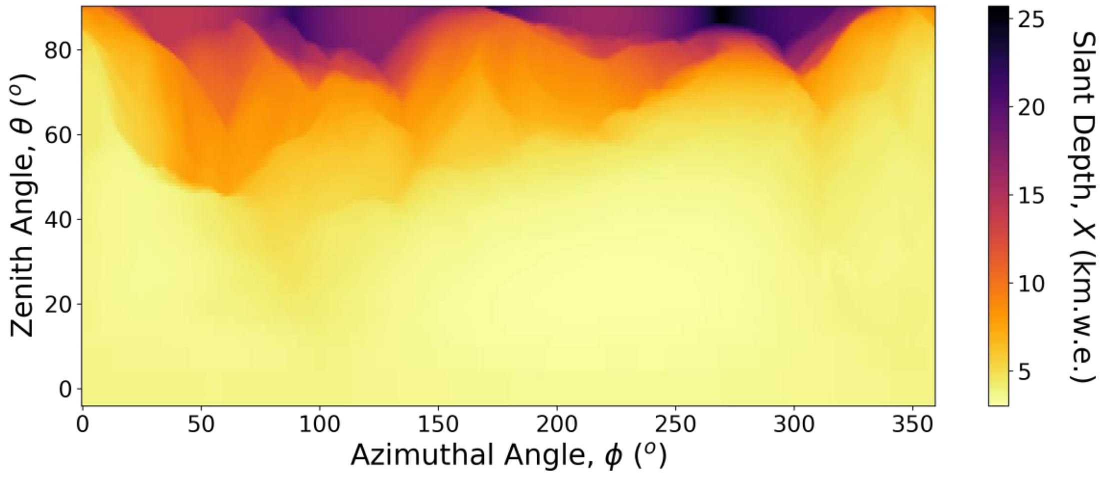
Underground Flux

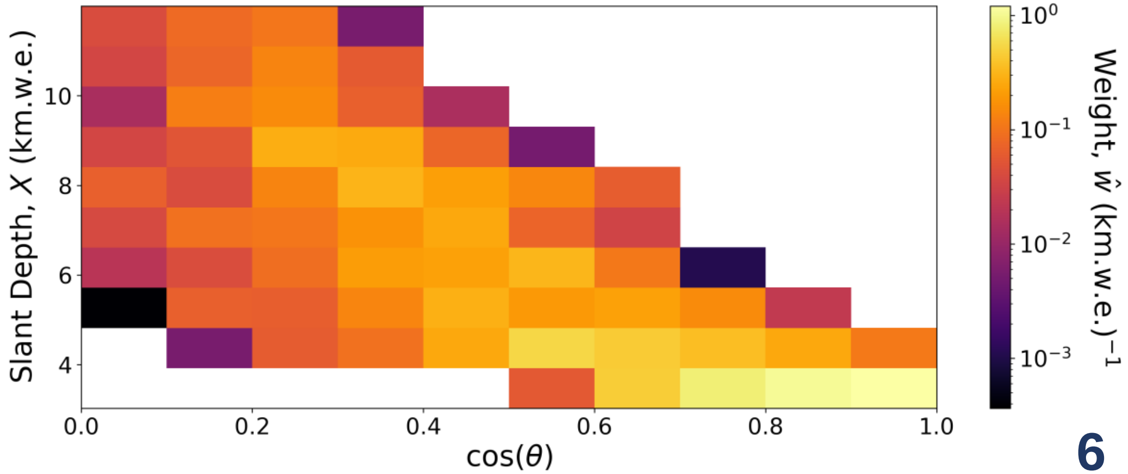


Non-Flat Overburdens



Gran Sasso





Underground Intensity

- Underground intensity:

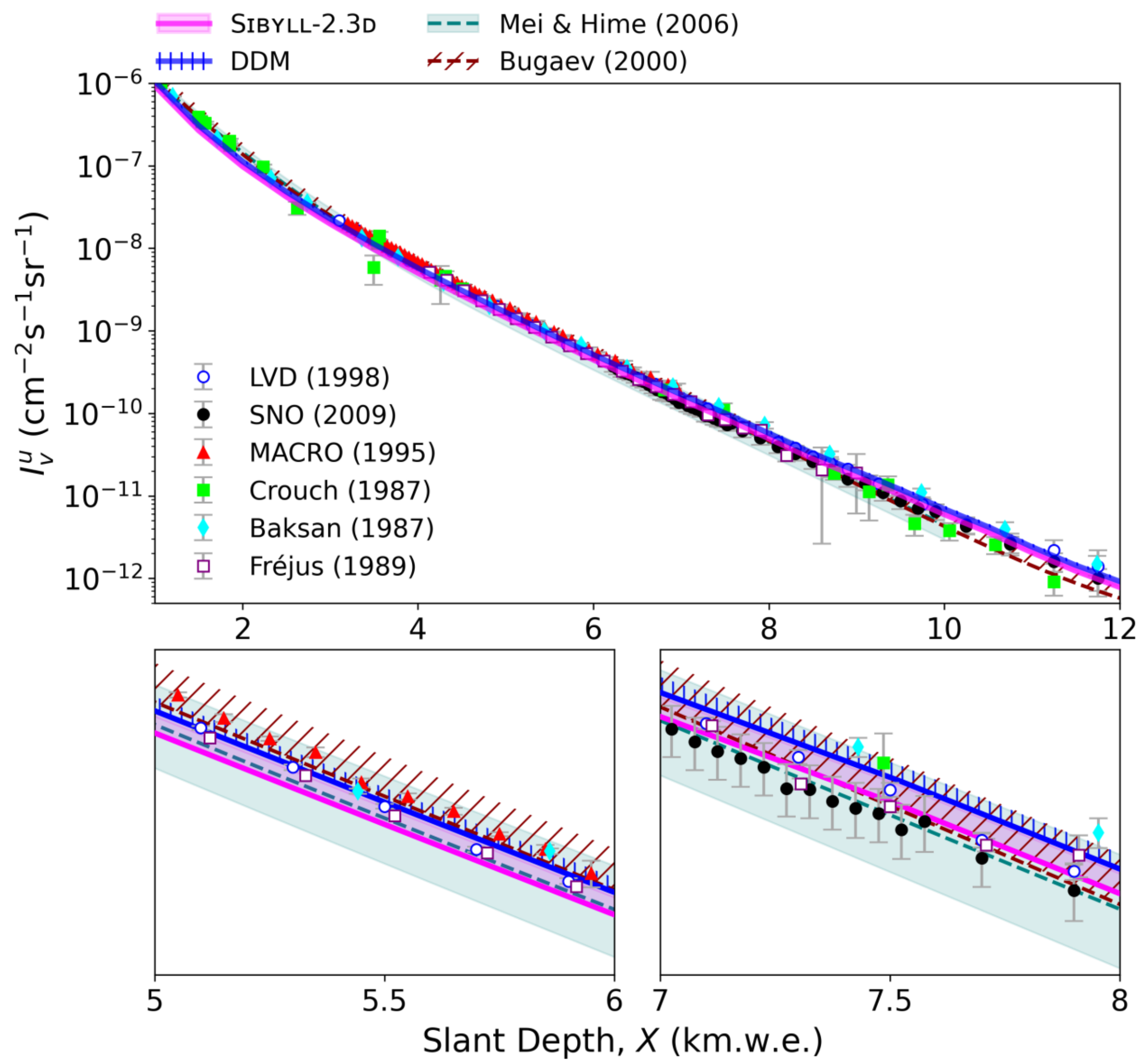
$$I^u(X,\theta) = \int_{E_{\min}}^{E_{\max}} \Phi^u(E^u, X, \theta)\,\mathrm{d}E^u$$

- Vertical-equivalent underground intensity:

$$I_v^u(X) = I^u\left(\frac{X_0}{\cos(\theta)}, \theta\right)\cos(\theta)$$

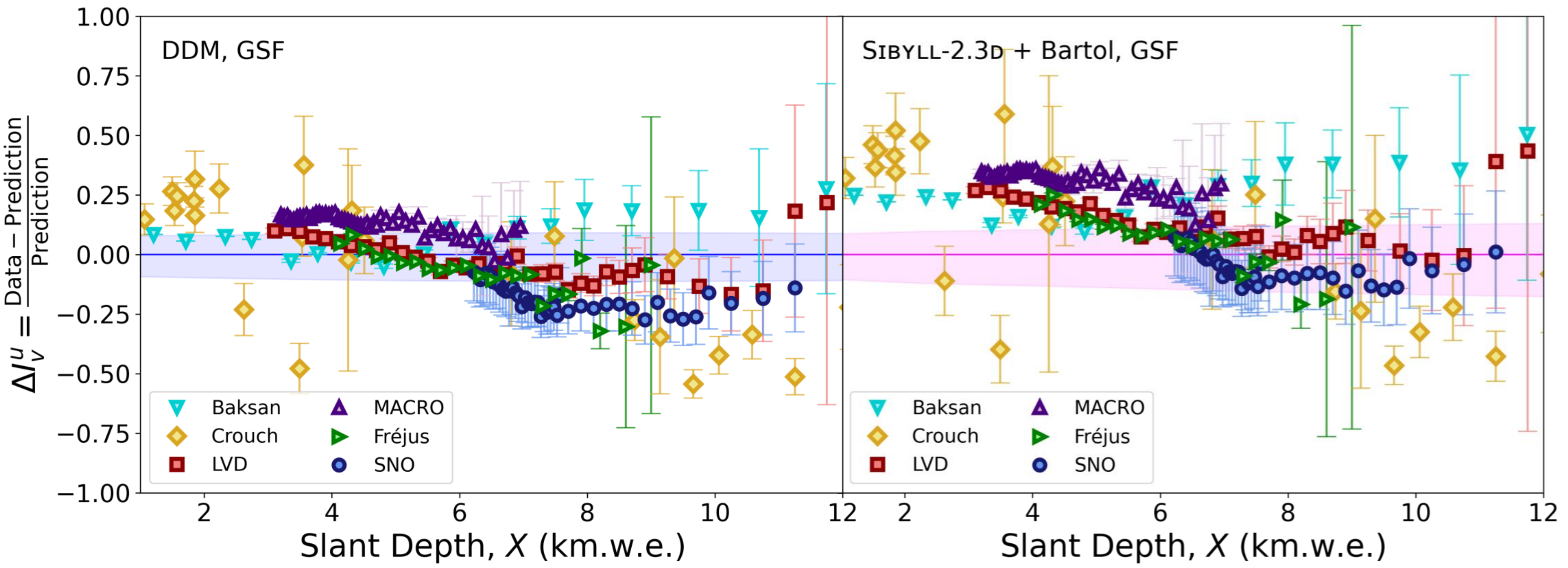
- True vertical underground intensity calculated for $\theta = 0°$ results in better agreement with the data than vertical-equivalent underground intensity.

- Good agreement with the data over the entire depth range.

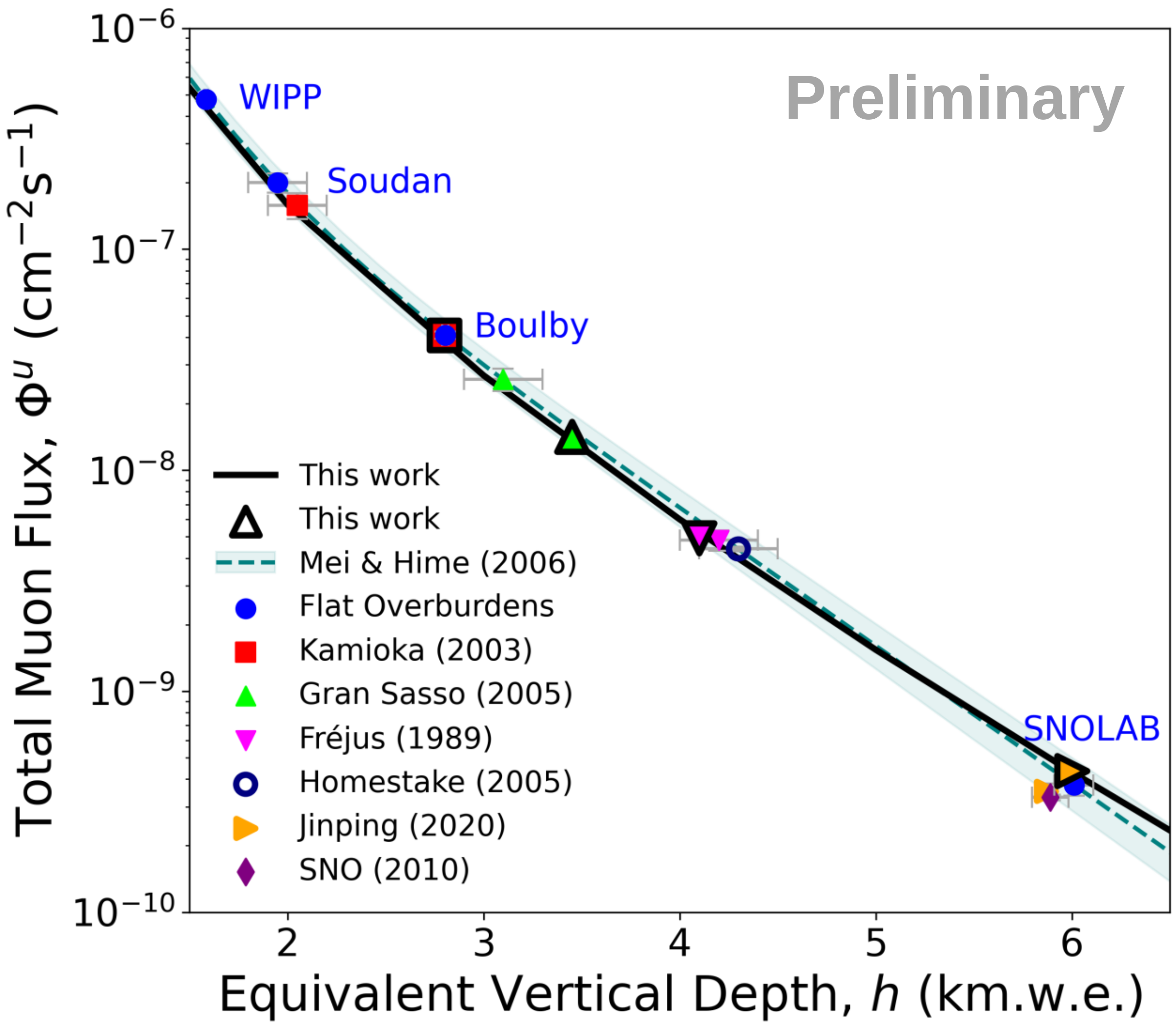


Comparison to Data

- DDM is better at describing shallow slant depths, and SIBYLL is better at deeper slant depths.
- Uncertainties on data are much smaller than those on theory, but systematics not included.
- Using our method, we can constrain hadronic and cosmic ray uncertainties.



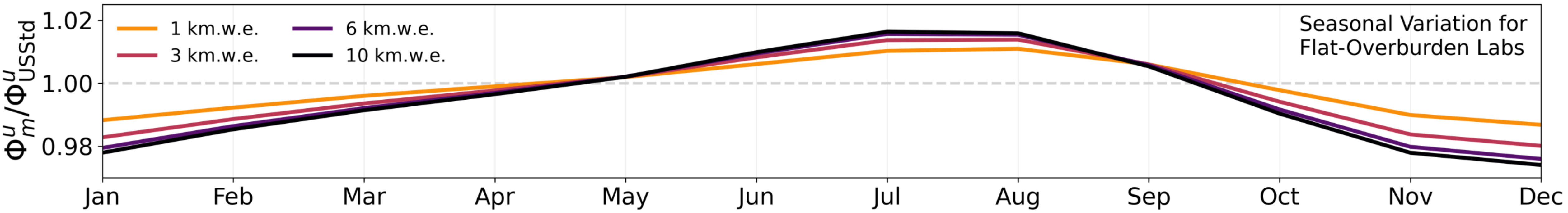
Total Underground Flux



- 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.
- 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.

Conclusion and Outlook

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



Thank you