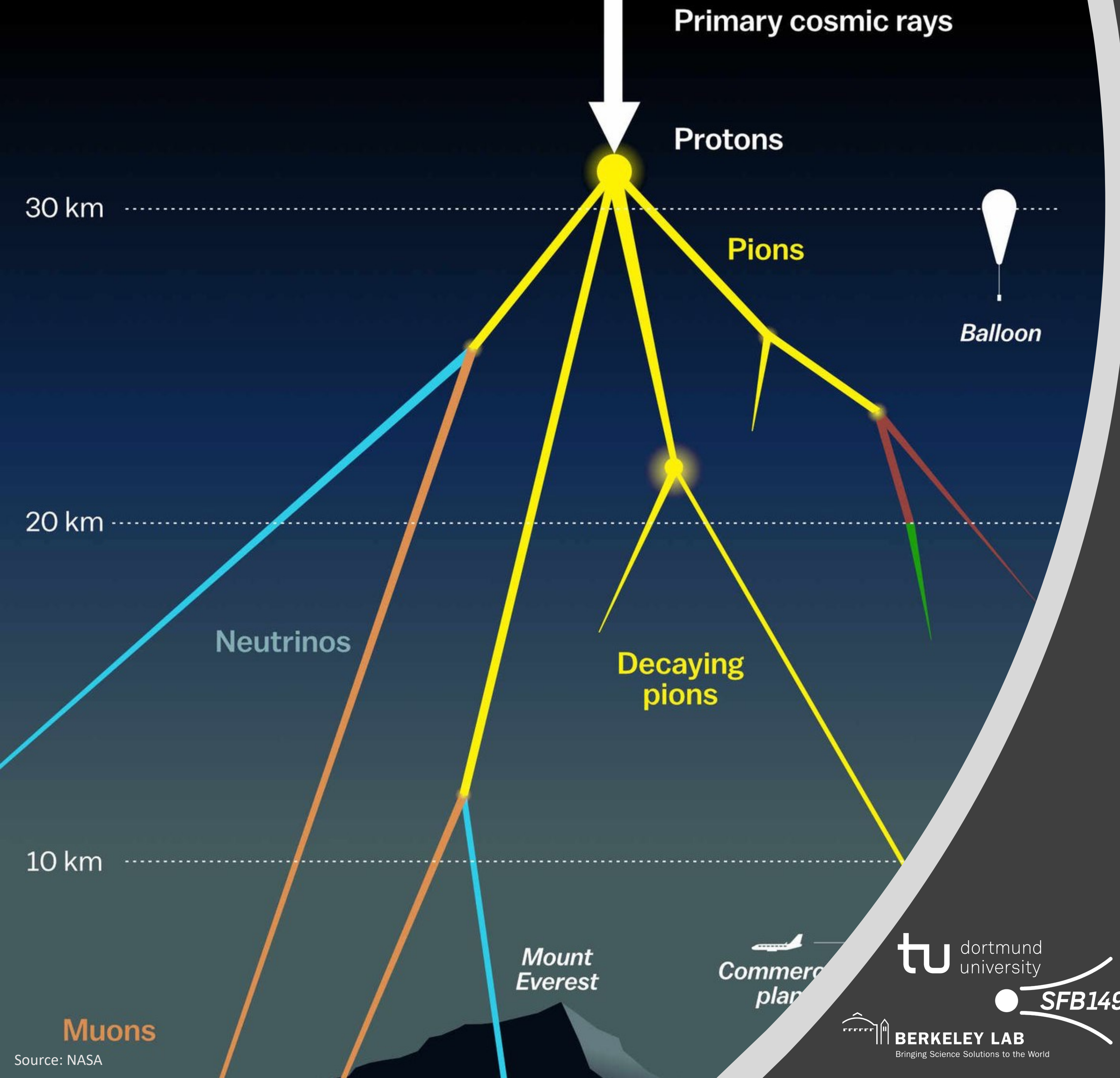


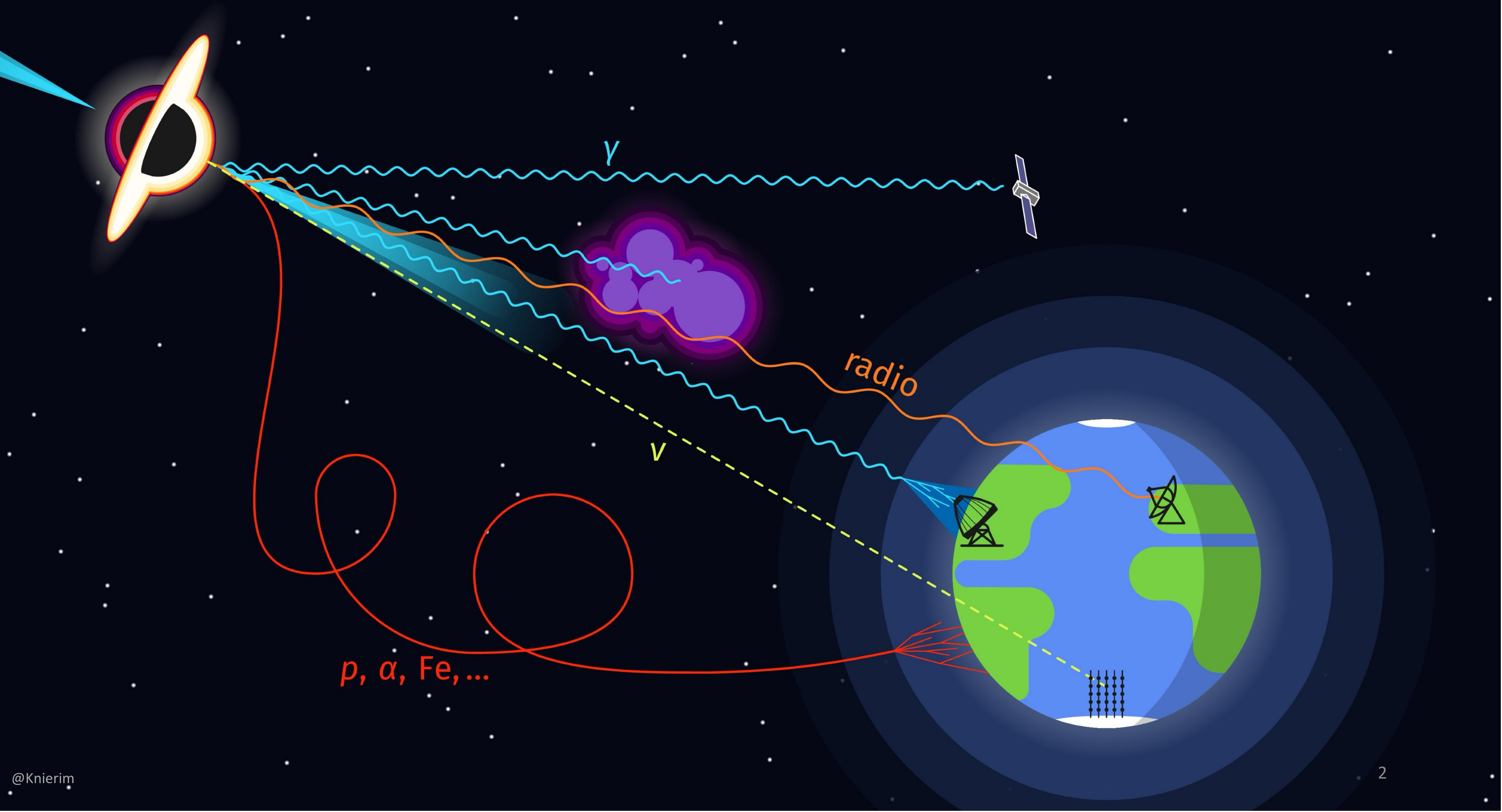
From Atmospheric Muons to Prompt Neutrinos: Unfolding the Muon Flux in IceCube to Constrain Charm Production

Pascal Gutjahr
for the IceCube Collaboration

TeV Particle Astrophysics 2026

Tendo, Japan

September 3, 2026



@Knierim

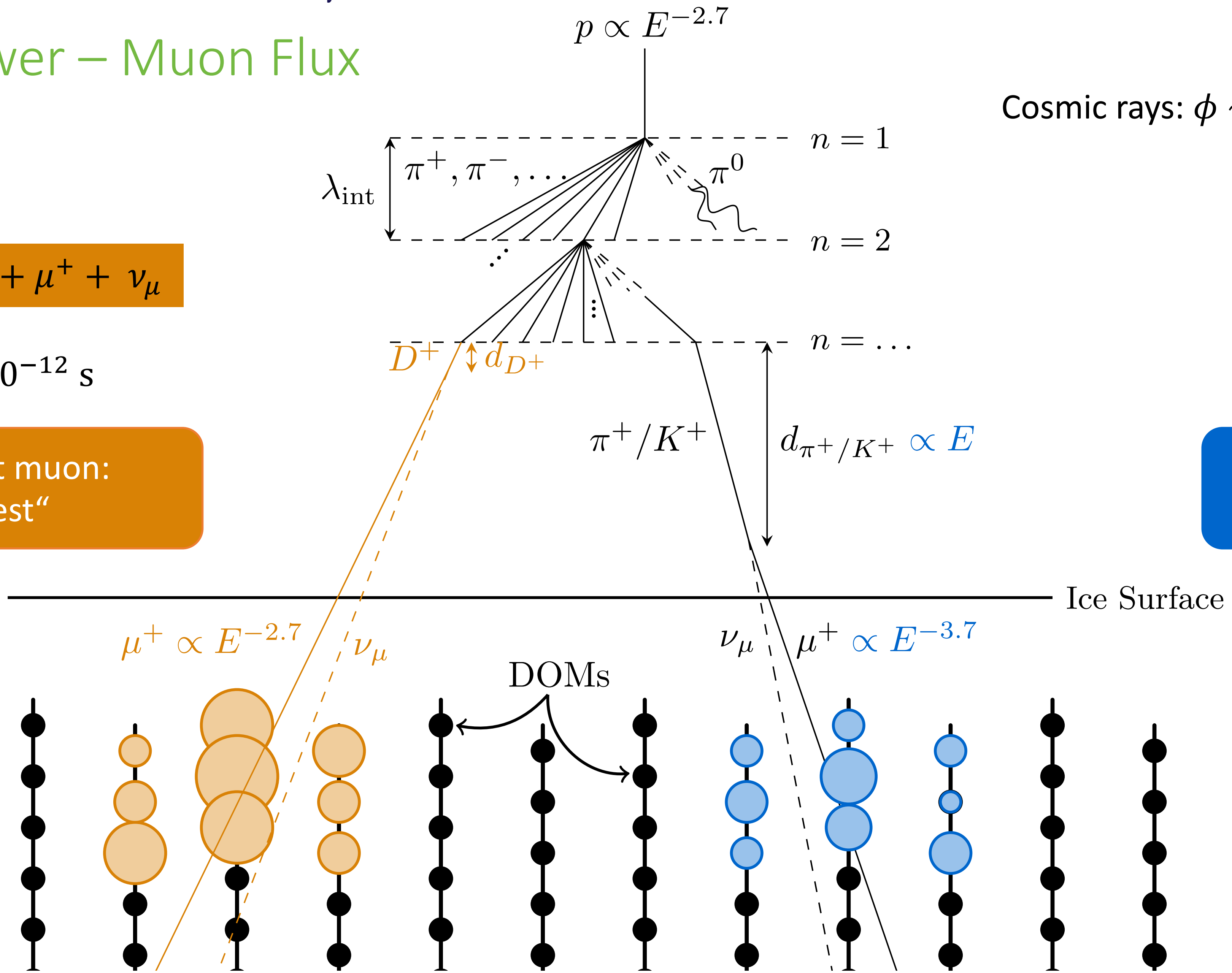
Air Shower – Muon Flux

Cosmic rays: $\phi \sim E^{-\gamma}$

$D^+ \rightarrow \overline{K}^0 + \mu^+ + \nu_\mu$

$\tau \sim 10^{-12}$ s

Prompt muon:
„Rest“



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

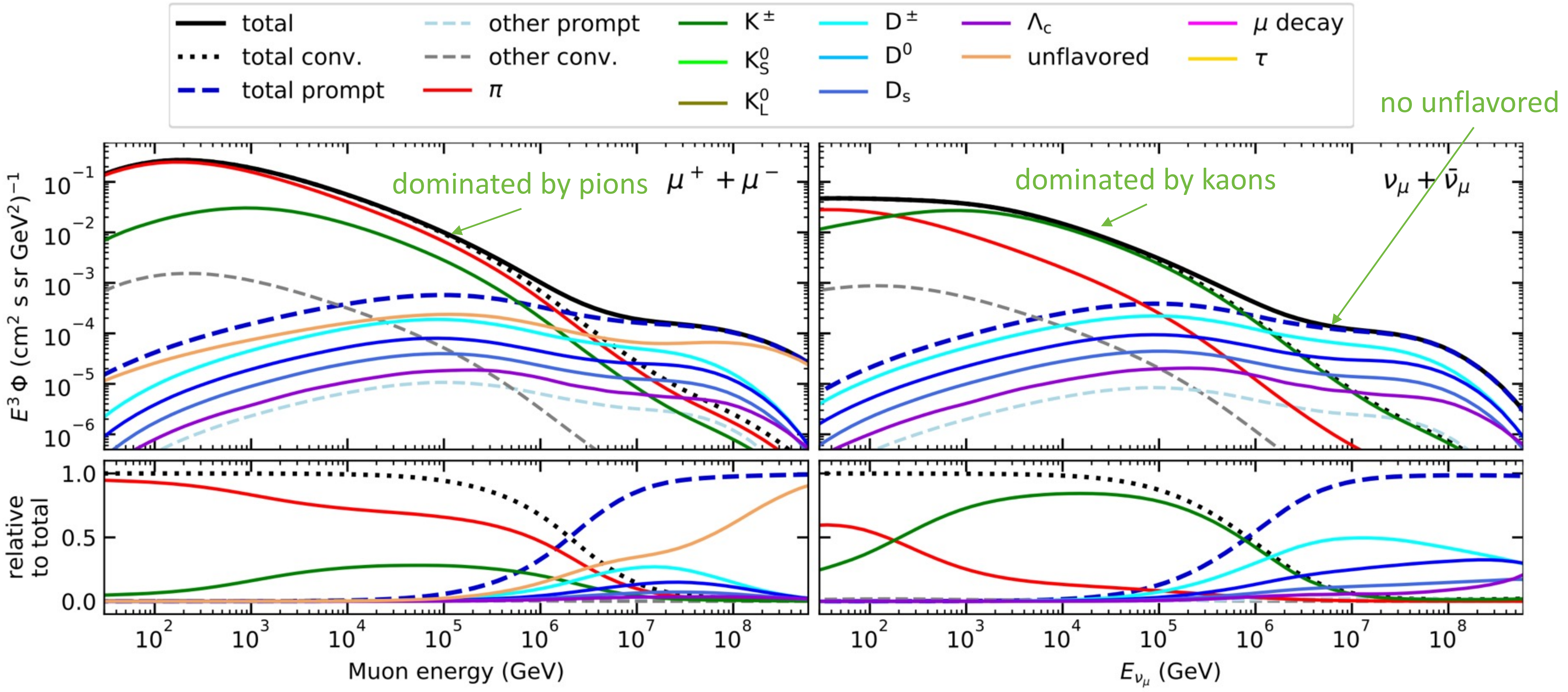
$\tau \sim 10^{-8}$ s

Conventional Muon:
Parent is pion or kaon

pascal.gutjahr@adelaide.edu.au

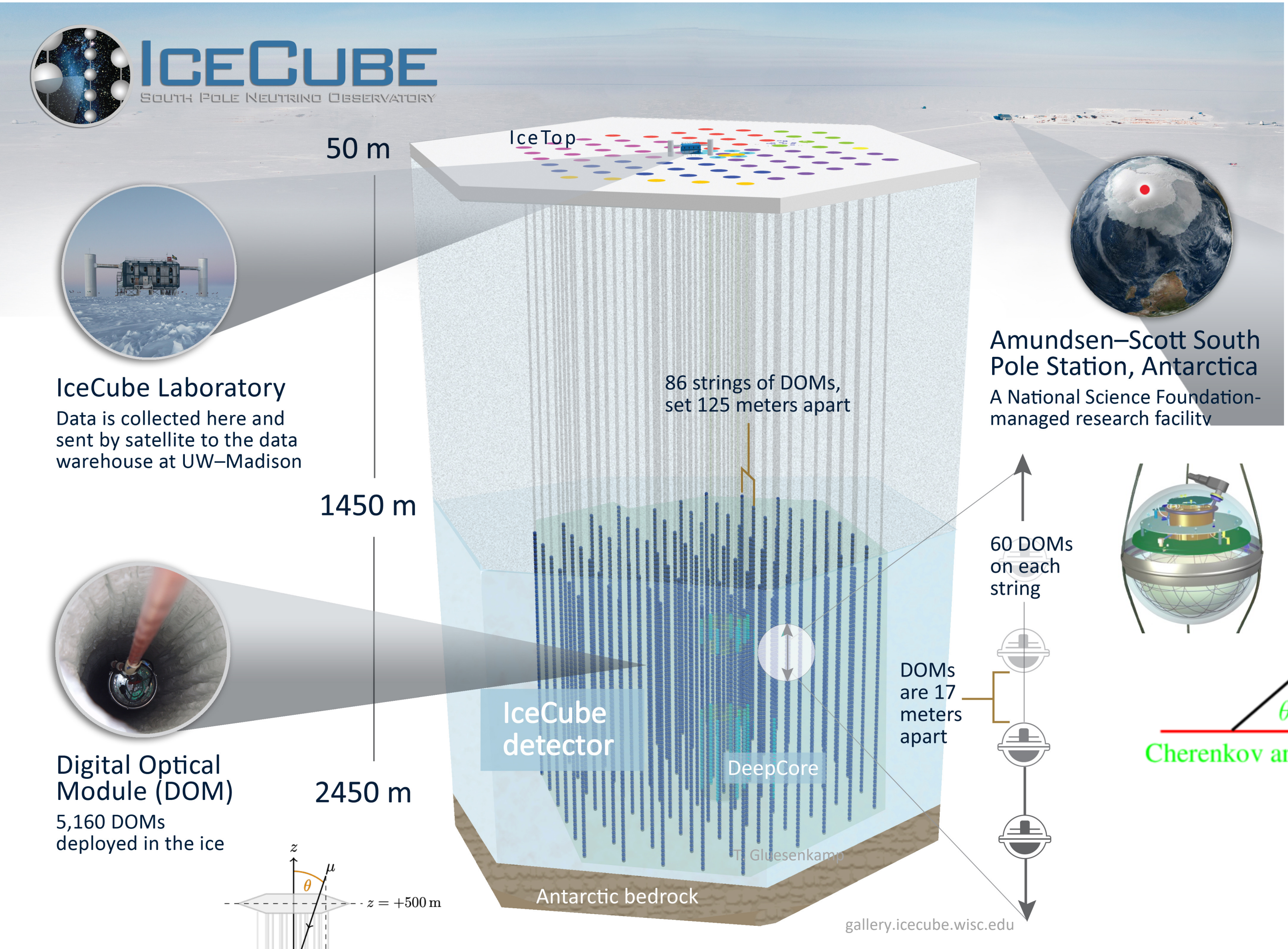
Atmospheric Muon and Muon-Neutrino Flux

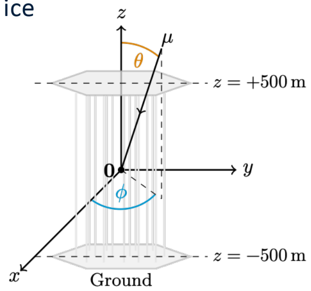
10.1103/PhysRevD.100.103018

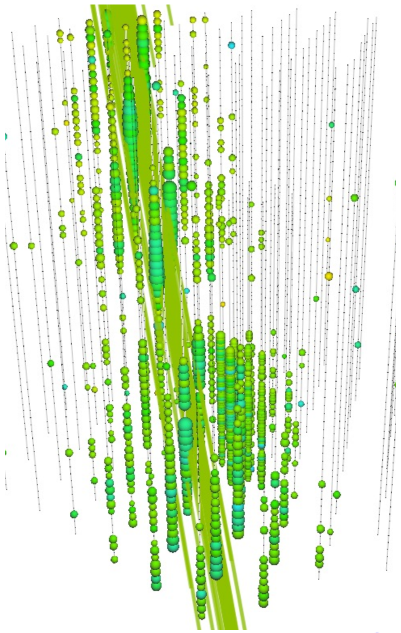


Goal: Measure atmospheric muon flux

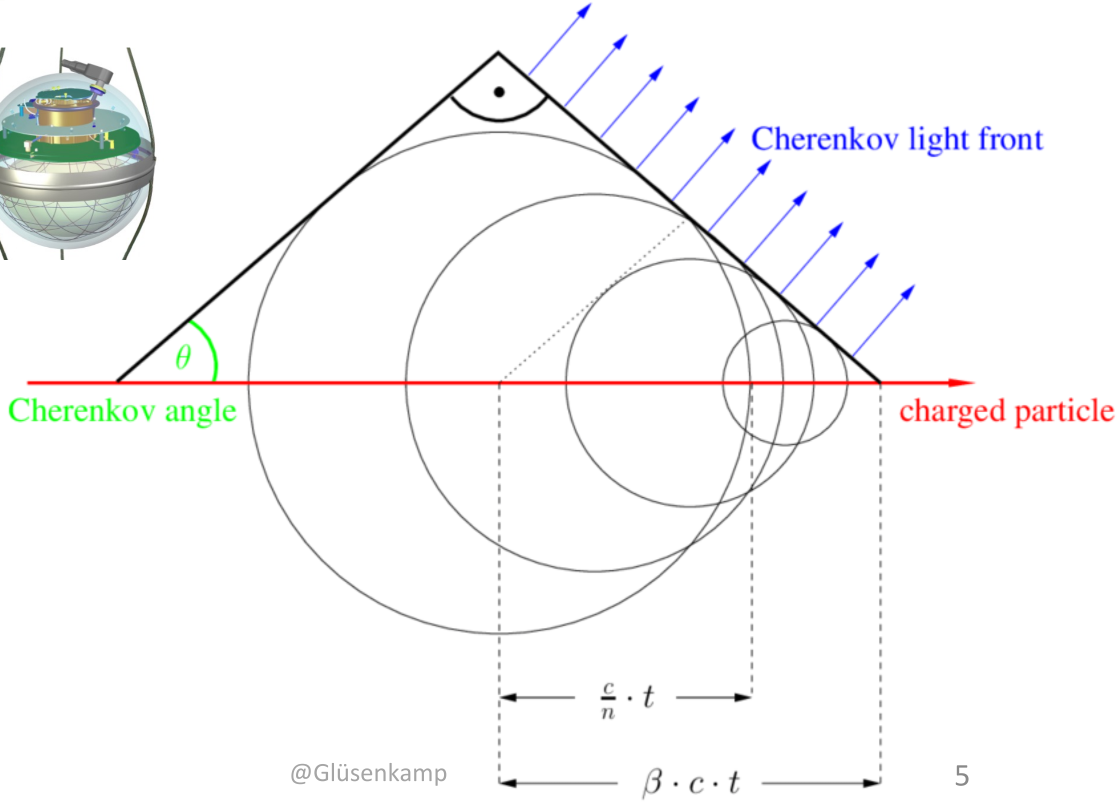
- Detect prompt component
- Handle on pion/kaon ratio
- Handle on charmed mesons → prompt neutrino prediction







- Muon bundle
- Multiple muon tracks
- ➢ Most energetic muon: “leading muon”



Analysis Overview

Simulation → Reconstruction → Selection → Unfolding

Simulation

- CORSIKA air-shower
- Particle and light propagation
- Detector response with optical properties of Antarctic ice

Reconstruction

DNN reconstructions

- Muon energies
- Muon direction
- Track geometry

Selection

High energy atmospheric muons

- Select tracks
- Remove low energy events
- Data-MC quality cuts
- Leading muon has to carry more than 40% of the bundle energy

Unfolding

Muon spectrum

- Unfold muon flux at surface

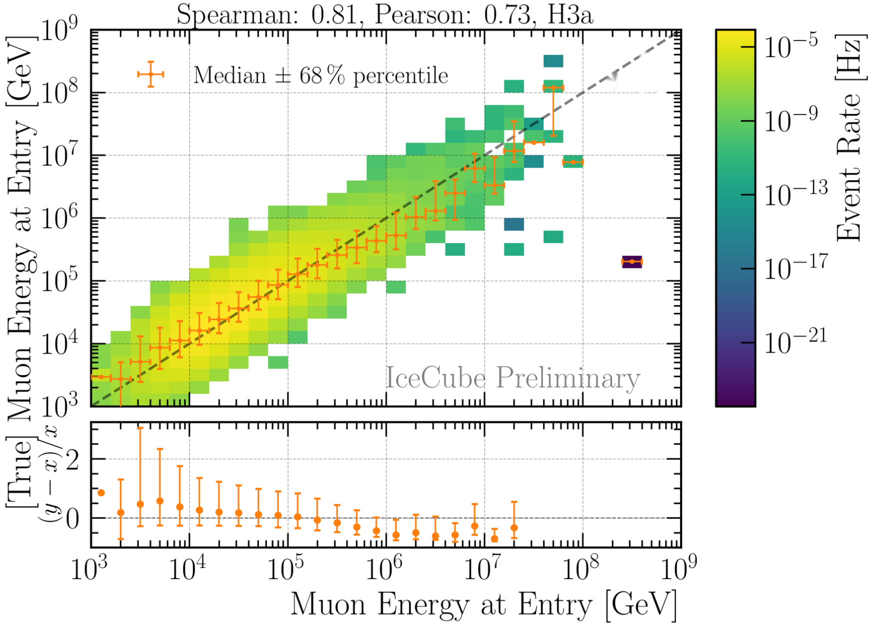
Fit flux components

- Prompt and conventional
- Detect prompt

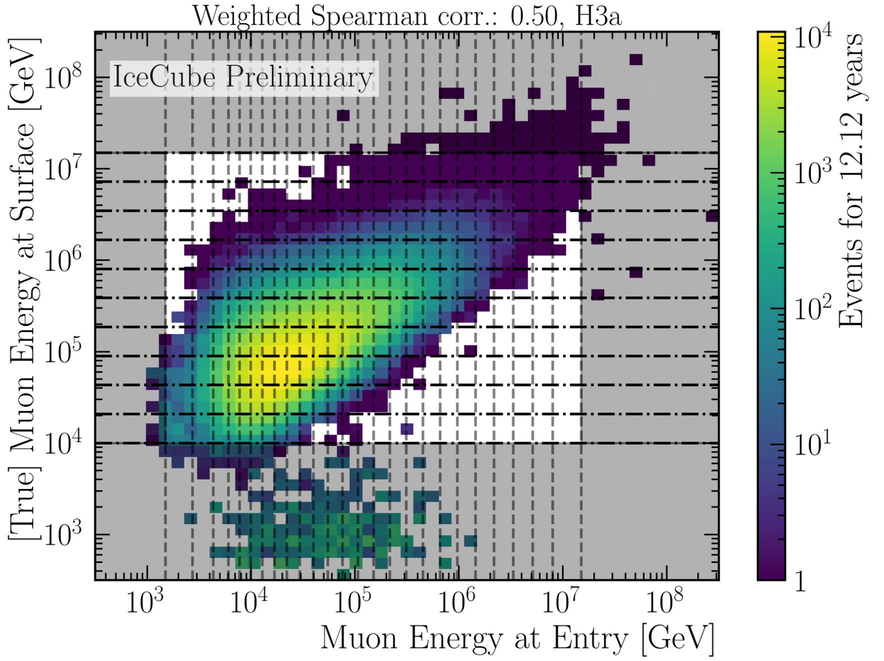
dortmund university BERKELEY LAB Adelaide University ICECUBE NEUTRINO OBSERVATORY

Unfolding Procedure

$$g(y) = \int_{E_0}^{E_1} A(E_\mu, y) f(E_\mu)\, \mathrm{d}E_\mu + b(y)$$



Use reconstructed leading muon energy at entry to unfold individual muon energy at surface



2. Maximum likelihod method:

$$\mathcal{L}(\vec{g}|\vec{f}) = \prod_{j=1}^{M} \frac{\lambda_j^{g_j}}{g_j!} \exp(-\lambda_j)$$

$$= \prod_{j=1}^{M} \frac{(A\vec{f})_j^{g_j}}{g_j!} \exp(-(A\vec{f})_j)$$

3. Thikonov regularization:

$$t(\vec{f}) = -\frac{1}{2} (C\vec{f})^T (\tau 1)^{-1} (C\vec{f})$$

4. Optical ice systematics:

$$\mathbf{A}' = \mathbf{w}_j^\top \cdot \mathbf{A}$$

5. Maximize $\log(\mathcal{L}(\vec{g}|\vec{f})) + t(\vec{f})$ with respect to $\vec{f}$

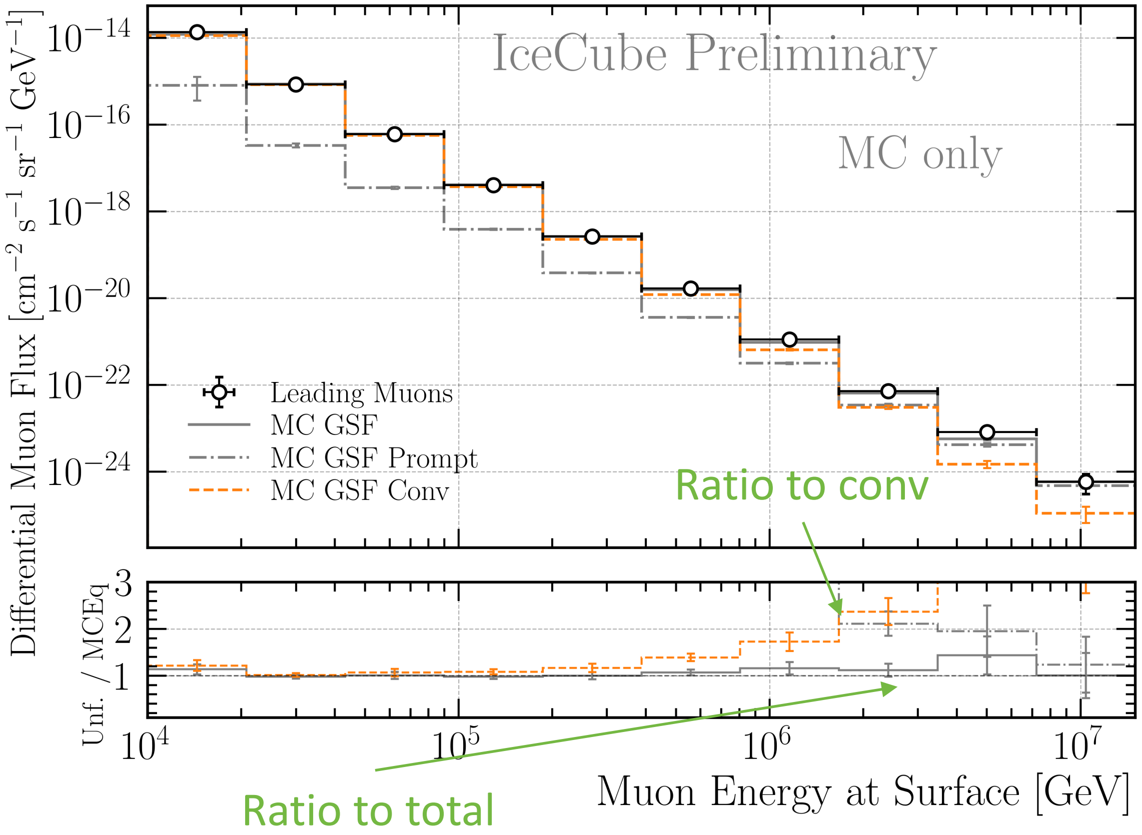
GitHub **funfolding** by M. Börner

6. Perform 4 unfoldings: one per primary model (H3a, H4a, GST, GSF)
→ Average = Final result

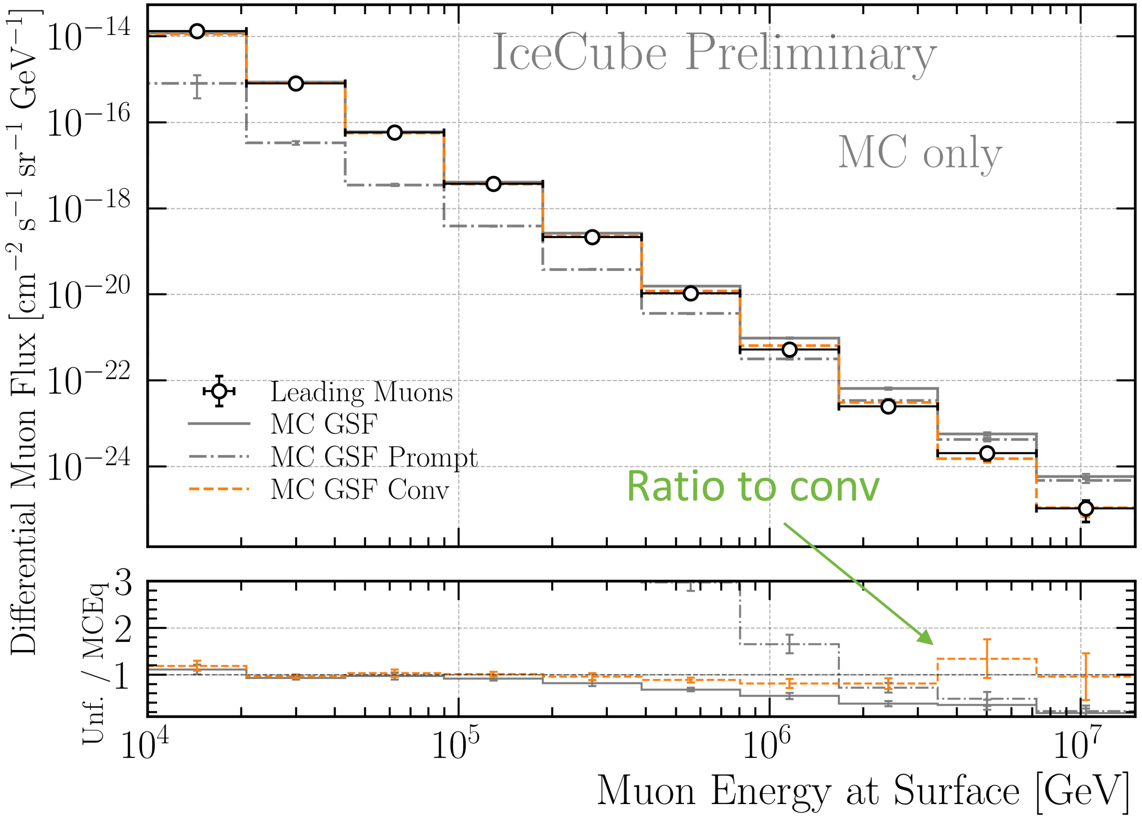
Sensitive to Prompt?

Sensitive to Prompt?

sample has prompt & conv



sample has only conv



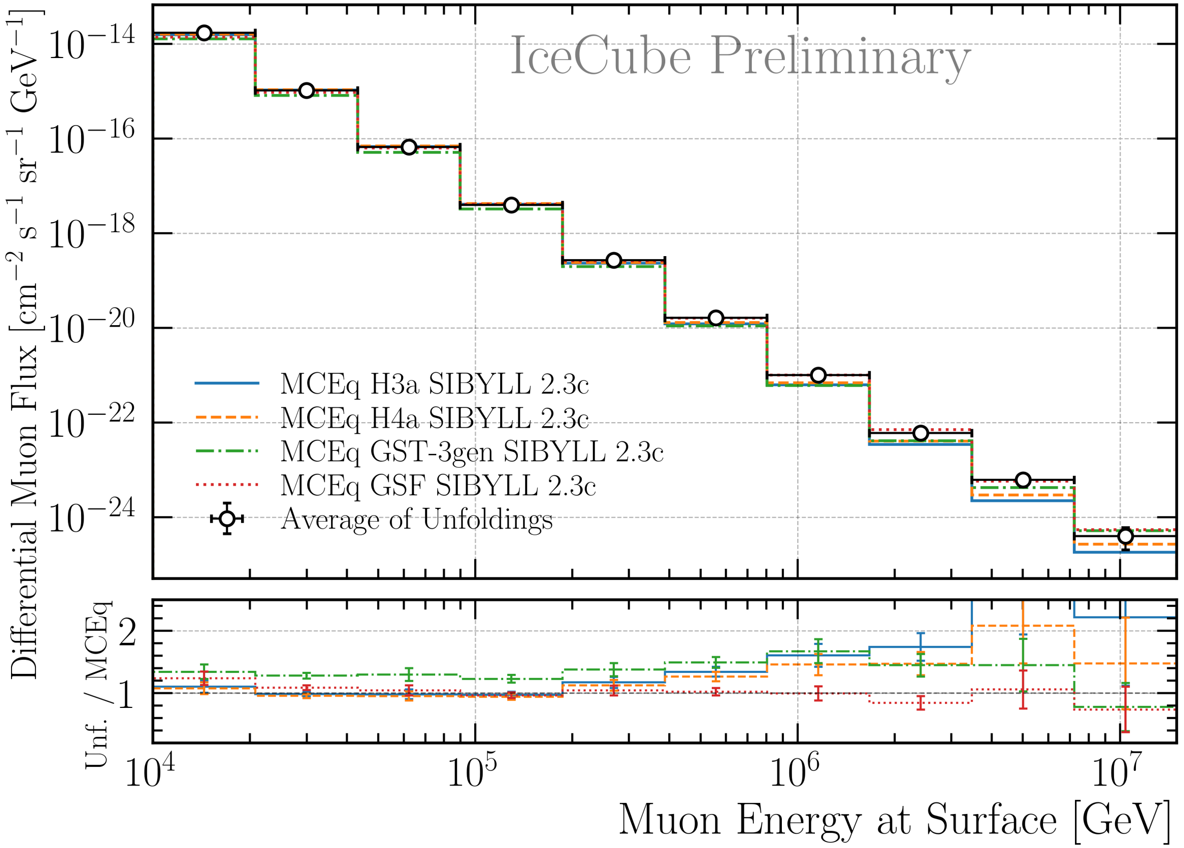
➢ Unfolding is sensitive to the prompt component

Final Unfolding Result

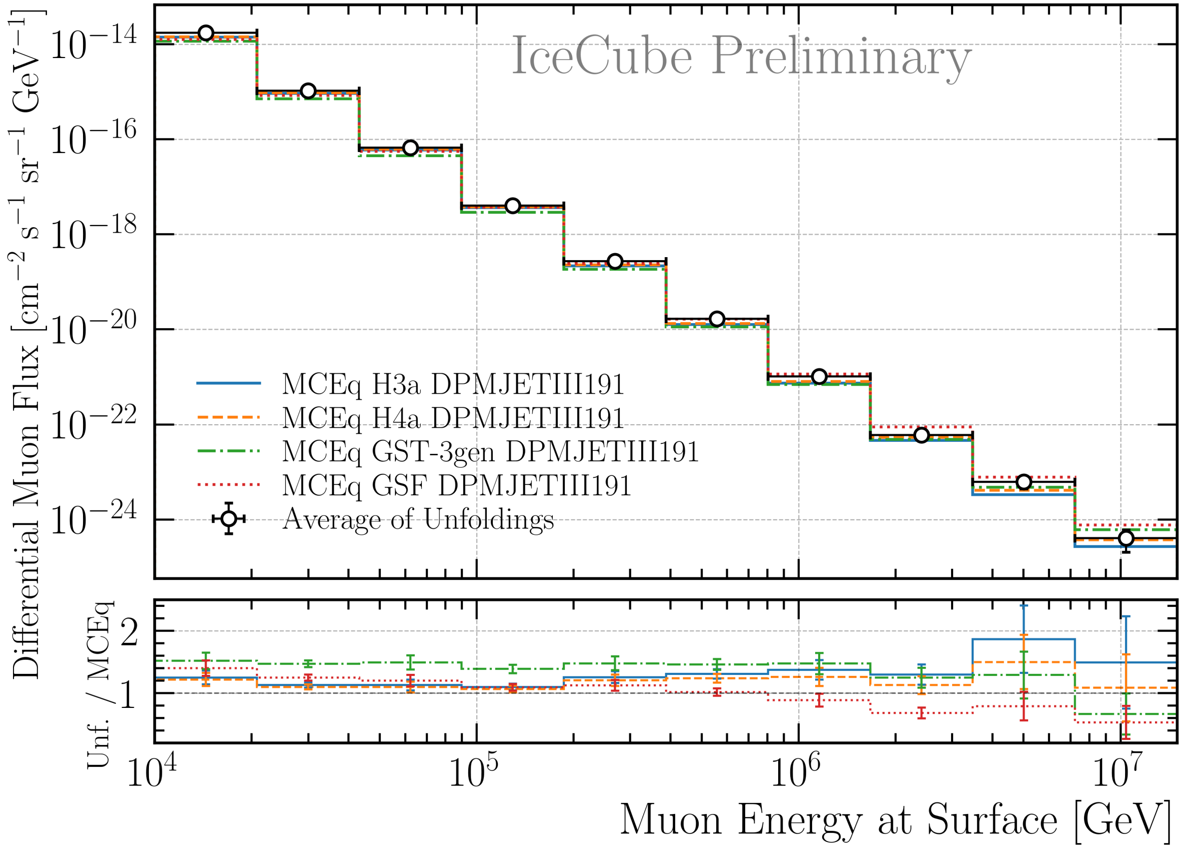
12.12 years of IceCube data

Compare Unfolded Flux with MCEq Predictions

SIBYLL 2.3c



DPMJET III 191



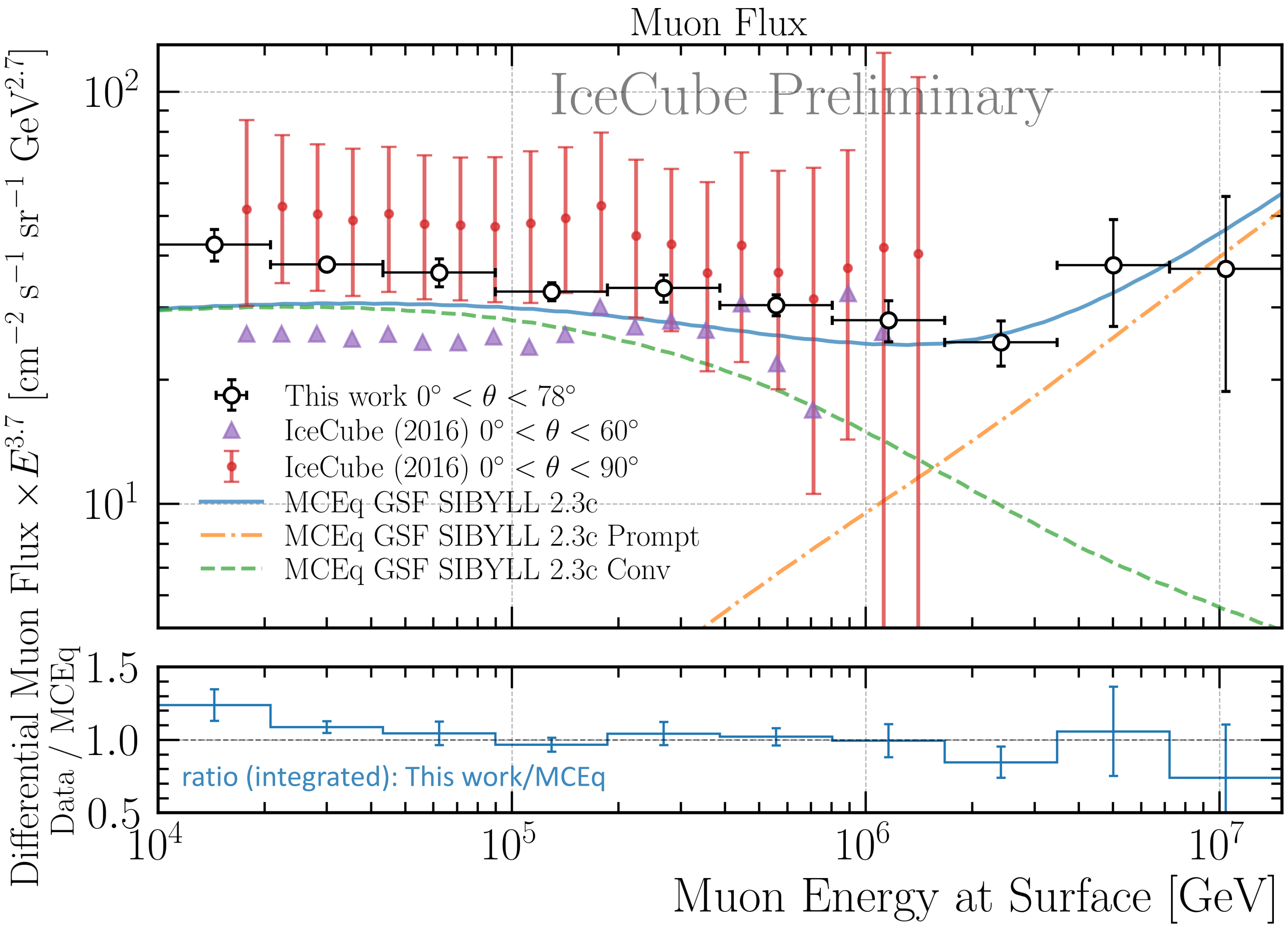
- Best agreement found for GSF with SIBYLL 2.3c

- For DPMJET: shapes fit to unfolded flux, but normalization offset (H3a/H4a/GST)
- GSF shows shape mismatch

Compare to Previous IceCube Result

- This work:
  zenith 0°-78°
- IceCube[1]:
  1. zenith 0°-90° (correlated unc.)
  2. zenith 0°-60° (no unc.)

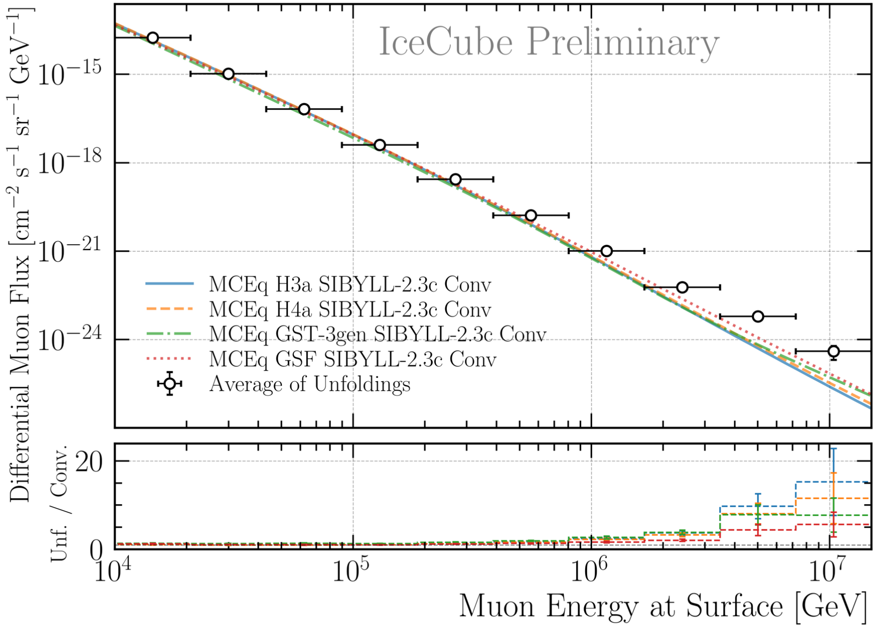
➢ Measurements are compatible
➢ Uncertainties significantly reduced
➢ Extended energy range by 1 order of magnitude

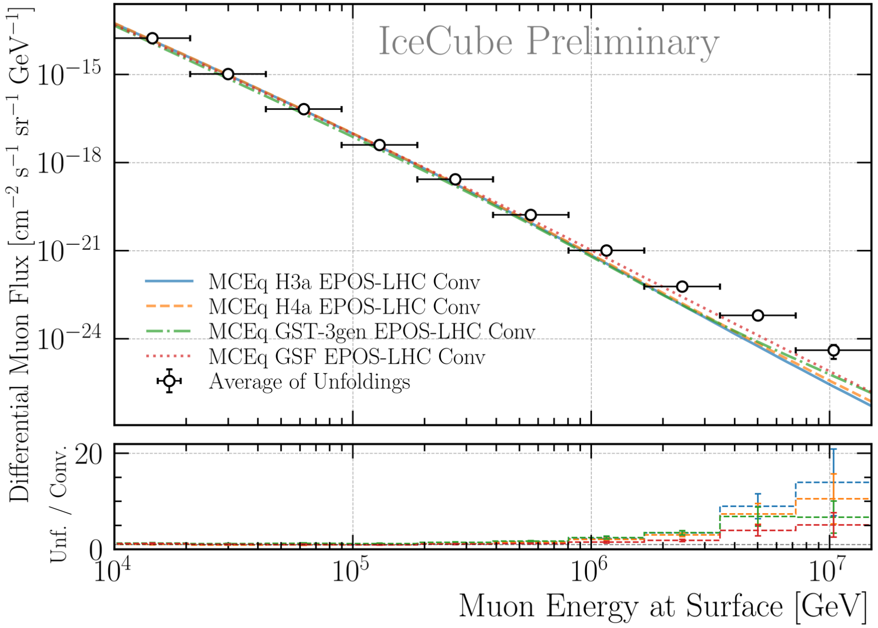


pascal.gutjahr@adelaide.edu.au

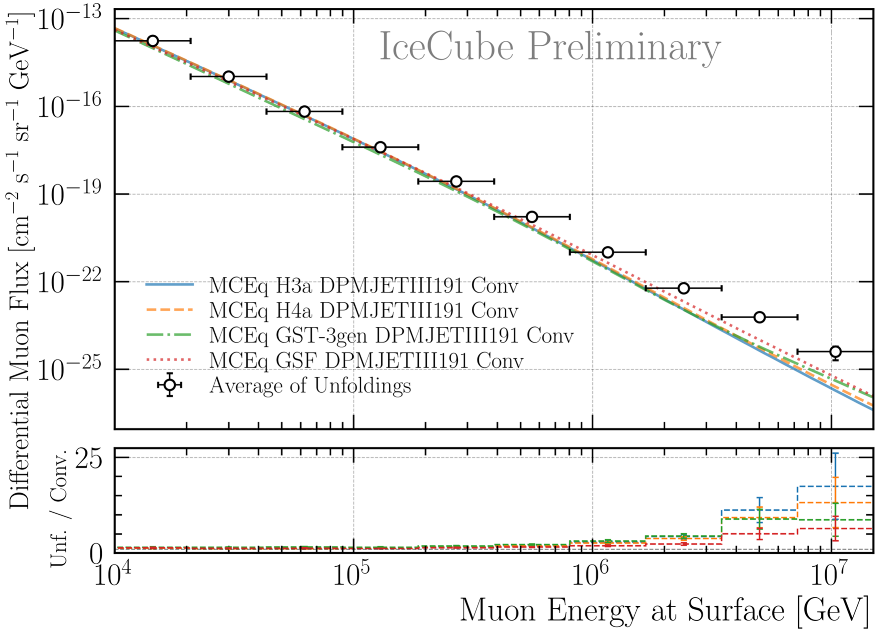
*Unfolded flux is scaled by the logarithmic bin center, which is an approximation

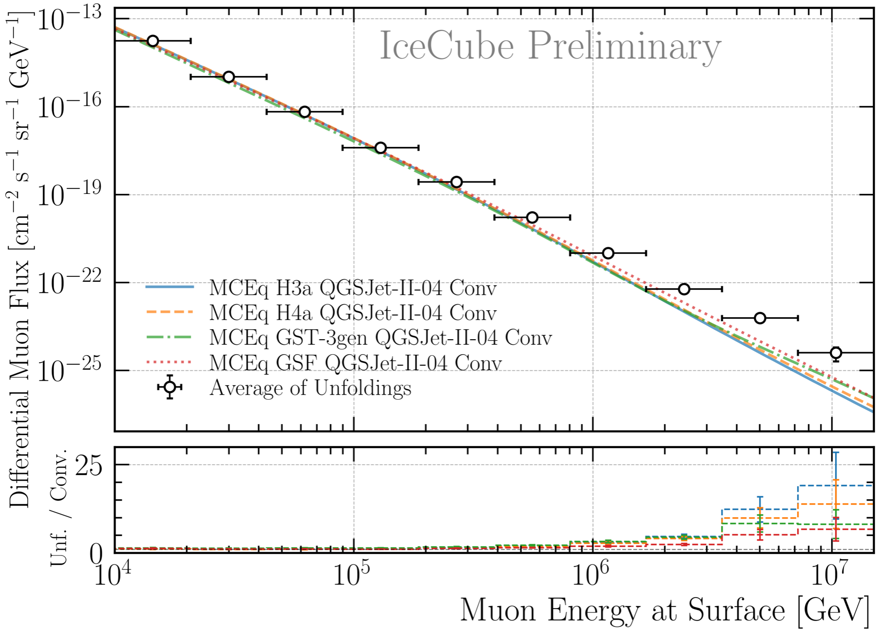
[1]Astropart.Phys. 78 (2016) 1-27





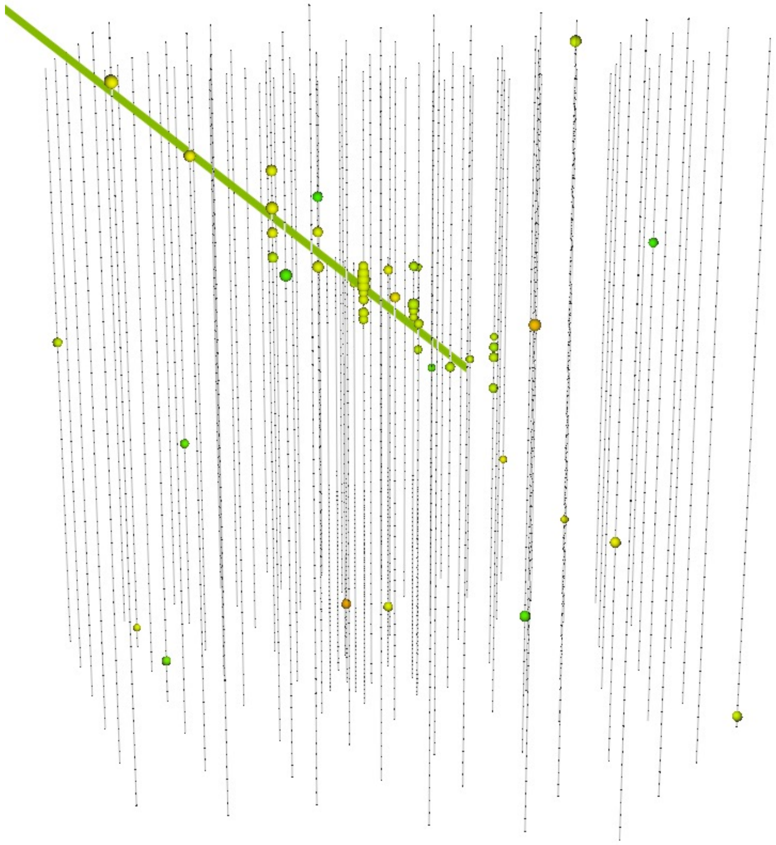
Compare Unfolded Flux vs Conventional Only Prediction

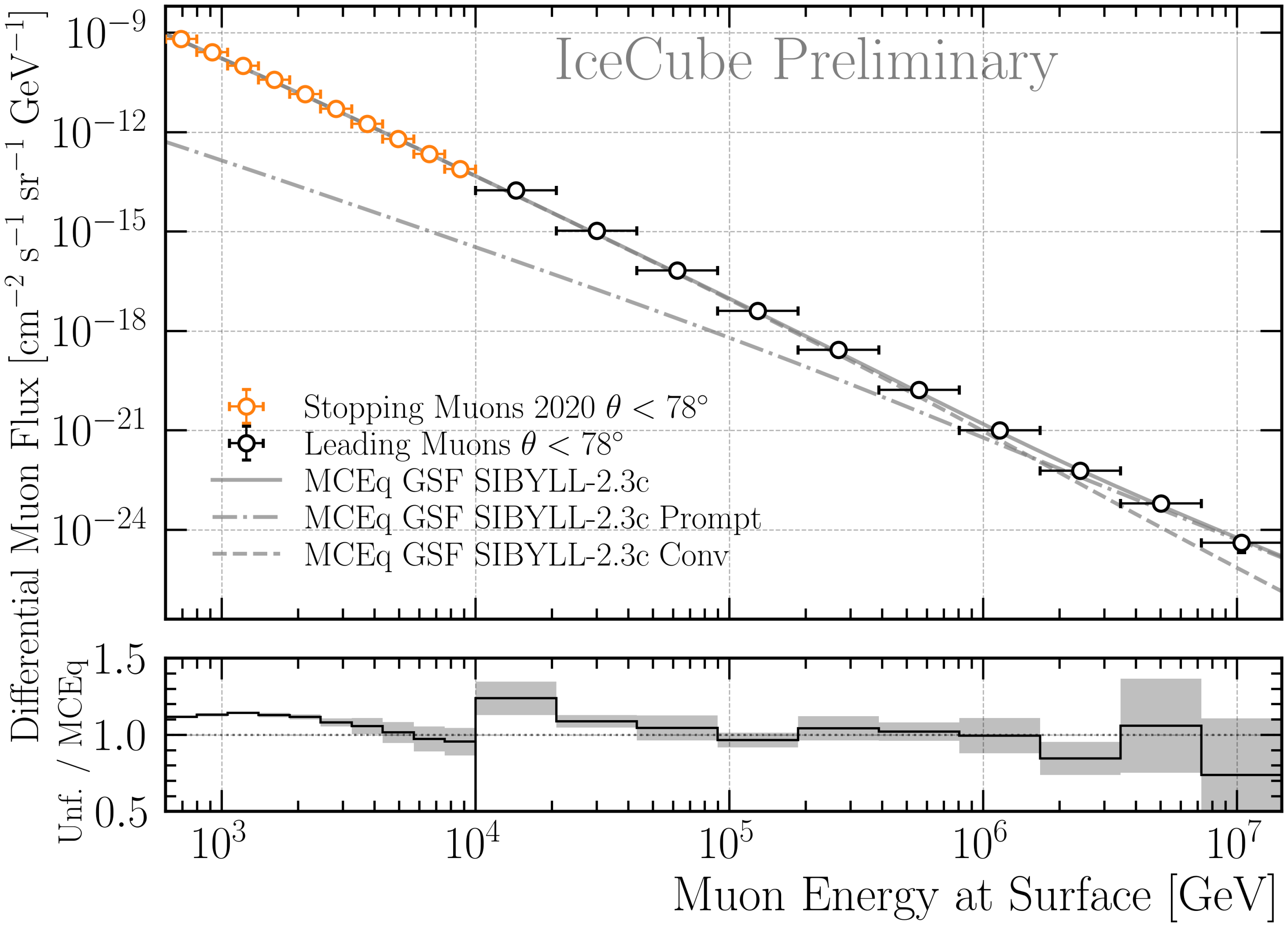




- Colored lines should deviate from 1 above 1 PeV in the ratio panel
  - ➢ Indicates prompt existence

Include Stopping Muons





Stopping muons
- Decay in the detector volume
- Sensitive to low-energy range from 600 GeV to 10 TeV (conventional component)

➢ Unfolded year 2020 of IceCube data → tension around 10 TeV

Fit Muon Flux Components

- Muon flux per bin *i*:

$$\mu_i(N_{\text{prompt}}, N_{\text{conv}}) = N_{\text{conv}} \cdot \Phi_{\text{conv},i}^{\text{baseline}} + N_{\text{prompt}} \cdot \Phi_{\text{prompt},i}^{\text{baseline}}$$

- Minimize Chi2 over all bins:

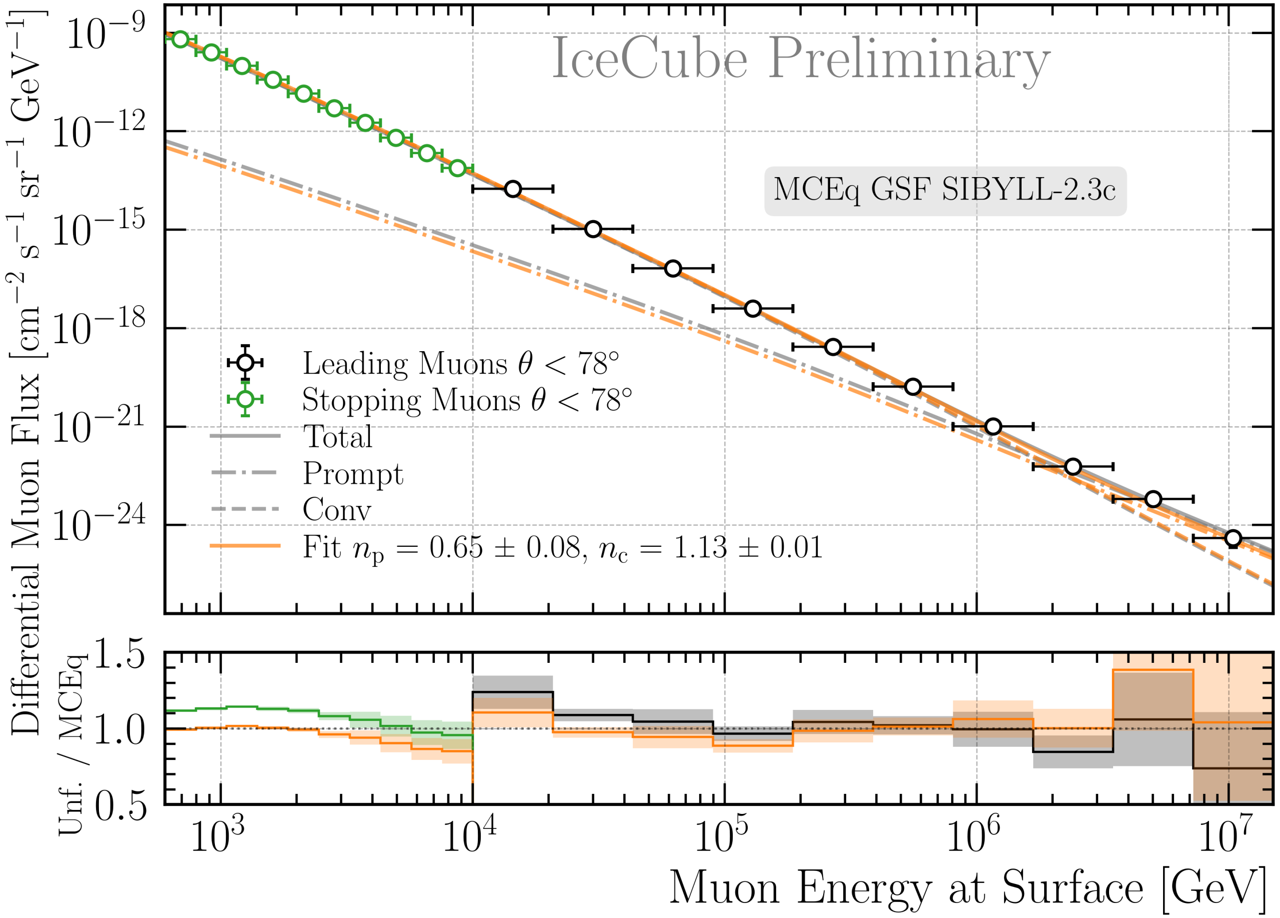
$$\chi^2(N_{\text{prompt}}, N_{\text{conv}}) = \sum_i \frac{(y_i - \mu_i)^2}{\sigma_i^2}$$

- Fit normalization for prompt and conventional for a given model prediction
  - Here: MCEq with SIBYLL 2.3c weighted to GSF

- Several model predictions can be tested

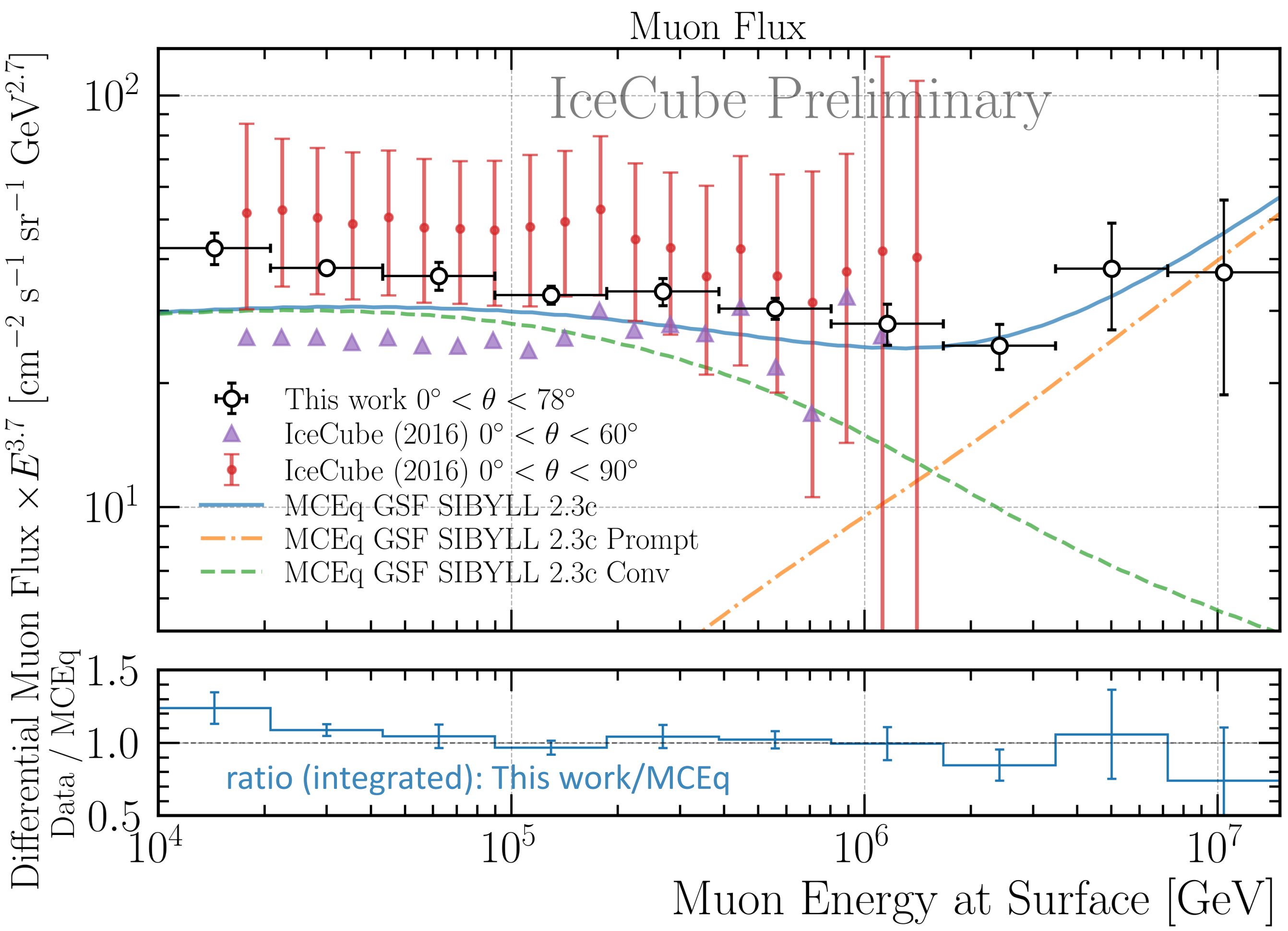
➢ Measure prompt muon flux
➢ Fine-tune hadronic interaction models

stopping and leading muons



Conclusion & Outlook

- DNN-based leading and stopping muon selection
- 12 years of IceCube data unfolding
- Best agreement with GSF and SIBYLL 2.3c



Outlook

- Extract charm production and make neutrino flux prediction
- Fine-tune hadronic interaction and cosmic ray models
- Stay tuned for *prompt* discovery

pascal.gutjahr@adelaide.edu.au

Thank you for your attention!

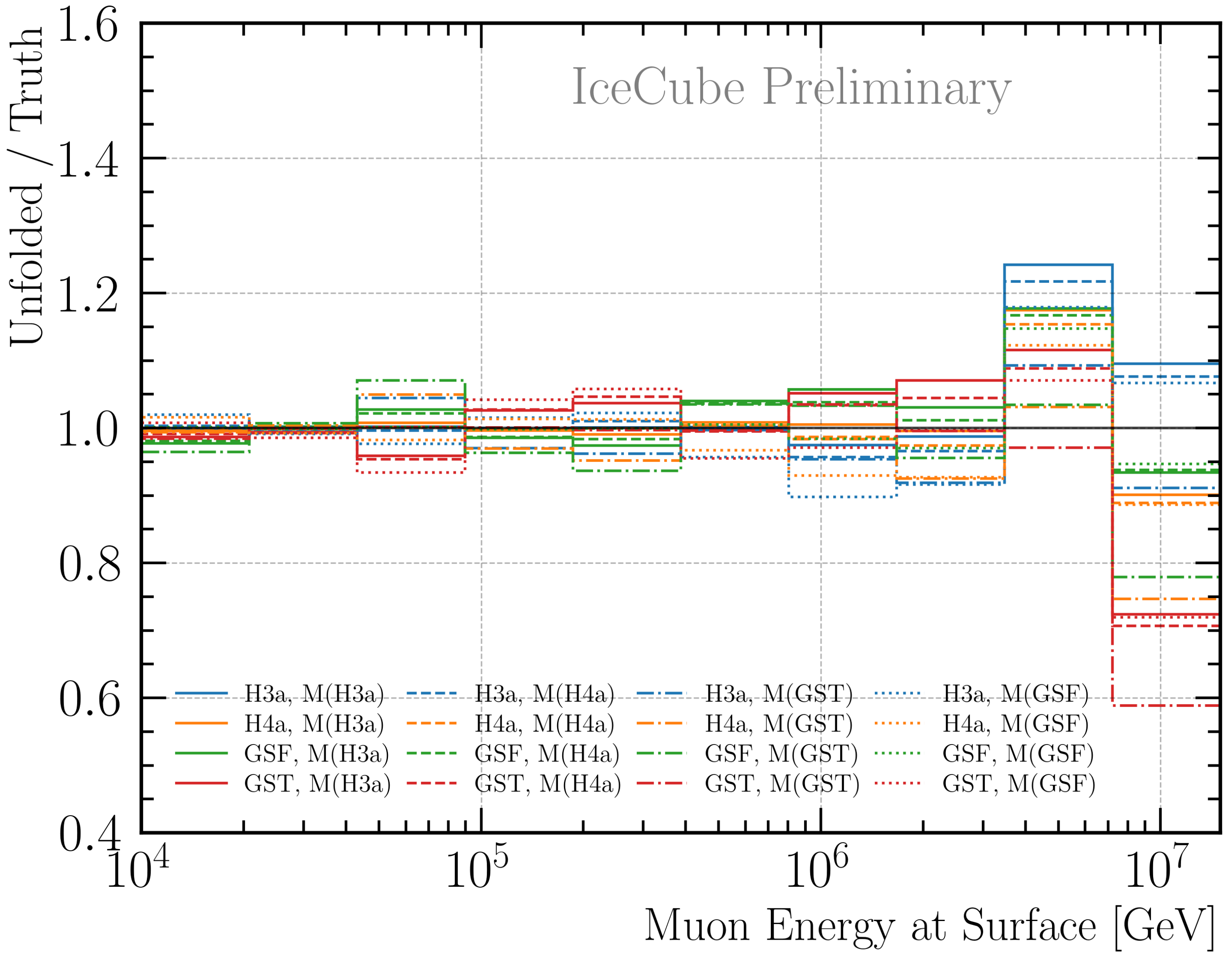
Backup

Injection Recovery Test

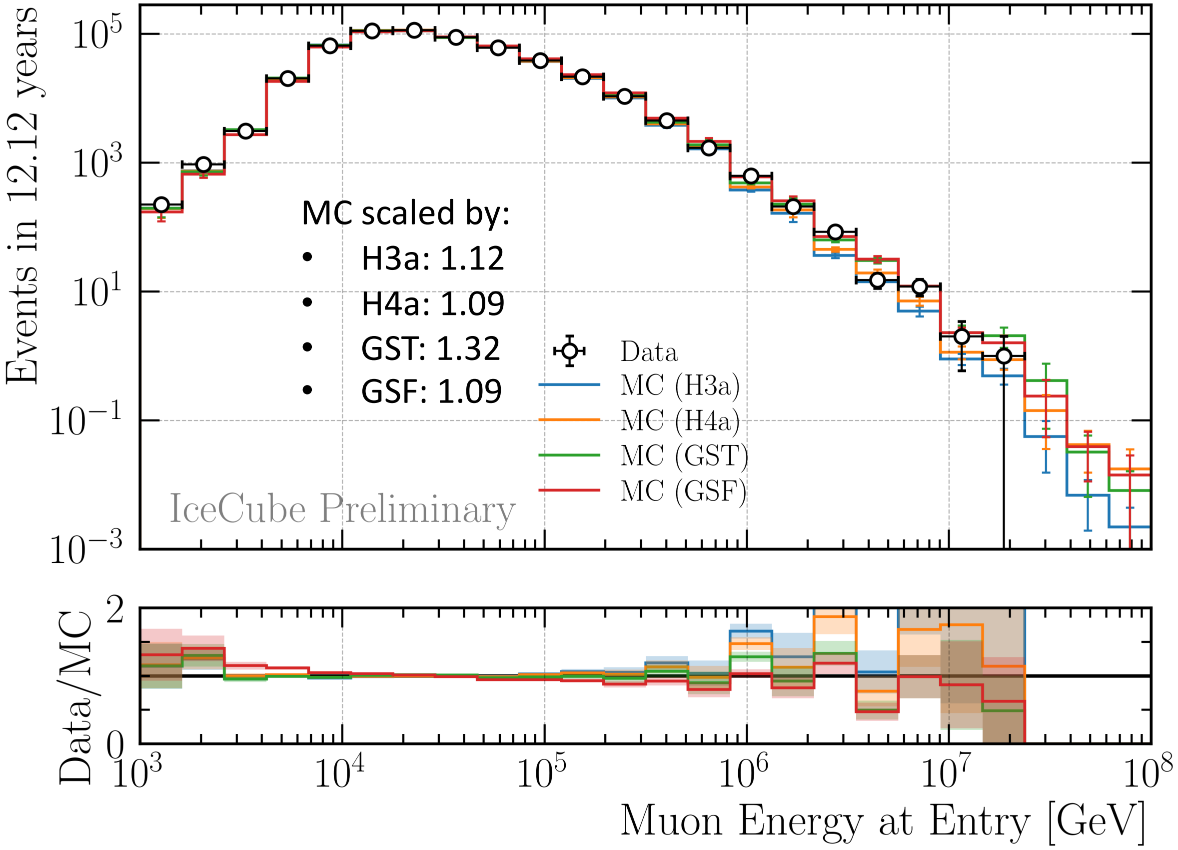
- Train unfolding on H3a, H4a, GSF, GST
- Unfold 4 MC weighted datasets for the 4 primary models
- Divide each unfolding by its true MC distribution
- 16 unfoldings in total

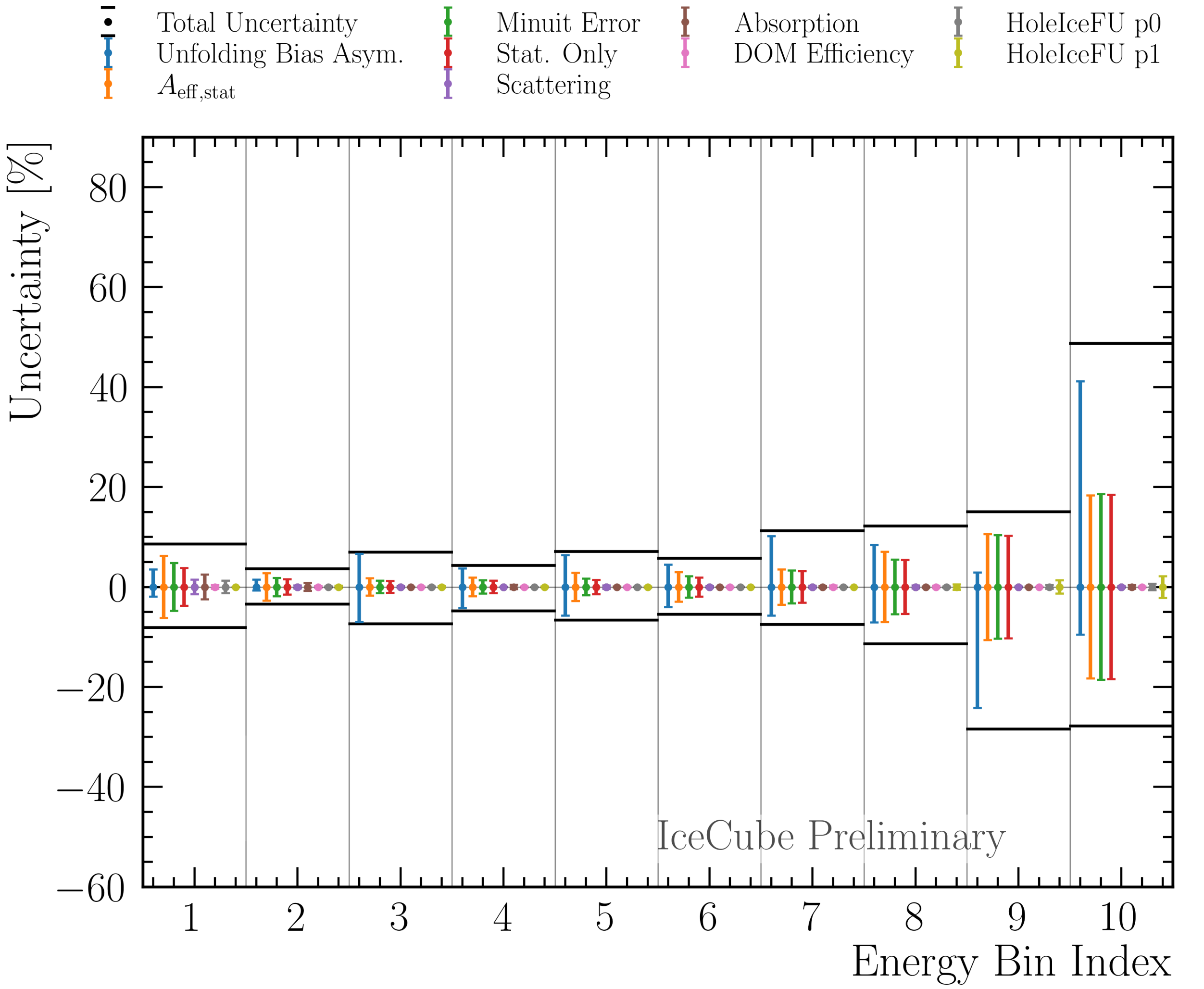
➢ Ratio of 1 expected
➢ Offset to 1 → bias

➢ Maximum distance to true distribution
➢ Add these biases as an uncertainty to the unfolding result



Data—MC and Uncertainties per bin

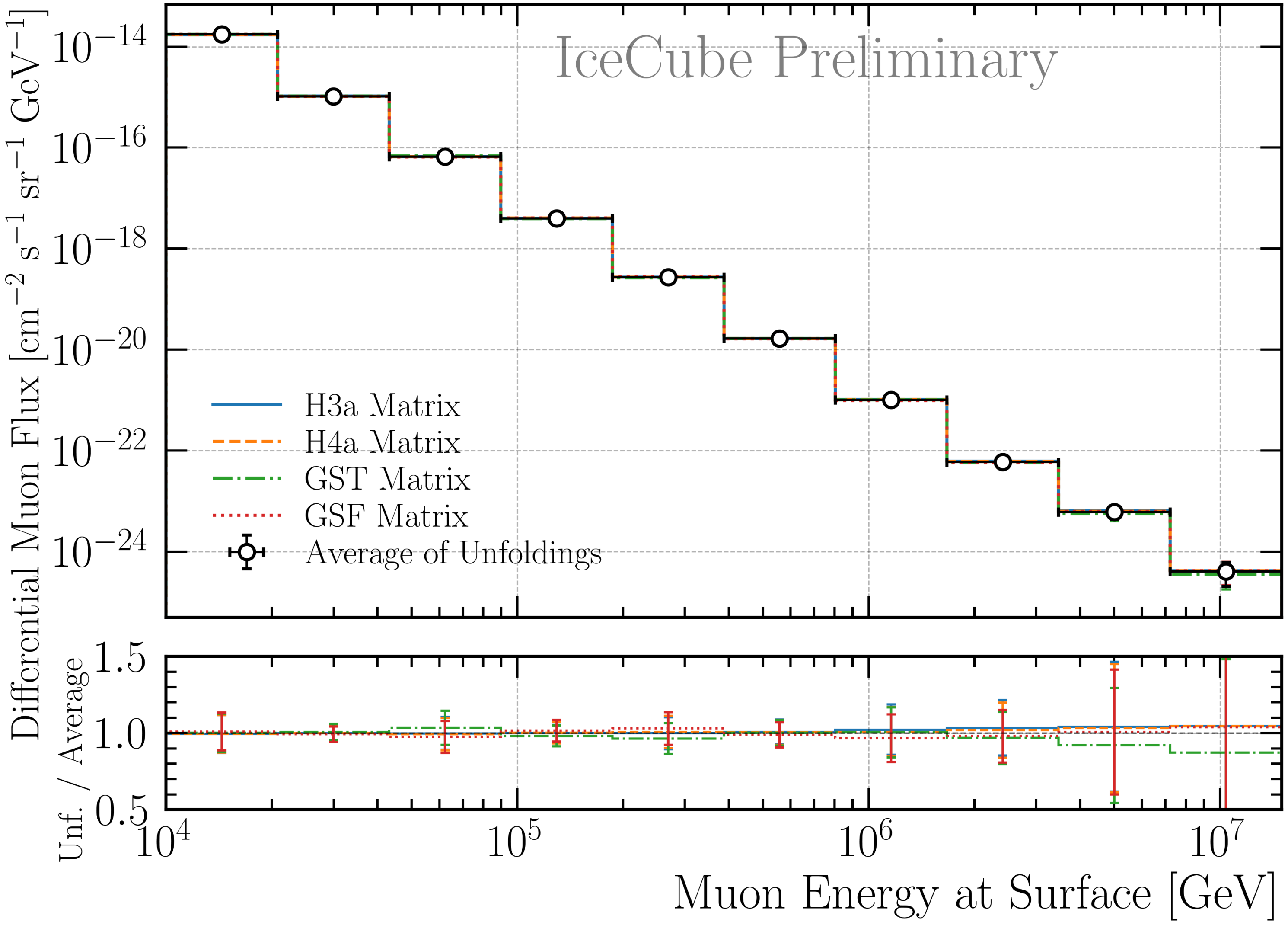




- (left) data—MC agreement for the unfolding proxy variable, (right) uncertainty per bin for the unfolding performed using GSF

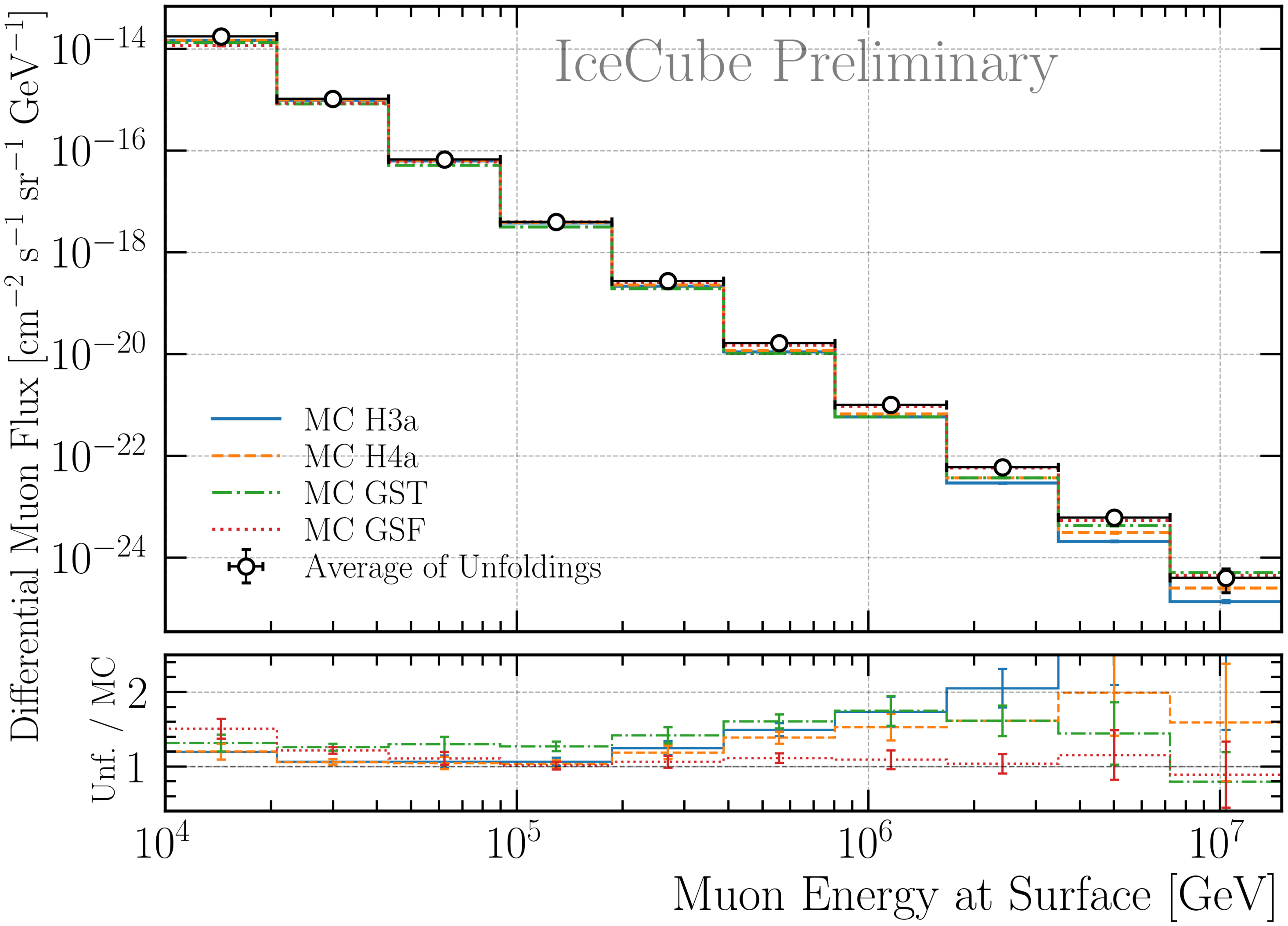
Check spread of the 4 individual unfoldings

- All 4 individual unfoldings agree within uncertainties

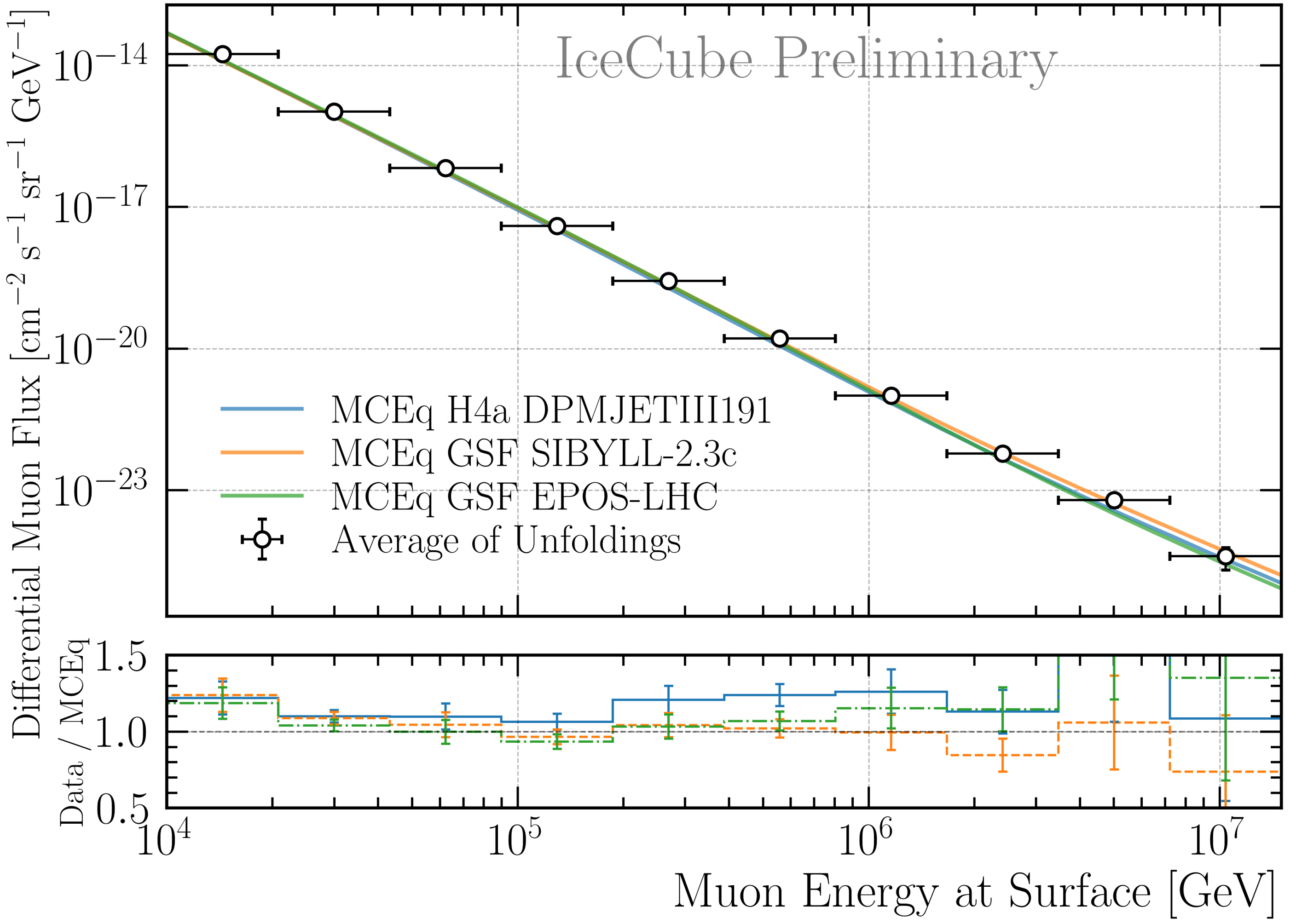


Compare Unfolded Flux with CORSIKA Predictions

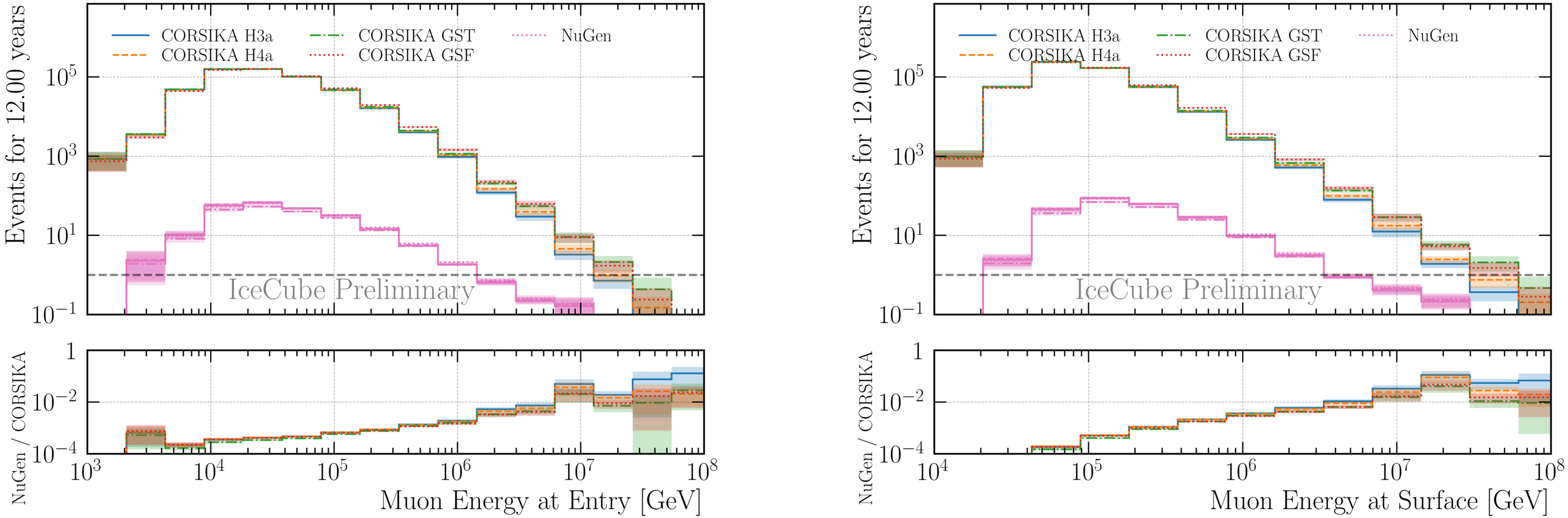
- Best agreement found for GSF
- SIBYLL 2.3d is used for these CORSIKA simulations



3 Models with the Best (Chi2) Agreement to Unfolded Flux

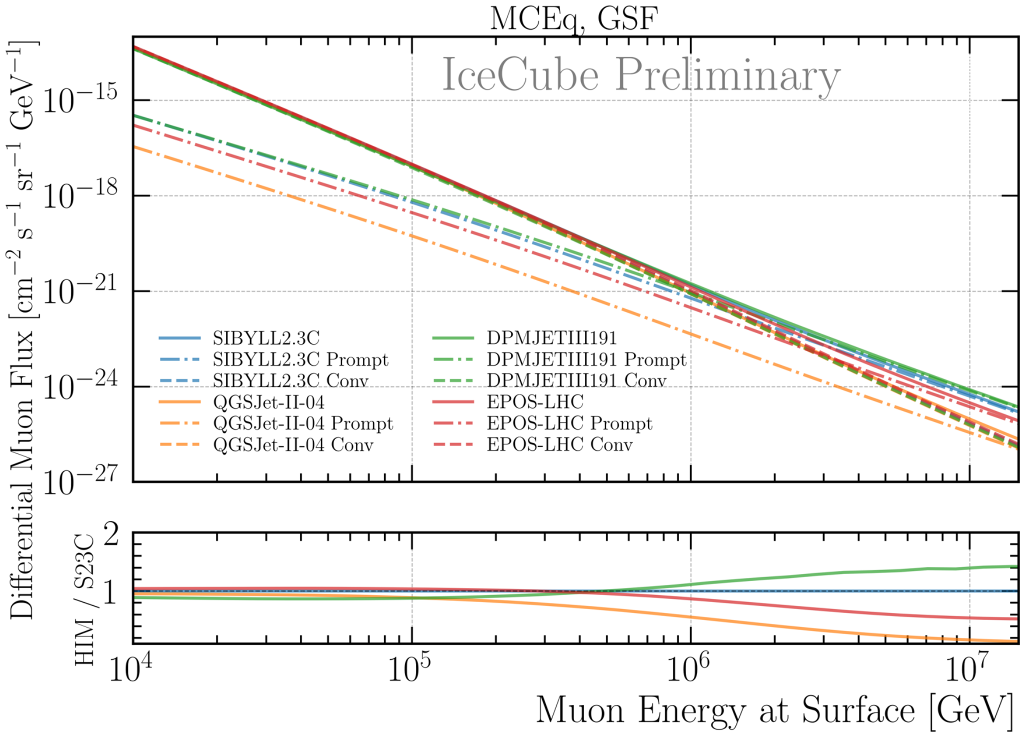


Neutrino Background: IceCube BPL ICRC 2025

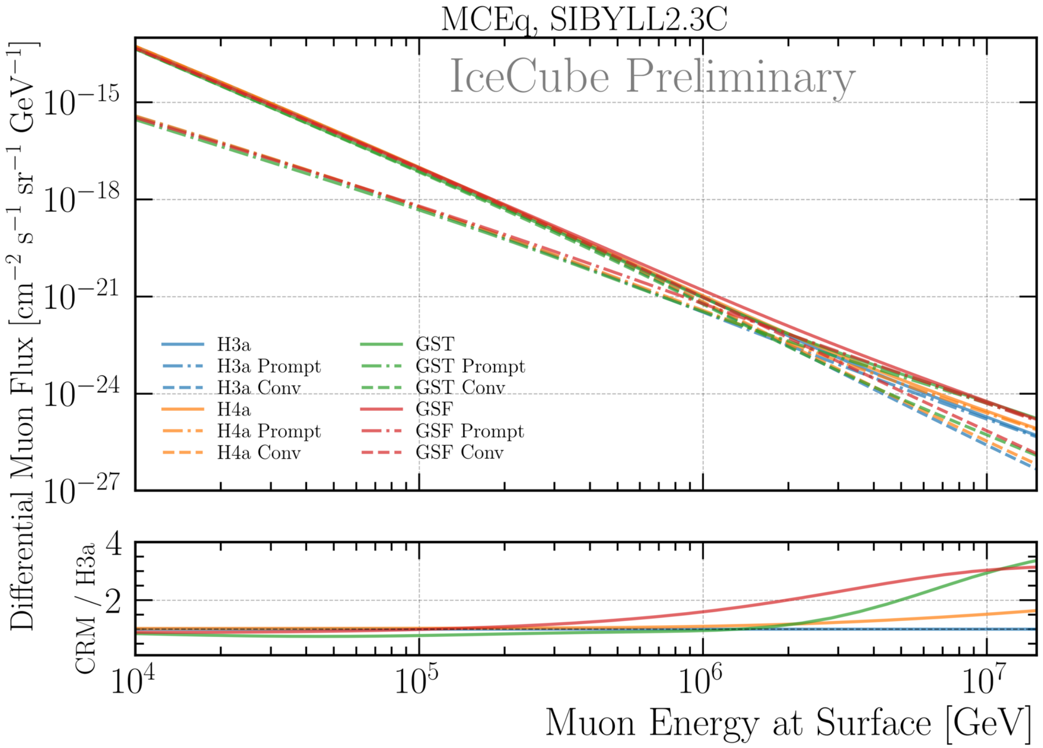


- Neutrino prediction includes atmospheric and astrophysical flux

Impact of Hadronic Interaction Models?



+50%



+250%

- Only SIBYLL and DPMJET include charm
- Constant offset < 100 TeV → irrelevant for unfolding
- Up to 50% difference at highest energies
- Difference between primary models about 250%
- Unfolding recovers this spectral index change within uncertainties

Unfolding Procedure

- Unfold dataset 4 times, once per primary model (H3a, H4a, GST, GSF)
- Uncertainty per unfolding k:

$$\sigma_k = \sqrt{\sigma^2_{\mathrm{unf},k} + \left(b_{\mathrm{unf,bias}}\,\hat{\phi}_k\right)^2 + \left(\delta_{A_{\mathrm{eff}}}\,\hat{\phi}_k\right)^2}$$

- Average: $$\bar{\Phi}_{\mathrm{unf}} = \frac{1}{4}\sum_{k=1}^{4}\hat{\phi}_k$$

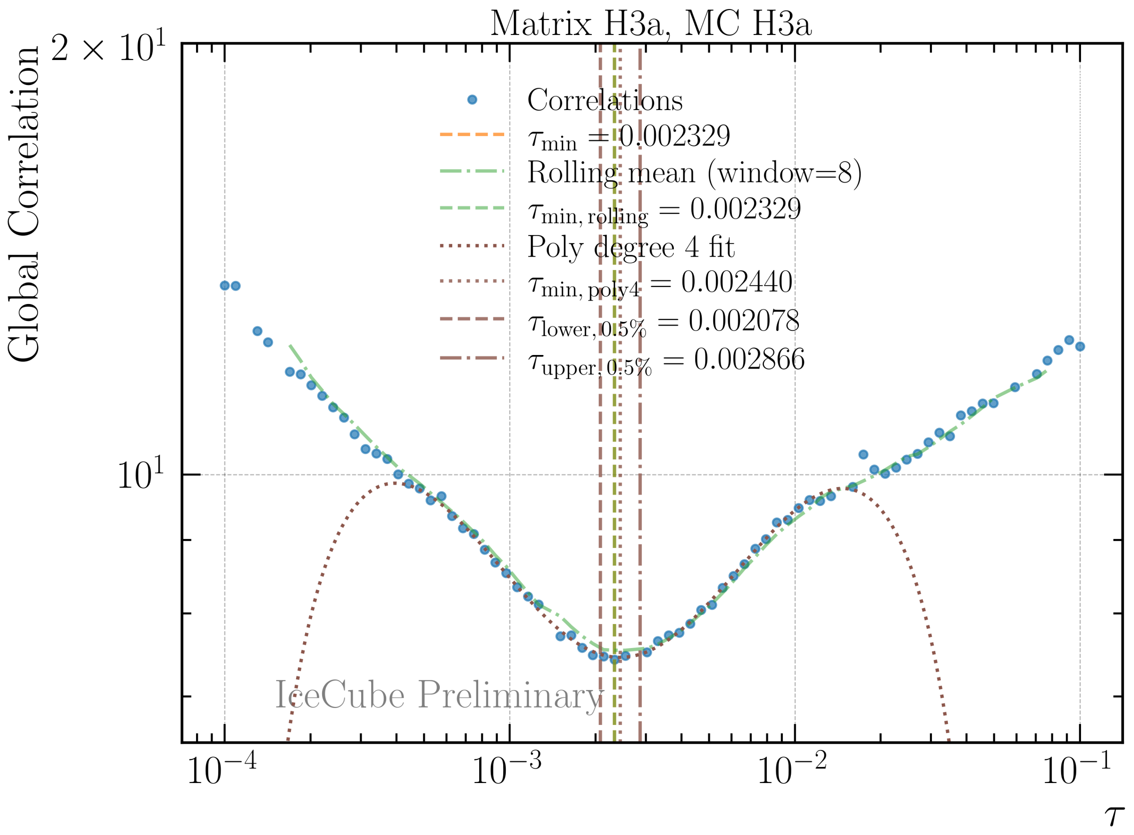
- Uncertainty on average: $$\sigma_{\mathrm{corr}} = \frac{1}{4}\sum_{k=1}^{4}\sigma_k$$

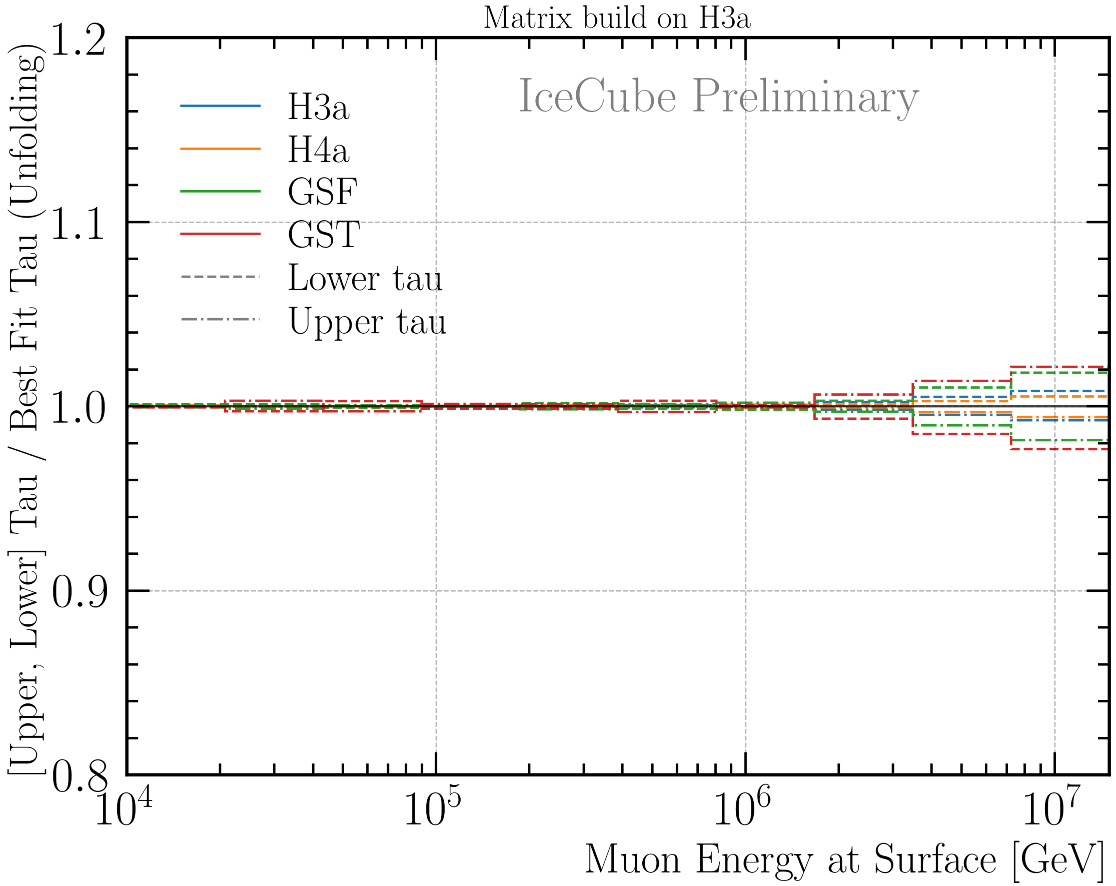
- Deviation between unfoldings:

$$\sigma_{\mathrm{spread}} = \sqrt{\frac{1}{4-1}\sum_{k=1}^{4}\left(\hat{\phi}_k - \bar{\Phi}_{\mathrm{unf}}\right)^2}$$

- Total uncertainty: $$\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{corr}} + \sigma^2_{\mathrm{spread}}}$$

Check Impact of Regularization Variations





Coincident Primary Background Estimation