Prompt Atmospheric Muons & Neutrinos

The Role of Charm and Unflavored Mesons

Laksha Pradip Das · University of Iowa

arXiv: 2512.17886 · D. Garg, M.V. Garzelli, M.H. Reno, G. Sigl · Supported by US Dept. of Energy

INTRODUCTION

Atmospheric leptons like muons and muon-neutrinos are produced from the decay and interactions of secondary hadrons (like pions, kaons, charmed hadrons) produced in the interactions of cosmic rays with air nuclei.

$$\phi_\mu = \phi_\mu^{\text{conv.}} + \phi_\mu^{\text{pQCD}} + \phi_\mu^{\text{unfl.}}$$
$$\phi_{\nu_\mu} = \phi_{\nu_\mu}^{\text{conv.}} + \phi_{\nu_\mu}^{\text{pQCD}}$$

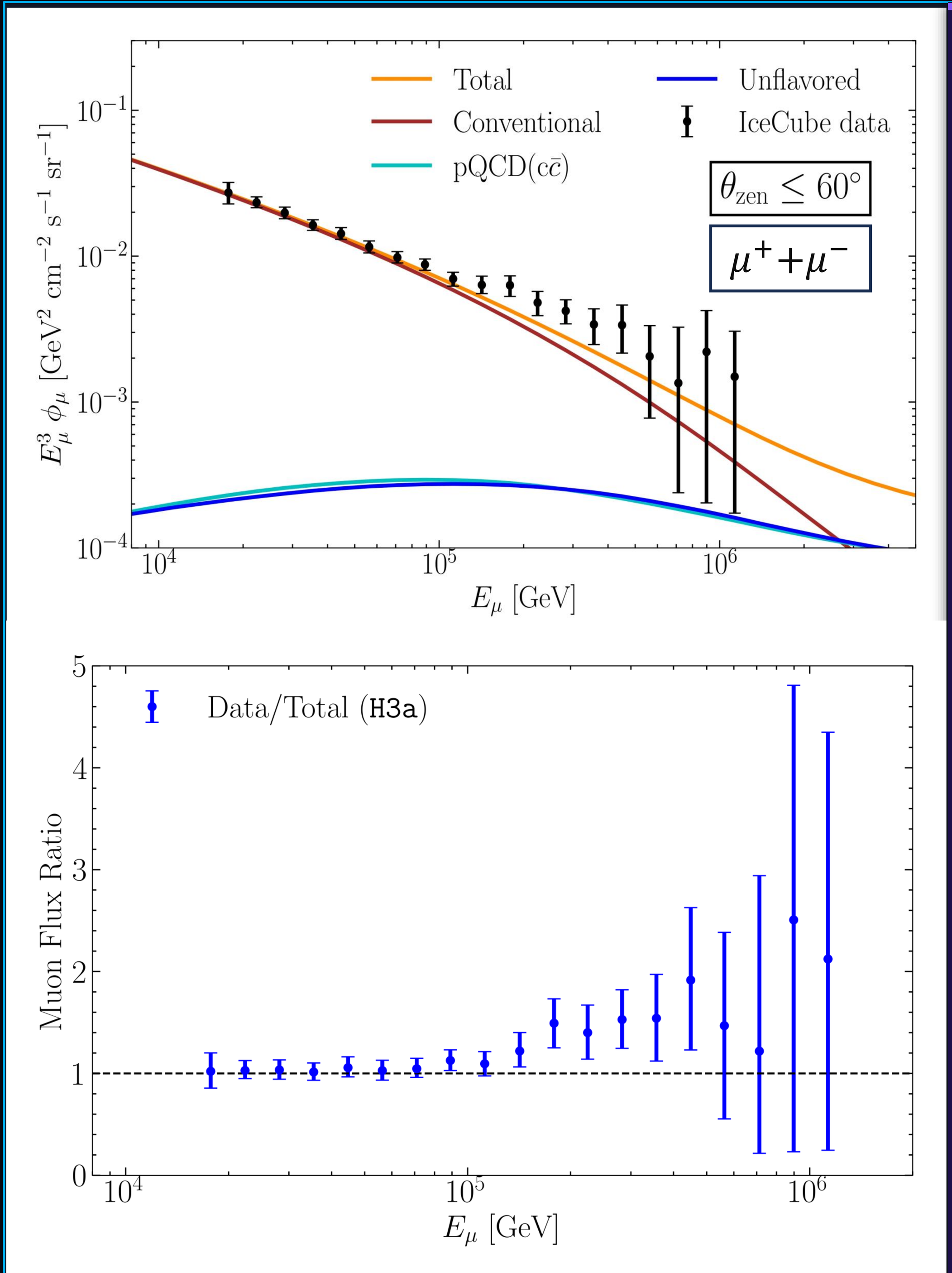
Conv. – from decays of pions and kaons
pQCD – from decays of charmed hadrons
Prompt – pQCD + unflavored contributions

Unflavored mesons (η, η', ρ^0, ω, φ)
Enhance prompt μ flux by ~2× relative to ν_μ at high E, via EM decays (B.R. ~10^{-5}–10^{-4})

- We use MCEq for flux evaluations with the following hadronic interaction, cosmic ray and atmospheric models.

Hadronic: SIBYLL 2.3c
Cosmic Ray: HillasGaisser2012, H3a
Atmosphere: CORSIKA3, USStd

THE TENSION WITH ICECUBE



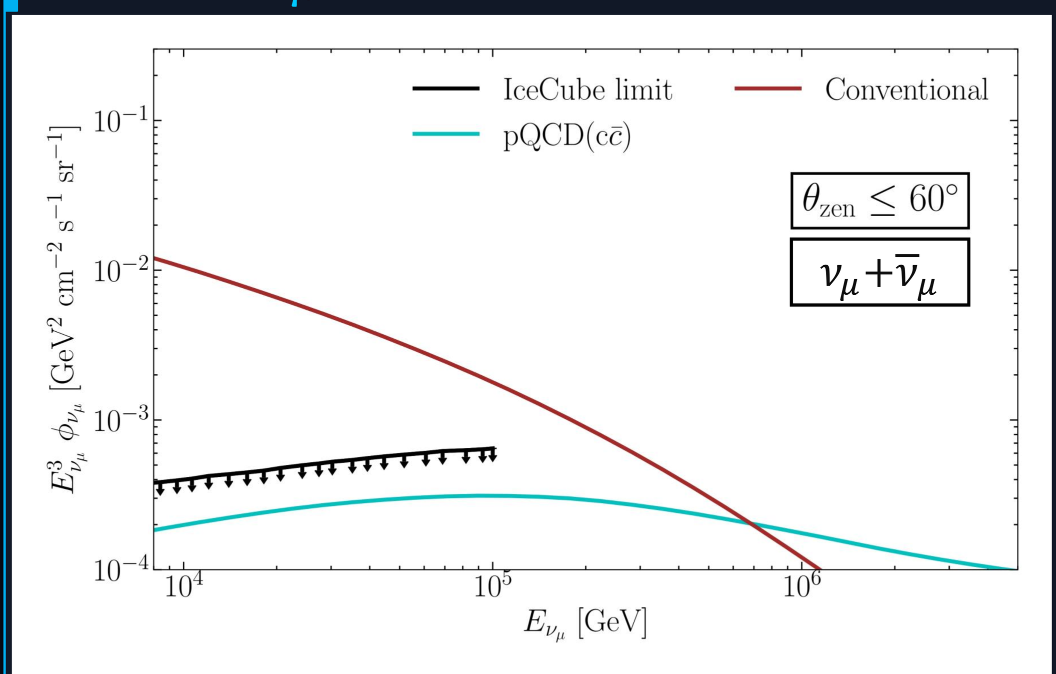
⚠ Quantified Tension:

MCEq[1] underpredicts IceCube muon data[2] by factor ~1.5–2 above 10^5 GeV.

1. A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, T. Stanev, *EPJ Web Conf. 99 (2015) 08001.*

2. M.G. Aartsen et al., *Astroparticle Physics, Volume 78, 2016.*

ICECUBE ν_μ UPPER BOUND

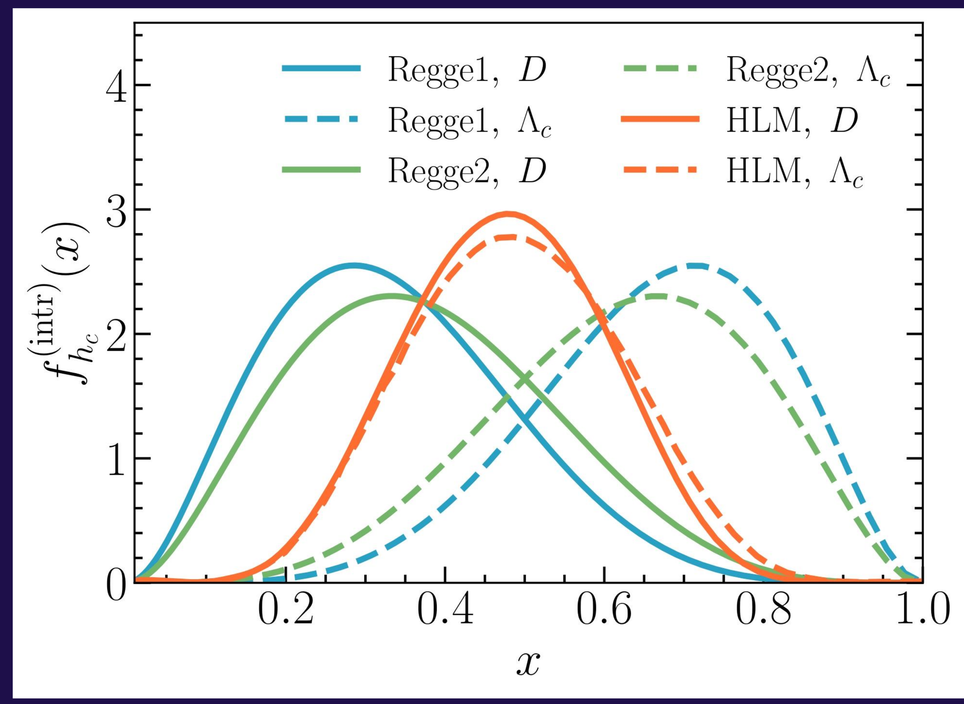


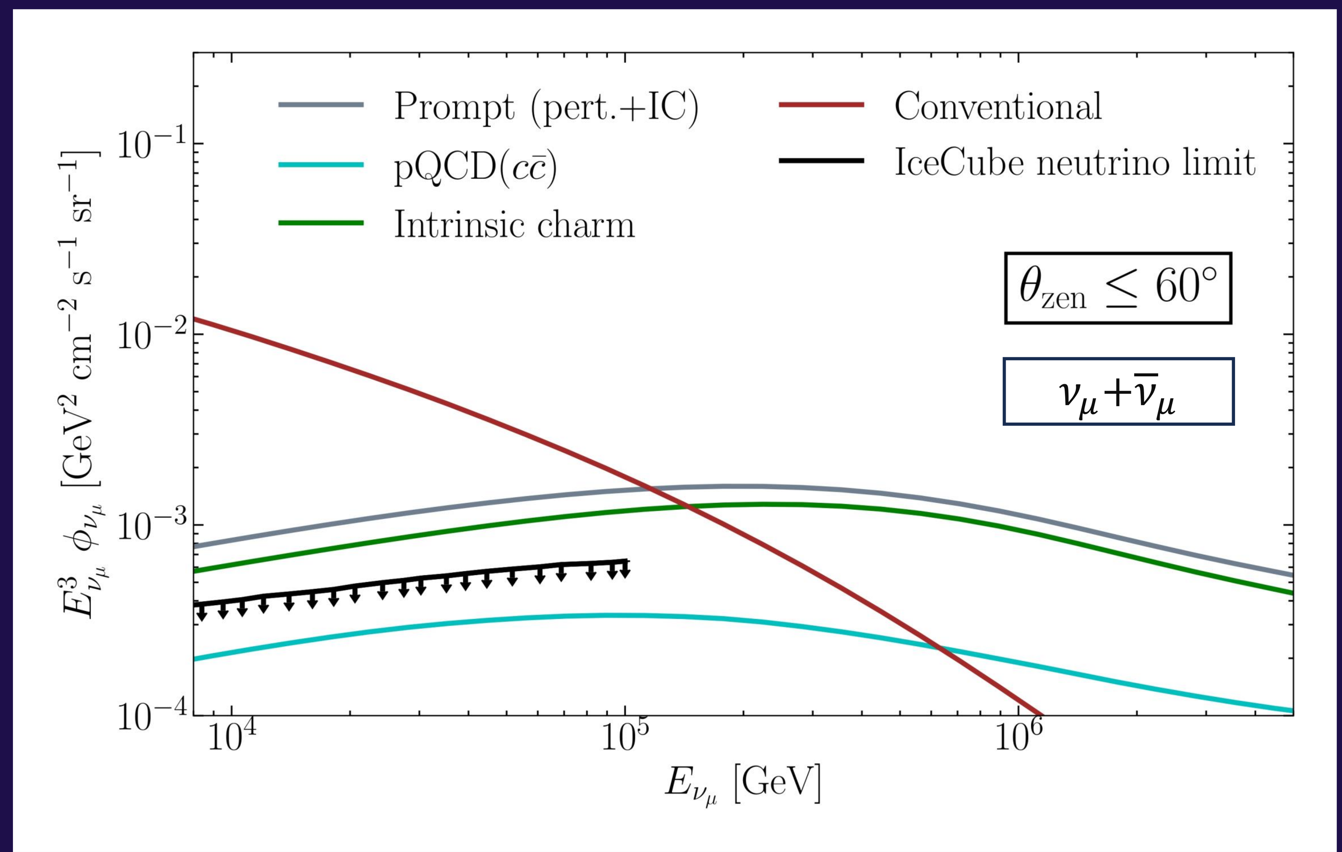
IceCube 2025 upper bound on prompt $\nu_\mu + \overline{\nu_\mu}$ flux[3]. Room for additional prompt contributions exists but limited.

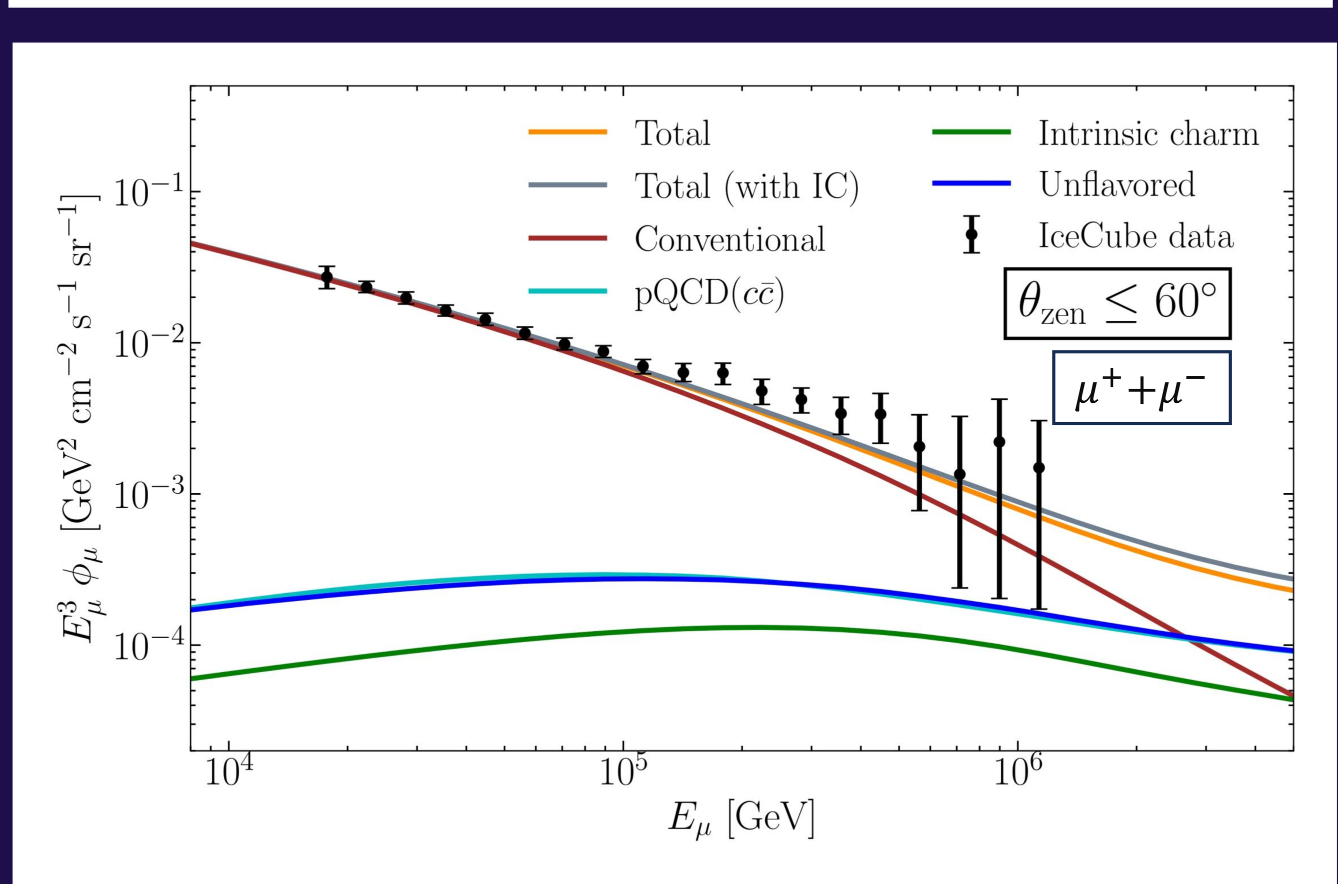
3. R. Abbasi et al., *2025.*

CAN INTRINSIC CHARM RESOLVE THE TENSION

- Nucleons carry a non-perturbative five-quark Fock state $|uudc\bar{c}\rangle$.
- Hadronization of this state in CR–air collisions produces forward-boosted charm hadrons: $p + A \to \overline{D^0} + \Lambda_c + X$ and $n + A \to D^- + \Lambda_c + X$.
- Implemented in MCEq via a single normalization: $\frac{d\sigma^{h_c}}{dx} = w_{\text{intr}}^c\,\sigma_{pA}\,f_{h_c}^{(\text{intr})}(x)$.
- Three fragmentation models tested — **Regge1** ($a_N = -0.5$), **Regge2** ($a_N = 0$), **HLM** (Hobbs, Londergan and Melnitchouk).



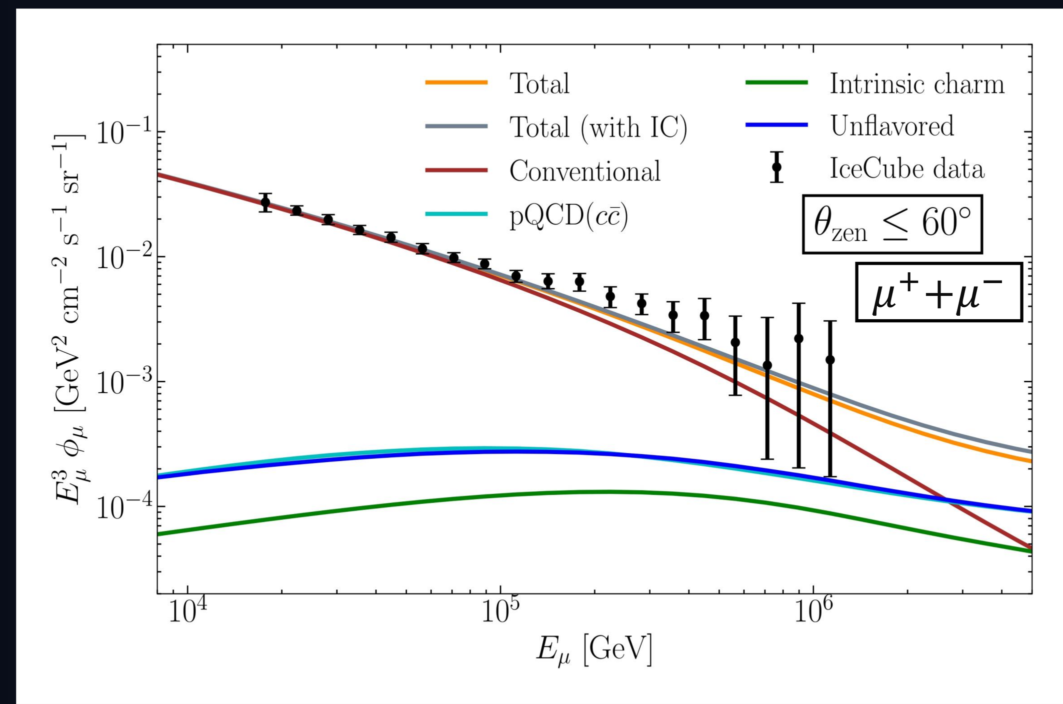




- Fitting IC to resolve the muon deficit requires w_c^{intr} ~ 3.93×10⁻³, but this overshoots the IceCube prompt ν_μ upper bound.
- Saturating the prompt ν_μ upper bound yields $w_c^{\text{intr}} \sim 1.01 \times 10^{-3}$, which has minimal impact on the muon flux.

UNFLAVORED MESON ENHANCEMENT + FLUX RATIOS

With IC constrained by ν_μ limits, scale unflavored meson contribution: $\phi_\mu^{\text{unfl}} = \alpha_{\text{unfl}} \times \phi_\mu^{\text{unfl(Sibyll2.3c)}}$



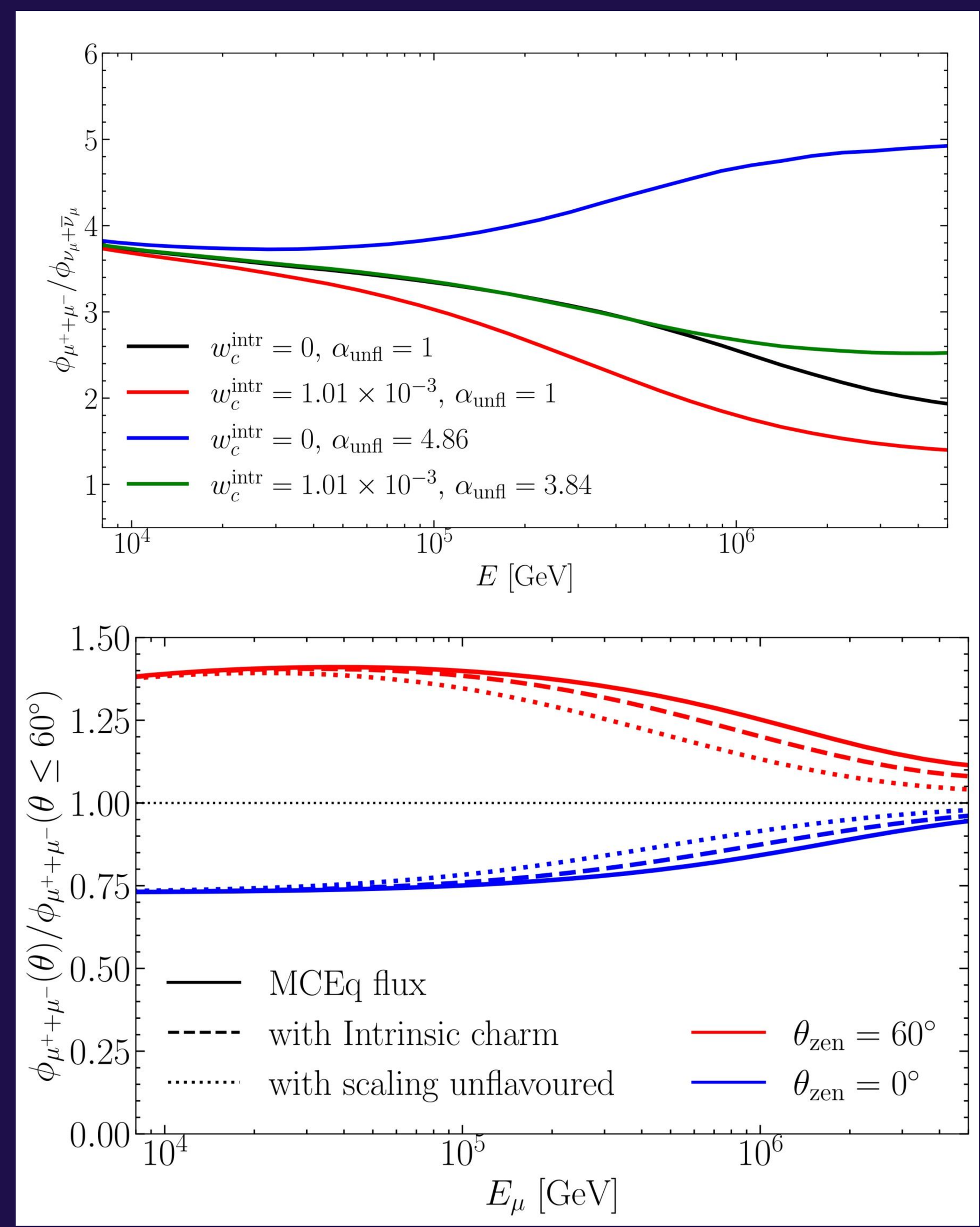
Best-fit $\alpha_{\text{unfl}} = 3.84$ ($w_c^{\text{intr}} = 1.01 \times 10^{-3}$)Muon flux substantially improved.

Best-fit Enhancement Factor

Best-fit values → 1σ intervals:
3.84(with IC) → [2.90–4.84]
4.86 (no IC) → [3.88–5.84]
Large enhancement required, pointing to significant MC generator uncertainties in unflavored meson production.

Muon to muon-neutrino flux ratio and unfolding

Helps differentiate between the different approaches to prompt lepton flux enhancements.



Enhanced prompt contributions (IC or scaled unflavored) drive faster approach to isotropy at high E.

DISCUSSION & CONCLUSIONS

01 IC Constrained by ν_μ Bound

- Fitting IC to the muon data overshoots IceCube's 2025 prompt ν_μ upper bound for all the intrinsic charm models considered.

02 Exploring Unflavored Mesons

- The IceCube limits on the prompt atmospheric ν_μ flux put significant constraints on the possibility that intrinsic charm can account for IceCube's high energy muon measurements.
- Scaling the unflavored meson component by α_{unfl} reconciles the muon data while remaining consistent with the neutrino bound, pointing to significant MC generator uncertainties in unflavored meson production.

03 μ/ν_μ Ratio as Discriminator

IC drives the ratio down at high energies (charm contributes equally to muons and neutrinos), while enhanced unflavored mesons drive it up (contributing exclusively to muons), making this ratio a clean discriminator between the two scenarios — making these observables (zenith angle unfolding and μ/ν_μ ratio) concrete targets for IceCube-Gen2 and KM3NeT.

OUTLOOK

1. The extraction of the prompt atmospheric muon and neutrino fluxes from neutrino telescope data remains a topic of tremendous interest.
2. Forward physics experiments (SHiP, LHC FPF) and improved MC modeling of unflavored meson production will be a factor in resolving the tension between theory and the high-energy atmospheric muon data.
3. Refined CR spectrum and composition measurements, such as from LHAASO, may further impact prompt atmospheric lepton predictions.