IOWA

# Atmospheric lepton fluxes and the potential role of intrinsic charm

## NBI Neutrino Summer School, 2025
## Student talk

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(Work in collaboration with D. Garg[1], M. V. Garzelli[2], M. H. Reno[1], and G. Sigl[2] and supported in part by US DOE)

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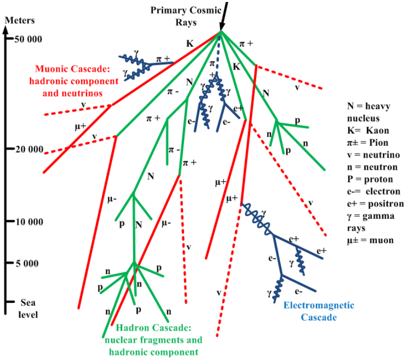
# Contents

# Cosmic rays and atmospheric interactions




**Source:** Gomez Toro 2014

- Cosmic-ray particles are highly energetic protons, helium, and other heavier nuclei that can interact with air nuclei.
- These N-Air interactions produce various secondary particles that can decay or interact again.
- These secondary particles decay to produce leptons and the corresponding neutrinos.

All flux calculations are made using MCEq[a] with the `SIBYLL-2.3c` interaction model and `Hillas-Gaisser2012(H3a)` primary cosmic-ray flux model.

[a] https://github.com/mceq-project/MCEq.git

# Atmospheric lepton flux

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For atmospheric muon neutrinos,

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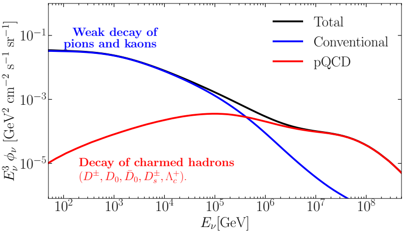

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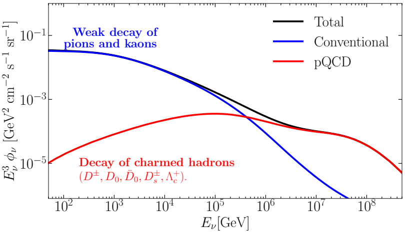
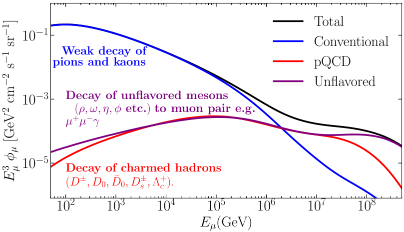
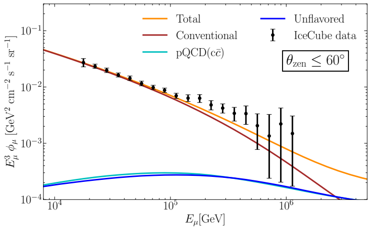


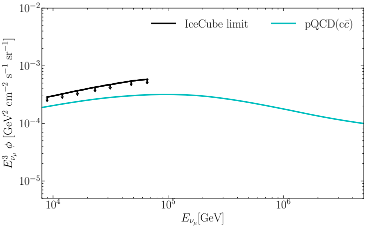

And, for atmospheric muons

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



# Atmospheric muon flux and prompt neutrino limit from IceCube




**Left:** Angle-averaged muon flux for $\theta_{zen} \leq 60°$ from MCEq and IceCube data with bin-by-bin error bars (Soldin et al. 2024; Soldin 2019; Aartsen et al. 2016a).

**Right:** Angle-averaged prompt neutrino spectrum from charm and upper limit on the prompt neutrino flux set by IceCube (Aartsen et al. 2016b).

# Introduce intrinsic charm (IC)?

- Intrinsic charm arises from the non-perturbative fluctuations of the nucleon states into four quark – one antiquark states.
- So, the proton (neutron) is assumed to have a Fock state decomposition of the following form:

$$|uud\rangle + C_{intr}\,|uudc\bar{c}\rangle$$

$$|udd\rangle + C_{intr}\,|uddc\bar{c}\rangle$$

  where, the overall weight of the Fock state containing the non-perturbative fluctuations ($C_{intr}$) is small but non-negligible.
- When CR nucleons interact with air nuclei in the atmosphere, hadronization of the five-quark state takes place with processes like $pA \to \overline{D}^0 \Lambda_c^+ X$ and $nA \to D^- \Lambda_c^+ X$

# IC models

We write the differential cross section for nucleon-air production of charm hadron $h_c$ via non-perturbative intrinsic charm as

$$\frac{d\sigma_{p-\text{air}}^{h_c(\text{intr})}(E, x_{h_c})}{dx_{h_c}} = w_{\text{intr}}^{c} \sigma_{p-\text{air}}(E) f_{h_c}^{(\text{intr})}(x_{h_c}) \,,$$

We use the Regge ansatz (Kaidalov and Piskunova 1986; Kaidalov 2003) for intrinsic charm where the form of the intrinsic charm fragmentation function, $f_{h_c}^{(\text{intr})}(x)$ is given as:

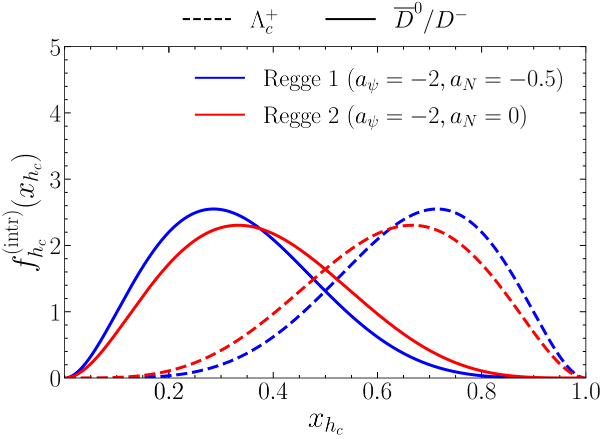
$$\begin{aligned} f_{h_c}^{\text{intr}}(x) &= N_{\text{intr}}\, x^{-a_\psi}(1-x)^{-a_\psi+2(1-a_N)} \\ N_{\text{intr}} &= \frac{\Gamma(-2a_\psi+4-2a_N)}{\Gamma(-a_\psi+1)\Gamma(-a_\psi+3-2a_N)} \,. \end{aligned}$$

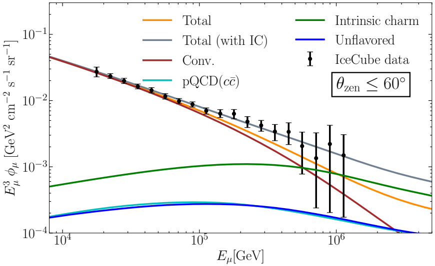
Results shown are obtained by using $a_\psi = -2$ and $a_N = -0.5$

We assume for the Regge ansatz that

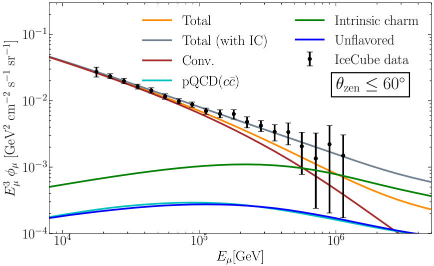
$$f_{D^-}^{(\text{intr})}(x_D) = f_{\overline{D}^0}^{(\text{intr})}(x_D)$$
$$f_{\Lambda_c}^{(\text{intr})}(x_\Lambda) = f_{\overline{D}^0}^{(\text{intr})}(1 - x_\Lambda) .$$

These functions are shown in the figure below,






Angle-averaged muon flux ($\mu^+ + \mu^-$) for $\theta_{\rm zen} \leq 60°$ with the addition of an intrinsic charm contribution with the weight $w^c_{\rm intr} = 3.91 \times 10^{-3}$.

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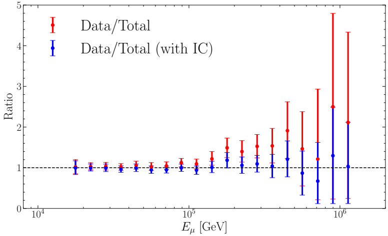
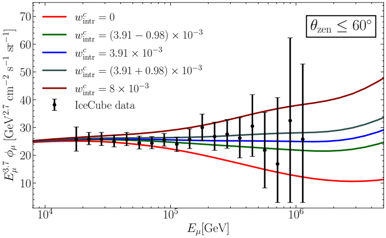
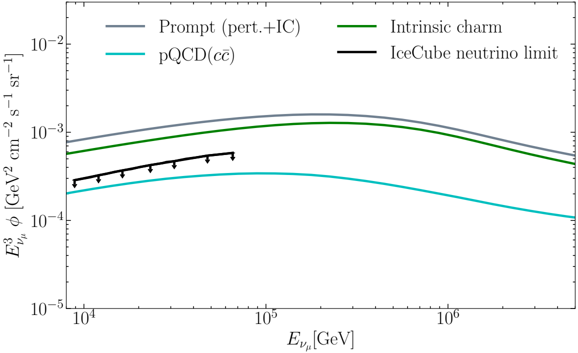
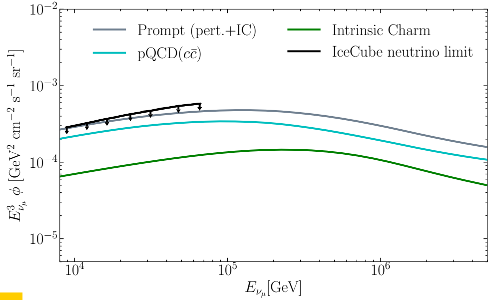


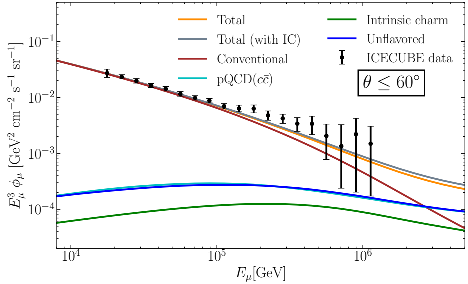





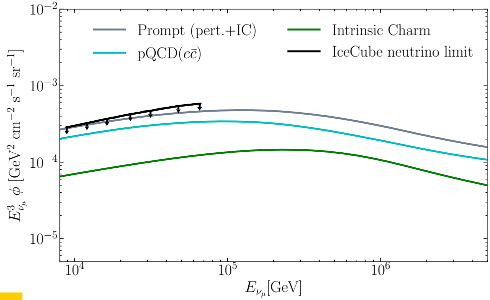

All-sky prompt atmospheric muon neutrino flux including intrinsic charm contribution with the weight $w^c_{\text{intr}} = 3.91 \times 10^{-3}$.




**Bottom:** Comparison of prompt neutrino spectrum $(\nu_\mu + \bar{\nu}_\mu)$ with the upper limit after including intrinsic charm contribution with $w^c_{\text{intr}} = 4.46 \times 10^{-4}$.




**Top:** Comparison of angle-averaged muon flux($\mu^+ + \mu^-$) with IceCube data after including intrinsic charm contribution with $w^c_{\rm intr} = 4.46 \times 10^{-4}$.

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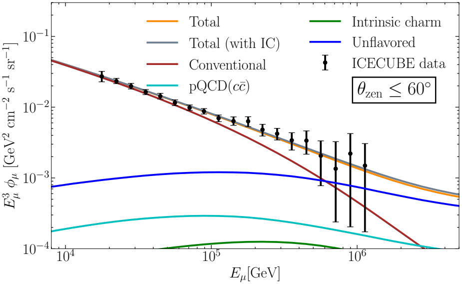
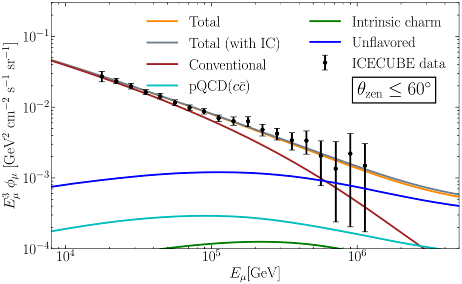
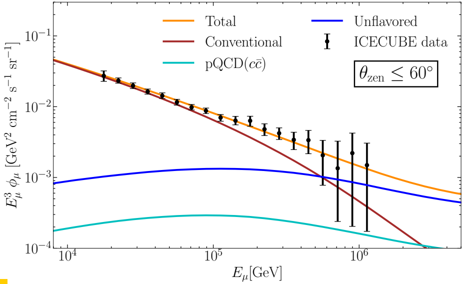



**Top:** The angle averaged muon flux after including intrinsic charm contribution with $w^c_{\rm intr} = 4.46 \times 10^{-4}$ and scaling the unflavored flux by a best-fit parameter of $\alpha_{\rm unfl} = 4.39$.




**Top:** The angle averaged muon flux after including intrinsic charm contribution with $w^c_{\rm intr} = 4.46 \times 10^{-4}$ and scaling the unflavored flux by a best-fit parameter of $\alpha_{\rm unfl} = 4.39$.

**Bottom:** Without any intrinsic charm contribution and scaling the unflavored flux by a best-fit parameter of $\alpha_{\rm unfl} = 4.84$.

# Effects of including intrinsic charm

Table 1: Best fit values of $w^c_{\text{intr}}$ for model-dependent fit to angle averaged muon energy spectrum along with the $1\,\sigma$ interval.

| **Model** | **Best fit** $\mathbf{w^c_{intr}}$ $(\times\mathbf{10^{-3}})$ | $\mathbf{1\sigma}$ **interval** $(\times\mathbf{10^{-3}})$ |
|---|---|---|
| Regge 1 $(a_\psi = -2, a_N = -0.5)$ | 3.91 | $2.93 - 4.89$ |
| Regge 2 $(a_\psi = -2, a_N = 0)$ | 3.53 | $2.65 - 4.42$ |
| Hobbs, Londergan, and Melnitchouk 2014(HLM)[1] | 3.02 | $2.26 - 3.77$ |

[1] Preliminary results

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Table 2: Best fit values for the scaling factor of the unflavored flux if we use $w_c^{\text{intr}}$ needed to meet the neutrino upper limit, along with the $1\sigma$ interval. For no intrinsic charm, we have $\alpha_{\text{unfl}} = 4.84$ and $1\sigma$ interval is $3.85 - 5.83$

| **Model** | **$\mathbf{w^c_{intr}}$ $(\times \mathbf{10^{-4}})$** | **Best fit $\alpha_{\text{unfl}}$** | **$1\sigma$ interval** |
|---|---|---|---|
| Regge 1$(a_\psi = -2, a_n = -0.5)$ | 4.46 | 4.39 | 3.40 - 5.38 |
| Regge 2$(a_\psi = -2, a_n = 0)$ | 4.15 | 4.38 | 3.39 - 5.37 |
| HLM[1] | 3.69 | 4.36 | 3.37 - 5.35 |

[1] Preliminary results

# Summary

- Using $w^c_{\text{intr}} = 3.91 \times 10^{-3}$ gives a good match between the atmospheric muon flux measured by IceCube and the theoretical estimation using MCEq. However, the prompt neutrino flux exceeds the upper limit set by IceCube.
- When we use $w^c_{\text{intr}} = 4.46 \times 10^{-4}$, the prompt muon neutrino flux is within the upper limit; however, there remains a discrepancy between the observed and calculated atmospheric muon flux.
- There are uncertainties in the muon flux from unflavored mesons. We tried to rescale the unflavored flux by a factor $\alpha_{\text{unfl.}}$ to match the calculated and observed muon flux. The results are included in Table 2.
- Large experimental error bars at high energies make a conclusive statement about the level of prompt contribution difficult.

Aartsen, M. G. et al. (2016a). “Characterization of the Atmospheric Muon Flux in IceCube”. In: *Astropart. Phys.* 78, pp. 1–27. DOI: 10.1016/j.astropartphys.2016.01.006. arXiv: 1506.07981 [astro-ph.HE].

— (2016b). “Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data”. In: *Astrophys. J.* 833.1, p. 3. DOI: 10.3847/0004-637X/833/1/3. arXiv: 1607.08006 [astro-ph.HE].

Gomez Toro, Daniel (Dec. 2014). “Temporal Filtering with Soft Error Detection and Correction Technique for Radiation Hardening Based on a C-element and BICS”. PhD thesis.

Hobbs, T. J., J. T. Londergan, and W. Melnitchouk (2014). “Phenomenology of nonperturbative charm in the nucleon”. In: *Phys. Rev. D* 89.7, p. 074008. DOI: 10.1103/PhysRevD.89.074008. arXiv: 1311.1578 [hep-ph].

Kaidalov, A. B. (2003). “$J/\psi c\bar{c}$ production in $e^+e^-$ and hadronic interactions”. In: *JETP Lett.* 77, pp. 349–352. DOI: 10.1134/1.1581958. arXiv: hep-ph/0301246.

Kaidalov, A. B. and O. I. Piskunova (1986). "Inclusive spectra of baryons in the quark-gluon strings model". In: *Z. Phys. C* 30, p. 145. DOI: 10.1007/BF01560688.

Soldin, D. (2019). "Atmospheric Muons Measured with IceCube". In: *EPJ Web Conf.* 208. Ed. by B. Pattison et al., p. 08007. DOI: 10.1051/epjconf/201920808007. arXiv: 1811.03651 [astro-ph.HE].

Soldin, D. et al. (2024). "Cosmic-ray physics at the South Pole". In: *Astropart. Phys.* 161, p. 102992. DOI: 10.1016/j.astropartphys.2024.102992. arXiv: 2311.14474 [astro-ph.HE].