Atmospheric Neutrino Flux from Charm Production

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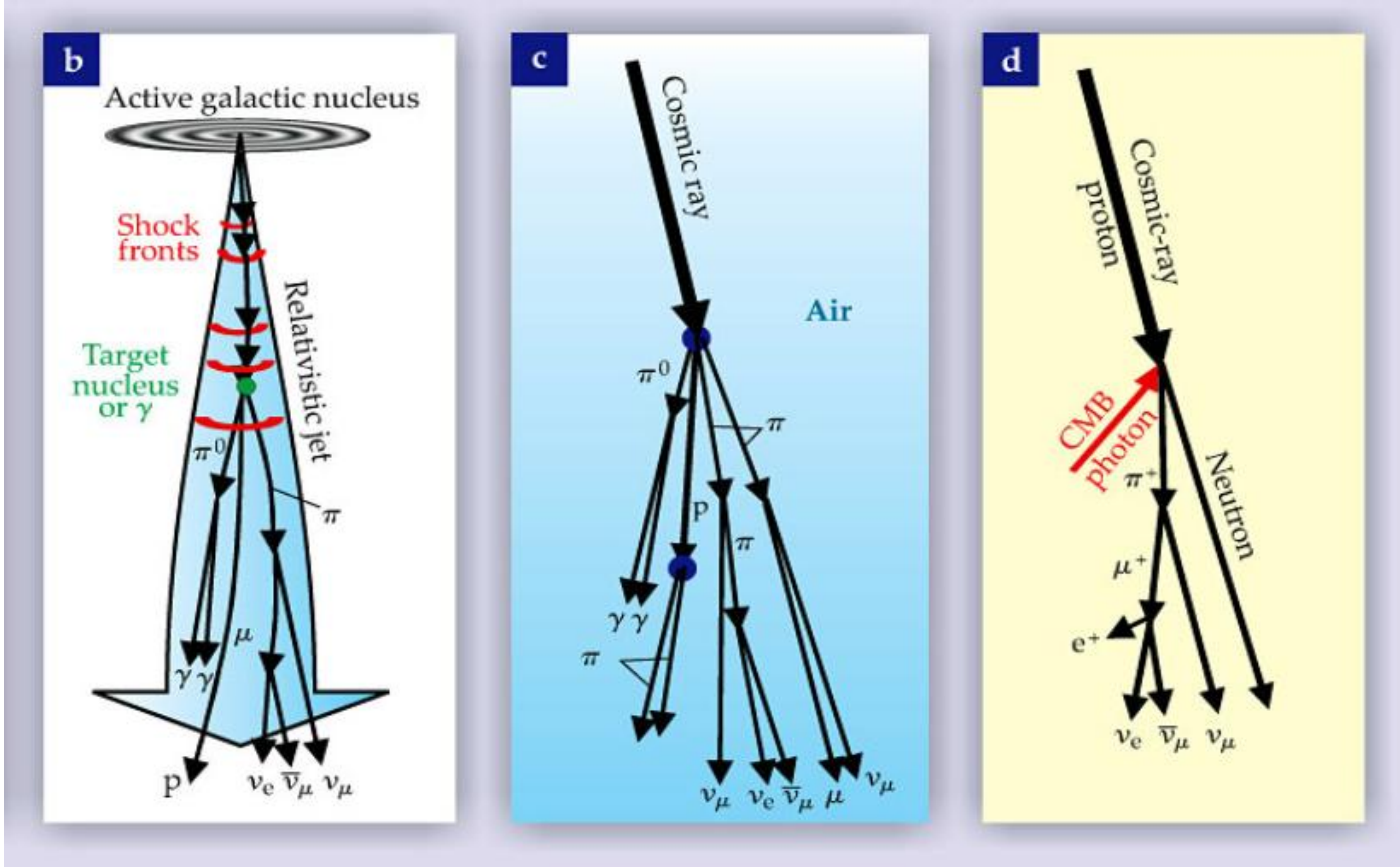
High Energy Neutrinos



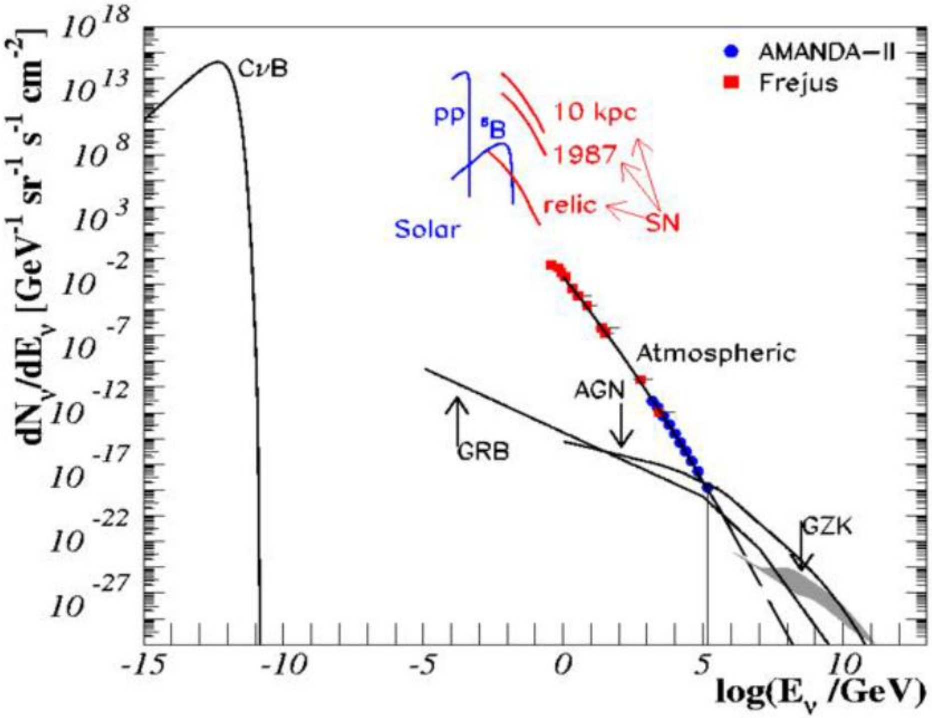
F. Halzen and S. Klein, Physics Today, May 2008

Atmospheric Neutrino

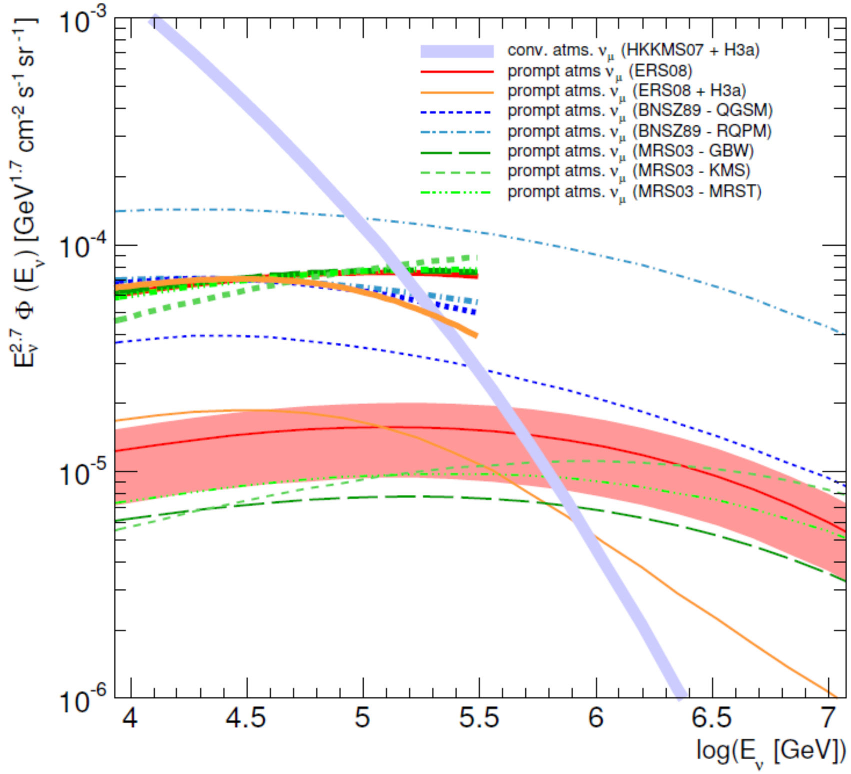
- Cosmic rays interact with air nuclei in the atmosphere and produce hadrons.

- Hadrons subsequently decay producing neutrinos.

- Background for astrophysical neutrinos.



Atmospheric Neutrinos Flux
Conventional vs. Prompt



IceCube 1311.7048

- Conventional flux
  - from the $\pi^{\pm}$ or $K^{\pm}$ decay
- Prompt flux
  - From the charmed hadron (e.g. D-meson)

E < ~700 TeV : Conventional flux dominates
E > ~700 TeV : Prompt flux dominates

Cascade Equation

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{dec}} + \sum_k S(k \to j)$$

Lepton flux is obtained by solving the coupled equations for nucleon, meson and lepton fluxes.

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY)$$

$$\frac{d\phi_M}{dX} = S(NA \to MY) - \frac{\phi_M}{\lambda_M} - \frac{\phi_M}{\rho d_M(E)} + S(MA \to MY)$$

$$\frac{d\phi_l}{dX} = \sum_M S(M \to lY)$$

(Re)generation Function

$$S(k \rightarrow j) = \int_E^{\infty} dE_k \, \frac{\phi_k(E_k)}{\lambda_k(E_k)} \, \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j}$$

dn/dE : energy distribution of the final state particle

$$\frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \rightarrow jY, E_k, E_j)}{dE_j}$$ for production

$$\frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} = \frac{1}{\Gamma_k} \frac{d\Gamma(k \rightarrow jY, E_j)}{dE_j}$$ for decay

Z-moments

$$S(k \to j) = Z_{kj}(E)\frac{\phi_k(E,X)}{\lambda_k(E)}$$

$$Z_{kj} \equiv \int_E^\infty dE_k \, \frac{\phi_k(E_k, X)}{\phi_k(E_j, X)} \frac{\lambda_k(E_j)}{\lambda_k(E_k)} \frac{dn(k \to j; E_k, E_j)}{dE_j}$$

Assumption : $\phi_k(E, X) = E^\beta \phi_k(X)$

$$Z_{kj} = \int_E^\infty dE_k \left(\frac{E_k}{E_j}\right)^\beta \frac{\lambda_k(E_j)}{\lambda_k(E_k)} \frac{dn(k \to j; E_k, E_j)}{dE_j}$$

P. Lipari, Astropart. Phys. 1 (1993) 195
P. Gondolo, G. Ingelman and M.Thunman, Astropart. Phys. 5 (1996) 309 (TIG)

Approximate Lepton Fluxes

$$\phi_l^{low} = Z_{Ml} \frac{Z_{NM}}{1 - Z_{NN}} \phi_N$$

$$\phi_l^{high} = Z_{Ml} \frac{Z_{NM}}{1 - Z_{NN}} \frac{\ln(\Lambda_M / \Lambda_N)}{1 - \Lambda_N / \Lambda_M} \frac{\varepsilon_M}{E} \phi_N$$

$$\Lambda_i = \lambda_i / (1 - Z_{ii}) \qquad i = N, M$$

The lepton flux can be obtained by interpolating these two solutions.

$$Z_{NM} = \int_{x_{E,\min}}^{1} \frac{dx_E}{x_E} \frac{\phi_N(E_M / x_E)}{\phi_N(E_M)} \frac{1}{\sigma_{pA}(E_M)} \frac{d\sigma(pp \to MX)}{dx_E}$$

$$\frac{d\sigma(pp \to MX)}{dx_E} \cong \frac{d\sigma(pp \to MX)}{dx_F}$$

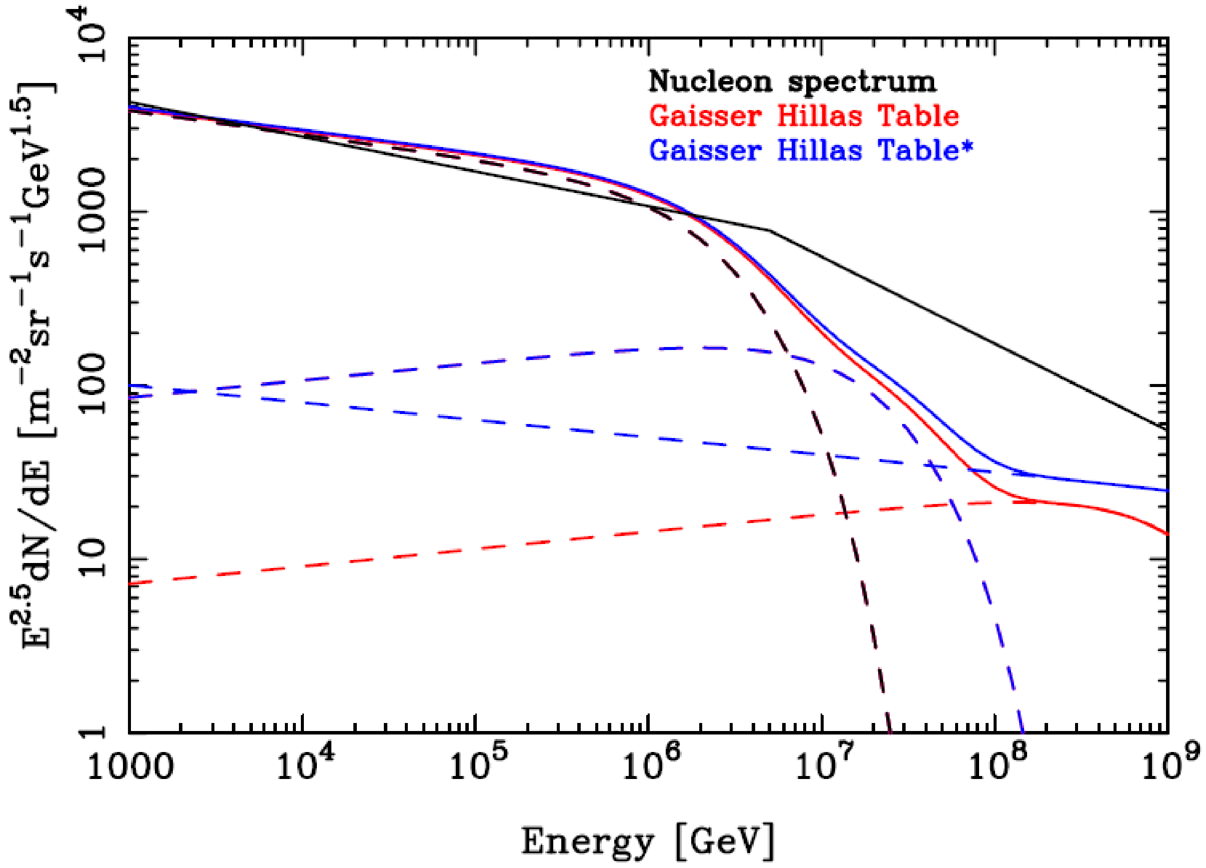
$$\frac{d\sigma(pp \to MX)}{dx_F}$$

can be obtained from the calculation of the charm production cross section in perturbative QCD or dipole model with fragmentation, and also from non-perturbative "intrinsic charm" production.

Z_{Ml} is calculated using the formula by Bugaev et al.
(PRD 58, 054001 (1998)

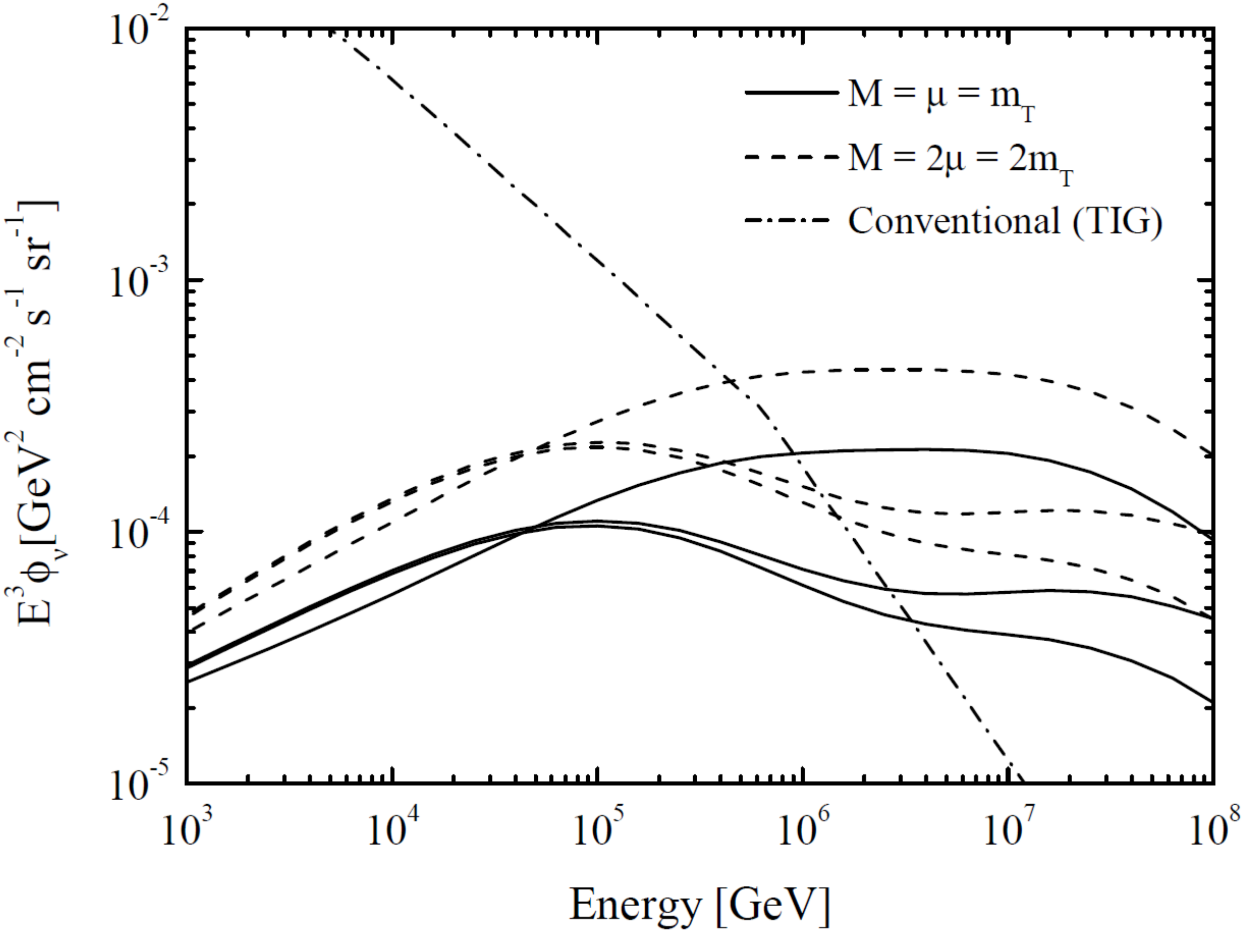
Z_{NN}, Z_{MM} are taken from TIG (1996).

Cosmic Ray Flux for Nucleon



T.K. Gaisser, Astropart. Phys. 35 (2012) 801

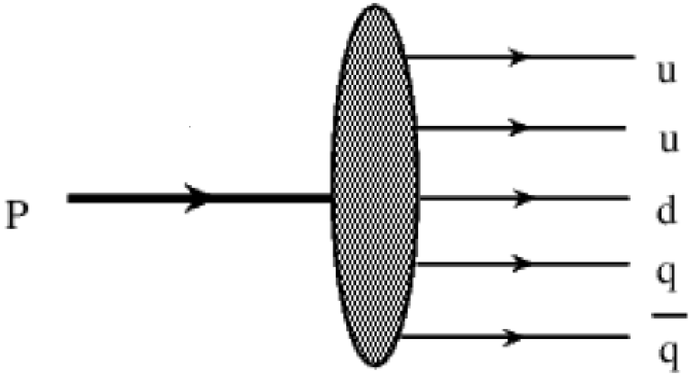
Prompt flux from the charmed meson
(preliminary)



Intrinsic charm

Charm can be produced from non-perturbative fluctuation of nucleon and it goes into a charmed baryon-meson pair.

e.g.) $p \rightarrow \Lambda_c^+ + \overline{D}^0$



$\Longrightarrow$ Meson-Baryon Model (MBM)

In the MBM, Λ_c^+ is produced through $D^0\Lambda_c^+$ and $\overline{D}^{*0}\Lambda_c^+$.

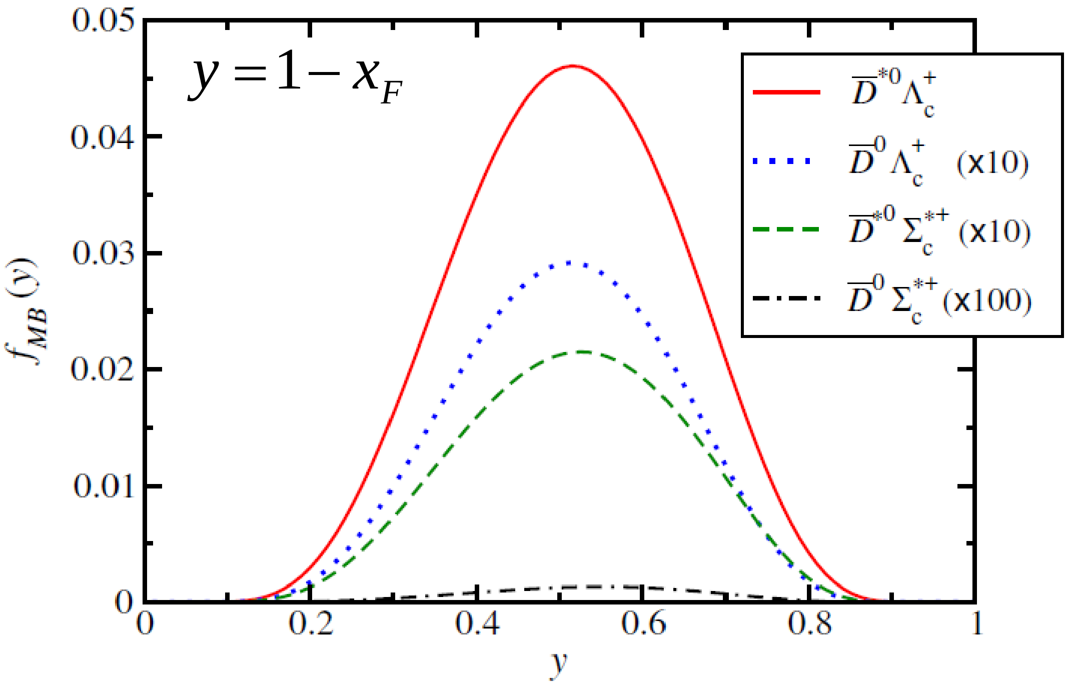
T.J. Hobbs, J.T. Londergan and W. Melnitchouk, PRD 89 074008 (2014) (HLM)

Intrinsic charm production cross section

$$\frac{d\sigma^{\Lambda_c}}{dx_F} \approx \sum_{M=D,D^*} f_{\Lambda_c M}(x_F)\,\sigma_{tot}^{Mp}$$

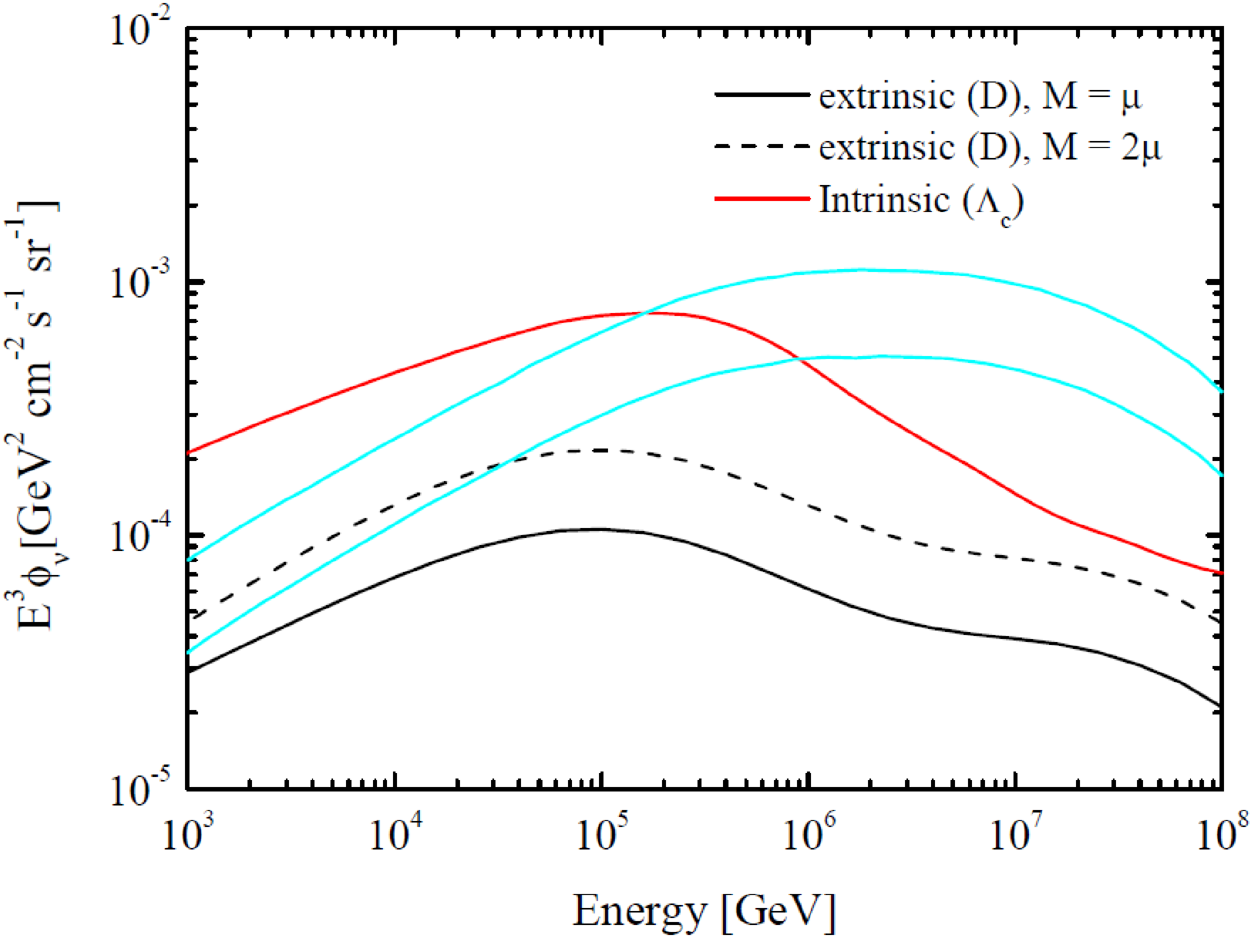
$$\sigma_{tot}^{Dp} \approx \sigma_{tot}^{D^* p} \approx 20 \pm 10\,\mathrm{mb}$$

$f_{\Lambda_c M}$ - splitting function



T.J. Hobbs, J.T. Londergan and W. Melnitchouk, PRD 89 074008 (2014) (HLM)

Extrinsic vs. Intrinsic (preliminary)



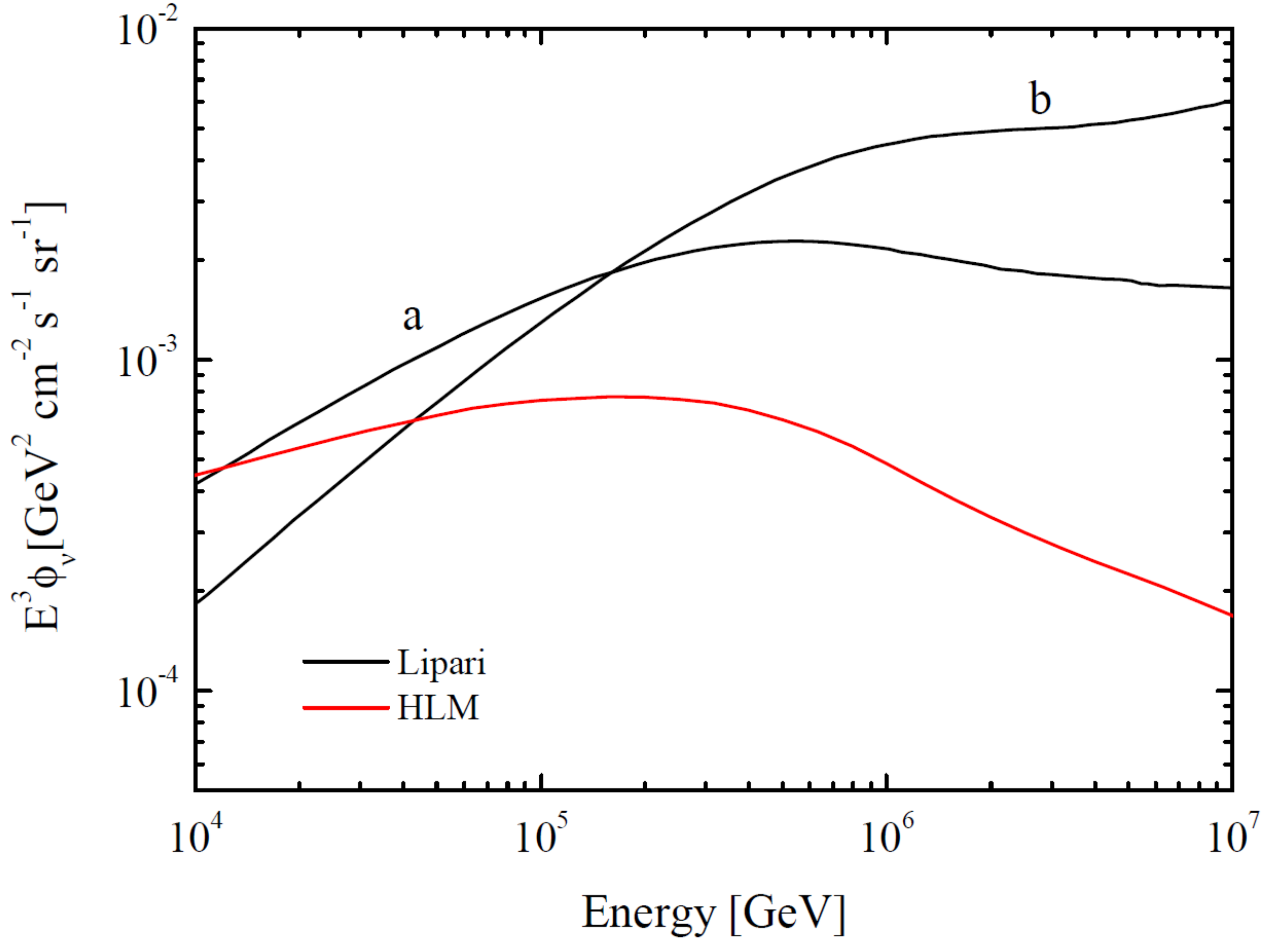
Hypothesis by P. Lipari

P. Lipari proposed that prompt flux from Intrinsic charm can explain the IceCube high energy events and suggest two ad hoc differential cross sections. (arXiv: 1308.2086)

$$\frac{d\sigma}{dx_F} \simeq 0.7 f_{\Lambda_c}\left[4(1-|x_F|)^3\right]\left(\sqrt{s}/(200\ \mathrm{GeV})\right)^{0.7}$$

$$\frac{d\sigma}{dx_F} \simeq 0.08 f_{\Lambda_c}\left[2(1-|x_F|)\right]\left(\sqrt{s}/(200\ \mathrm{GeV})\right)^{1.2}$$

Lipari vs HLM



Conclusion

- The prompt flux with more realistic cosmic ray nucleon spectrum is reduced relative to the prompt spectrum using the broken power law. At 1 PeV, the reduction in flux is about a factor of 3.

- Work on pinning down a NLO perturbative result is in progress with new PDFs and the new CR spectrum.

- Intrinsic charm contribution based on the Hobbs et al MBM results are not as significant as the hypothesis proposed by Lipari, but may be important. – work in progress

- More update
  - with dipole model result
  - with separate lepton flavors