Charm production and IceCube backgrounds

Hallsie Reno
University of Iowa

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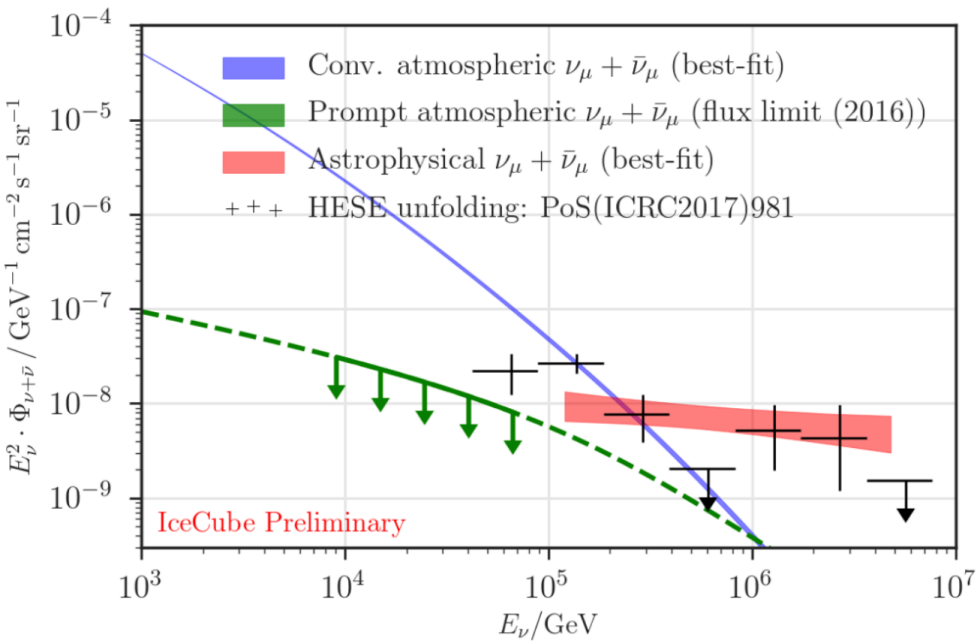
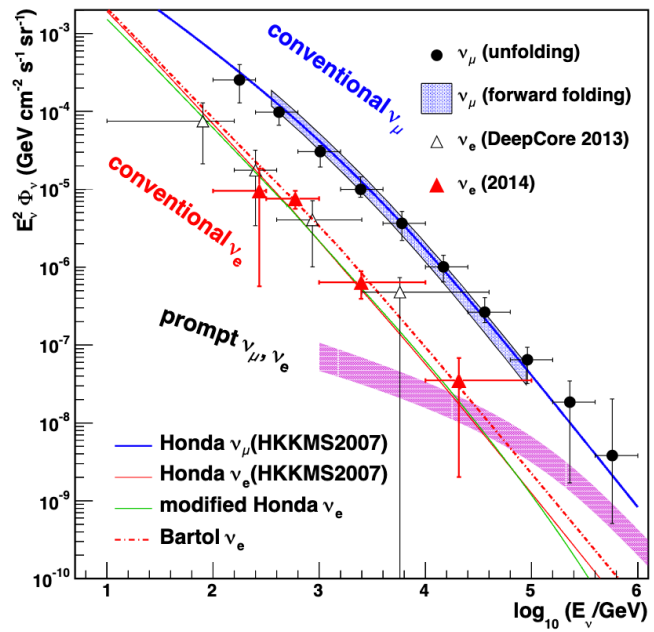
Atmospheric neutrino flux background to astrophysical neutrino flux



IceCube, PoS (ICRC2017) 1005



IceCube, PRD 91 (2015) 122004

Charm production in the atmosphere is primary source of prompt neutrinos.

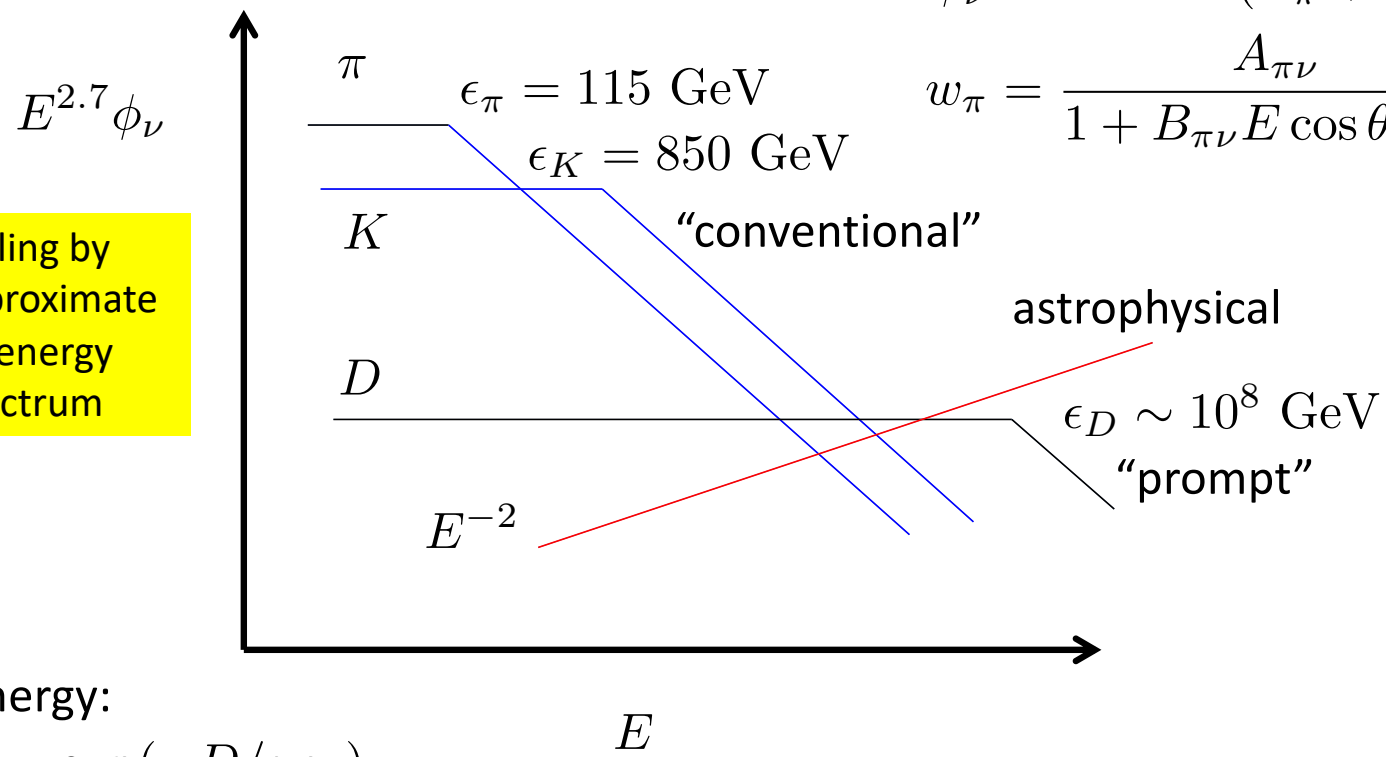
Energy dependence, schematically

approximate atm nu flux:

$$\phi_\nu = C \cdot E^{-\alpha}(w_\pi + w_K + w_D)$$

$$w_\pi = \frac{A_{\pi\nu}}{1 + B_{\pi\nu} E \cos\theta^* / \epsilon_\pi}$$

Scaling by approximate CR energy spectrum



extra power of energy:

$$P_{decay}(E) = 1 - \exp(-D/\gamma c\tau)$$
$$\simeq D/\gamma c\tau = E_c/E$$

Cascade equations, *Z*-moment approximate solutions

$N = CR$ nucleon

Cascade equations: $j = N,\ \pi,\ K,\ D,\ \nu_i,\ \mu$

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

Source terms and *Z*-moment approximations:

$$S(k \to j) = \int_E^\infty dE' \frac{\phi_k(E', X)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

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

$$Z_{kj}(E) = \int_E^\infty dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

$$\phi_\nu^{\rm low} = \sum_M \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \phi_N^{\rm CR}$$

prompt

$$\phi_\nu^{\rm high} = \sum_M \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \times \frac{\ln(\Lambda_M/\Lambda_N)}{1 - \Lambda_N/\Lambda_M} \frac{\epsilon_M}{E} \phi_N^{\rm CR}$$

conventional

$$\Lambda_M = \lambda_M/(1 - Z_{MM})$$

e.g., CR spectrum weighted differential cross sections

Z_{pD} $\quad p + {\rm Air} \to c\bar{c}X$

Ingredients for the prompt neutrino flux

$N = CR$ nucleon

- Cosmic ray flux: spectrum and composition.
- Cosmic ray cross section with air for Λ_N, weak energy dependence comes into *Z*-moment.
- Leading nucleon energy distribution for spectrum weighted *Z*-moment Z_{NN}.
- Charm production cross section and fragmentation.
- Charm hadron energy distributions for the CR spectrum weighted *Z*-moment.
- (Charm re-scattering distribution.)
- Charm hadron decay distribution.

$$\phi_\nu^{\text{low}} = \sum_M \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \phi_N^{\text{CR}}$$

prompt

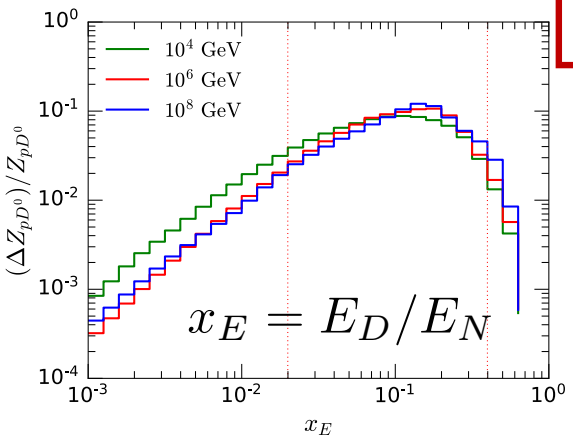
$$\phi_\nu^{\text{high}} = \sum_M \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \times \frac{\ln(\Lambda_M/\Lambda_N)}{1 - \Lambda_N/\Lambda_M} \frac{\epsilon_M}{E} \phi_N^{\text{CR}}$$

conventional

$$Z_{kj}(E) = \int_E^\infty dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

Example: Z_{pD}

from $p + \text{Air} \to c\bar{c}X$



Z_{pD}

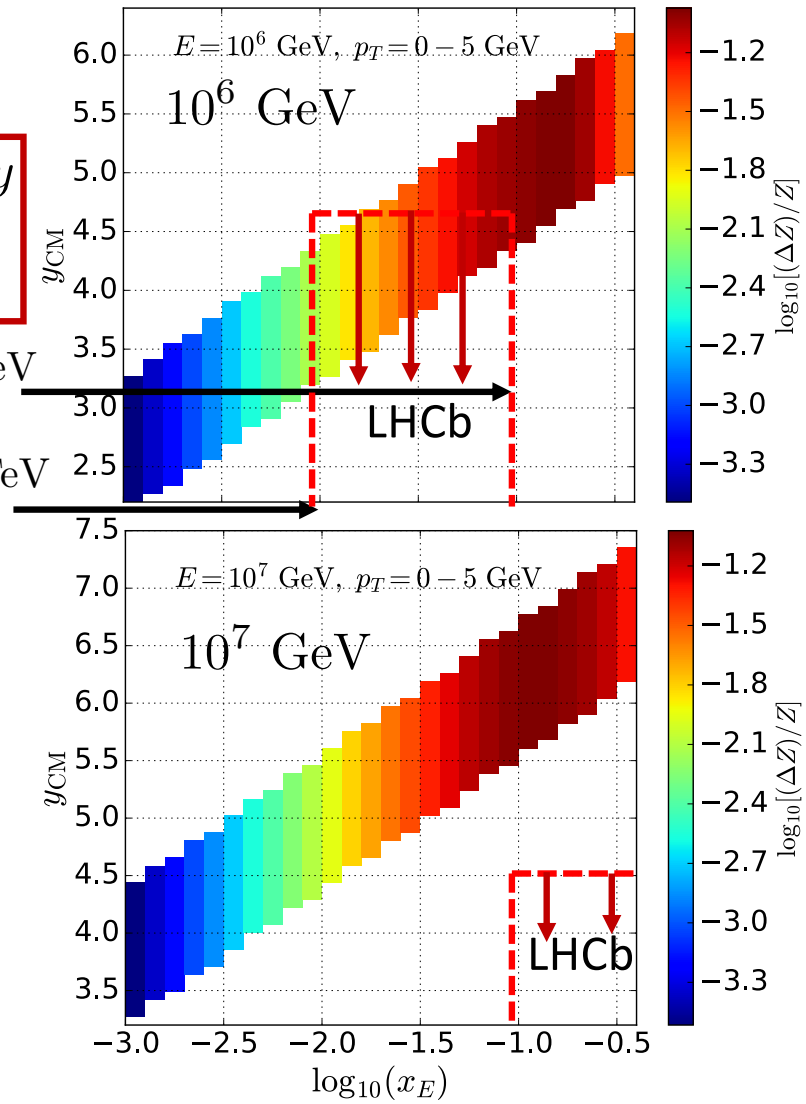
Translate "lab" to "CM" frame

$x_E(\sqrt{s}, p_T) \to y$

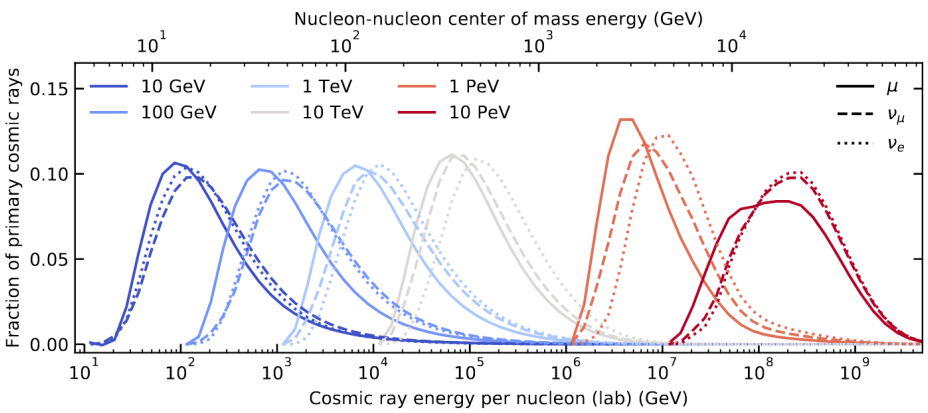
dashed boxes: approx LHCb ranges

$\sqrt{s} = 4.3$ TeV

$\sqrt{s} = 13.7$ TeV

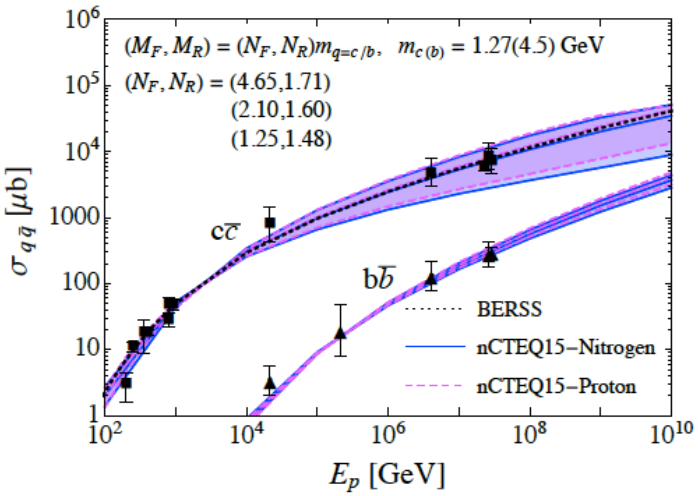


Take home message – a wider range of rapidity measurements at the LHC would narrow prompt predictions.

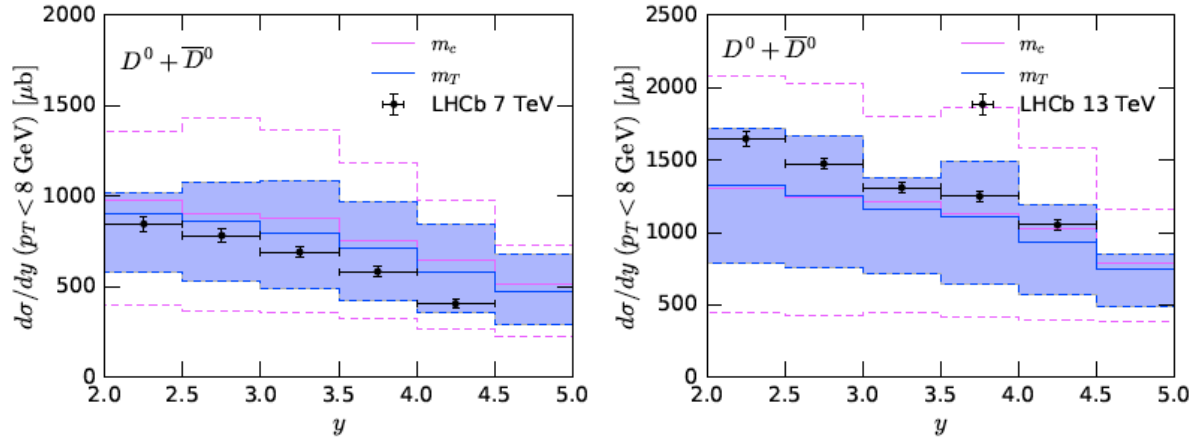


Fedynitch et al., PRD 100 (2019) 103018

Use LHCb data



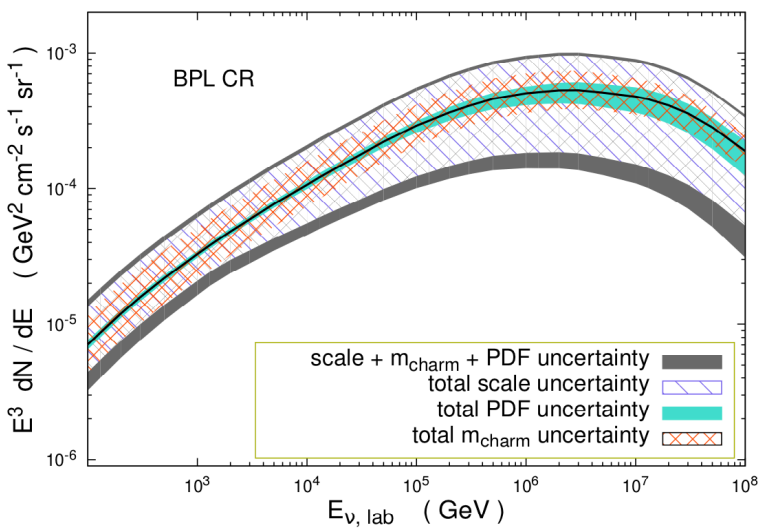
Bhattacharya et al, JHEP 06 (2015) 110 (BERSS) and JHEP 11 (2016) 167



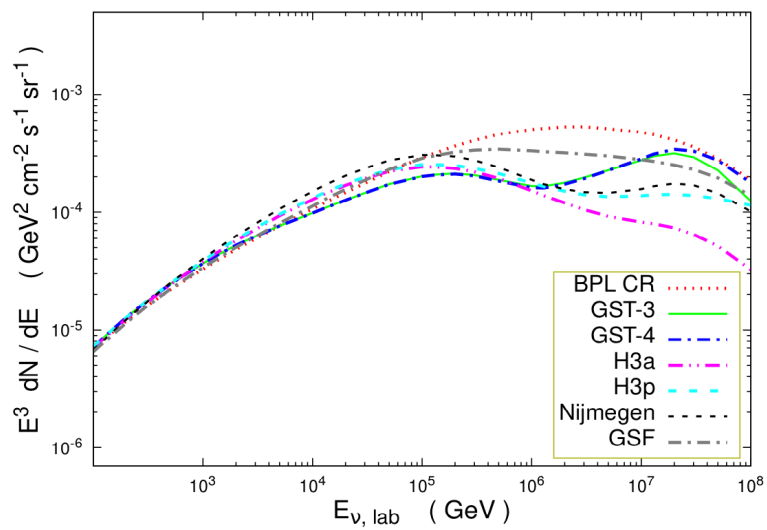
- Range of predictions depending on approaches: pQCD collinear approximation, k_T factorization, dipole approximation.
- NLO QCD evaluation has a strong dependence on renormalization, factorization scales (seen in these figures).
- LHCb data cross-checks for forward rapidity.

Sample prediction of prompt atmospheric neutrino flux with NLO QCD evaluation

CR flux: broken power law (ν_μ + anti-ν_μ) flux

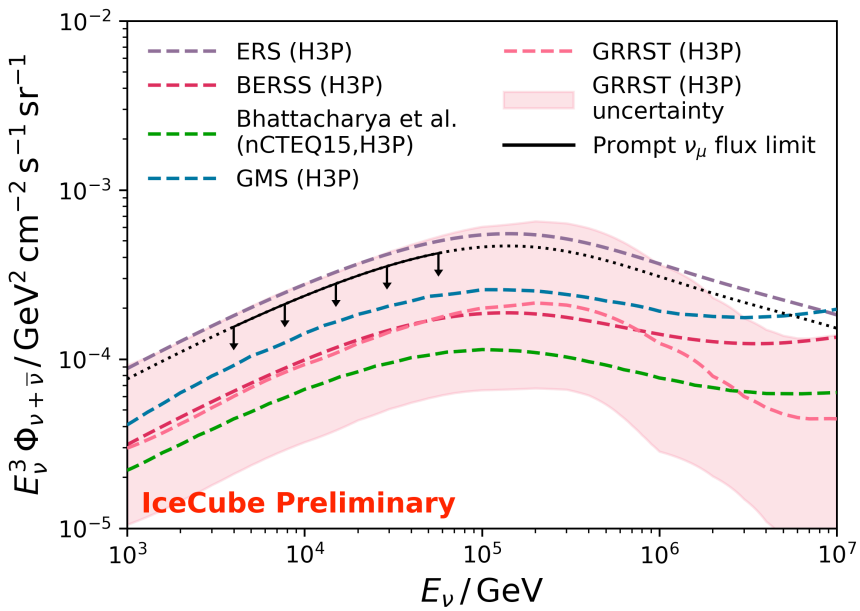


(ν_μ + anti-ν_μ) flux CR flux: mix of inputs



PROSA Collaboration, Zenaiev et al, JHEP 118 (2020) with scale, charm mass, PDF uncertainty (left), and range of input CR spectra & composition (right).

IceCube upper bound on prompt atmospheric neutrino flux



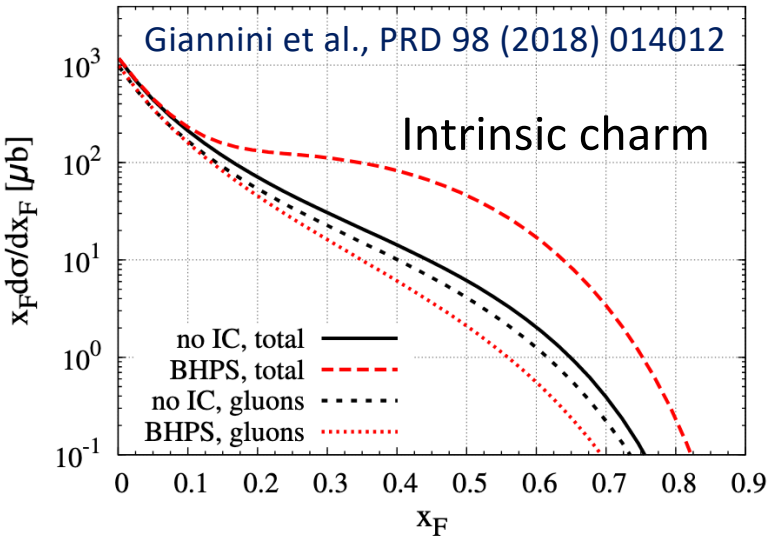
As in IceCube, ApJ 833 (2016), updated

Enberg et al, PRD 78 (2008)
Bhattacharya et al, JHEP (2015) 110
Gauld et al, JHEP (2016) 130
Garzelli et al, JHEP (2015) 115

Notes:

- prompt flux from b-quarks ~ 10% of flux from c-quarks
- prompt flux of tau neutrinos ~ 10% of prompt flux of muon neutrinos
- nuclear corrections potentially play a role – small *x* parton distribution functions

High-energy, forward measurements of charm production are needed



Maximal BHPS model of intrinsic charm translates to an increase in the prompt neutrino flux prediction (factor of 1.5).

- Uncertainty band expands with introduction of intrinsic charm.
- Measure forward charm, neutrino production:
  pions, kaon, charm
- New opportunities with tau neutrino measurements

$$D_s \to \tau \nu_\tau$$
$$\tau \to \nu_\tau X$$

e.g., SHiP, FASERν, Forward Physics Facilities

Alekhin et al., Rept. Prog. Phys. 79 (2016), Abreu et al., 2001.03073, Buontempo et al. 1804.04412,Beni et al., 1910.11340, Bai et al., JHEP 06 (2020) 032, Albrow, 2006.11680 and others

Cosmic – Energy – Neutrino Frontiers

Talks by Jonathan Feng, Michael Albrow in this session.
See also session 92. Non-perturbative QCD dynamics at colliders.