Relevance for neutrino telescopes

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LHC Neutrinos

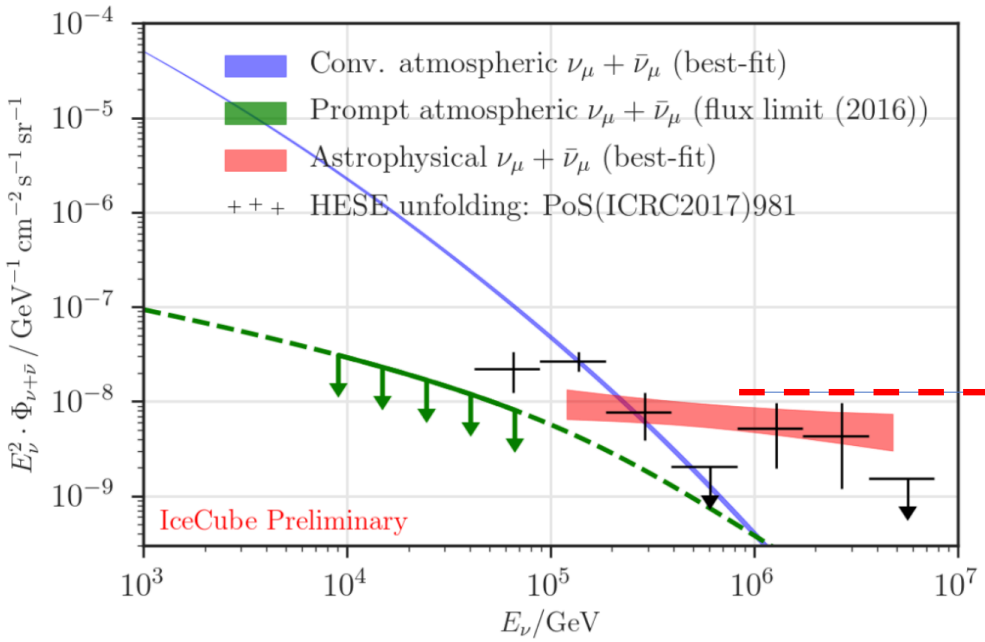
Work supported in part by the US Department of Energy

Relevance to neutrino telescopes

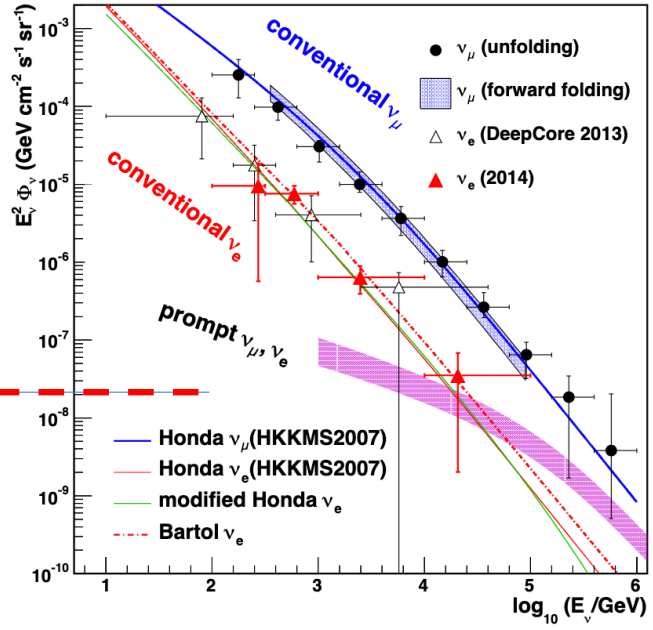
1) Charm production and the prompt neutrino flux
2) Neutrino cross sections
3) Forward physics, neutrinos and muons from pions, kaons, other light mesons

Atmospheric neutrino background to astrophysical neutrino flux

energy scaling E^2



IceCube, PoS (ICRC2017) 1005



IceCube, PRD 91 (2015) 122004

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

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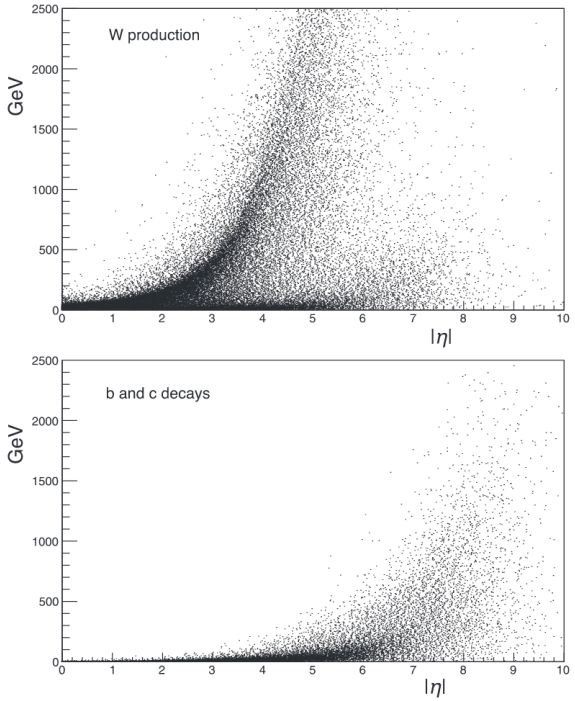
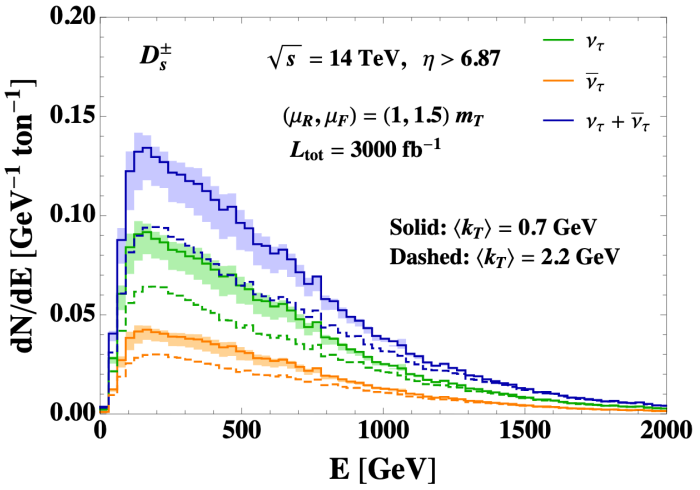
- Tight connection between forward physics with neutrinos at the LHC and the atmospheric lepton fluxes at high energies through charm production.

Beni et al., J Phys G 47 (2020) 12



Variation in kT



Bai et al, HEP 06 (2020) 032

Charm production in the atmosphere, schematically

approximate atm nu flux:

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

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

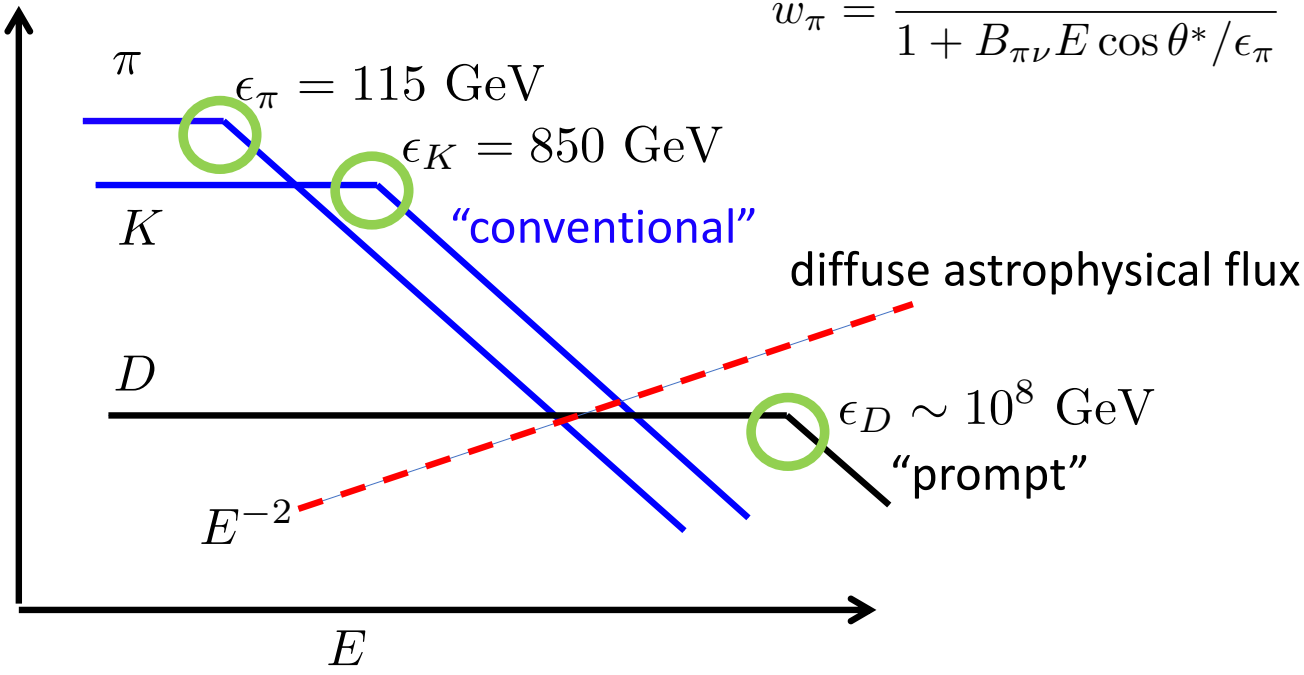
Energy dependence

$E^{2.7}\phi_\nu$

Scaling by approximate CR energy spectrum

$\sigma_{c\bar{c}} < \sigma_{\pi,K}$

At critical energy, more probable to interact than decay.



extra power of energy:

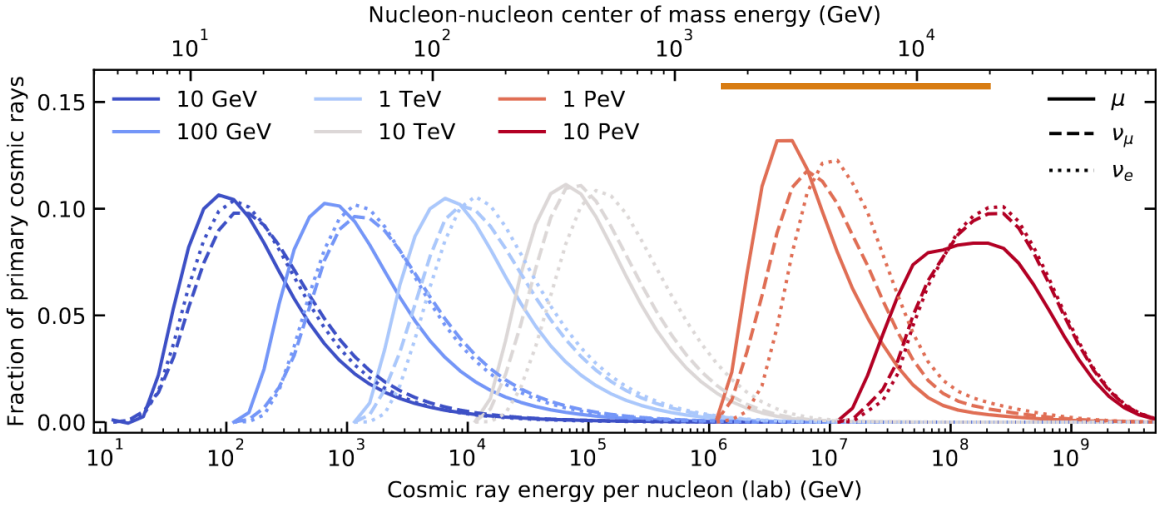
$$P_{\rm decay}(E) = 1 - \exp(-D/\gamma c\tau_i)$$
$$\simeq D/\gamma c\tau = \epsilon_i/E$$

(not the usual energy scaling here)

Spectrum weighted charm cross section

$$E^{-2.7} - E^{-3}$$

$$S(\mathrm{CR} \to c) = \int_{E_c}^{\infty} dE_{\mathrm{CR}} \frac{\phi_{\mathrm{CR}}(E_{\mathrm{CR}}, X)}{\lambda_{\mathrm{CR}}(E_{\mathrm{CR}})} \frac{1}{\sigma_{\mathrm{CR}}(E_{\mathrm{CR}})} \frac{d\sigma(\mathrm{CR} \to c; E_{\mathrm{CR}}, E_c)}{dE_c}$$



Fedynitch et al., PRD 100 (2019) 103018

Example:
1 PeV neutrino comes from 1 PeV - >100 PeV energy/nucleon CR.

$$\left\langle \frac{E_c}{E_N} \right\rangle \sim 0.1$$

Atmospheric neutrinos from charm

$$x_E = E_D / E_p$$
$$x_E(\sqrt{s}, p_T) \rightarrow y$$

- Higher neutrino energies, weighted with falling cosmic ray spectrum, mean higher charm rapidities.
- Combination of large *x* and small *x* (gluon) pdfs - which can be probed by LHC forward neutrino production via charm

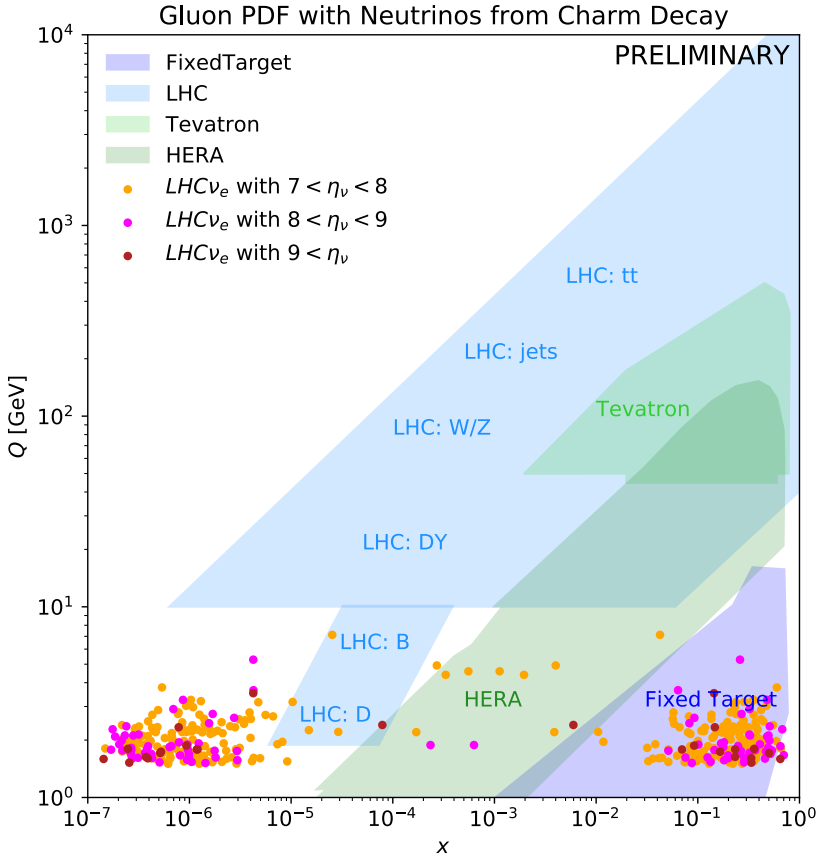
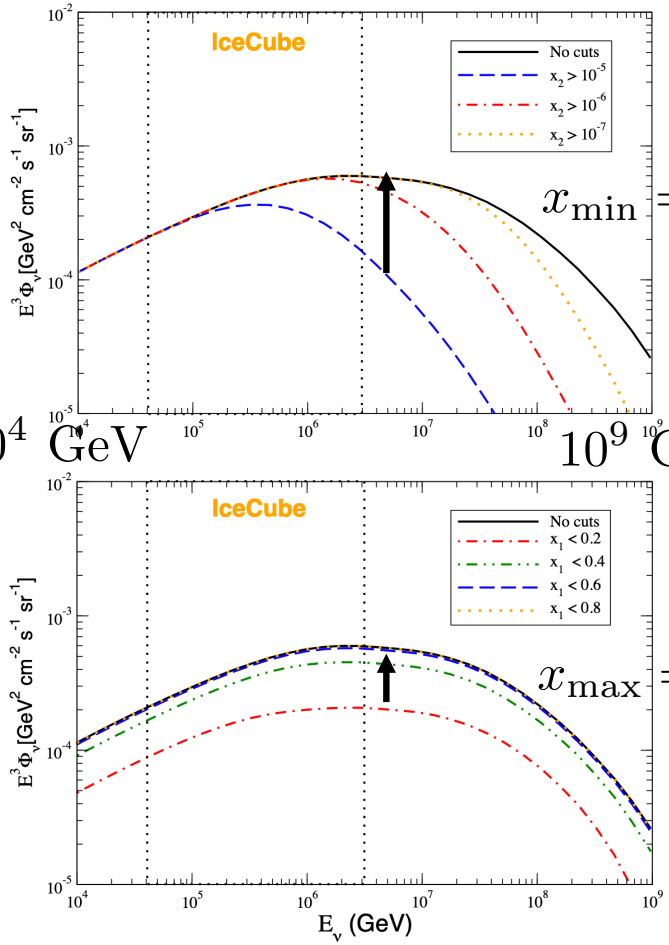


Figure courtesy of F. Kling

Goncalves, Maciula, Pasechnik and Szczurek, PRD 96 (2017)

prompt neutrino flux, energy scaling E^3



$x_{\min} = 10^{-5} \rightarrow 10^{-7}$

10^4 GeV 10^9 GeV

$x_{\max} = 0.2 \rightarrow 0.8$

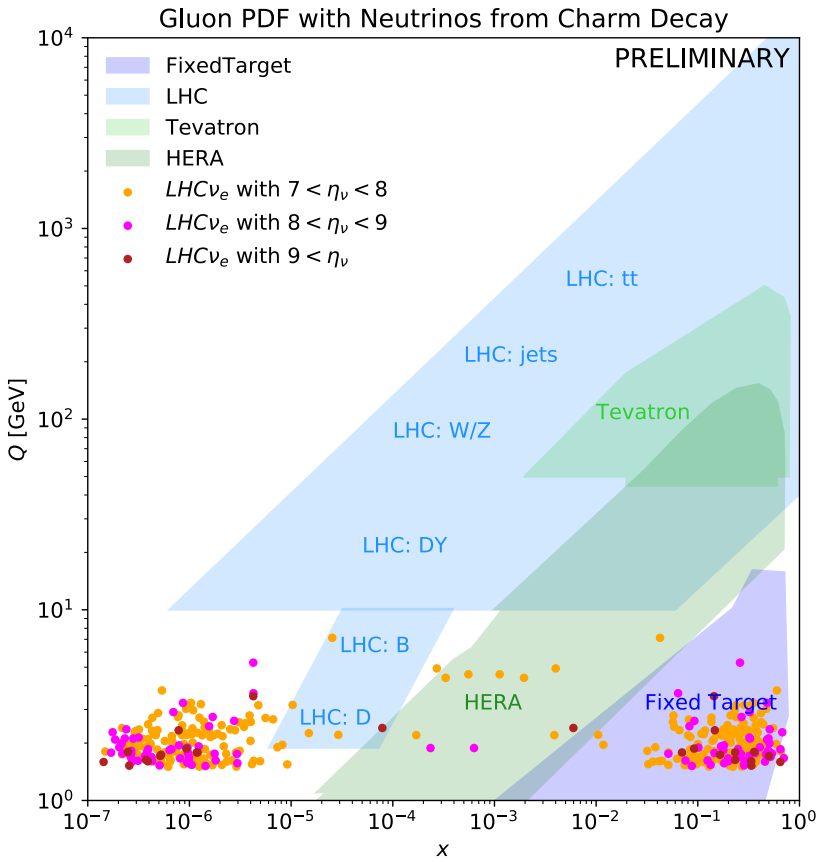
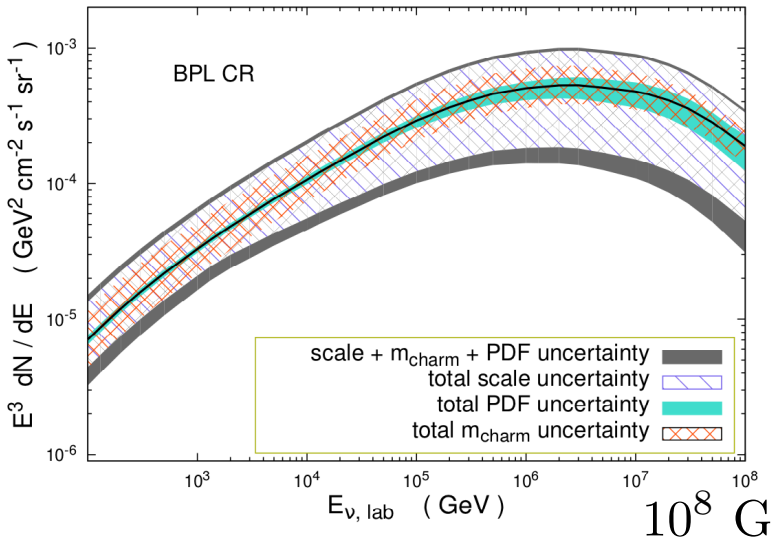


Figure courtesy of F. Kling

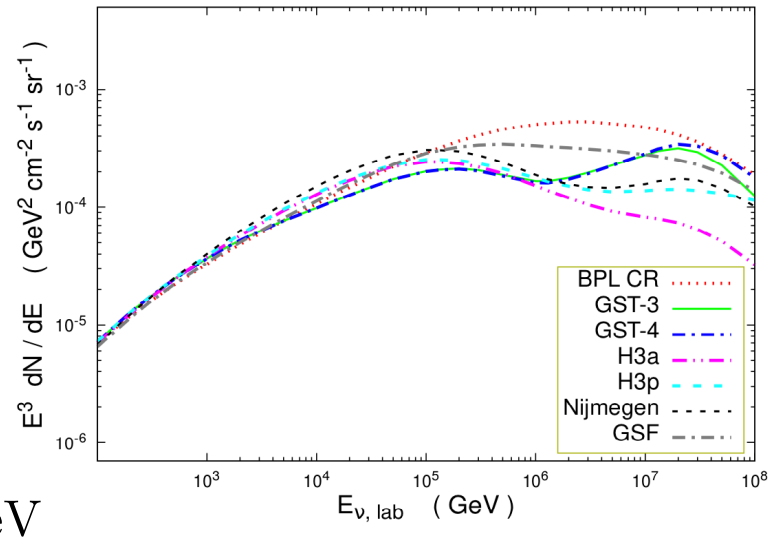
Sample predictions of prompt atmospheric neutrino flux with NLO QCD evaluation

Direct measurements of charm production in the forward region will constrain inputs to prompt flux calculations.

CR flux: broken power law $(\nu_\mu + \text{anti-}\nu_\mu)$ flux



$(\nu_\mu + \text{anti-}\nu_\mu)$ flux CR flux: mix of inputs



10^8 GeV

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

Sample predictions of prompt atmospheric neutrino flux with NLO QCD evaluation

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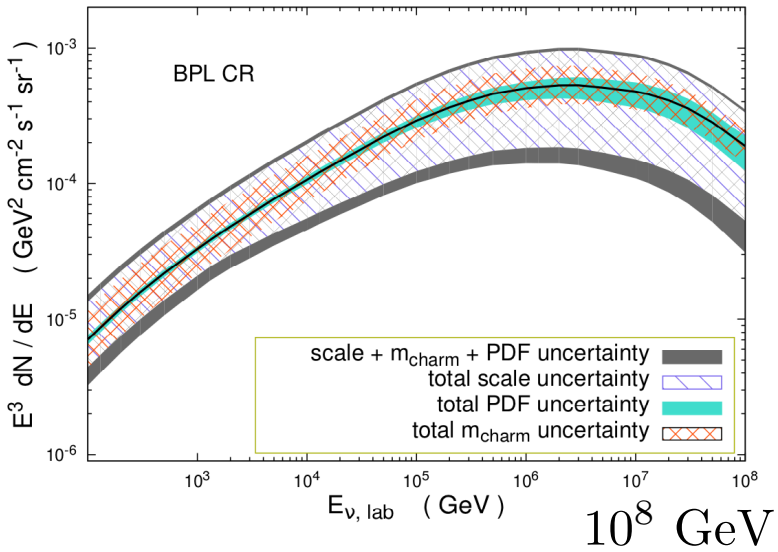
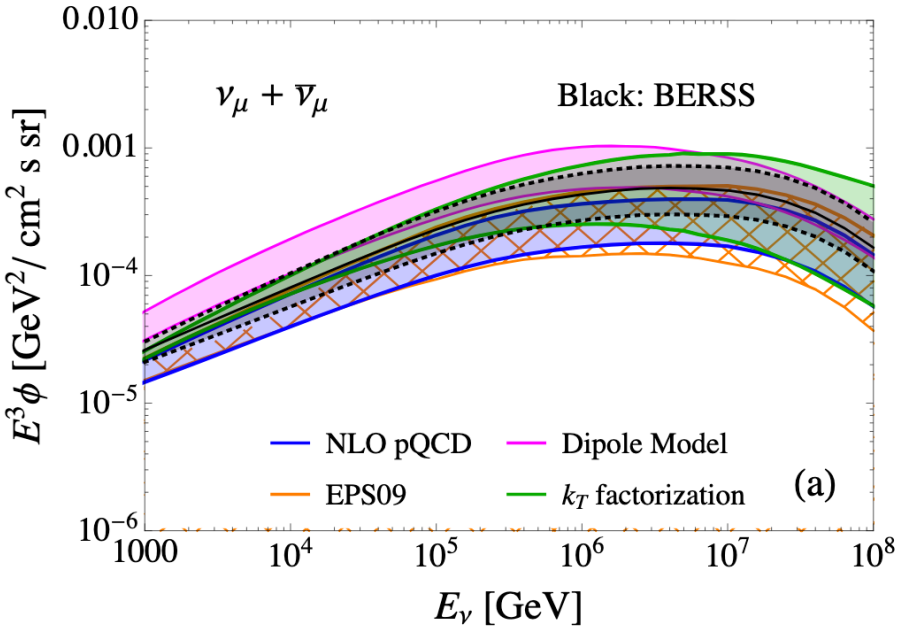


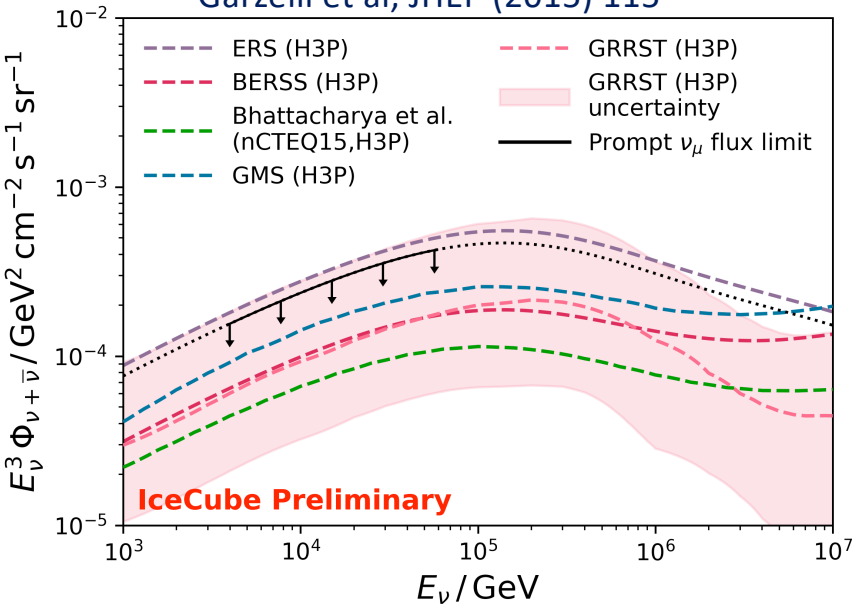
PROSA Collaboration, Zenaiev et al, JHEP 118 (2020) with scale, charm mass, PDF uncertainty (left)



Bhattacharya et al, JHEP 167 (2016)

IceCube upper bound on prompt atmospheric neutrino flux

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



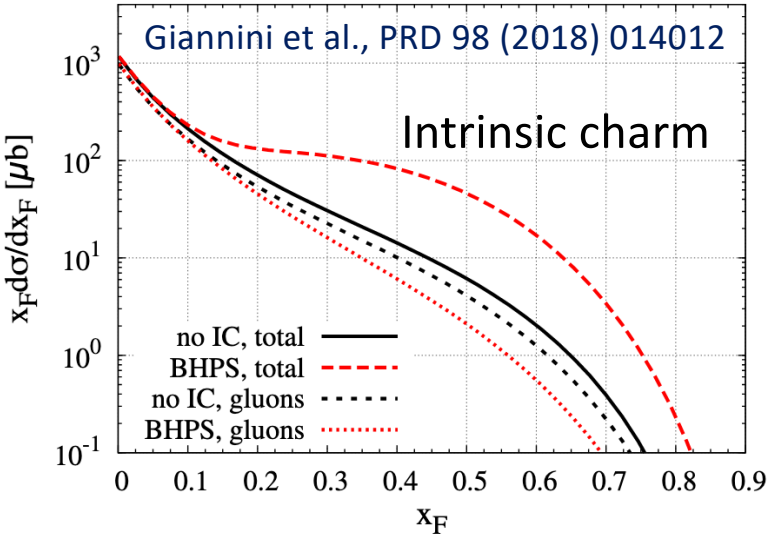
As in IceCube, ApJ 833 (2016), updated

Direct measurements of charm production in the forward region will constrain inputs to prompt flux calculations.

- 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

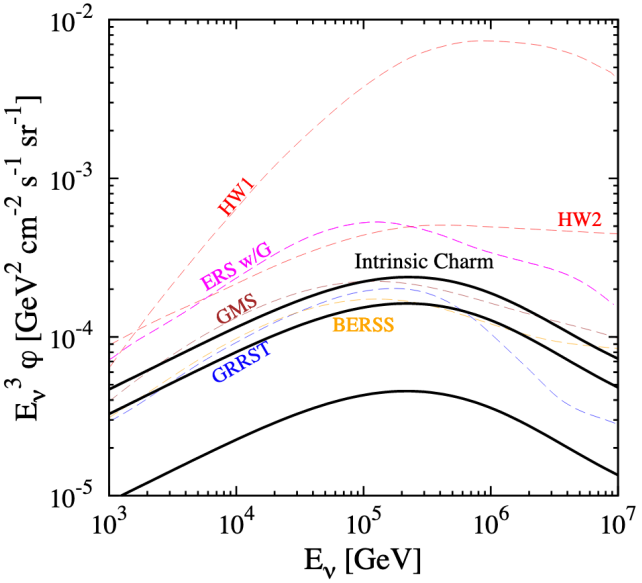
Forward charm enhancements

Direct measurements of charm production in the forward region will constrain inputs to prompt flux calculations.



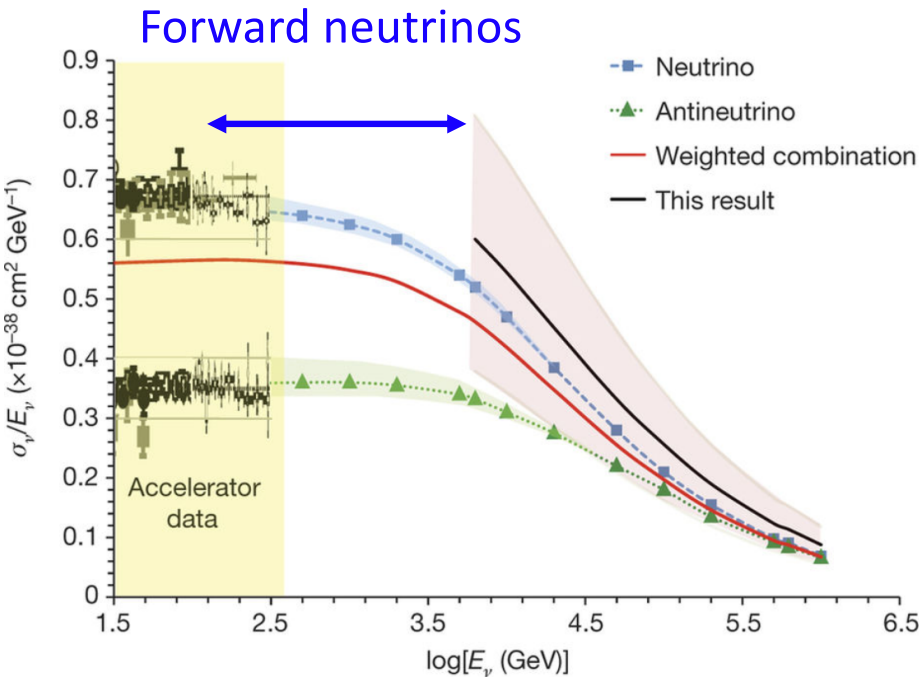
$\sqrt{s} = 13$ TeV

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



Laha and Brodsky, PRD 96 (2017) 123002
See also, Halzen & Wille, PRD 94 (2016) 1, coalescence of charm with valence quarks.

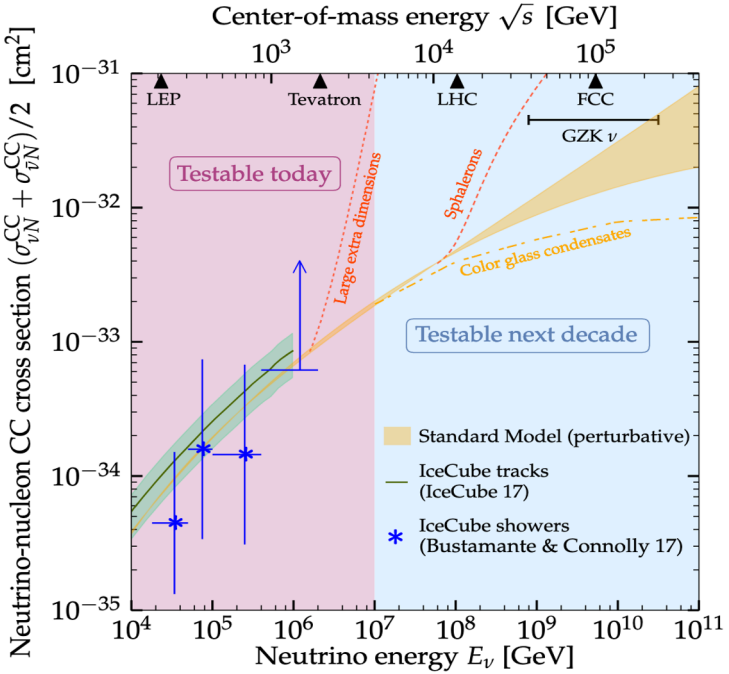
2) Neutrino cross sections



IceCube, Nature 551, 596 (2017)

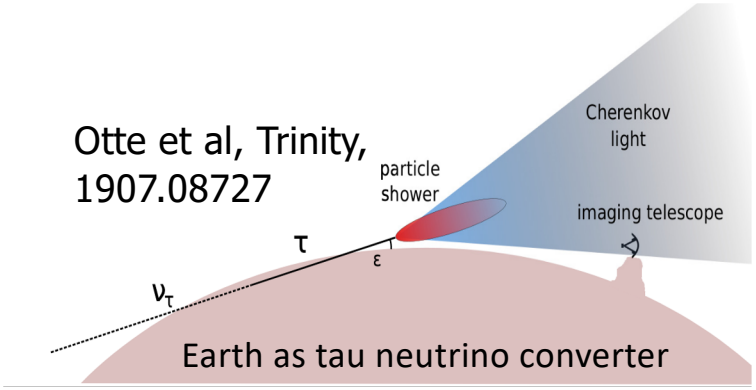
Close the measurement gap!

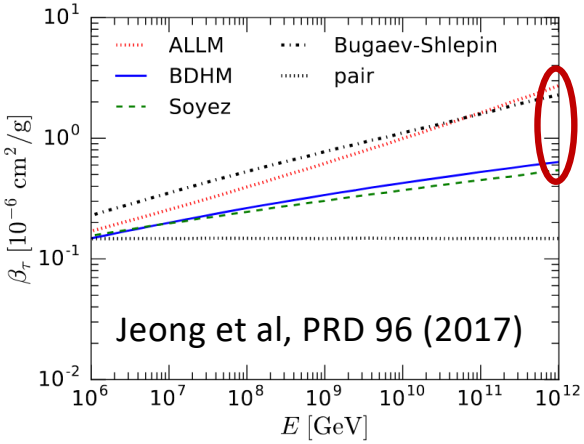
Ackermann et al., 1903.04333



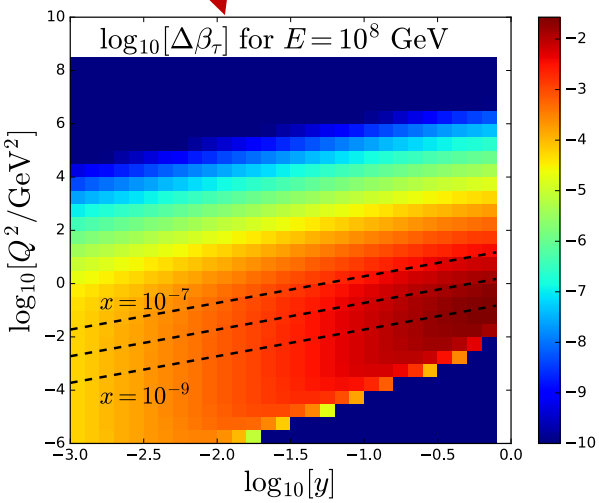
- Direct cross section measurements above 350 GeV.
- Tau neutrinos!
- Small-*x* PDFs for the UHE neutrino-nucleon cross section.

Small-*x* PDFs and UHE neutrinos: EM energy loss





photonuclear energy loss



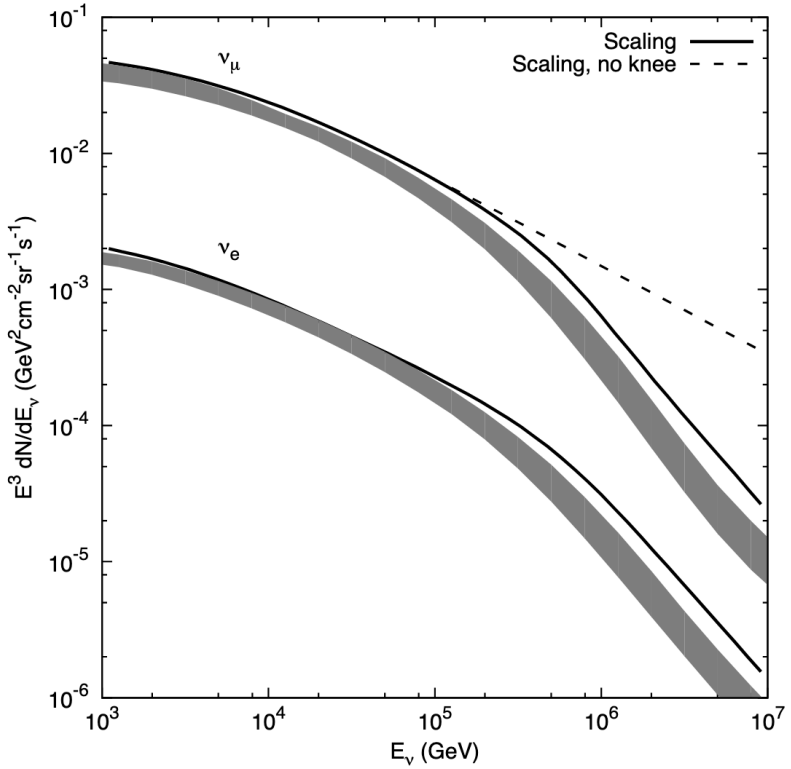
Skimming tau neutrinos: Tau neutrino showers play a big role in some detection methods (optical or radio Cherenkov): on surface or on balloons/satellite, e.g., GRAND, Trinity, ANITA, POEMMA

Neutrino interacts, then tau loses energy in the Earth. Photo-nuclear energy loss of the tau depends on small-*x*, small Q^2 PDFs, (electromagnetic) structure function.

$$\left\langle \frac{dE}{dX} \right\rangle \simeq -\beta E$$

$$y = \frac{E - E'}{E}$$

3) Forward physics of pions, kaons

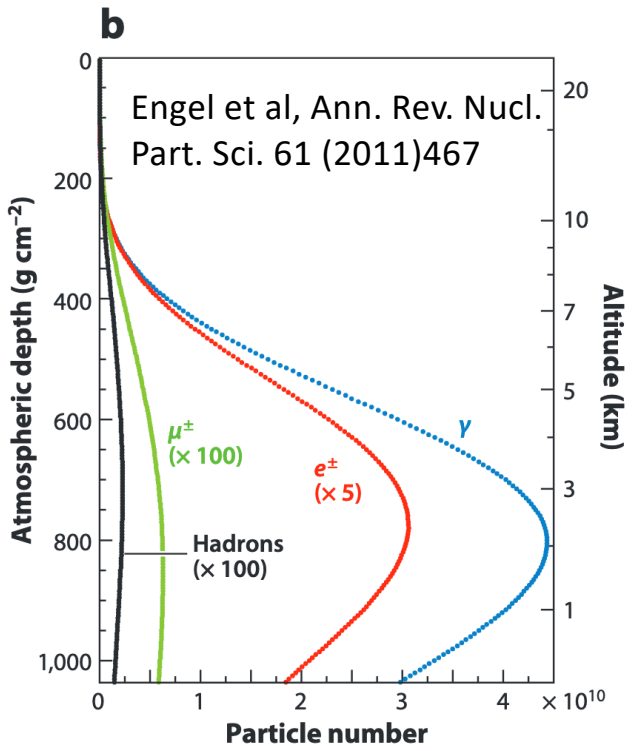


Gaisser, https://arxiv.org/pdf/1910.08851.pdf

Uncertainties in modeling the HE conventional flux.

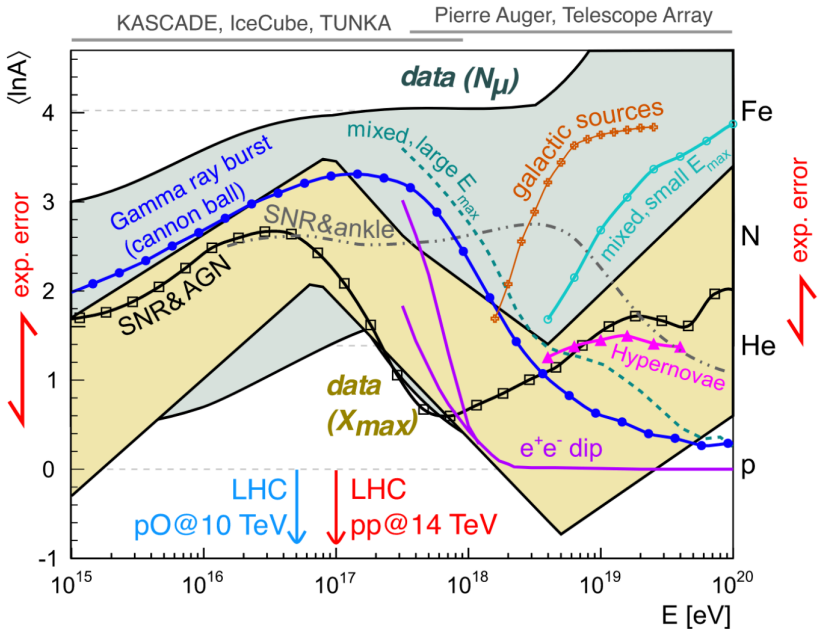
Shaded band: Sib2.1, EPOS-LHC, QGSJet II-04, Sib2.3
Variation up to +- 40% above PeV energies, larger than uncertainties from primary CR nucleon spectra.

Muon problem



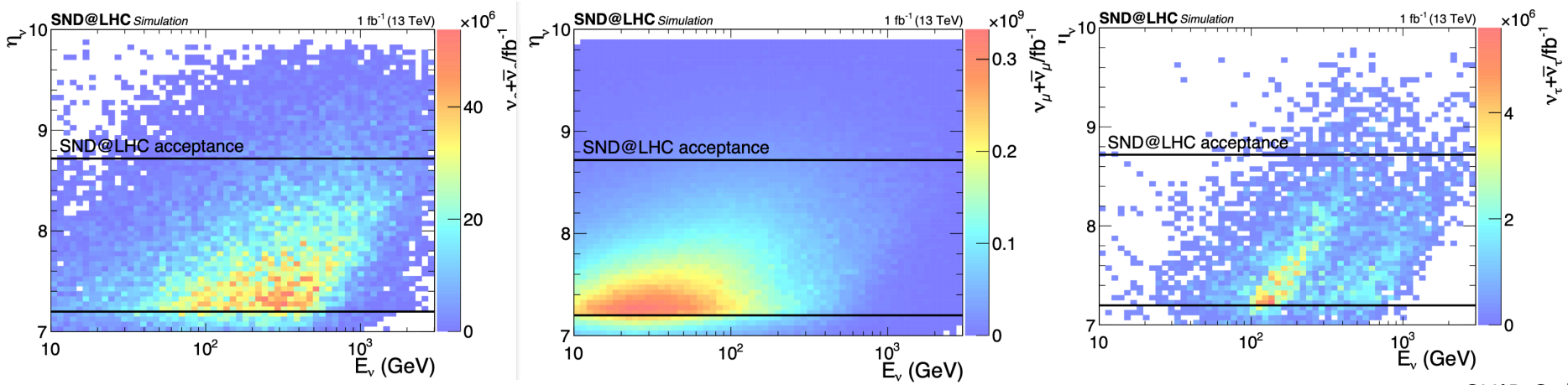
longitudinal shower profile E(proton)=1e+19 eV

Discrepancy between CR mass composition results using X_{max} and N_{mu}

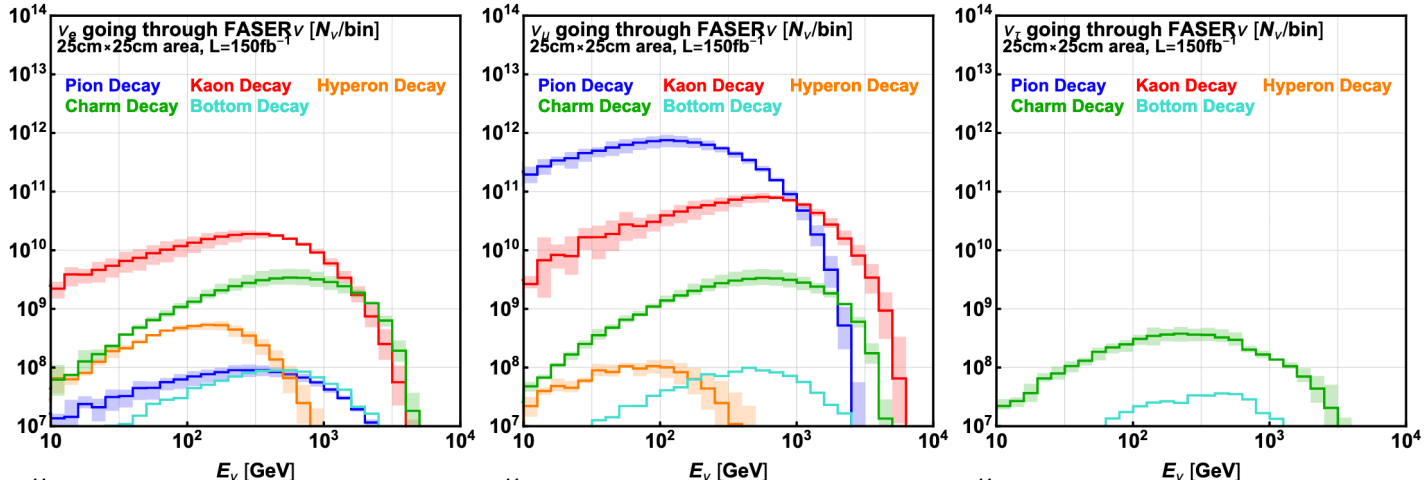


Kampert & Unger, Astropart. Phys. 35 (2012) 660
Dembinski et al. 1902.08124

Composition important to understand UHECR, also for atmospheric neutrino flux calculations.



SHiP Collab.,
2002.08722



FASER Collab,
Eur. J. Phys. C80 (2020) 81
1908.02310

Pion and kaon production and decay contribute to muon (electron) neutrinos to differing degrees, depending on rapidity.

Relevance to neutrino telescopes

- Cosmic ray flux: spectrum and composition
- ✱ Cosmic ray cross section with air
- Leading nucleon energy after interaction

- ✓ Charm production cross section and fragmentation
- ✓ Charm hadron energy distributions
- ✓ Charm hadron decay distribution
- Charm re-scattering distribution

1) Charm production and the prompt neutrino flux
(also charm production in astrophysical sources Carpio et al, PRD 102 (2020) 103001)
2) Neutrino cross sections –direct measurements, PDFs
✱ 3) Forward physics, neutrinos and muons from pions, kaons, other light mesons