Prompt atmospheric neutrino flux predictions: QCD models and nuclear effects

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Neutrinos produced in the atmosphere

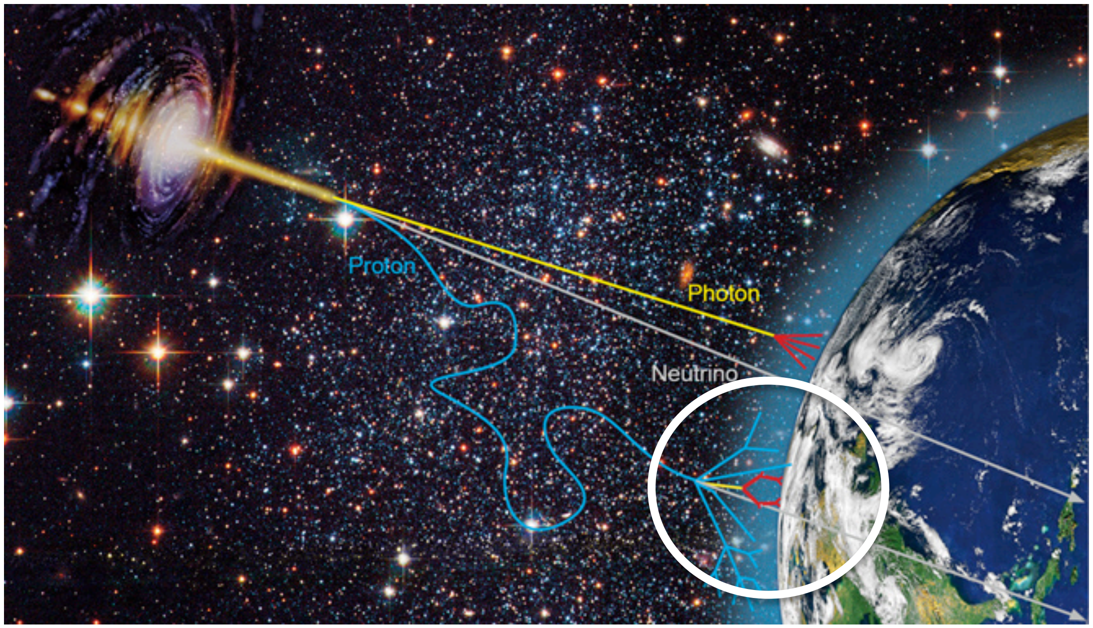


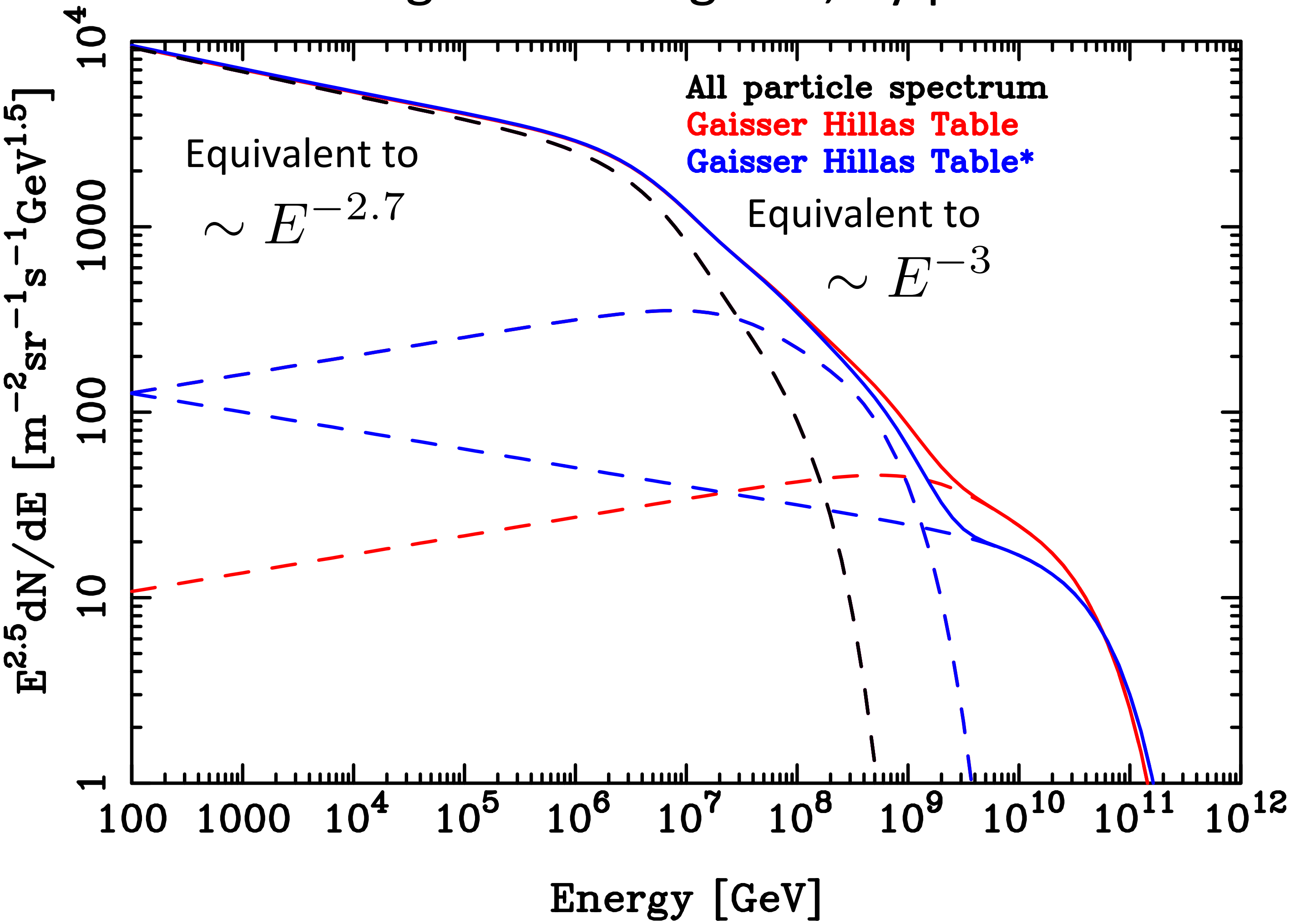
Figure from https://astro.desy.de/

Inputs include:

- cosmic ray (CR) flux and composition
- CR interactions with air nuclei to produce mesons/baryons that decay
- focus here on charm (and b quark) production

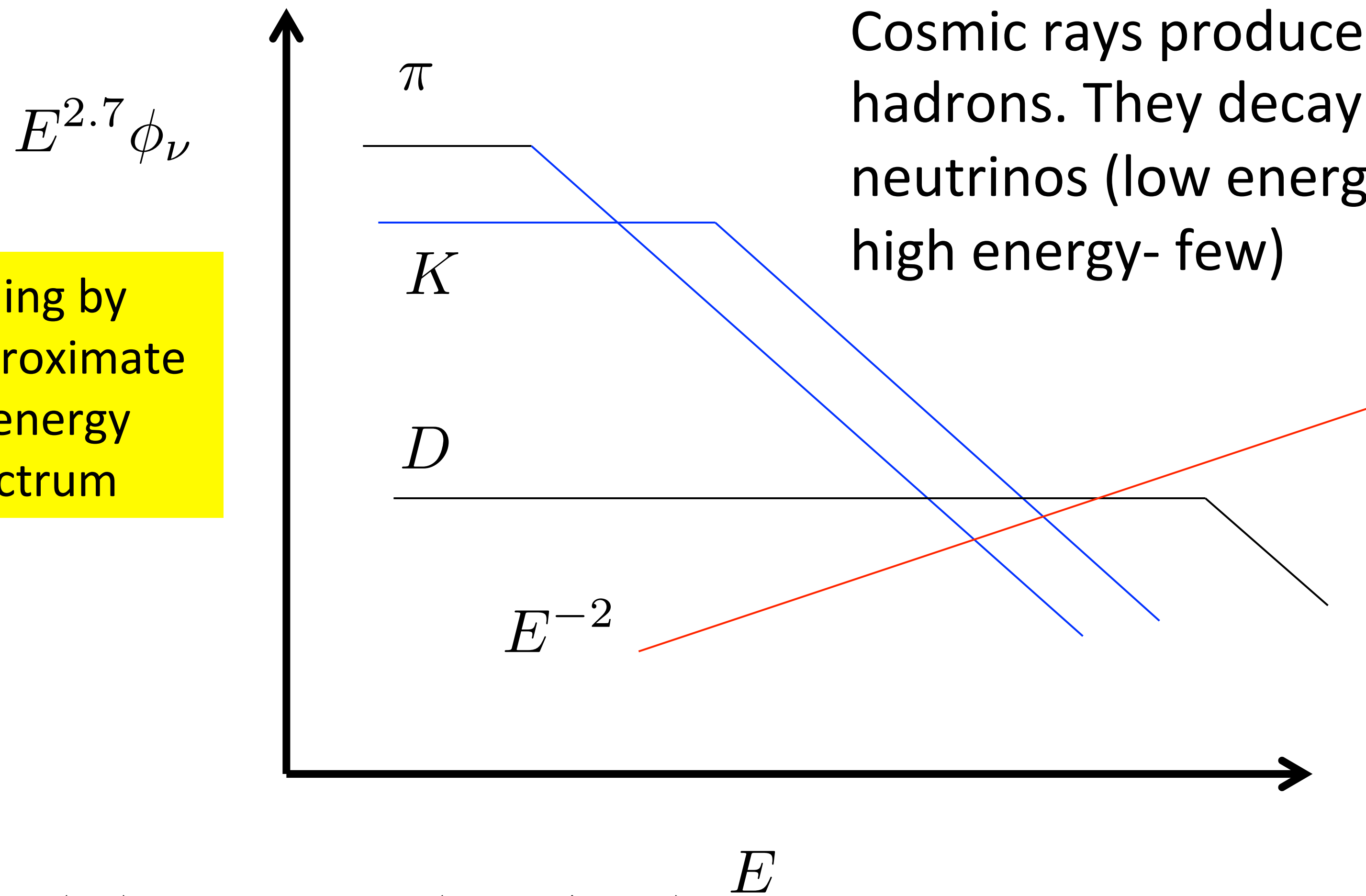
CR all particle spectrum

traditional rescaling in other figures, by power of 2.7 or 3



From Table 1, Gaisser, Astropart. Phys. 35 (2012) 801

Why charm? Energy dependence, schematically, neglecting break in power law of cosmic rays



Scaling by approximate CR energy spectrum

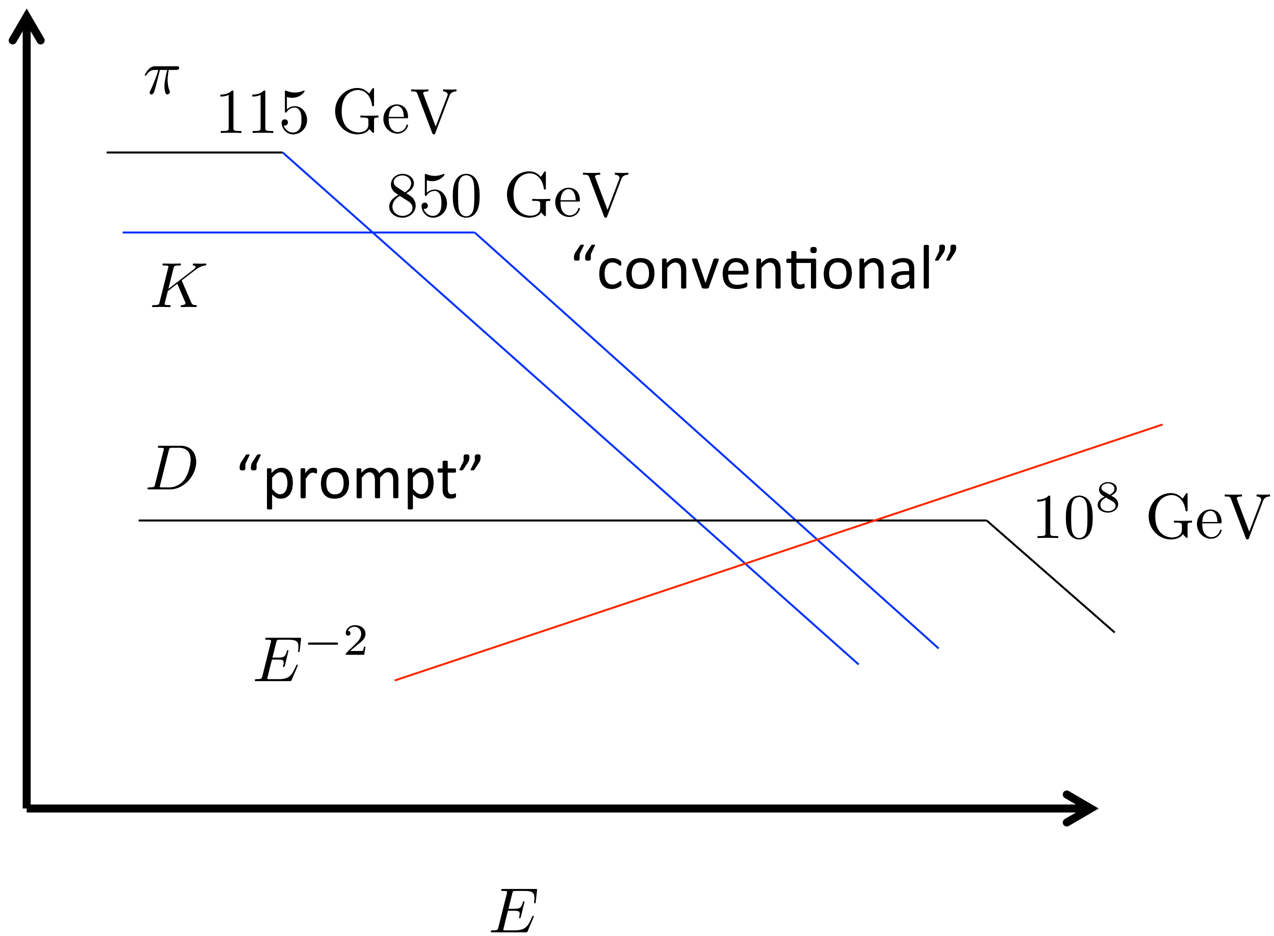
Cosmic rays produce hadrons. They decay to neutrinos (low energy-all, high energy- few)

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

$$\phi \sim \frac{1.7}{E_{\rm GeV}^{2.7}} \frac{1}{\rm cm^2 s\, sr\, GeV}$$

Energy dependence, schematically

Scaling by approximate CR energy spectrum



Electron neutrino flux from K-short, Gaisser & Klein, Astropart. Phys. 64 (2015) 1.2×10^5 GeV

Small parton fractional momentum *x* is important for charm in atmosphere

- Steeply falling flux convoluted with differential cross section for charm production.
- Favors forward production of charm (highest energy)

$x_1,\ x_2:$

$$x_F = x_1 - x_2$$
$$x_F \simeq x_E = E/E'$$

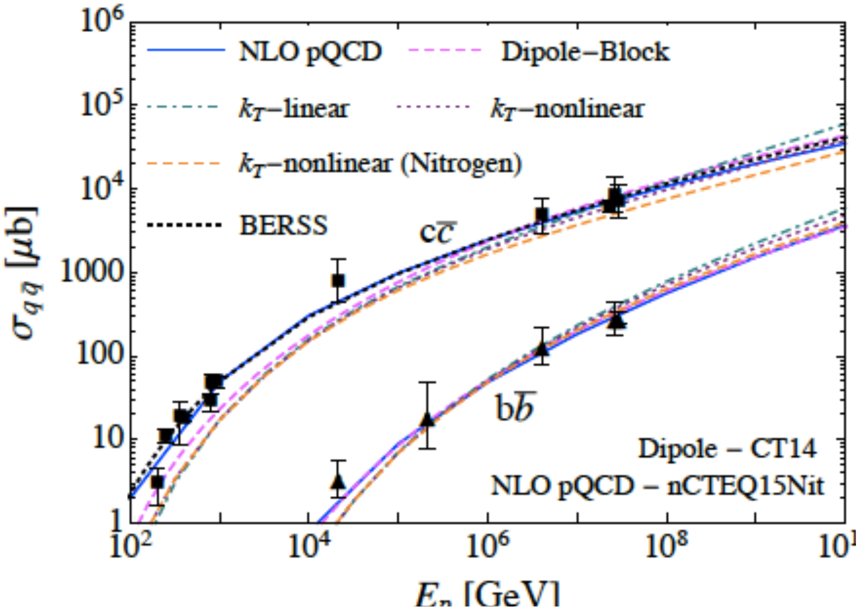
$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

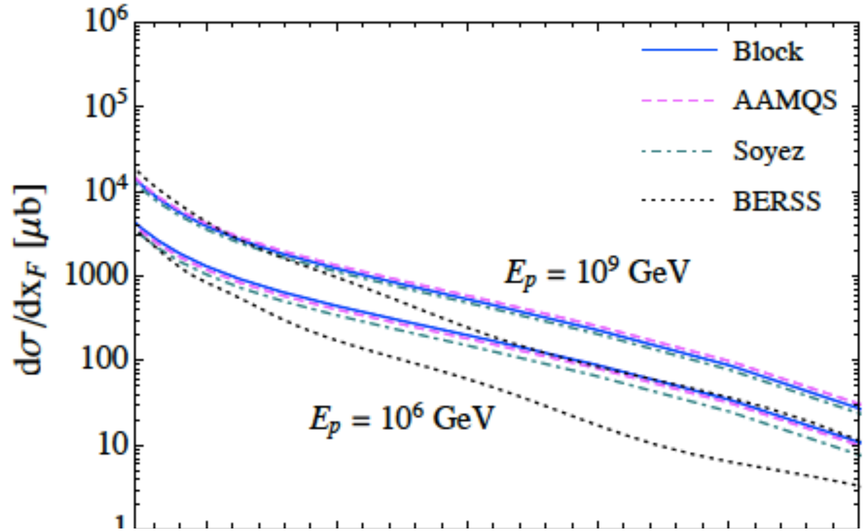
$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7\ \mathrm{GeV} \to x_2 \sim 10^{-6}$$

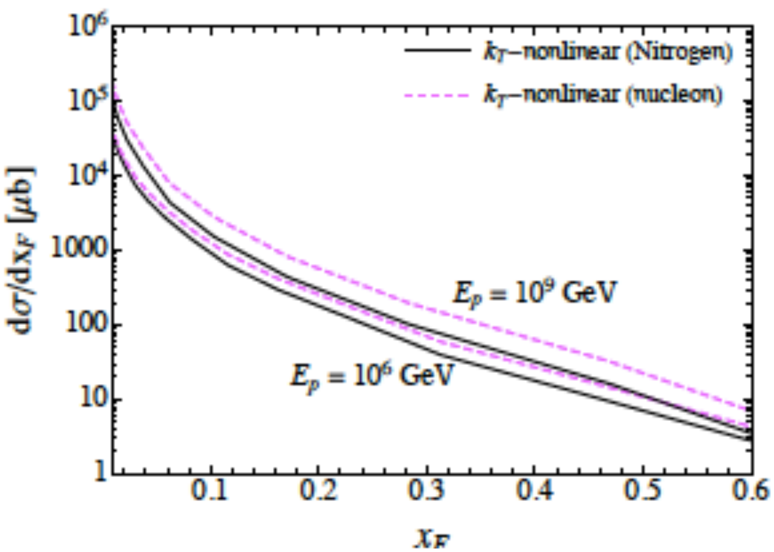
What is new in this prompt charm evaluation?

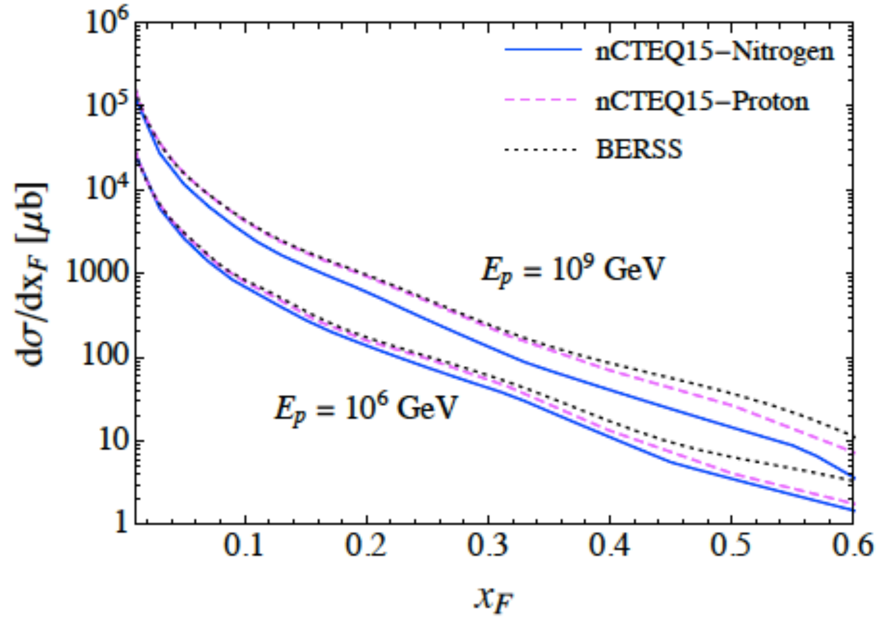
- NLO QCD evaluation of charm pair cross section and energy distribution with nuclear corrections. Cacciari, Greco, Nason, JHEP 9805 (1998); Cacciari, Frixion, Nason, JHEP 0103(2001); Mangano, Nason, Ridolfi, NP B273 (1992); Nason, Dawson, Ellis, NP B303 (1988), NP B373 (1992); Lai et al, PRD 82 (2010)
- Dipole Model: Soyez, Block et al. approximation, AAMQS (Soyez in ERS). Multiple ways to include nuclear corrections. Soyez, Phys. Lett. 655B (2007) 32, Block, Durand, Ha, Phys. Rev. D 89 (2014) 094027, Albacete et al. Phys. Rev. D 80 (2009) 034031. Enberg, MHR & Sarcevic, PRD 78 (2008).
- kT factorization, low x off-shell gluon. Catani, Ciafaloni and Hautmann, Nucl. Phys. B 366 (1991) 135; Collins and Ellis, Nucl. Phys. B360 (1991) 3, Kutak and Sapeta, Phys. Rev. D 86 (2012) 094043.

Cross section for charm, b quarks

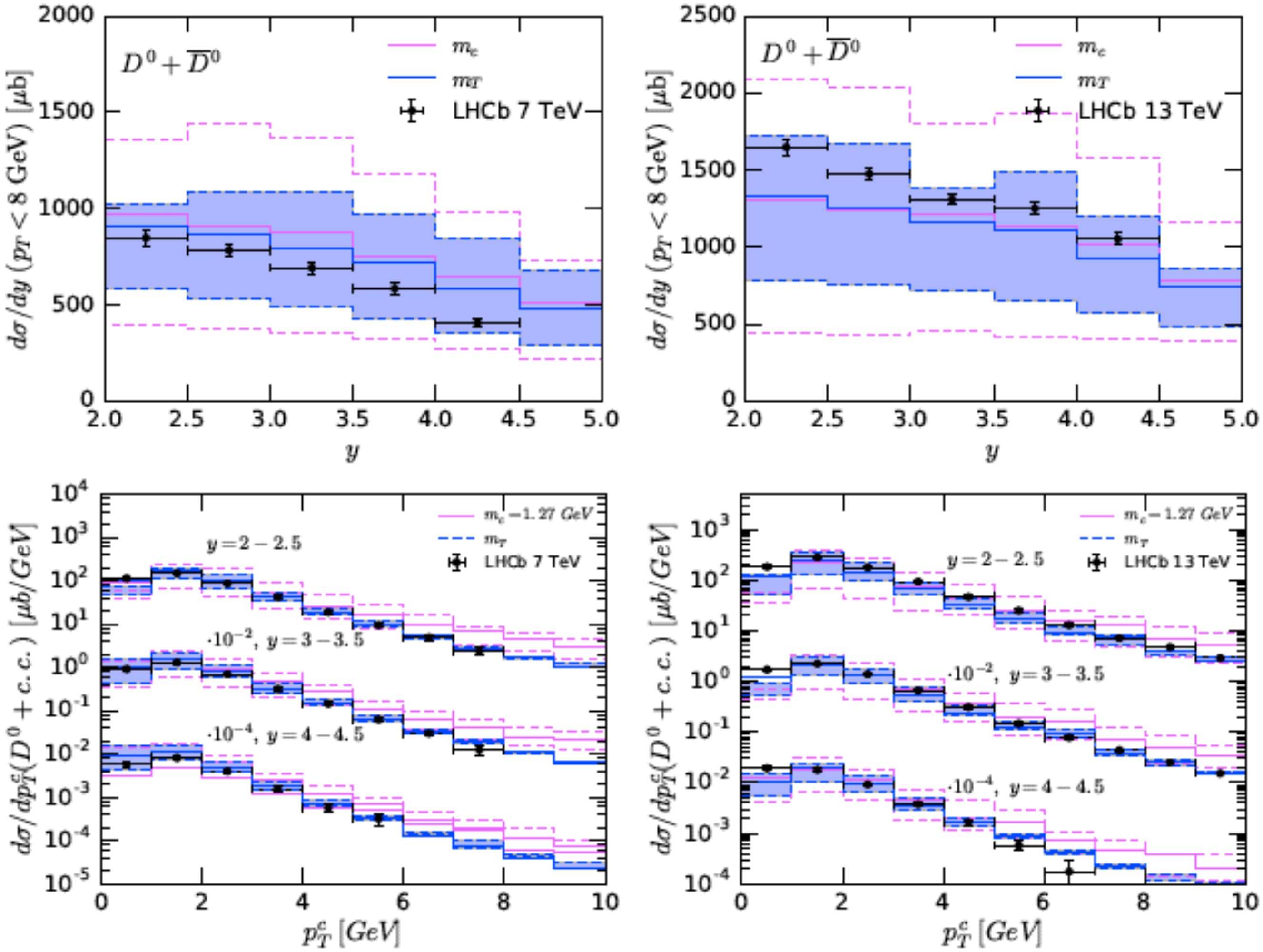








Compare with LHC data for charm

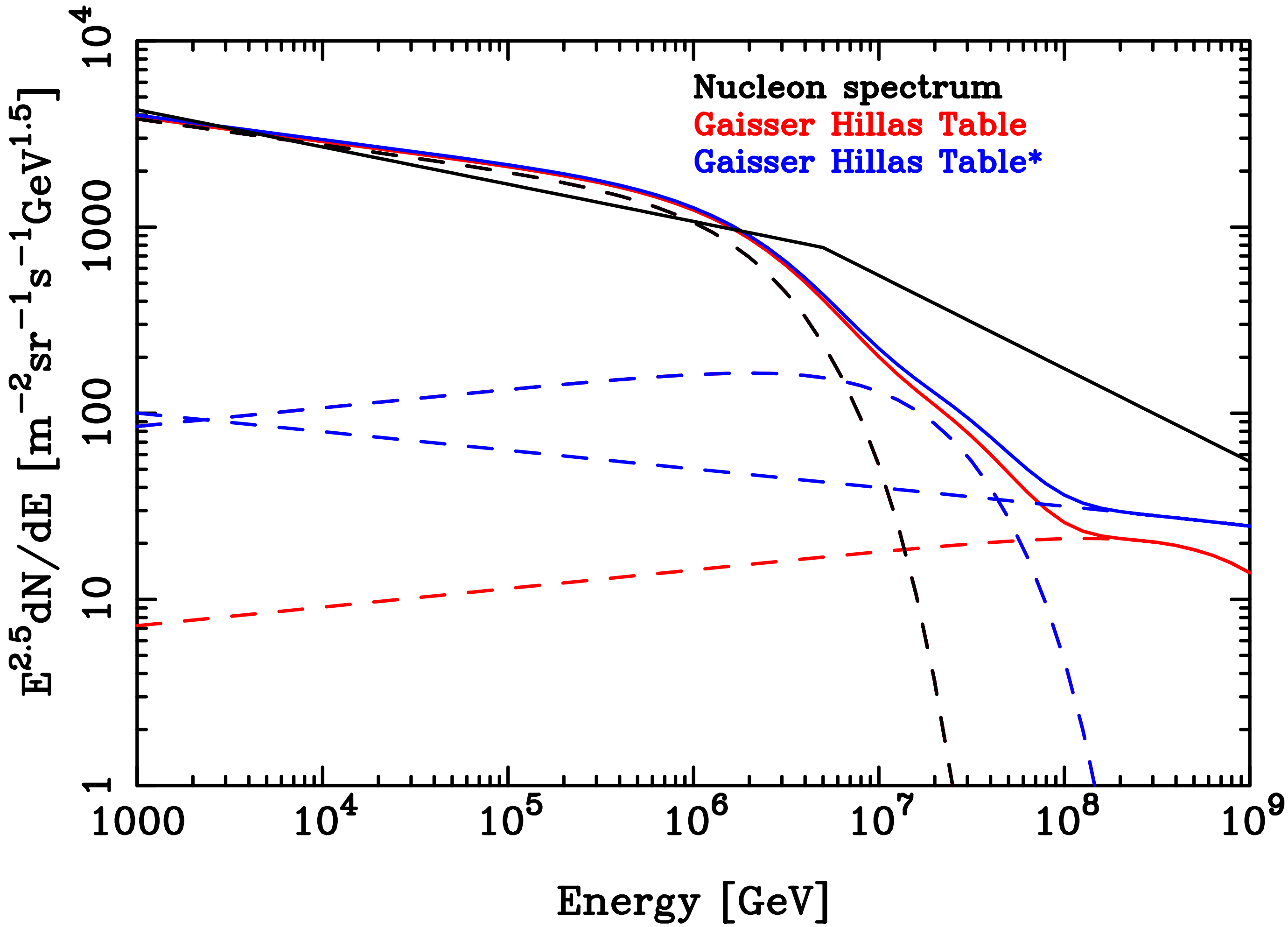


NLO perturbative for example. For the prompt flux from charm, need even larger rapidities.

LHCb, Nucl. Phys. B 871 (2013) 1; JHEP 03 (2016) 159

CR nucleon spectrum

Broken power law? Not really.....



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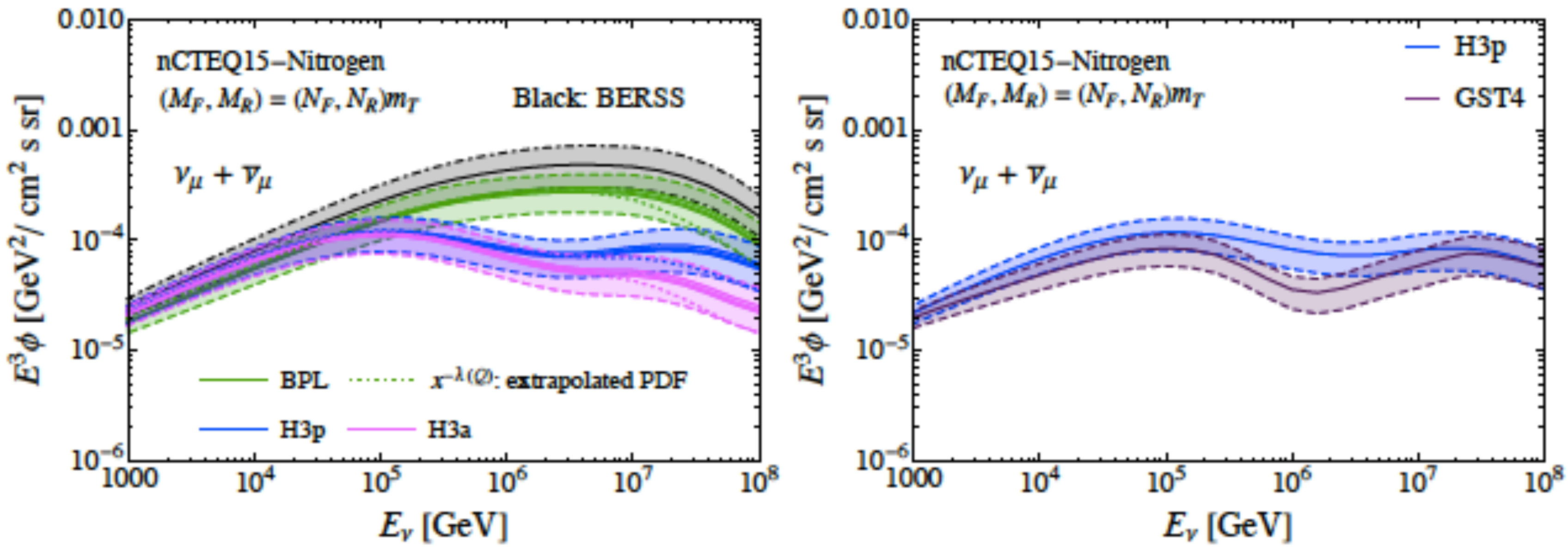
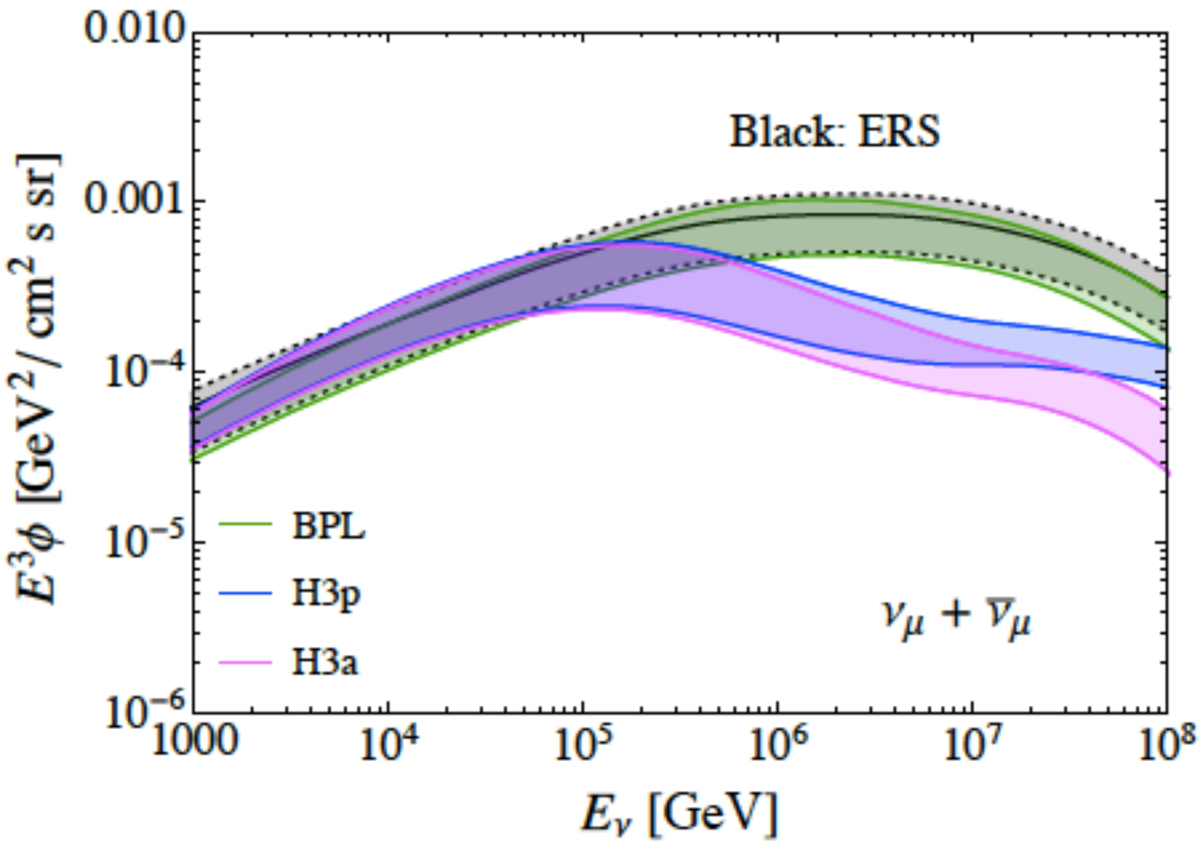
NLO QCD result for flux



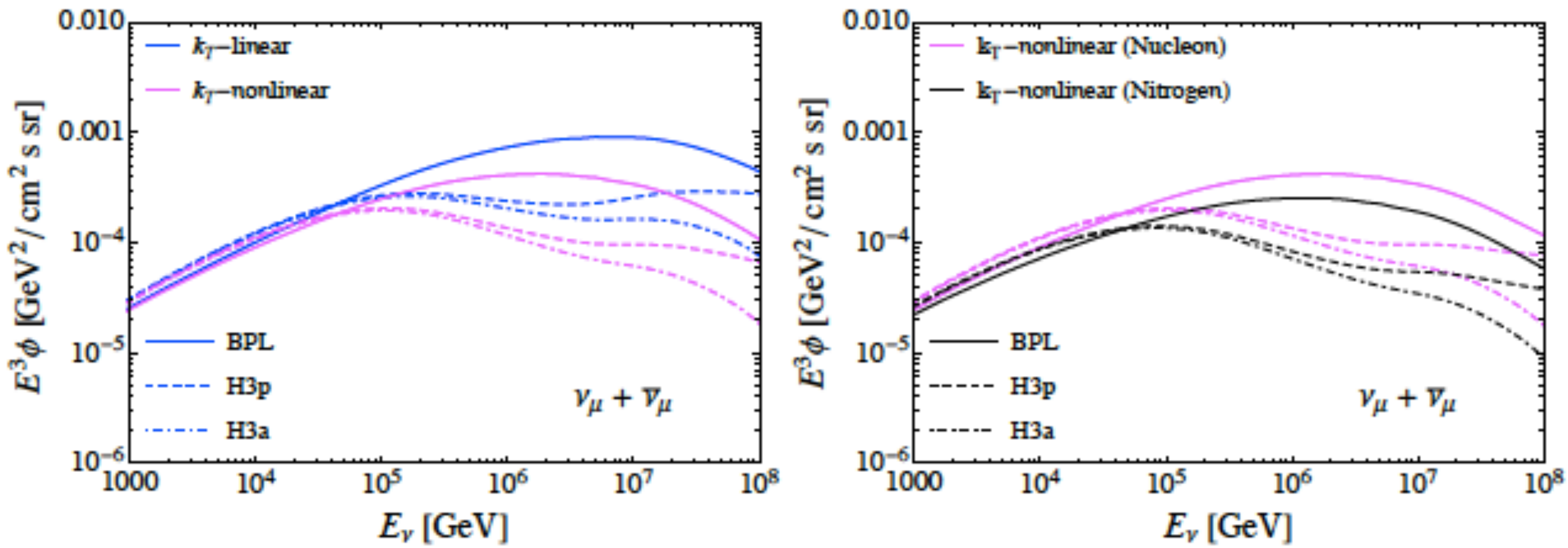
BERSS: Bhattacharya et al., JHEP 06 (2015) 110 uses CT10 PDFs with no nuclear corrections.
Nuclear corrections via nCTEQ15 parton distribution functions are significant.

Dipole model

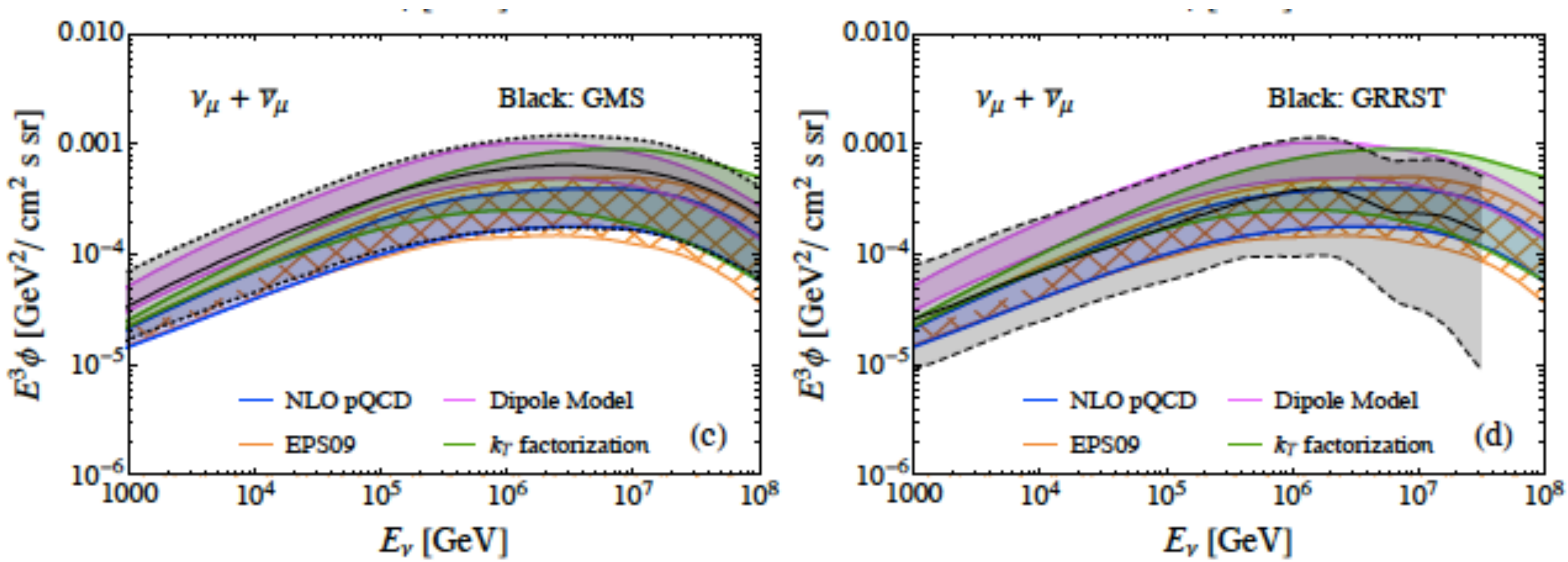


Muon neutrino, approximately same as electron neutrino and muons, isotropic at “low energies.

KT factorization



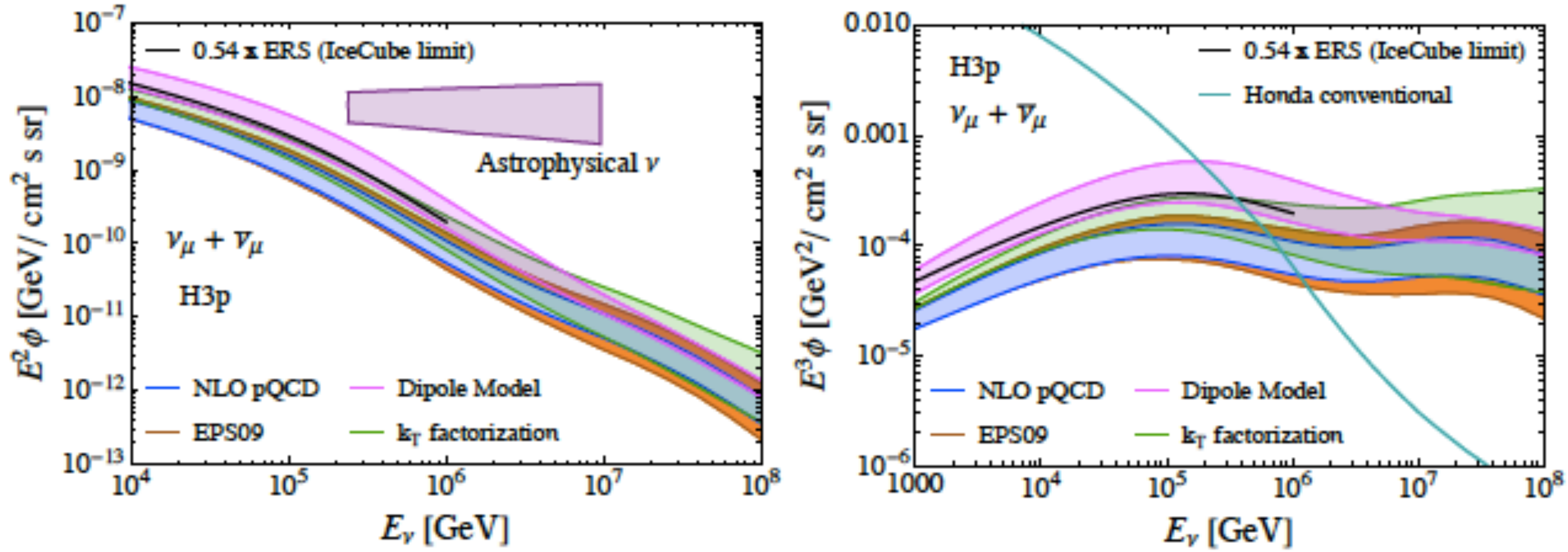
Comparison with other recent results



Use the broken power law for comparison with recent results from other groups

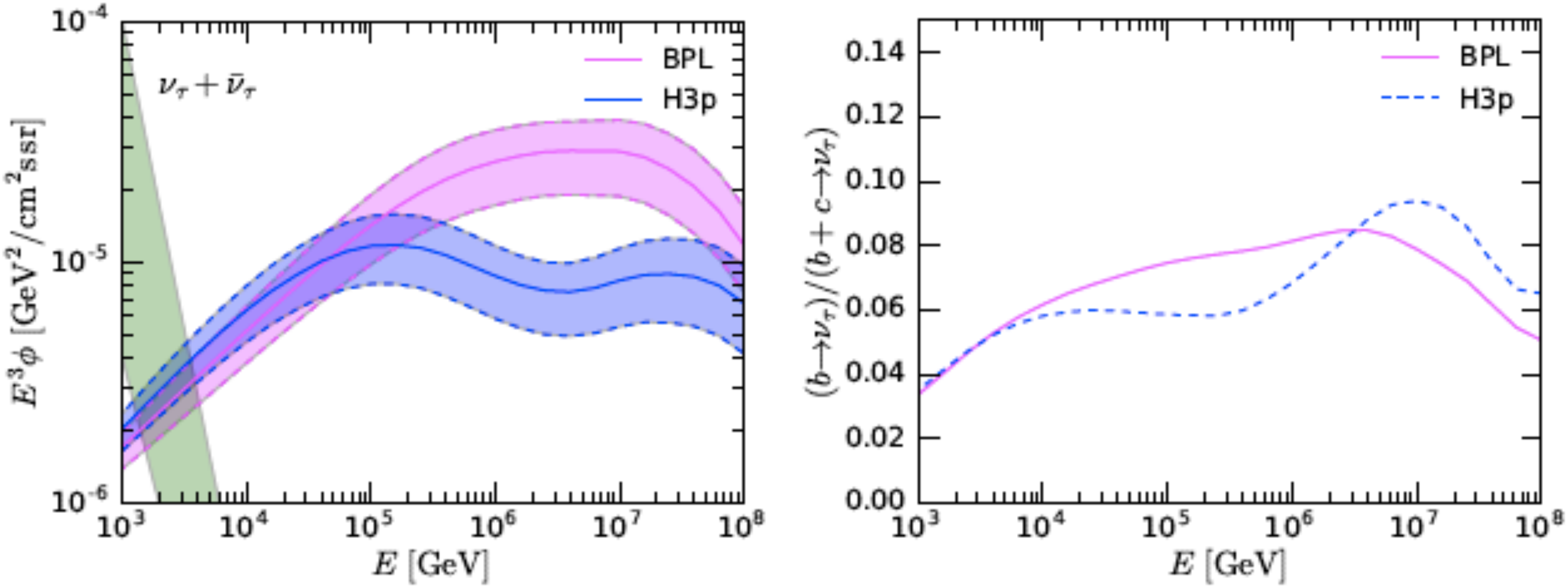
GMS: Garzelli, Moch and Sigl, JHEP 10 (2015) 115 using POWHEG BOX and Pythia; GRRST: Gauld et al, JHEP 02 (2016) 130 with different assessment of PDF uncertainties.

Prompt fluxes with different scaling



Suggested upper limit on prompt flux: 0.54 ERS from Radel and Schoenen for IceCube, ICRC 2015 (2015) 1079.

Tau neutrinos plus antineutrinos



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

Summary

- If we had a completely reliable calculational method, we wouldn't need three different approaches.
- Our new NLO pQCD results are lower than BERSS, because of nCTEQ15 PDFs for nitrogen, which have small-x suppression.
- A limit of 0.54*ERS cuts into dipole model range of flux predictions, and kT factorization without nuclear corrections.
- Have not talked about intrinsic charm, see, e.g., Halzen and Wille, Phys. Rev. D94 (2016) 014014; Laha and Brodsky, 1607.08240.