Atmospheric neutrino fluxes and prompt neutrinos from heavy flavor

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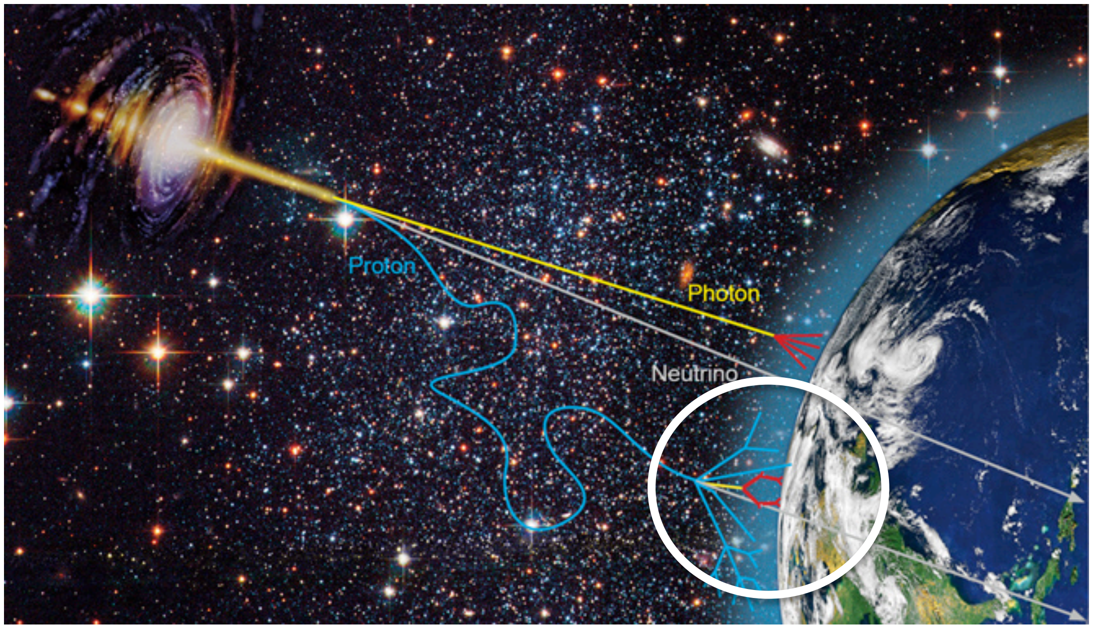
JHEP 1506 (2015) 110

Neutrinos produced in the atmosphere by cosmic ray interactions



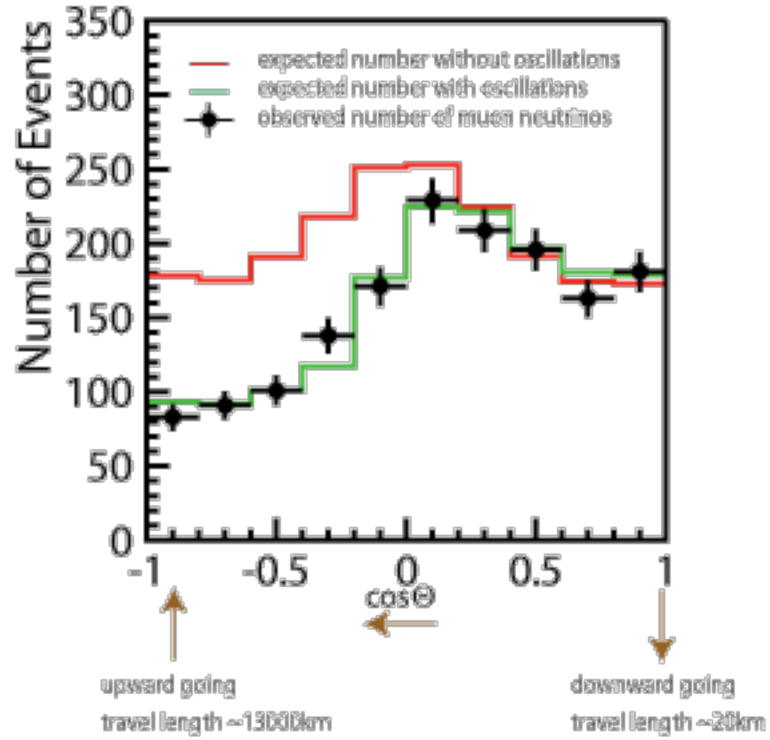


Figure from https://astro.desy.de/

Atmospheric flux intrinsically interesting, not just a background to the astrophysical flux!

1998 SuperKamiokande discovery of neutrino oscillations

Neutrinos produced in the atmosphere by cosmic ray interactions

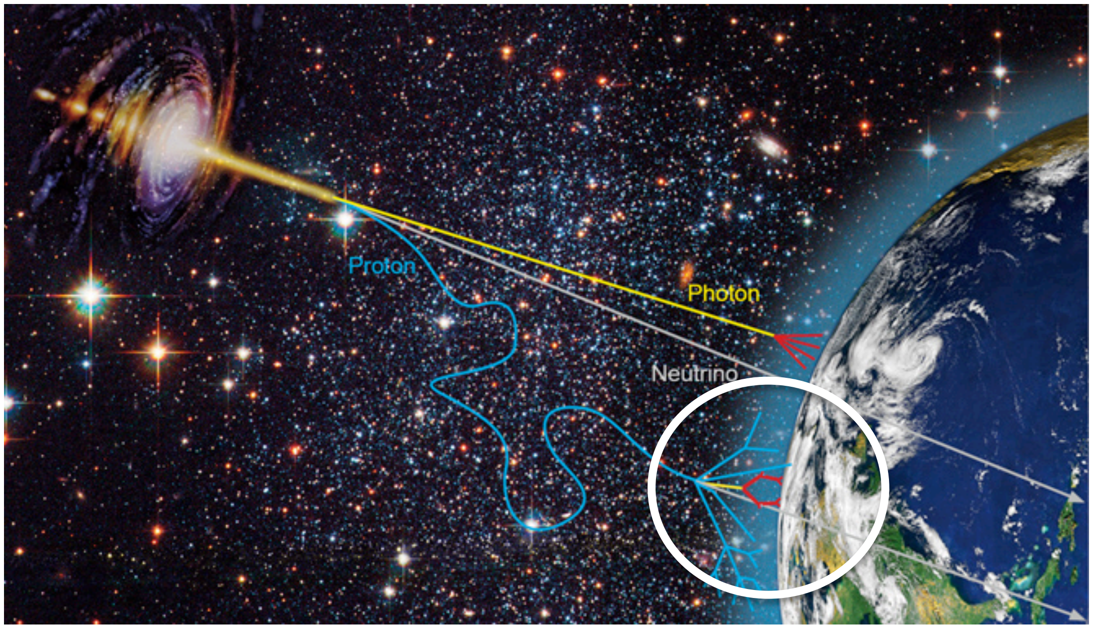


Figure from https://astro.desy.de/

Inputs include:

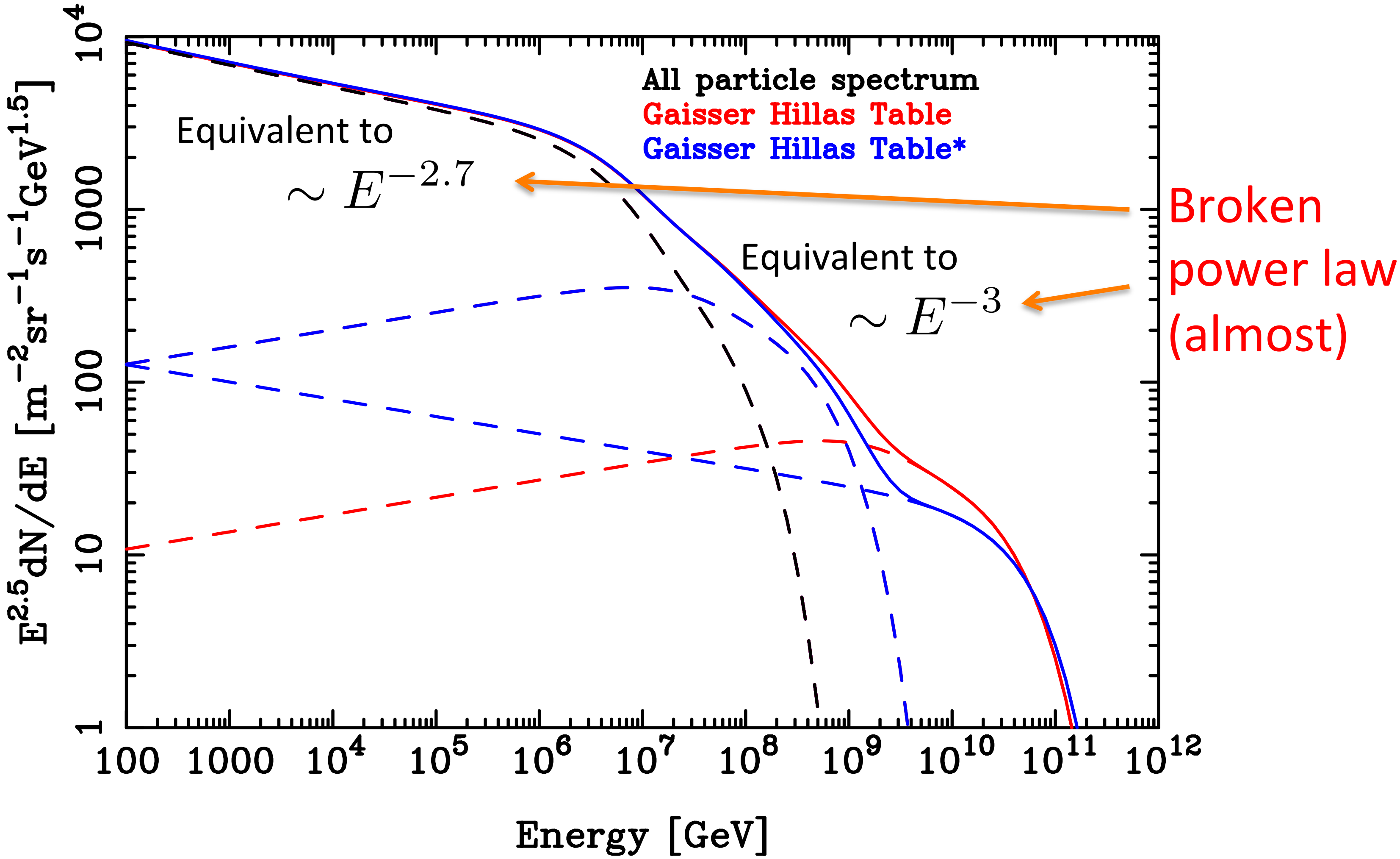
- cosmic ray (CR) flux and composition
- Particle physics inputs: CR interactions with air nuclei to produce mesons/baryons that decay

Plan

- Review the energy dependence of the atmospheric neutrino flux.
- Review some features of the "conventional flux" of neutrinos from pion and kaon decays. Compare and contrast with the flux from heavy flavor decays ("prompt flux").
- Discuss some of the details of the flux at high energies – neutrinos from heavy flavor decays (predominantly charmed particles) where theoretical uncertainties are the largest.

Energy dependence of the CR all particle spectrum

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

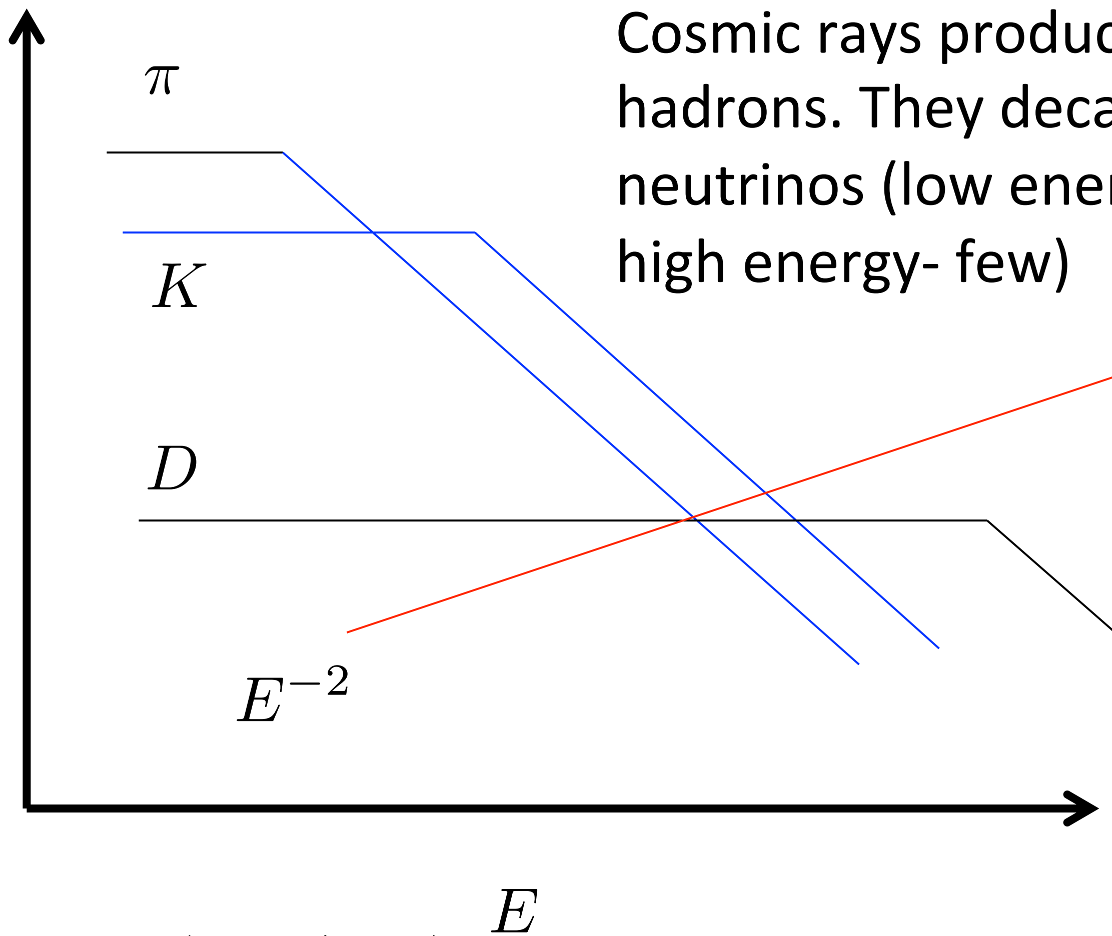


From Table 1, Gaisser, Astropart. Phys. 35 (2012) 801

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

$E^{2.7}\phi_\nu$

Scaling by approximate CR energy spectrum

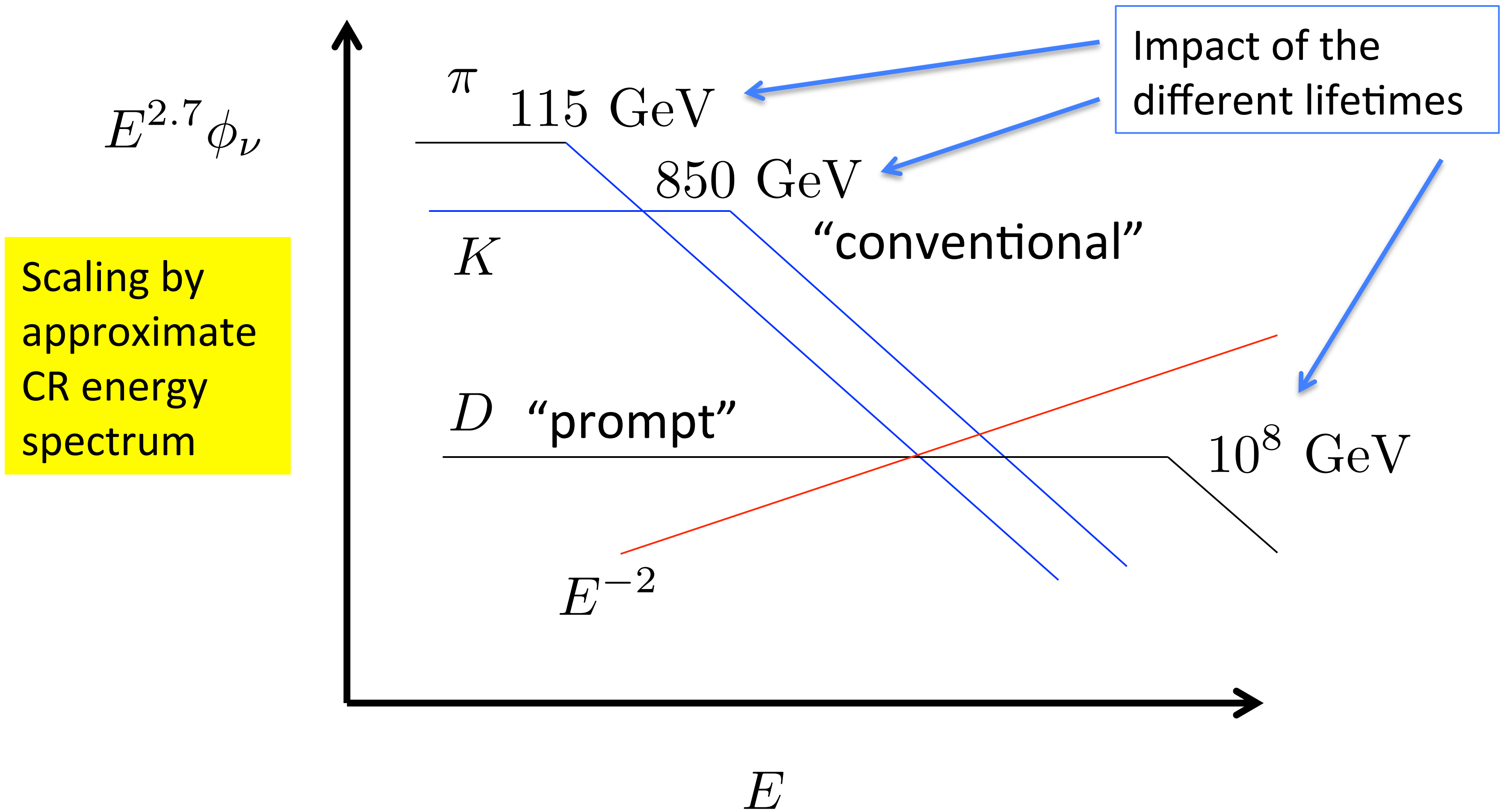


Cosmic rays produce hadrons. They decay to neutrinos (low energy-all, high energy- few)

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

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

Energy dependence, schematically, similar (with different critical energies)



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

Features-conventional flux

- Angular dependence
- Flavor ratios

- Honda et al., Phys. Rev. D 83 (2011) and earlier work.
- Bartol: Barr et al., Phys. Rev. D 70 (2004) and earlier work.
- FLUKA: Battistoni et al., Astropart. Phys. 19 (2003).
- MCeQ: e.g., Fedynitch et al., PoS (ICRC2017) 1019.

Conventional flux (charged mesons):

$$\pi \to \mu\nu_\mu \ (100\%)$$

$$K \to \mu\nu_\mu \ (64\%)$$

$$K \to \pi^0 \ell\nu_\ell \ (3-5\%)$$

Neutral kaons:

$$K_L \to \pi^\pm \ell\nu_\ell \ (27-41\%)$$

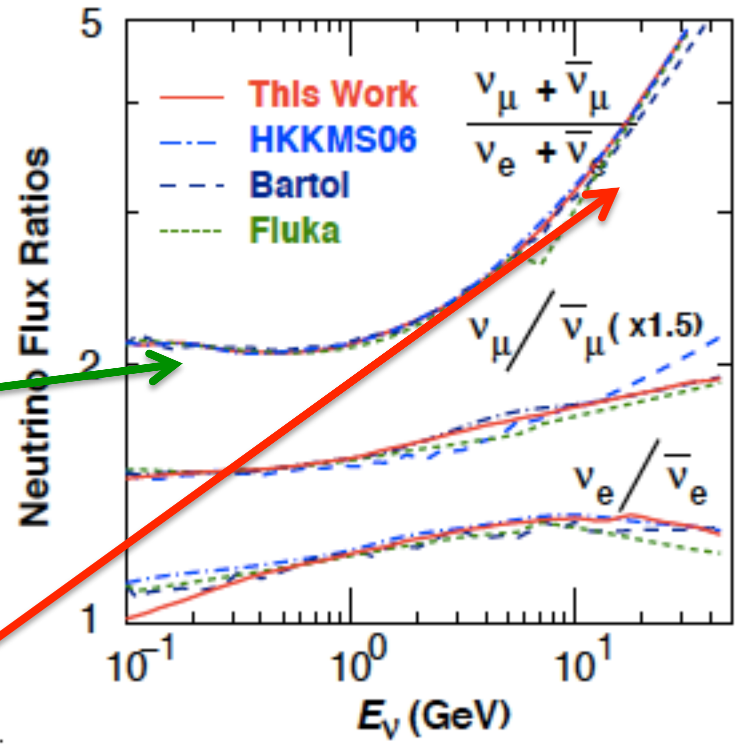
$$K_S \to \pi^\pm e\nu_e \ (0.07\%)$$

Features-conventional flux

- Angular dependence
- **Flavor ratios**

Muons decay

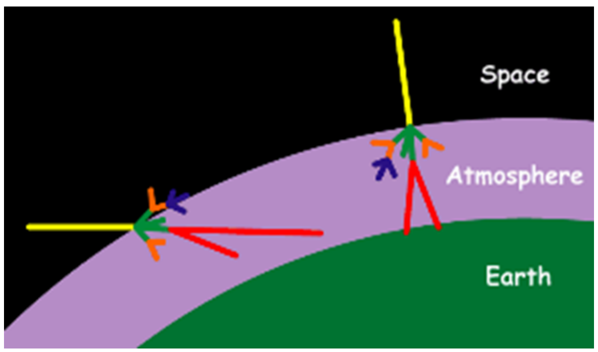
Muons don't decay



- Honda et al., Phys. Rev. D 83 (2011).

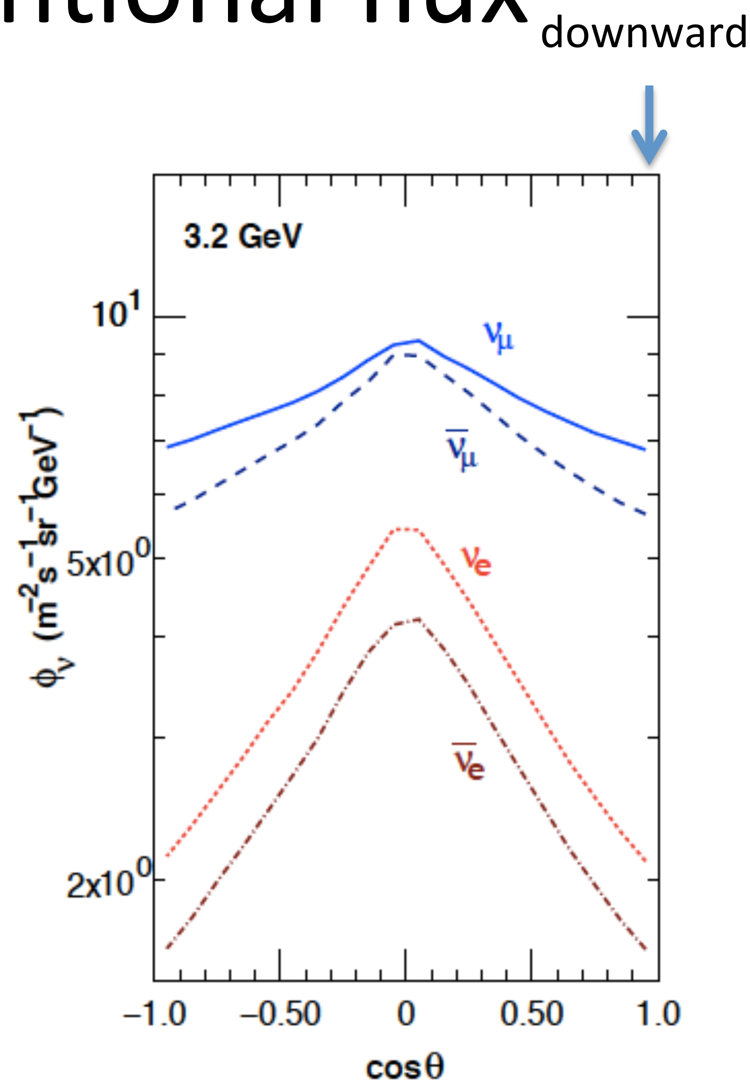
Features-conventional flux

- **Angular dependence**
- Flavor ratios



www2.slac.stanford.edu/vvc/cosmic_rays.html

- Honda et al., Phys. Rev. D 83 (2011).



At Kamioka, averaged over azimuth, including geomagnetic effects.

Features-prompt flux

- Angular dependence
- Flavor ratios

- ERS: Enberg, Reno, Sarcevic , Phys. Rev. D 78 (2008)
- BERSS: Bhattacharya et al., JHEP 06 (2015) 110
- Bhattacharya et al., JHEP 1611 (2016)
- GMS: Garzelli, Moch and Sigl, JHEP 10 (2015) 115
- GRRST: Gauld et al, JHEP 02 (2016) 130
- Benzke et al., 1705.10386

Prompt flux:

$$D^+ \to \ell^+ \nu_\ell X \ (16 - 17\%)$$

$$D^0 \to \ell^+ \nu_\ell X \ (6 - 7\%)$$

$$D_s \to e \nu_e X \ (6.5\%)$$

$$D_s \to \tau \nu_\tau \ (5.5\%)$$

Assume flavor equality for electron neutrinos and muon neutrinos. Tau neutrinos are special!

Features-prompt flux

- **Angular dependence**
- **Flavor ratios**

$$\nu_e : \nu_\mu : \mu = 1 : 1 : 1$$

Isotropic up to high energies, since all of the D's have "prompt" decays.

Prompt flux:

$$D^+ \to \ell^+ \nu_\ell X \ (16 - 17\%)$$

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Cascade Equations

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

High enough energies that muons are "stable".

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

$$j = N,\ \pi,\ K,\ D,\ \nu_i,\ \mu$$

e.g., $pA \to DX$

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

Production

e.g., $D \to \nu_\mu X$

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\Gamma_K} \frac{d\Gamma(k \to jY; E_k, E_j)}{dE_j}$$

Decay

Need cosmic ray flux (j=N) and energy distribution of the final state particle.

We use Z-moments: spectrum weighted moments

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

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

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

Approximate relation – flux factorizes so Z only depends on E.

Calculate the differential cross section or decay distribution, convolute with the flux, integrate to get Z.
Spectrum weights favor forward production of charm – want the largest E (charmed meson) given E’ (cosmic ray nucleon).

Approximate formulae

Cosmic ray – nucleon flux

$$\phi_\ell^{low} = \frac{Z_{NM} Z_{M\ell}}{1 - Z_{NN}} \phi_N$$

$$\phi_\ell^{high} = \frac{Z_{NM} Z_{M\ell}}{1 - Z_{NN}} \frac{\ln(\Lambda_M/\Lambda_N)}{1 - \Lambda_N/\Lambda_M} \frac{\epsilon_c^M}{E} \phi_N$$

$$\epsilon_c^\pi = 115 \text{ GeV}$$

$$\epsilon_c^K = 850 \text{ GeV}$$

$$\epsilon_c^D \sim 10^8 \text{ GeV}$$

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

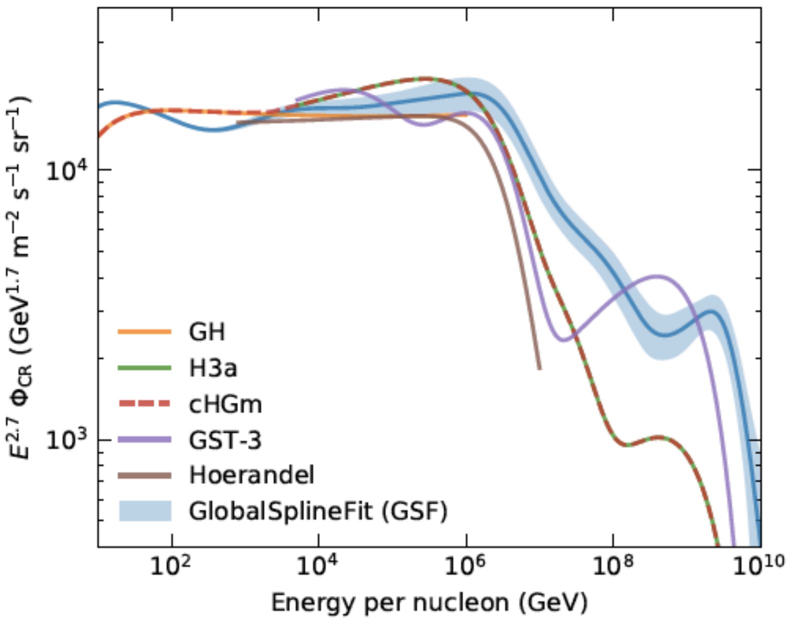
Exponential atmosphere, 1D, approximate factorization of depth dependence.

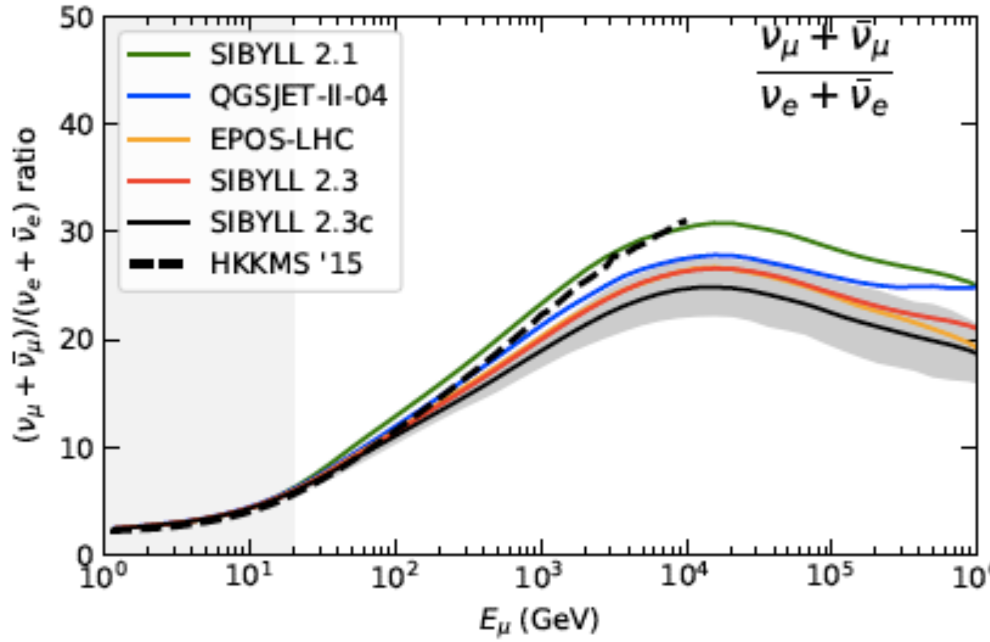
$$Z_{ND},\ Z_{D\ell},\ \Lambda_D \qquad c \to s\mu^+\nu_\mu \quad c \to se^+\nu_e$$

Cosmic Rays and Particle Physics, T. Gaisser, Cambridge U Press; L. V. Volkova, Sov. J. Nucl. Phys. 31 (1980);P. Lipari, Astropart. Phys. 1 (1993)

A numerical tool: MCEq

[1]https://github.com/afedynitch/MCEq





Dembinski et al., and Fedynitch et al., PoS (ICRC2017) 1019.

MCEq: numerical solution to cascade equations, Fedynitch et al., arXiv: 1503.0054

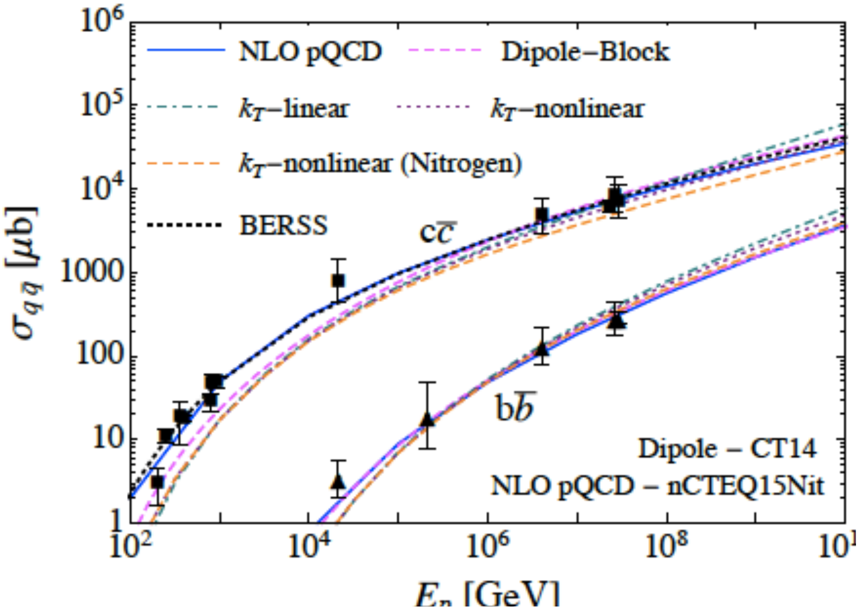
Error band around black curve shows SIBYLL error band.
See also, e.g., Barr et al., Phys. Rev. D 74 (2006).
Geomagnetic and 3D effects not included (shaded region below 20 GeV).

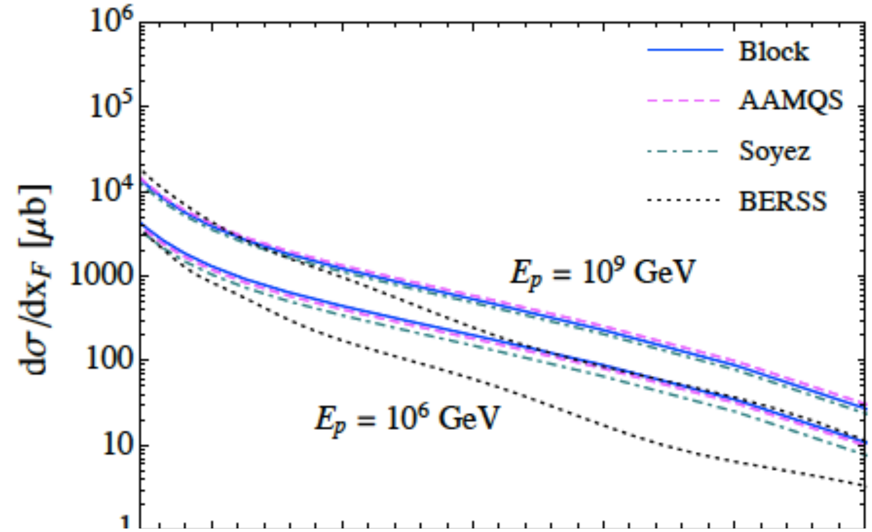
What is new in our prompt charm evaluation using the Z-moment method?

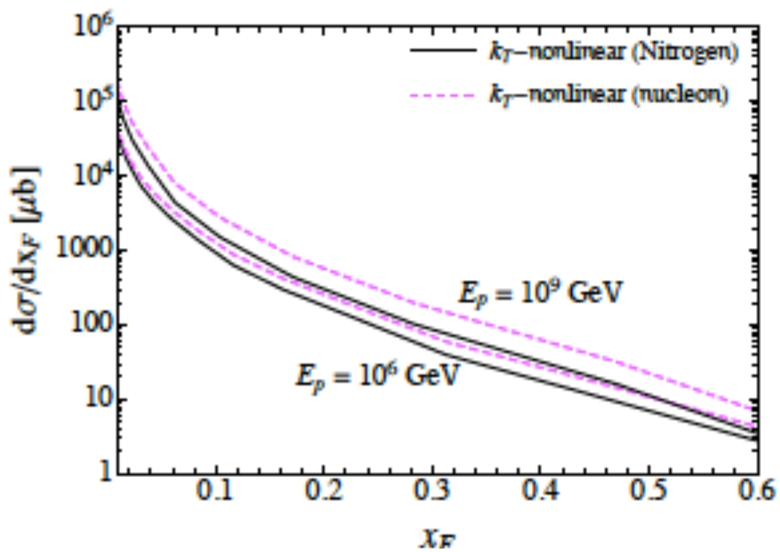
- NLO QCD evaluation of charm pair cross section and energy distribution with nuclear corrections. Cacciari, Greco, Nason, JHEP 9805 (1998); Cacciari, Frixion, Nason, JHEP 0103(2001); Mangano, Nason, Ridolfi, NP B273 (1992); Nason, Dawson, Ellis, NP B303 (1988), NP B373 (1992); Lai et al, PRD 82 (2010)
- 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.

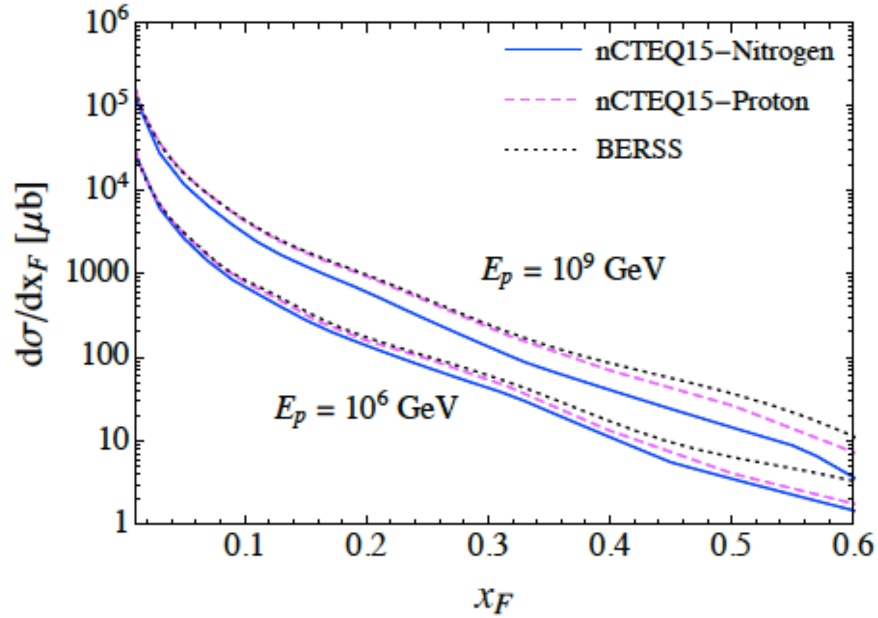
Forward production means small-x in parton distribution function or dipole cross section.

Cross section for charm, b quarks

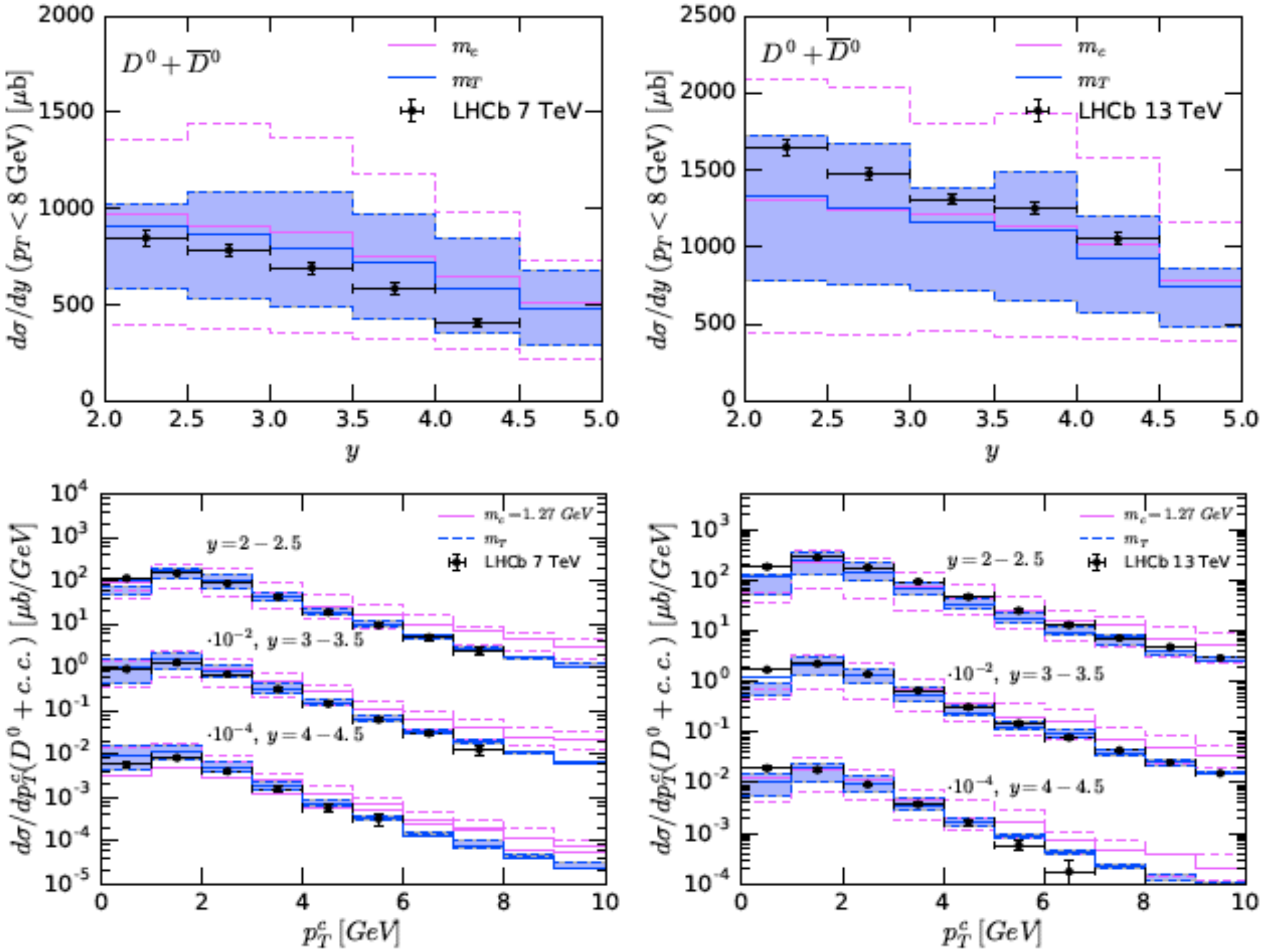








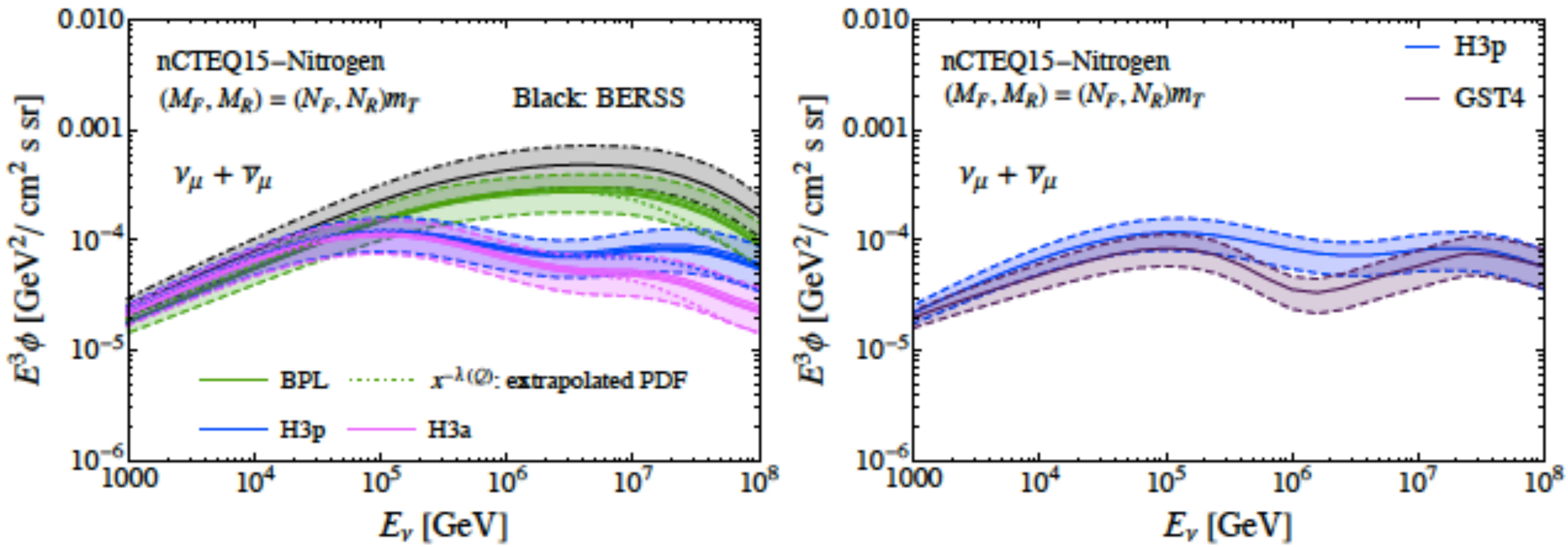
Compare with LHC data for charm



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

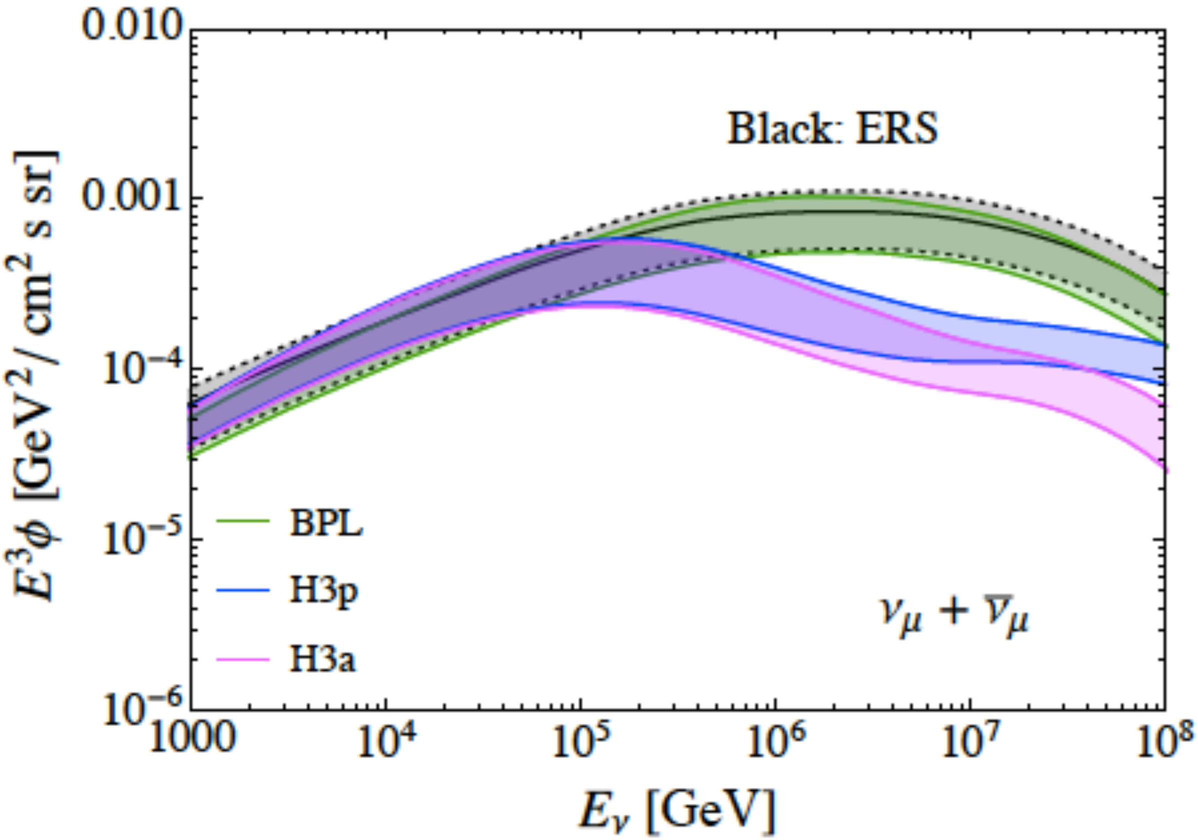
NLO QCD result for flux



BERSS: Bhattacharya et al., JHEP 06 (2015) 110 uses CT10 PDFs with no nuclear corrections.

Nuclear corrections via nCTEQ15 parton distribution functions are significant.

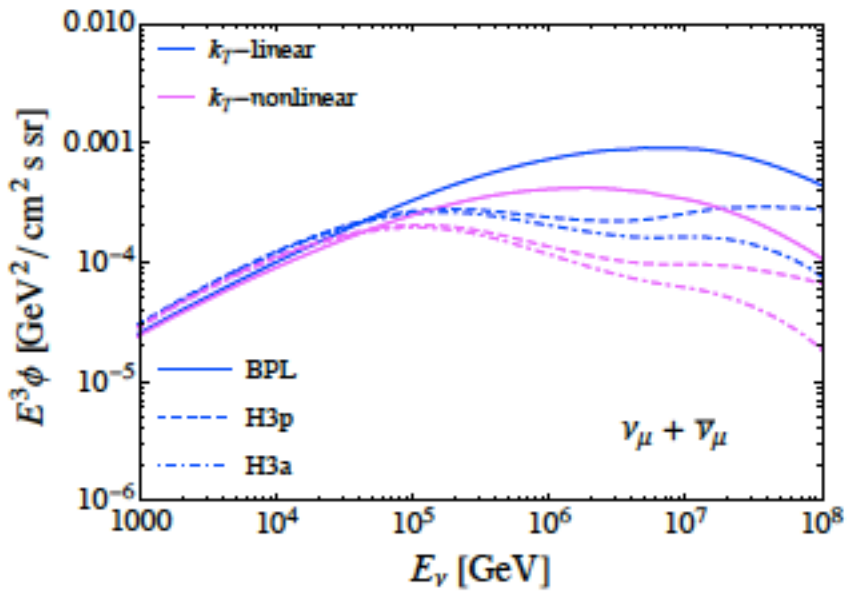
Dipole model

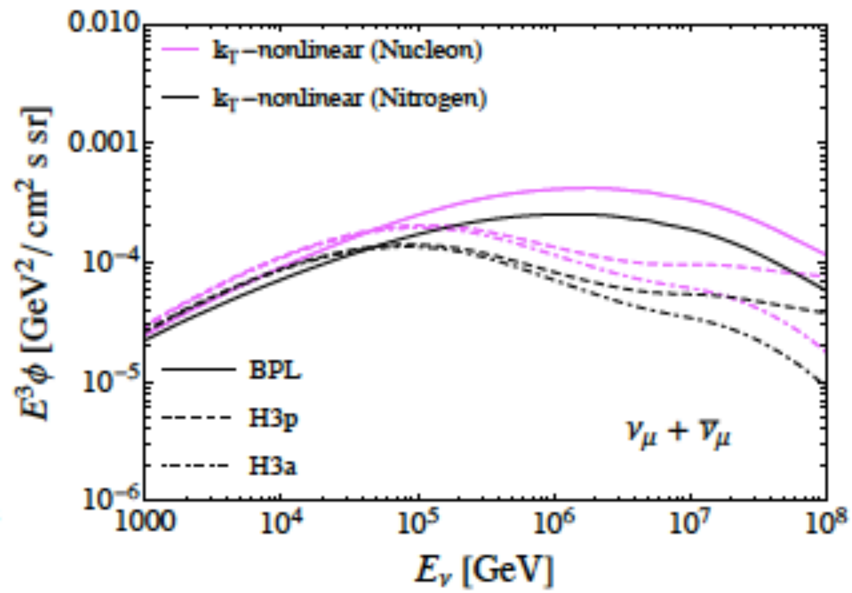


ERS: Enberg, Reno, Sarcevic, PRD 78 (2008) 043005

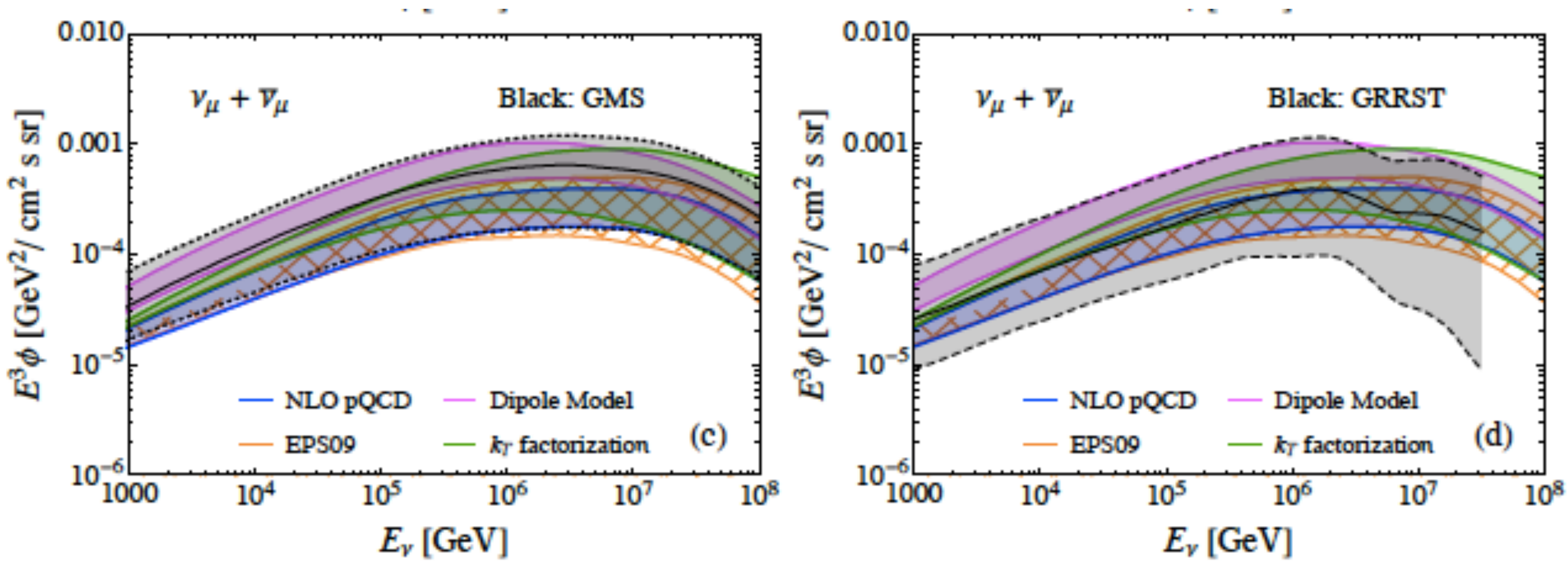
Nuclear corrections in dipole model are 10-20% reduction. Here, updated Z-moments, gluon PDF, more dipole models for uncertainty band.

KT factorization





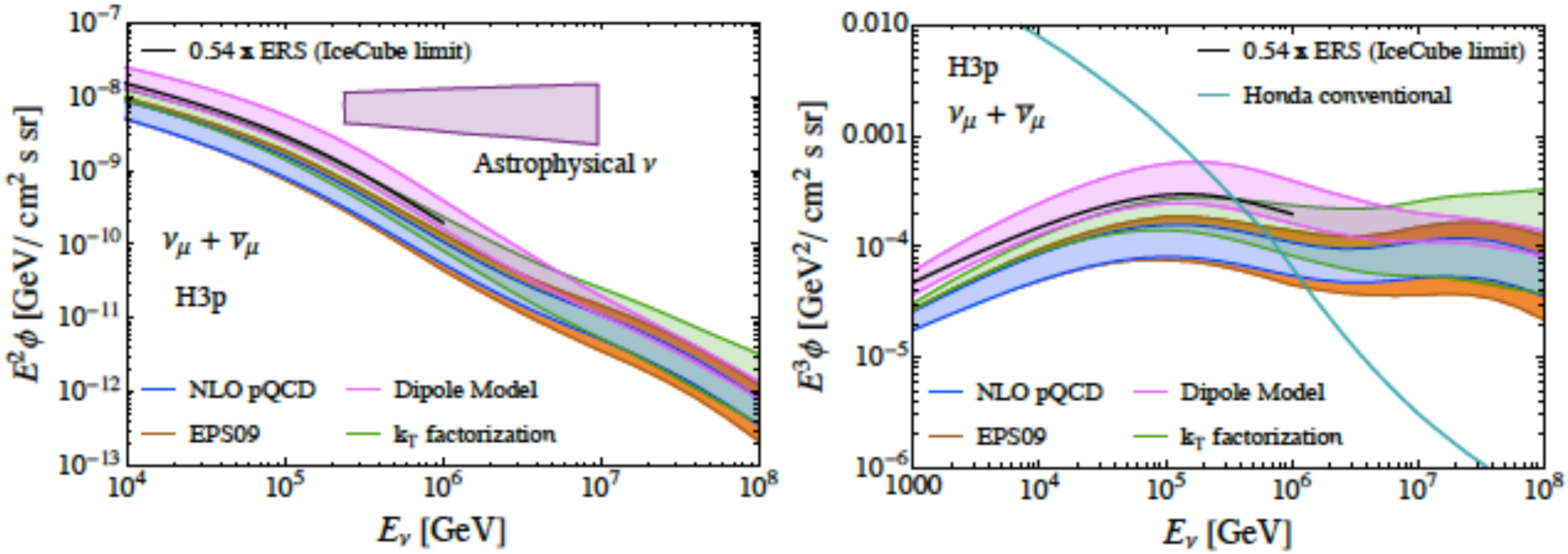
Comparison with other recent results



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

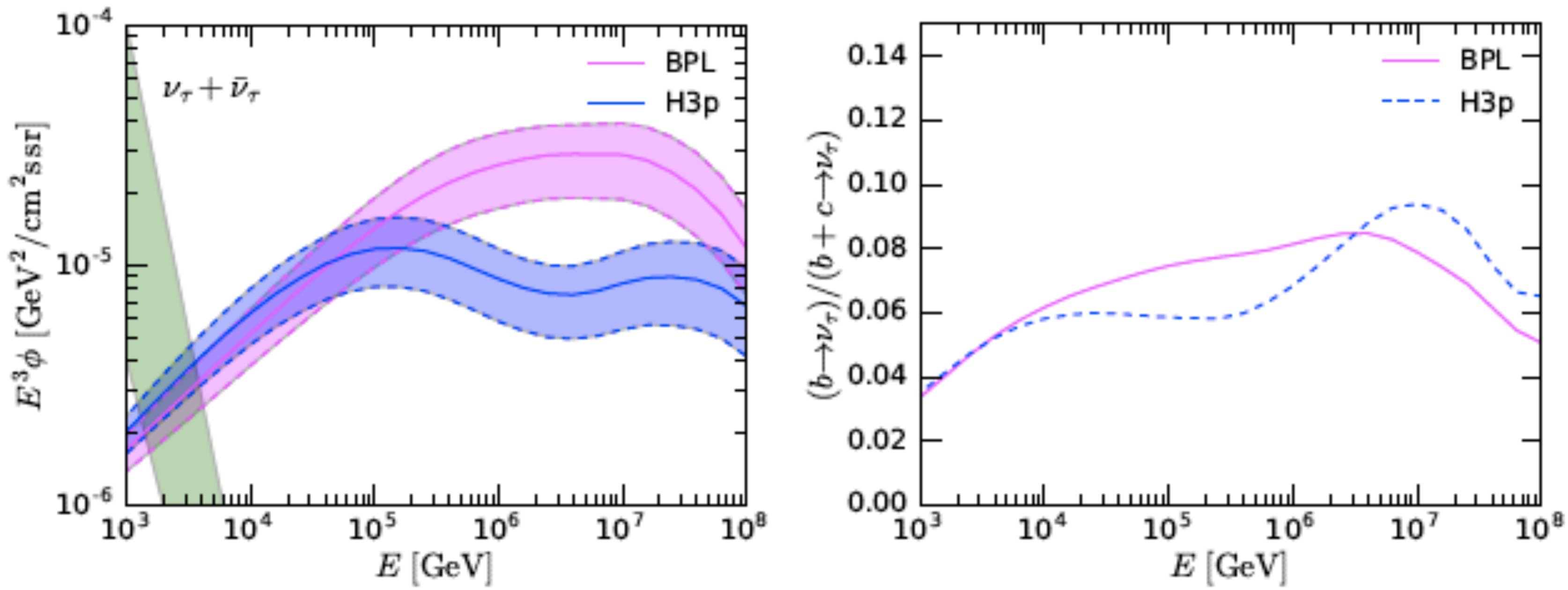
GMS: Garzelli, Moch and Sigl, JHEP 10 (2015) 115 using POWHEG BOX and Pythia; GRRST: Gauld et al, JHEP 02 (2016) 130 with different assessment of PDF uncertainties.

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

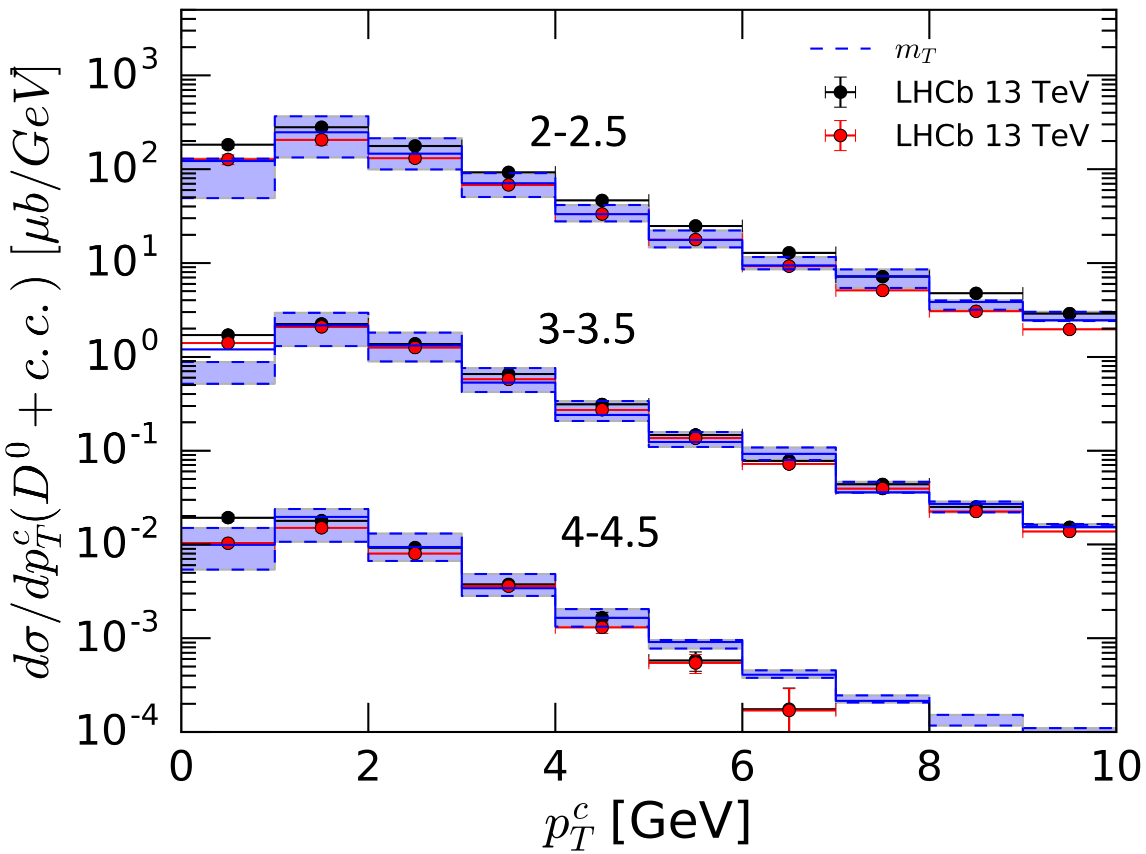


$D_s \to \tau\nu_\tau \qquad \tau \to \nu_\tau X$

Summary

- If we had a completely reliable calculational method for charm production, 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. There are still nuclear uncertainties.
- 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/spectator charm, see, e.g., Halzen and Wille, Phys. Rev. D94 (2016) 014014; Laha and Brodsky, 1607.08240.

LHCb update



LHCb, red updated with errata published in JHEP05 (2017) 074.