Prompt neutrinos from charm: atmospheric and beam dump fluxes

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Rept.Prog.Phys. 79 (2016) 124201 & in progress.
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Neutrinos produced in the atmosphere

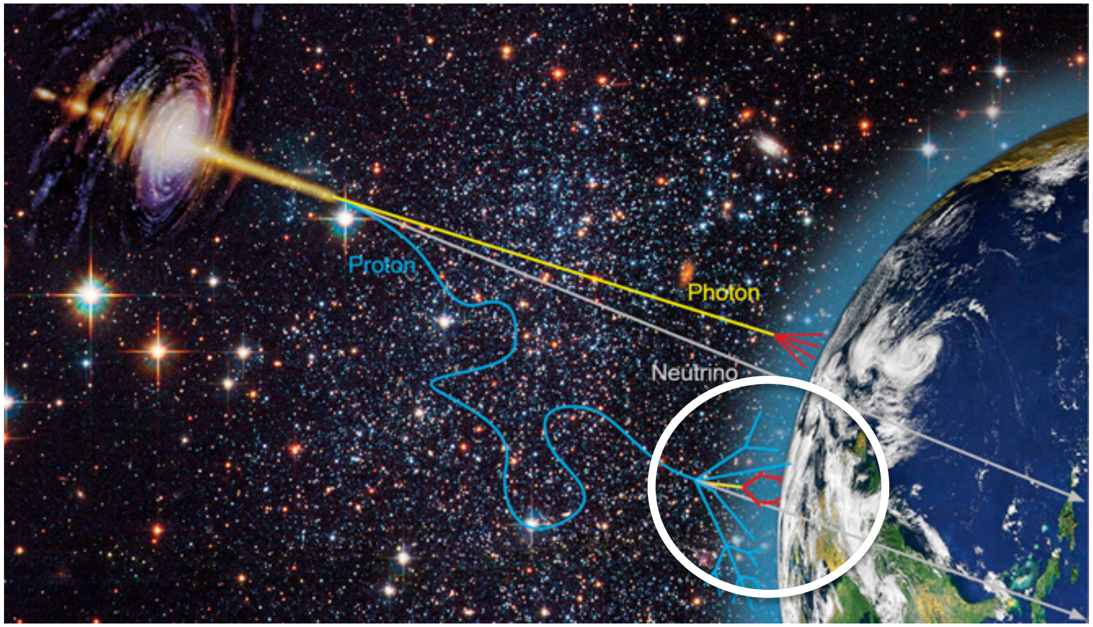


Figure from https://astro.desy.de/

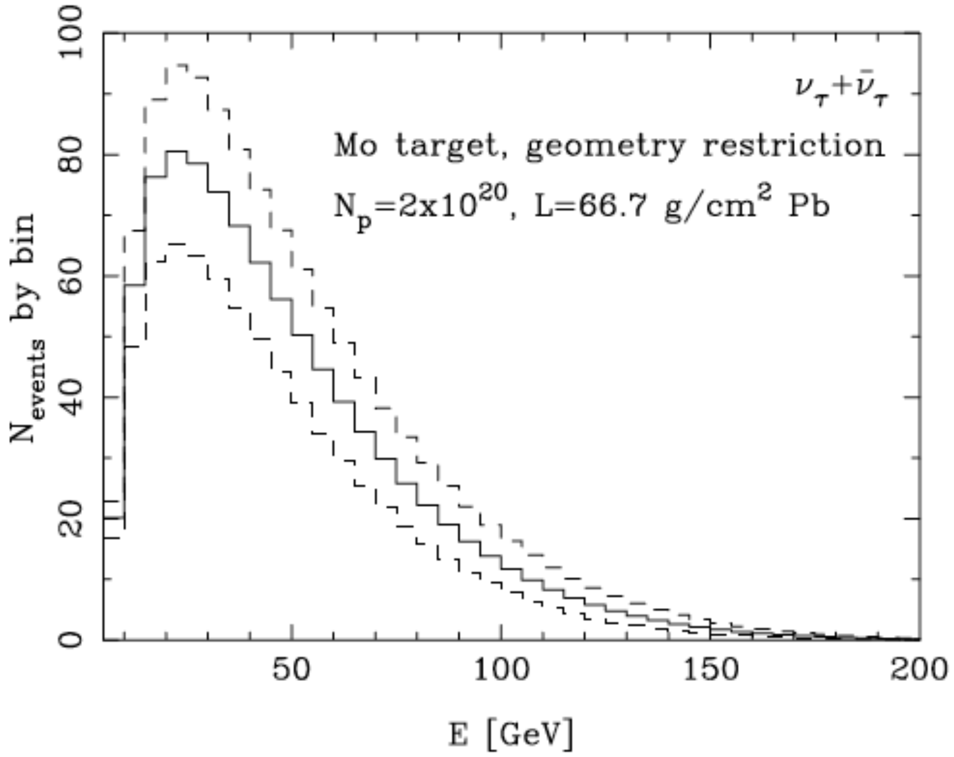
Inputs include:

- 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

Beam dump neutrino fluxes

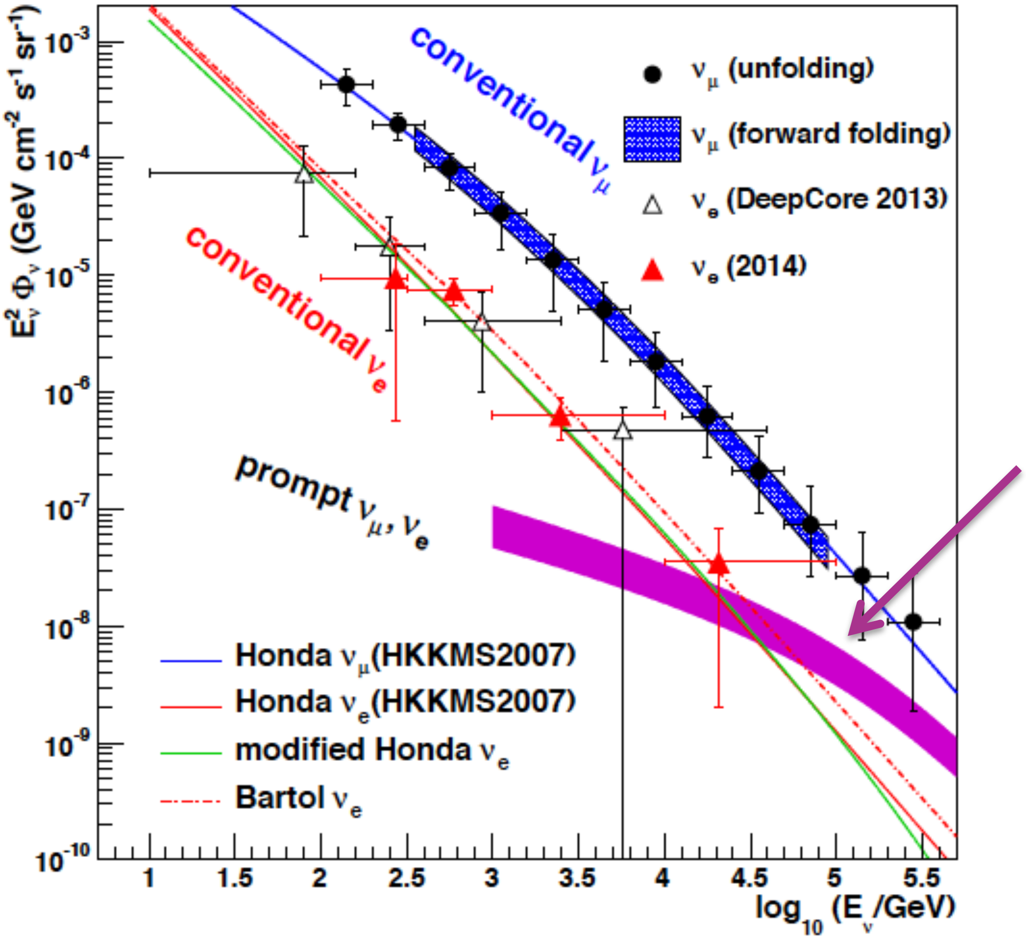
SHiP

Search for Hidden Particles



400 GeV proton beam incident on molybdenum target. Designed to look for “hidden particles” but would be a copious source of tau neutrinos as well.

Improve earlier work on the prompt atmospheric neutrino flux



Neutrinos from charm (prompt)
ERS: Enberg, Reno & Sarcevic, PRD 78 (2008),
shown here with a cosmic ray flux correction.

IceCube, arXiv:1504.03753

Background to astrophysical neutrino flux (the cosmic neutrino flux)

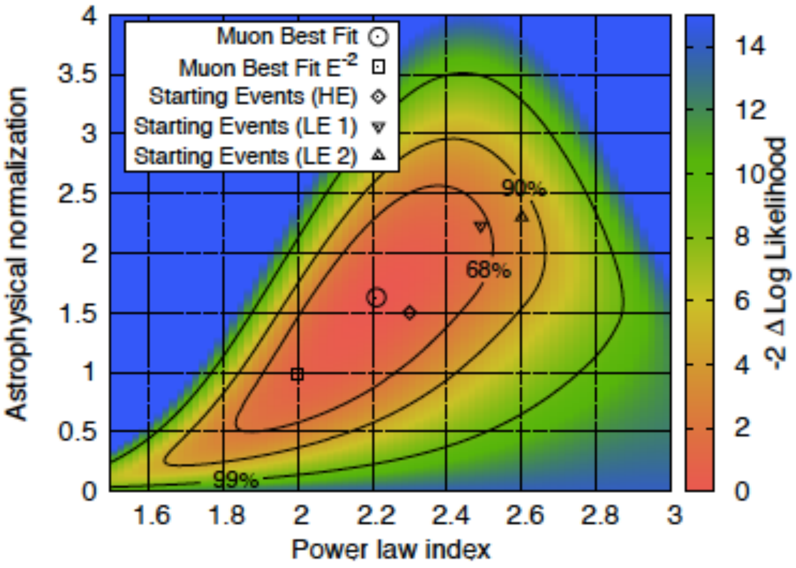


FIG. 3. Likelihood profile of the astrophysical flux power-law index and the flux normalization at 100 TeV in units of $10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$. While the E^{-2} result is well within the 68% contour, it is not the overall best fit. Also shown are the best fits from various IceCube analyses of starting events, which generally have good agreement: Starting Events (HE) [4], Starting Events (LE 1) [31], Starting Events (LE 2) [32].

IceCube Collaboration, arXiv: 1507.04005, PRL 115 (2015) 081102

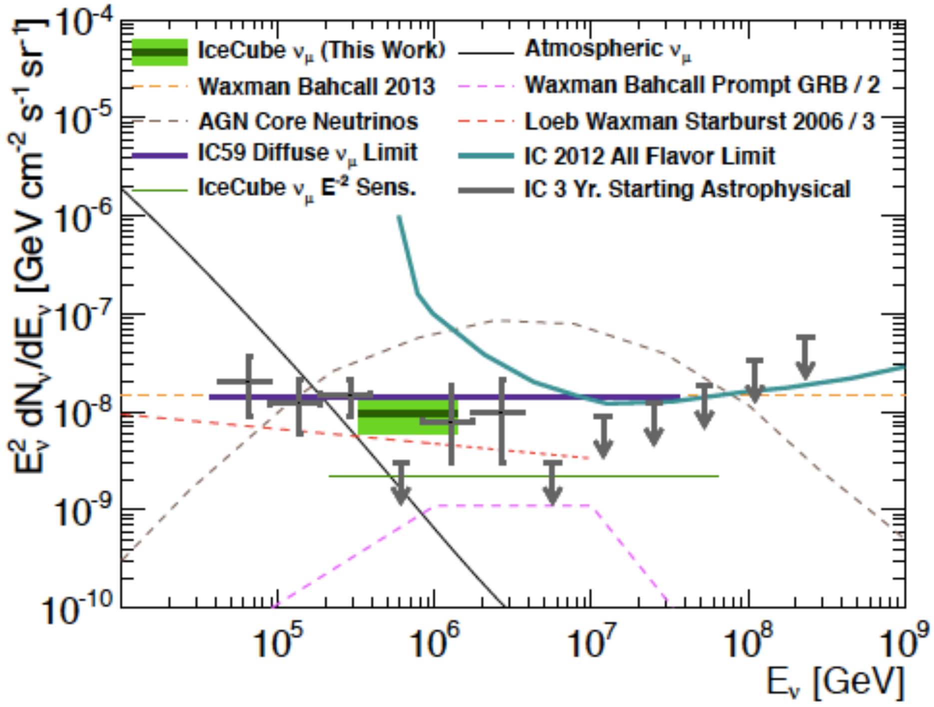
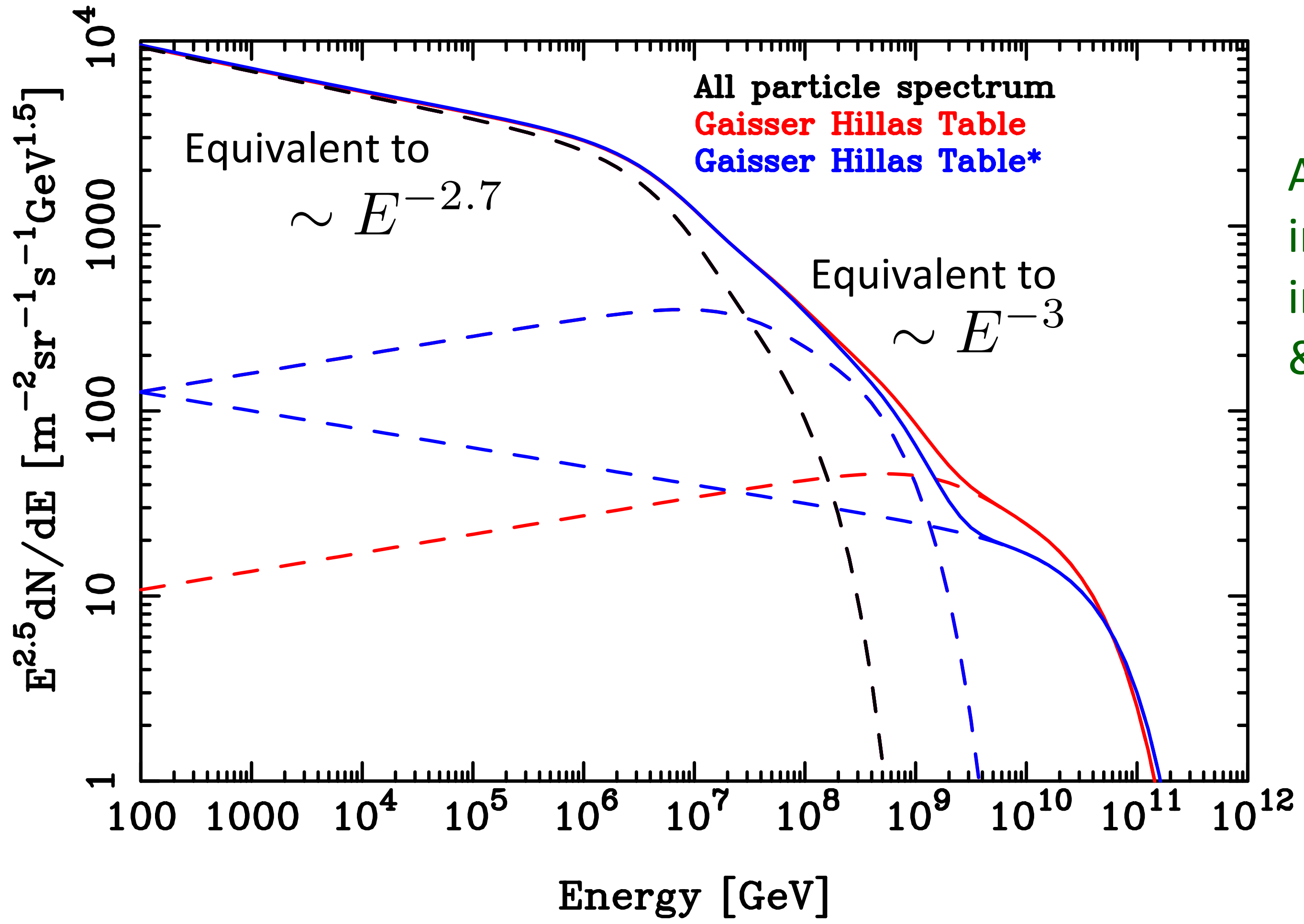


FIG. 4. Comparison of the best fit per-flavor astrophysical flux spectrum of E^{-2} from this work, assuming a flavor ratio of 1:1:1, (shown in dark green with the 68% error range in lighter green) to other selected IceCube measurements (heavy lines) [4, 12] and theoretical model predictions (thin, dashed lines) [5–7, 17, 20, 28]. The sensitivity of this analysis is also shown as the thin, green line.

- Why interesting?
  - Background to IceCube measurement of the diffuse flux, eventually detectable component of their measurement.
  - Hadronic physics connected to LHC (LHCb): charm production.
  - Connection to fixed target experiments.
- Atmospheric flux from charm: “prompt”
  - Discussion of generic energy scaling
  - Brief review of calculational procedure
  - Inputs and results
  - Discussion of uncertainties
- Beam dump fluxes: single beam energy
  - Tau neutrinos and antineutrinos at SHiP
  - Intrinsic charm: constraints from SHiP

Input- cosmic accelerator: CR all particle spectrum

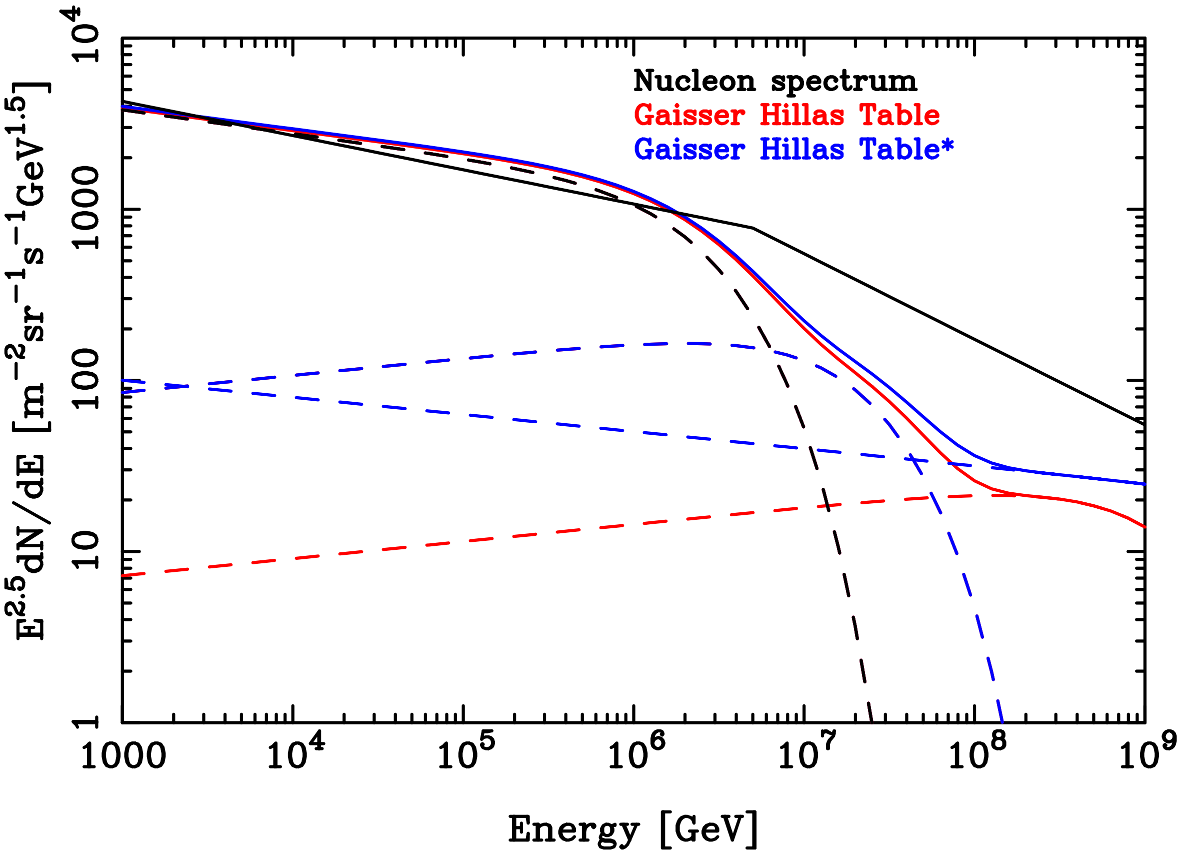
traditional rescaling in other figures, by power of 2.7 or 3



All particle spectrum: important elements include composition & energy dependence

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

CR nucleon spectrum



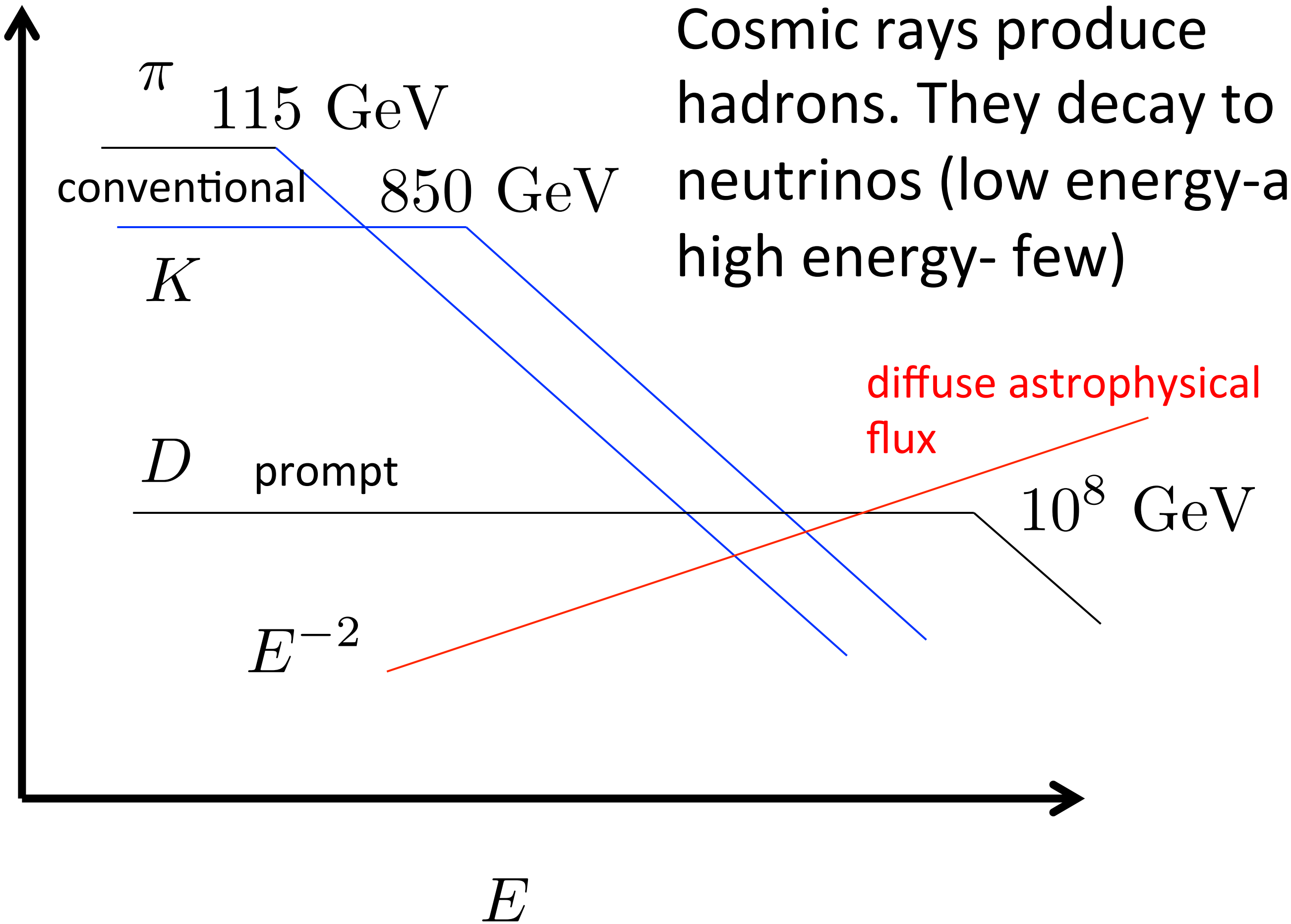
Broken power law? Not really…. input spectrum and composition.

Tradition: to use the broken power law for comparisons between calculations.

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)

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

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

Z-moments: spectrum weighted moments for approximate flux calculation, favors large energy fractions for charm production

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

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

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

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.

What is new in this prompt charm evaluation?

- NLO QCD evaluation of charm pair cross section and energy distribution with nuclear corrections (nCTEQ pdfs). 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: Glauber-Gribov or A-dependent saturation scale. 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. Nuclear effects through nonlinear term scaling like cube root of A. 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.

Charm cross section using perturbative QCD: gluon fusion dominated

PDF = parton distribution function

$$\sigma(pp \to c\bar{c}X) \simeq \int dx_1\, dx_2\, G(x_1,\mu)G(x_2,\mu)\hat{\sigma}_{GG\to c\bar{c}}(x_1 x_2 s)$$

One approach, perturbative QCD with PDFs:

$x_1,\ x_2:$

$$x_F = x_1 - x_2 \qquad x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_F \simeq x_E = E/E'$$

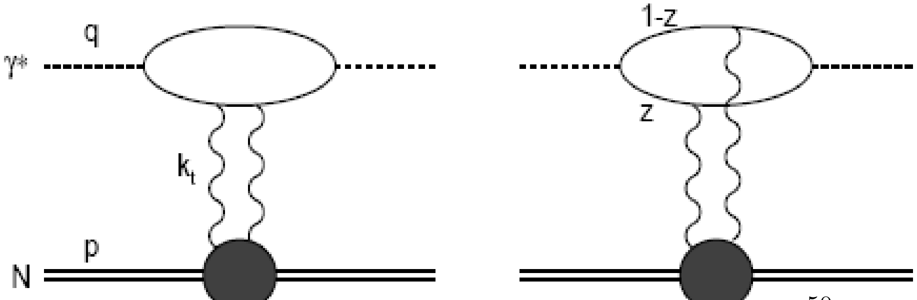
$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7\ \mathrm{GeV} \to x_2 \sim 10^{-6}$$

See Goncalves, Maciula, Pasechnik, Szczurek, PRD 96 (2017) for more quantitative discussion.

Disadvantage: need gluon PDF in low x, not very big Q range.

Refs: e.g., Thunman, Ingelman, Gondolo, Astropart. Phys. (1996) at LO,
Pasquali, MHR, Sarcevic, Phys. Rev. D (1999) at NLO modeled with x dependent k-factor (PRS)
Necessarily involve extrapolations at low x (sometimes explicit, sometimes implicit).
What about large logarithms? $\ln(1/x)$

Dipole model



Electromagnetic scattering converted to heavy flavor production.

Dipole cross section we use:
Soyez (2007)
AAMQS (2010)
“Block” (solid line) from

$$\sigma_{dip}(x,r) = \pi^3 r^2 Q^2 \frac{\partial}{\partial Q^2} F_2^{\gamma p}|_{Q^2=(z_0/r)^2}.$$

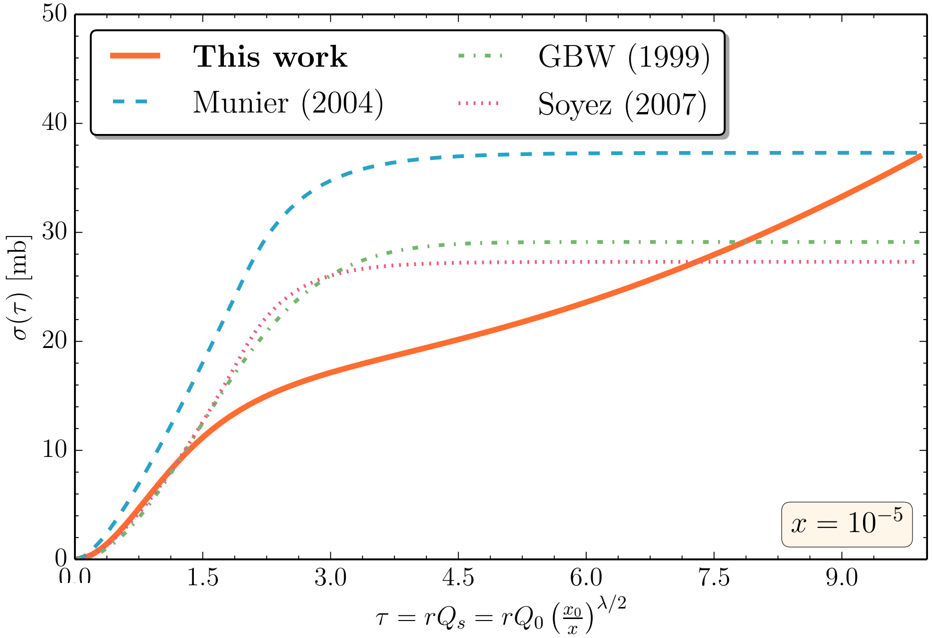
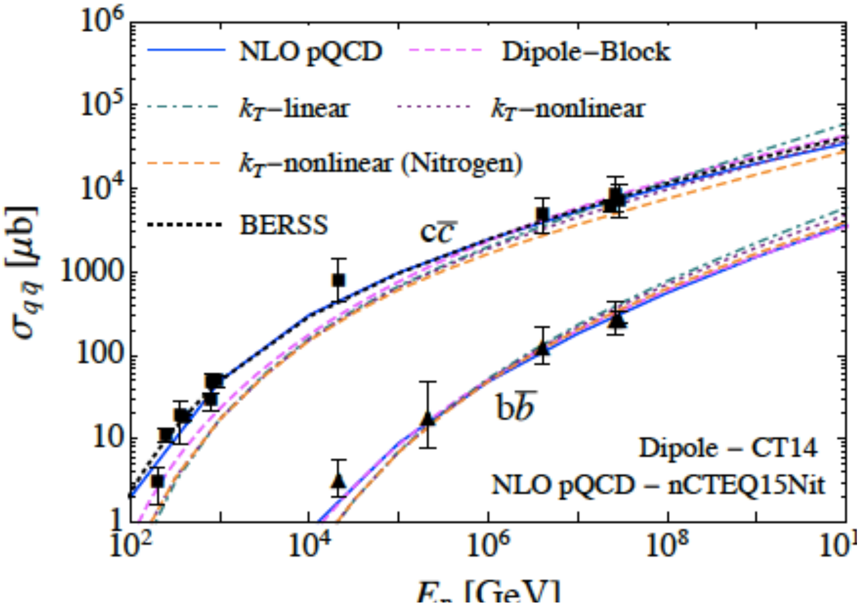


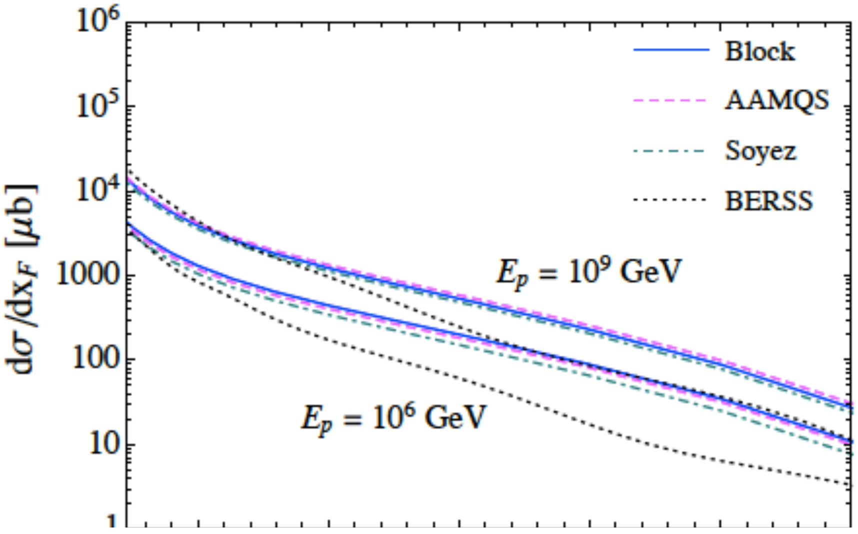
Fig. from Arguelles et al, PRD 92 (2015)

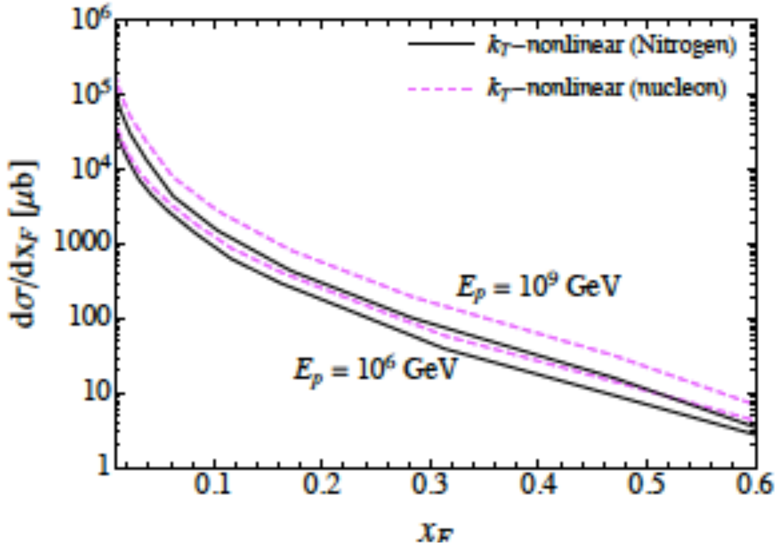
kT factorization

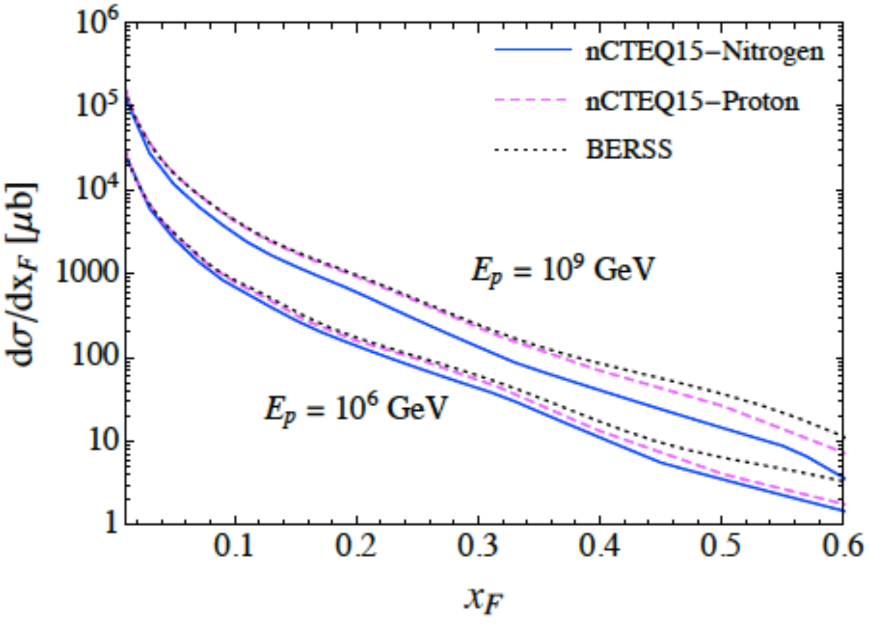
- Take the “large-x” gluon from cosmic ray on-shell, small-x target gluon off-shell (hybrid formalism)
- Unintegrated PDF – resummed version of BFKL evolution, see Kwiecinski, Martin, Stasto (1997), Kutak, Stasto (2005), used unintegrated distribution of Kutak and Sapeta (2012), with and without saturation (non-linear term in the evolution).

Cross section for charm, b quarks

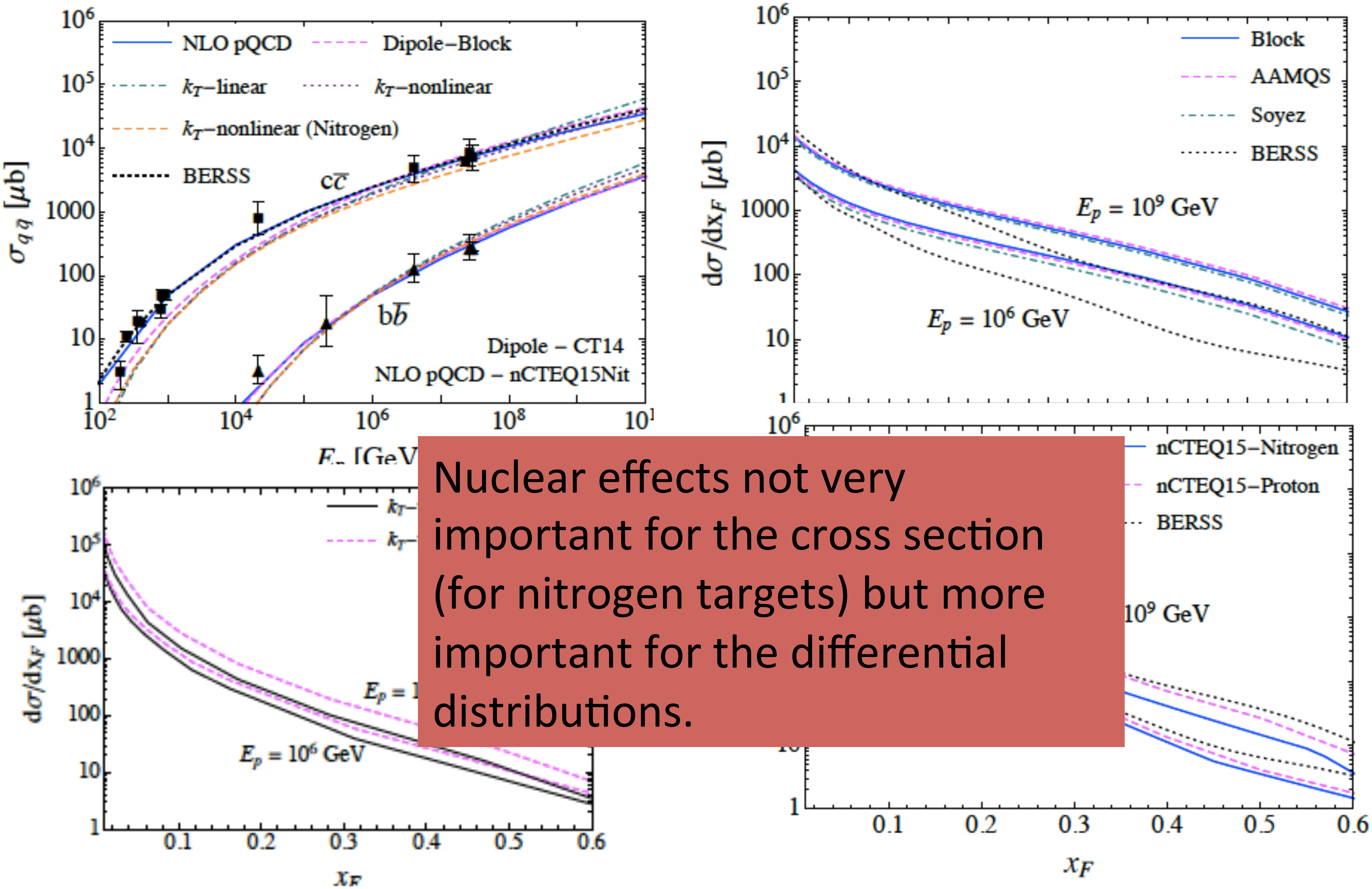






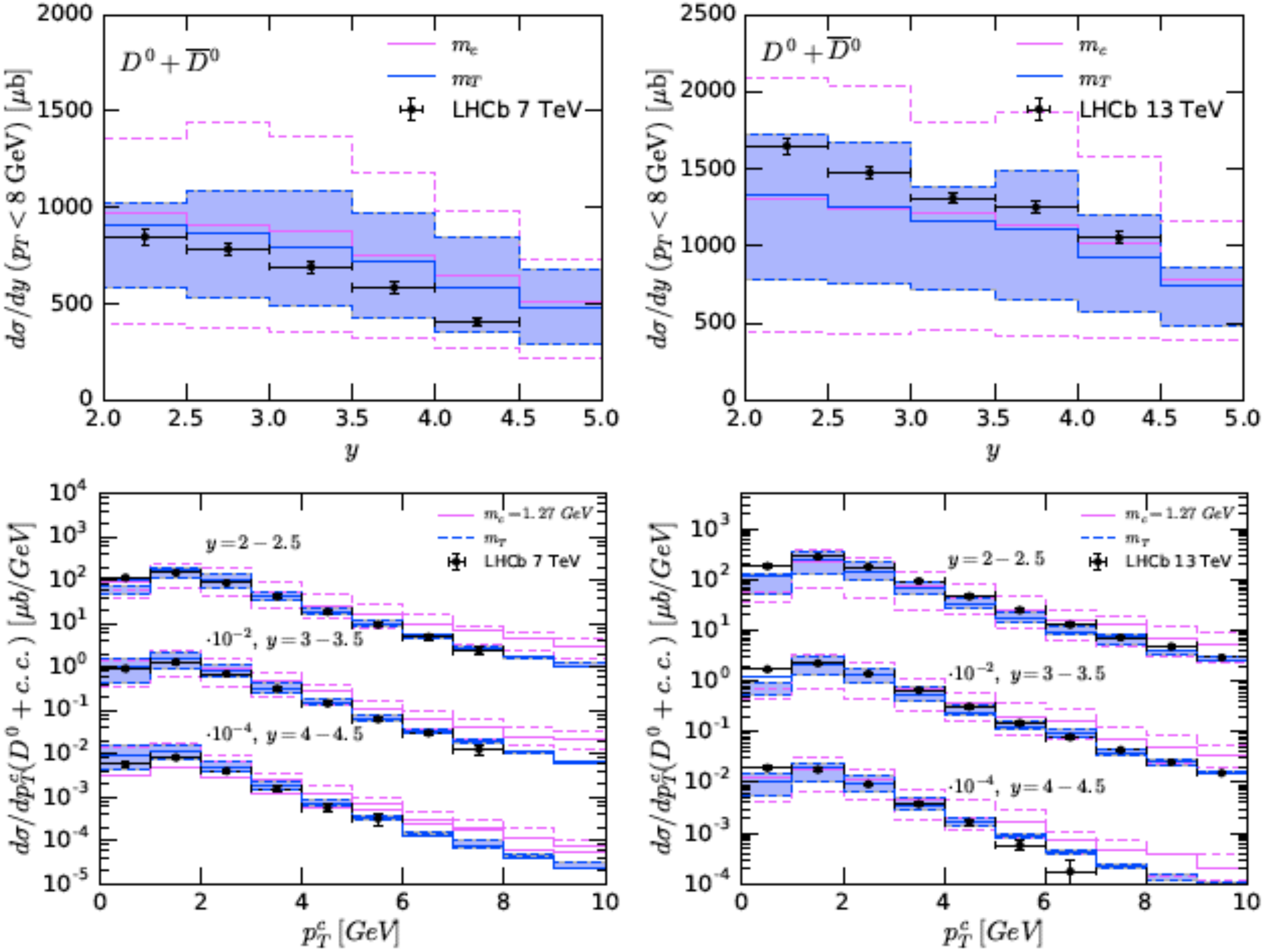


Cross section for charm, b quarks



Nuclear effects not very important for the cross section (for nitrogen targets) but more important for the differential distributions.

Compare with LHC data for charm

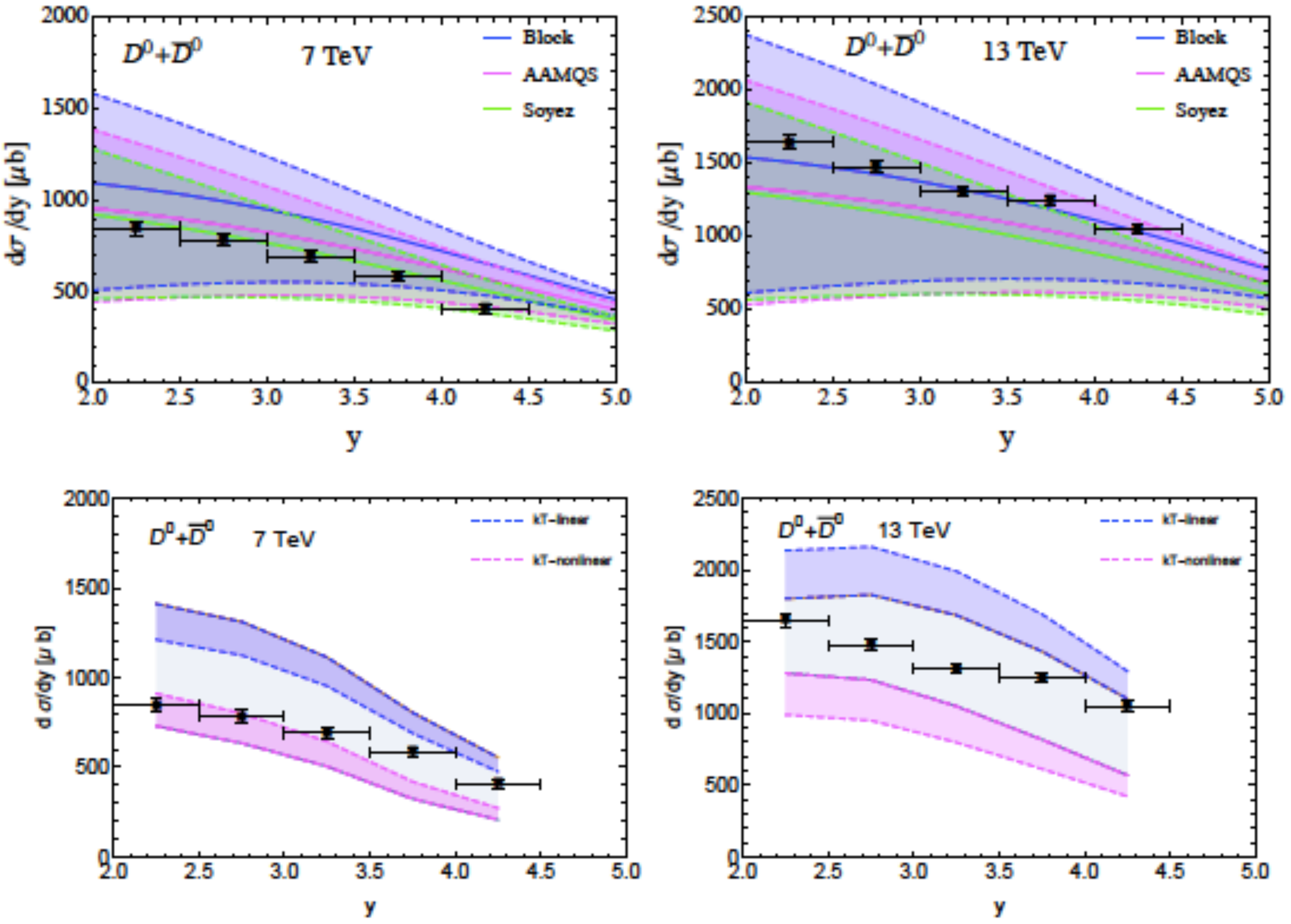


NLO perturbative for example, with a range of scale factors and dependence.

For the prompt flux from charm, need even larger rapidities.

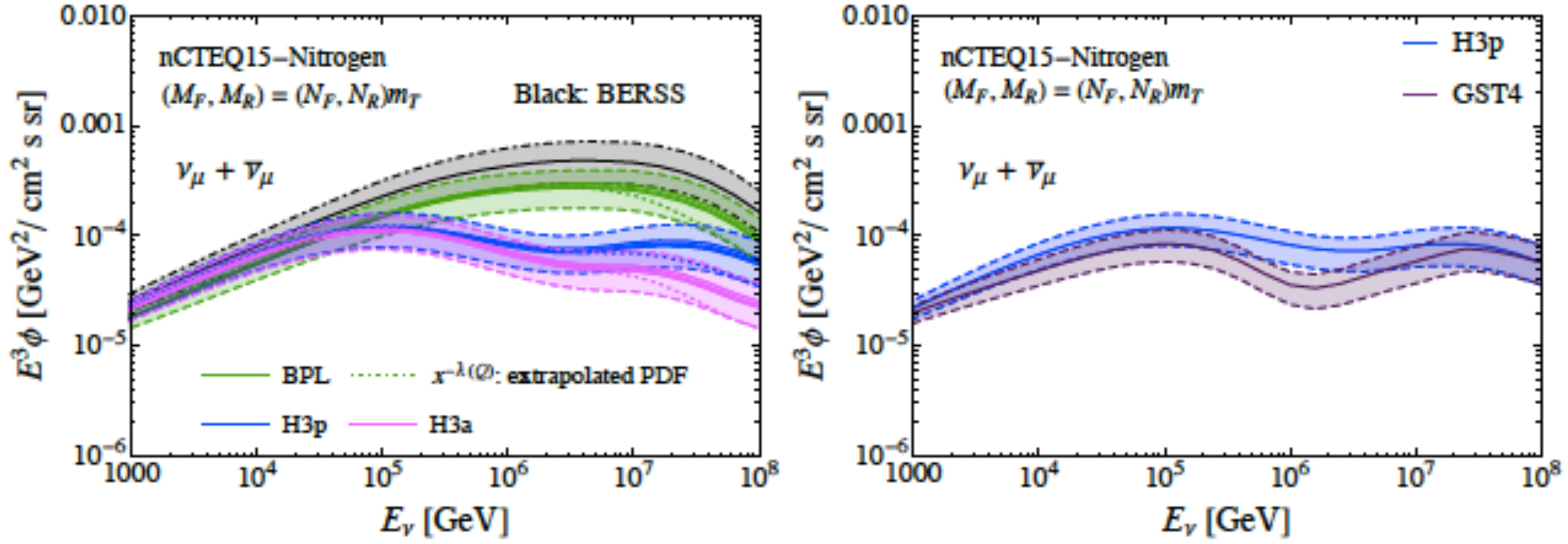
LHCb, Nucl. Phys. B 871 (2013) 1; JHEP 03 (2016) 159

Compare with LHC data



Dipole and kT factorization comparisons.

NLO QCD result for prompt neutrino flux

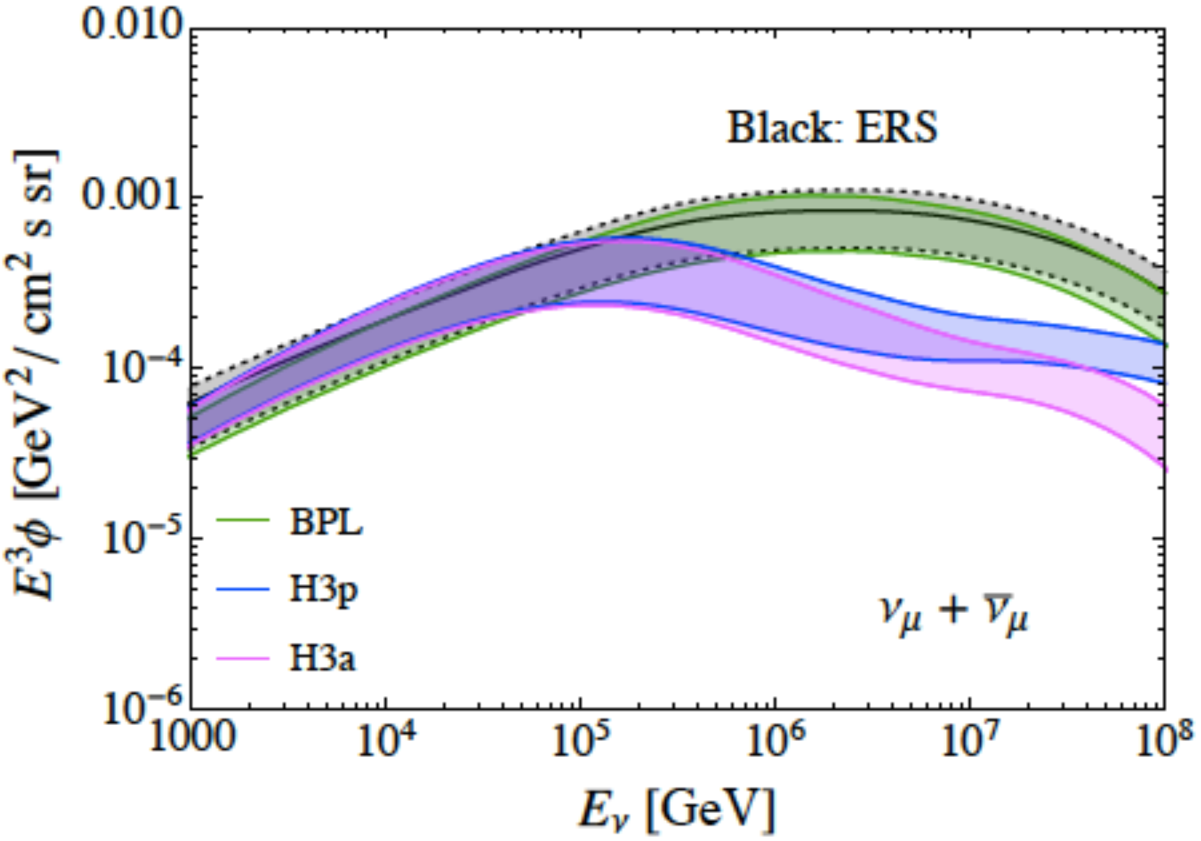


BERSS: Bhattacharya et al., JHEP 06 (2015) 110 uses CT10 PDFs with no nuclear corrections.

Nuclear corrections via nCTEQ15 parton distribution functions are significant.

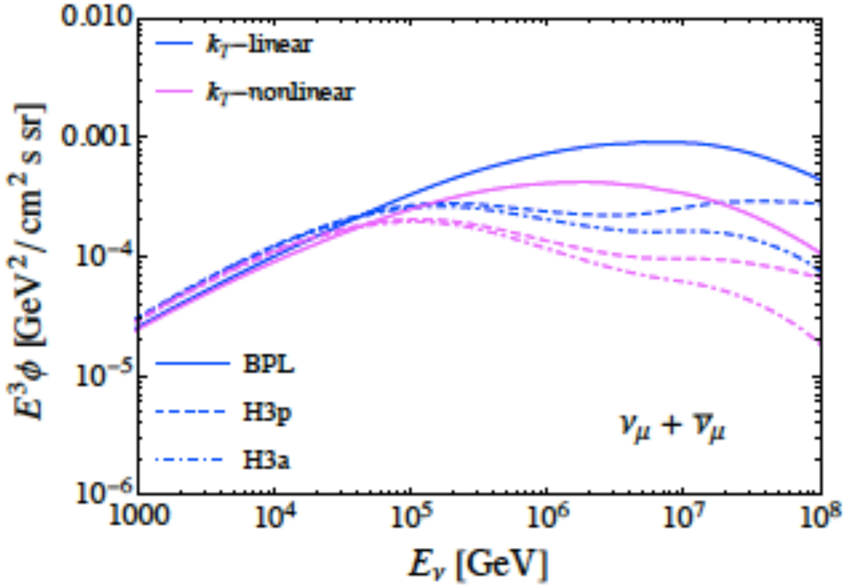
Multi-component cosmic ray flux – two models, Gaisser et al.

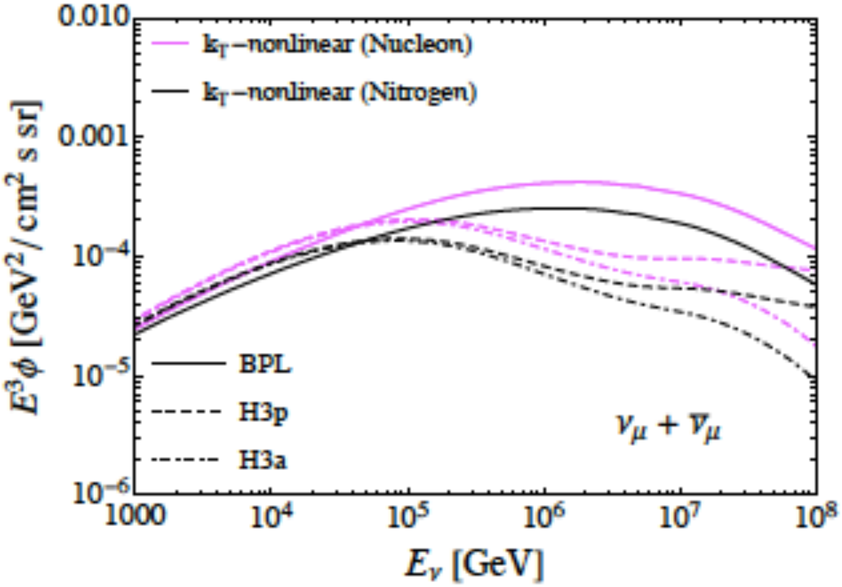
Dipole model



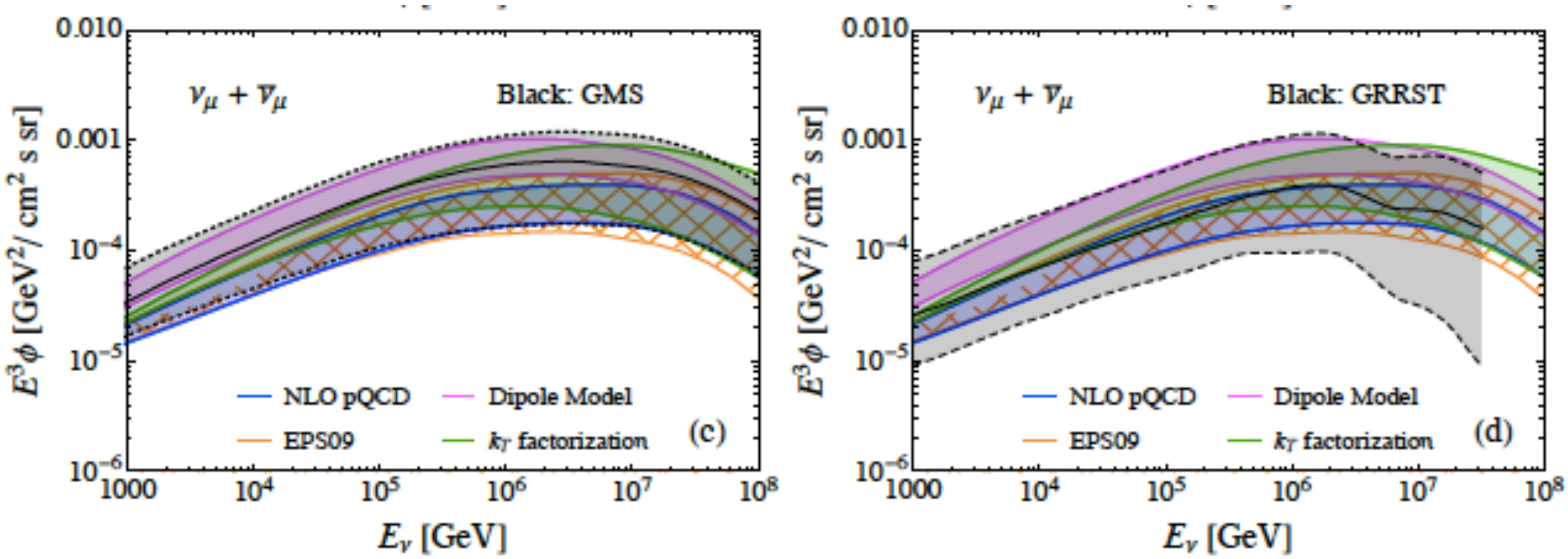
Muon neutrino, approximately same as electron neutrino and muons, isotropic at “low energies.

kT factorization





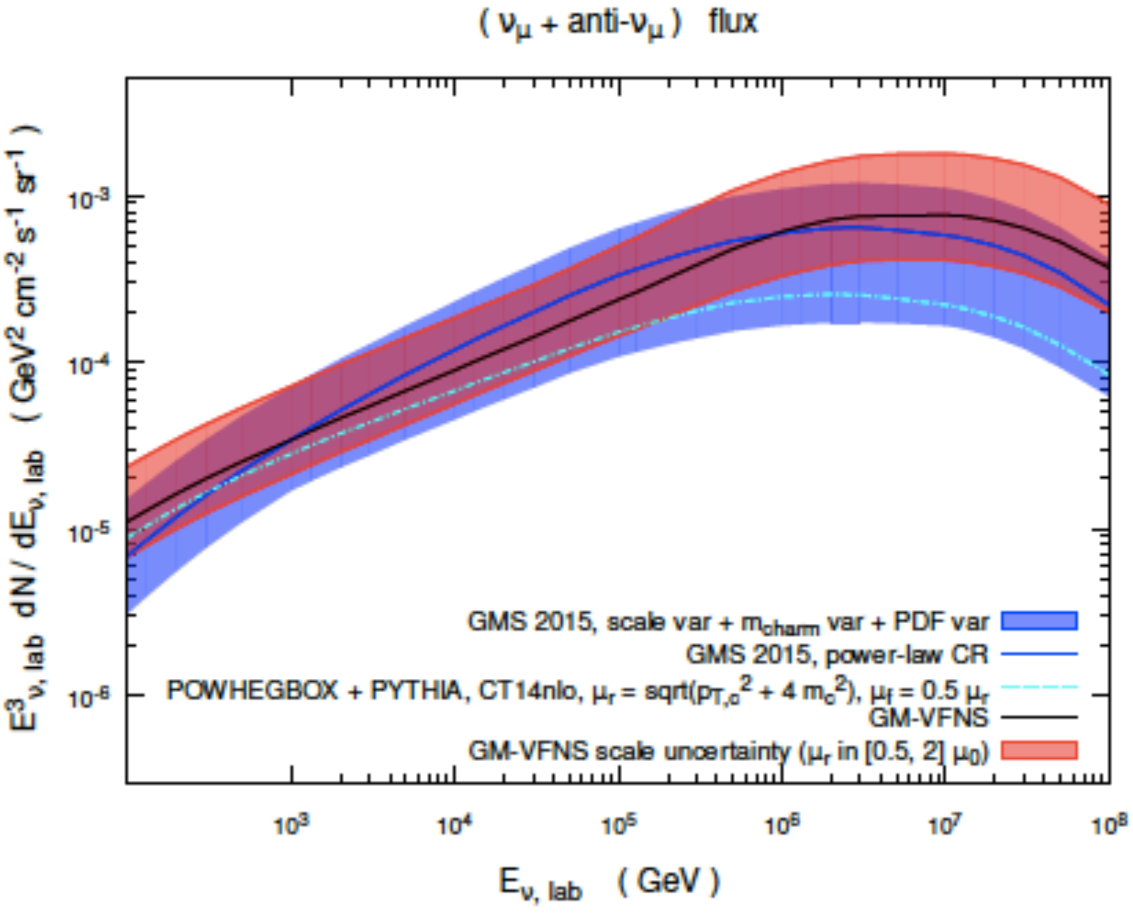
Comparison with other recent results



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

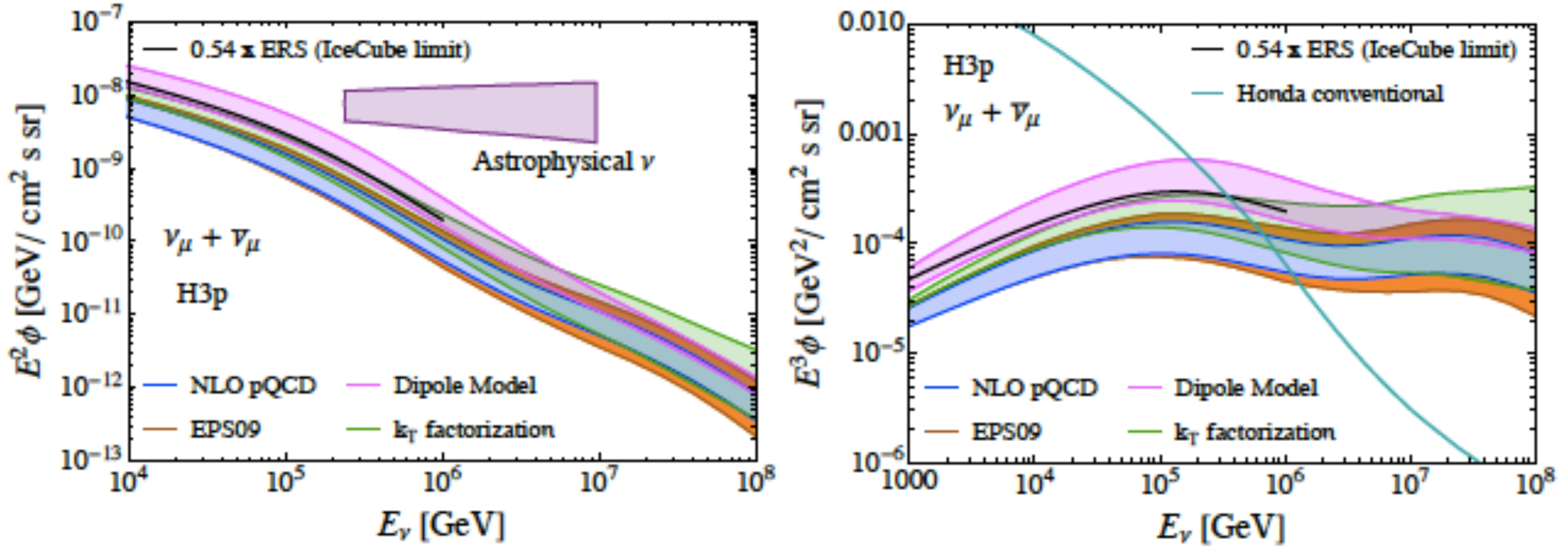
GMS: Garzelli, Moch and Sigl, JHEP 10 (2015) 115 using POWHEG BOX and Pythia; GRRST: Gauld et al, JHEP 02 (2016) 130 with different assessment of PDF uncertainties.

Powheg-Box FFNS (GMS) and GM-VFNS approaches



Charm mass, Pythia vs FF, scale dependence, figure from 1705.10386, Benzke, Garzelli, Kniehl, Kramer, Moch, Sigl.

Prompt neutrino fluxes with different scaling



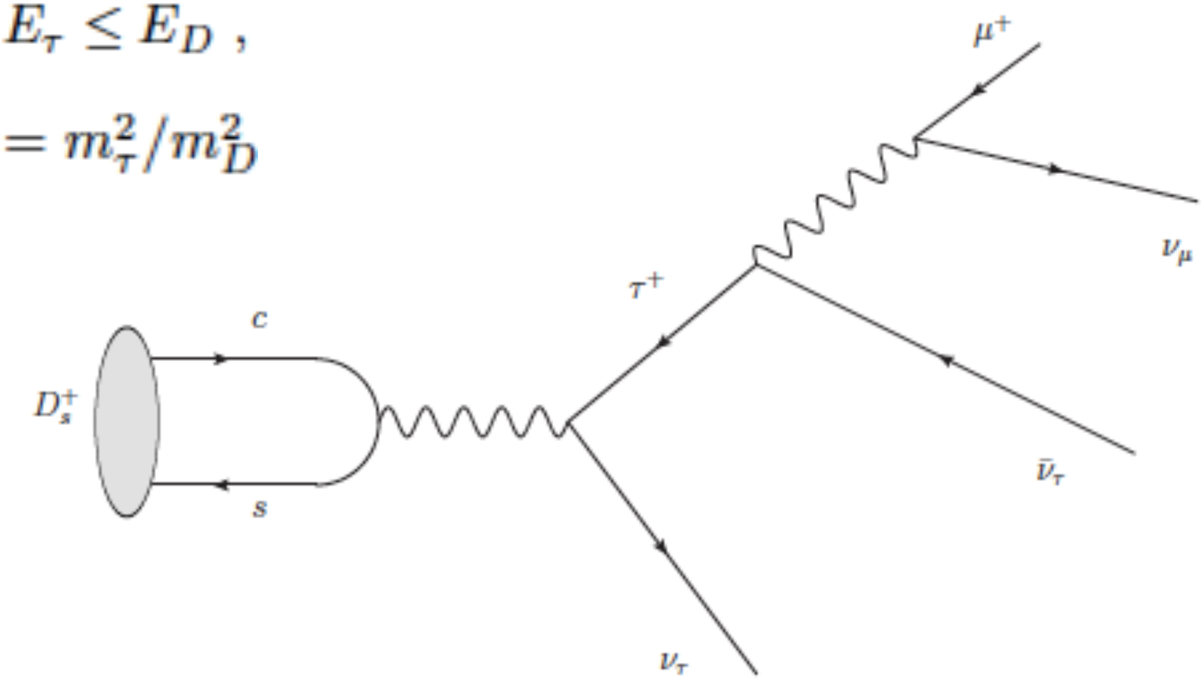
Suggested upper limit on prompt flux: 0.54 ERS from Radel and Schoenen for IceCube, ICRC 2015 (2015) 1079.

Tau neutrinos plus antineutrinos

$$0 \leq E_\nu \leq (1 - R_\tau) E_D$$

$$R_\tau E_D \leq E_\tau \leq E_D \; ,$$

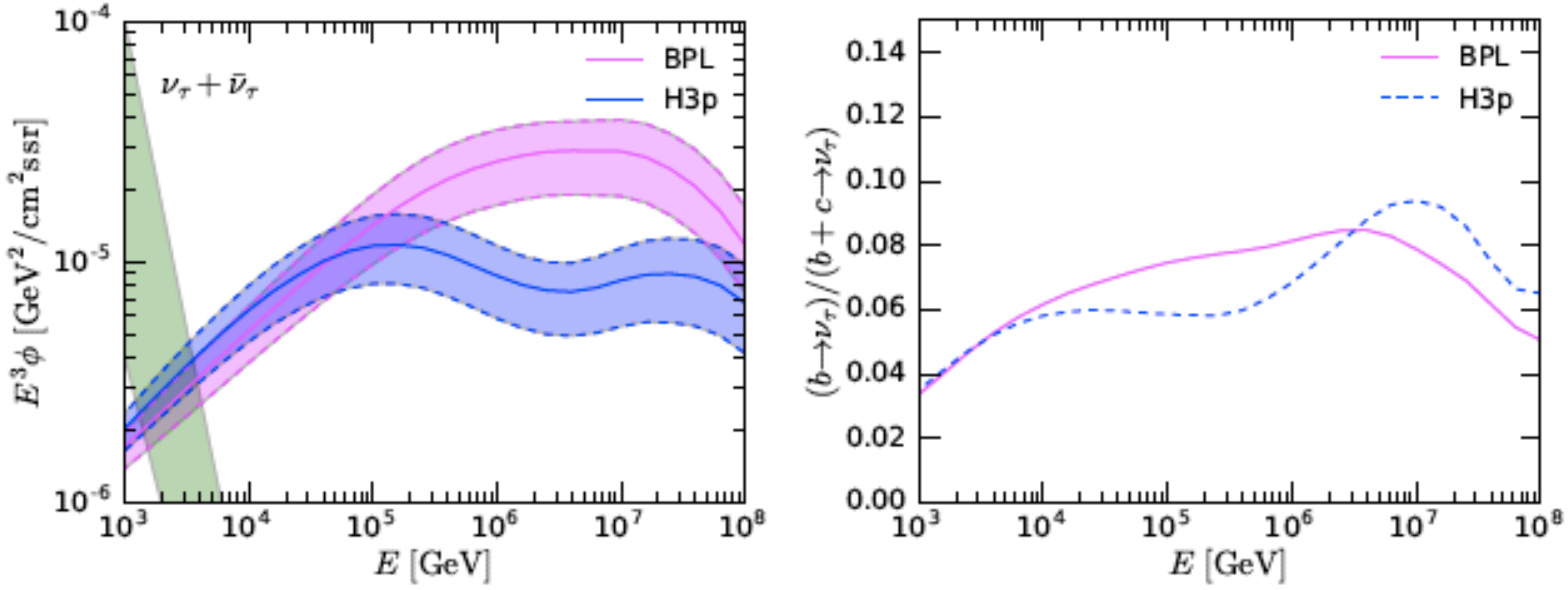
$$R_\tau = m_\tau^2 / m_D^2$$



$$\langle E_\tau \rangle \simeq 0.9 E_D$$

Also B meson/b quark contributions

Prompt atmospheric tau neutrinos plus antineutrinos



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

Prompt flux - perspectives

- 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, or other modifications, see, e.g., Halzen and Wille, PRD 94 (2016); Laha and Brodsky, PRD 96 (2017),* unfavored fragmentation of light quarks in D mesons, Maciula, Szczurek, PRD 97 (2018).
- We have not included the outlier PDFs. If these are included, a much larger band of uncertainty in the prompt neutrino flux will appear, as shown by other authors.

Beam dump proposal - SHiP

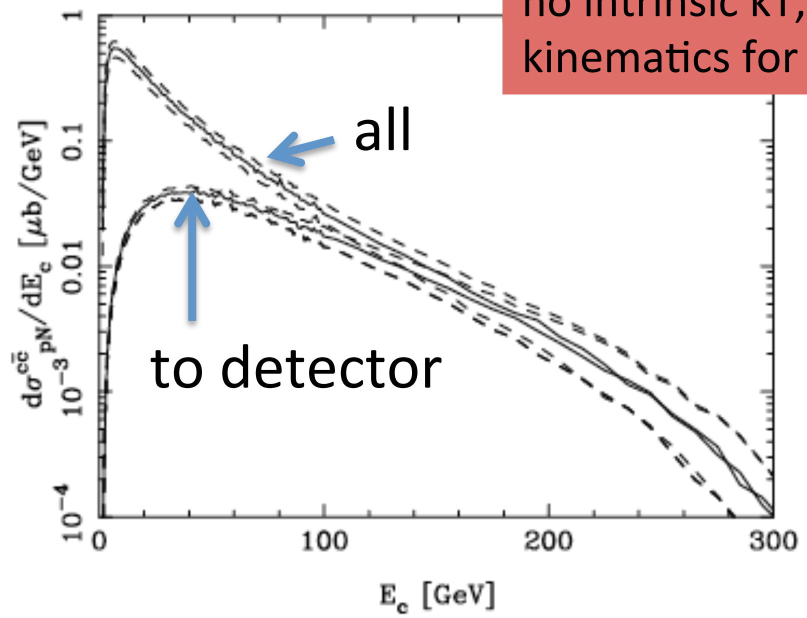
- Search for hidden particles with 400 GeV proton beam incident on Molybdenum target. Neutrinos a happy by-product!
- Beam dump neutrino beam, here a large flux of neutrinos from charmed mesons.
- Initial estimates: on the order of 900 tau neutrino plus antineutrino events. (DONUT has 9 events, OPERA has 4 events.)
- Show here: intrinsic transverse momentum reduces the number of tau neutrino plus antineutrino events, by a factor of about 3.
- Intrinsic charm could significantly increase the rates.

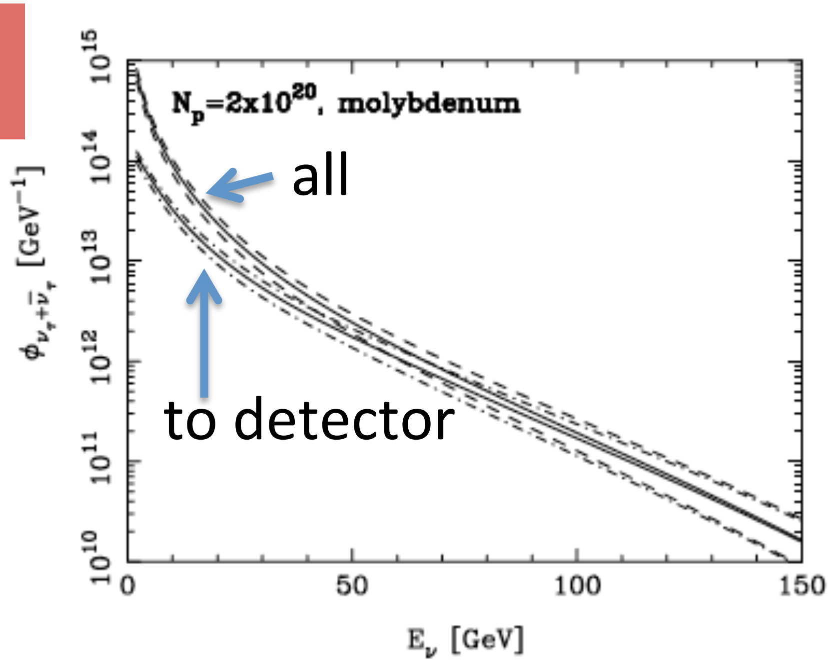
arXiv:1504.04855

Charm/tau neutrino energy distributions from NLO pQCD

$$\phi_{\nu_\tau+\bar{\nu}_\tau} \simeq 2\int_{E_\nu}^{E_b} dE_{D_s}\,\frac{N_p}{\sigma_{pA}}\,\frac{d\sigma_{pA\to D_sX}}{dE_{D_s}}(E_b,E_{D_s})\times\sum_i \frac{dn_i}{dE_\nu}(E_{D_s},E_\nu)$$

no intrinsic kT, 1D kinematics for decays

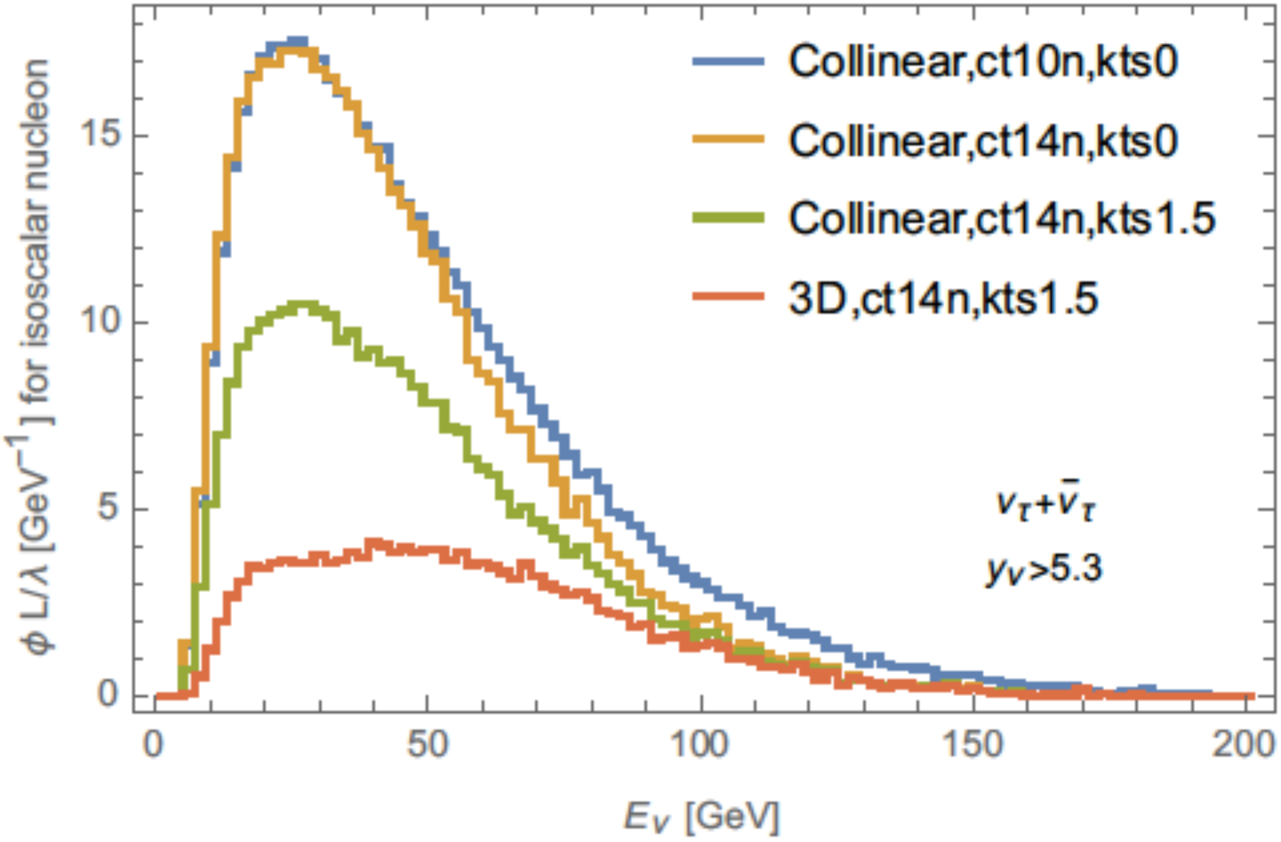




$$E = 400\ \mathrm{GeV}$$

Detector 51.5 m downstream, 2m x 0.75m arXiv:1504.04855

Impact of intrinsic kT and 3D treatment of the decays:



$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2 x + \frac{m_\tau y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})y\right] F_2$$

$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \Bigg),$$

Bai and Reno, in progress

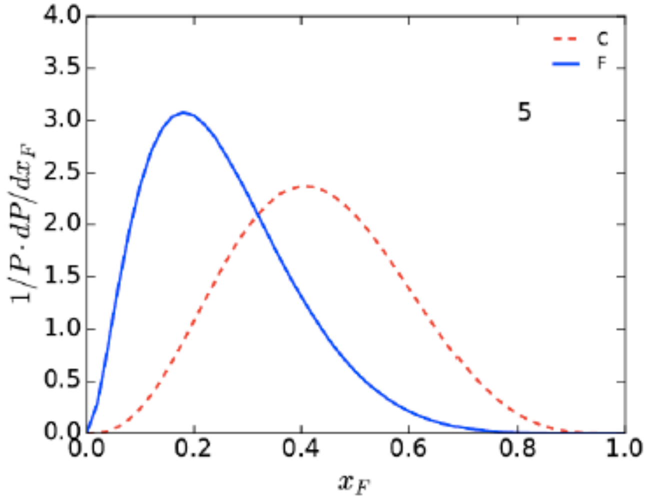
Intrinsic charm, a la Brodsky & Vogt & Gutierrez

$$\frac{d\sigma_{ic}(pN)}{dx_F} = \sigma^{in}_{pN}\frac{\mu^2}{4\hat{m}_c^2}\left(\frac{dP^F_{ic}}{dx_F} + \frac{dP^C_{ic}}{dx_F}\right)$$

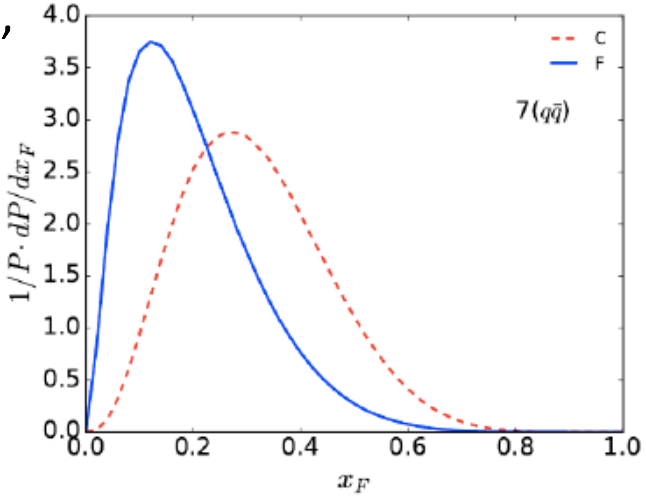
independent uncorrelated fragmentation (F)
coalescence distribution (C)

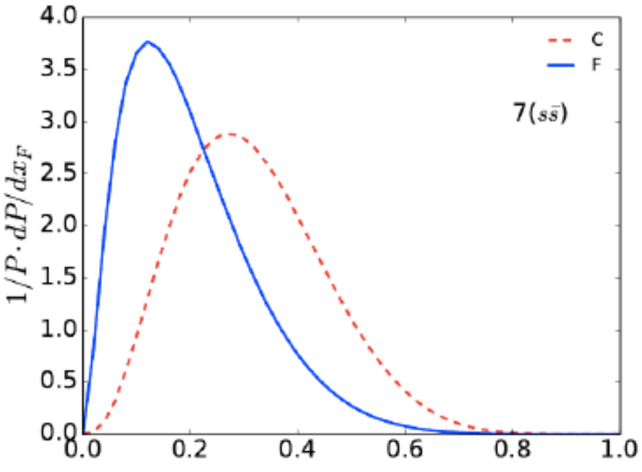
$$|uudc\bar{c}\rangle$$

$$|uudc\bar{c}q\bar{q}\rangle$$

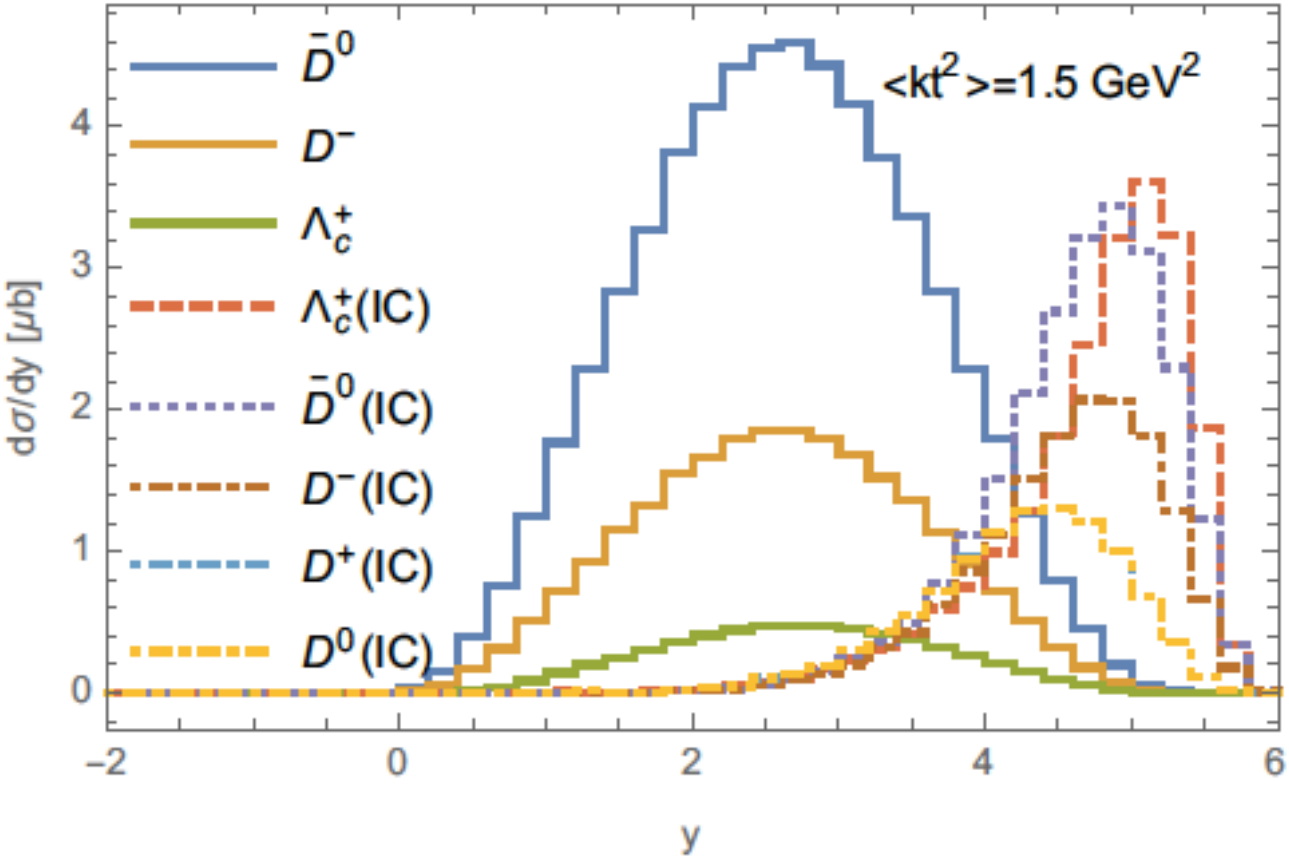


Brodsky et al, PL 93B (1980); Vogt & Brodsky, NP B438 (1995); Gutierrez & Vogt, NP B539 (1999)





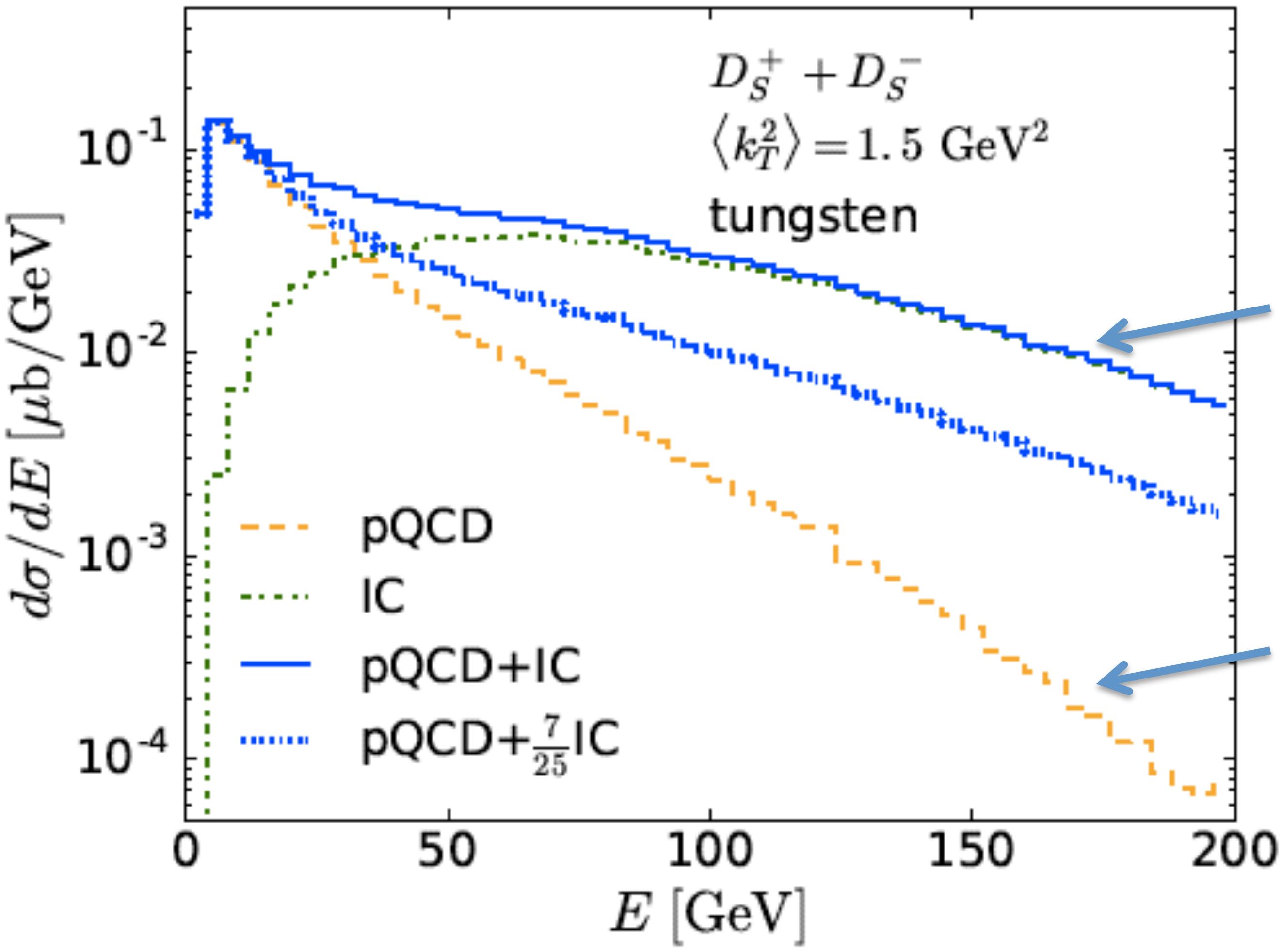
Intrinsic charm, a la Brodsky & Vogt & Gutierrez, rapidity distribution for protons with E=400 GeV on nucleon target



Asymmetries in intrinsic charm distributions, cross sections.

Bai and Reno, in progress

DsTau Experiment at CERN: 400 GeV protons on a thin tungsten target. Look for kinks in tracks in emulsion for Ds to tau + nutau (1000 events according to perturbative estimate).



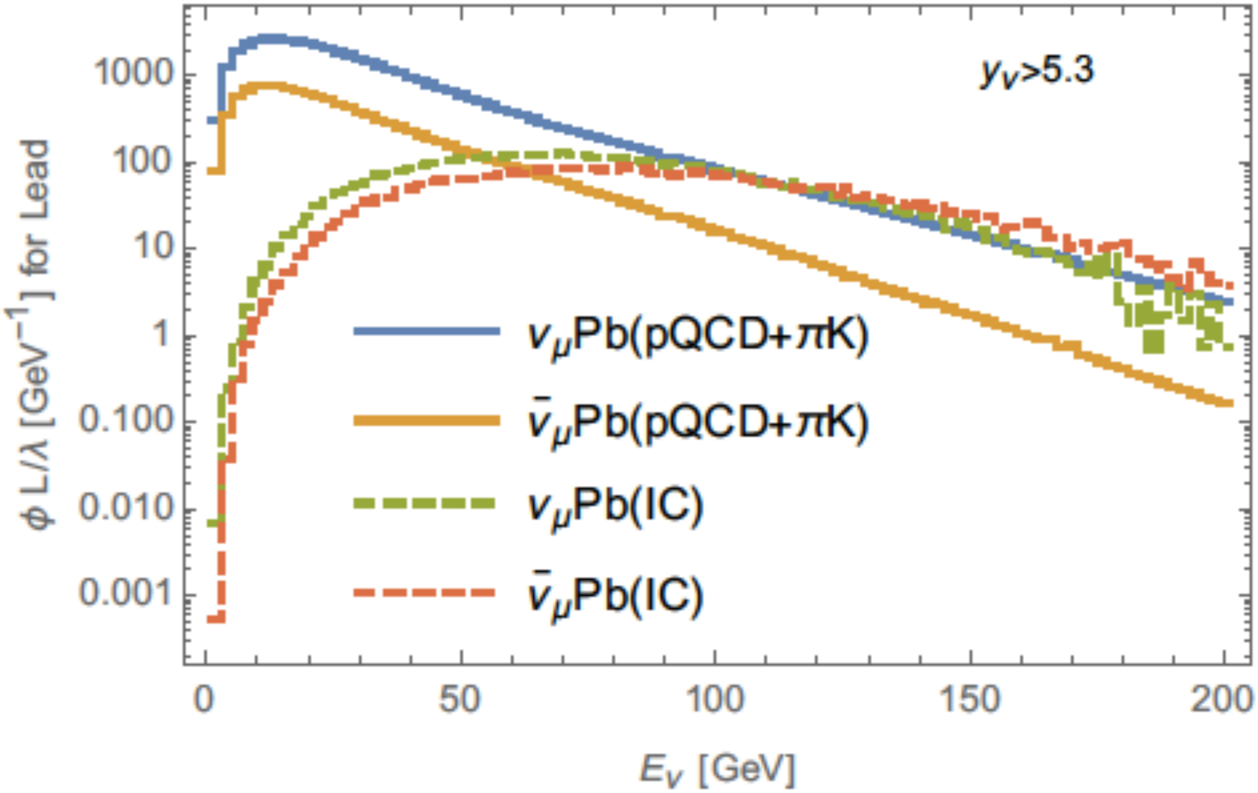
intrinsic charm

perturbative

$$\nu_\mu \to \mu^-$$

$$\bar{\nu}_\mu \to \mu^+$$

Intrinsic charm will modify the relative rates. Look for particle/antiparticle asymmetries.



Conclusions & Future Work

- The modern PDFs and high energy constraints on the cross section are a start to developing an understanding of the QCD uncertainties in the prediction. Ideally, higher rapidity measurements would be made for charm distributions. Nuclear corrections are important.

- Beam dump fluxes of tau neutrinos would also probe charm production & would offer a significantly larger data set of tau neutrino+anti-neutrino events. This could be a test of some intrinsic charm models or other leading particle enhancements for charm. Geometry of detector is (of course) important.

- Work in progress to understand asymmetries in muon neutrino-antineutrino production at SHiP.

Comparison with ERS

- PDFs nearly the same, but the differential energy distribution of the charm is different: dipole model vs perturbative calculation. The Z-moment emphasizes large xE, which does not have a large contribution to the cross section. The ratio of the Z-moments is approx. factor of 1.5 (ERS approximately 1.5xBERSS).
- We use a different value of Zpp: in ERS, we used the Thunman et al (TIG, Astropart. Phys. 5 (1996)) PYTHIA value,

$$Z_{pp}^{ERS}(10^3\ \mathrm{GeV}) \simeq 0.5$$

$$Z_{pp}^{BERSS}(10^3\ \mathrm{GeV}) \simeq 0.27$$

Here: $$\frac{d\sigma}{dx_E} \sim (1-x_E)^{0.51}$$

Approximate formulae

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

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

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

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

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

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

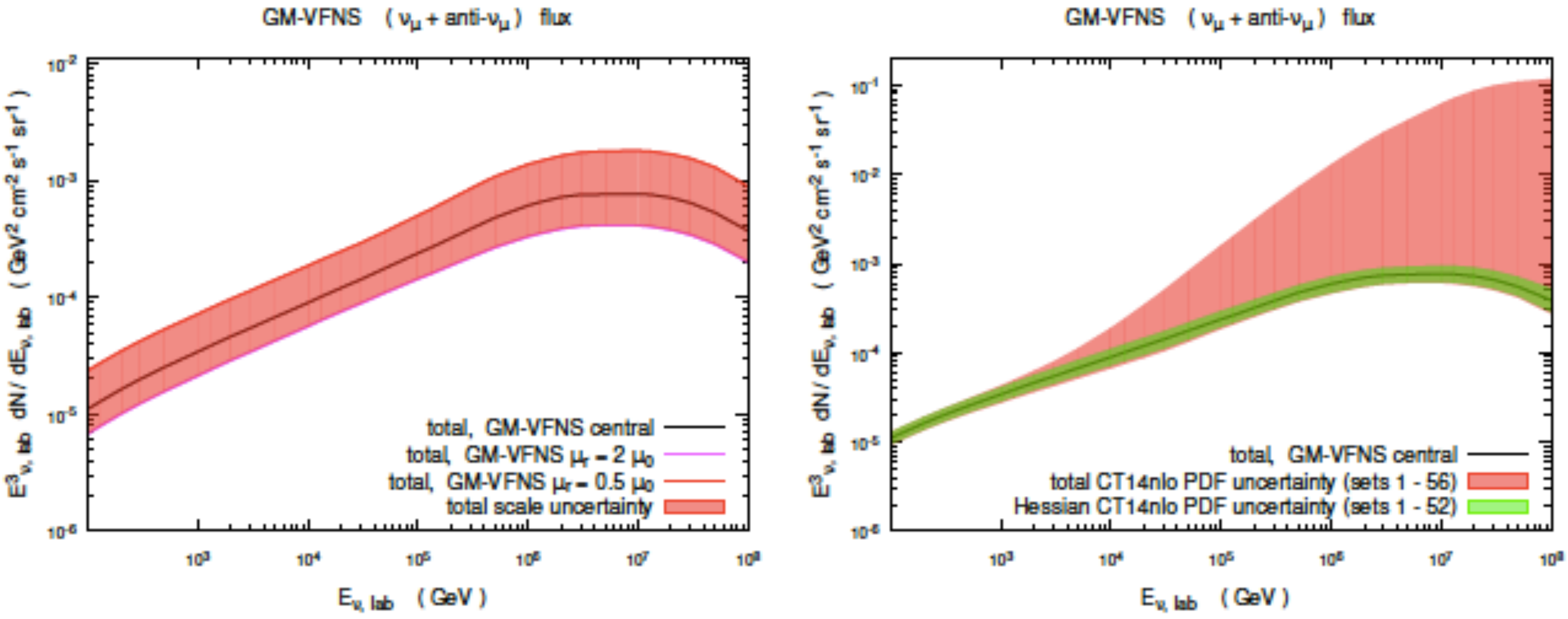
Exponential atmosphere, 1D, approximate factorization of depth dependence.

$$Z_{ND},\ Z_{D\ell},\ \Lambda_D$$

$$c \to s\mu^+\nu_\mu \quad c \to s e^+ \nu_e$$

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)

Comparison with recent results



Broken power law, with CT14nlo fit and GM-VFNS, 1705.10386