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Hadronic Physics, April 8-10, 2015

Perturbative Charm Production and the Prompt Atmospheric Neutrino Flux in light of RHIC and LHC

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A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic
and A. Stasto, arXiv:1502.01076

The idea is to use measured charm cross section at RHIC and LHC to constrain pQCD parameters and with these parameters evaluate prompt atmospheric neutrino flux

Atmospheric prompt neutrino flux is the flux of neutrinos from charmed meson decays, where charmed mesons are produced in p-Air collisions (p-Air →charm → D-mesons)

Atmospheric neutrino flux has been measured with IceCube up to PeV energies

Charm Production and Cross Sections using pQCD and PDFs

The total charm cross section in pQCD is given by:

$$\sigma(pp \to c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \hat{\sigma}_{gg \to c\bar{c}}(x_1 x_2 s)$$

and differential charm cross section

$$\frac{d\sigma_{\rm LO}}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1 + x_2)s} \sigma_{gg \to c\bar{c}}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2)$$

where

$$x_1,\ x_2 :$$

$$x_F = x_1 - x_2$$

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

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

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1$$

$$E \sim 10^7\ \mathrm{GeV} \to x_2 \sim 10^{-6}$$

$$x_{1,2} \sim m_c/2m_p E_\nu$$

For high energies we need gluon PDF for small x, and low Q^2

Charm Production in Hadronic Collisions

- Recent comprehensive study of charm cross section in hadronic collisions (Nelson, Vogt, Frawley PRC 87 (2013)) using FONLL and NLO QCD. They considered range of factorization and normalization scales, PDFs and charm quark mass

- They have constrained QCD parameters (factorization and renormalization scale, PDFs, charm quark mass) with fixed target, RHIC and LHC charm cross section measurements

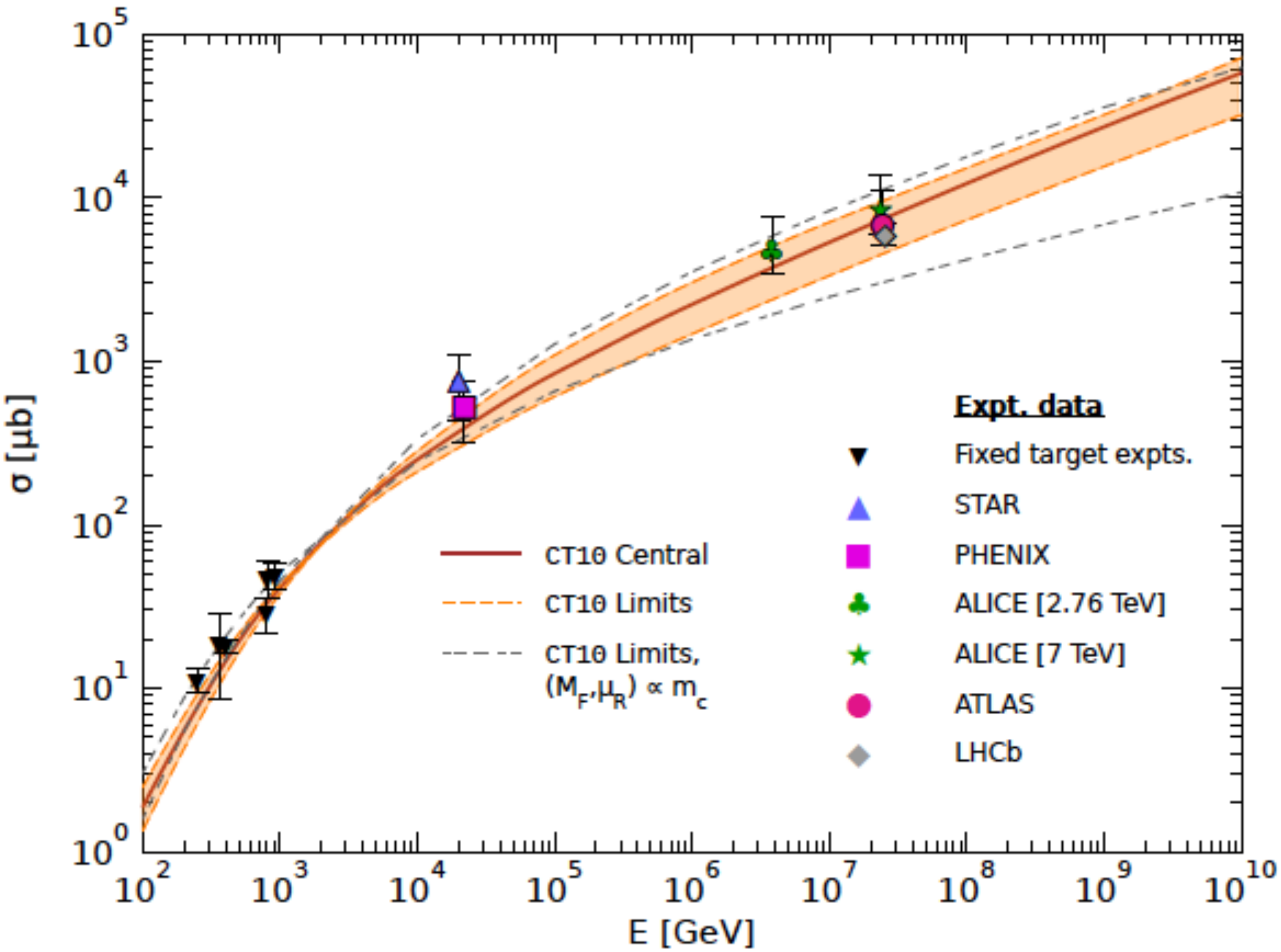


Figure 1: The charm production cross section $\sigma_{pN\to c\bar{c}+X}$ at NLO with $m_c = 1.27$ GeV using the CT10 parton distributions for a range of scales described in the text, with the central set with factorization and renormalization scales $M_F = 2.10m_T$ and $\mu_R = 1.6m_T$, respectively. Apart from experimental data points listed in table 1, results from HERA-B [43] and lower energy experiments summarized in [44] for pN scattering are shown (labelled as `Fixed target expts.`). For comparison, we also show the lower and upper limits (grey fine-dashed curves) when the renormalization and factorization scales are made to vary proportionally to m_c rather than to m_T.

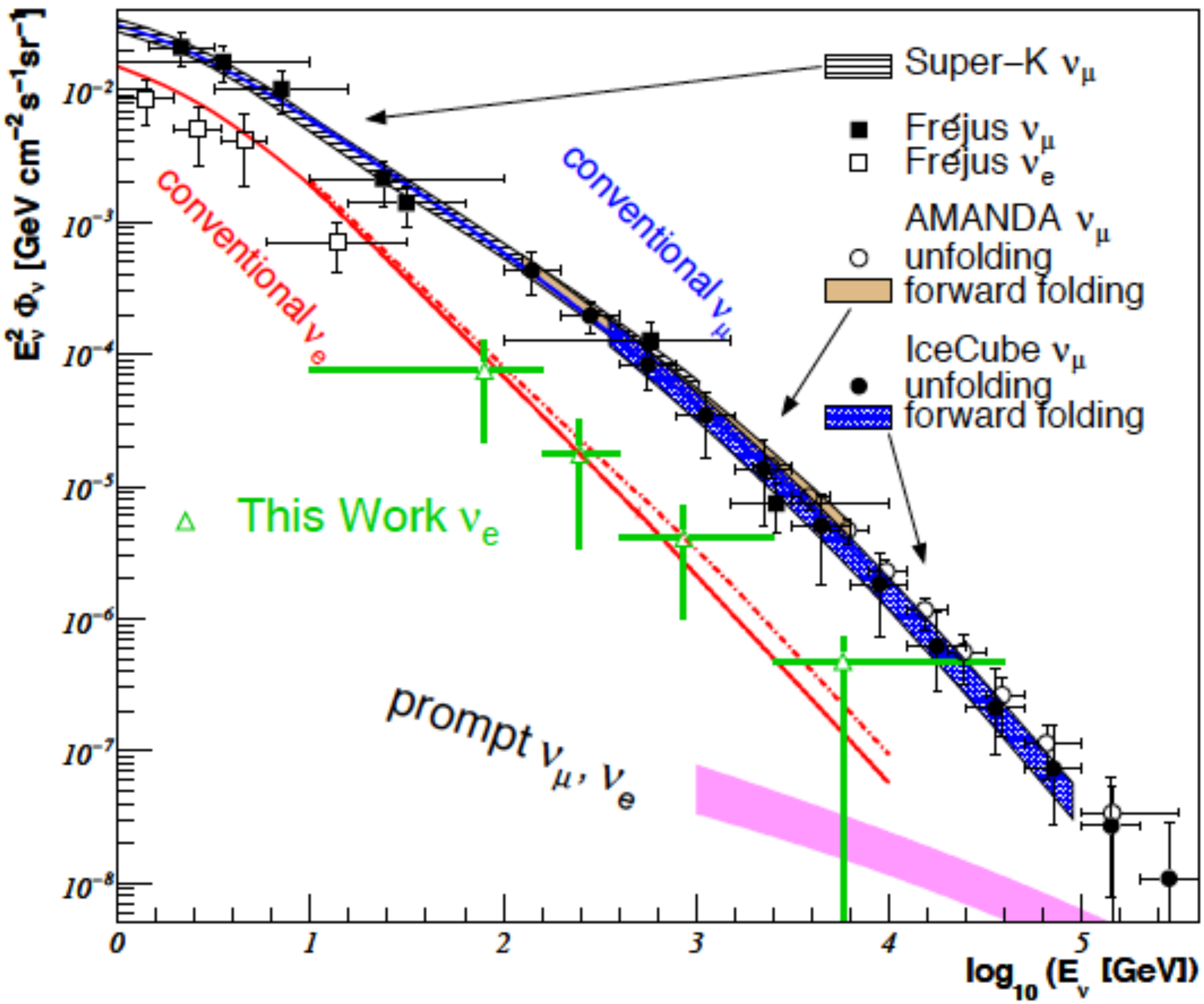
How does this constrained range of QCD parameters in hadronic charm production affect prompt atmospheric neutrino flux?

- Prompt neutrinos come from charmed meson decays, where charm mesons are produced in p-Air collisions

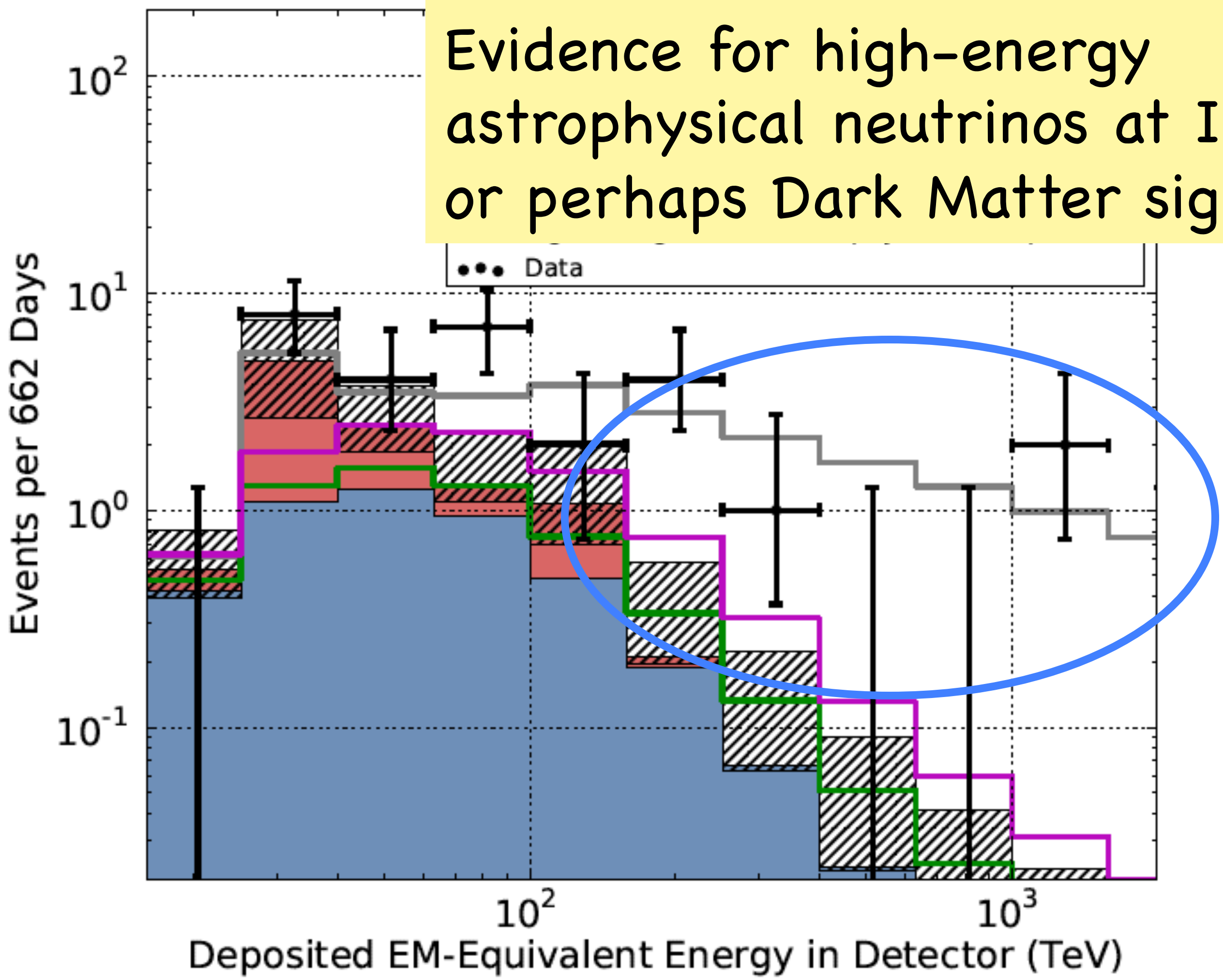
(i.e. p-air → charm → D-mesons)

IceCube has detected atmospheric neutrinos, and neutrino access in 10TeV to few PeV energy range (prompt neutrinos are the most important background). Detection of prompt neutrinos interesting in itself, probes pQCD

Atmospheric Neutrino Flux Measurements



Atmospheric Neutrinos are the Main Backaround

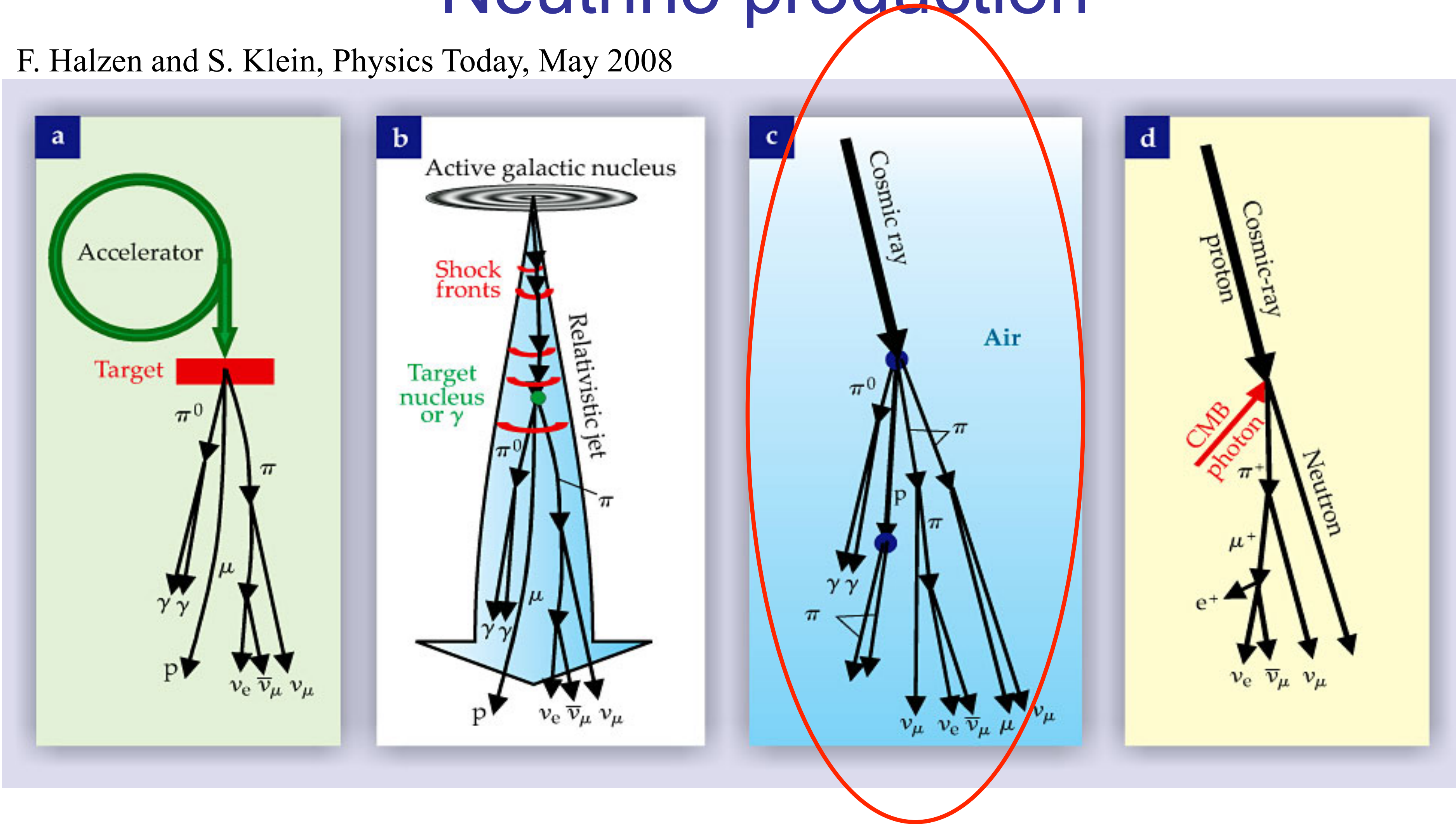


Evidence for high-energy astrophysical neutrinos at IceCube or perhaps Dark Matter signal

IceCube, Science 342 (2013), arXiv:1311.5238

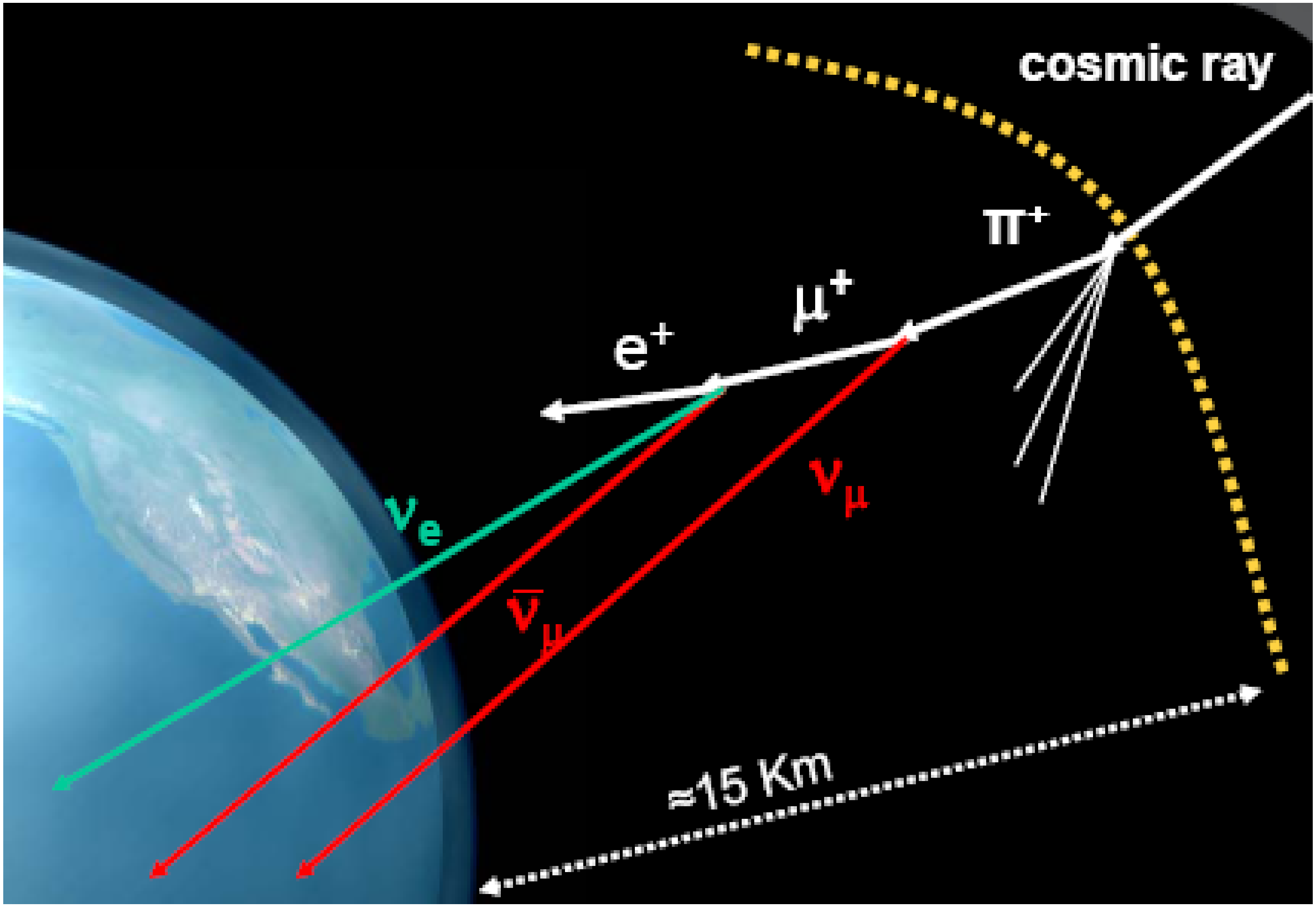
Neutrino production

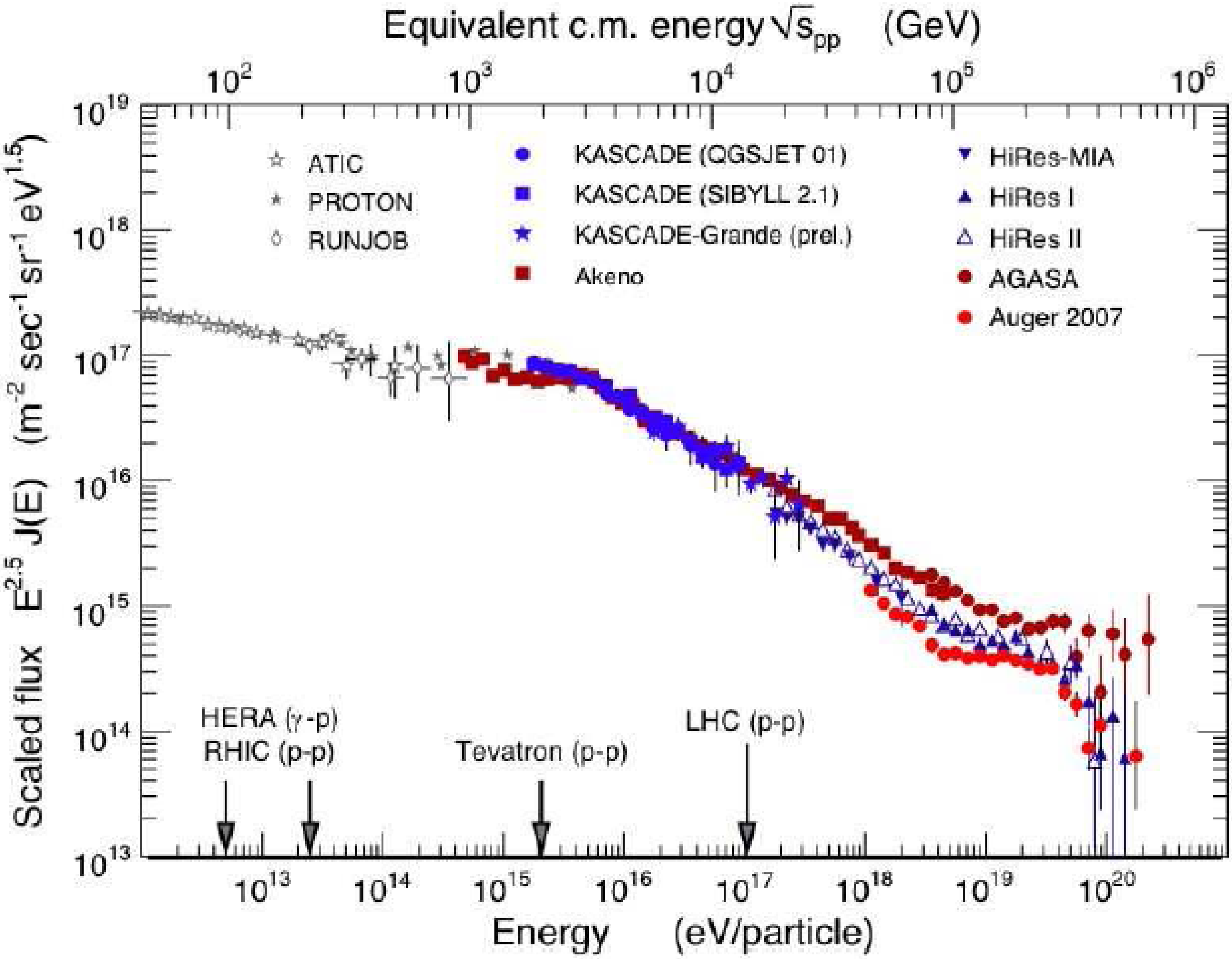
F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

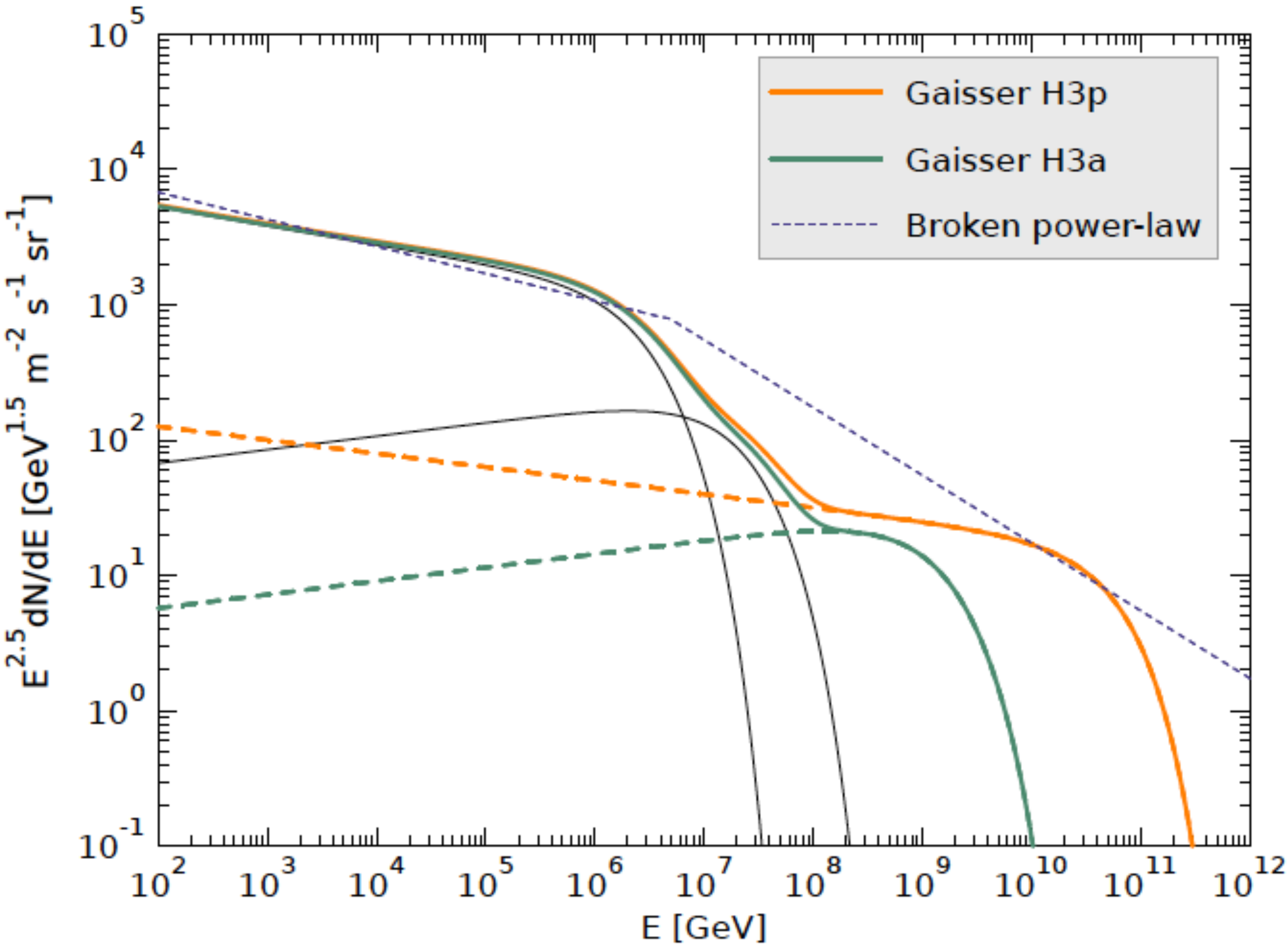
Cosmic Rays





Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Proton Flux



Gaisser H3p
Gaisser H3a
Broken power-law
$E^{2.5}dN/dE$ [$GeV^{1.5}$ m^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}

Prompt neutrino flux

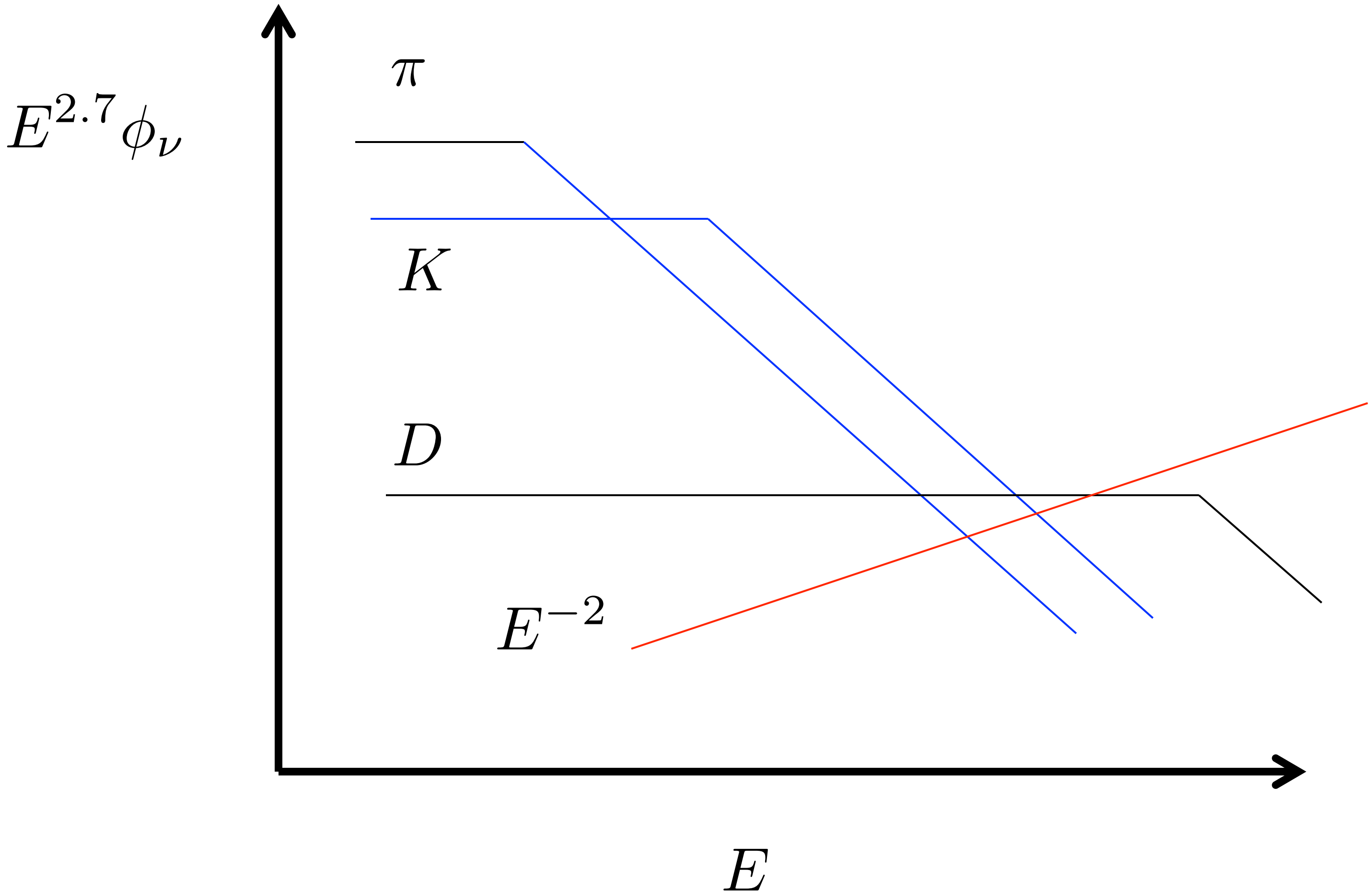
- Hadrons containing heavy quarks *(charm or bottom)* are extremely short-lived:
  ⇒ decay before losing much energy
  ⇒ neutrino energy spectrum is harder

- However, production cross-section is much smaller

- There is a cross-over energy above which prompt neutrinos dominate over the conventional flux

- This is called the atmospheric *prompt neutrino flux*

Schematically



Transport equations for evaluating atmospheric neutrino flux

- To find the neutrino flux we must solve a set of cascade equations given the incoming proton flux:

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY)$$

$$\frac{d\phi_M}{dX} = S(NA \to MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \to MY)$$

$$\frac{d\phi_\ell}{dX} = \sum_M S(M \to \ell Y)$$

- X is the slant depth: "amount of atmosphere"
  ρd_M is the decay length, with ρ the density of air
  λ_M is the interaction length for hadronic energy loss

Z-moments

- We solve the transport equations by introducing Z-moments:

$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E',X,\theta)}{\phi_k(E,X,\theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

- Then

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\rho d_M} - \frac{\phi_M}{\lambda_M} + Z_{MM}\frac{\phi_M}{\lambda_M} + Z_{NM}\frac{\phi_N}{\lambda_N}$$

- Solve equations separately in low- and high-energy regimes where attenuation is dominated by decay and energy loss, respectively, and interpolate

Particle production

The particle physics inputs are the energy distributions for production and decay:

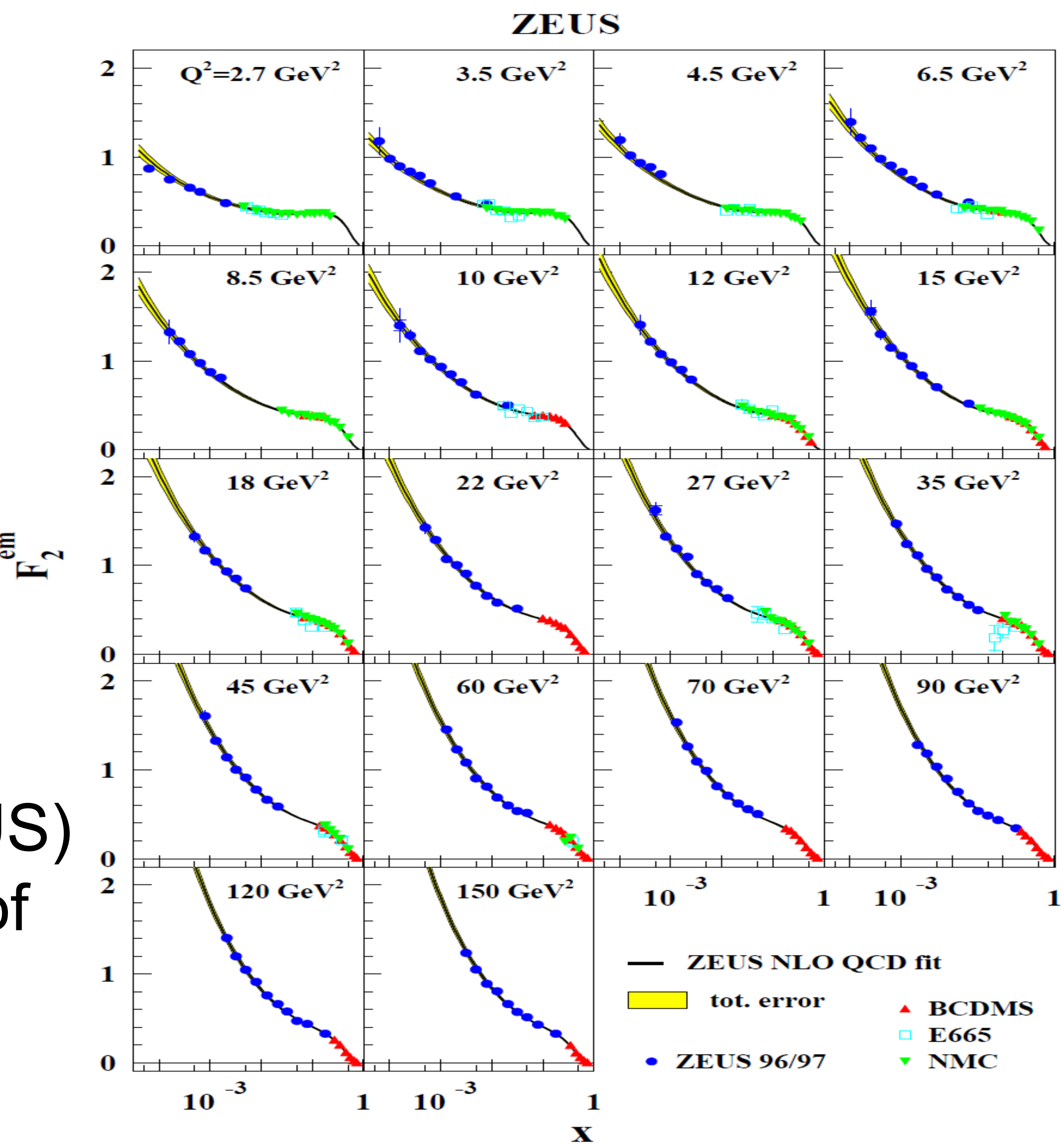
$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \to jY, E_k, E_j)}{dE_j}$$

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

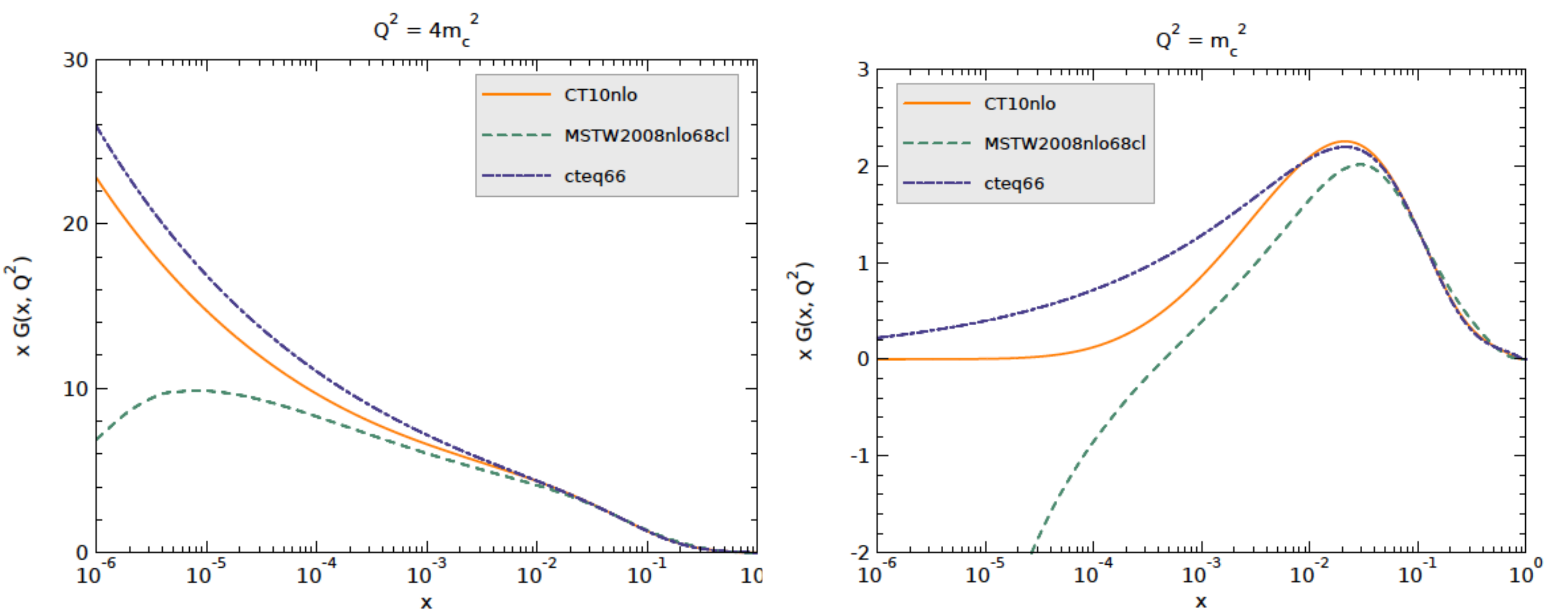
along with the interaction lengths, or cooling lengths

$$\lambda_N(E) = \frac{\rho(h)}{\sigma_{NA}(E) n_A(h)}$$

F2 measured at HERA (ZEUS) as a function of Bjorken-x.



Gluon distributions at low Q^2 (updated PDFs: CT10, MRSTW and CTEQ66)



Charm Differential Cross Section

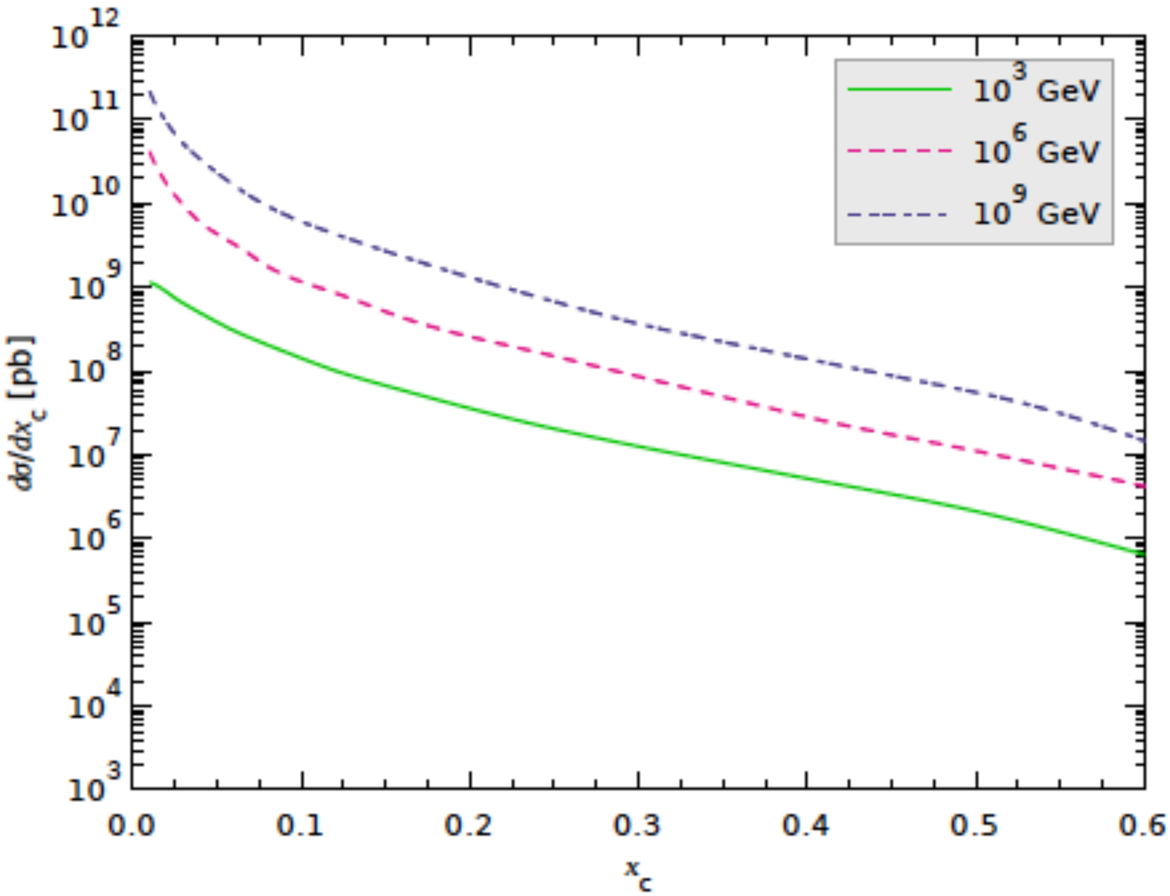


Figure 2: The differential cross section $d\sigma/dx_c$ for the charmed quark, as a function of x_c for $E = 10^3,\ 10^6,\ 10^9$ GeV for $m_c = 1.27$ GeV and $M_F = 2.1 m_T$, $\mu_R = 1.6 m_T$ using the CT10 NLO PDFs.

A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic and A. Stasto, arXiv:1502.01076

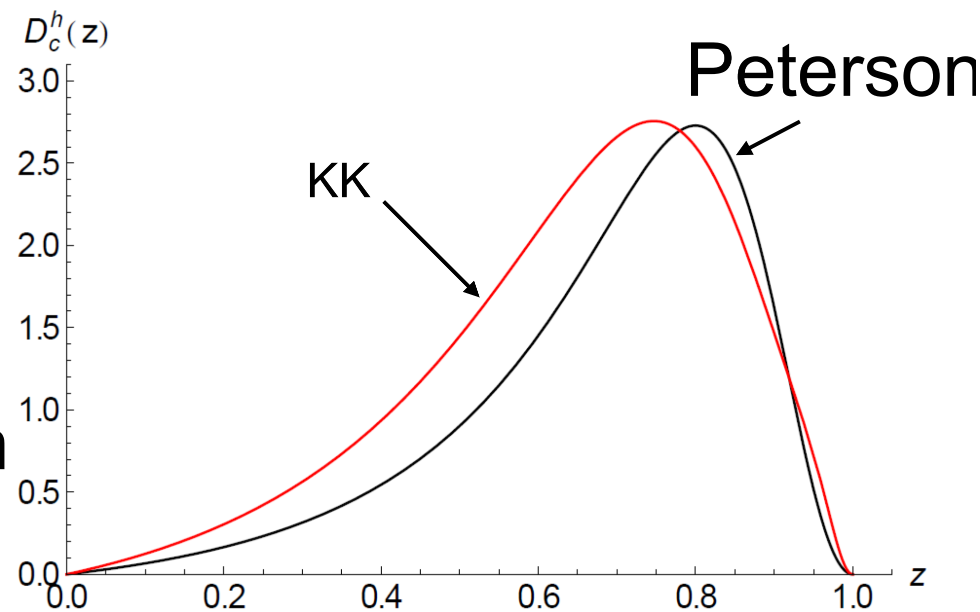
Quark fragmentation to hadrons

Hadronization degrades energy of quark compared to Hadron: Use fragmentation functions fitted to data

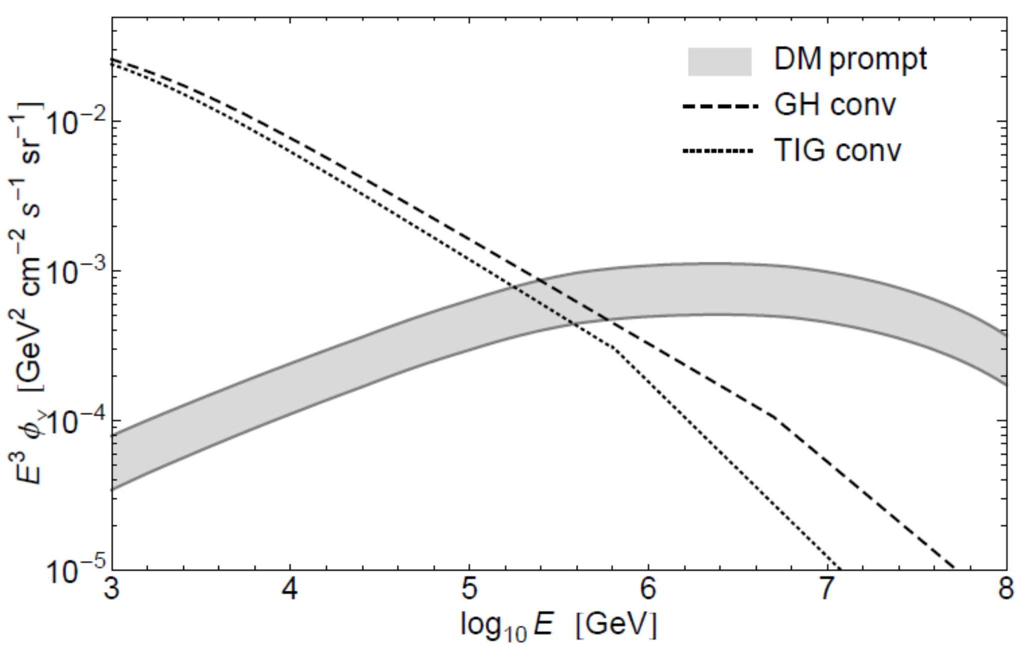
$$\frac{d\sigma(pp \to hX)}{dE_h} = \int_{E_h}^{\infty} \frac{dE_c}{E_c} \frac{d\sigma(pp \to cX)}{dE_c} D_c^h(E_h/E_c)$$

Used Kramer-Kniehl (KK) and Peterson functions

Uncertainty in normalization and average energy fraction



For reference: results for prompt muon neutrino flux (vertical) with dipole model evaluation



DM=dipole model

GH=Gaisser-Honda

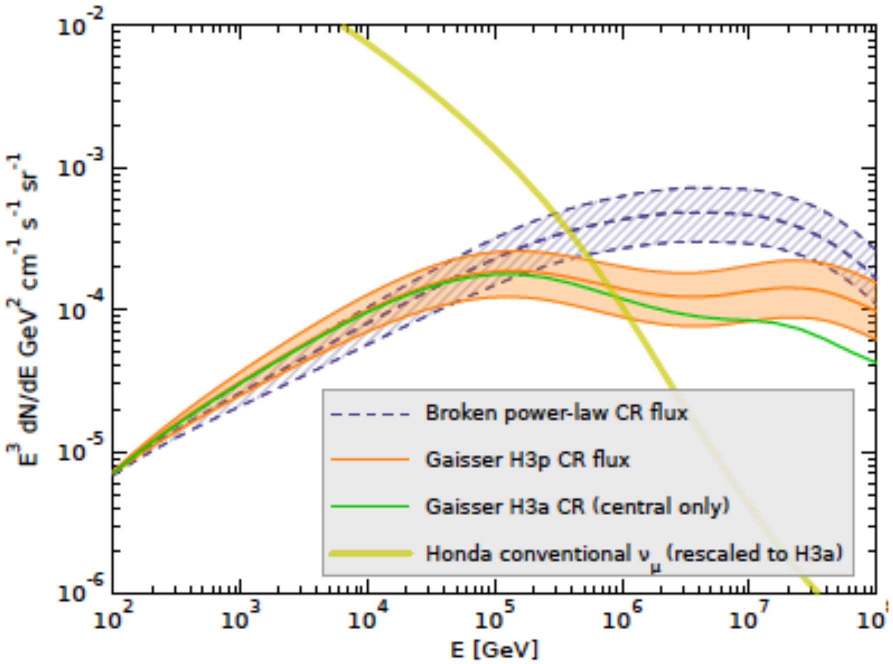
TIG=Thunman et al.

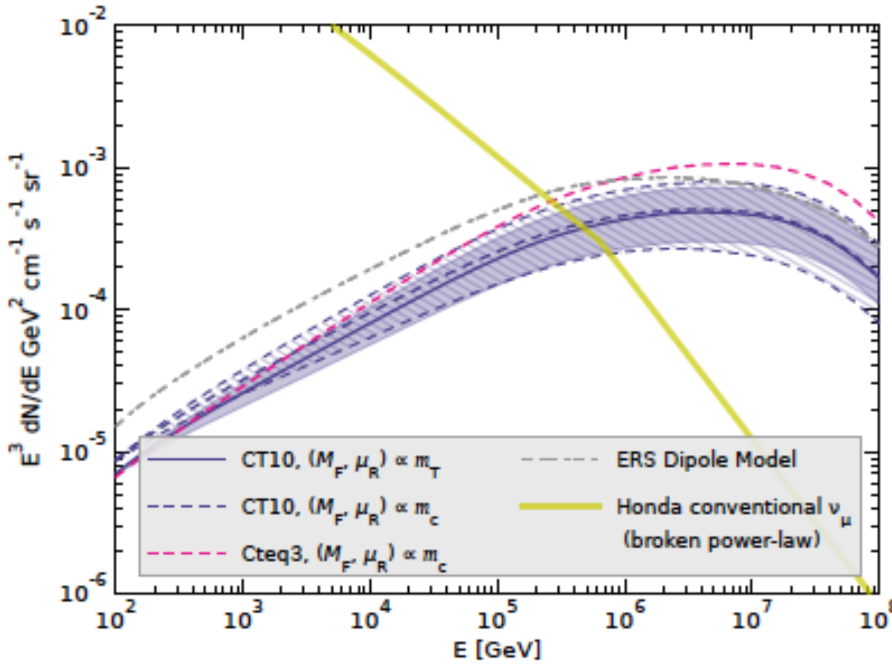
Conventional in vertical direction

Uncertainties include: charm mass, gluon PDF, dipole parameters, scales

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Prompt Neutrino Flux





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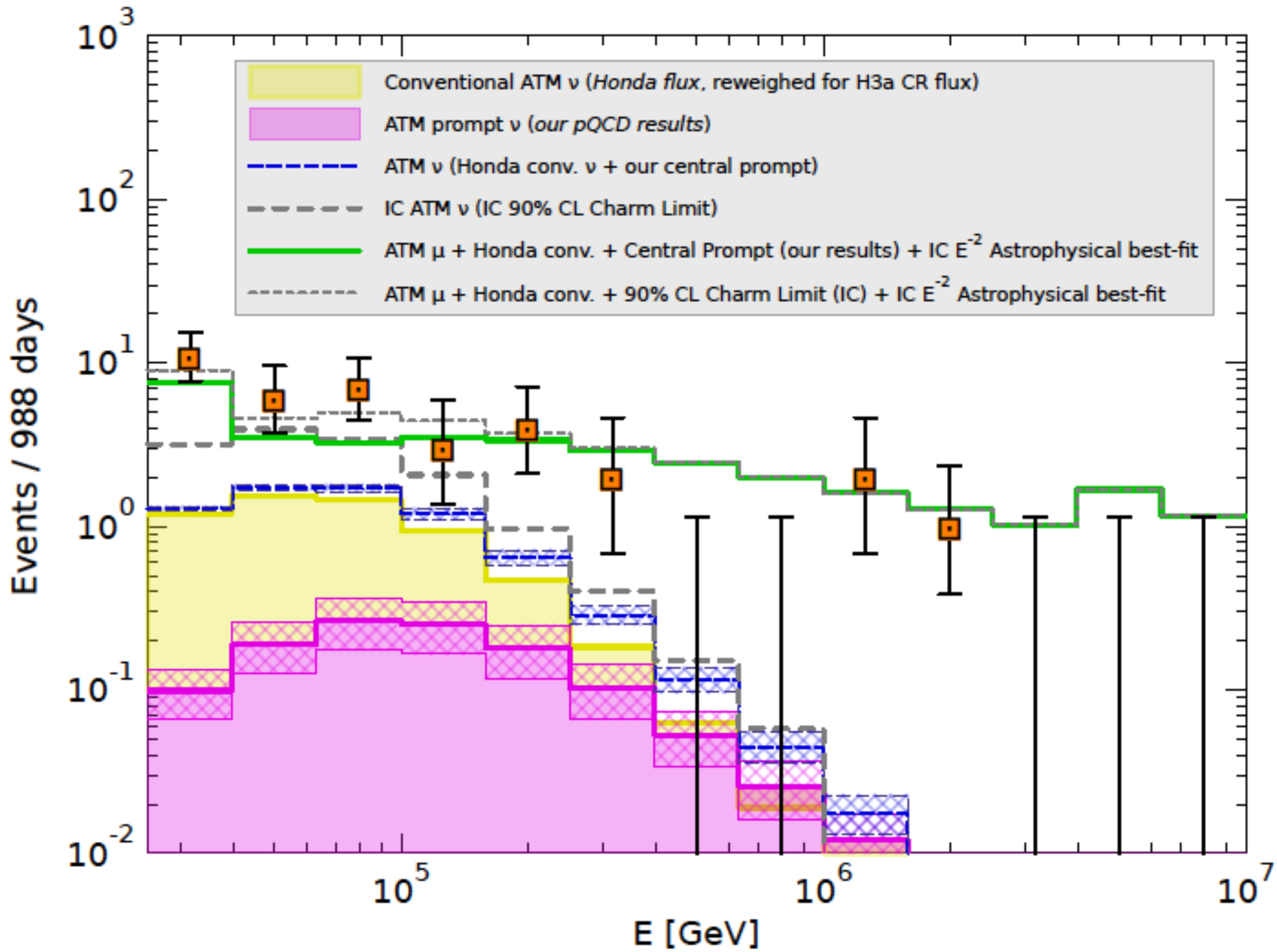
Event Rates at IceCube from Prompt Atmospheric Neutrinos



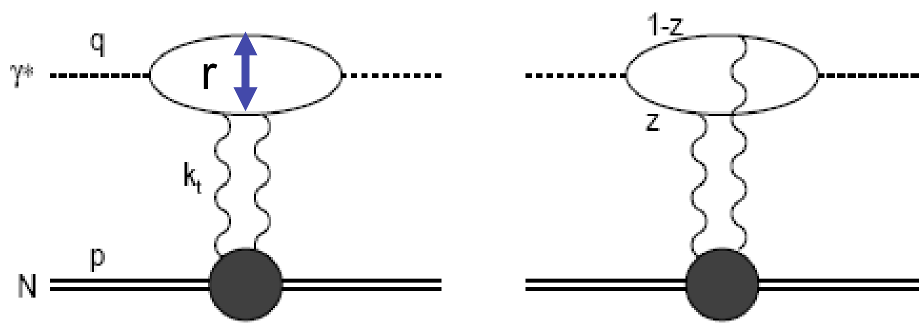
Conclusion

- Atmospheric flux calculations are well developed in the lower energy regime where pions and kaons are the dominant intermediate states.
- At higher energies, prompt neutrinos from charm are dominant contribution to atmospheric neutrinos
  - Theoretical evaluation of charm production includes energy distribution which depends on PDFs, choice of renormalization and factorization scale, charm quark mass, etc.
  - Reduce theoretical uncertainty by using RHIC and LHC data on charm production
- Atmospheric lepton flux is a background to diffuse neutrino flux searches, but interesting in its own right as it probes low-x QCD.

Back-up Slides

Prompt neutrinos: charm contributions with dipole approach

Advantage: don't need small x gluon PDF



$$\gamma^* \rightarrow q\bar{q}$$
$$q\bar{q}\,N \rightarrow X$$

heavy quarks:

$$\gamma^* \rightarrow c\bar{c}$$
$$c\bar{c}\,N \rightarrow c\bar{c}X'$$

$$\sigma_T(\gamma^* N) = \int_0^1 dz \int d^2r \mid \Psi_T(z,\mathbf{r},Q^2) \mid^2 \sigma_{dN}(x,\mathbf{r})$$

- Golec-Biernat & Wusthoff (GBW, PRD 59 (1999))
- Data show as small x that the virtual photon-proton cross section scales: dipole model includes this scaling (Stasto, Golec-Biernat & Kwiecinski, PRL 86 (2001))
- Improved QCD motivated form – Balitsky-Kovchegov (BK) evolution
- Modified for gluon -> charm anticharm pair

Dipole approach

$$\frac{d\sigma(pp \to Q\bar{Q}X)}{dy} \simeq x_1 G(x_1, \mu^2) \sigma^{Gp \to Q\bar{Q}X}(x_2, \mu^2, Q^2)$$

$$\sigma^{Gp \to Q\bar{Q}X} = \int dz\, d^2\mathbf{r} |\Psi_G^Q(z, \mathbf{r})|^2 \sigma_{dG}(x, \mathbf{r})$$

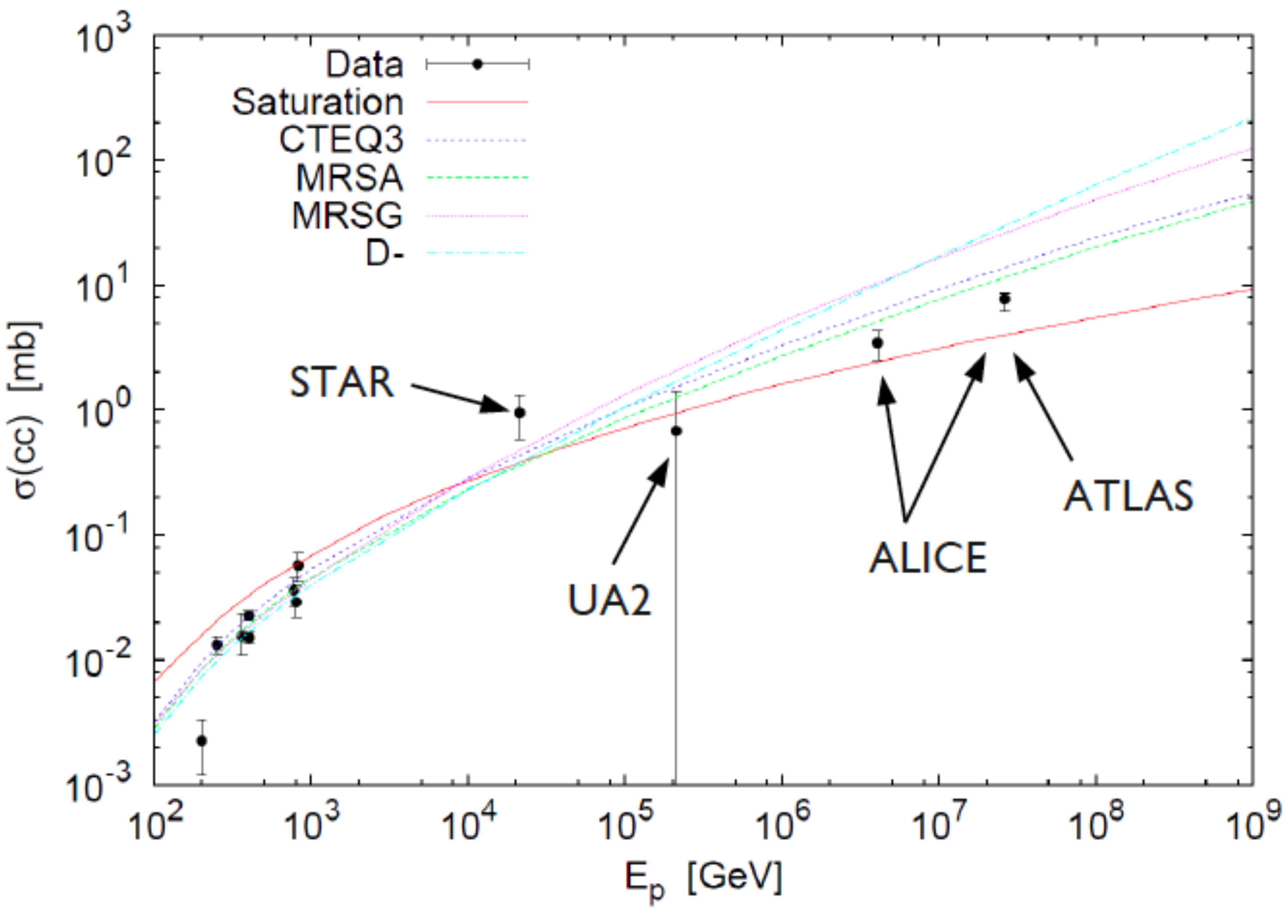
- Using dipole model parameterization of Soyez, Phys. Lett. B 655 (2007) fit to the IMM approximate solution to the BK equations, (Iancu, Itakura, Munier PLB 590 (2004)), prescription for hadronic scattering by Nikolaev, Piller & Zakharov, ZPA 354 (1996).
- Kramer-Kniehl (KK) and Peterson fragmentation functions for c-quark to charmed mesons for our earlier work, now also BCFY fragmentation functions.
- Work in progress, comparing results using other dipole cross sections. Preliminarily – not much difference.

Higher energies in accelerators

- With either approach:
  - Need new comparisons with new measured high energy cross sections.

High rapidity most important for prompt flux calculation.

Range of cross section predictions from theory still quite large (mass of charm quark, scale dependence).



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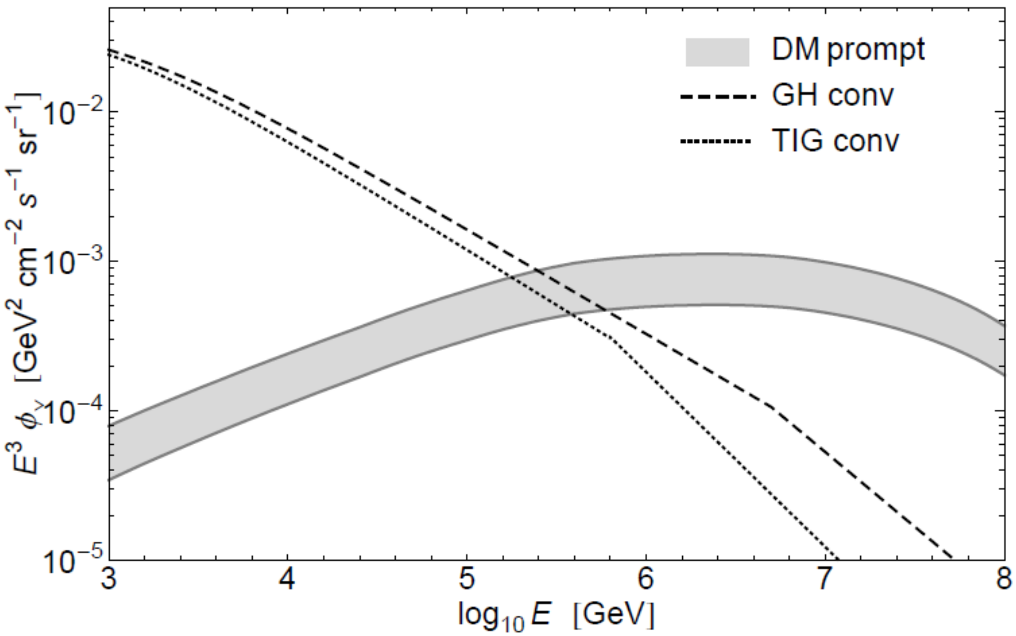


DM=dipole model

GH=Gaisser-Honda

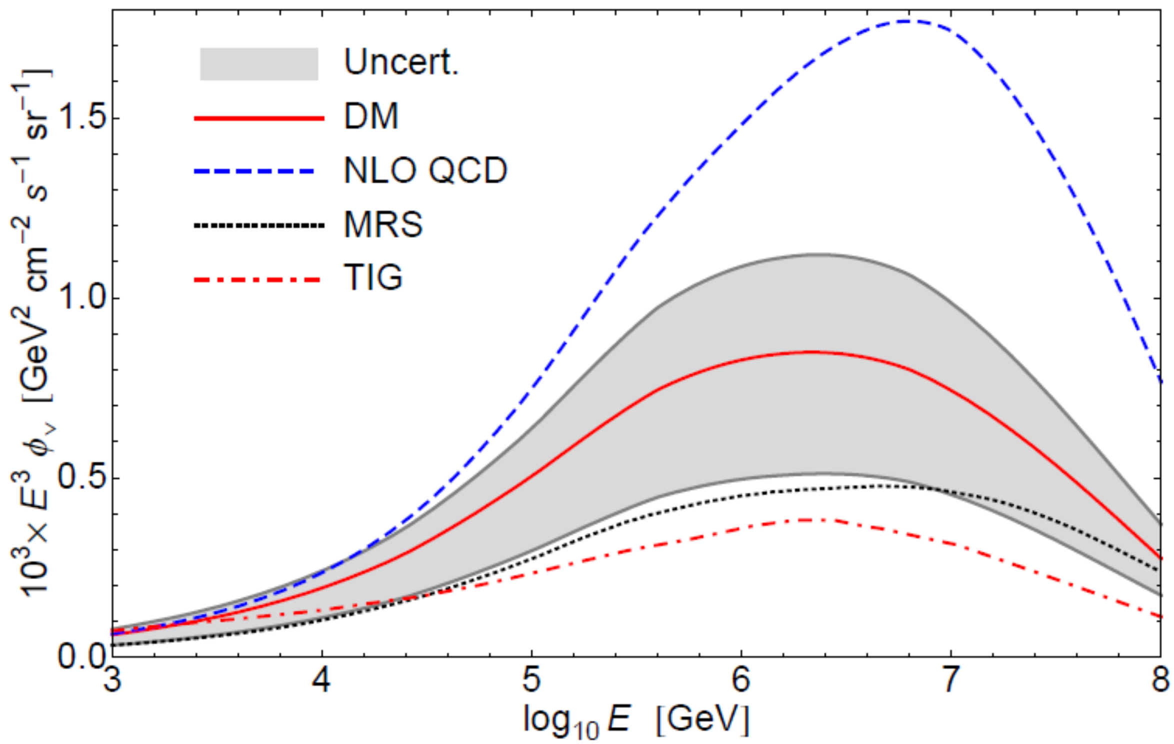
TIG=Thunman et al. (PDF + pythia, small x extrapolation)

Conventional in vertical direction

Uncertainties include: charm mass, gluon PDF, dipole parameters, scales

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Prompt flux: dipole model and others



A range of predictions:

DM=our dipole model

MRS=Martin, Roberts, Stasto, Acta Phys. Polon. B34 (2003), uses a simpler form for dipole model cross section.

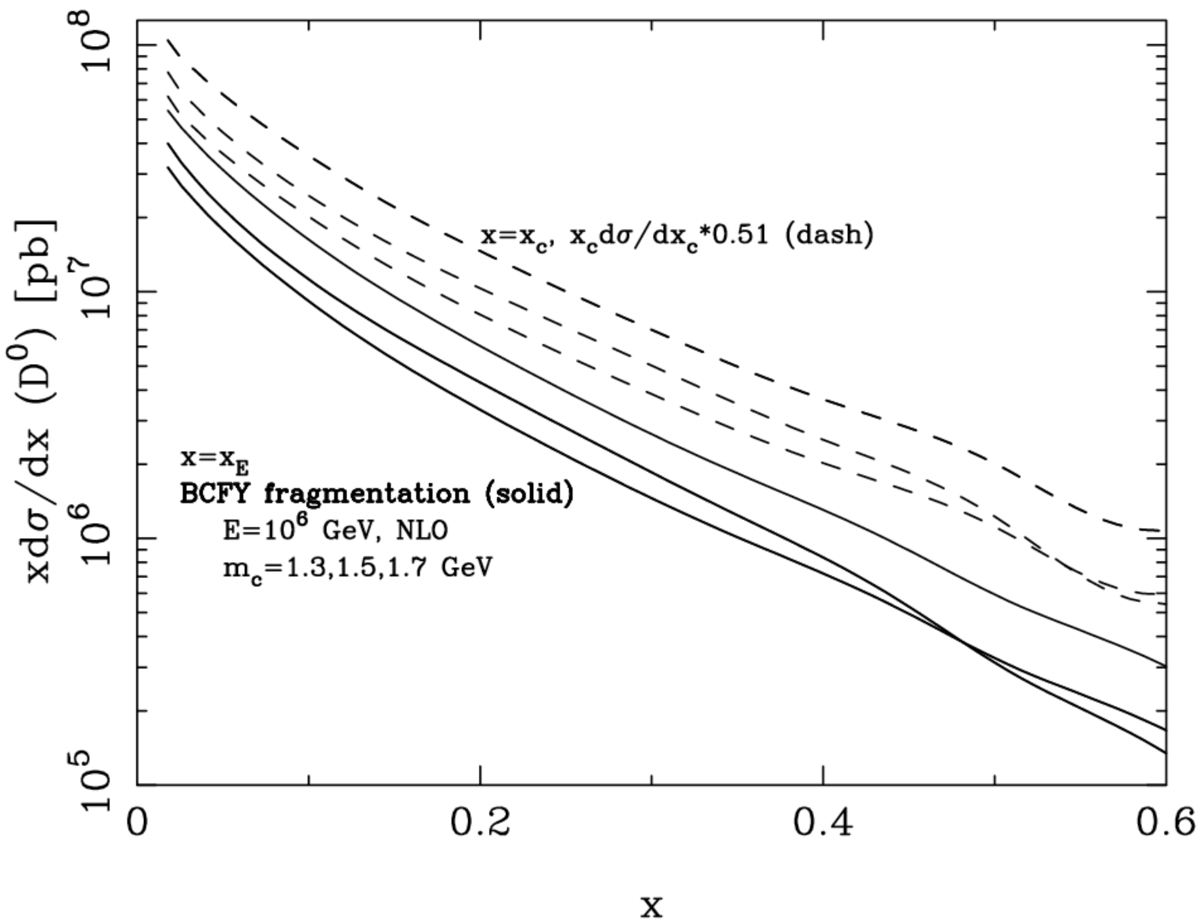
Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Fragmentation (Charm → D-meson)

BCFY=Braaten, Cheung, Fleming & Yuan, PR D51 (1995), Cacciari and Nason, JHEP 0309 (2003).

$$x_c = \frac{E_c}{E_p}$$

$$x_E = \frac{E_D}{E_p}$$



Using FONLL method, updated PDFs.

Neutrino Fluxes

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

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

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

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

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

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

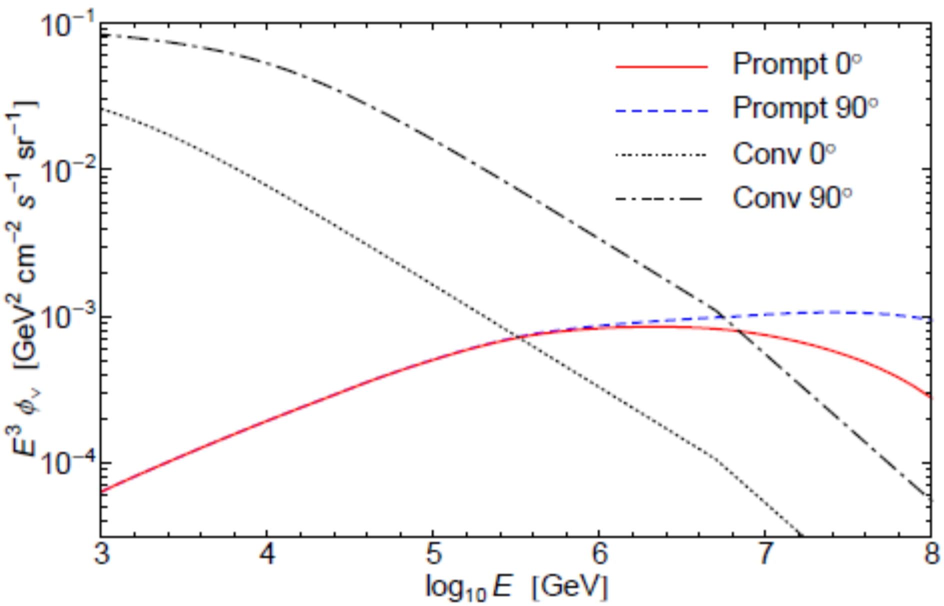
For prompt lepton flux: electron and muon neutrinos (and antineutrinos) and muons (essentially stable), need:

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

$$c \to s e^+ \nu_e$$

$$c \to s \mu^+ \nu_\mu$$

Atmospheric neutrinos-angular dependence

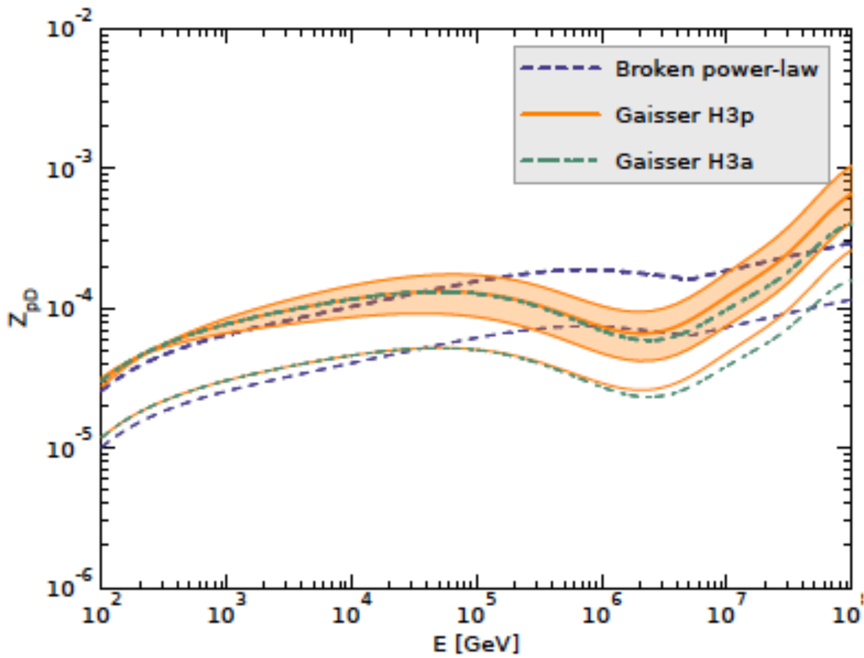


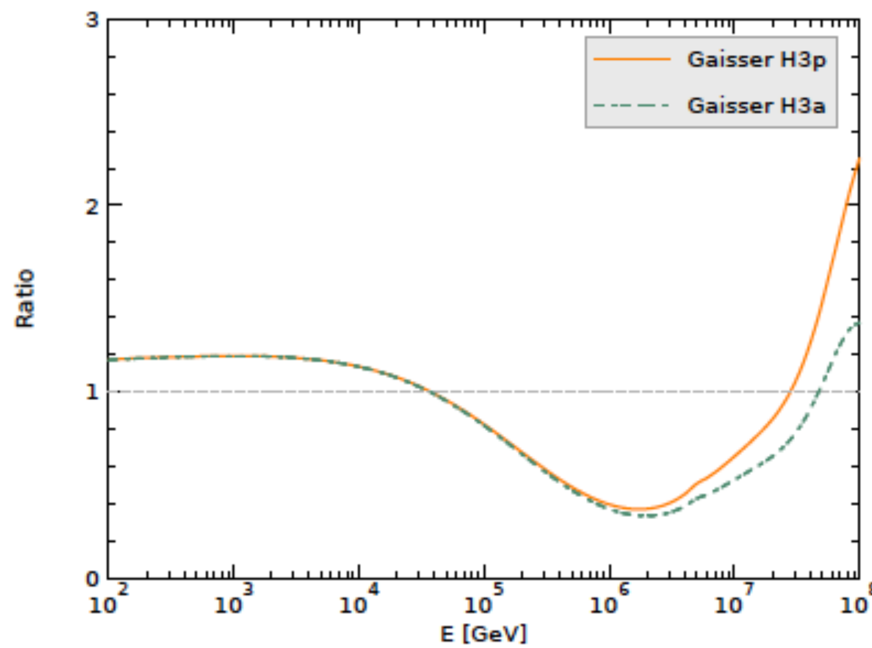
Muon neutrino plus antineutrino flux, from our dipole model "prompt" calculation.

Conventional flux from Gaisser-Honda.

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Z-moments for pN → D-mesons





$$M = D^0 + \bar{D}^0$$

thick curves

$$M = D^{\pm}$$

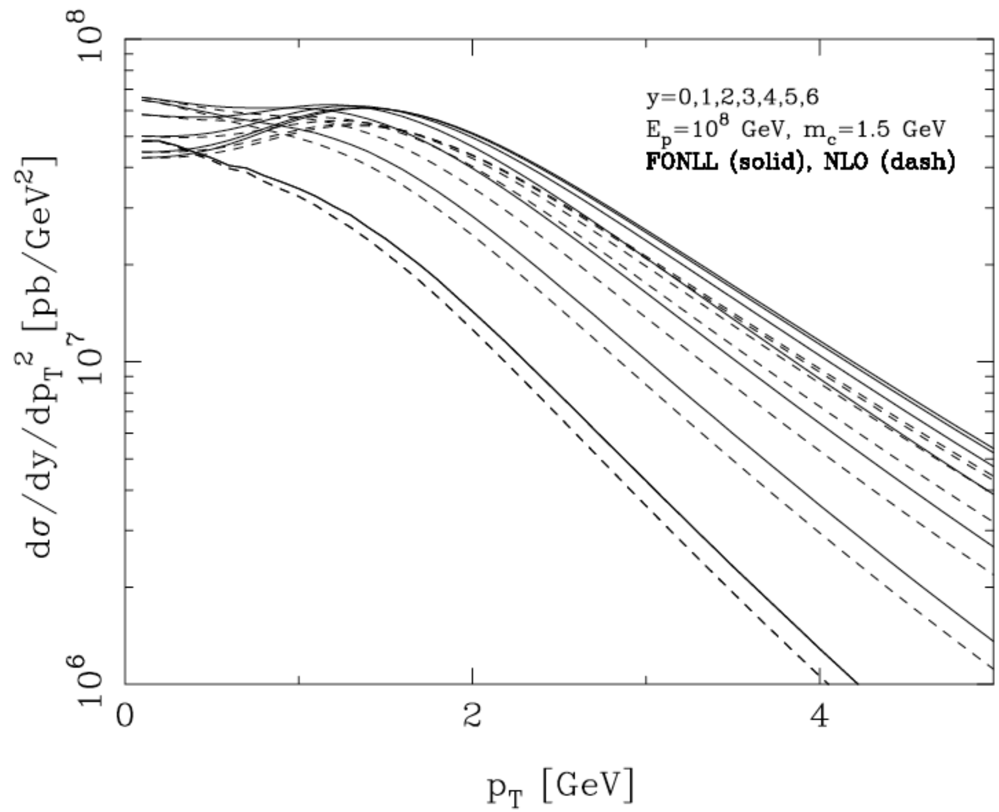
thin curves

PDFs with updated perturbation theory (FONLL)

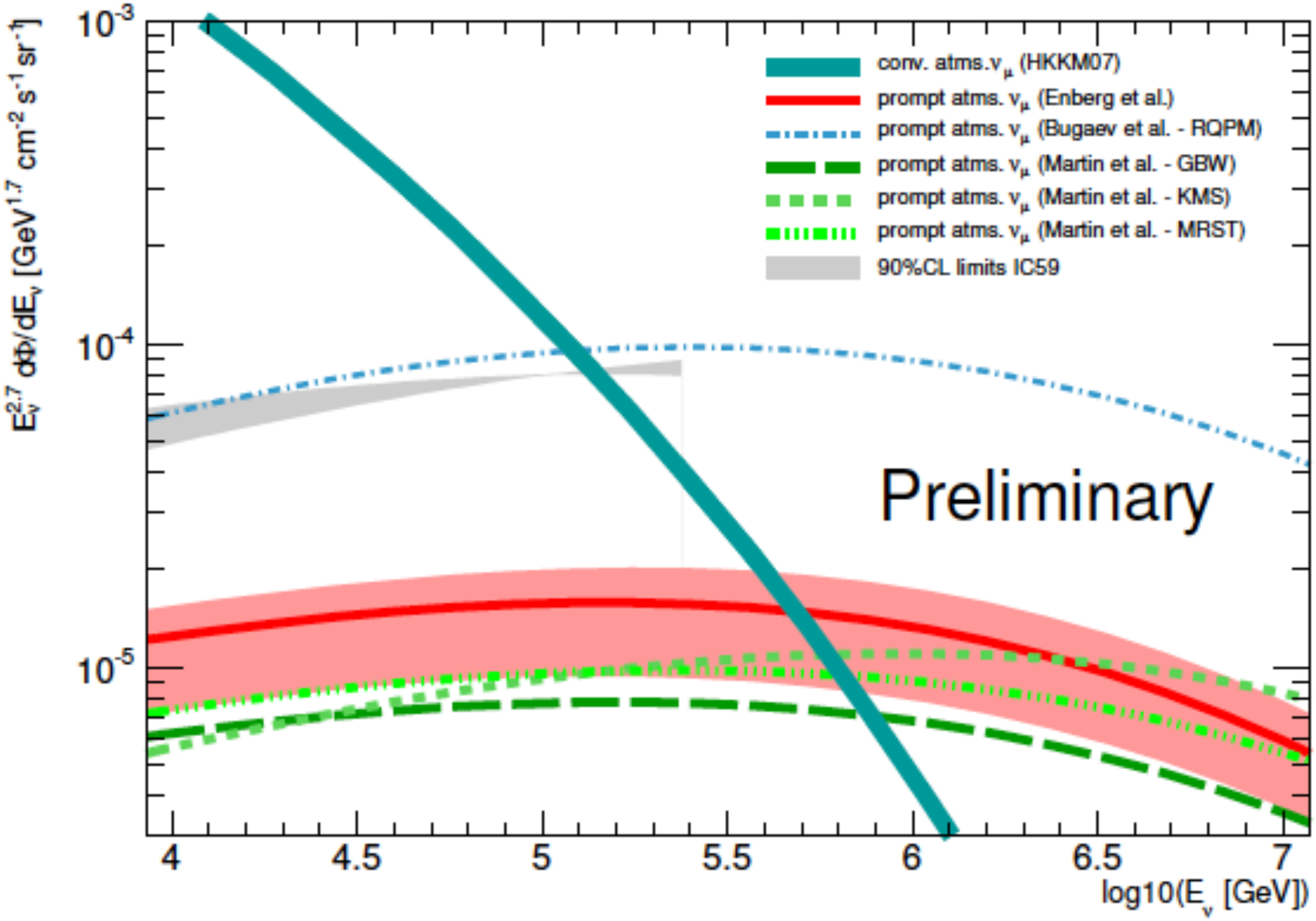
- With the PDF approach:
  - Improvements to hard scattering with the Fixed Order Next-to-Leading Log (FONLL) approach, which includes resummed logs log(pt/mc) to fixed order result.

Need low pT, high rapidity. E.g., for 10^8 GeV, rapidity around 5-7 for pT less than 10 GeV.

FONLL Refs: M. Cacciari, M. Greco & P. Nason, JHEP (1998); Cacciari, Frixione & Nason, JHEP (2001)



Prompt Neutrino Flux IceCube Limits



A. Schukraft for IceCube, Nucl. Phys. B Proc. Suppl., arXiv:1302.0127