Atmospheric neutrinos from charm/ leptons from charm

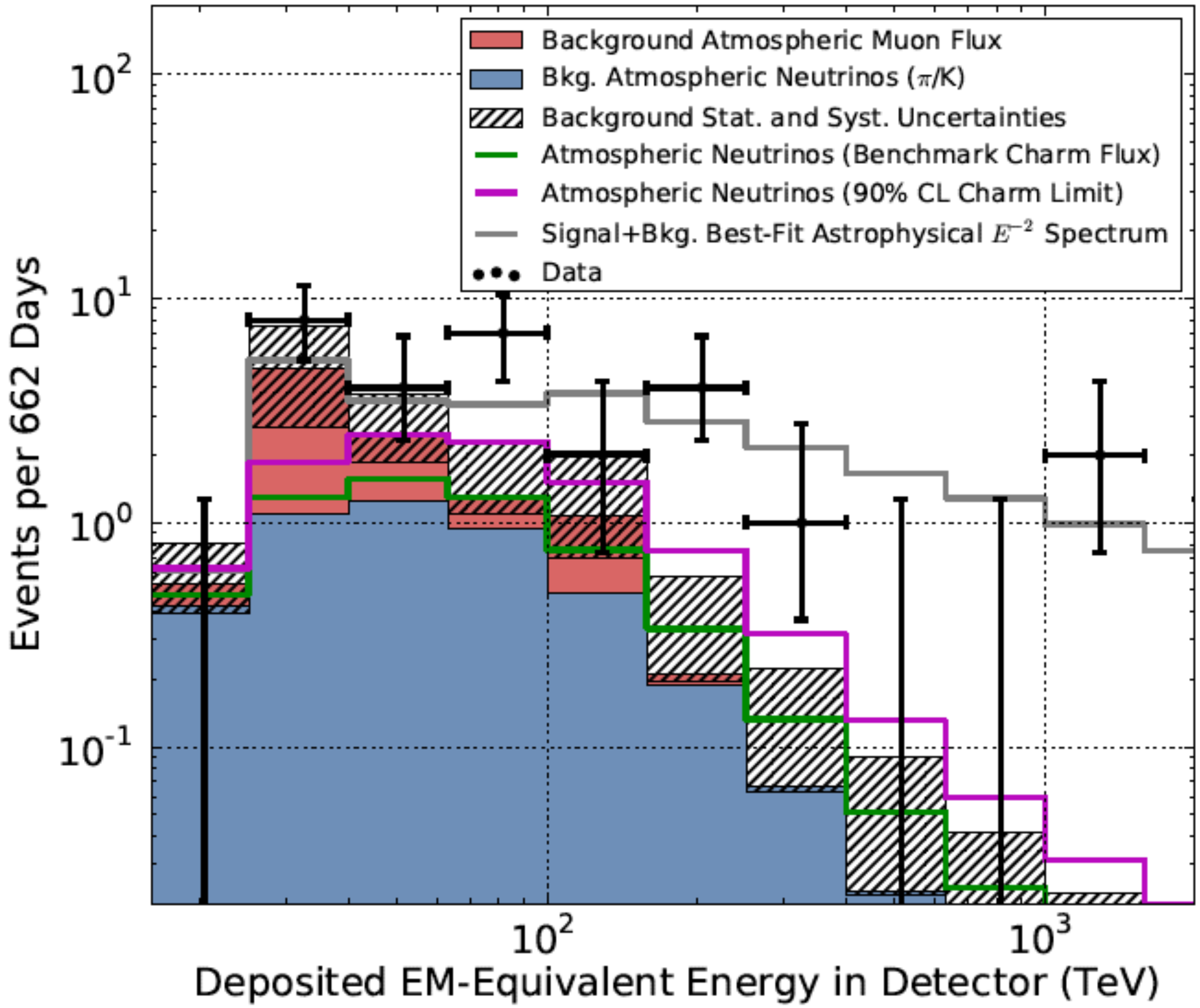
Hallsie Reno (University of Iowa)

April 25, 2014

NuNews - Nordita

Collaborators: Ina Sarcevic, Atri Bhattacharya and Rikard Enberg +

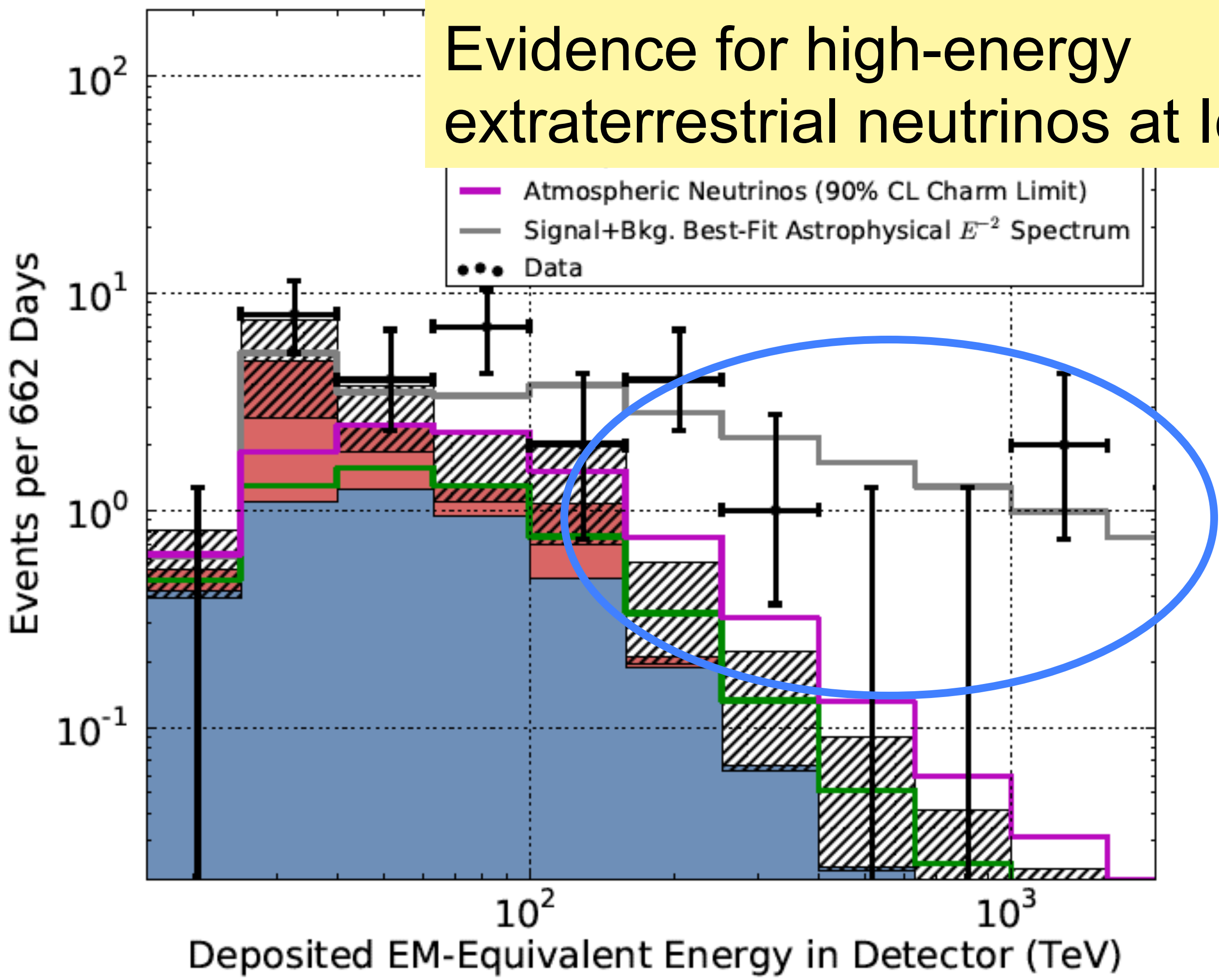
Intrinsic interest & as a background



IceCube, Science 342 (2013), arXiv:1311.5238

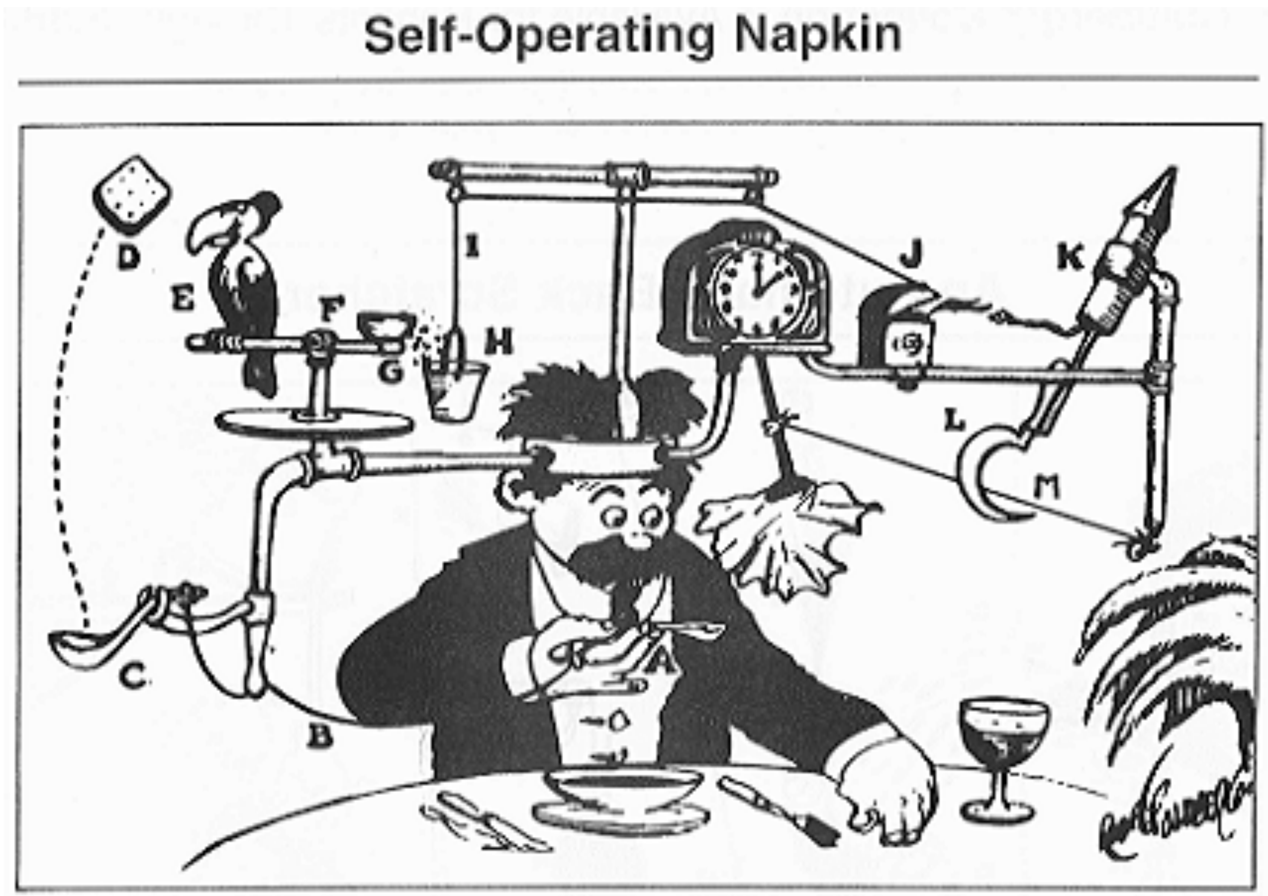
Intrinsic interest & as a background

Evidence for high-energy extraterrestrial neutrinos at IceCube



IceCube, Science 342 (2013), arXiv:1311.5238

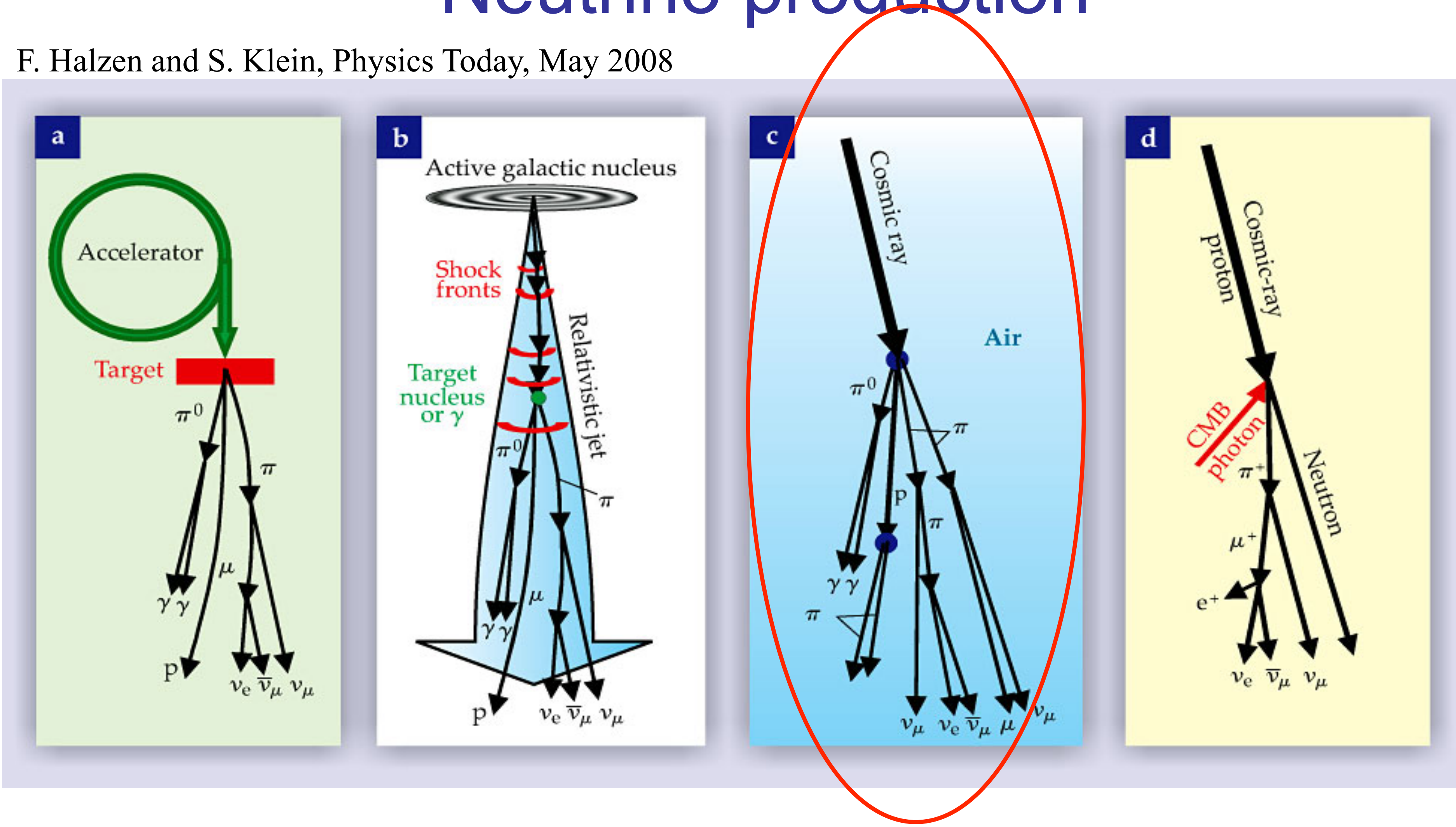
Plan



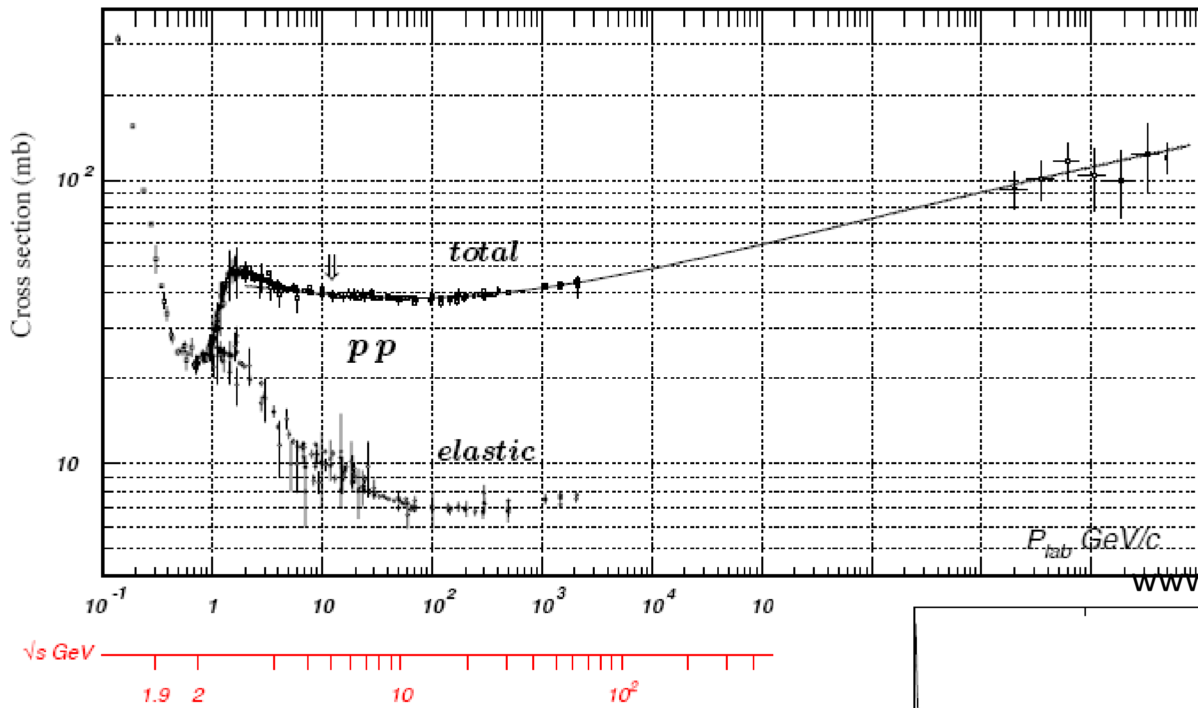
- Sketch features of the atmospheric flux
- Show you some of the moving parts

Neutrino production

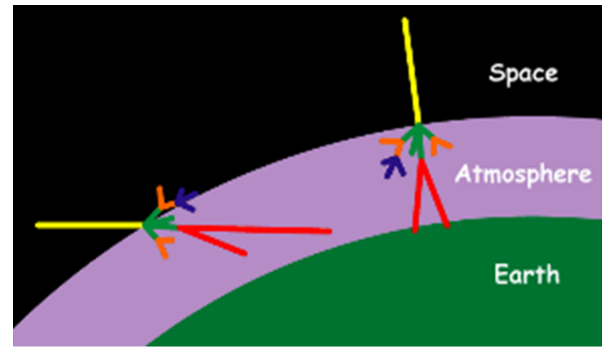
F. Halzen and S. Klein, Physics Today, May 2008



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



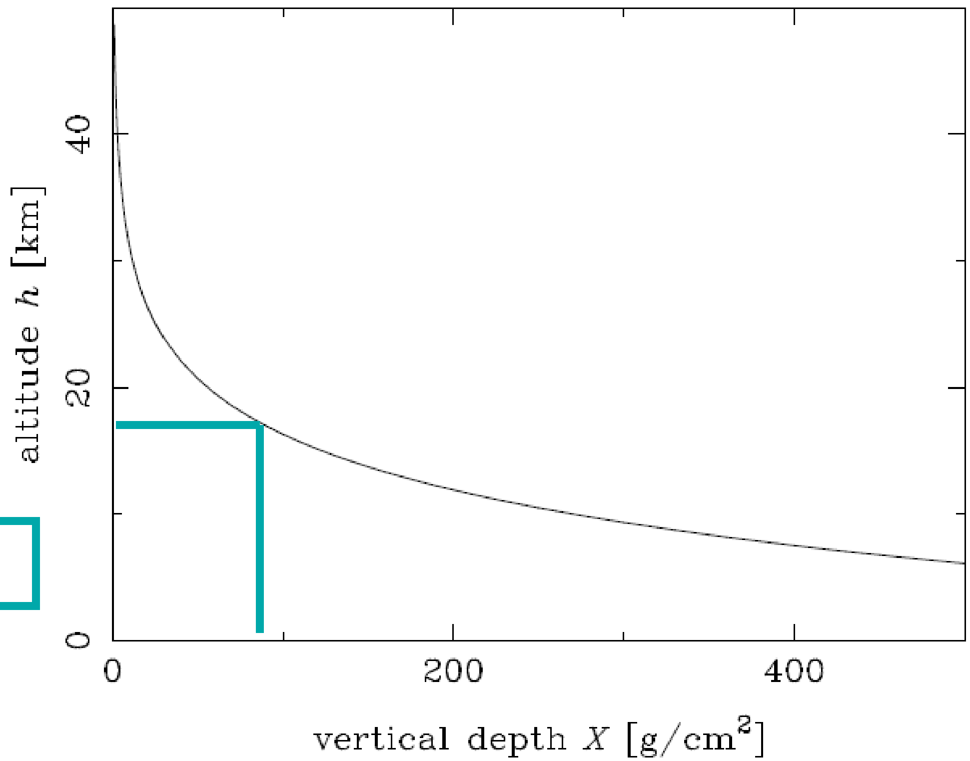
pdg.lbl.gov



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

$$\sigma_{N\,\mathrm{air}} = 300\ \mathrm{mb}$$

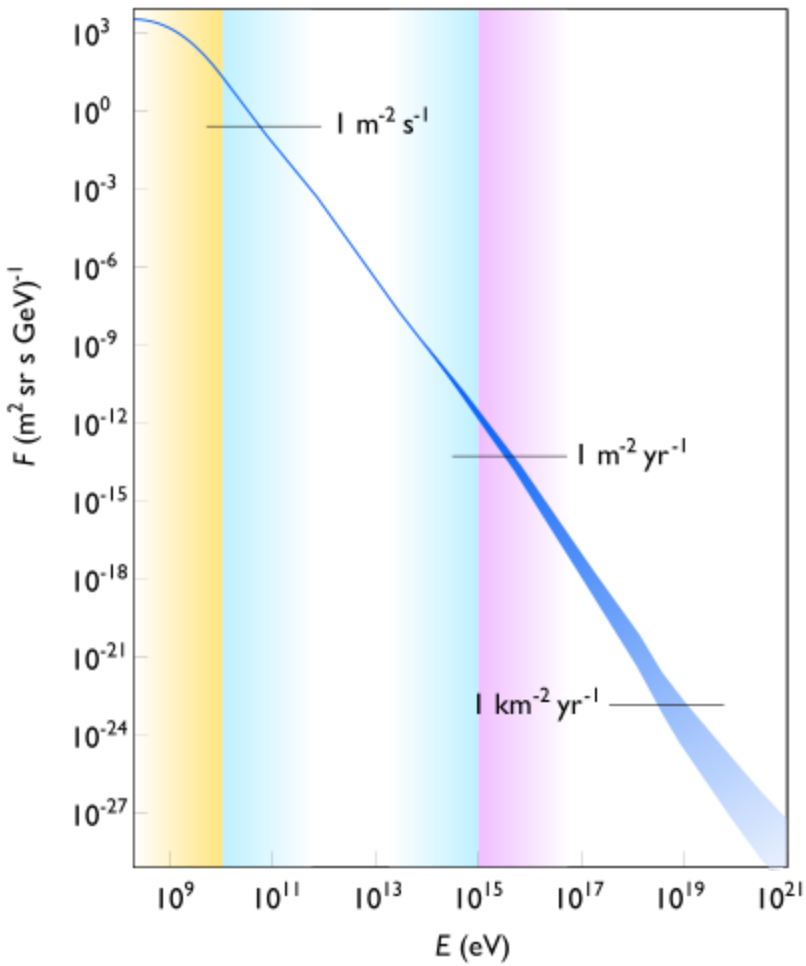
$$\lambda_N \simeq 80\ \mathrm{g/cm^2}$$



Altitude of interaction: approx. 15 km

$$X_v = \int_h^\infty \rho(h')\, dh'$$

Starting point, cosmic ray flux



S. Lafebre, http://en.wikipedia.org/wiki/Cosmic_rays following S. Swordy.

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

Cosmic rays produce unstable particles, mesons such as pions.

$$\Phi_M \sim \Phi_{CR}$$

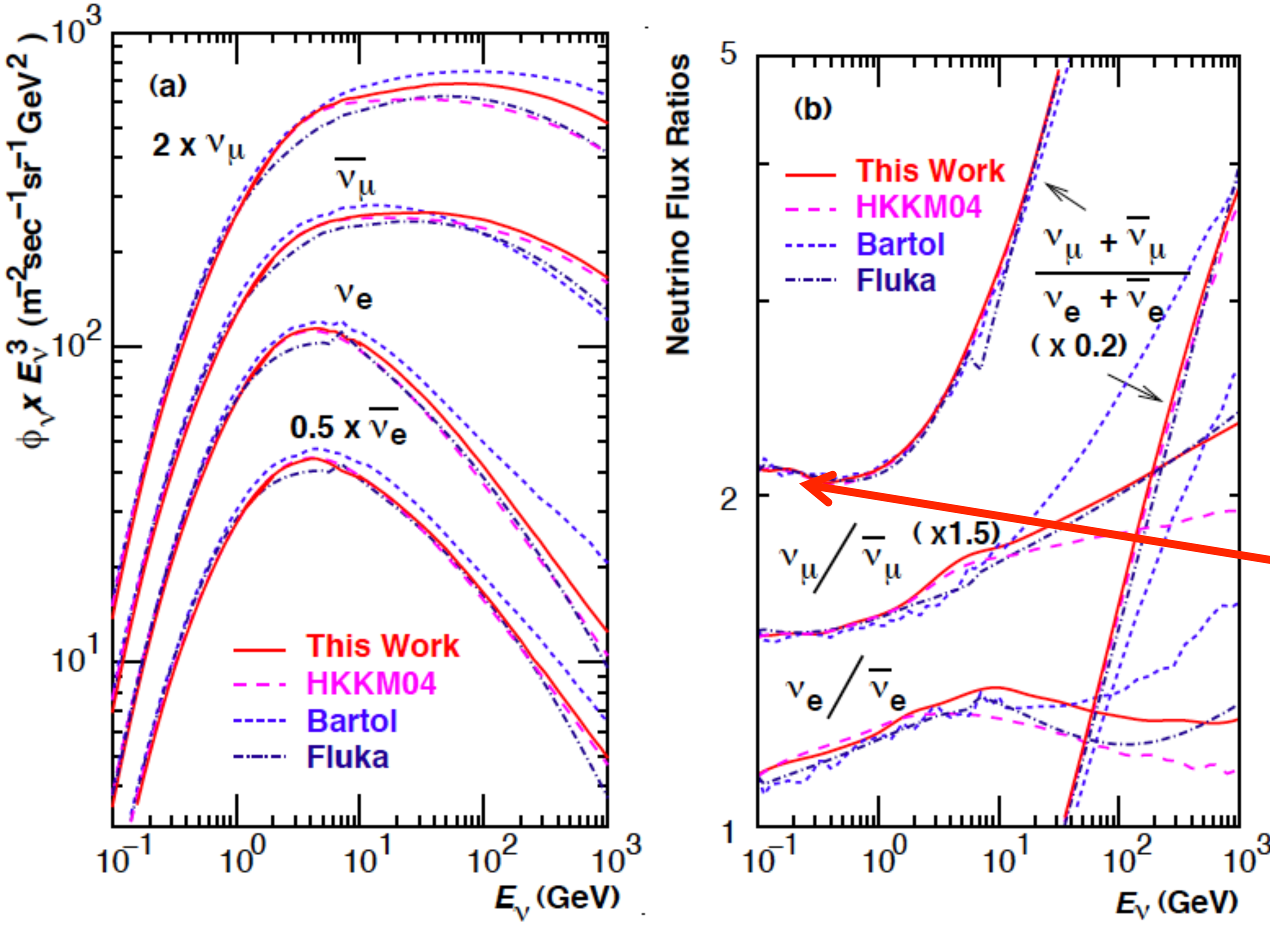
Charged pions decay to muons and neutrinos – if pions all decay before interacting, then:

$$\Phi_\nu \sim \Phi_M$$

Otherwise, $\Phi_\nu \sim \Phi_M P_{decay}(E)$

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

Conventional flux: pion and kaon contributions



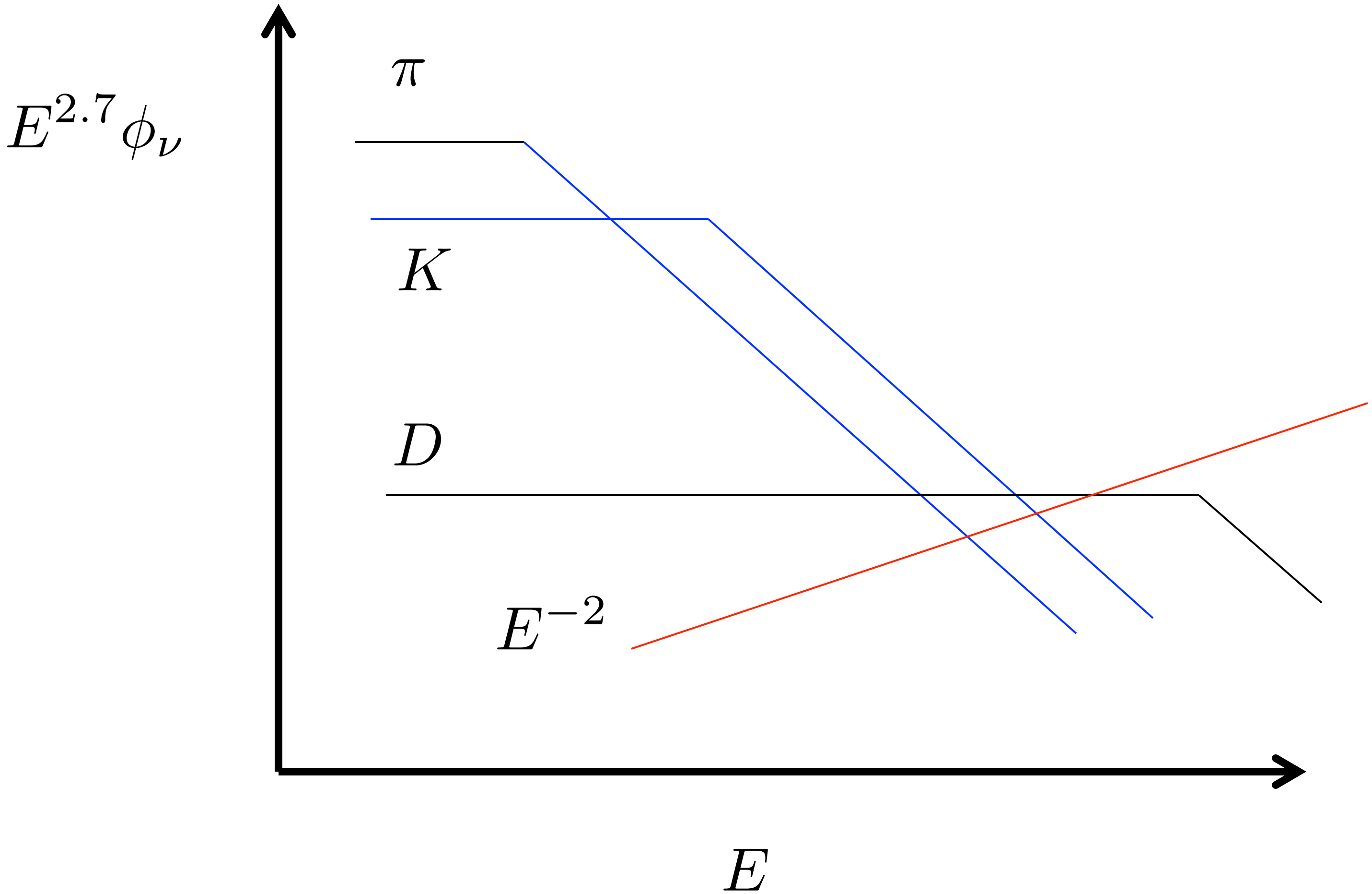
Still uncertainties in the calculated high energy conventional flux, especially extrapolated past 1 TeV.

Muon decays

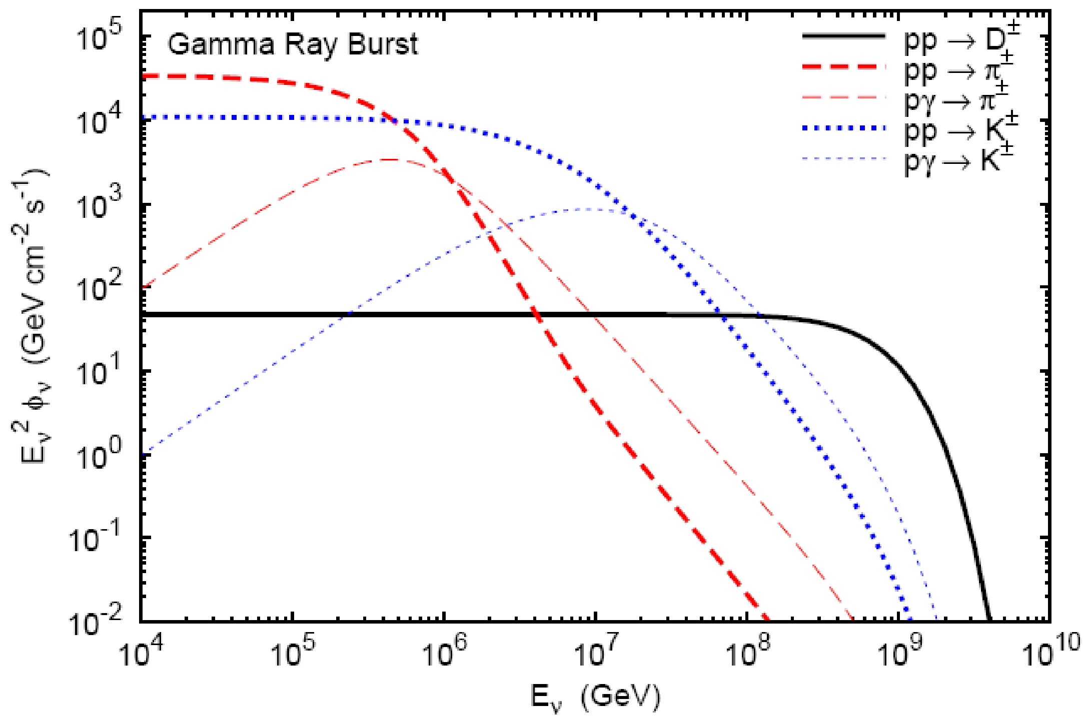
$$\pi^- \rightarrow \mu\bar{\nu}_\mu$$
$$\mu \rightarrow e\nu_\mu\bar{\nu}_e$$

E.g., Honda et al., PRD 75 (2007), using DPMJET-III, for Kamioka, calibrated to observed atmospheric muon flux, incl 3-dim & geomagnetic corrections.
See also Barr et al., PRD 70 (2004).

Schematically



An aside…



Enberg, Reno and Sarcevic, PRD 79 (2009)

References

- Cosmic Rays and Particle Physics, T. Gaisser, Cambridge U Press
- Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. 52 (2002) 153 and references therein. (GH label below)
- L. V. Volkova, Sov. J. Nucl. Phys. 31 (1980)
- P. Lipari, Astropart. Phys. 1 (1993)

and focus on charm: e.g.,

- Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005
- Thunman, Ingelman, Gondolo, Astropart. Phys. (1996)
- Pasquali, Reno, Sarcevic, Phys. Rev. D (1999)
- Bugaev et al, Phys. Rev. D 58 (2010)

We are working on an update and assessment of theoretical uncertainties, to the extent possible.

Transport equations

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

High enough energies that muons are "stable".

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

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

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

Production

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

Decay

Need cross section and energy distribution of the final state particle.

Z-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.

Approximate formulae

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

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

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

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

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

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

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

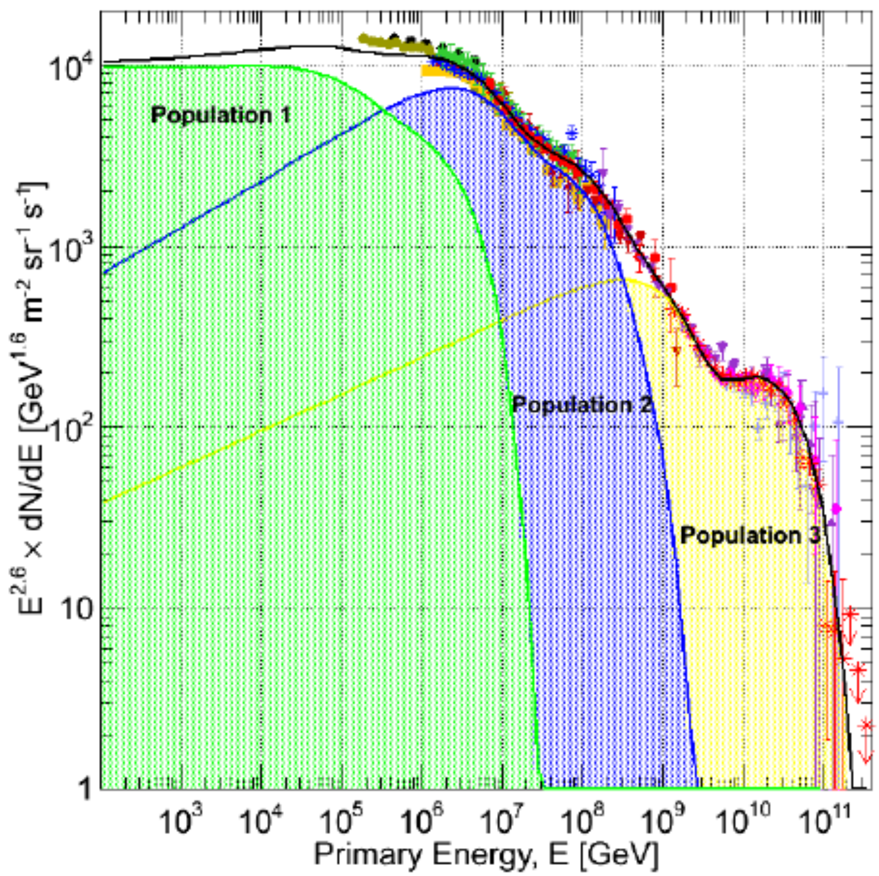
For prompt lepton flux: electron and muon neutrinos (and antineutrinos) and muons (essentially stable), need:

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

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

Moving part

- Cosmic ray flux and composition, e.g., Gaisser, Stanev & Tilav, 1303.3565.



Moving part

- The charm cross section (proton – Air and A-Air).
- Ultimately, what we need is the differential distribution for charm production, a function of outgoing charm energy.
- Convert charm to hadrons via fragmentation function.
  Z_{pD} from $p + Air \to DX$
- This is our major focus – we need forward production, $m_c \simeq 1.4$ GeV, energies higher than LHC.

Prompt neutrinos: charm contributions using parton distribution functions

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, pQCD with PDFs.

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

$$x_F = x_1 - x_2$$

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

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

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

Necessarily involve extrapolations at low x (sometimes explicit, sometimes implicit).
What about large logarithms? Approximate unified DGLAP/BFKL solutions.

PDF extrapolations

- Thunman, Ingelman & Gondolo (1996):

$$xg(x,Q^2) \simeq x^{-\lambda},\ \lambda \sim 0.08, x < 10^{-4}$$

- Pasquali, Reno & Sarcevic (1999), K factor for QCD corrections:

$$xg(x,Q^2) \simeq x^{-\lambda},\ \lambda \sim 0.3 - 0.5, x < 10^{-5}$$

- Martin, Ryskin & Stasto, Acta Phys. Polon. B 34 (2003) 3273:

MRST

$$xg(x,Q^2) \ \simeq \ x_0 g(x_0,Q_0^2)\ \exp\left(\sqrt{\frac{16N_C}{b}\ln\frac{\alpha_S(Q)}{\alpha_S(Q_0)}\ln\frac{x}{x_0}}\right)$$

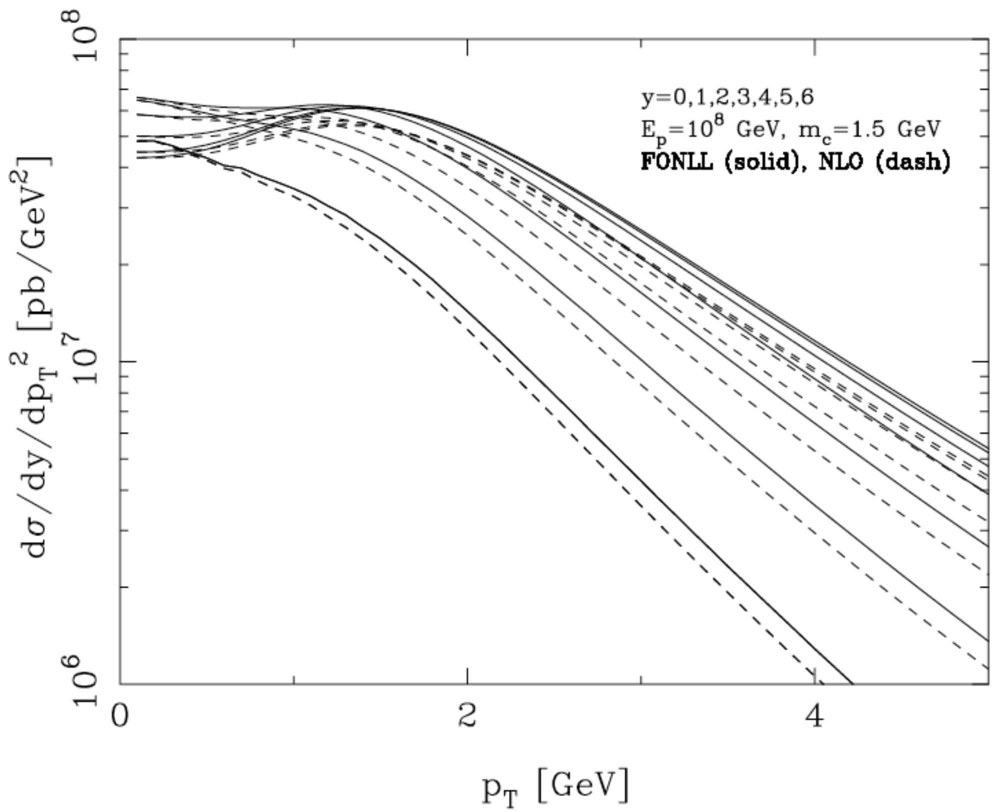
KMS, no K factor, $xg(x,Q^2) \simeq x^{-\lambda},\ \lambda \sim 0.3$

Work in progress, 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 matches resummed logs log(pt/mc) to fixed order result.

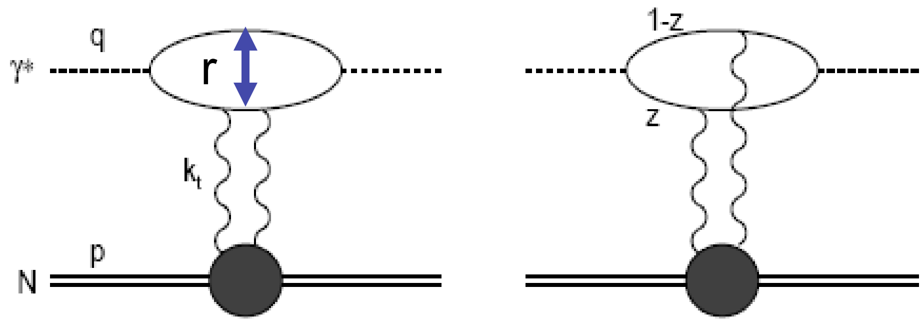
Need low-ish pT, high rapidity. E.g., for 10^8 GeV, rapidity around 5-7 for pT less than 10 GeV.

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



Prompt 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.

Intrinsic charm/alternatives

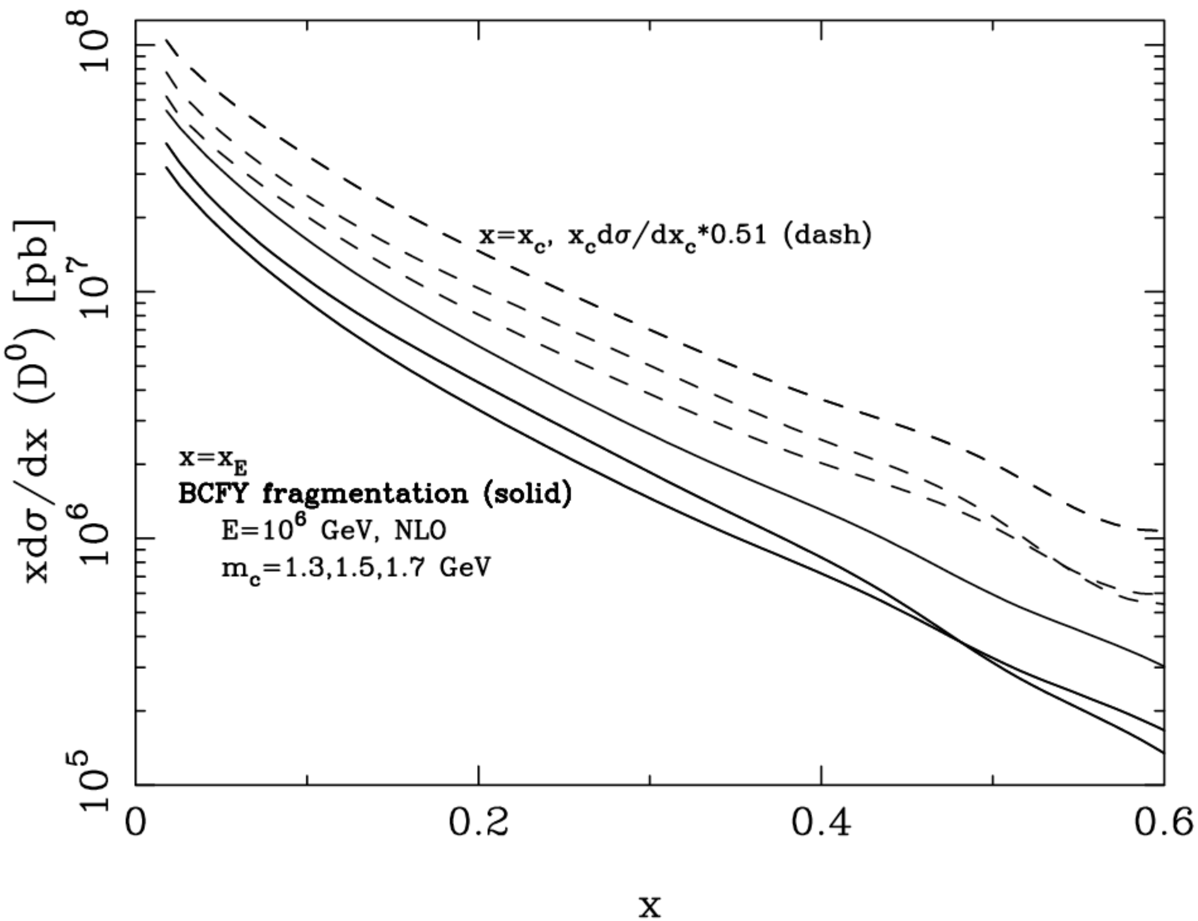
- E.g., Brodsky, Hoyer, Peterson and Sakai, Phys. Lett. B93 (1980).
- Element of the Recombination Quark Parton Model (RQPM) – see Bugaev et al., Phys. Rev. D 58 (1998) for atmospheric flux example.
- Recent global analysis allowing intrinsic charm that is “valence-like” and “sea-like” from Dulat et al (CTEQ) 1309.0025
- Lipari – toy model for charm production (arXiv:1308.2086)

Charm to mesons-Fragmentation

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

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

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



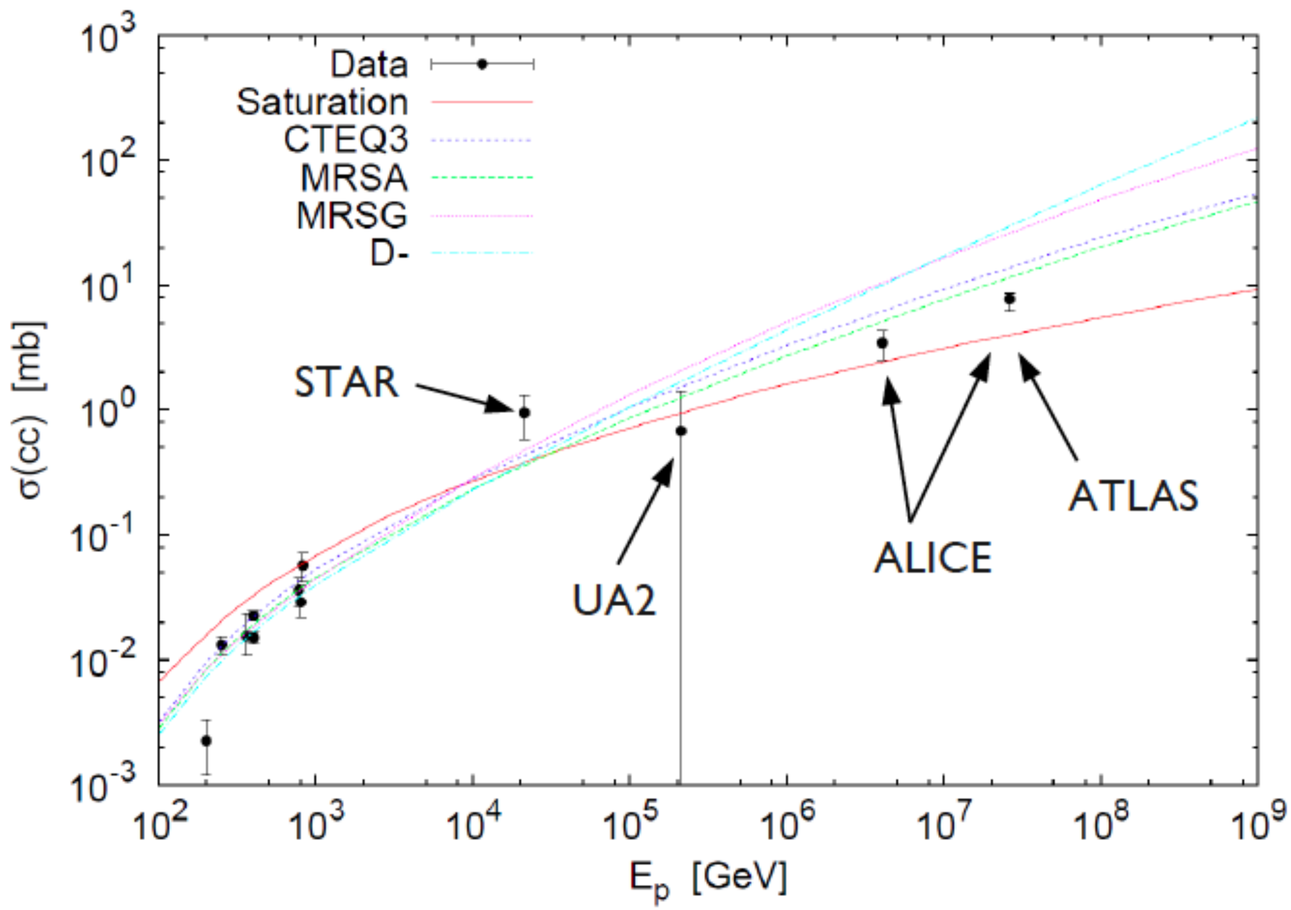
Using FONLL method, updated PDFs.

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).



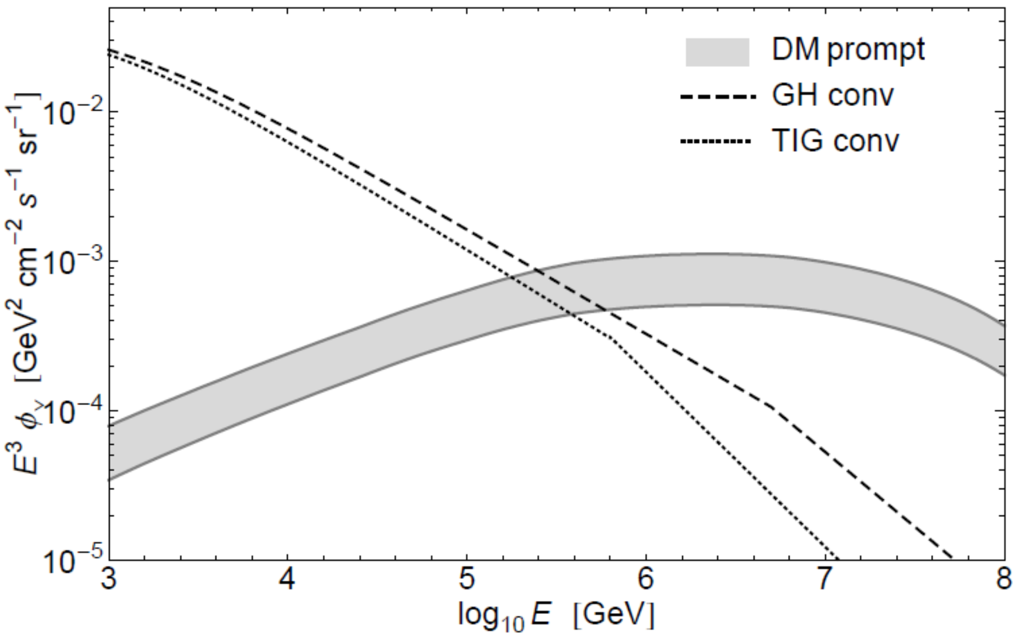
Moving parts

- Charm rescattering (see, e.g., Barcelo et al, 1010.0894), suggesting that charmed hadrons penetrate more into the atmosphere because they lose less energy with each collision.
- Important for the “high energy” regime for charm.

$$\Lambda_D = \lambda_D/(1 - Z_{DD})$$

- More careful evaluation of decays. To first approximation, energy ratios of 1/3:1/3:1/3, but V-A interactions modify that.
- Flavor ratios and particle:antiparticle ratios, where intrinsic charm and forward production may come into play.

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



DM=dipole model

GH=Gaisser-Honda

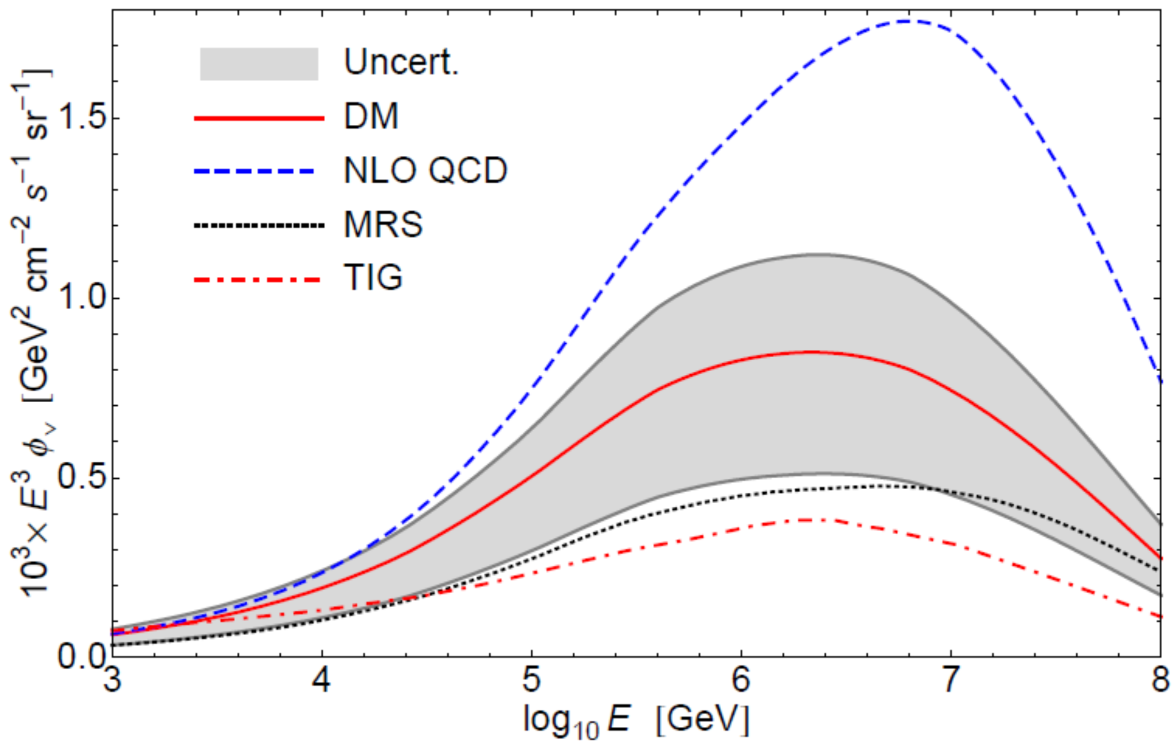
TIG=Thunman et al. (PDF + pythia, small x extrapolation)

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



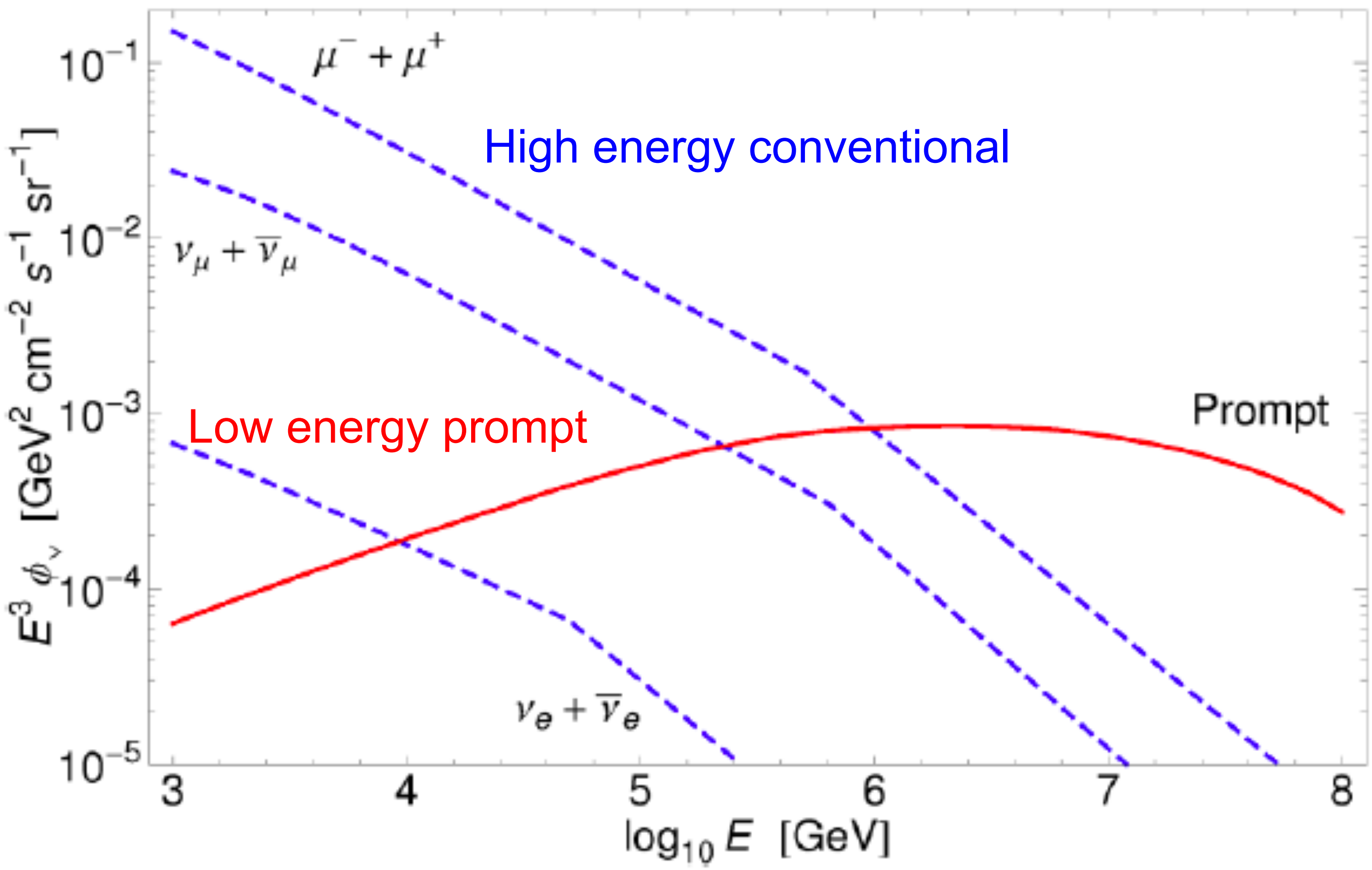
A range of predictions:

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

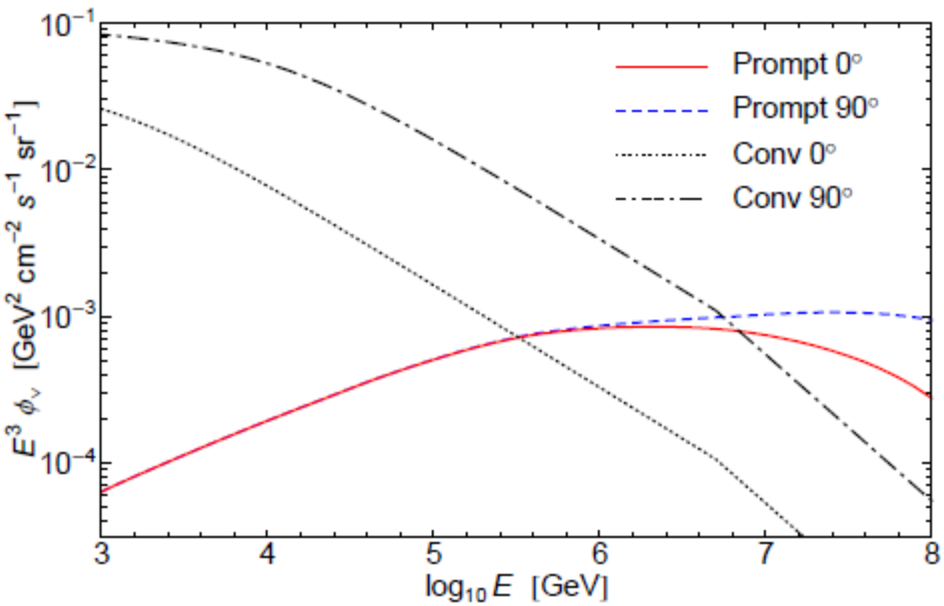
Energy behavior – vertical flux – dipole model



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

$$\nu_e \simeq \nu_\mu \simeq \mu$$

Atmospheric neutrinos-angular dependence

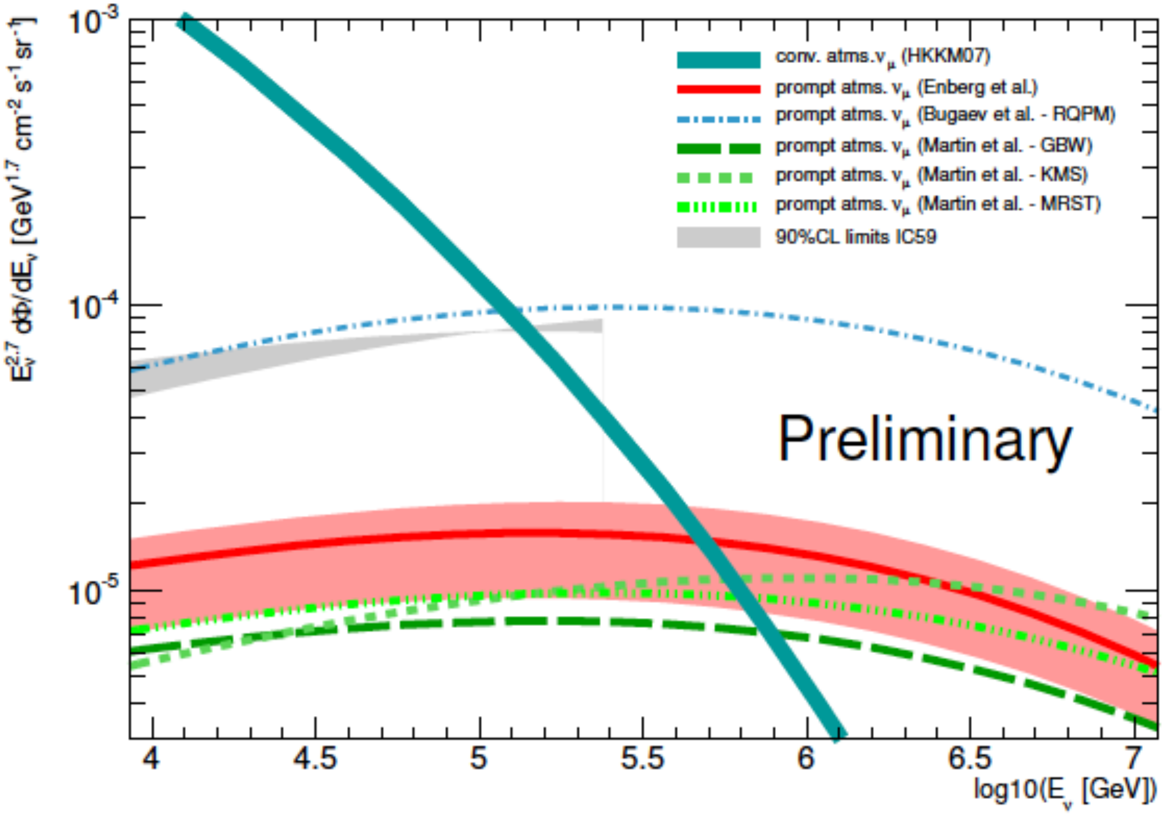


Muon neutrino plus antineutrino flux, from our dipole model "prompt" calculation.

Conventional flux from Gaisser-Honda.

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

Prompt flux limits

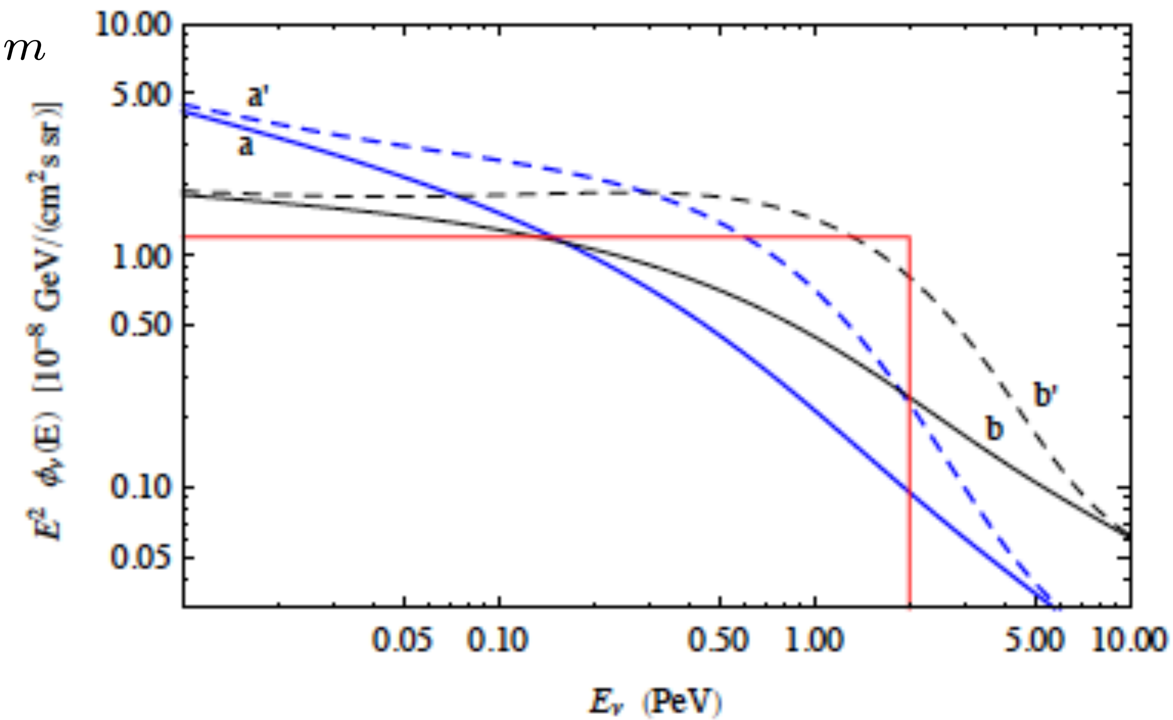


A. Schukraft for IceCube, Nucl. Phys. B Proc. Suppl., arXiv: 1302.0127

Phenomenological cross section – toy models Λ_c

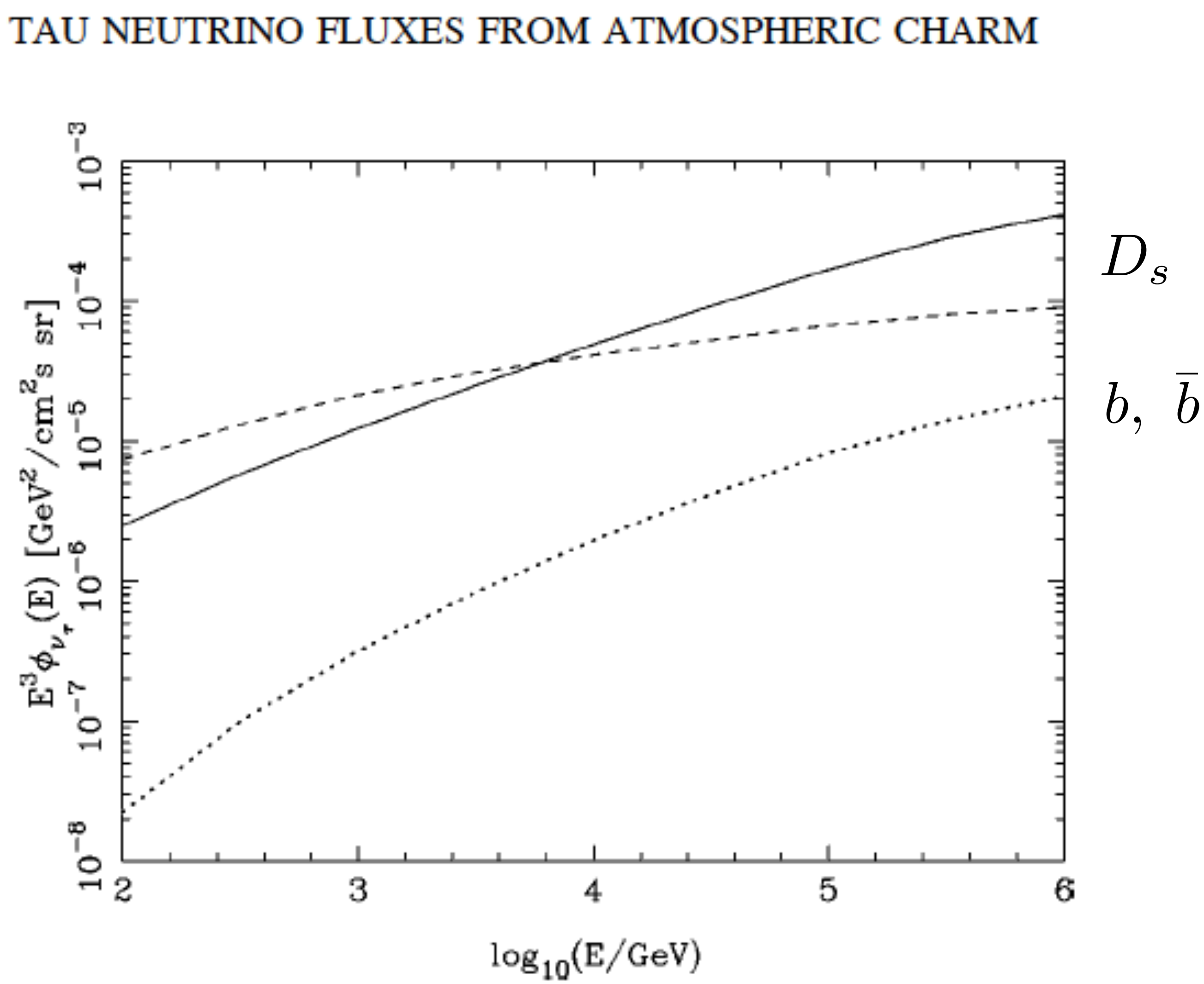
$\sigma \sim E^{0.7},\ d\sigma/dx \sim (1-x)^3$ $\qquad$ $\sigma \sim E^{1.2},\ d\sigma/dx \sim (1-x)$

$x = E_c/E_{beam}$



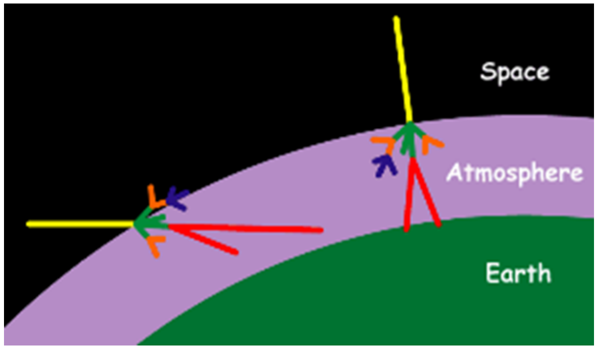
Lipari, arXiv:1308.2086, Volkova used $(1-x)^{n_i},\ n_D = 5$

NLO range: $n \sim 6-10$ Fixed target: $n \sim 5-9$



Two different evaluations from perturbative QCD, Pasquali & Reno, PR D (1999), see also Martin, Ryskin & Stasto, Acta Phys. Polon. B34 (2003)

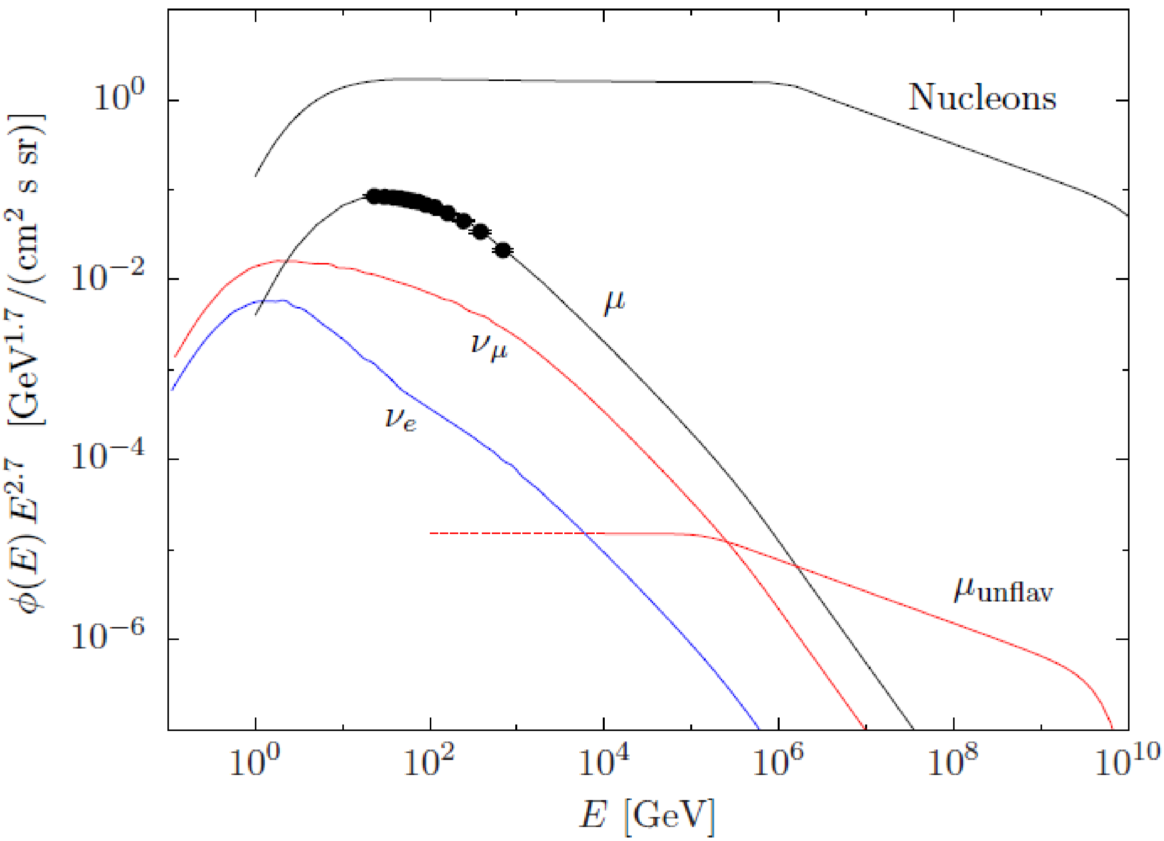
High pT muons from charm



- See Abbasi et al, PRD 87 (2013) 012005,
- Look for charm production at "high pT" where "high" is larger than 6 GeV for 1 TeV muons: separation of the muon from charm decay and the muons from shower core.
- Muons from the conventional flux are at lower pT and thus lower separation between muon from pion/kaon and shower core.
- Sensitive to the cosmic ray composition.
- Potential to pick out the charm contribution at lower energies than a PeV because of the separation.
- FONLL calculation is the way to go here.

Unflavored – prompt – electromagnetic decays to muons

$\eta,\ \eta',\ \rho^0, \omega ...$

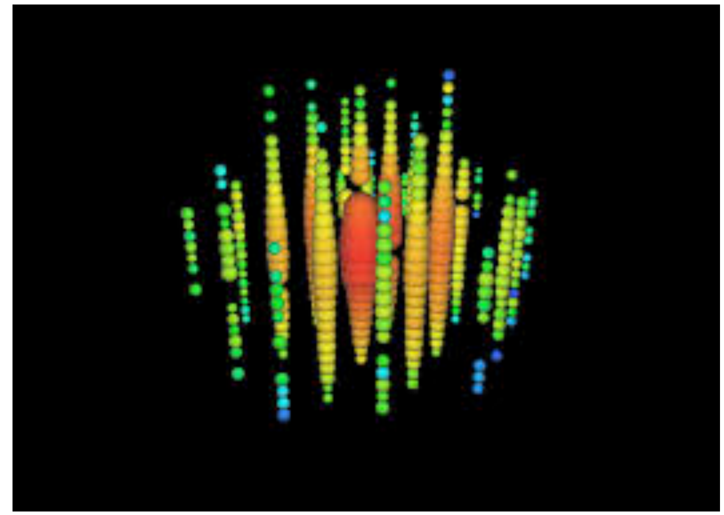


Illana, Lipari, Masip and Meloni, arXiv:10105084, Astropart. Phys. 34 (2011) 663

Final Remarks

- Atmospheric flux calculations are especially well developed in the lower energy regime where pions and kaons are the dominant intermediate states.
- At higher energies, there is still room for refinements of the calculations –
  - Theoretical evaluation of charm production, including energy distribution.
  - Will be informed by LHC data on charm production, and on small x PDFs, high rapidity.
  - Potential for extracting lower energy prompt flux from muon separations in IceCube.
- Atmospheric lepton flux is a background to diffuse neutrino flux searches, but interesting in its own right.

Roz Chast, from Symmetry publication, May 2007



IceCube: that neutrino is named Bert!

Seasonal variations

- Desiati and Gaisser, PRL 105 (2010)
- Look for seasonal variations in the flux of atmospheric leptons, as atmosphere expands and contracts – temperature fluctuations affect the conventional flux, but the prompt flux doesn't change in the relevant energy region:

$$h_0(T)$$