Atmospheric lepton fluxes at high energies

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IPA Symposium

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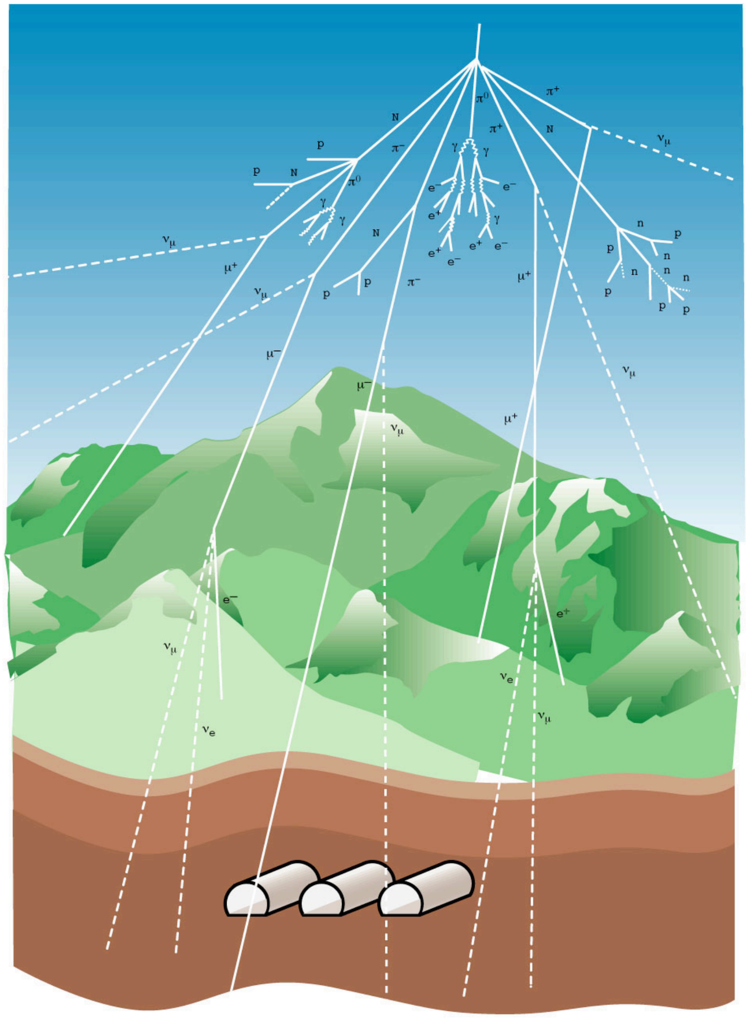
Atmospheric neutrino production



prog-cngs.web.cern.ch

Cosmic ray interactions with air nuclei,

Production of mesons: pions, kaons, charmed mesons,

Meson interaction and decay.

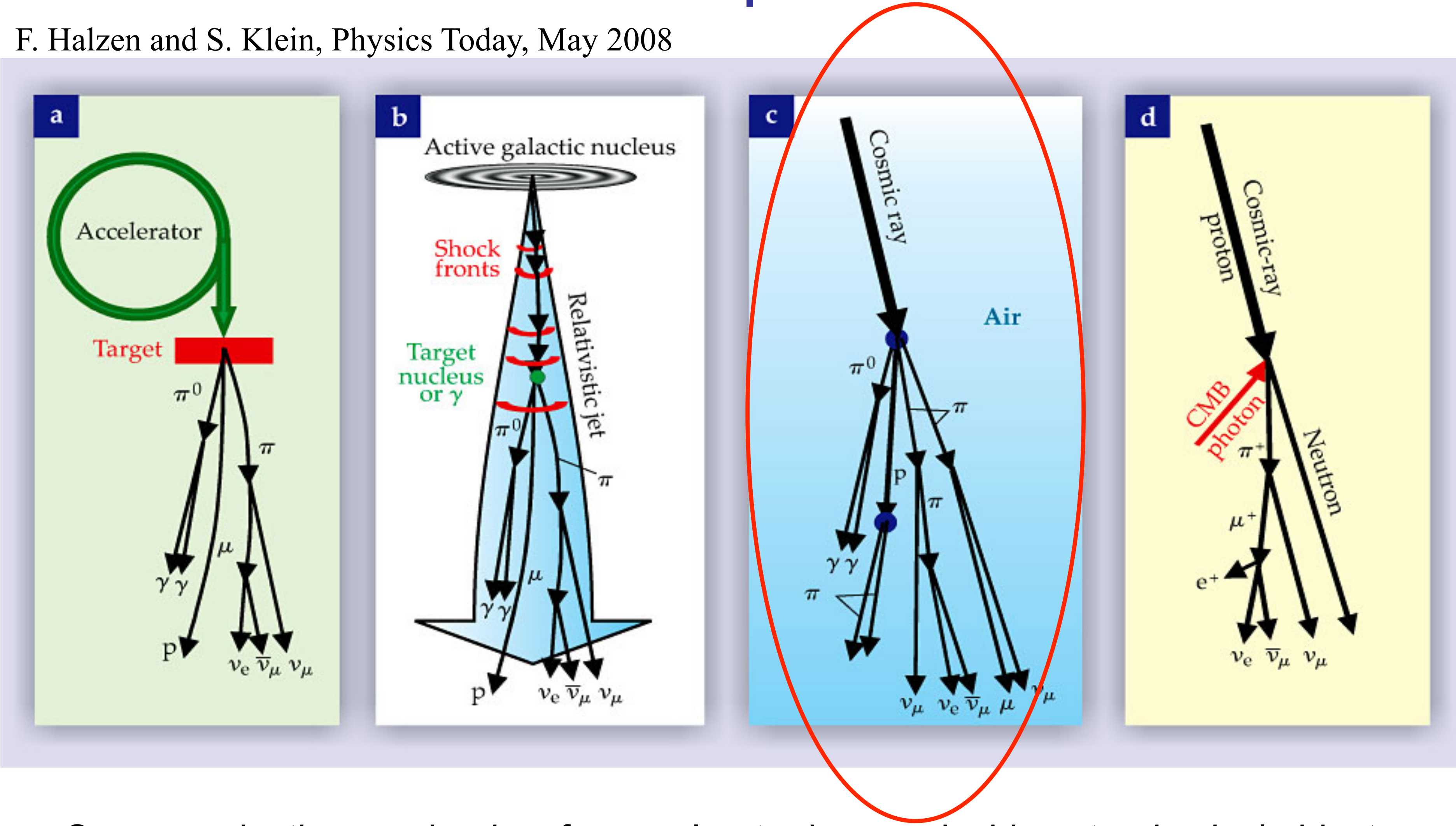
Here, review of atmospheric flux calculation, with emphasis on charm production.

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

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

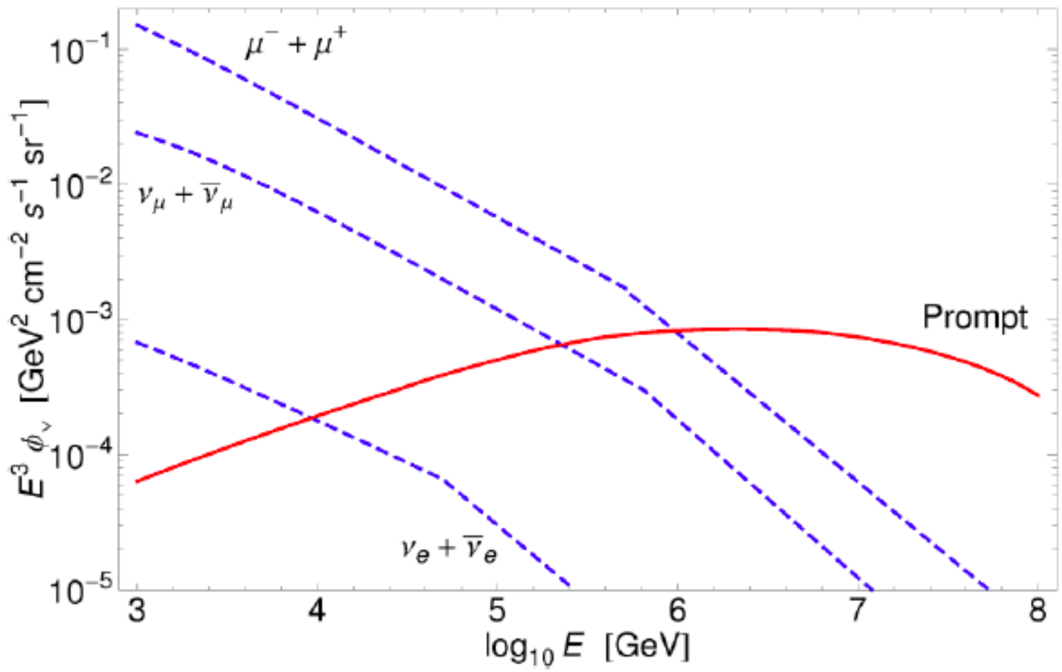
Neutrino production

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



Same production mechanism for accelerator beams, inside astrophysical objects, cosmogenic neutrino flux.

Atmospheric neutrino flux

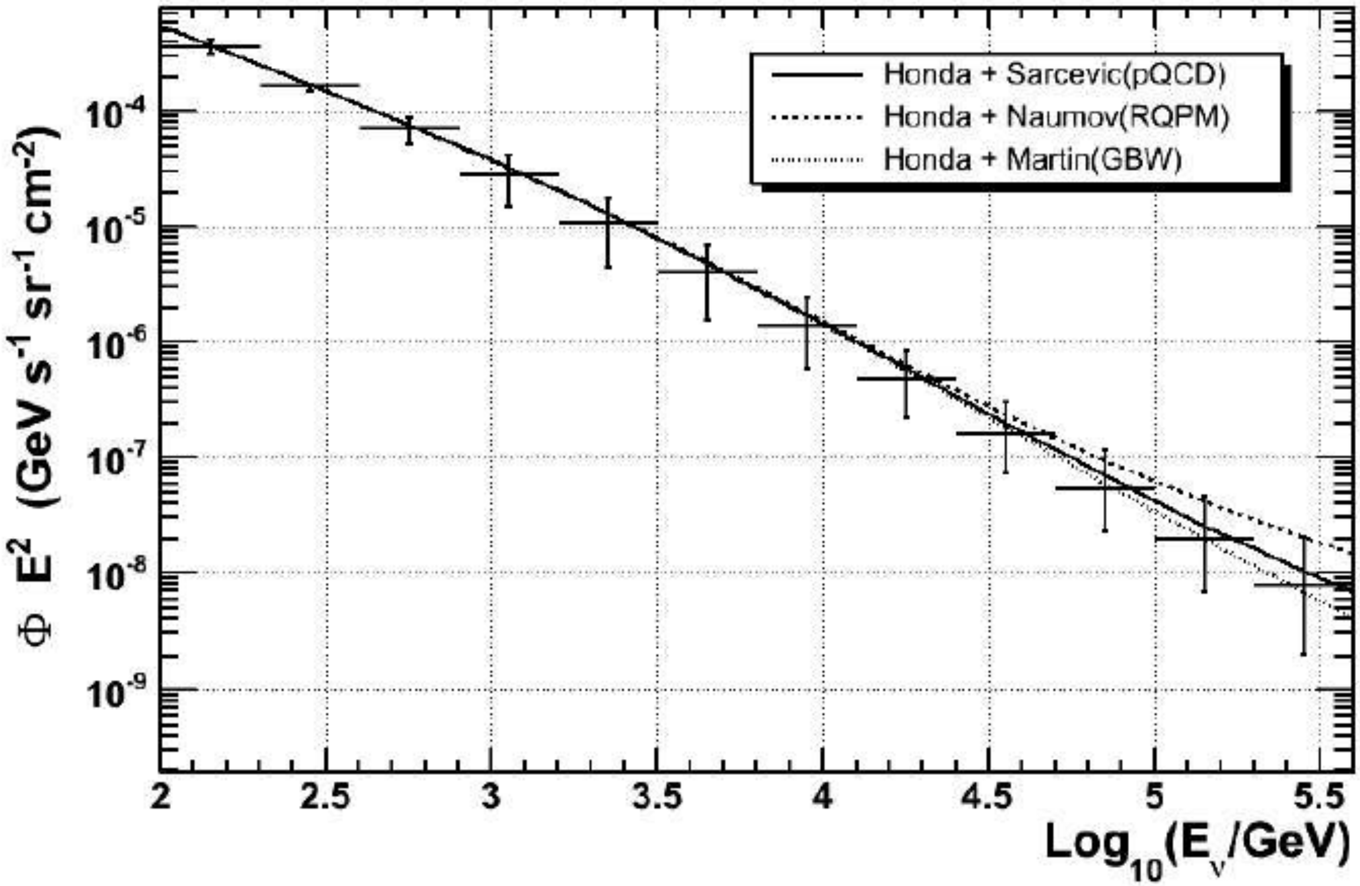


Review how the flux scales with energy, for "conventional" and "prompt" neutrino fluxes.

Theoretical considerations in the "prompt" flux from charm. (Results from ERS (2008))

Enberg, Reno, Sarcevic (ERS), Phys. Rev. D 78 (2008) 043005
Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. 52 (2002) 153 and refs. therein.

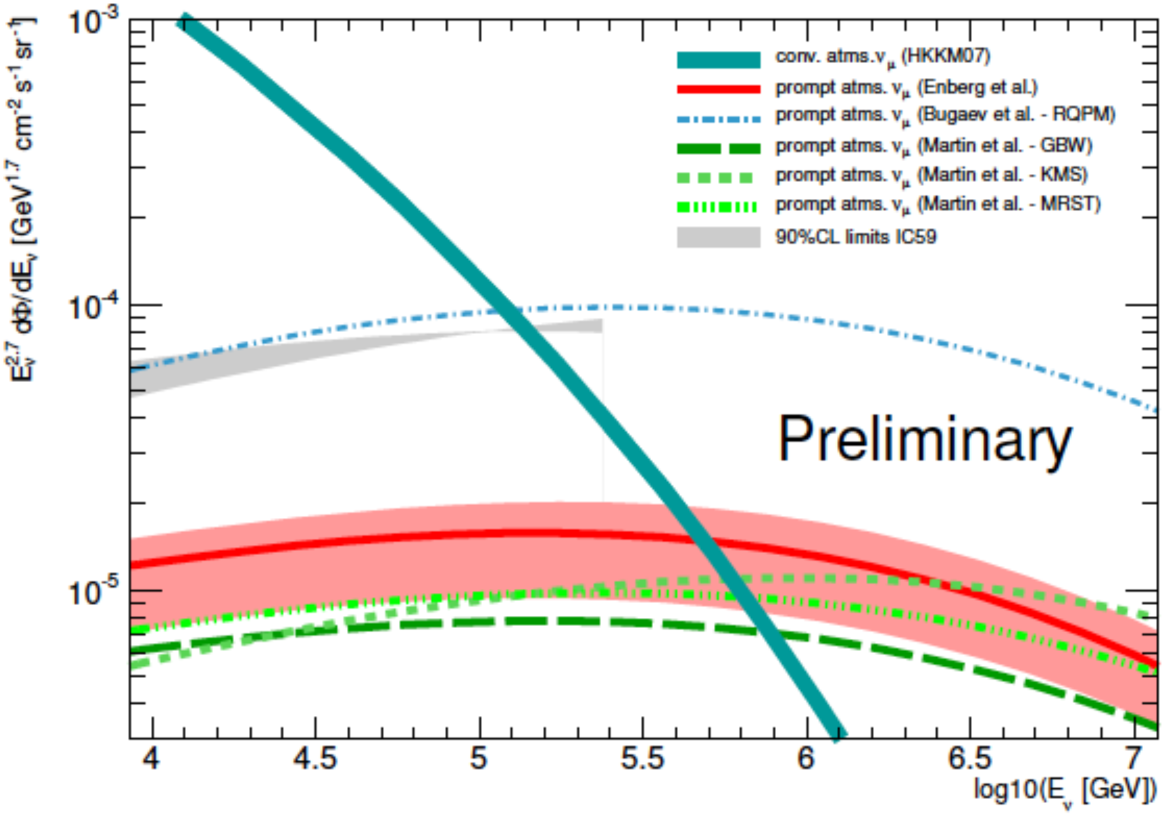
IceCube Results



ERS (2008)

IceCube, Abbasi et al, PRD83 (2011) 012001.

Prompt flux limits



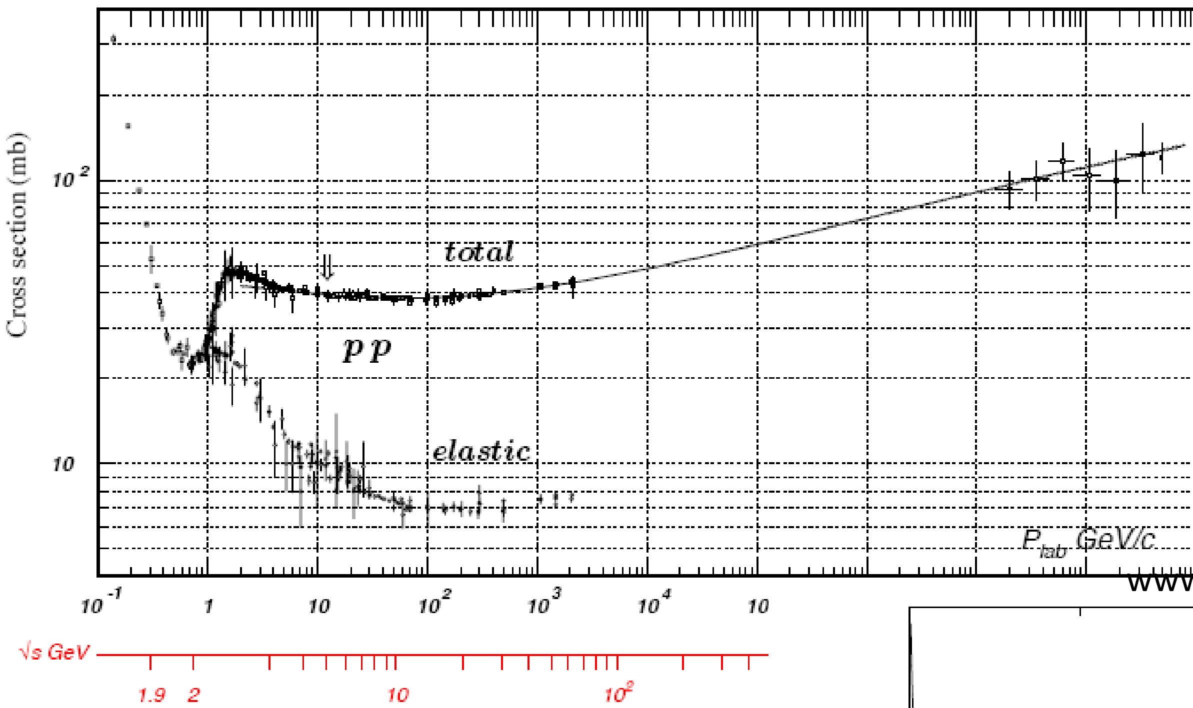
A. Schukraft for IceCube, Nucl. Phys. B Proc. Suppl., arXiv: 1302.0127

Atmospheric lepton flux

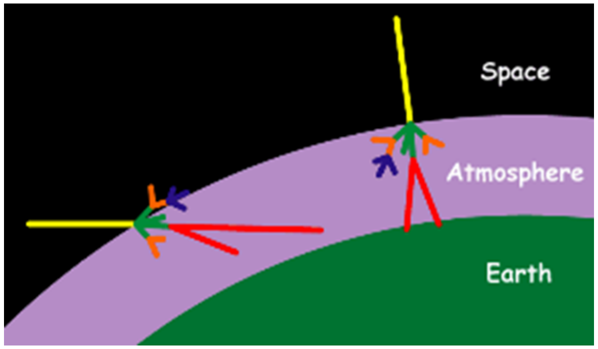
- Cosmic ray flux – energy spectrum and composition (first approximation, protons)
- CR interaction cross section with air nuclei (A = 14.5)
  - Regeneration of CRs
  - Production of mesons, including the energy distributions
- Meson interactions and decays, including energy distribution of leptons
- Coupled transport equations of CRs, mesons and leptons

REFS, e.g.,

- 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)



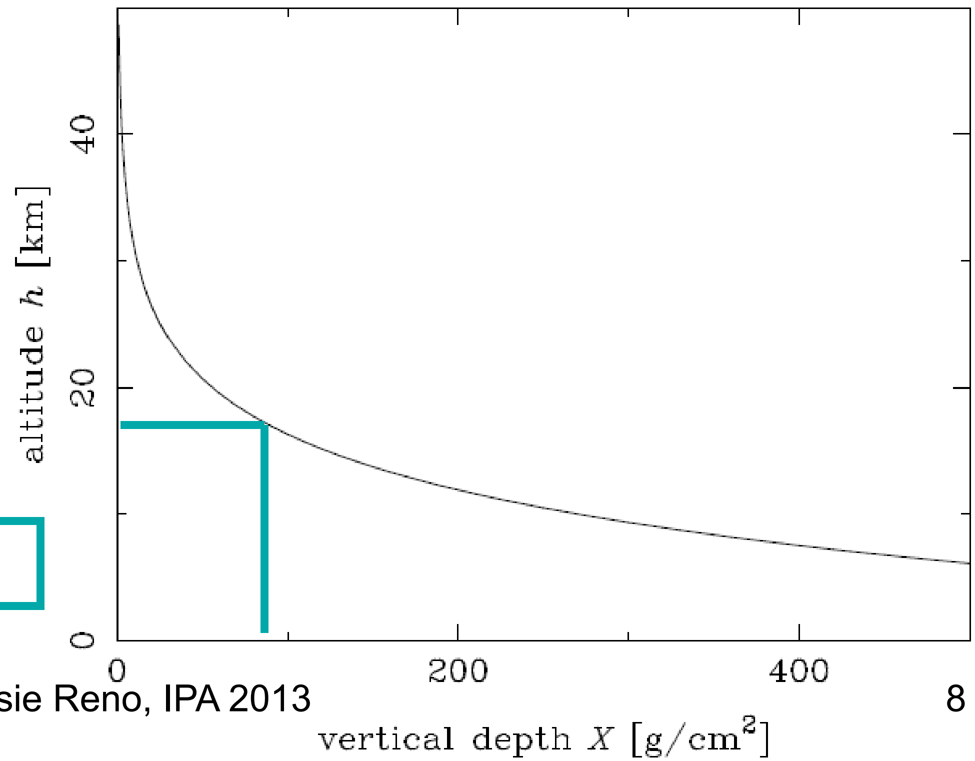
pdg.lbl.gov



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

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

Hallsie Reno, IPA 2013

pA collisions produce hadrons and eventually leptons (etc)

$$pA \to \pi^{\pm}$$
$$\to \pi^0$$
$$\to K^{\pm}$$
$$\to K_L,\ K_S$$
$$\to D^{\pm} \ldots$$

Electron neutrinos, muon neutrinos and muons.

$$\pi^- \to \mu \bar{\nu}_\mu \quad B = 100\%$$
$$\pi^0 \to \gamma\gamma \quad B = 98.8\%$$
$$K^- \to \mu \bar{\nu}_\mu \quad B = 63.5\%$$
$$K_L \to \pi \ell \bar{\nu}_\ell \quad B(K_{e3}) = 38\%,\ B(K_{\mu 3}) = 27.2\%$$

Energy distributions of muons and neutrinos -

"conventional atmospheric flux" from pions and kaons

Conventional and prompt

	$c\tau_0$ [cm]		$c\tau_0$ [cm]
$\pi^{\pm}$	730	$D^{\pm}$	0.028
$K^{\pm}$	371	D^0	0.013
μ	30,000		

Decay lengths for relativistic particles

	$\gamma c\tau_0$ [m]		$\gamma c\tau_0$ [m]
$\pi^{\pm}$	$52\ E/\mathrm{GeV}$	$D^{\pm}$	$1.5\times 10^{-4}\ E/\mathrm{GeV}$
$K^{\pm}$	$7.5\ E/\mathrm{GeV}$	D^0	$7\times 10^{-5}\ E/\mathrm{GeV}$

$$\rho = \rho_0 e^{-h/h_0}\quad \rho_0 \simeq 2\times 10^{-3}\ \mathrm{g/cm^3},\ h_0 \simeq 6.4\ \mathrm{km}$$

"Critical energies" for vertical mesons: decay lengths=h0

$$E_c^{\pi} = 290\ \mathrm{GeV}\qquad E_c^{D^{\pm}} = 10^8\ \mathrm{GeV}\qquad \epsilon_c^{\pi} = 115\ \mathrm{GeV}$$

$$E_c^{K} = 2\ \mathrm{TeV}\qquad E_c^{D^0} = 2\times 10^8\ \mathrm{GeV}\qquad \epsilon_c^{K} = 850\ \mathrm{GeV}$$

Conventional lepton flux

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

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

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

Example: proton to proton

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

Z-factor approximately independent of *X*

$$\phi_N(E, X) = \exp(-X(1 - Z_{NN})/\lambda_N)\phi_N(E, 0), \quad Z_{NN} \simeq 0.4$$

attenuated flux

$$\frac{1}{\Lambda_N} = \frac{1 - Z_{NN}}{\lambda_N}$$

Another example – pion decay to neutrinos:

$$\phi_\pi \simeq Z_{N\pi} \times \text{factor} \times \phi_N(E, 0)$$

$$\phi_\nu \simeq P^{\rm dec}_{\pi\to\nu} Z_{\pi\nu} \times \text{factor} \times \phi_\pi$$

High energy: $P^{\rm dec}_{\pi\to\nu} = 1 - \exp(-ct/\gamma c\tau) \simeq E_c^\pi/E$

Low energy: $P^{\rm dec}_{\pi\to\nu} \simeq 1$

$$Z_{N\pi} = 0.1$$

$$Z_{\pi\nu} = 0.06$$

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

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

Prompt lepton flux

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

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

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

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

Another example – D meson decay to neutrinos:

$$\phi_D \simeq Z_{ND} \times \text{factor} \times \phi_N(E, 0)$$

$$\phi_\nu \simeq P^{\rm dec}_{D\to\nu} Z_{D\nu} \times \text{factor} \times \phi_D$$

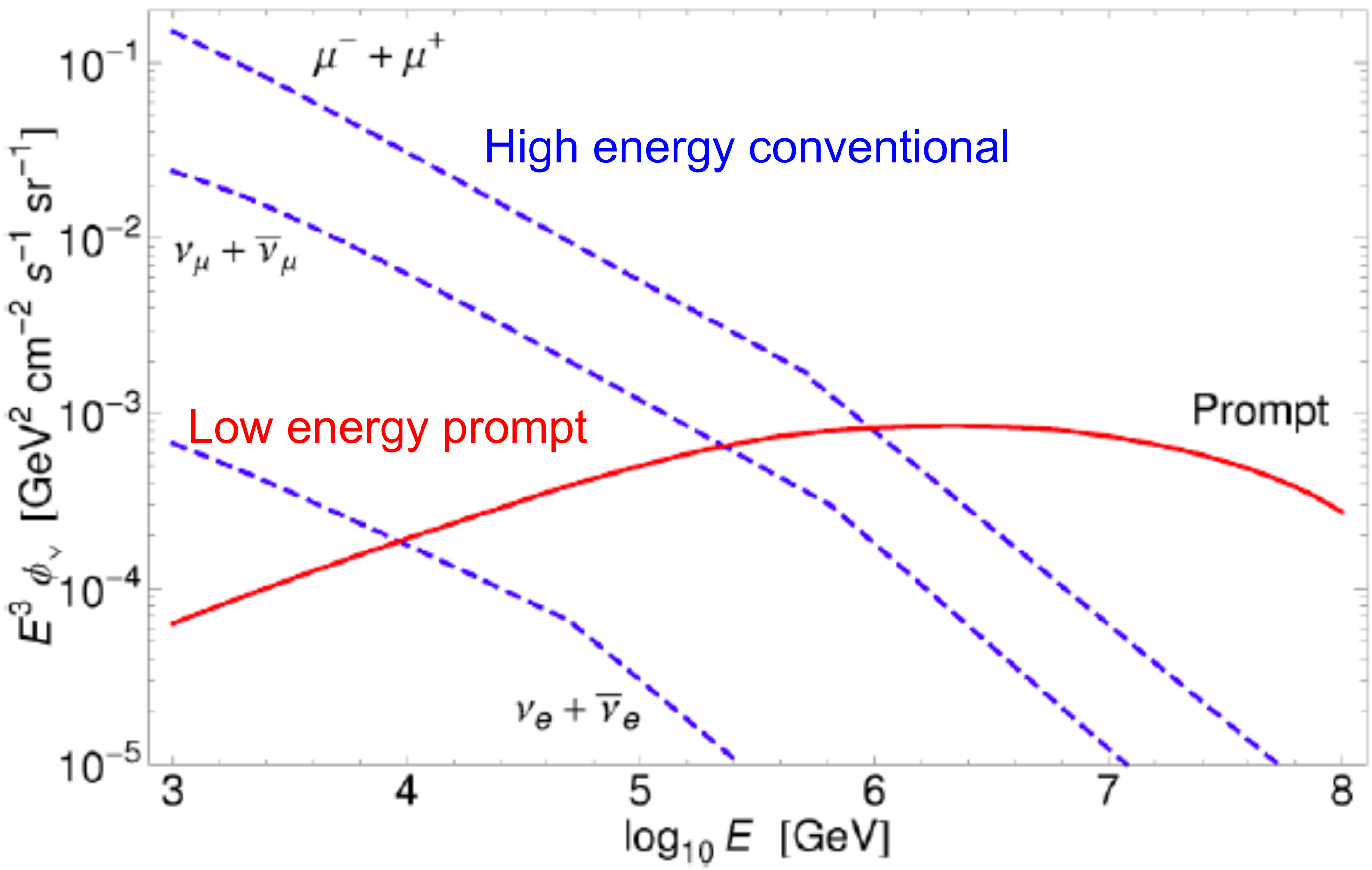
High energy: $P^{\rm dec}_{D\to\nu} \simeq E_c^D / E$

Low energy: $P^{\rm dec}_{D\to\nu} \simeq 1$

$$Z_{N\pi} = 0.1$$
$$Z_{\pi\nu} = 0.06$$
$$E_c^\pi = 115 \text{ GeV}$$
$$E_c^D \sim 10^8 \text{ GeV}$$

"low energy" charm up to very high energies!

Energy behavior



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.

$$x_1,\ x_2:$$

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

$$x_F = x_1 - x_2$$

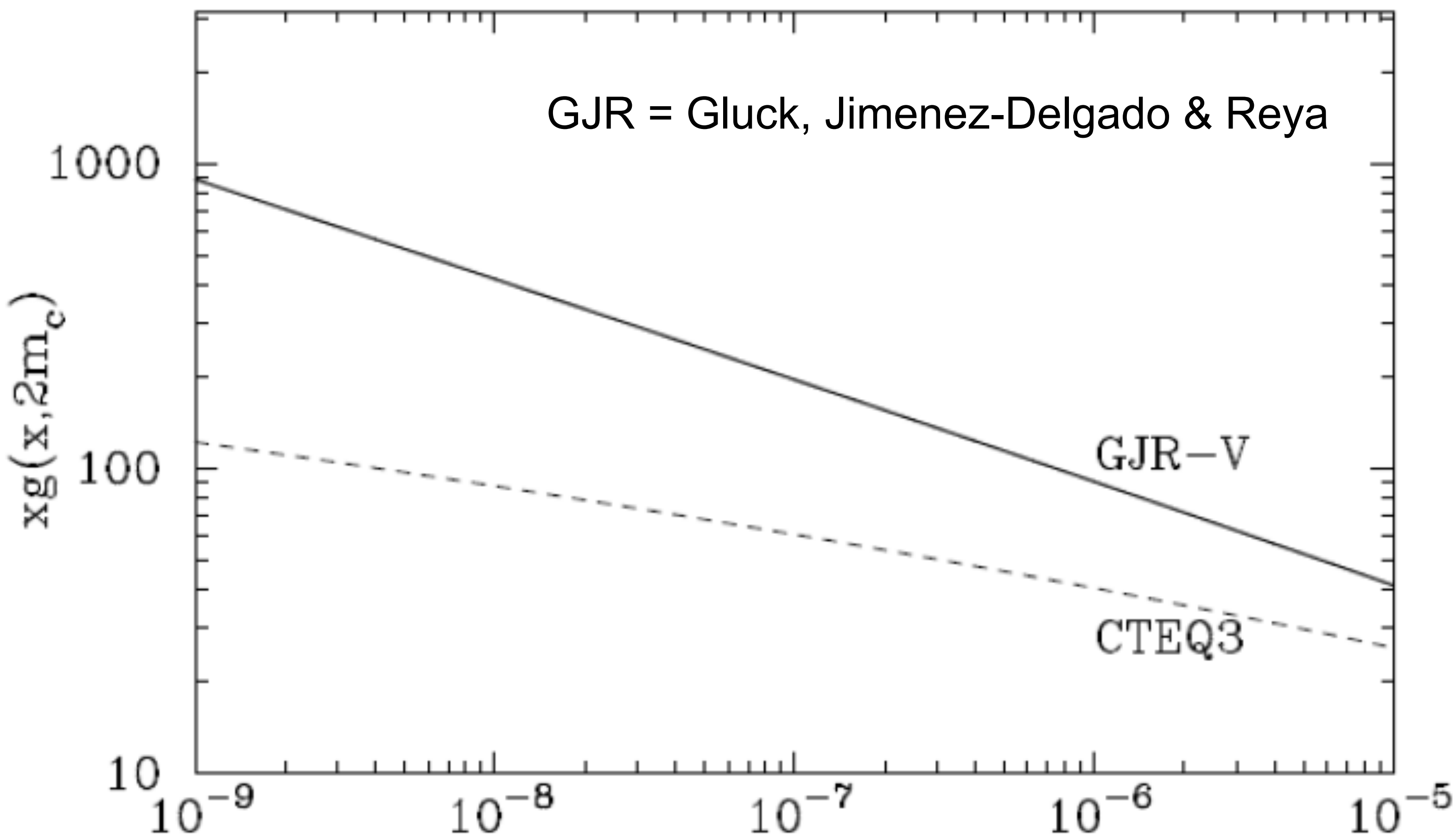
$$x_F \simeq x_E = E/E'$$

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

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.
Necessarily involve extrapolations at low x (sometimes explicit, sometimes implicit).
What about large logarithms? $\ln(1/x)$
Approximate unified DGLAP/BFKL solutions.

PDFs – extrapolations….



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:

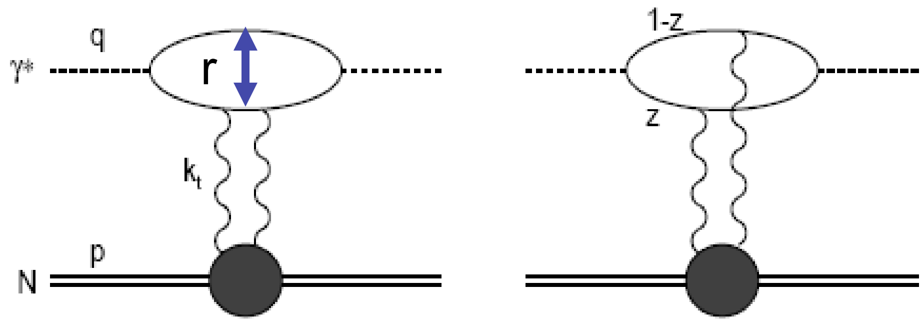
MRST

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

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

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:

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

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

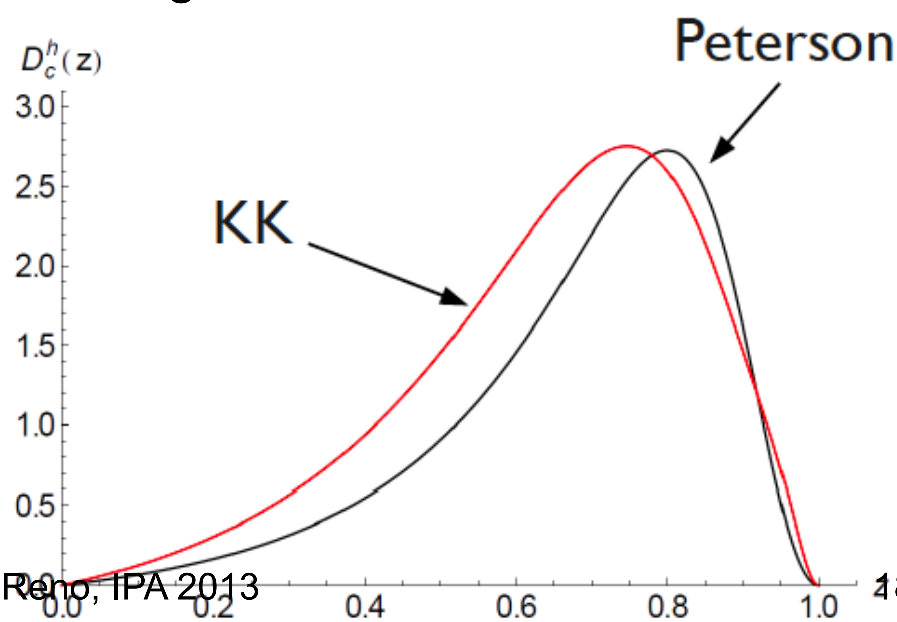
- Golec-Biernat & Wusthoff (GBW, PRD 59 (1999))
- Data show as small x that the virtual photon-proton cross section scales: dipole model includes this scaling (Stasto, Golec-Biernat & Kwiecinski, PRL 86 (2001))
- Improved QCD motivated form – Balitsky-Kovchegov (BK) evolution
- Modified for gluon ->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

Dipole approach

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

- 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.

Enberg, Reno & Sarcevic, PRD 78 (2008) 043005



Dipole cross section

- Iancu, Itakura and Munier, based on analytic approximate solutions in two different regions, with Soyez parameter updates including charm.

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

$\sigma_{dG}(x,\mathbf{r})$ related to $\sigma_d = \sigma_0 \mathcal{N}(rQ_s, Y)$

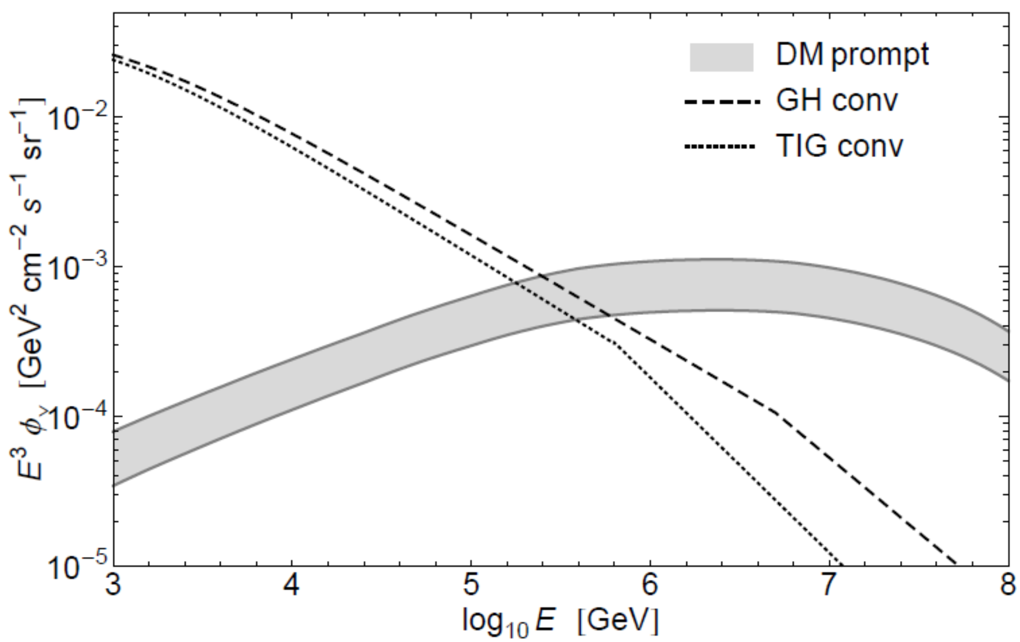
$$Q_s = Q_0(x_0/x)^{\lambda/2} \qquad \mathcal{N}(rQ_s,Y) = \begin{cases} \mathcal{N}_0 \left(\frac{\tau}{2}\right)^{2\gamma_{\rm eff}(x,r)}, & \text{for } \tau < 2 \\ 1 - \exp\left[-a \ln^2(b\tau)\right], & \text{for } \tau > 2 \end{cases}$$

$$Y = \ln(1/x)$$

$$\tau = rQ_s \qquad \gamma_{\rm eff}(x,r) = \gamma_s + \frac{\ln(2/\tau)}{\kappa\lambda Y}$$

Martin, Ryskin and Stasto GBW: different parameterization of $\sigma_{dG}(x,\mathbf{r})$

Results for prompt lepton flux (vertical) with dipole model evaluation



DM=dipole model

GH=Gaisser-Honda

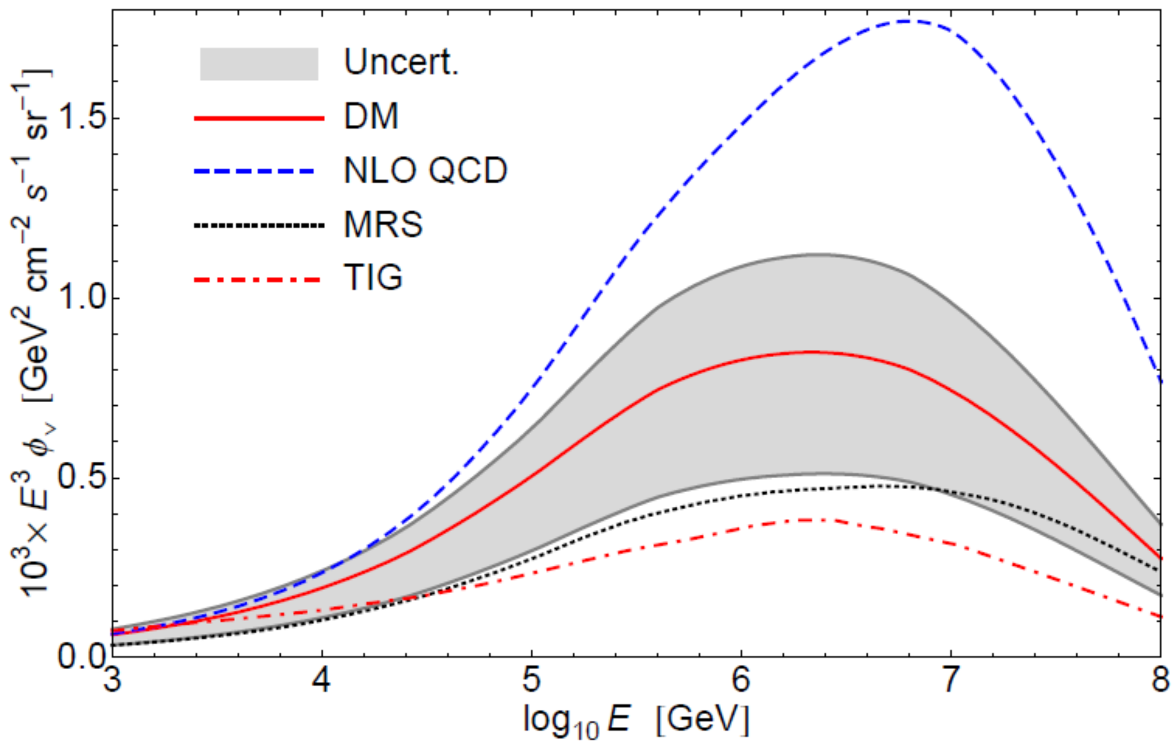
TIG=Thunman et al. (PDF + pythia, small x extrapolation)

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



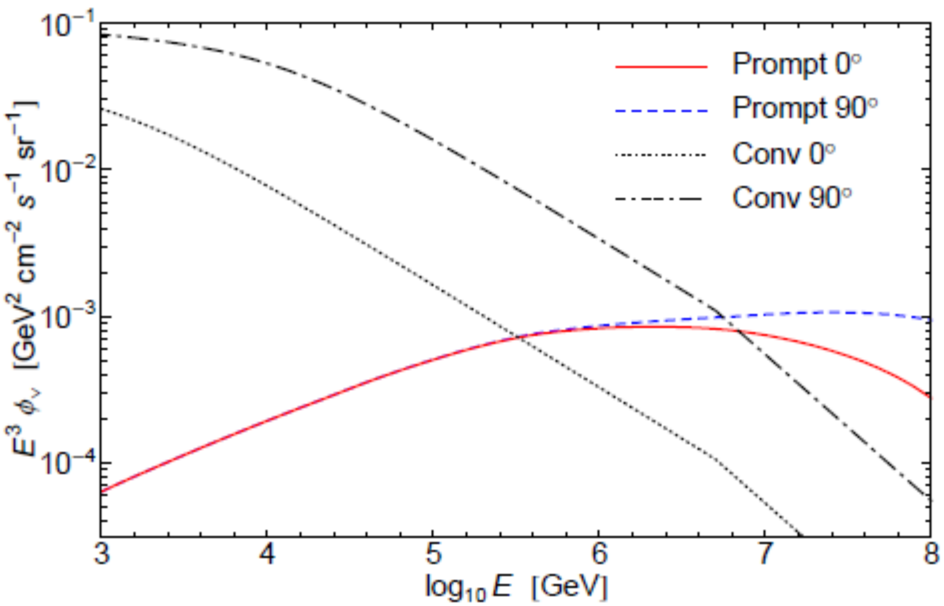
Range of predictions

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

Atmospheric neutrinos-angular dependence



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

Conventional flux from Gaisser-Honda.

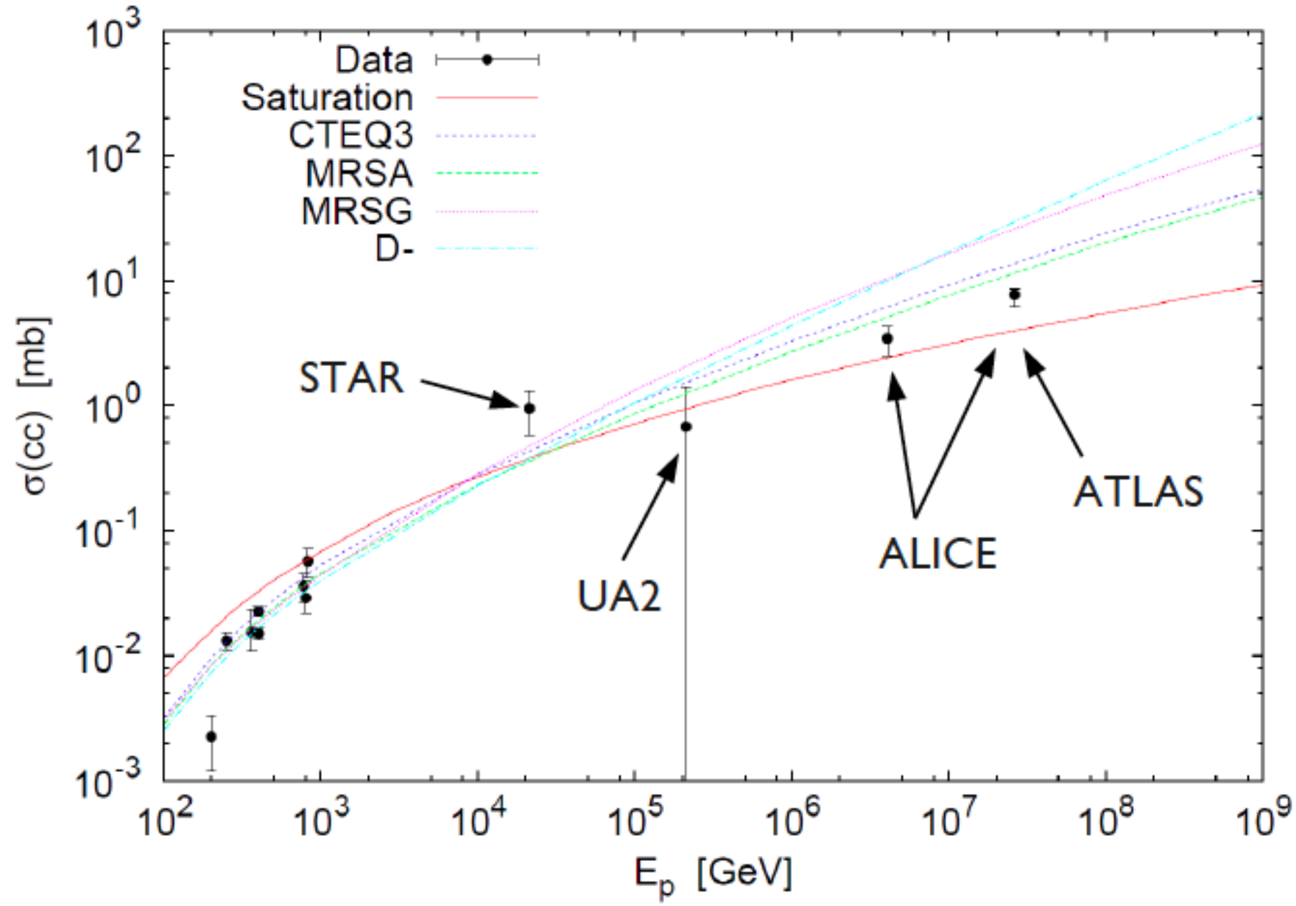
Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Higher energies in accelerators

- With the PDF approach:
  - Need new comparisons, with updated PDFs, with new measured high energy cross sections.

High rapidity most important for prompt flux calculation.

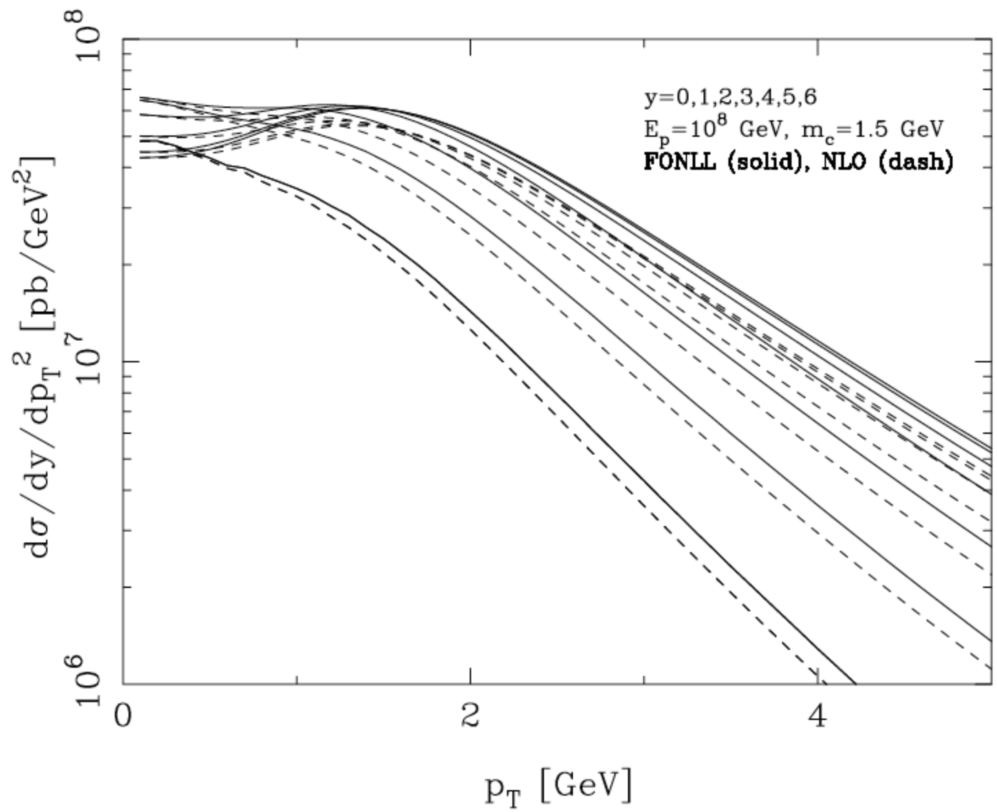
Range of cross section predictions from theory still quite large (mass of charm quark, scale dependence).



Work in progress

- 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.

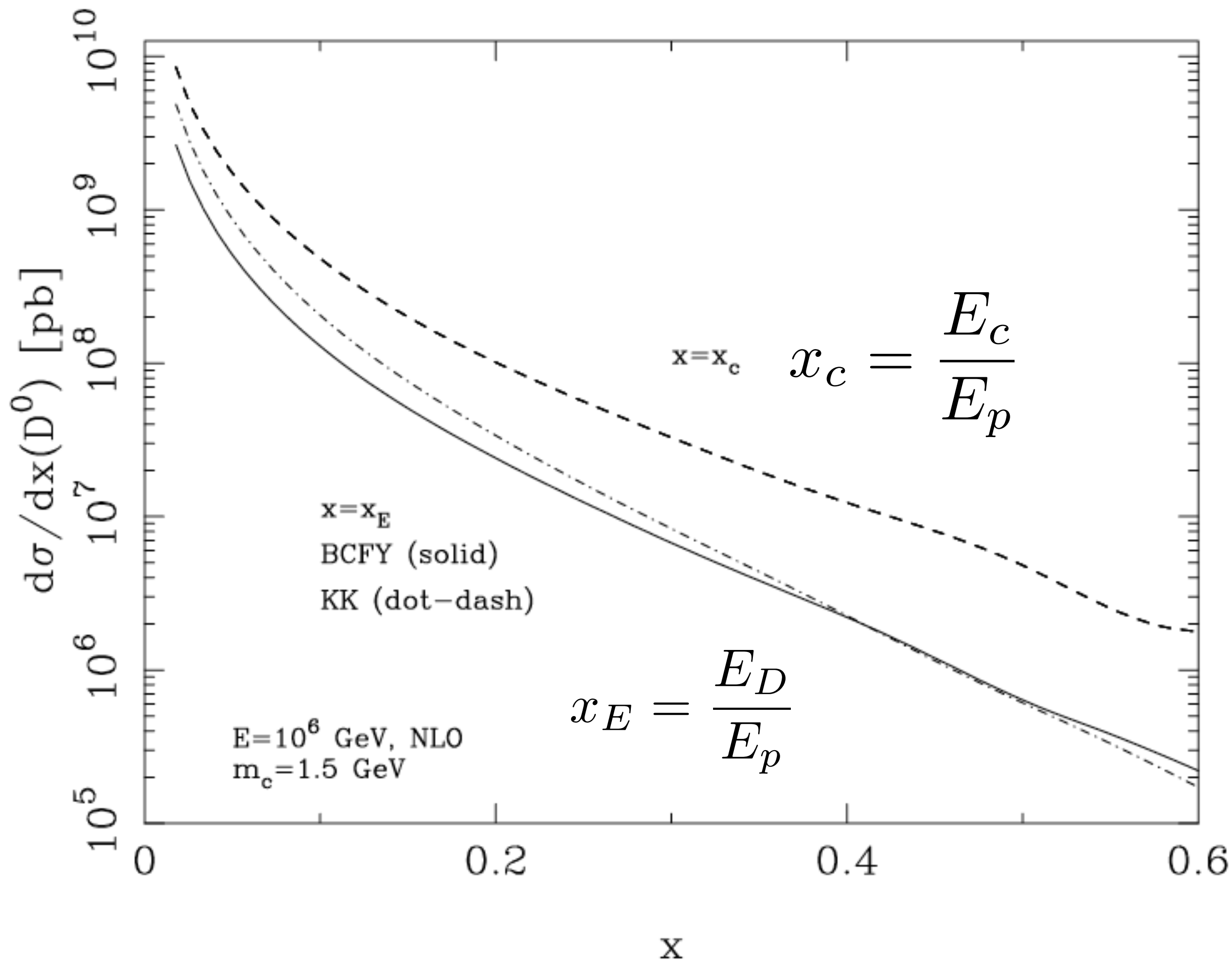


FONLL Refs: M. Cacciari, M. Greco & P. Nason, JHEP (1998); Cacciari, Frixione & Nason, JHEP (2001)

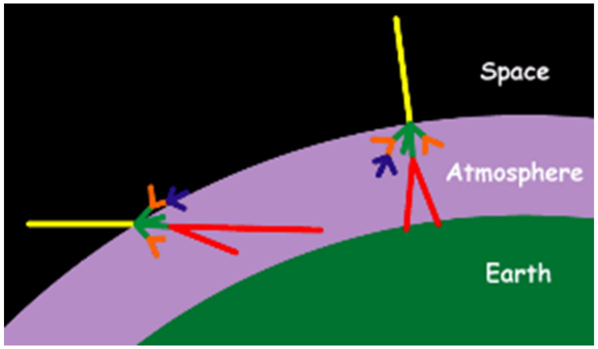
Charm to mesons-Fragmentation

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

KK=Kramer & Kniehl



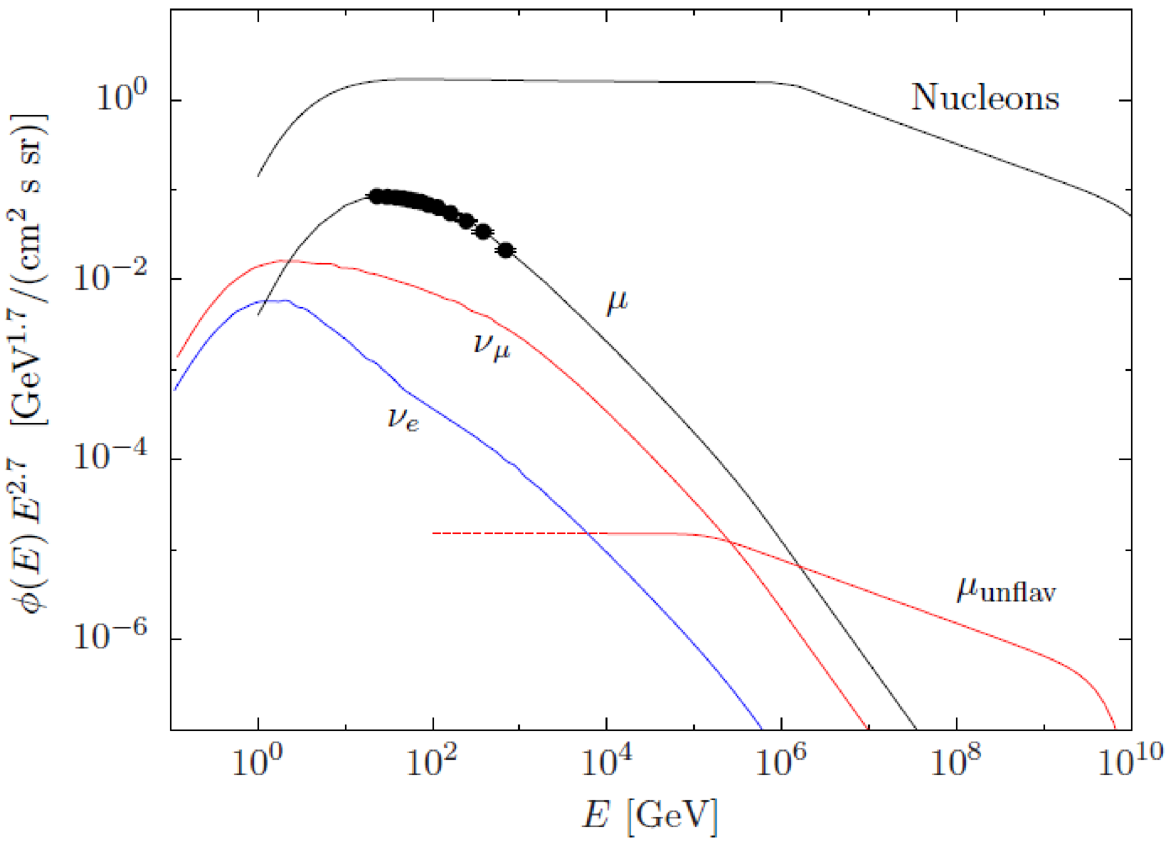
High pT muons from charm



- 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.

Transport equations

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

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

For which particles? High enough energies that muons are "stable".

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

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

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.

Approximate formulae

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

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

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

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

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

Work in progress - kinematics