Prompt neutrinos and charm in light of RHIC and the LHC

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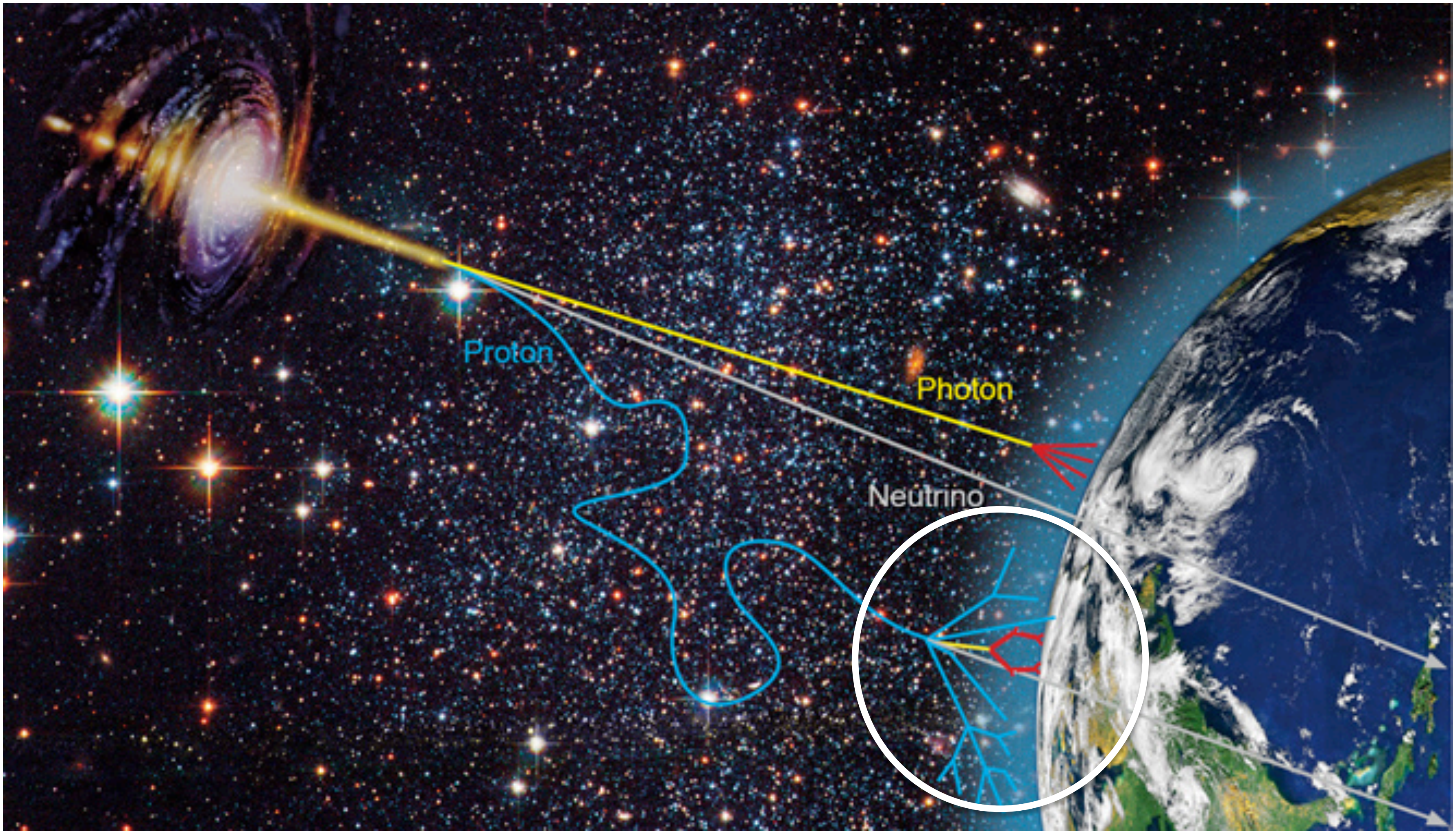
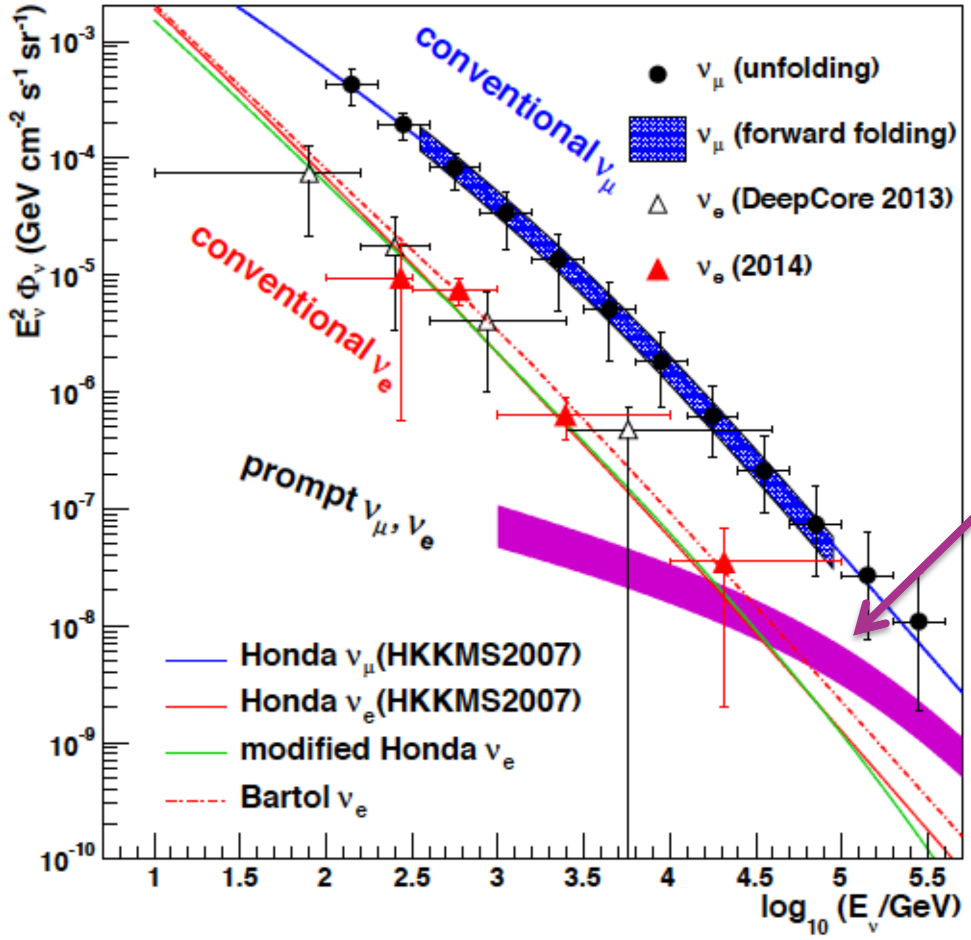
INT Workshop, June 18, 2015

arXiv:1502.01076, to appear in JHEP

Neutrinos produced in the atmosphere



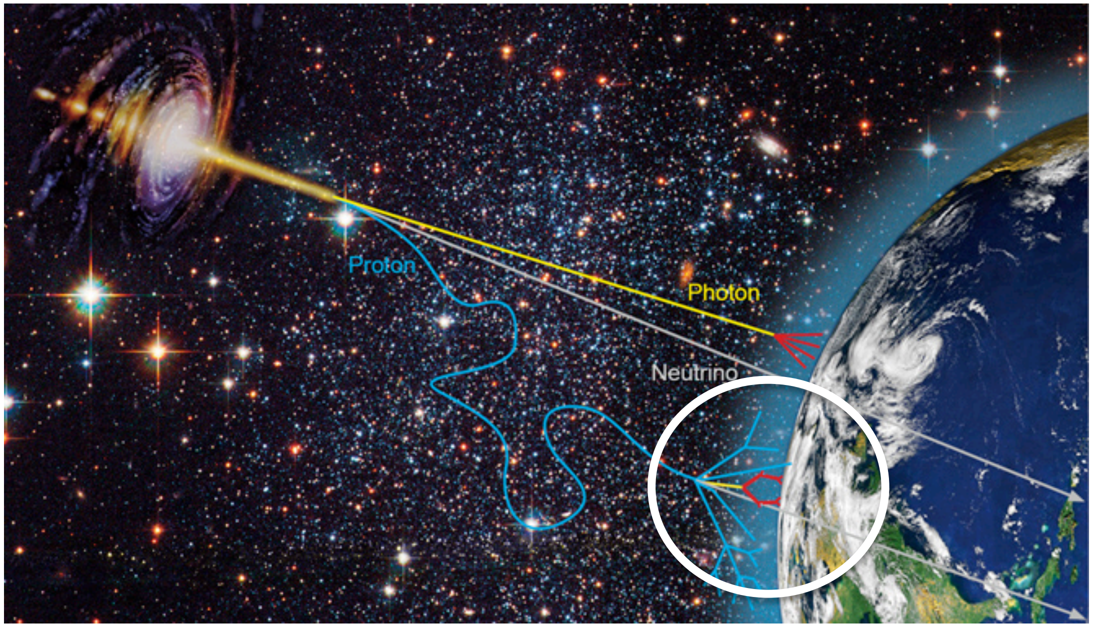
Update/improve earlier work on the prompt flux



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

IceCube, arXiv:1504.03753

Neutrinos produced in the atmosphere

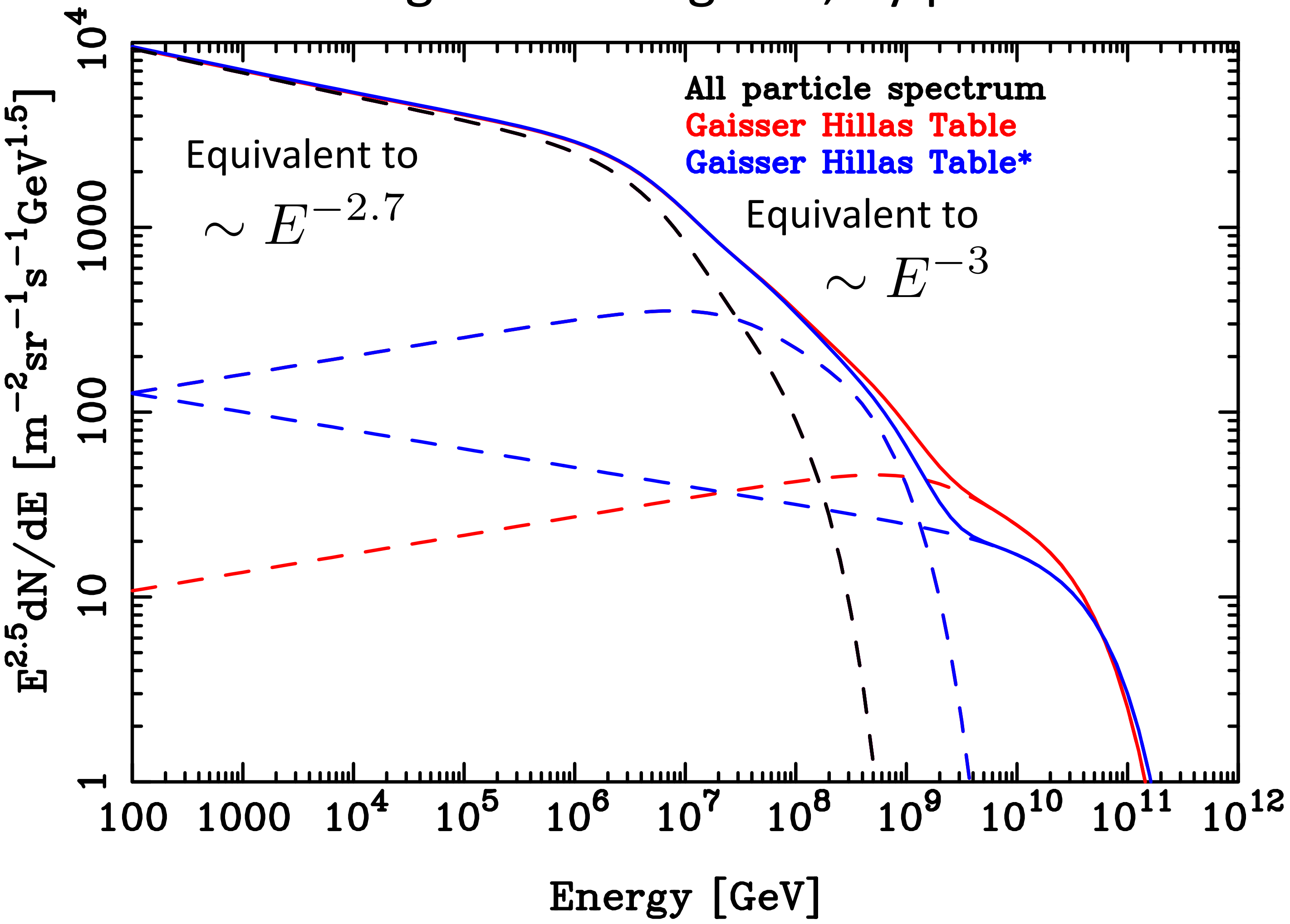


Inputs include:

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

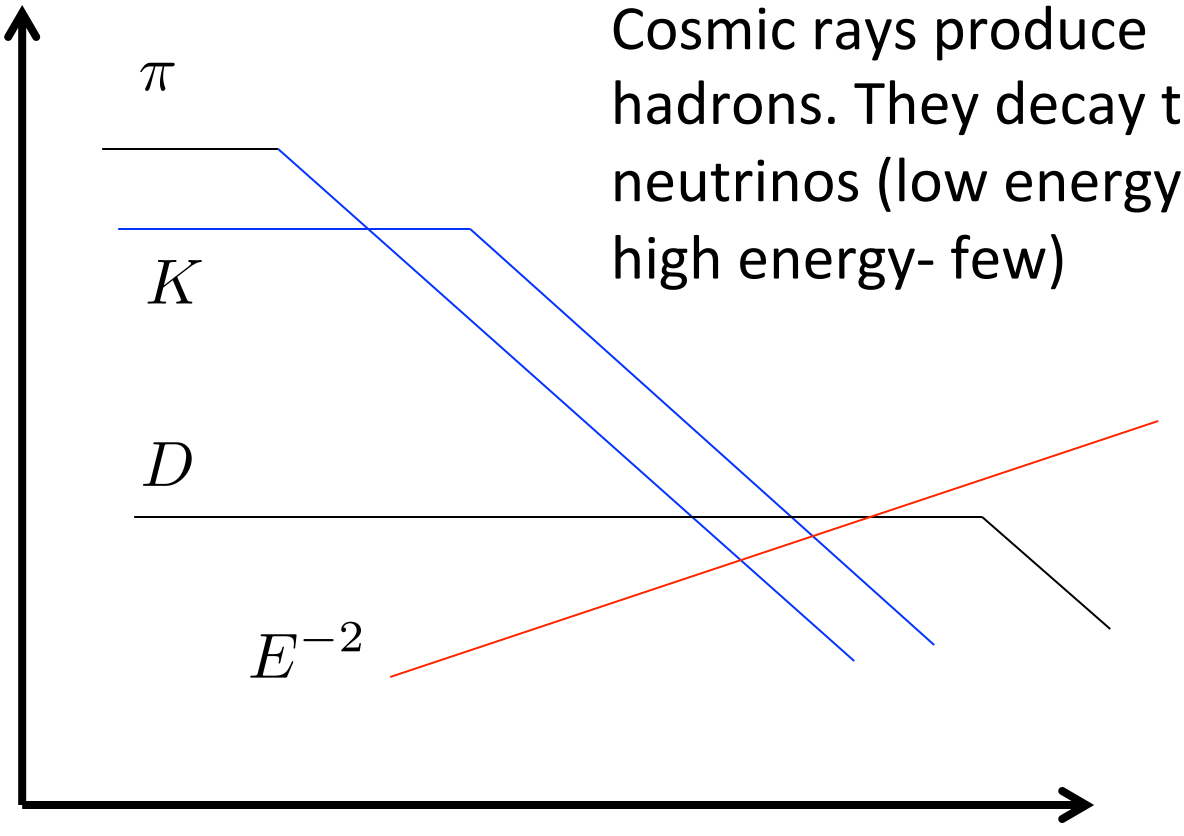
CR all particle spectrum

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



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

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



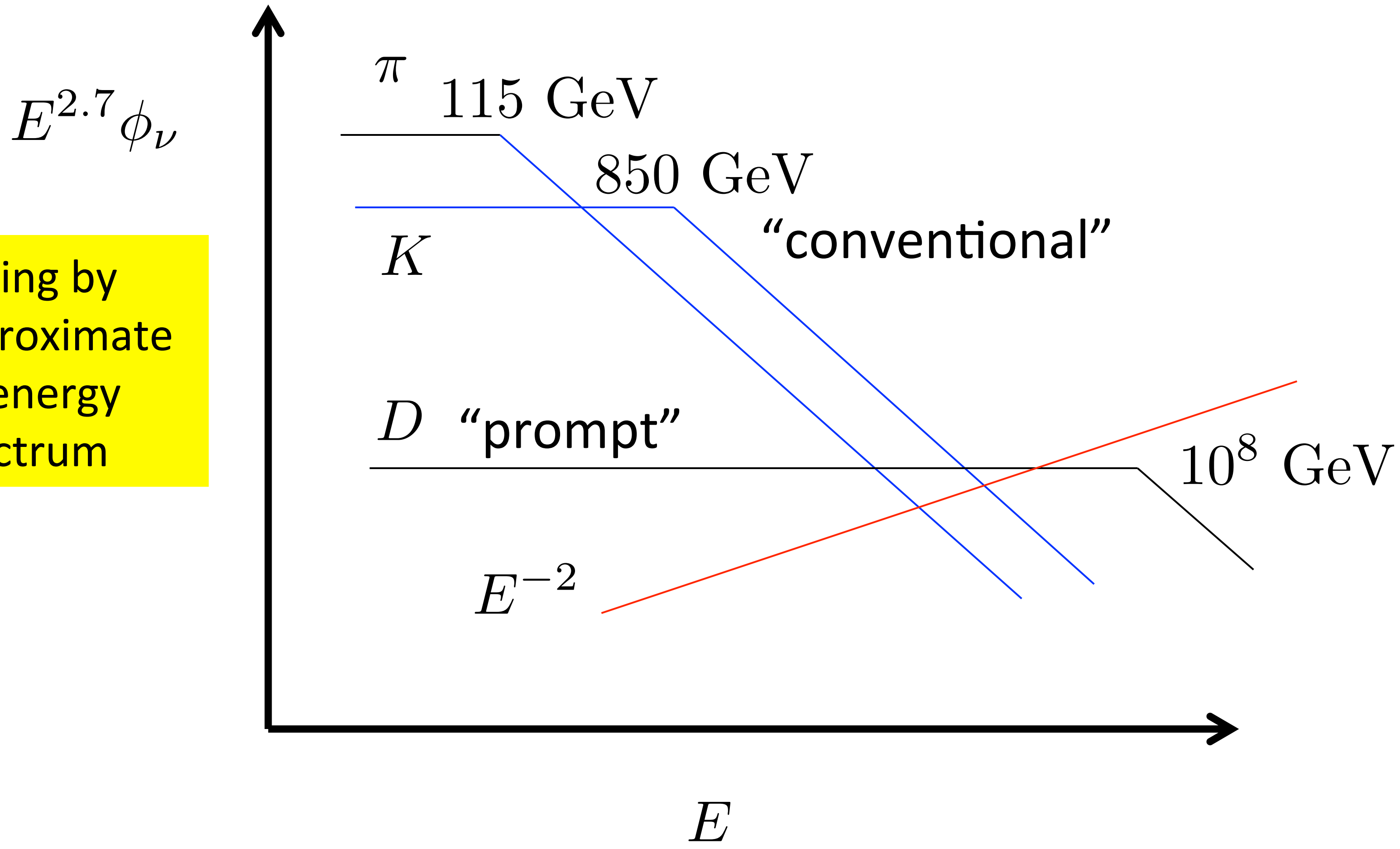
Scaling by approximate CR energy spectrum

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

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

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

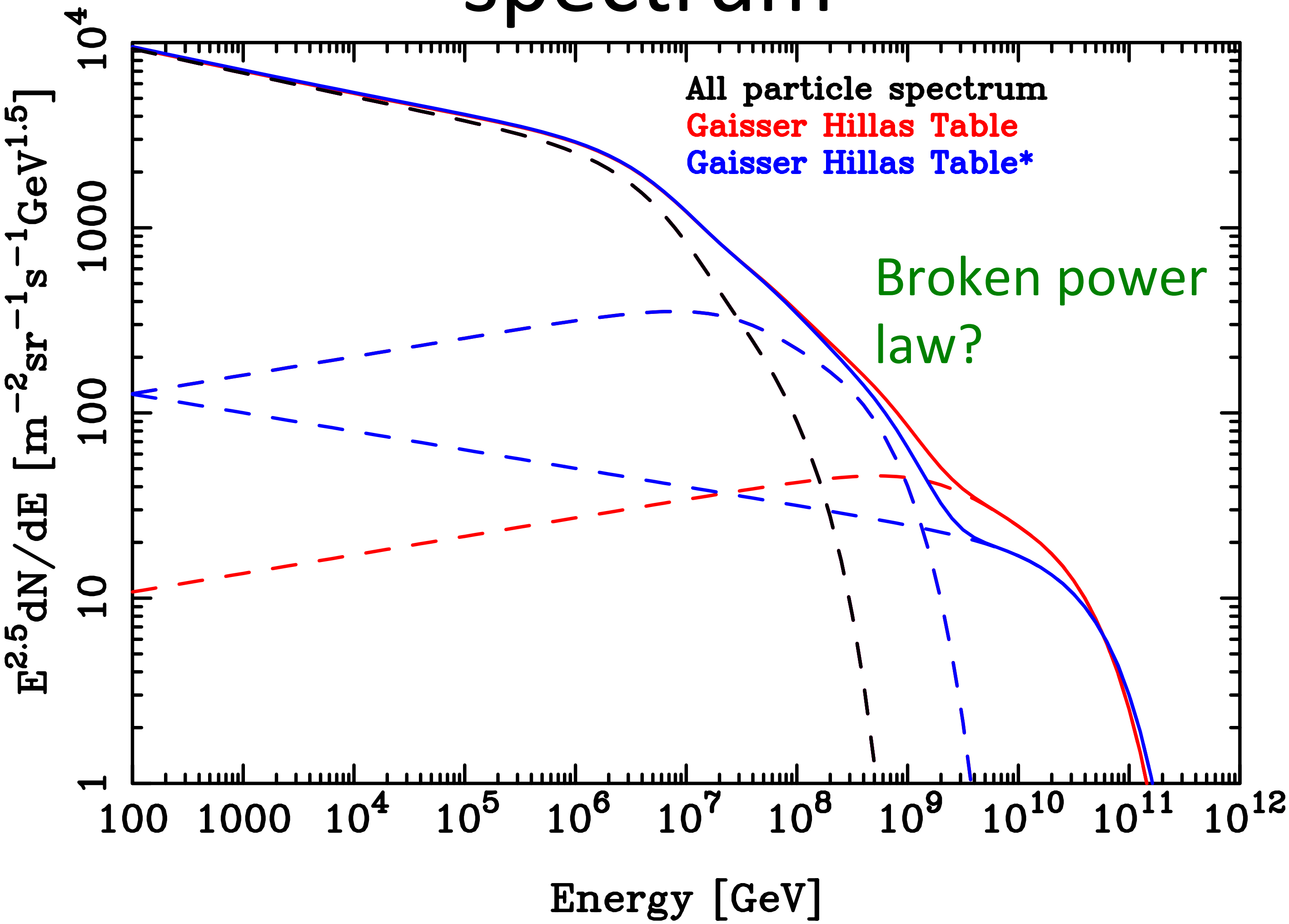
Energy dependence, schematically



Scaling by approximate CR energy spectrum

Electron neutrino flux from K-short, Gaisser & Klein, Astropart. Phys. 64 (2015) $1.2 \times 10^5\ \mathrm{GeV}$

Cosmic ray inputs: CR all particle spectrum

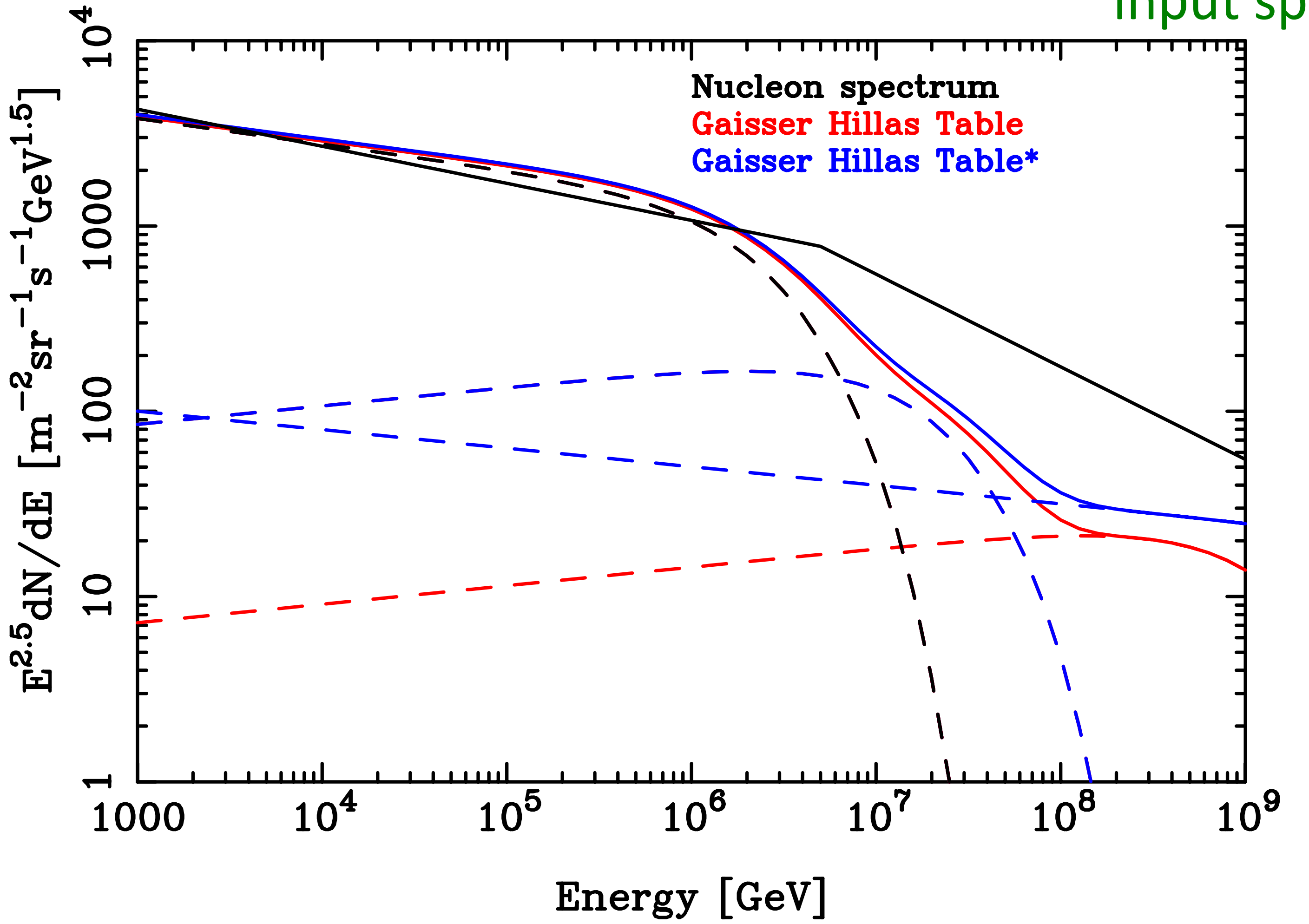


Broken power law?

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

CR nucleon spectrum

Broken power law? Not really…. New input spectrum.



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

What is new in this perturbative evaluation of the charm cross section?

- Full NLO QCD evaluation of charm pair cross section and energy distribution using the FONLL code (low pT, so no log(pT/mc) required here) with CT10 PDFs (modern 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)

- Differential cross section then convoluted with … cosmic ray nucleon spectrum from Gaisser (2012).

  Gaisser, Astropart. Phys. 35 (2012); Gaisser, Stanev & Tilav, NIM A742 (2014)

Charm cross section using perturbative QCD

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:

$x_1,\ x_2$:

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

$$x_F = x_1 - x_2$$

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

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

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 modeled with x dependent k-factor (PRS)
Necessarily involve extrapolations at low x (sometimes explicit, sometimes implicit).
What about large logarithms? $\ln(1/x)$

NLO perturbative contributions

$$q + \bar{q} \to Q + \bar{Q}, \qquad \alpha_S^2, \alpha_S^3,$$

$$g + g \to Q + \bar{Q}, \qquad \alpha_S^2, \alpha_S^3,$$

$$q + \bar{q} \to Q + \bar{Q} + g, \qquad \alpha_S^3,$$

$$g + g \to Q + \bar{Q} + g, \qquad \alpha_S^3,$$

$$g + q \to Q + \bar{Q} + q, \qquad \alpha_S^3,$$

$$g + \bar{q} \to Q + \bar{Q} + \bar{q}, \qquad \alpha_S^3.$$

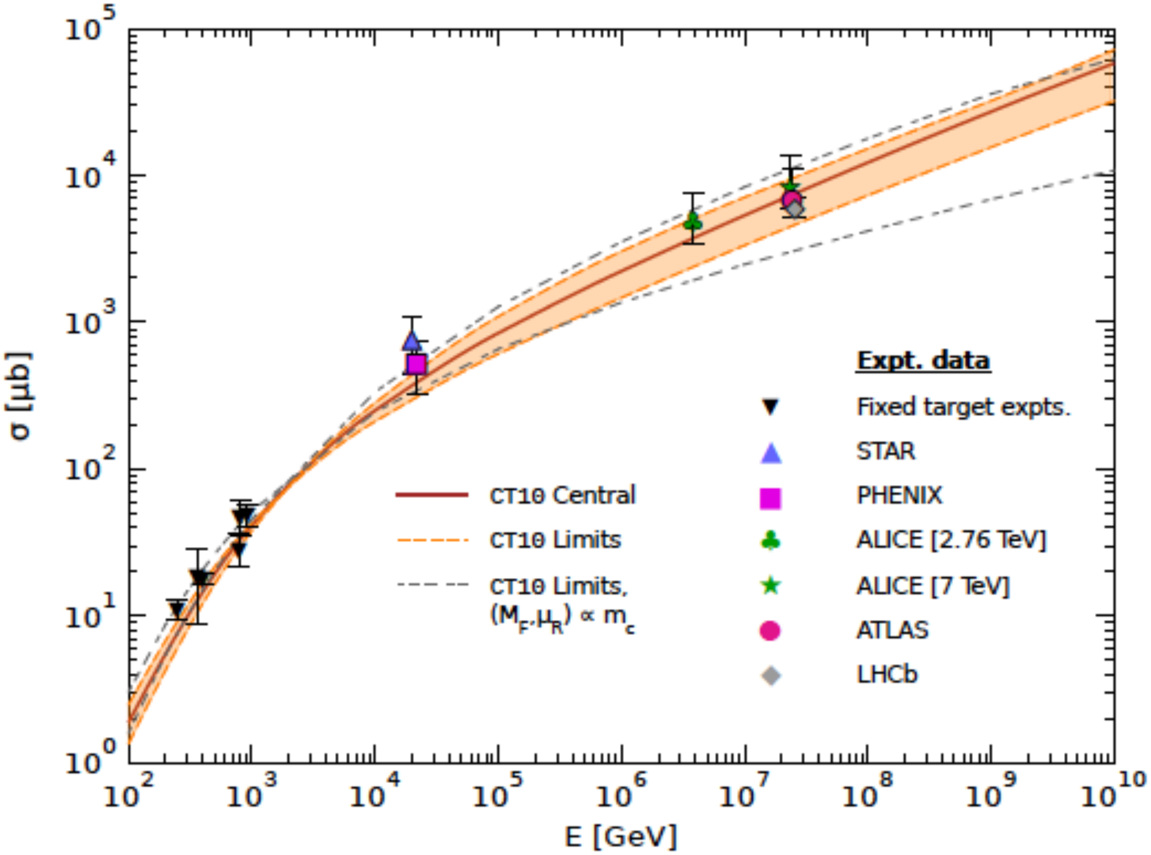
We use the FONLL program that incorporates these processes. We take

$$m_c = 1.27\ \mathrm{GeV}$$

$$M_F, \mu_R \propto m_T = \sqrt{m_c^2 + p_T^2}$$

Nason, Dawson & Ellis, Nucl. Phys. B303(1988); Nucl. Phys. B327 (1989); Mangano, Nason, Ridolfi, Nucl. Phys. B373 (1992);
FONLL: Cacciari, Greco and Nason, JHEP 9805 (1998); Cacciari, Frixione and Nason, JHEP 0103 (2001),

Charm pair cross section guides our choices of scales



$$m_c = 1.27 \text{ GeV}$$

Central

$$M_F = 2.1 m_T$$

$$\mu_R = 1.6 m_T$$

Shaded band

$$M_F = 1.25 - 4.65 m_T$$

$$\mu_R = 1.48 - 1.71 m_T$$

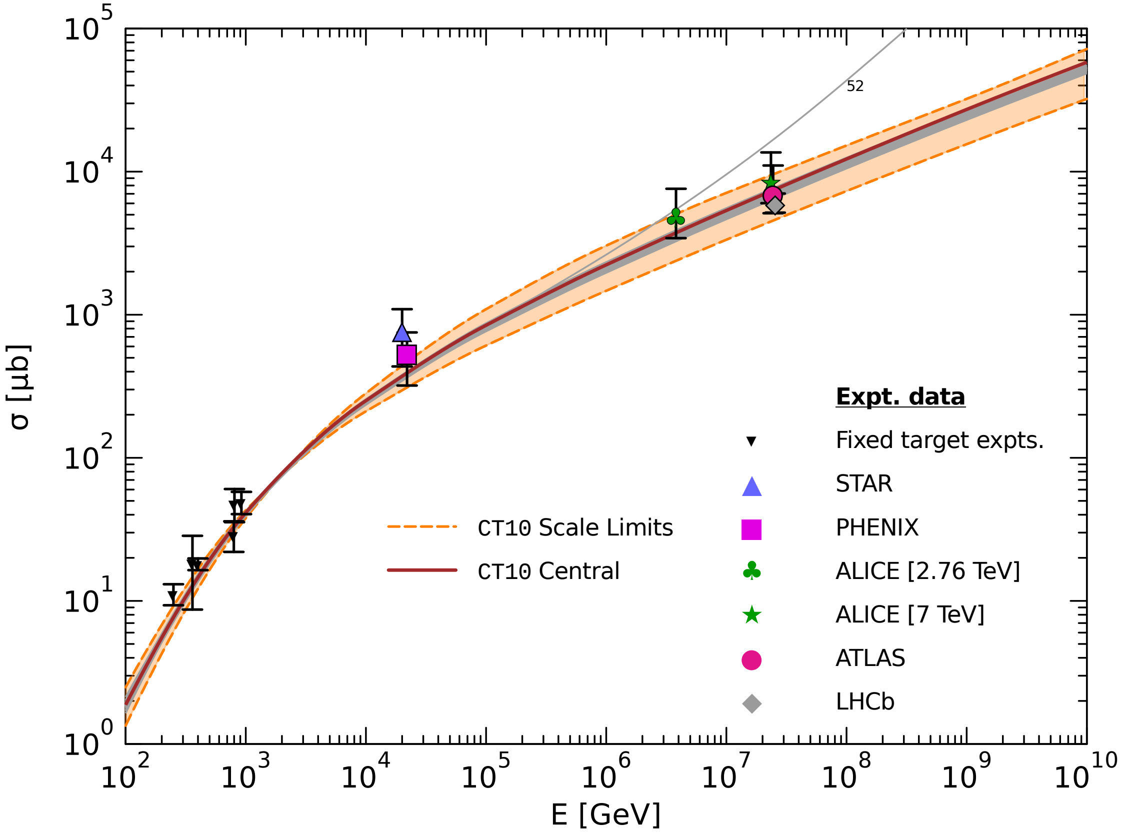
Dashed band

$$M_T, \mu_R \propto m_c$$

arXiv:1502.01076

Guidance from Nelson, Vogt & Frawley, PRC 87 (2013)

Charm pair cross section: CT10 uncertainties



arXiv:1502.01076

$$m_c = 1.27 \text{ GeV}$$

Central

$$M_F = 2.1 m_T$$

$$\mu_R = 1.6 m_T$$

Orange shaded band

$$M_F = 1.25 - 4.65 m_T$$

$$\mu_R = 1.48 - 1.71 m_T$$

Grey shaded band CT10 variations except for set 52.

Calculational method: we use transport equations and Z-moments

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

High enough energies that muons are "stable".

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

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

$$\boxed{pA \to DX}$$

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

Production

$$\boxed{D \to \nu_\mu X}$$

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

Decay

Need energy distribution of the final state particle.

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.

Approximate formulae

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

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

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

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

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

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

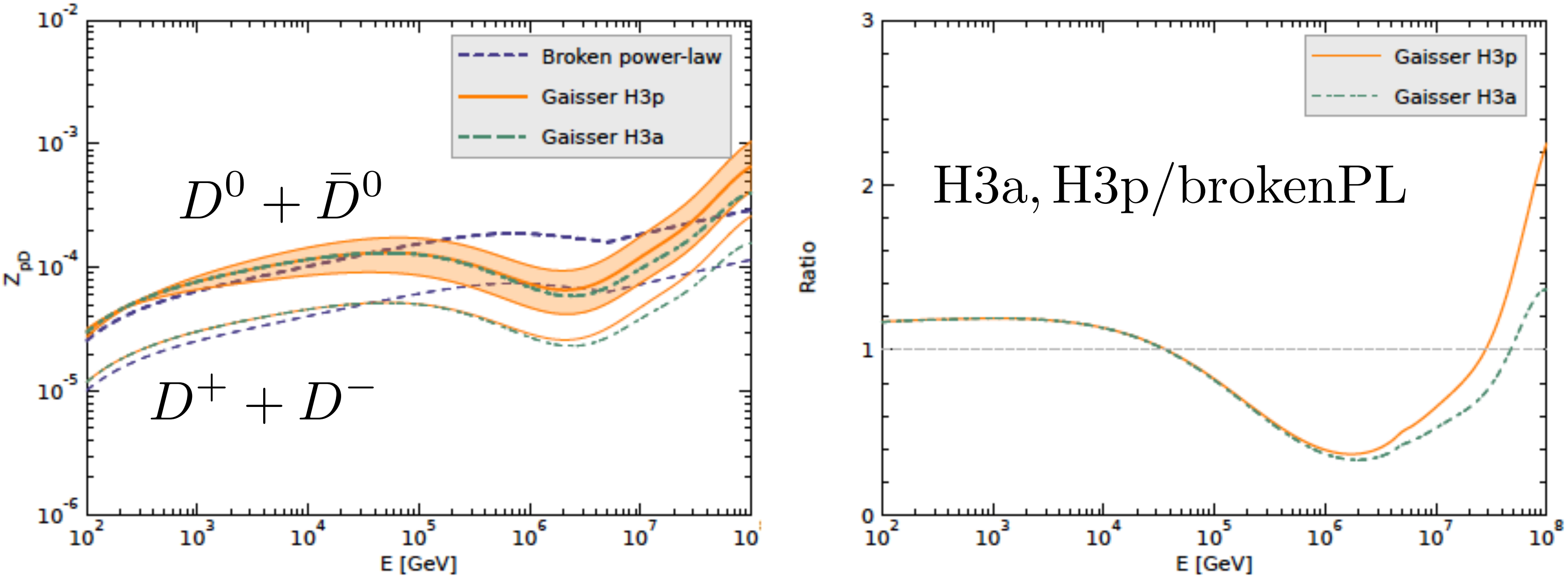
Exponential atmosphere, 1D, approximate factorization of depth dependence.

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

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

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)

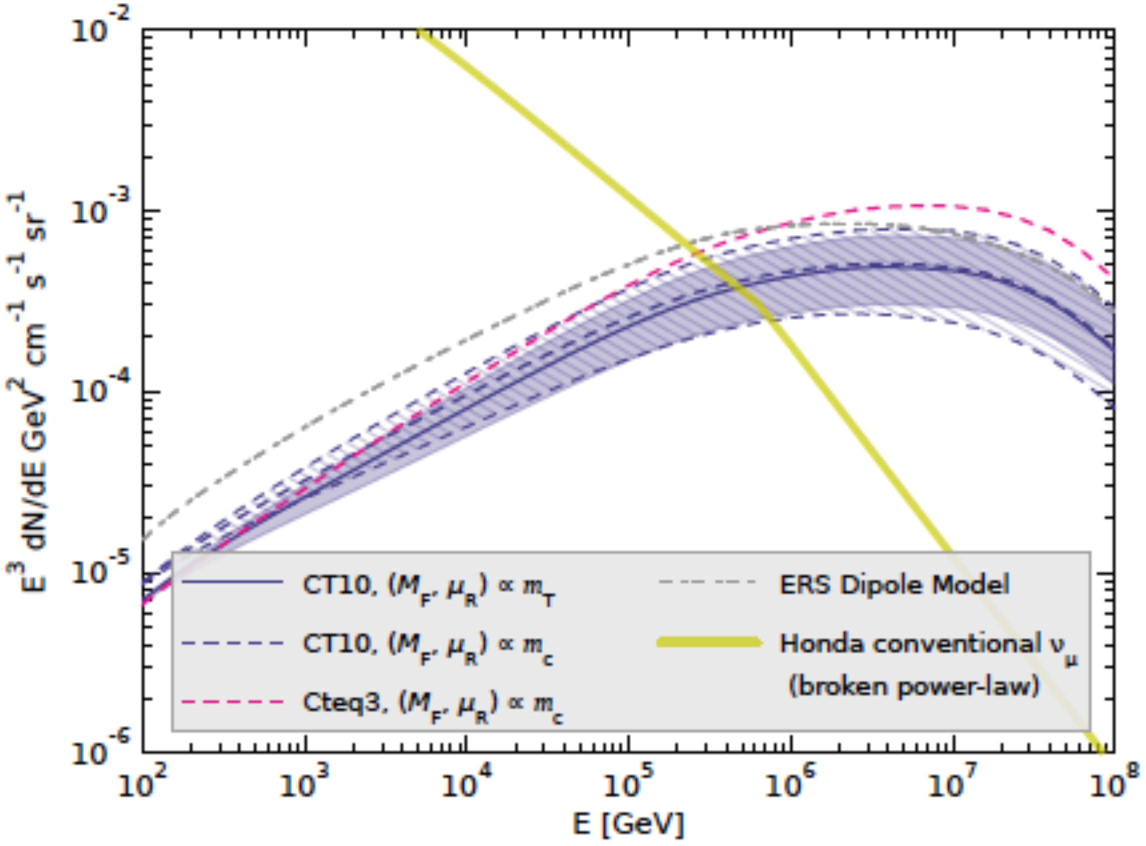
Z moments - production



Impact of the input cosmic ray nucleon flux evident.

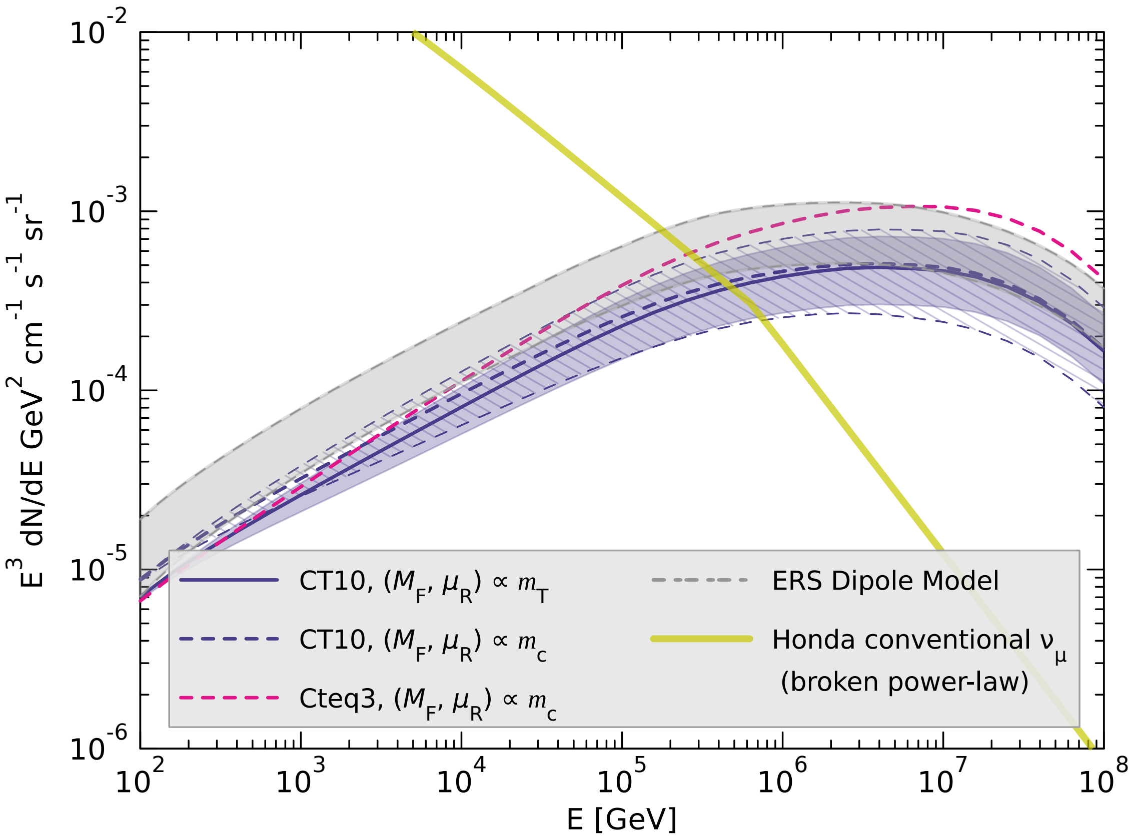
arXiv:1502.01076

Broken power law CR flux: muon neutrinos plus antineutrinos



arXiv:1502.01076, Honda et al., PRD75 (2007)

Comparison with ERS



Upper band: ERS (dipole model)

arXiv:1502.01076, Honda et al., PRD75 (2007)

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,

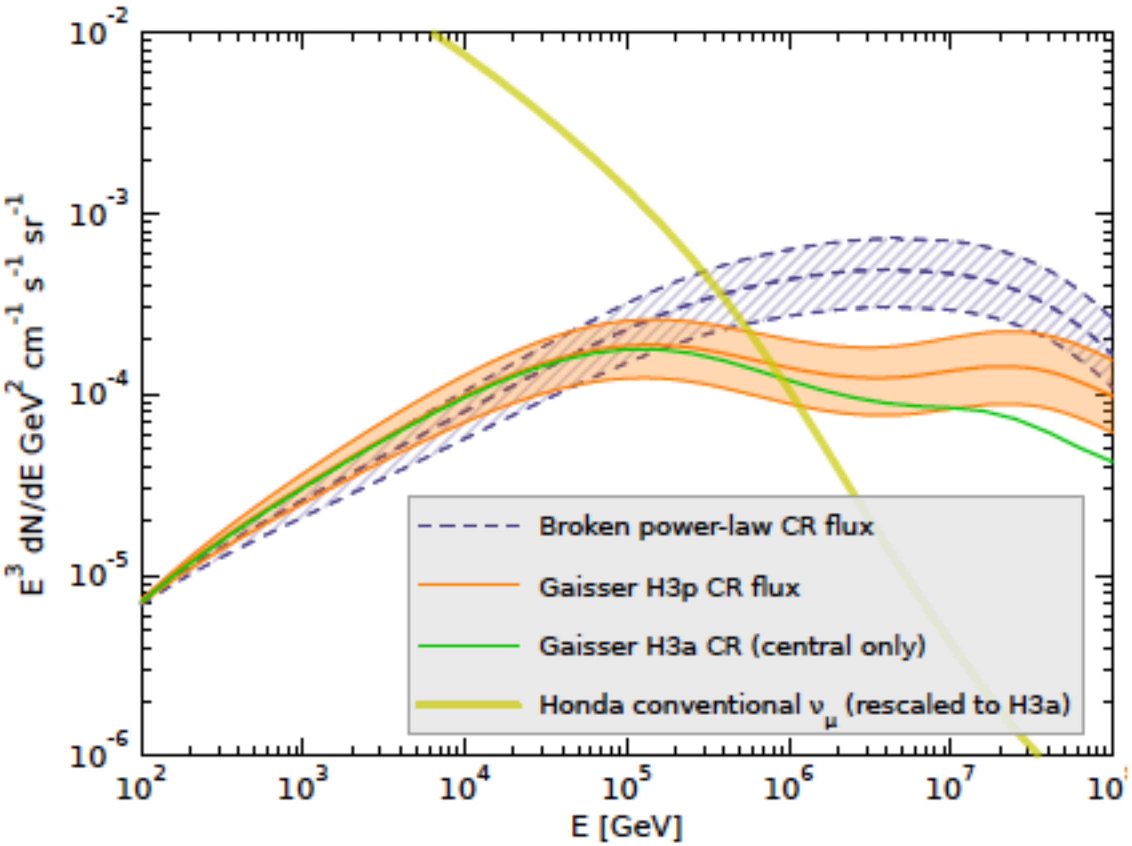
$$Z_{pp}^{ERS}(10^3\ \mathrm{GeV}) \simeq 0.5$$

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

Here:

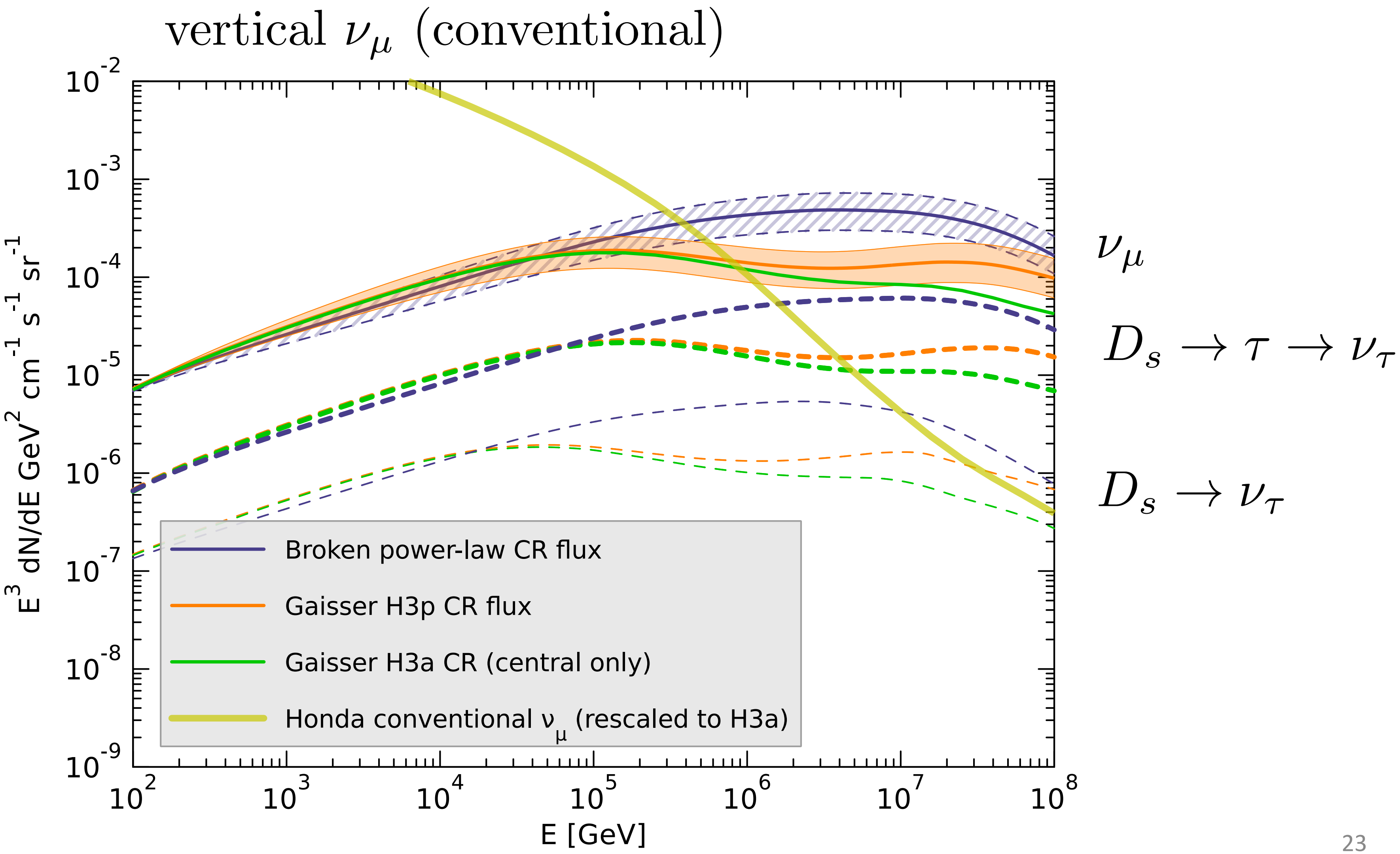
$$\frac{d\sigma}{dx_E} \sim (1-x_E)^{0.51}$$

Muon neutrinos plus antineutrinos: broken power law and H3 CR fluxes

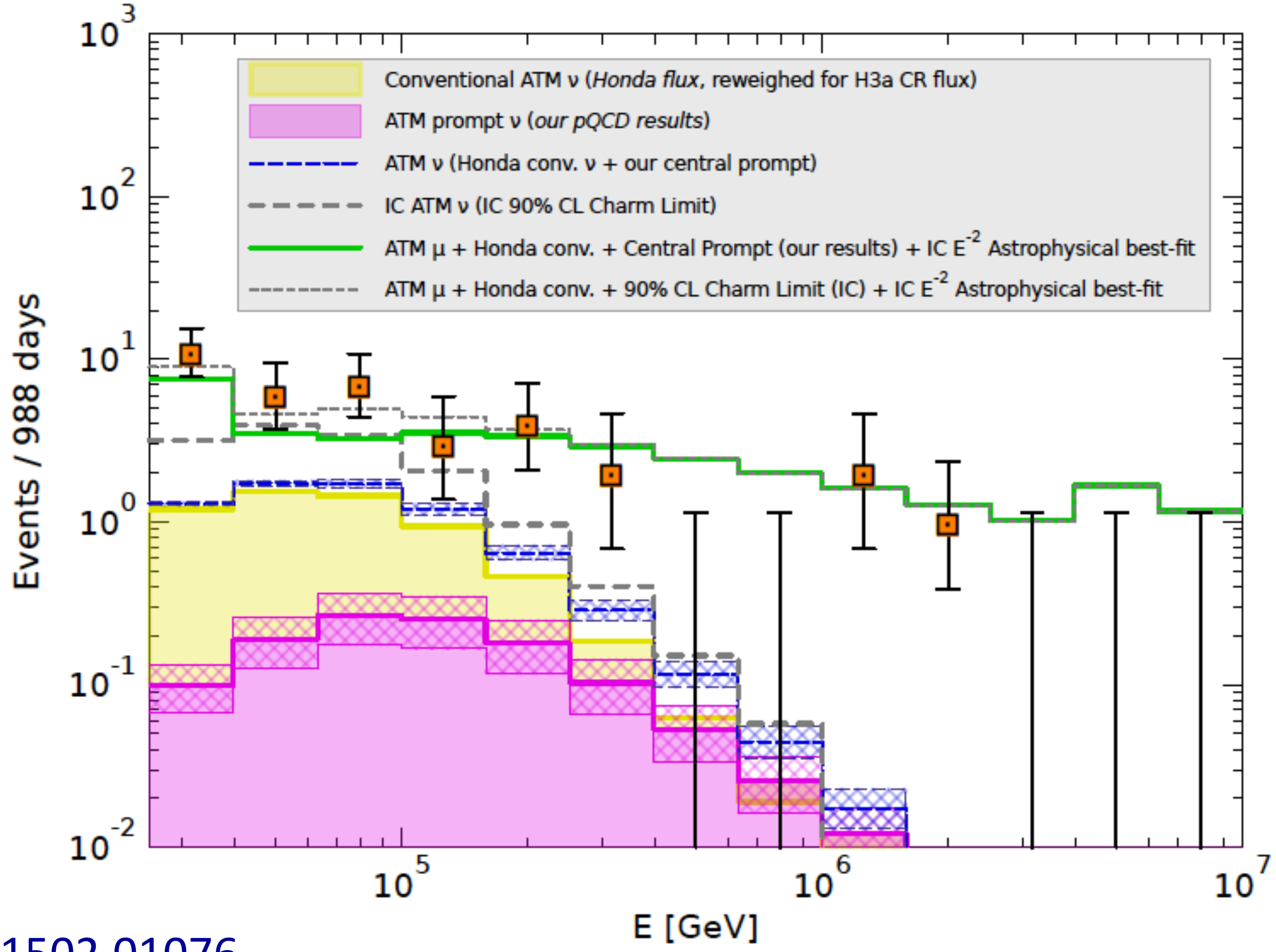


arXiv:1502.01076, Honda et al., PRD75 (2007)

Tau neutrinos plus antineutrinos



Event rates at IceCube with new prompt flux evaluation



arXiv:1502.01076

Conclusions & Future Work

- The cosmic ray spectrum and composition is crucial – corrections from broken power law to more realistic composition and spectrum mean a lower prompt flux.
- 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.
- The perturbative approach is not the only way to proceed. We are re-evaluating the prompt flux using the dipole model to get a better handle on the range of theoretical predictions.