Ultrahigh-Energy Neutrinos

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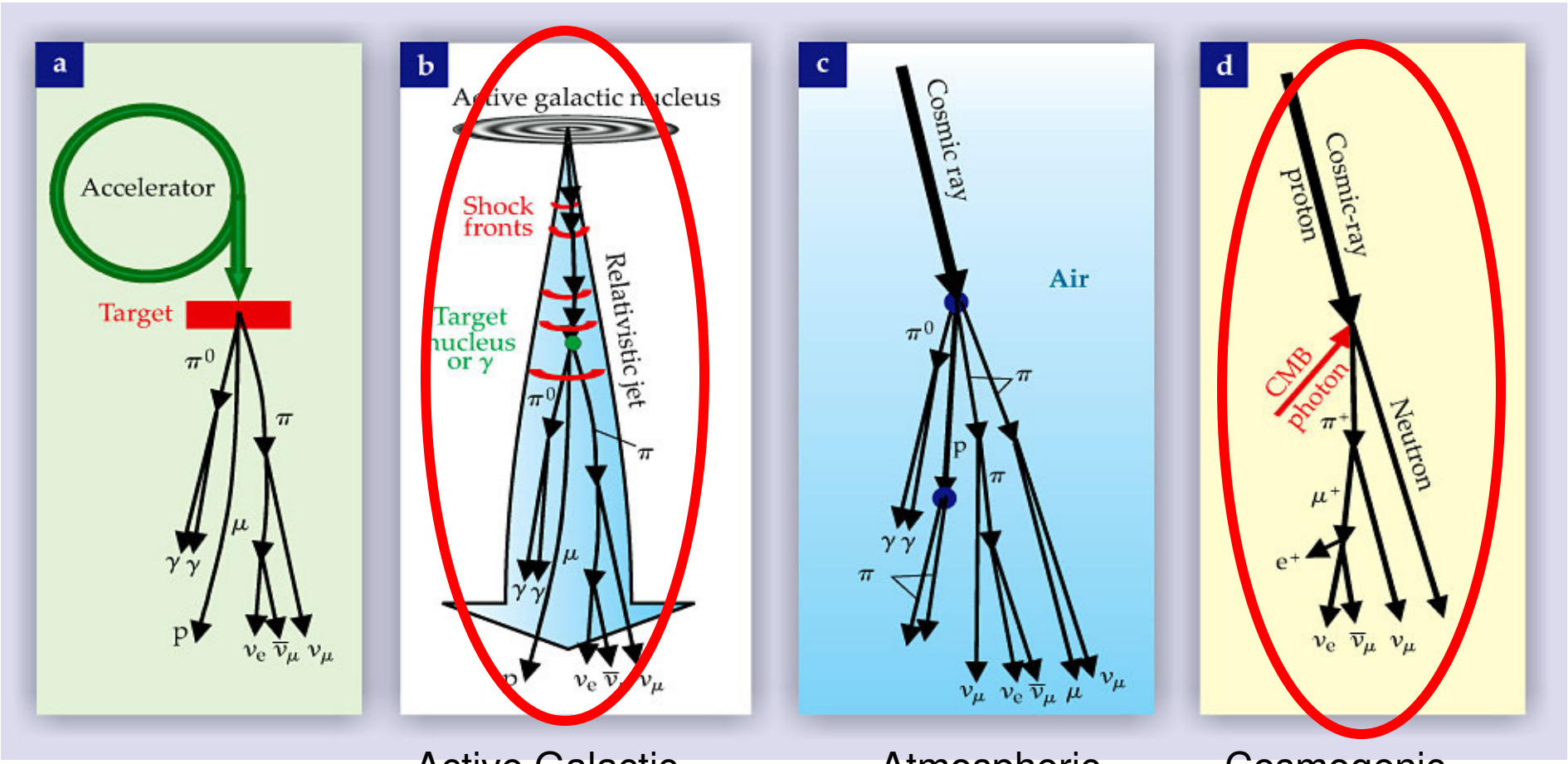
University of Iowa
December 15, 2009

What neutrinos?



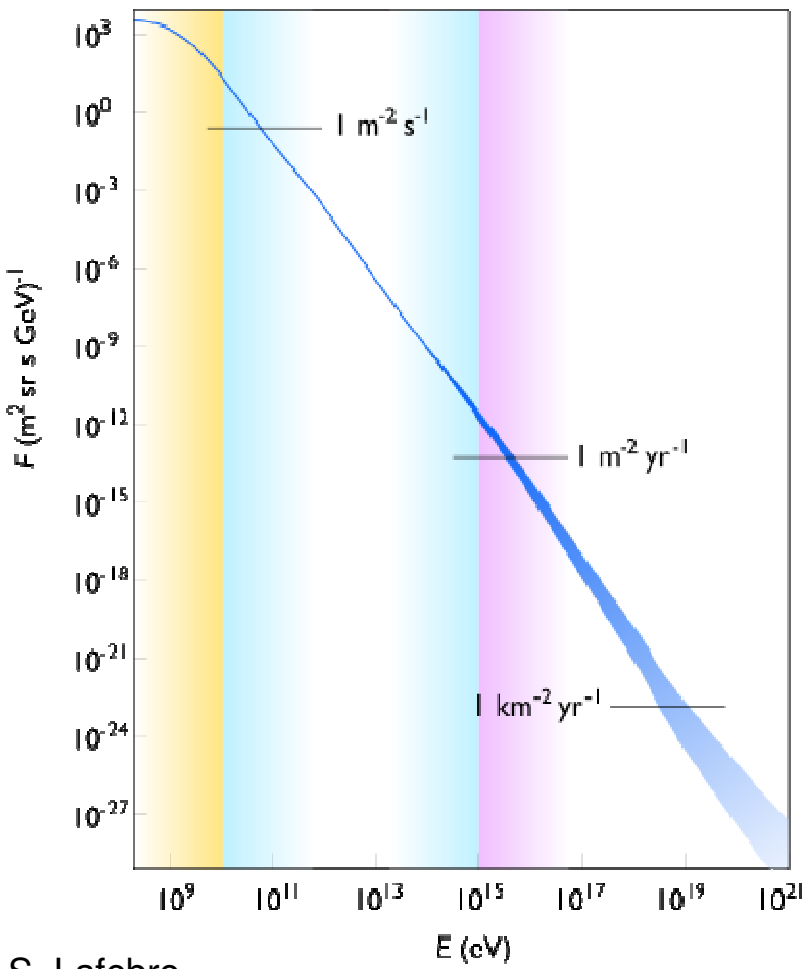
Active Galactic Nucleus or Gamma Ray Burst

Atmospheric neutrinos

Cosmogenic neutrinos, “GZK” neutrinos

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

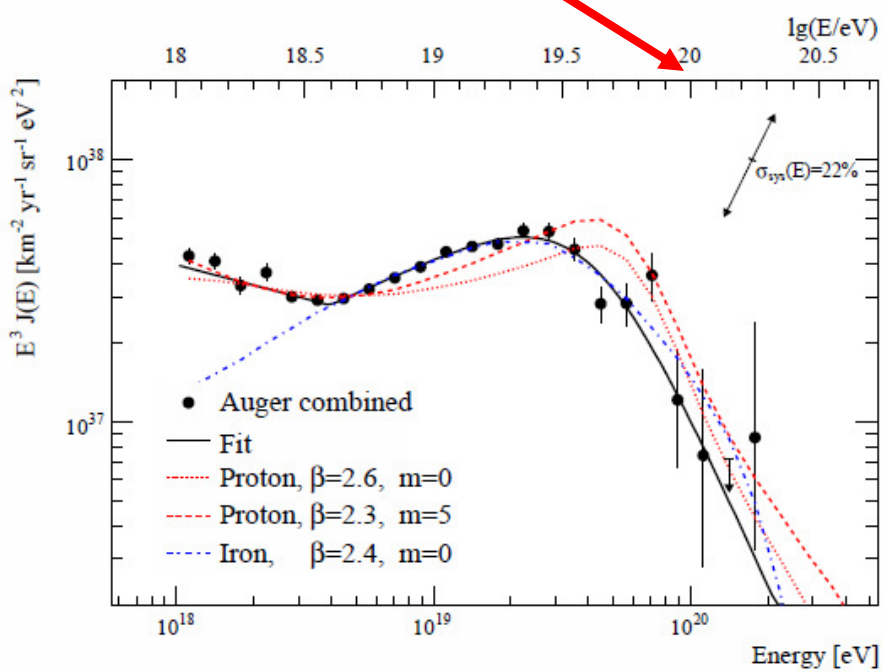
UHE cosmic rays



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

Cosmic ray measurements, show that highest energies are about 10^{12} GeV, which is why we are interested that high in energy.

$$10^{20}\ \mathrm{eV} = 10^{11}\ \mathrm{GeV}$$



m, cosmological evolution parameter

F. Schussler for Auger Collab., ICRC 2009

Neutrino messengers from astrophysical sources of cosmic rays and photons

rlv.zcache.com/

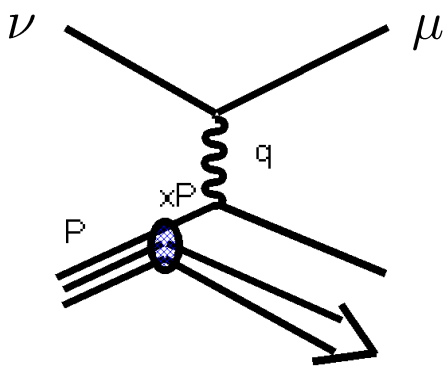
Unlike charged particles, neutrinos are not deviated by magnetic fields.

Unlike photons, neutrinos are not absorbed by the intervening medium.*

Ideally, we could observe sources via photons and neutrinos – “multimessengers”.

* Caveat: cosmic-neutrino absorption spectroscopy, Barenboim, Mena Requejo and Quigg (2005).

Ultra-high energy neutrino nucleon scattering cross section: essential ingredient



Medium energy, $\sigma \sim G_F^2 s \simeq 2.8 \cdot 10^{-39}\ \mathrm{cm}^2 \cdot s/\mathrm{GeV}^2$

High energy: $Q^2 \to M_W^2$ Given $xys = Q^2$

$x_{\min} \to M_W^2/s \quad (y = (E_\nu - E_\mu)/E_\nu \sim 0.2 - 0.5)$

$$\frac{d^2\sigma}{dx\,dy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[xq(x,Q) + x\bar{q}(x,Q)(1-y)^2\right]$$

W boson propagator

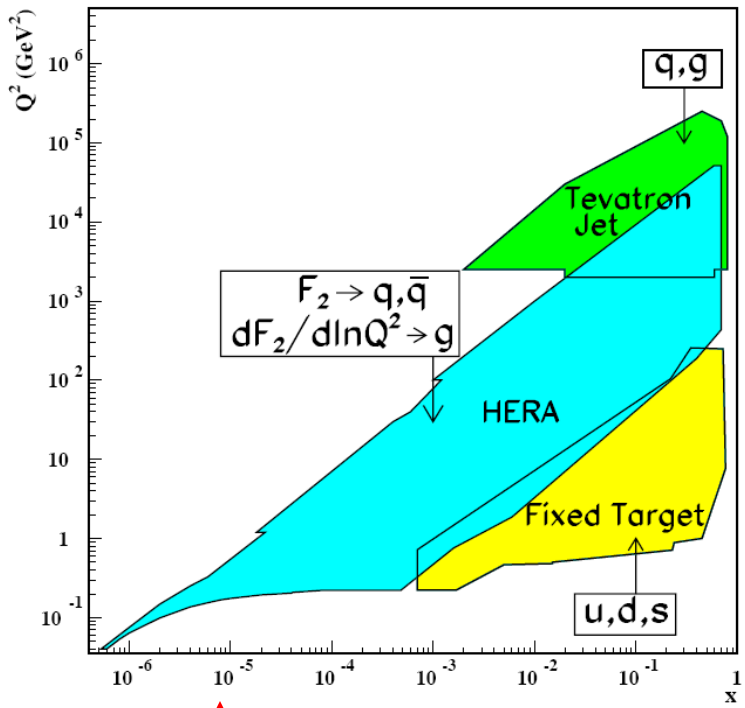
Quark (parton) distribution functions

High energies mean small parton x ….

$$E_\nu = 10^9\ \mathrm{GeV} \Longrightarrow x \sim 10^{-5}$$

LHC! Takes us up to $s \sim 10^9\ \mathrm{GeV}^2$

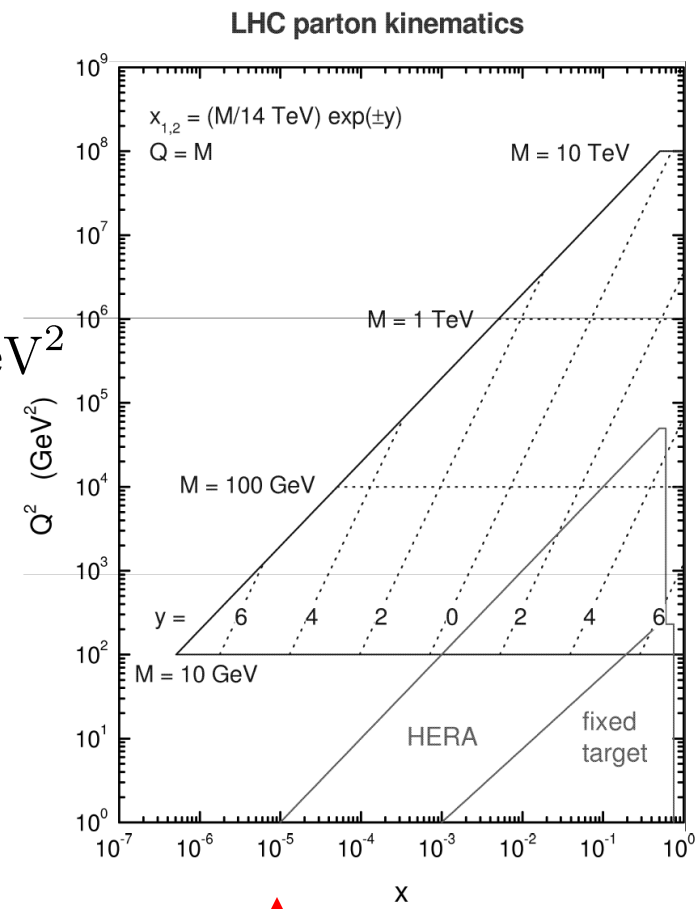
Q^2



$x = 10^{-5}$

$10^4\ \mathrm{GeV}^2$

Q^2

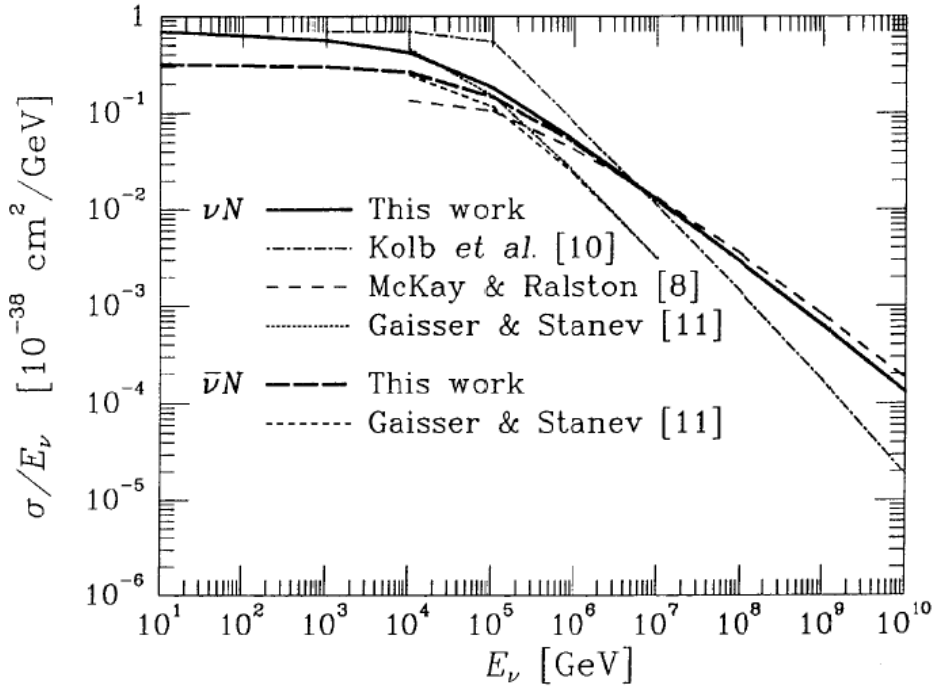


$x = 10^{-5}$

pdg.lbl.gov,

http://projects.hepforge.org/mstwpdf/plots/plots.html

Cross sections at UHE, then…



Quigg, Reno, Walker (1986); McKay & Ralston (1986)

Q evolution of PDF enhances cross section, Andreev, Berezinsky & Smirnov, PLB (1979)

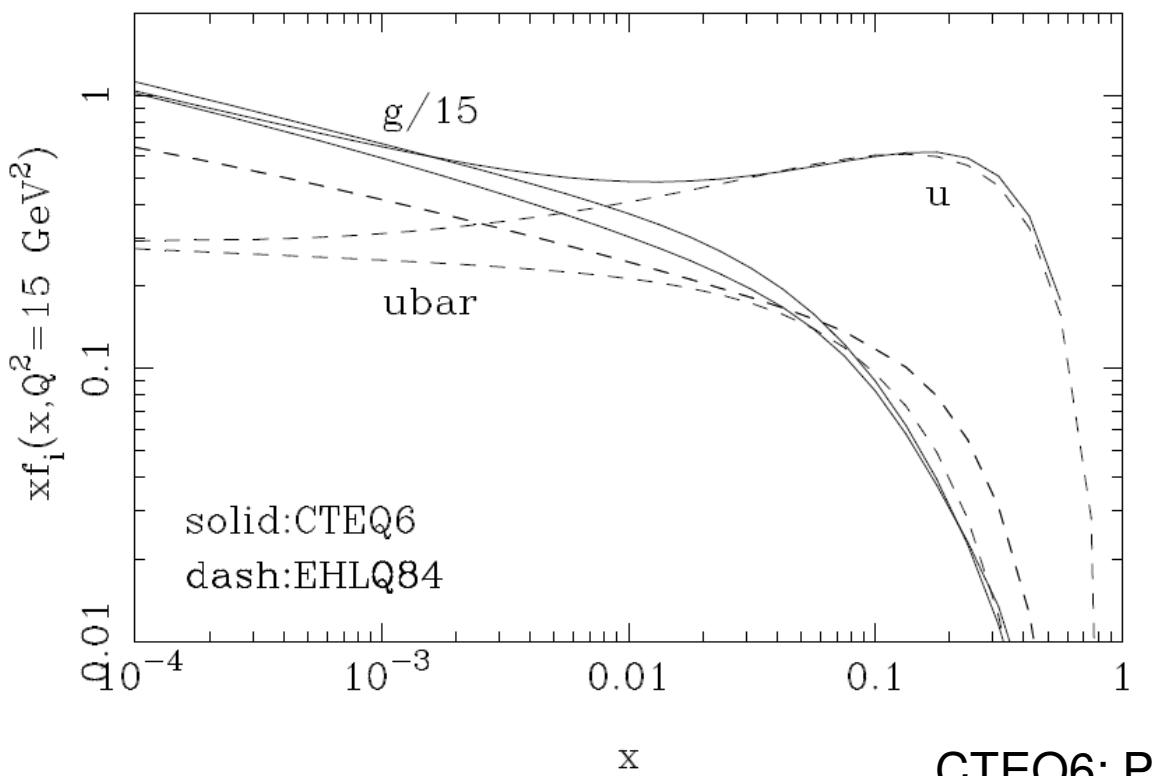
"This work" used the Eichten, Hinchliffe, Lane and Quigg PDFs, EHLQ (1984,1986).

Application to DUMAND, acoustic version, with

$$100\ \mathrm{km}^3$$

(Quigg & Reno, 1987)

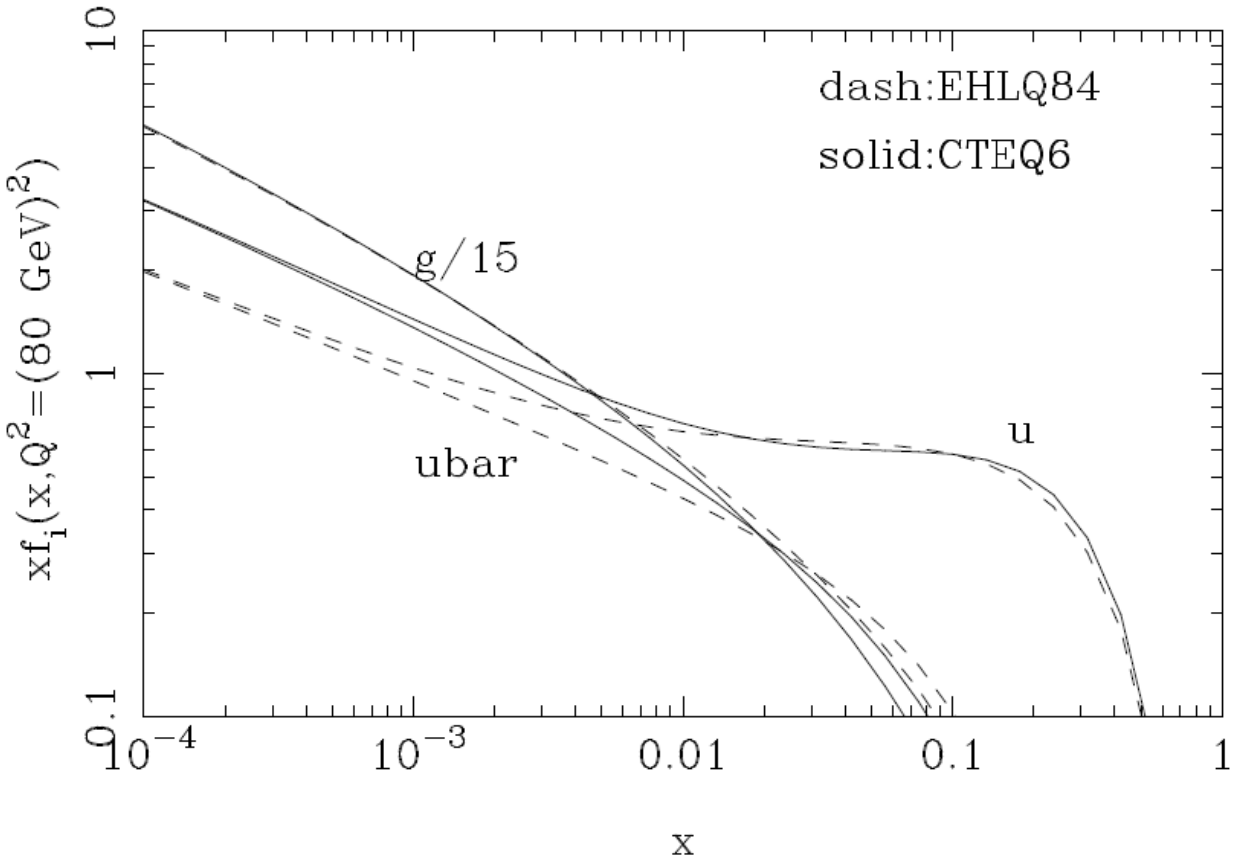
“… many experiments have nourished the steady improvement of the parton distributions …”, GQRS 1996



CTEQ6: Pumplin et al. (2002)

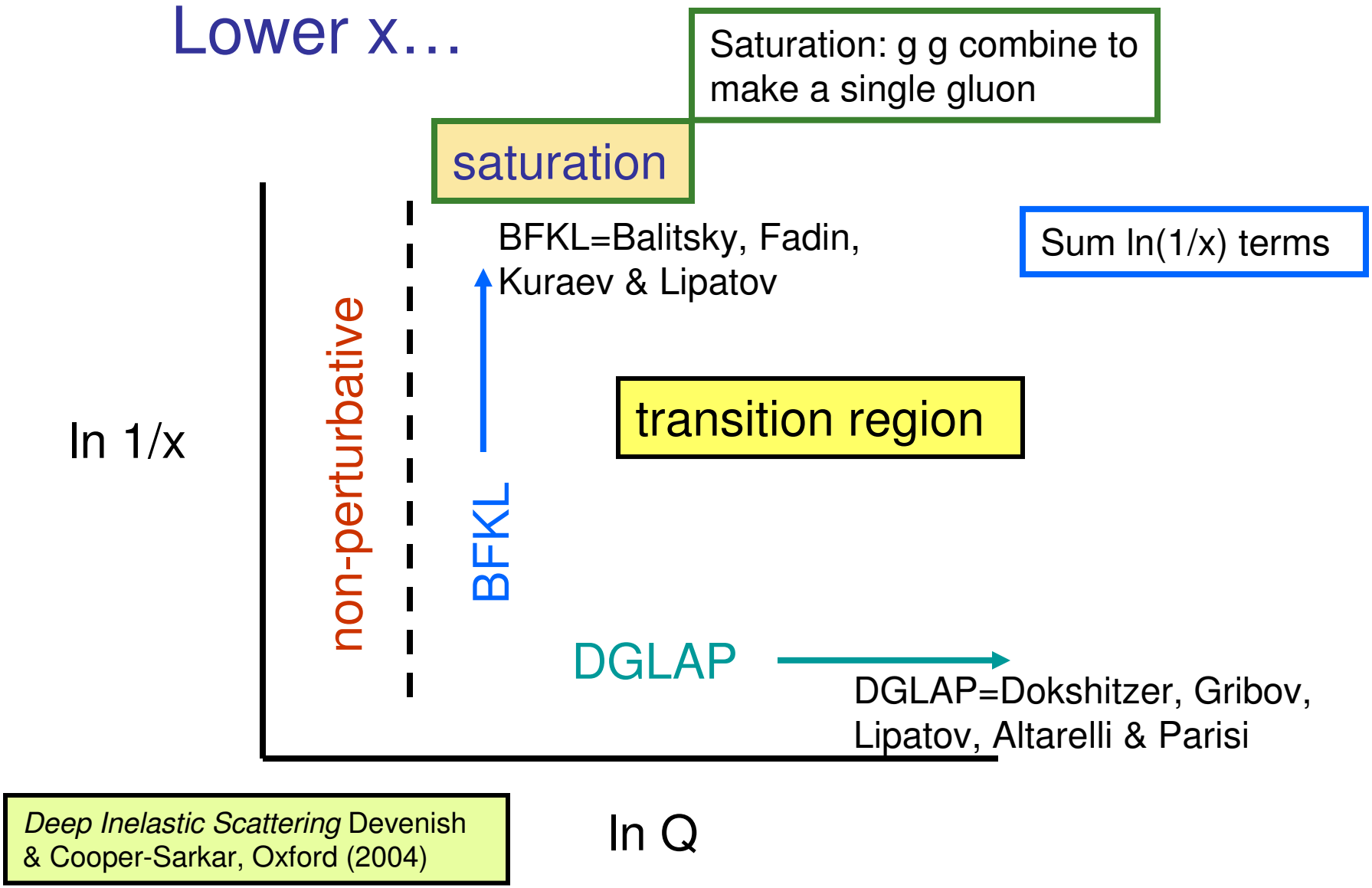
$$Q^2 = 15\ \mathrm{GeV}^2$$

Impact of “low” x extrapolation at higher Q



$$Q^2 = (80\ \mathrm{GeV})^2$$

Lower x…

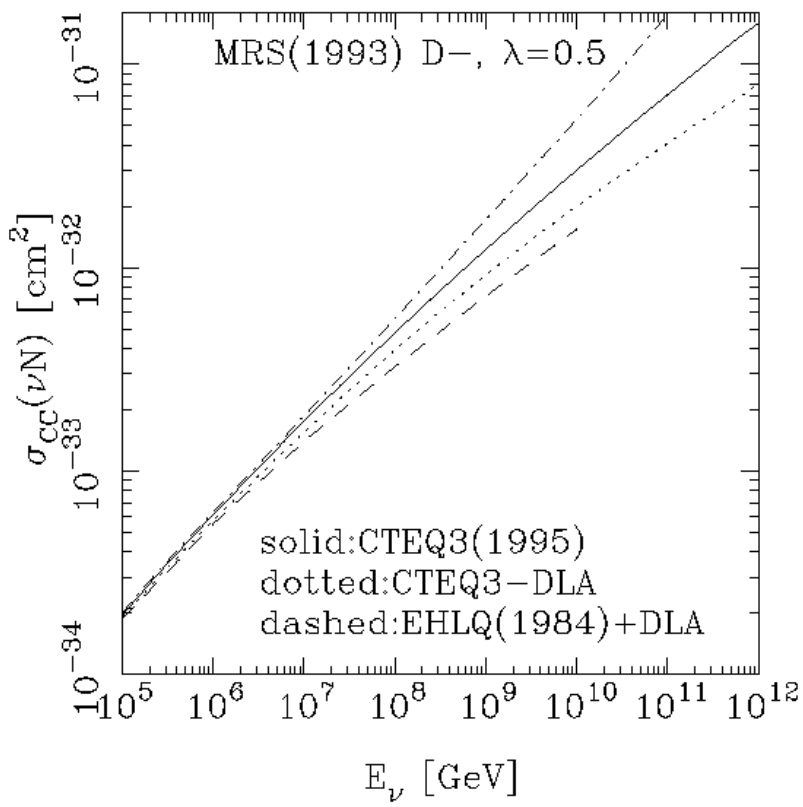


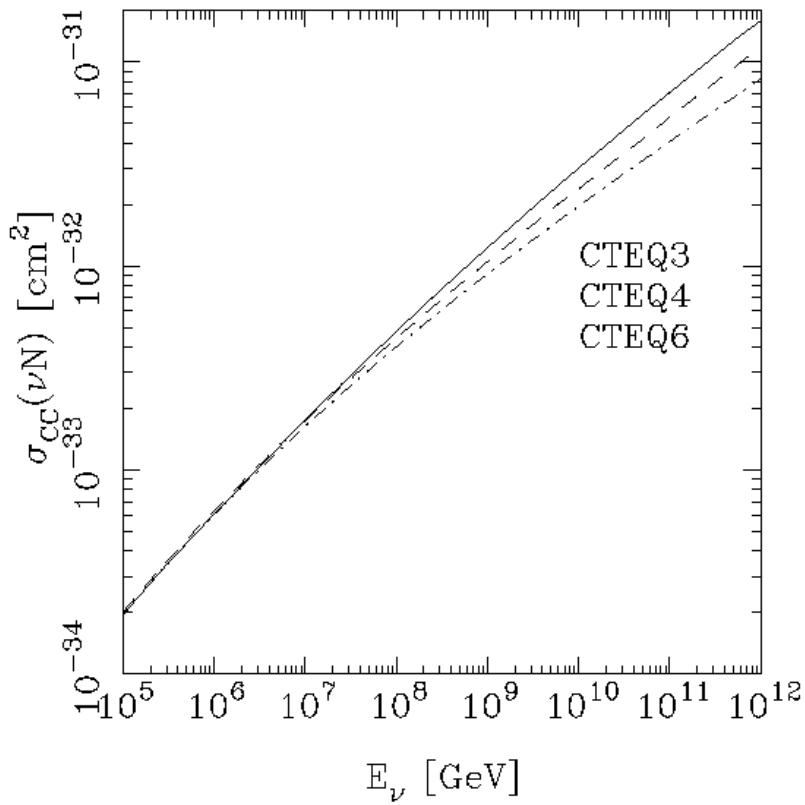
Deep Inelastic Scattering Devenish & Cooper-Sarkar, Oxford (2004)

DLA: double logarithmic approximation, Gribov, Levin, Ryskin, Phys. Rept. (1983)

Power law extrapolation: e.g., Ellis, Kunszt & Levin, NPB (1994) $xf(x,Q) \sim x^{-\lambda}$

Cross sections at UHE, not so long ago … DLA or power law extrapolations



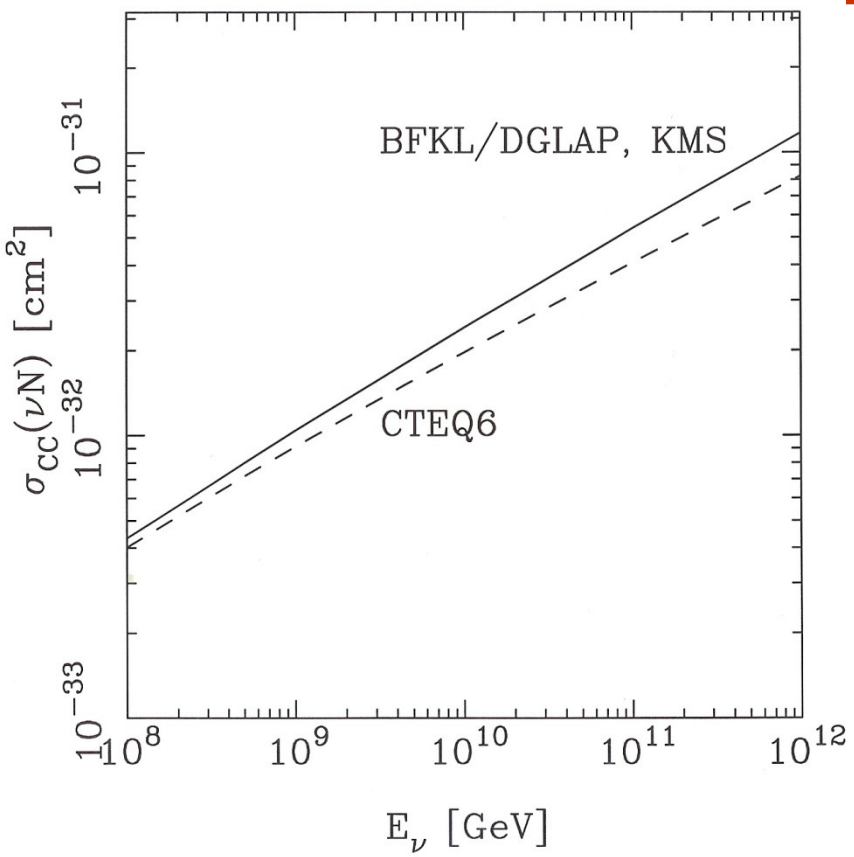


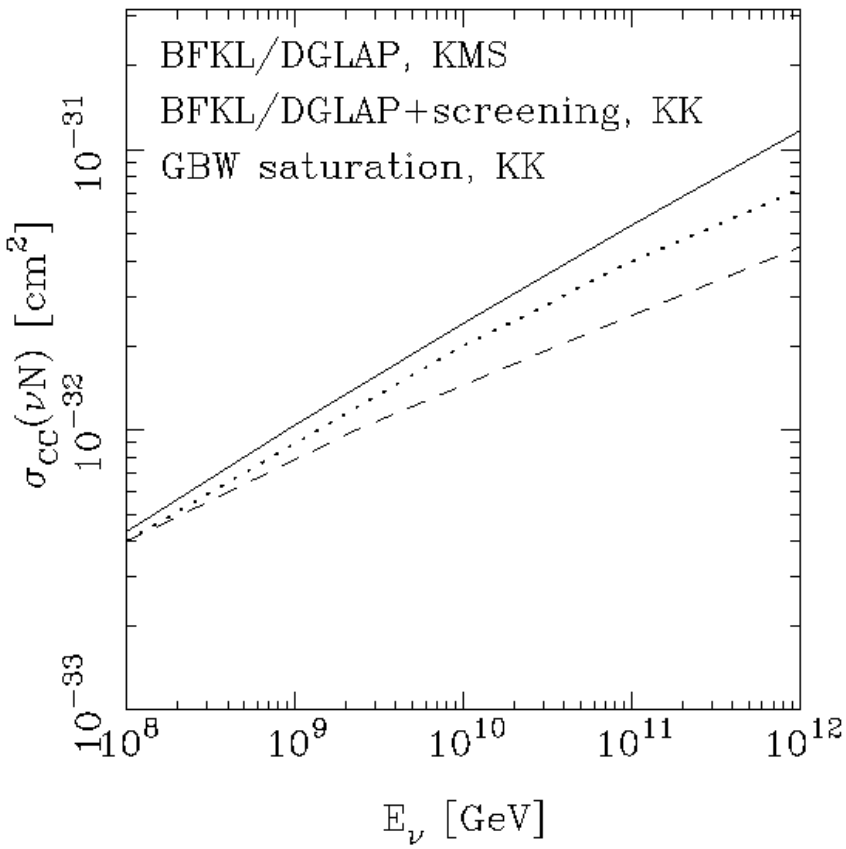
Gandhi, Quigg, Reno & Sarcevic (1996)

BFKL/DGLAP vs DGLAP

Kwiecinski, Martin & Stasto, PRD 59 (1999)093002

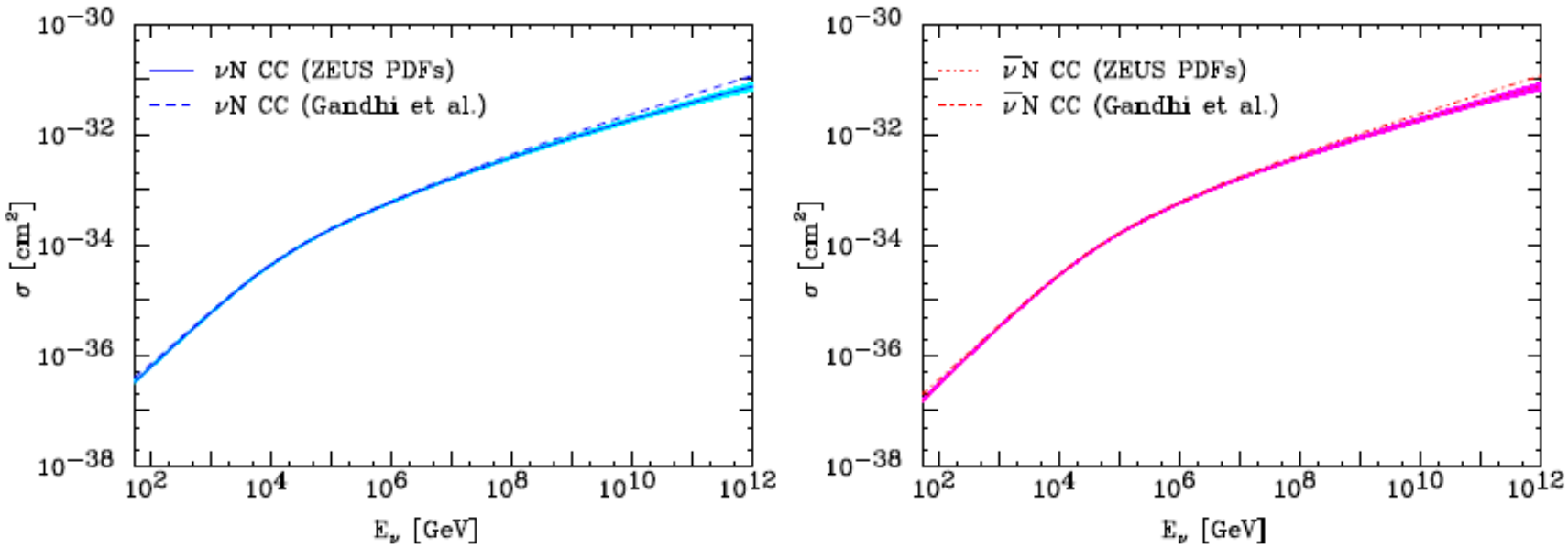
KK: Kutak & Kwiecinski, EPJ (2003) Golec-Biernat & Wusthoff model (1999), color dipole interactions for screening.





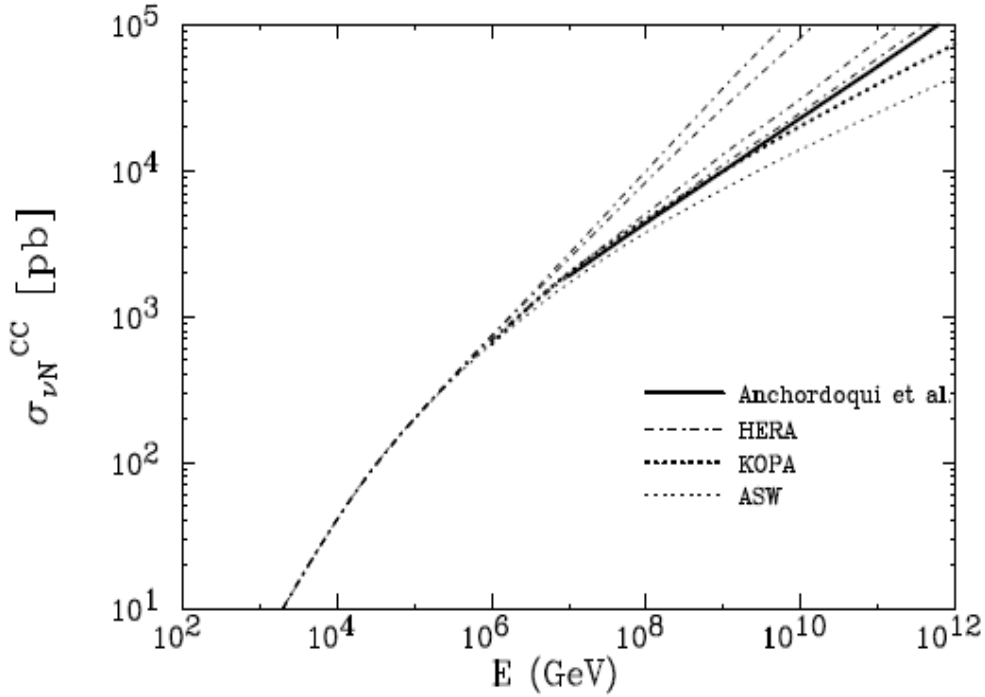
BFKL evolution matched to DGLAP accounting for some subleading ln(1/x), running coupling constant,matched to GRV parton distribution functions

More recent results



Cooper-Sarkar & Sarkar, JHEP 0801 (2008), new analysis of HERA data incl. heavy flavor, lower cross section at UHE (closer to CTEQ6 results, which also have a better extraction of heavy flavor.

Other recent results



HERA: extrapolations with lambda=0.5,0.4,0.38

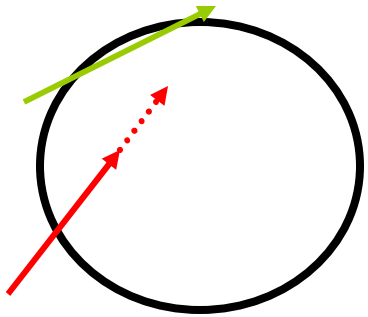
KOPA: DLA, Kotikov & Parente

ASW: saturation effects, Armesto, Salgado & Wiedeman

Fig. from Armesto, Merino, Parente & Zas, Phys. Rev. D 77 (2008)

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, Phys. Rev. D 74 (2006)

Sensitivity to the neutrino nucleon cross section



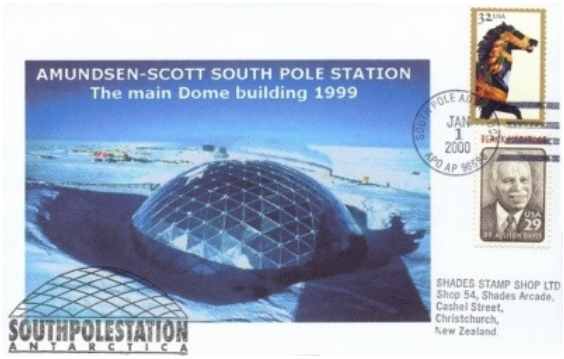
- upward going skimming tau neutrinos (with attenuation) versus horizontal air showers

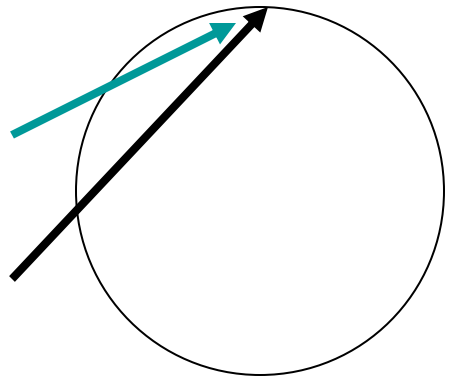
E.g., Palomarez-Ruiz, Irimia, Weiler, PRD 73 (2006), Kusenko, Weiler, PRL 88 (2002), Anchordoqui, Han, Hooper, Sarkar, Astropart. Phys. 25 (2006)

- ANITA: ice sheet (nearly horizontal) versus ice shelf (downward with reflection) may distinguish extreme enhancements.

Barwick, Wu, ICRC 07 Proceedings

Angle-integrated upward rate



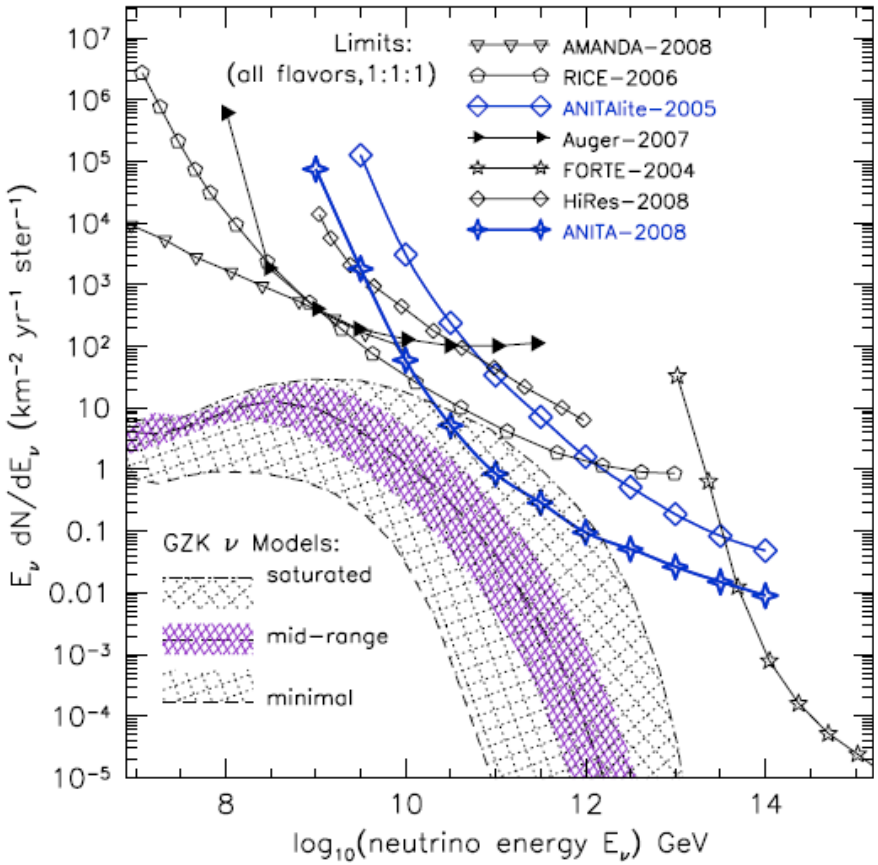


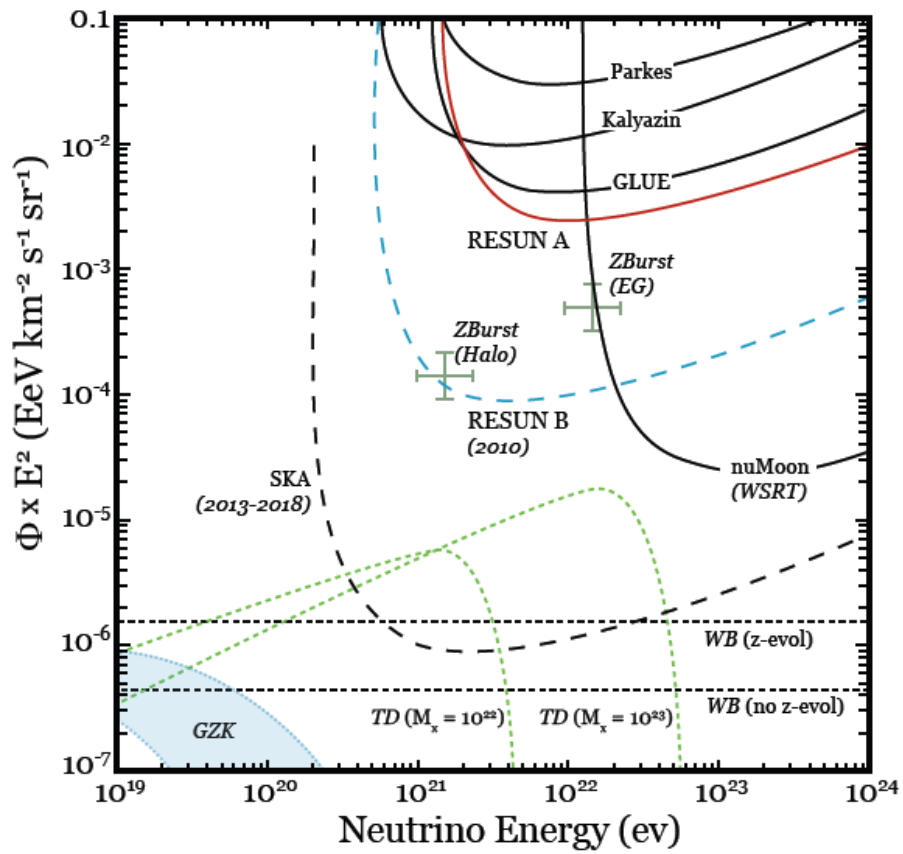
Hussain, Marfatia, McKay, PRD 77 (2008), see also
Hussain, Marfatia, McKay & Seckel, PRL 97 (2006)

- for a factor of 10 range in the cross section around the standard model cross section, the upward cosmogenic event rate varies by less than 50%, as long as total and charged current rates scale proportionately (as would be the case for standard model uncertainities).

http://www.newzeal.com/theme/bases/SP/SouthPoleJan12000pcc.jpg

Observations at UHE? Sample limits….

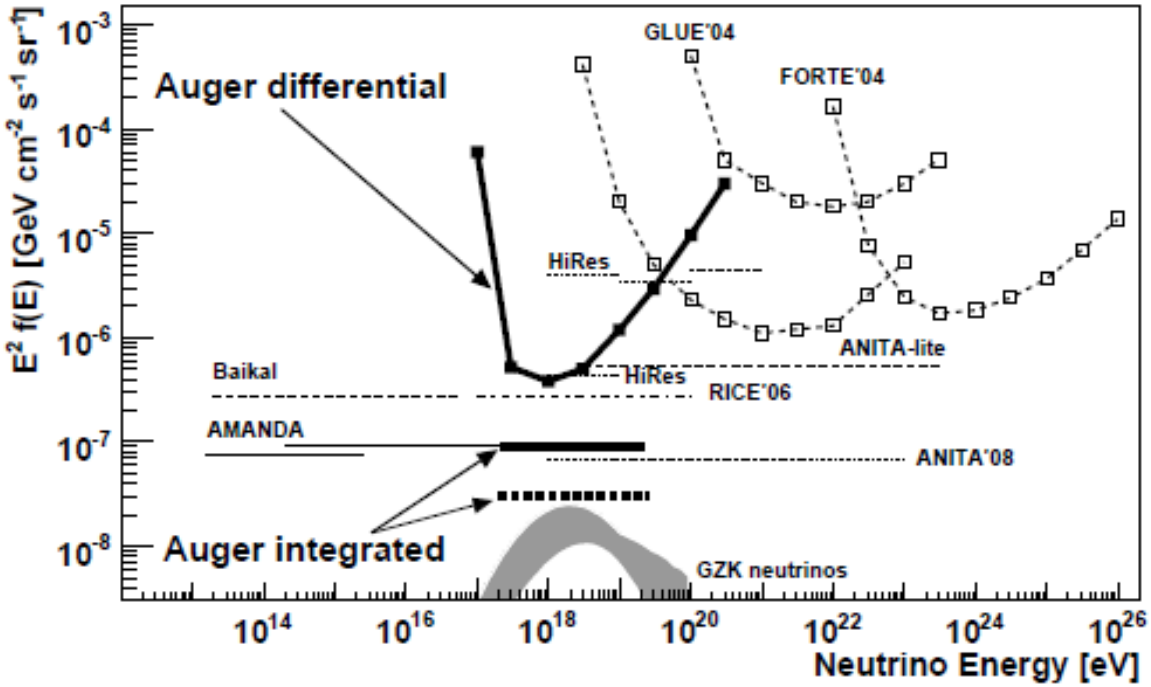




ANITA, PRL (2009), radio Cherenkov in ice.

Jaeger, Mutel, Gayley, arXiv:0910:5949, radio Cherenkov in lunar regolith.

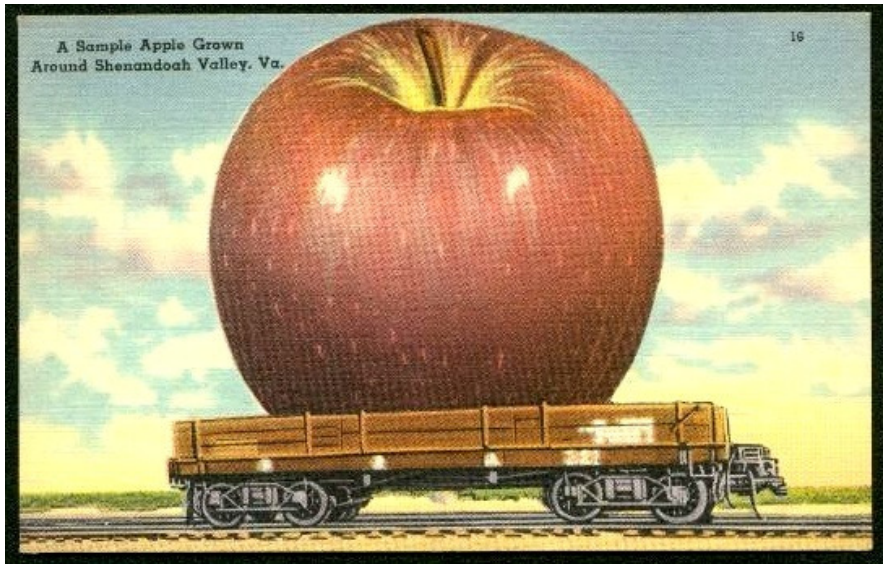
Limits on tau neutrino flux



Auger Collaboration, arXiv:0903.3385

http://www.aspera-eu.org/images/stories/news/january09/auger_mail.jpg

Neutrinos we do observe…



Apple variety neutrinos: atmospheric! Another opportunity to look at small-x physics.

http://www.ferrum.edu/news/2003spring/postcards/postcard--giant%20apple%202.jpg

Atmospheric neutrinos at high energies

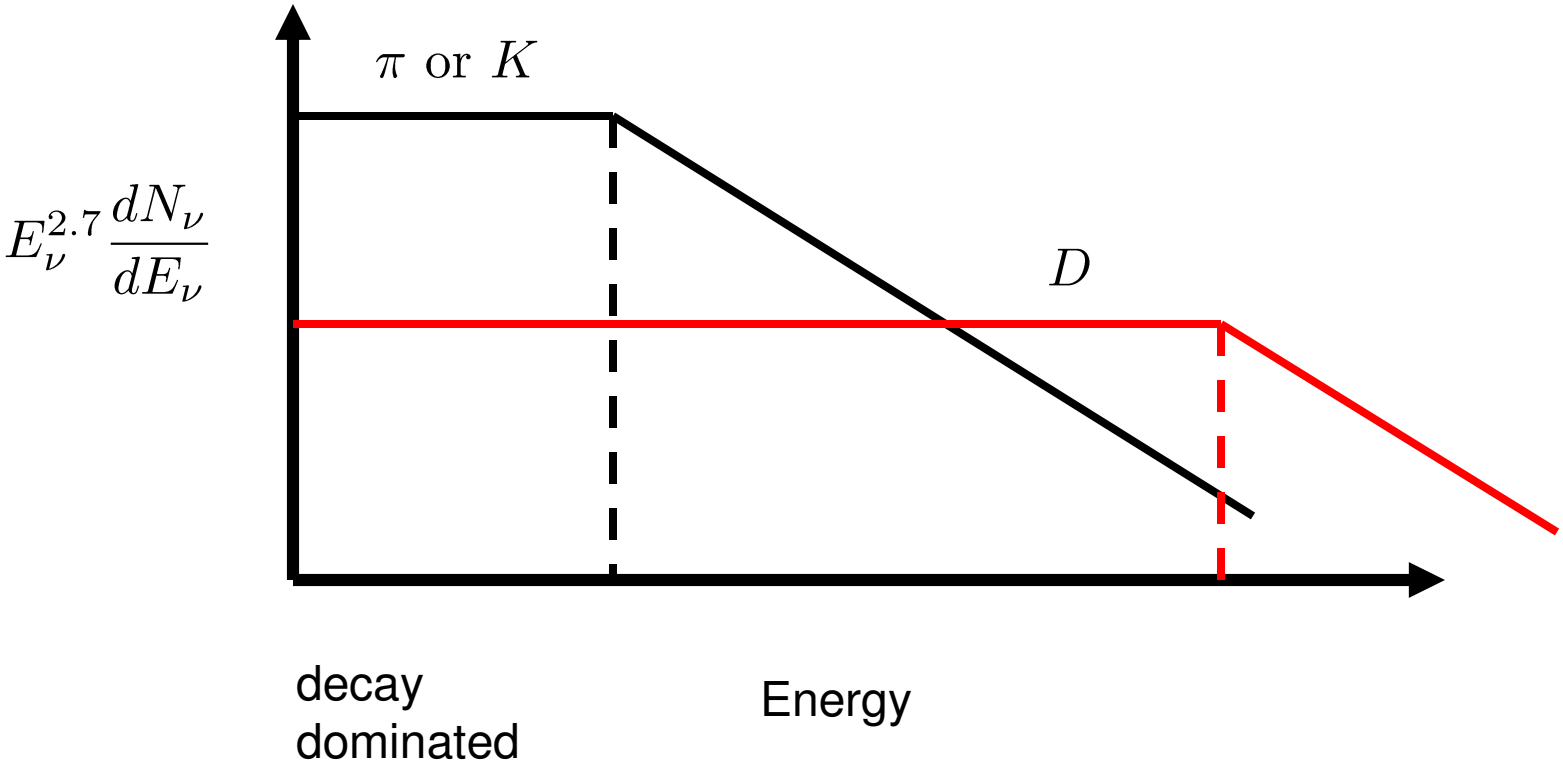
- Incident flux of cosmic rays, $\phi \sim E^{-2.7}$
- Relevant times for mesons are decay, interaction time, and time to hit the ground
- Low energy: mesons decay $\phi_\nu \sim E_\nu^{-2.7}$
- High energy: decays are rare $\phi_\nu \sim E_\nu^{-3.7}$

Pion and kaon contributions: “conventional”

Charm contributions “prompt” (lots of uncertainties here due to treatment of small x)

REFS: 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); Thunman, Ingelman and Gondolo, Astropart. Phys. 5 (1996) (TIG label below)

Schematic energy dependence



Small x PDFs again for charm

PDF = parton distribution function

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

$$\begin{aligned} x_1,\ x_2 : & \qquad \text{momentum fractions} \\ x_F &= x_1 - x_2 = \text{Feynman} - x \\ x_F &\simeq x_E = E/E' \end{aligned}$$

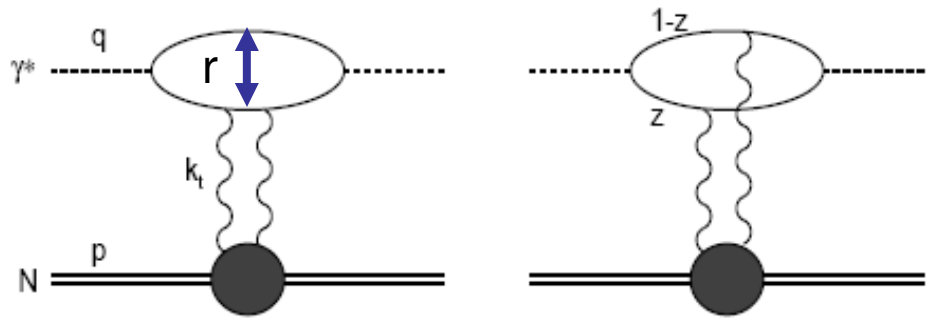
$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}^2}{s}} \pm x_F\right) \qquad x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1$$

Disadvantage: need gluon PDF in low x, not very big Q range, in fact, for Q much lower than the W mass.

Dipole approach-start with DIS

Advantage: don't need small x gluon PDF

$$W^2 = Q^2\left(\frac{1}{x} - 1\right) + M^2$$



$$\begin{aligned} \gamma^* &\rightarrow q\bar{q} \\ q\bar{q}\,N &\rightarrow X \end{aligned}$$

heavy quarks:

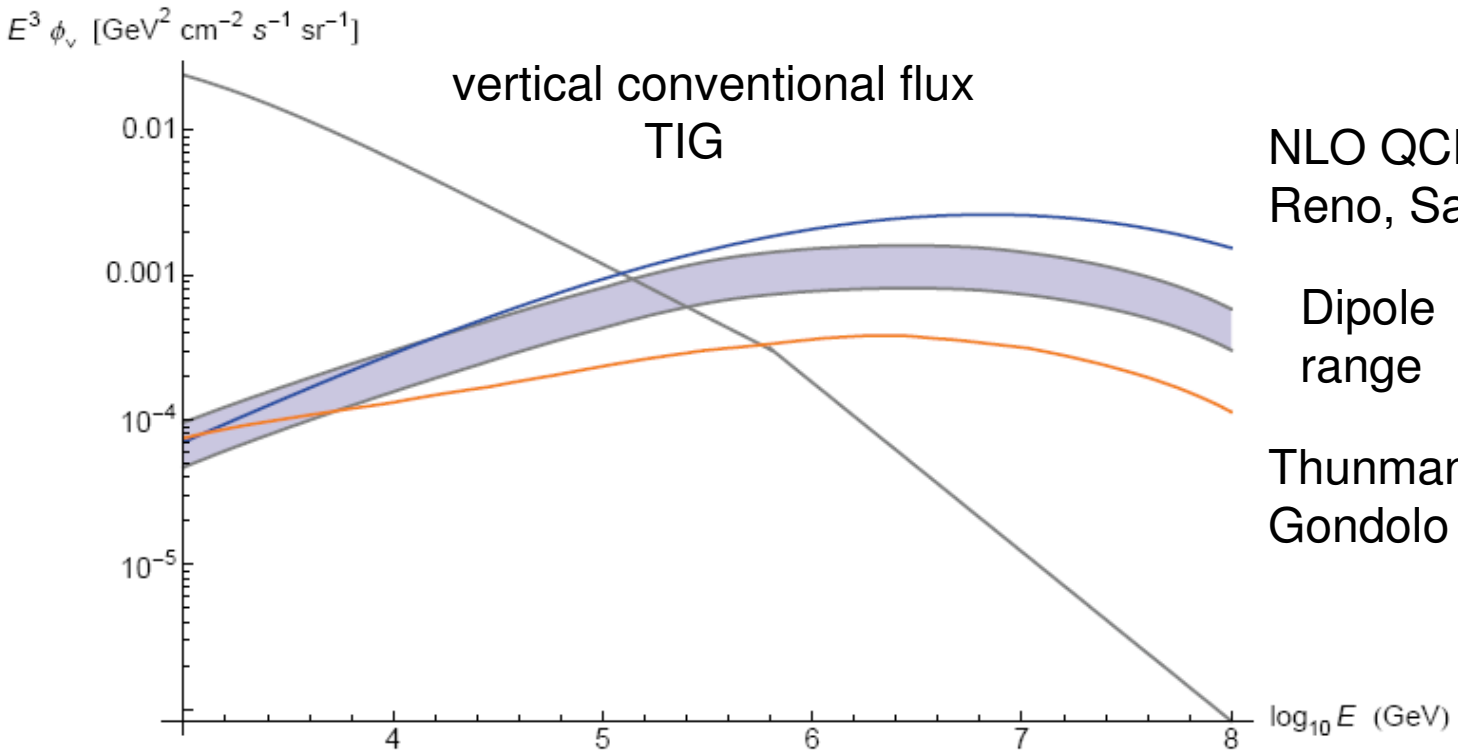
$$\begin{aligned} \gamma^* &\rightarrow c\bar{c} \\ c\bar{c}\,N &\rightarrow c\bar{c}X' \end{aligned}$$

gluon initiated: $G \rightarrow c\bar{c}$

Soyez, Phys. Lett. B 655 (2007) fit to the IMM approximate solution, (Iancu, Itakura, Munier PLB 590 (2004))

Nikolaev, Piller and Zakharov, ZPA 354 (1996) for charm pairs in proton-proton collisions.

Comparison



NLO QCD:Pasquali, Reno, Sarcevic (1999)

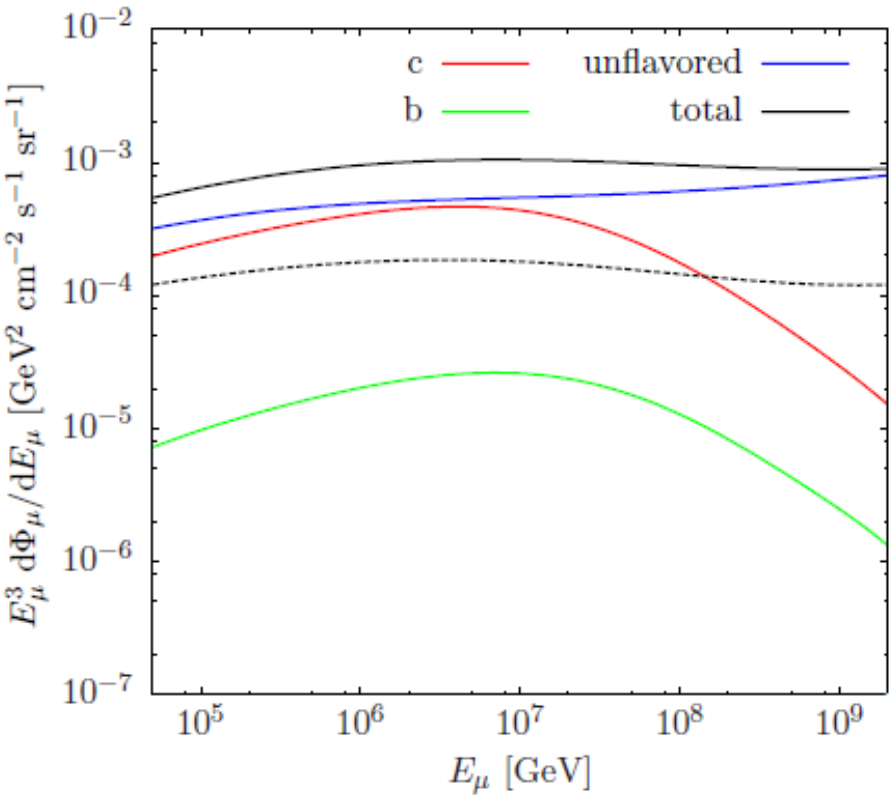
Dipole range

Thunman, Ingelman, Gondolo (1996): Pythia

Enberg, Reno, Sarcevic, PRD (2008)

Would like to see measurements of the prompt flux of neutrinos and muons.

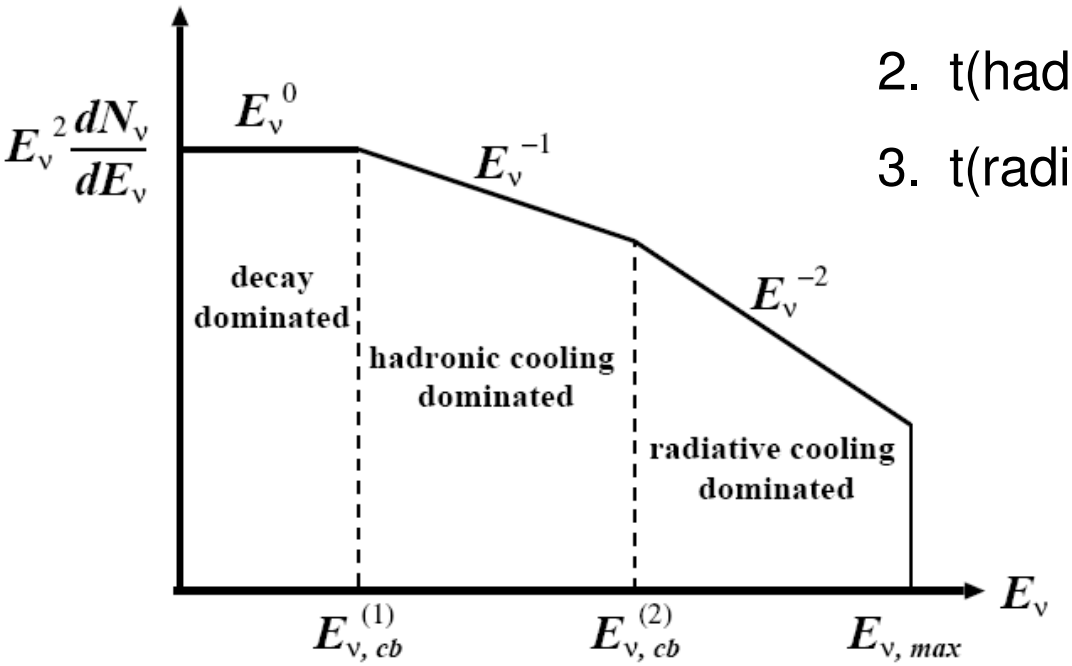
Other mesons at HE for atmospheric flux?



η mesons with prompt electromagnetic decays, here denoted as "unflavored"

Illana, Masip & Maltoni, JCAP (2009)

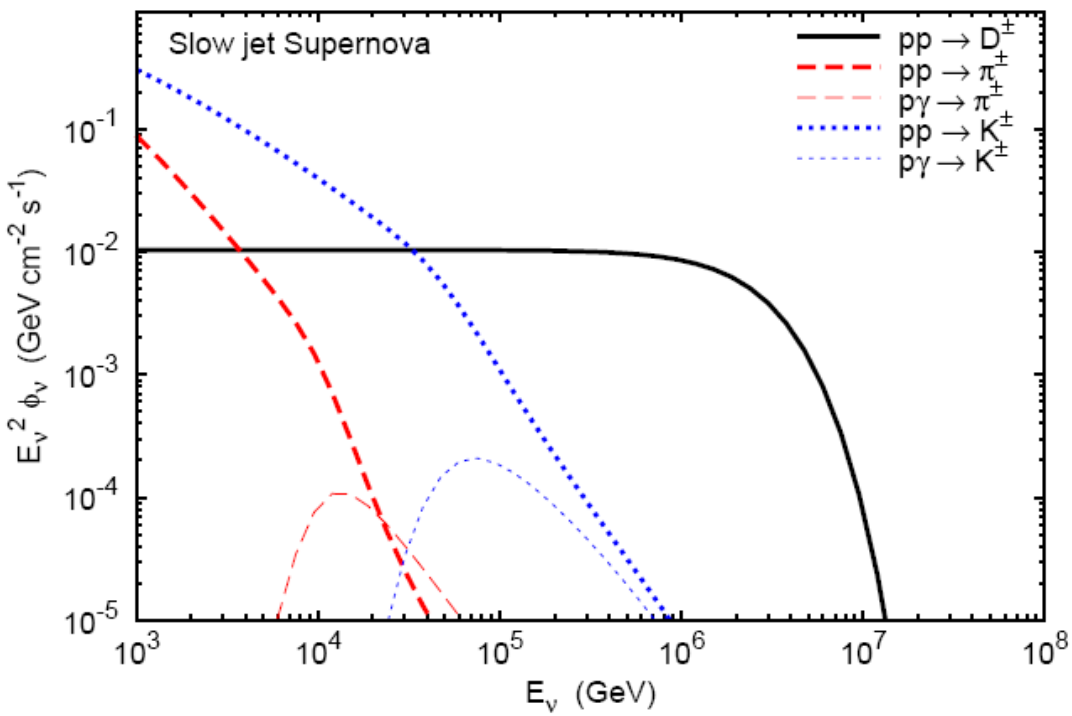
Sources – neutrino energy dependence for pp interactions



1. Mesons decay right away
2. t(hadronic)/t(decay) ~ 1/*E*
3. t(radiative)/t(decay) ~ $1/E^2$

Schematic energy dependence, Fig. from Ando & Beacom, PRL (2005)

Astrophysical sources: slow jet supernova example



Depends on magnetic field, luminosity, bulk lorentz factor…

Normalized to a source at 20 Mpc with jet luminosity of log10(L)=50.5.

We have used a Z-moment method, smoother transitions between energy regimes.

SJS model from Razzaque, Meszaros, Waxman, Mod Phys Lett A (2005)
Enberg, Reno and Sarcevic, PRD 79 (2009)

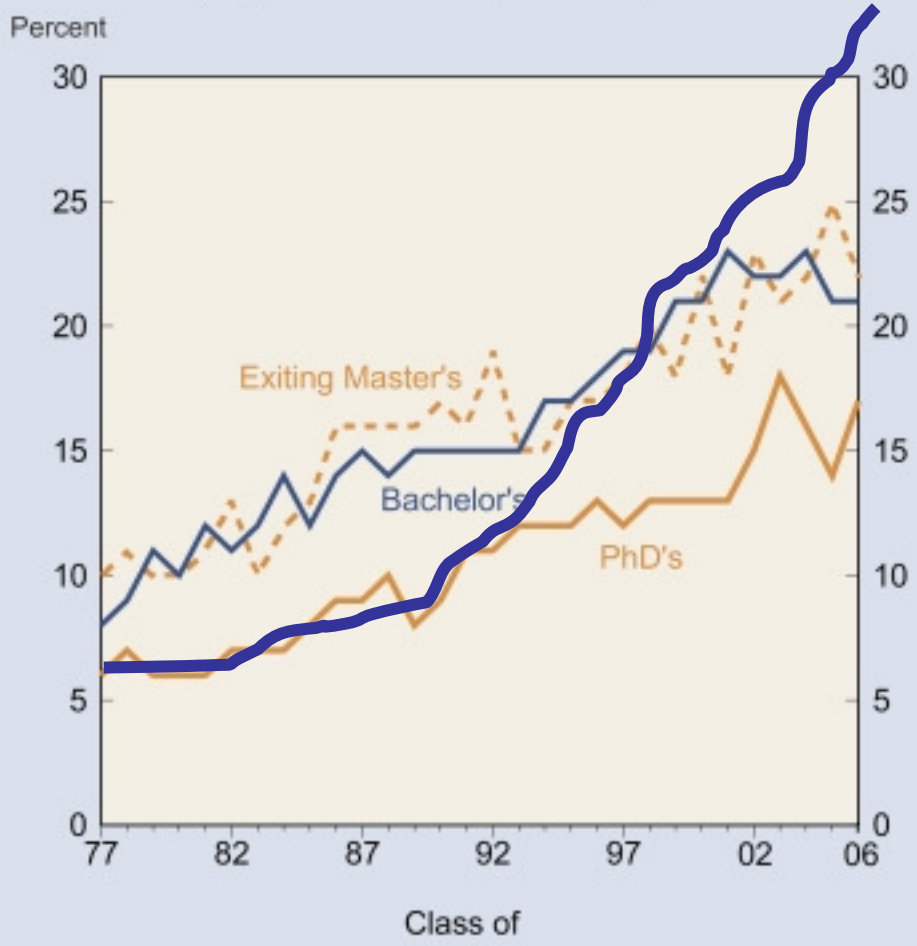
- LHC will help pin down some of the uncertainties in the HE neutrino cross section (but not all the way to UHE).
- Astrophysical neutrinos, in principle produced by cosmic rays in the sources of cosmic rays – important continuing goal of neutrino telescopes to observe these neutrinos.
- Atmospheric neutrinos interesting in their own right – push to higher energies.

http://www.particlezoo.net/shop.html

Final remarks, another extrapolation

Chris Quigg series, leads to…

Figure 18. Percent of bachelor's, master's and doctorates in physics earned by women, 1977-2006.



Note: A form change occured in 1994 resulting in a more accurate representation of women among physics bachelors. Some of the increase in 1994 only, may be a result of that change.

AIP Statistical Research Center, Enrollments and Degrees Report.