ISVHECRI 2014

Low x Parton Densities and High Energy Neutrino Cross Section

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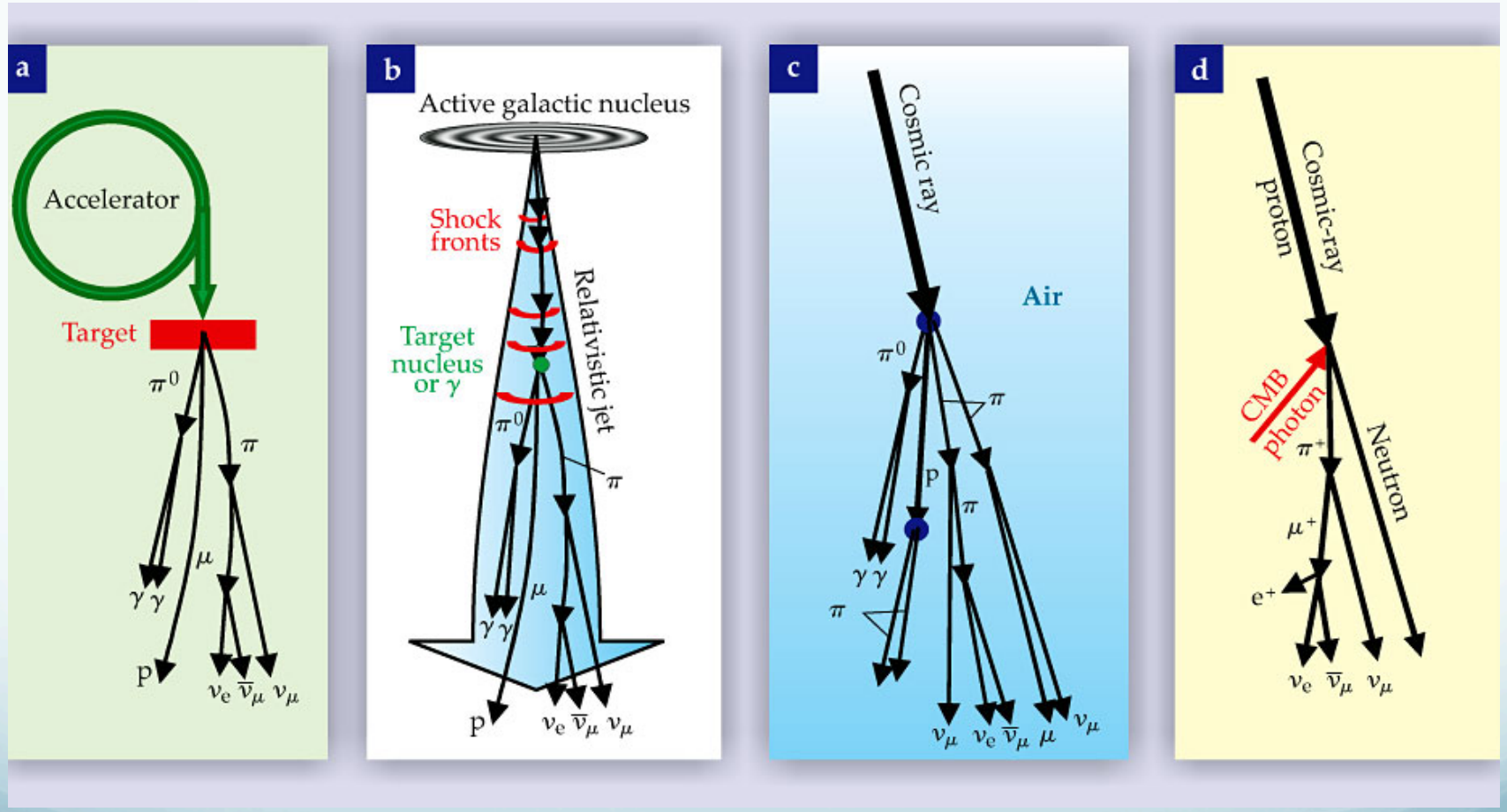
Origin of High Energy Neutrinos: Cosmic Accelerators

- Particles (electrons, protons, etc) are accelerated to high energies via Fermi shock acceleration
- High energy protons collide with ambient protons and photons
- Hadronic production of pions, kaons and D-mesons which decay into neutrinos

Cosmic Accelerators

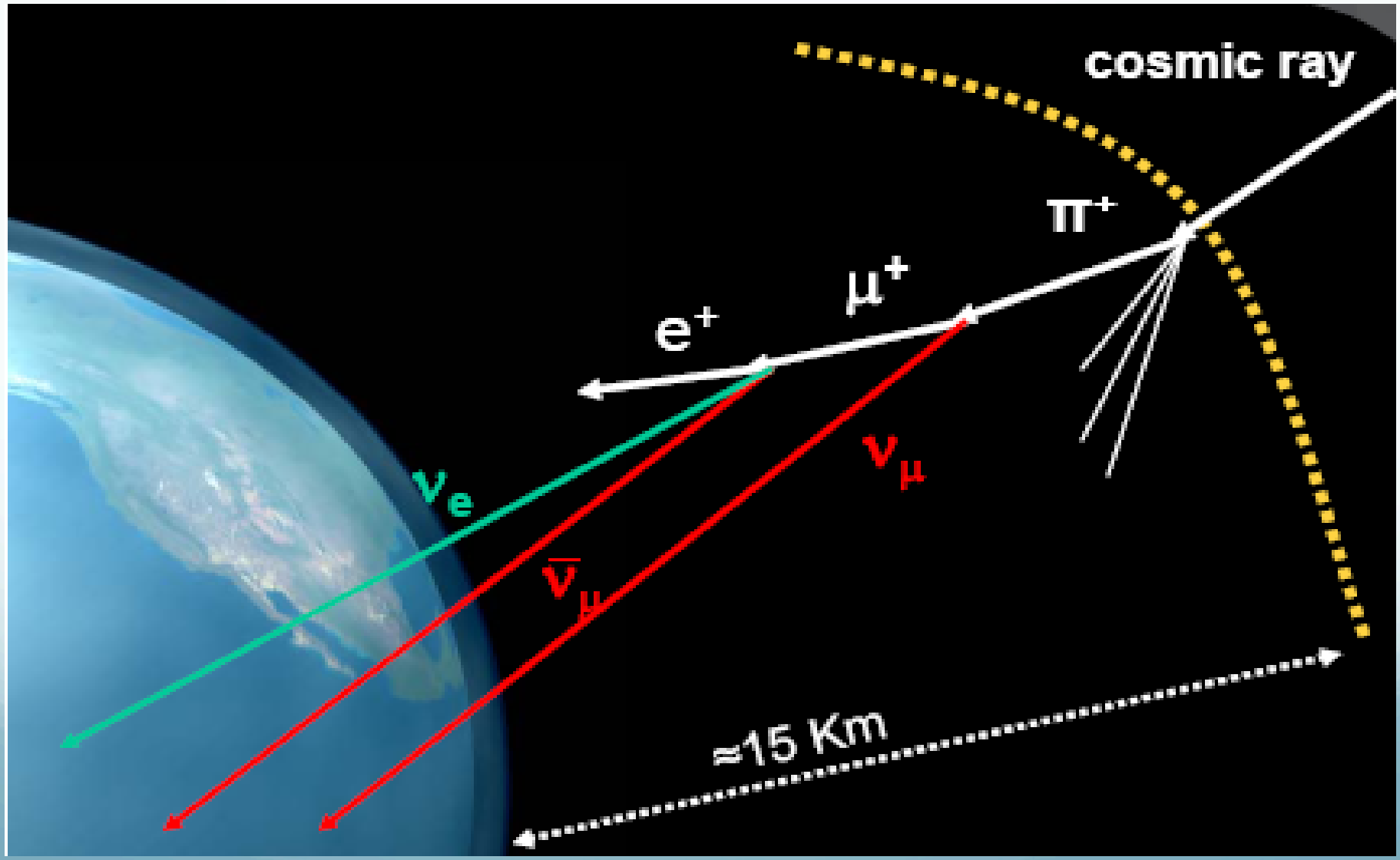


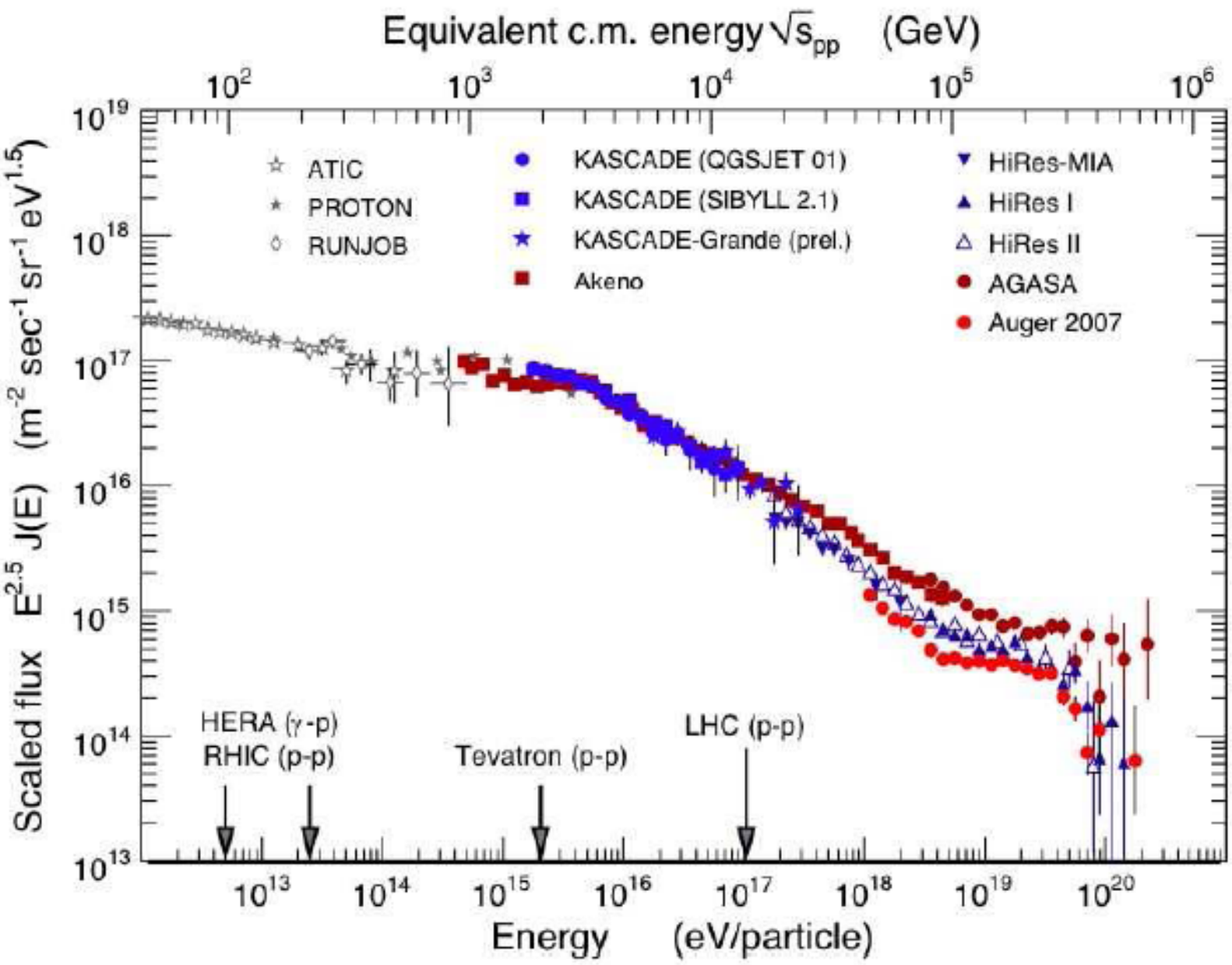
Physics Today 2009

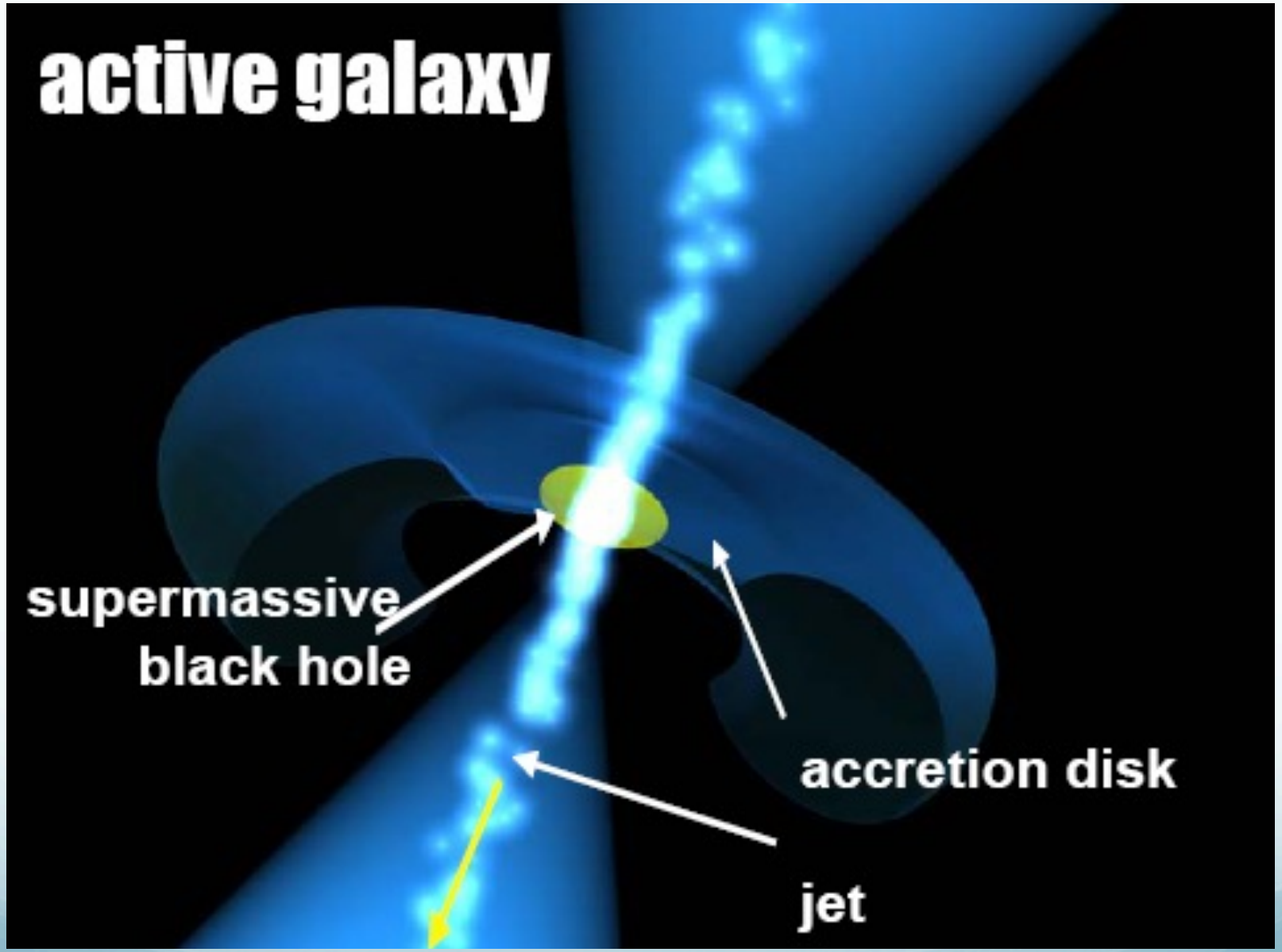
Observed High Energy Particles from the Sky

- Cosmic Rays (energy up to 10^{21} eV)
- Gamma - rays (energy up to 10^{13} eV)
- Atmospheric Neutrinos (energy up to 10^{9} eV)

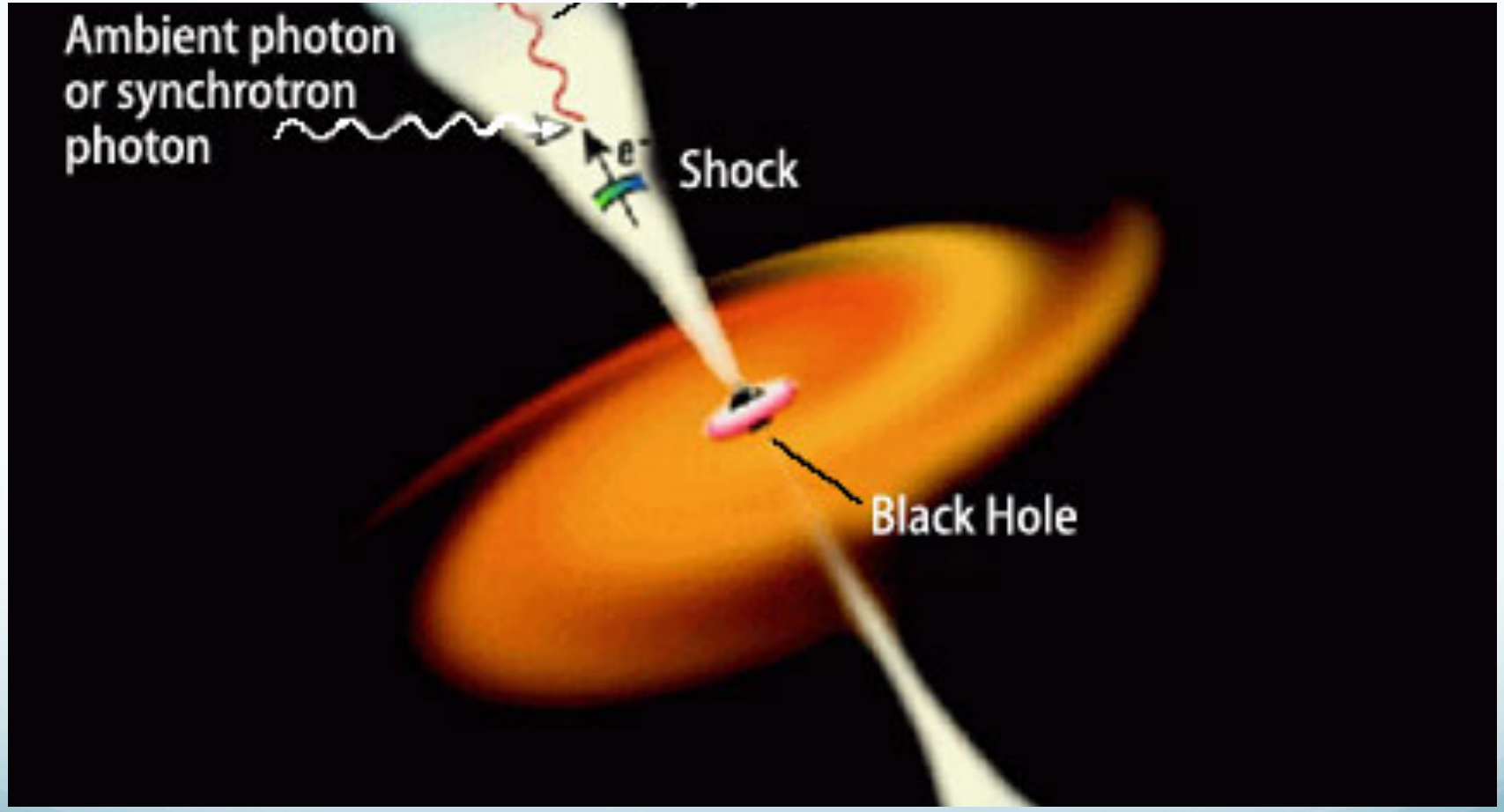
Cosmic Rays




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)


active galaxy
supermassive
black hole
accretion disk
jet

Active Galaxy



High Energy Gamma Rays

- Active Galactic Nuclei (AGNs) are prodigious particle accelerators and the most powerful radiation sources known in the Universe, with luminosities ranging from $10^{42} - 10^{48}$ erg/s.
- Over 50 AGNs observed by EGRET in MeV energy range, and about 15 AGNs in TeV range.

- The observed photon energy spectrum is a power-law:

$$\frac{dN_\gamma}{dE_\gamma} \approx E_\gamma^{-2}$$

for $100\text{MeV} \leq E_\gamma \leq 2TeV$

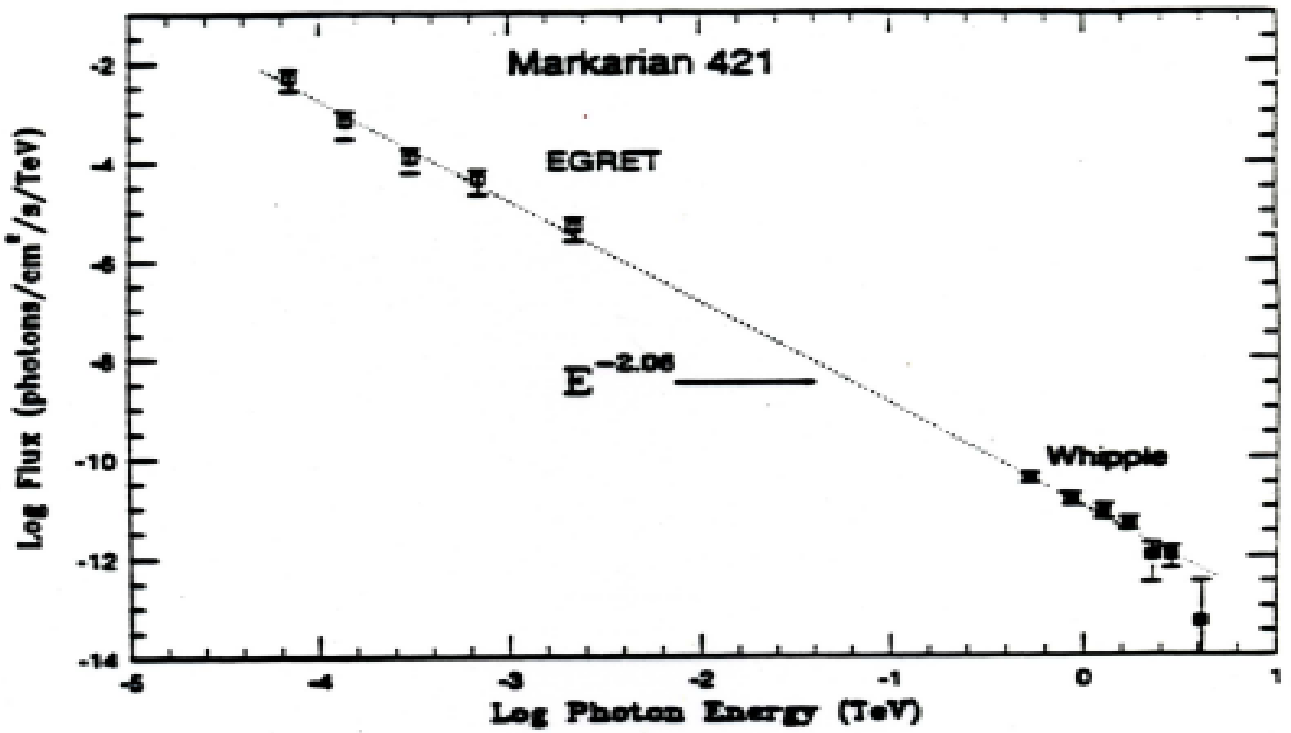


Figure 2. Differential energy spectrum from both the EGRET (Lin *et al.* 1992 and Whipple observations of Markarian 421. The EGRET observations wer taken 27 June - 11 July, 1991; the Whipple observations 24 March - 2 Jun 1992. A single power-law, with energy exponent 2.06 ± 0.04, is an acceptabl description of the combined dataset. Possible systematic errors in the exponen are not included. They are difficult to estimate because of the differing technique by which the fluxes have been measured and because of the non-contemporaneou nature of the observations.

Cosmic Neutrinos

- Solar Neutrinos (MeV energies)
- SN 1987A (MeV energies)
- Atmospheric Neutrinos (GeV to TeV energies)
- Extragalactic Neutrinos (AGN, GRB, cosmogenic, etc; GeV to EeV energies)
- Neutrinos from Dark Matter Annihilation

Cosmic Neutrinos

- Solar Neutrinos (MeV energies)
- SN 1987A (MeV energies)
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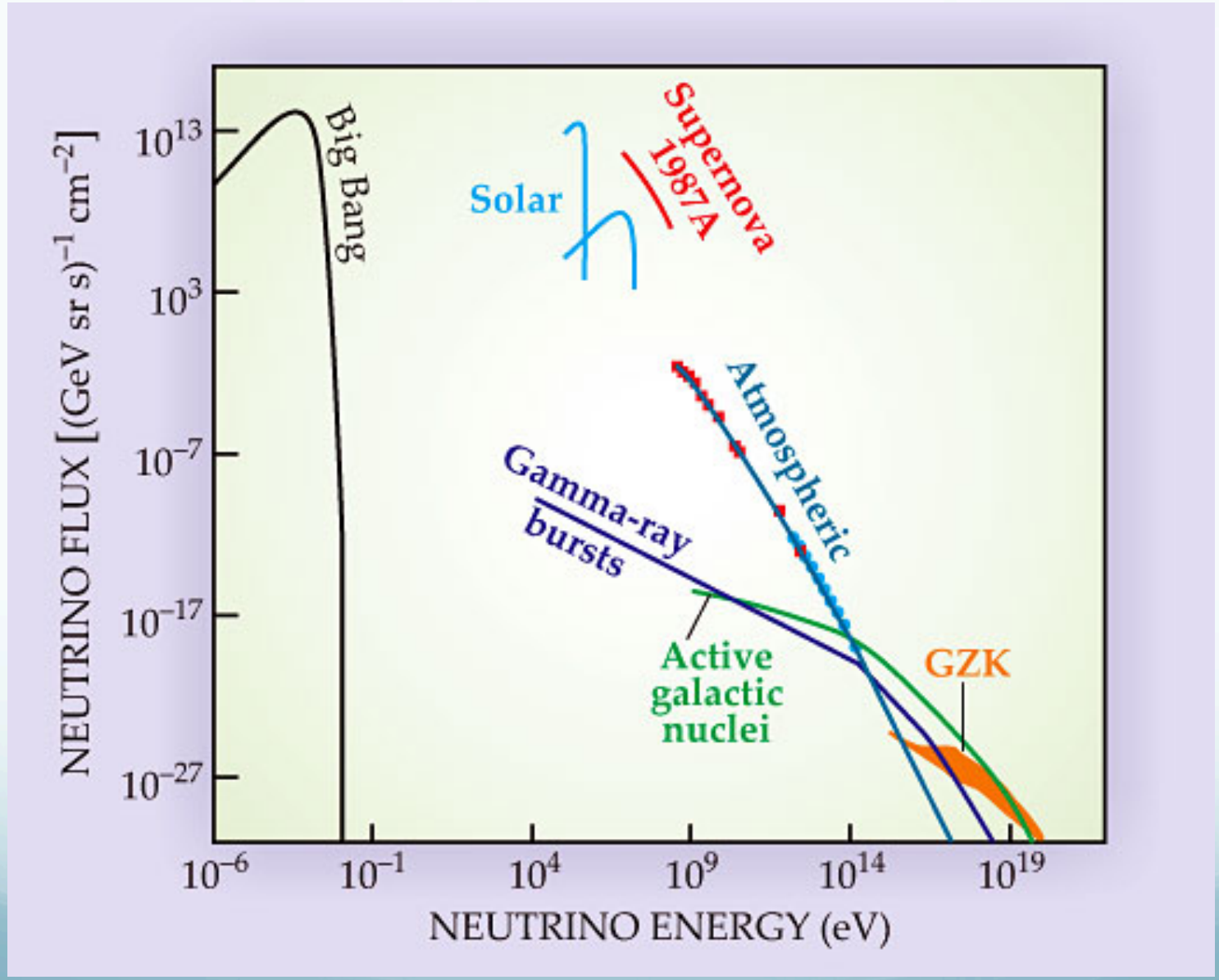
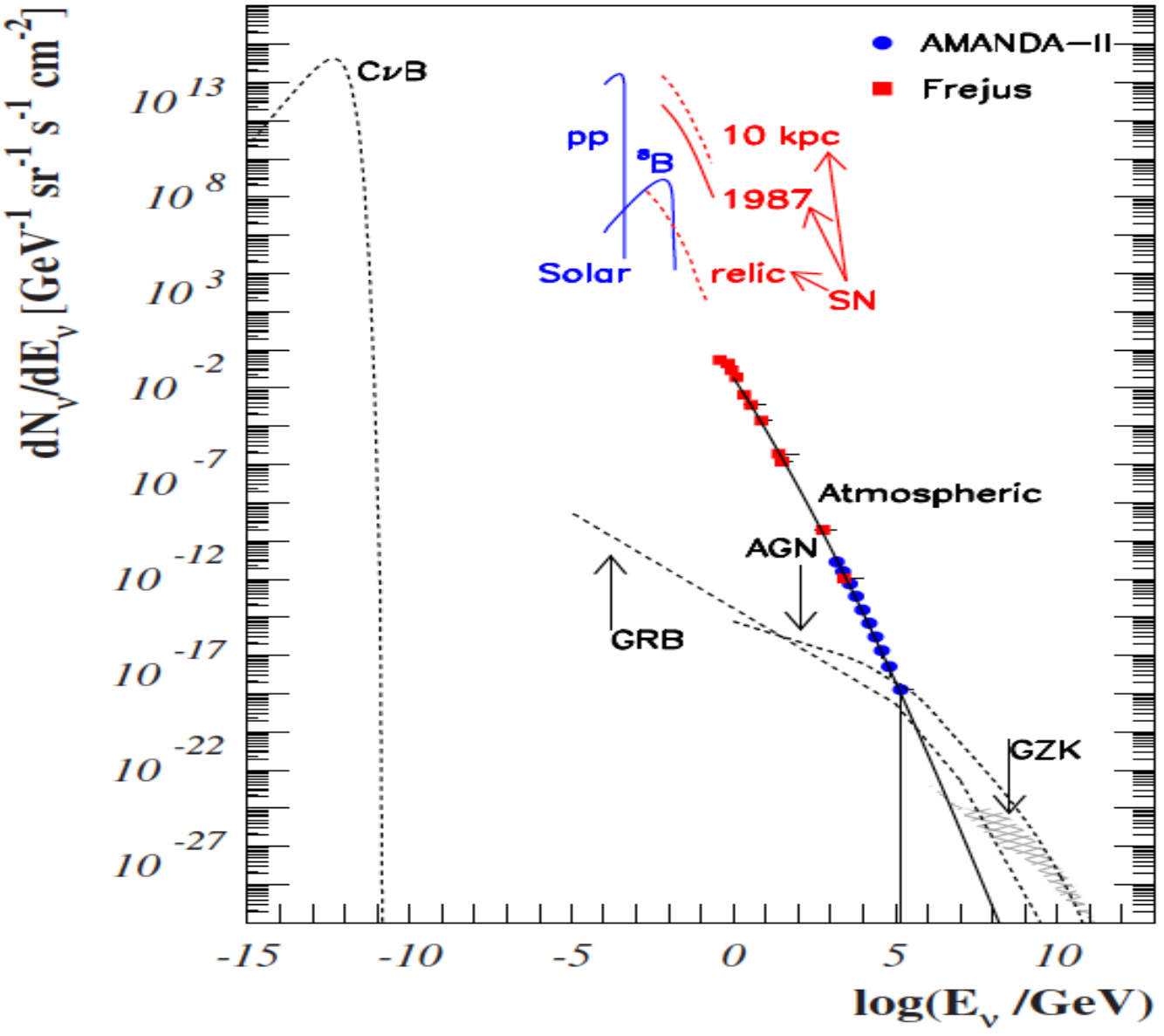
Cosmogenic ("GZK") neutrinos from interactions of cosmic rays with microvawe background radiation are "guaranteed" source of high energy neutrinos

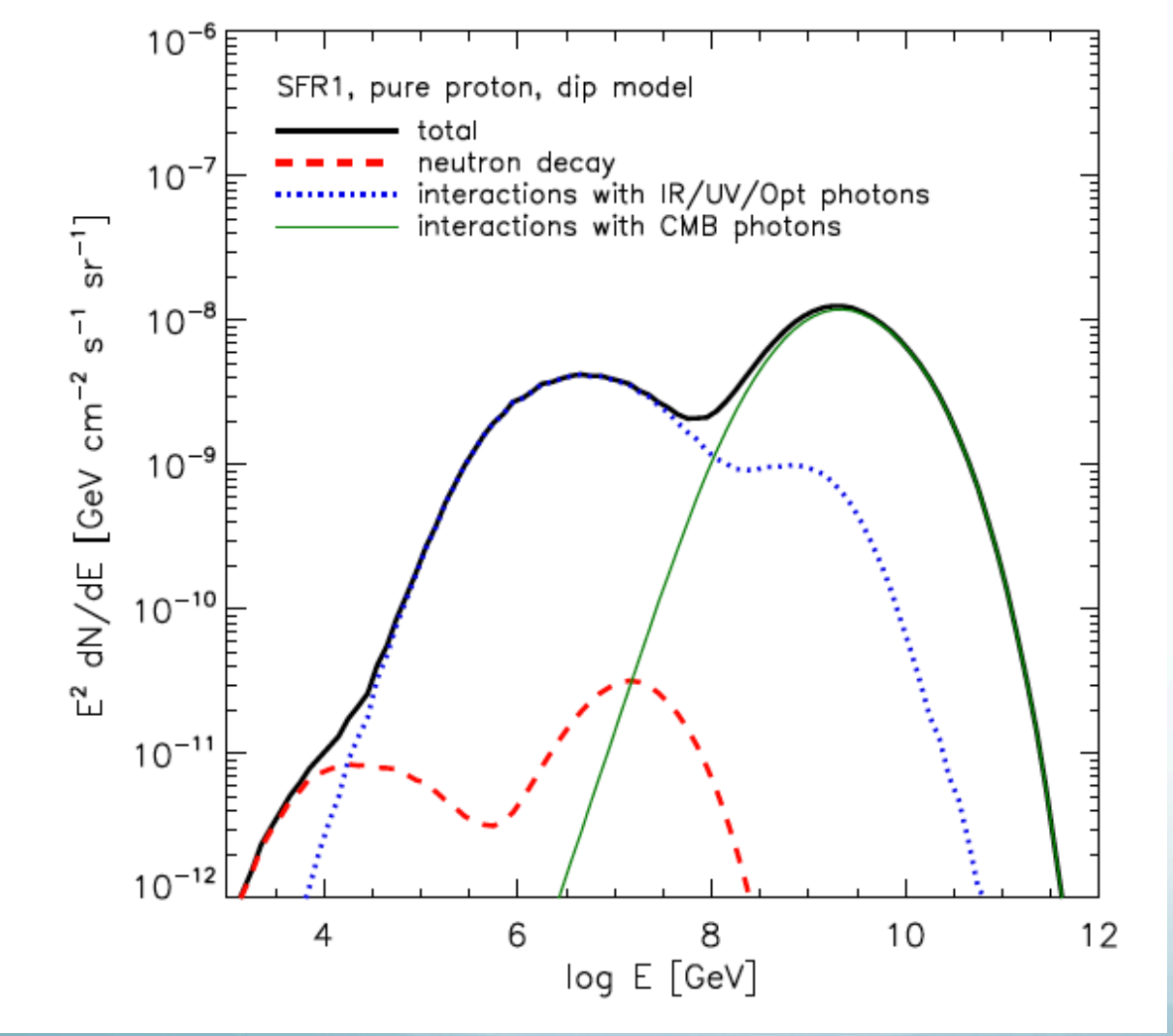
Neutrino fluxes



Rev. Sci. Instrum. **81**, 081101 (2010)



Sources of UHE neutrino: cosmogenic or "GZK"



Kotera, Allard and Olinto, JCAP 1010 (2010) 013

$$p\gamma \to \pi N$$

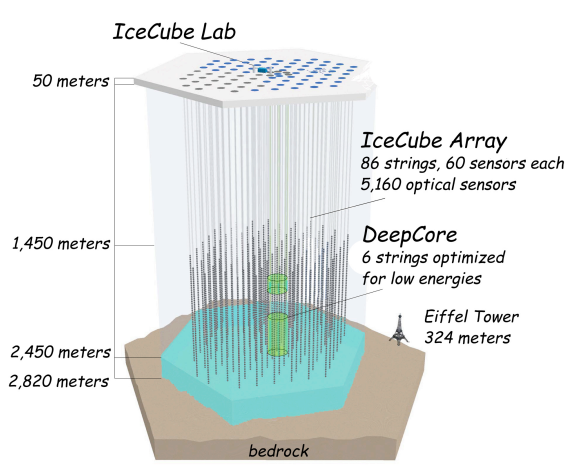
$$\pi^+ \to \mu^+ \nu_\mu$$

$$n \to pe\bar{\nu}_e$$

$$E_\nu \sim 10^{12}\ \mathrm{GeV}$$

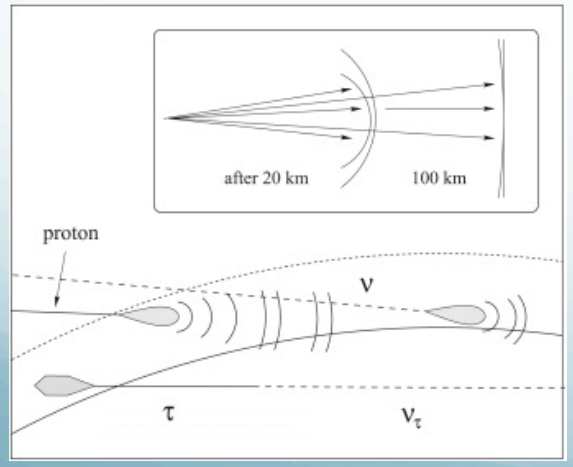
$$10^{21}\,\mathrm{eV}$$

High Energy Neutrino Detection

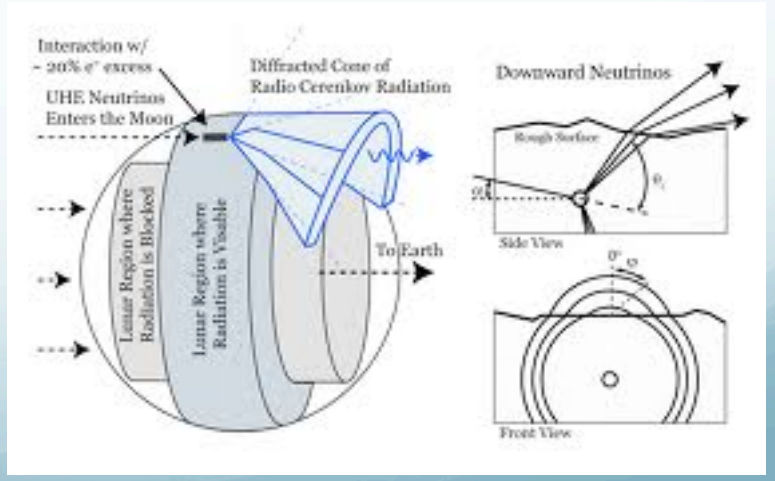


IceCube, Cherenkov in Ice

Radio Cherenkov, in ice



TA, Auger, energies above 0.1 EeV



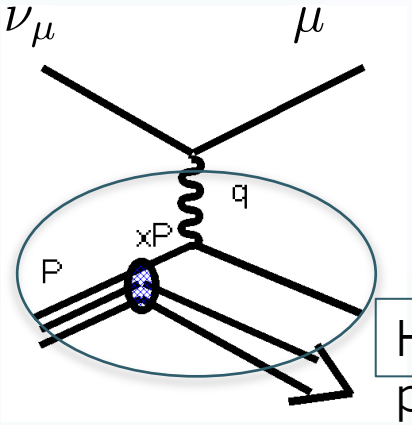
Also, JEM-EUSO

Neutrino interactions

- Fundamental couplings:

- Review neutrino-nucleon cross sections

Neutrino Cross Section



Hadronic physics

$$Q^2 = -q^2$$

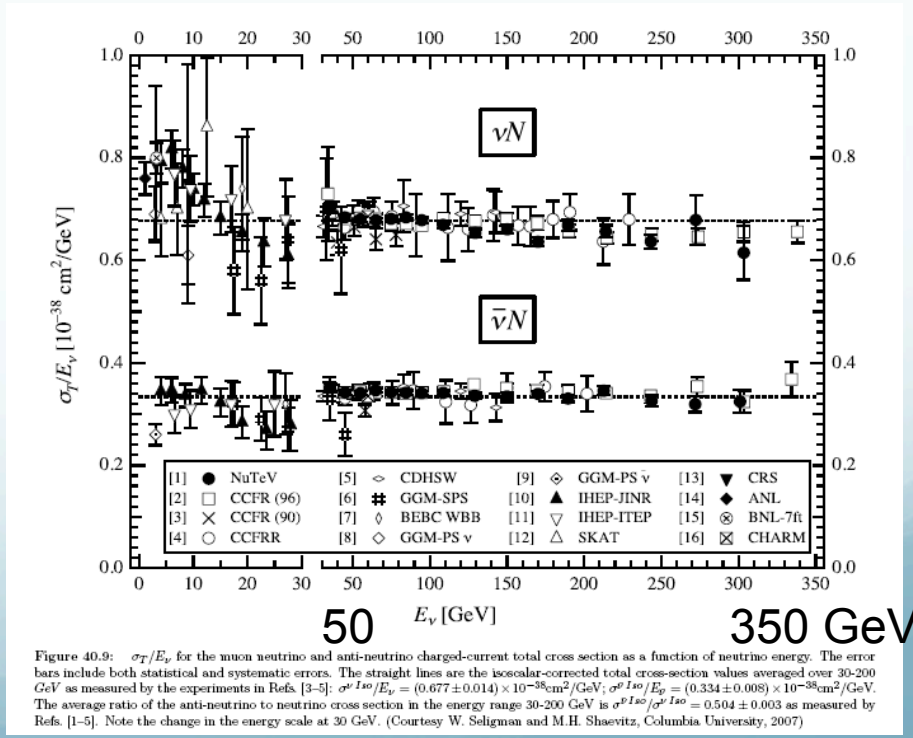
$$x = \frac{Q^2}{2p \cdot q}$$

$$s = (k+P)^2 \simeq 2M_p E_\nu$$

At low energies :

$$\sigma \sim \left(\frac{g^2}{Q^2 + M_W^2}\right)^2 s \sim G_F^2 s$$

$$\frac{\sigma}{E_\nu} \sim \text{constant}$$



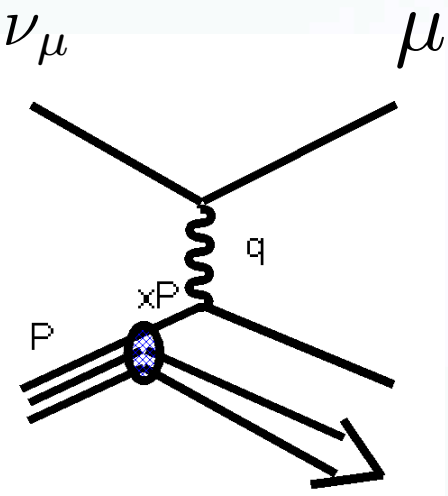
50 350 GeV

Figure 40.9: σ_T/E_ν for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the isoscalar-corrected total cross-section values averaged over 30-200 GeV as measured by the experiments in Refs. [3–5]: $\sigma^{\nu\,Iso}/E_\nu = (0.677 \pm 0.014) \times 10^{-38}$cm^2/GeV; $\sigma^{\bar{\nu}\,Iso}/E_{\bar{\nu}} = (0.334 \pm 0.008) \times 10^{-38}$cm^2/GeV. The average ratio of the anti-neutrino to neutrino cross section in the energy range 30-200 GeV is $\sigma^{\bar{\nu}\,Iso}/\sigma^{\nu\,Iso} = 0.504 \pm 0.003$ as measured by Refs. [1–5]. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2007)

Particle data group http://pdg.lbl.gov

Neutrino and antineutrino beams

Ultrahigh energy neutrino-nucleon scattering



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

At high energies W-propagator important

$$x_{\min} = M_W^2 / 2 m_N E_\nu$$

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

W boson propagator

Quark distribution functions

For E > 10^8 GeV, $x_{min} < 10^{-5}$, we need parton distributions at small x and large Q

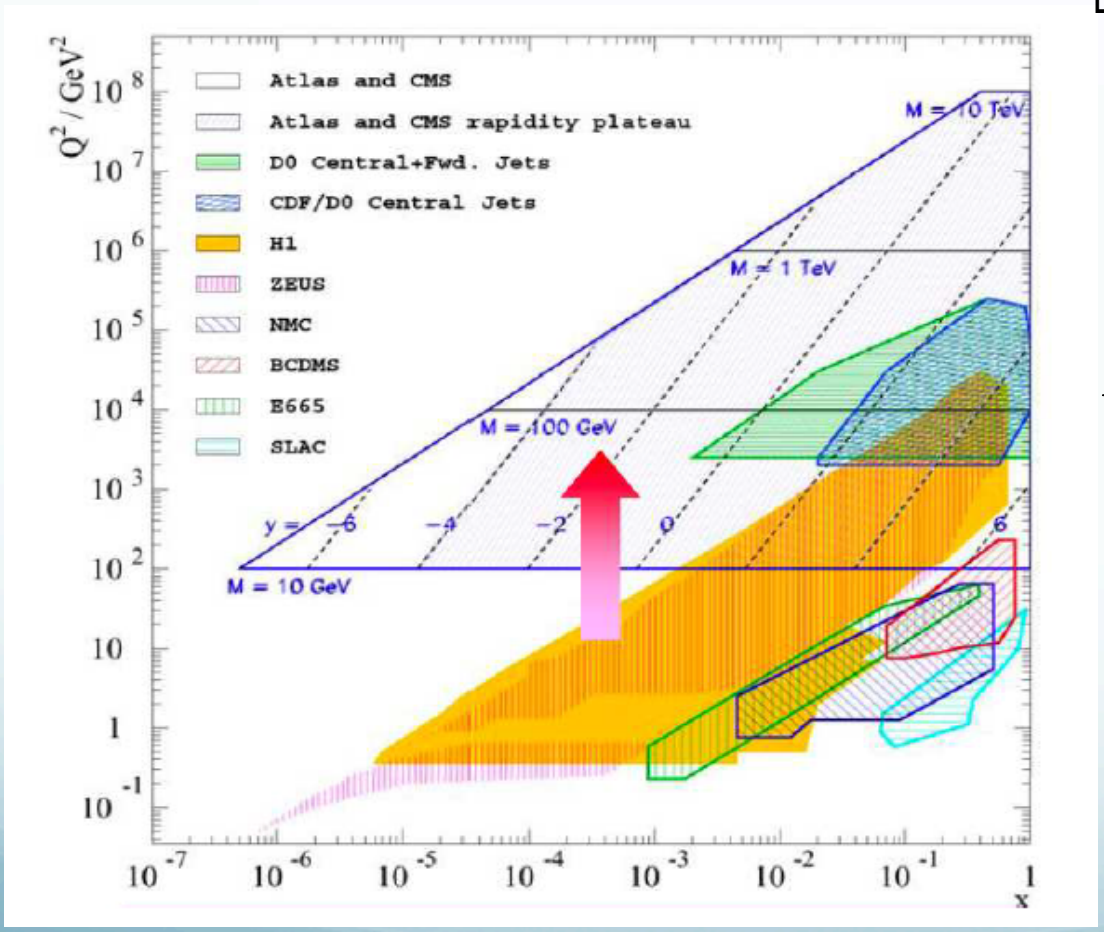
Gandhi, Reno, Quigg and Sarcevic, PRD 58 (1998); Astropart. Phys. 5 (1996)

Quark distribution functions, i.e. parton densities

$$q(x,Q^2) = \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + s_s(x,Q^2) + b_s(x,Q^2)$$

$$\bar{q}(x,Q^2) = \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + c_s(x,Q^2) + t_s(x,Q^2),$$

Structure functions used to get parton distributions (PDF)



LHC energies

$$s \sim 10^9 \text{ GeV}^2$$

Probing x down to

$$x \sim 10^{-5}$$

$$E_\nu = 10^{12} \text{ GeV means}$$

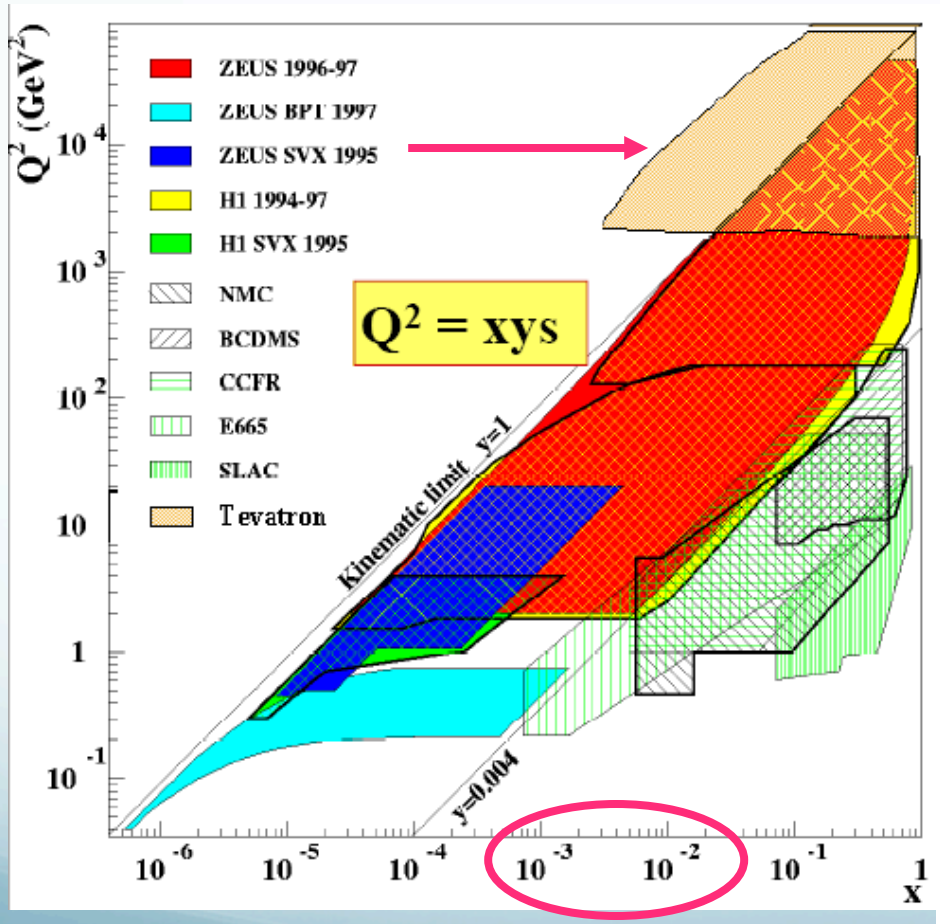
$$x \sim 10^{-8}$$

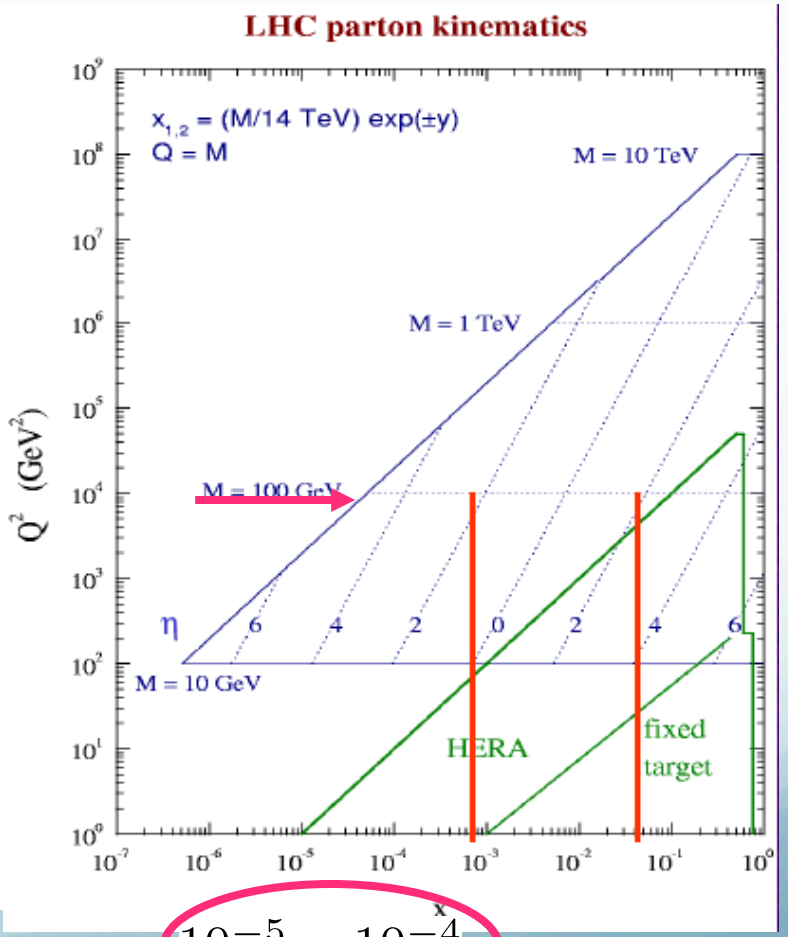
so small-x extrapolations of parton distribution functions or structure functions needed.

Boonekamp et al., Acta Phys.Polon. B40 (2009) 2239-2321

Structure functions used to get PDFs

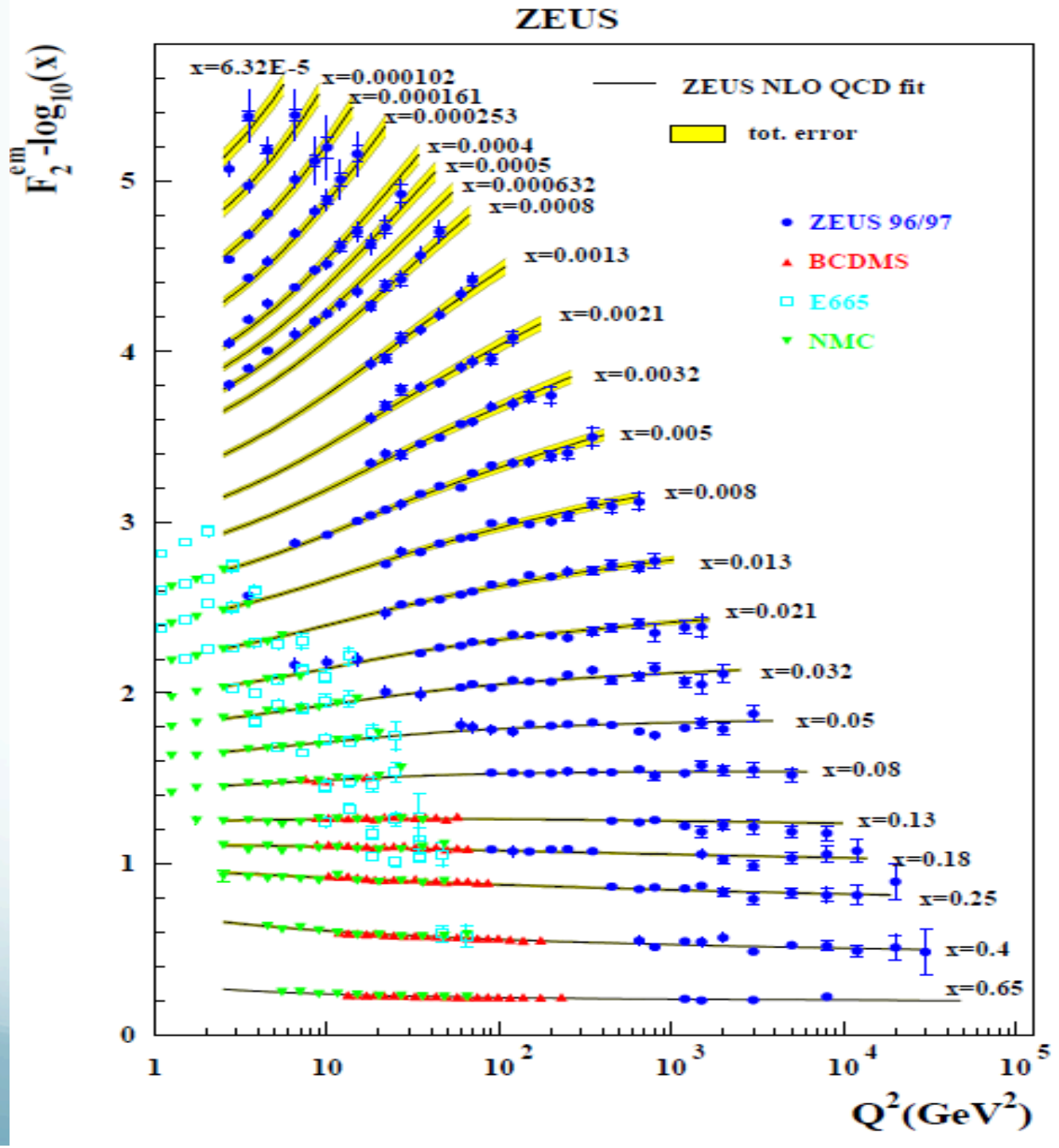
LHC up to $s \sim 10^9\ \mathrm{GeV}^2$



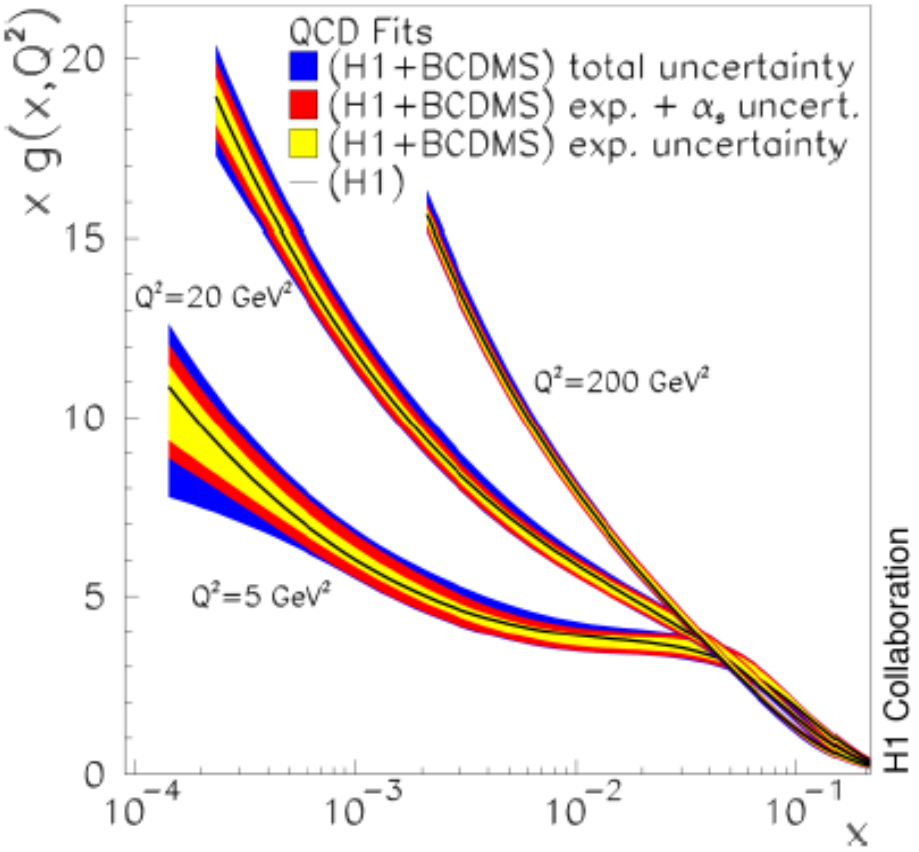


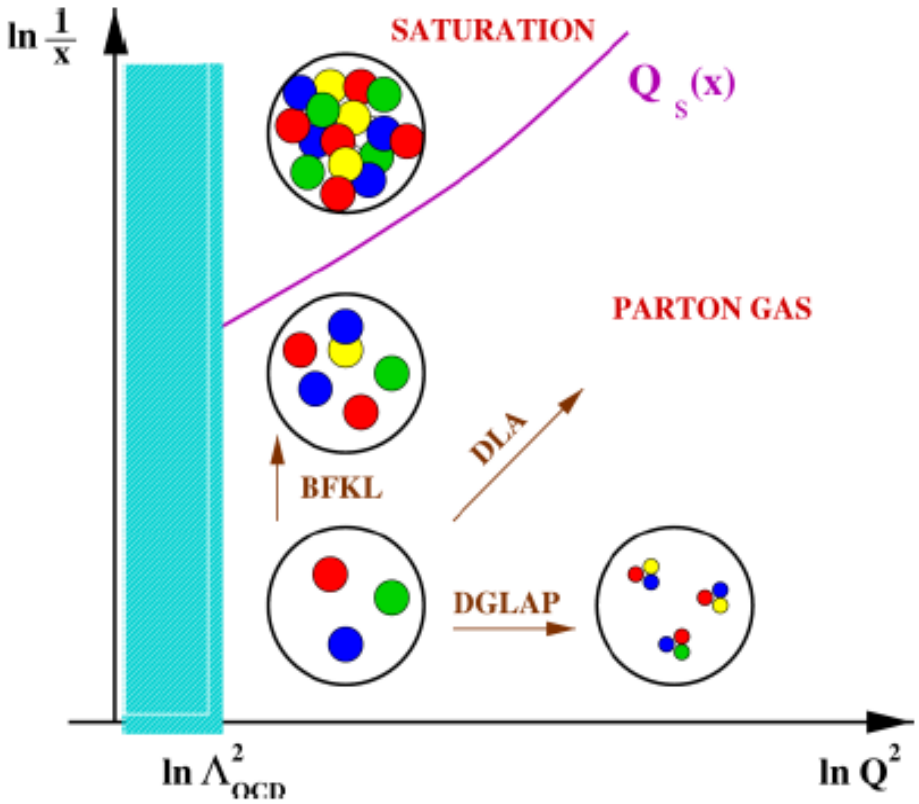
$10^{-5} - 10^{-4}$

From B. Foster's 2002 Frascati Talk


ZEUS
F_2^{em} -log$_{10}$(x)
ZEUS NLO QCD fit
tot. error
ZEUS 96/97
BCDMS
E665
NMC
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
0
1
2
3
4
5
1
10
10^2
10^3
10^4
10^5
Q^2(GeV^2)

The problem of small x

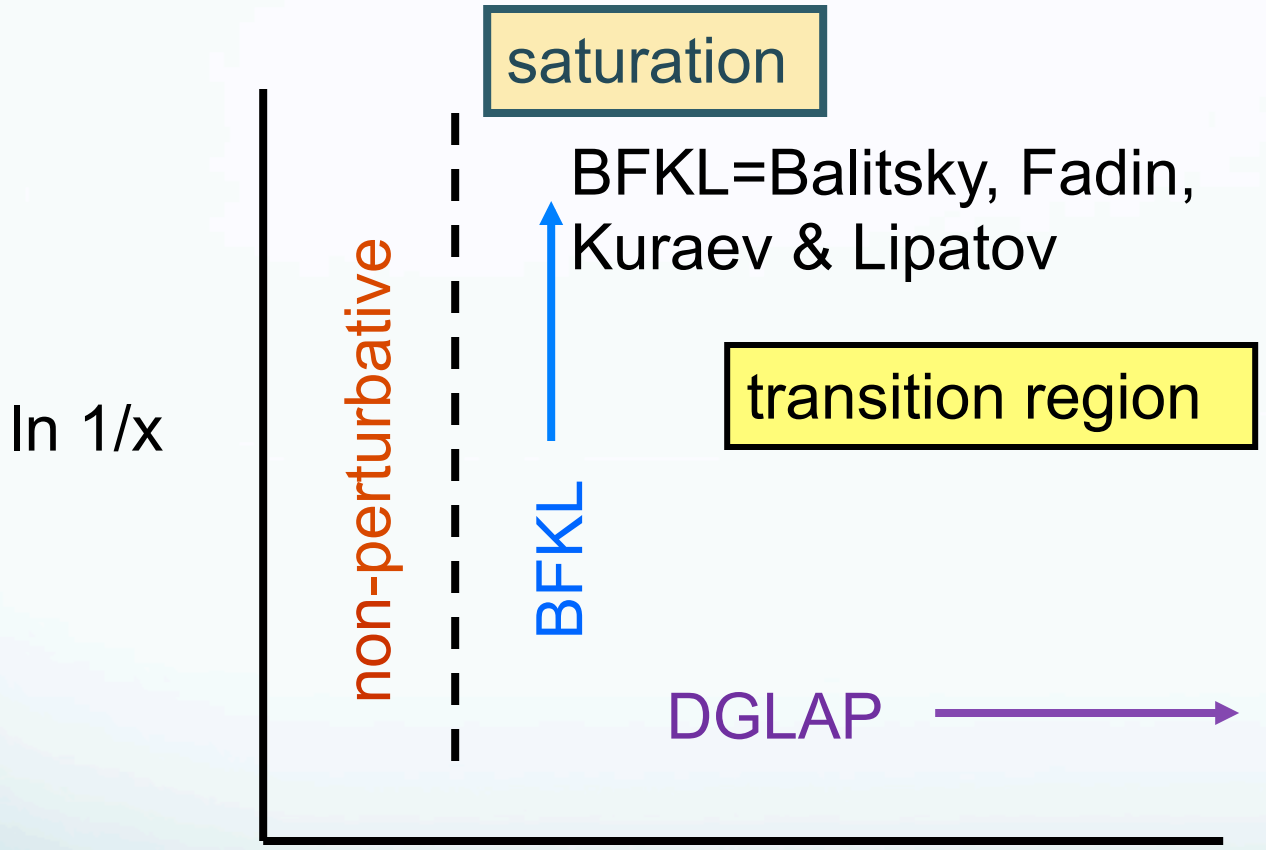




Gluon distribution grows rapidly as x→0: gluons start overlapping

and may start recombining: saturation of cross section

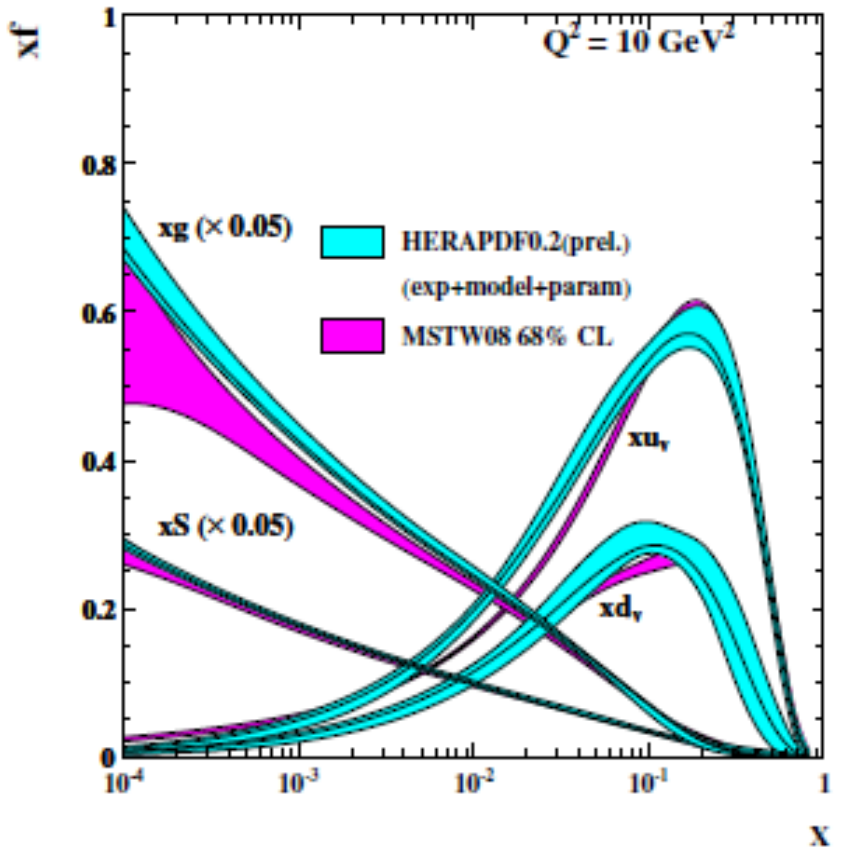
Theory Issues: how to extrapolate?

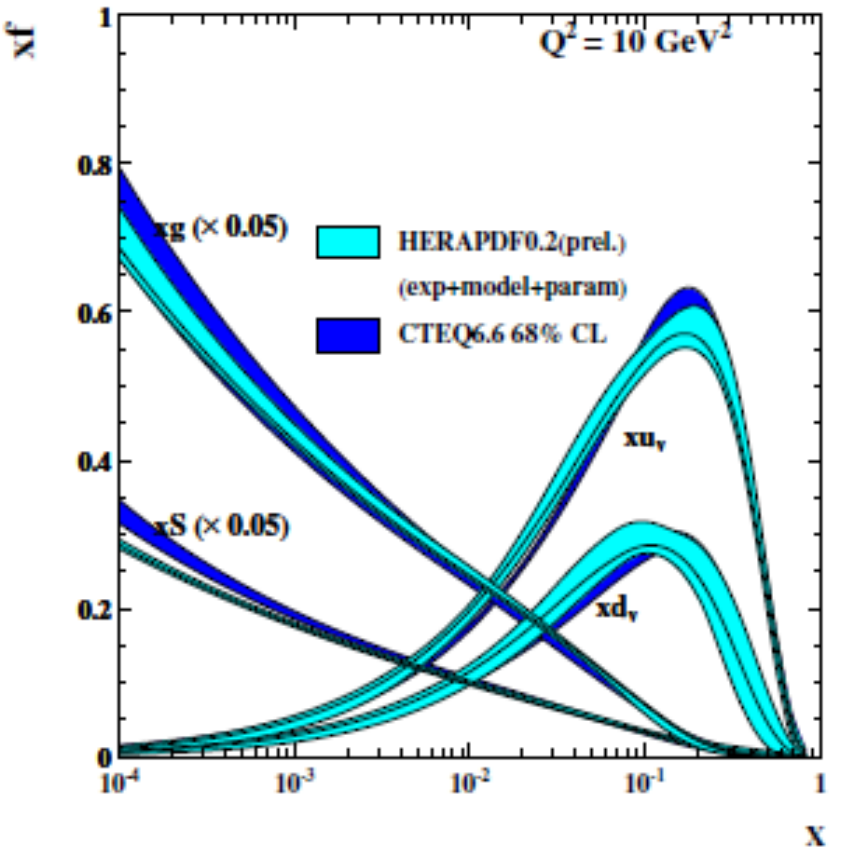


Deep Inelastic Scattering Devenish & Cooper-Sarkar, Oxford (2004)

DGLAP=Dokshitzer, Gribov, Lipatov, Altarelli & Parisi

HERA PDF comparison with MRSTW and CTEQ





Raicevic (H1 and ZEUS), Nucl. Phys. B198 (2010)

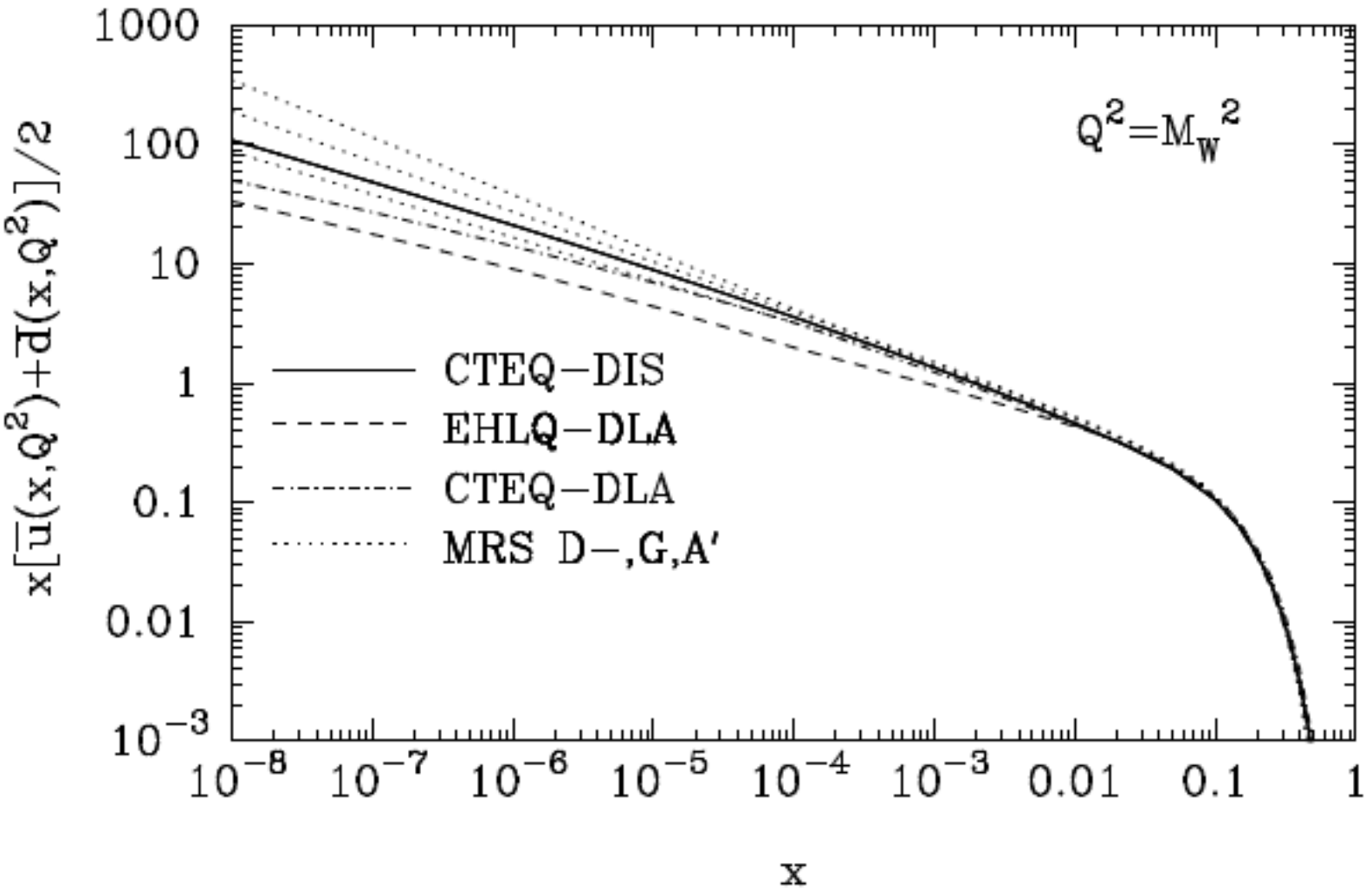
Some approaches

Power law extrapolations, consistent with basic QCD behavior, e.g., Gandhi, Quigg, MHR, Sarcevic, PRD 58 (1998) & subsequently.

Incorporate additional small x correction in QCD evolution, including saturation, however, not completely clear at large Q. e.g., Kwiecinski, Martin & Stasto, PRD 59 (1999) 093002; Kutak & Kwiecinski, EPJ (2003)

Model structure functions with non-perturbative hadronic structure, e.g., dipole model. E.g., Golec-Biernat & Wusthoff dipole by Kutak & Kwiecinski, 2003

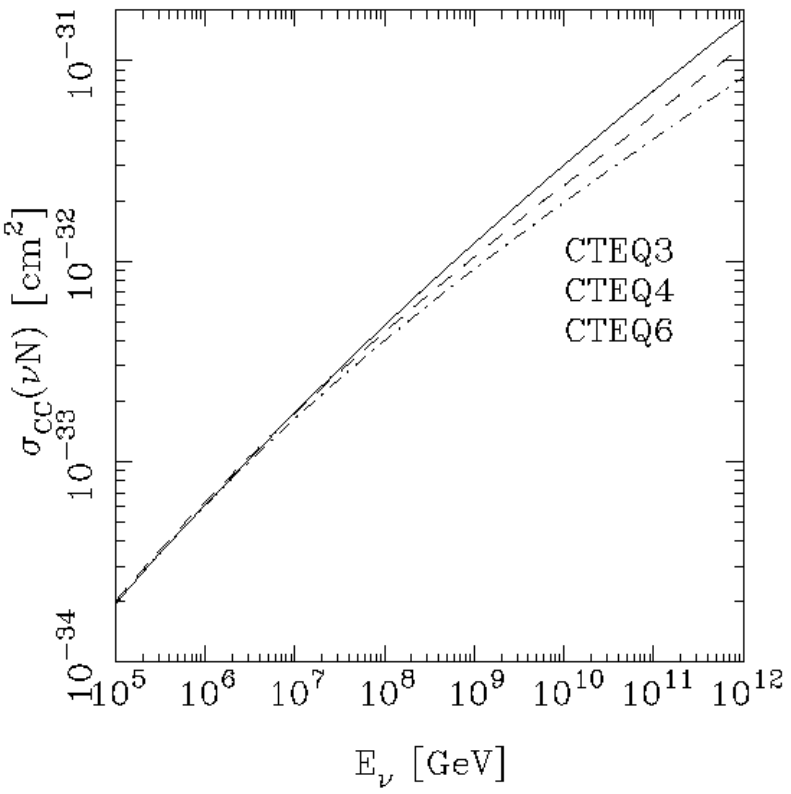
Parameterize structure functions with guidance from unitarity (Froissart bound). E.g., Block, Durand, Ha and McKay, PRD 88 (2013)

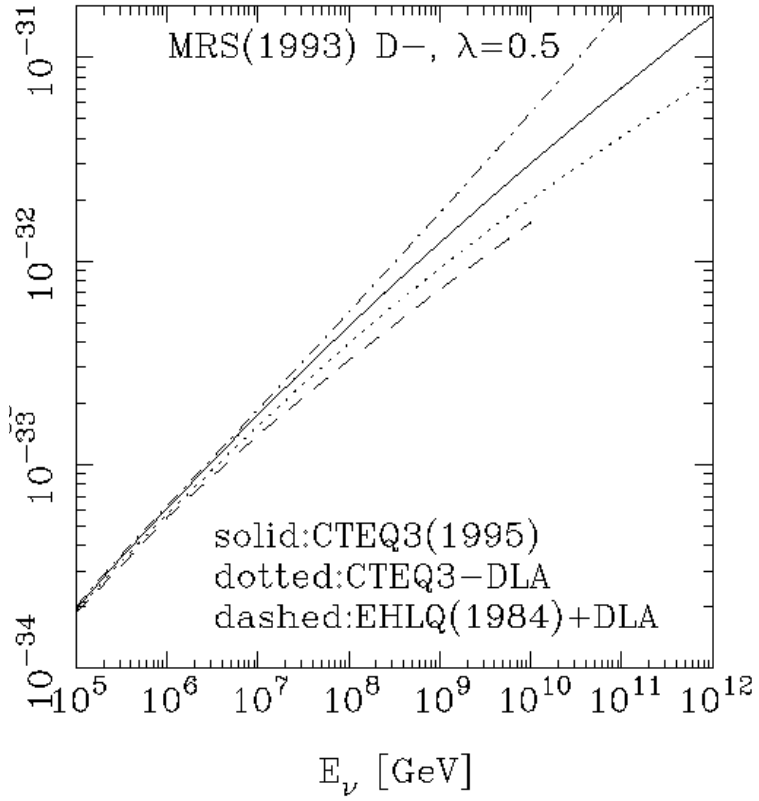


Gandhi, Quigg, Reno and Sarcevic (1996,1998)

Some extrapolations: historical

DGLAP evolution: log Q. Shown here are power law and double logarithmic extrapolations at small x.



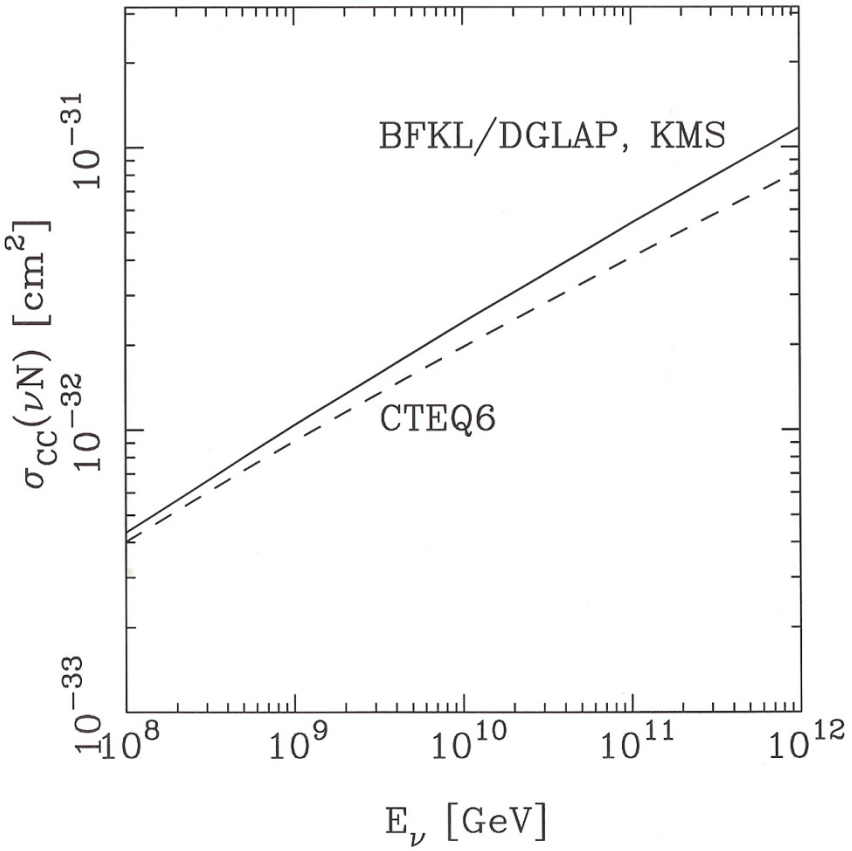


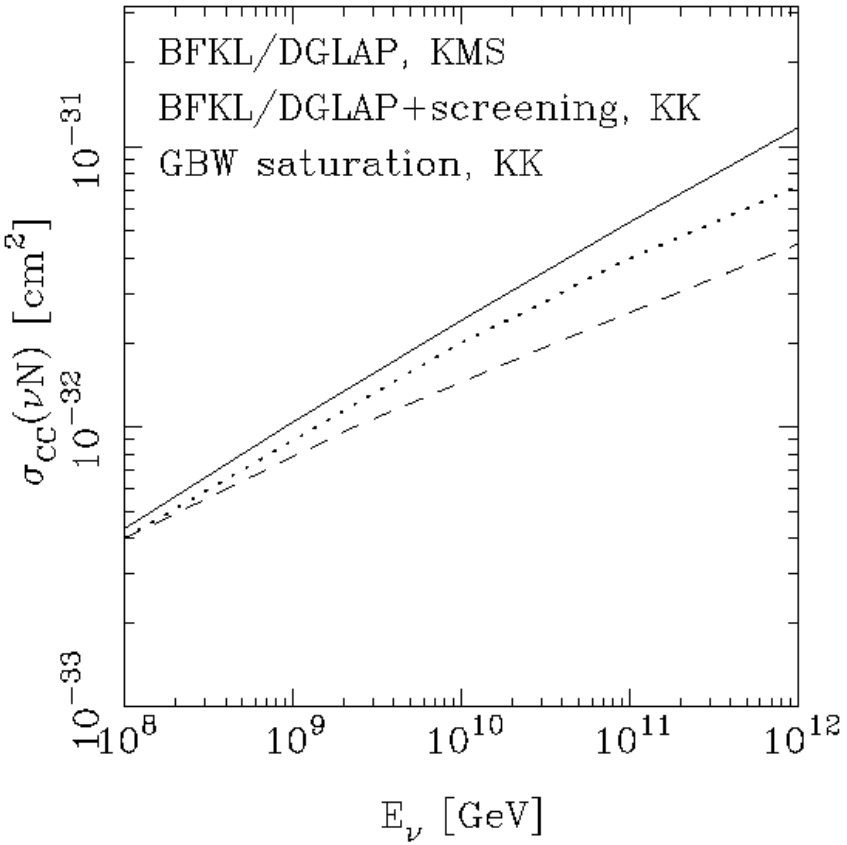
Gandhi, Quigg, Reno and Sarcevic. (1996,1998)

Including additional resummation, recombinations

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

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



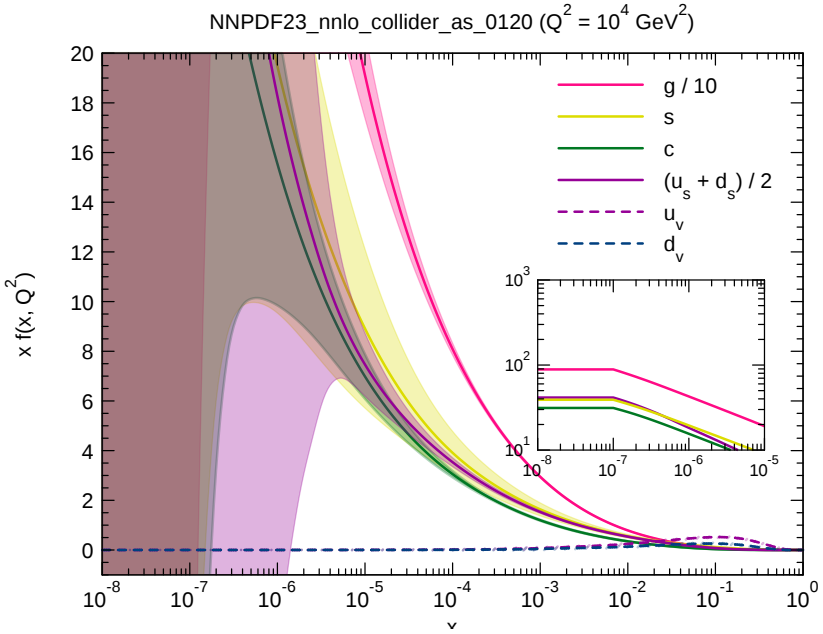


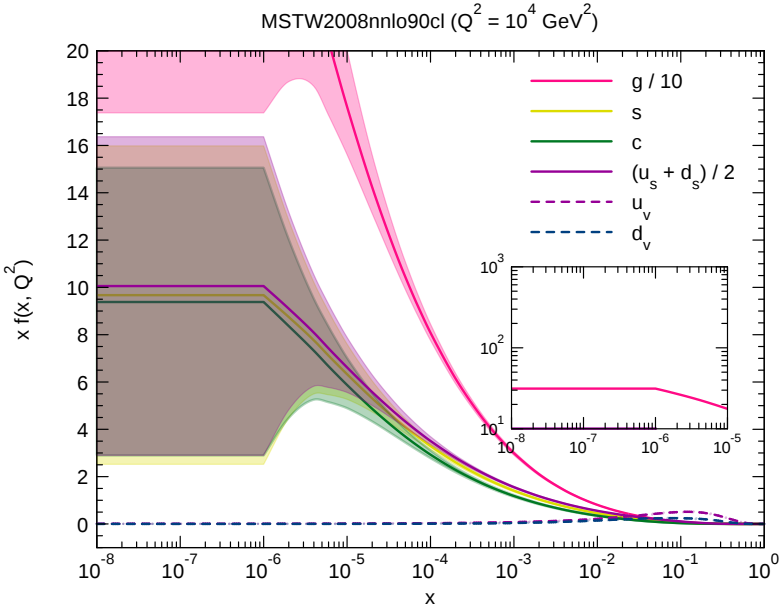
BFKL evolution matched to DGLAP accounting for some subleading ln(1/x), running coupling constant,matched to GRV parton distribution functions

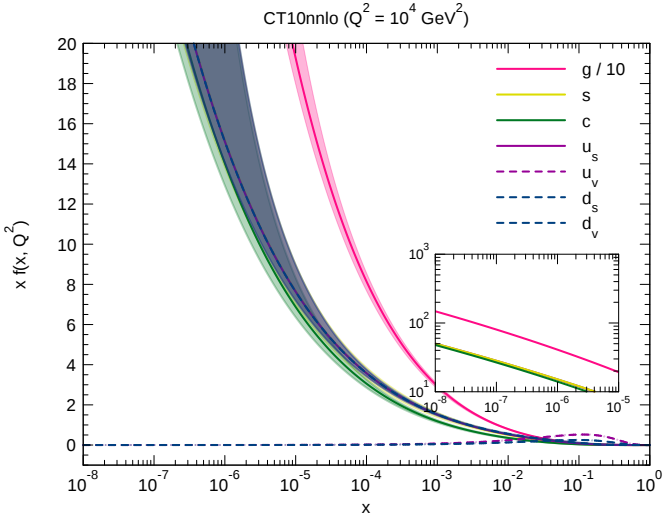
Updated PDFs

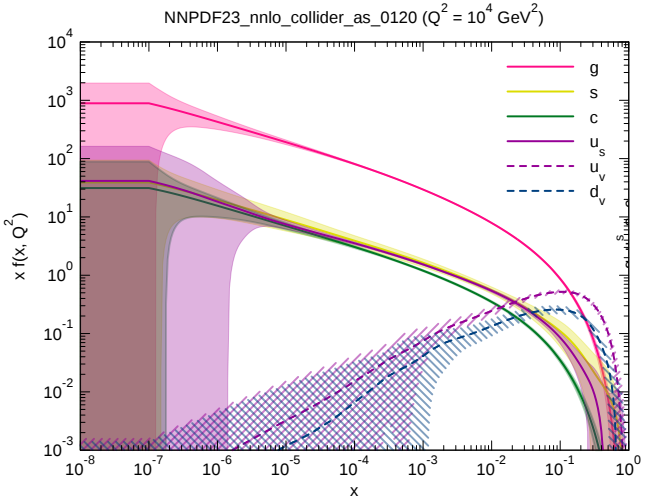
- MRSTW (2008): includes HERA data
- CT10: includes most recent HERA data
- NNPDF (includes also LHC data)

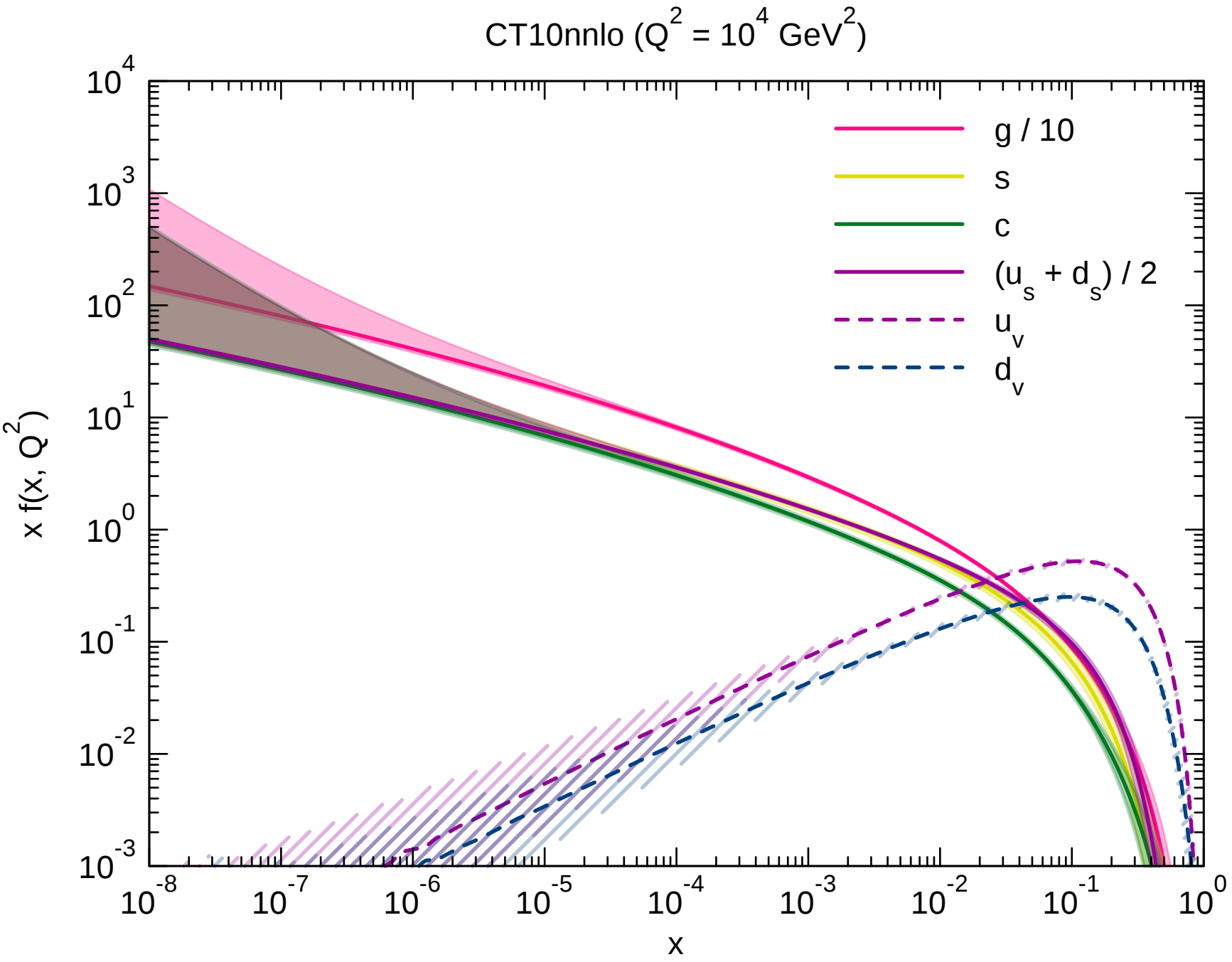
Extrapolations and Large uncertainties for $x < 10^{-5}$



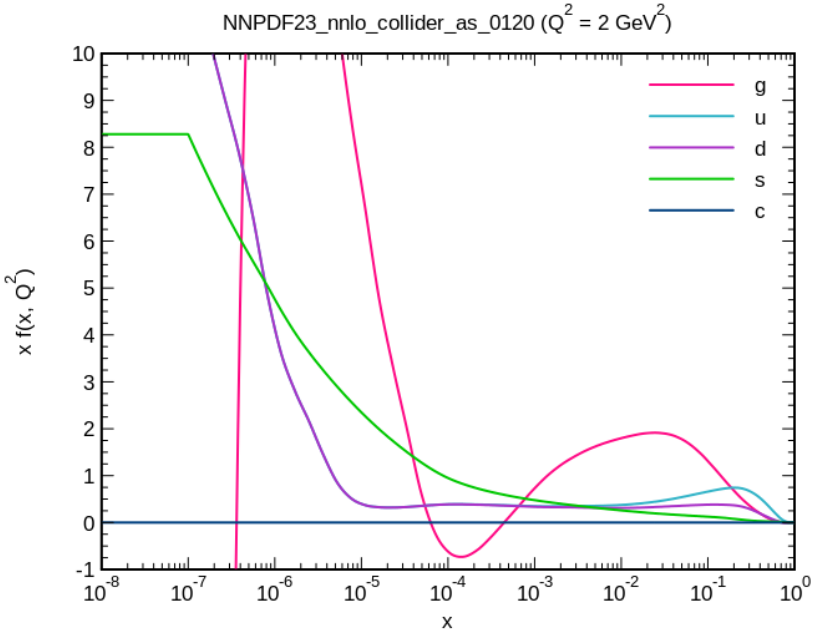


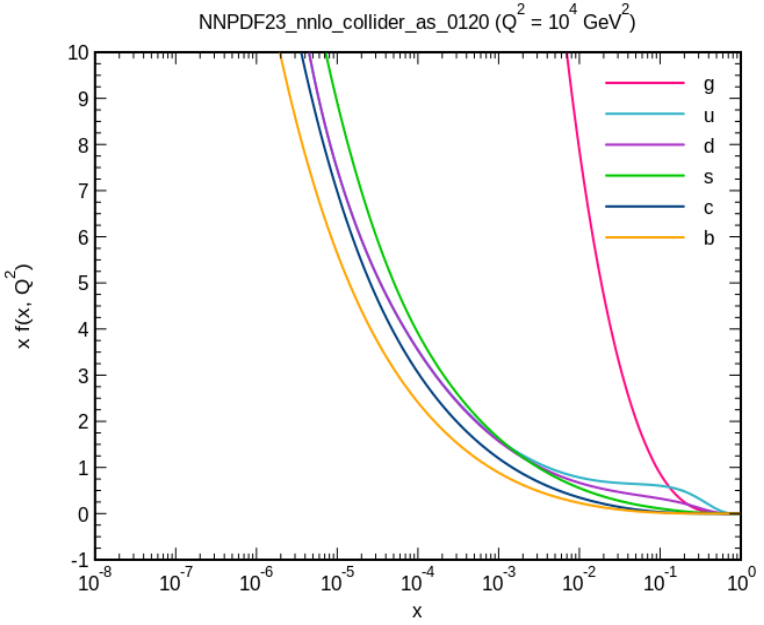


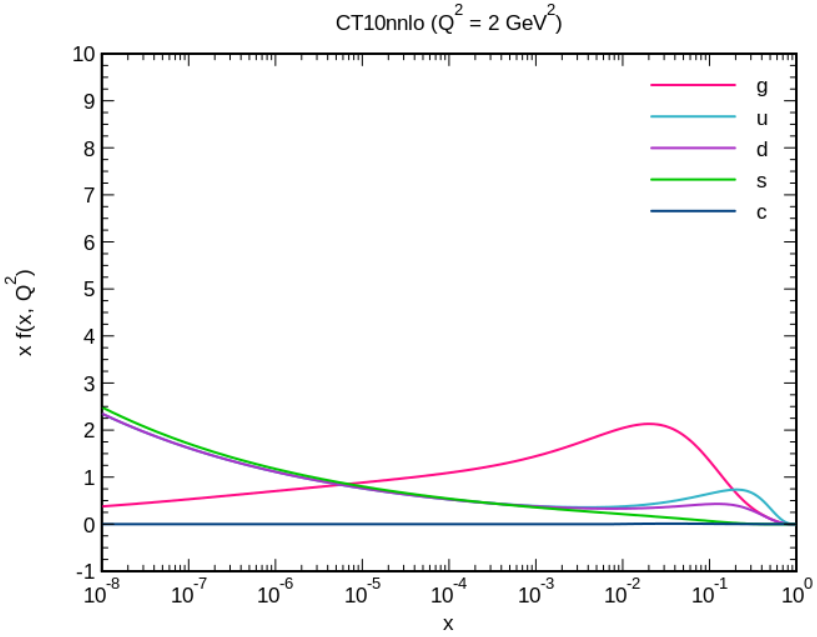


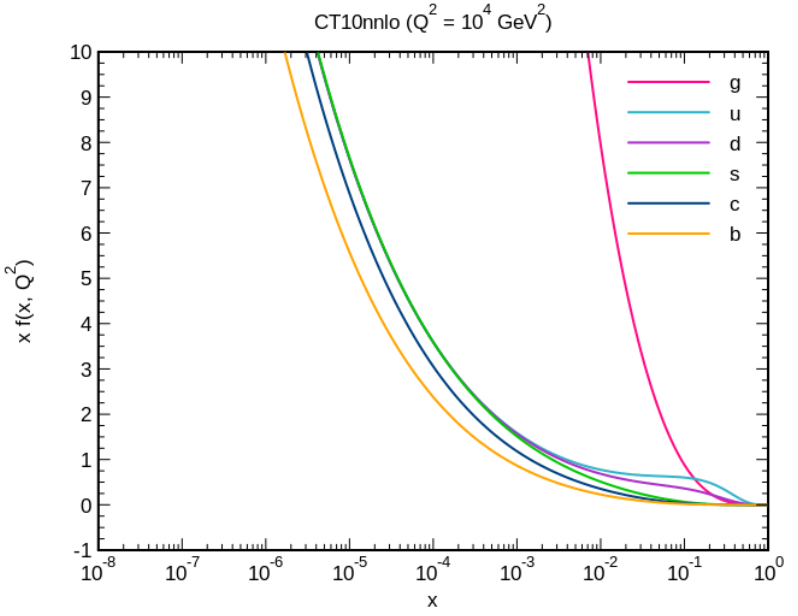

CT10nnlo ($Q^2 = 10^4$ GeV^2)
g / 10
s
c
$(u_s + d_s) / 2$
u_v
d_v
x f(x, Q^2)
x
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

NNPDF and CT10 PDFs

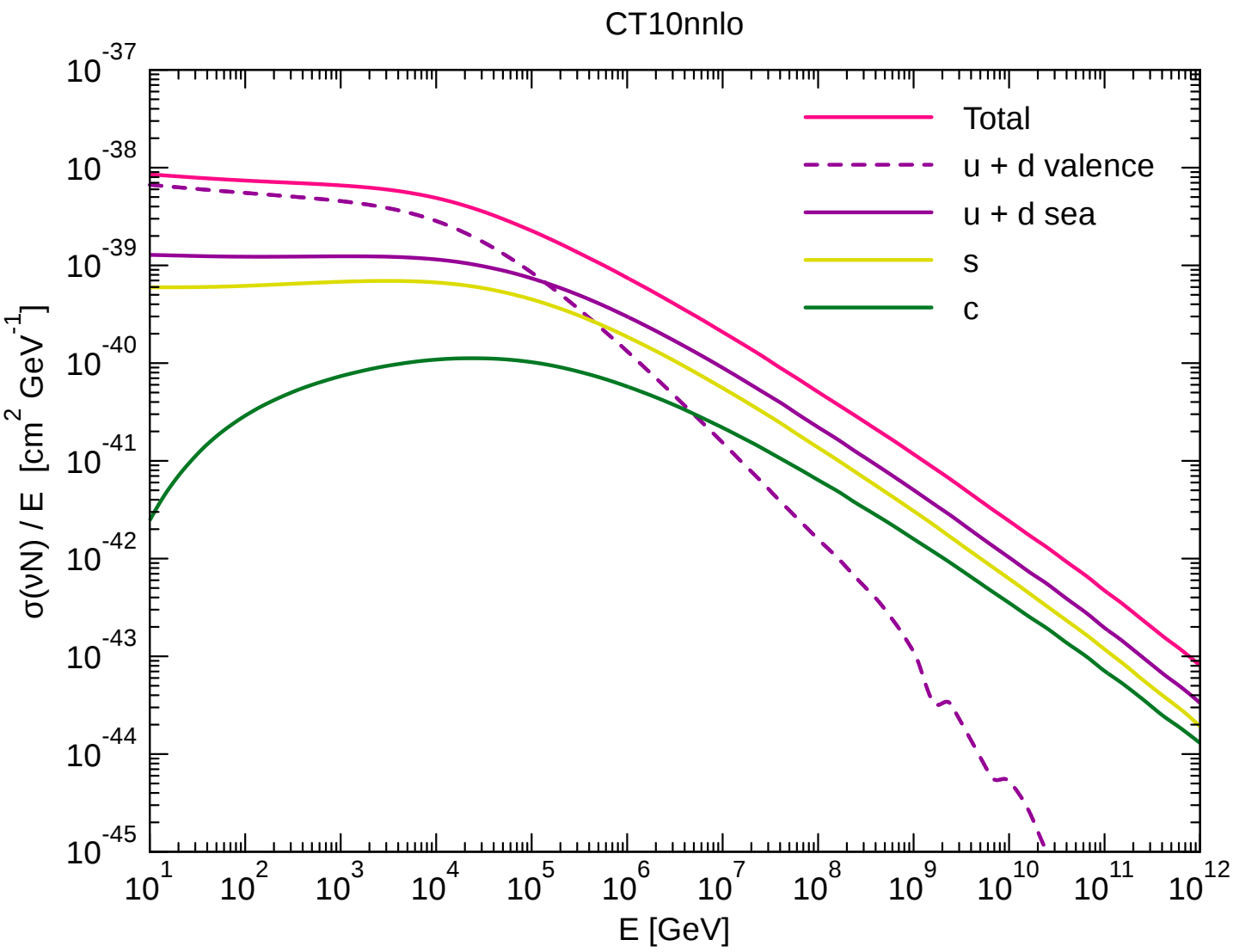




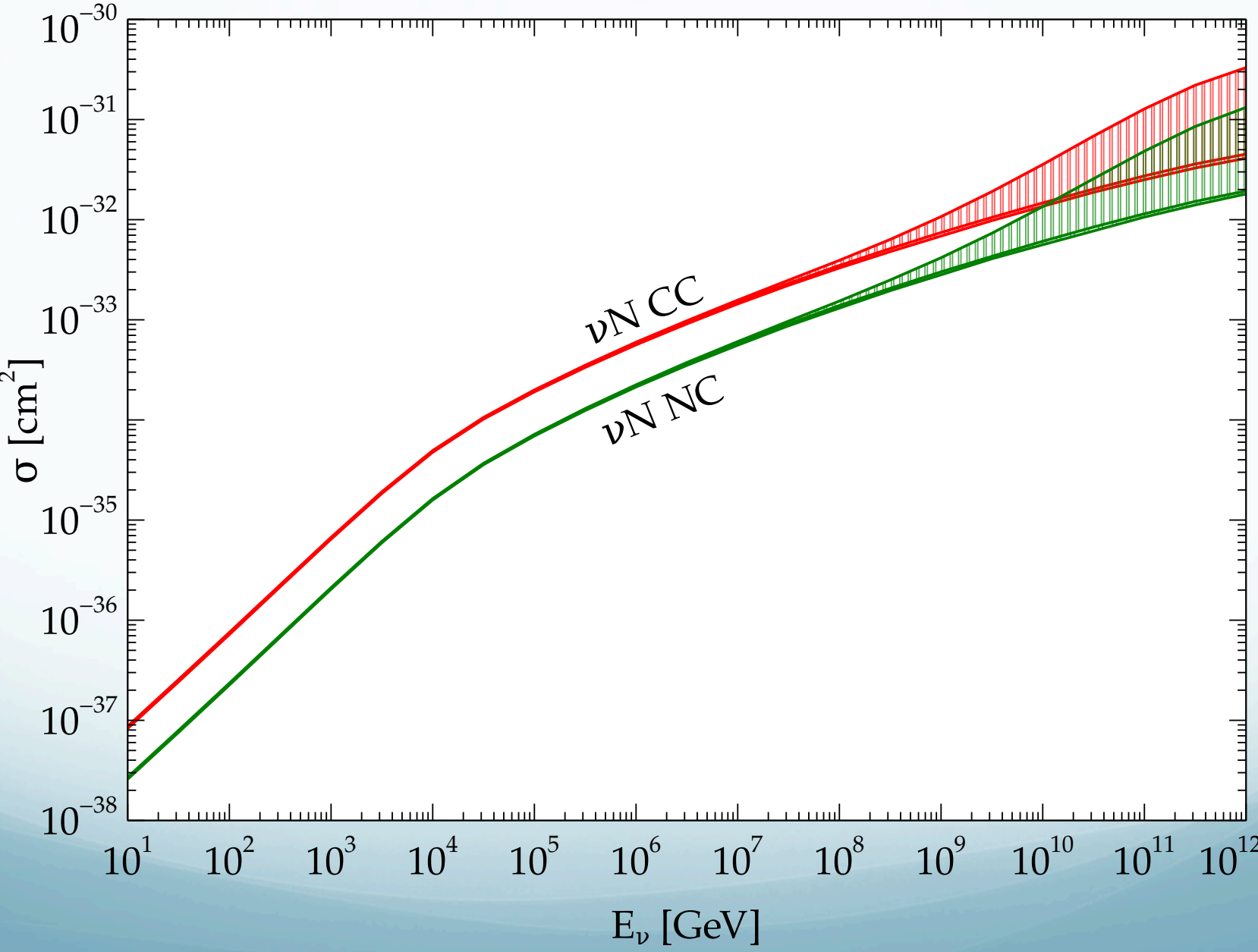




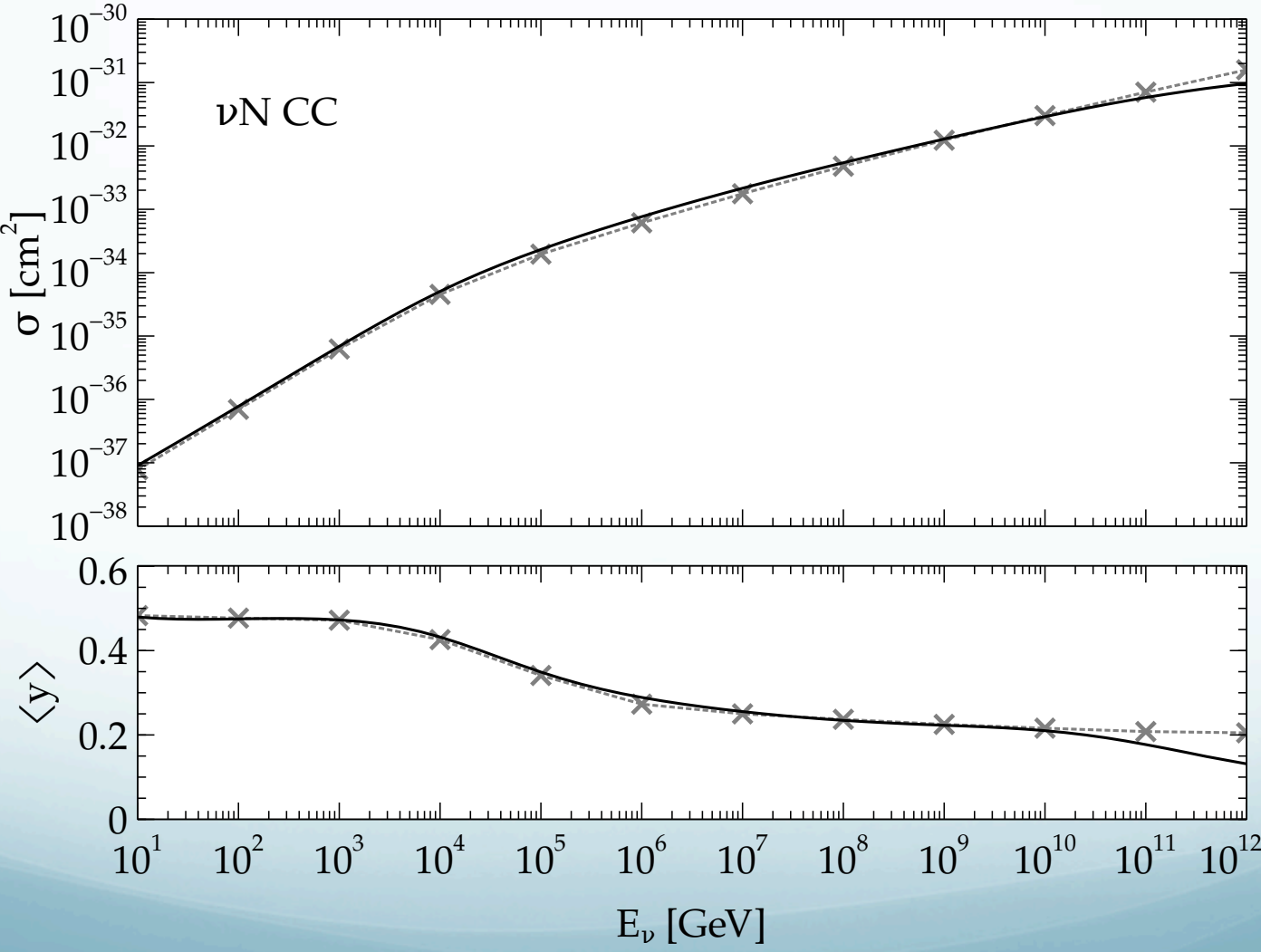
Contributions to the total neutrino cross section



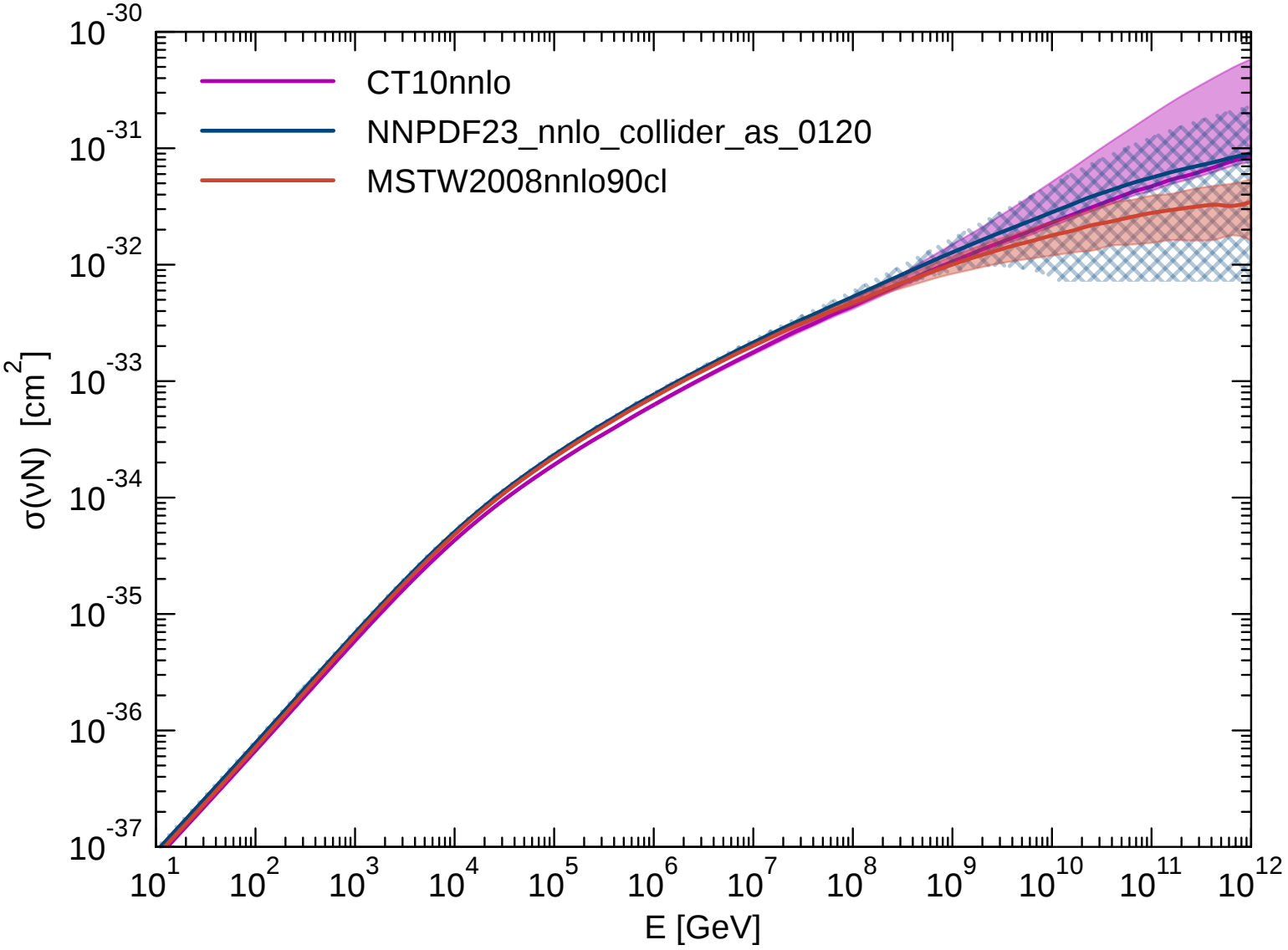
Neutrino Cross Sections

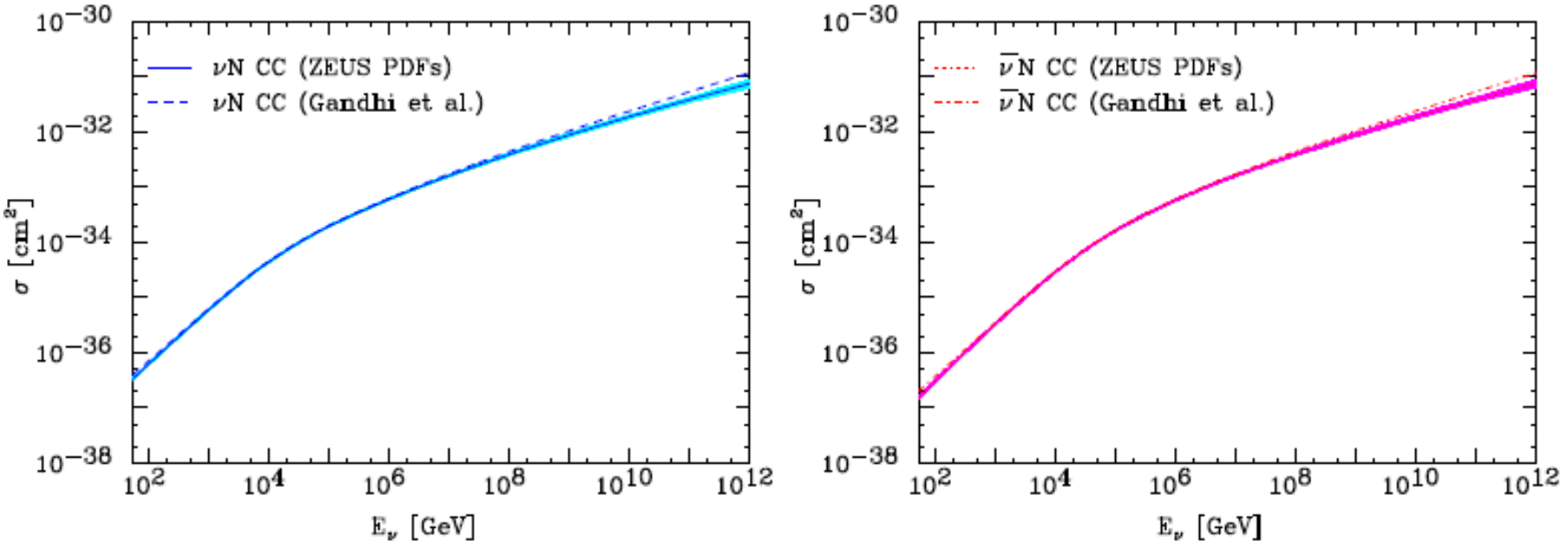


Comparison with GRQS

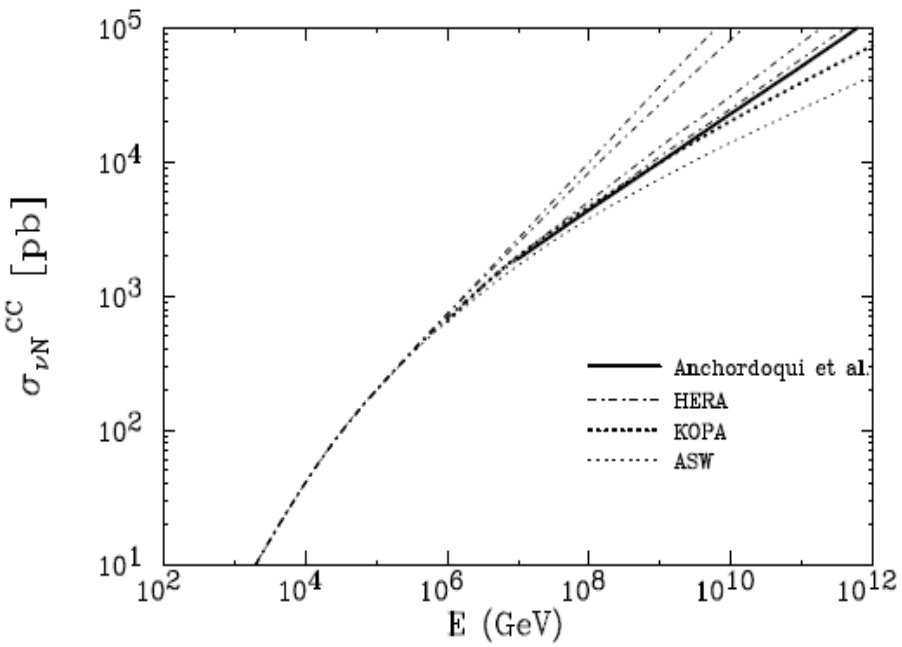


Neutrino Cross Sections





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



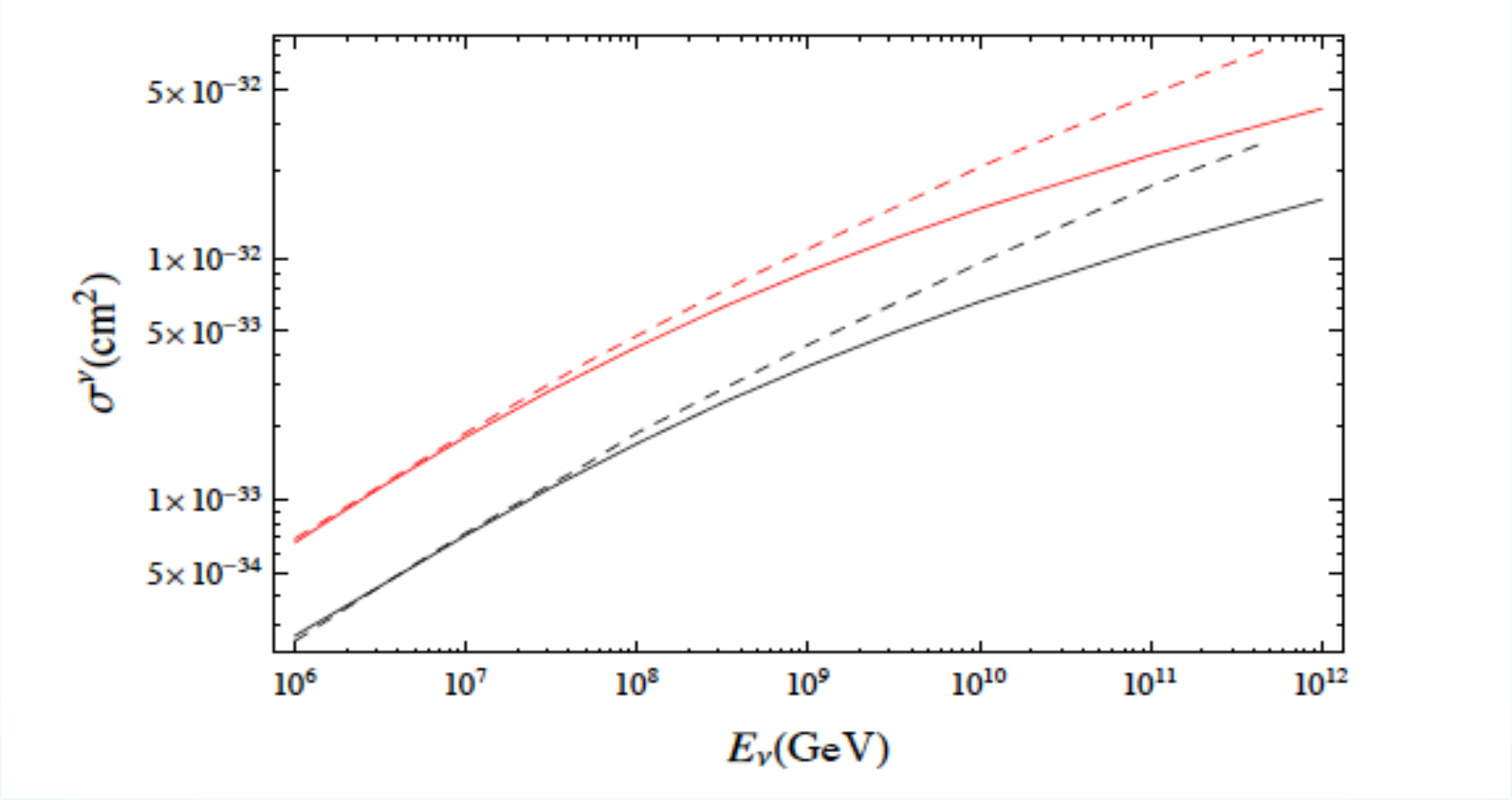
HERA: extrapolations with ¸=0.5,0.4,0.38

KOPA: DLA, Kotikov & Parente

ASW: saturation effects, Armesto, Salgado & Wiedeman

Armesto, Merino, Parente & Zas, PR D 77 (2008)

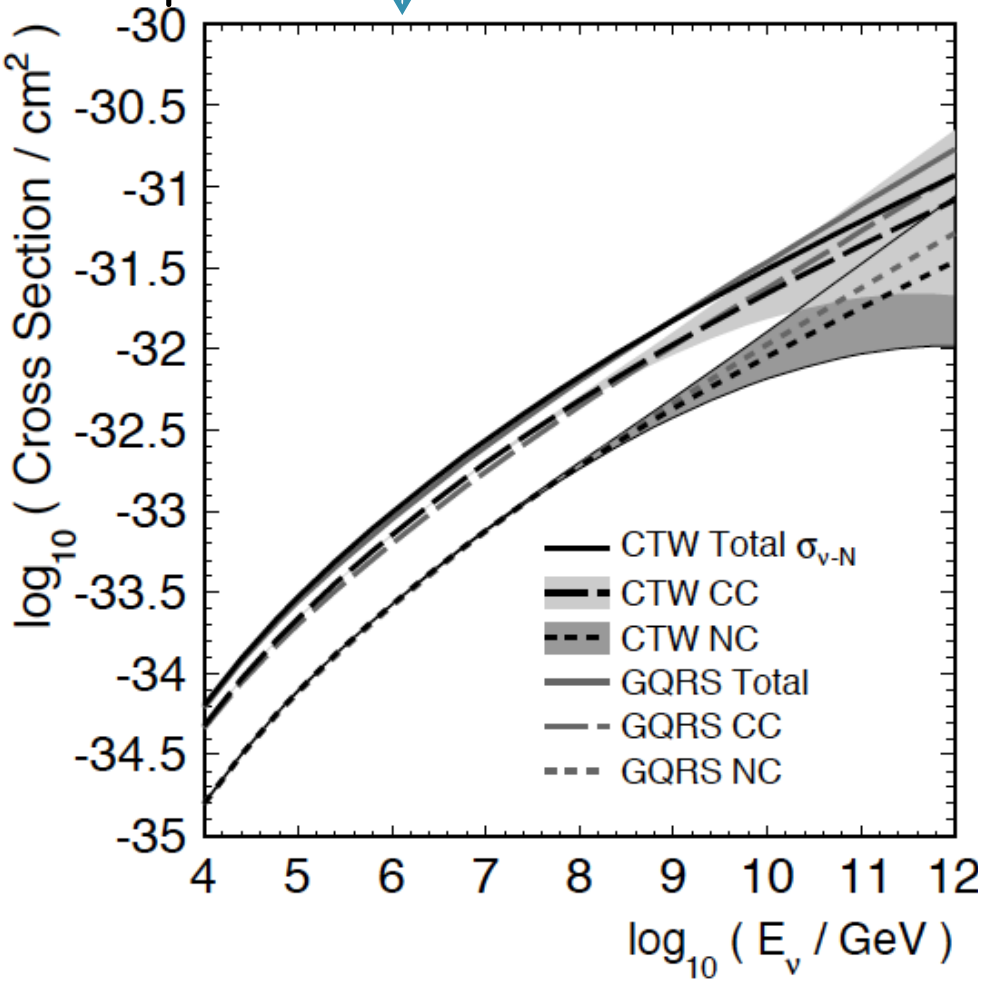
Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, Phys. Rev. D 74 (2006)



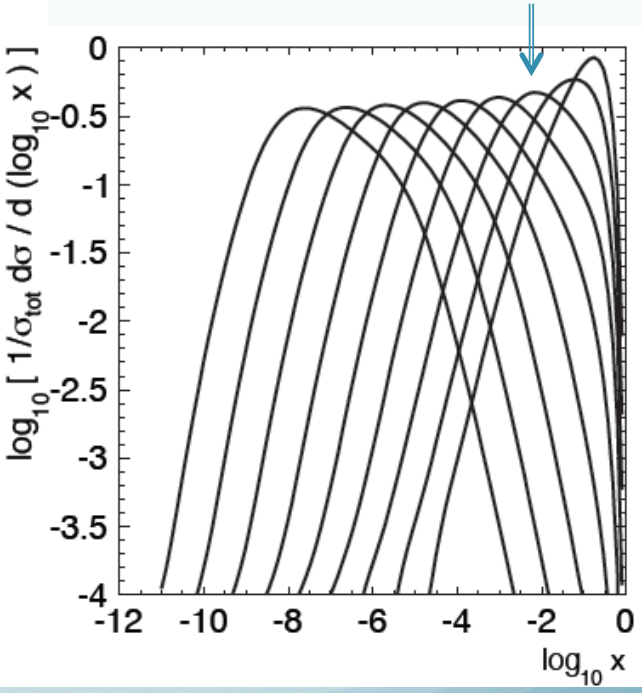
Solid, Block, Durand, Ha & McKay, PRD 89 (2014) from Froissart bounded fit to the electromagnetic structure function F2

Dashed, Cooper-Sarkar, Mertsch & Sarkar, JHEP 1108:42 (2011) from PDF extrapolations

IceCube: PeV, not much uncertainty in this prediction



Block et al., -31.3 at highest energy

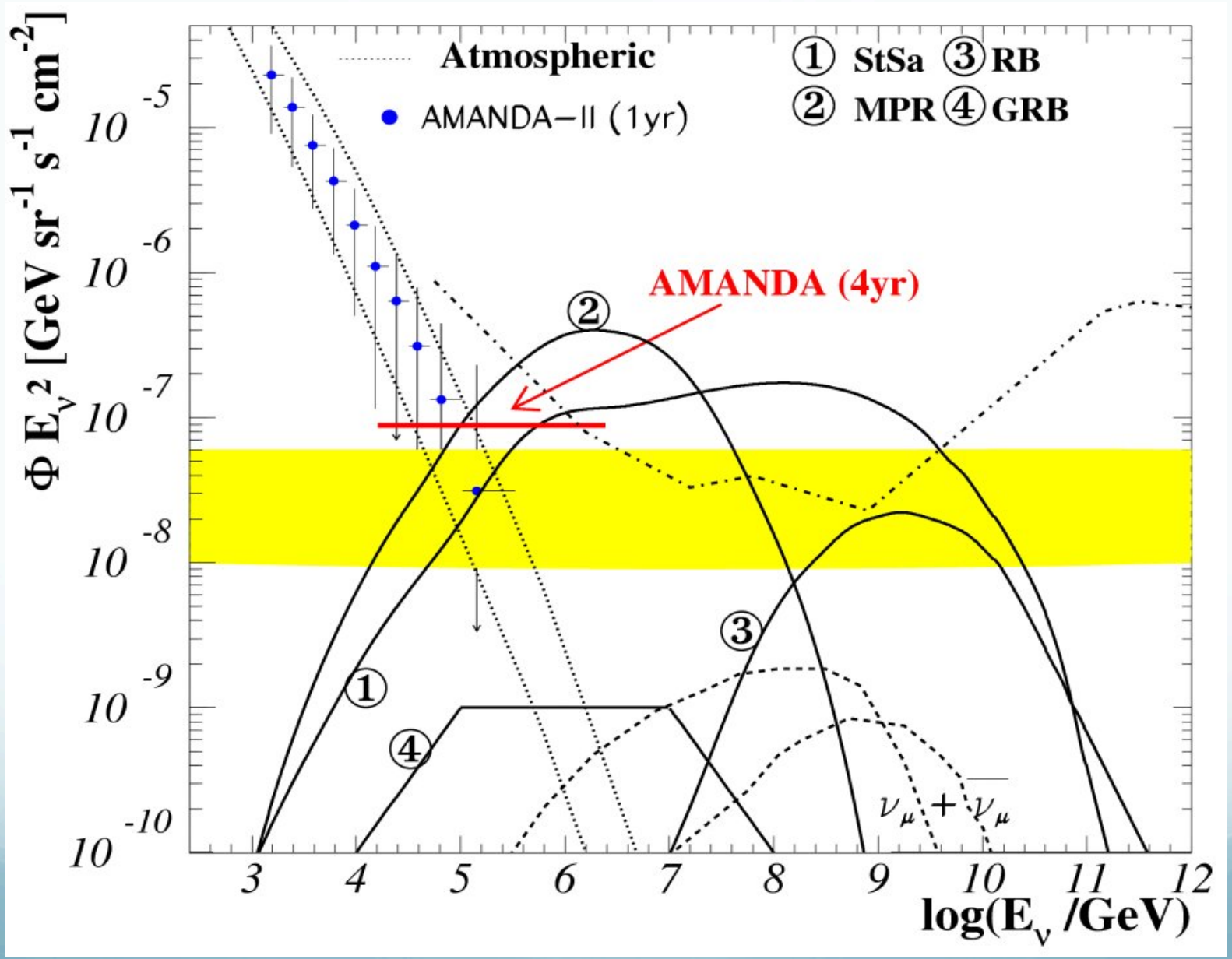


Connolly, Thorne and Waters, PRD 83 (20

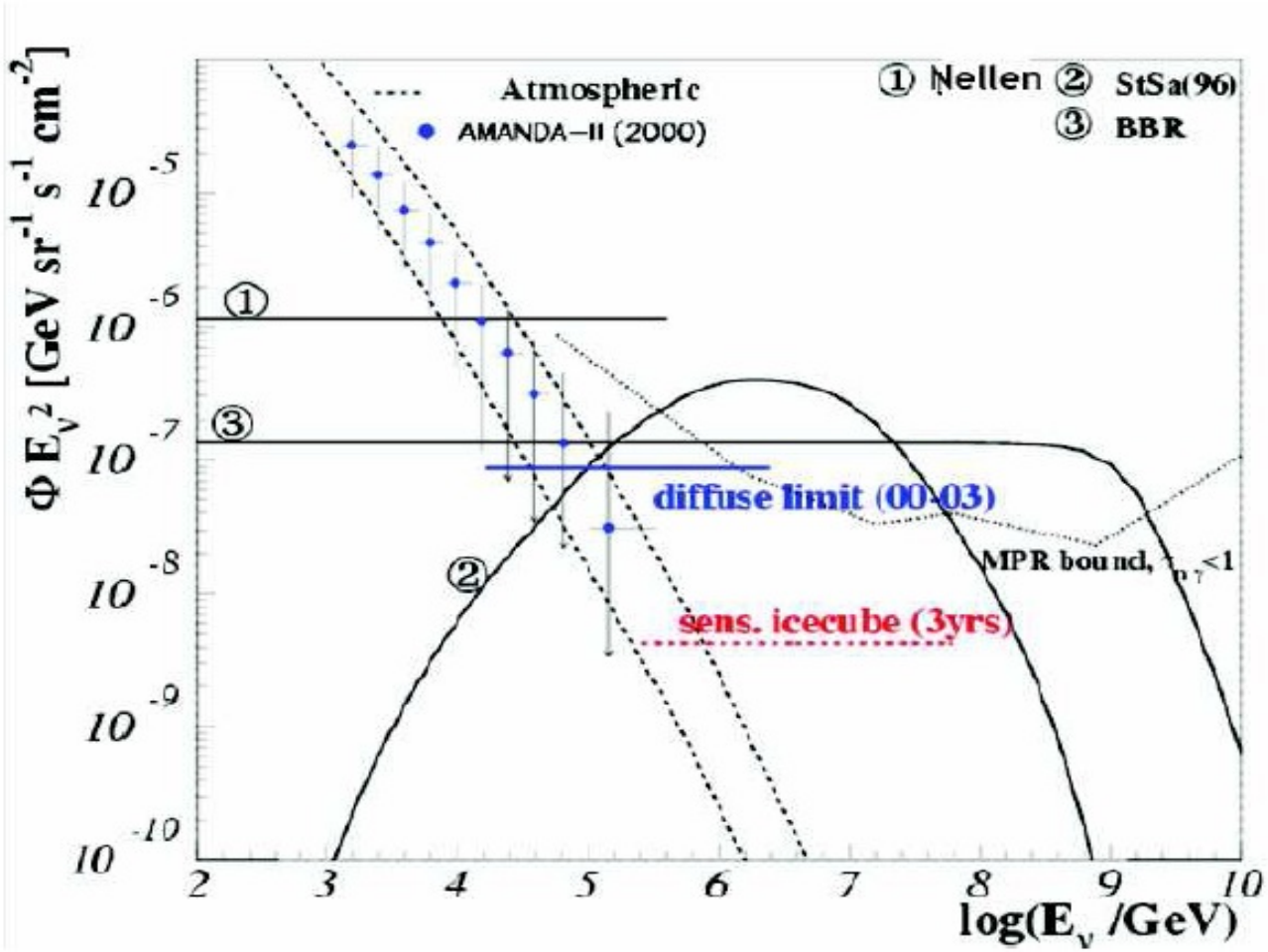
Neutrino Detection

Neutrino Telescopes:

- AMANDA/IceCube/Hypercube
- Antares, Nestor
- RICE
- ANITA, ARIANA
- Pierre Auger
- Euso, OWL


Atmospheric
AMANDA−II (1yr)
① StSa ③ RB
② MPR ④ GRB
AMANDA (4yr)
ΦE_ν^2 [GeV sr^{-1} s^{-1} cm^{-2}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
3
4
5
6
7
8
9
10
11
12
log(E_ν /GeV)
$\nu_\mu + \bar{\nu}_\mu$

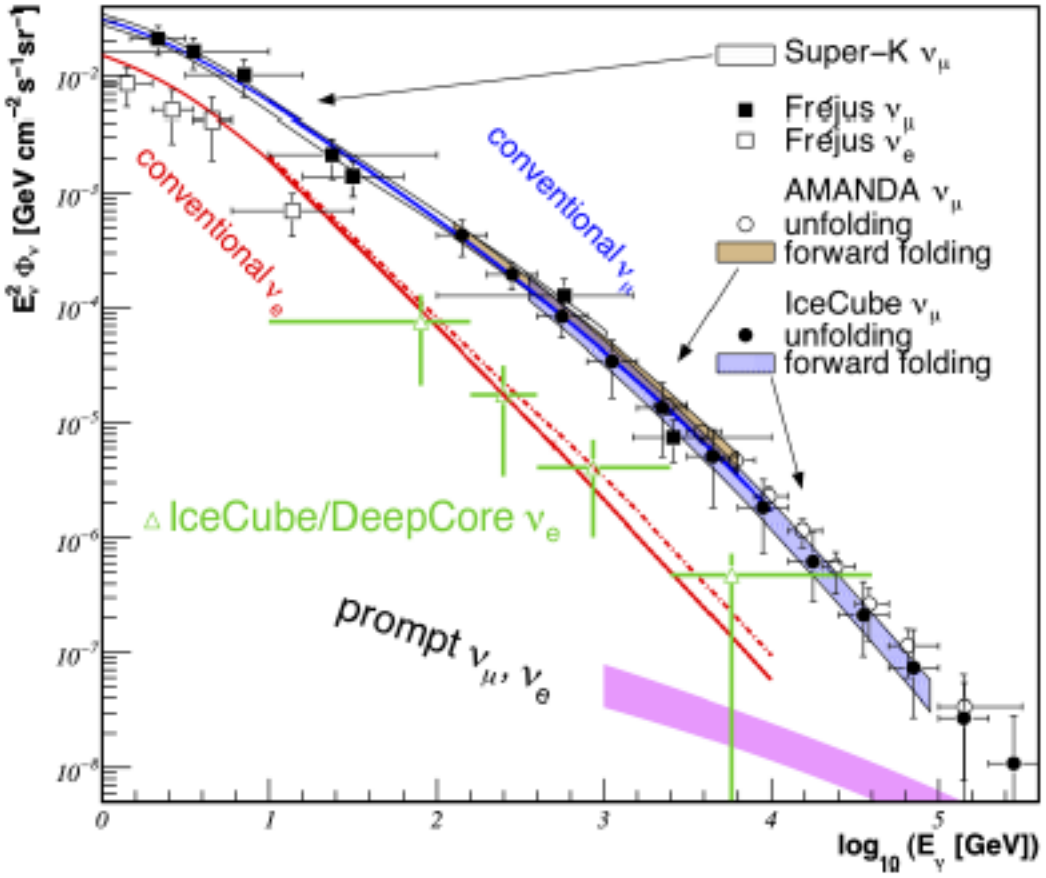
Amanda neutrino flux limit and IceCube sensitivuty



IceCube Collaboration, presented at TeV Particle Astrophysics

Workshop, Madison, August 2006

Atmospheric ν measurements



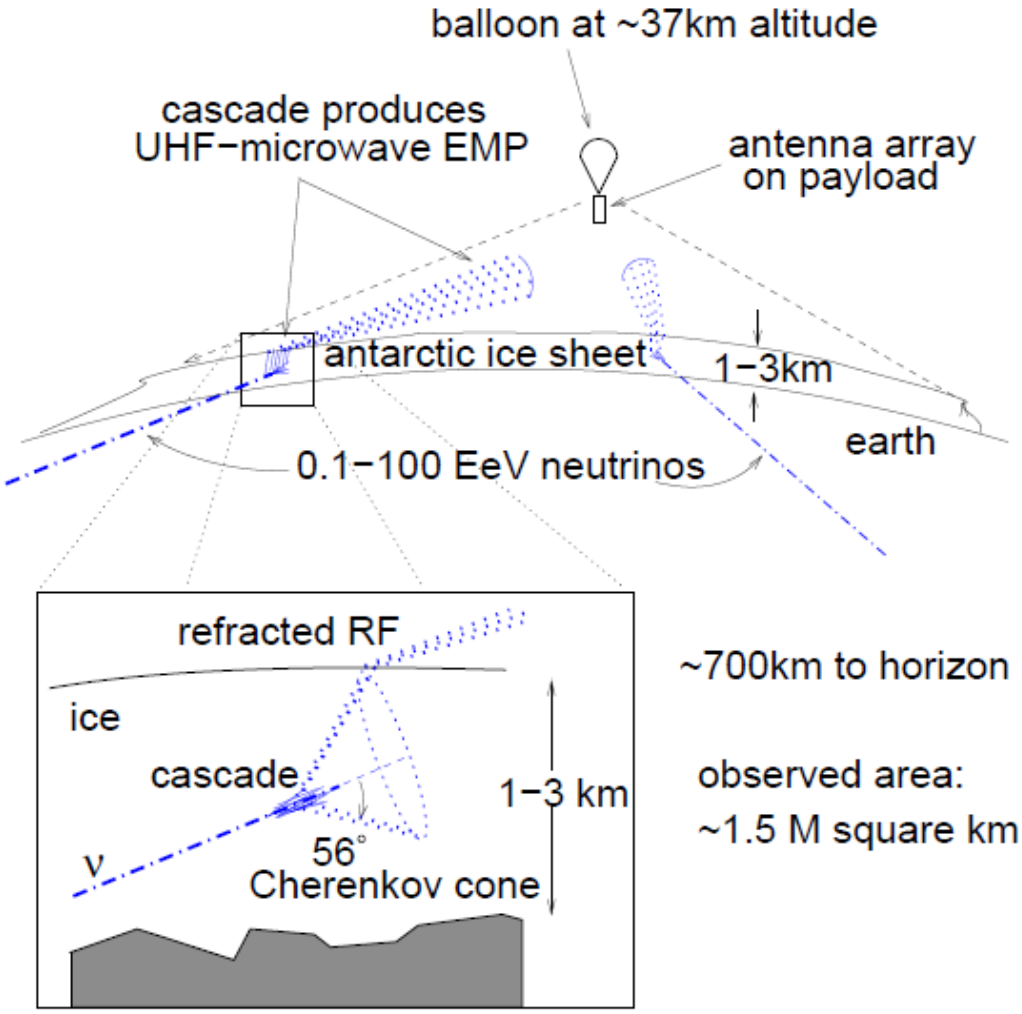
- ν_μ
- Data: 2008-2009
- ***100 GeV to 400 TeV***

Phys. Rev. D 83, 012001 (2011) by IceCube

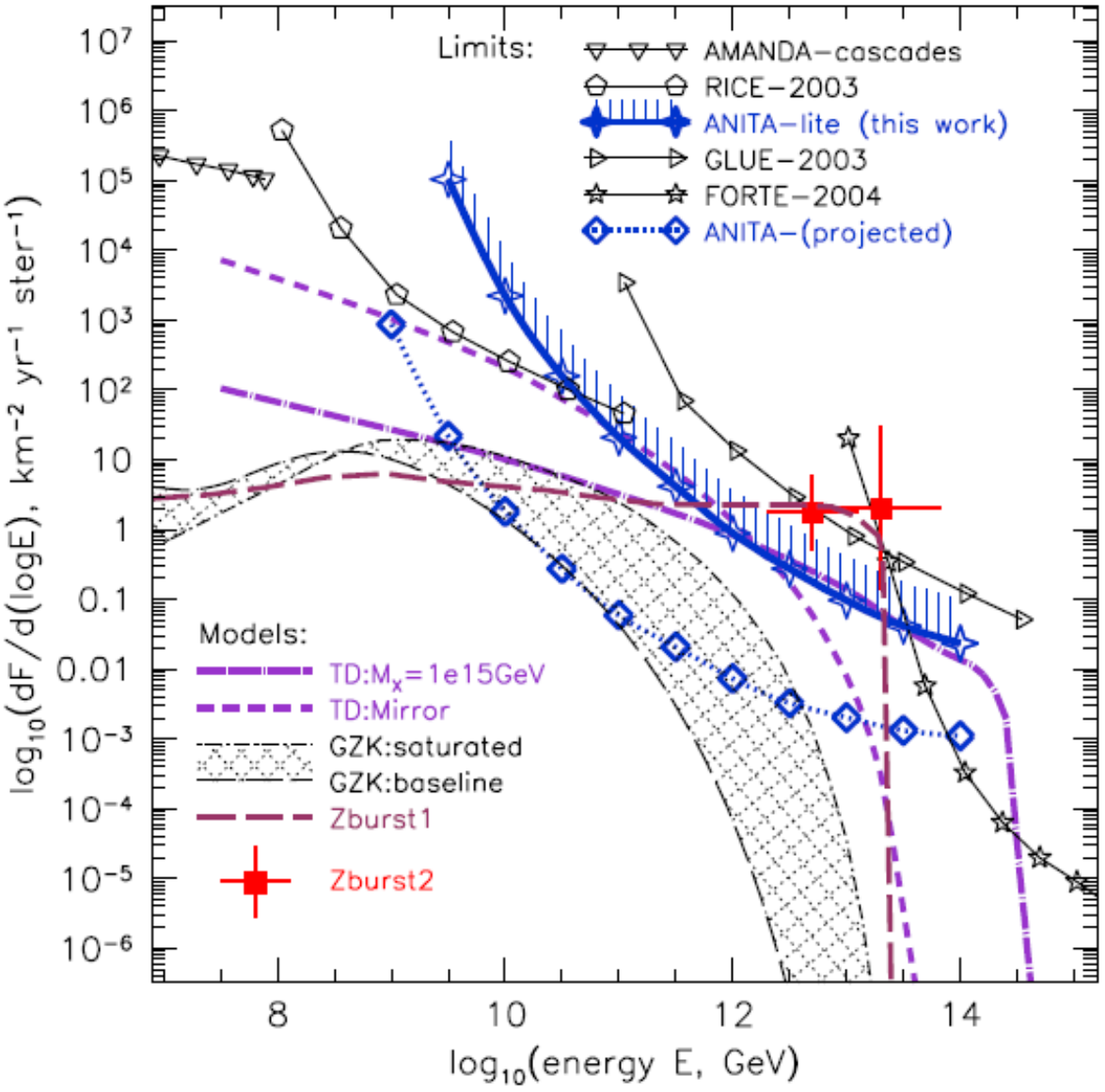
- ν_e
- Data: 2010-2011
- DeepCore
- ***80 GeV to 6 TeV***

Phys. Rev. Lett. 110, 151105 (2013) by IceCube

ANITA: Antarctic Impulsive Transient Antenna

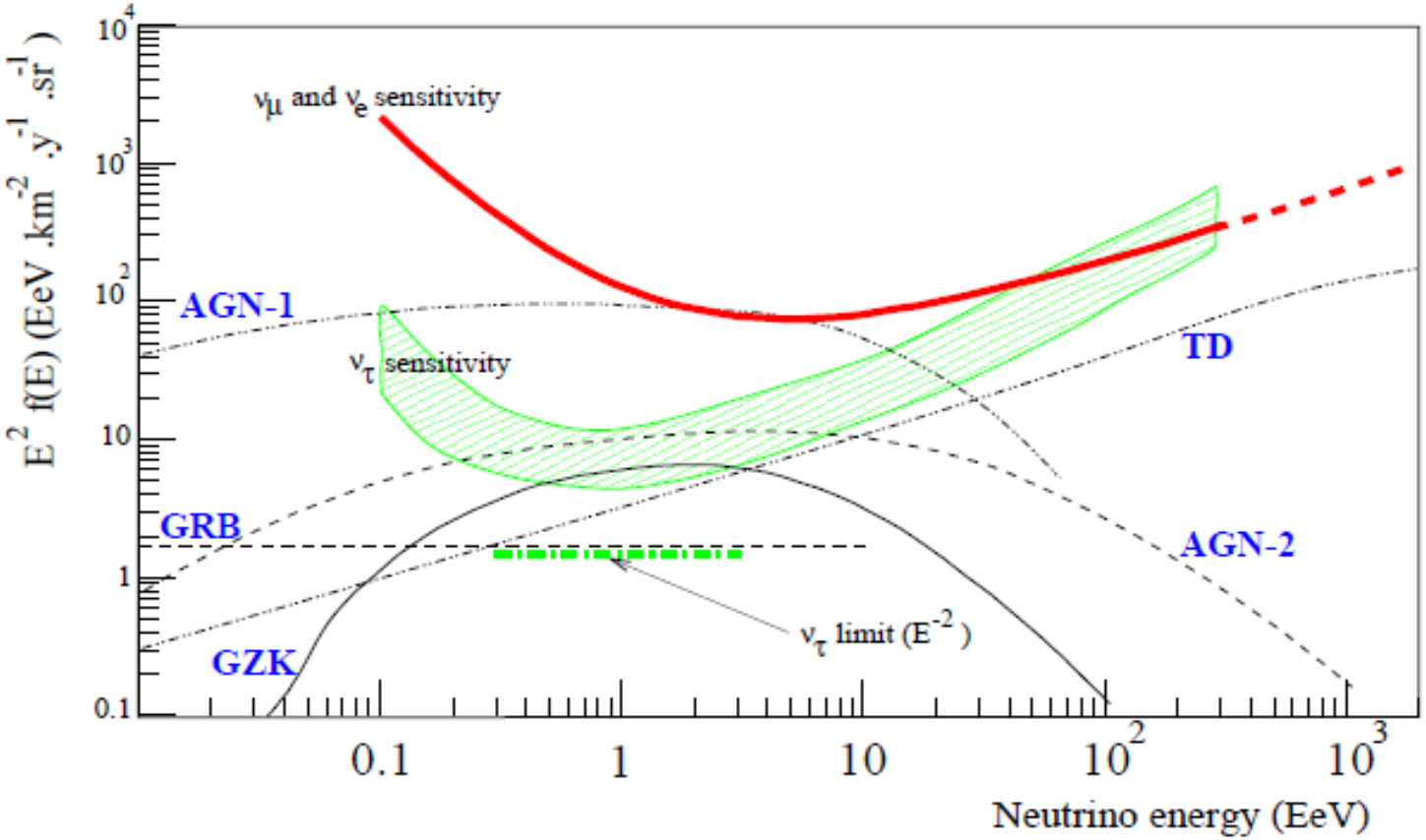


Neutrino Flux limits (ANITA and ANITA-lite)



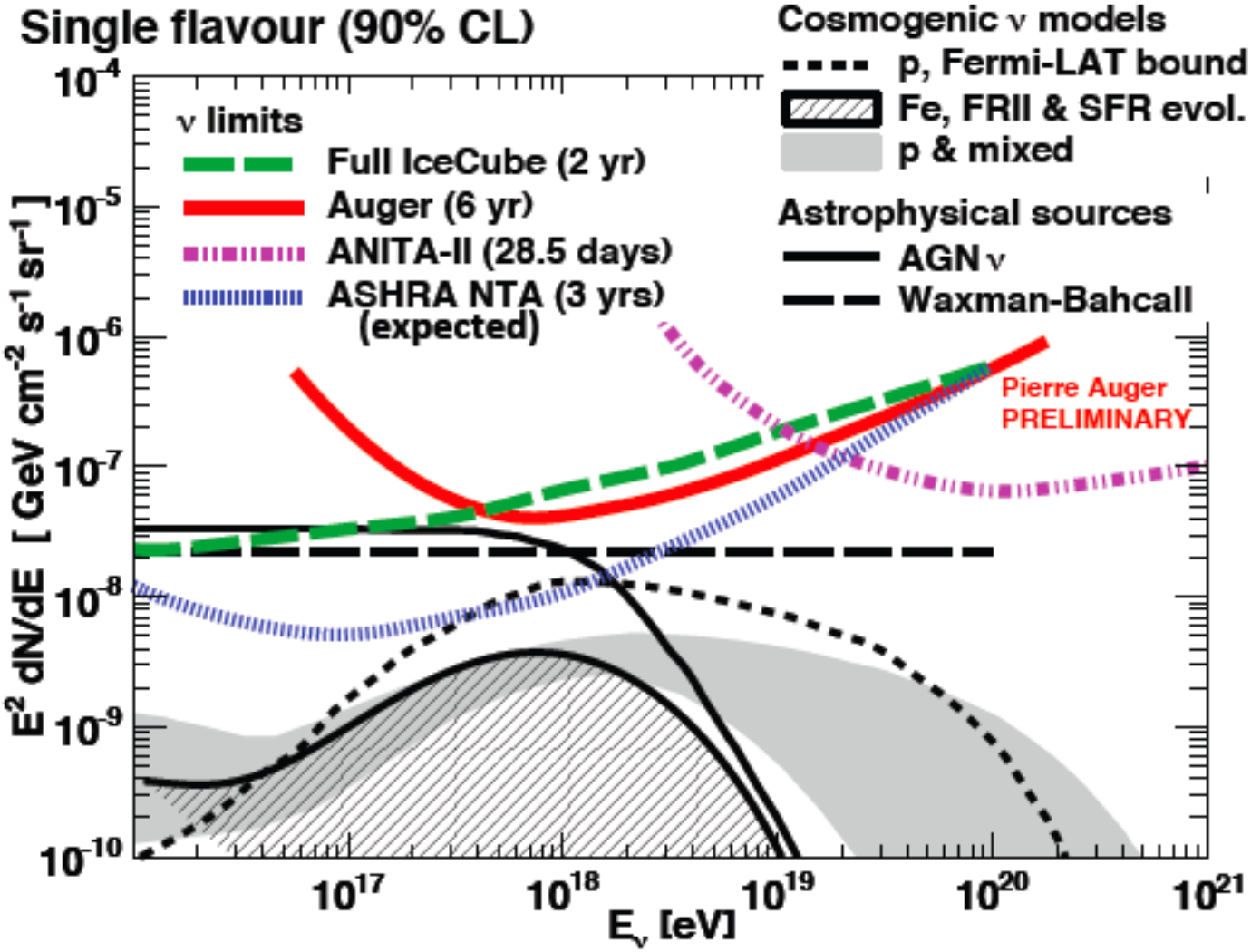
Anita Collaboration, PRL 96 (2006)

Auger neutrino flux sensitivity



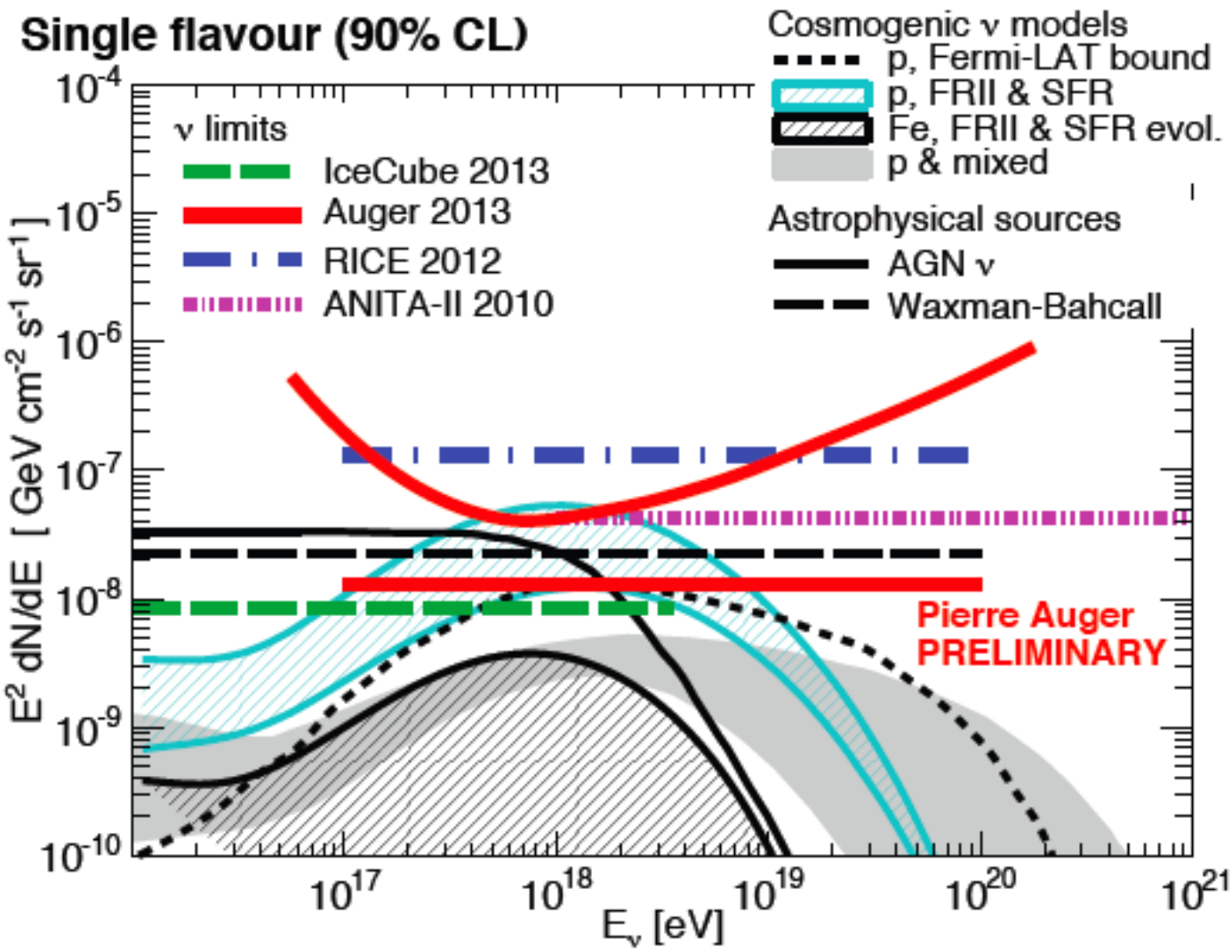
X. Bertou et al., Astropart. Phys. 17 (2002)

Differential limits to diffuse flux of UHEν



Jaime Alvarez-Muniz (for Auger), VHEPA2014

Limits to diffuse flux of UHEν

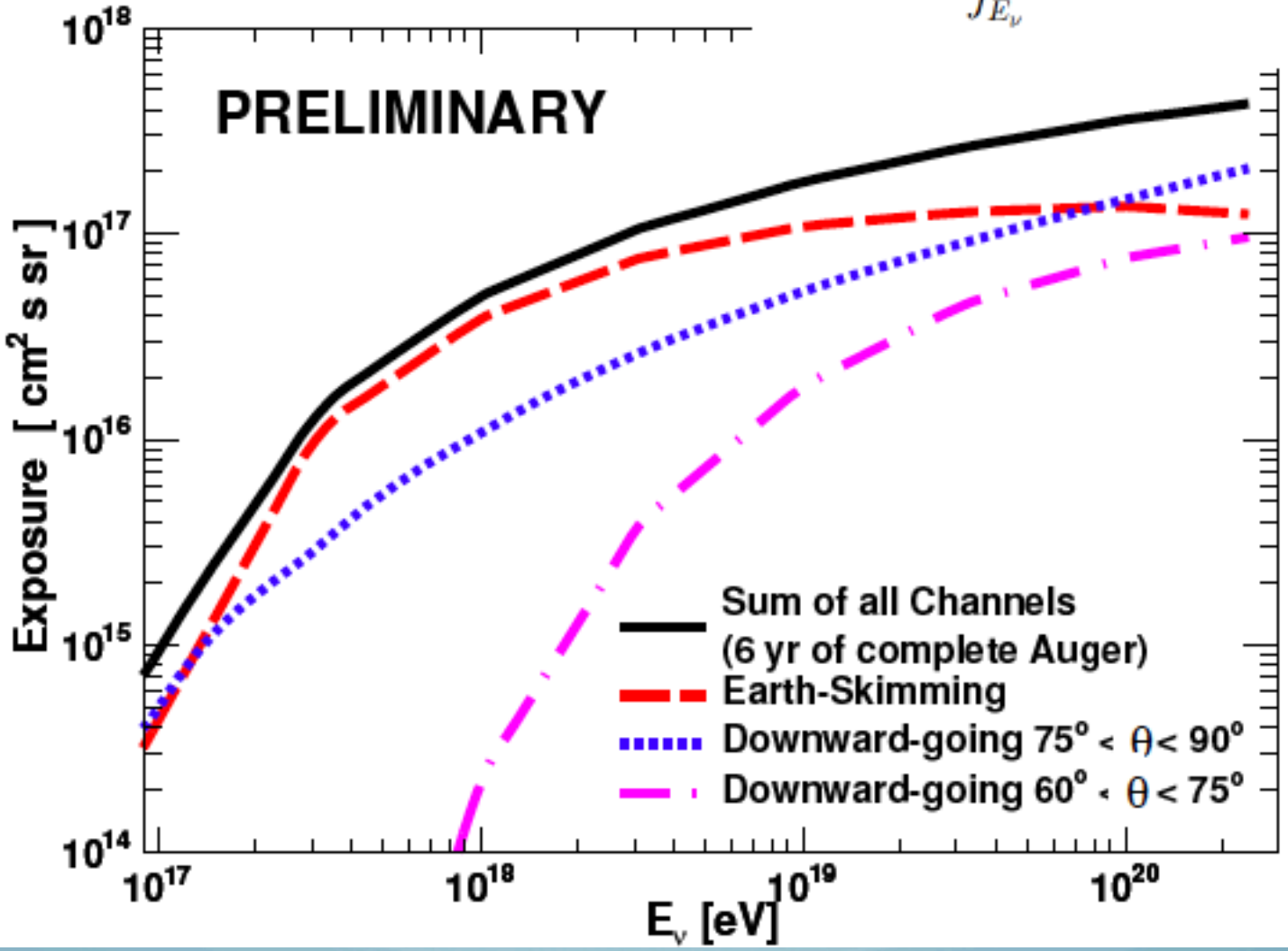


Jaime Alvarez-Muniz (for Auger), VHEPA2014

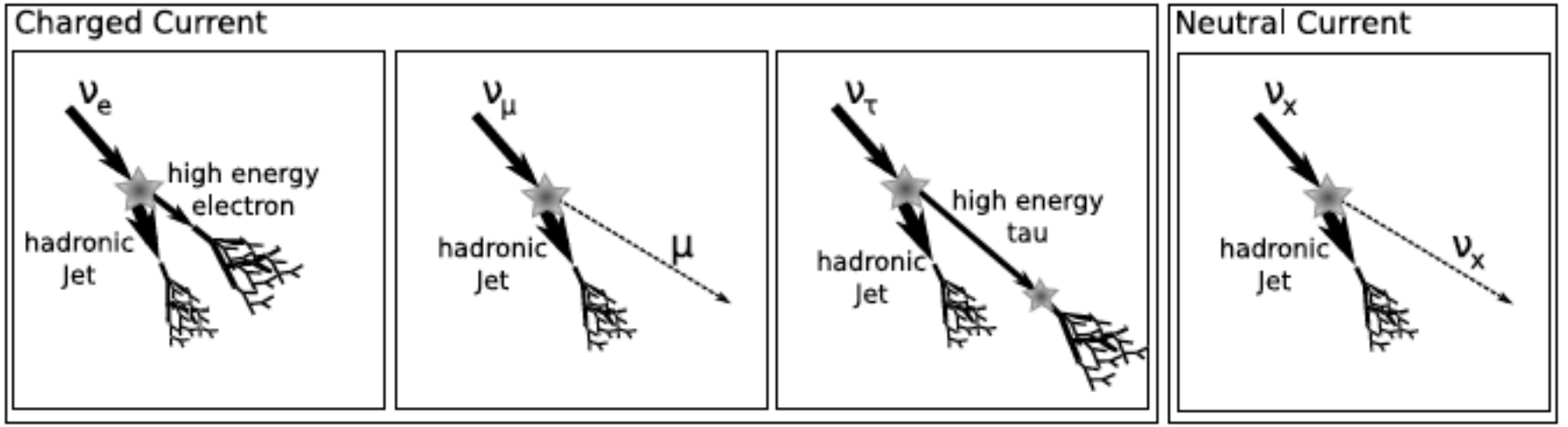
Exposure: 1 Jan 04 – 31 Dec 12

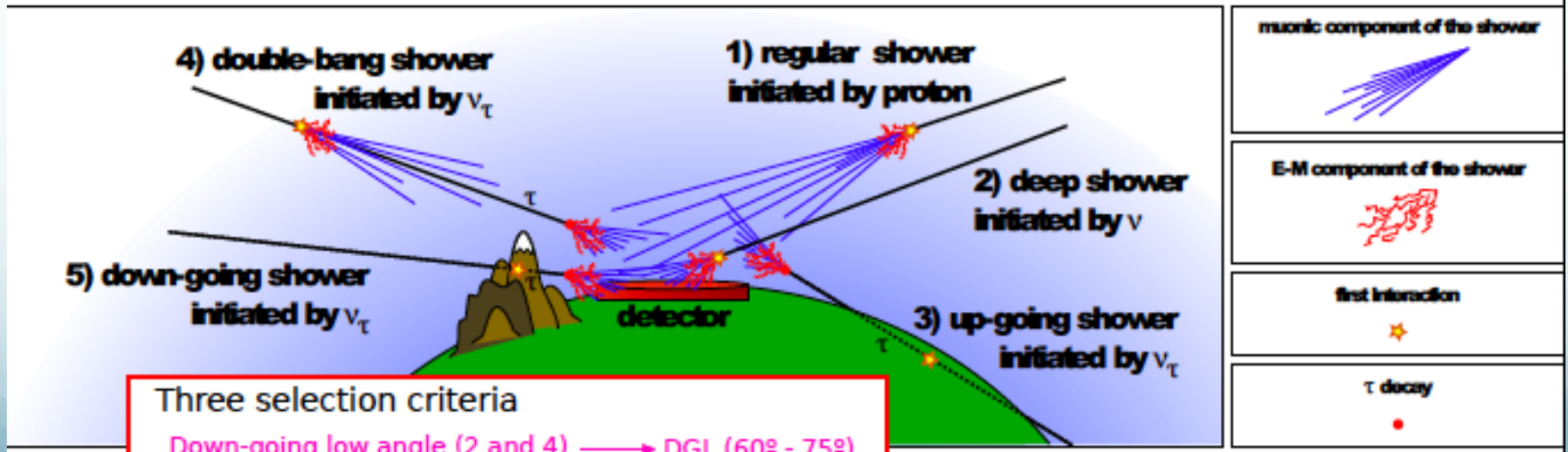
(excluding training data periods)

$$N_{\text{events}} = \int_{E_\nu} \Phi(E_\nu)\, \varepsilon_{\text{tot}}(E_\nu)\, \mathrm{d}E_\nu$$



Sensitivity to all flavours & channels





Three selection criteria

Down-going low angle (2 and 4) → DGL (60º - 75º)
Down-going high angle (2, 4 and 5) → DGH (75º - 90º)
Earth-skimming (3) → ES (90º - 95º)

Auger sensitivity to UHE neutrinos

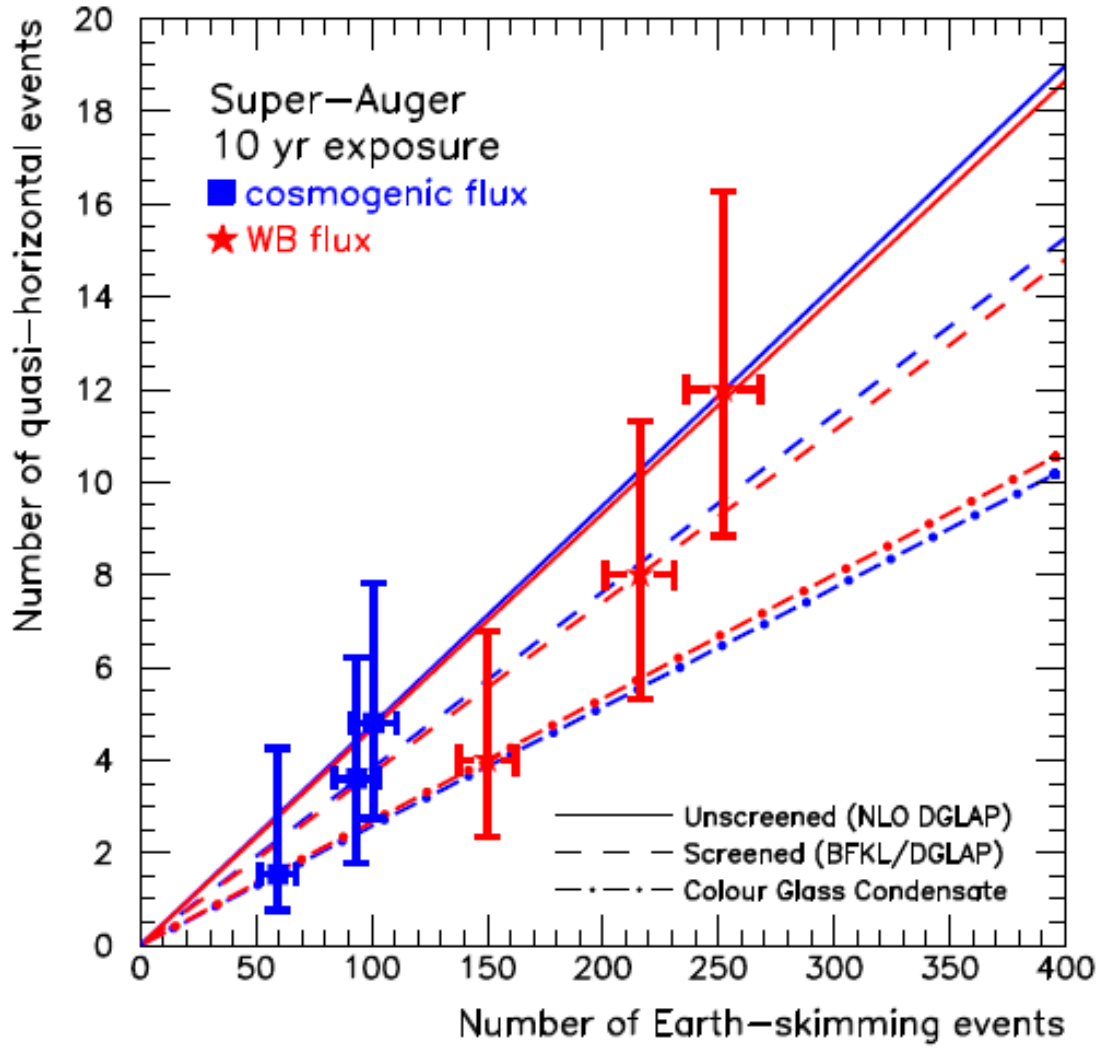
- Auger is not a dedicated neutrino observatory but …

with the **surface detector** we have good sensitivity to UHE neutrinos at EeV energies and above.

- Challenge: Identifying **neutrino-induced showers** in the dominant background of showers induced by cosmic rays (p & nuclei).

- The interaction probability & discrimination power is enhanced when looking at **inclined showers:** $\theta > 60^{o}$

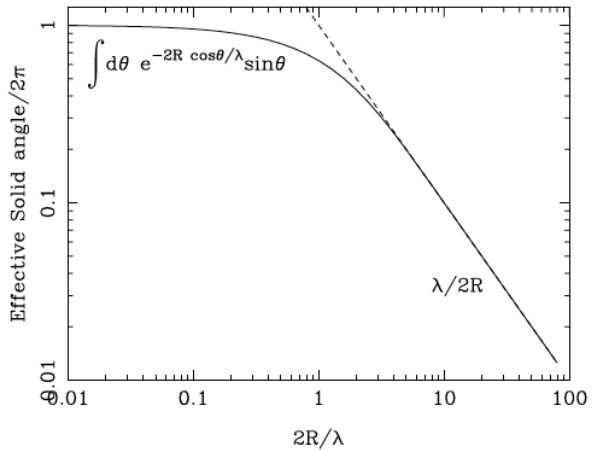
Determining UHE Neutrino Cross Sections

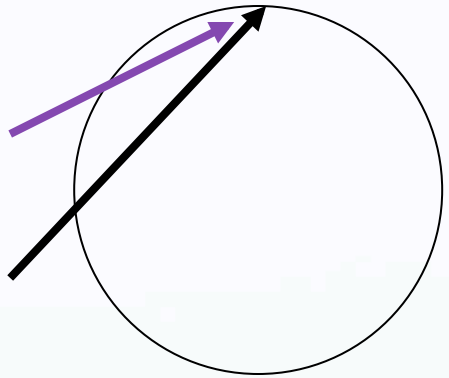


Anchordoqui et al., PR D76 (2007)

$$\mathcal{N}_{\rm QH} \propto \int {\rm d}E_{\rm sh}\ \sigma_{\nu N}(E_\nu)\ A_{\rm QH}(E_{\rm sh},\theta_{\rm z})\ \phi^{\nu}(E_\nu)$$

Angle-integrated upward rate



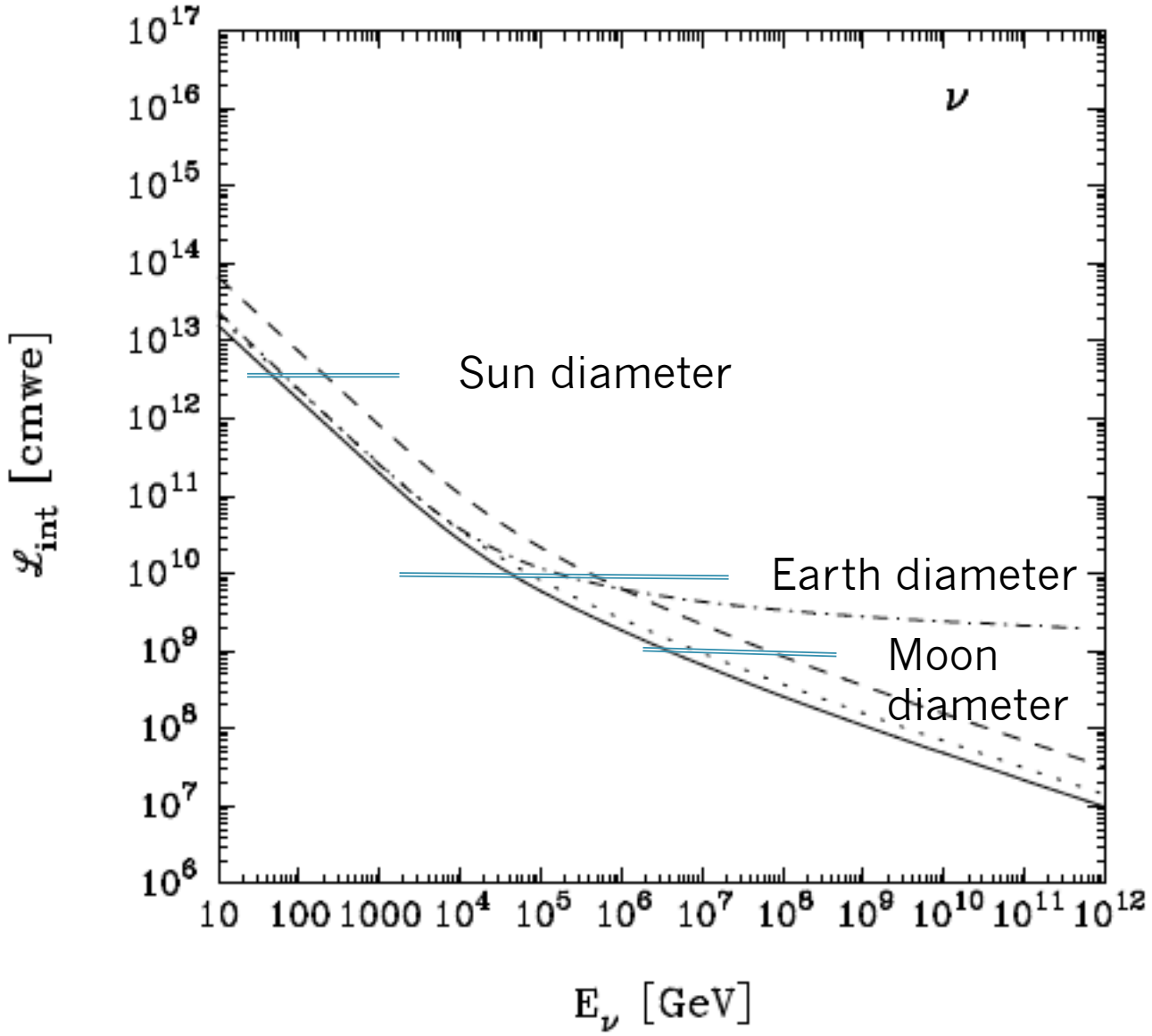


Effective solid angle scales as the inverse cross section for strong attenuation.

Hussain, Marfatia, McKay, PRD 77 (2008), see also Hussain, Marfatia, McKay & Seckel, PRL 97 (2006) Jeong, Reno, Sarcevic, Astropart. Phys. (2012)

- 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).

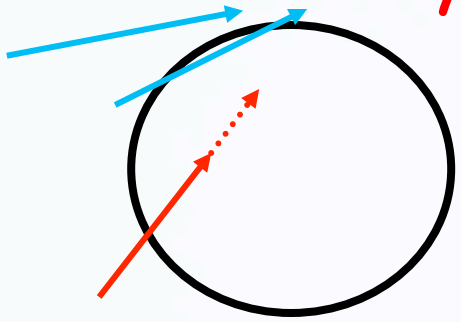
Interaction length, neutrino nucleon scattering



Atmospheric column depth:

Vertical: 1,033 cmwe
Horizontal: 36,000 cmwe

Sensitivity to the neutrino nucleon cross section



- Starting with an unknown flux, upward going skimming tau neutrinos (with attenuation) versus horizontal air showers

Kusenko, Weiler, PRL 88 (2002), Anchordoqui, Han, Hooper, Sarkar, Astropart. Phys. 25 (2006), Anchordoqui et al. PRD 82 (2010)

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

Barwick, ICRC 07 Proceedings

UHE neutrino cross section tied to hadronic physics, described by the structure functions which has large uncertainty at low x

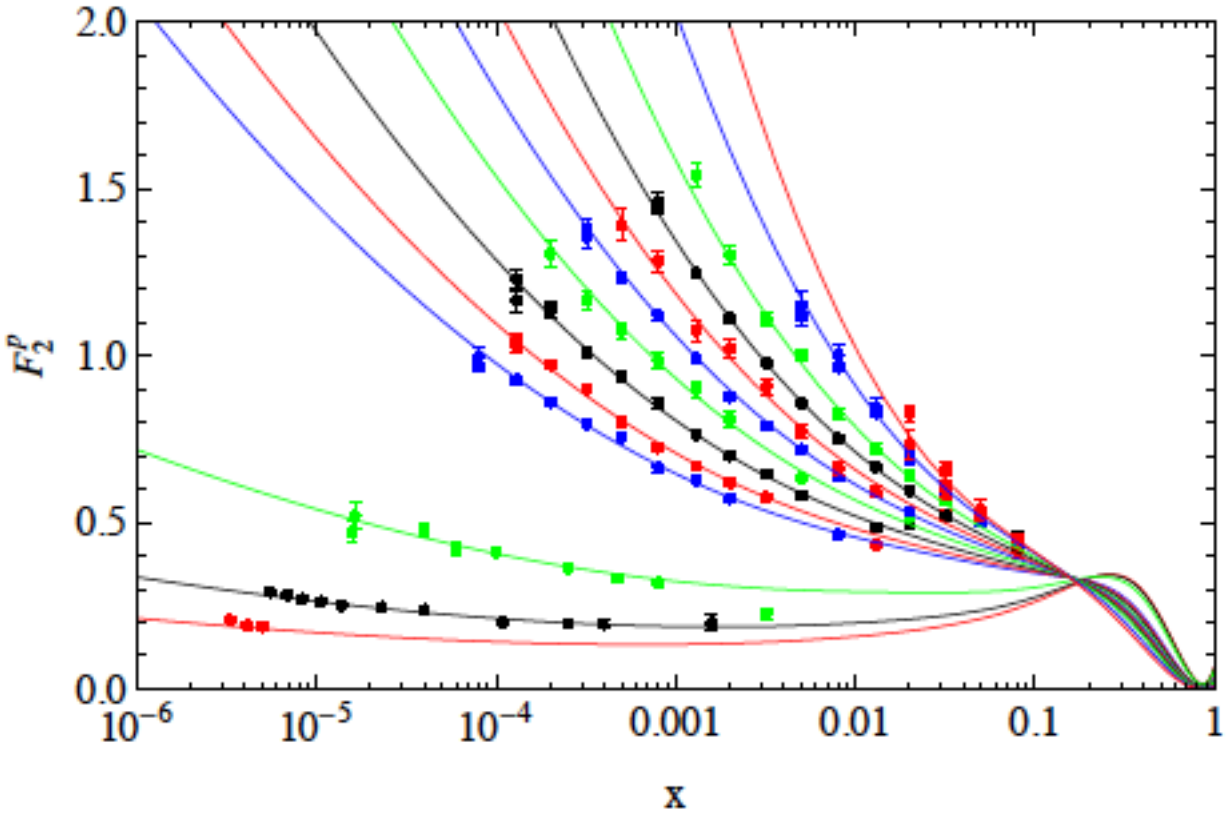
Unknown flux normalization makes determining the cross section difficult, but the cross section does cancel out in integrated solid angle * interaction probability.

Conclusions

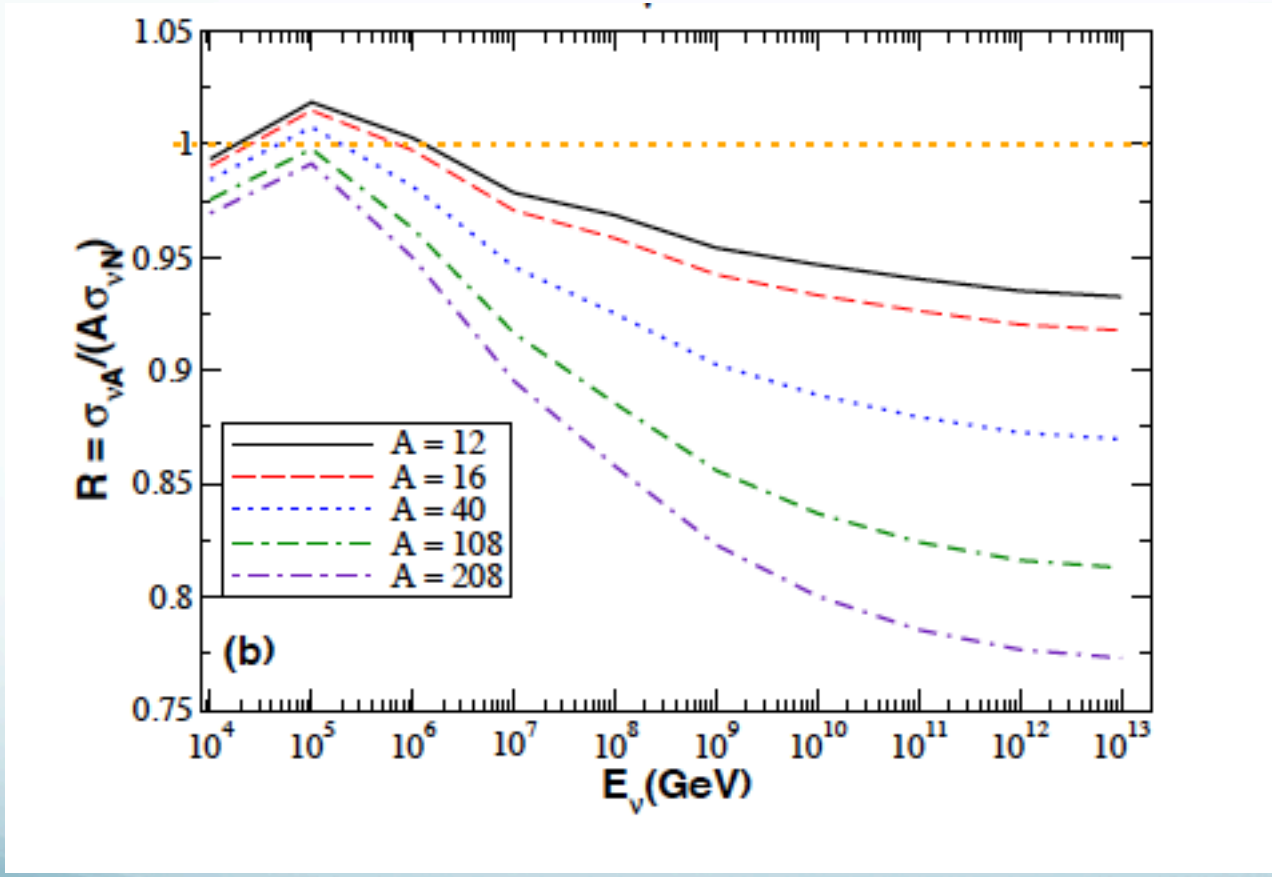
- Atmospheric neutrinos detected up to PeV energies. IceCube has recently detected large excess; potentially astrophysical neutrinos
- Neutrino detection depends on neutrino cross section which relies on small-x extrapolations of parton distributions (large Q^2) well beyond the experimental measurements
- Cosmic neutrinos can be used as probes of small-x QCD

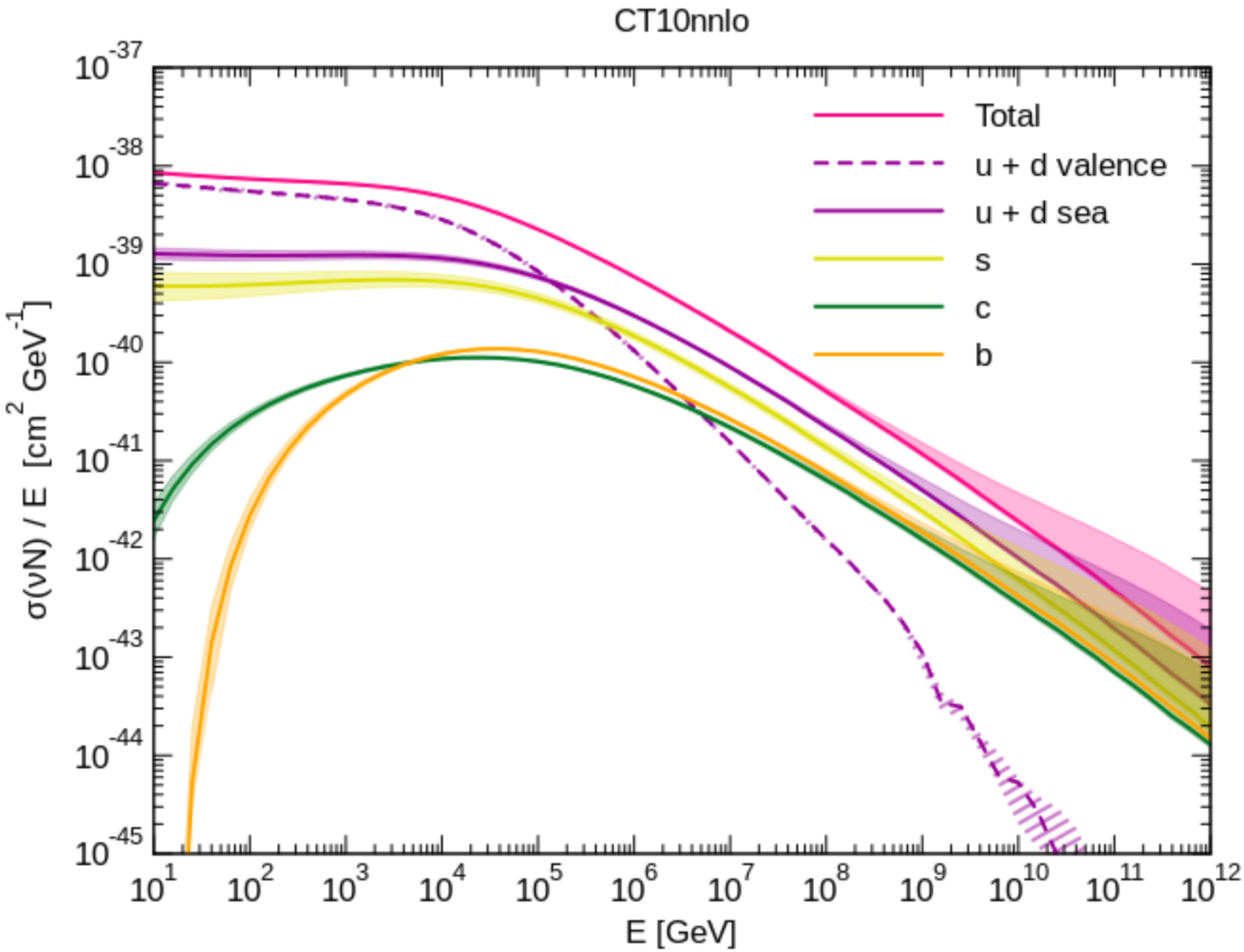
- UHE neutrino cross section depends on extrapolations well beyond experimental measurements, however, many extrapolations end in the same "neighborhood" for the cross section.
    - The cross section affects overall event rates, but also attenuation.

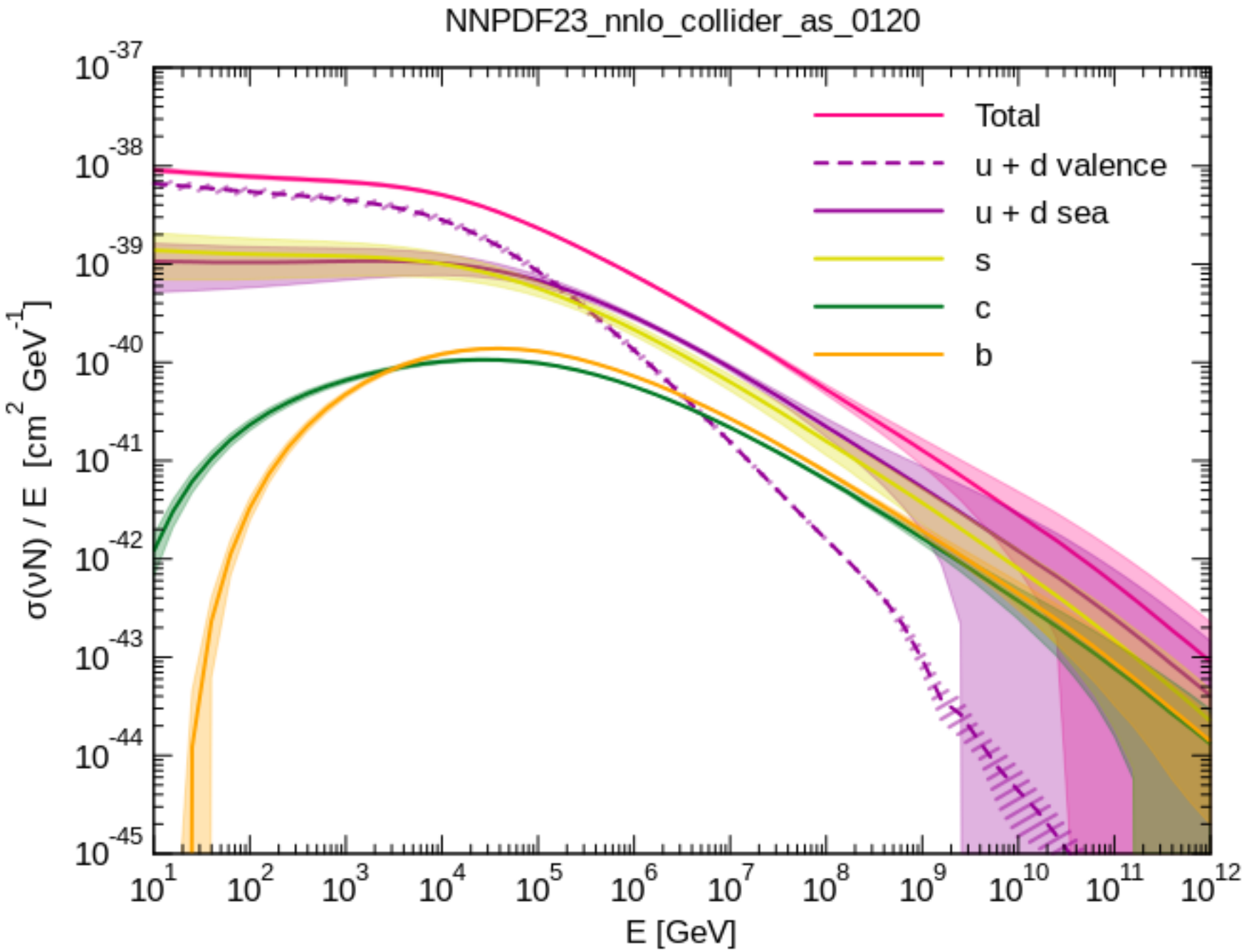
Back-up Slides

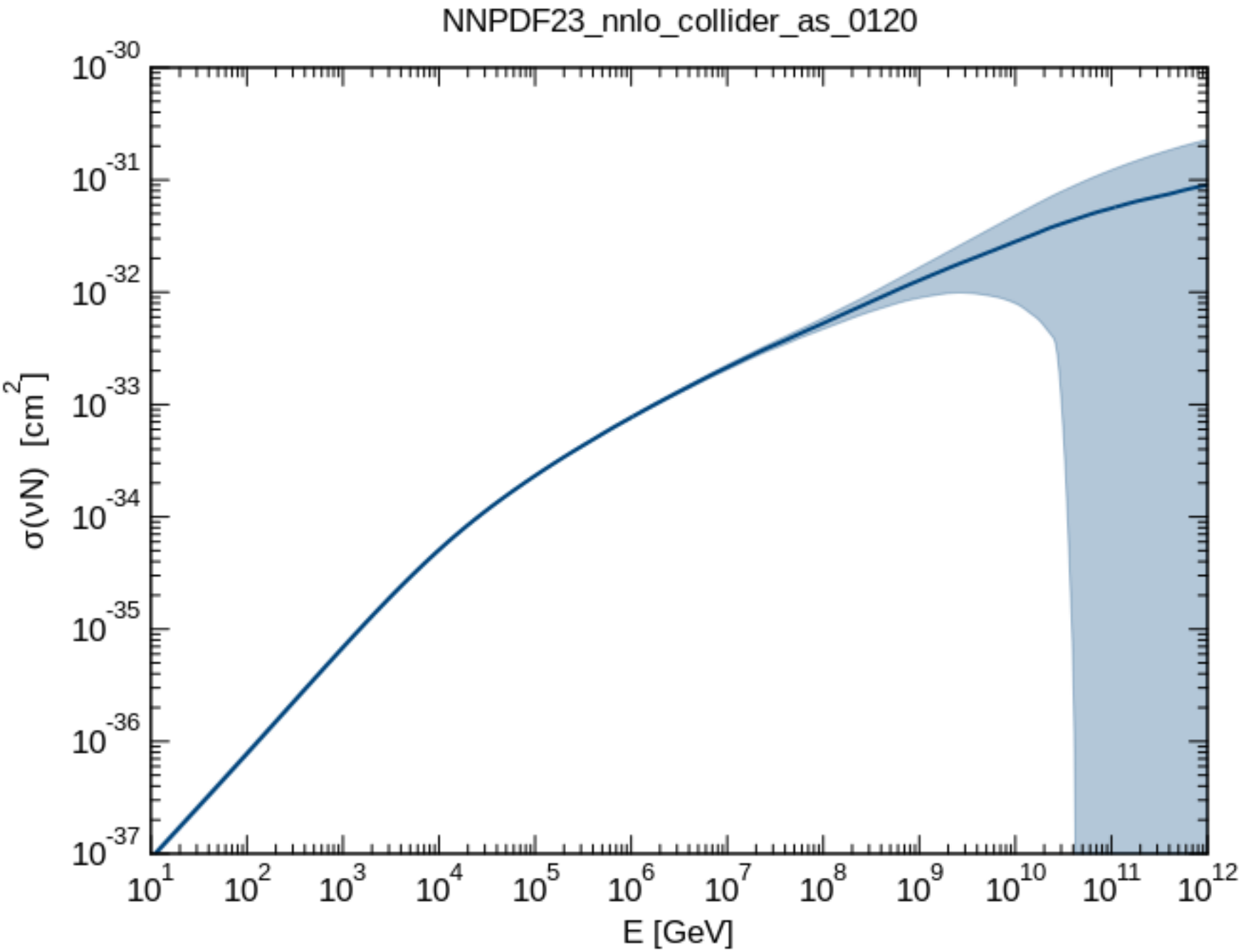

2.0
1.5
1.0
0.5
0.0
F_2^p
10^{-6}
10^{-5}
10^{-4}
0.001
0.01
0.1
1
x

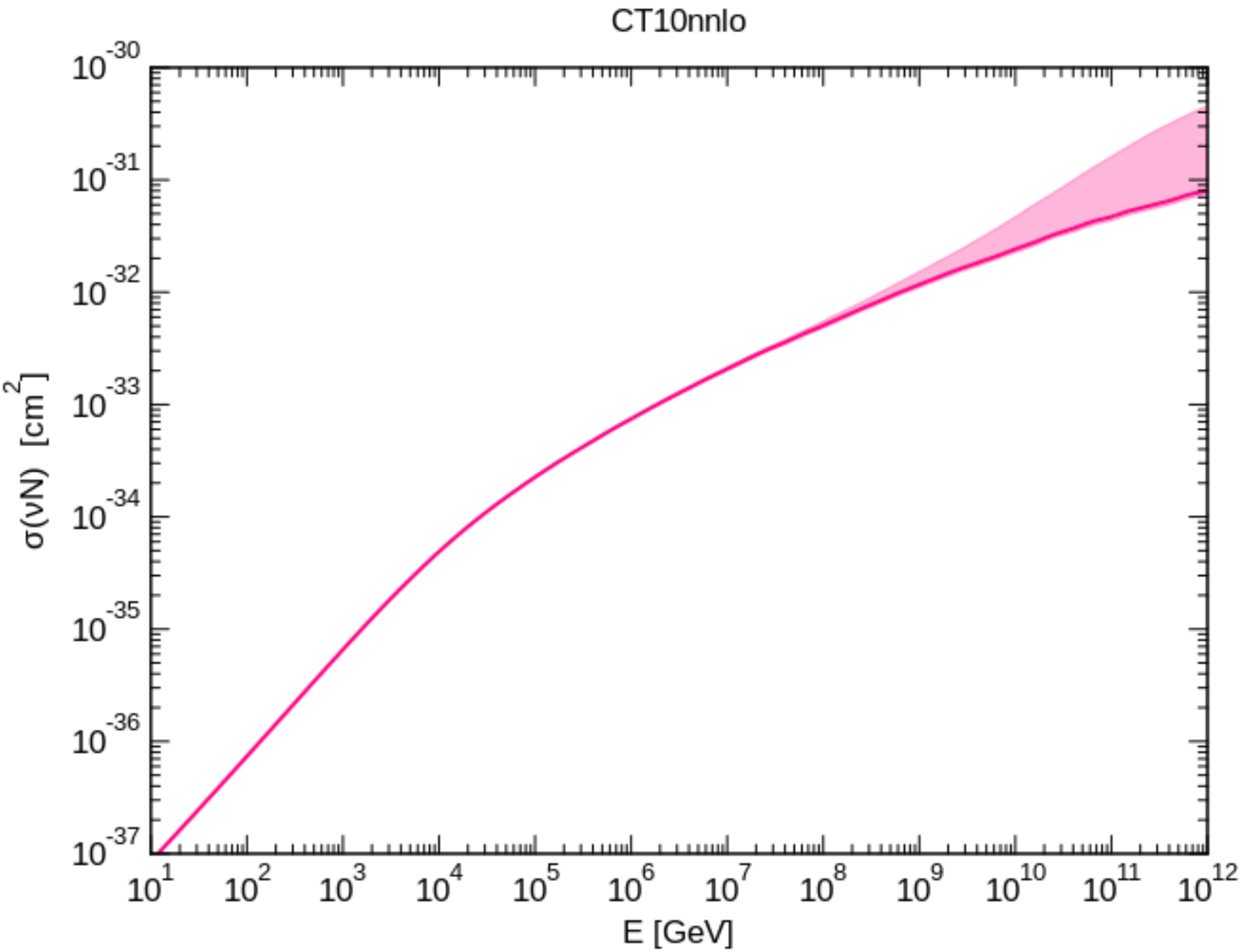
Nuclear effects, for example, Goncalves and Gratieri, arXiv:1307.1621, still uncertainties in proper treatment of nuclei.

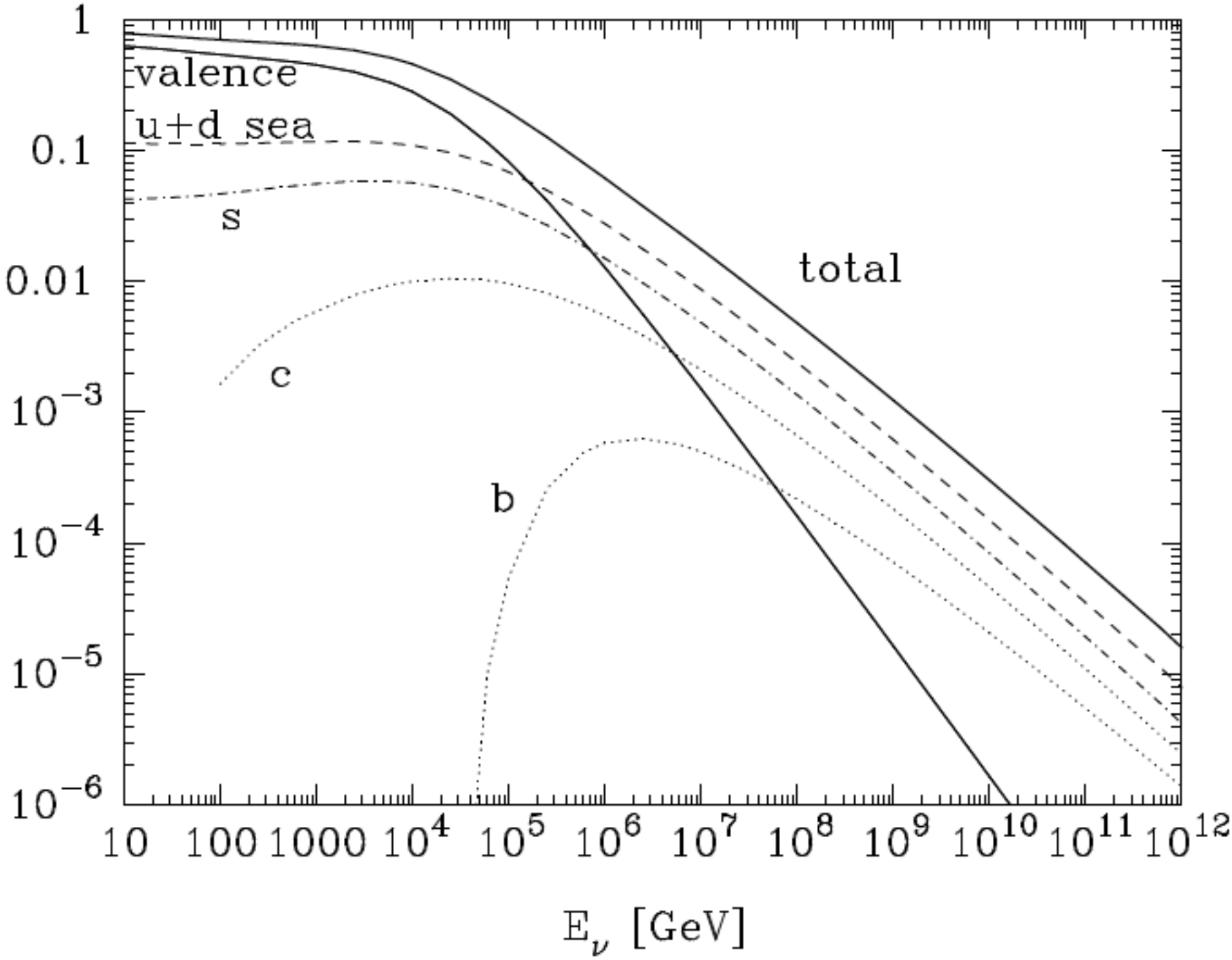


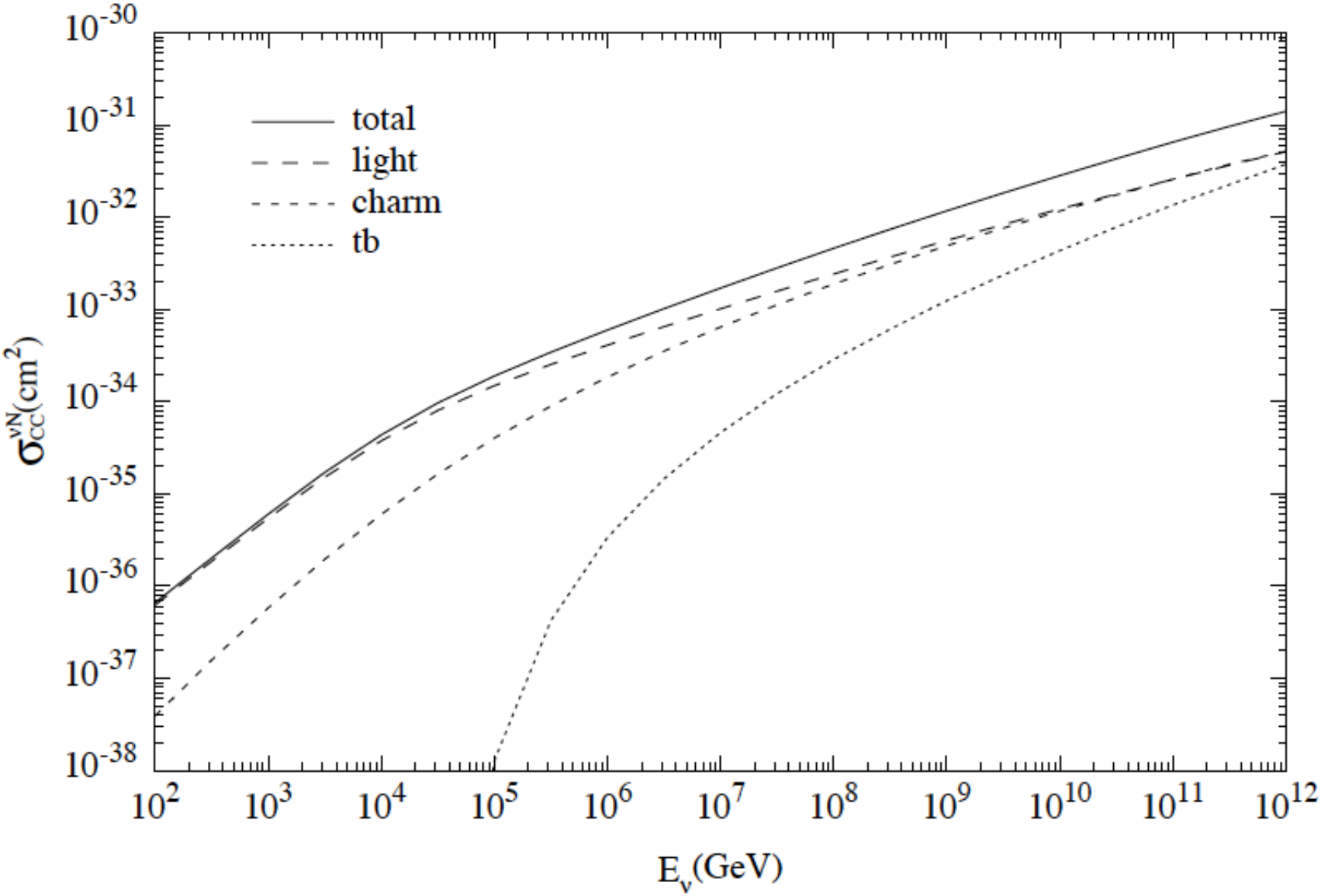

CT10nnlo
Total
u + d valence
u + d sea
s
c
b
σ(νN) / E [cm^2 GeV^-1]
E [GeV]
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12


NNPDF23_nnlo_collider_as_0120
Total
u + d valence
u + d sea
s
c
b
σ(νN) / E [cm^2 GeV^-1]
E [GeV]
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12

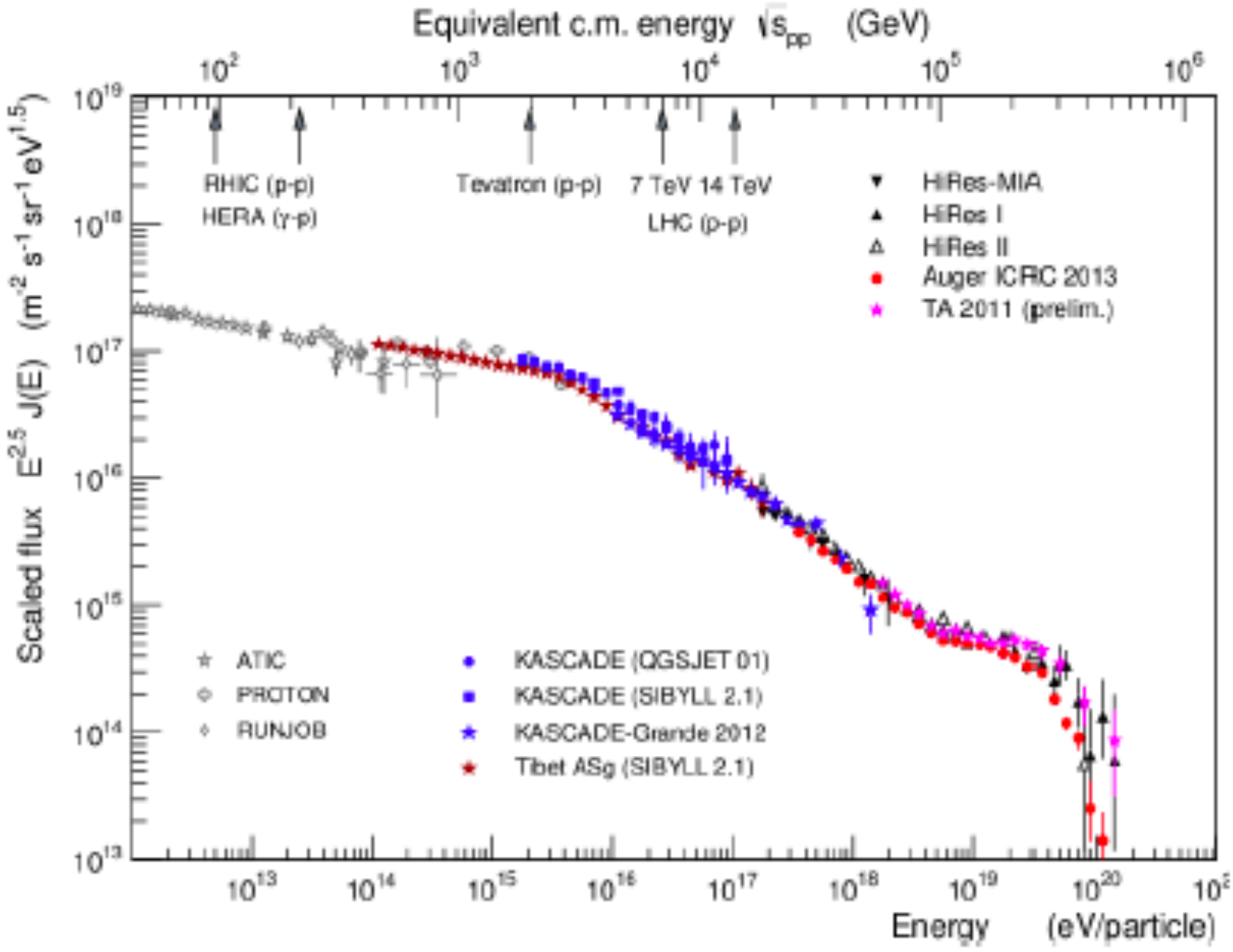

NNPDF23_nnlo_collider_as_0120
σ(νN) [cm²]
10^-30
10^-31
10^-32
10^-33
10^-34
10^-35
10^-36
10^-37
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
E [GeV]

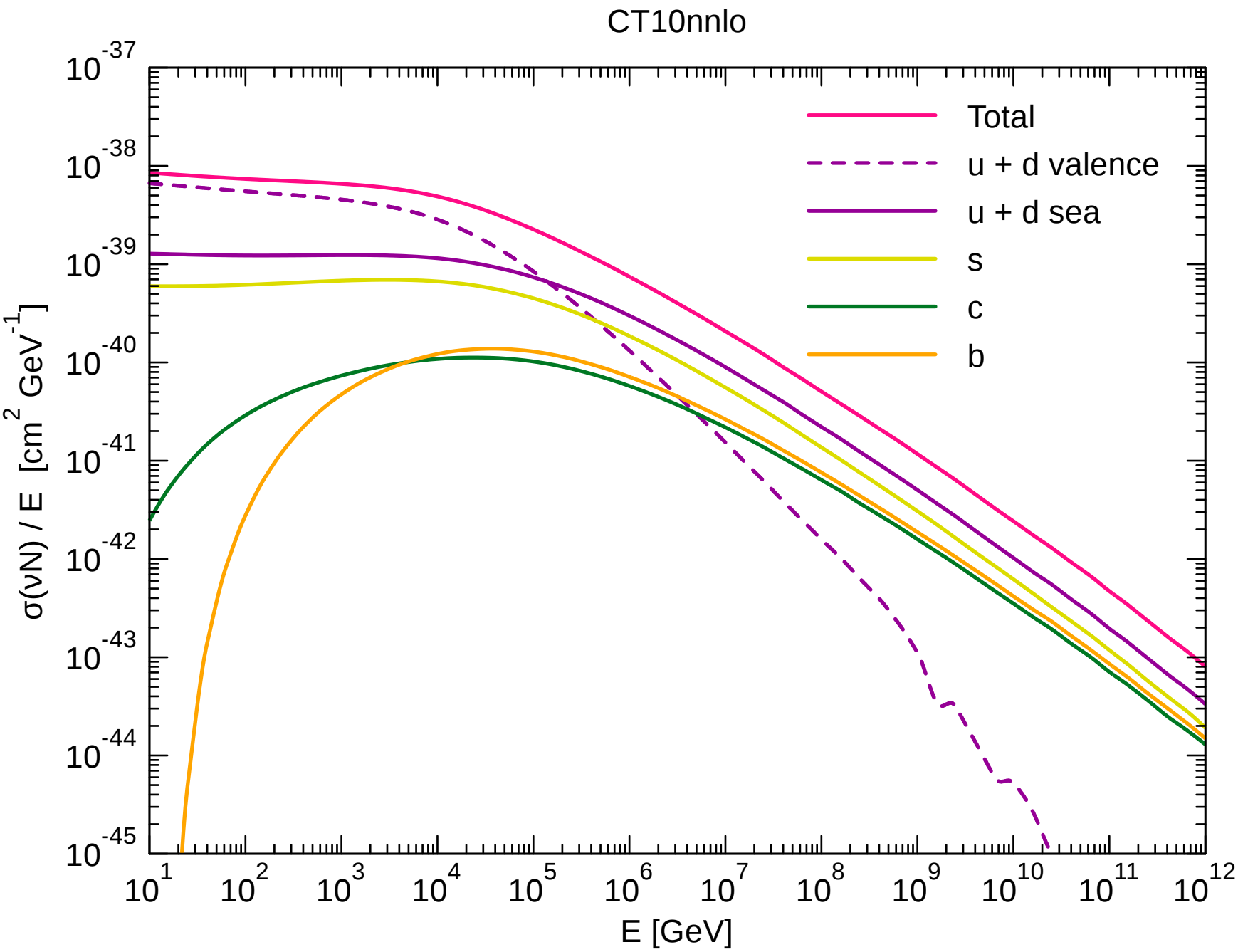

CT10nnlo
σ(νN) [cm²]
10^-30
10^-31
10^-32
10^-33
10^-34
10^-35
10^-36
10^-37
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
E [GeV]

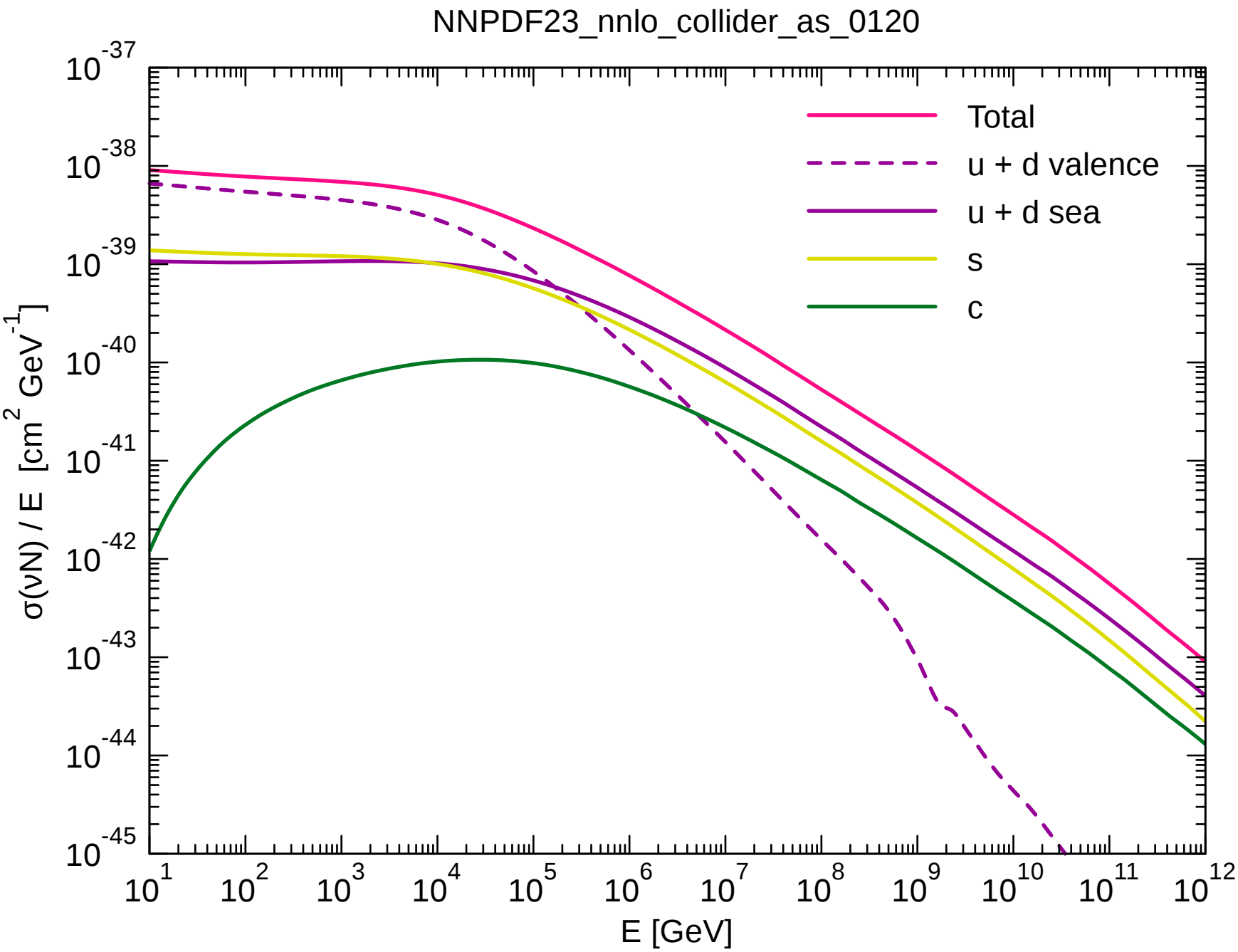

1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
valence
u+d sea
s
c
b
total
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
E_ν [GeV]



Gluck, Jimenez-Delgado, Reya, PRD 81 (2010) 097501


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA 2011 (prelim.)
Scaled flux $E^{2.5} J(E)$ $(m^{-2} s^{-1} sr^{-1} eV^{1.5})$
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 2012
Tibet ASg (SIBYLL 2.1)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)


CT10nnlo
Total
u + d valence
u + d sea
s
c
b
σ(νN) / E [cm^2 GeV^-1]
E [GeV]
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12


NNPDF23_nnlo_collider_as_0120
Total
u + d valence
u + d sea
s
c
σ(νN) / E [cm^2 GeV^-1]
E [GeV]
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12