$\nu_\tau\,(\bar{\nu}_\tau)$ Cross sections across all energies - theory

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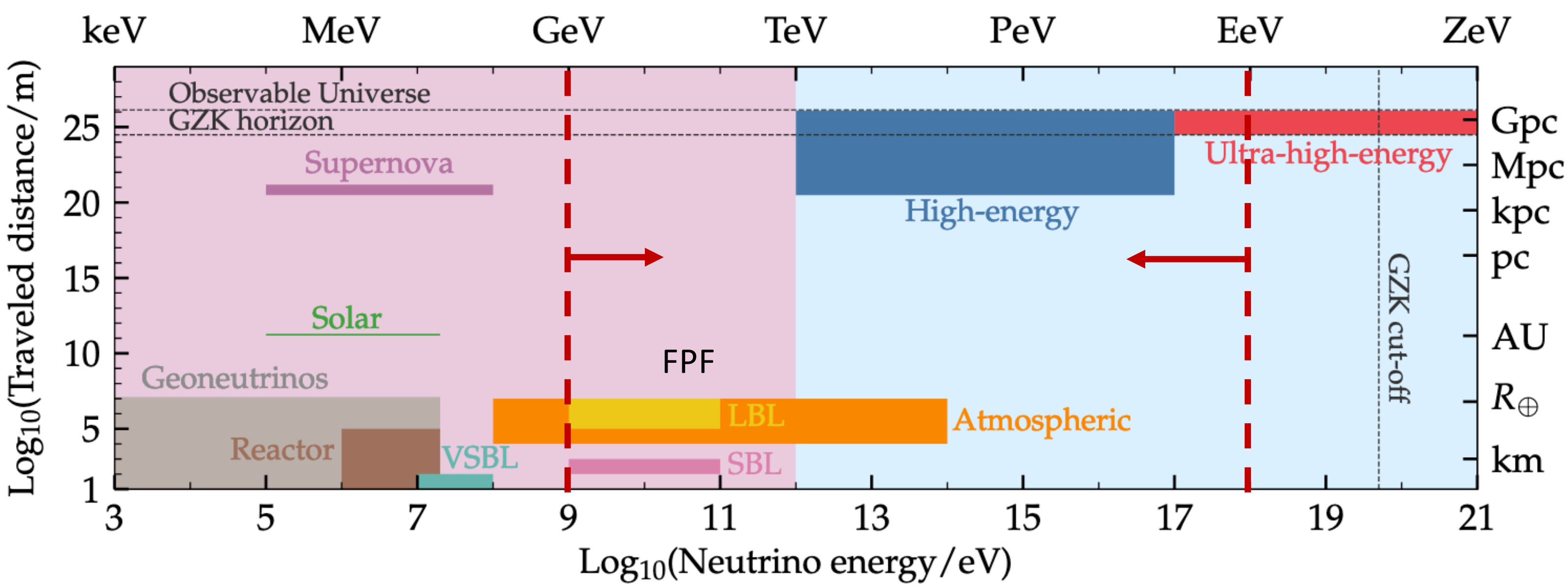
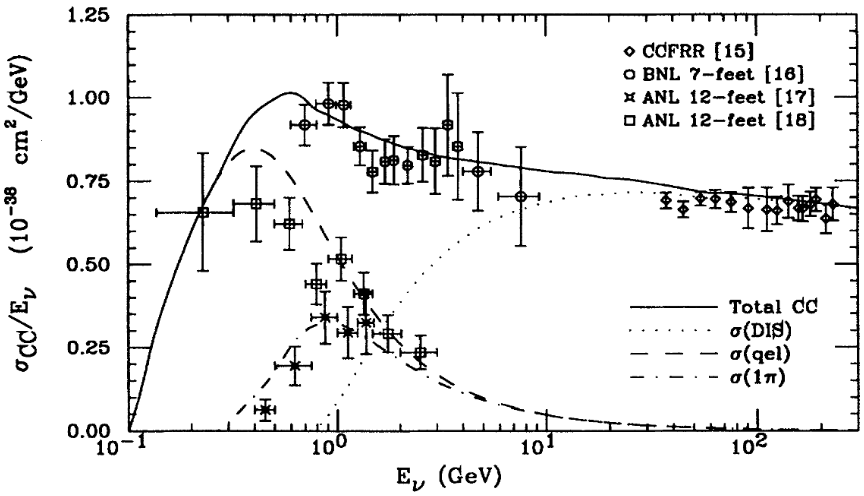
Energy range of interest for this workshop

- Cross section for detection.
- Cross section for neutrino flux attenuation.
- Focus on *nucleon* targets.

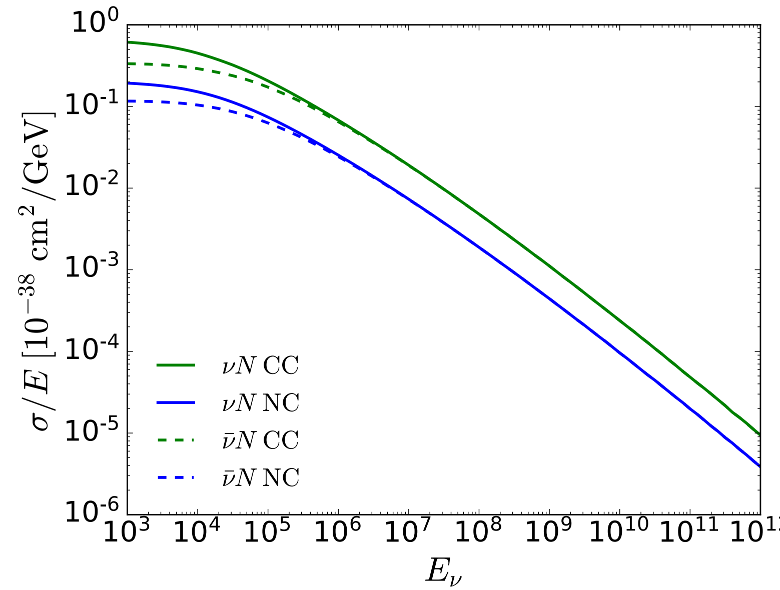


M. Ackerman et al., Astro2020 Science White Paper, arXiv:1903.04333

ν_μ-nucleon charged-current (CC) cross section



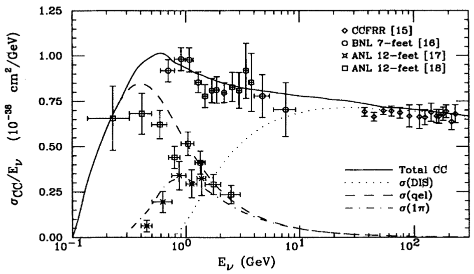
Lipari, Lusignoli and Sartogo, PRL 74 (1995) 4384

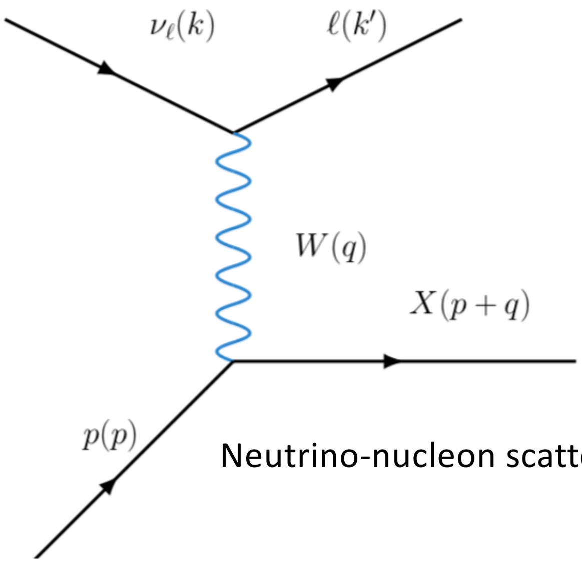


Cross section divided by energy

For reviews, see: Formaggio and Zeller, Rev. Mod. Phys. 84 (2012) 1307, NuSTEC Alvarez- Ruso et al, Prog. Part. Nucl. Phys. 100 (2018) 1, Athar and Morfin, J. Phys. G: Nucl. Part. Phys. 48 (2021) 034001

ν_μ, ν_τ CC cross sections with nucleon targets





Neutrino-nucleon scattering

Quasi-elastic: $\nu_\tau n \to p\tau^-$

$$\bar{\nu}_\tau p \to n\tau^+$$

Resonant, e.g. Delta production:

$$\nu_\tau n \to \Delta^+\tau^-,\ \Delta^+ \to n\pi^+,\ \Delta^+ \to p\pi^0$$

$$\nu_\tau p \to \Delta^{++}\tau^-,\ \Delta^{++} \to p\pi^+$$

DIS: $\nu_\tau N \to \tau^- X$

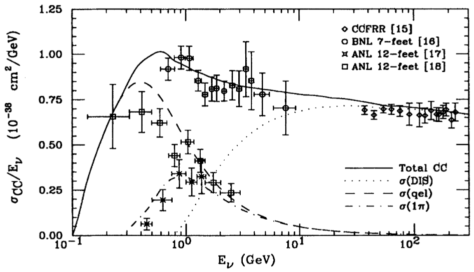
$$\boxed{W^2 = (p+q)^2}$$

$$Q^2 = -q^2 = -(k-k')^2 \qquad y = p\cdot q/p\cdot k$$

$$x = Q^2/(2p\cdot q) \qquad \nu = p\cdot q/M$$

$$k'^2 = m_\ell^2 \qquad p^2 = M^2$$

ν_μ, ν_τ CC cross sections with nucleon targets



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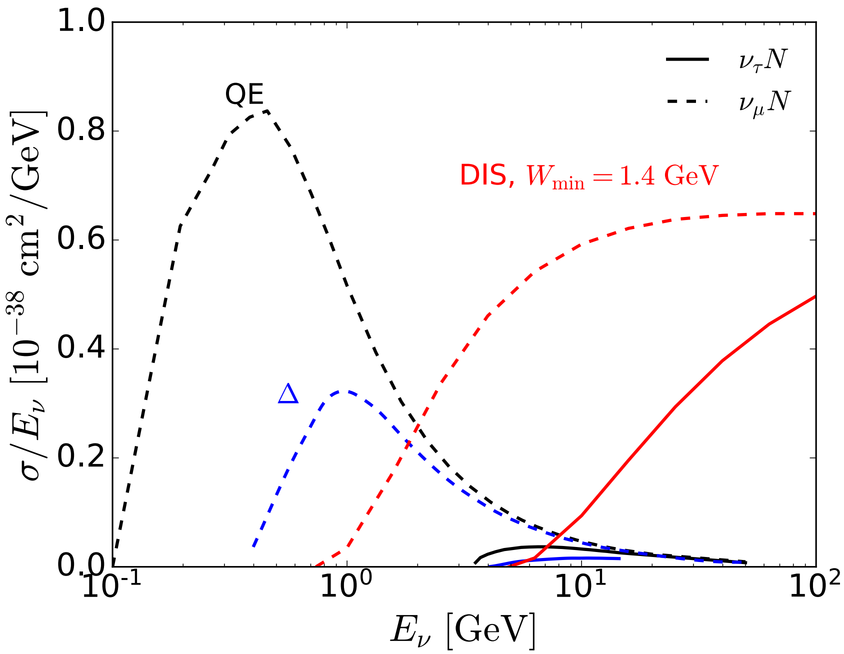
MONTE CARLO GENERATORS
GENIE, Andreopoulos et al, NIM A614 (2010) 87
NEUT, Hayato, Nucl. Phys. Porc Suppl. 112 (2002) 171
GiBUU, Buss et al, Phys. Rep. 512 (2012) 1
NuWro, Juszczak et al., Nucl. Phys. Proc. Suppl. 159 (2006) 211
Nuance, Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161

NuSTEC Alvarez- Ruso et al, Prog. Part. Nucl. Phys. 100 (2018) 1

NuSTEC: Neutrino Scattering Theory Experiment Collaboration
Neutrino-nucleon/nucleus theory, experiments, generators.

ν_μ, ν_τ CC cross sections with nucleon targets

Quasi-elastic scattering with nucleons



QE & RES in fig. from K. Hagiwara et al., NPB 668 (2003) 364

Tomalak – Friday, Oct 1, afternoon

Threshold energy: $E_{\nu_\tau} \geq (\sim 3.5\ \mathrm{GeV})$

Mass dependence: Tomalak, PRD 103 (2021) 013006, Fatima, Athar, Singh, PRD 102 (2020) 113009

$$\tau = \frac{Q^2}{4M^2}, \quad r = \frac{m_\tau}{2M}, \quad \nu = \frac{E_\nu}{M} - \tau - r^2$$

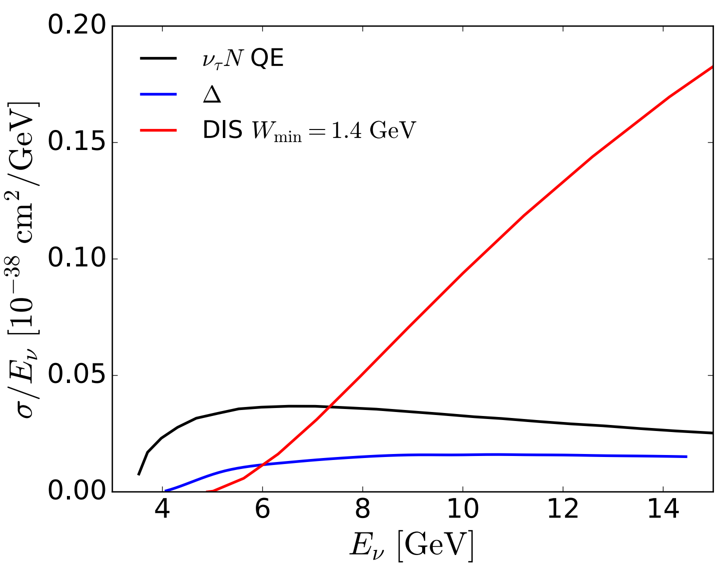
$$\frac{d\sigma}{dQ^2} = \frac{c^2_{qq'}}{16\pi}\frac{M^2}{E_\nu^2}\left[(\tau + r^2)A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau}C(Q^2)\right]$$

$$\eta = \pm 1 \qquad A = \tau(G_M^V)^2 - (G_E^V)^2 + (1+\tau)F_A^2 - r^2((G_M^V)^2 + F_A^2 - 4\tau F_P^2 + 4F_A F_P),$$

$$B = 4\eta\tau F_A G_M^V,$$

$$C = \tau(G_M^V)^2 + (G_E^V)^2 + (1+\tau)F_A^2,$$

ν_τ CC cross sections with nucleon targets



QE & RES from K. Hagiwara et al., NPB 668 (2003) 364

Summary of RES region models/approaches by NuSTEC collaboration, arXiv:2011.07166.

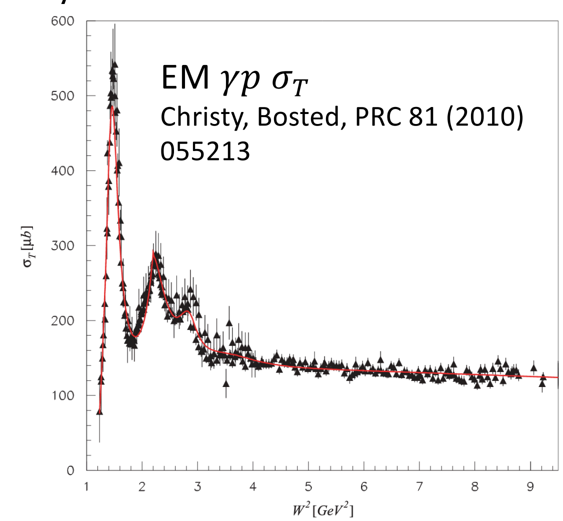
Quasi-elastic scattering with nucleons

Mass dependence: Tomalak, PRD 103 (2021) 013006, Fatima, Athar, Singh, PRD 102 (2020) 113009

- Polarization asymmetries for target, recoil and tau with H, D targets may help measurements of axial vector and pseudoscalar form factors.
- Tau polarization affects its decay distributions.

RES and few π production, scattering with nucleons

- Resonant and non-resonant contributions.
- Many resonances in the range to W ~ 2 GeV.
- EM scattering.
- Many approaches.



ν_τ CC DIS cross sections

$$
\begin{aligned}
\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2} & \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M_N}) F_1^{W^\pm} \right. \\
& + \left[(1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{M_N x}{2E_\nu}) y \right] F_2^{W^\pm} \\
& \pm \left[xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M_N} \right] F_3^{W^\pm} \\
& \left. + \frac{m_\tau^2 (m_\tau^2 + Q^2)}{4E_\nu^2 M_N^2 x} F_4^{W^\pm} - \frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm} \right\} .
\end{aligned}
$$

Albright-Jarlskog relations:

$$F_4(x,Q^2) \simeq 0$$

$$2xF_5(x,Q^2) \simeq F_2(x,Q^2)$$

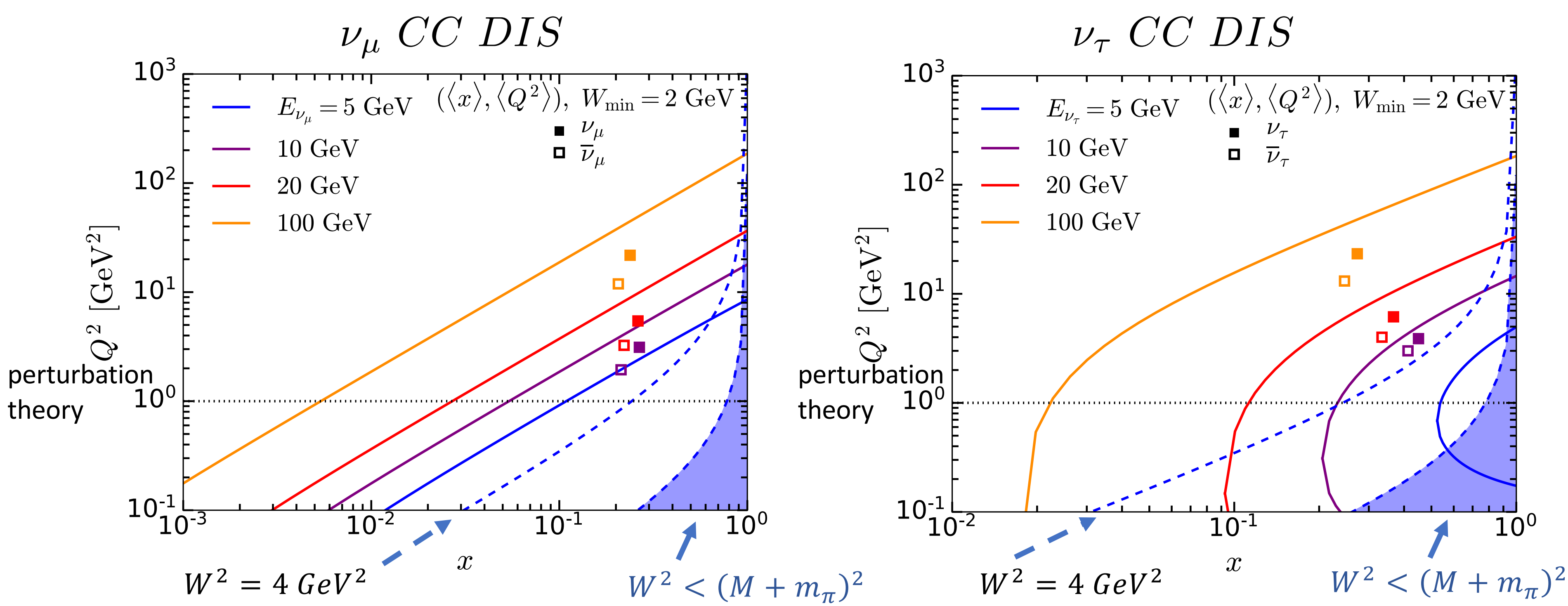
For *E*=100 GeV, F_5 contributes ~10% for $\nu_\tau N$ and ~30% for $\bar\nu_\tau N$ CC cross section.

Ansari – Friday, Oct 1, afternoon

- Several comparable mass scales: nucleon, tau, charm quark. Need target mass corrections, quark mass corrections.
- Low *Q* needs to be treated. One approach: modify PDFs Bodek Yang (& Xu) arXiv:2108.09240. Another approach, phenomenological structure function for low Q, e.g., MHR, PRD 74 (2006) 033001. Both tied to EM scattering.
- Avoid double-counting with “RES.”

TMC + charm for taus: Kretzer, MHR, PRD 69 (2004) 034002, 66 (2002) 113007.
For discussion of non-perturbative and higher order effects, see Ansari et al, PRD 102 (2020) 113007.

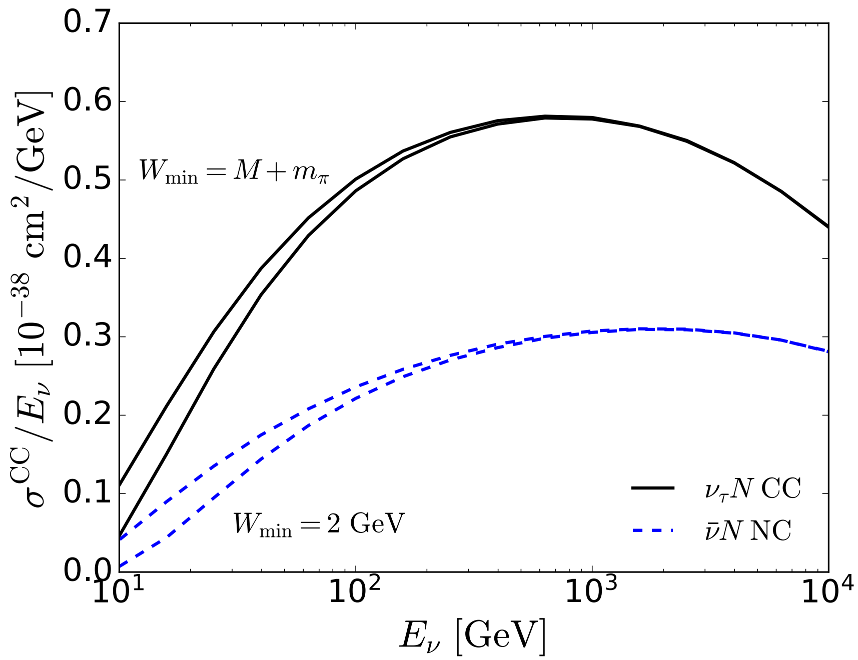
Allowed DIS kinematic regions as a function of E_ν

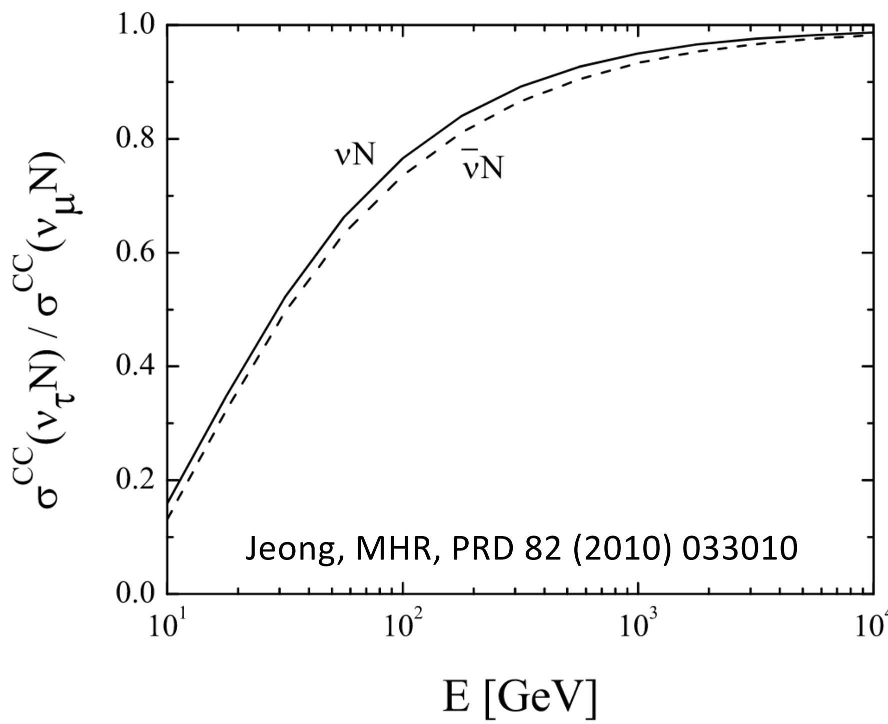


Limitations in x and Q (or alternately x and y) due to tau mass.

Making the transition from RES to DIS without double counting is an issue, also uncertainties in the “shallow” inelastic scattering regime. See Athar, Morfin, J.Phys.G 48 (2021) 034001 for a review.

ν_τ CC DIS cross sections with nucleon targets



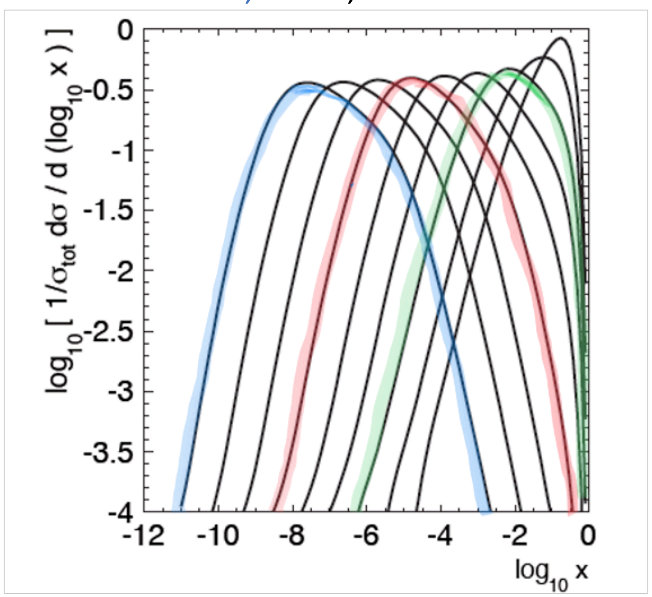


Extrapolation below Q^2=2 GeV^2 with CKMT structure functions as in J&R. See, MHR, PRD 74 (2006) 03001.

$\nu_\mu = \nu_\tau$ CC DIS cross sections at UHE

$x_{\min} \rightarrow M_W^2/s \quad (y \sim 0.2 - 0.5) \qquad Q^2 \rightarrow M_W^2$

1 ZeV, 1 EeV, 1 PeV

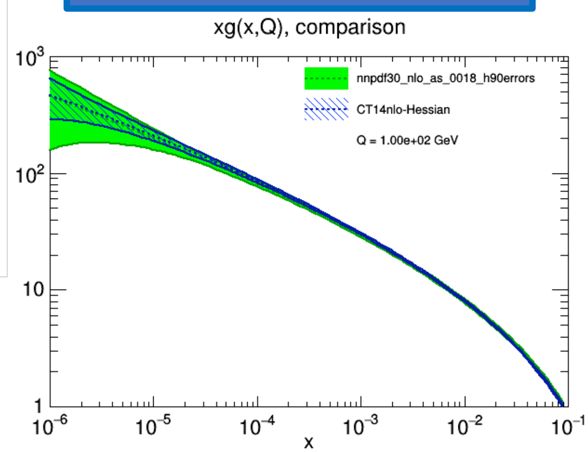


Connolly, Thorne, Waters, PRD 83 (2011) 113009

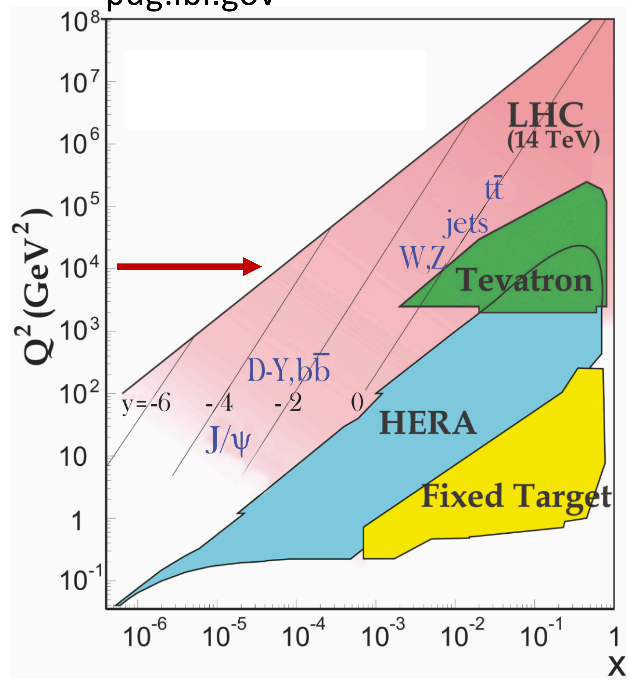
x ranges for UHE cross section:

- at highest energies, beyond measurements
- small *x* extrapolations required

gluon and sea uncertainties

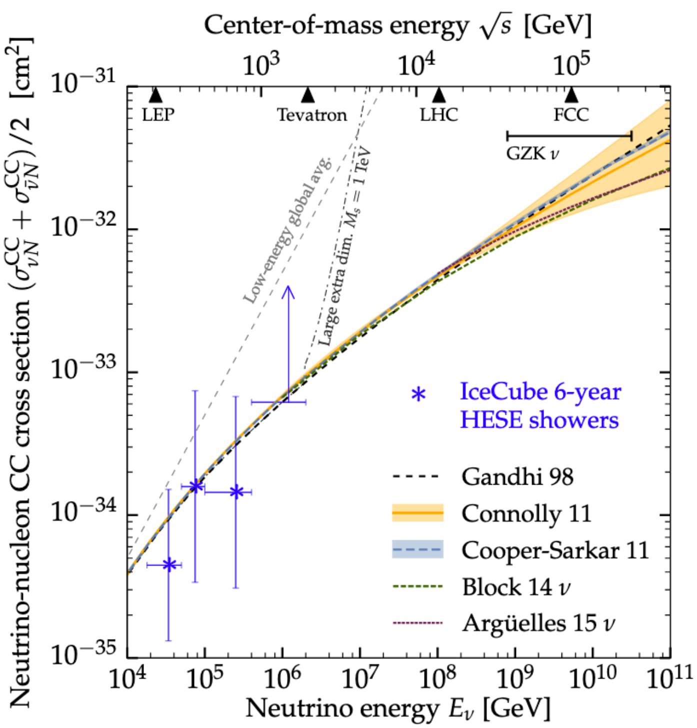


pdg.lbl.gov

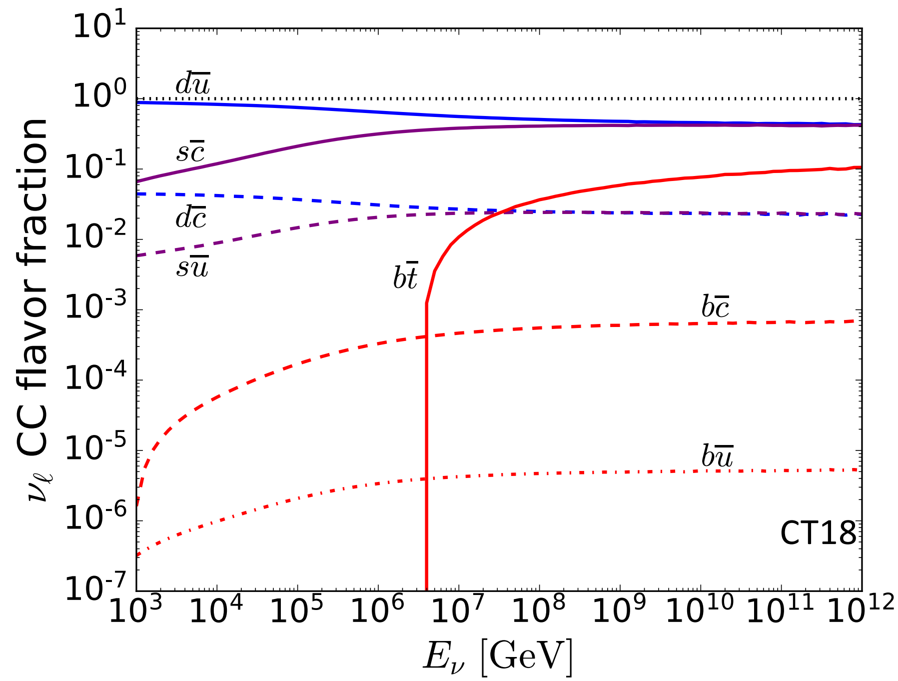


Increasing uncertainty in the small x extrapolations lead to increasing UHE cross section uncertainties.

$\nu_\mu = \nu_\tau$ CC UHE cross section



Bustamante, Connolly, PRL 122 (2019) 041101

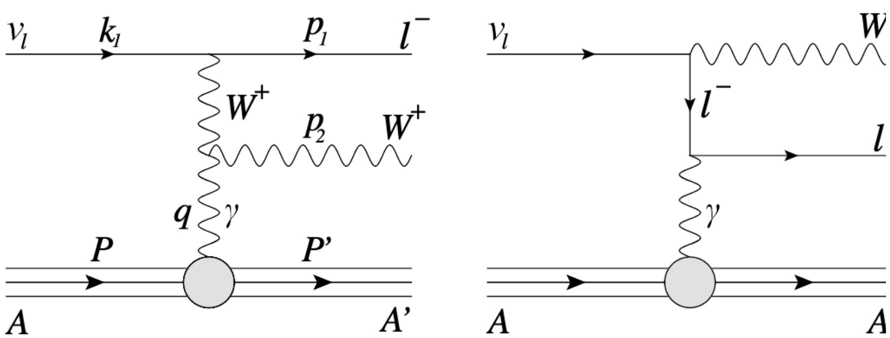


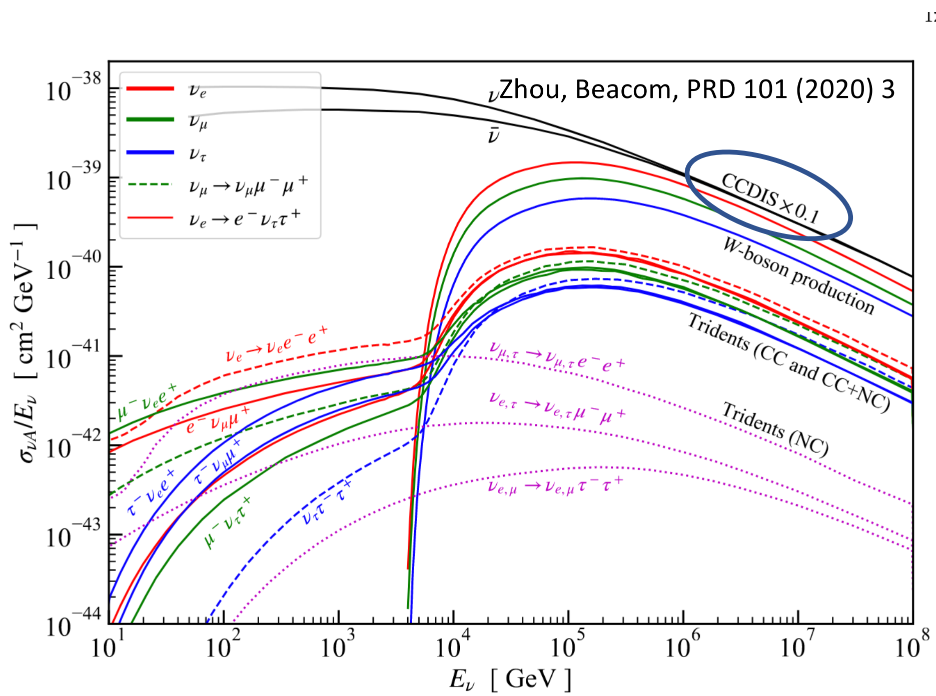
Detailed discussion of quark mass effects in this context:
Garcia, Gauld, Heijboer, Rojo, JCAP 09 (2020) 025

Sub-leading effects

Zhou, Beacom, Phys. Rev. D 101 (2020) 3

See also:
Seckel, PRL 80 (1998) 900
Alikhanov, PLB 756 (2016) 247, PLB 741 (2015) 295





Example: real W boson production.

Hadronic coupling to virtual photons to produce *W*-bosons.

Several regimes:

- inelastic (quark charges, photon PDF-which dominates),
- coherent scattering (Z^2, also important),
- diffractive (Z).

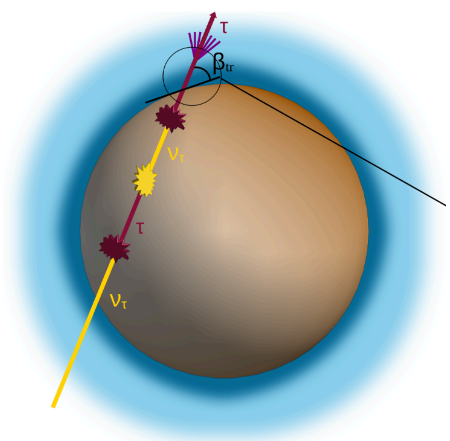
Correction for tau neutrinos:
~ 3.5% of CCDIS on O(16) targets

ν_τ-regeneration at UHE

More talks today and tomorrow

Space/balloon based for up-going air shower detection: e.g.,POEMMA (Krizmanic), ANITA, EUSO-SPB2

Ground/underground (Glaser): e.g., BEACON, GRAND (Piotrowski), Trinity, IceCube, ARA

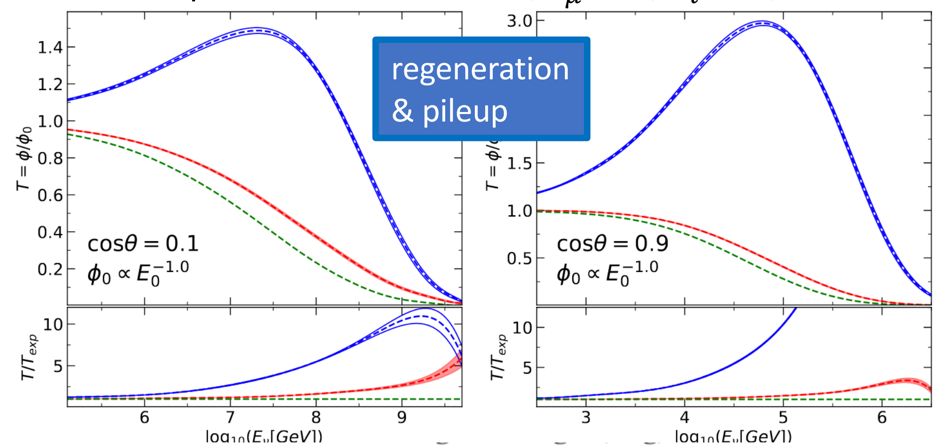


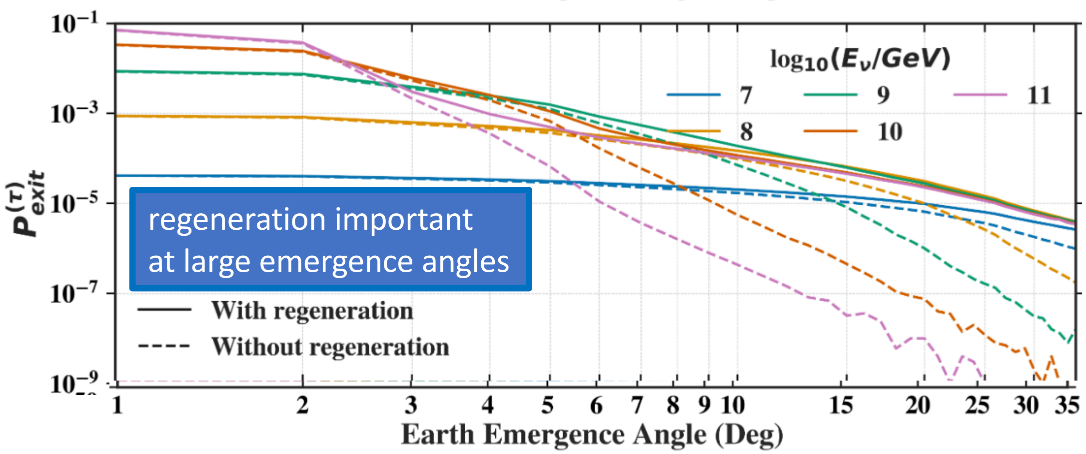
"..the Earth never becomes opaque to ν_τ … "
Halzen, Saltzberg, PRL 81 (1998) 4305

Garcia – Friday, Oct 1, afternoon

Garcia, Gauld, Heijboer, Rojo, JCAP 09 (2020) 025

Exponential attenuation, ν_μ flux, ν_τ flux, E^{-1}





Tau exit probabilities, Patel et al, nuPyProp.

Recent Monte Carlo simulations

Emerging taus:

nuPyProp (nuSpaceSim): Patel et al., PoS(ICRC2021)1204, github.com/NuSpaceSim/nupyprop

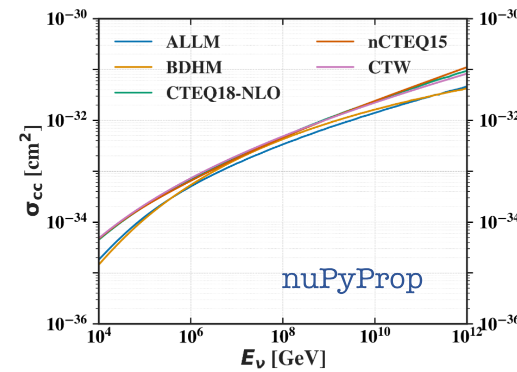
nuTauSim: Alvarez-Muniz et al., PRD 97 (2018) 023021

TauRunner: Safa et al., JCAP 01 (2020) 012

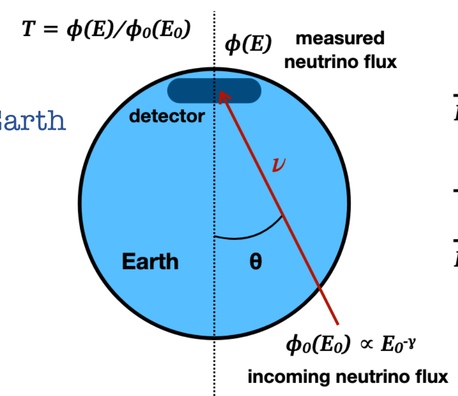
Emerging neutrinos:

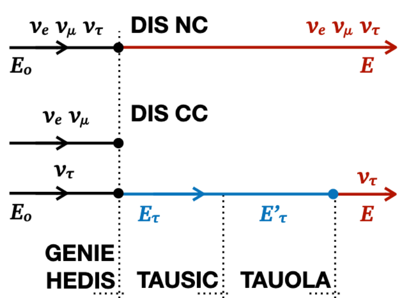
NuFate: Vincent, Arguelles, Kheirandish, JCAP 1711 (2017)012

nuPropEarth: Garcia, Gauld, Heijboer, Rojo, JCAP 09 (2020) 025

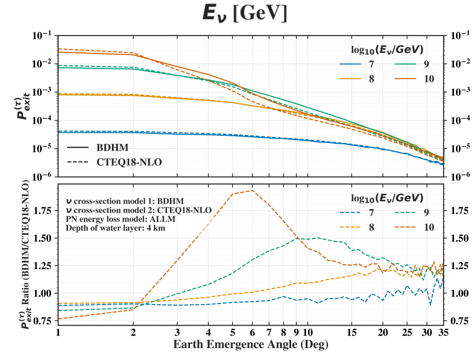


nuPropEarth





Tau exit probabilities



Earth emergence angles

Summary

- Summarized tau neutrino cross sections from GeV to EeV.
- At *low energies*, kinematic are part of the difference between muon and tau neutrino cross sections, but not the only difference: mass effects in the cross section, access to F_P and F_5.
- At *high energies*, there are common uncertainties in extrapolating the cross sections.
- At *high energies*, neutrino flux attenuation compounds cross section effects to some degree.
- Additional complications of nuclear targets, common to both muon neutrino and tau neutrino scattering. Nuclear effects: nuclear physics with nucleons, final state interactions, in-medium effects at low energies; nuclear PDFs at high energies.
- Also in common: the transition between RES and DIS, a topic of much discussion.
- Inclusive $\rightarrow$ final state particles.