Neutrino cross-sections (at all energies) - experiment

Spencer Klein, LBNL & UC Berkeley

Presented at the

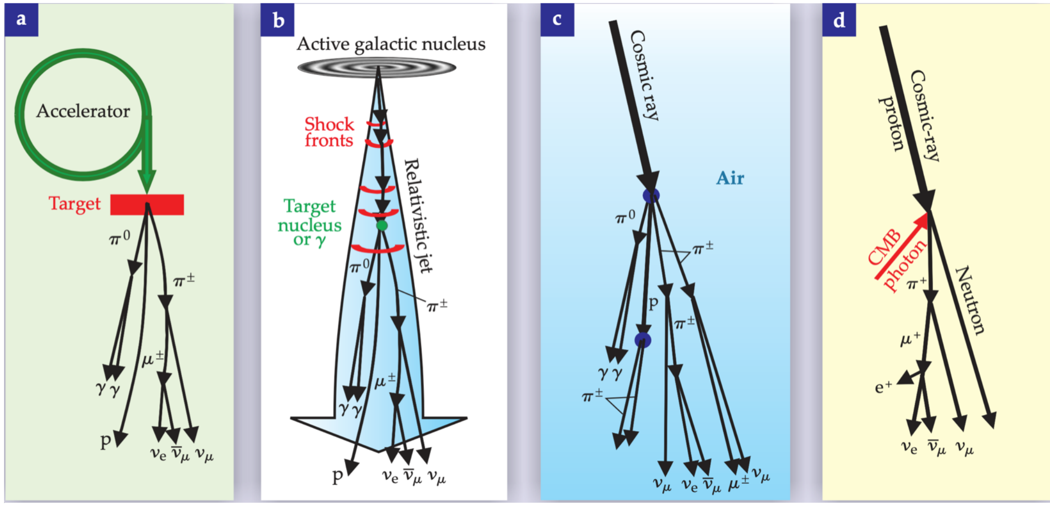
Workshop on Tau Neutrinos from GeV to EeV 2021 Collider

Sept. 28-Oct. 1, 2021

- Fixed target accelerator Measurements
  - (Some) Current studies
  - Future studies
- FASERν at the LHC
- Neutrino Telescope Measurements
  - Low-energy studies
- Prospects with radio-detection of neutrinos
- Conclusions

Classes of experiments

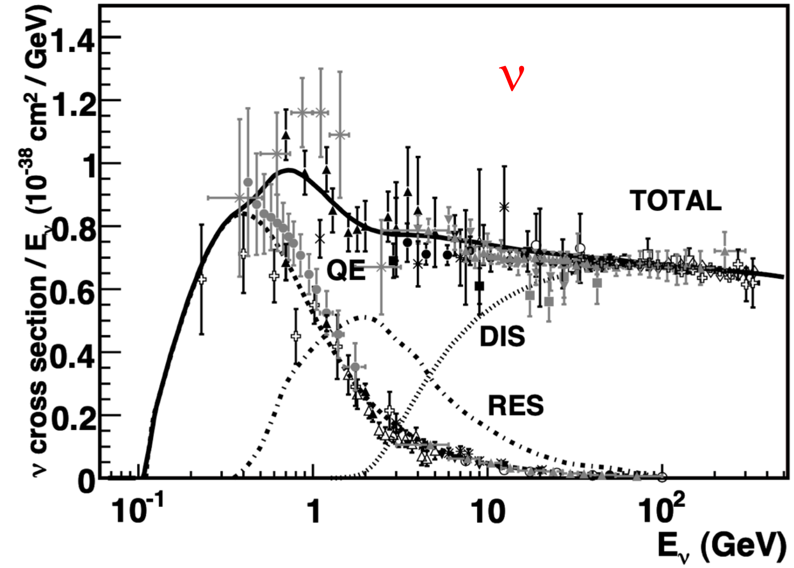
- $N_{evts} \sim \sigma$ * flux * volume * time
  - Accelerator
  - Low-energy νTelescope studies
  - Requires good knowledge of flux
- ν absorption studies
  - In the Earth
  - High-energy νTelescope
  - ~ mostly flux independent, but must know angular distribution
  - Other systematics
- For both, ν/νbar ratio matters

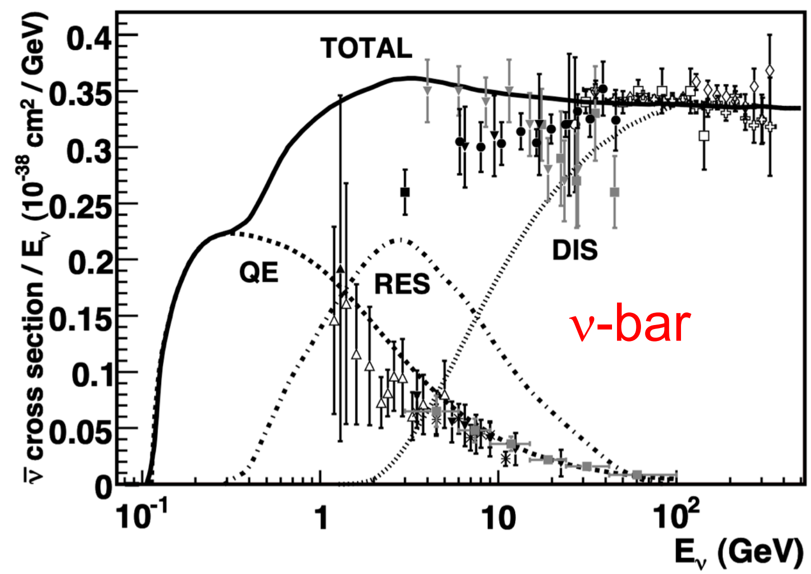


SK and F. Halzen, Phys. Today, May 2008.

The cross-section landscape

- Deep Inelastic Scattering dominates for E_ν > 100 GeV
  - Charged and neutral current
- Resonant reactions: $\nu N \to \nu N^* \pi / \ldots$
  - Relative rates to different final states are not well known
  - Much nuclear physics enters
- Quasi-elastic: $\nu N \to \nu N(^*)$
- $\sigma(\nu) > \sigma(\nu \text{bar})$ due to valence quarks
  - Difference disappears as E-> ∞
- Nuclear composition affects σ
- Diffractive reactions & Glashow resonances appear at high energies

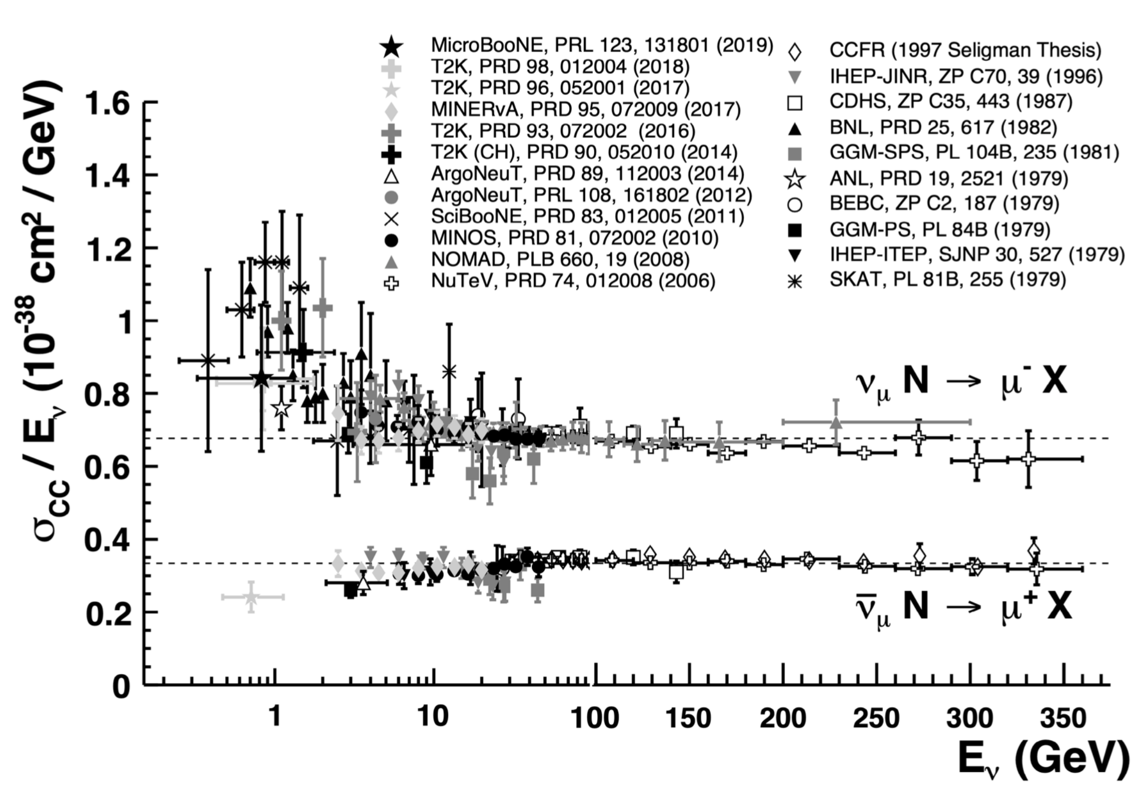




Formaggio & Zeller, Rev. Mod. Phys. **84**, 1307 (2012)

Accelerator studies

- Historically – ν energies up to 400 GeV at Fermilab
  - 5-10% precision possible
- Current focus – lower energy ν are better for oscillations studies -> current maximum available E_ν ~ 50 GeV
- Few new measurements of ν cross-sections

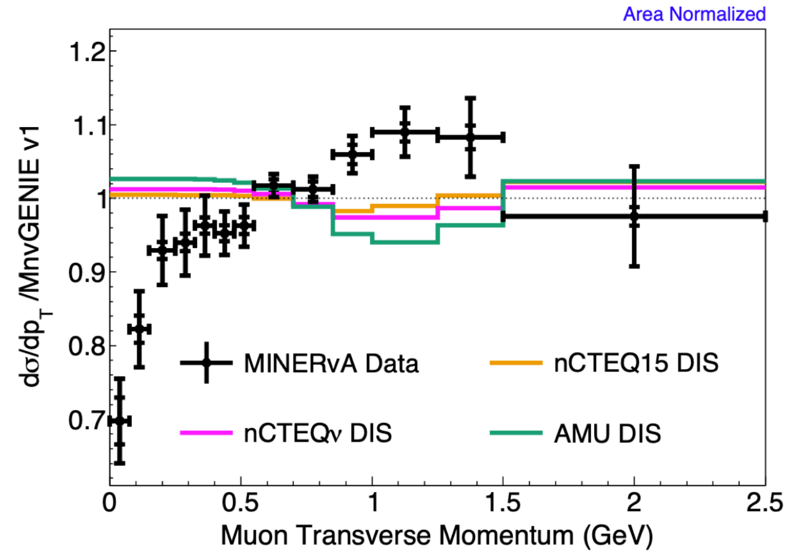


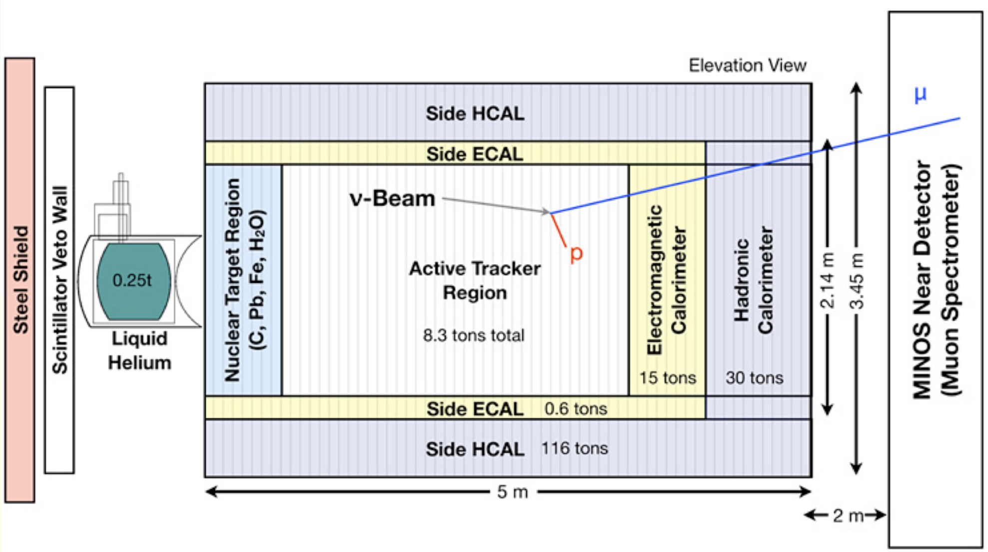
Particle Data Group

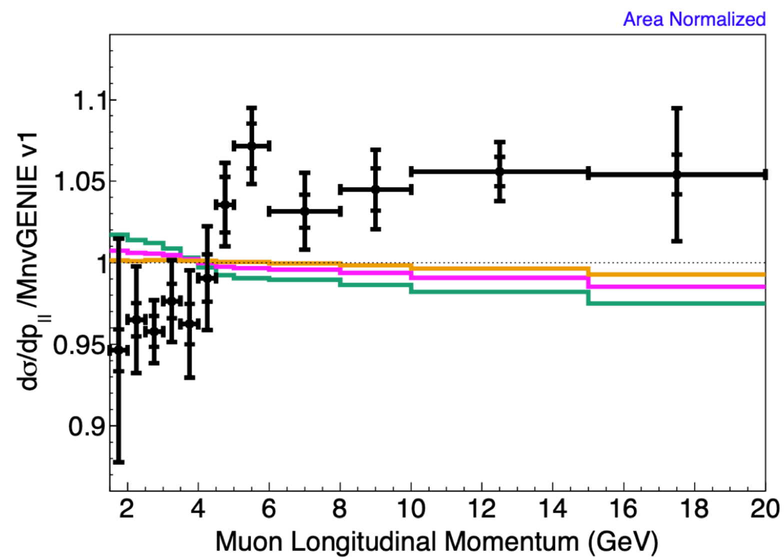
MINERνA

- MINERνA is a Fermilab experiment to study ν interactions on a variety of nuclear targets
- Useful for tuning models (GENIE)

Hydrogen target



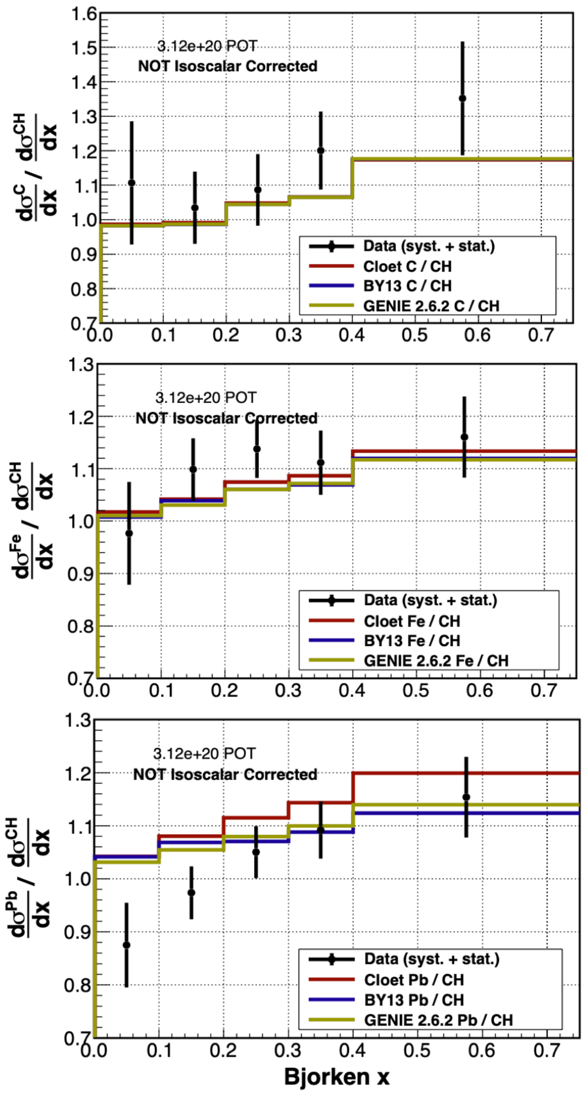




MINERνA, Phys. Rev. D **101**, 112007 (2020)

Nuclear Targets in MINERνA

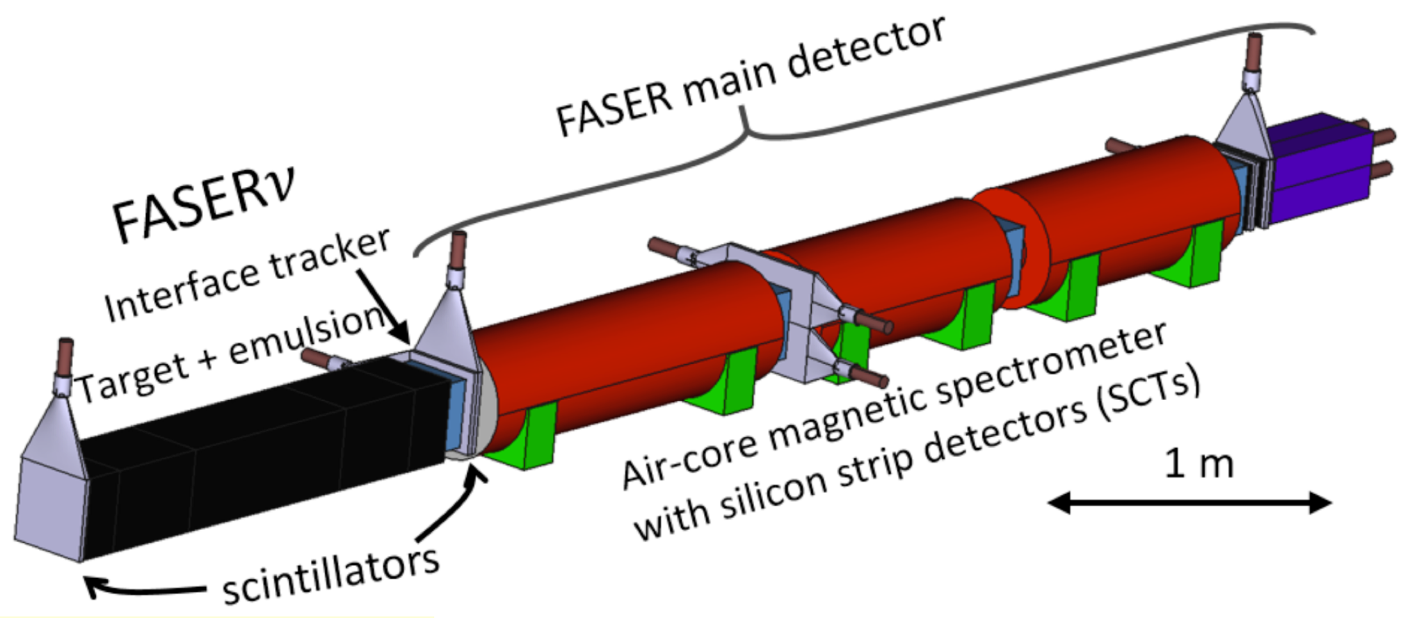
- Charged Current DIS: μ + hadronic shower
  - x, Q^2 determined from scattered muon
  - Requires $Q^2 > 1\ GeV^2$
- Data on carbon, iron and lead targets
- Significant nuclear shadowing at low x in lead
  - Not reproduced in the models that they used



MINERνA, Phys. Rev. D **93**, 071101 (2016)

Future accelerator prospects

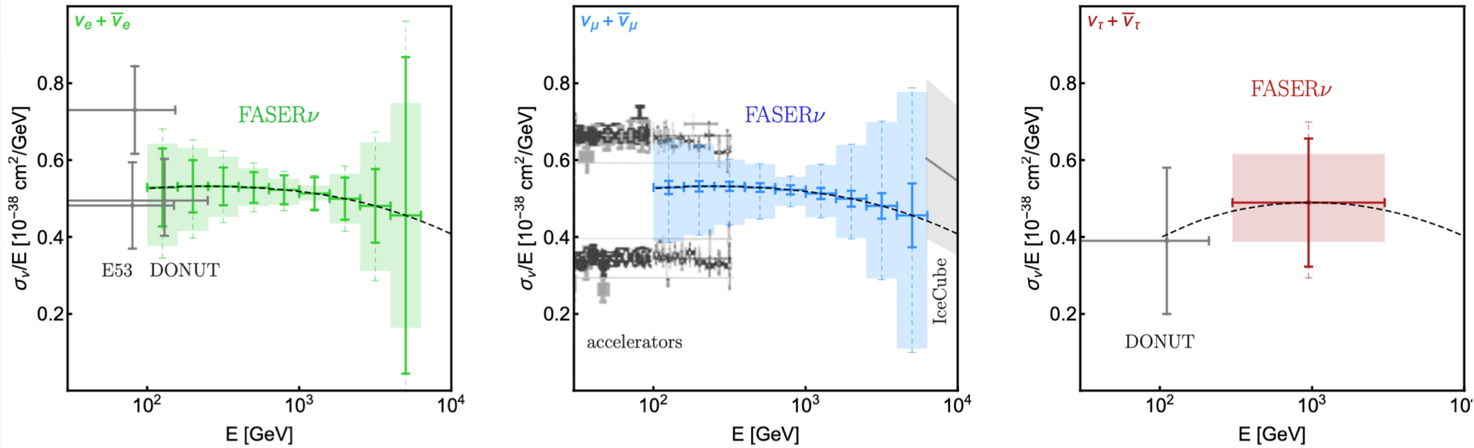
- DUNE – argon targets; well covered elsewhere in workshop
- FASERν at CERN
  - Forward neutrinos from the LHC
    - 480 m downstream from ATLAS
    - W-emulsion in front of FASER spectrometer (μ charge, energy…)
  - ν cross-sections for all three flavors up to E ~ 5 TeV



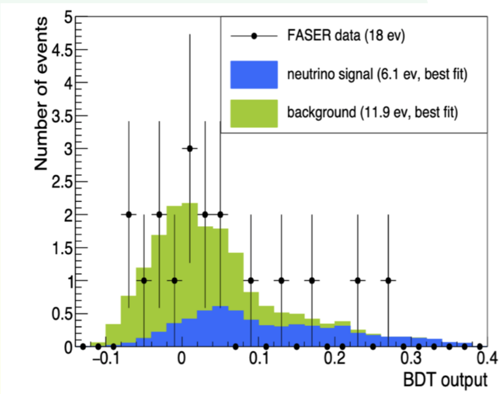
FASERν Technical Proposal, arXiv:2001.03073

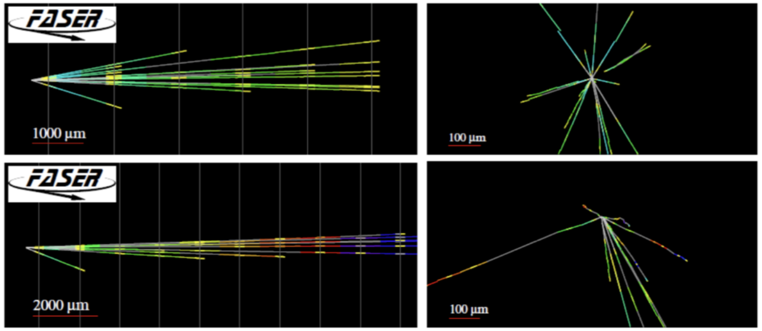
FASERν cross-section projections

- ν cross-sections for all three flavors up to E ~ 5 TeV



- ν events seen in a 2018 pilot run



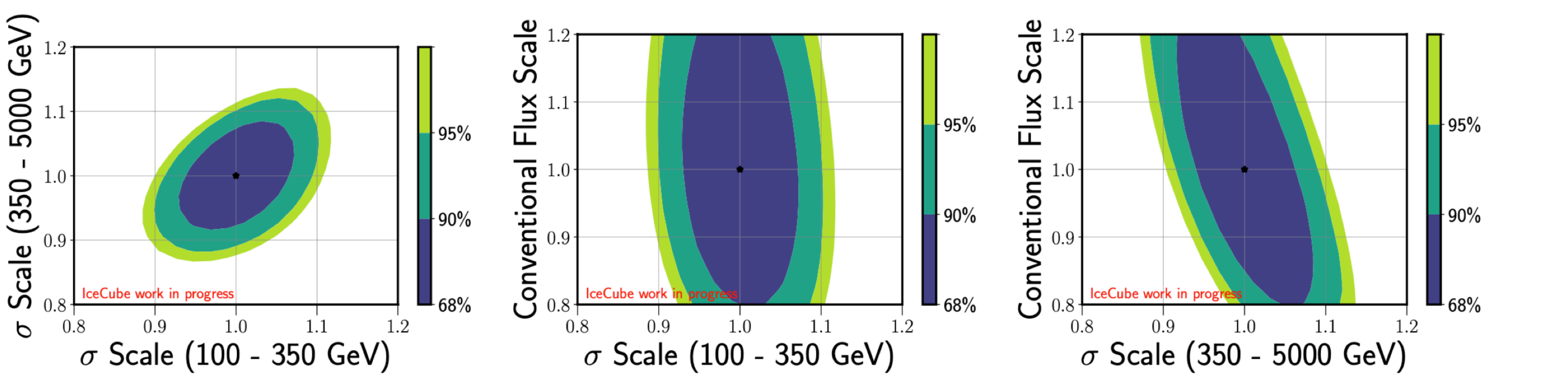


- Full detector installation ~ now for LHC Run 3
- Follow-on experiments possible

C. Dozen, presented at LHCP 2021

IceCube intermediate energy measurement

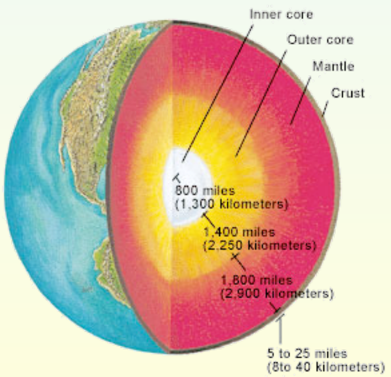
- $N_{evts} \sim \sigma$ * flux * volume * time
  - Relies on knowing atmospheric flux
  - Tied to accelerator measurements to constrain flux
    - Predicted uncertainties ~ 10%
- 9 years of ν_μ data
- Energy range 100 GeV to 5 TeV
  - A very wide energy range (a feature of most νTelescope studies)
  - ν/νbar ratio affects measured cross-section

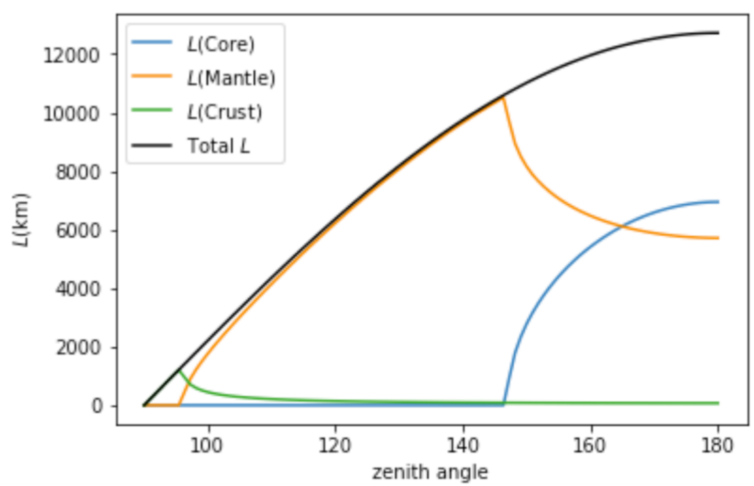


Sarah Nowicki, arXiv:2107.09764

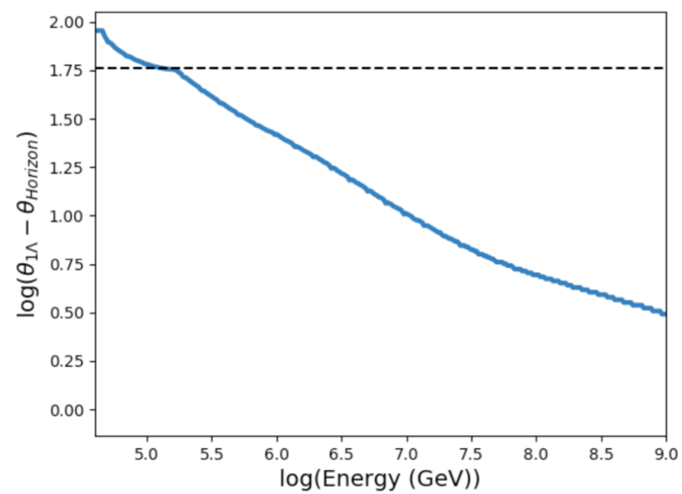
Earth absorption measurements – where to look

- Earth absorption increases with increasing E_ν & with increasing path length
  - Density increases with depth -> more absorption for small Θ_z
  - At 15 TeV, a chord with $\Theta_z = 180$ degrees is 1 absorption length
- The most sensitive angle (for σ) decreases with increasing E_ν
  - At 10-100 TeV, absorption is mostly visible for $\Theta_z > 135$ degrees
  - At 10^{18+} eV, neutrinos are only visible near the horizon





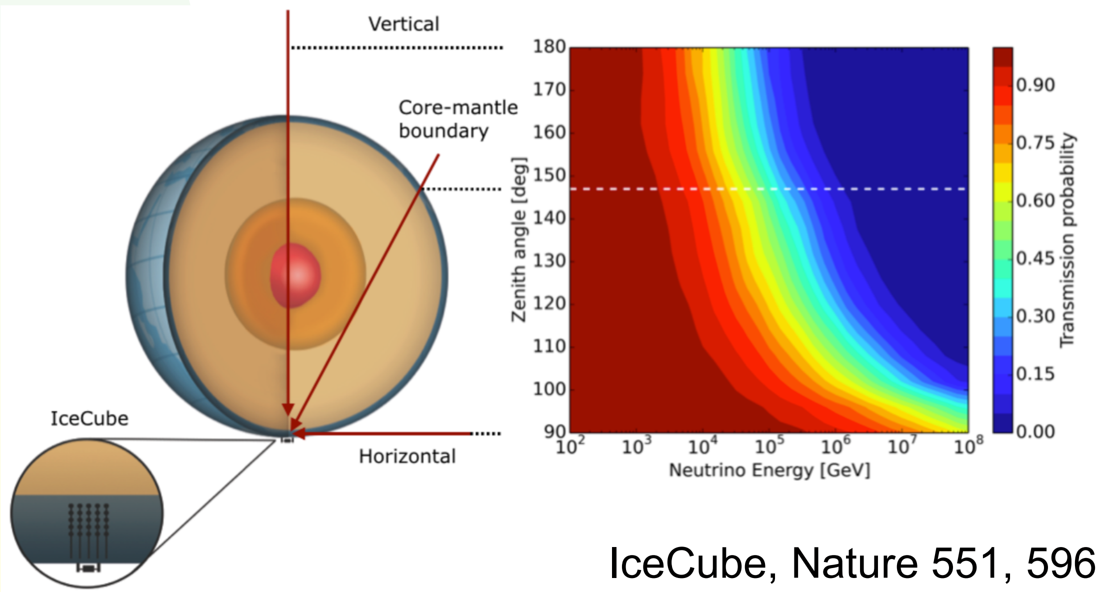
Log(angle below horizon corresponding to 1Λ interaction length)



SK, Sally Robertson and Ramona Vogt, Phys. Rev. C102 015808 (2020)

IceCube ν_μ absorption measurement

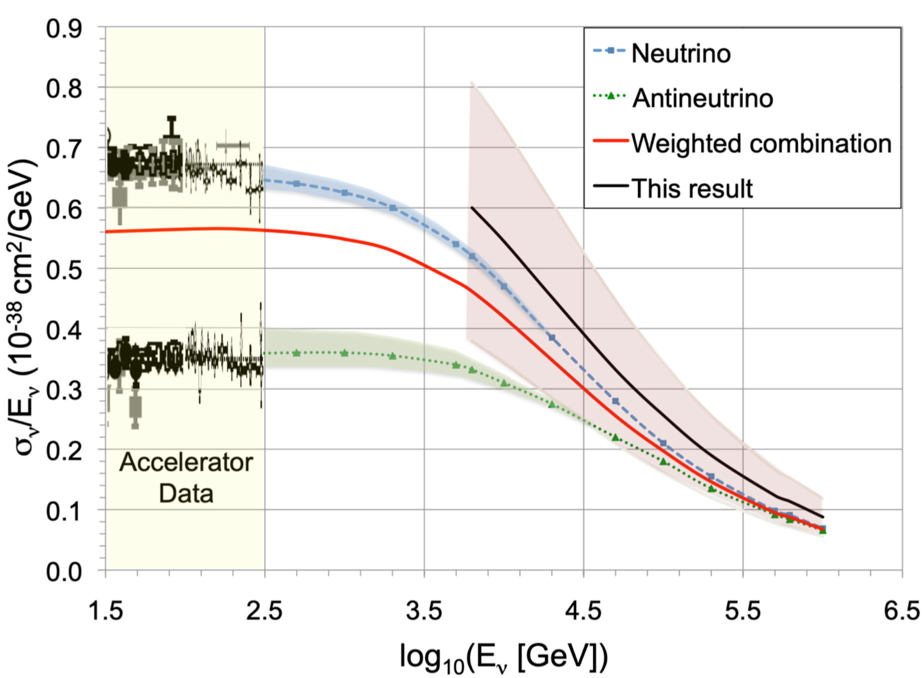
- 1 year of IC79 data, 10,784 up-going events with E_μ > 1 TeV
- Mixture of atmospheric and astrophysical ν
- PREM model for earth density as function (radius)
- Assume σ is a multiple *R* of the standard model
  - R is same for CC and NC
- Calculate transmission probability as a function of *R*, E_ν and Θ_z
  - NC events cause ν energy loss-> some spectral dependence
  - Same for τ regeneration, but it is not important here



IceCube, Nature 551, 596 (2017)

Cross-section measurement

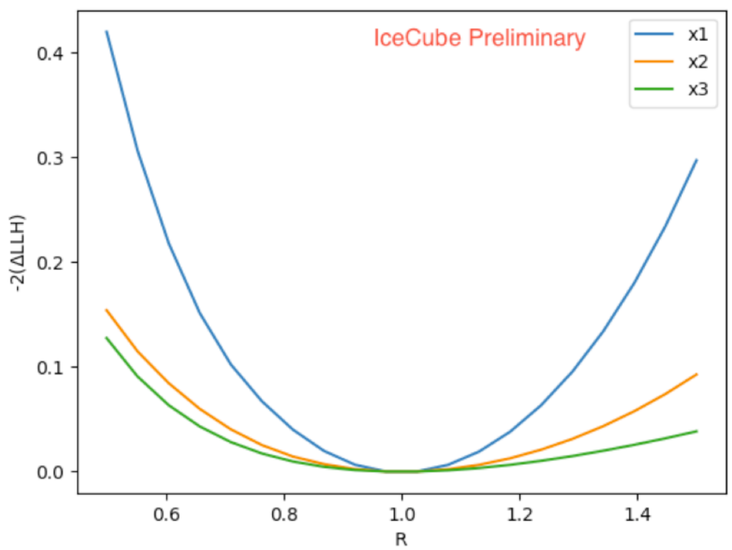
- Fit $N_{evts}(E_\mu, \Theta_z)$ to find best R*flux (R* flux to reduce flux sens.)
- Nuisance params for atmospheric & astrophysical ν uncertainties
  - Astrophysical flux and spectral index
  - Atmospheric flux, spectral index, K/π ratio, ν/νbar
  - Astrophysical ν assumed isotropic with $\Phi(\nu) = \Phi(\nu\text{bar})$
- Energy range determined by studying change in significance by setting absorption =0 at lower/higher energies
  - Other methods would give different ranges



IceCube, Nature **551**, 596 (2017)

Future IceCube ν_μ measurement

- 8 years of data; selection from astrophysical ν_μ study
  - 300,000 events (30*previous study)
- Three energy bins:1-10 TeV, 10 TeV-1 PeV, and > 1 PeV
- Transmission probability fit with splines
- Improved systematic errors – better model of optical properties of ice etc.

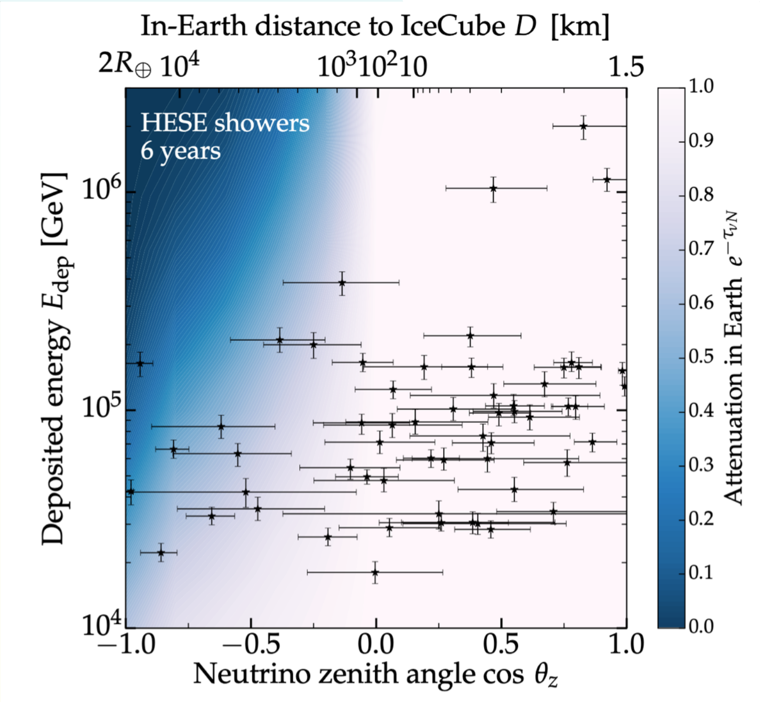


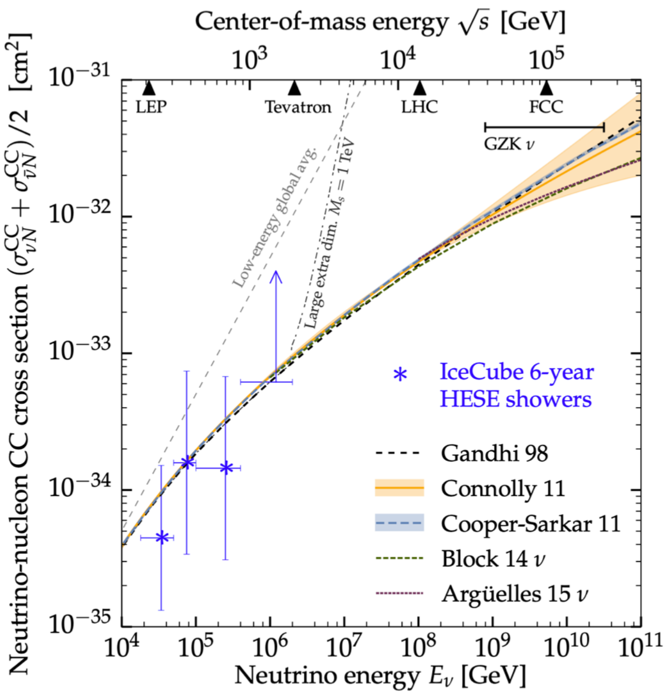
Asimov likelihood for 3 energy ranges

Sally Robertson, arXiv:2108.04965

Energy Dependent Cross-sections

- Independent analysis of 6 years (58 events) of Icecube HESE (starting events) cascades (showers)
  - Small number of events limits precision
  - Cascades = ν_e CC + all-flavor NC
    - NC showers contain only part of E_ν

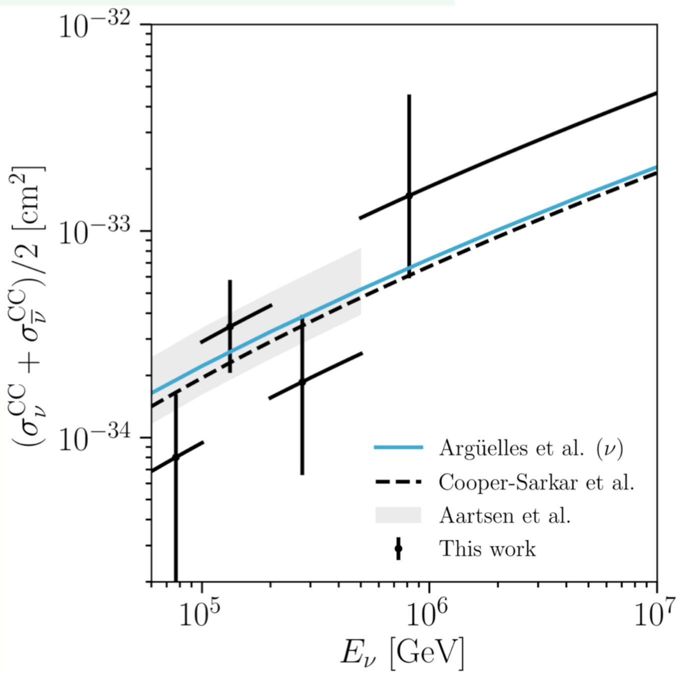




Mauricio Bustamante and Amy Connolly, Phys. Rev. Lett. **122**, 041101 (2019)

IceCube cross-section with starting events

- 7.5 year "HESE" (high energy starting event) sample
  - 60 events with deposited energy > 60 TeV
- Fit approach is broadly similar to the ν_μ track study
  - Better energy resolution, worse zenith angle resolution, and fewer events -> larger uncertainties
  - Ternary Particle ID (shower/track/double-shower
- Provided both Bayes and frequentist results



Parameter	Energy range	68.3% HPD	68.3% CI
x_0	60 TeV to 100 TeV	$0.21^{+0.52}_{-0.21}$	$0.48^{+0.49}_{-0.37}$
x_1	100 TeV to 200 TeV	$1.65^{+1.49}_{-0.84}$	$1.50^{+1.03}_{-0.60}$
x_2	200 TeV to 500 TeV	$0.68^{+1.11}_{-0.43}$	$0.54^{+0.60}_{-0.35}$
x_3	500 TeV to 10 PeV	$4.31^{+13.26}_{-3.32}$	$2.44^{+5.10}_{-1.47}$

IceCube, arXiv:2011.03560

IceCube measurement energy ranges

- Low energy limit: Earth absorption > measurement uncertainty
- High energy limit: enough flux for a measurement
- Not much flavor/sample dependence
  - Some dependence on the method used to find the sensitive range

Publication	Sample	Livetime	Energy range	NBins	Flavor PID
Ref. [71]	Upgoing tracks	1 yr	6.3 TeV to 980 TeV	1	μ
Ref. [84]	HESE cascades	6 yr	18 TeV to 2 PeV	4	e
Ref. [85]	HESE ternary	7.5 yr	60 TeV to 10 PeV	4	e, μ, τ

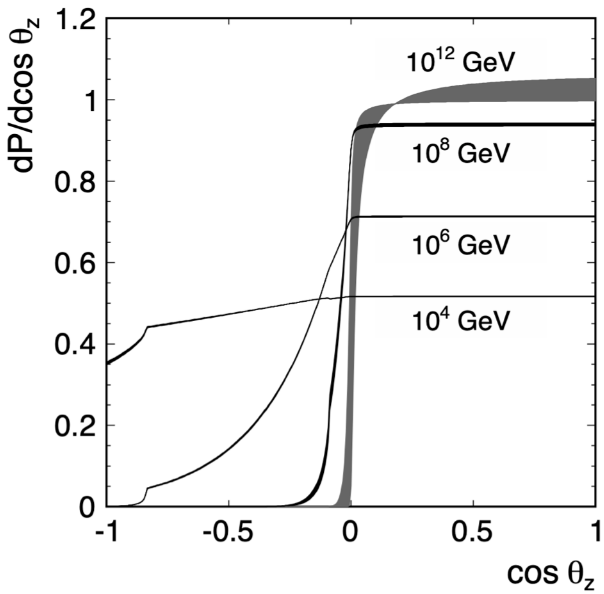
Table 1: Comparison of the three cross section measurements performed with IceCube data. All analyses fixed $\sigma^{\mathrm{CC}}/\sigma^{\mathrm{NC}}$ and $\sigma_{\nu}/\sigma_{\bar{\nu}}$ ratios based on the Standard Model predictions. In addition, $y^{\mathrm{NC}} = 0.25$ was assumed in Ref. [84].

Flux drops rapidly with increasing energy (depending on spectral index); increases in maximum sensitive energy will be fairly modest (until the Gen2/radio era).

Teppei Katori, Juan Pablo Yanez & Tianlu Yuan, arXiv:2109.04430

Radiodetection

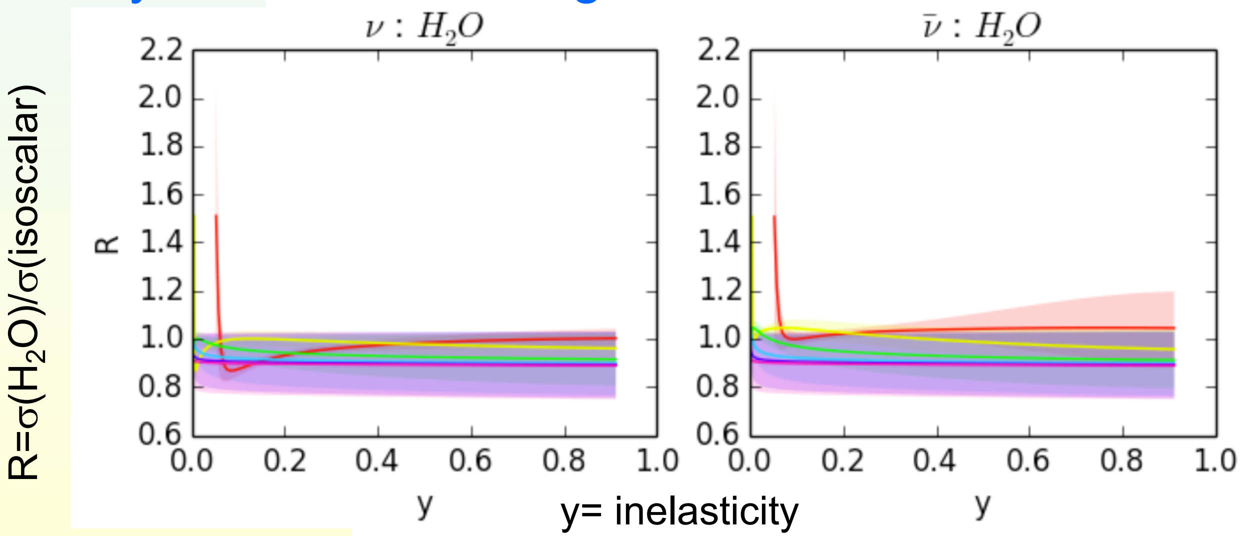
- In the next ~ decade, radio-detection experiments could see neutrinos with energies > 10^{17} eV
  - If UHE cosmic rays are mostly protons, from the GZK process
    - $p + \gamma$(cosmic microwave background radiation)-> Δ^+ -> $n\pi^+$
    - Heavier ions produce fewer ν
- Cross section sensitivity is from ν just below the horizon
  - Good angular resolution is required



A. Connolly, R. S. Thorne & D. Waters, Phys. Rev. D **83**, 113009 (2011).

What are we measuring?

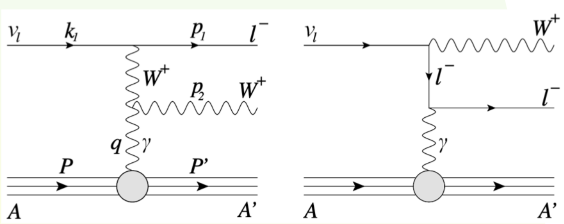
- Current TeV+ measurements give the per-nucleon cross-section for DIS on assumed isoscalar targets.
  - H_2O is not isoscalar
- Nuclear shadowing reduces the cross-section for heavy targets
  - 2-4% reduction - small effect
- Diffractive interactions contribute to σ for E> 100 TeV
- The Glashow resonance for few PeV < E_ν < 10 PeV
  - DIS very difficult in this region, unless ν/νbar ratio well known

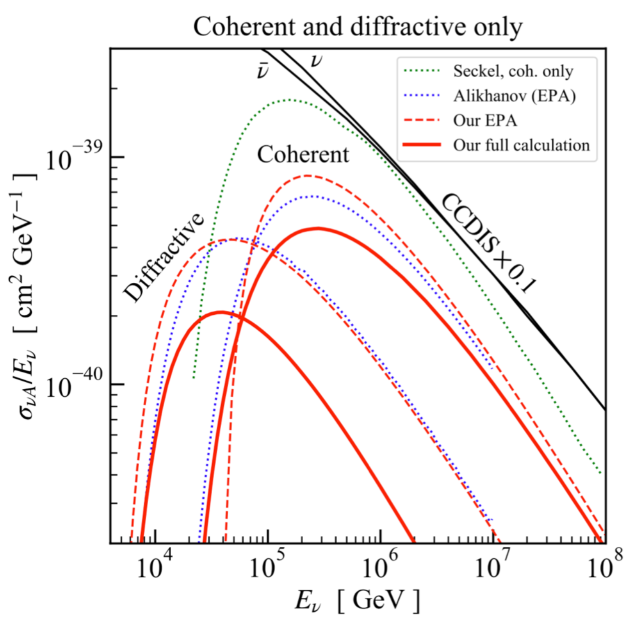


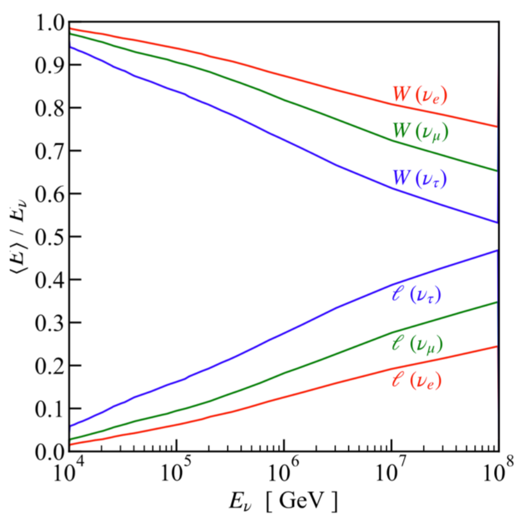
SK, Sally Robertson and Ramona Vogt, Phys. Rev. C **102** 015808 (2020); Zhou and Beacom, Phys. Rev. D 101, 036010 (2020); D **101**, 036011 (2020)

Diffractive interactions

- Diffractive interactions (DI) occur via ν -> virtual $W^{\pm}l^{\mp}$ pair fluctuations, which interact with the Coulomb field of a nucleus, becoming real
- In coherent interactions $\sigma \sim Z^2$, breaking the per-nucleon paradigm
  - Complicates Earth absorption studies
- DI have different inelasticity distributions than DIS



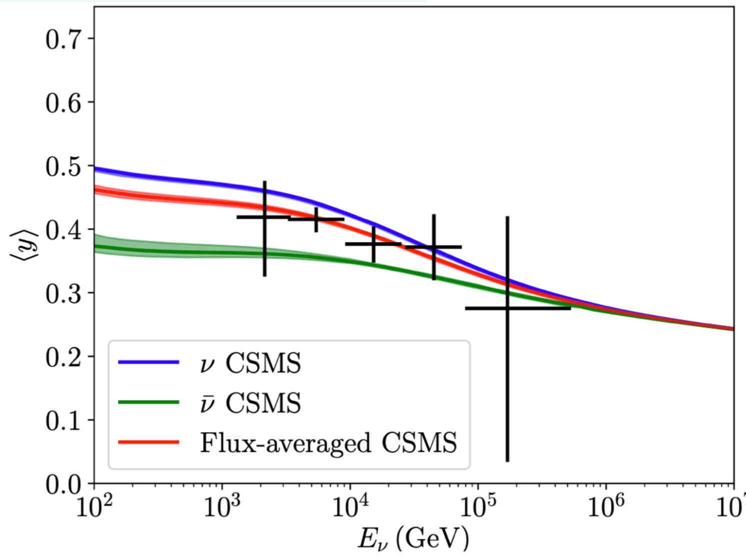


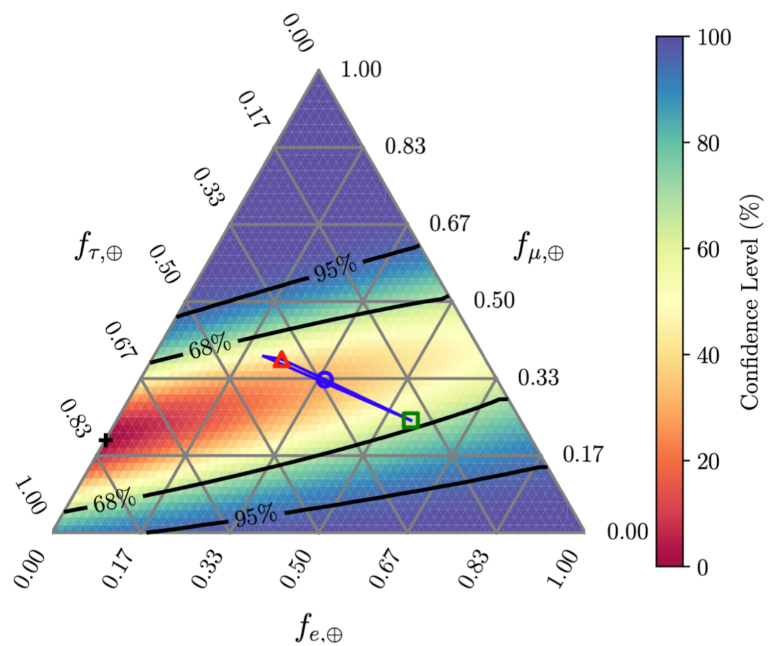


Zhou & Beacom, Phys. Rev. D **101**, 036010 (2020); D **101**, 036011 (2020)

Additional discrimination - inelasticity

- Inelasticity probes different types of interactions, including ν_τ
- $y = E_{\text{hadronic shower}}/E_\nu$
- ν_τ interactions + $\nu_\tau \rightarrow \mu\nu\nu$ have higher <inelasticity> then ν_μ
- IceCube measured inelasticity in 2,650 starting track events
- Complementary probe to cross-section





IceCube, Phys. Rev. D **99**, 032004 (2019)

What about ν_τ?

- $\sigma(\nu_\tau)$ is difficult to measure at low energies, due to the low flux and small cross-section for identifiable CC events.
- Most atmospheric ν_τ are from oscillation from other flavors; determining the flux depends on oscillation parameters
  - FASERν has a short baseline & should see enough ν_τ for a measurement.
- For astrophysical ν, oscillation is assumed to be complete, and the ν_τ flux is as well known as the other flavors.
- Identifying ν_τ events is hard. With a big enough detector, at PeV+ energies, double-bang events could be used. At energies >10^{17} eV, the τ lives long enough that this is difficult. Measurement of hadronic shower + lepton dE/dx (ala IceCube inelasticity study) may be a useful signature.
- Earth-skimming experiments observe a fairly narrow range of zenith angles. Is this enough to both normalize the flux and determine the cross-section?

Conclusions

- Accelerator experiments have measured the neutrino cross-section at energies up to 400 GeV
  - The standard model looks good, at the few percent level.
- In the next few years, FASERν at the LHC will extend accelerator measurements up to several TeV.
- Higher energies are probed by observing ν absorption in the Earth.
  - Current experiments cover the TeV to PeV range. Near-future data will improve the precision in this energy range, while longer-term radio-detection experiments could reach the EeV range.
    - These experiments will probe low-x, high Q^2 structure functions, and are sensitive to BSM physics.
  - Absorption studies are subject to significant systematic uncertainties, including due to limited knowledge of the ν beam.
    - This is not a problem for BSM studies, where orders-of-magnitude increase in the cross-section are expected, or for searches for large saturation effects. It will limit precision parton measurements.

Backup/extra