Muon Collider Synergies

(Orsay, France)

Ideas for High-Energy Neutrino Experiments

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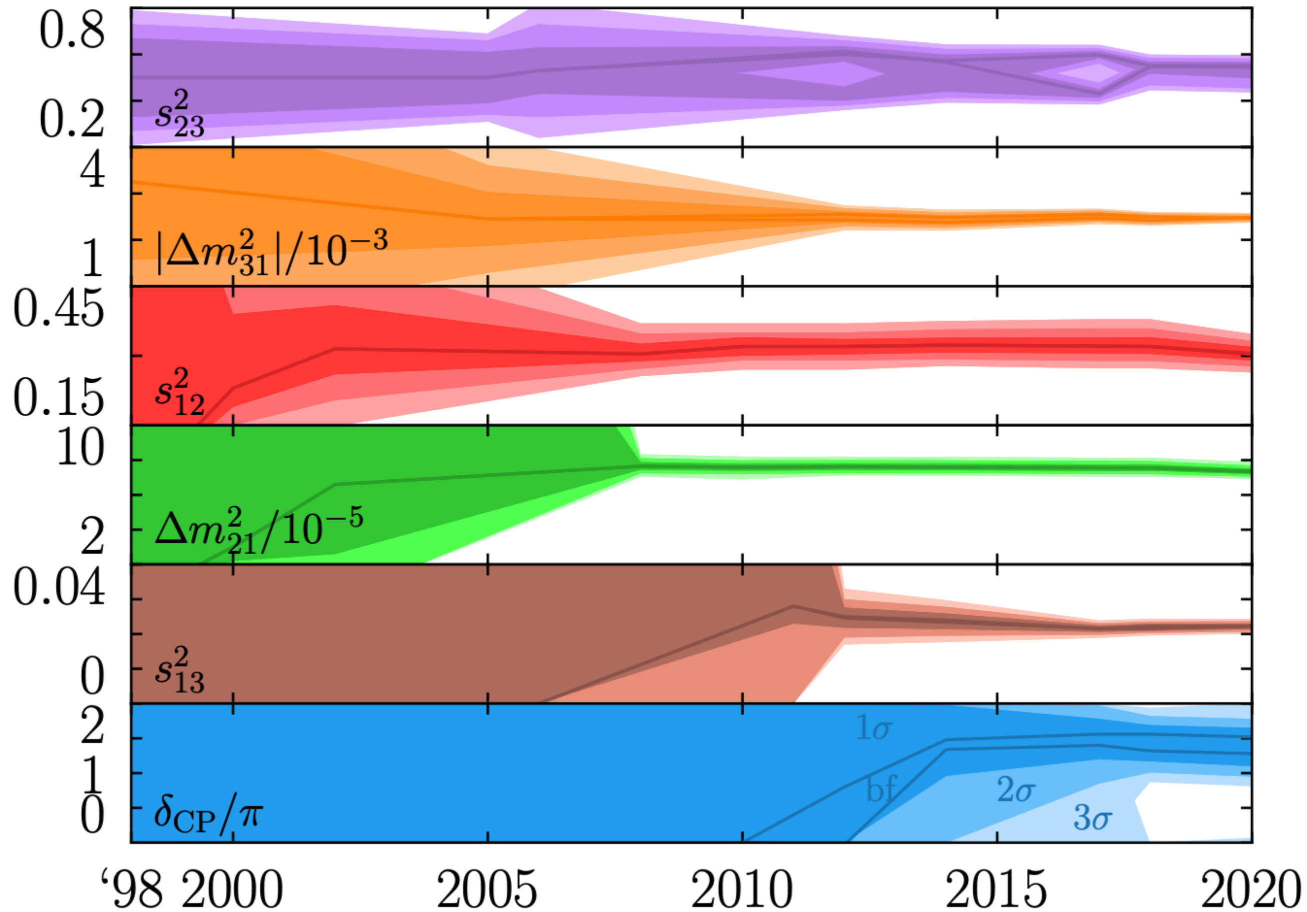
*Disclaimer: my own vision of the topic

- What will we know about neutrinos in 2045?
- What else can we learn with a powerful neutrino beam -> specifications?

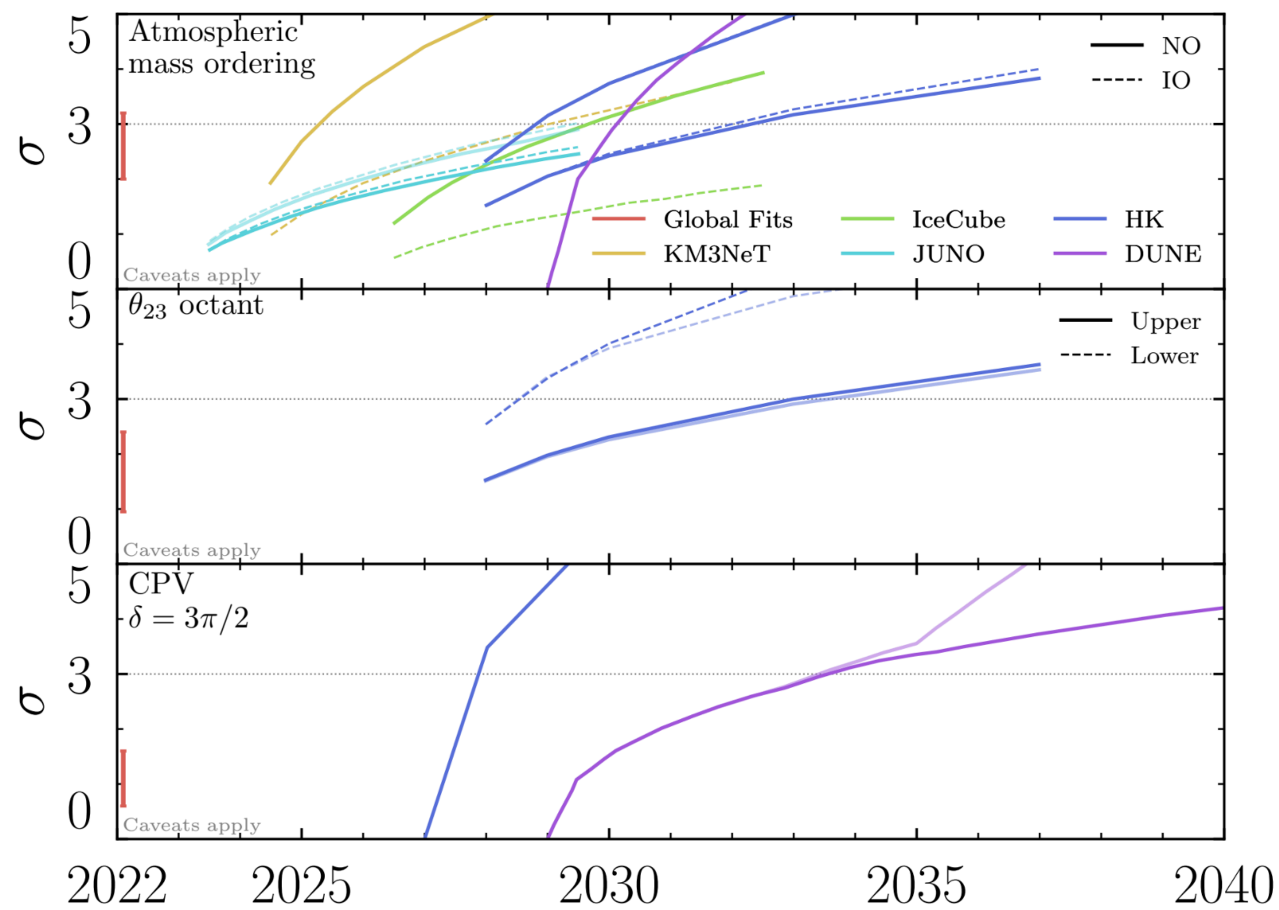
Neutrino oscillations

- Current challenges:
  - CP violation and mass ordering.
- Will they be an interesting topic in 2045?
  - DUNE, HyperK, JUNO, KM3NeT, IC-Upgrade should be there -> precession physics.

arXiv:2212.00809

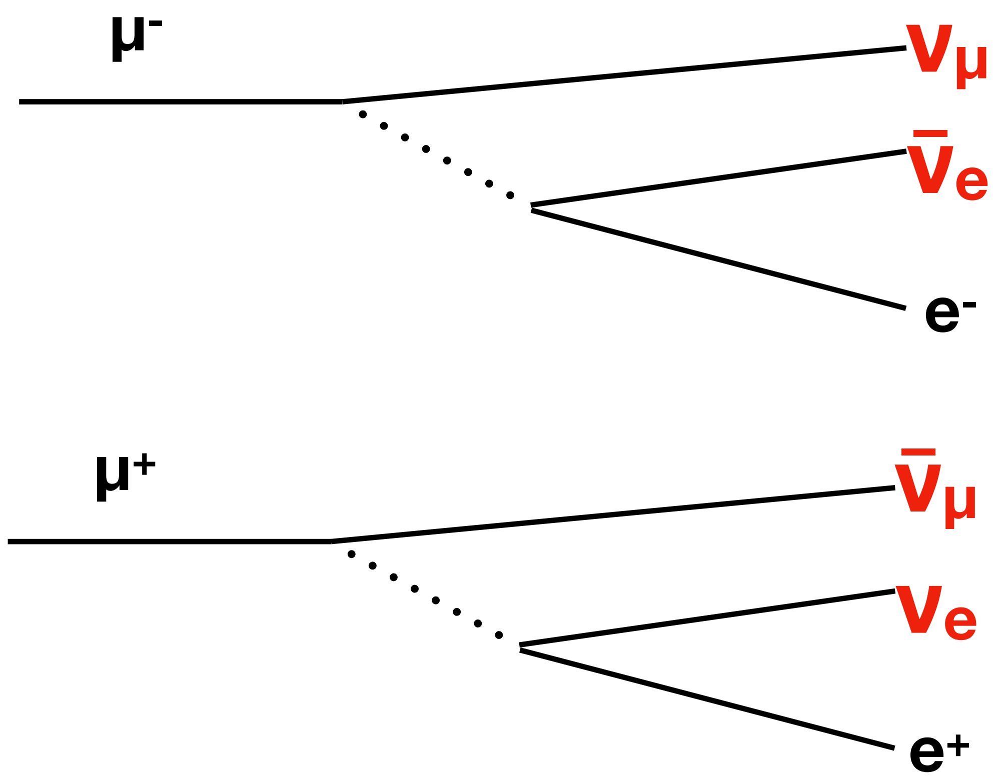


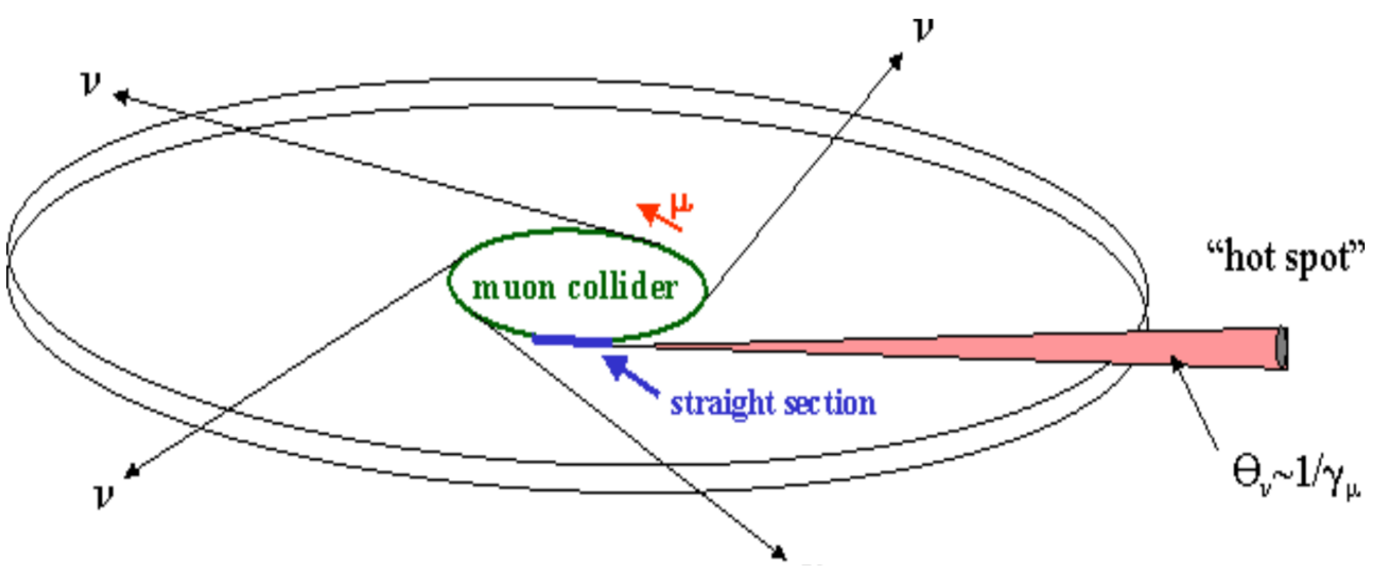
Snowmass - NF01 Report Draft v1



Muon collider

- Intense beam of neutrinos:
  - Known composition: ν_μ and $\bar{\nu}_e$.
  - Energies expanding from GeV to TeV.
  - Can we change polarity (i.e. direct μ^+ instead of μ^- decays)?

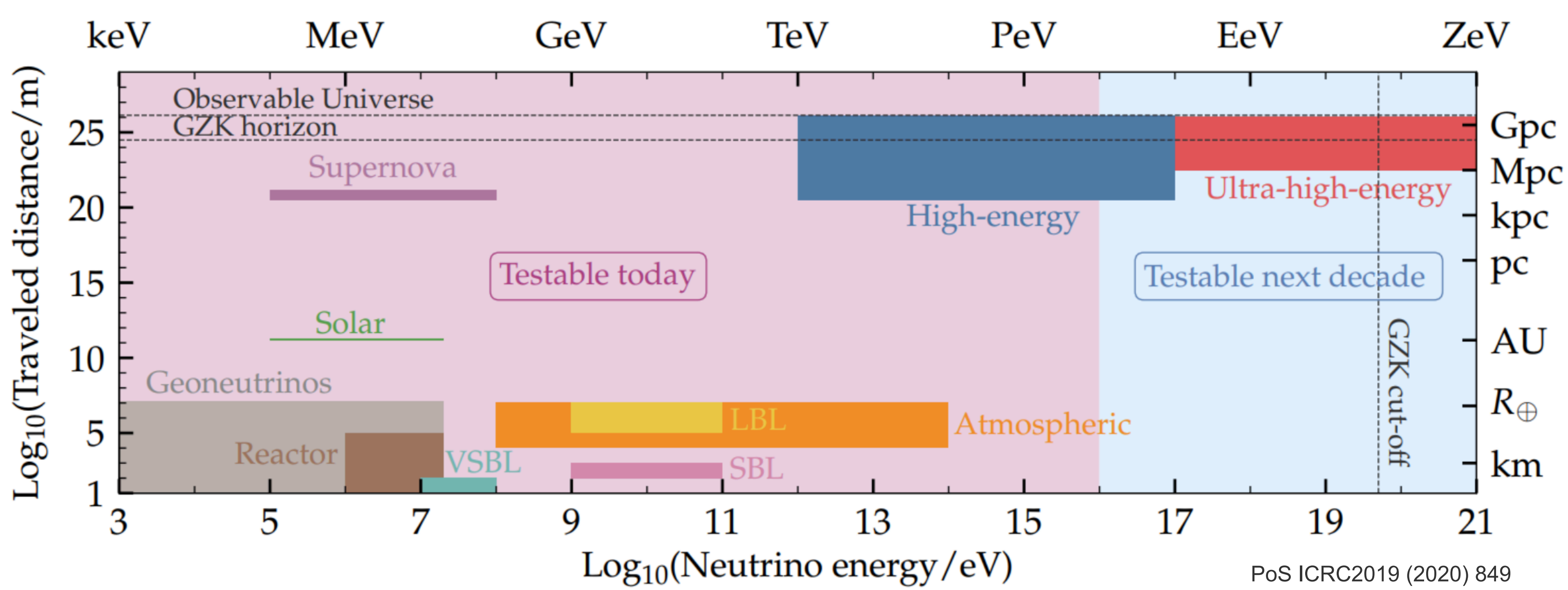




arXiv:hep-ex/0005006

Where can Muon Collider make in impact?

- E<10 GeV
  - Already explored with current and next generation of experiments.
- 10 GeV<E<100 GeV
  - Atmospheric neutrinos -> Large uncertainties in flux and poor resolutions! ✅
  - NuTEV/NOMAD -> Focus on no-oscillation regime.
- E>100 GeV
  - Atmospheric neutrinos -> Large uncertainties in flux and poor resolutions! ✅
  - FPF -> Uncertainties in flux!

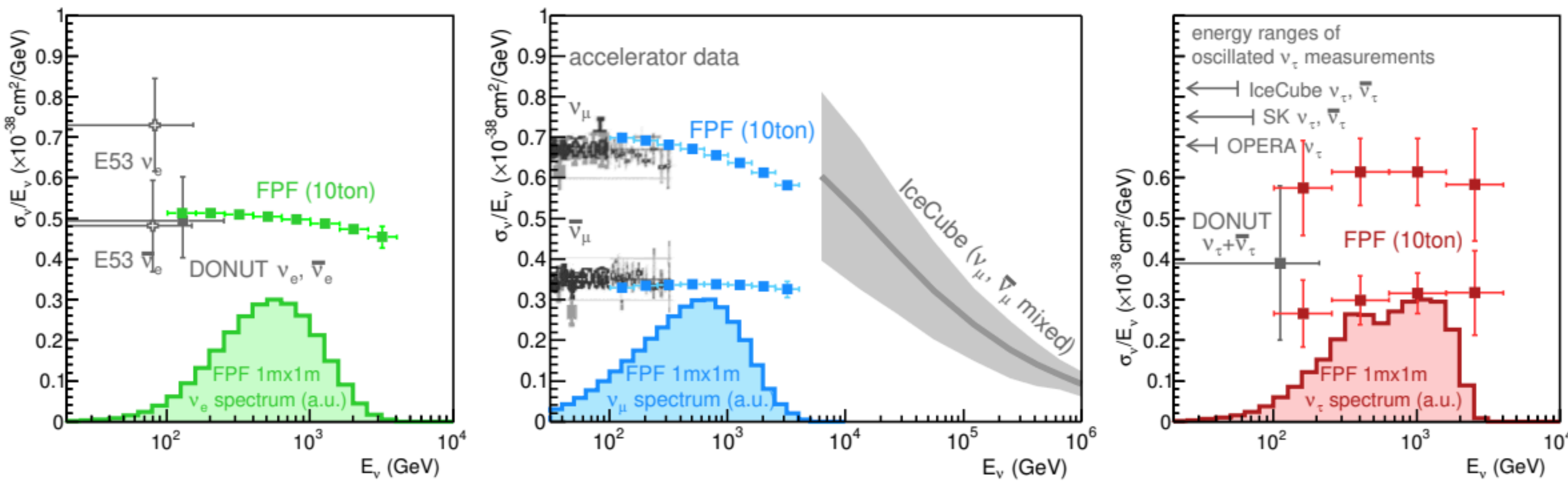


PoS ICRC2019 (2020) 849

Neutrino cross sections

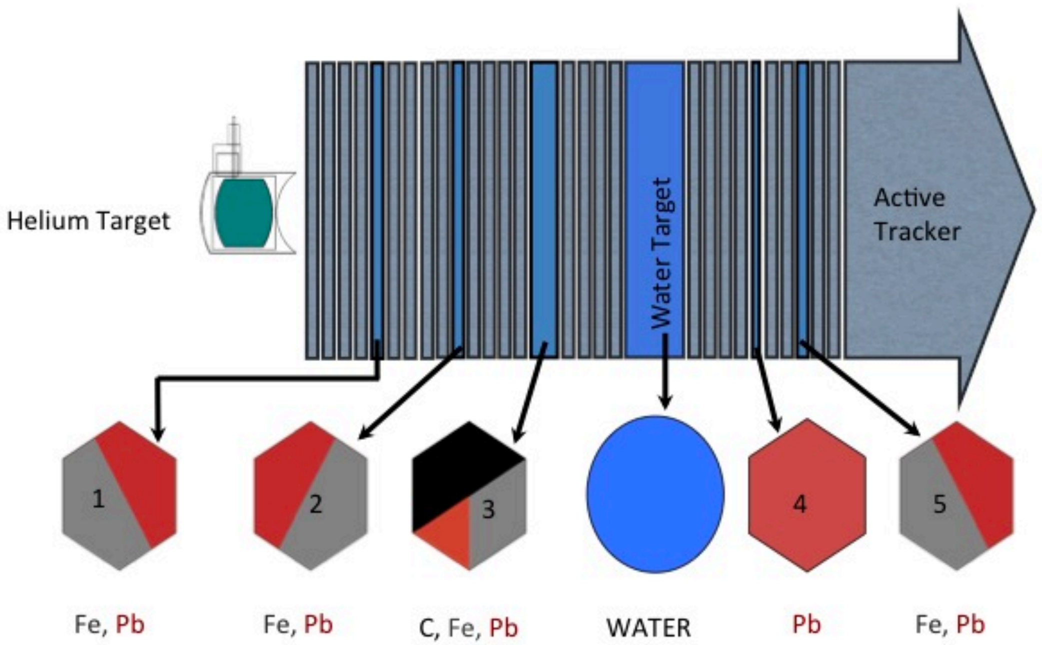
- Follow FPF strategy -> Detector close to the collider.
  - High statistics.
  - Control flux.
  - Precise measurement of neutrino cross section.

arXiv:2203.05090

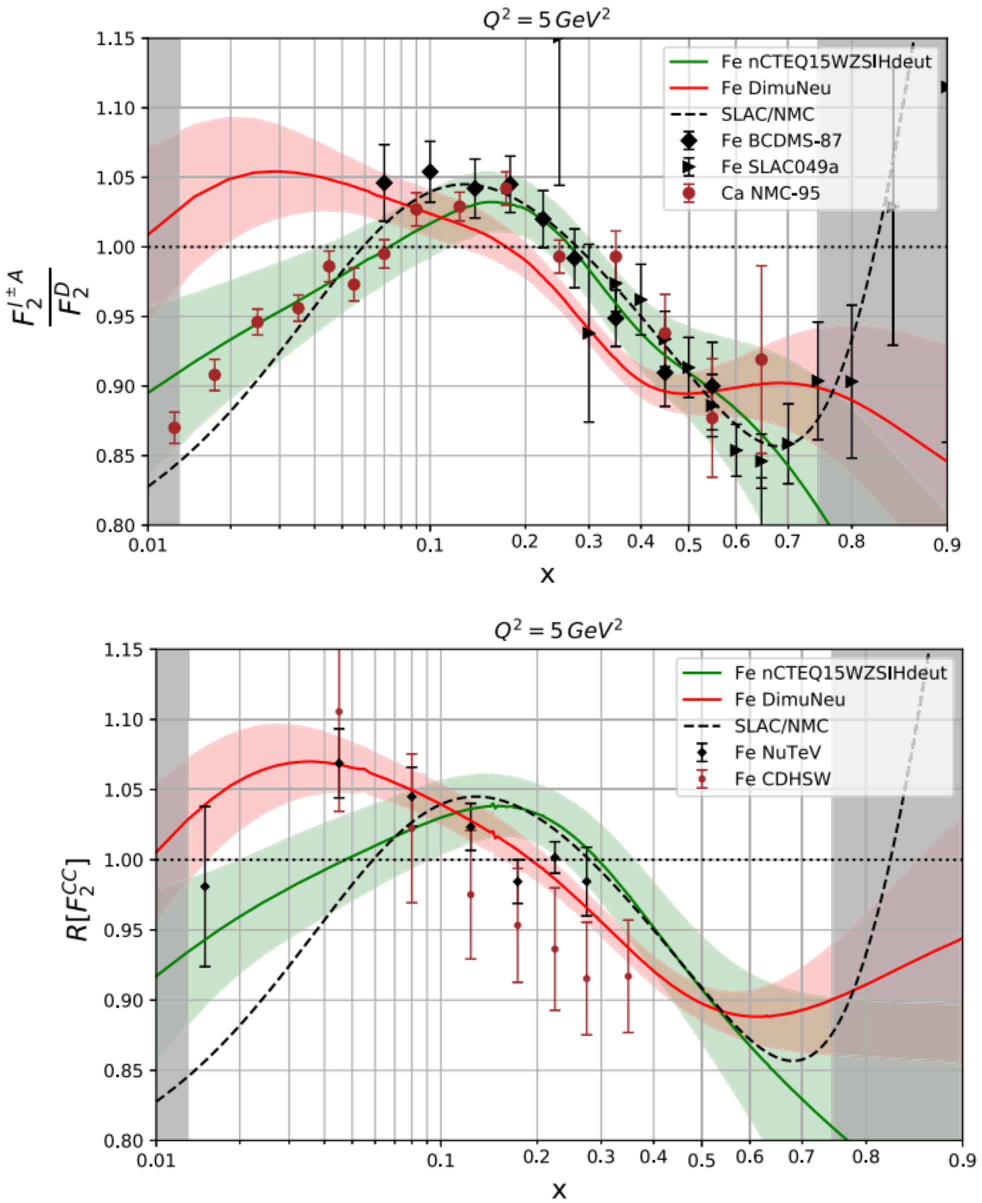


Neutrino cross sections

- Multi target experiment (a la MINERvA)?
  - Might allow us to study nuclear effects.
  - EMC, shadowing, etc.
  - We need H/He target!
- Dimuons -> strange composition of proton

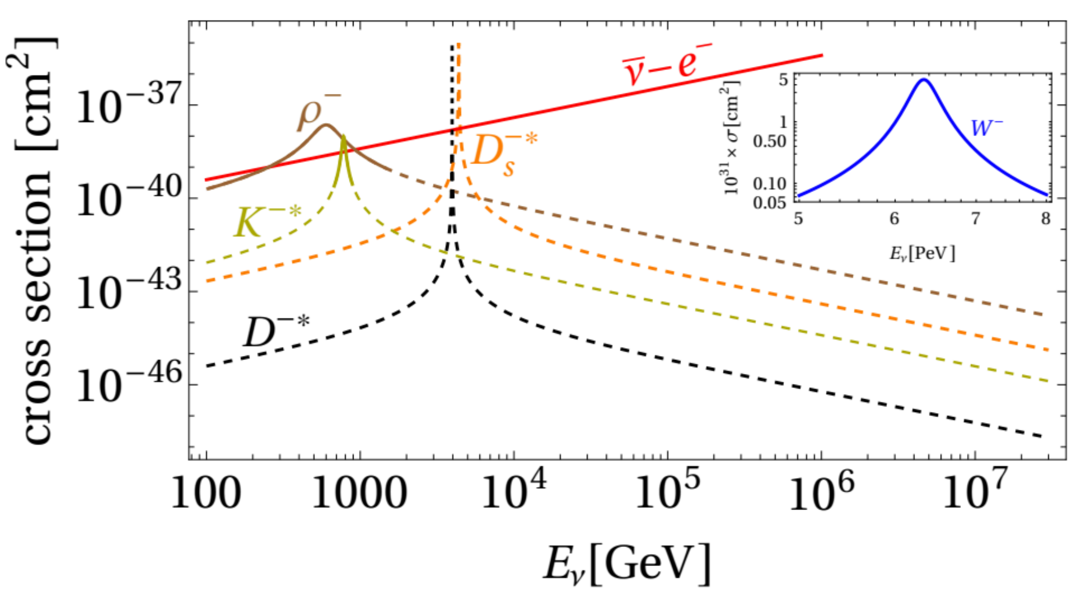


arXiv:2204.13157

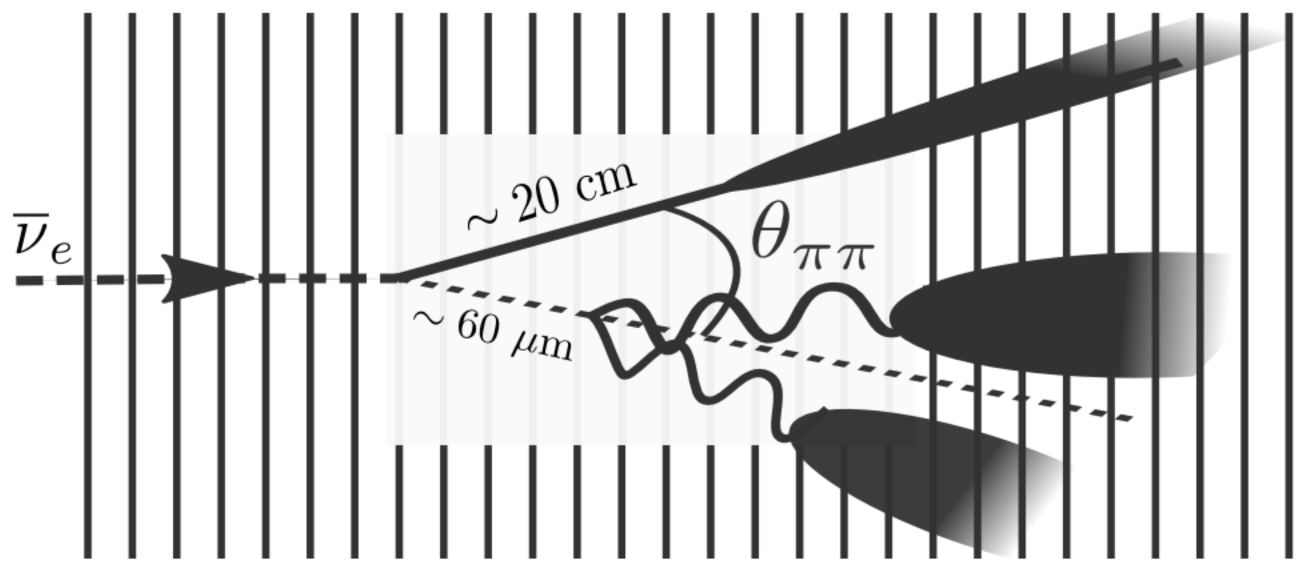


Neutrino cross sections

- Meson resonance from antineutrino-electron scattering
  - O(100) interactions in FPF experiments.
  - Background from DIS and through-going muons.
  - LArTPCs and emulsion detector are the most promising technologies.



arXiv:2112.03283



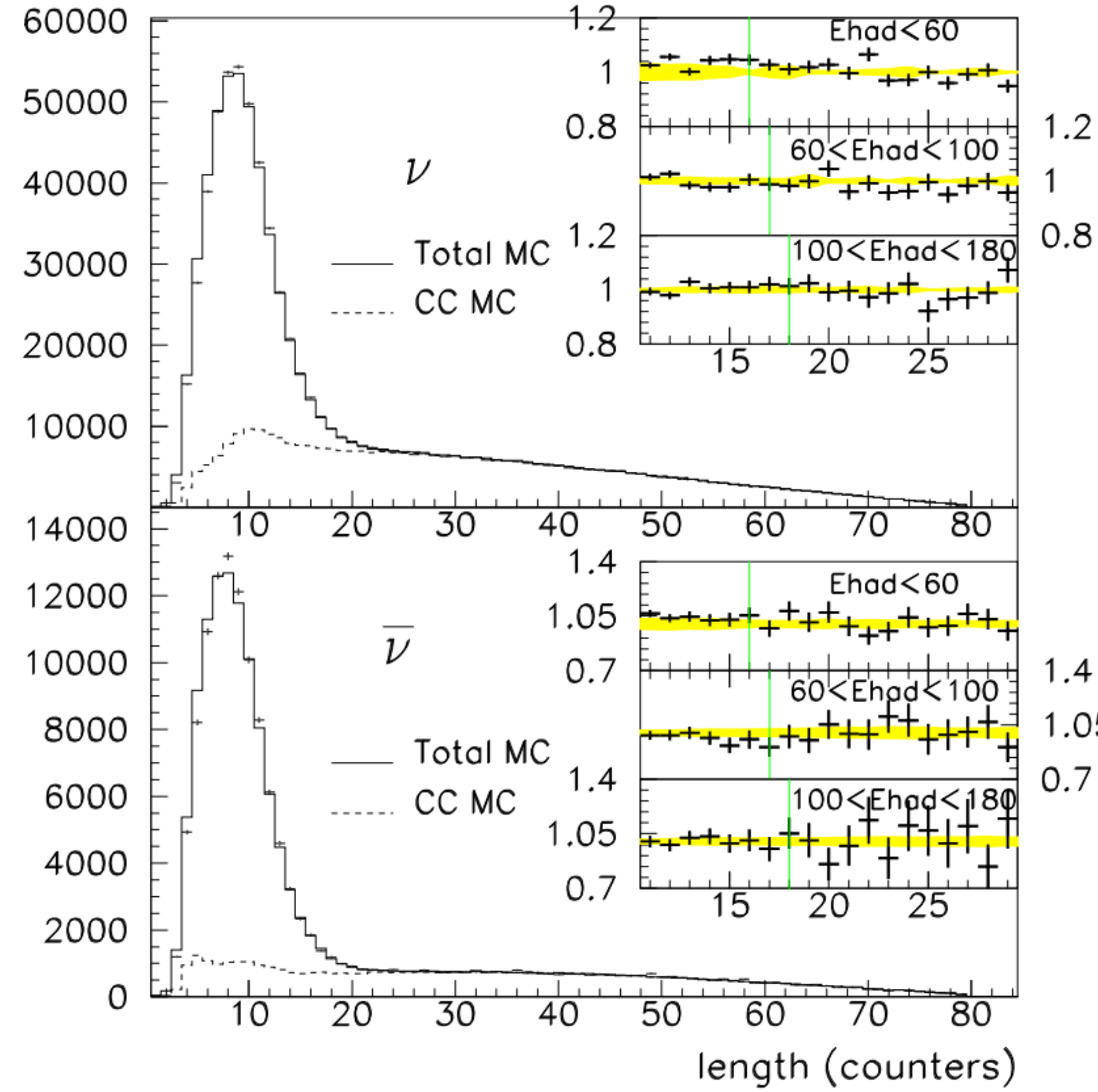
Test EW

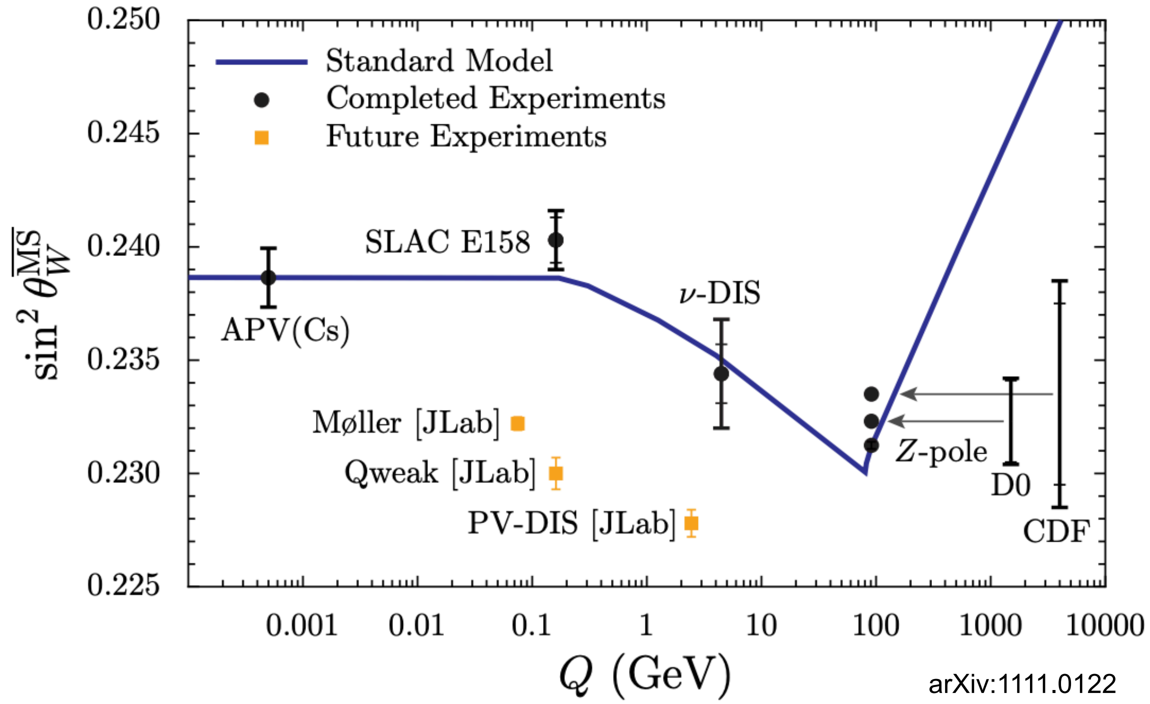
- NuTeV "anomaly":
  - Pure beam of muon (anti)neutrinos (<2% wrong sign+flavor).
  - Paschos-Wolfenstein (PW) relation:

$$R = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}} \approx 1/2 - \sin^2\theta_W$$

  - 3 sigma tension with SM
  - Overall consensus nucleon charge symmetry violating effects, strange sea quarks, and nuclear corrections.

arXiv:hep-ex/0110059





arXiv:1111.0122

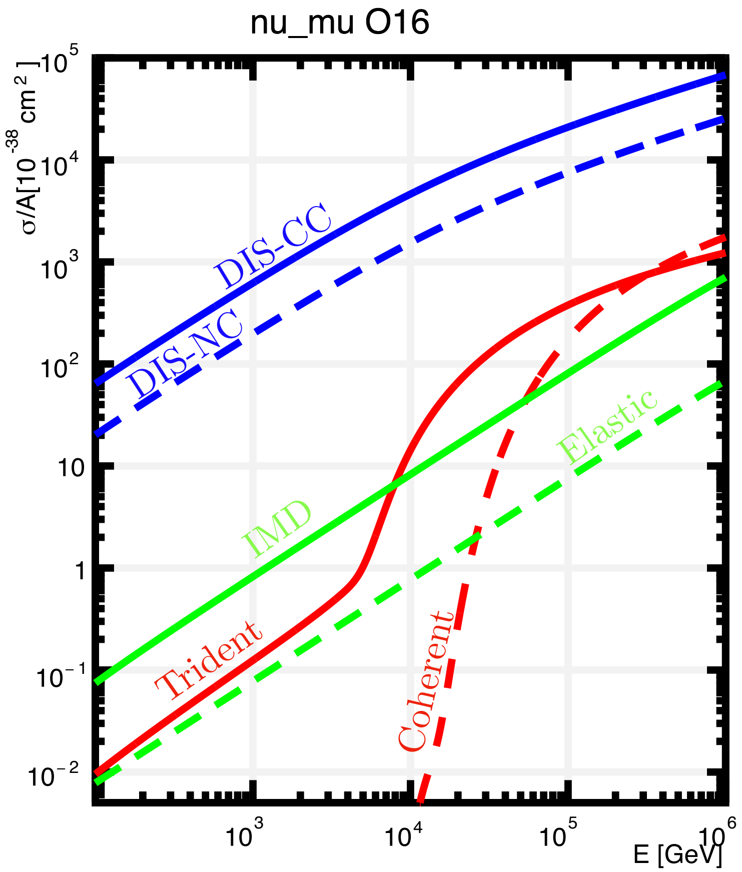
Test EW

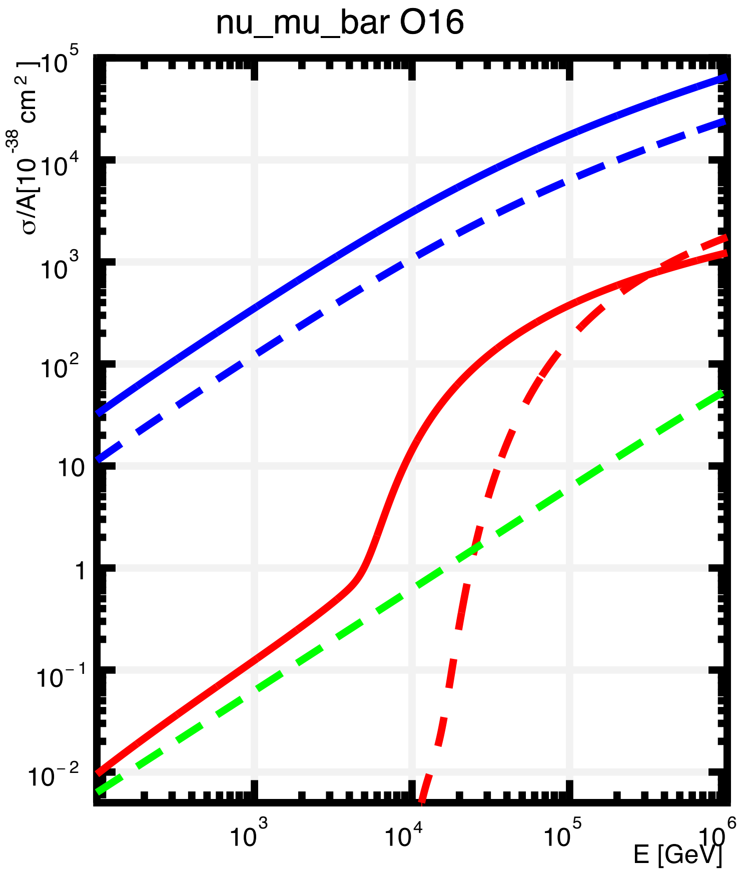
CAVEAT: Muon collider has large electron-flavor content unlike the NuTeV/NuSong style beams. But it is a very well defined electron-flavor content

- NuSOnG: arXiv:0907.4864
  - Looking also at electron scattering from pure ν_μ and $\bar{\nu}_\mu$ beams.
  - IMD and low-nu used to constrain the flux.

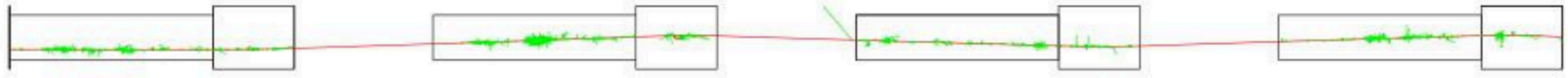
$$\frac{N(\nu_\mu e^- \to \nu_\mu e^-)}{N(\nu_\mu e^- \to \mu^- \nu_e)} = \frac{\sigma_{NC}^{\nu e} \times \Phi^\nu}{\sigma^{IMD} \times \Phi^\nu}.$$

$$\frac{N_{\nu DIS}^{low\ E_{had}}}{N_{\bar{\nu} DIS}^{low\ E_{had}}} \times \frac{N(\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-)}{N(\nu_\mu e^- \to \mu^- \nu_e)} = \frac{\Phi^\nu}{\Phi^{\bar{\nu}}} \times \frac{\sigma_{NC}^{\bar{\nu} e} \times \Phi^{\bar{\nu}}}{\sigma^{IMD} \times \Phi^\nu}.$$



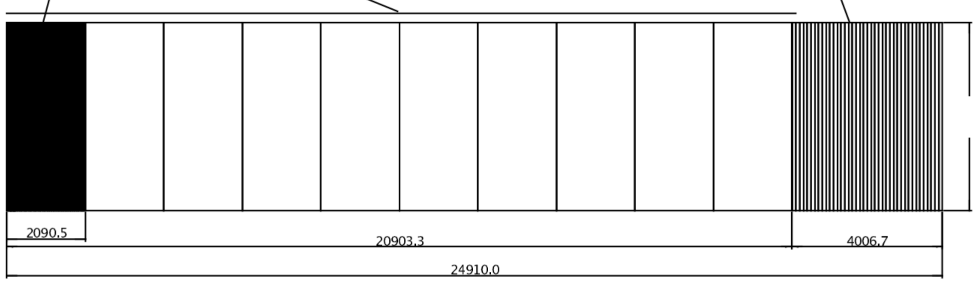


Test EW



- NuSOnG: arXiv:0907.4864
  - Four calorimeters+muon spectrometer separated by 15m.
  - Each calorimeter has 500 layers of glass and active detectors.

- Why glass?
  - Long radiation length -> PID
  - Short detector -> calibration
  - Isoscalar.



Neutrino mode

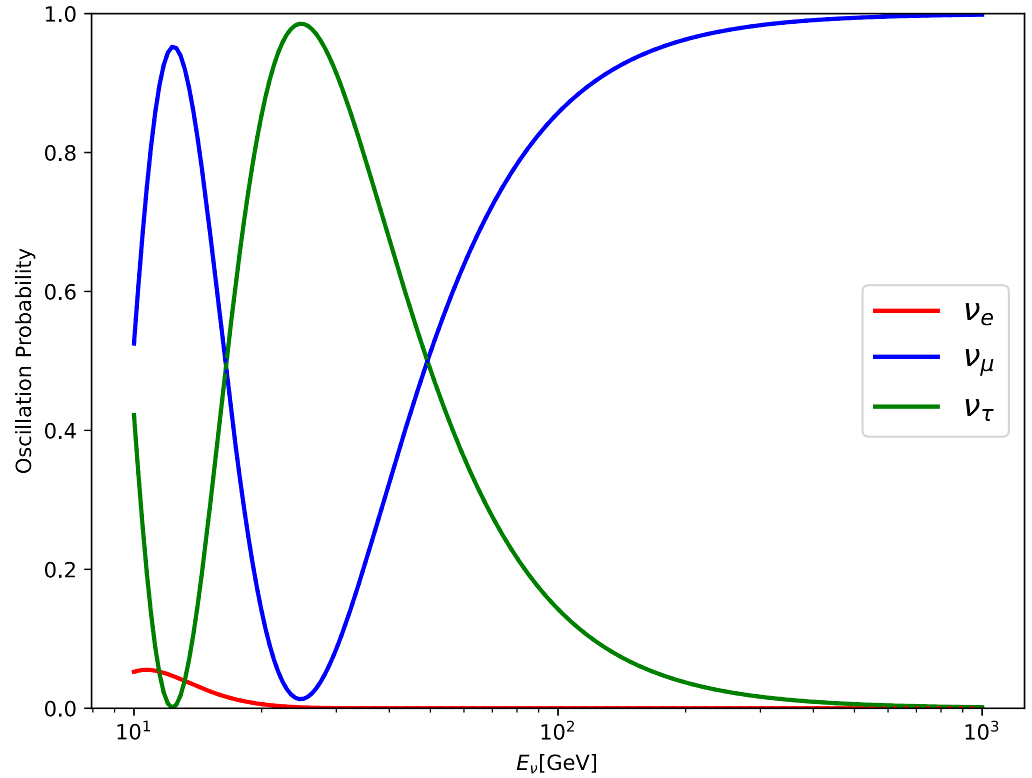
$507k$	ν_μ CC quasi – elastic scatters
$178k$	ν_μ NC – elastic scatters
$1016k$	ν_μ CC π^+
$302k$	ν_μ CC π^0
$272k$	ν_μ NC π^0
$226k$	ν_μ NC $\pi^\pm$
$1379k$	ν_μ CC and NC Resonance multi – pion
$202M$	ν_μ CC Deep Inelastic Scattering
$63M$	ν_μ NC Deep Inelastic Scattering
$24k$	ν_μ neutrino – electron NC elastic scatters
$235k$	ν_μ neutrino – electron CC quasielastic scatters(IMD)

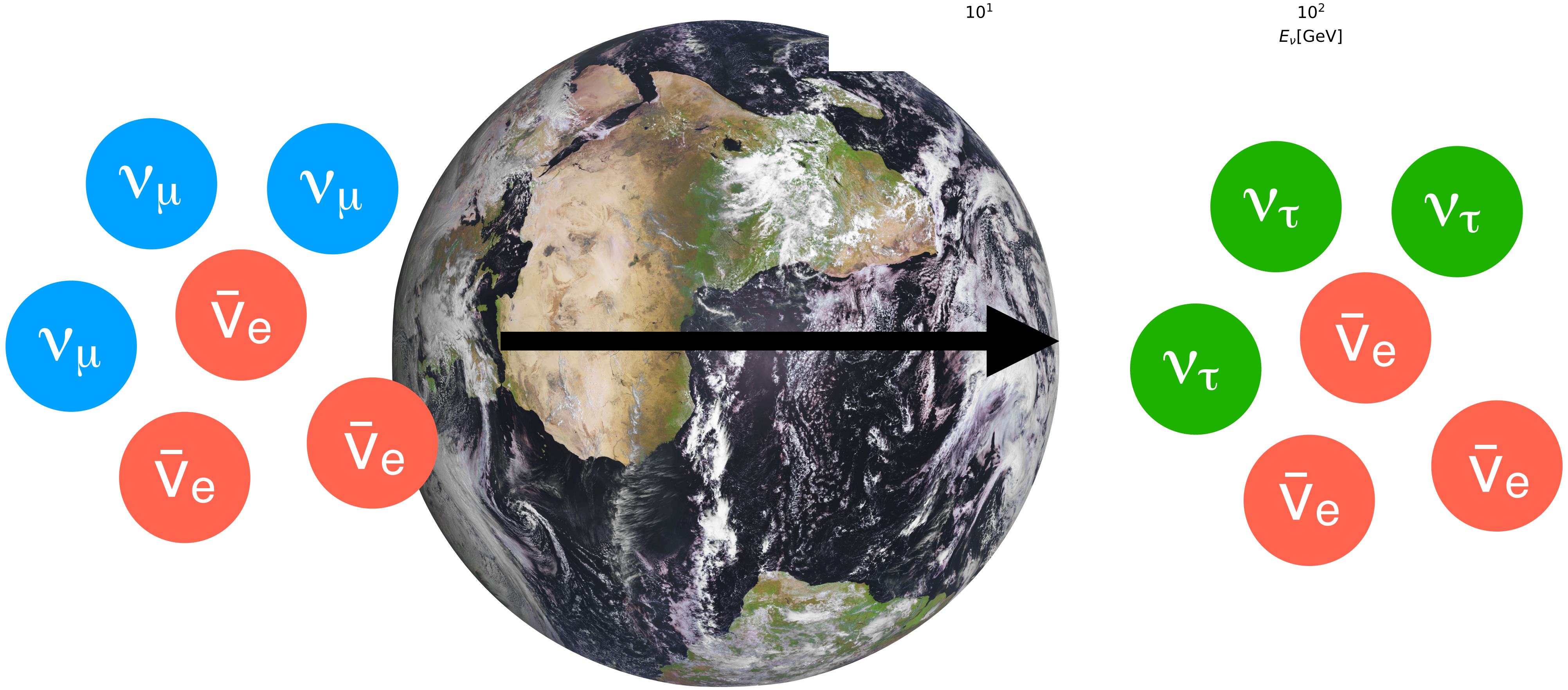
Antineutrino mode

$548k$	$\bar{\nu}_\mu$ CC quasi – elastic scatters
$195k$	$\bar{\nu}_\mu$ NC – elastic scatters
$1103k$	$\bar{\nu}_\mu$ CC π^+
$321k$	$\bar{\nu}_\mu$ CC π^0
$297k$	$\bar{\nu}_\mu$ NC π^0
$246k$	$\bar{\nu}_\mu$ NC $\pi^\pm$
$1516k$	$\bar{\nu}_\mu$ CC and NC Resonance multi – pion
$102M$	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering
$36M$	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering
$21k$	$\bar{\nu}_\mu$ neutrino – electron NC elastic scatters
$0k$	$\bar{\nu}_\mu$ neutrino – electron CC quasielastic scatters (IMD)

Tau appearance

- Earth as baseline (L~12000km).
  - Large ν_τ appearance at 20-100 GeV.
  - P_{ee}=1.

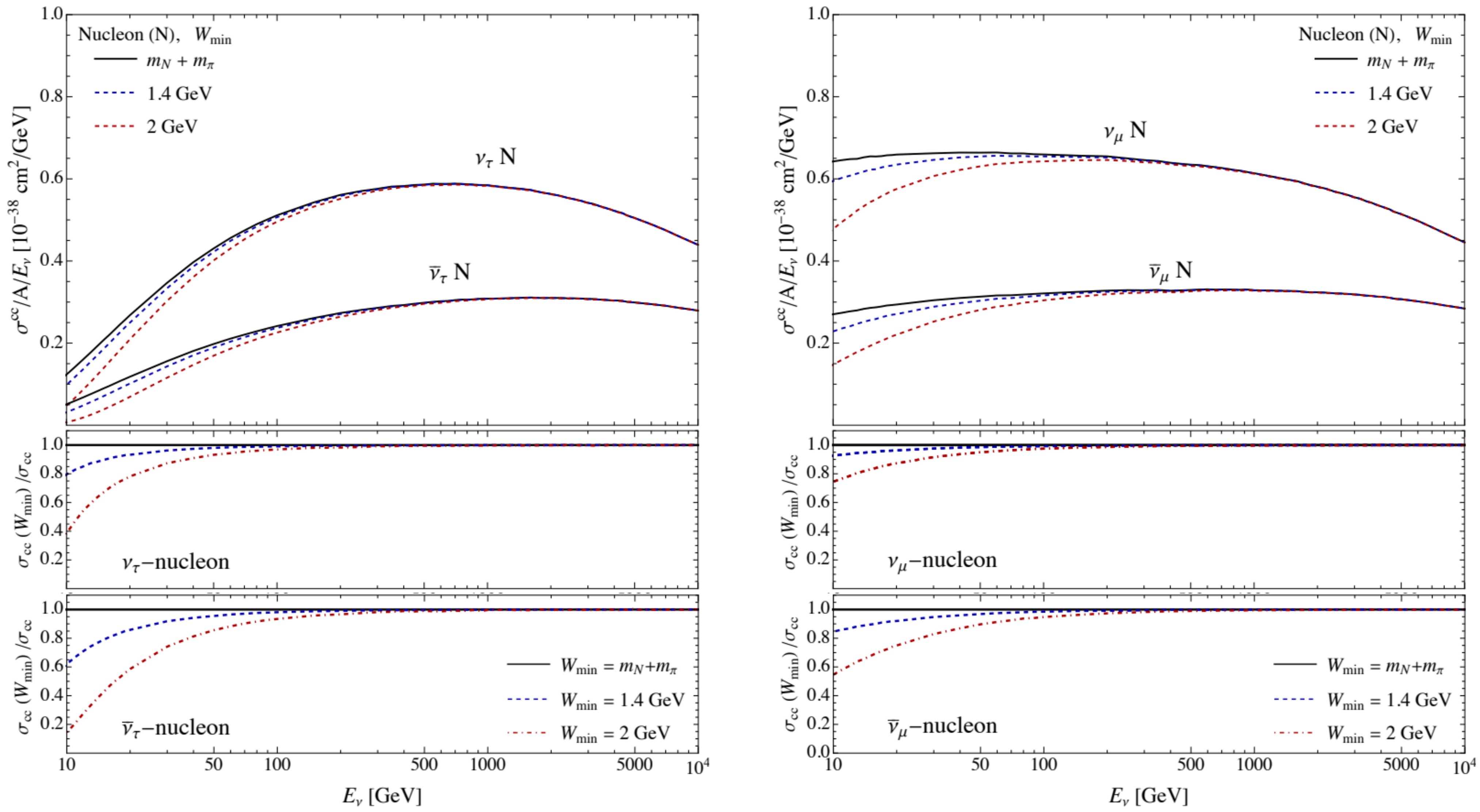




Tau appearance

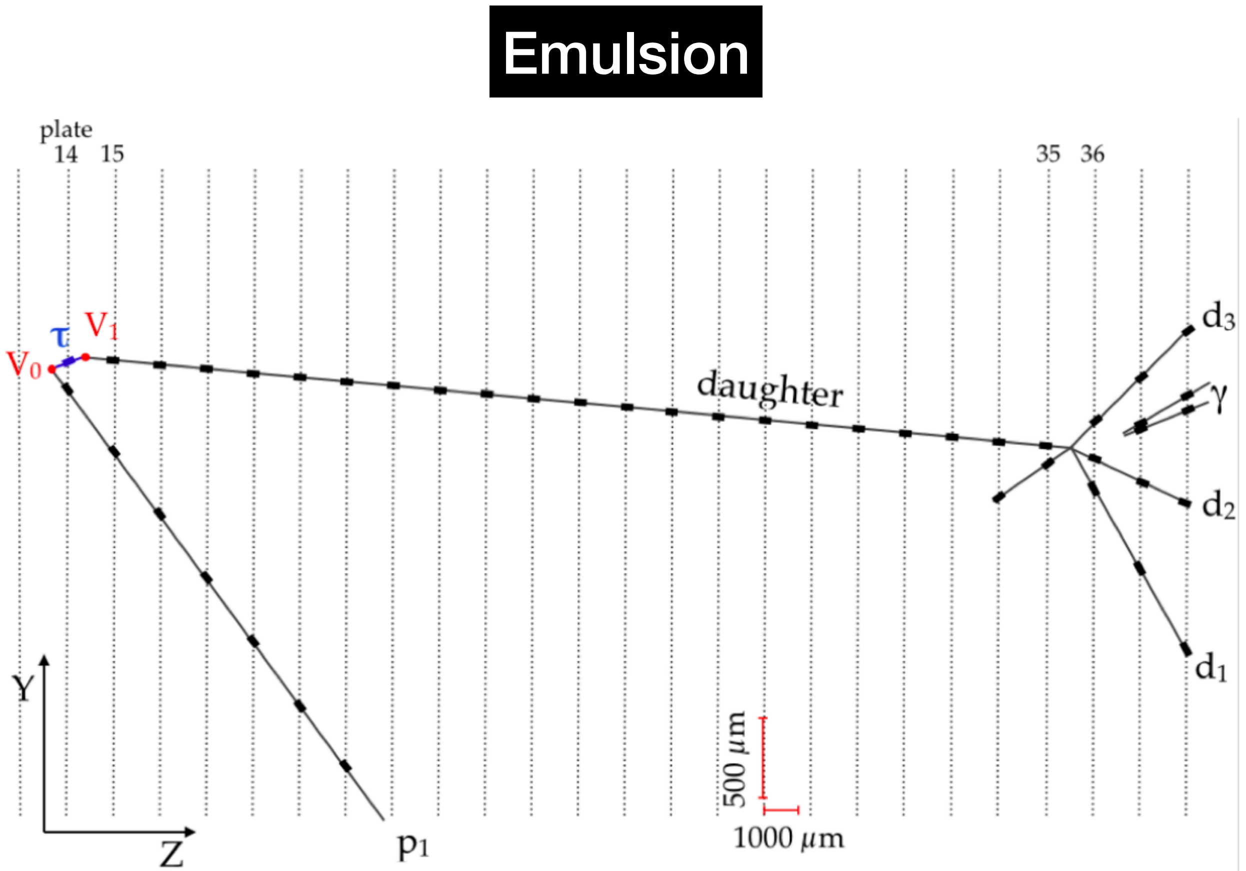
- Enough energy to interact via charged current.
  - Factor ~0.4(0.75) with respect to ν_μ at 20(100) GeV.

arXiv:2203.05090

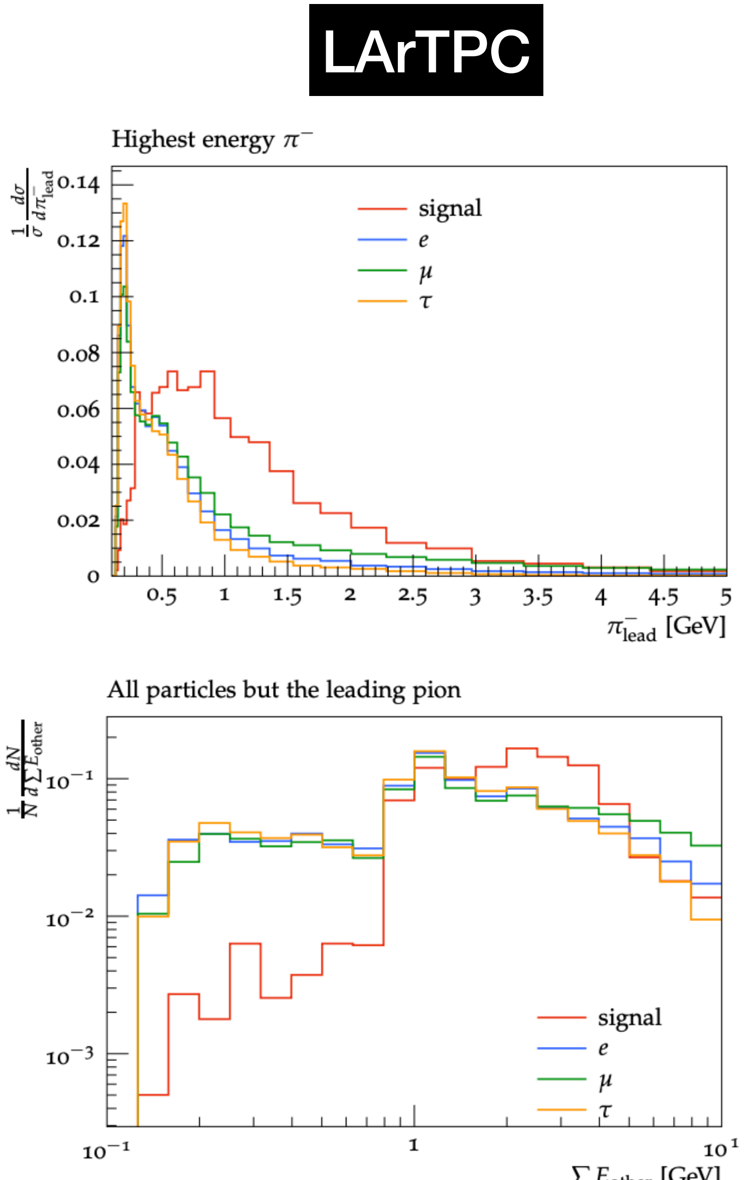


Tau appearance

- Identify tau neutrino interactions
  - Event by event -> Reconstruct secondary vertex with <1cm from the interaction point.
  - Distribution -> Hadron kinematics



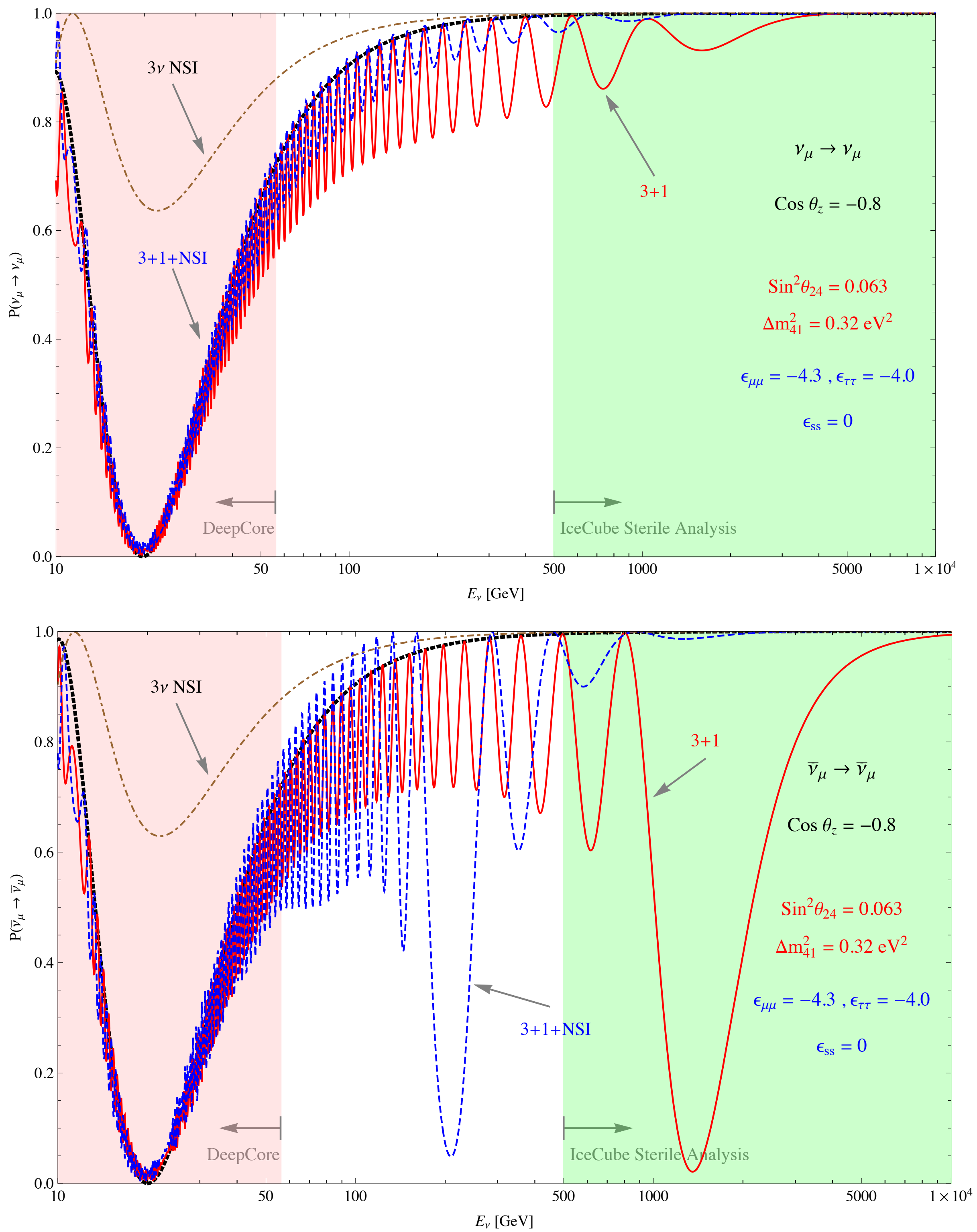
arXiv:1507.01417



arXiv:2007.00015

Tau appearance

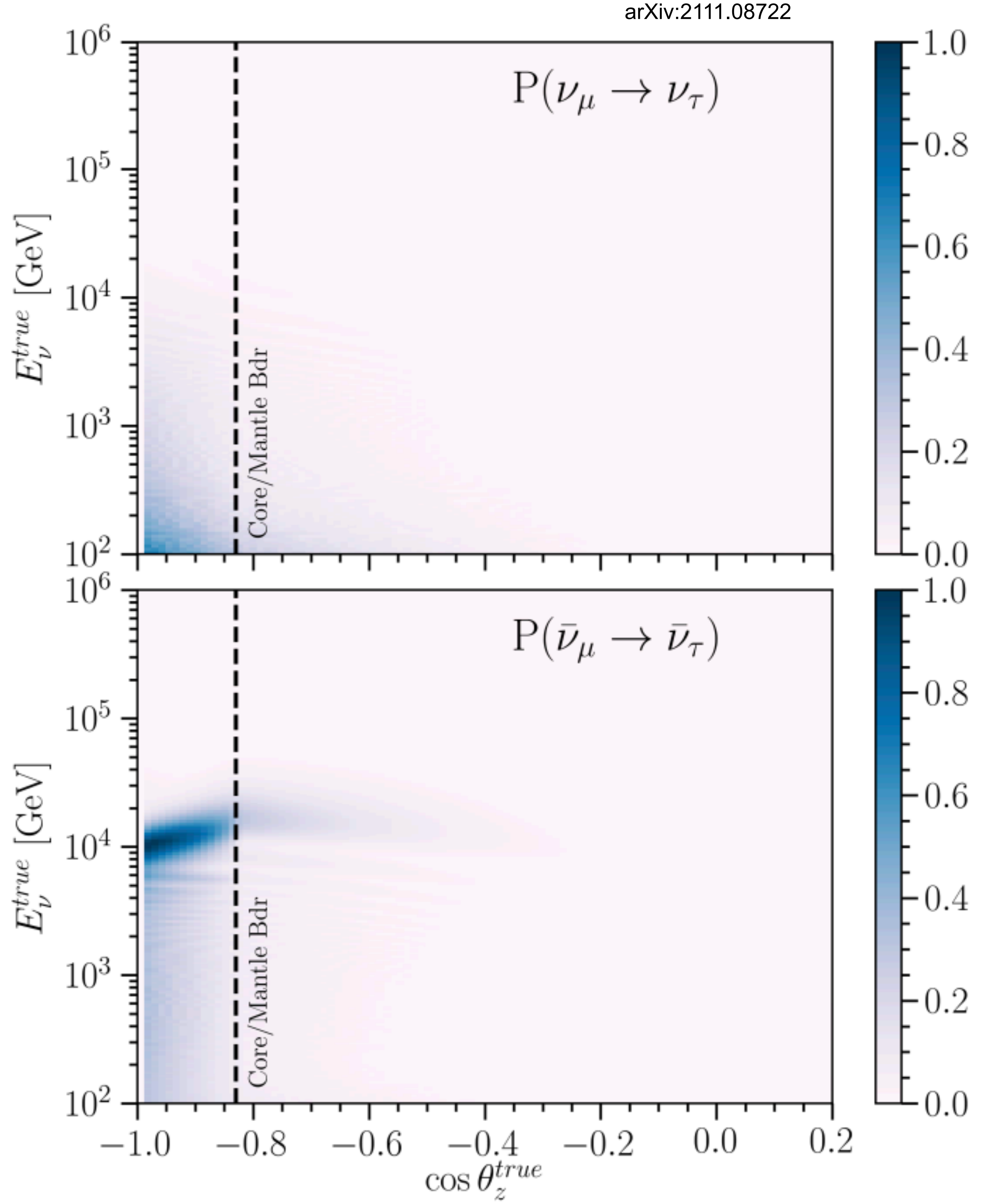
- What can we study?
  - ν_μ disappearance.
  - Interesting portal to BSM.



arXiv:1810.11940

Tau appearance

- What can we study?
  - ν_τ vs $\bar{\nu}_\tau$ appearance.
  - Interesting portal to BSM.



Conclusion

- Neutrino beam from muon collider:
  - Expand along a wide energy range.
  - Very good understanding of flavor composition.
  - Instense!
- Which areas can benefit from it?
  - Neutrino cross sections -> nuclear effects, secondary interactions.
  - EW measurements.
  - Tau appearance.
- Concentrating on tomorrow's physics, not today's.
  - Technological challenges for engineers -> let them stew on it

Acknowledgements

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