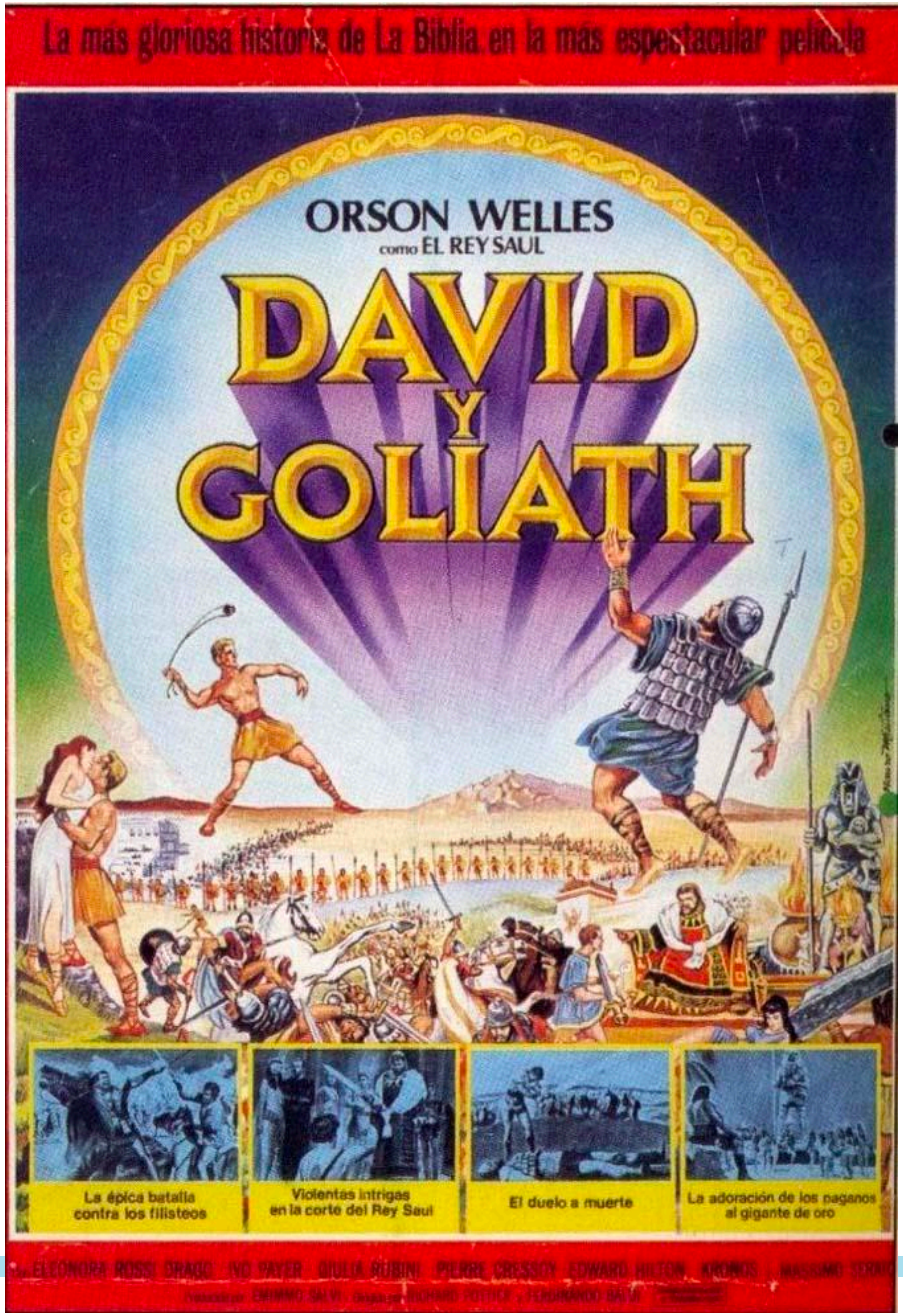
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

IceDUNE: oscillations and friends!

Pedro A. N. Machado

June 16th, 2021



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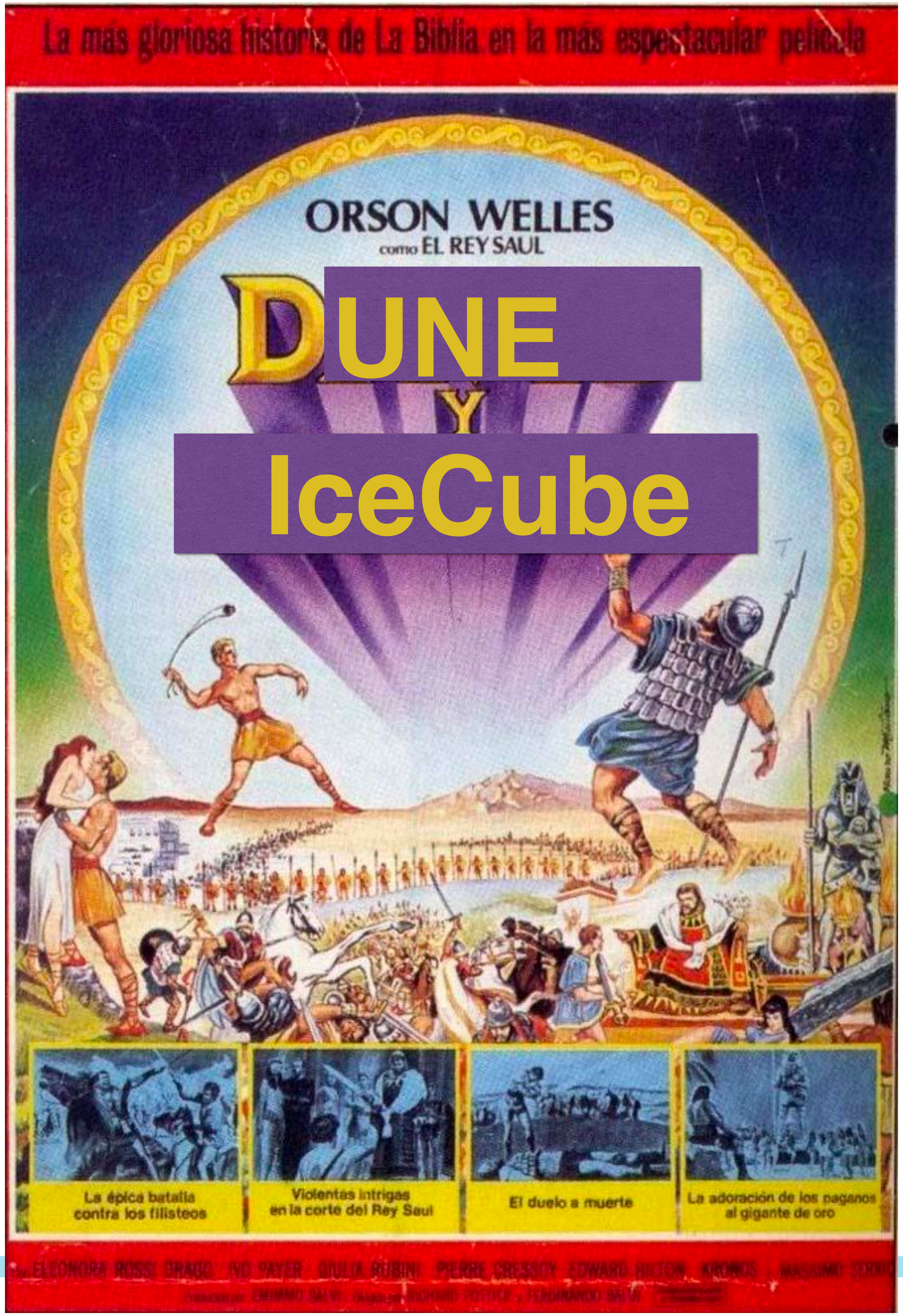

Imagine what can happen if they partner up…

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Atmospheric neutrinos below the GeV scale and CP violation

Some thoughts on what else could be done with it

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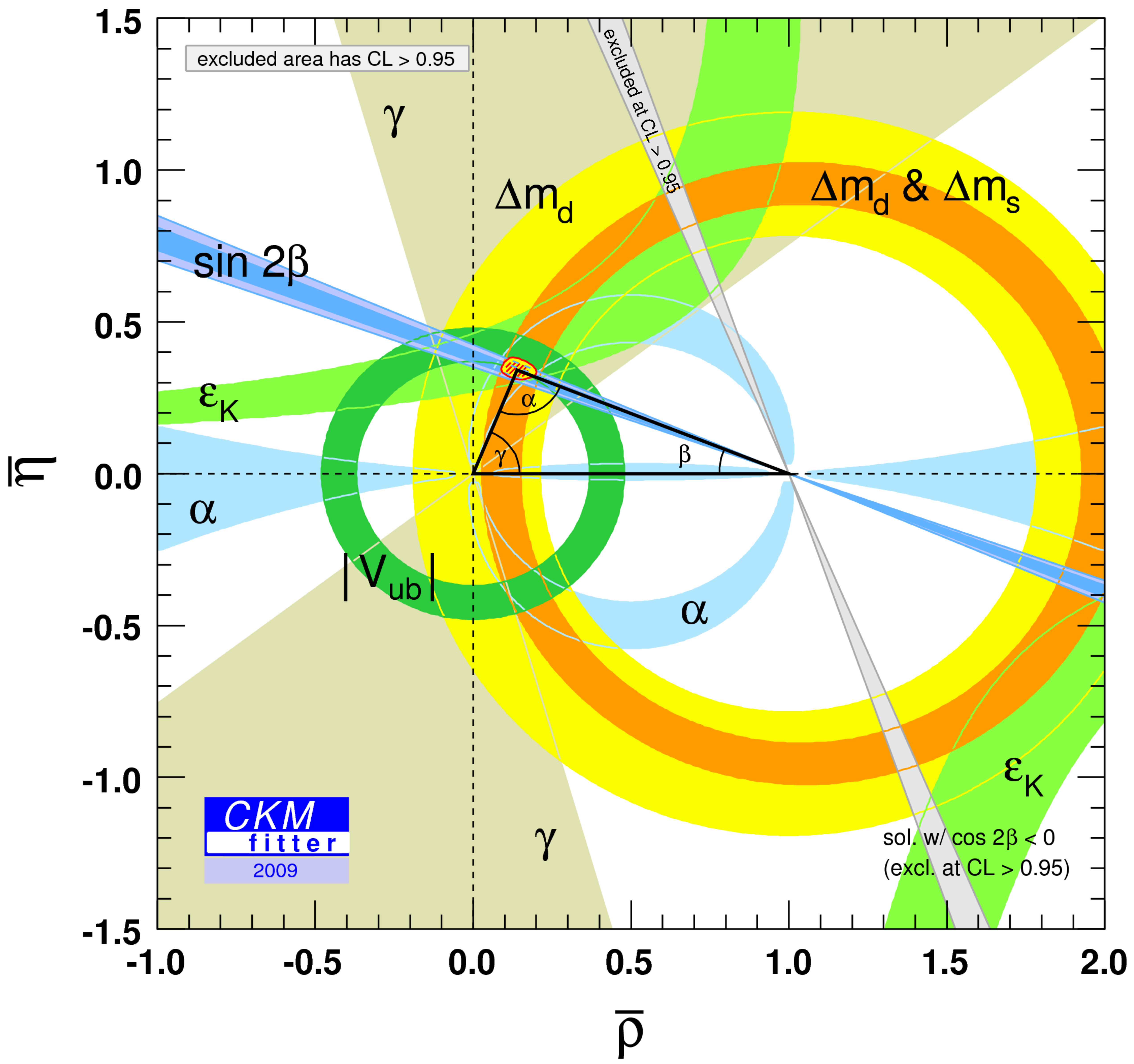
Redundancy = robustness

How to be redundant in the the neutrino sector?



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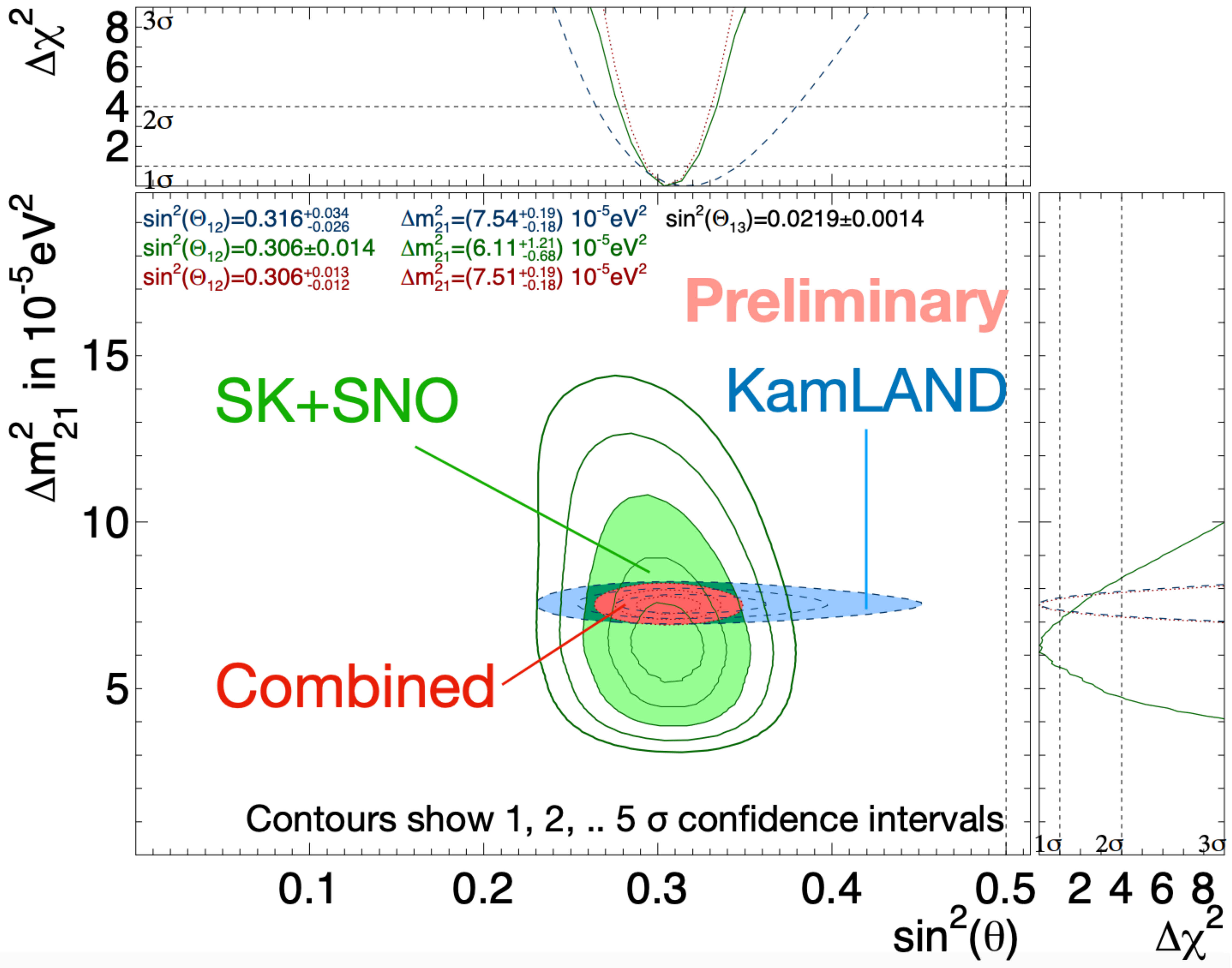
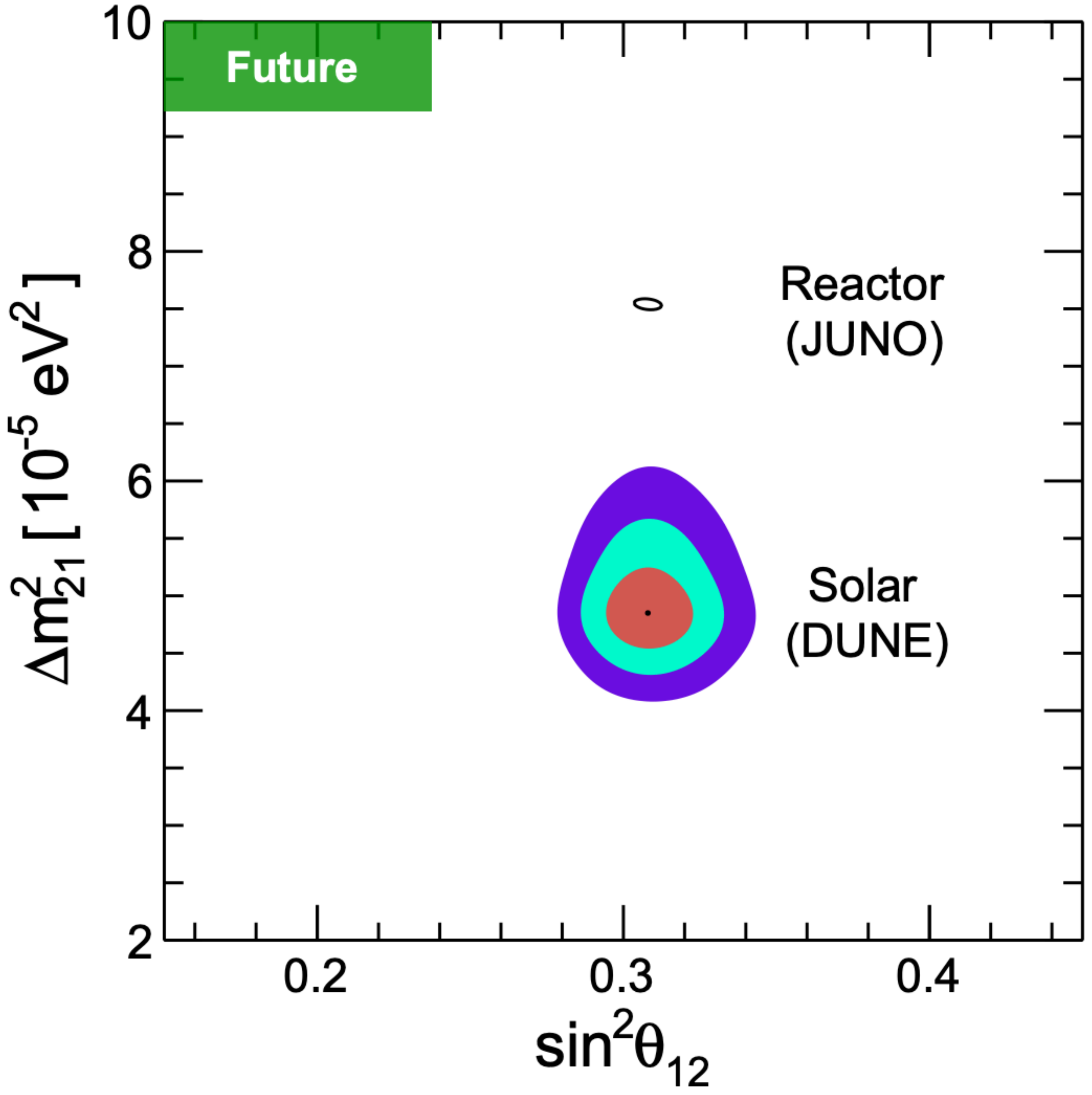
Nakajima@Neutrino2020



Capozzi et al 1808.08232



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Leading measurements of CP violation will be done with accelerator neutrinos

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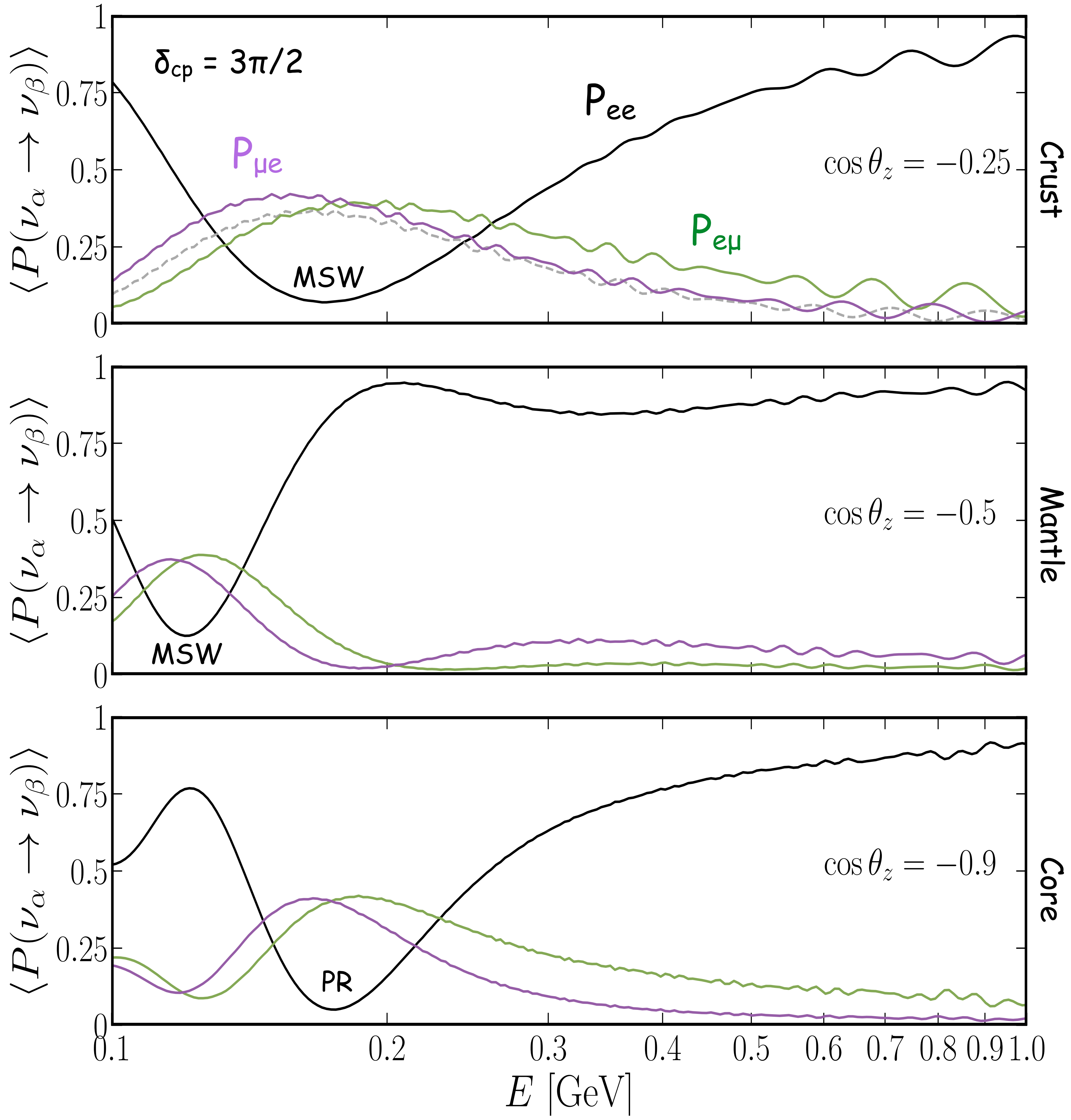
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751

Sub-GeV atmospheric neutrinos are one of the richest neutrino samples we have access to.



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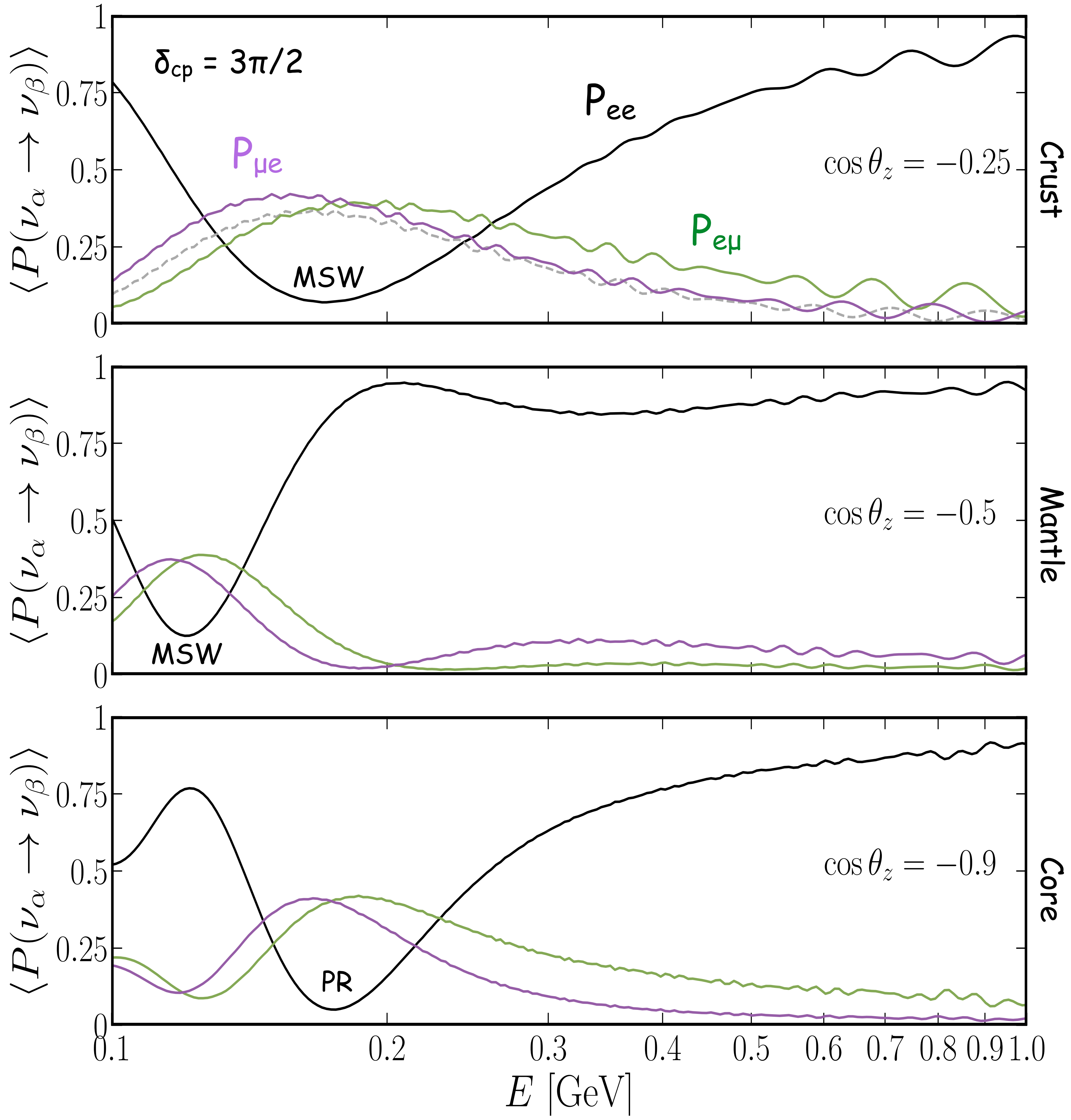
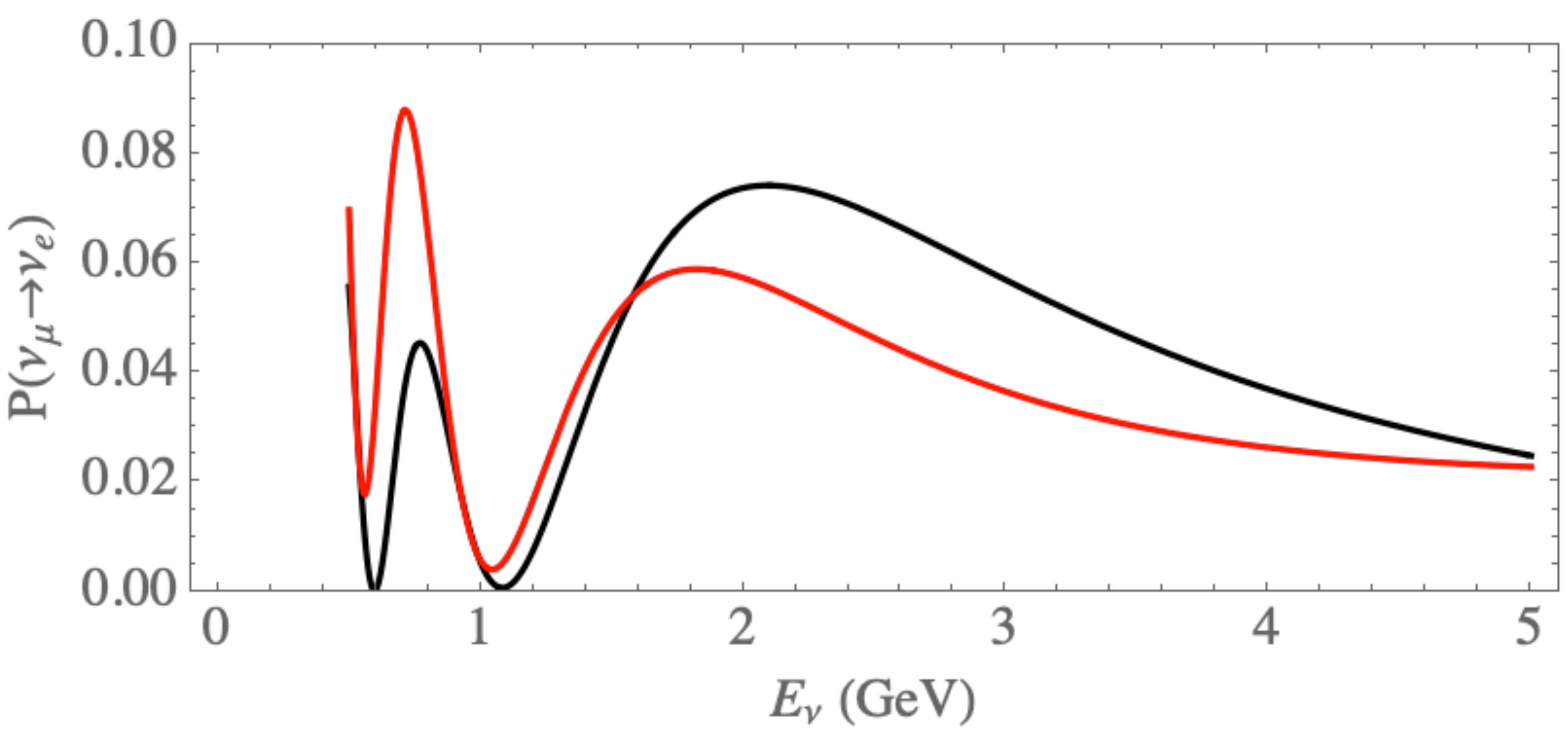


The main goal of DUNE is to measure leptonic CP violation

For DUNE's beam, CP will be a small effect (few %)



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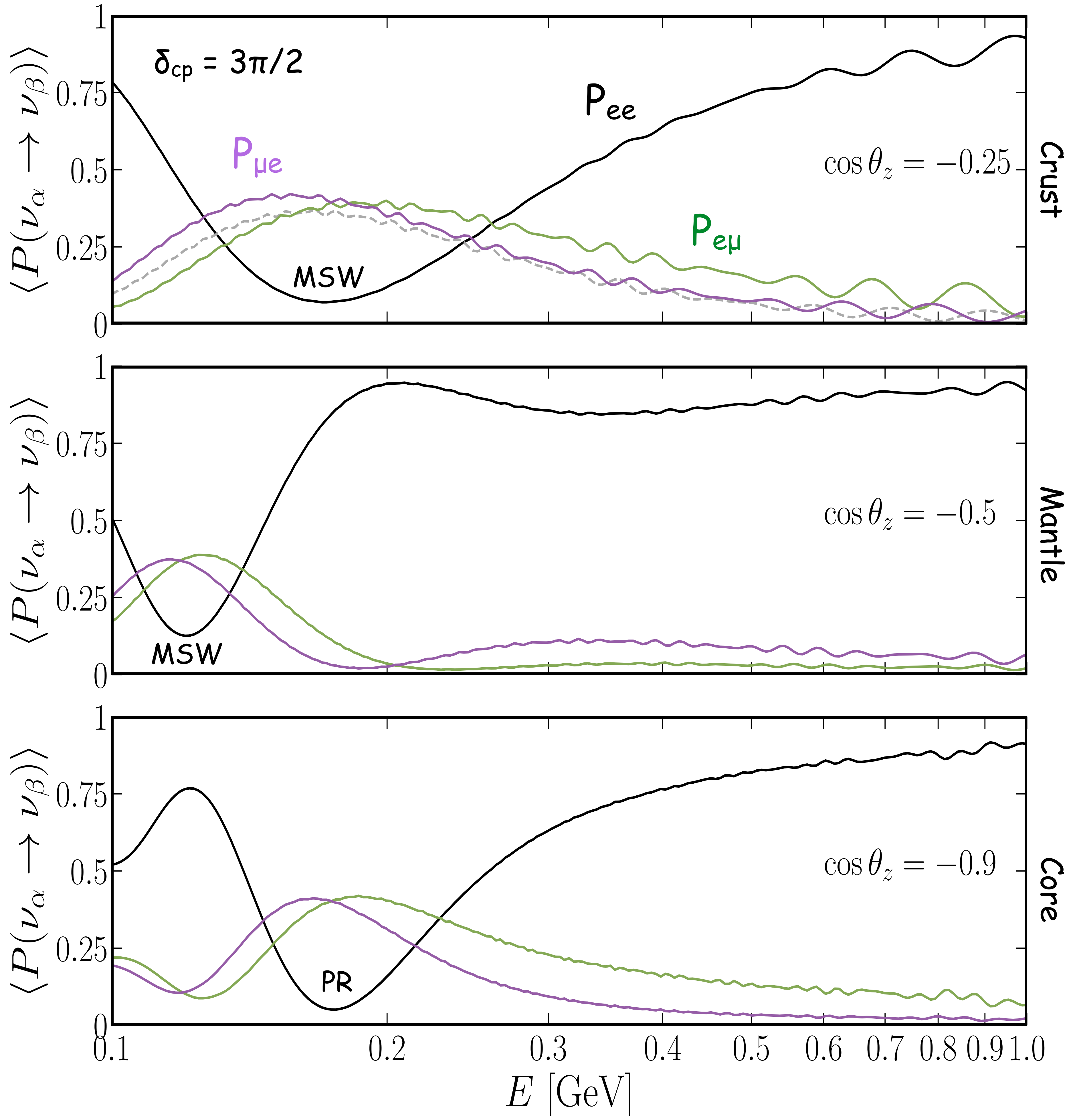

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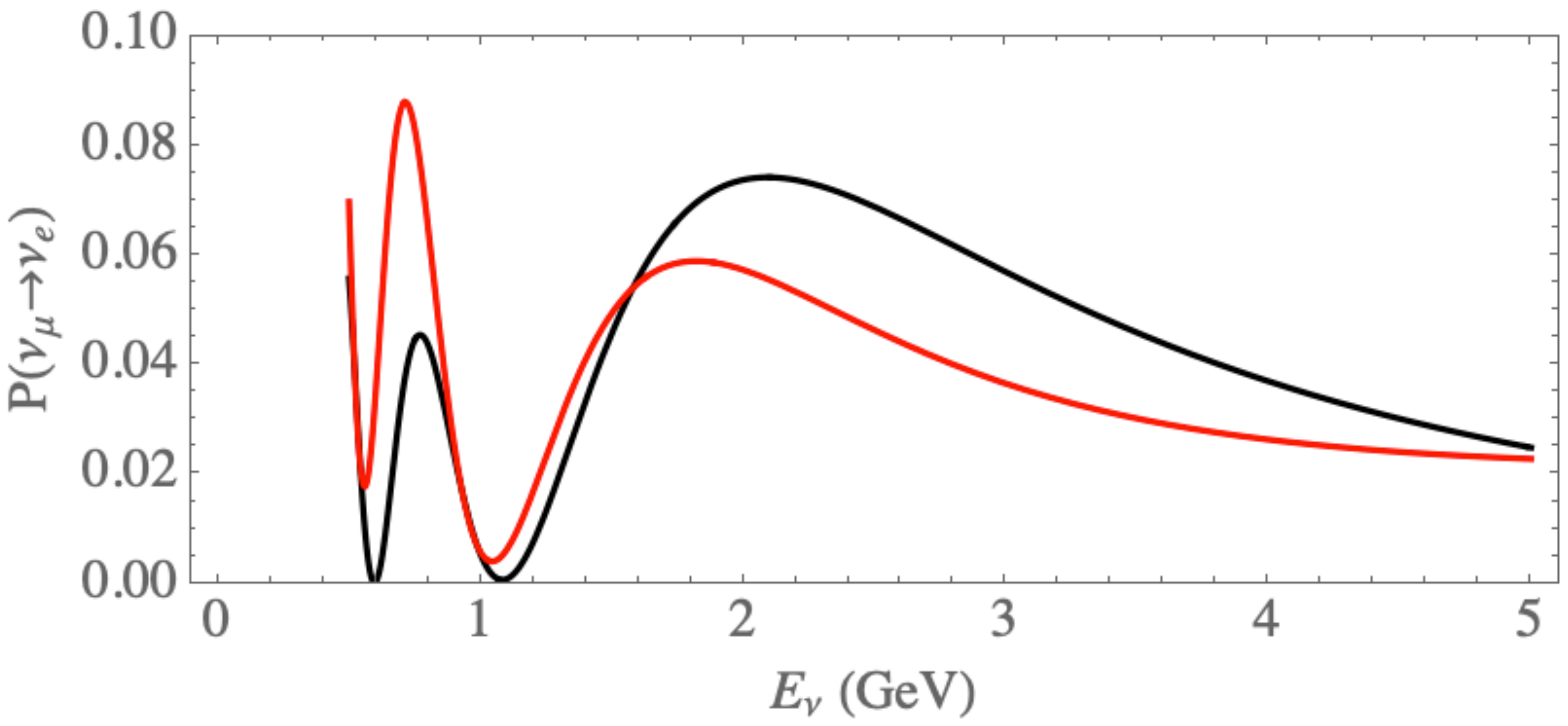
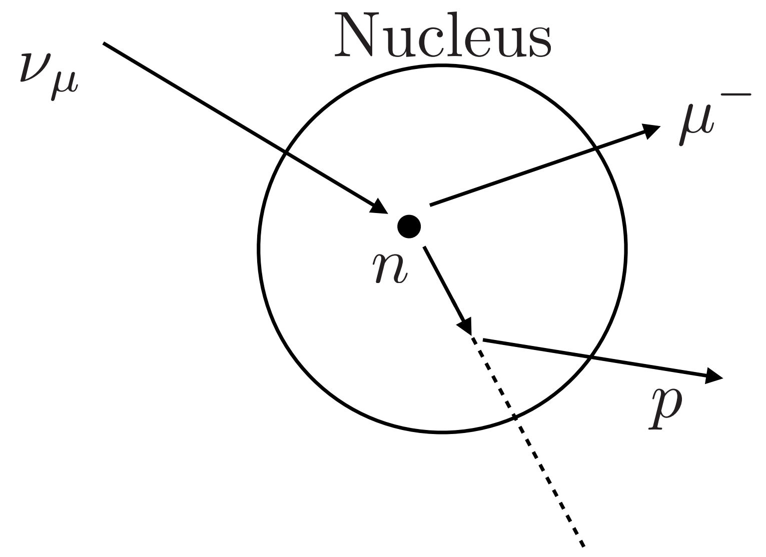


But sub-GeV atmospherics are very difficult...



Needs to know neutrino direction

Low E protons are invisible @ Cherenkov detectors

Liquid Argon TPCs can do it!

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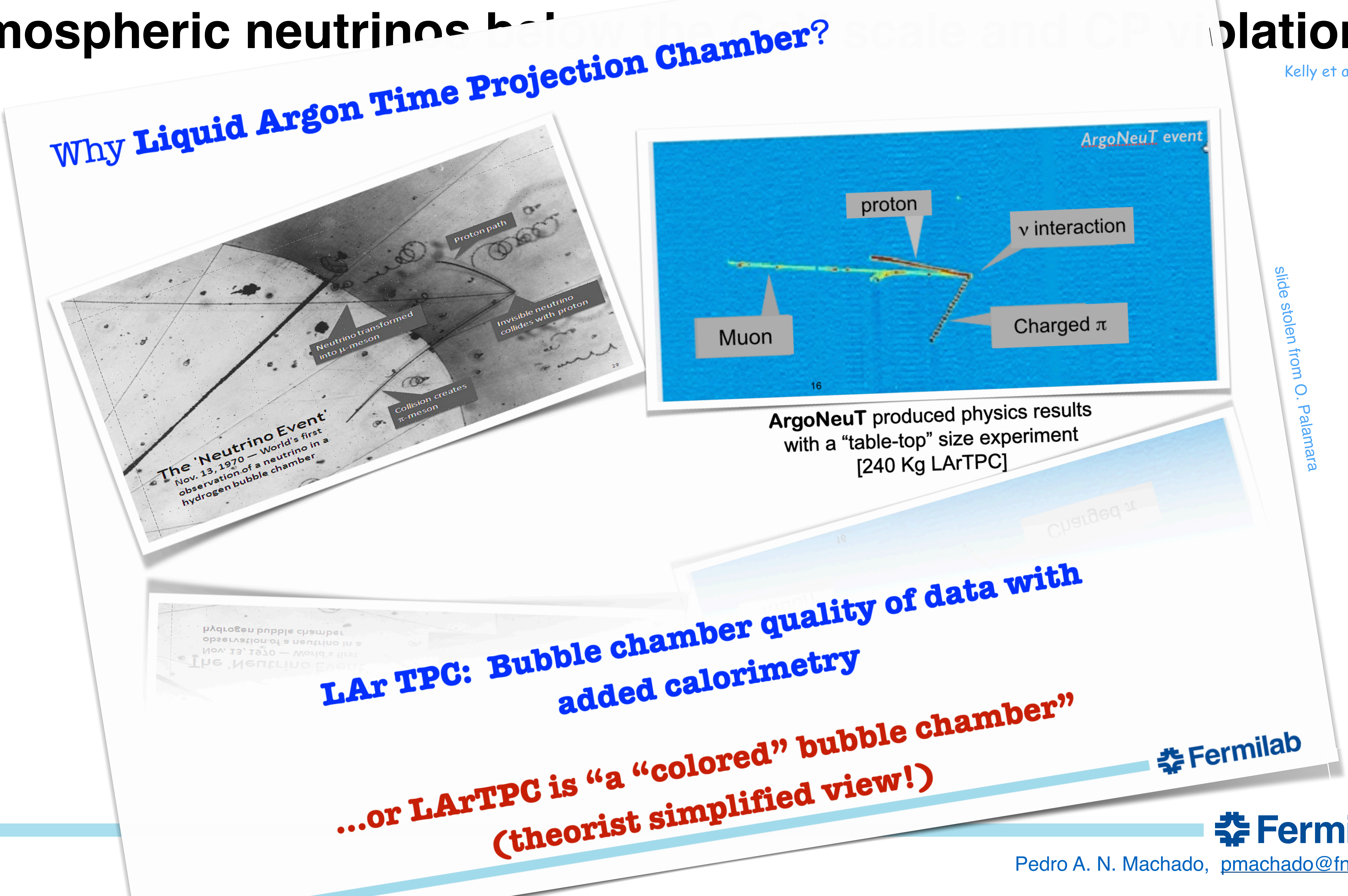
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751



slide stolen from O. Palamara

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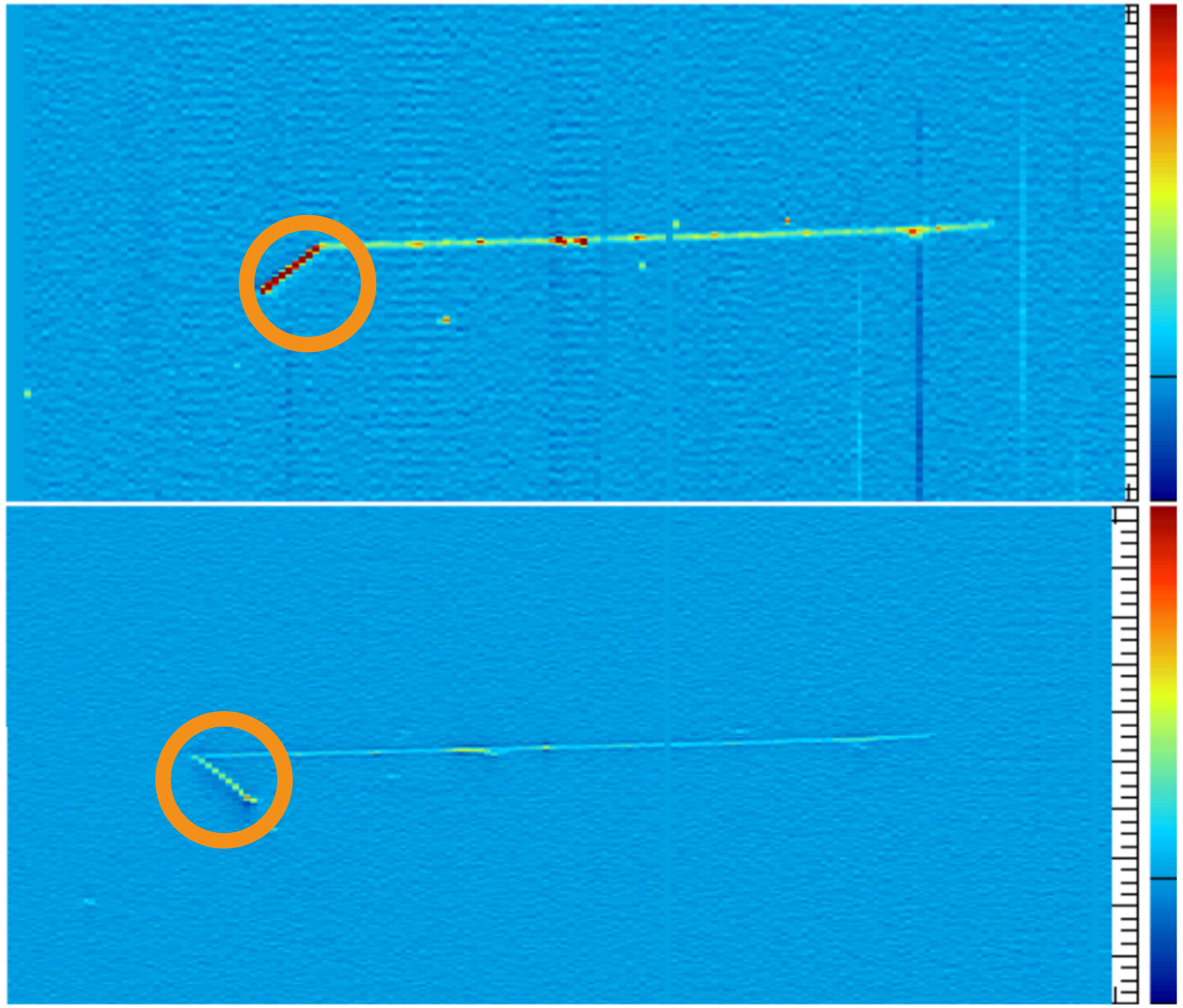
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751

ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons.

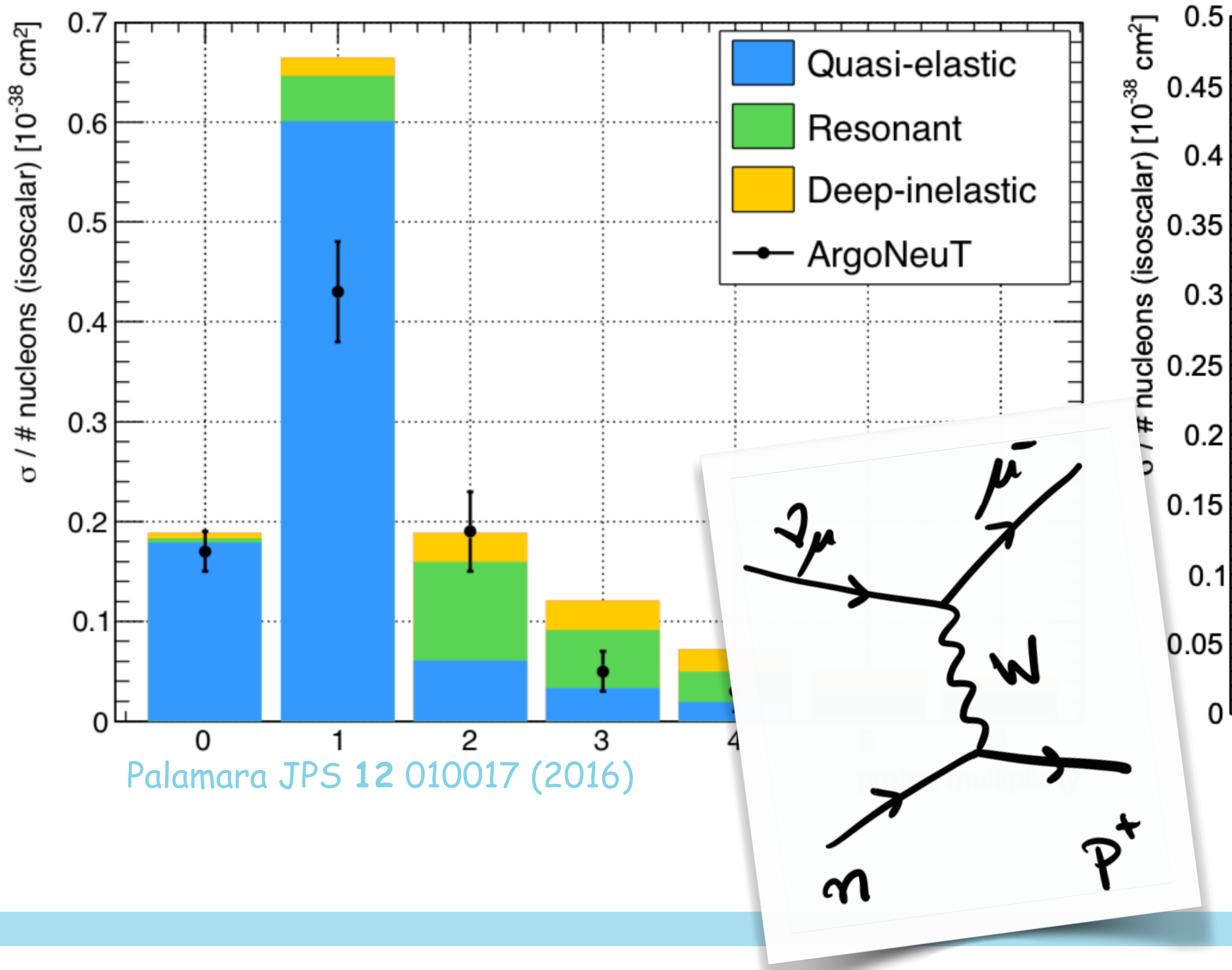
ArgoNeuT 1810.06502



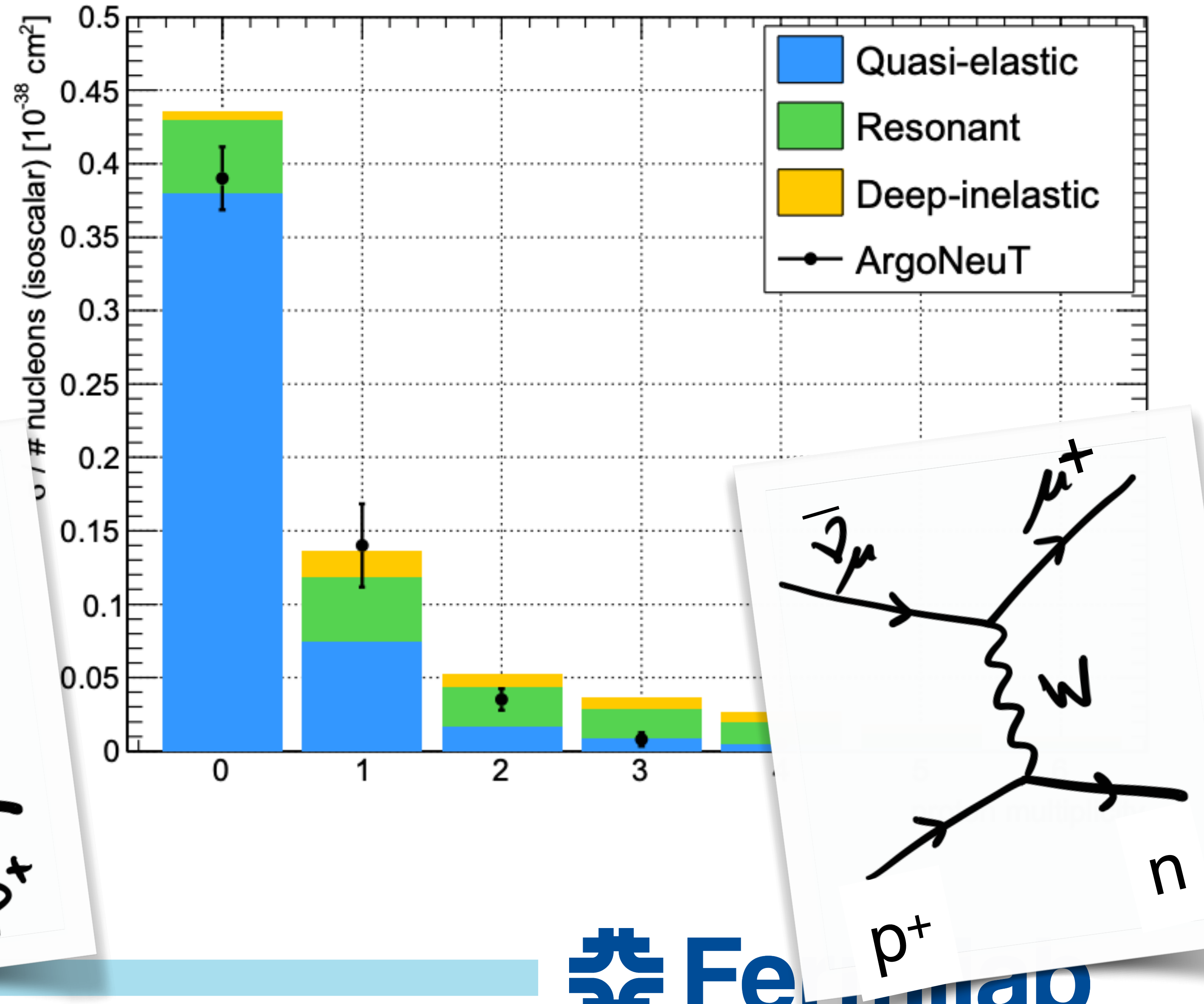
Reconstruct, identify and point.

For comparison, SK can only see protons that emit Cherenkov light, that is, protons with kinetic energy above ~ 1.4 GeV

Event topology carries extra information



Palamara JPS **12** 010017 (2016)



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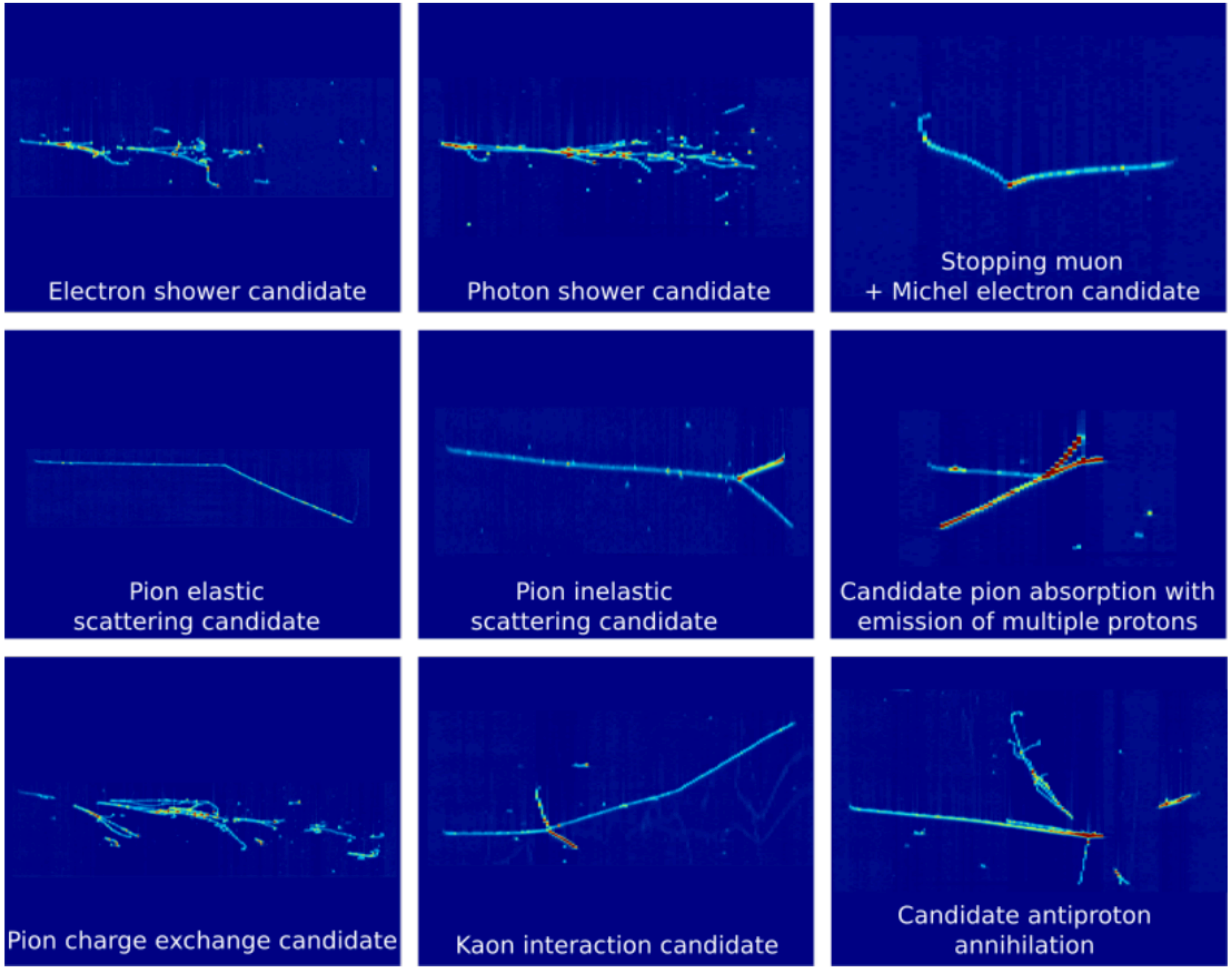
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751



LArIAT 1911.10379

Muons:

$\mu^+ \rightarrow e^+ \, \overline{\nu}_\mu \, \nu_e$
$\mu^- p^+ \rightarrow \nu_\mu + n$

Pions:

$\pi^+ n \rightarrow \pi^0 p^+$
$\pi^- p^+ \rightarrow \pi^0 n$

Topology depends on particle and its charge

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Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

$$\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$$

Account for uncertainties of atmospheric neutrino fluxes

40% normalization, 5% e/μ ratio, 2% nu/nubar ratio, ± 0.2 spectral distortion coefficient

Realistic LArTPC capabilities

Δp = 5%, 5%, 10%, $\Delta\theta$ = 5°, 5°, 10°, for e, μ, p, K_p = 30 MeV

Classify events by final state topology (number of protons)

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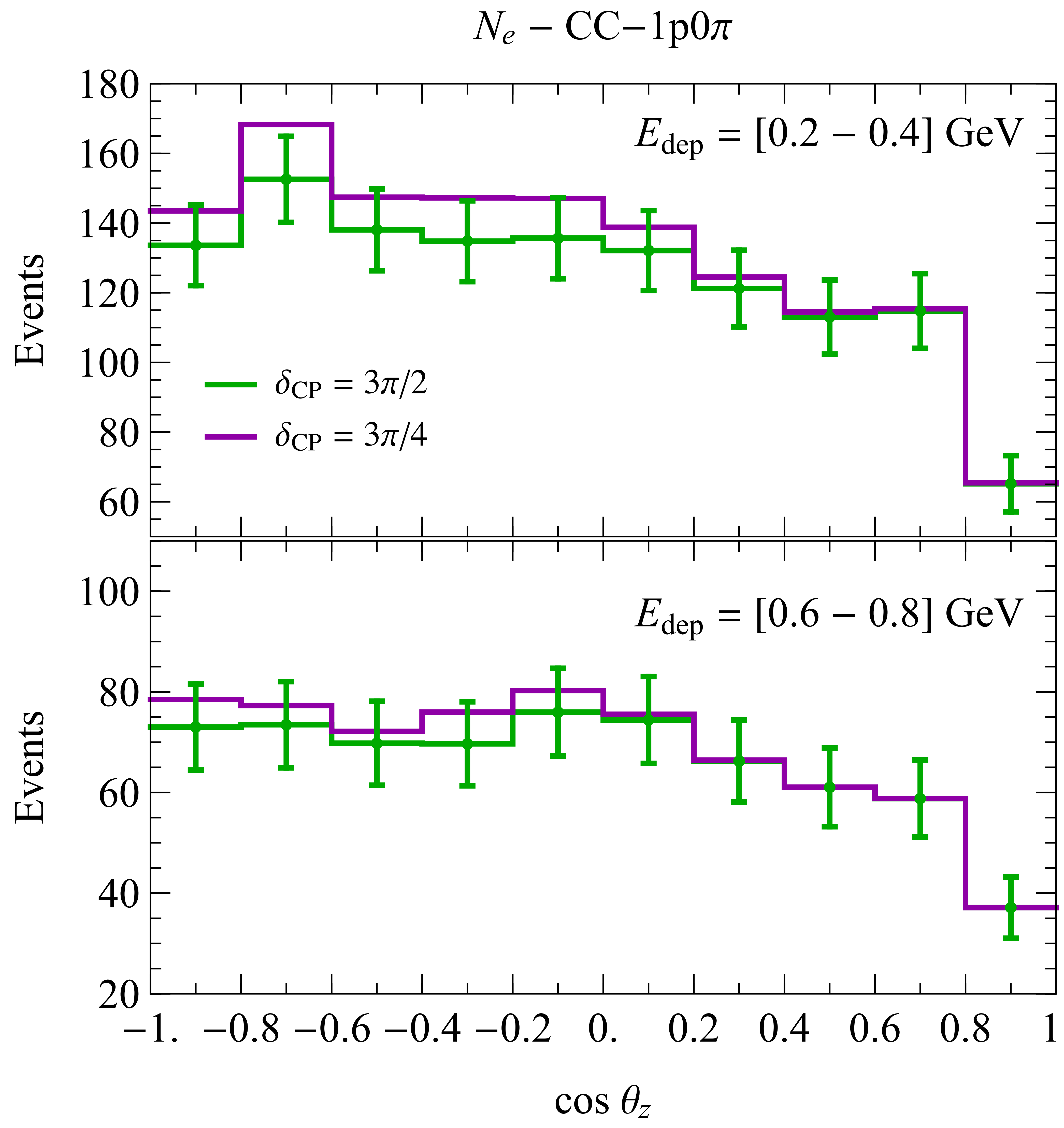
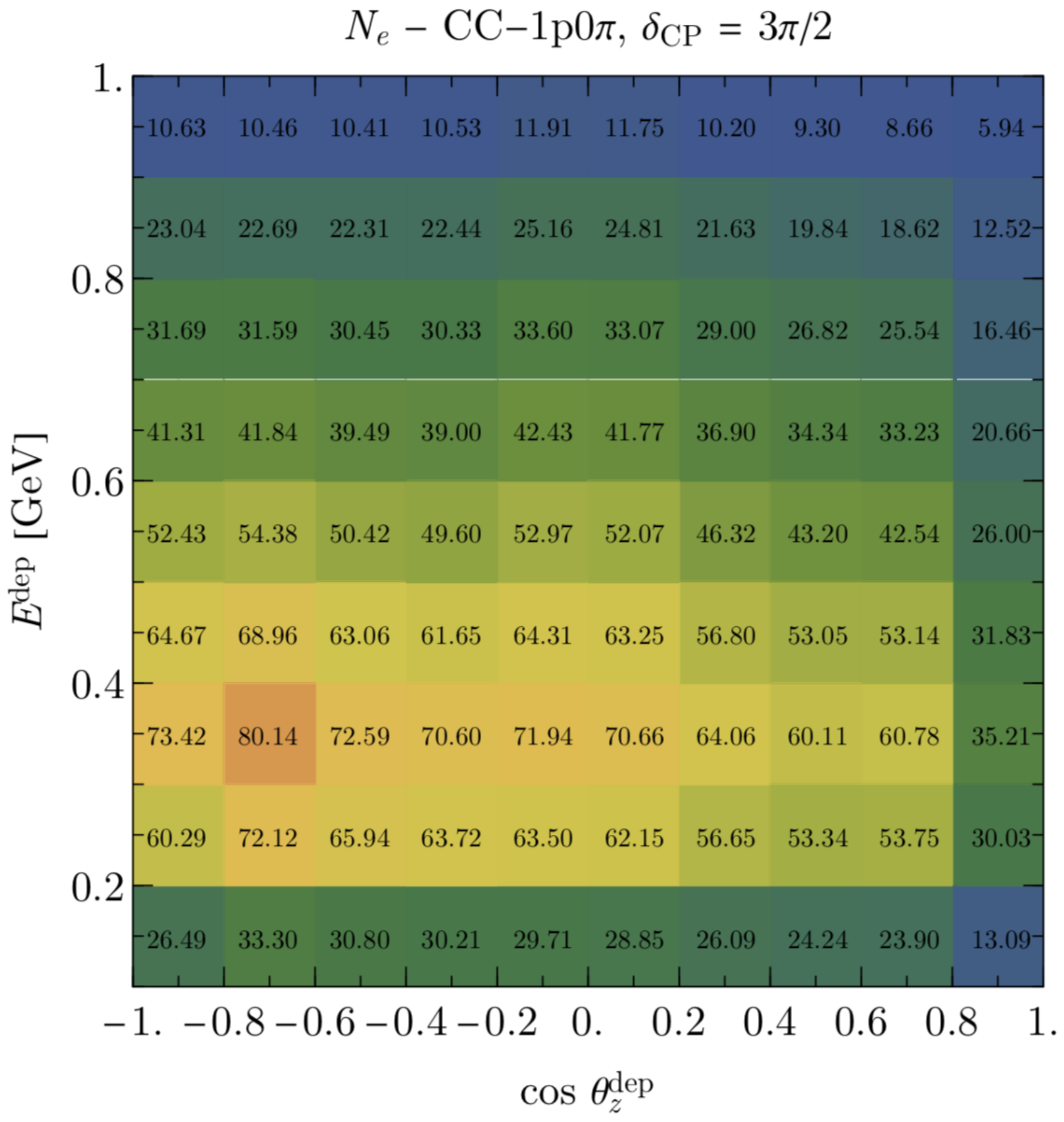
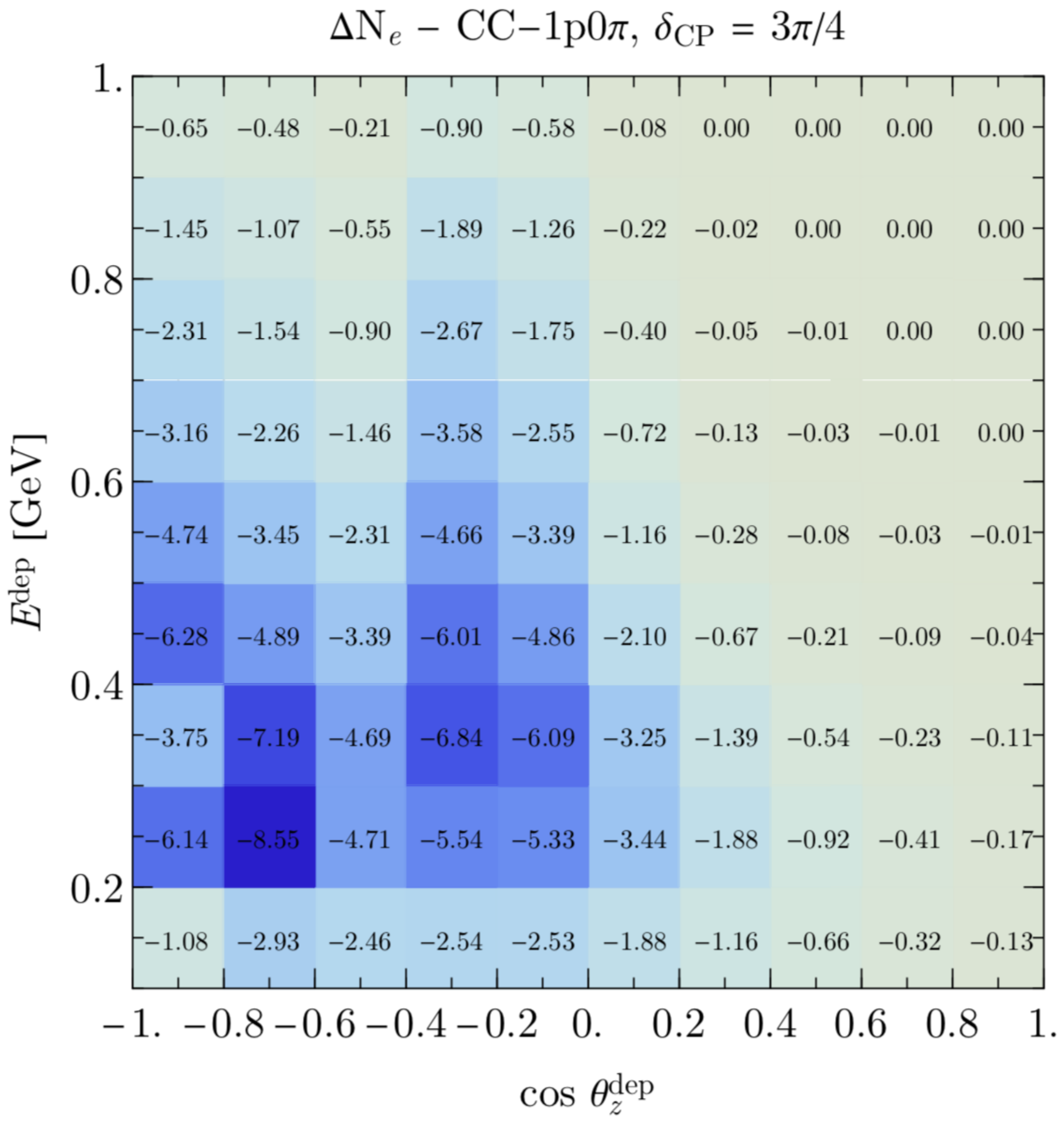
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751







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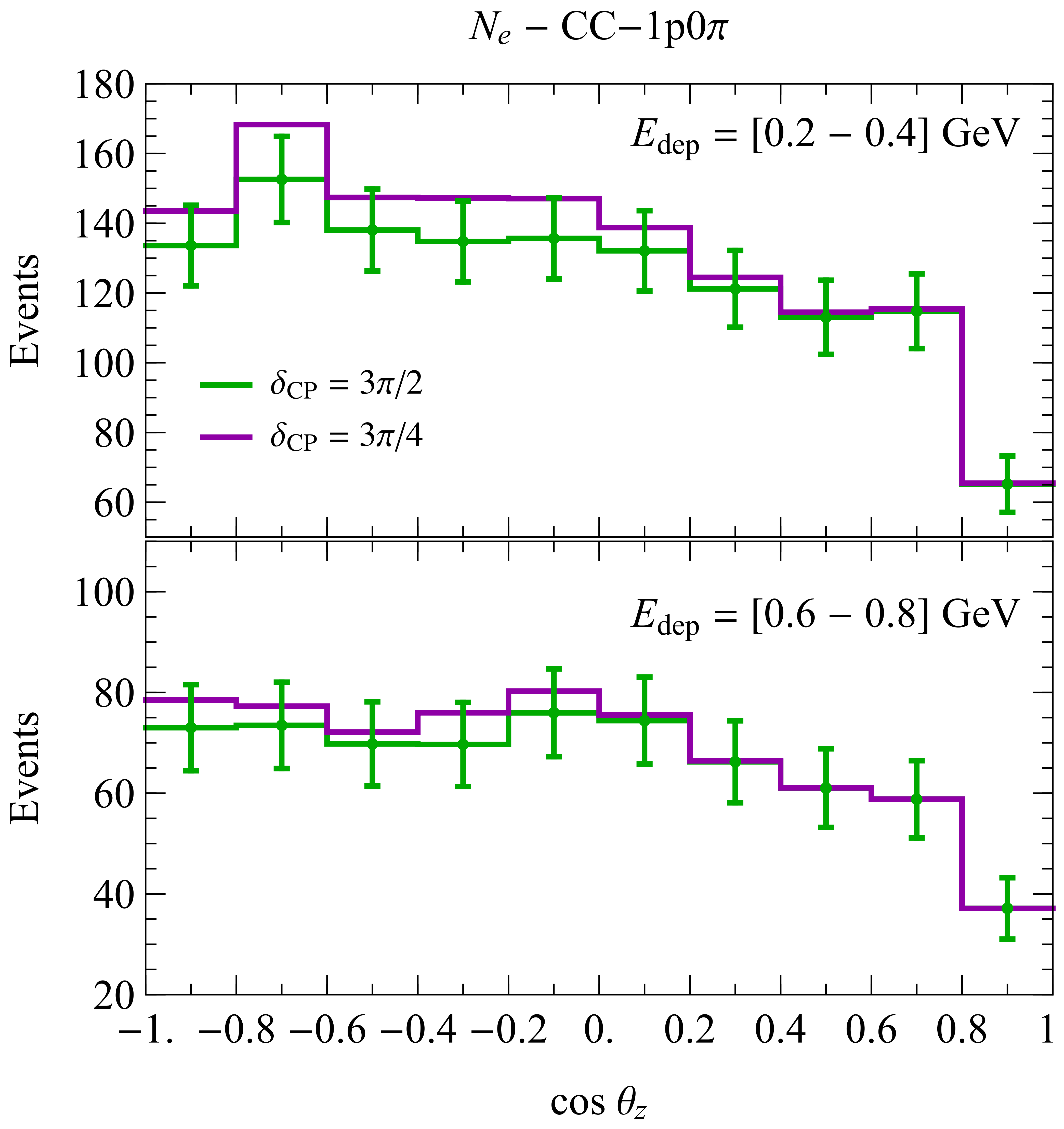

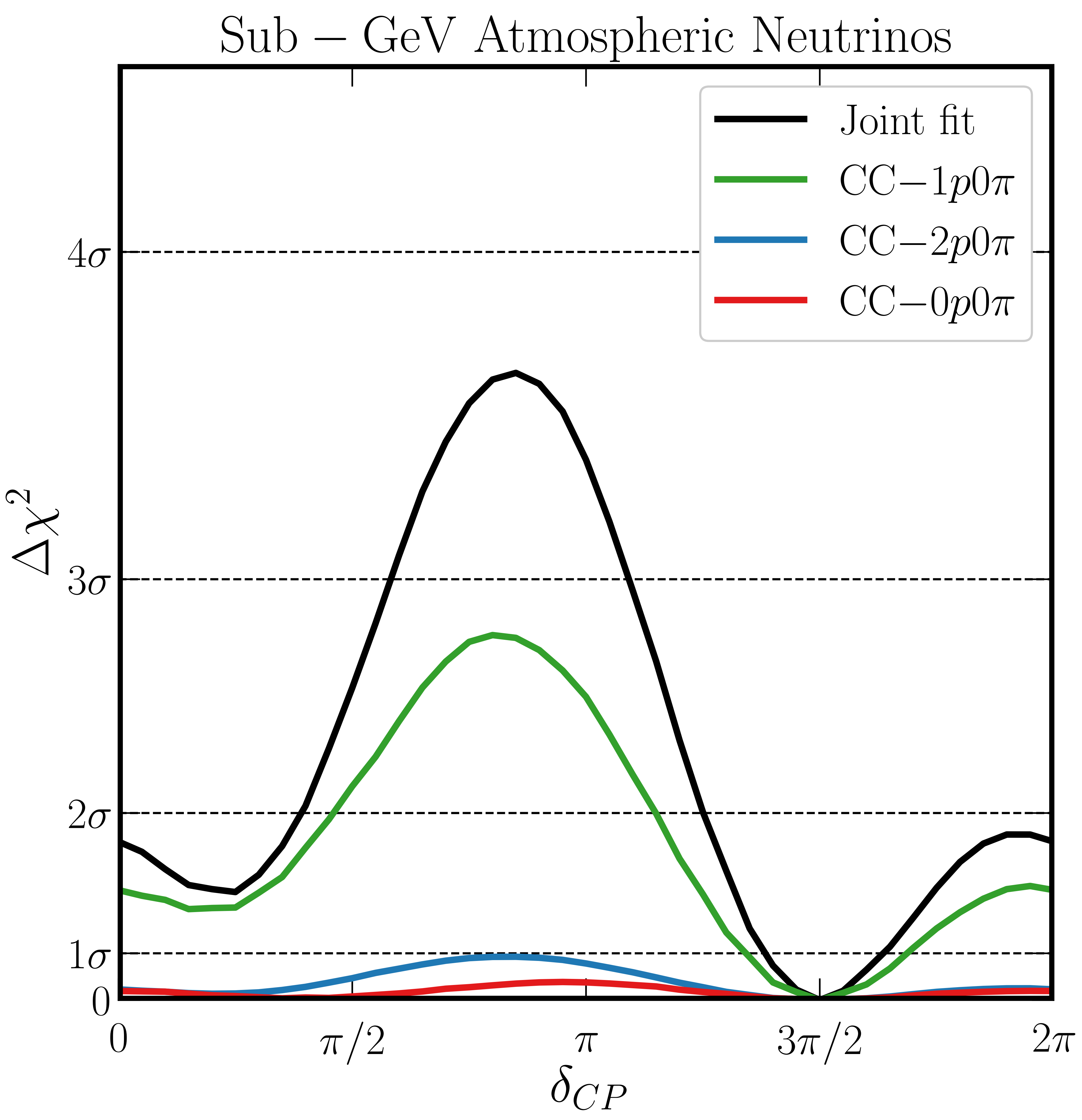

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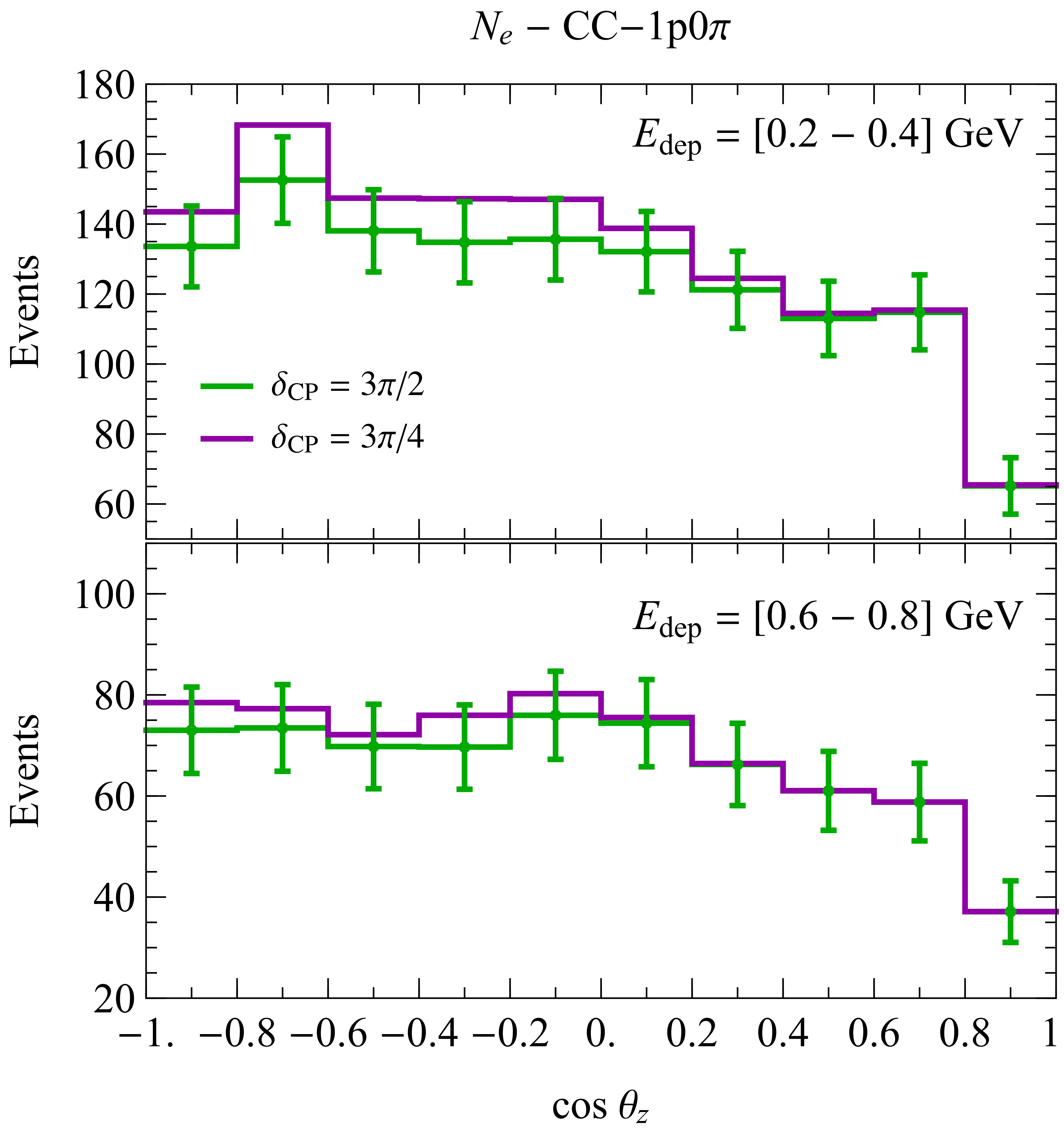

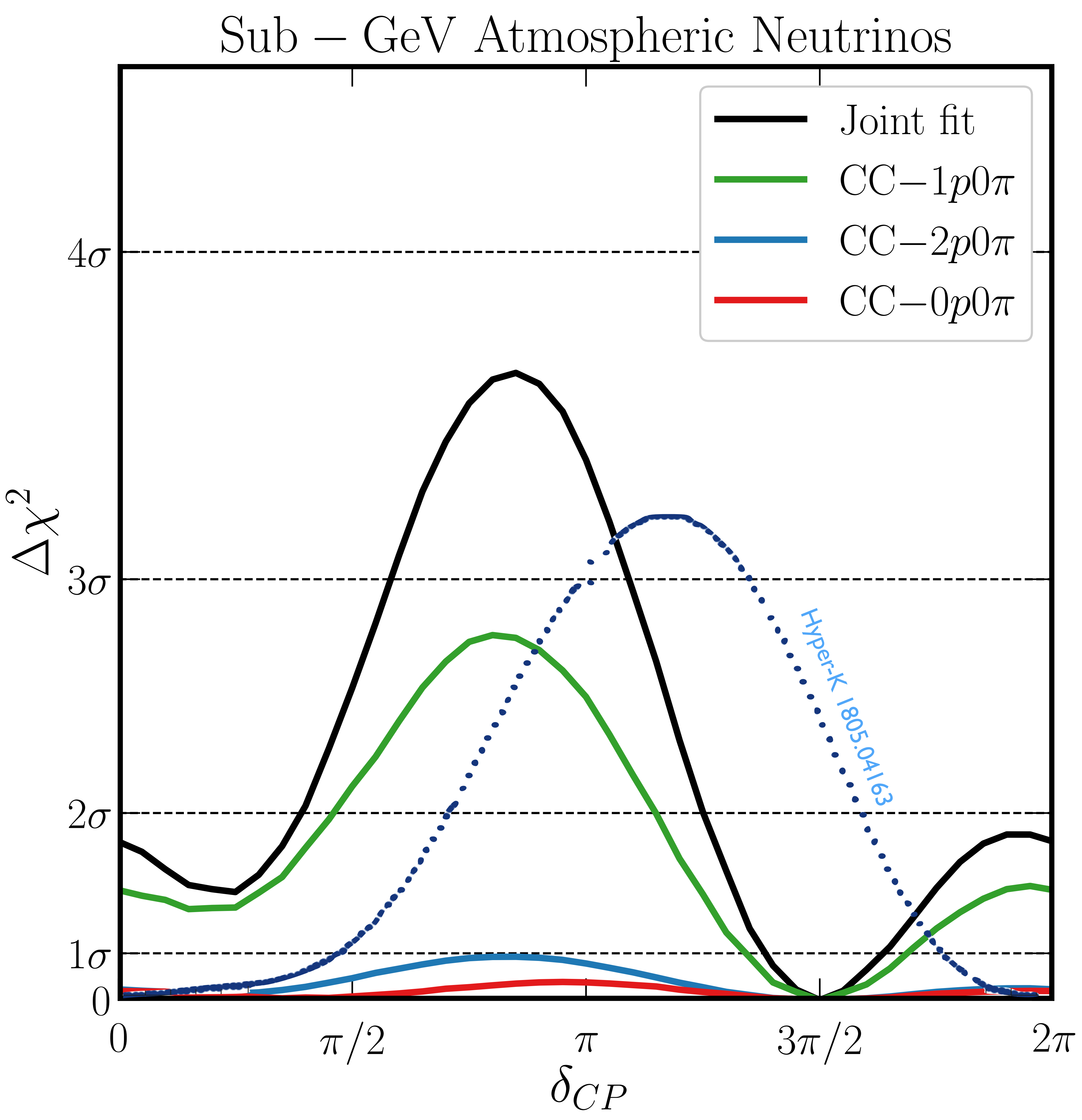

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Take home message

DUNE has a unique opportunity to study sub-GeV neutrinos

This opens up the possibility of measuring CP violation independently of the beam

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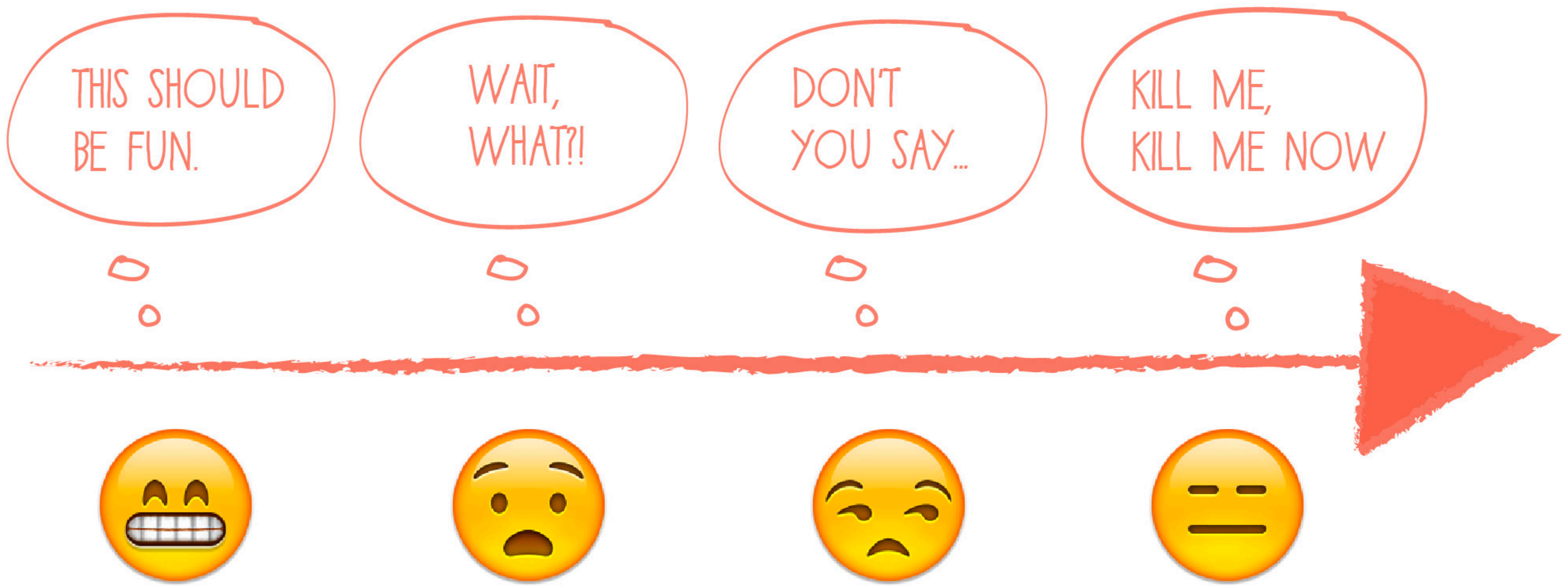
Atmospheric neutrinos below the GeV scale and CP violation

Some thoughts on what else could be done with it



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DUNE: MSW resonance at the solar splitting

IceCube: MSW resonance at the atmospheric splitting

What do we learn when we combine both?

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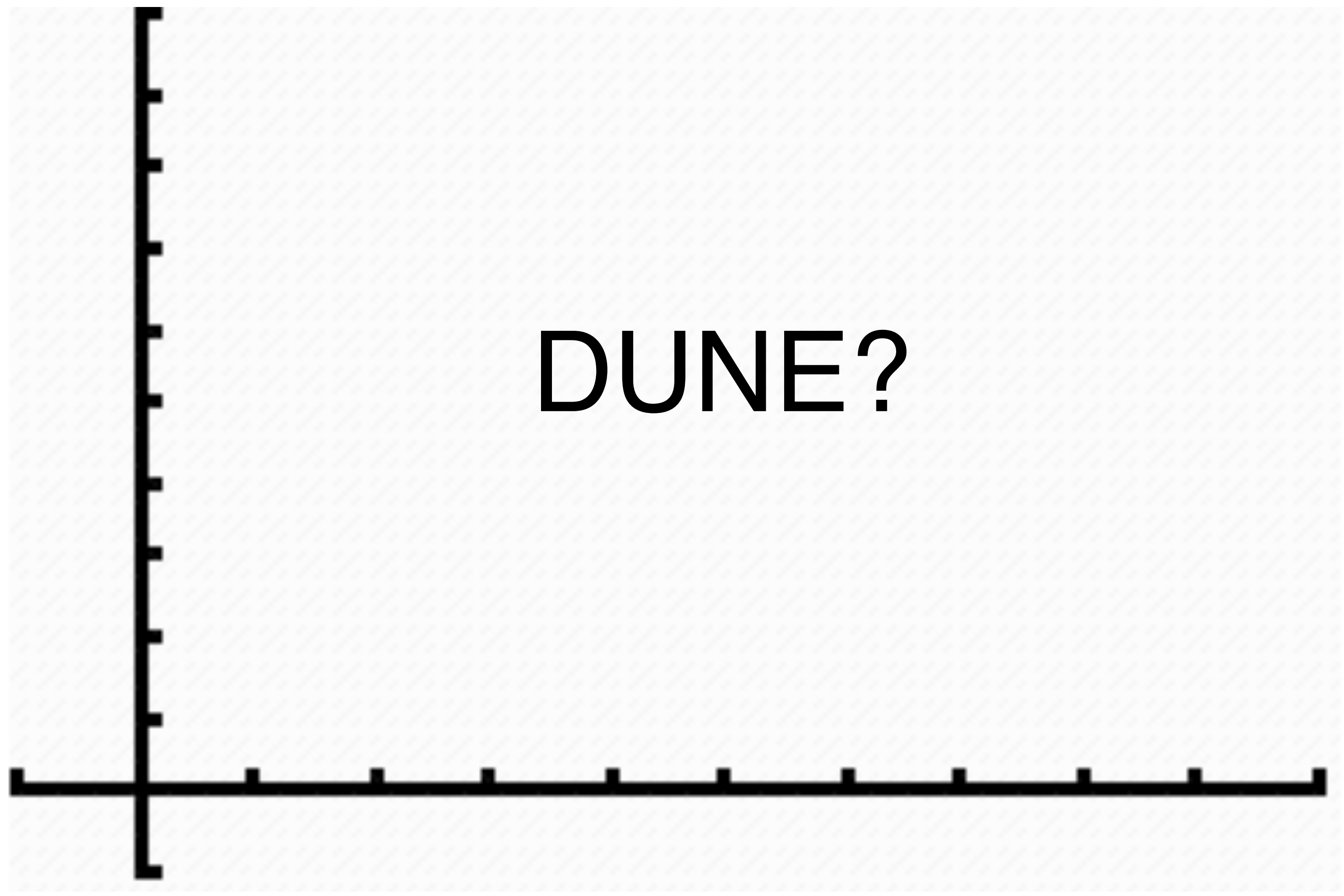
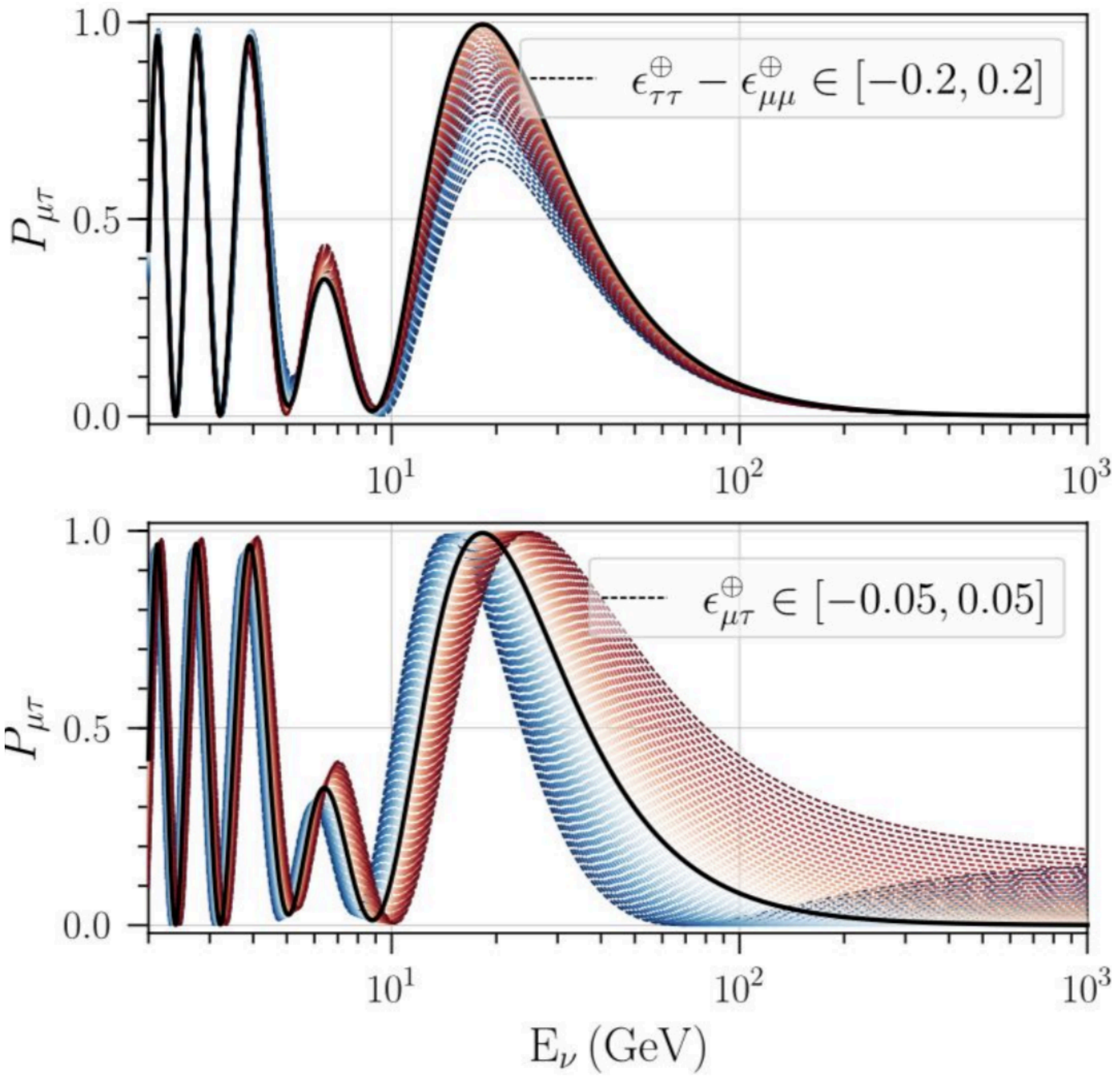
IceCube: Grant Parker @ VLVnT 2021

NSIs are relevant for high energy, but also low energy due to solar Δm^2 driven oscillations





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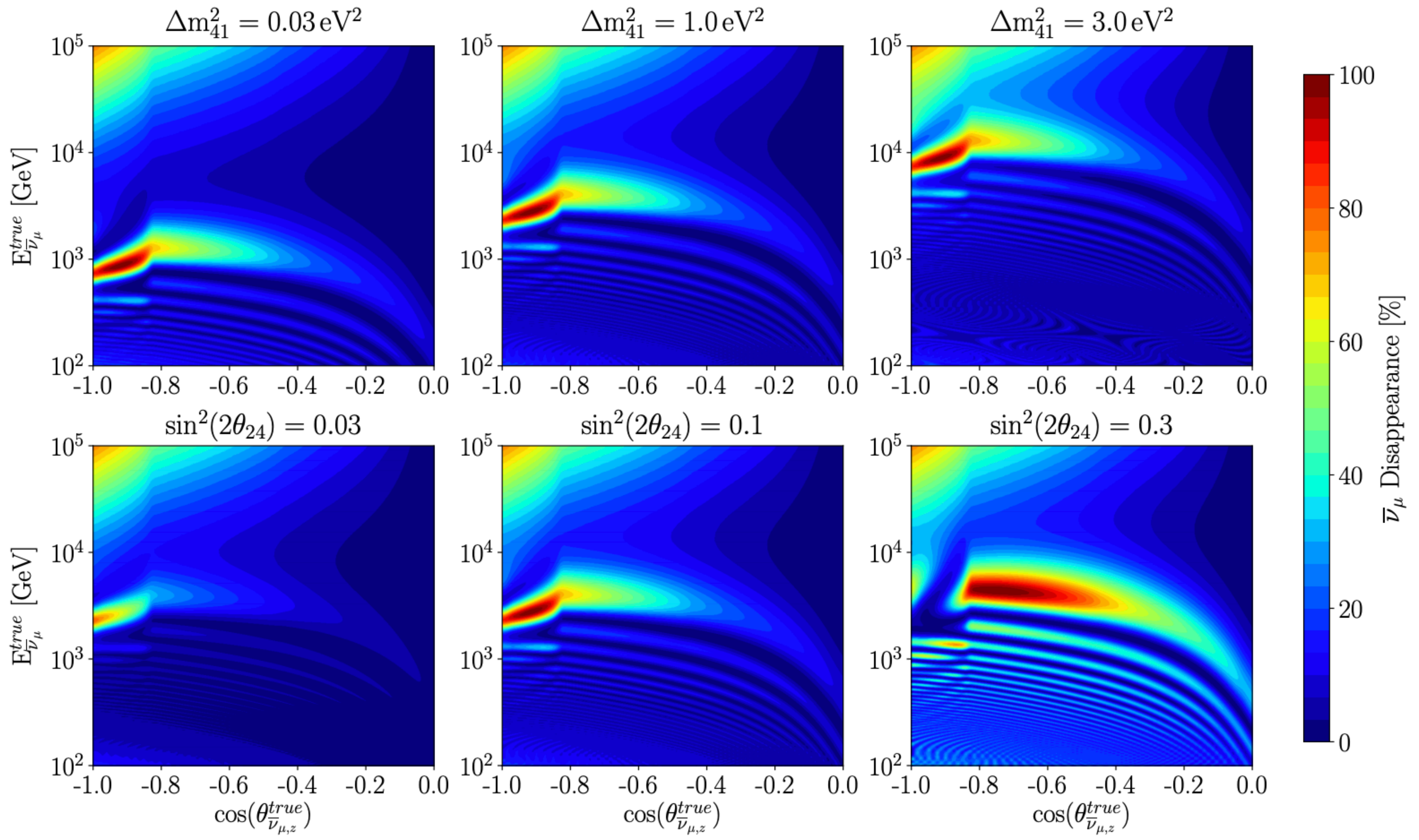
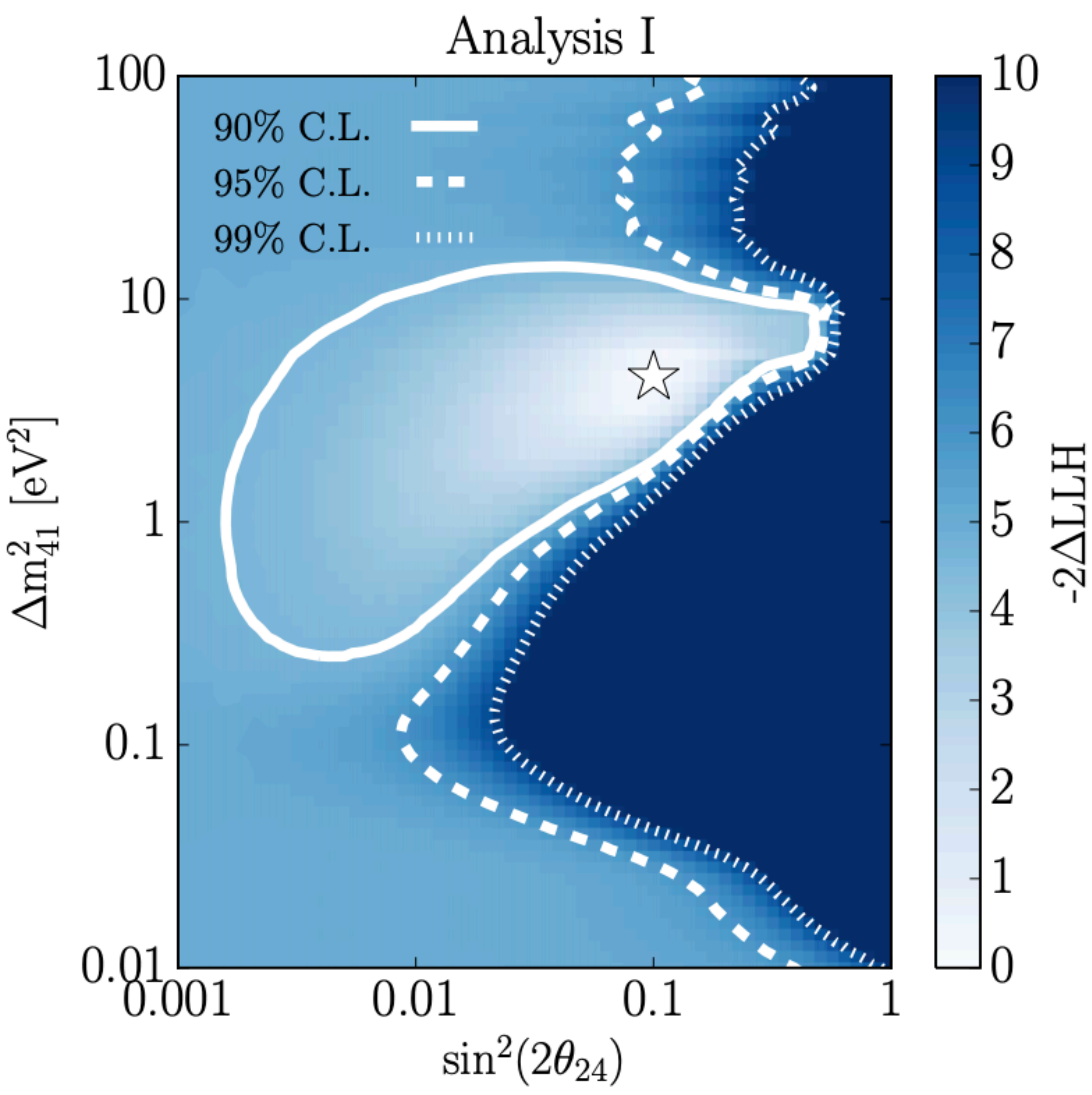
Sterile neutrinos

IceCube 2005.12943

Idea: Nunokawa, Peres, Zukanovich-Funchal hep-ph/0302039





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Sterile neutrinos

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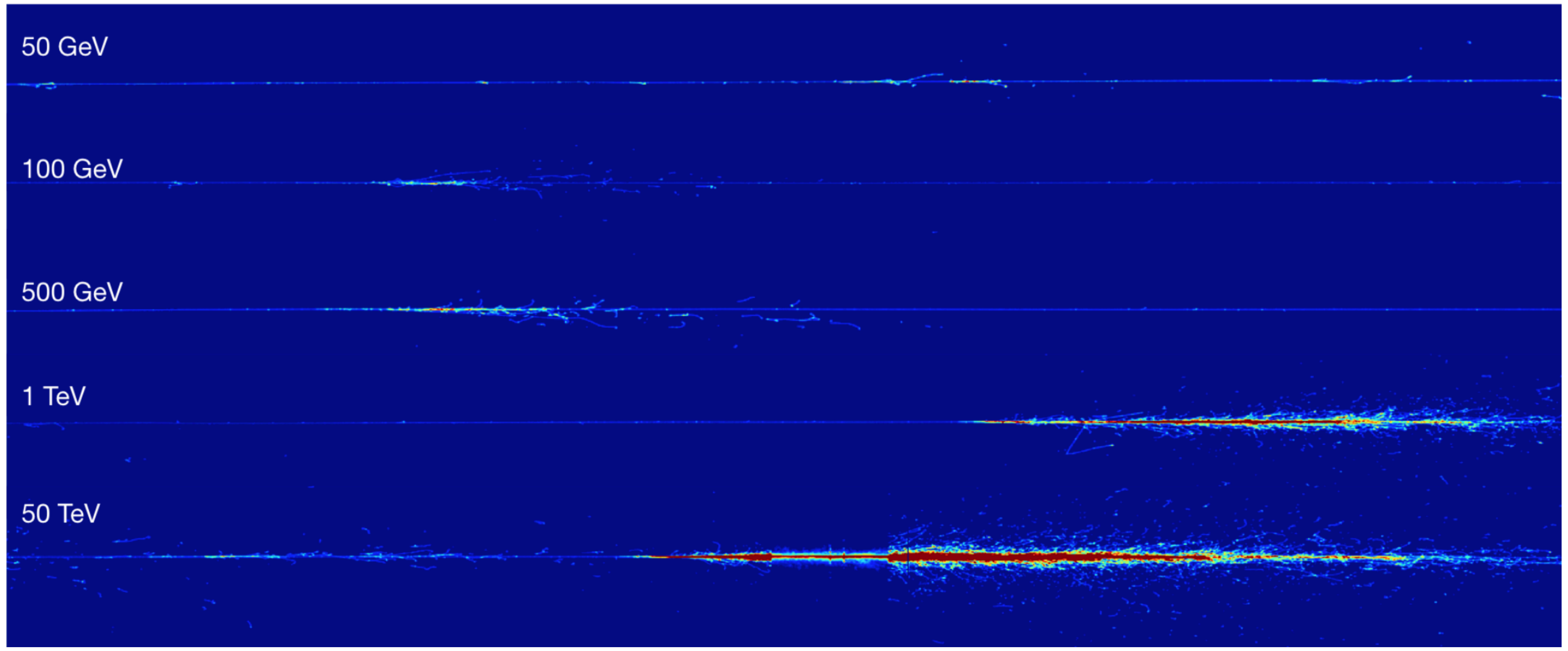
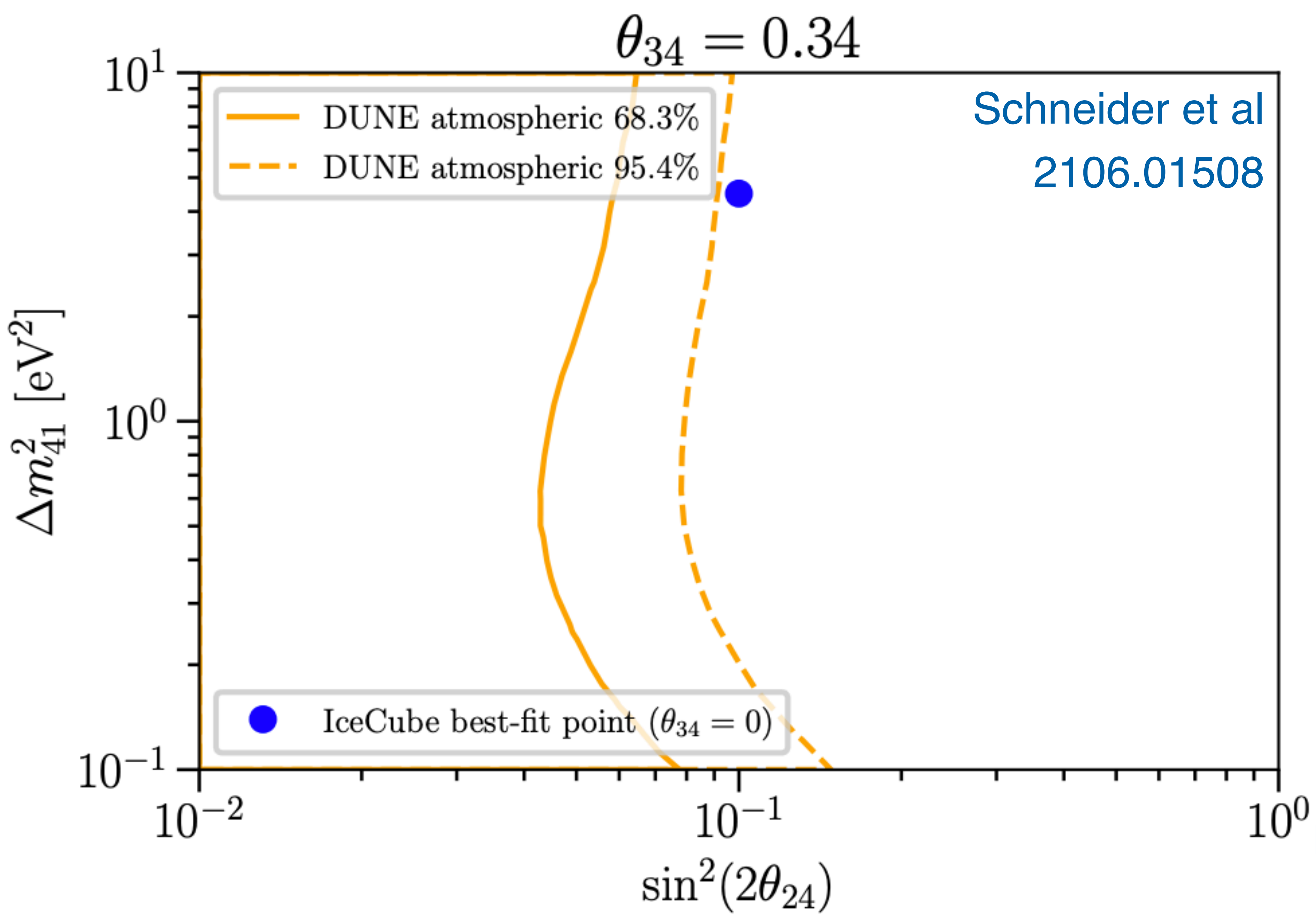
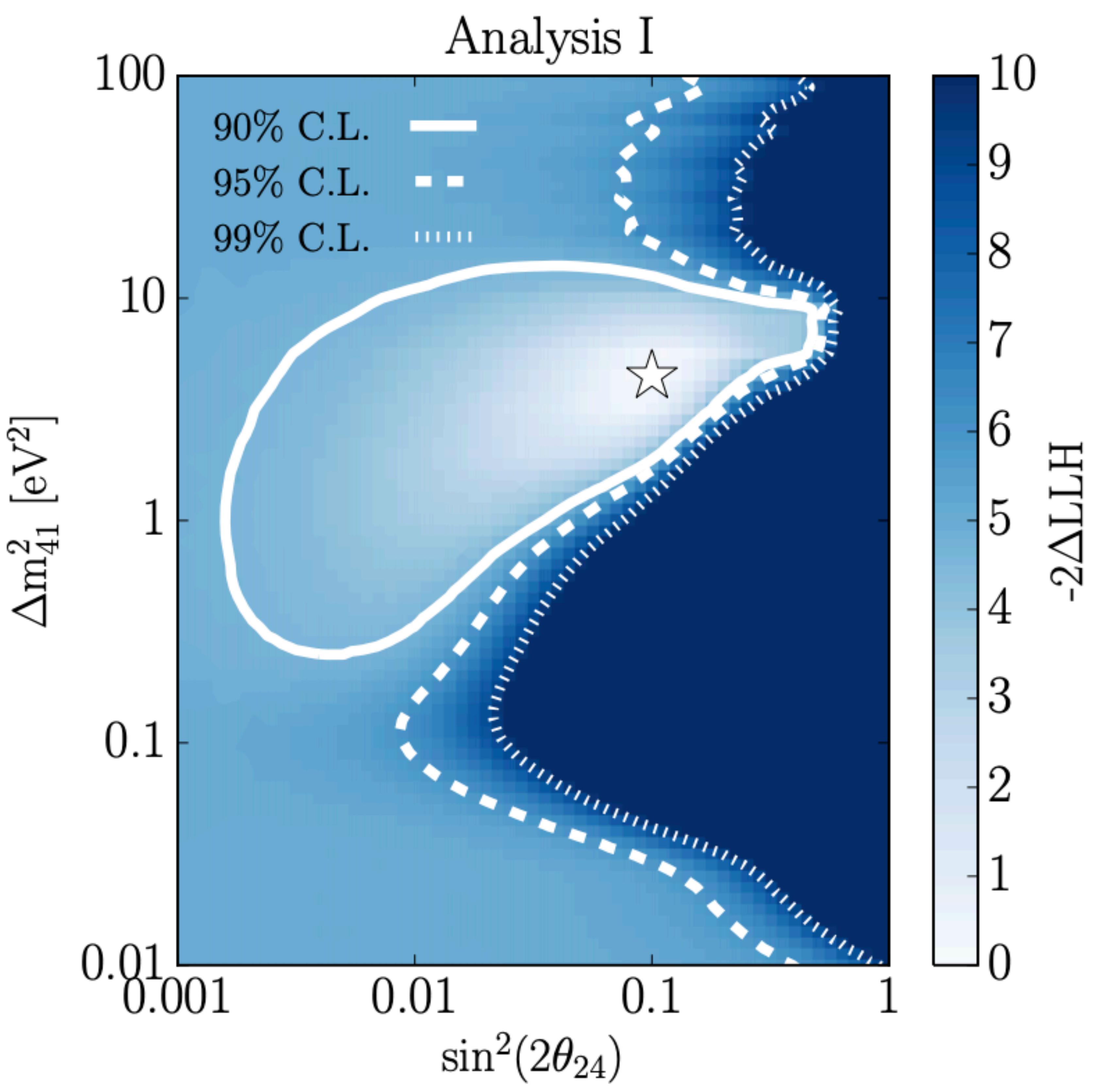




Schneider et al
2106.01508



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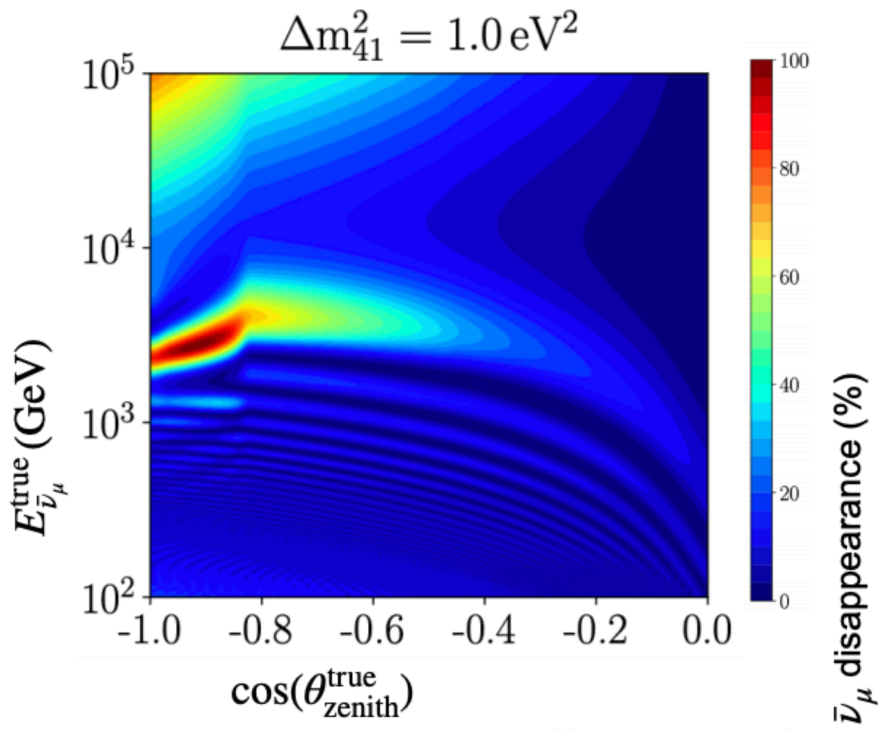
Sterile Oscillations at High and Low Energies

IceCube: Alexander Trettin @ VLVnT 2021

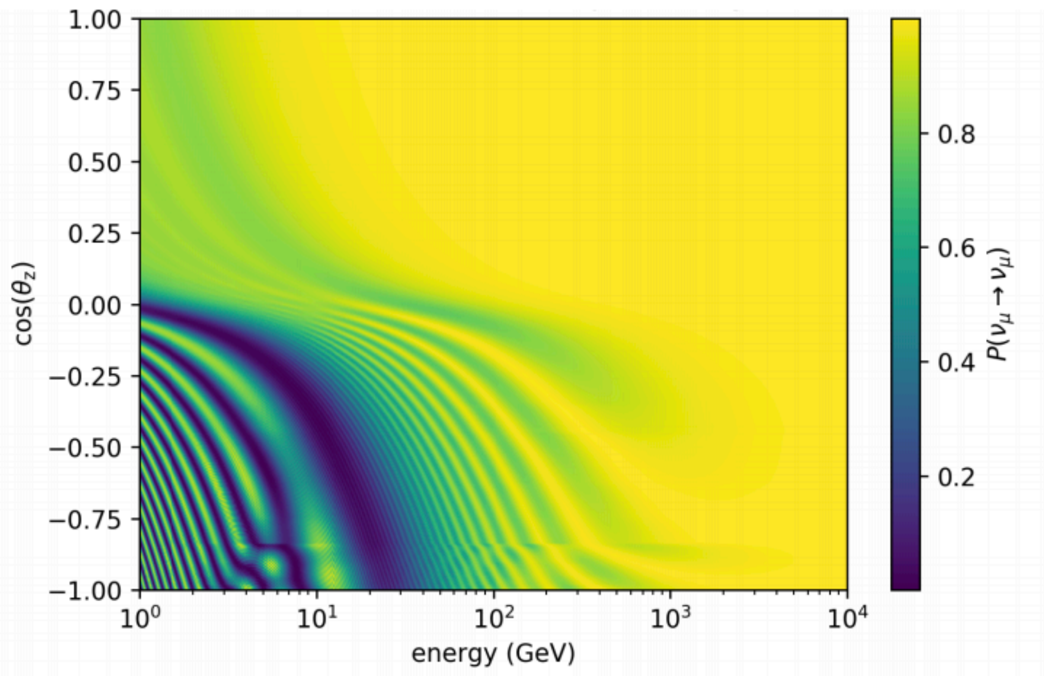
High Energies (> 500 GeV)



> matter resonance effect at $\mathcal{O}$(TeV) energies

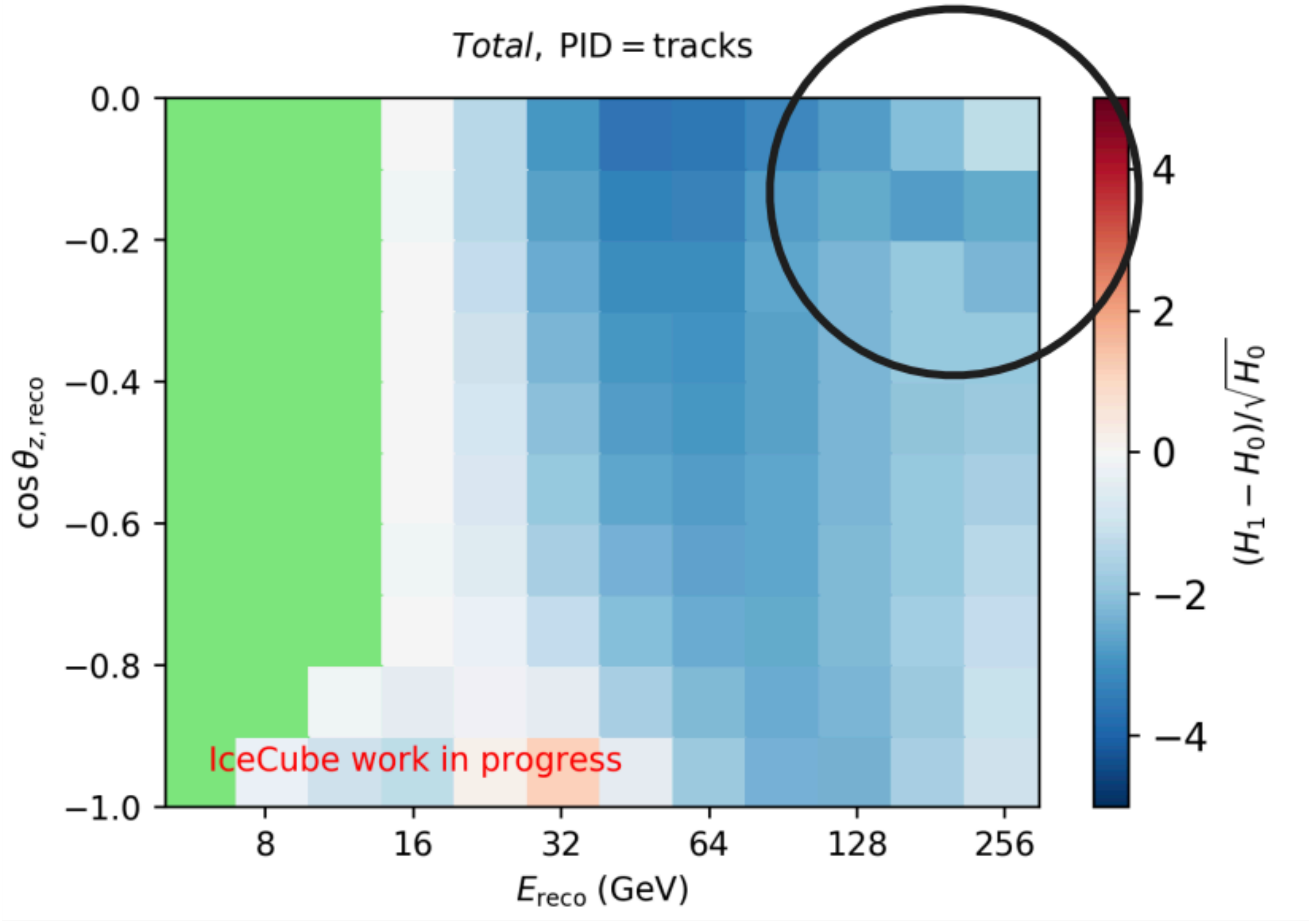
This Talk

Low Energies (< 500 GeV)

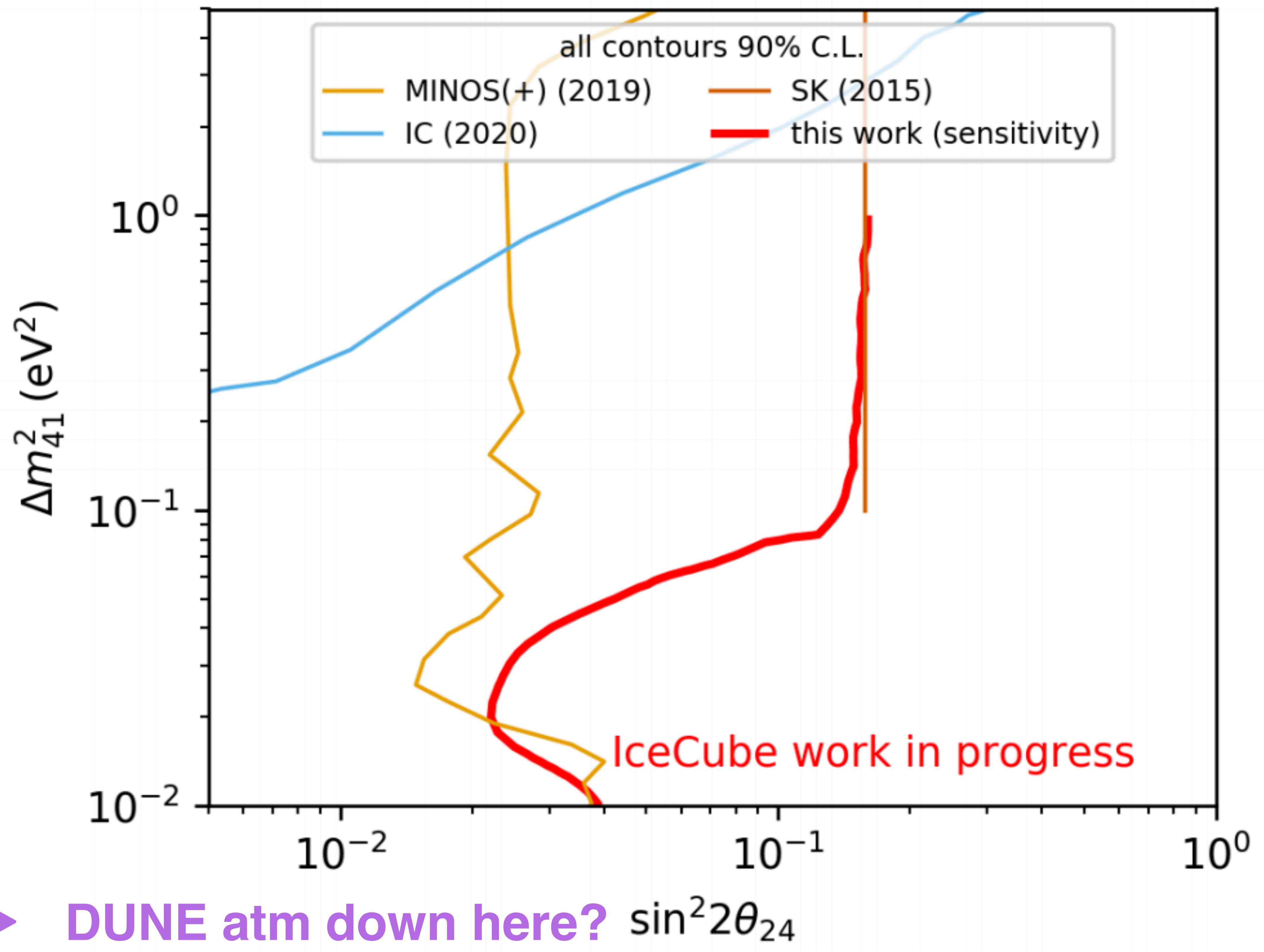


> fast oscillations overlaid on standard three-flavor oscillation pattern

visible high-energy oscillation minimum



Sensitivity contours calculated at null hypothesis (no steriles)



DUNE atm down here?

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Conclusions

Atmospheric neutrinos still have lots of potential

Low energy, high energy

CP violation, steriles, NSIs, novel particles, …

We need to get to work.

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Backup

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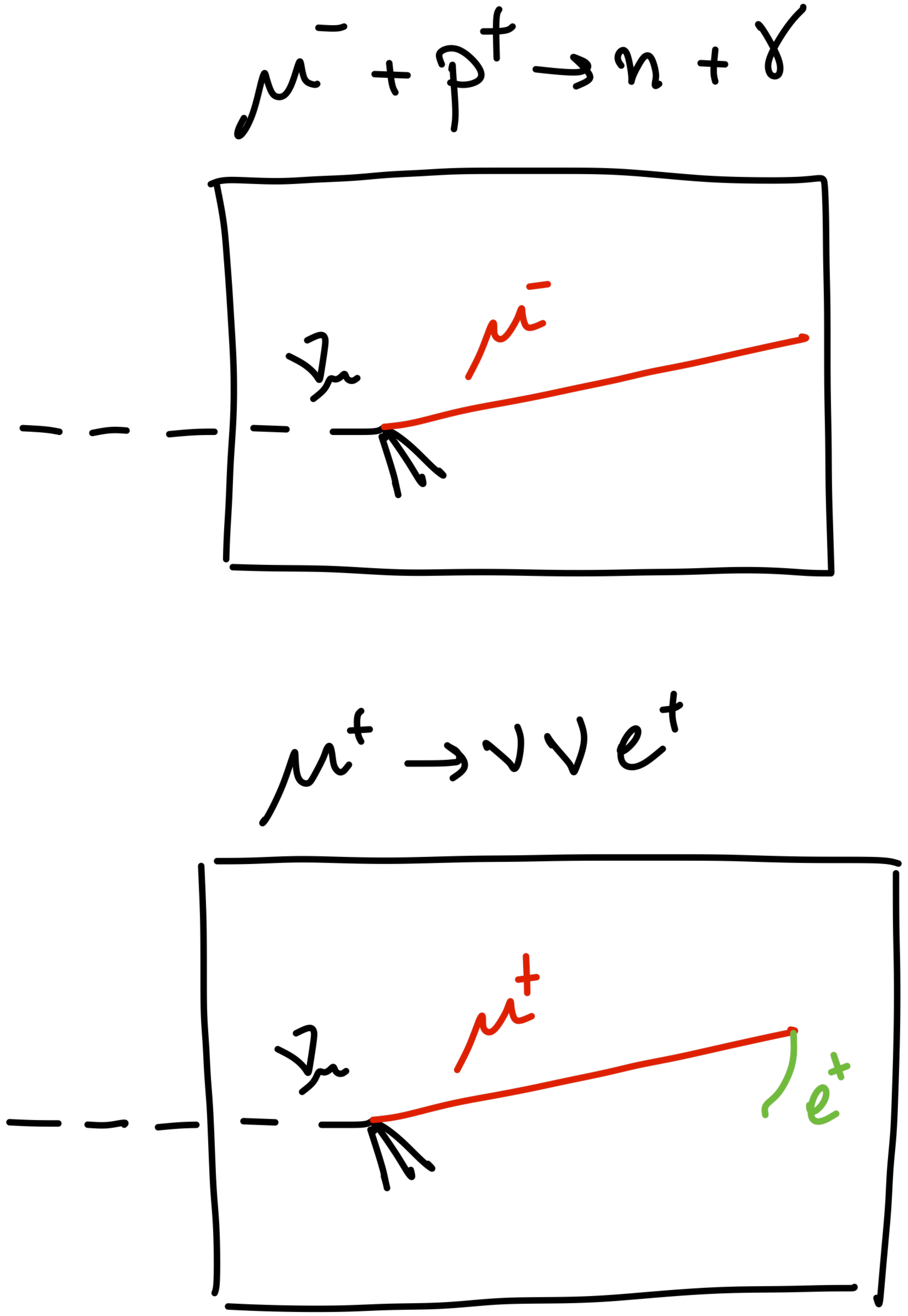
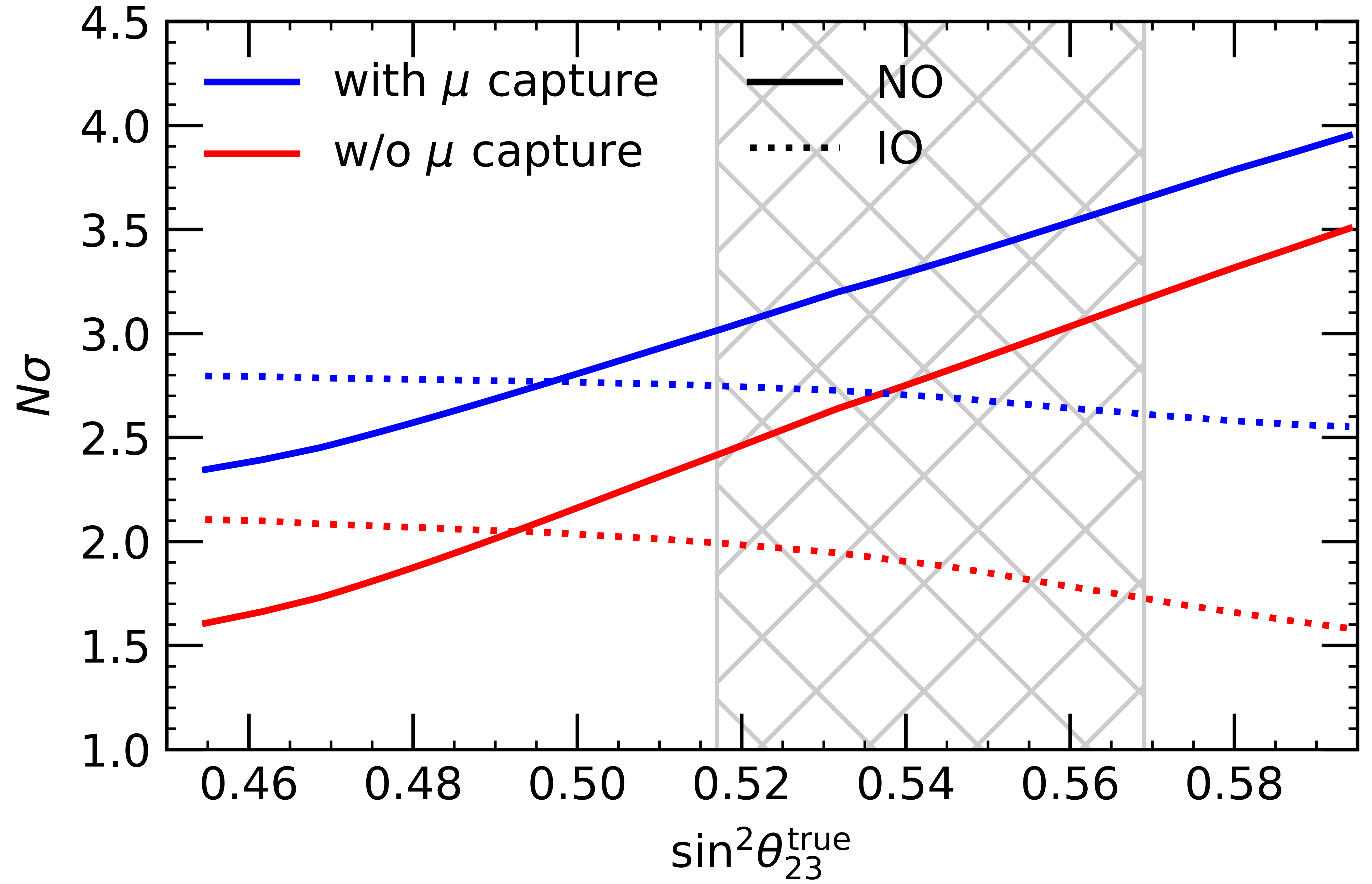


Statistical charge ID! Ternes et al 1905.03589



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