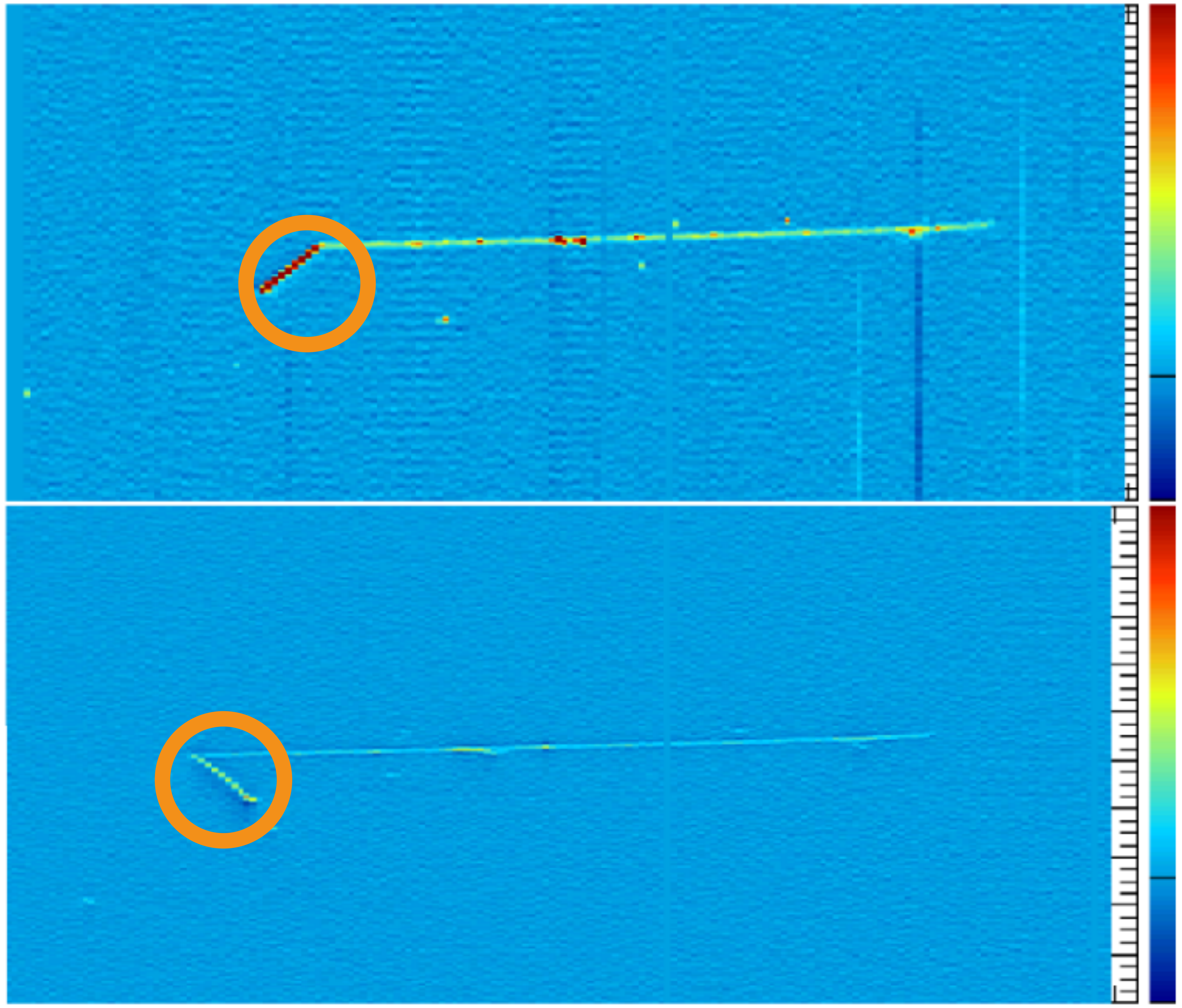
The first part of this talk is on the blackboard..

Sub-GeV atmospheric neutrinos

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

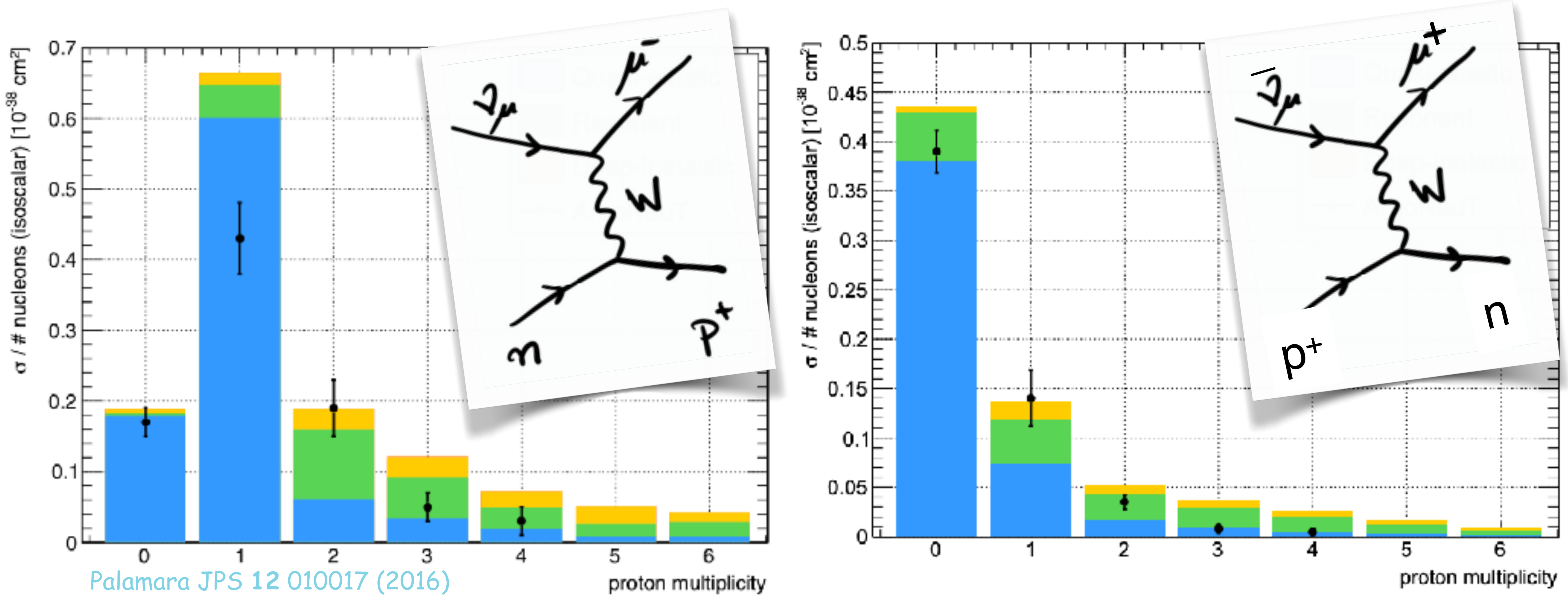
ArgoNeuT 1810.06502



Reconstruct, identify and point.

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

Event topology carries information



Palamara JPS **12** 010017 (2016)

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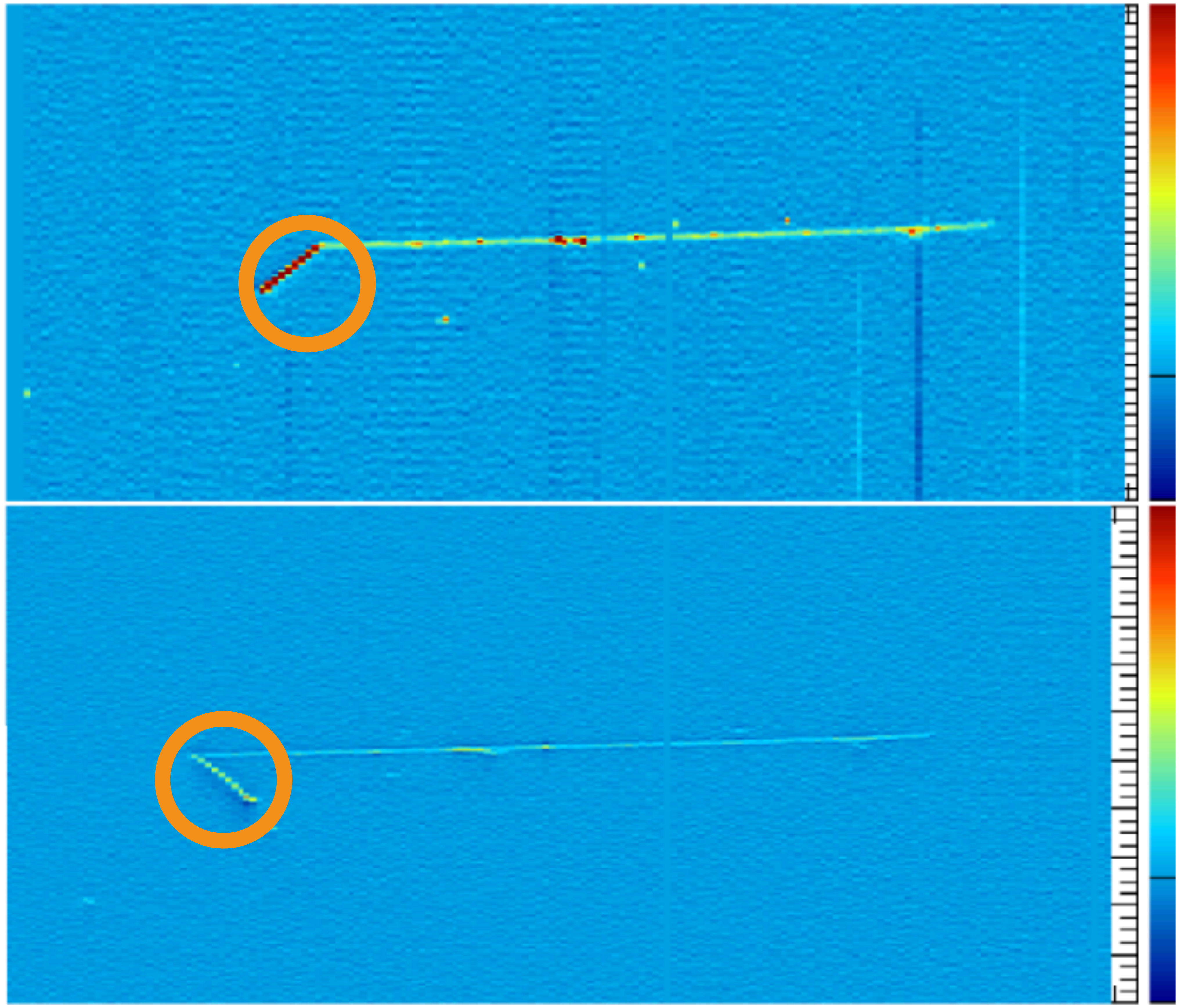
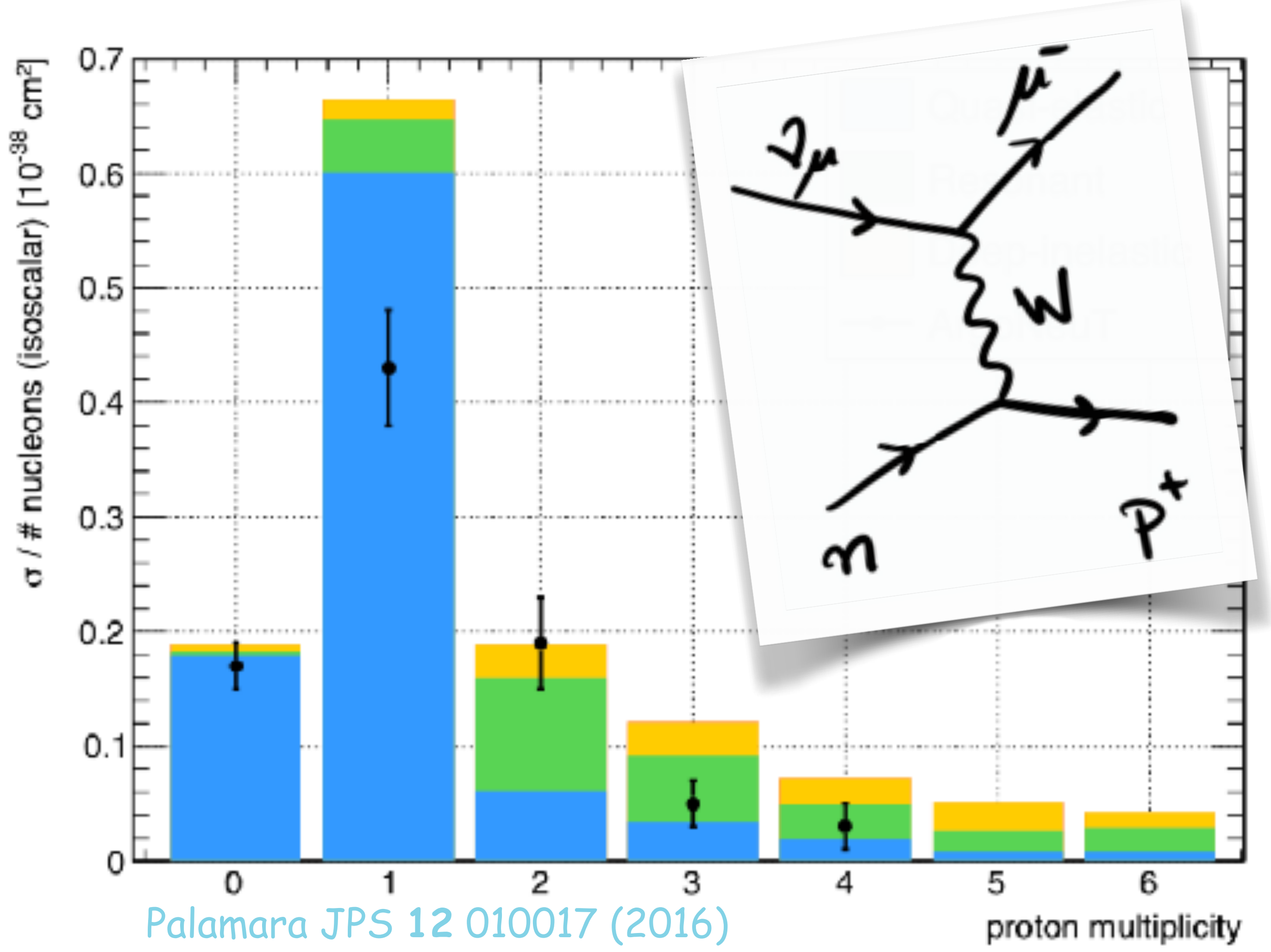


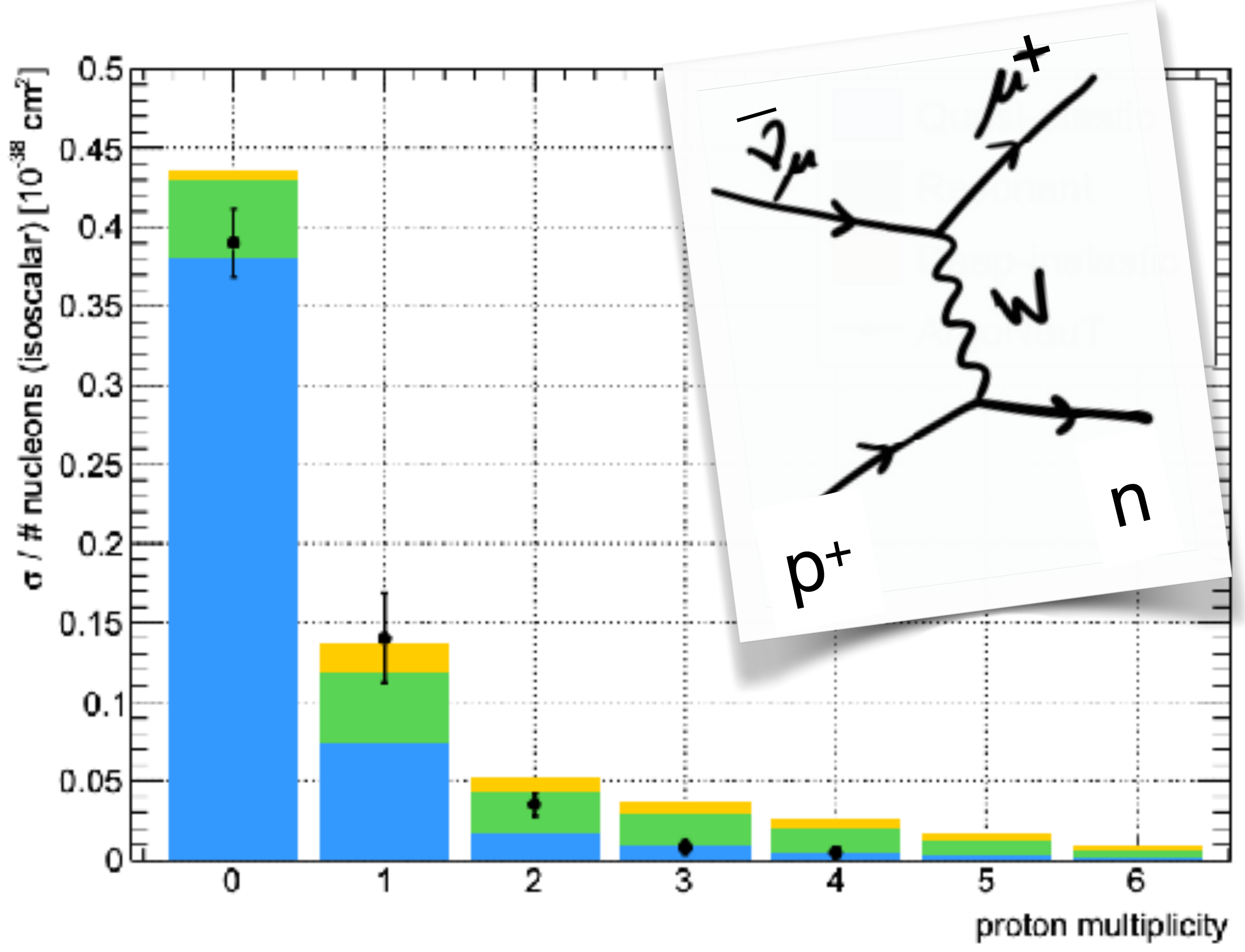
Neutrino events tend to be proton rich
Antineutrino events tend to be proton poor

Classifying events by number of protons provides a statistical handle on neutrinos versus antineutrinos

Event topology carries information



Palamara JPS 12 010017 (2016)



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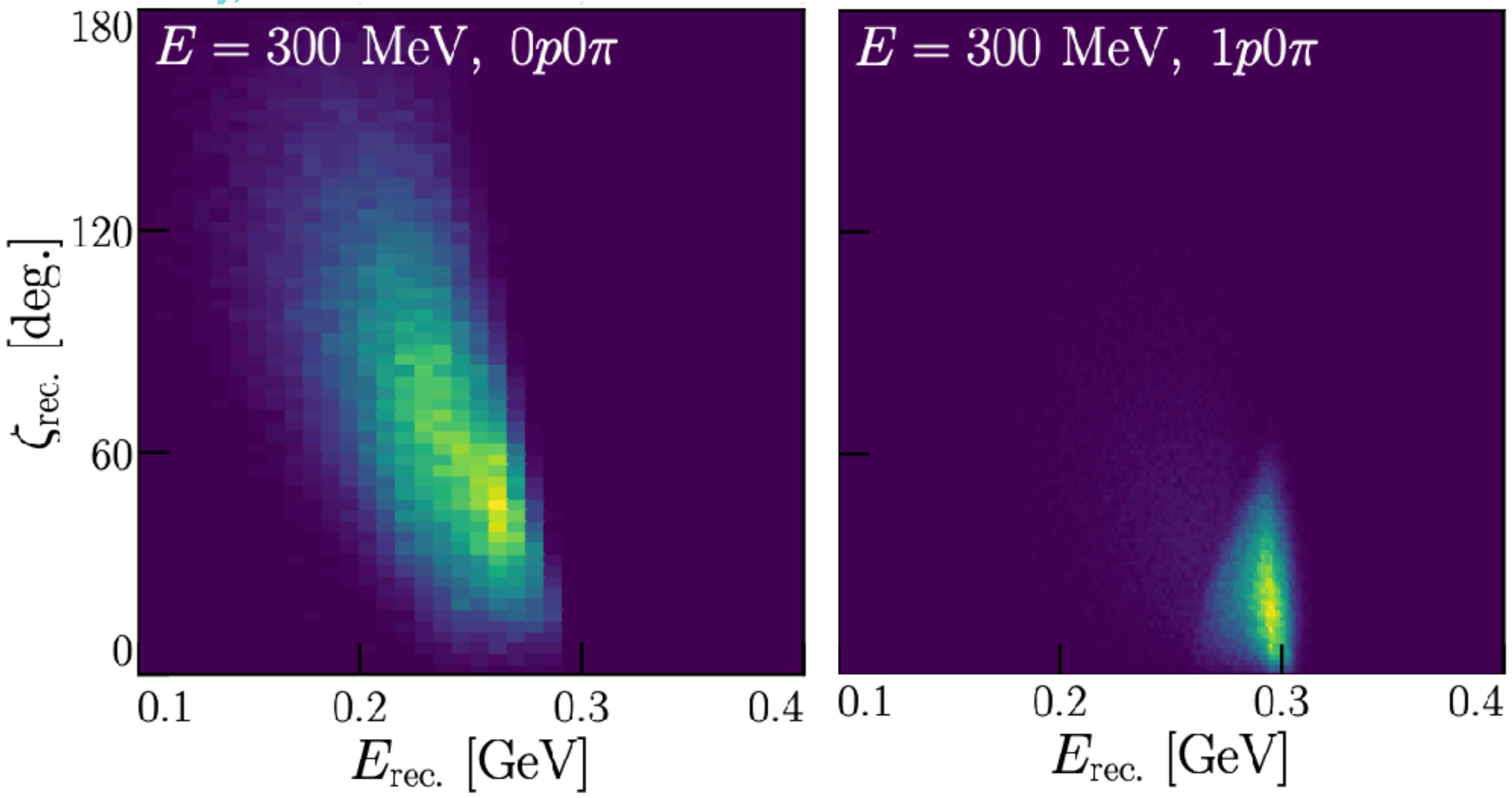
Sub-GeV atmospheric neutrinos

Kelly, PM et al 2110.00003



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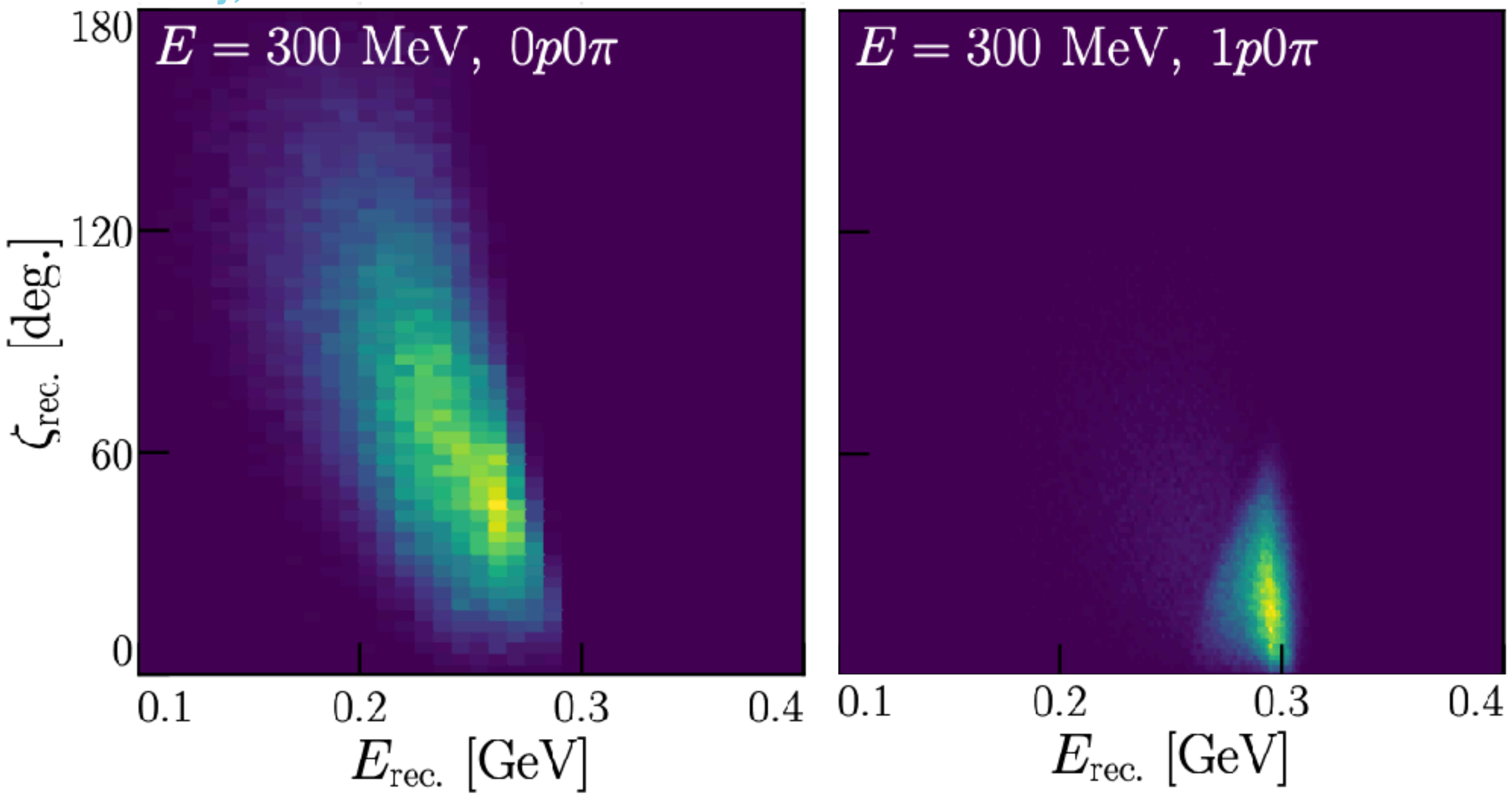


Details:

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

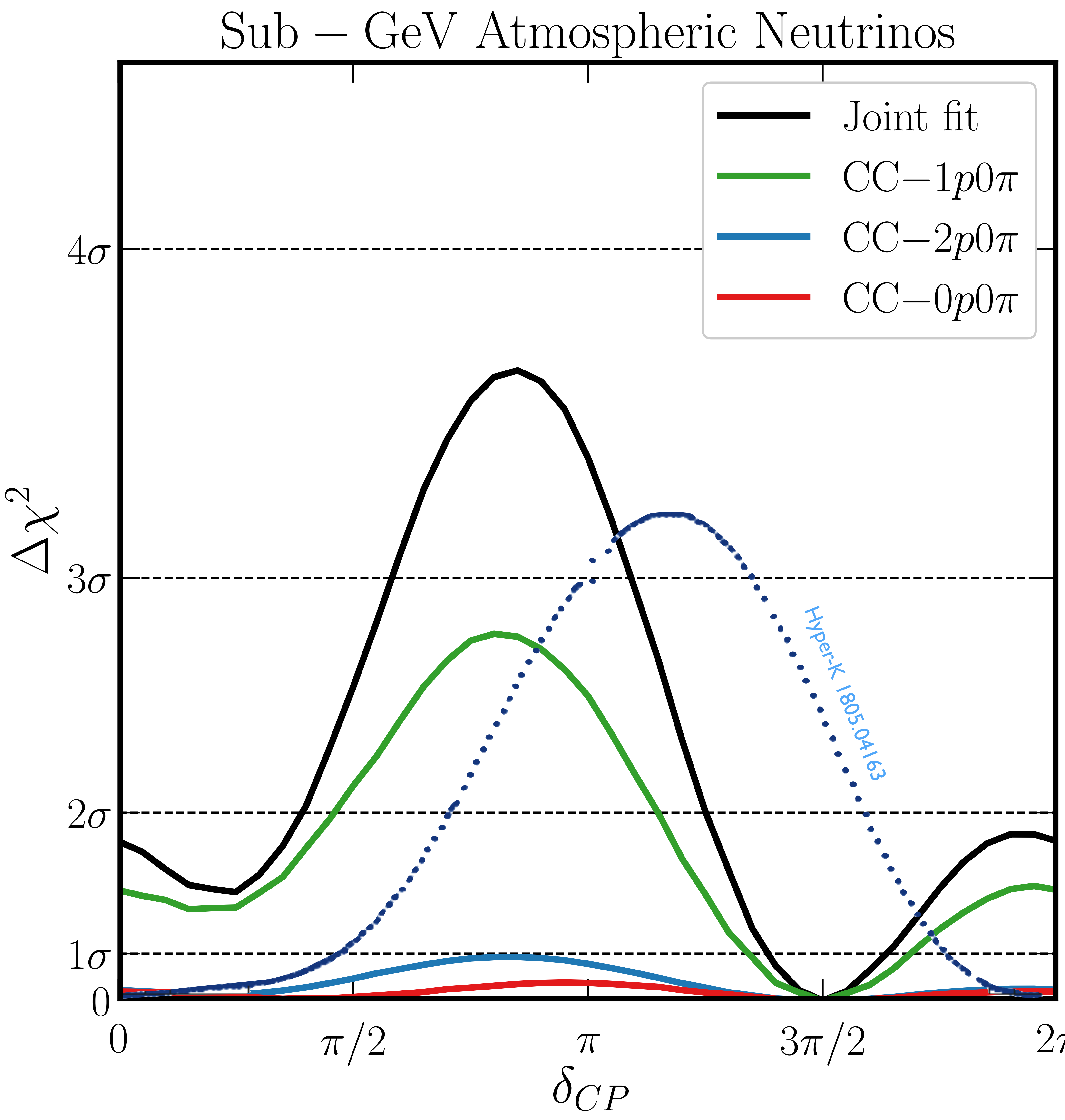
Account for uncertainties of atmospheric neutrino fluxes $\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$

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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BONUS: Earth tomography

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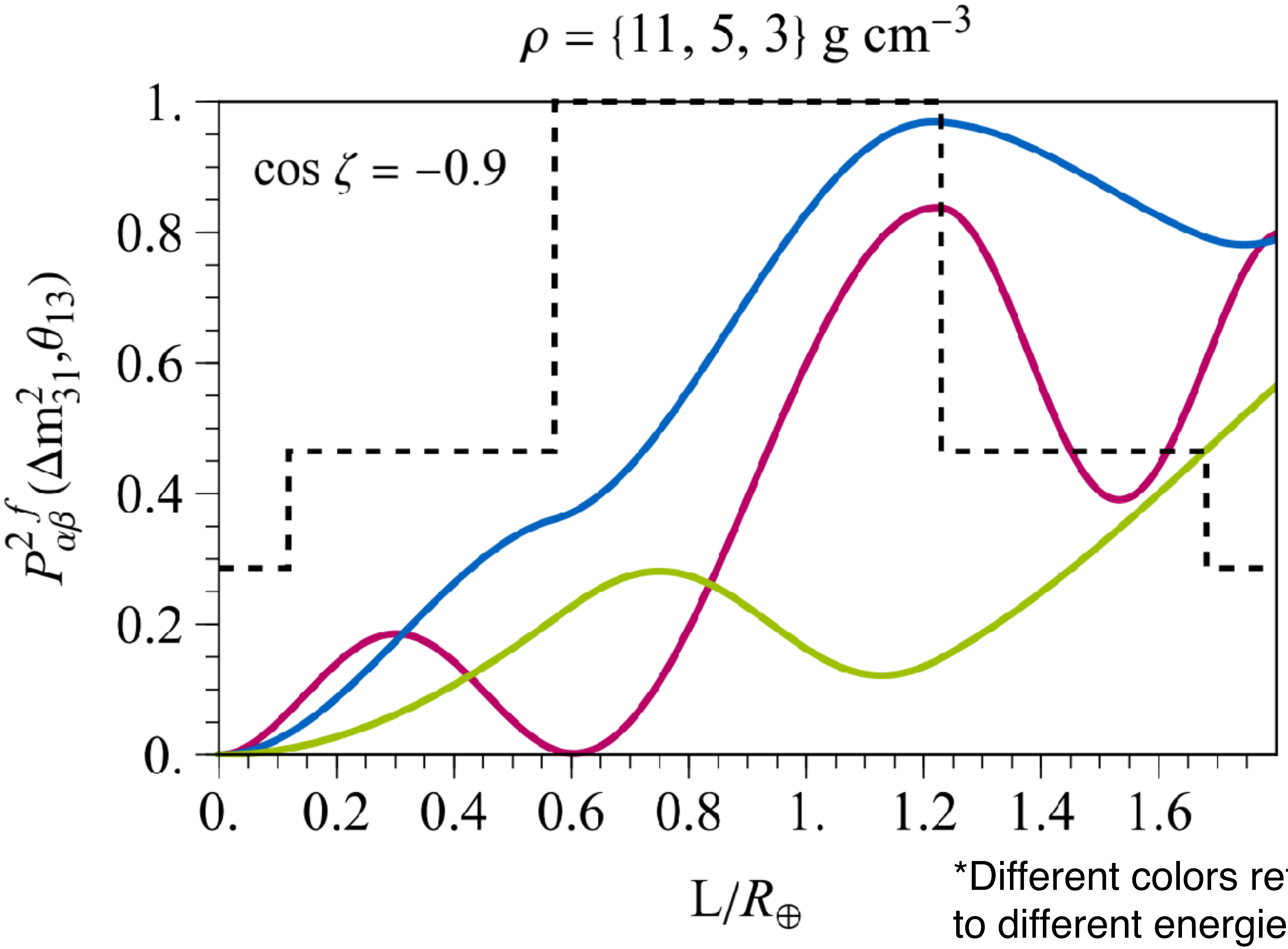

*Different colors refer to different energies

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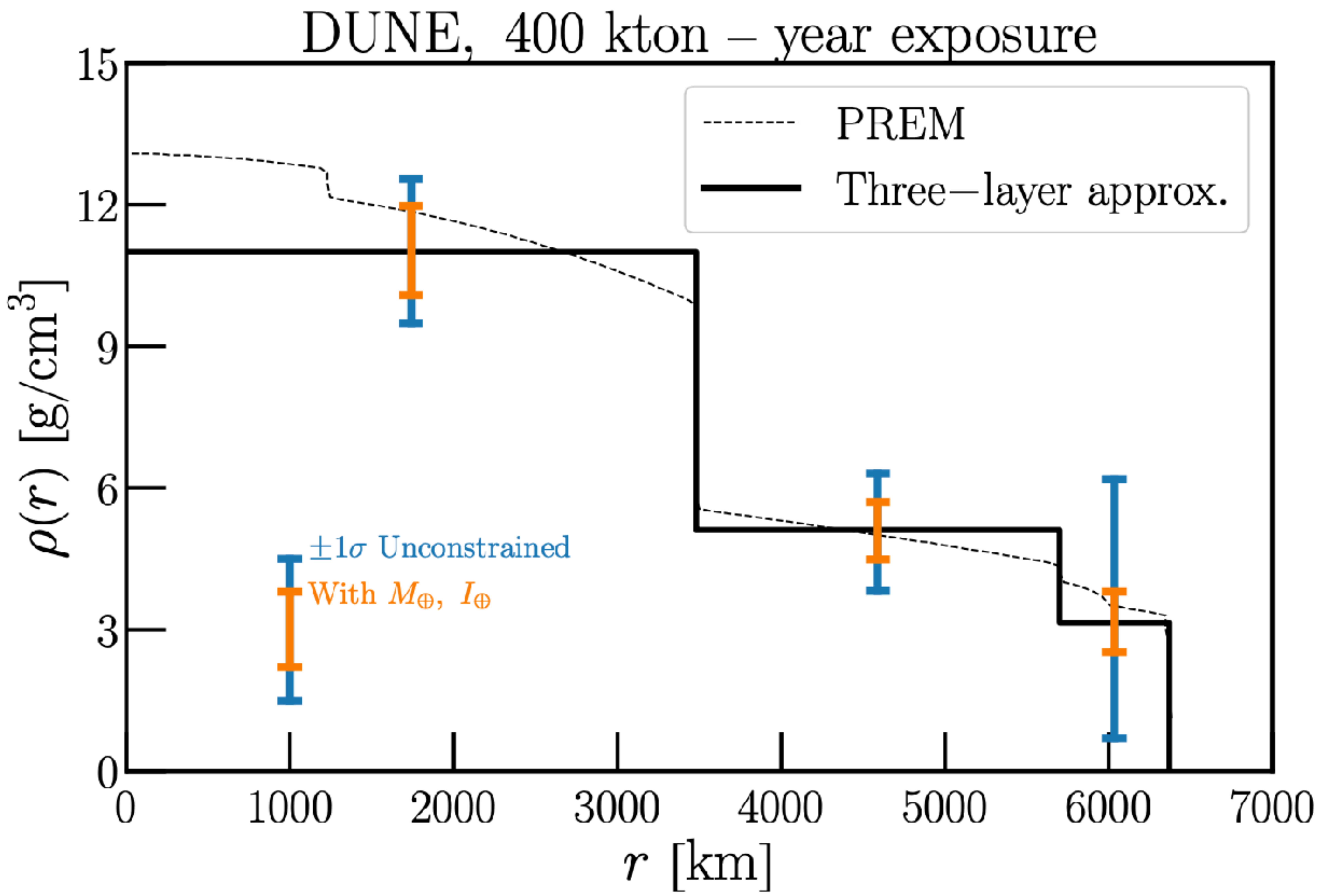
BONUS: Earth tomography

Kelly, PM et al 2110.00003



$$\rho_C = 11.0 \times (1^{+0.088}_{-0.083}) \text{ g/cm}^3$$
core

$$\rho_{LM} = 5.11 \times (1^{+0.12}_{-0.13}) \text{ g/cm}^3$$
lower mantle

$$\rho_{UM} = 3.15 \times (1^{+0.22}_{-0.20}) \text{ g/cm}^3$$
upper mantle

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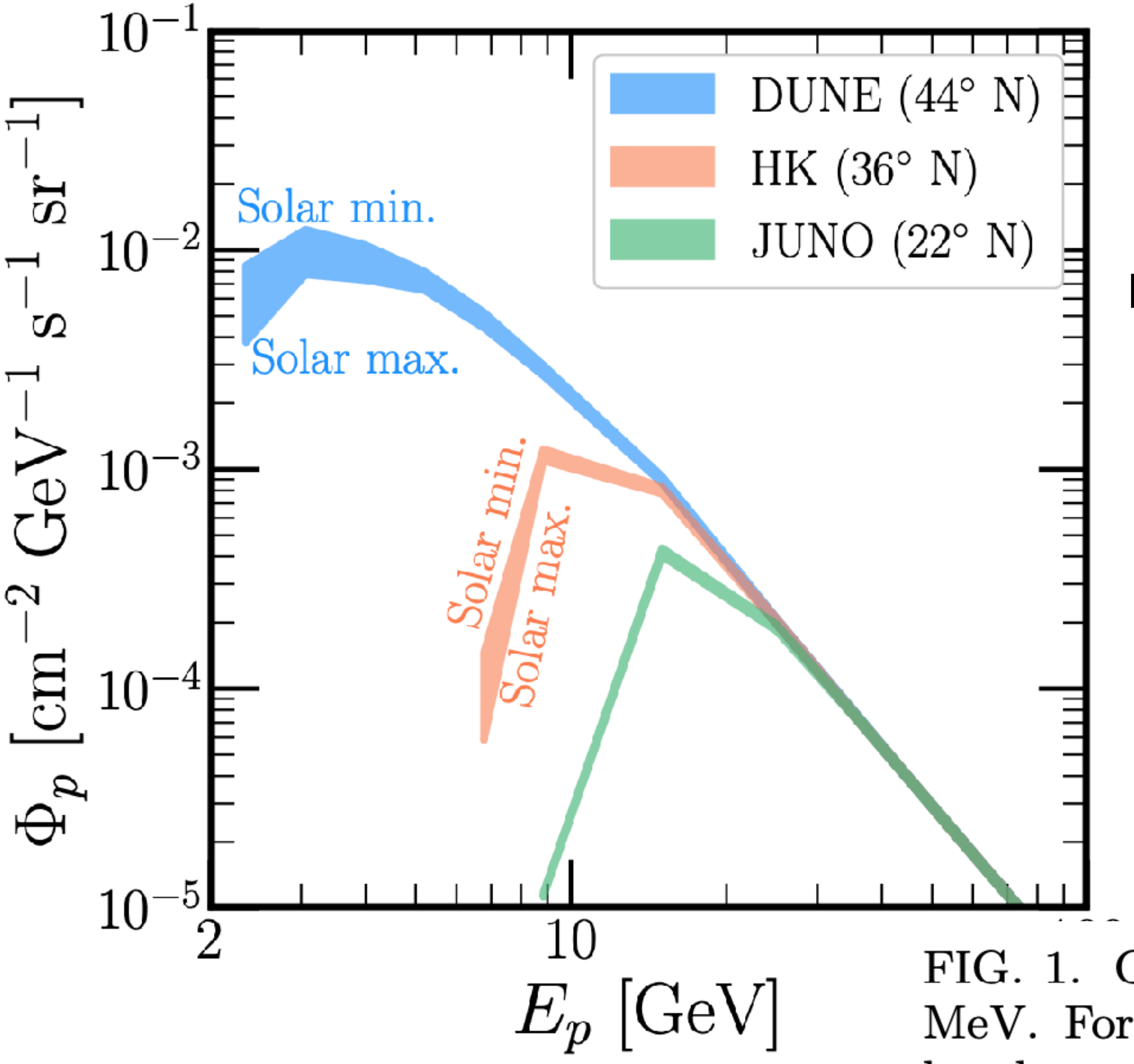
BONUS: Solar cycle

Mishra Zhuang et al 2304.04689



CRs diffuse through the solar wind, so there is an expected modulation from the solar cycle

Rigidity (momentum/charge) cutoff from geomagnetic field is different for each location on Earth.
Low-energy CR spectrum is different for different locations: asymmetry in the low-energy atmospheric flux

FIG. 1. Cosmic ray protons producing neutrinos $E_\nu > 100$ MeV. For each spectrum (latitudes indicated), the shaded band represents the differences between solar min and solar max.

BONUS: Solar cycle

Mishra Zhuang et al 2304.04689

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Summary

Sub-GeV atmospheric neutrinos are invaluable: more statistics, lots of oscillation physics, more solar modulation effects, …

We will finally tap into this potential with DUNE due to the LArTPC capabilities

Complementary information on δ_{cp}, independent from beam uncertainties and at different energy scale

DUNE could provide the leading measurement of Earth tomography

DUNE could measure the effect of the solar cycle on atmospheric neutrinos for the first time

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Backup

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Why sub-GeV atmospheric neutrinos?

CP violation and Earth tomography

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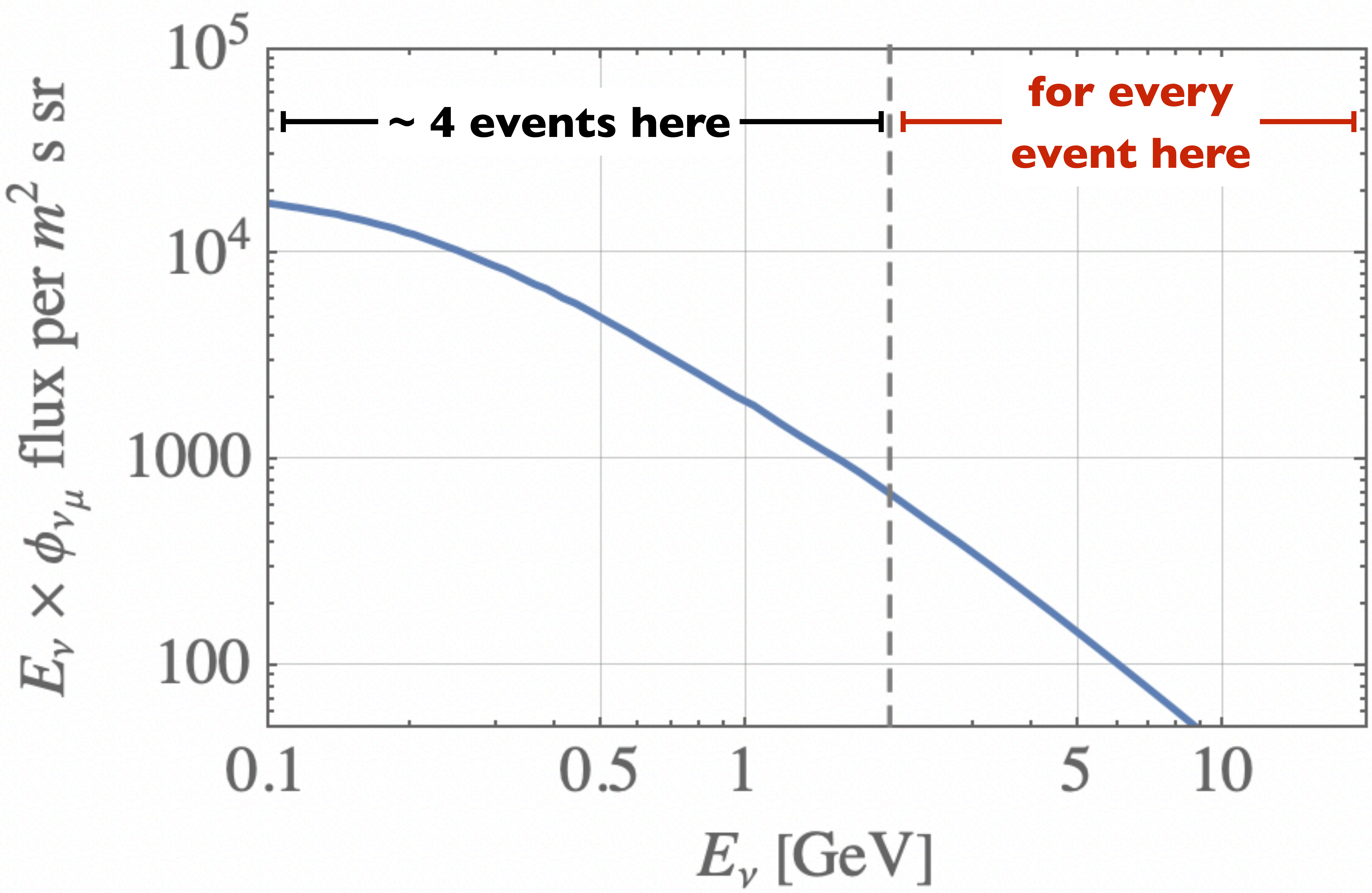
Sub-GeV atmospheric neutrinos

Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801



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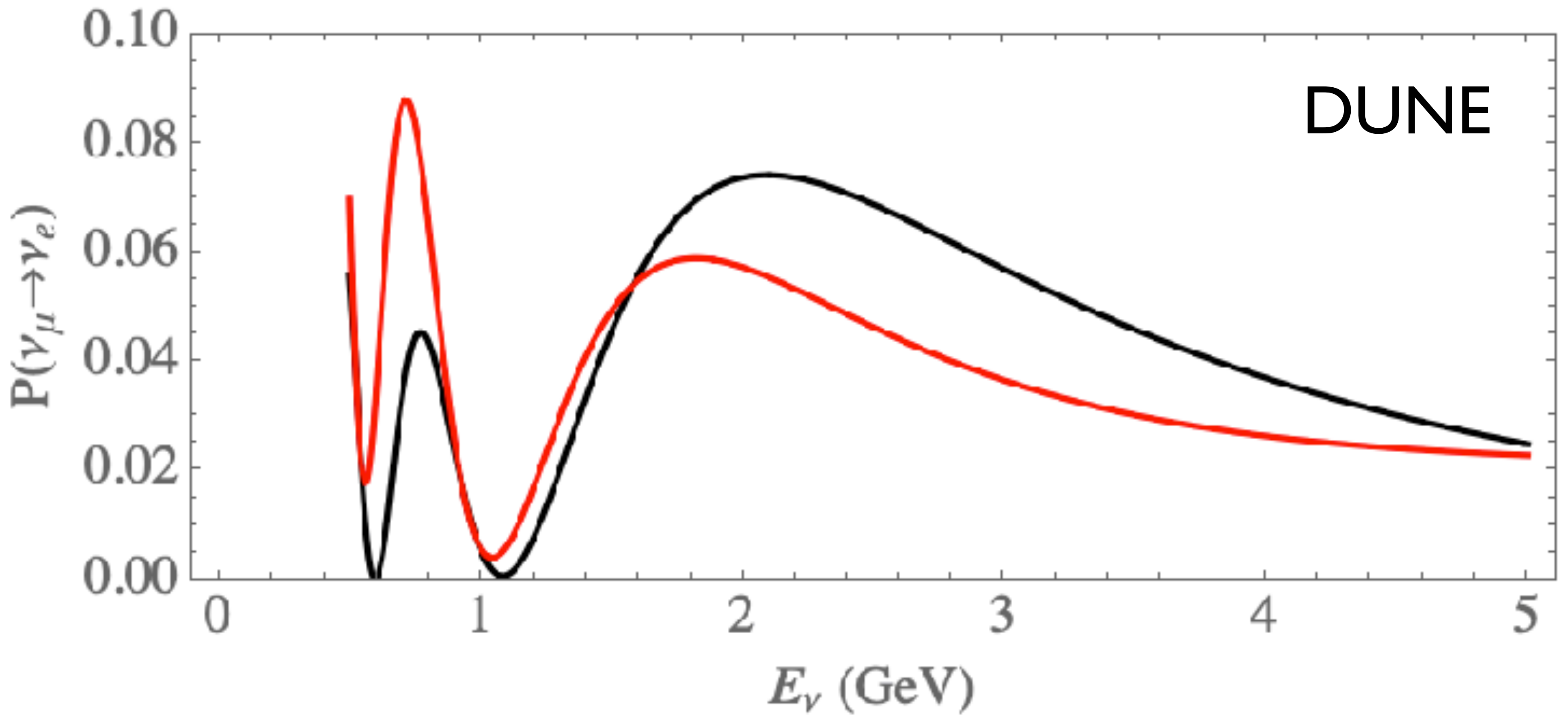
Sub-GeV atmospheric neutrinos

Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

CPV in sub-GeV atmospherics is about 10x larger than in beam neutrinos.

$$P_{CP} = -8 J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$



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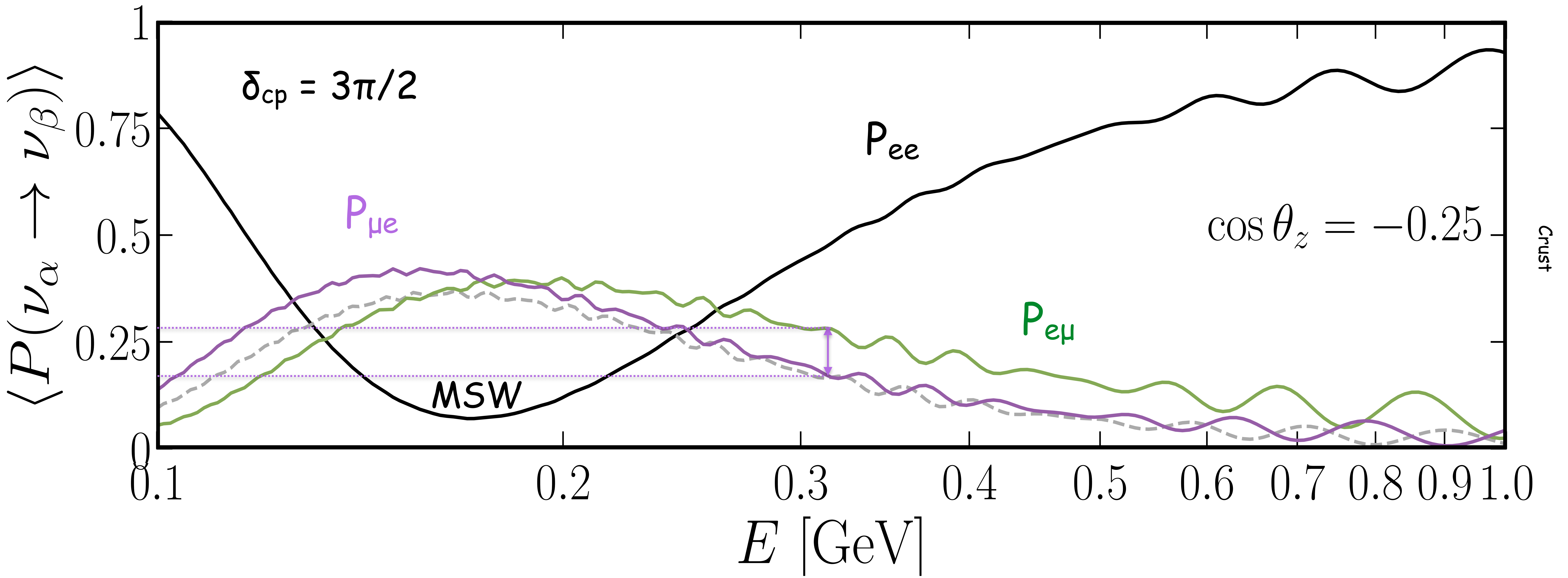

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Sub-GeV atmospheric neutrinos

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

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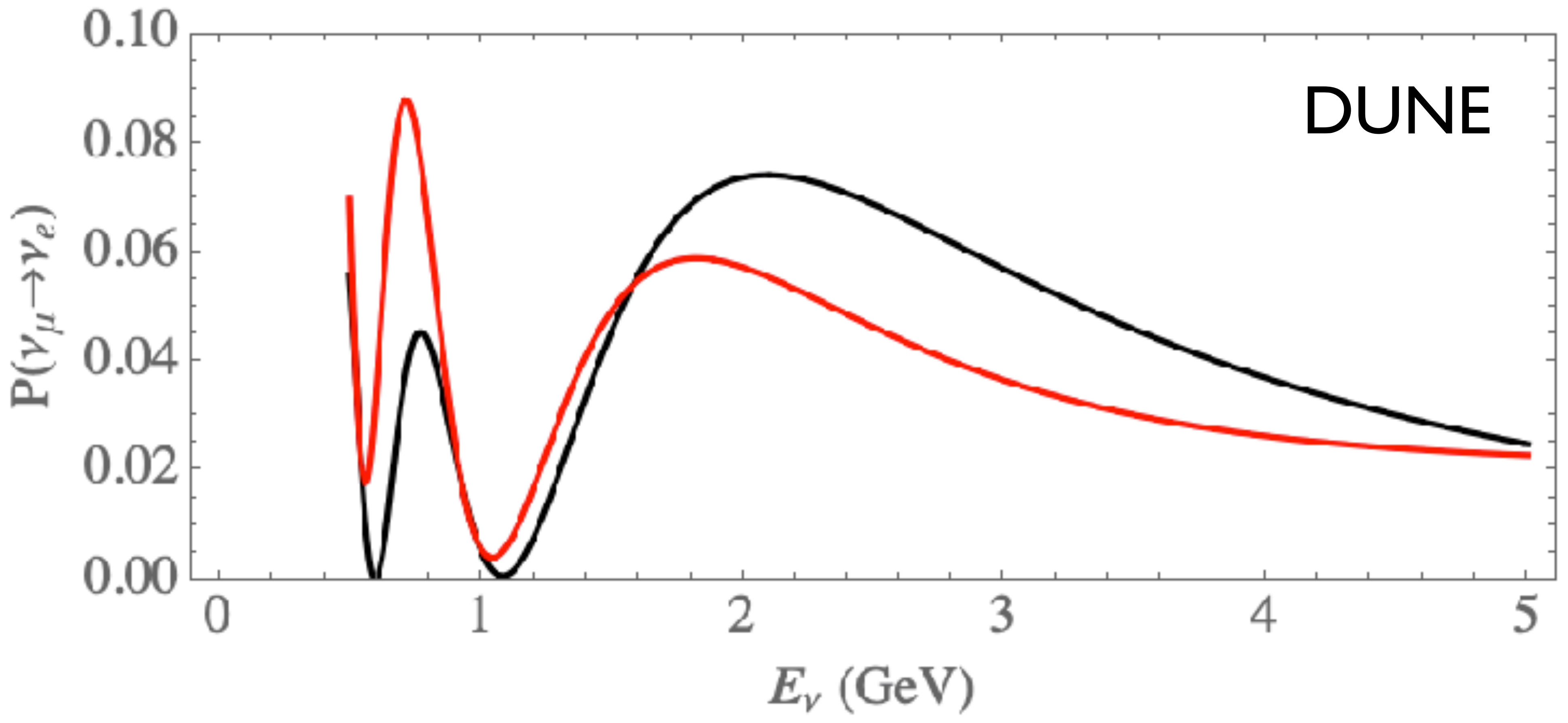

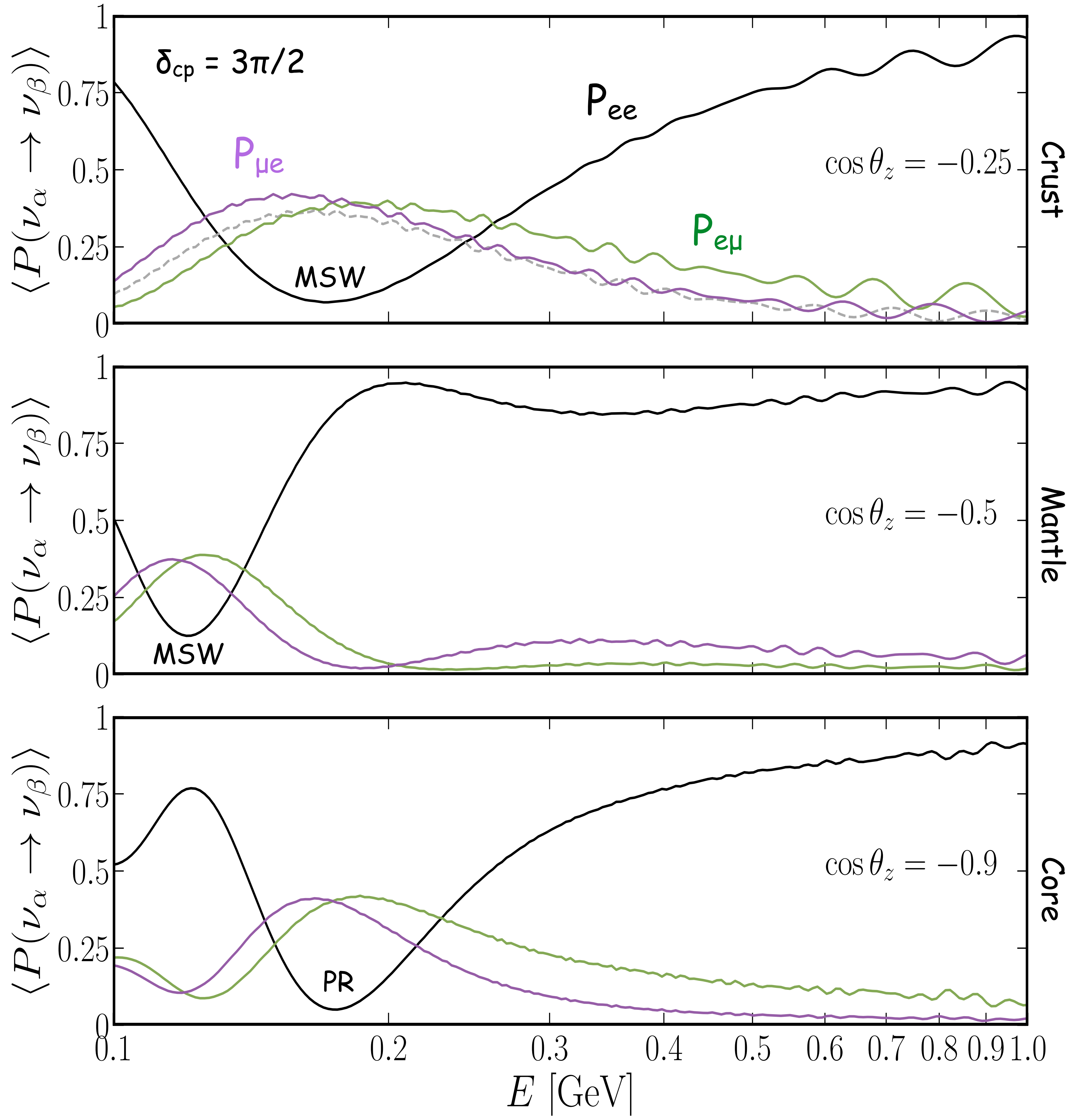

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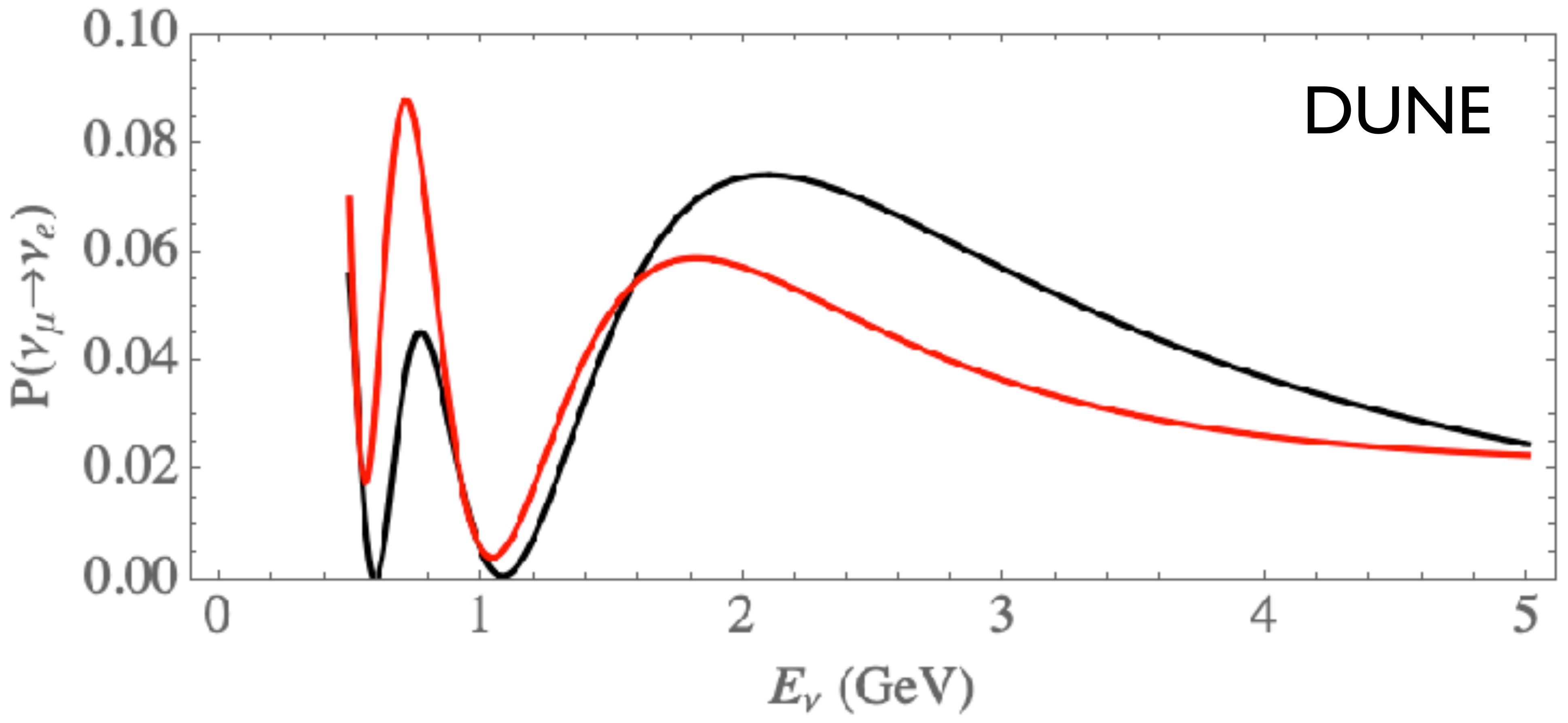

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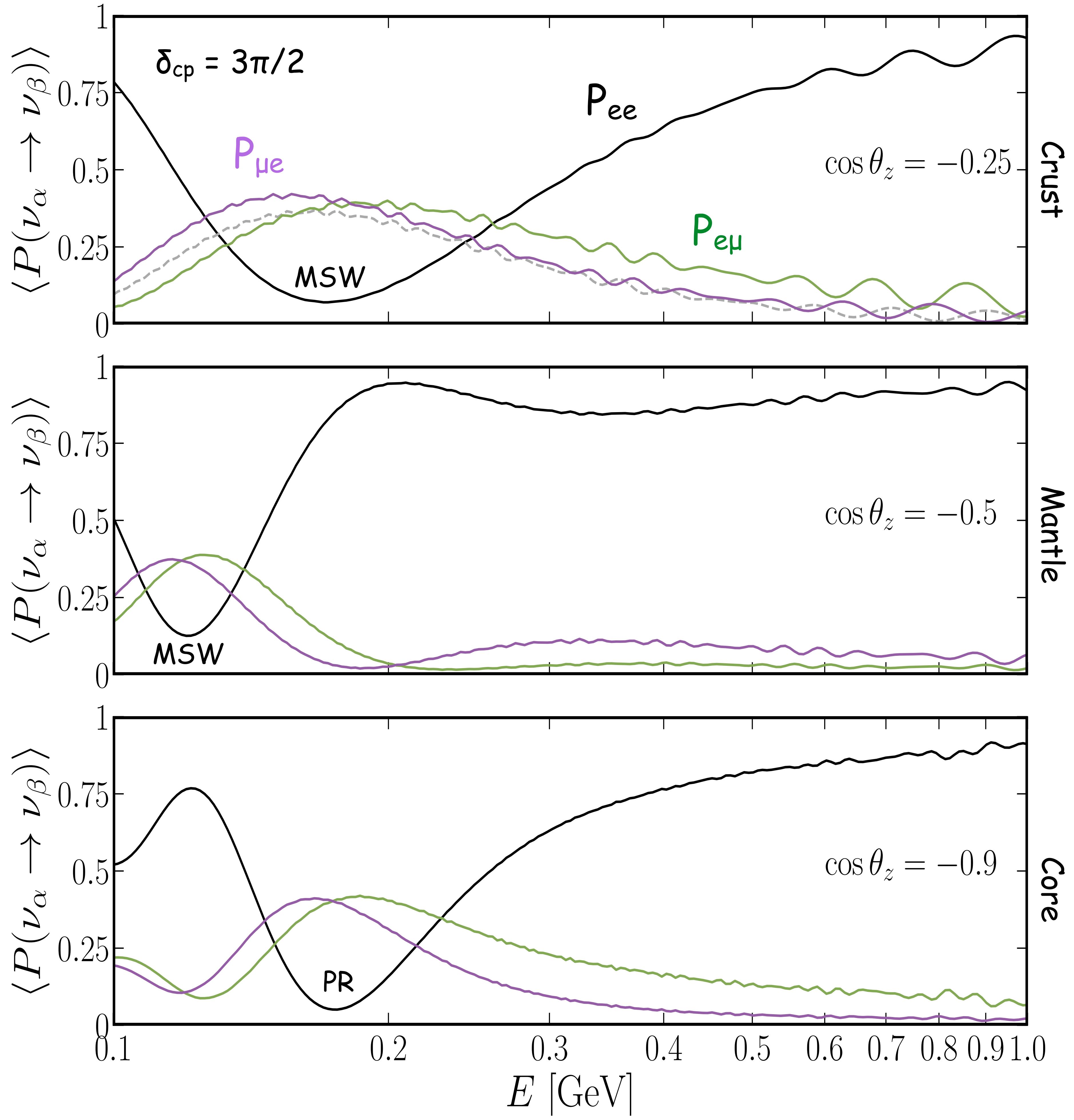
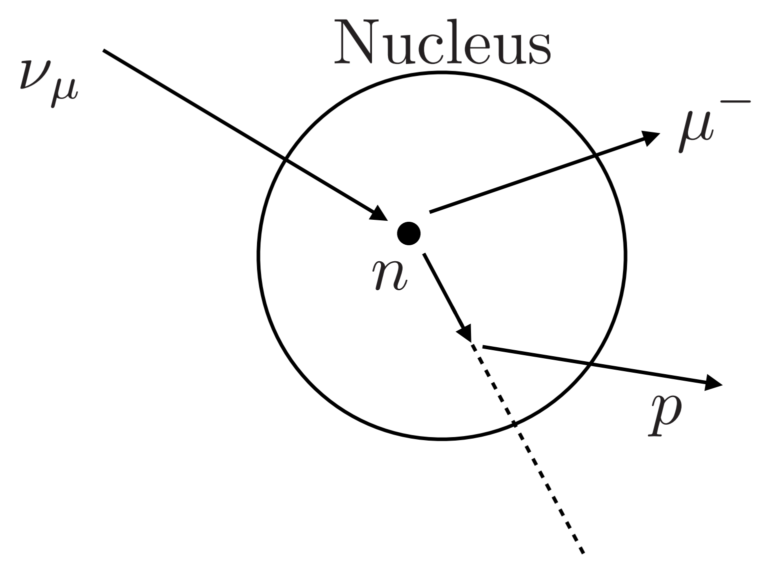


But sub-GeV atmospherics are very difficult…



Needs to know neutrino direction

Low E protons are invisible @ Cherenkov detectors

Liquid Argon TPCs can do it!

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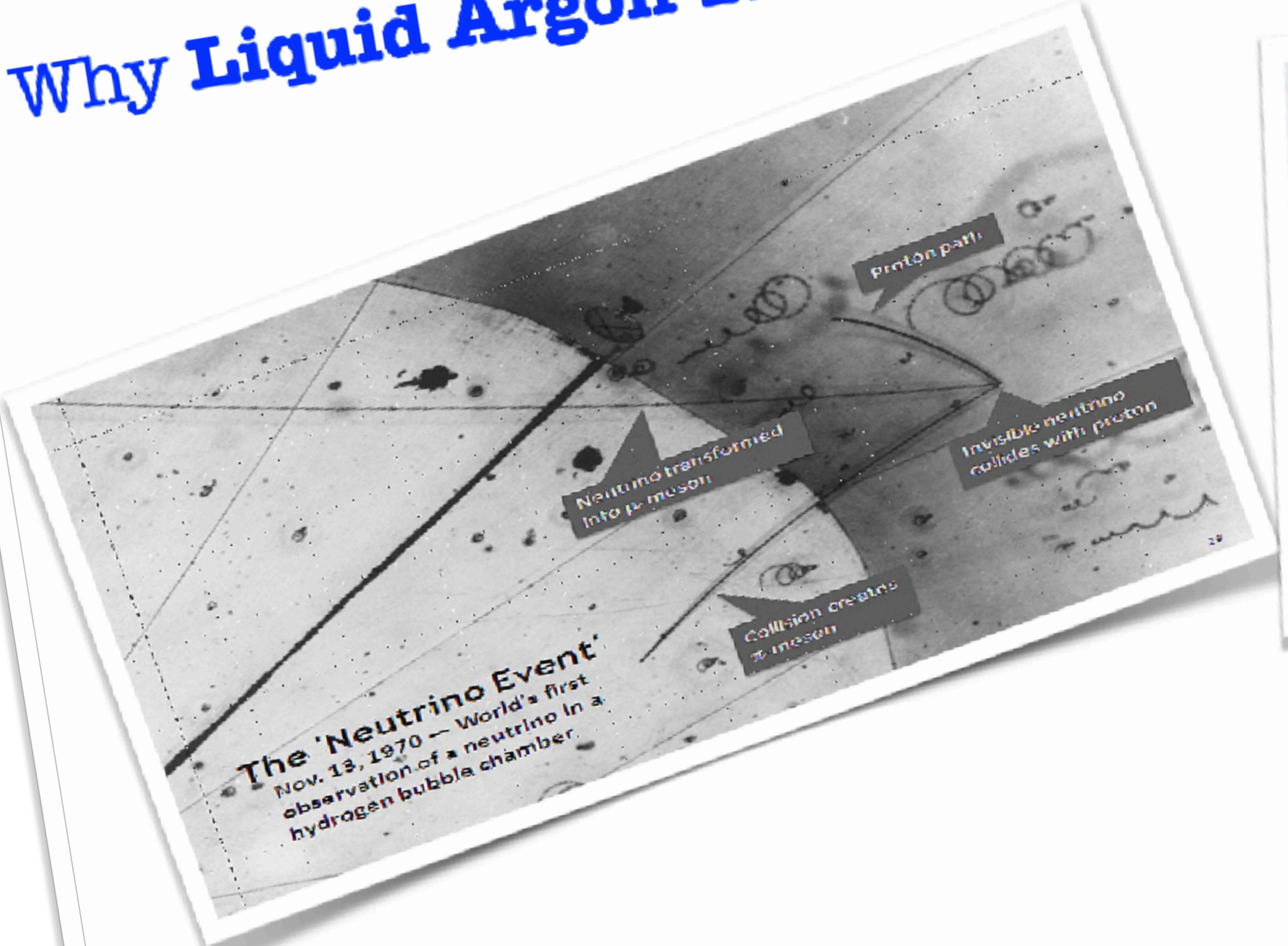
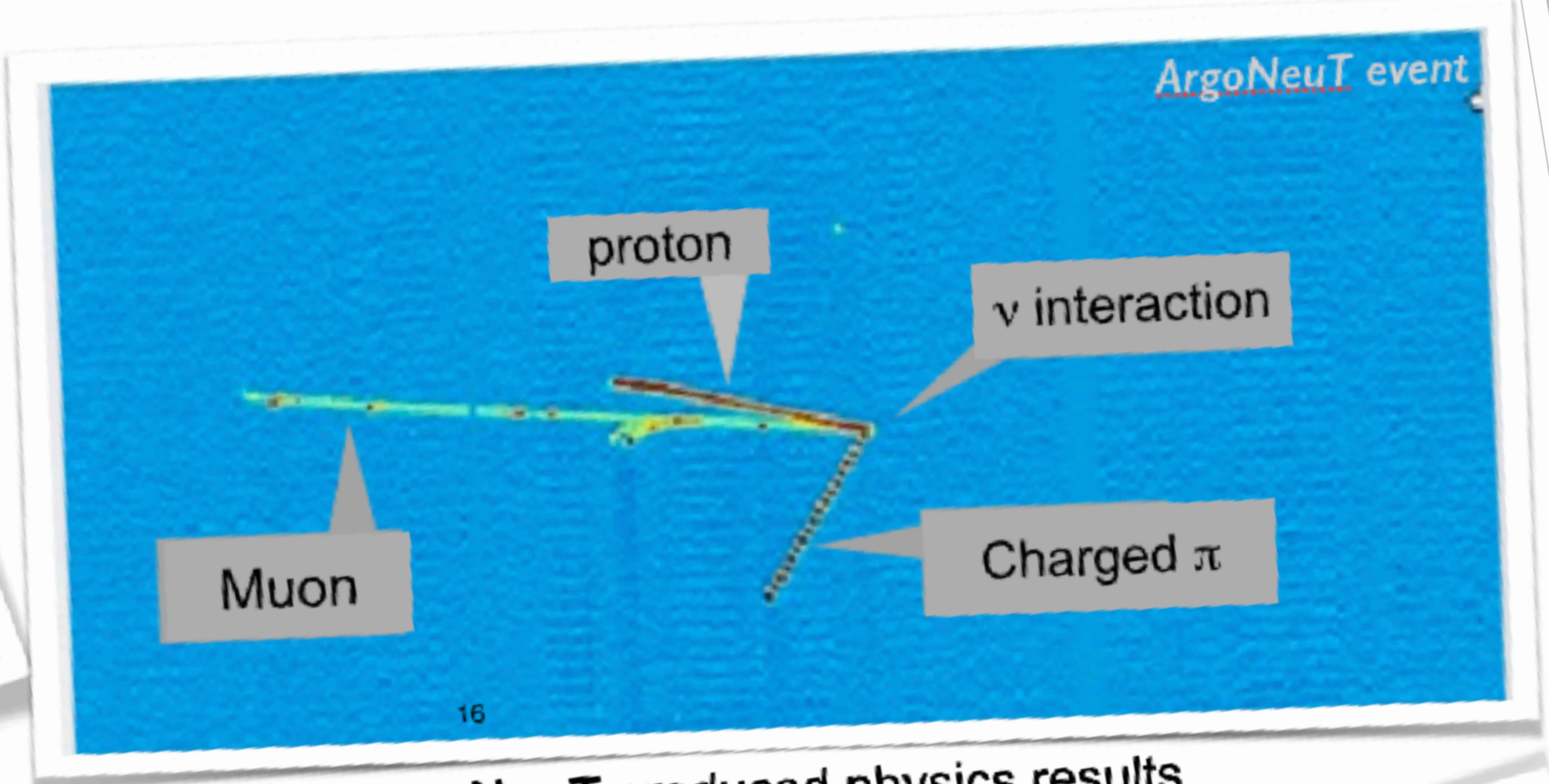
Why Liquid Argon Time Projection Chamber?





ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

LAr TPC: Bubble chamber quality of data with added calorimetry

...or LArTPC is "a "colored" bubble chamber" (theorist simplified view!)

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slide stolen from O. Palamara

Table 1. Assumptions of DUNE Far Detector reconstruction and identification capability that enter our analysis.

Particle	Minimum K.E.	Angular Uncertainty	Energy Uncertainty
Proton	30 MeV	10°	10%
Pion	30 MeV	10°	10%
Λ	30 MeV	10°	10%
$\mu^\pm$	5 MeV	2°	5%
$e^\pm$	10 MeV	2°	5%

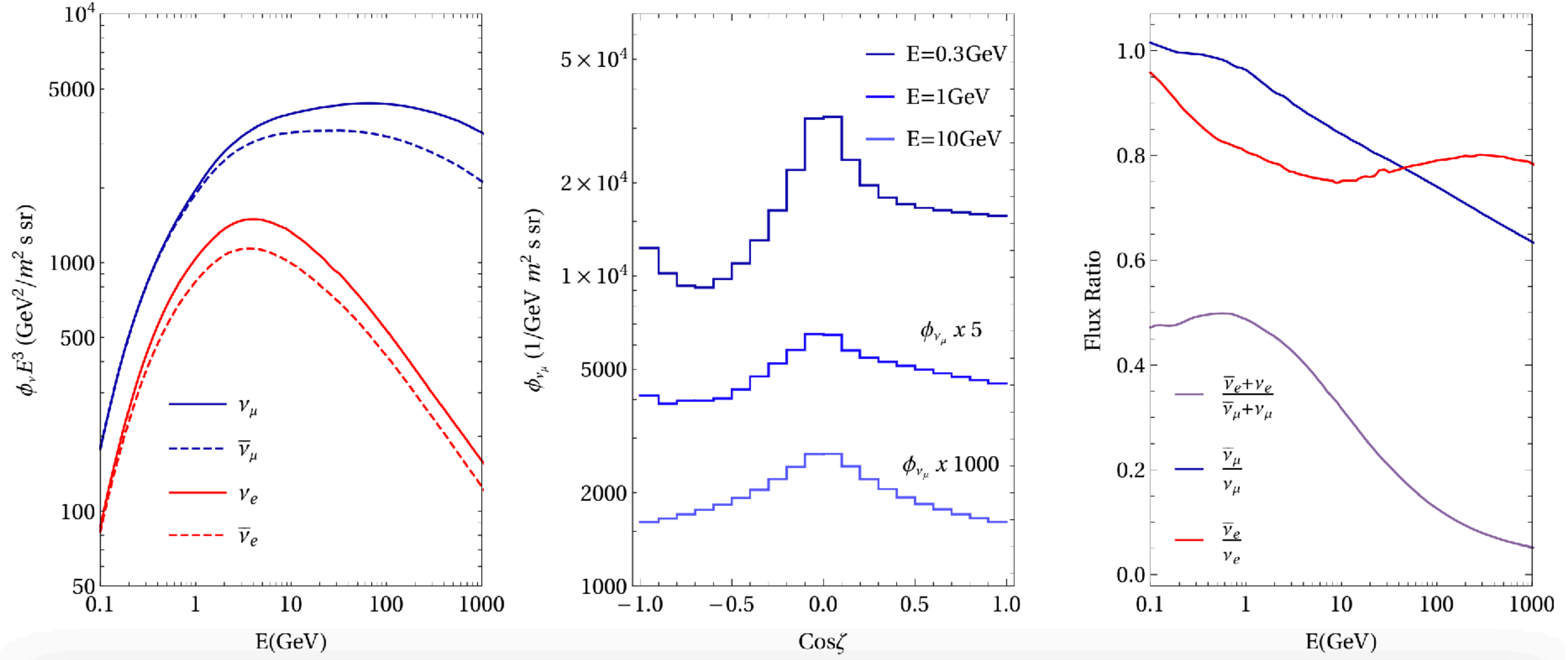

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Table 2. Uncertainties and priors in the atmospheric neutrino flux used in our analysis.

Systematic	Uncertainties/Priors
Normalization (Φ_0)	40%
Flavor ratio (ν_e/ν_μ)	5%
Neutrino to antineutrino ratio ($\overline{\nu}/\nu$)	2%
Energy distortion (δ)	0 ± 0.2
Zenith distortion ($C_{u,d}$)	0 ± 0.2

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$$M_\oplus = \frac{4\pi}{3}\left[\rho_{\rm C} R_{\rm C}^3 + \rho_{\rm LM}\left(R_{\rm LM}^3 - R_{\rm C}^3\right) + \rho_{\rm UM}\left(R_\oplus^3 - R_{\rm LM}^3\right)\right],$$

$$I_\oplus = \frac{8\pi}{15}\left[\rho_{\rm C} R_{\rm C}^5 + \rho_{\rm LM}\left(R_{\rm LM}^5 - R_{\rm C}^5\right) + \rho_{\rm UM}\left(R_\oplus^5 - R_{\rm LM}^5\right)\right].$$

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