Neutrino-nucleus interactions from a neutrino phenomenology point of view

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Why do we need to:

1) Reconstruct incoming neutrino energy?
2) Reconstruct incoming neutrino direction?
3) Properly calculate backgrounds?

Answer with examples:

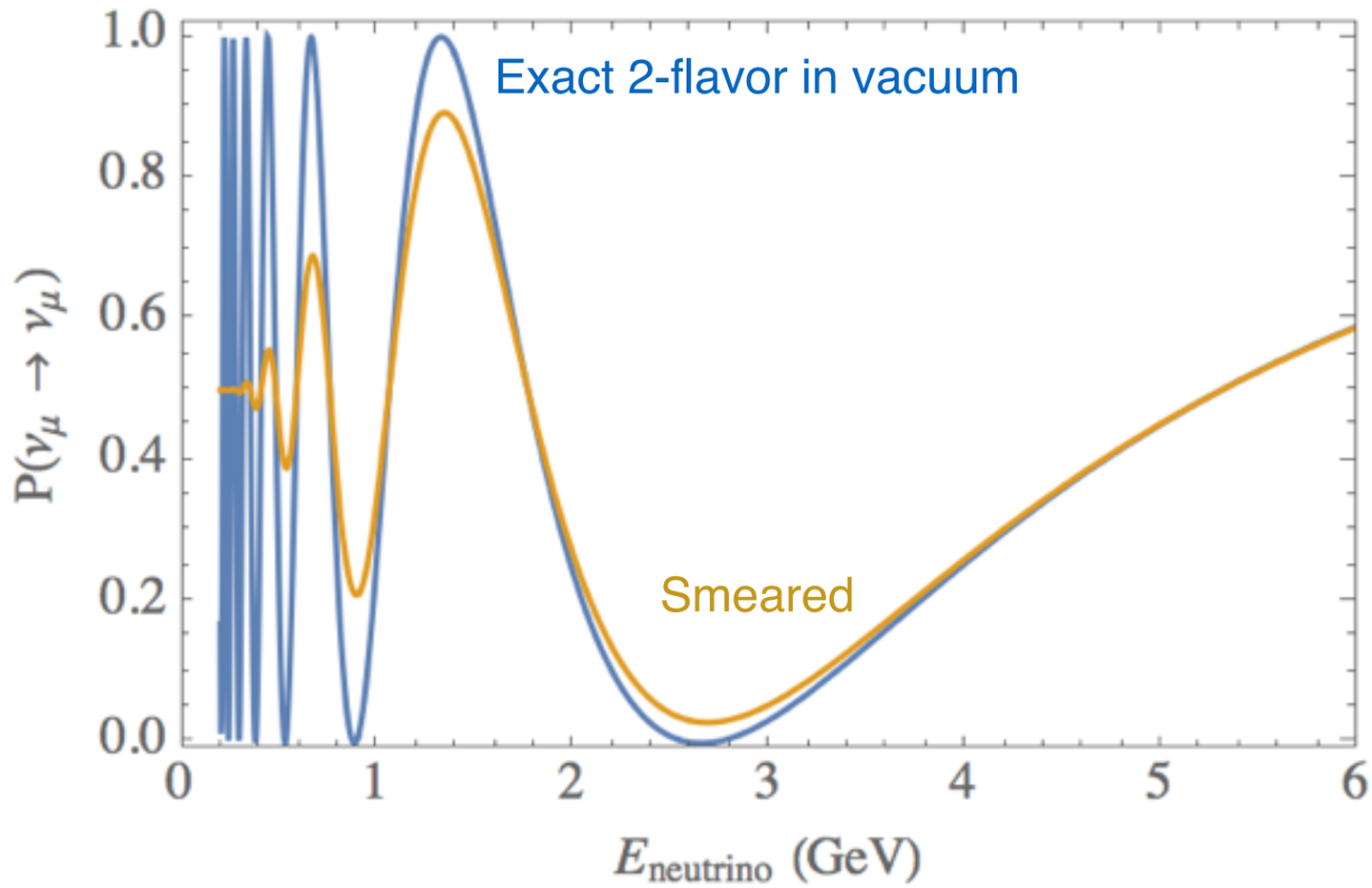
1) Precision oscillation physics
2) Atmospheric neutrinos
3) Short-baseline anomalies and new physics searches

Case 1: Neutrino energy and precision oscillation physics

Neutrino oscillation is an energy dependent phenomenon

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E[\mathrm{GeV}]} \right)$$

(simplified 2 flavor oscillations in vacuum)



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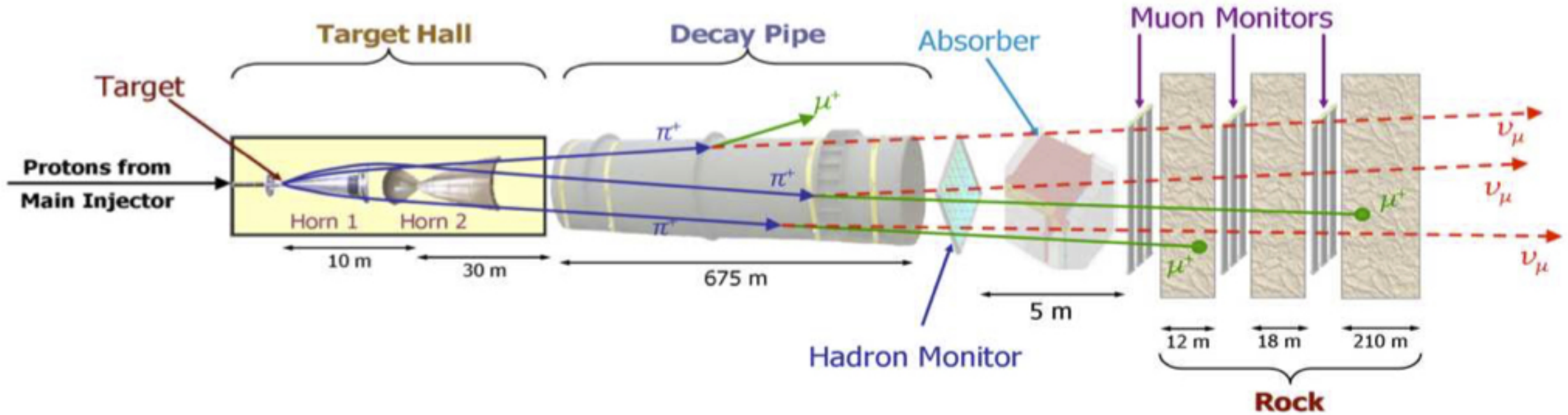
Case 1: Neutrino energy and precision oscillation physics

Difficulty 1: Beam neutrinos are produced via QCD…



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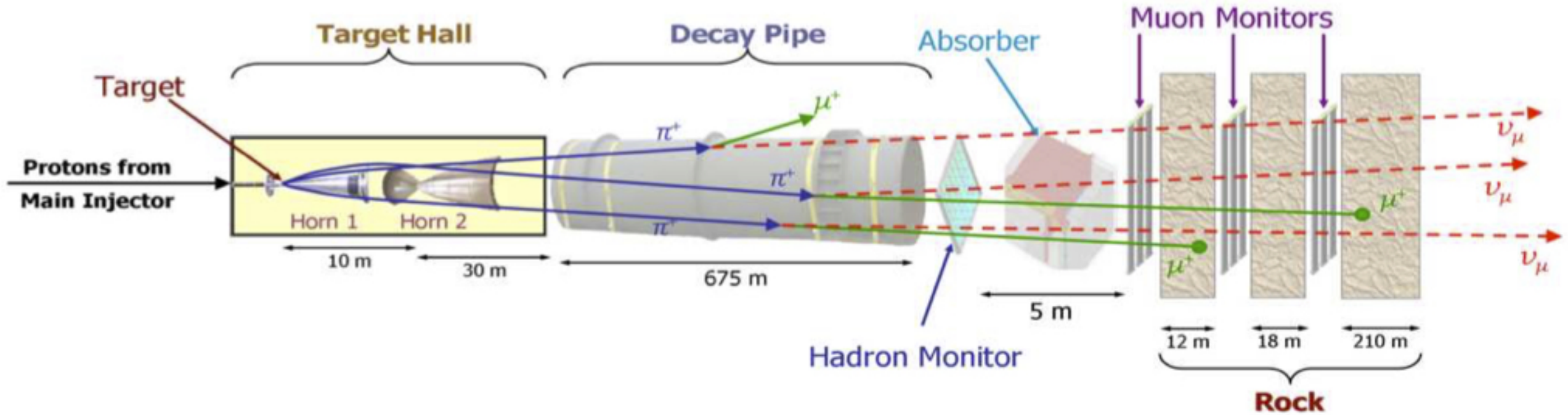
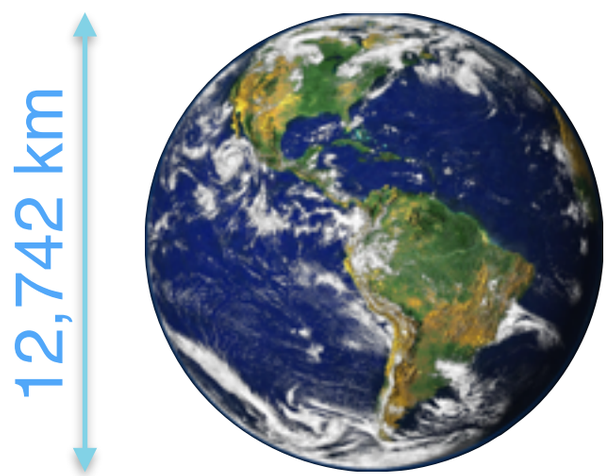


Difficulty 2: Most useful neutrino energies: 0.4 ~ 5 GeV scale

Produce muons: E_ν above 100 MeV

Δm^2 L/E = 1 implies L/E = 400 km/GeV



Neutrino-electron scattering cross section is too small for our needs

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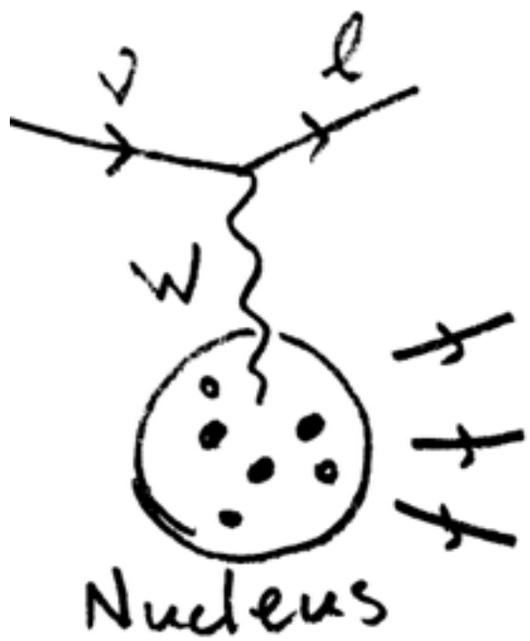
Case 1: Neutrino energy and precision oscillation physics

What do we measure?

Detector dependent but

- Charged leptons
- Charged hadrons
- Sometimes the presence of neutrons



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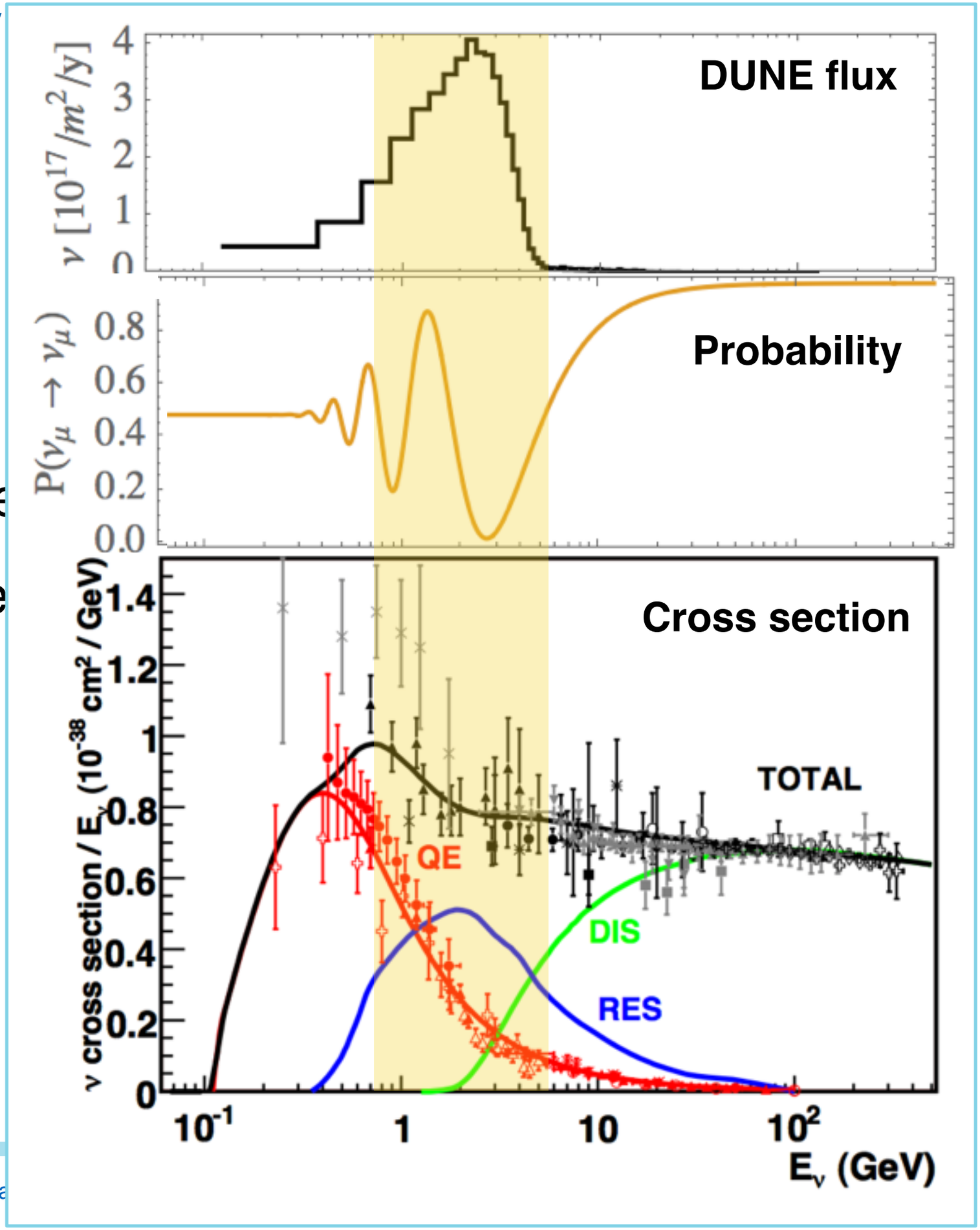

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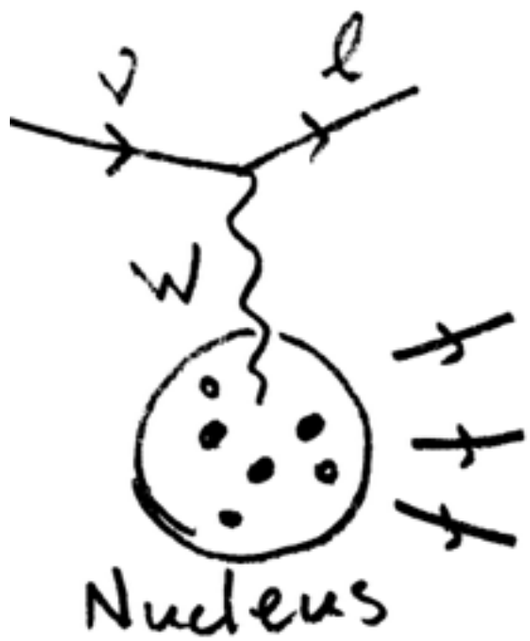

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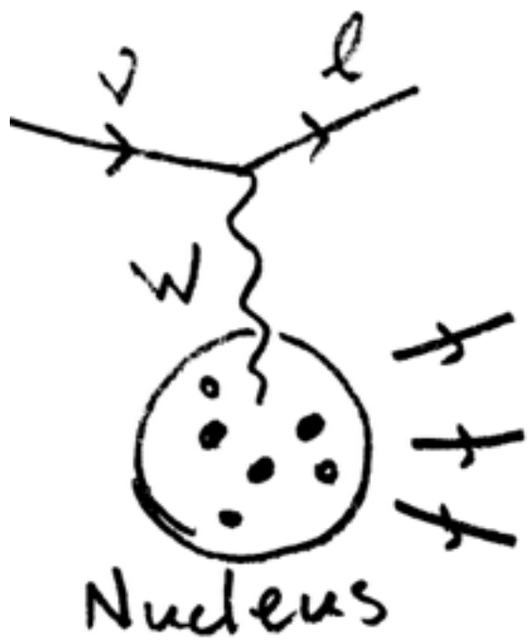

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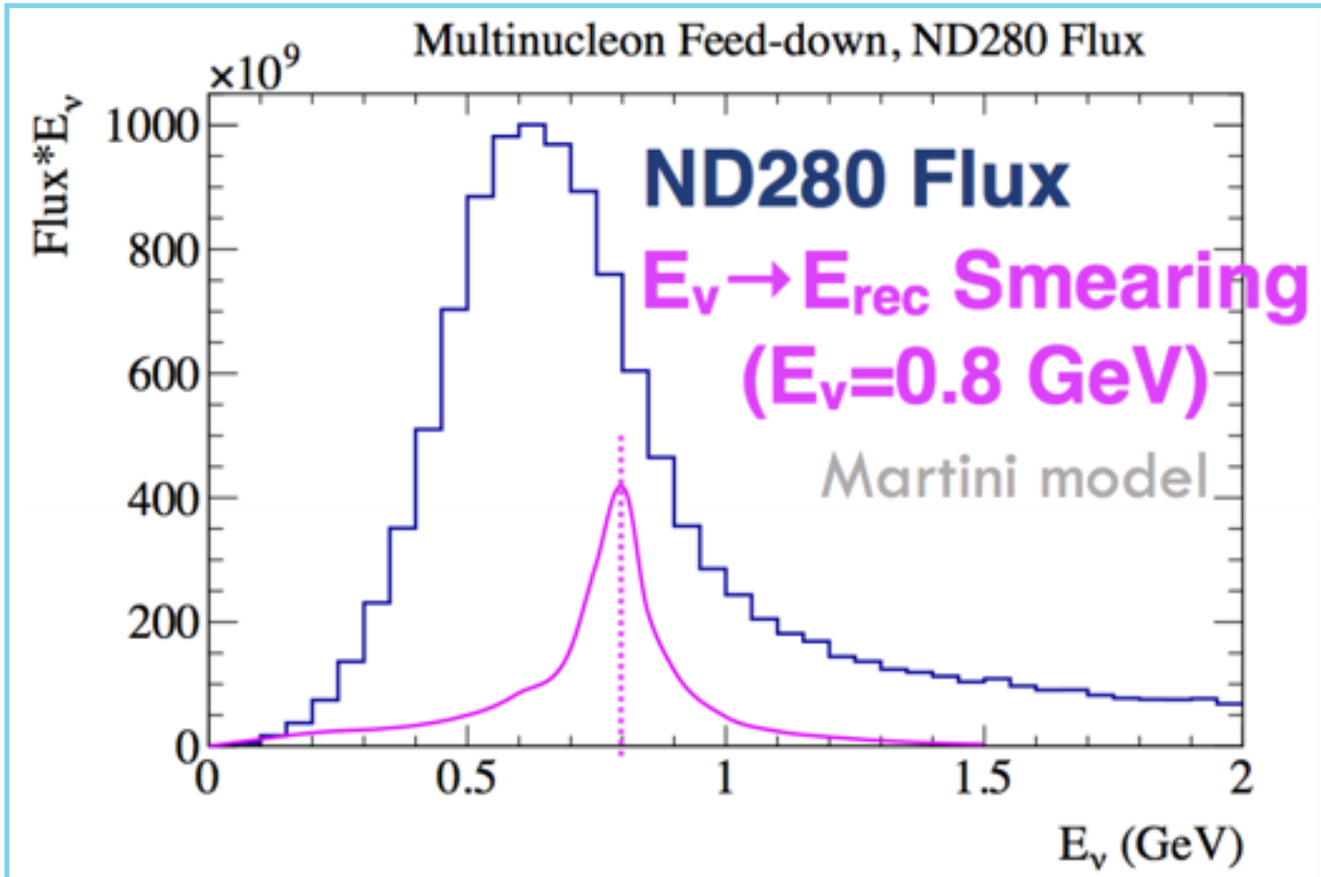
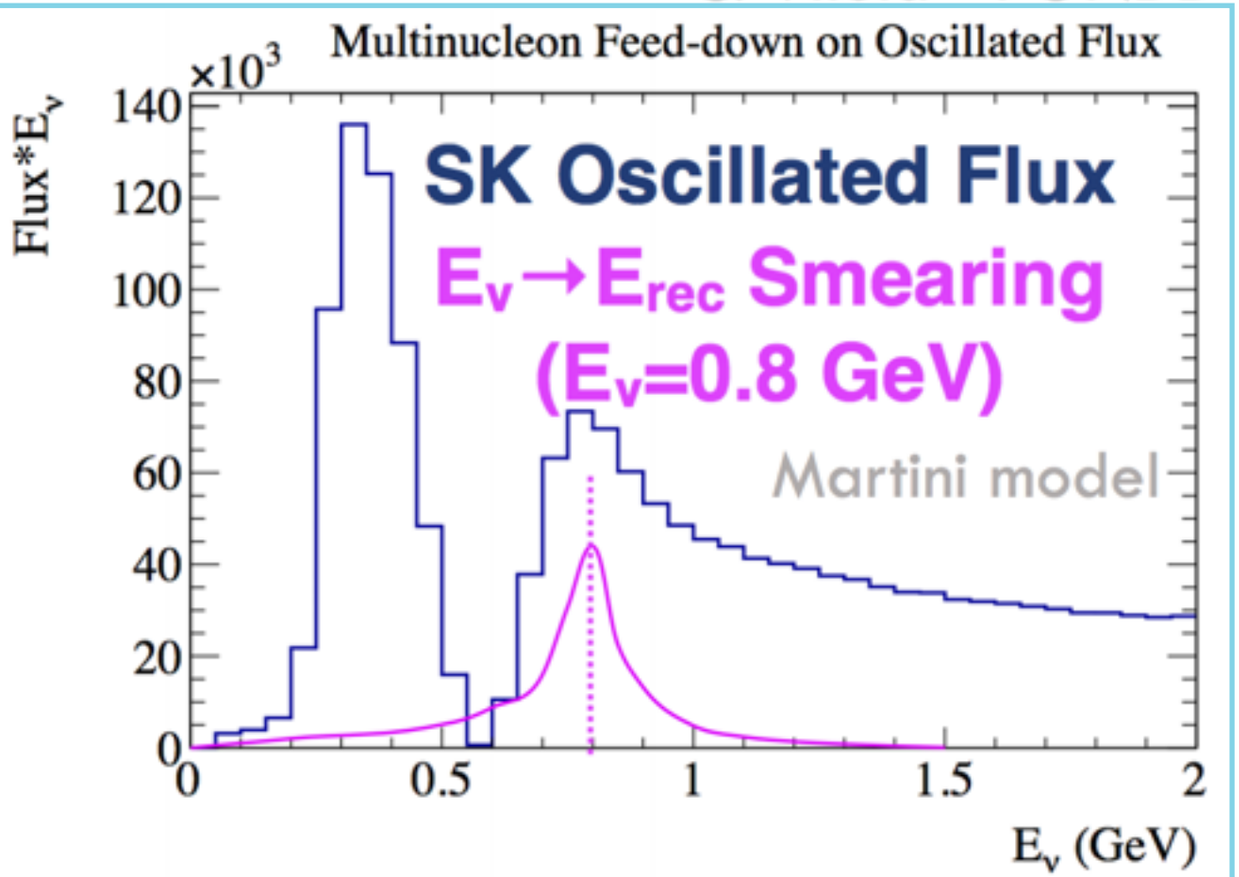
C. Vilela - PONDD





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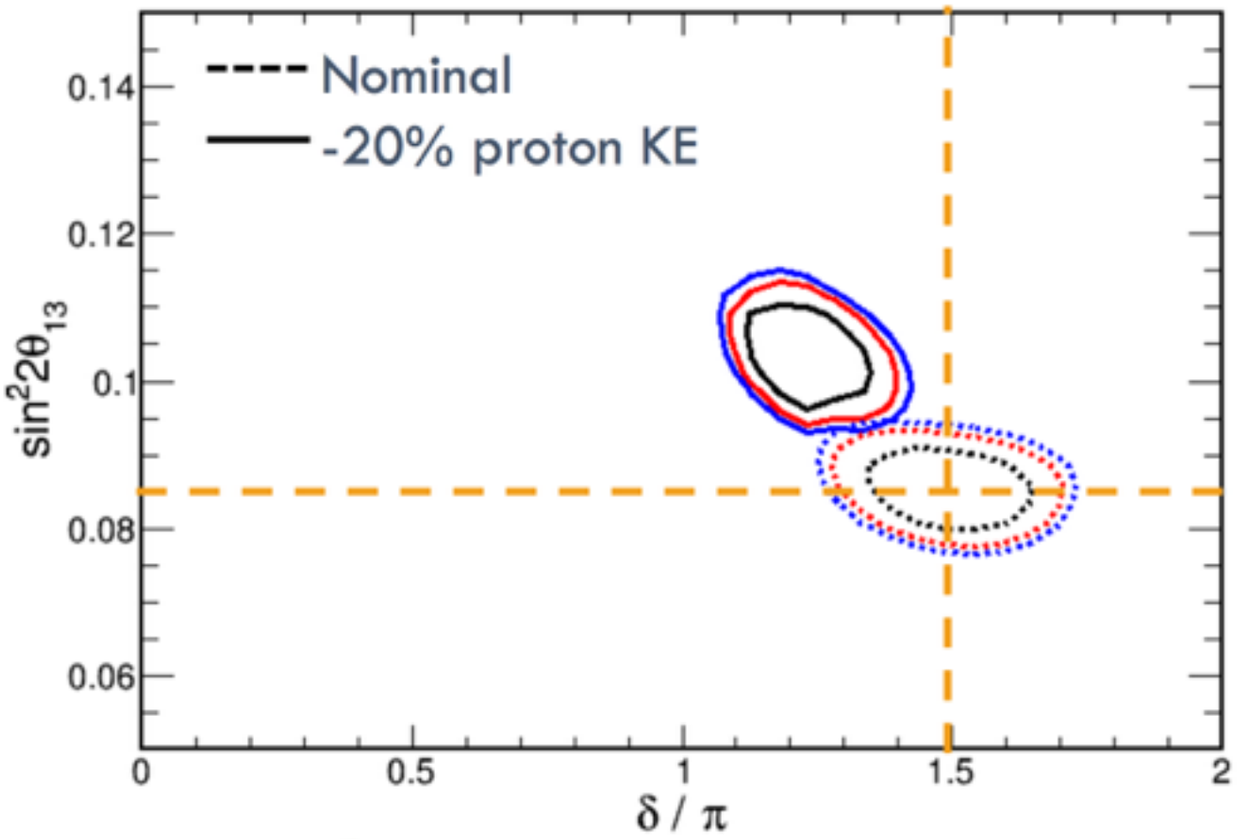

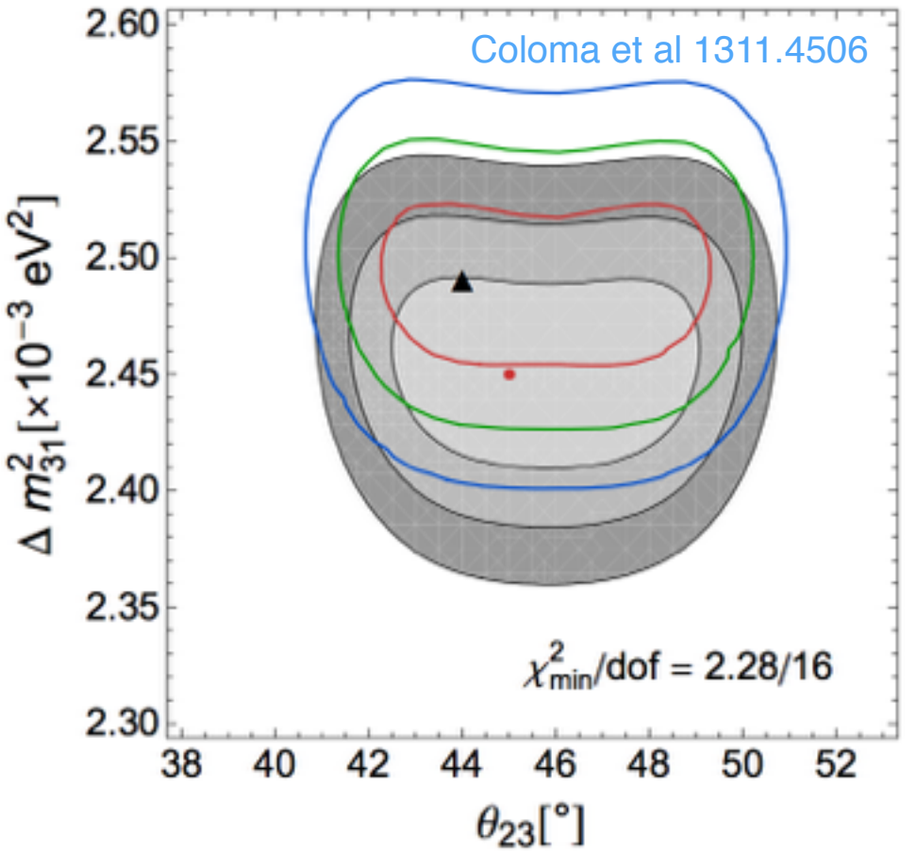

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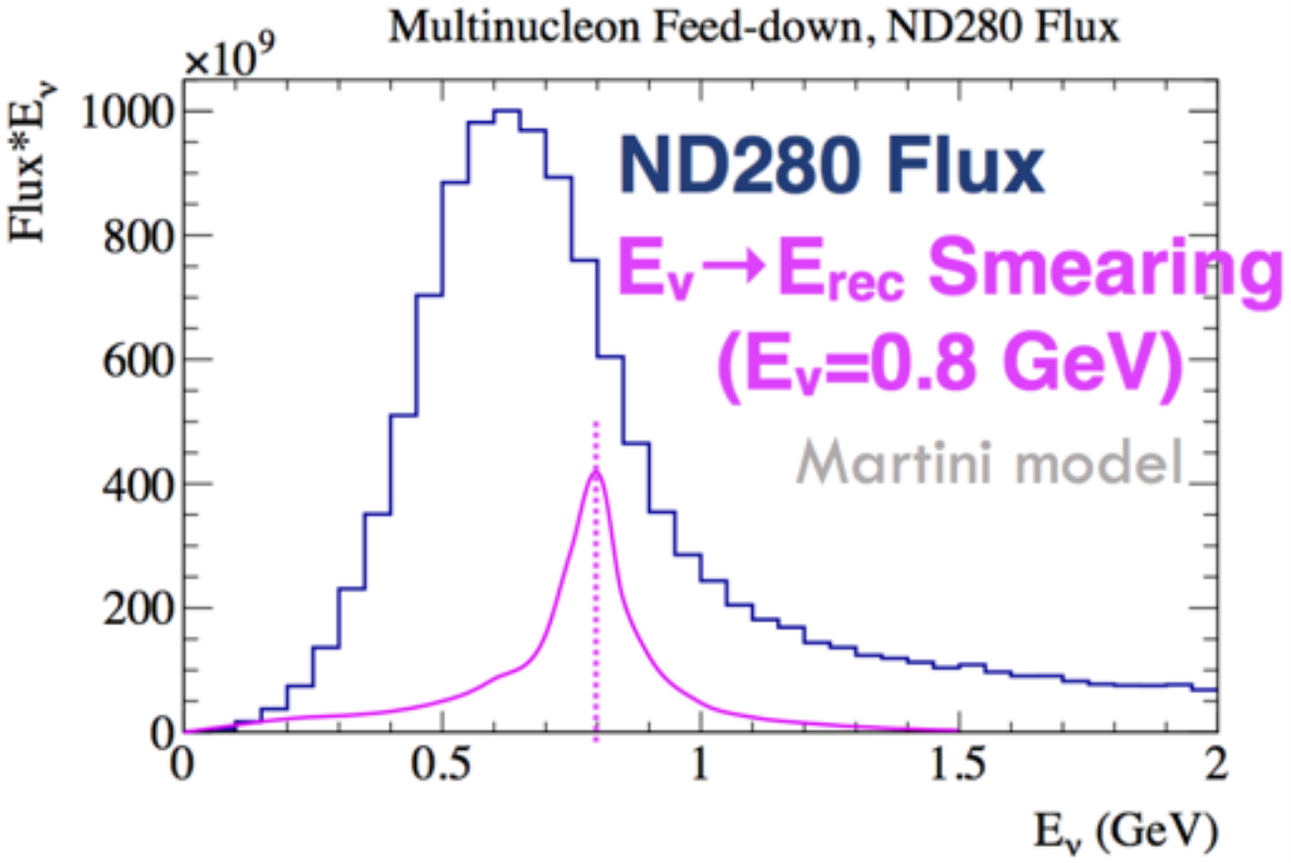

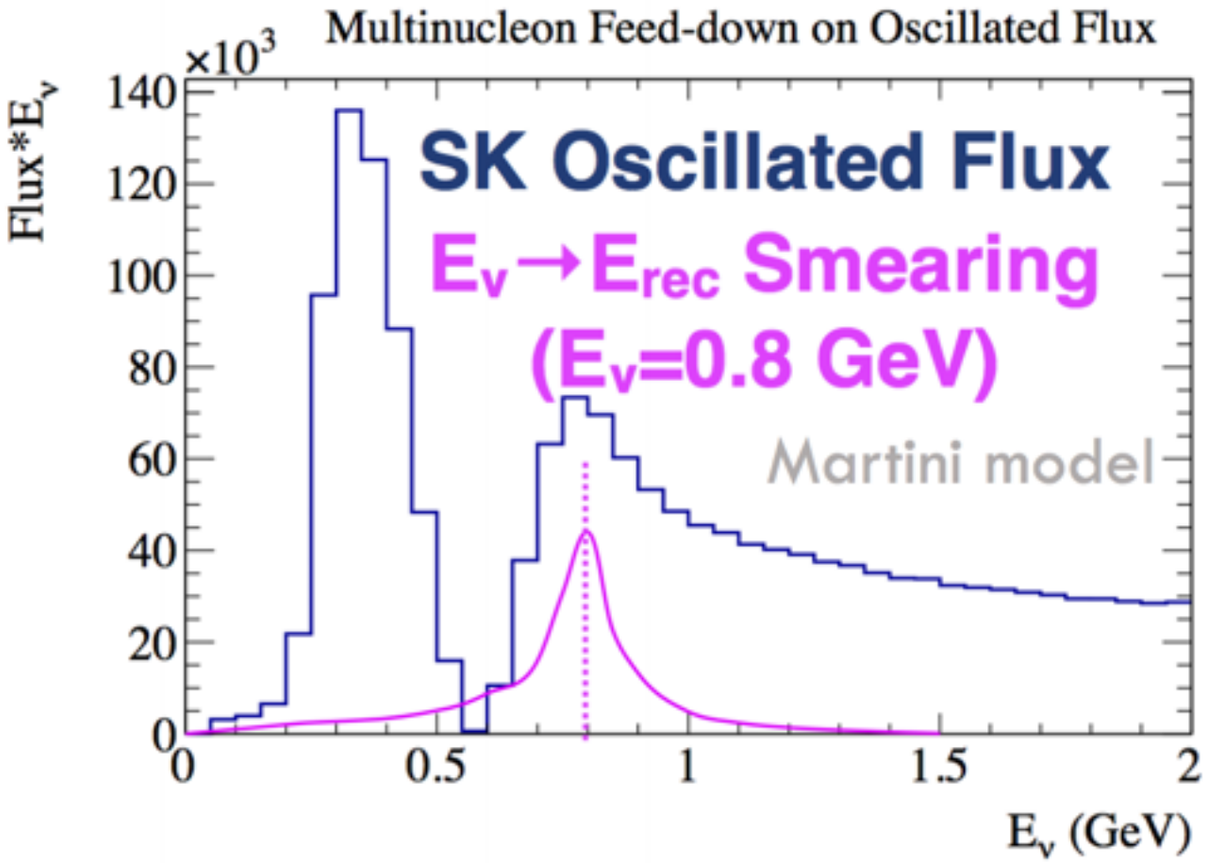

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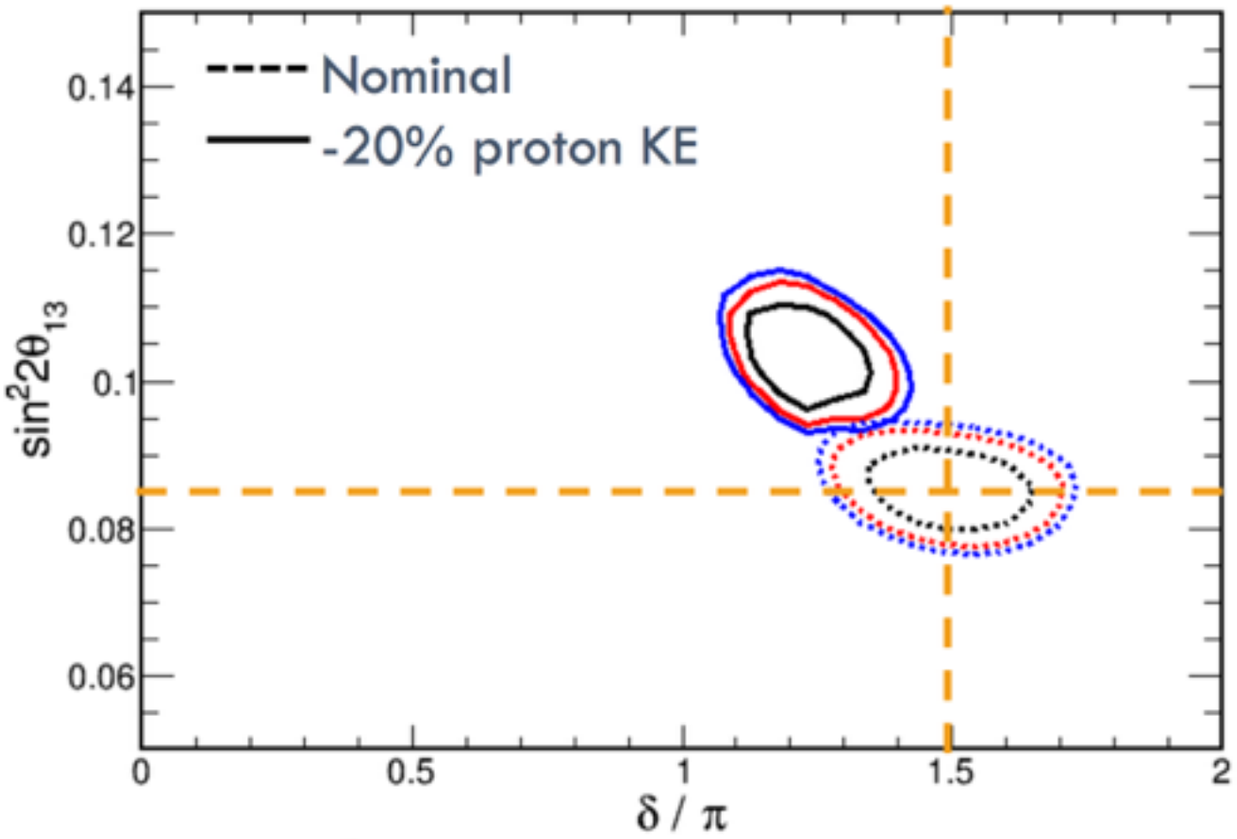
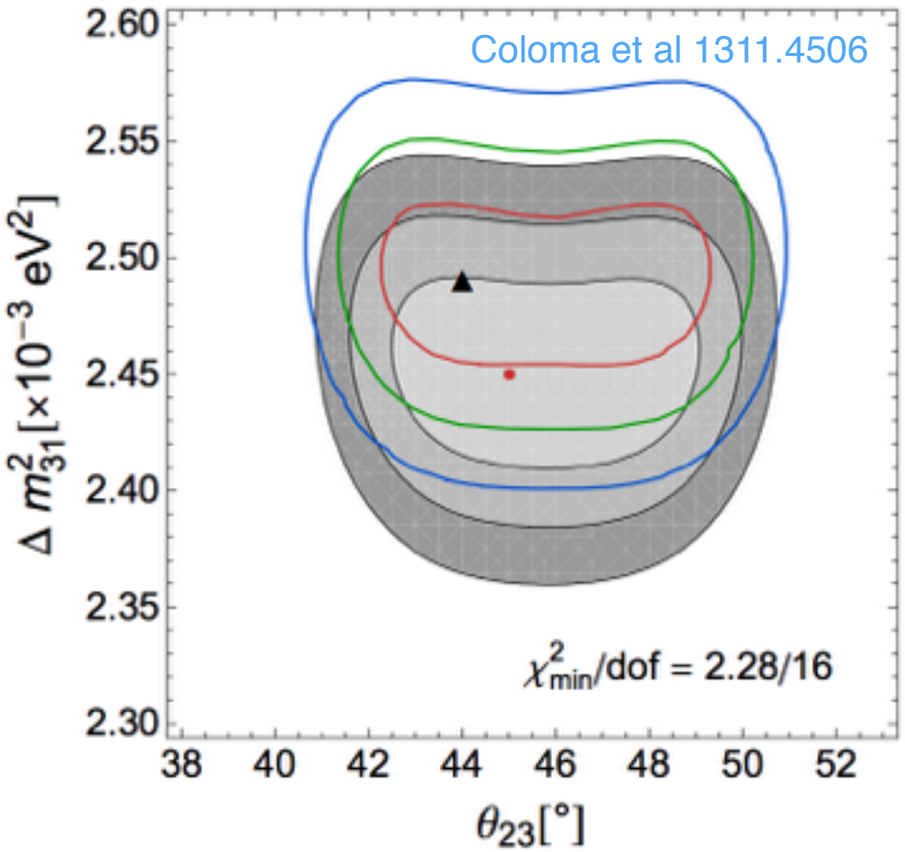
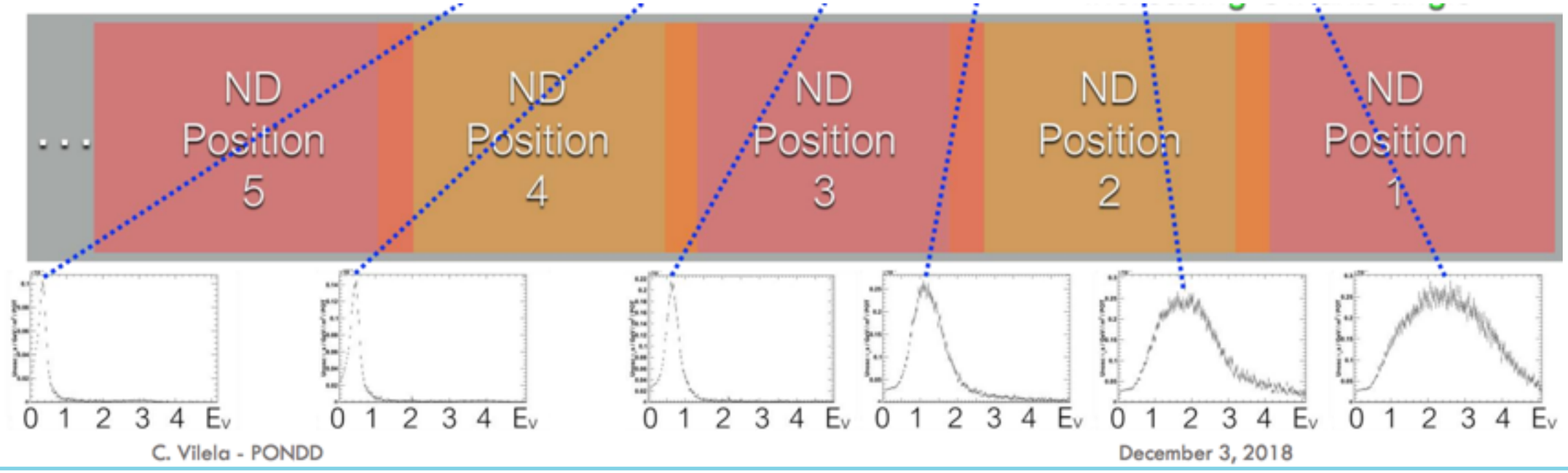




DUNE-PRISM concept: movable near detector to disentangle neutrino interaction effects from the neutrino flux



Case 1: Neutrino energy and precision oscillation physics

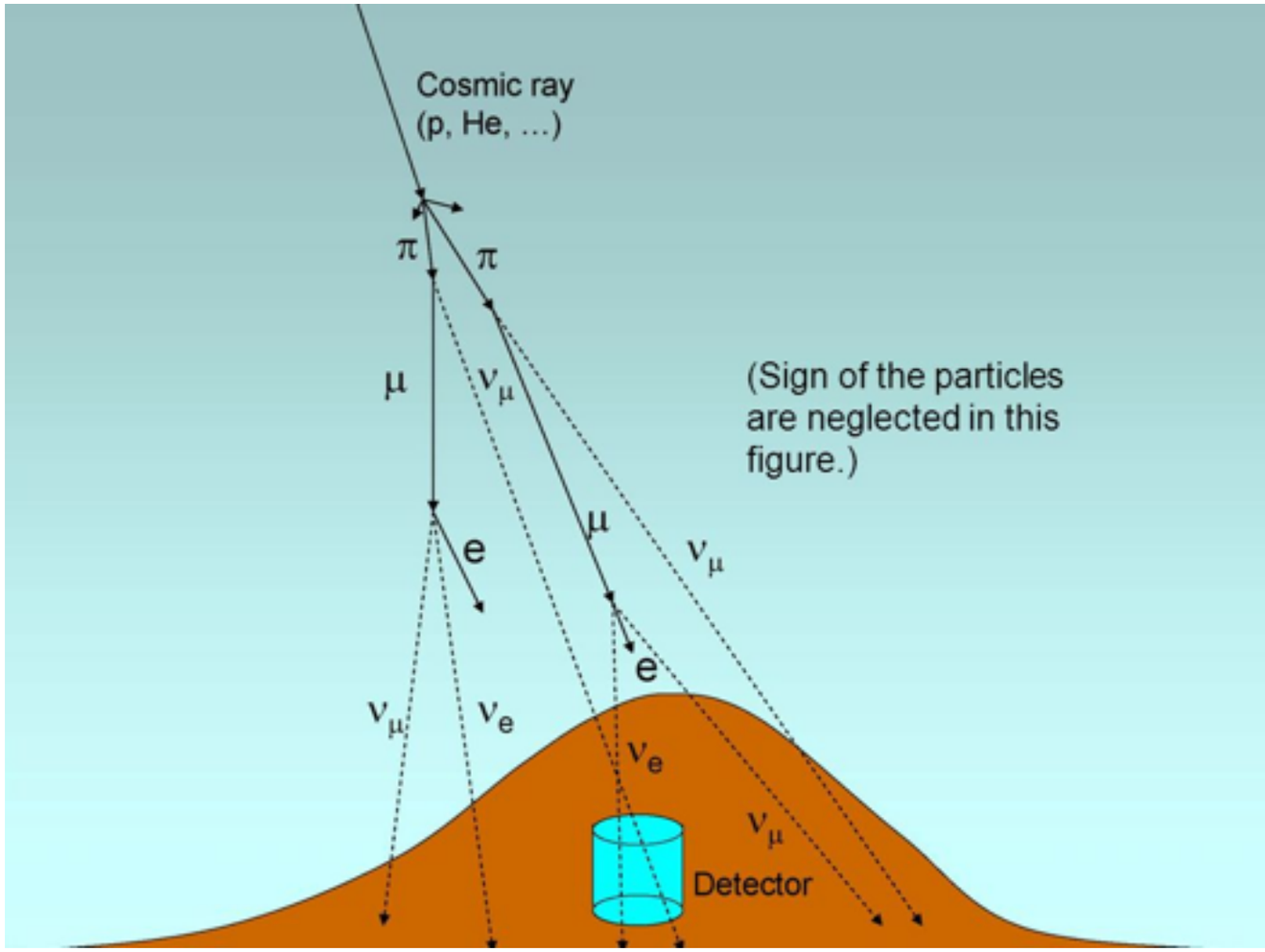
Uncertainties on neutrino interactions will play an important role on the precision neutrino physics program

Mis-modeling neutrino interactions can lead to **wrong results**

Wish list:

- Characterize impact of neutrino interaction uncertainties on oscillation parameter measurement. What exactly do we need to know/calculate?
- Systematically evaluate the impact of DUNE-PRISM. How much can we rely on it?

Case 2: Neutrino direction and atmospheric neutrinos



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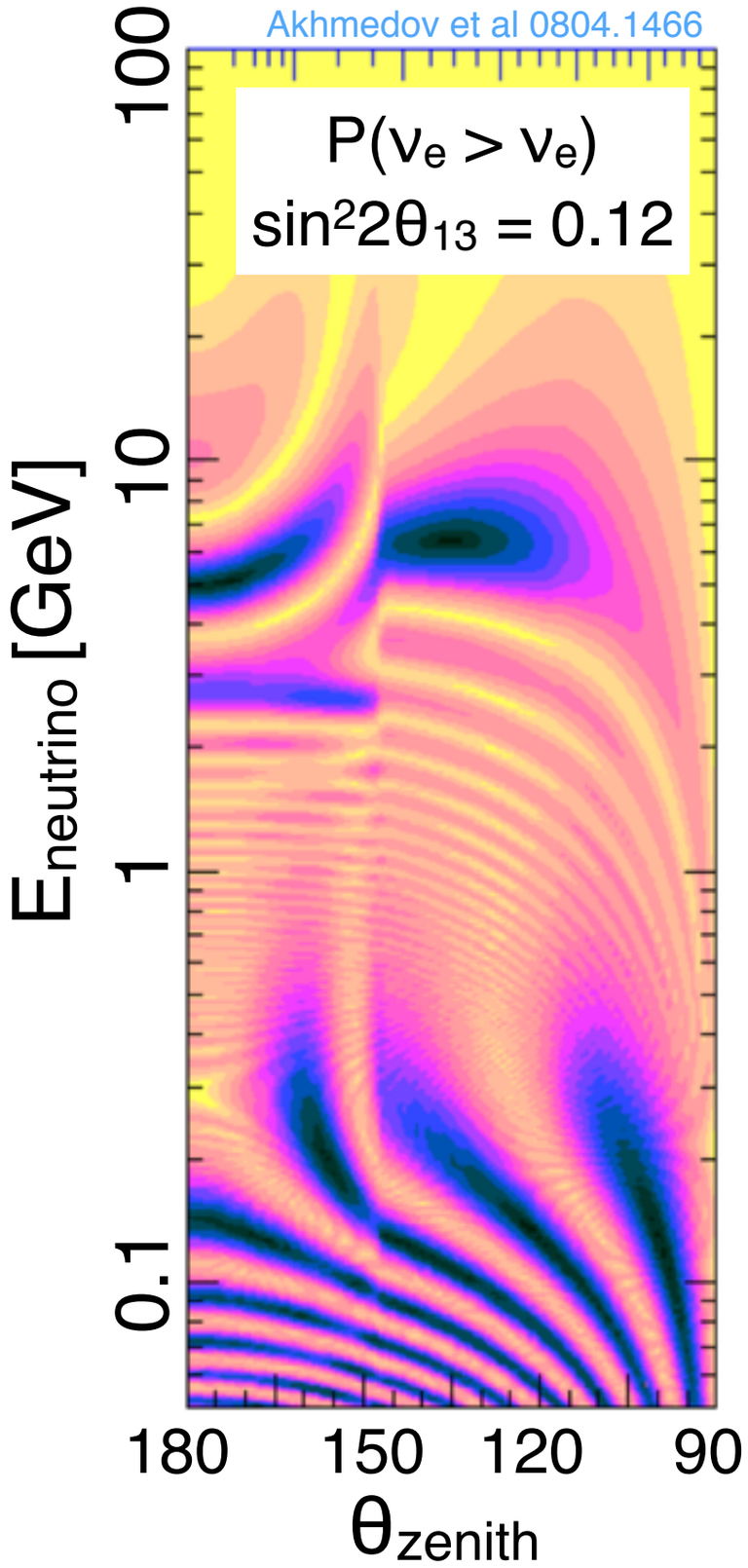

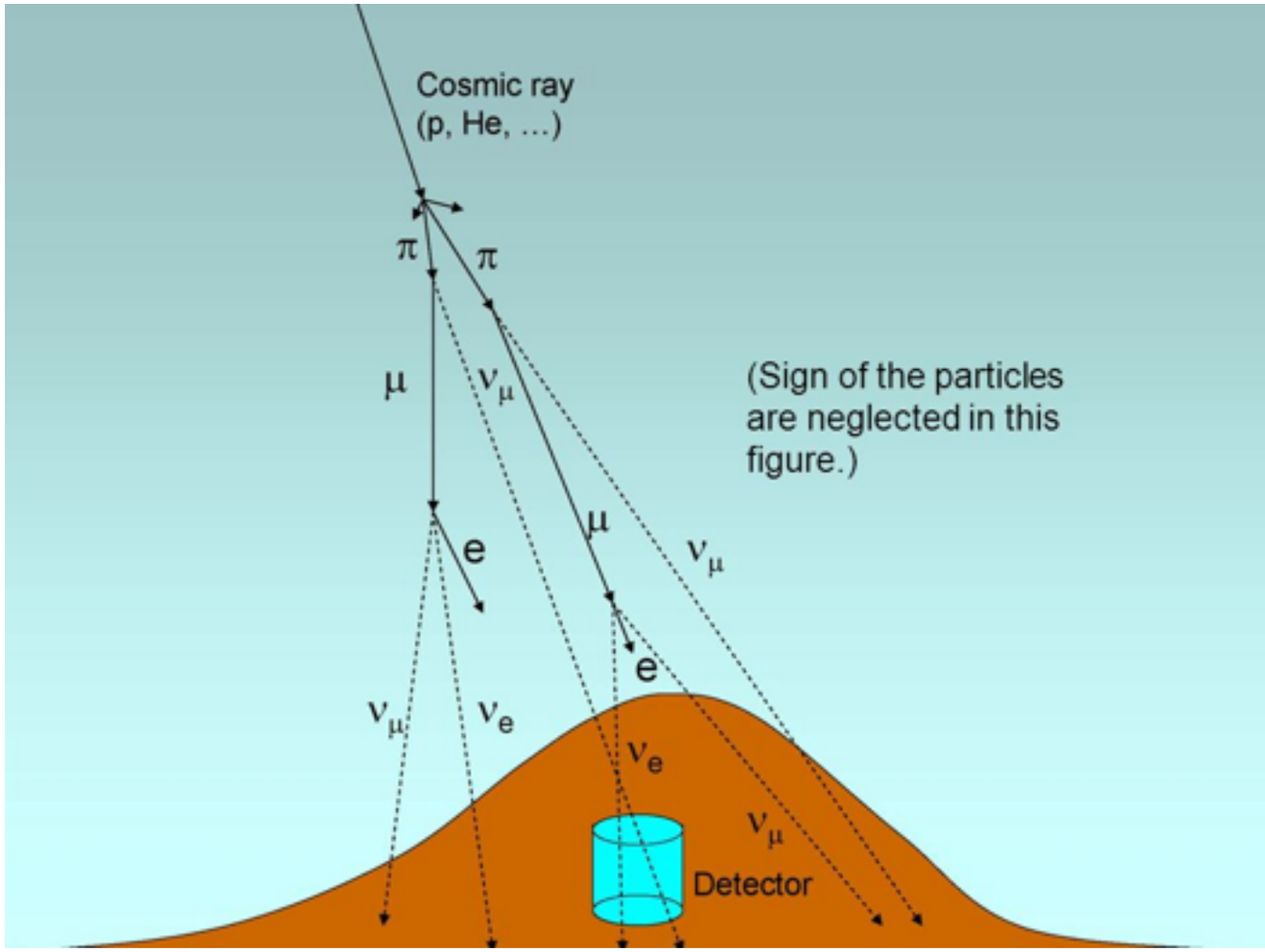

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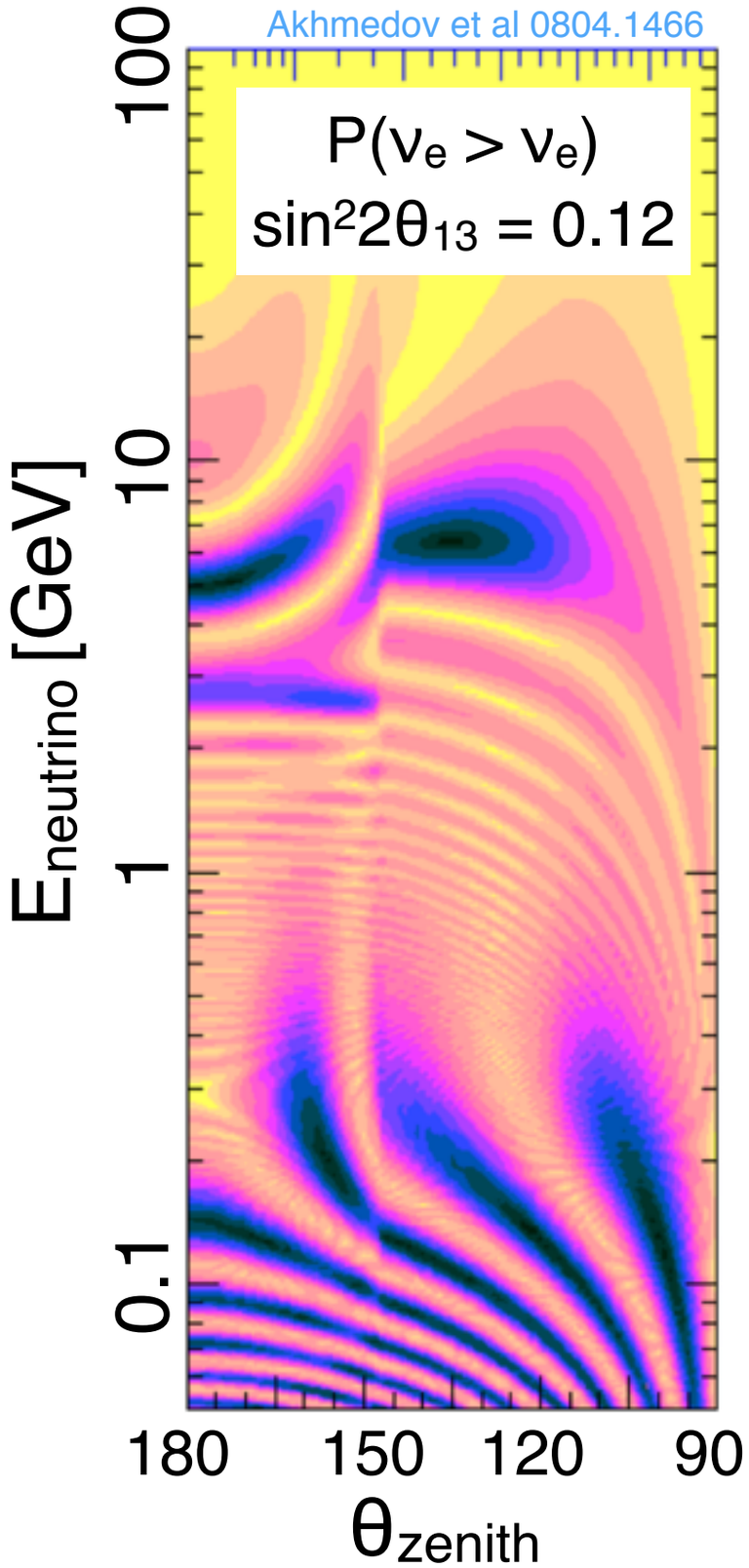

MSW resonance condition

$$\Delta m^2 \cos\theta = 2\sqrt{2} E_\nu G_F n_e$$

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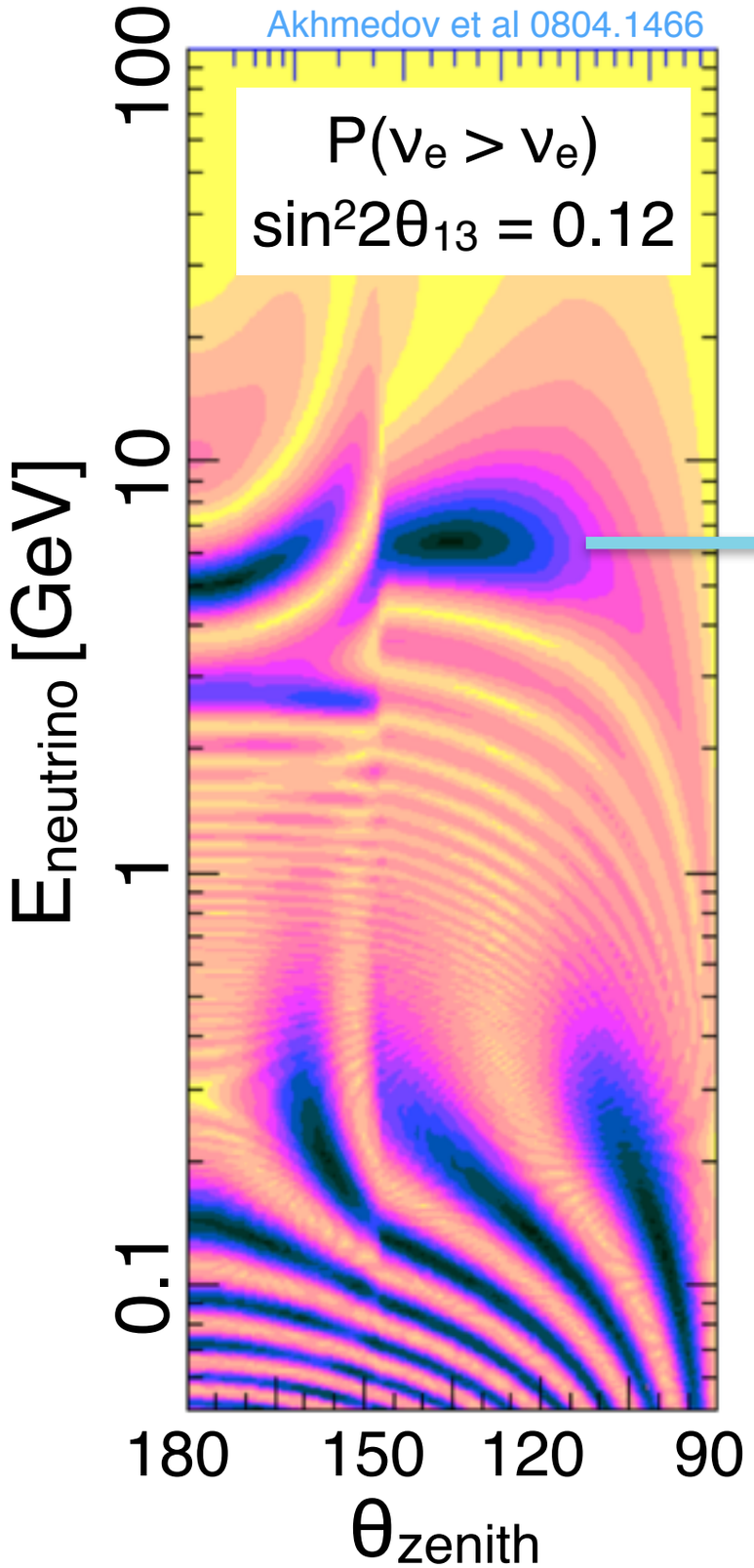

MSW resonance condition

$$\Delta m^2 \cos\theta = 2\sqrt{2} E_\nu G_F n_e$$

MSW resonance (Δm^2_{31}):

– mass ordering, small CP effect

– broad zenith, needs E_ν

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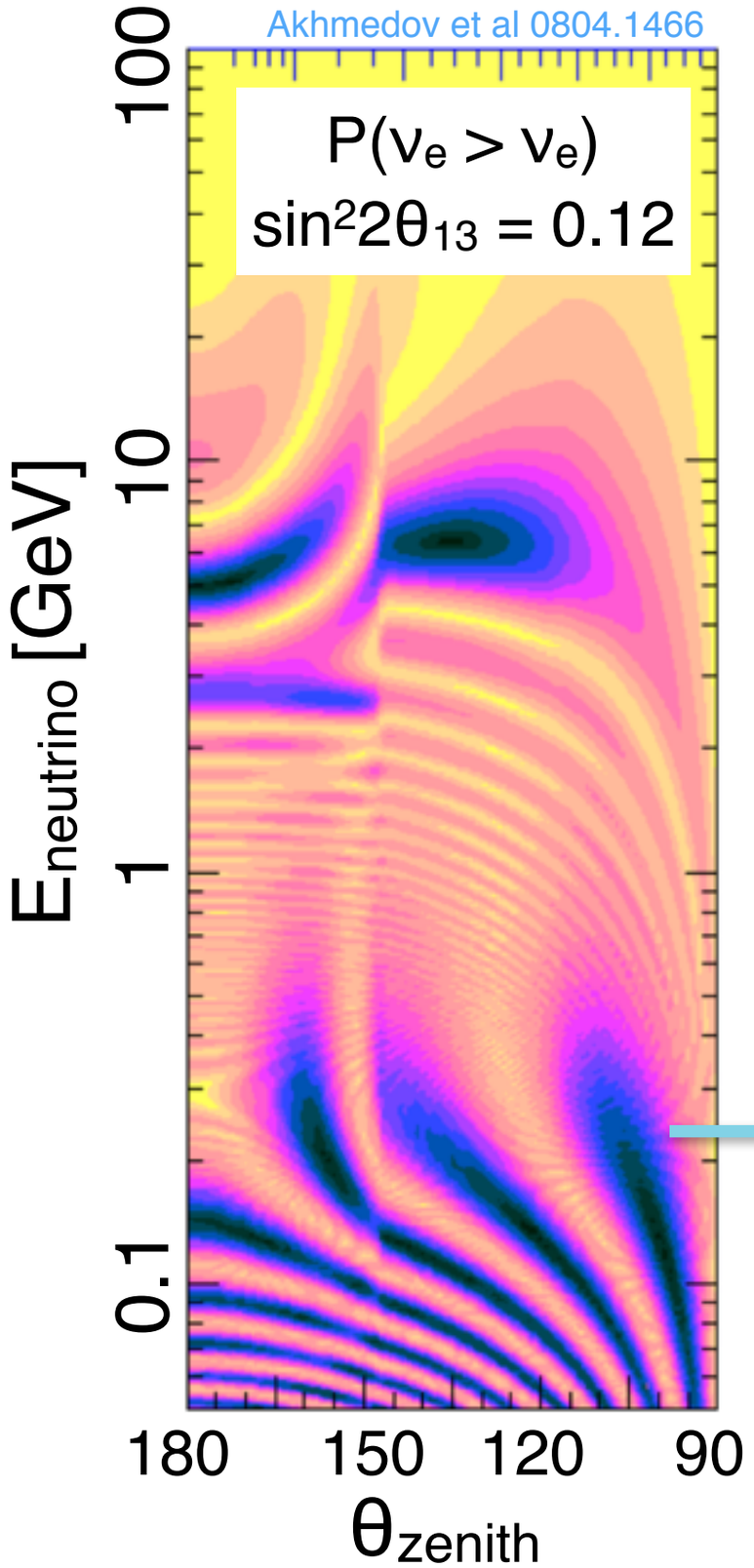

MSW resonance (Δm^2_{21}):

– Solar splitting, large CP effect

– broad E_ν, needs pointing

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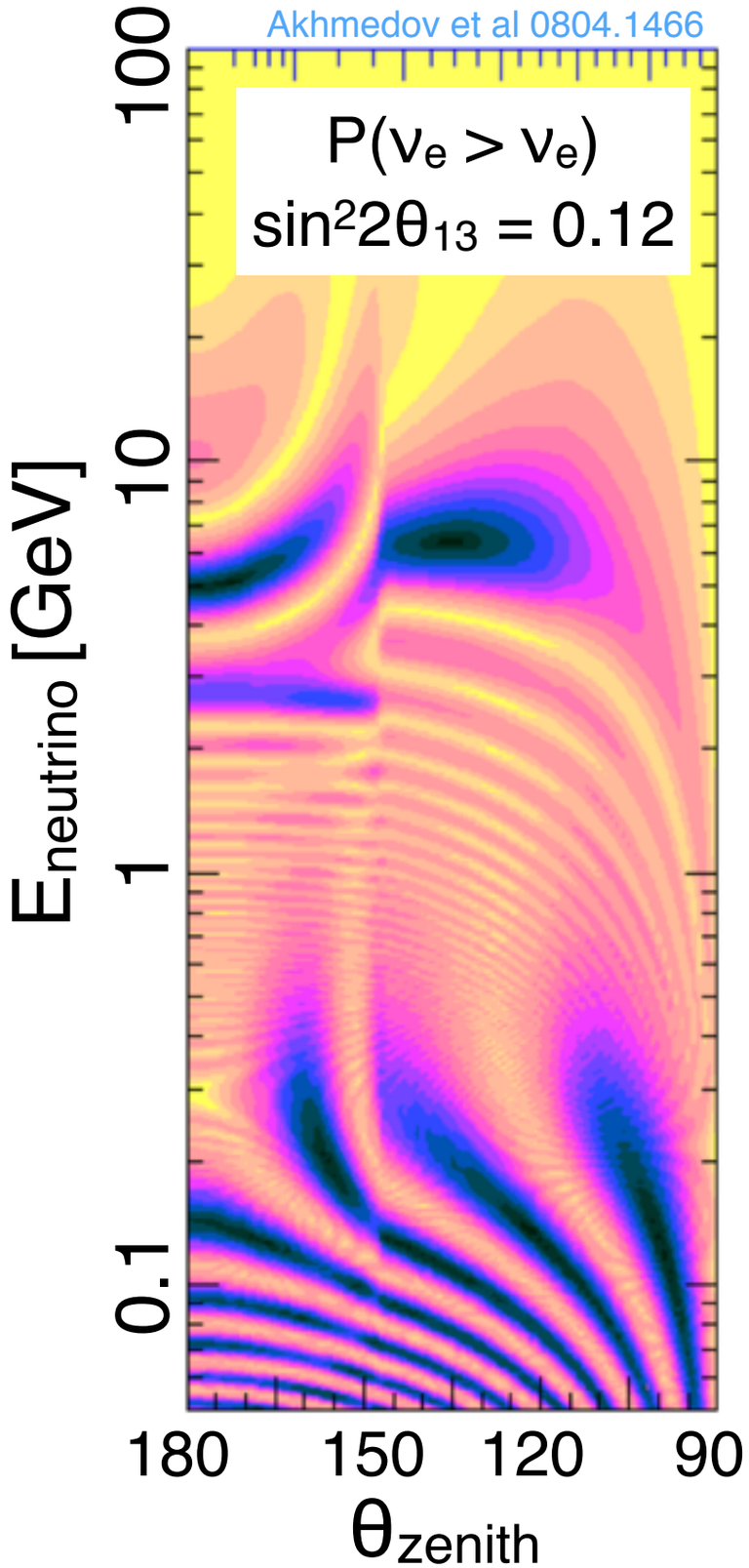
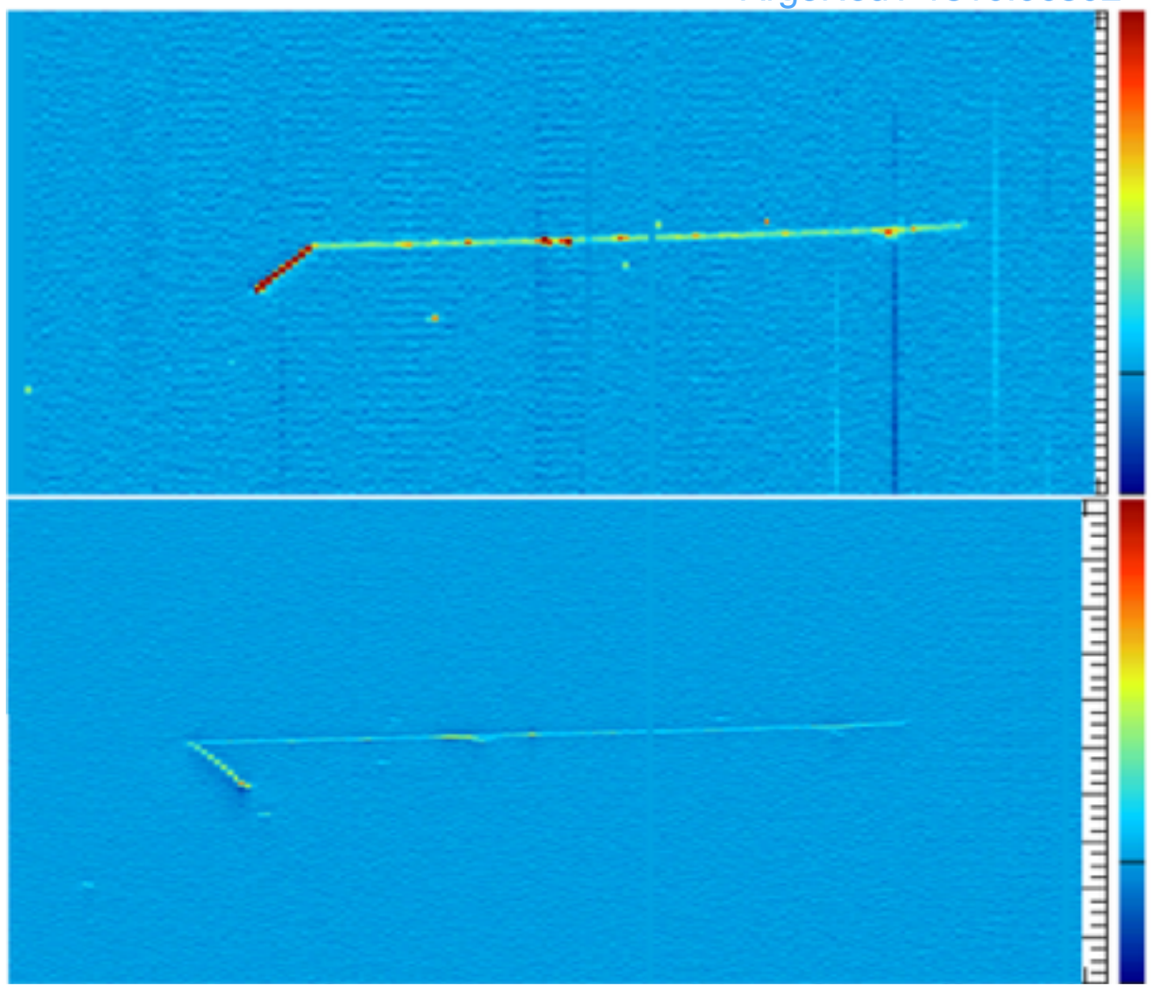


LArTPCs are ideal for the low energy:

– Low thresholds ($K_p > 21$ MeV in ArgoNeuT!)

– Detailed, 3D event reconstruction

ArgoNeuT 1810.06502



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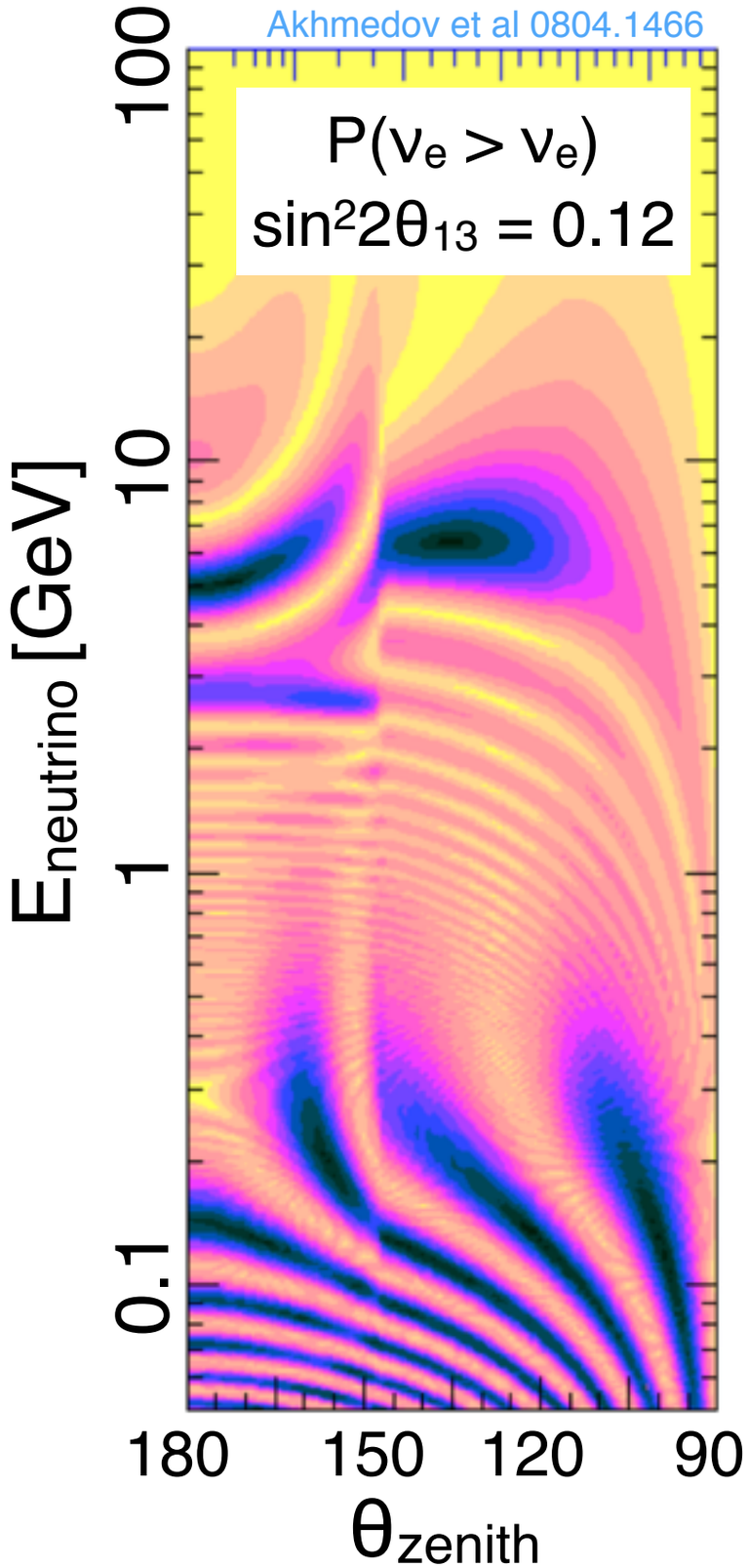
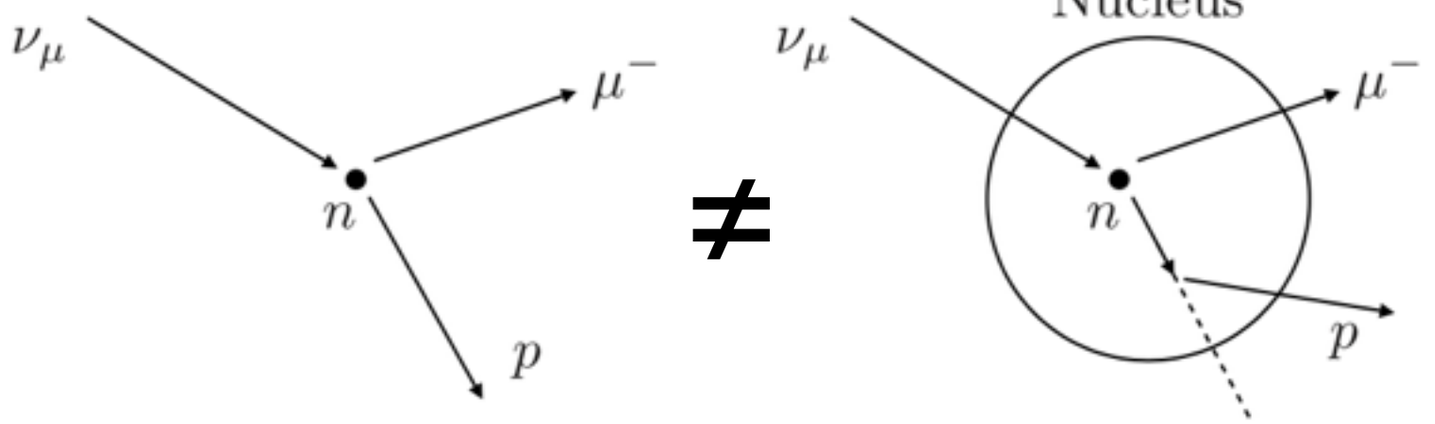
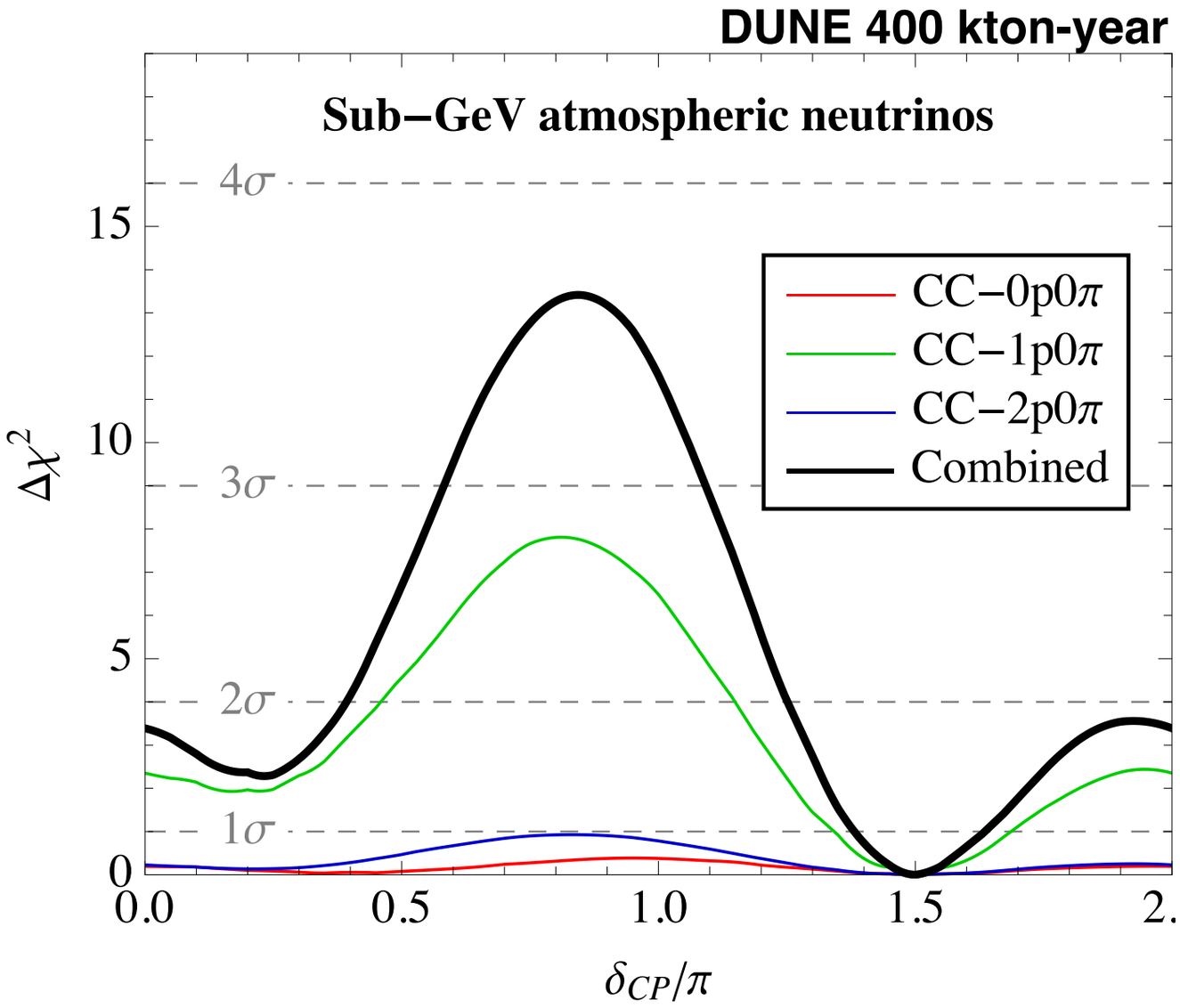


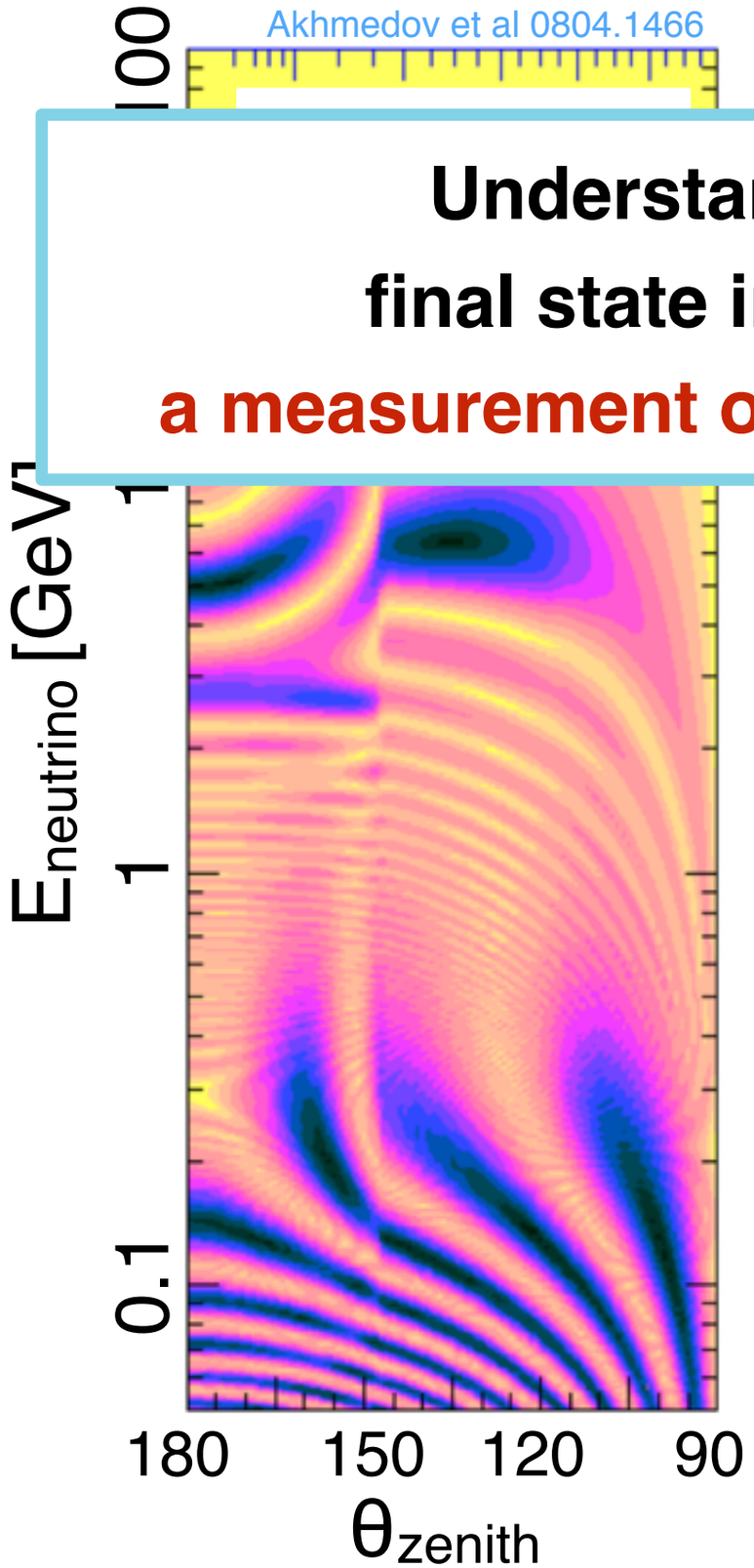


Kelly M Martines-Soler Parke Perez-Gonzalez 1904.02751



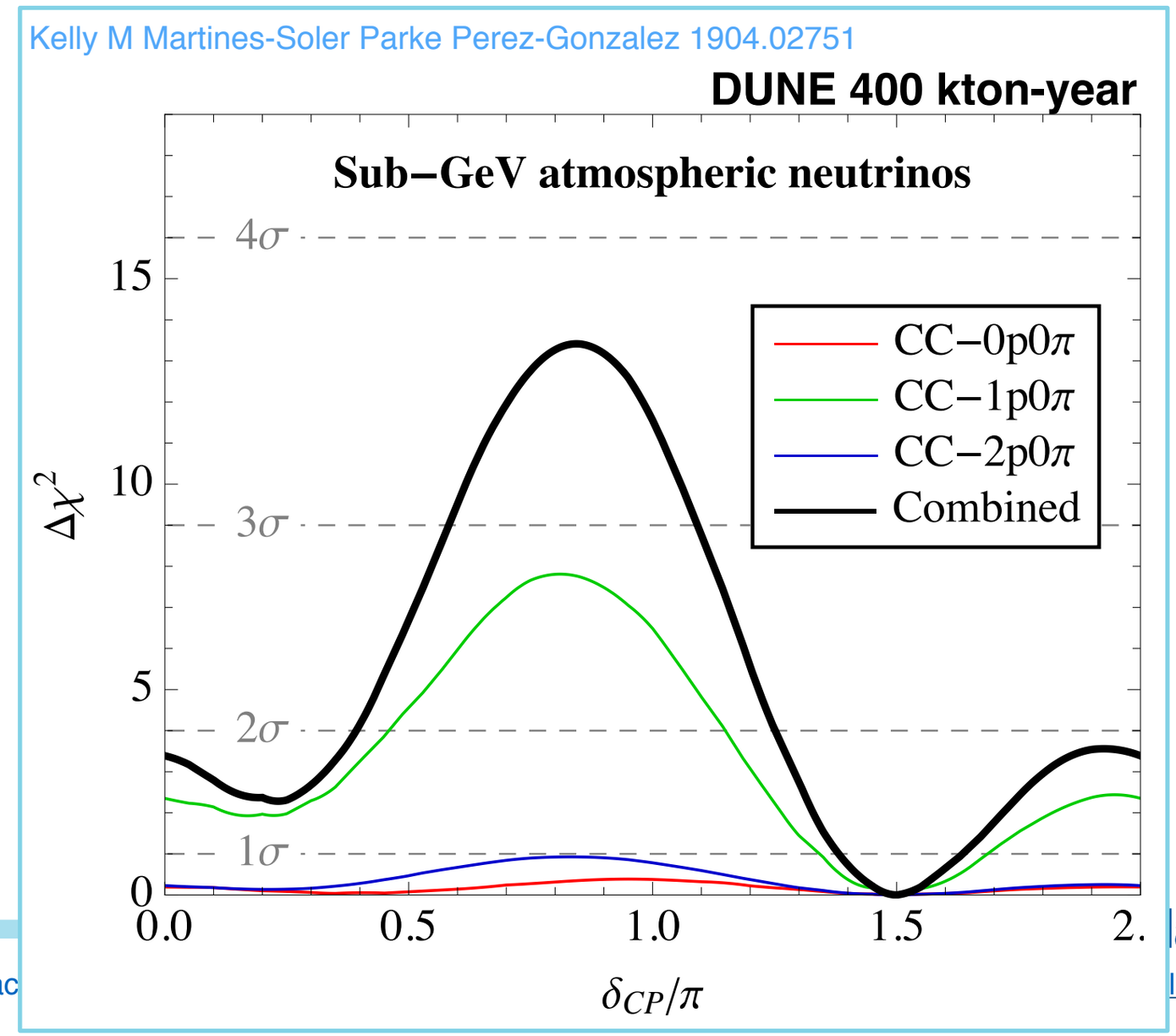
Case 2: Neutrino direction and atmospheric neutrinos

Akhmedov et al 0804.1466



Understanding nucleus ground state and final state interactions will be crucial to have a measurement of δ_{CP} independent from beam neutrinos

Kelly M Martines-Soler Parke Perez-Gonzalez 1904.02751



Case 3: SM backgrounds and new physics

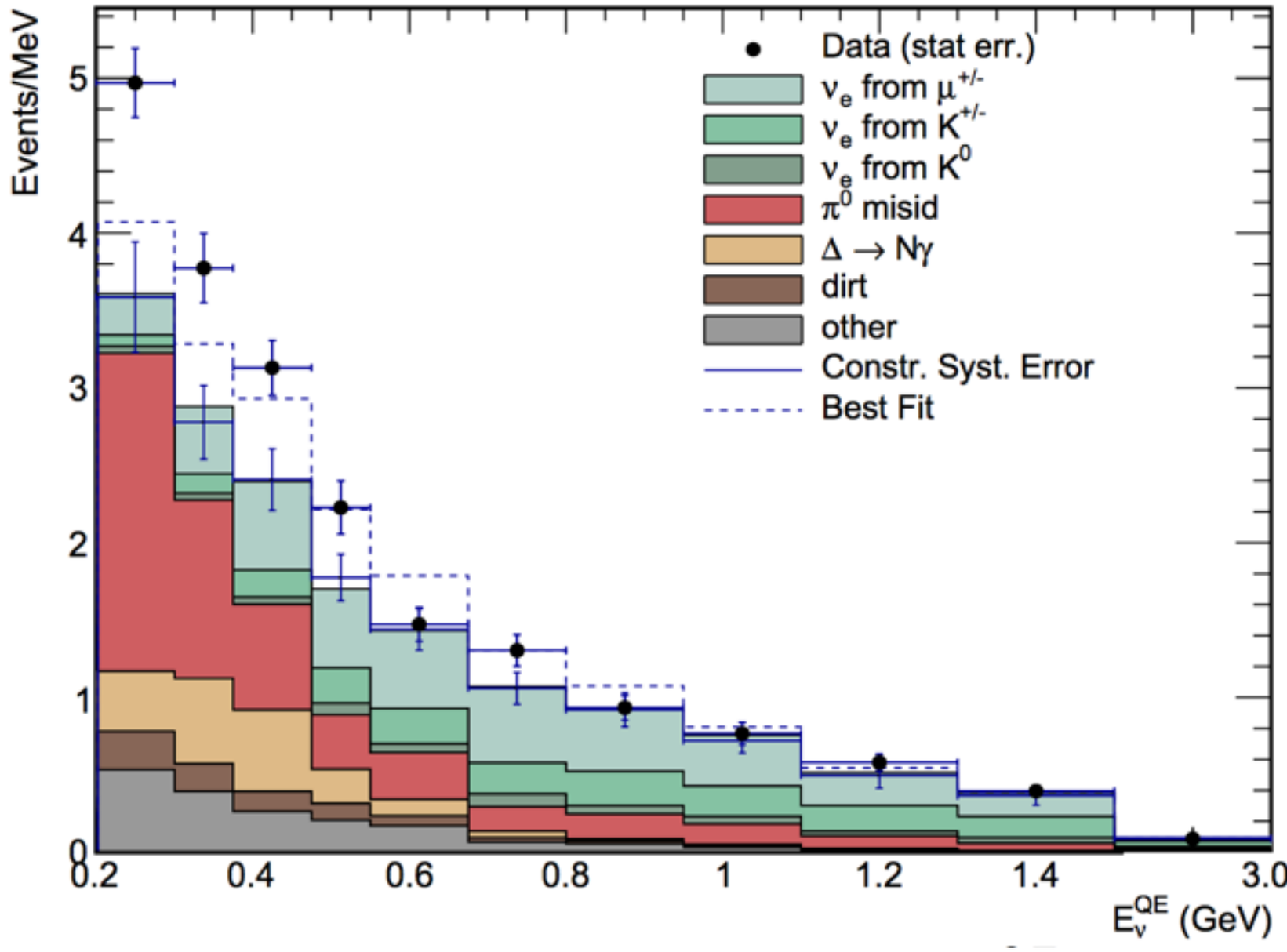
The MiniBooNE Collaboration

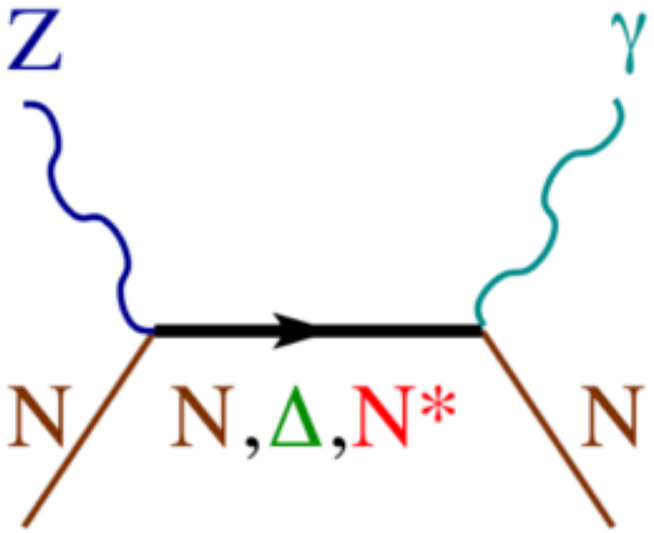
Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

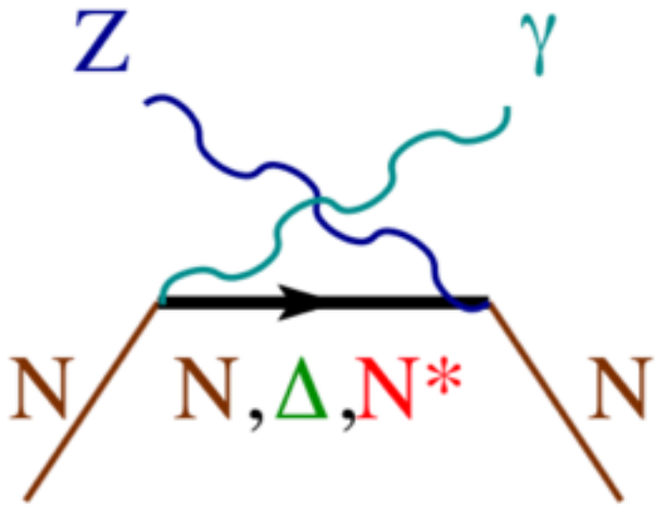
arXiv:1805.12028v1 [hep-ex] 30 May 2018

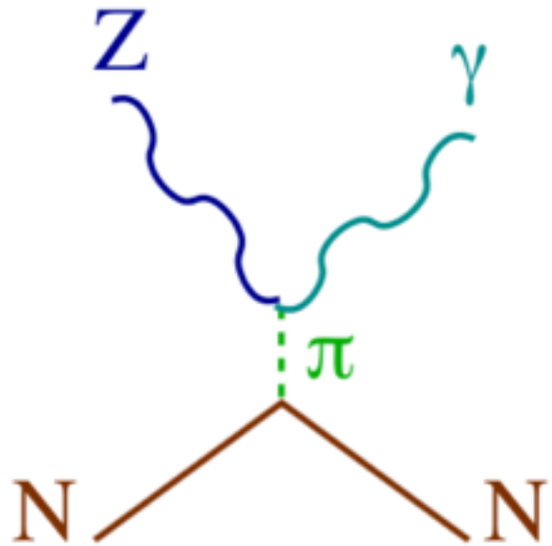
Double neutrino-mode data in 2016-2017 (6.46×10^{20} + 6.38×10^{20} POT)

Event excess: 381.2 ± 85.2 (4.5σ)

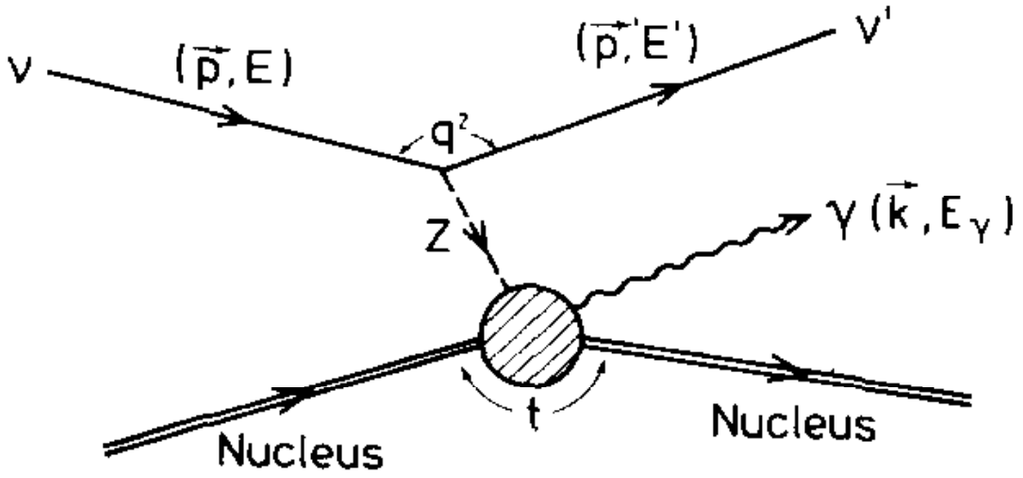




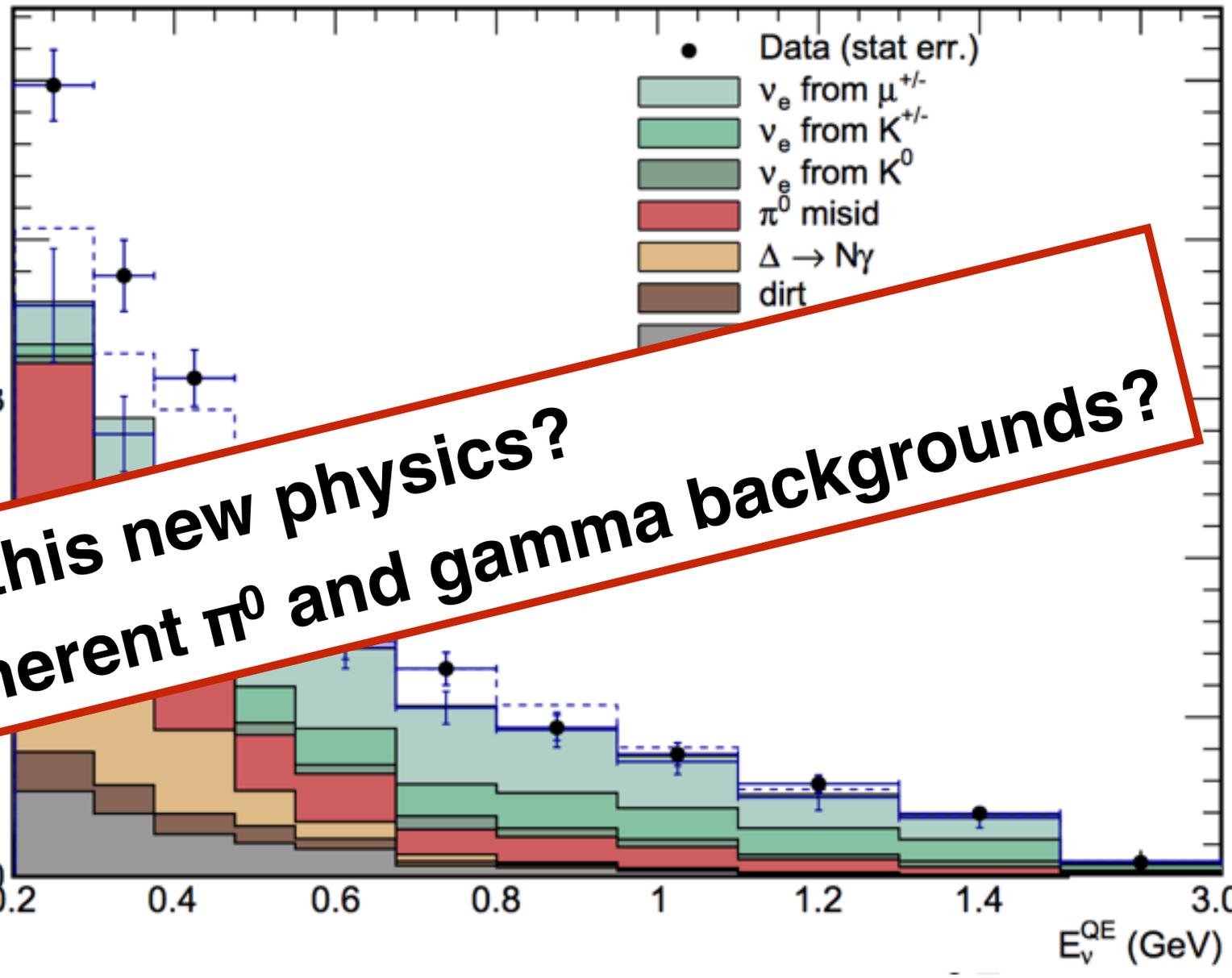




BooNE



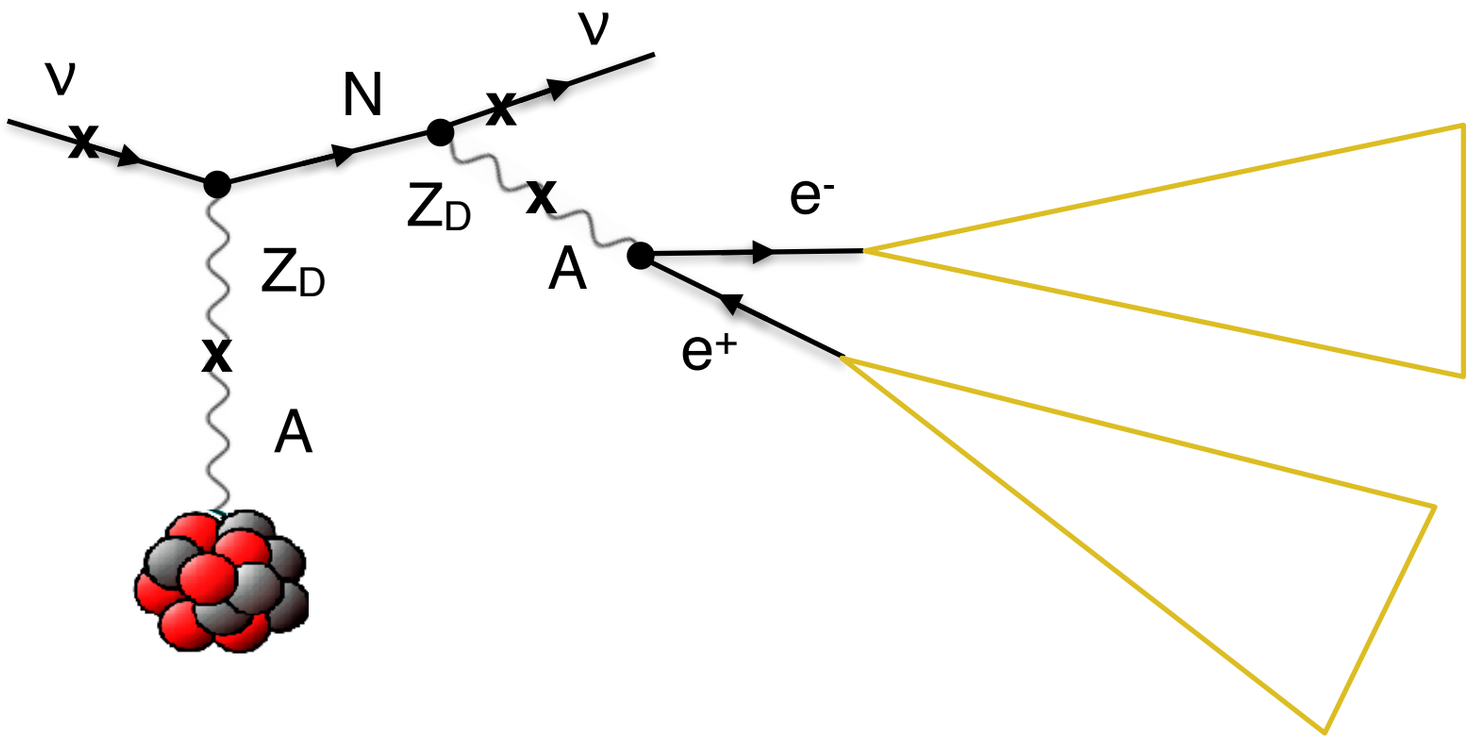
see e.g.
Rein Sehgal 1981
Alvarez-Ruso Nieves Wang 2015



Is this new physics?

What about e.g. coherent π^0 and gamma backgrounds?

Case 3: SM backgrounds and new physics



Mixing mixing mixing:

1) N has new interaction (Z_D)
2) N mixes with ν, ν gets new interaction
3) Z_D mixes with photon, now all charged particles acquire tiny Z_D charge

Bertuzzo Jana M Zukanovich 1807.09877

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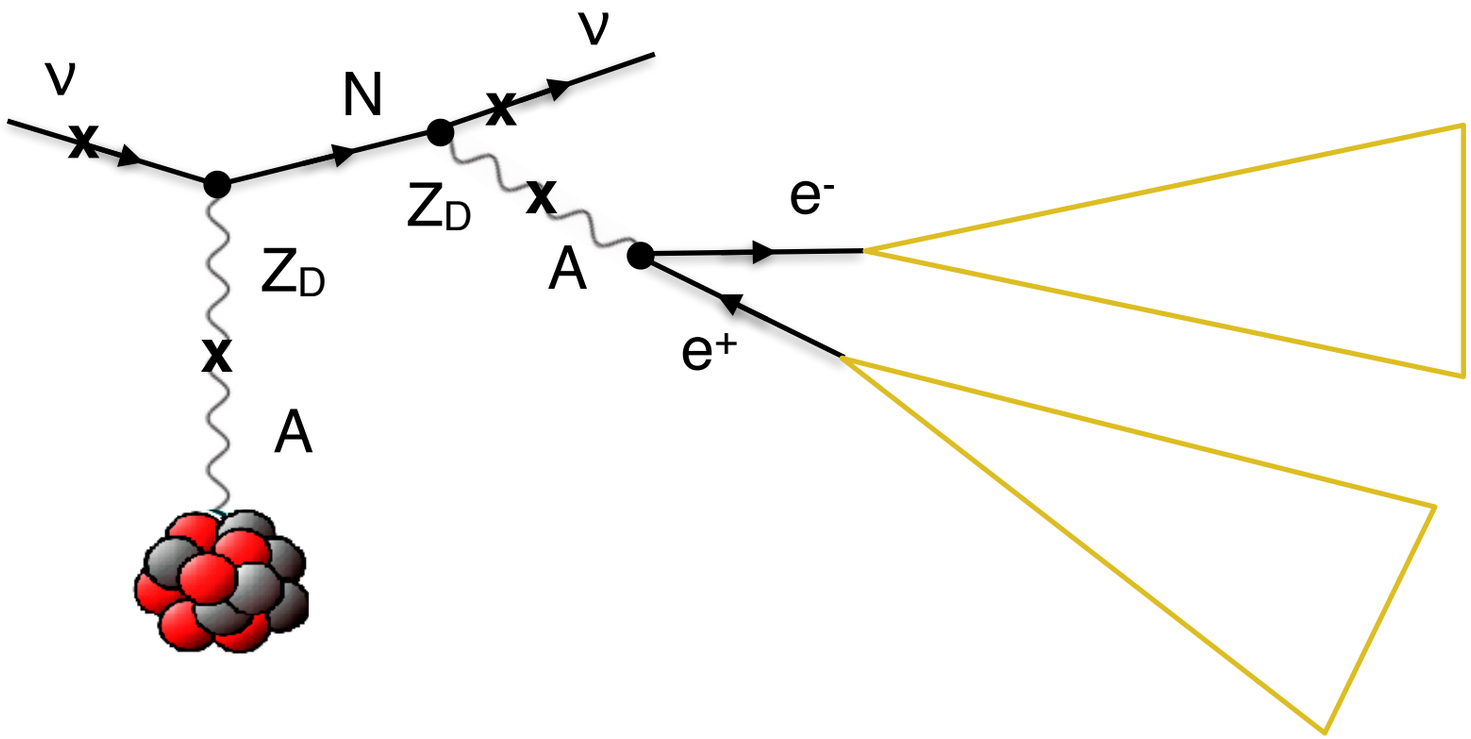

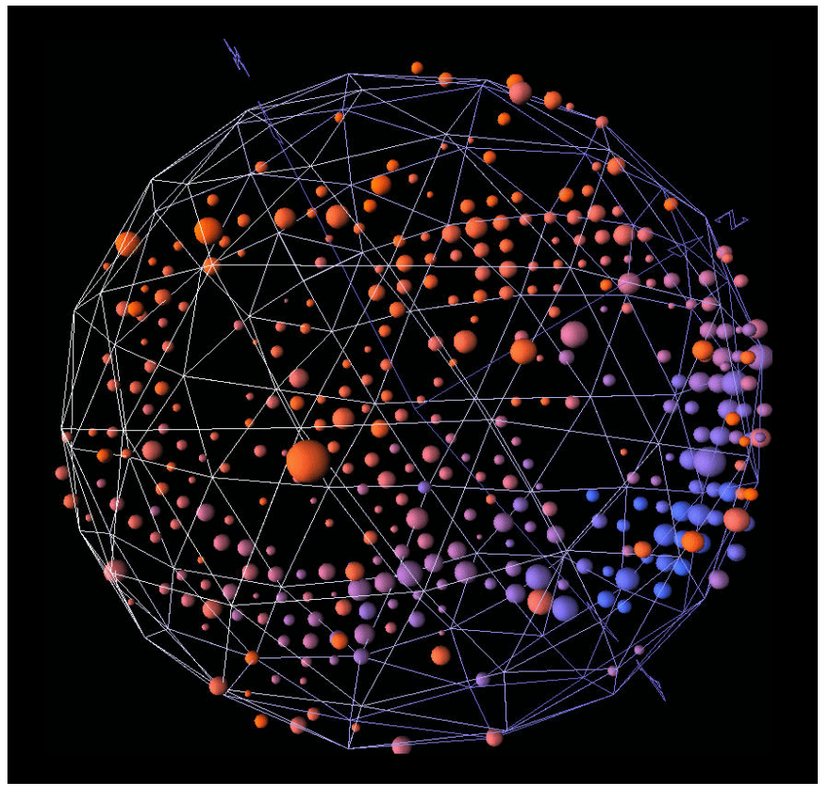

If e^+e^- pair is not collimated, event will not look e-like

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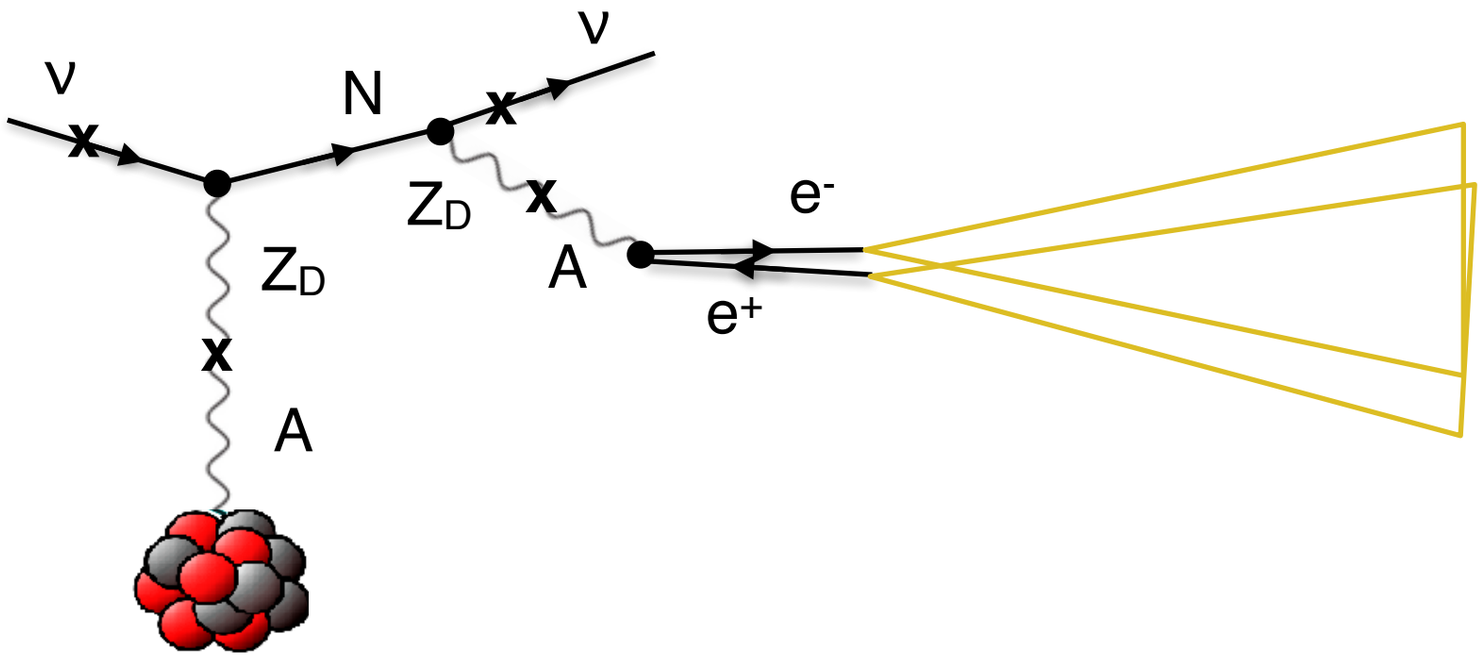
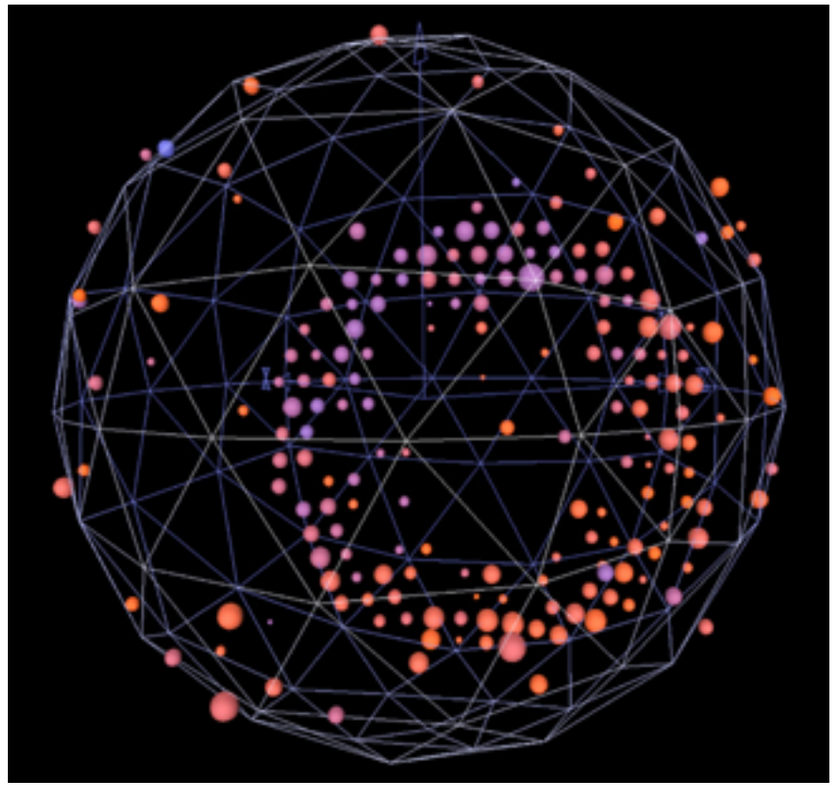
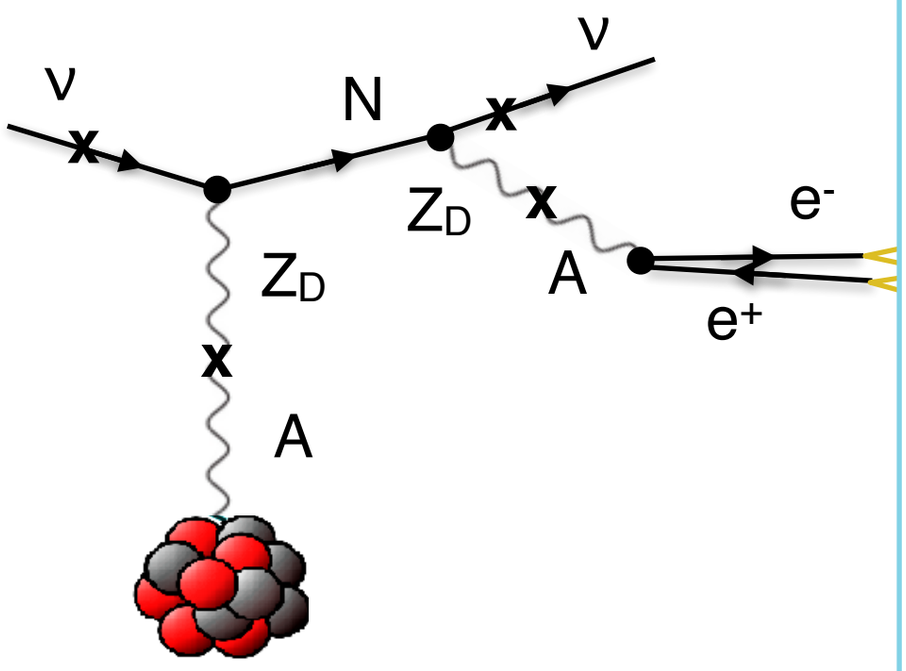


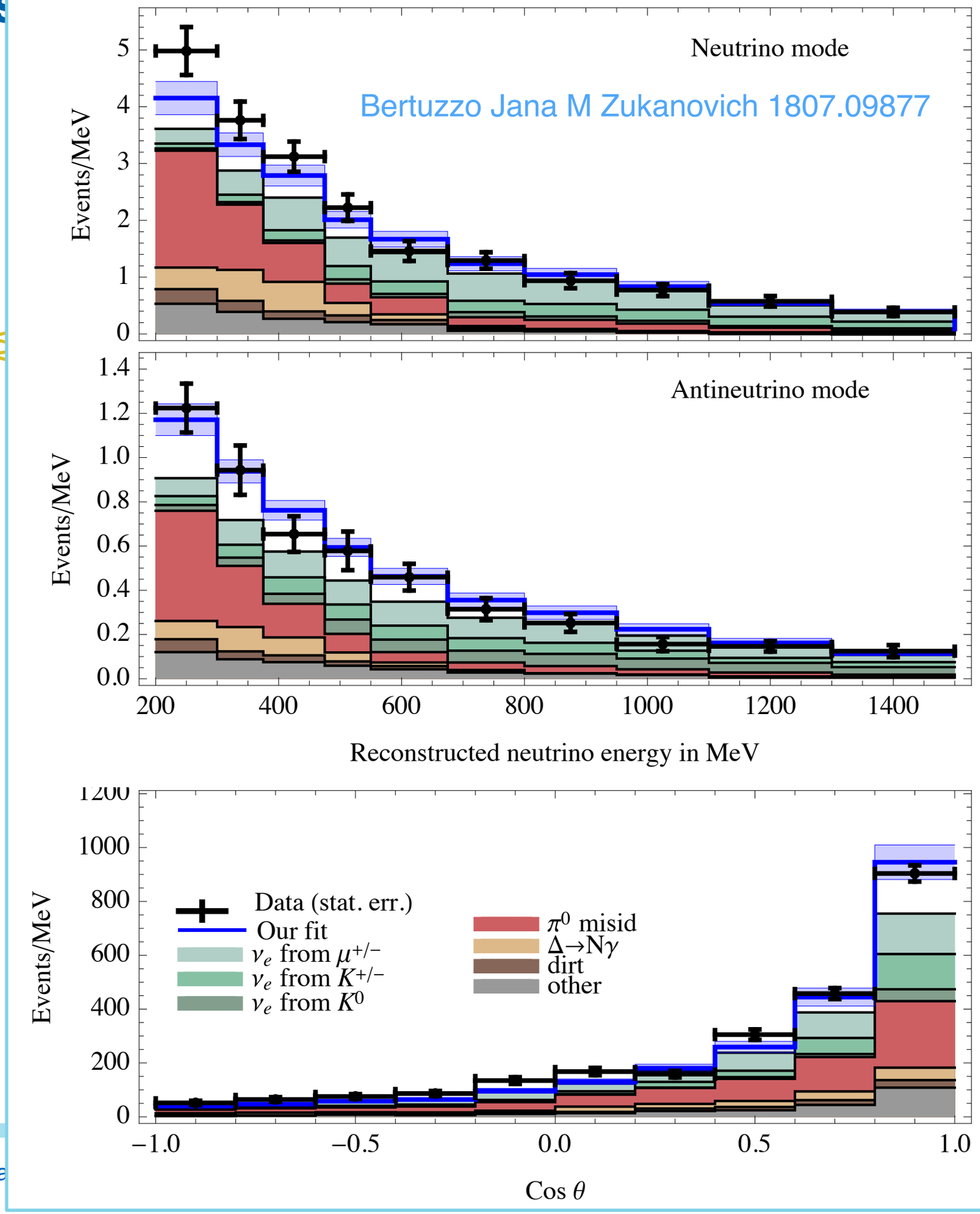


If e^+e^- pair is collimated ($\cos\theta_{ee} > 0.99$-ish), it will be classified as e-like

Case 3: SM backgrounds



How do we test it???



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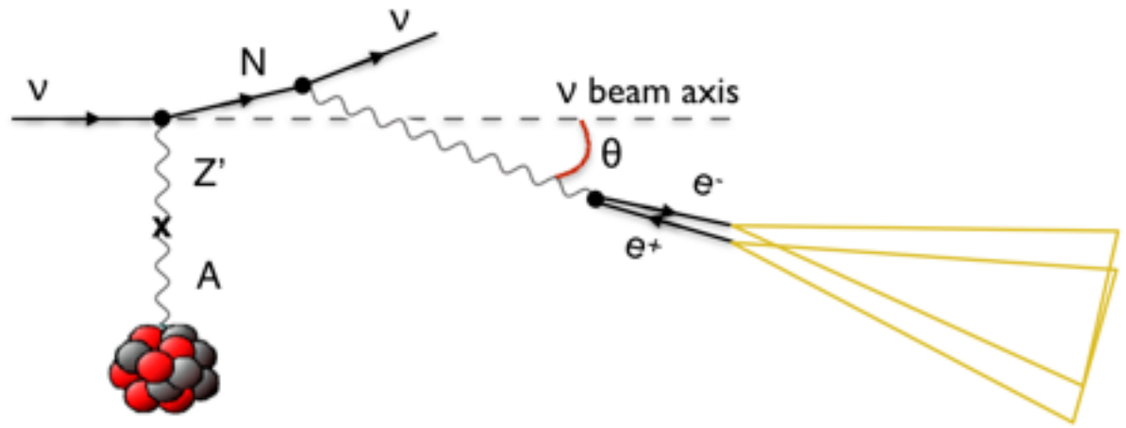
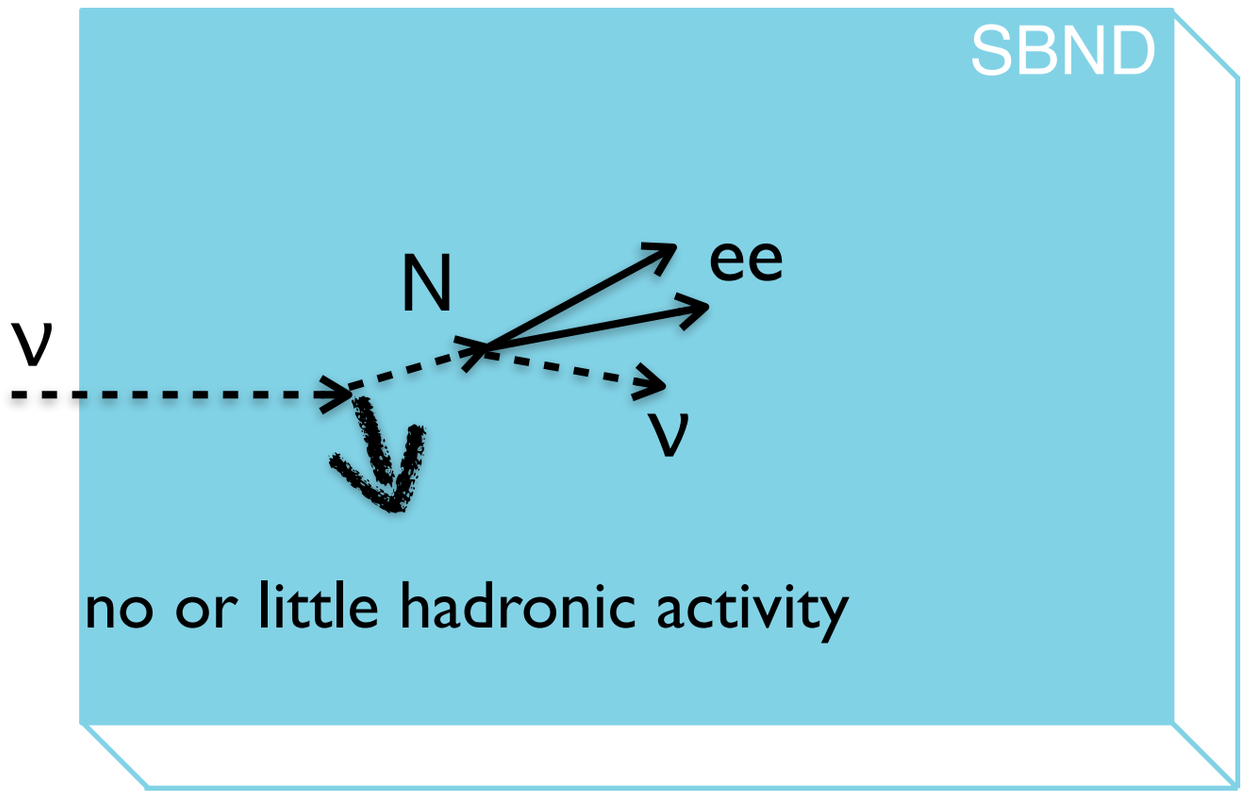


No baseline dependence

Almost no hadronic activity to tag interaction vertex

Decays to collimated e^+e^- pairs

More events due to coherence:
$_6C$ vs $_{18}Ar$ ~ 3 times more events for same exposure



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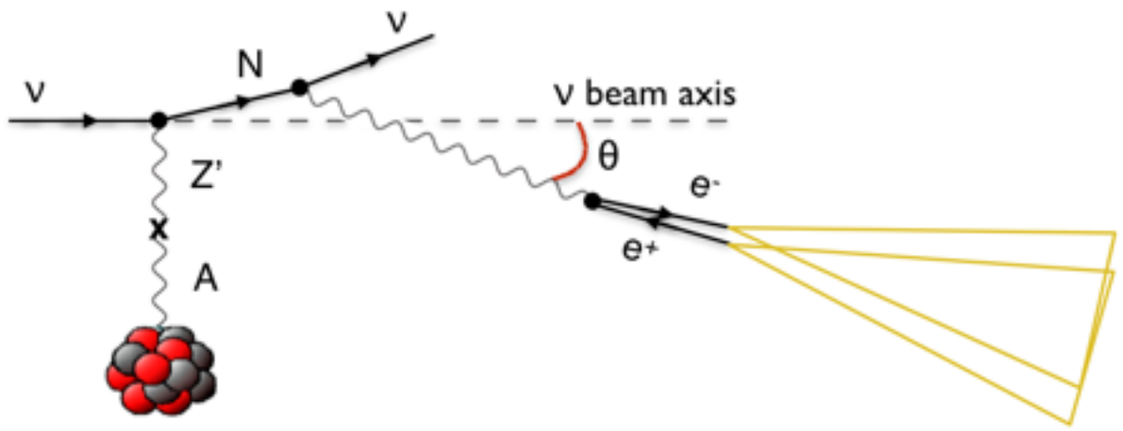

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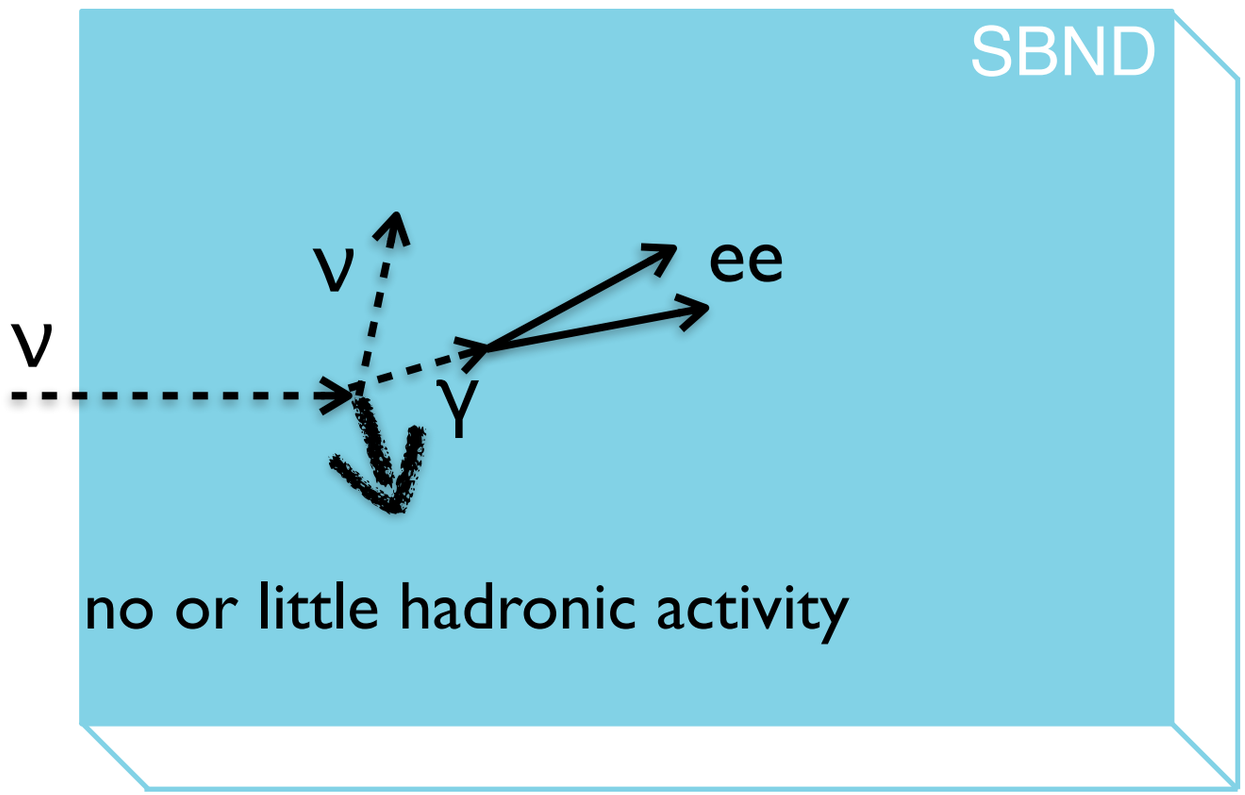


What about the coherent π^0 and gamma production?

If we do not understand the question neither the answer, it gets difficult…

Conclusions

Understanding neutrino interactions is needed for

1) Perform a **precision neutrino physics program**
2) Enrich this program with **novel searches and measurements**
3) Look for new physics that is **not attainable at colliders**

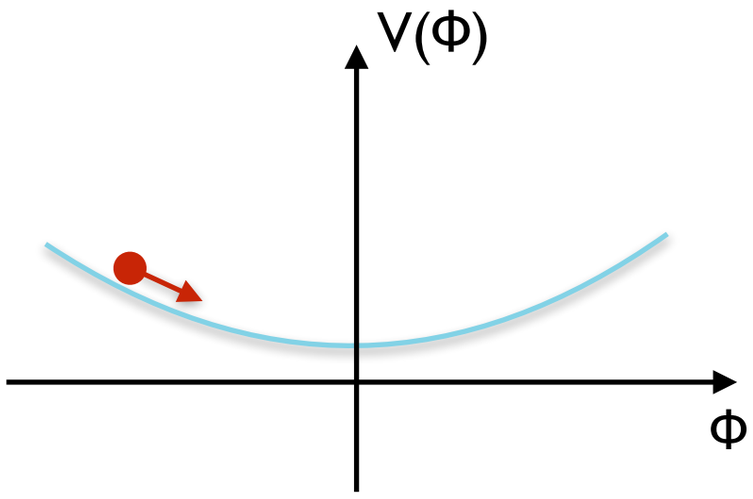
We need to **understand theoretically (this workshop)** or **measure experimentally (DUNE-PRISM, electron scattering)** (or **both!**) how neutrinos interact with matter

Backup

Discovering BSM and messing it up

(how can we reconstruct the neutrino energy)

Ultra-light dark matter



Very light scalar DM (<< eV):

- very high occupation number
- classical field

φνν coupling induce temporal changes in neutrino mass matrix!

$$\Delta m^2_{ij}(t) = (m^2_i - m^2_j)\left[1 + \epsilon\cos(\omega t)\right]^2 \simeq \Delta m^2_{ij}\left[1 + 2\epsilon\cos(\omega t)\right]$$

$$\theta_{ij}(t) = \theta_{ij}[1 + \epsilon\cos(\omega t)]$$

~ 10^{-12} eV — interesting region — ~ 10^{-23} eV

2.7 msec (L = 800 km) — ~ 10 years

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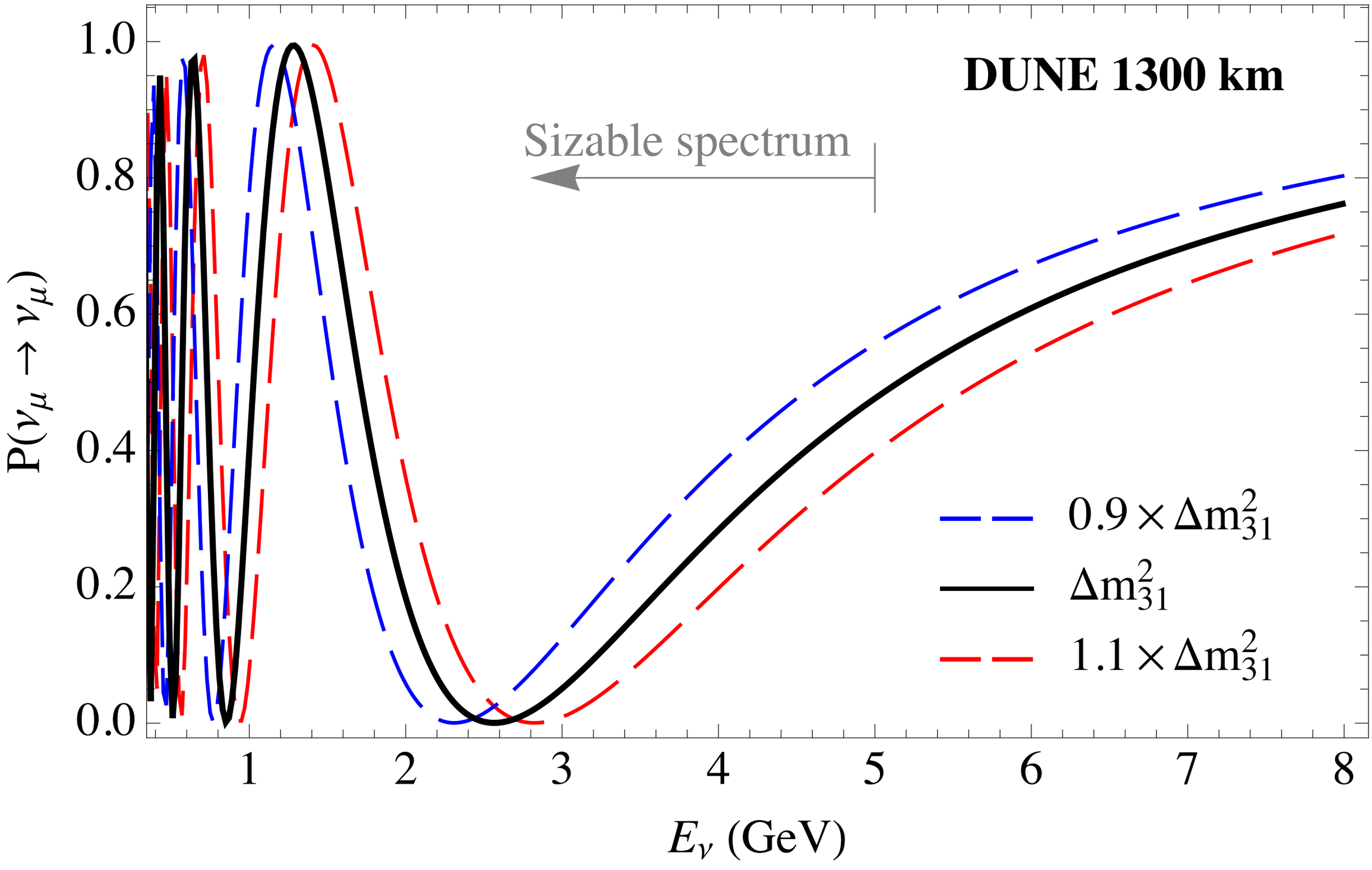
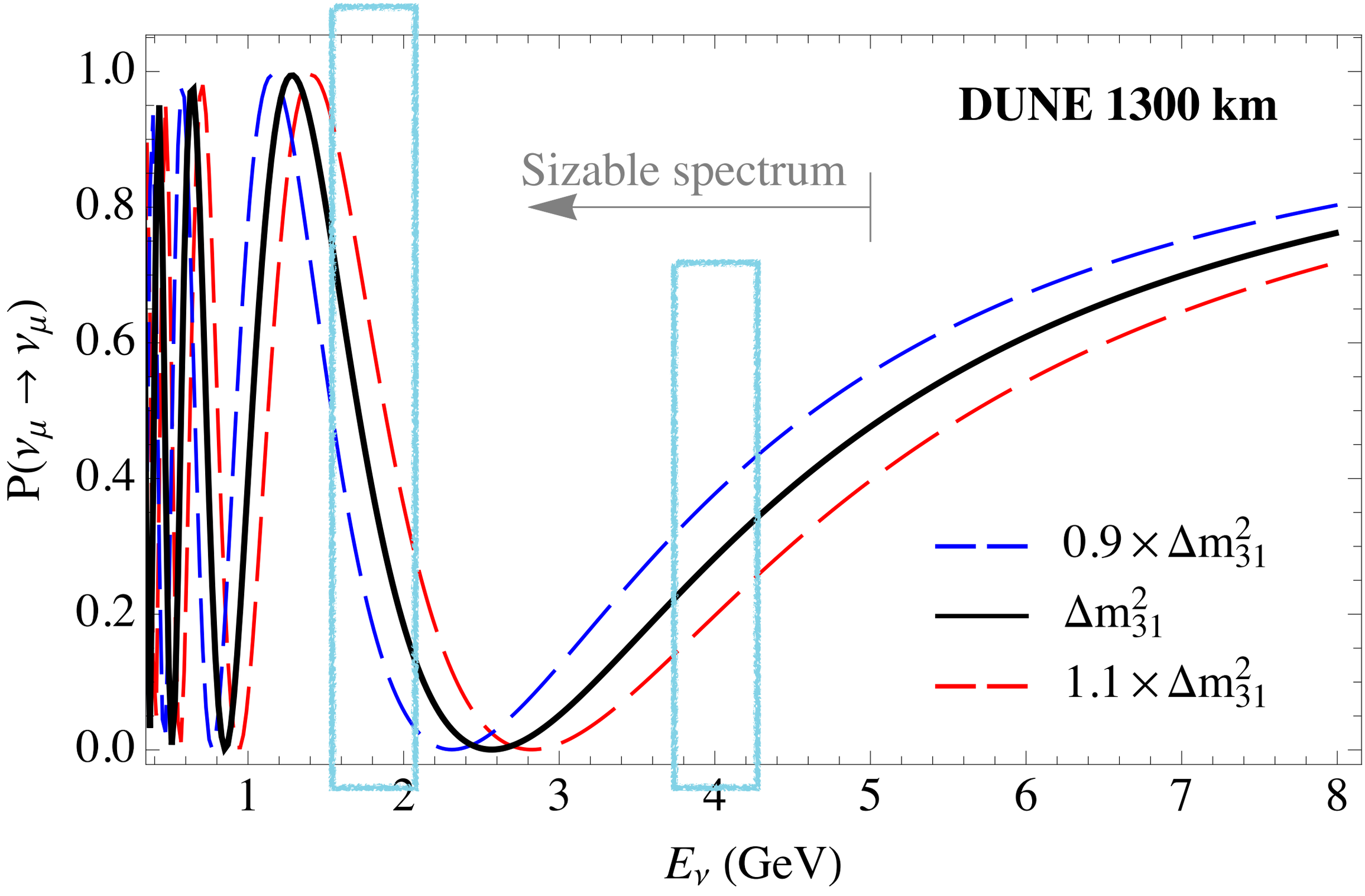
Ultra-light dark matter - signal periodicity



Ultra-light dark matter - signal periodicity



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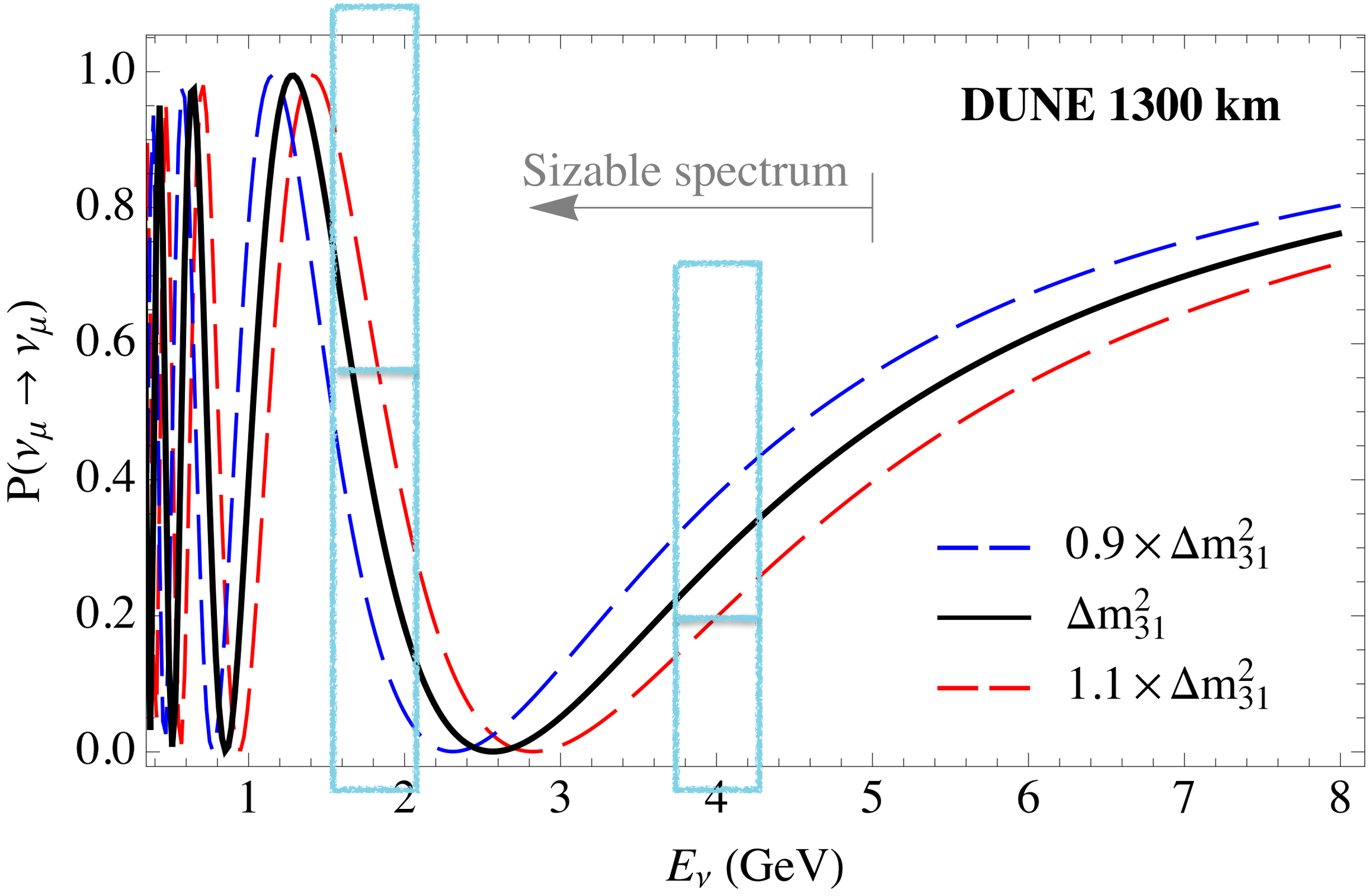
Ultra-light dark matter - signal periodicity



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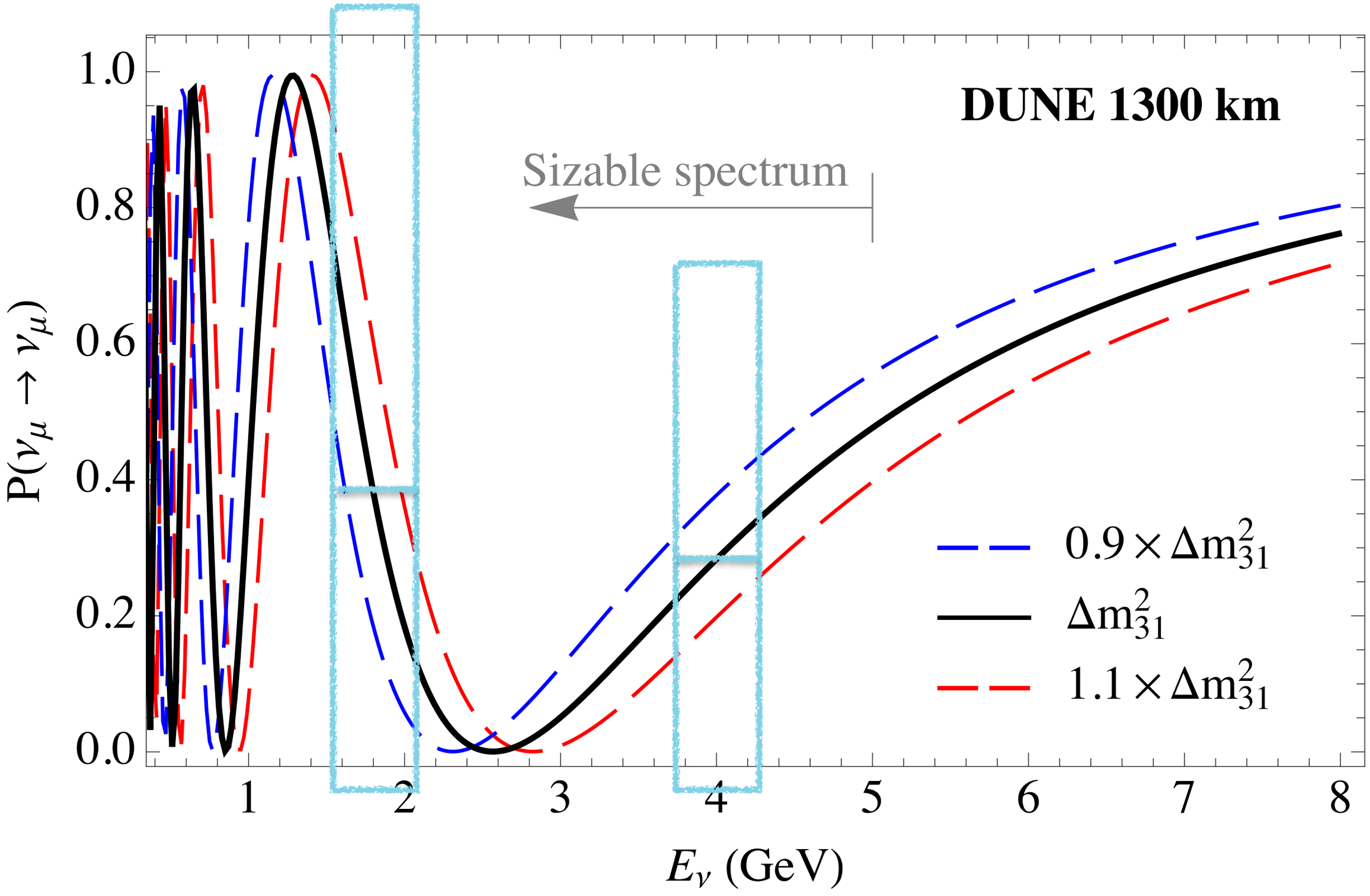
Ultra-light dark matter - signal periodicity



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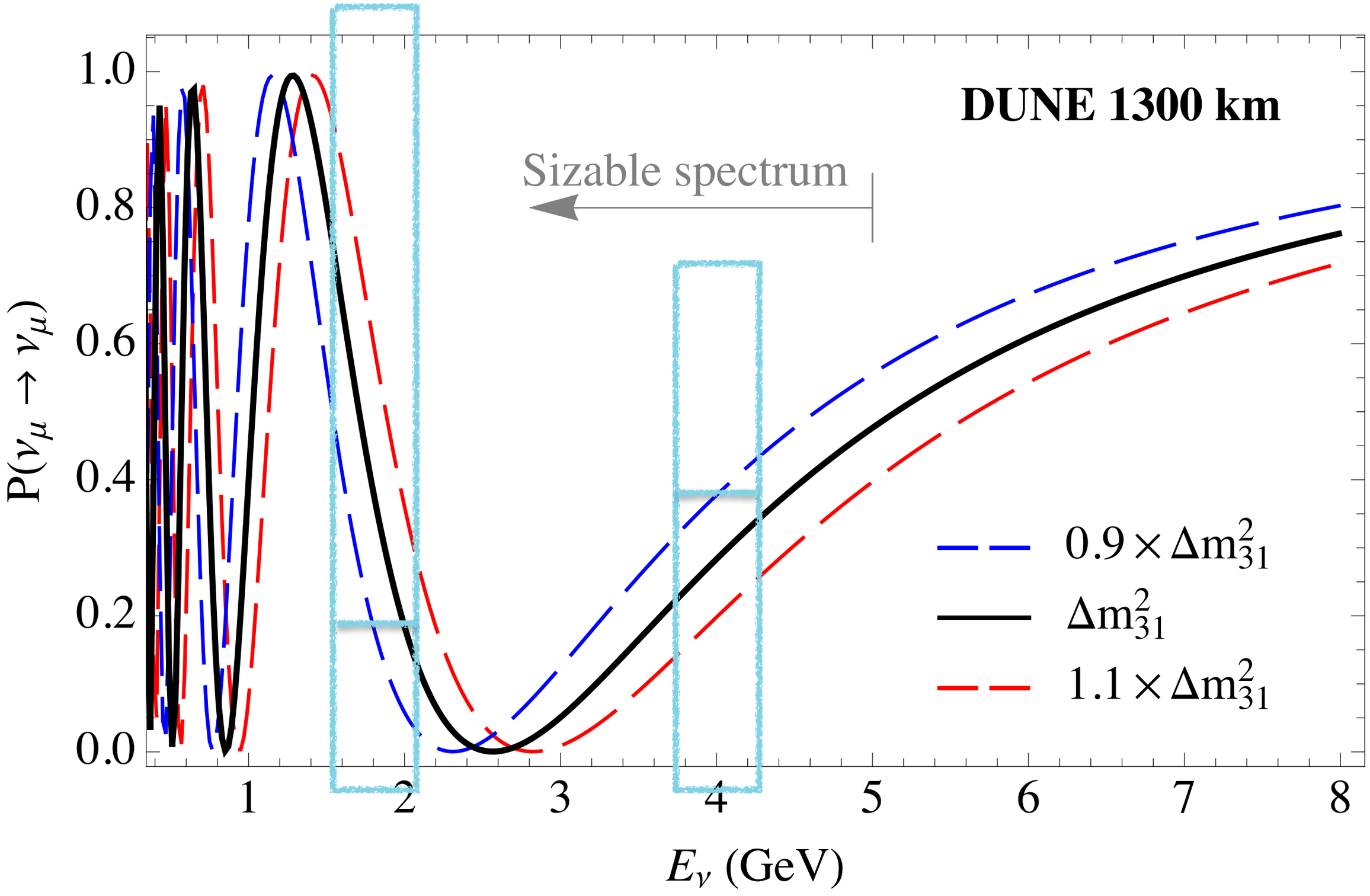
Ultra-light dark matter - signal periodicity



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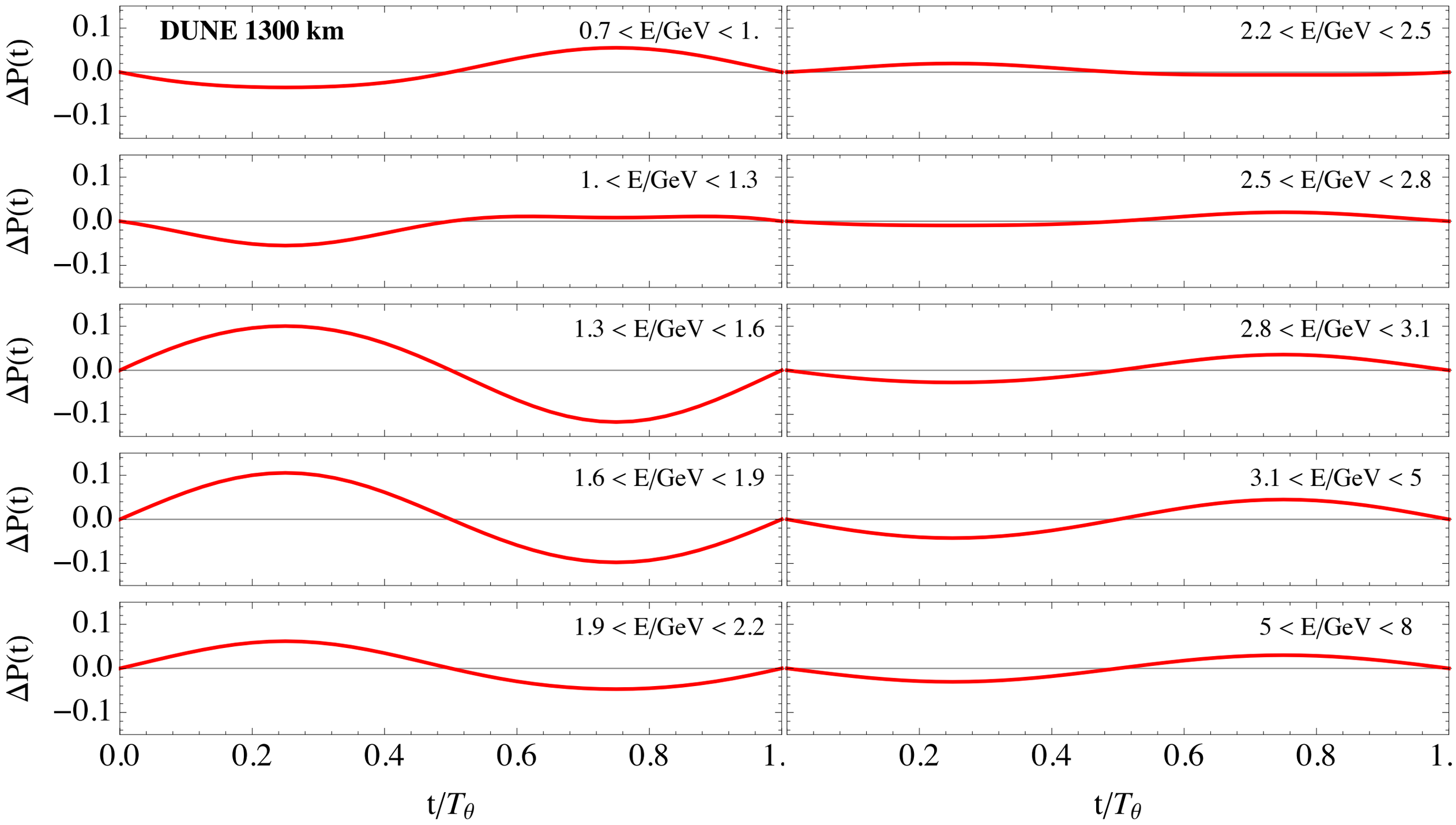
Ultra-light dark matter - signal periodicity



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Ultra-light dark matter - signal periodicity

Why do we need to understand neutrino interactions?

Assumption: **discovery**

This scenario leads to modulation at the probability level

Modulation at different energies are correlated or anti-correlated

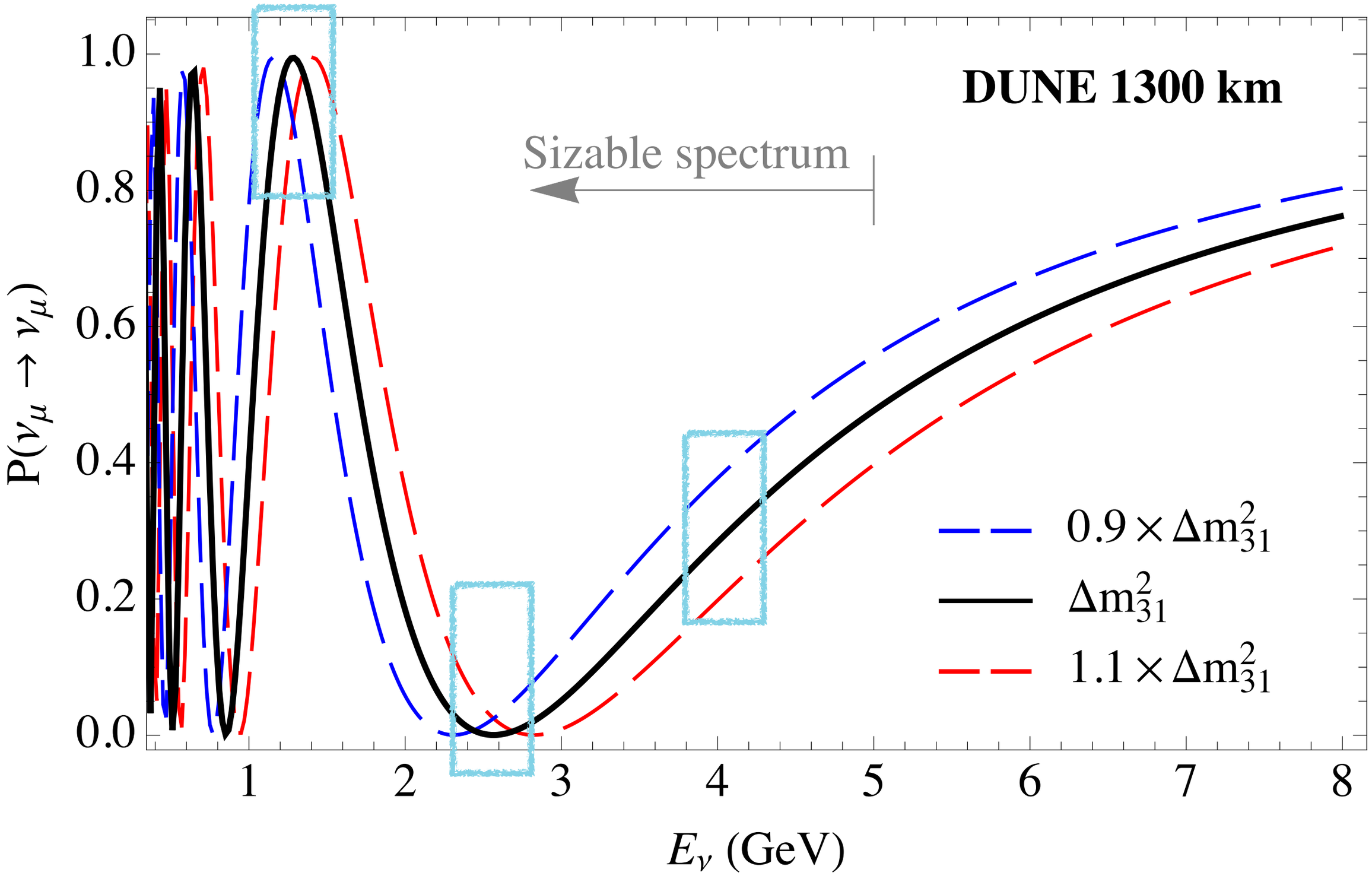
Wrong neutrino energy reconstruction can change the interpretation of the discovery!

Backup

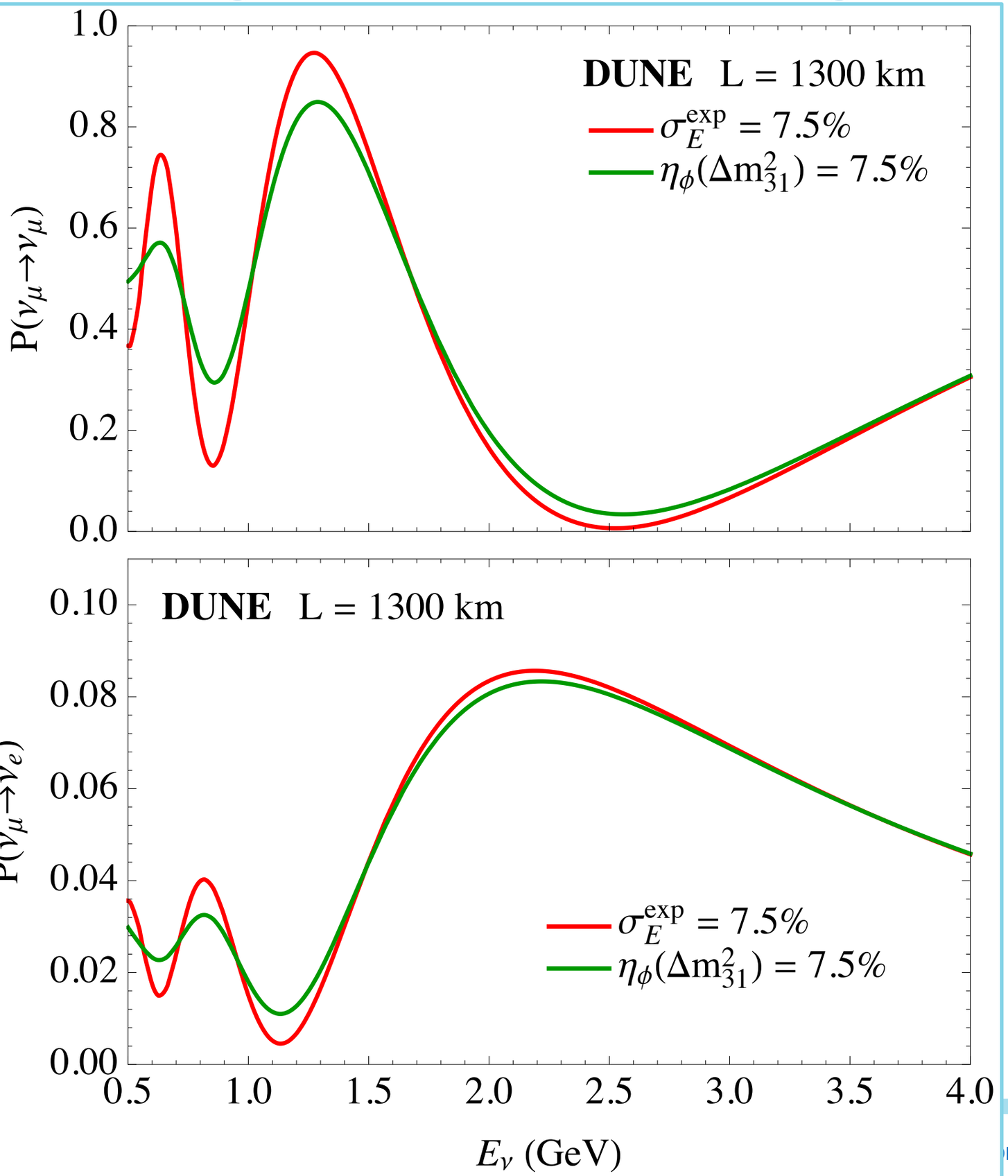
Messing it up and thinking we discovered BSM

(how can we reconstruct the neutrino energy)

Ultra-light dark matter - averaged DiNO



Ultra-light dark matter - averaged DiNO



Ultra-light DM can lead to averaging of oscillation probability

Understanding of energy reconstruction is crucial here

If we mess it up, we may think we discovered it…

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