Explaining the MiniBooNE Excess Through a Mixed Model of Oscillation and Decay

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Based on our preprint: 2105.06470

Overview

- Tension in eV-scale oscillation global fits
- The HNL dipole model
- MiniBooNE fit results

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- **Tension in eV-scale oscillation global fits**
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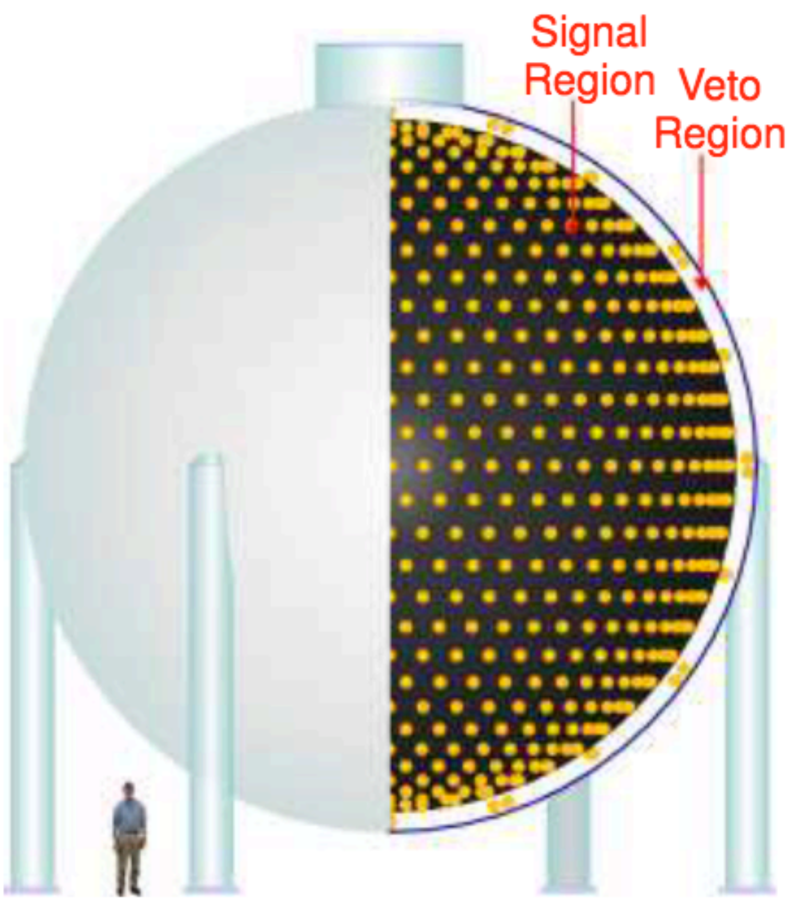
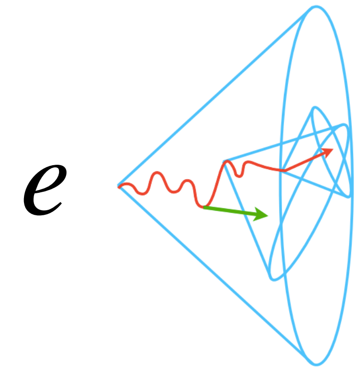
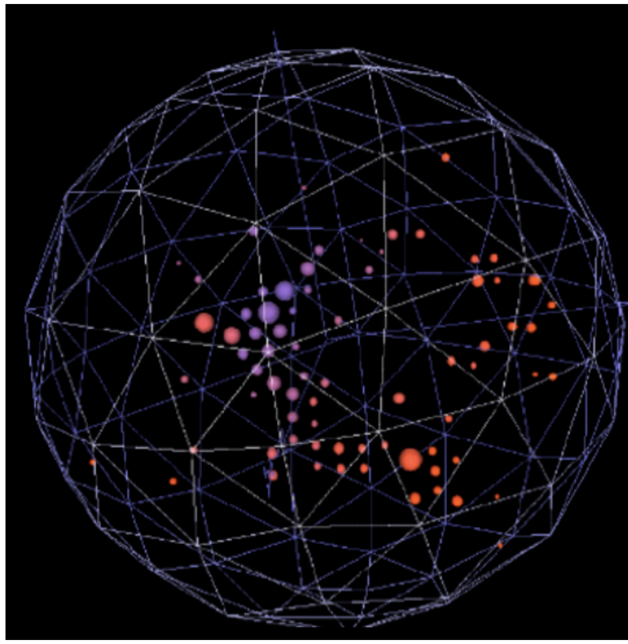
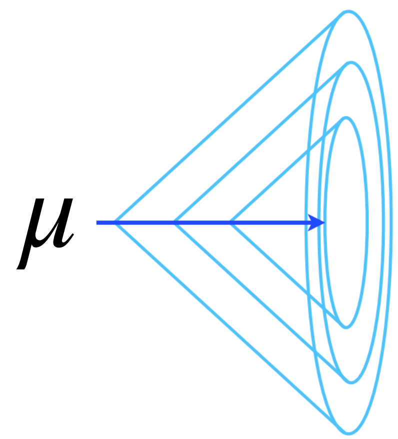
The MiniBooNE Experiment

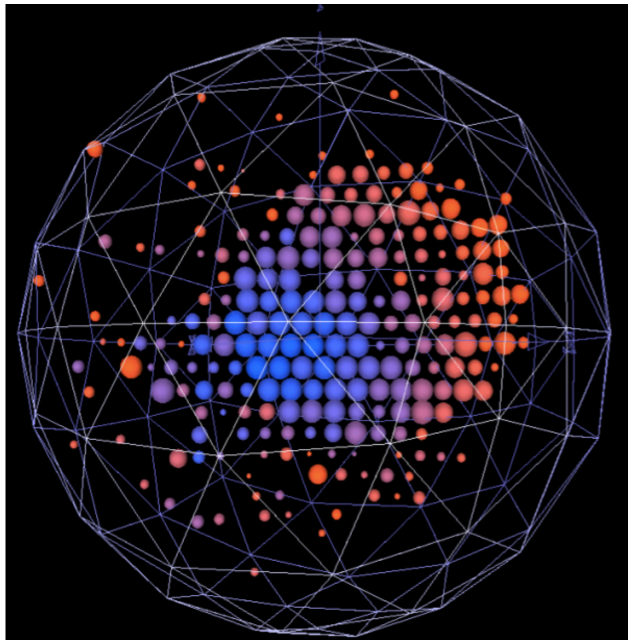
- 818 ton CH_2 Cherenkov detector at Fermilab's Booster Neutrino Beam
- 4.8σ excess of electron-like events in complete neutrino-mode dataset

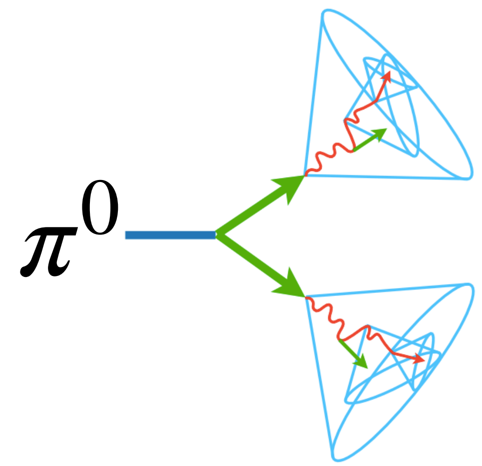


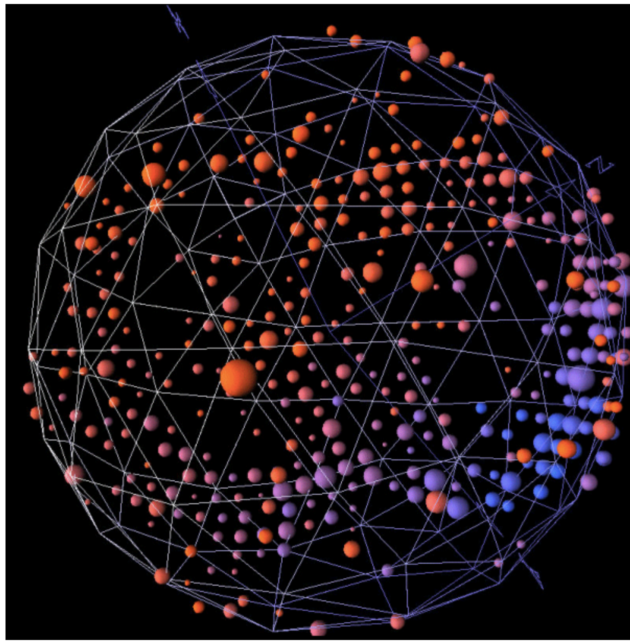






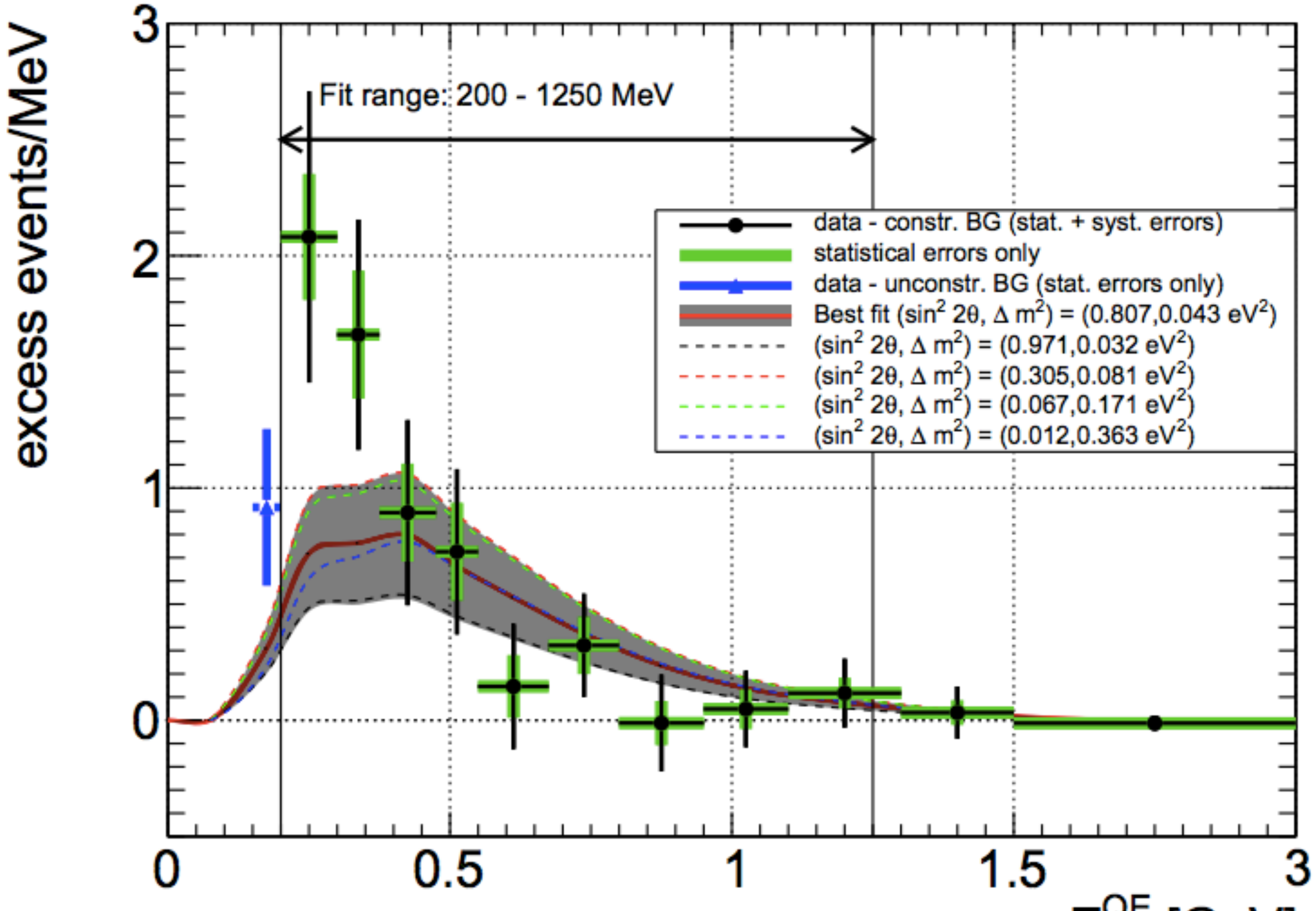




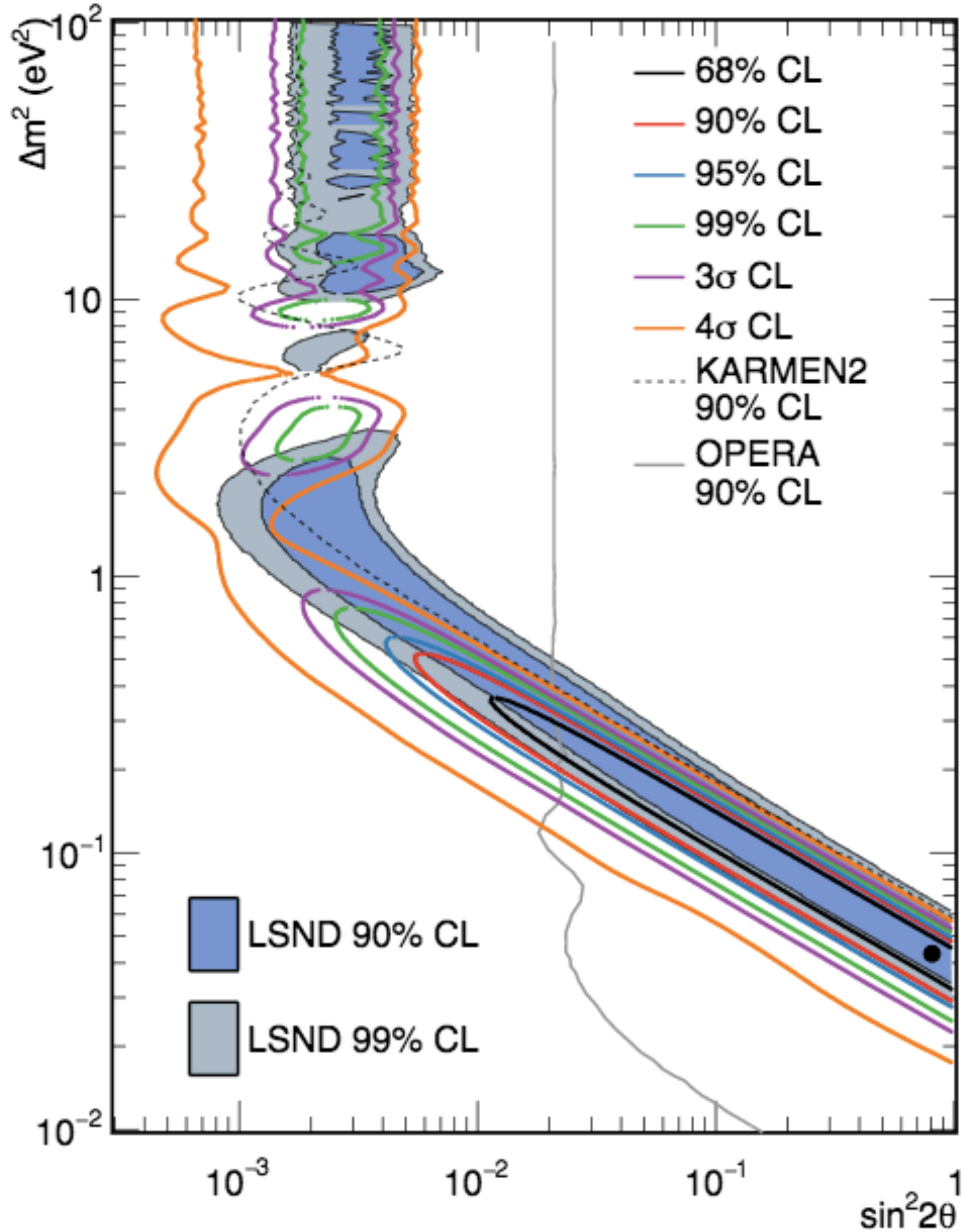


eV-scale Sterile Oscillations

The most common model used to explain the MiniBooNE excess invokes short-distance muon-to-electron neutrino oscillations though the addition of a sterile neutrino

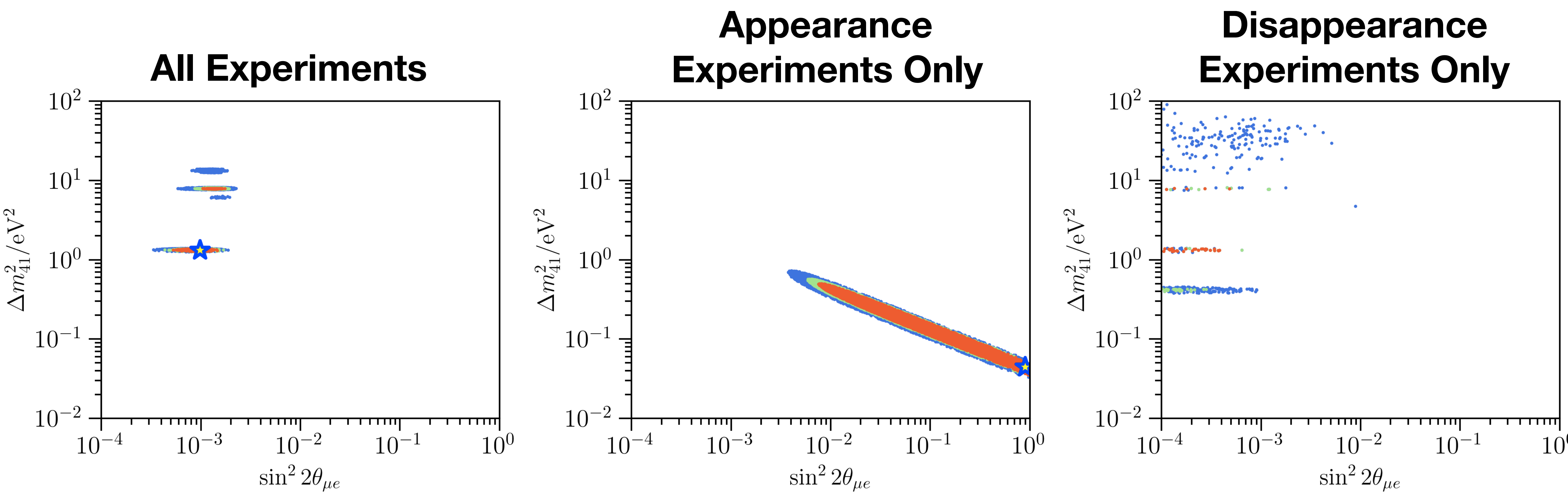


Phys. Rev. D 103, 052002



Global Fit Tension

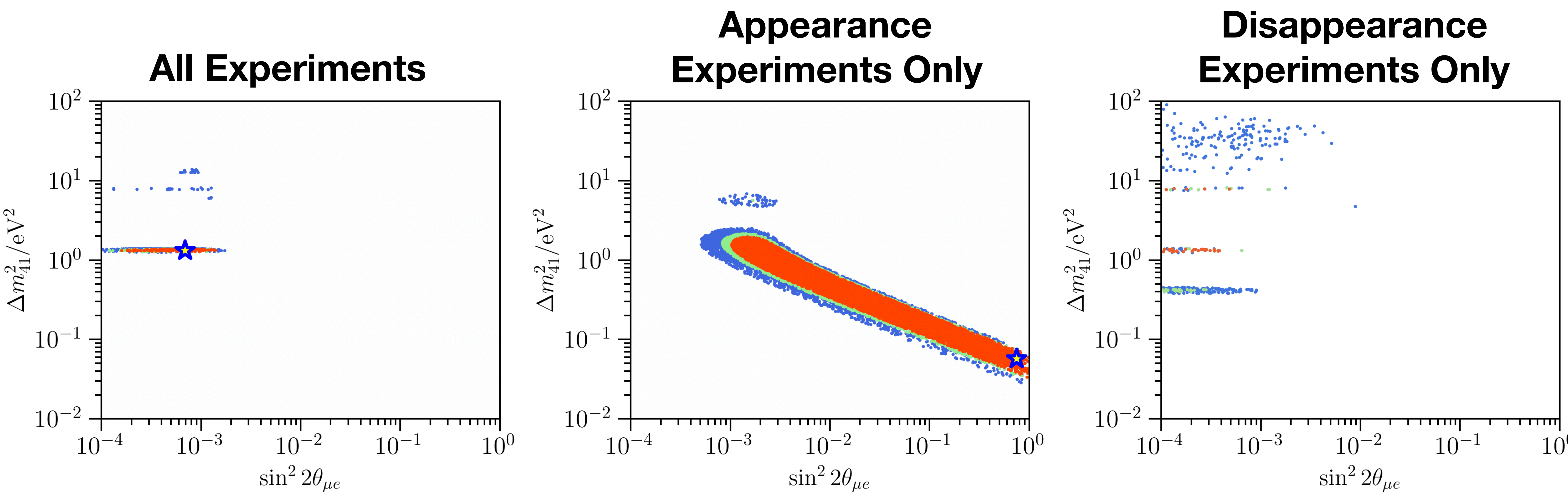
- One can look for the effect of such a sterile neutrino in other ν_e appearance experiments (e.g. LSND), ν_e disappearance experiments (e.g. reactors), and ν_μ disappearance experiments (e.g. long baseline accelerators)



$$p_{\mathrm{PG}}^{\mathrm{w/\ MiniBooNE}} = 8 \times 10^{-7}\,(4.8\sigma)$$

Global Fits Without MiniBooNE

- We can repeat the same procedure after removing MiniBooNE from the list of appearance experiments



$$p_{\mathrm{PG}}^{\mathrm{w/o\ MiniBooNE}} = 7 \times 10^{-3}\,(2.5\sigma)$$

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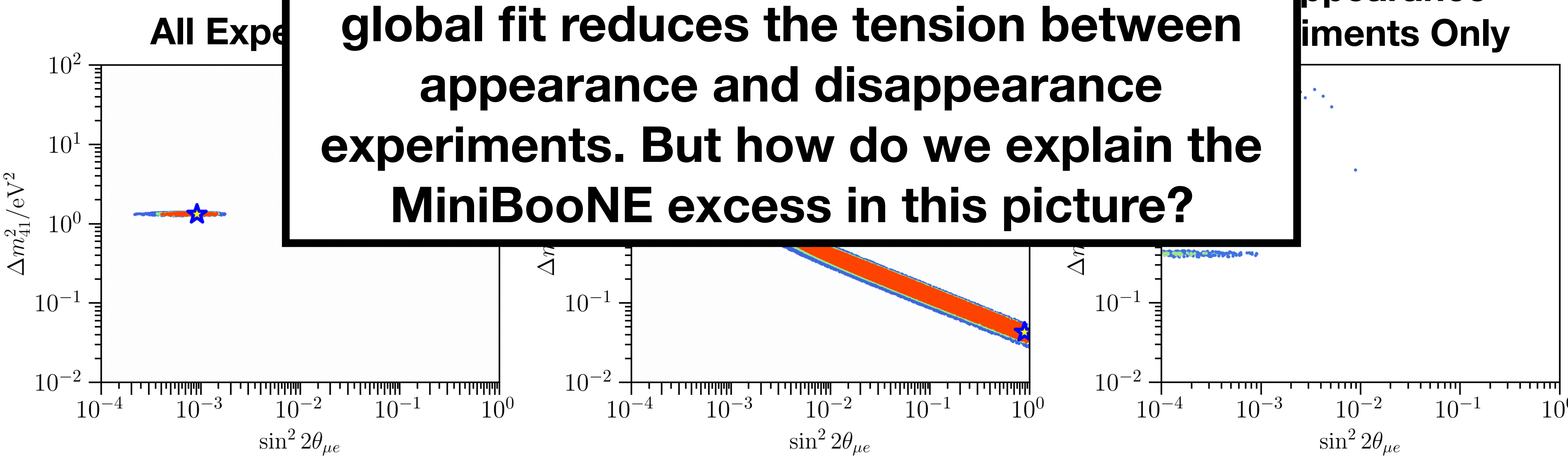


Clearly removing MiniBooNE from the global fit reduces the tension between appearance and disappearance experiments. But how do we explain the MiniBooNE excess in this picture?

$$p_{\text{PG}}^{\text{w/o MiniBooNE}} = 7 \times 10^{-3}\,(2.5\sigma)$$

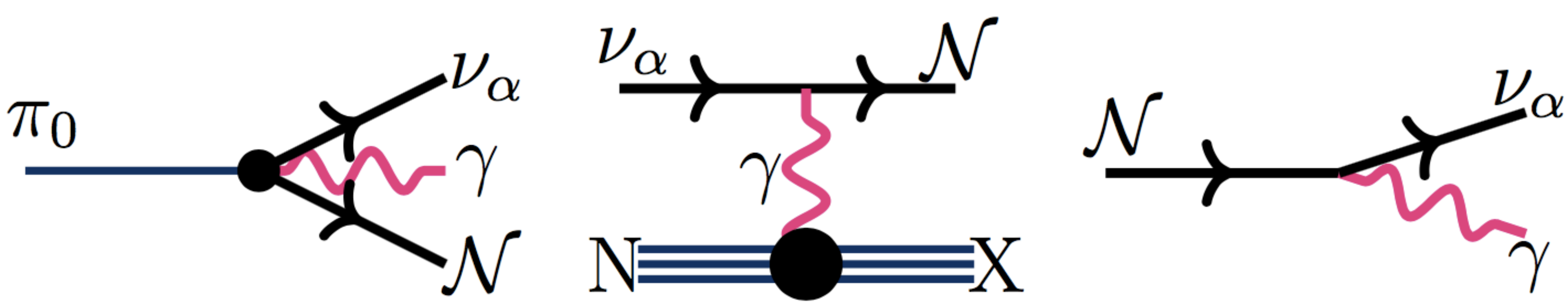
Overview

- Tension in eV-scale oscillation global fits
- **The HNL dipole model**
- MiniBooNE fit results

Dipole + Oscillation Model

$$\mathcal{L} \supset \mathcal{L}_{SM} + \sum_{j=1}^{3} \bar{\mathcal{N}}_j (i\partial\!\!\!/ - M_j)\mathcal{N}_j + \sum_{i=1}^{3} (d_{i,j}\bar{\nu}_i \sigma_{\mu\nu} F^{\mu\nu} \mathcal{N}_j + h.c.)$$

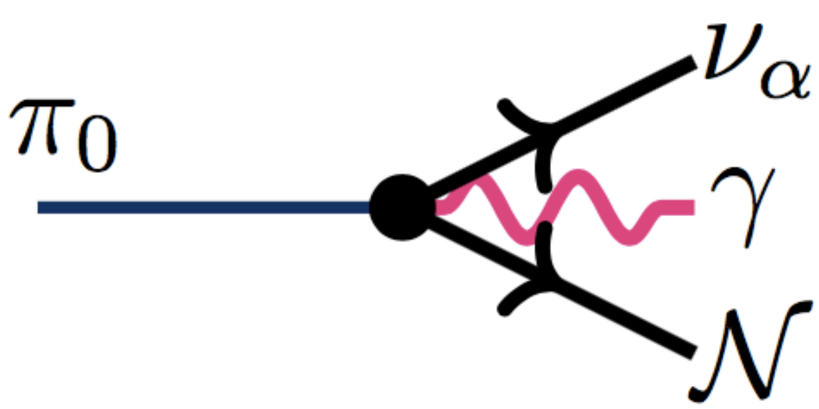
- We only consider oscillations involving the lightest HNL, as the masses of the other two are assumed to be too large
- The dipole term introduces the interactions shown below, where we define $\mathcal{N} \equiv \mathcal{N}_3$



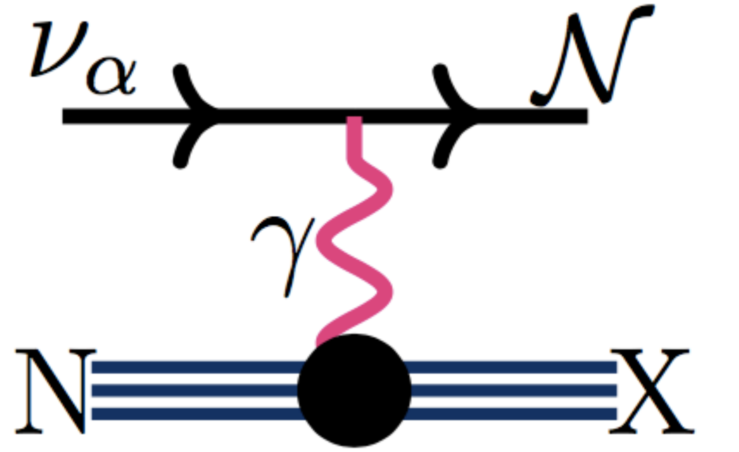
Other dipole portal studies: Phys. Rev. Lett. 45, 963 (1980), Phys. Rev. D 25, 766 (1982), Phys. Rev. D 98, 115015, JHEP09(2005)048, JHEP01(2013)106, 2105.09699

HNLs In MiniBooNE

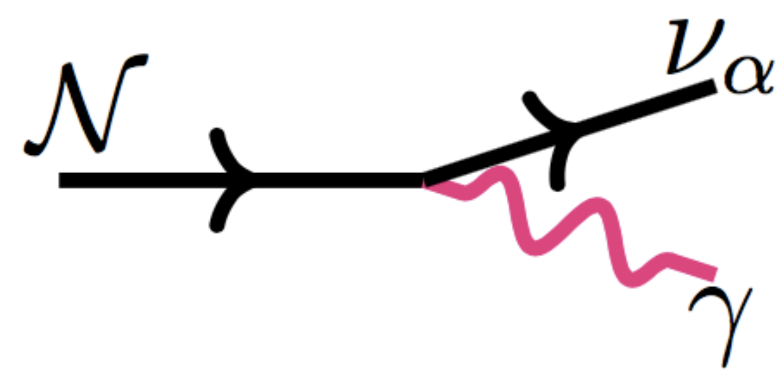
1: Dalitz-like Pion Decay

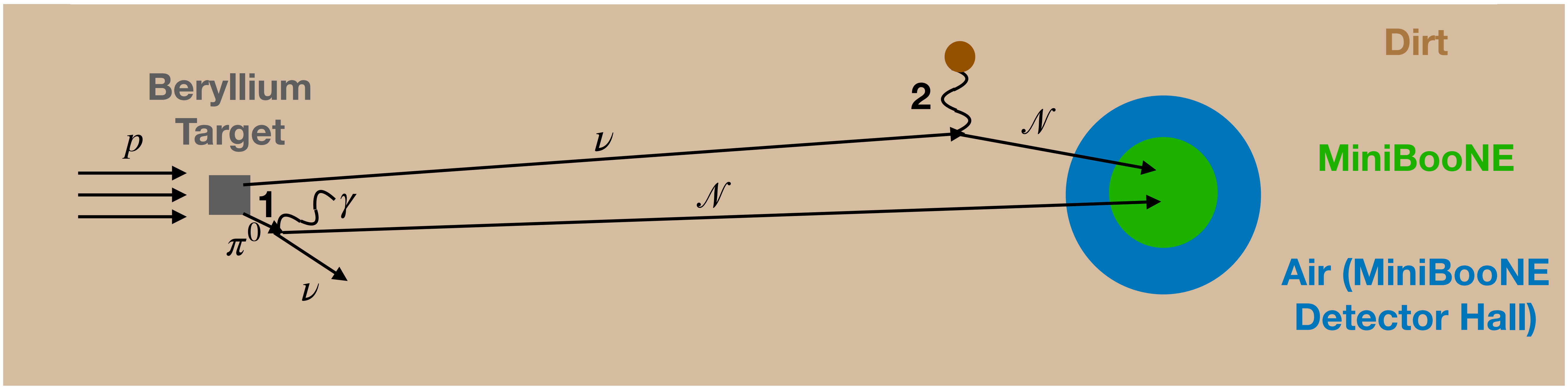


2: Primakoff Upscattering



3: HNL Decay





For the mass range under consideration in this study (10-1000 MeV), Primakoff upscattering is found to be the dominant HNL production mode

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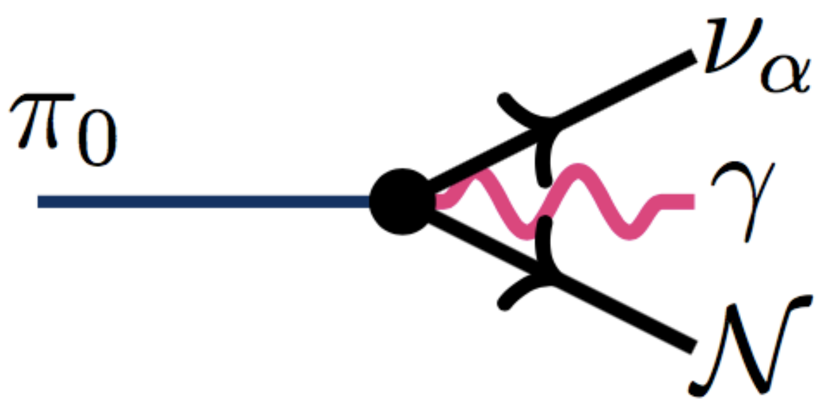

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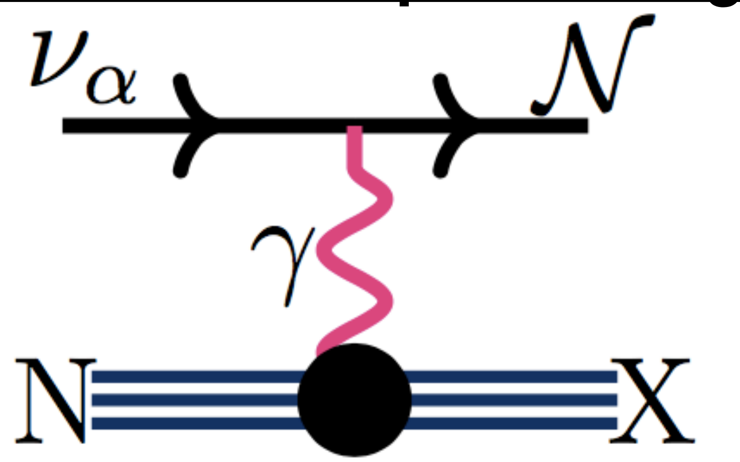

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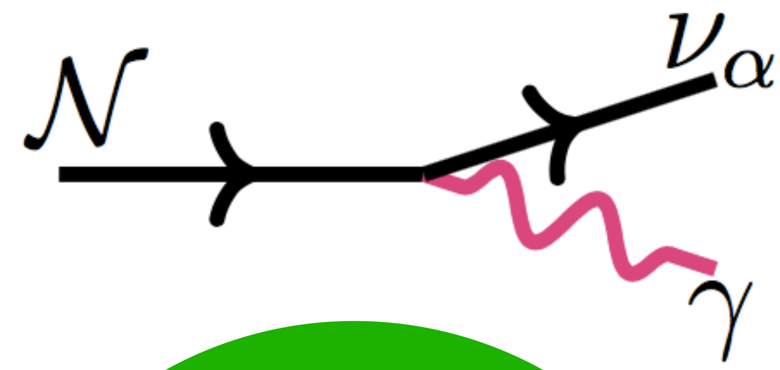
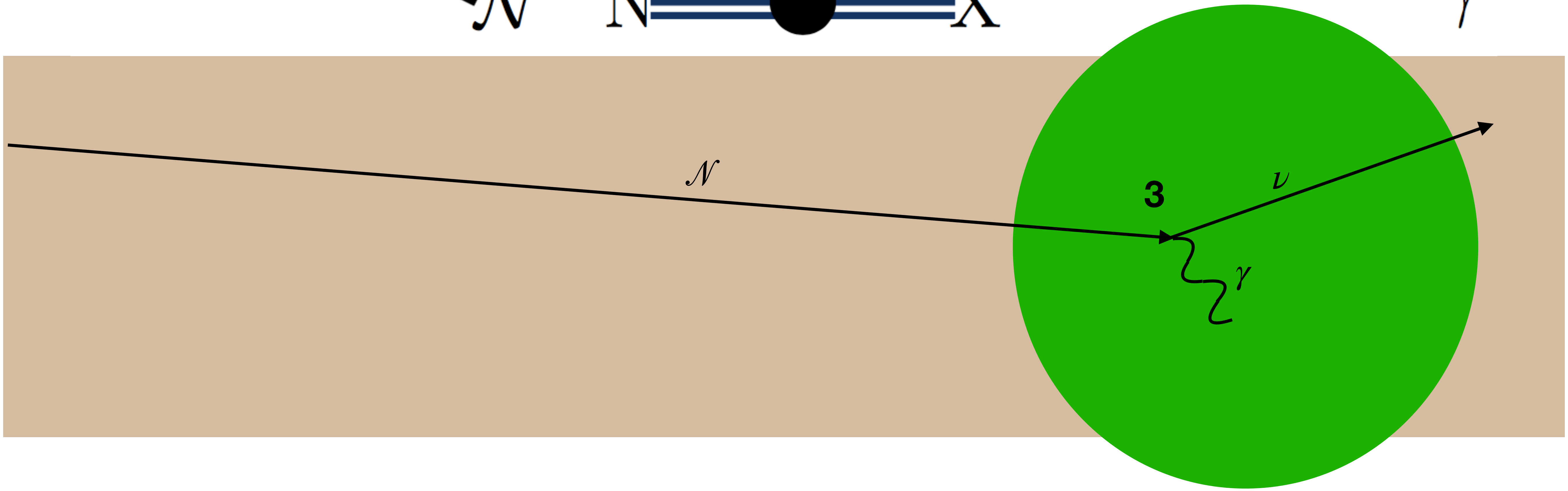




As electrons and photons are indistinguishable in MiniBooNE, this decay would contribute to the electron-like excess

Simulation Details: Production

- Primakoff upscattering events can happen…
  - Coherently off a nucleus or incoherently off a nucleon
  - In the dirt before MiniBooNE or within MiniBooNE itself
- The event-by-event HNL kinematics are determined using the differential cross section

$$\frac{d\sigma}{dt} = \frac{2\alpha d^2}{m}\Bigg[F_1^2(t)\Big(\frac{1}{E_r} - \frac{1}{E_\nu} + m_\mathcal{N}^2 \frac{E_r - 2E_\nu - M}{4E_\nu^2 E_r M} + m_\mathcal{N}^4 \frac{E_r - M}{8E_\nu^2 E_r^2 M^2}\Big) + \frac{F_2^2(t)}{4M^2}\Big(\frac{2M}{E_\nu^2}((2E_\nu - E_r)^2 - 2E_r M) + m_\mathcal{N}^2 \frac{E_r - 4E_\nu}{E_\nu^2} + \frac{m_\mathcal{N}^4}{E_\nu^2 E_r}\Big)\Bigg]$$

$$E_r = -t/2M \qquad E_\mathcal{N} = E_\nu - E_r \qquad \cos(\theta) = \frac{E_\nu - E_r - ME_r/E_\nu - m_\mathcal{N}^2/2E_\nu}{\sqrt{E_\nu^2 + E_r^2 - 2E_\nu E_r - m_\mathcal{N}^2}}$$

Phys. Rev. D 98, 115015

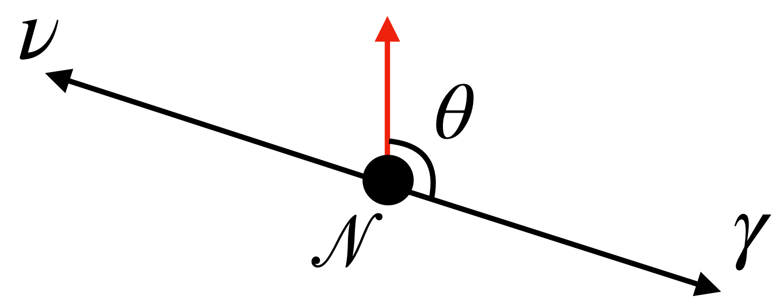
Simulation Details: Decay

- HNLs that reach MiniBooNE decay with a decay length

$$L_{decay} = 4\pi \frac{\beta E_{\mathcal{N}}}{d^2 m_{\mathcal{N}}^4}$$

- The angular distribution of photons from right handed HNLs is given by*

$$\frac{d\Gamma}{d\cos\theta} \propto 1 - \cos\theta$$



- The photons are boosted to the lab frame, smeared according to the MB energy/angle resolution, weighted by detection efficiency

***requires Dirac HNL among other things (see 1805.00922)**

Overview

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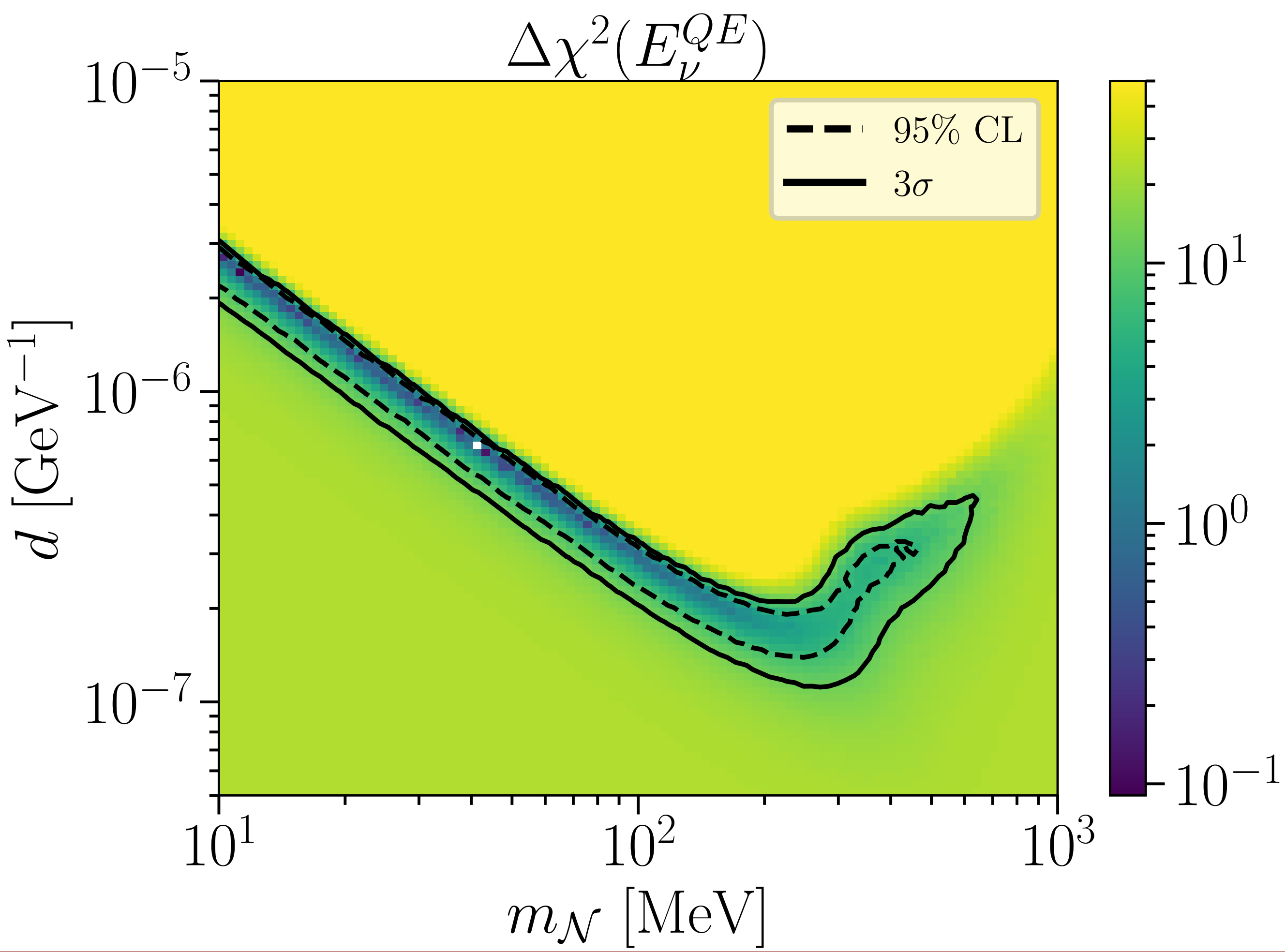
- **MiniBooNE fit results**

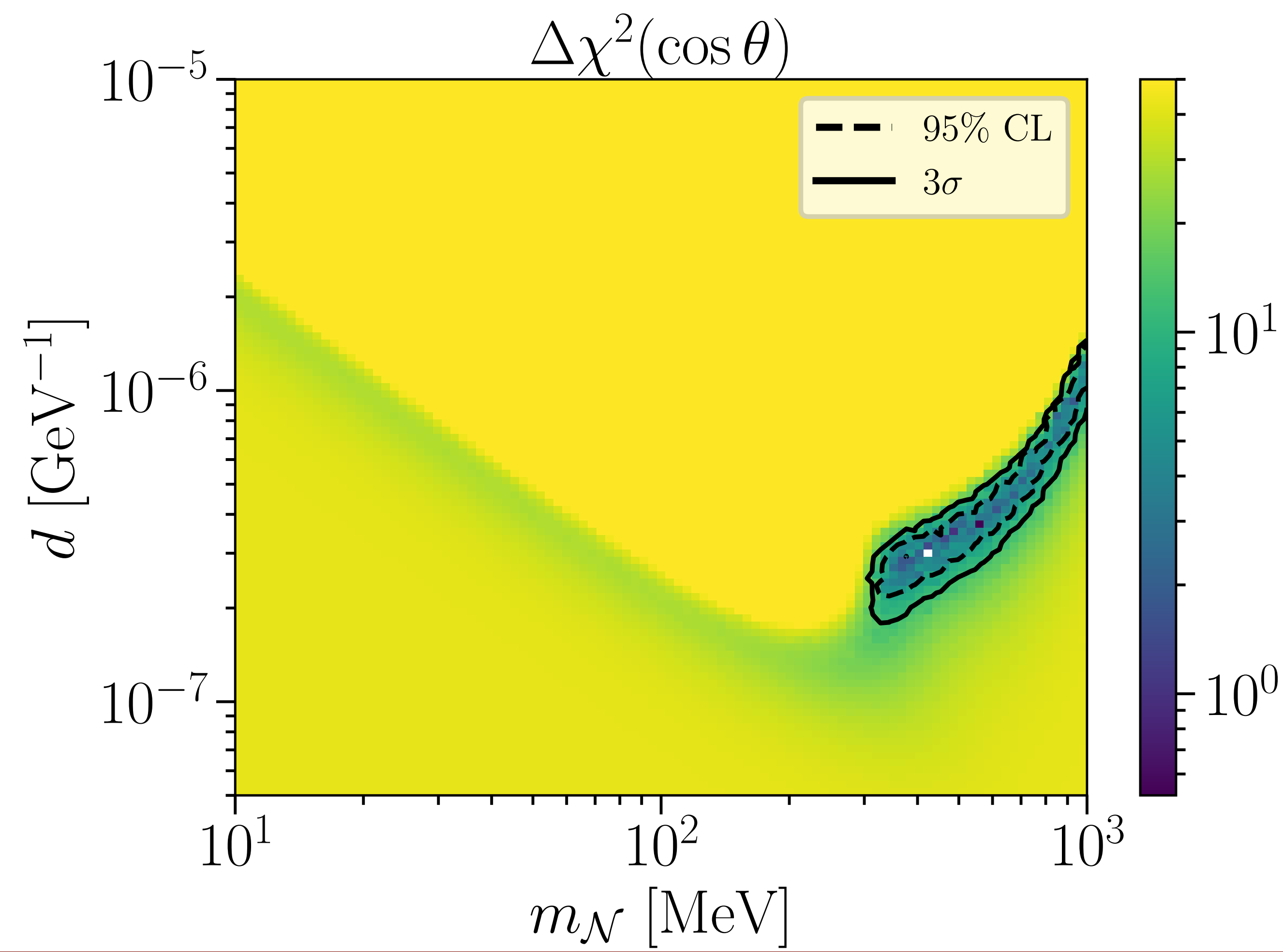
Energy and Angular Fits

- We consider an oscillation contribution from the best fit to the 3+1 model without MB:

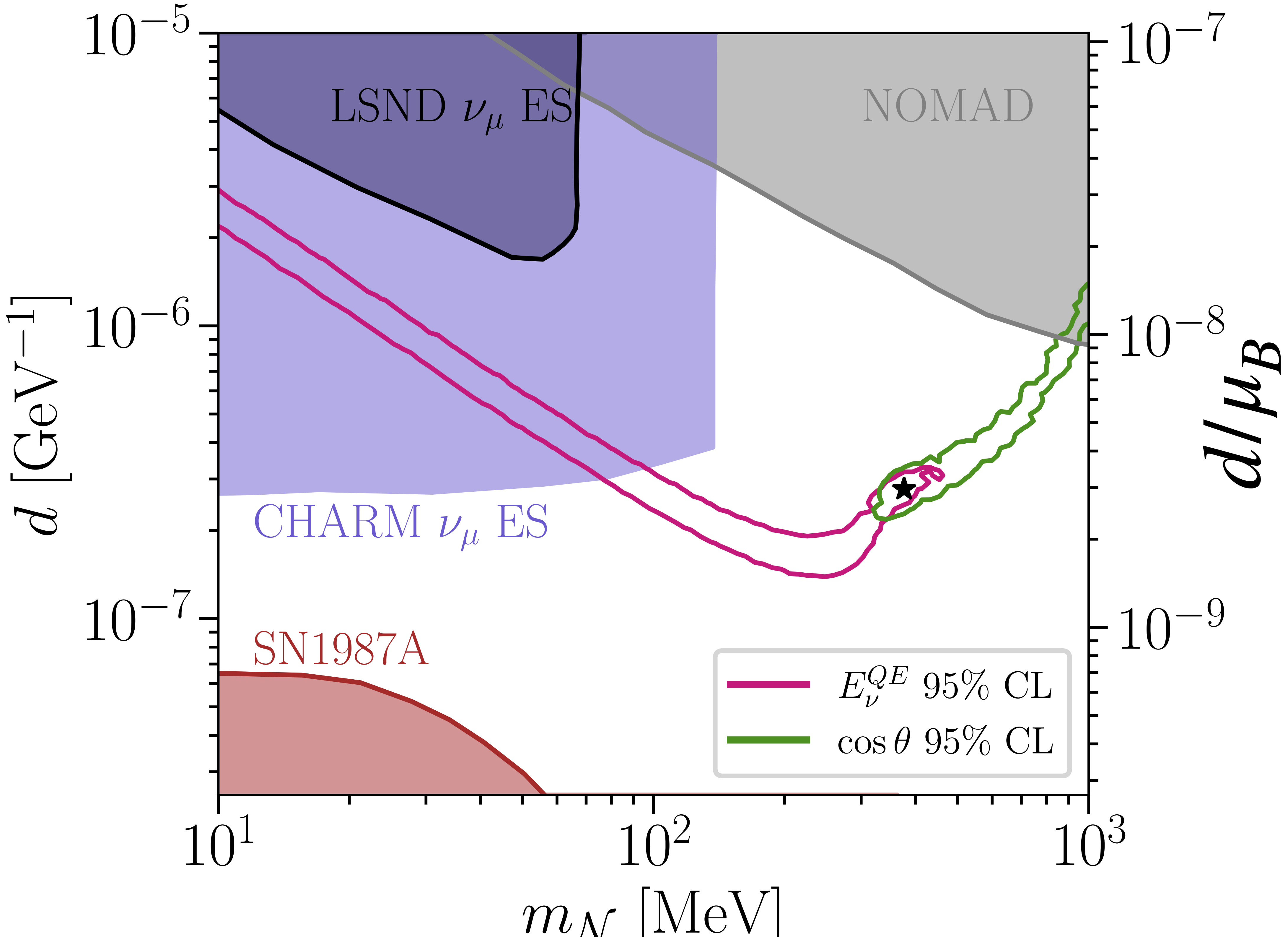
$$\Delta m^2 = 1.3\,\mathrm{eV}^2 \qquad \sin^2(2\theta_{\mu e}) = 6.9 \times 10^{-4}$$

- The remaining excess is fit to the HNL dipole contribution





Energy and Angular Fits



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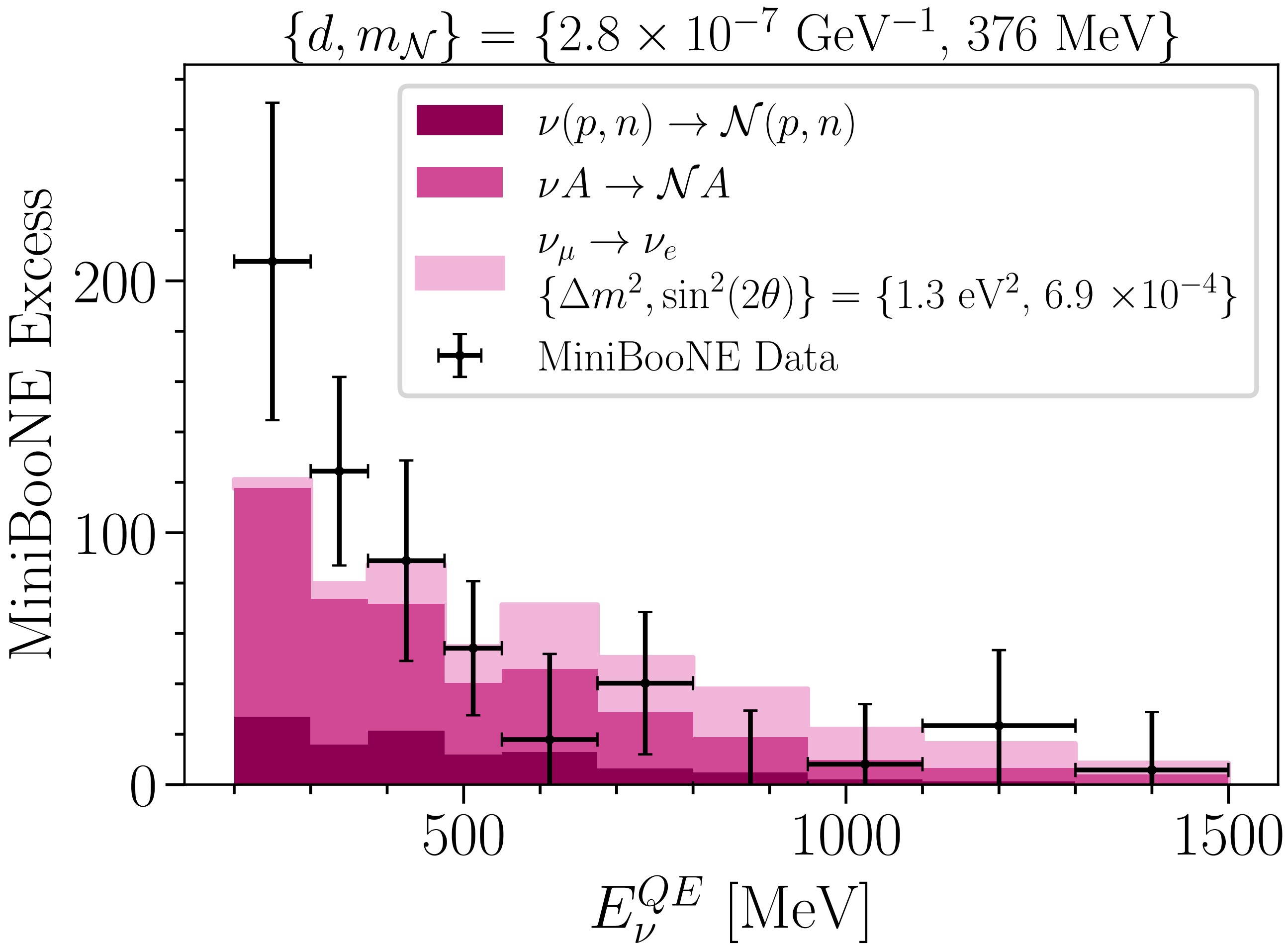
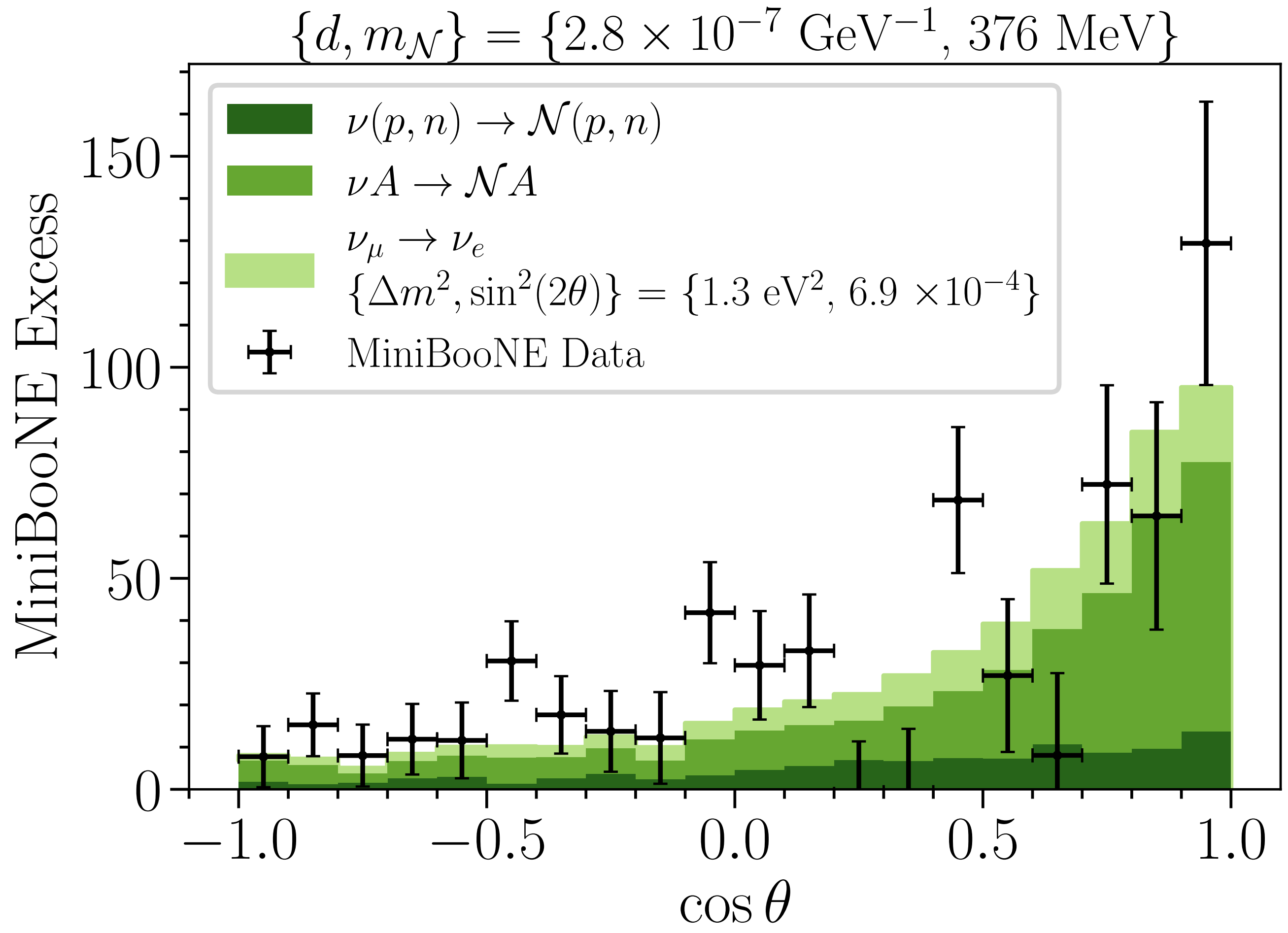




These plots correspond to the dipole parameters that give the best energy fit within the joint 95% CL allowed region

Note: systematic errors are only available for the neutrino energy—the angular fit considers only statistical error

Final Results

Smaller Oscillation Contribution

Larger Oscillation Contribution

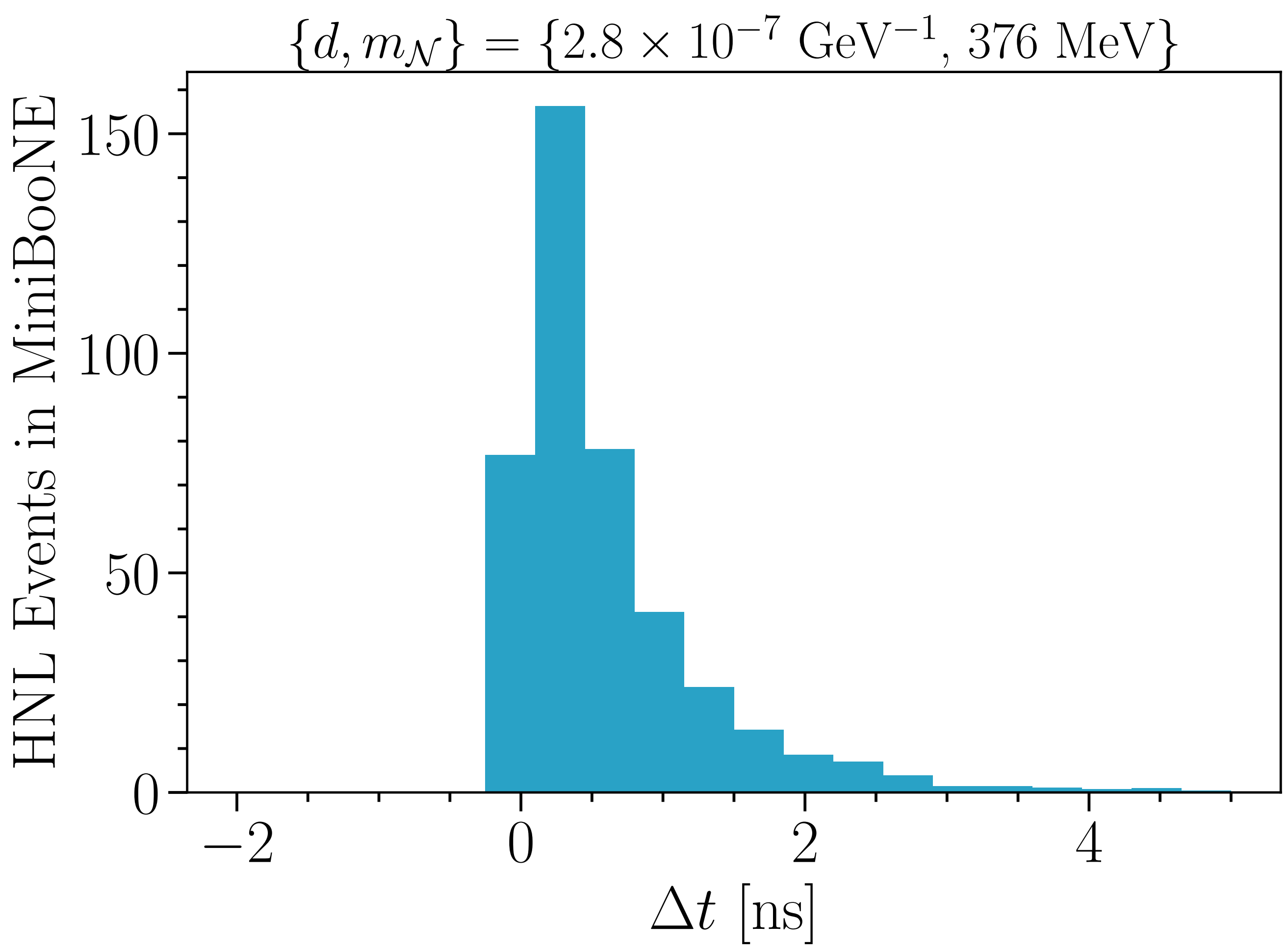
Parameters	χ^2/dof			
$(\sin^2 2\theta, d, m_{\mathcal{N}})$	$3+1+\mathcal{N}$		$3+1$	
	E_ν^{QE}	$\cos\theta$	E_ν^{QE}	$\cos\theta$
(0.30, 3.1, 376)	5.7/8	32.1/18	30.5/10	86.4/20
(0.69, 2.8, 376)	7.9/8	31.4/18	27.3/10	71.8/20
(2.00, 5.6, 35)	20.2/8	36.7/18	27.6/10	40.8/20
(0, 0, 0)	34.1/10	99.4/20	same	same

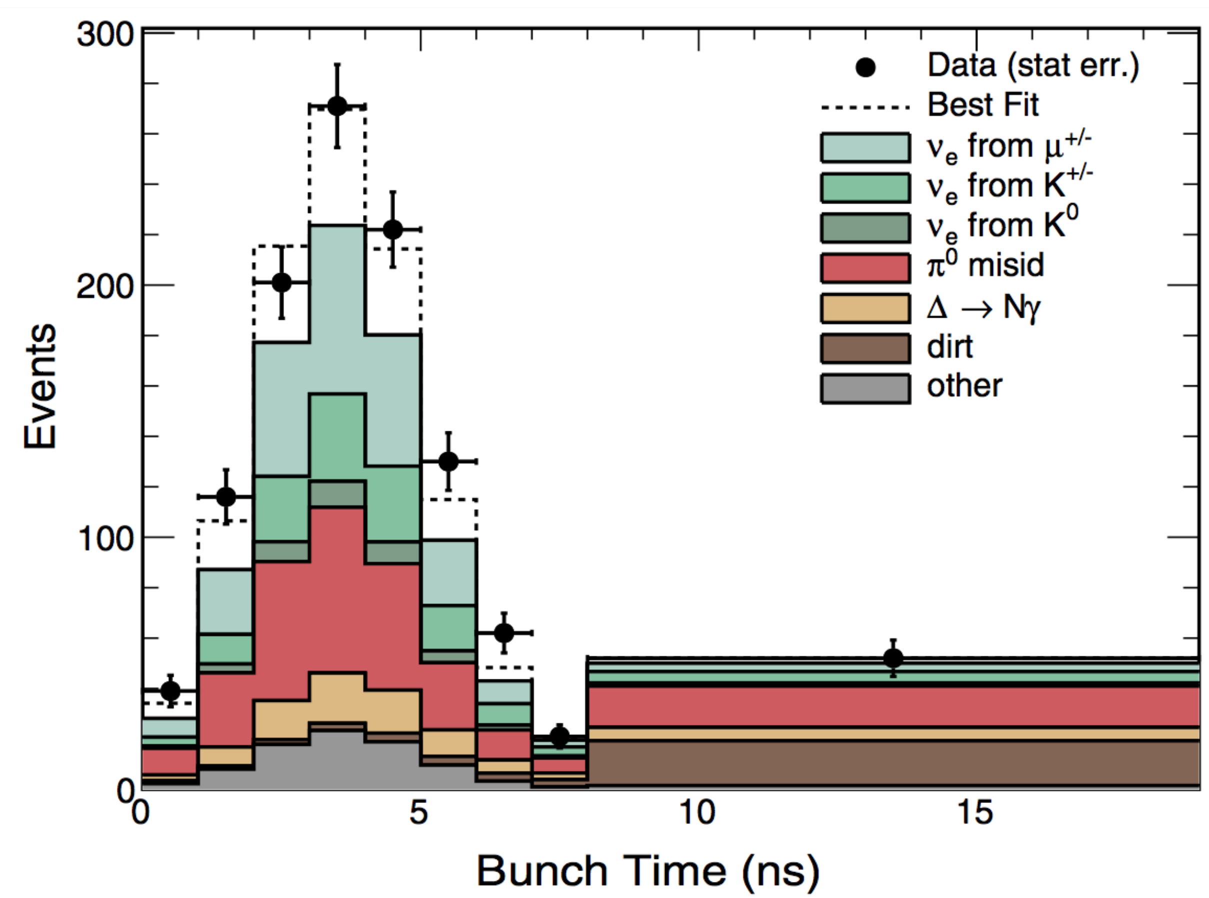
TABLE II. χ^2/dof values for $3+1$ and $3+1+\mathcal{N}$-decay models obtained by comparing expectations to the MiniBooNE excess in E_ν^{QE} and $\cos\theta$. The parameters in column one refer to $(\sin^2 2\theta_{\mu e} \times 10^{-3}$, $d \times 10^{-7}$ [GeV^{-1}], $m_{\mathcal{N}}$ [MeV]). The mass splitting is 1.32 eV^2 in all cases. The null case (no oscillations and no HNL decay) is also shown in the last row.

Takeaway: the 3+1+HNL decay model gives a good fit to the MiniBooNE energy and angular distributions while also relieving tension in the global 3+1 picture

Cross Check: Timing

- MB excess lives within ~4 ns of the proton beam bunch timing
- Simple timing delay calculations are well within those constraints
- Motivates further investigation by MB collaboration



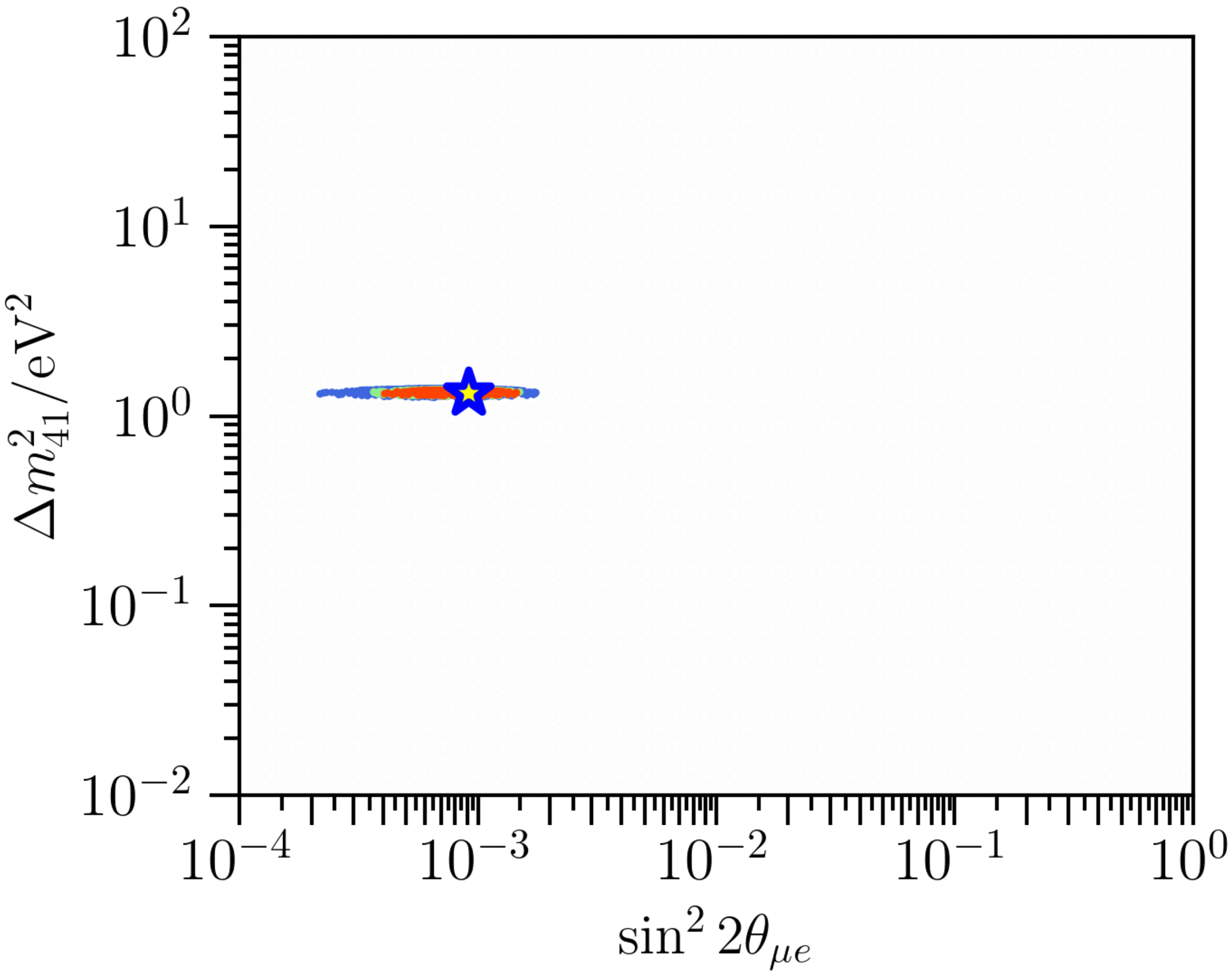


Conclusion

- The exclusion of MiniBooNE from the 3+1 model global fit relieves tension between appearance and disappearance experiments
- The combination of oscillations from the MiniBooNE-less 3+1 fit with HNL decays via a dipole model gives a good fit to the energy and angular distributions of the MiniBooNE excess
- This results in a highly predictive HNL dipole model which evades existing experimental limits and can be tested by future experiments
- Preprint available now: 2105.06470

Oscillation Amplitude Range

- The 3+1 fit without MB gives a very tight fit on the mass-squared splitting, but gives a 90% CL allowed range on the oscillation amplitude of roughly [0.0003, 0.002]
- We perform the same HNL dipole fit for each end of this allowed range

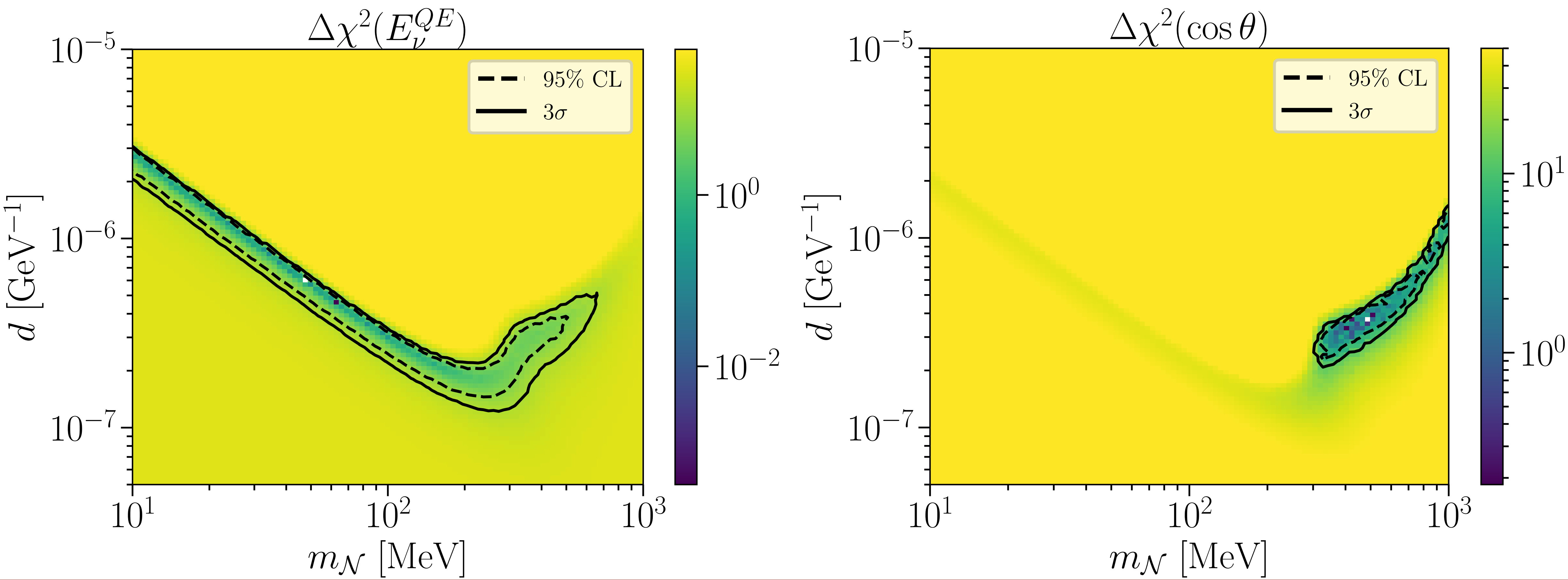


Smaller Oscillation Contribution

$\Delta m^2 = 1.3\,\mathrm{eV}^2$

$\sin^2(2\theta_{\mu e}) = 3 \times 10^{-4}$

- Results are similar to the best fit oscillation amplitude case



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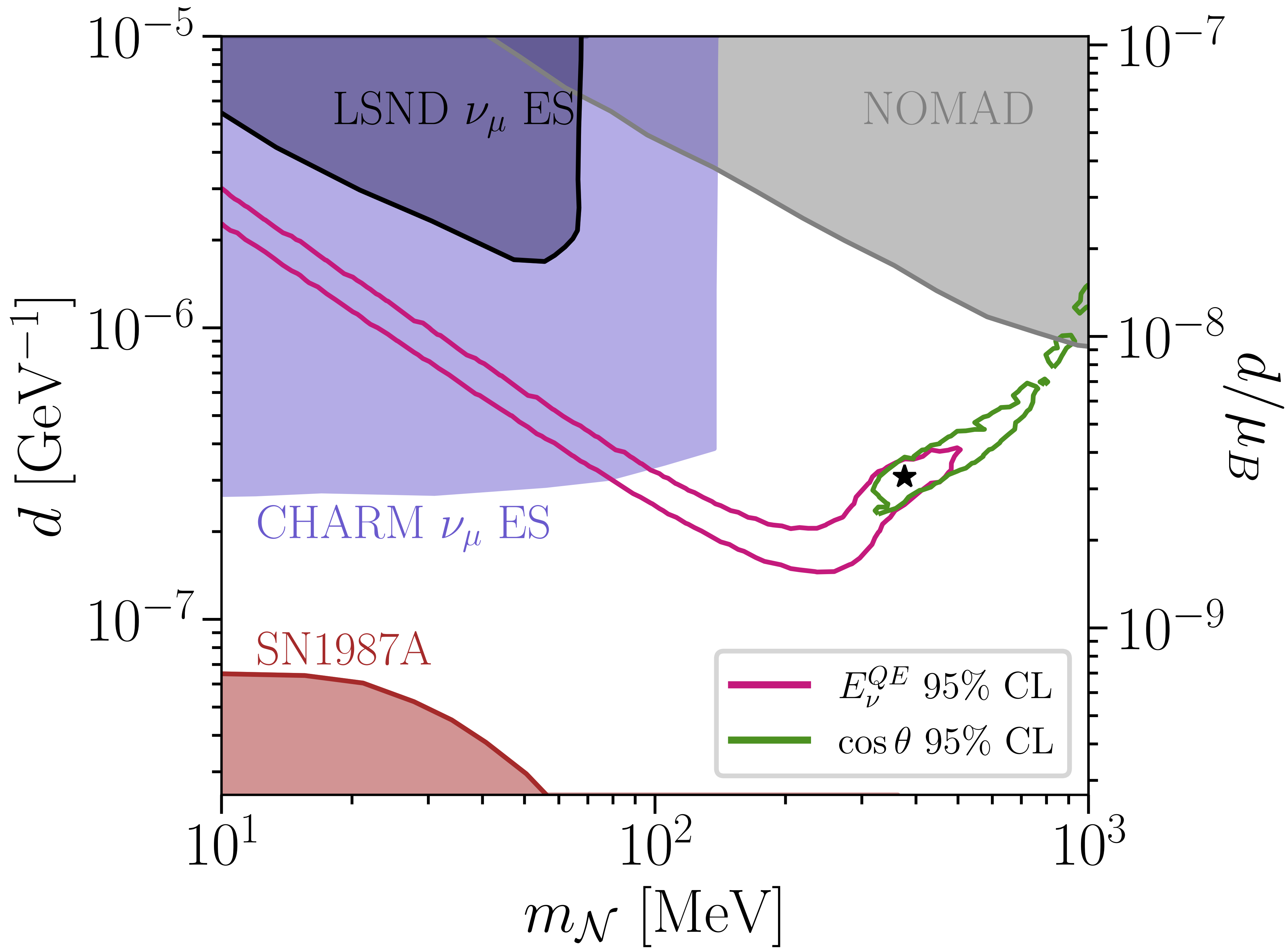

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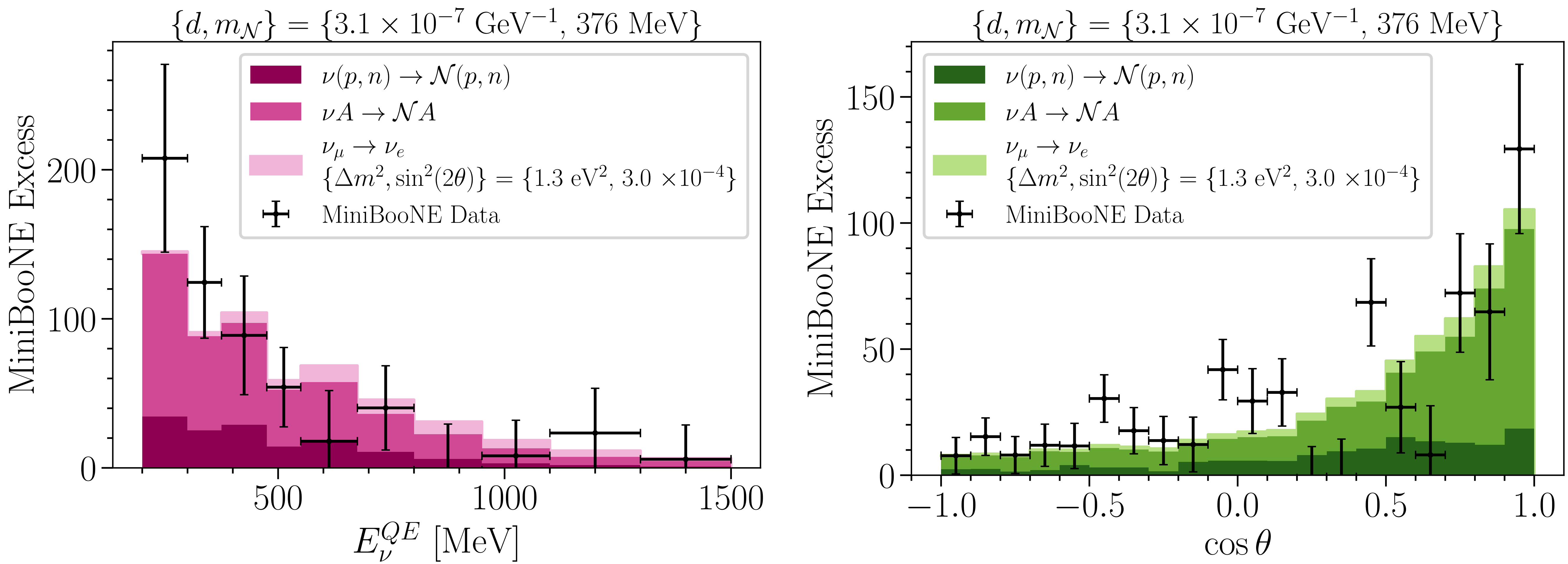


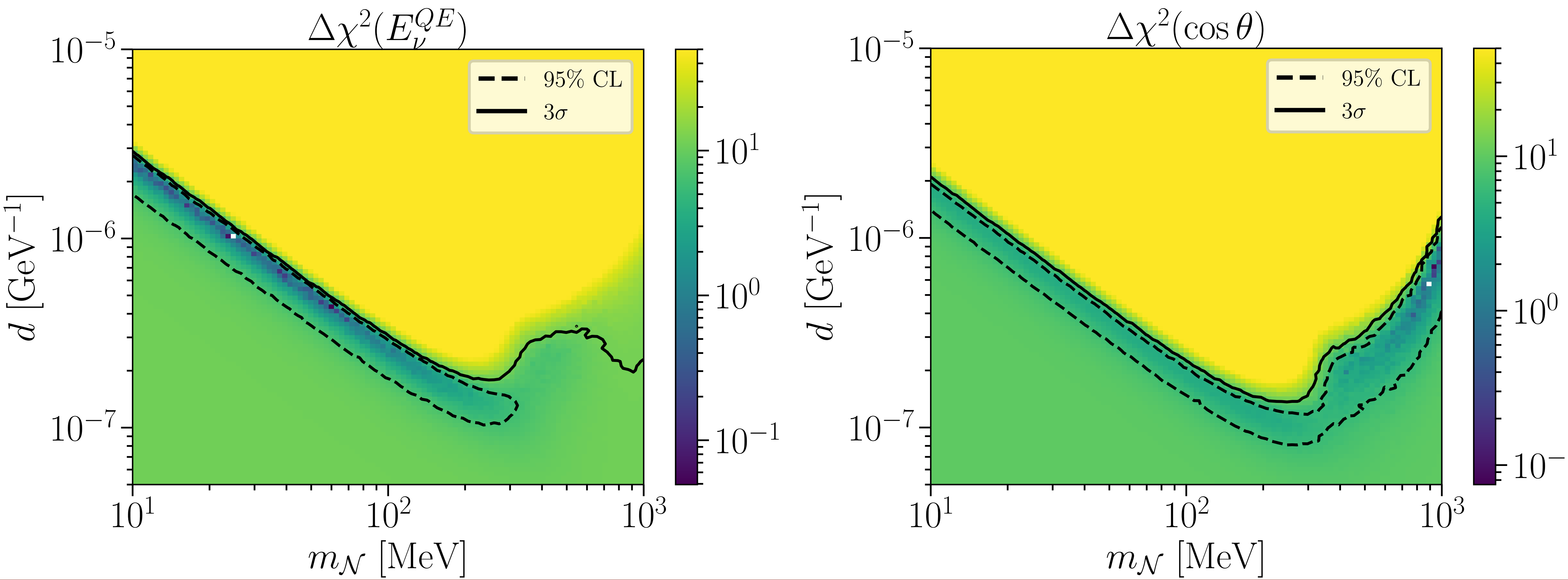
Slightly larger dipole coupling preferred compared to the best fit oscillation amplitude case

Larger Oscillation Contribution

$$\Delta m^2 = 1.3\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{\mu e}) = 2 \times 10^{-3}$$

- Results are quite different here—no closed contours at the three sigma level



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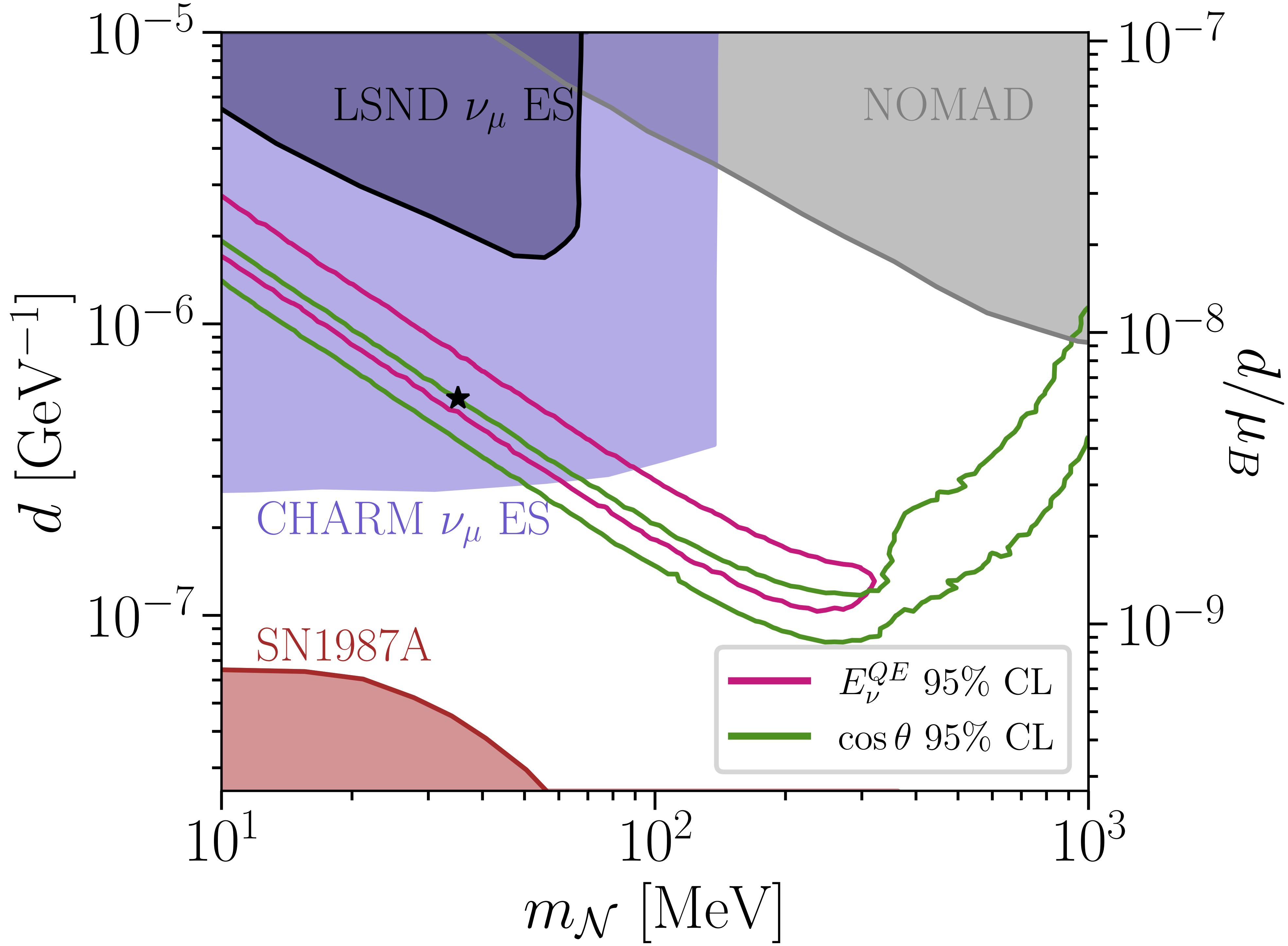

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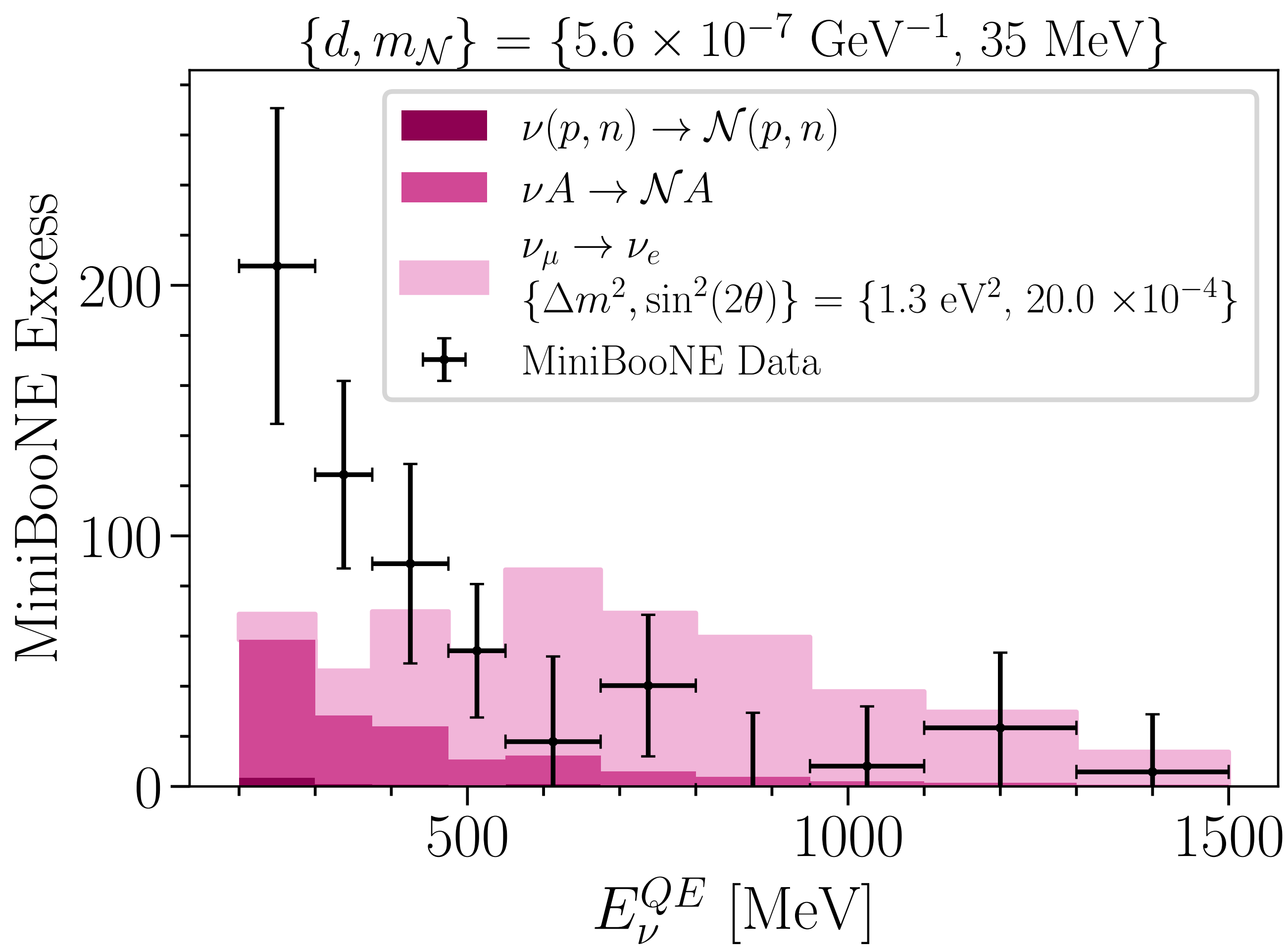
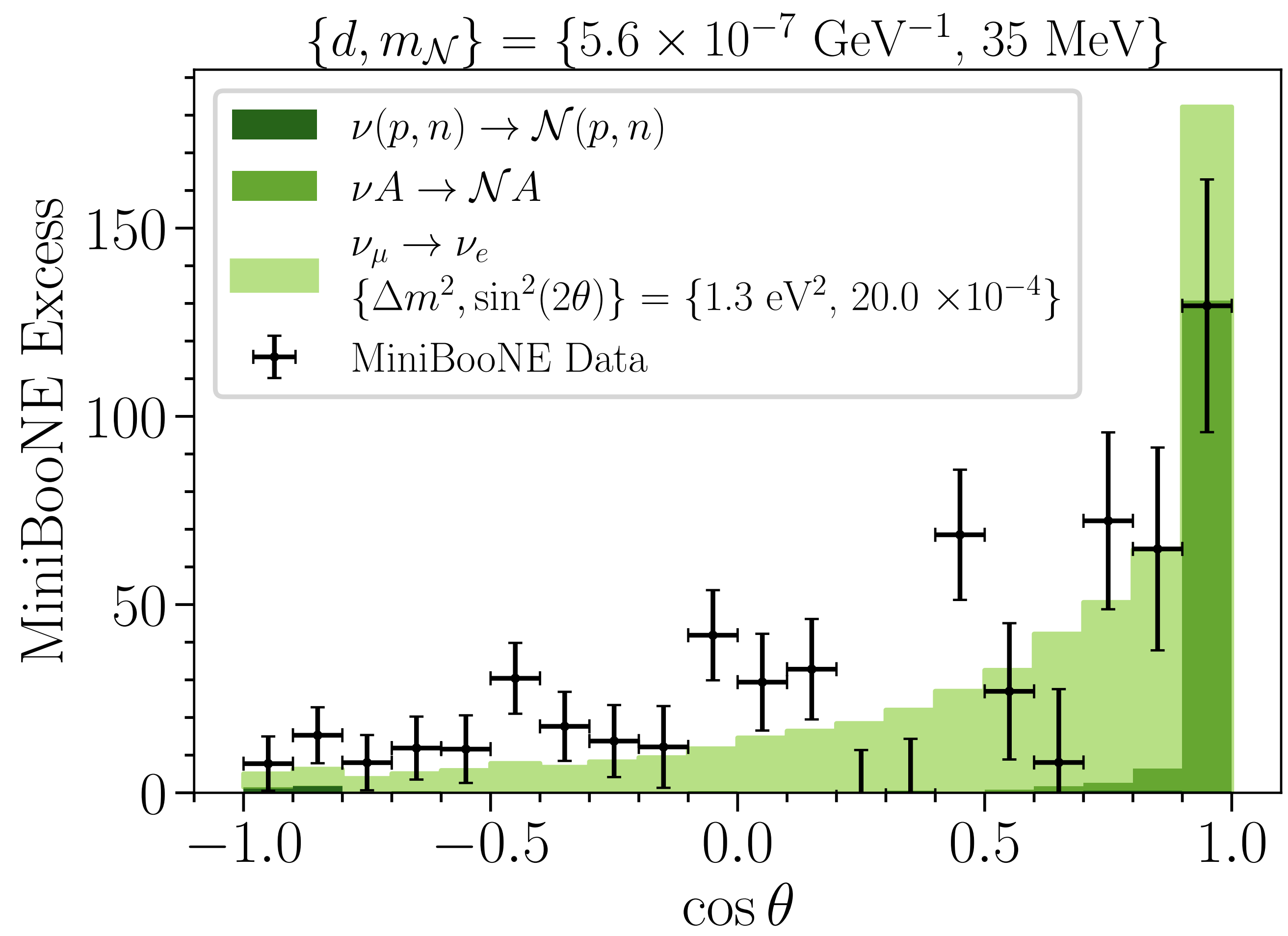
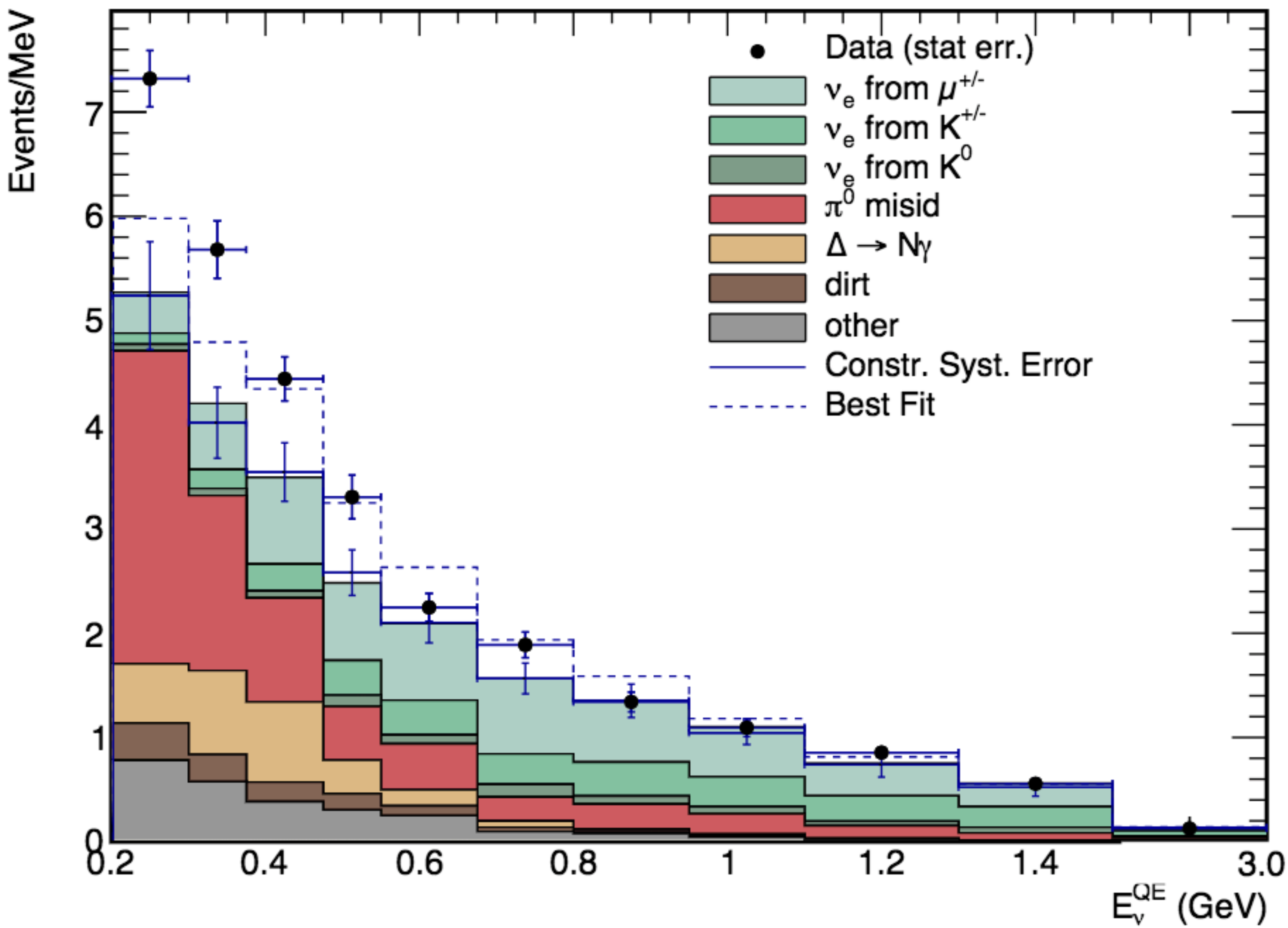
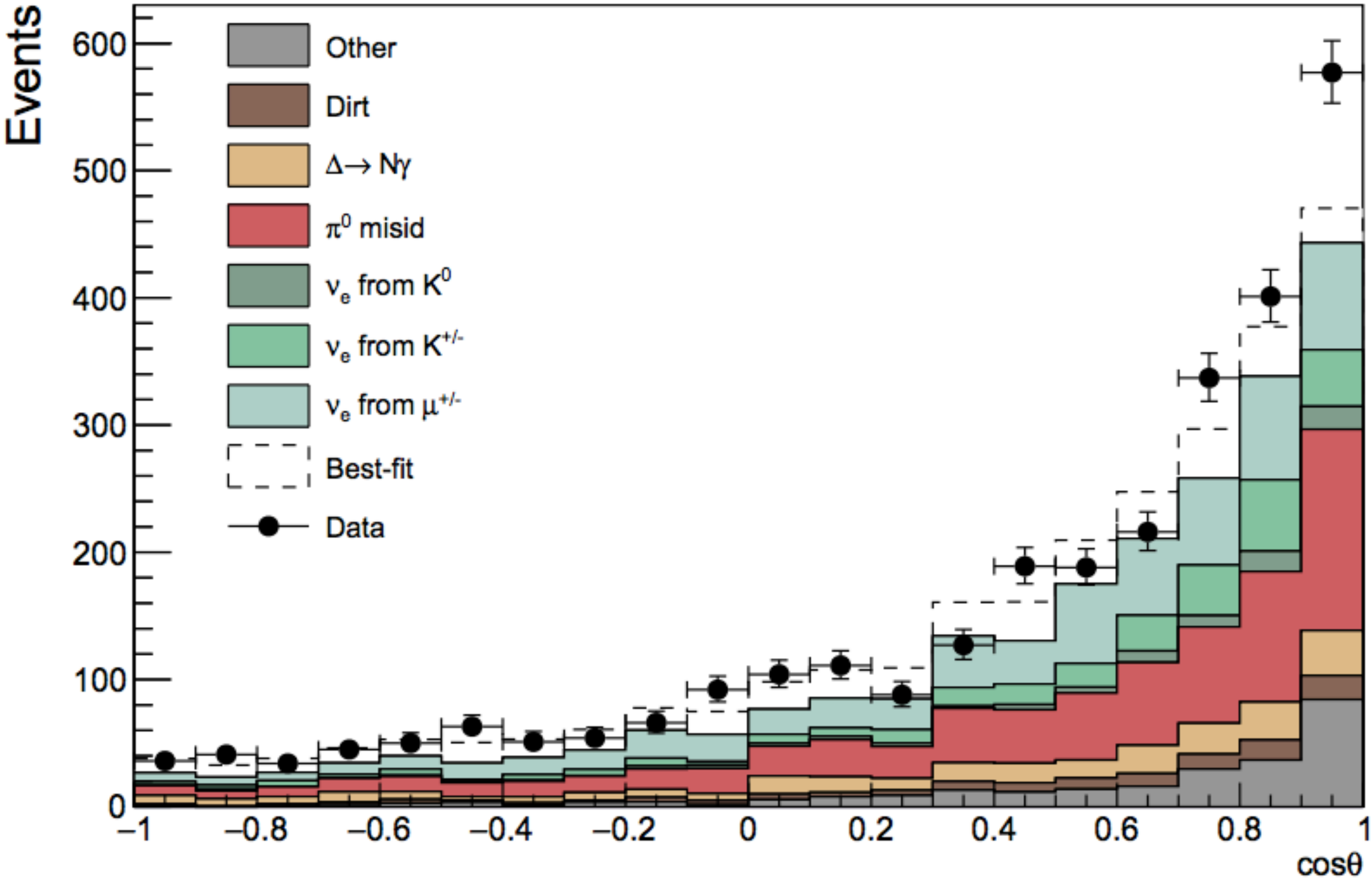
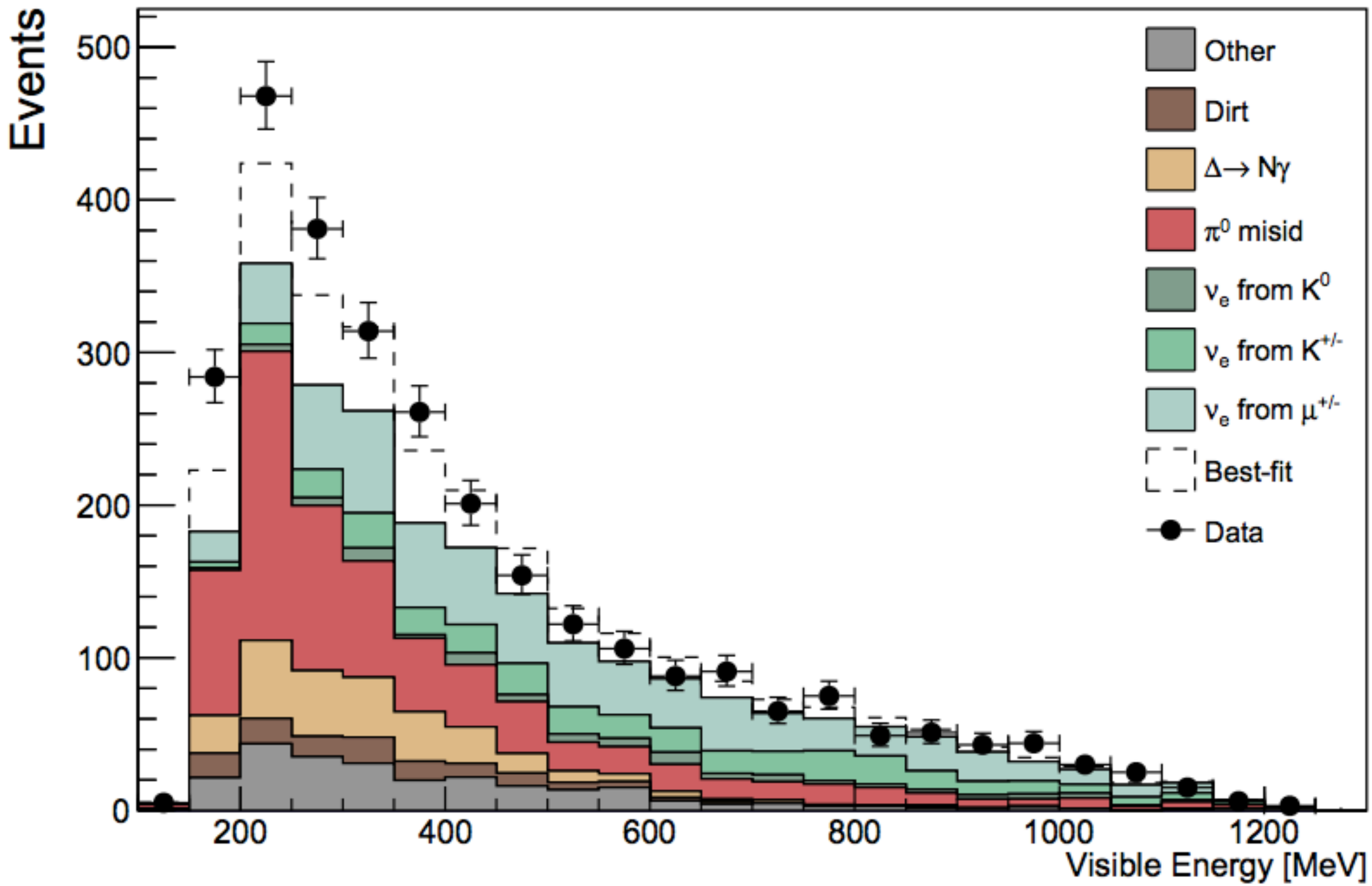




Preference for a smaller HNL mass here, but fits are worse in general


Events/MeV
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
3.0
E_ν^{QE} (GeV)
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Best Fit


Events
600
500
400
300
200
100
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cosθ
Other
Dirt
Δ→ Nγ
π^0 misid
ν_e from K^0
ν_e from $K^{+/-}$
ν_e from $\mu^{+/-}$
Best-fit
Data



Events
500
400
300
200
100
0
200
400
600
800
1000
1200
Visible Energy [MeV]
Other
Dirt
Δ→ Nγ
π^0 misid
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