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

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Based on our preprint: 2105.06470

Overview

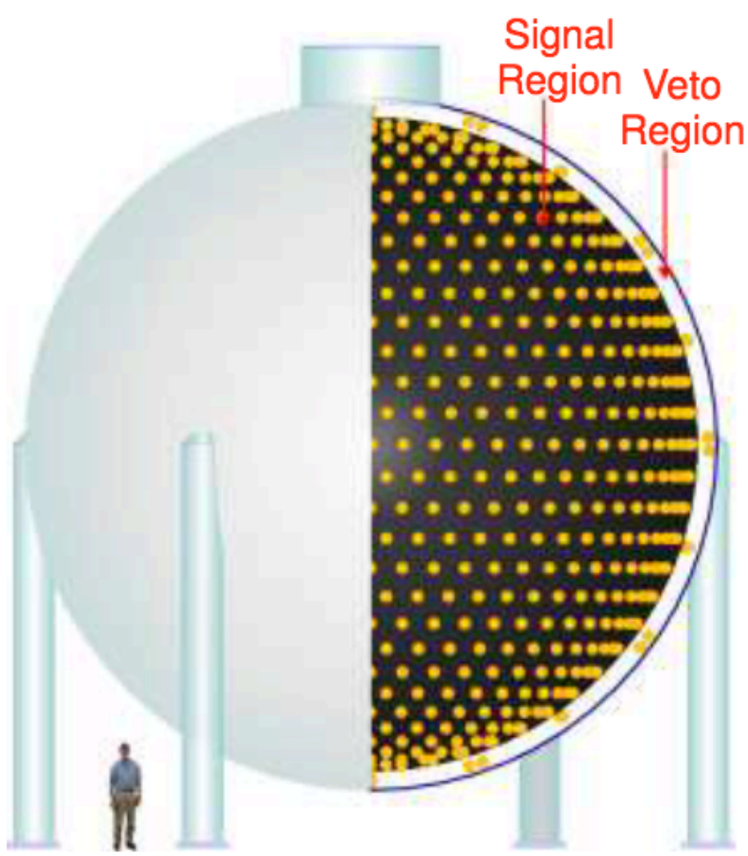
- Tension in eV-scale oscillation global fits
- The HNL dipole model
- MiniBooNE fit results

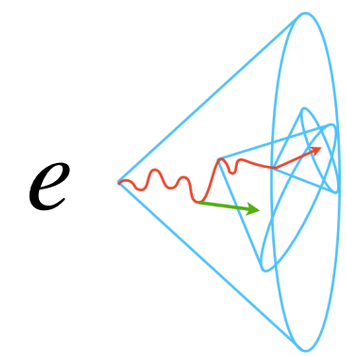
Overview

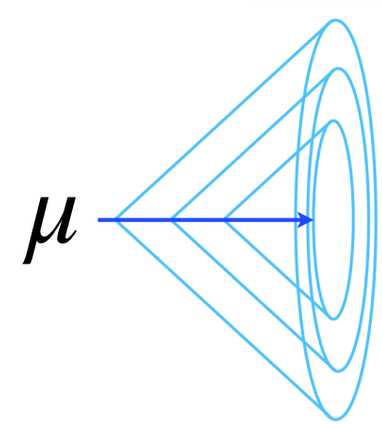
- **Tension in eV-scale oscillation global fits**
- The HNL dipole model
- MiniBooNE fit results

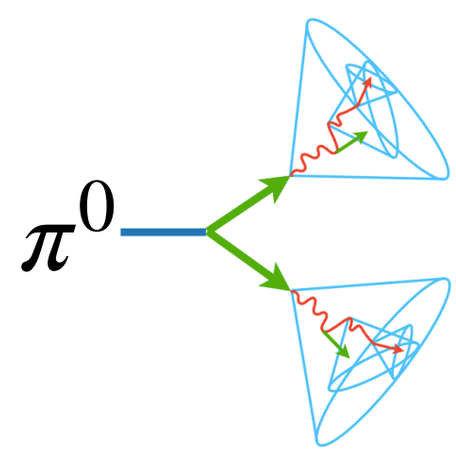
The MiniBooNE Experiment

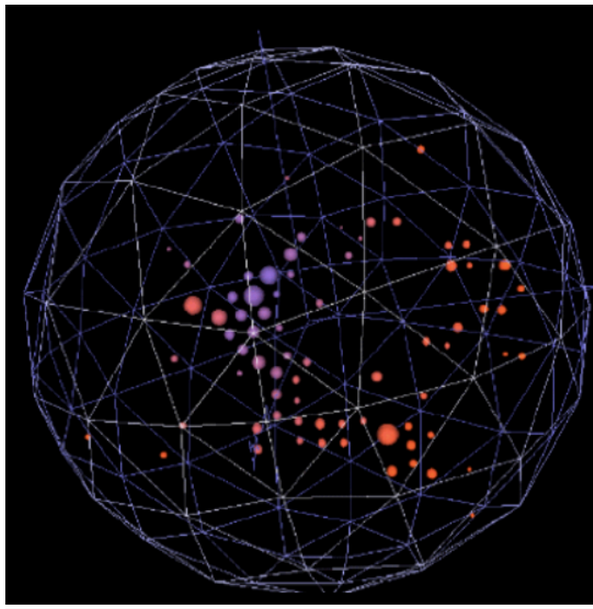
- 818 ton CH_2 Cherenkov detector at Fermilab's Booster Neutrino Beam
- 4.8σ excess of electron-like events in complete neutrino-mode dataset

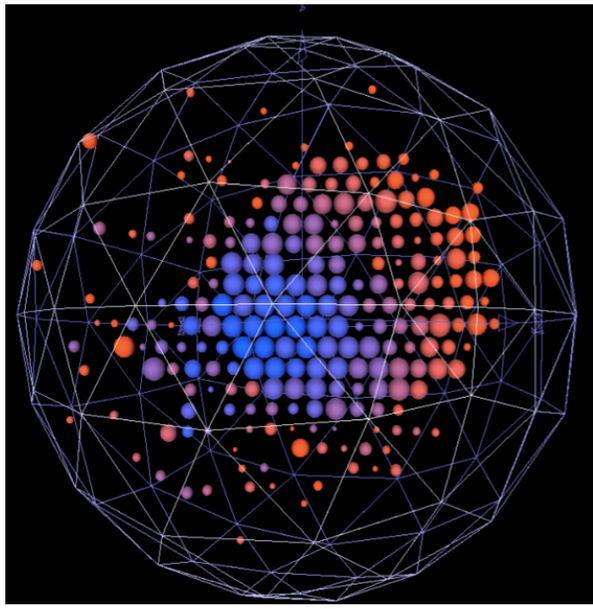


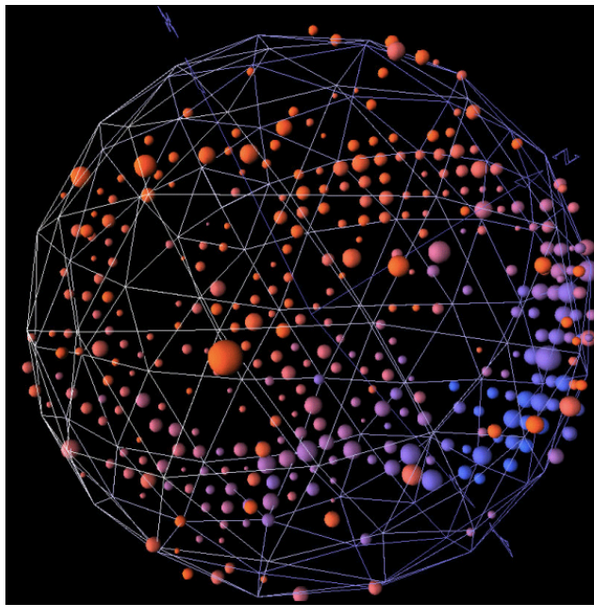






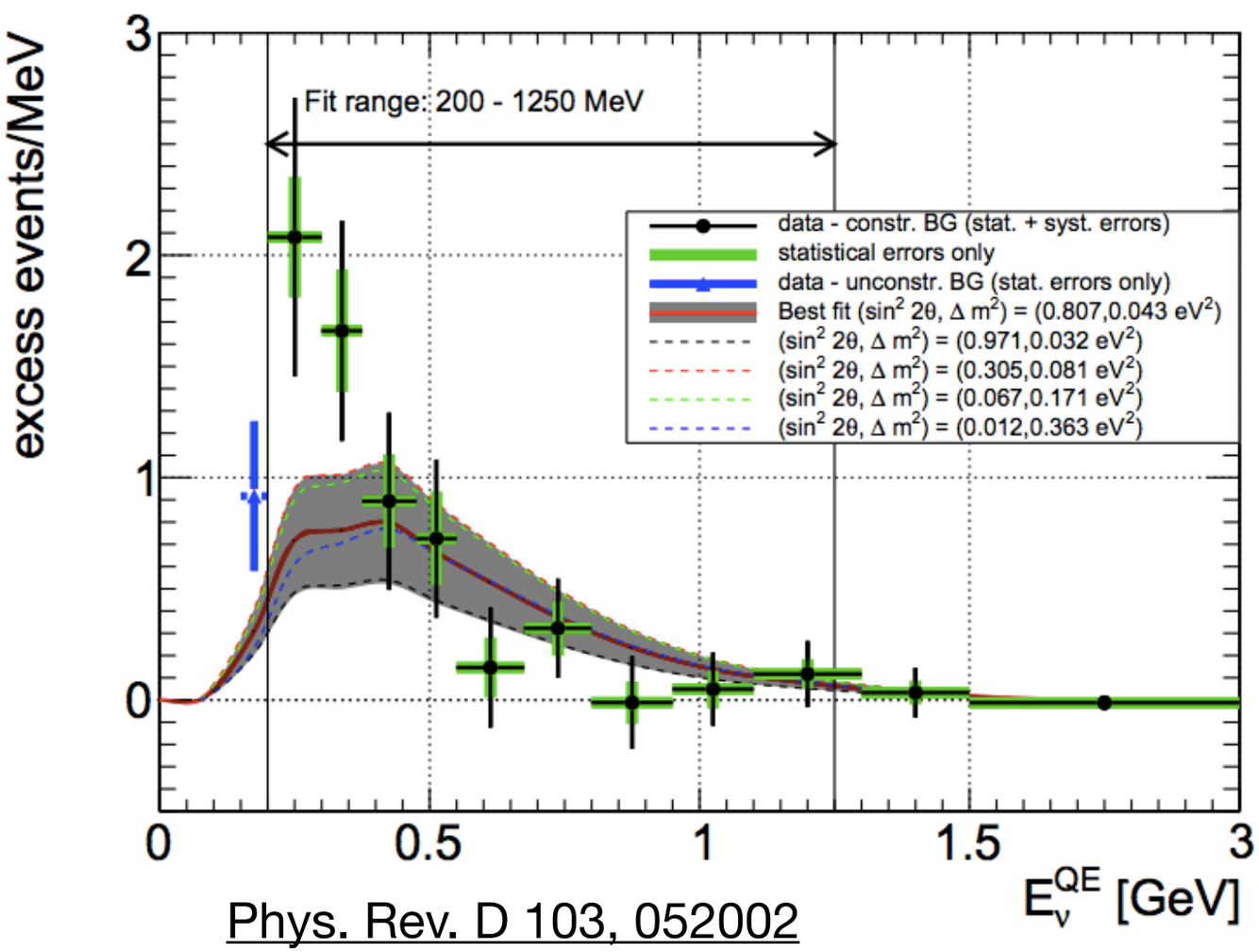




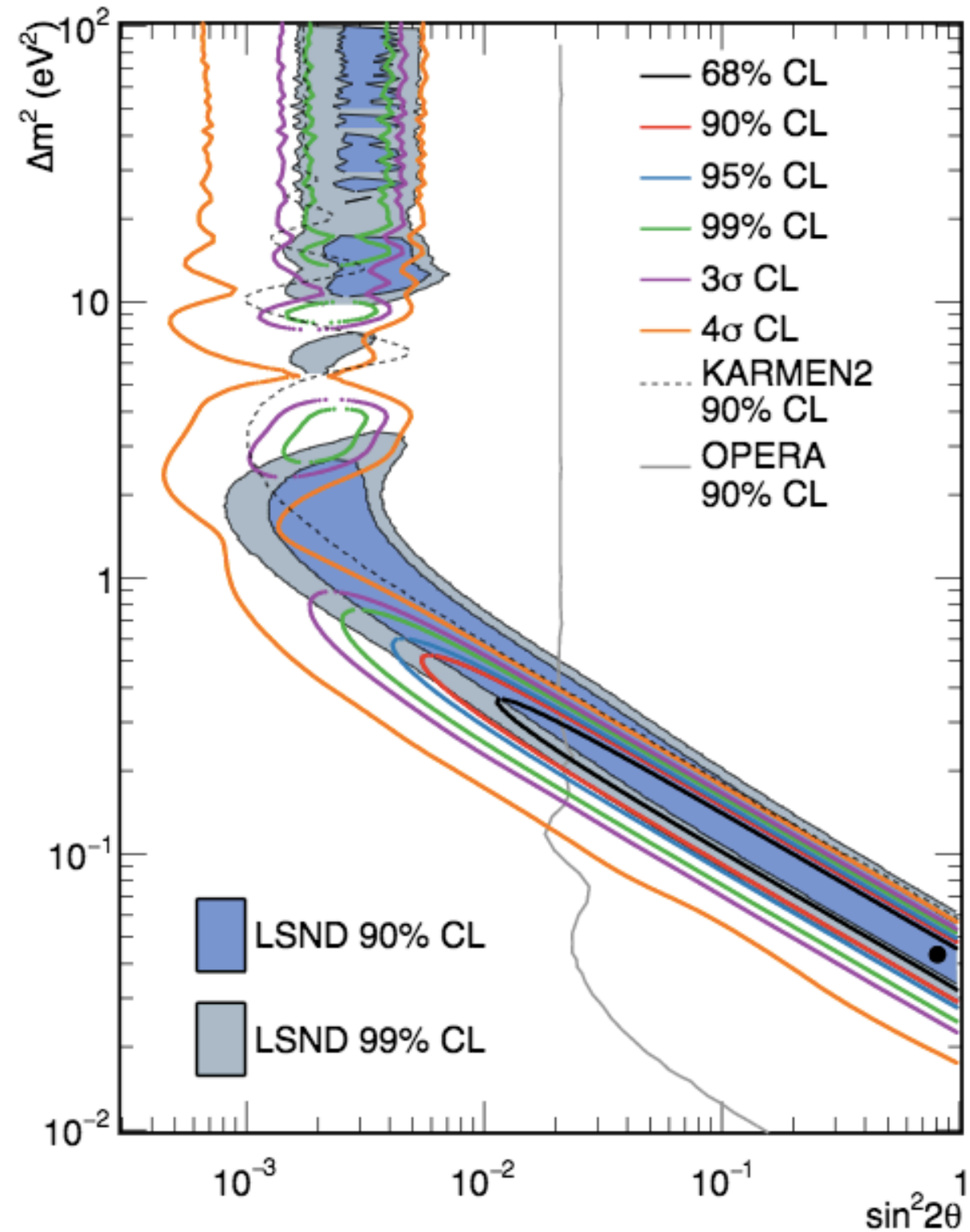


eV-scale Sterile Oscillations

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

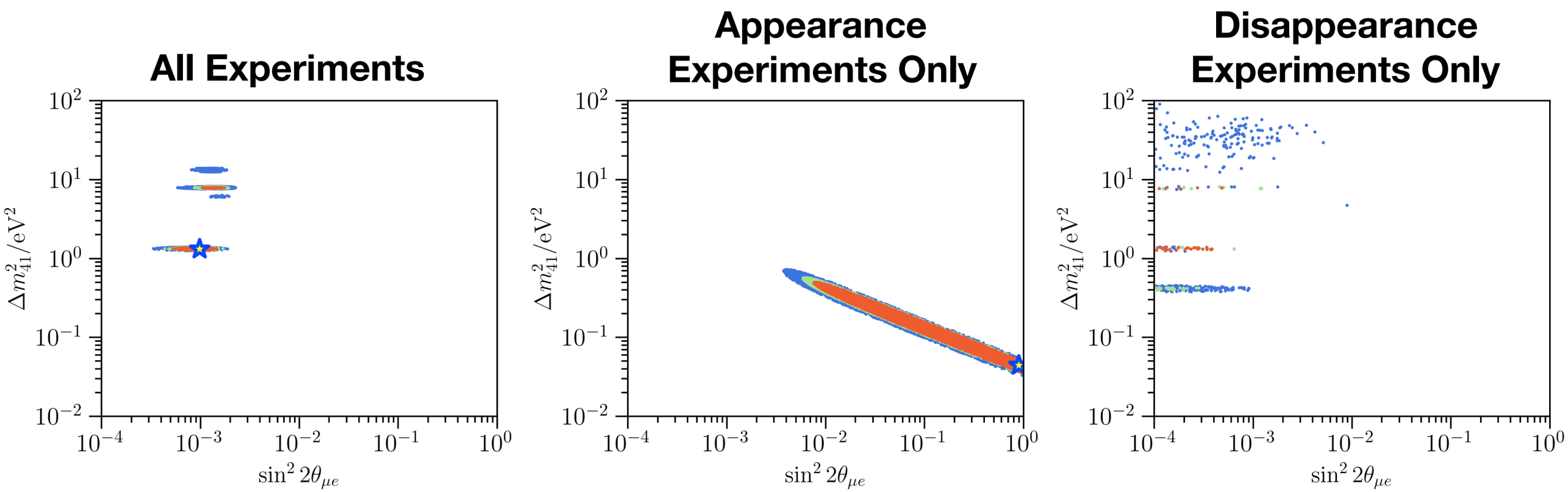


Phys. Rev. D 103, 052002



Global Fit Tension

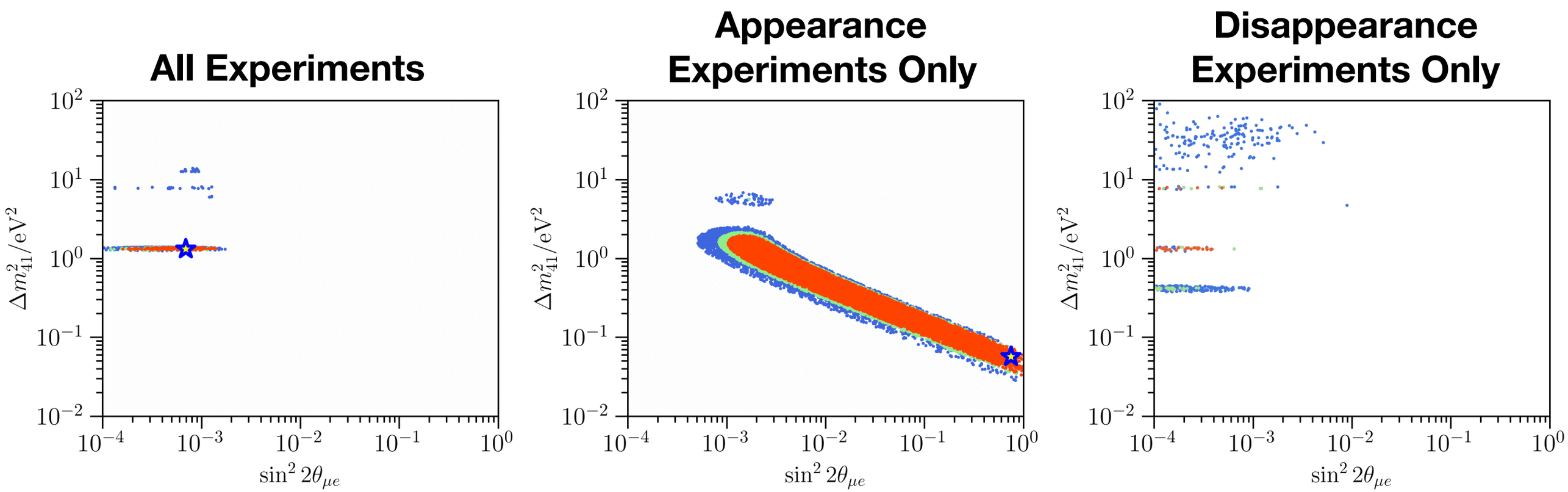
- One can look for the effect of such a sterile neutrino in other ν_e appearance experiments (e.g. LSND), ν_e disappearance experiments (e.g. reactors), and ν_μ disappearance experiments (e.g. long baseline accelerators)



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

Global Fits Without MiniBooNE

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

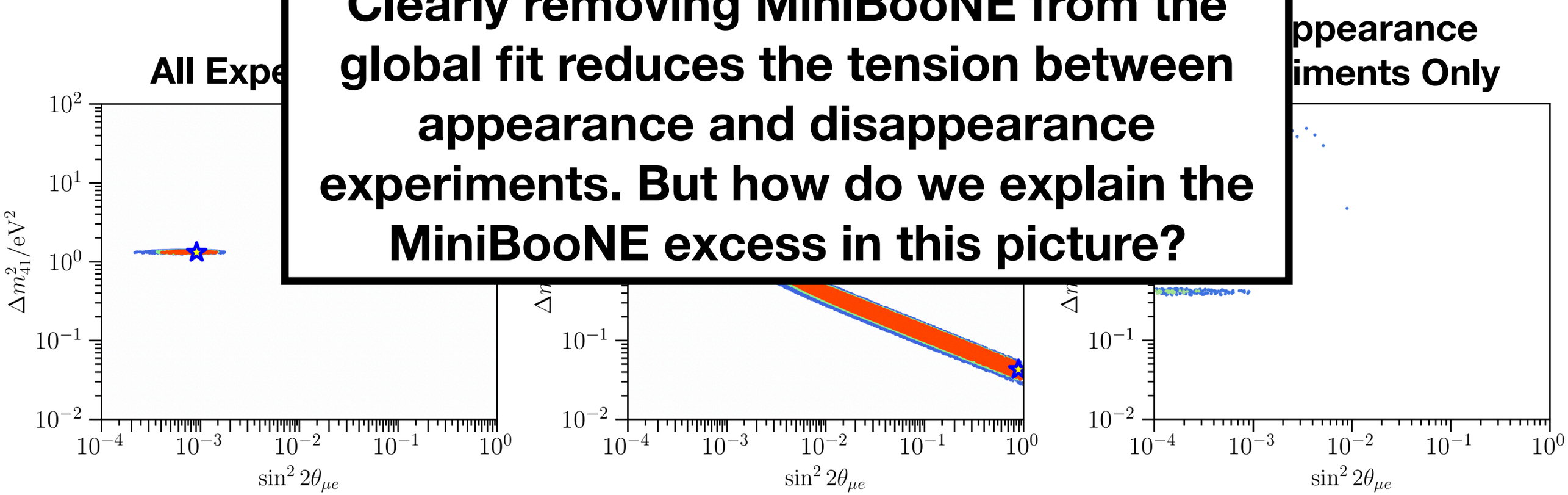


$$p_{\mathrm{PG}}^{\mathrm{w/o\,MiniBooNE}} = 7 \times 10^{-3}\,(2.5\sigma)$$

Global Fits Without MiniBooNE

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

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?



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

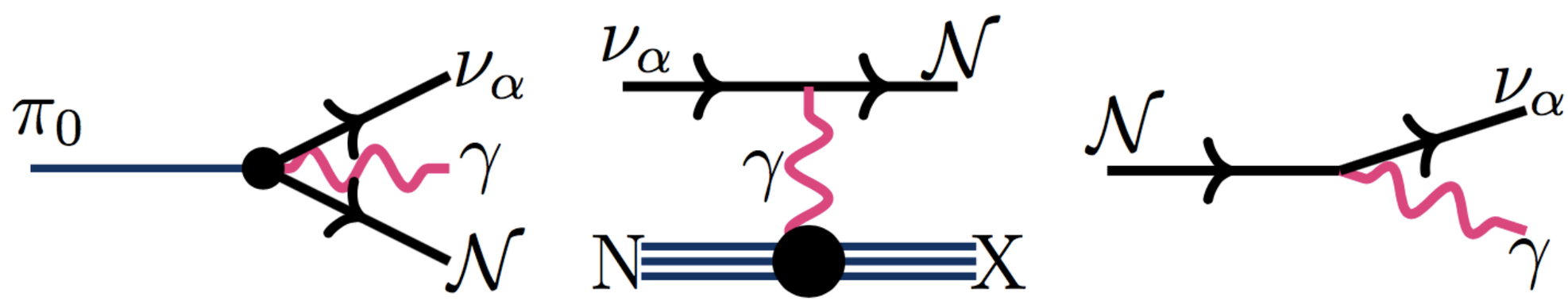
Overview

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

Dipole + Oscillation Model

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

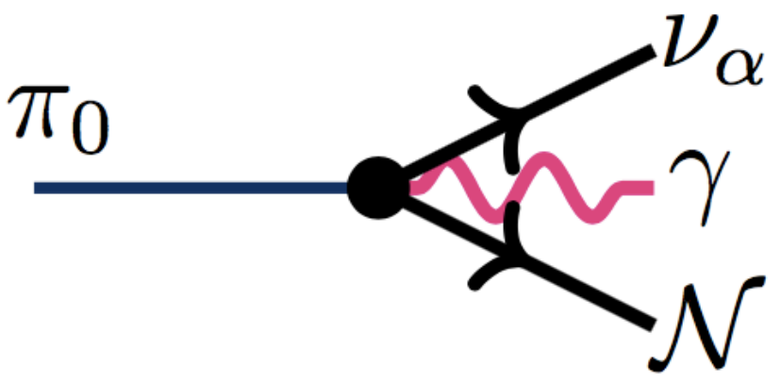
- We only consider oscillations involving the lightest HNL, as the masses of the other two are assumed to be too large
- The dipole term introduces the interactions shown below, where we define $\mathcal{N} \equiv \mathcal{N}_3$



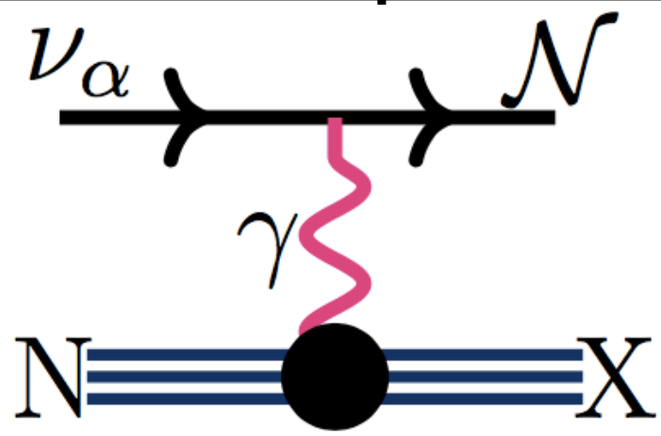
Other dipole portal studies: Phys. Rev. Lett. 45, 963 (1980), Phys. Rev. D 25, 766 (1982), Phys. Rev. D 98, 115015, JHEP09(2005)048, JHEP01(2013)106, 2105.09699

HNLs In MiniBooNE

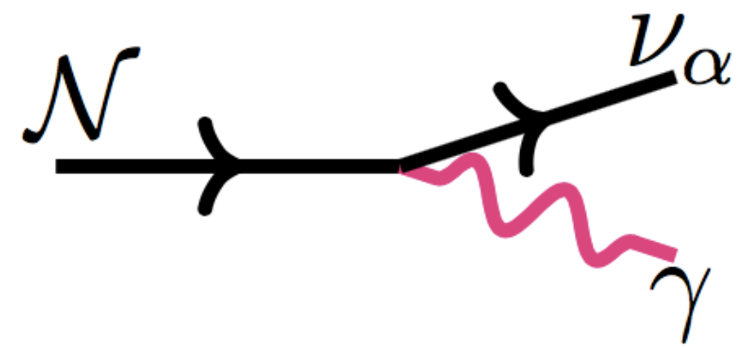
1: Dalitz-like Pion Decay

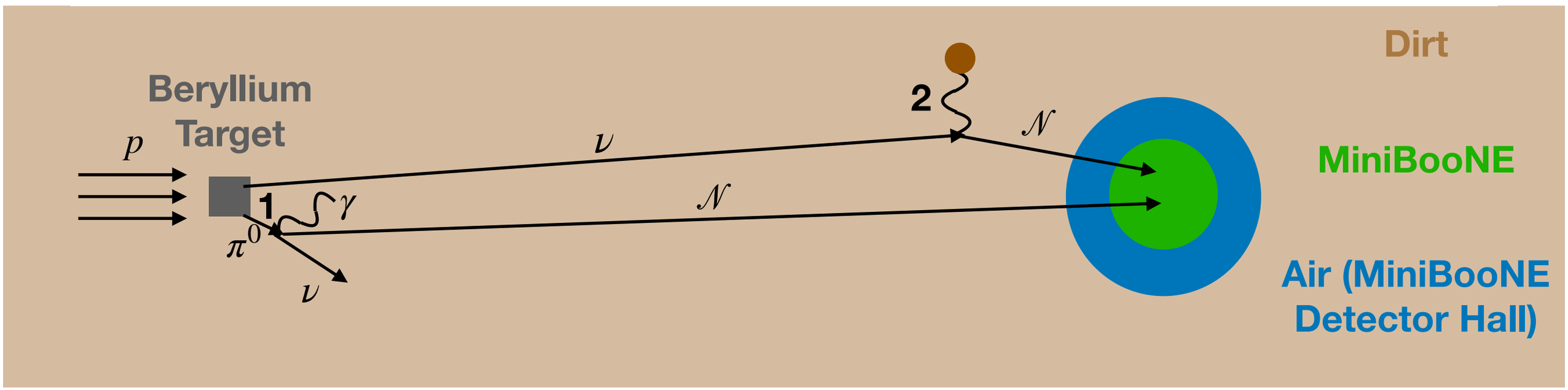


2: Primakoff Upscattering



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

HNLs In MiniBooNE

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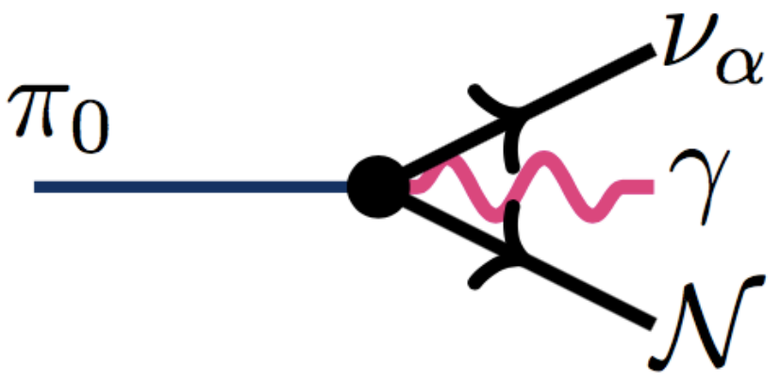

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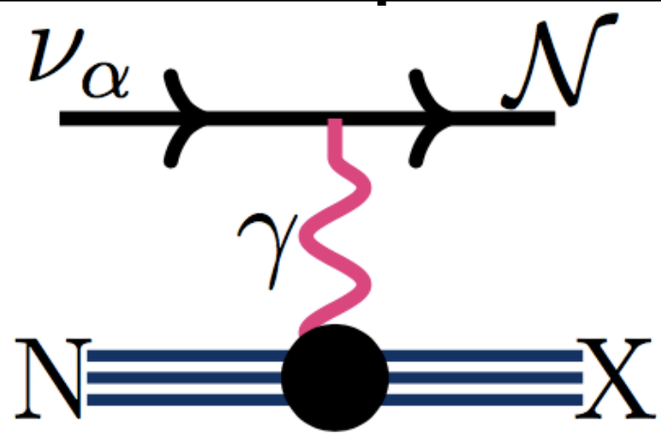

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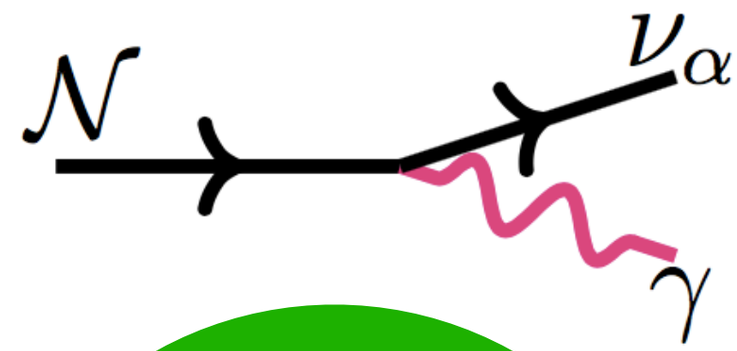
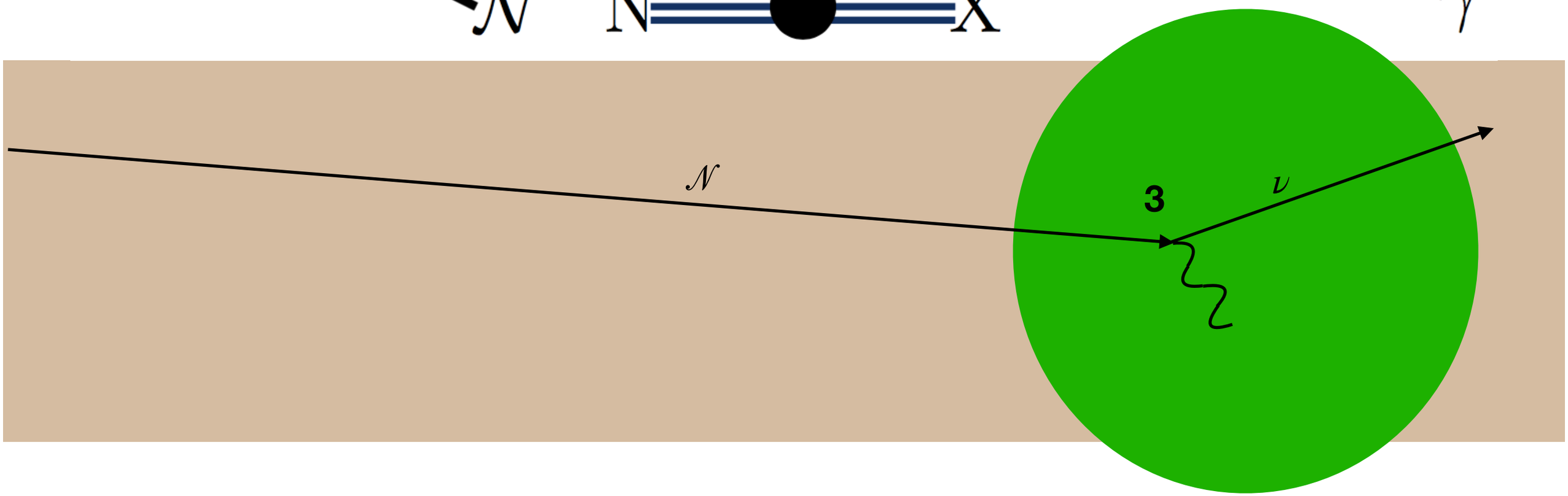




As electrons and photons are indistinguishable in MiniBooNE, this decay would contribute to the electron-like excess

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

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

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

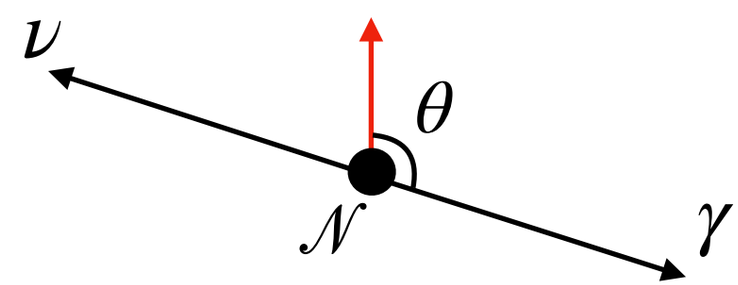
Simulation Details: Decay

- 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

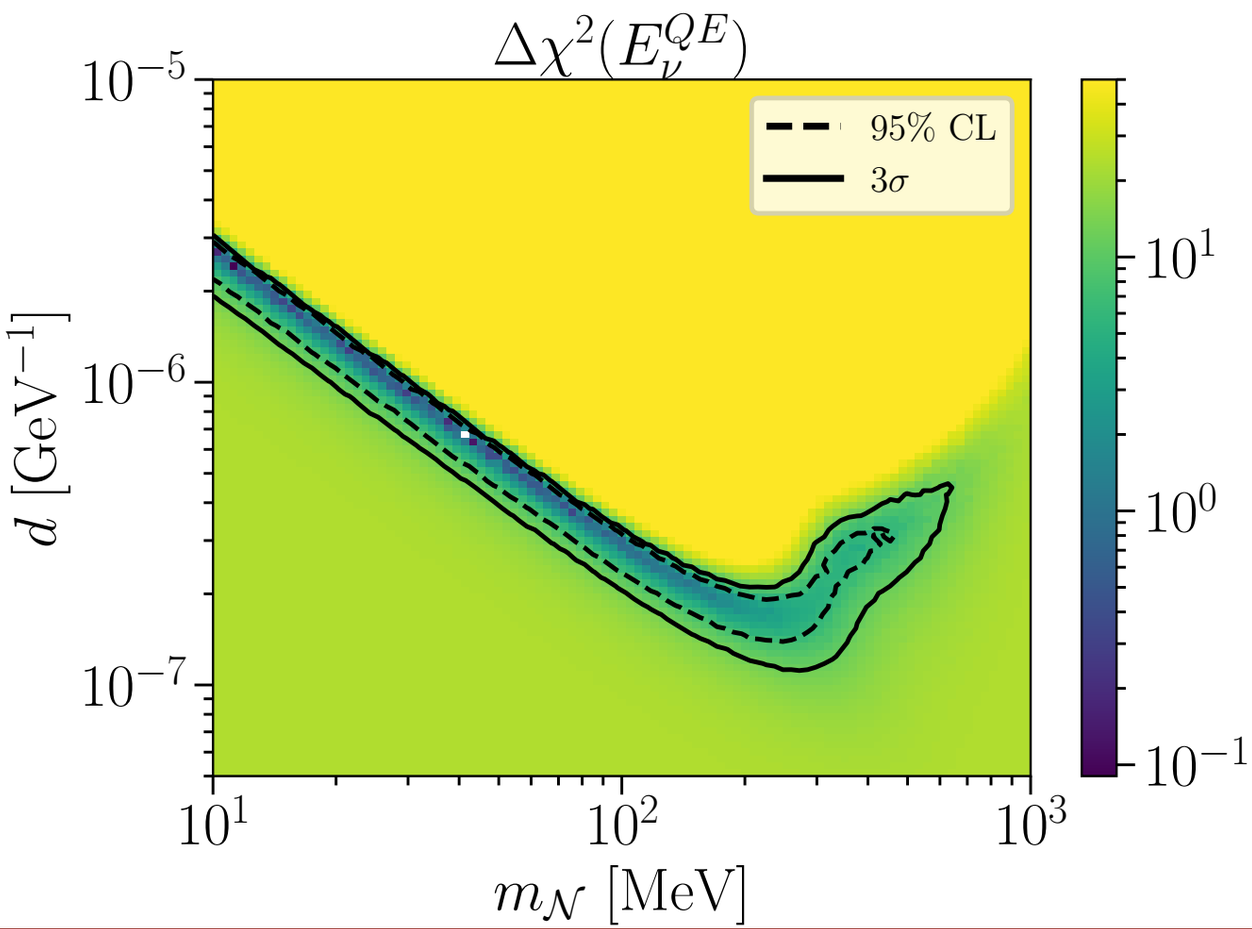
- Tension in eV-scale oscillation global fits
- The HNL dipole model
- **MiniBooNE fit results**

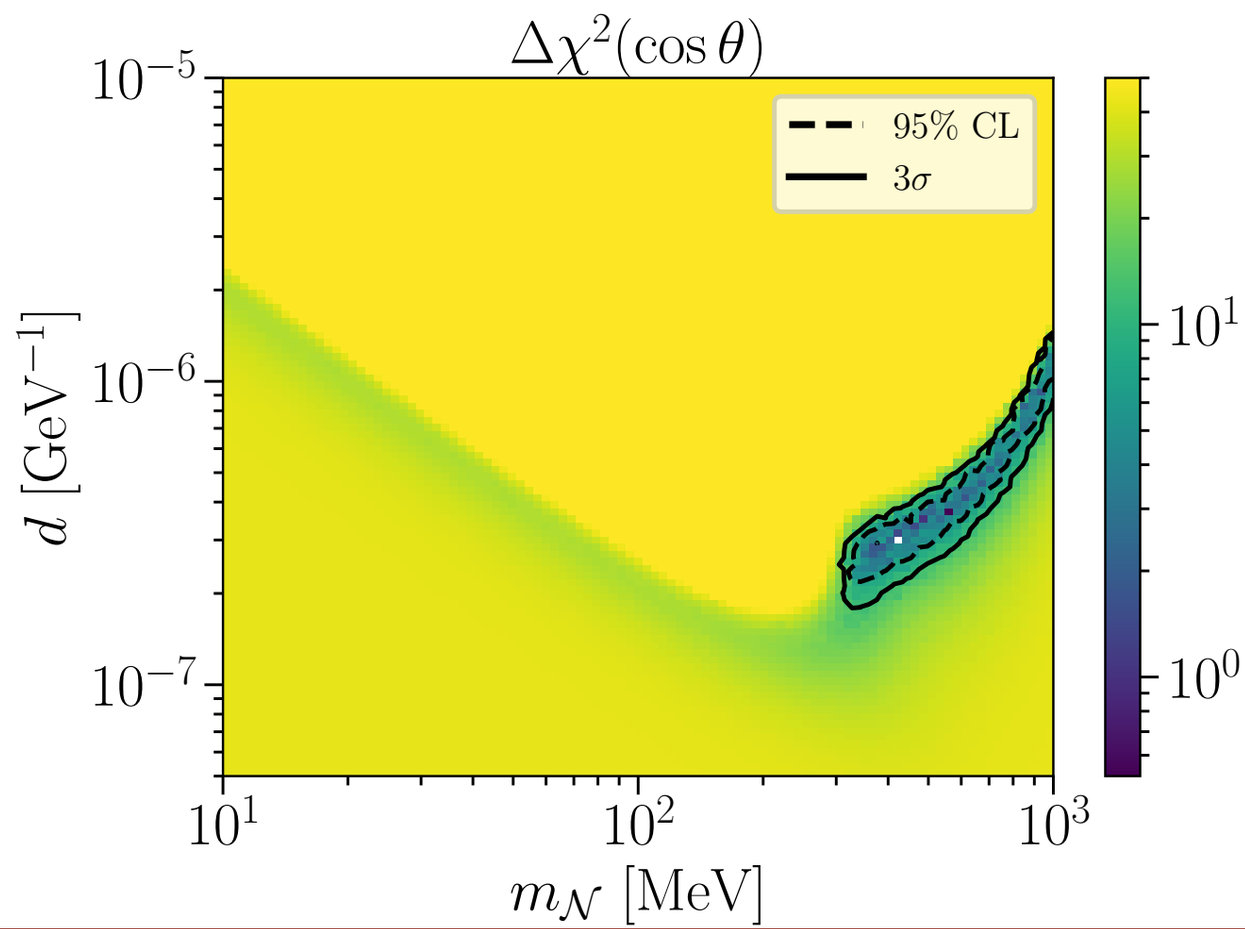
Energy and Angular Fits

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

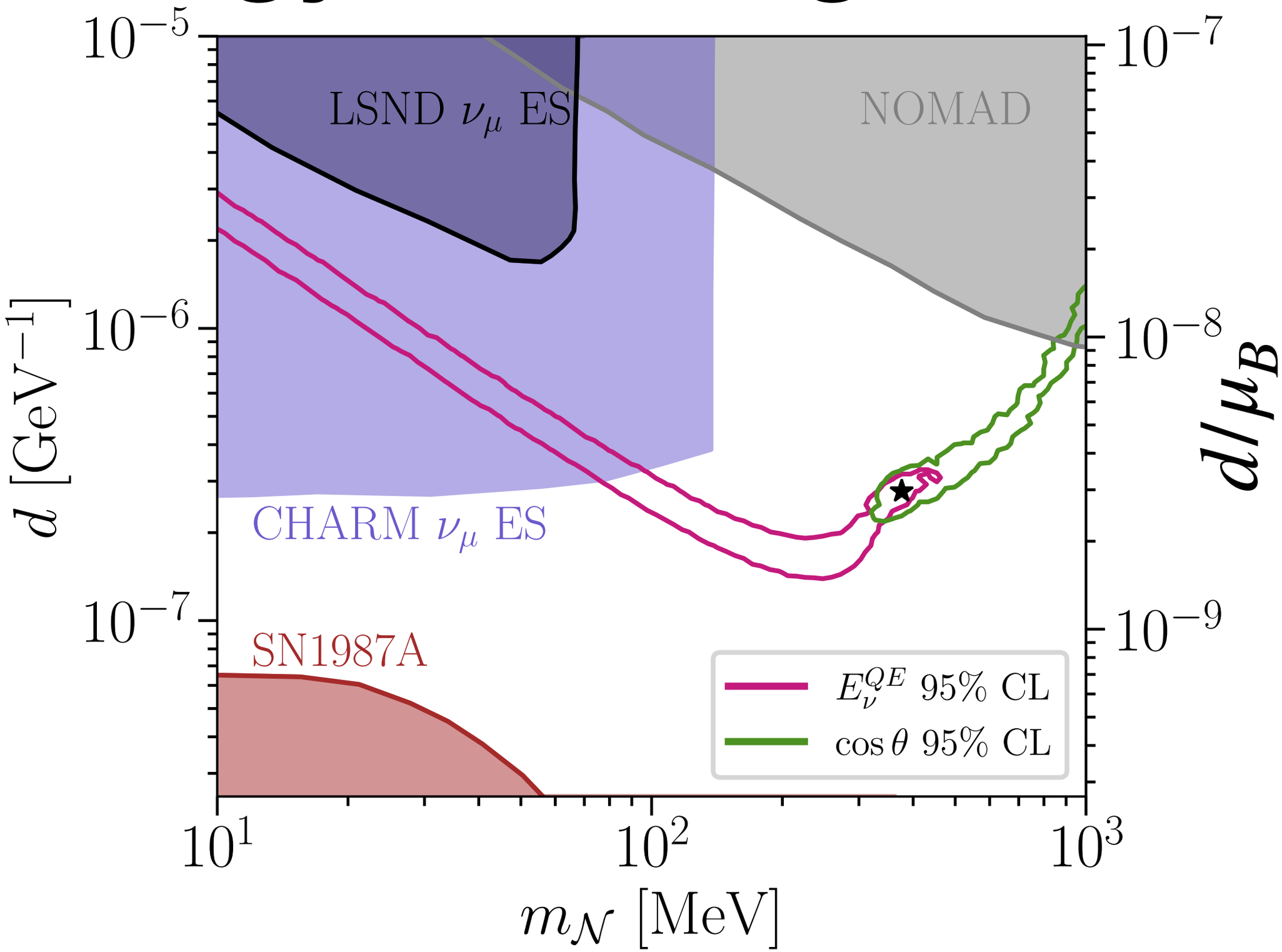
$$\Delta m^2 = 1.3\,\mathrm{eV}^2 \qquad \sin^2(2\theta_{\mu e}) = 6.9 \times 10^{-4}$$

- The remaining excess is fit to the HNL dipole contribution





Energy and Angular Fits



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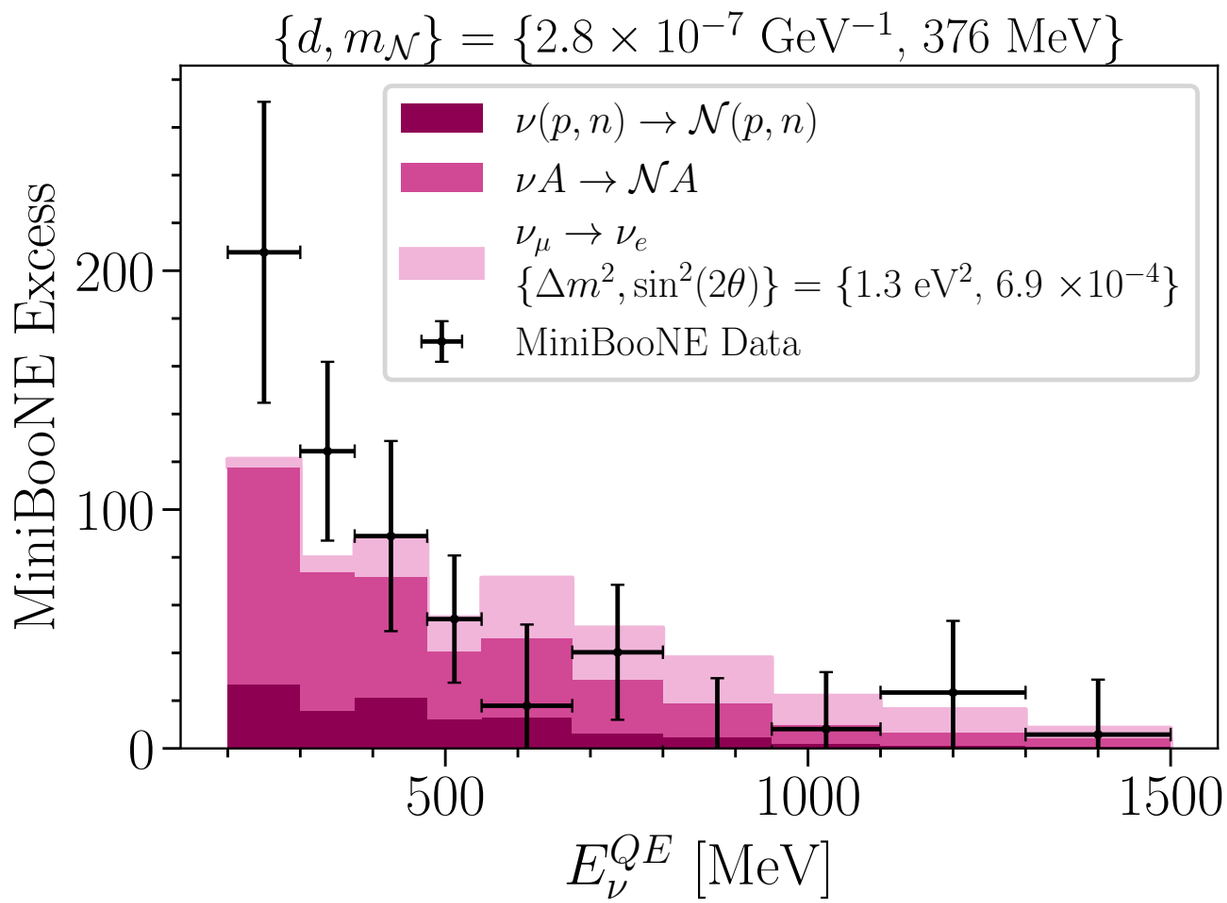
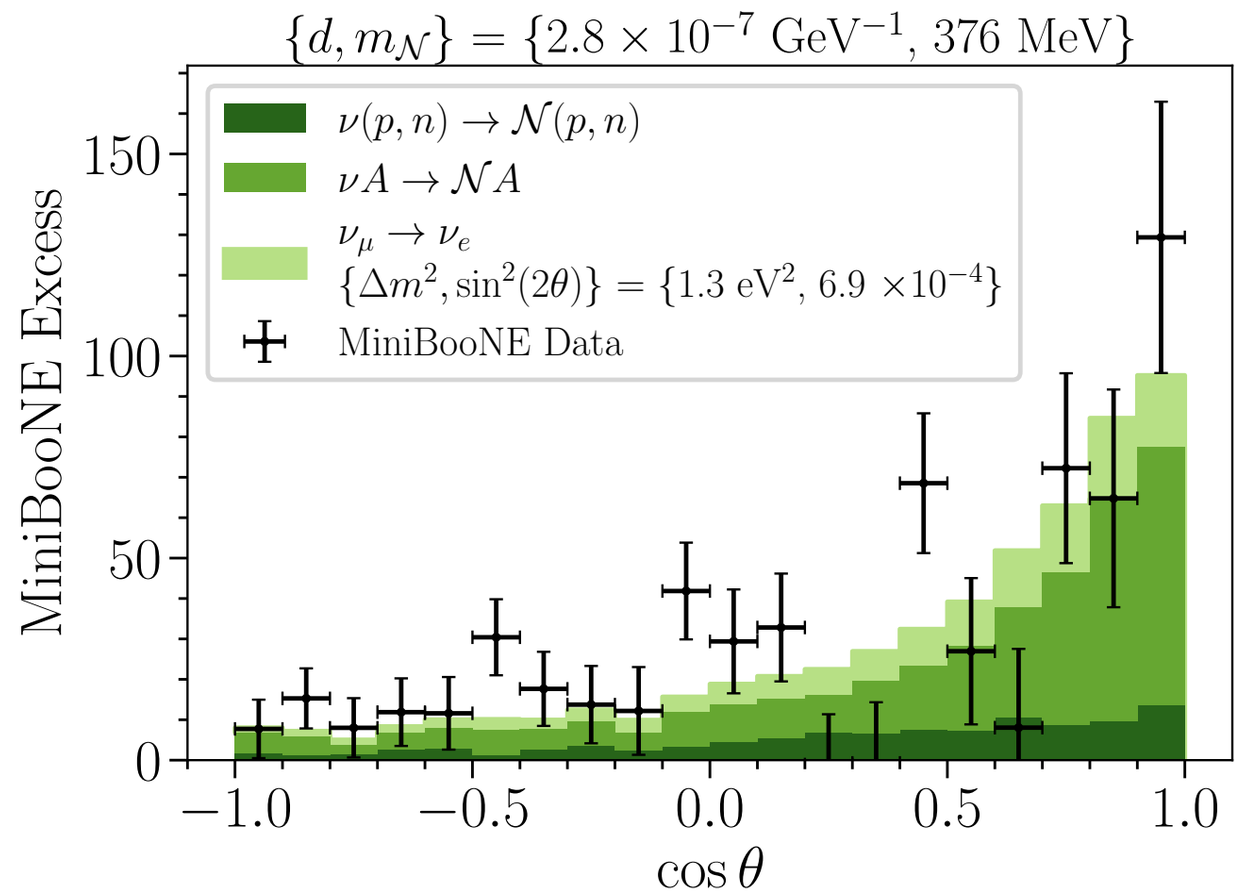




These plots correspond to the dipole parameters that give the best energy fit within the joint 95% CL allowed region

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

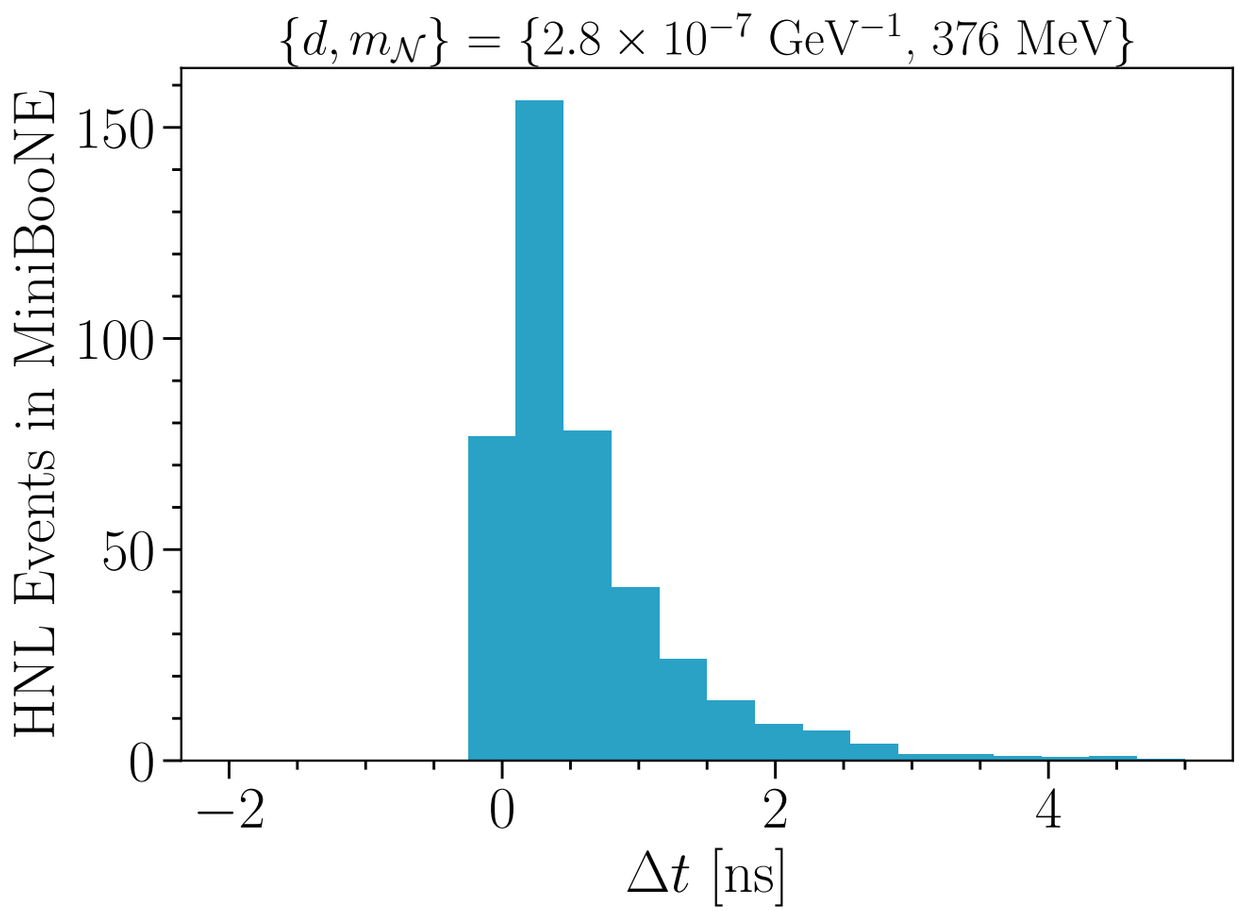
Parameters	χ^2/dof			
$(\sin^2 2\theta, d, m_{\mathcal{N}})$	$3+1+\mathcal{N}$		$3+1$	
	E_ν^{QE}	$\cos\theta$	E_ν^{QE}	$\cos\theta$
(0.30, 3.1, 376)	5.7/8	32.1/18	30.5/10	86.4/20
(0.69, 2.8, 376)	7.9/8	31.4/18	27.3/10	71.8/20
(2.00, 5.6, 35)	20.2/8	36.7/18	27.6/10	40.8/20
(0, 0, 0)	34.1/10	99.4/20	same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

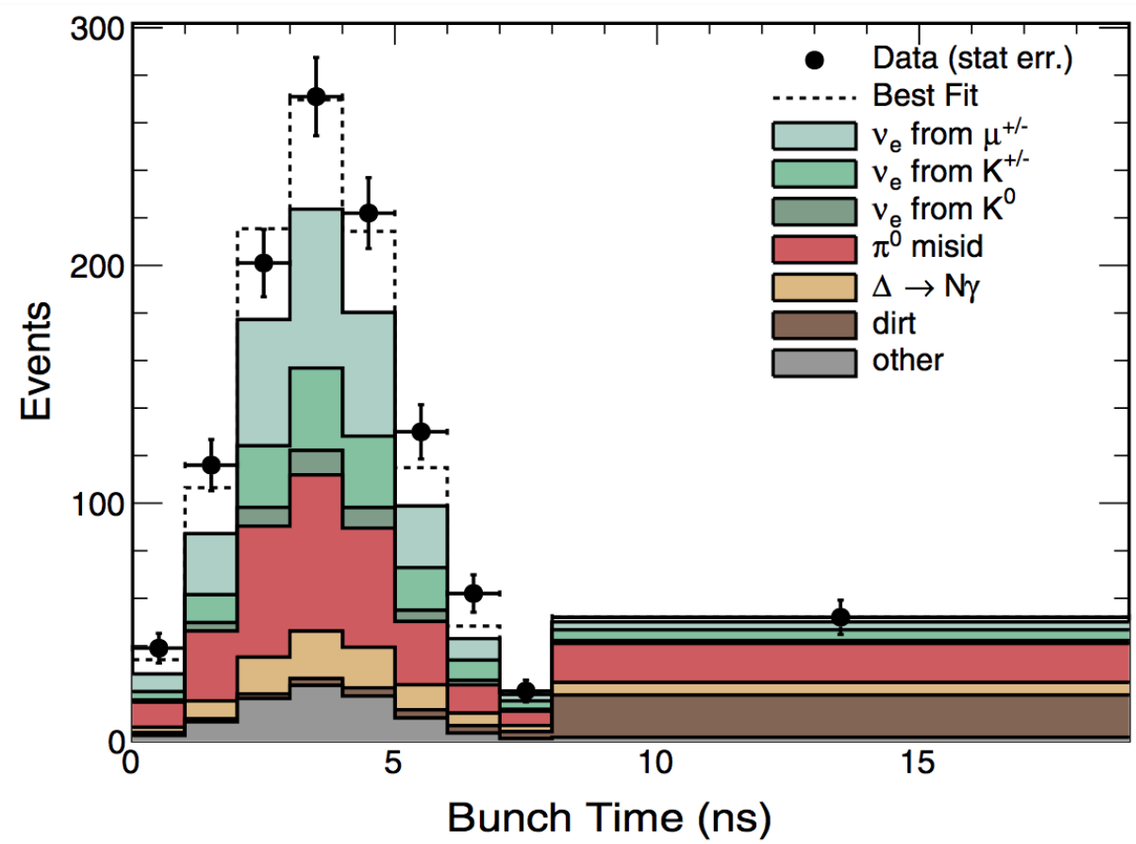
TABLE II. χ^2/dof values for $3+1$ and $3+1+\mathcal{N}$-decay models obtained by comparing expectations to the MiniBooNE excess in E_ν^{QE} and $\cos\theta$. The parameters in column one refer to $(\sin^2 2\theta_{\mu e} \times 10^{-3},\ d \times 10^{-7}\ [\mathrm{GeV}^{-1}],\ m_{\mathcal{N}}\ [\mathrm{MeV}])$. 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



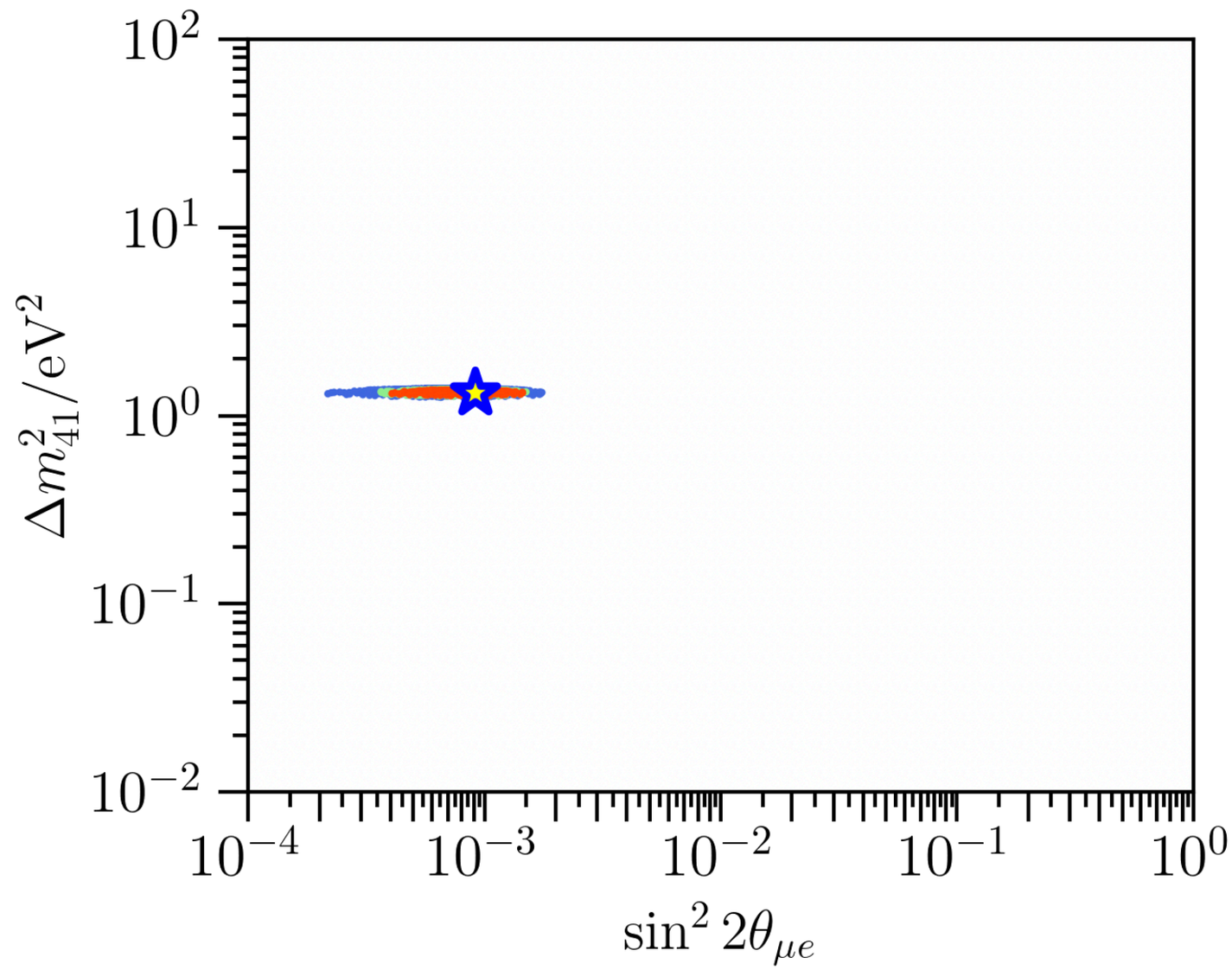


Conclusion

- 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

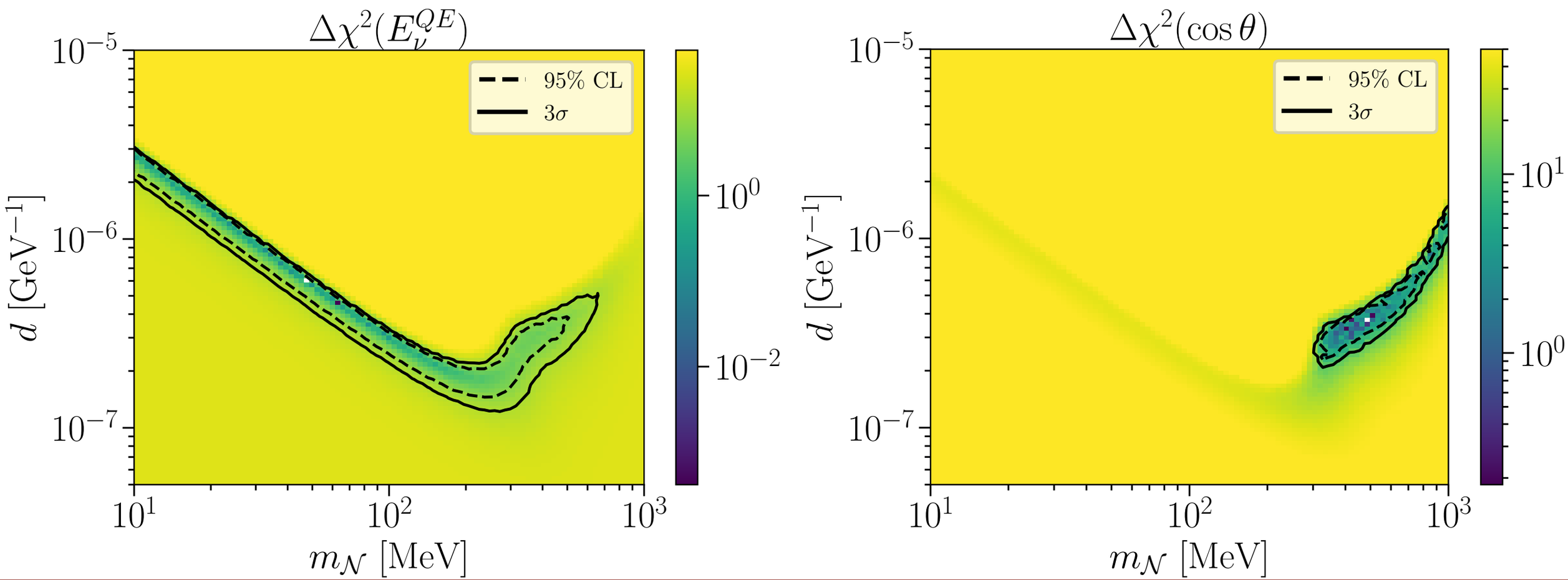


Smaller Oscillation Contribution

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

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

- Results are similar to the best fit oscillation amplitude case



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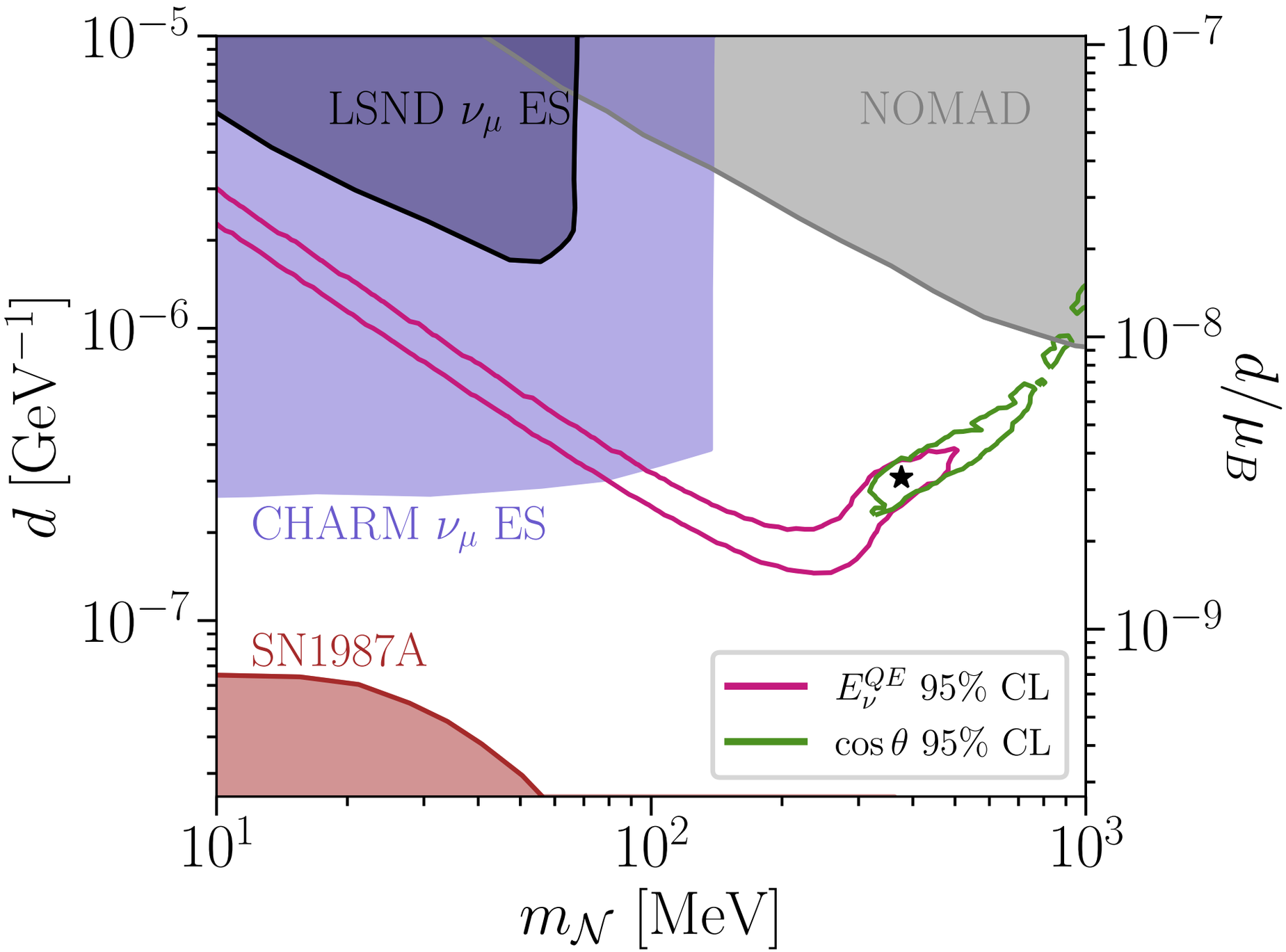

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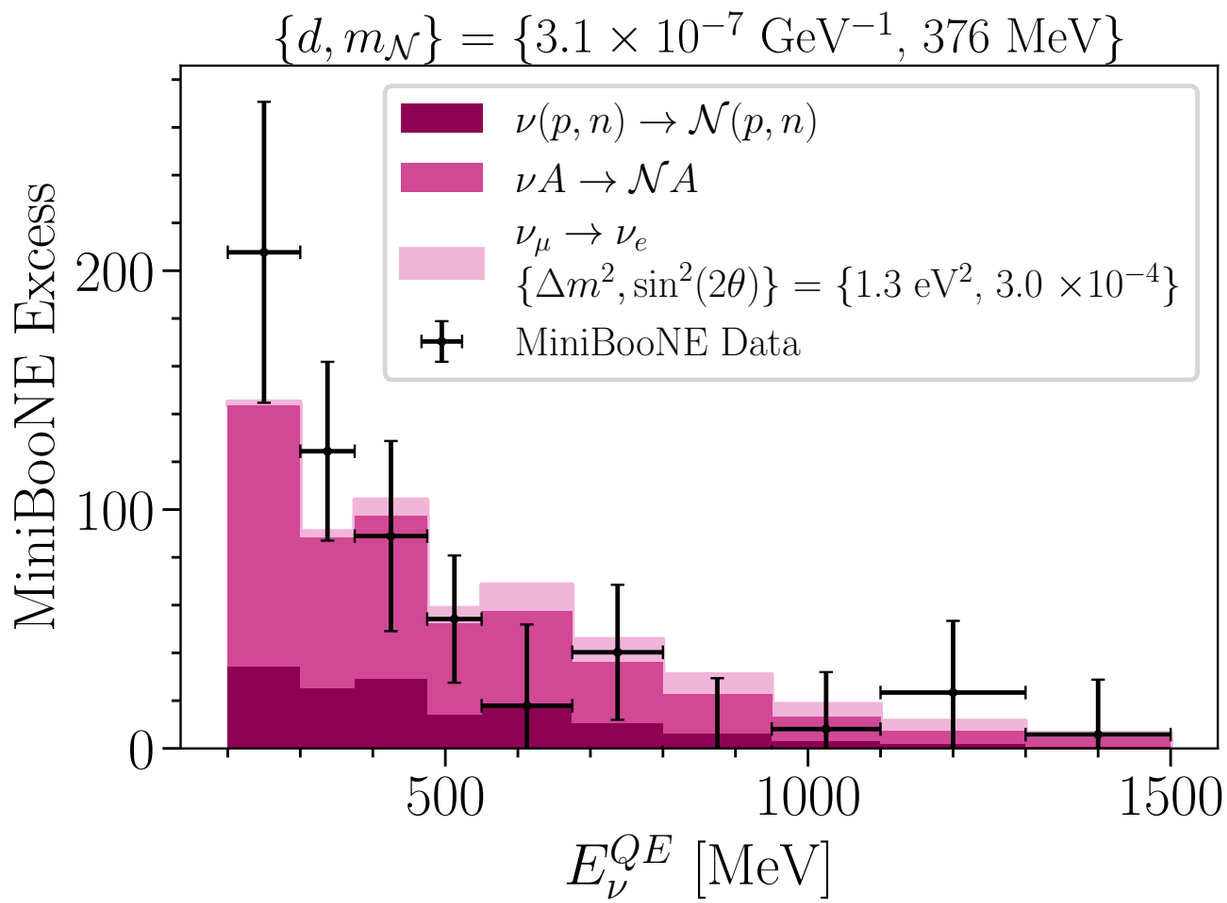
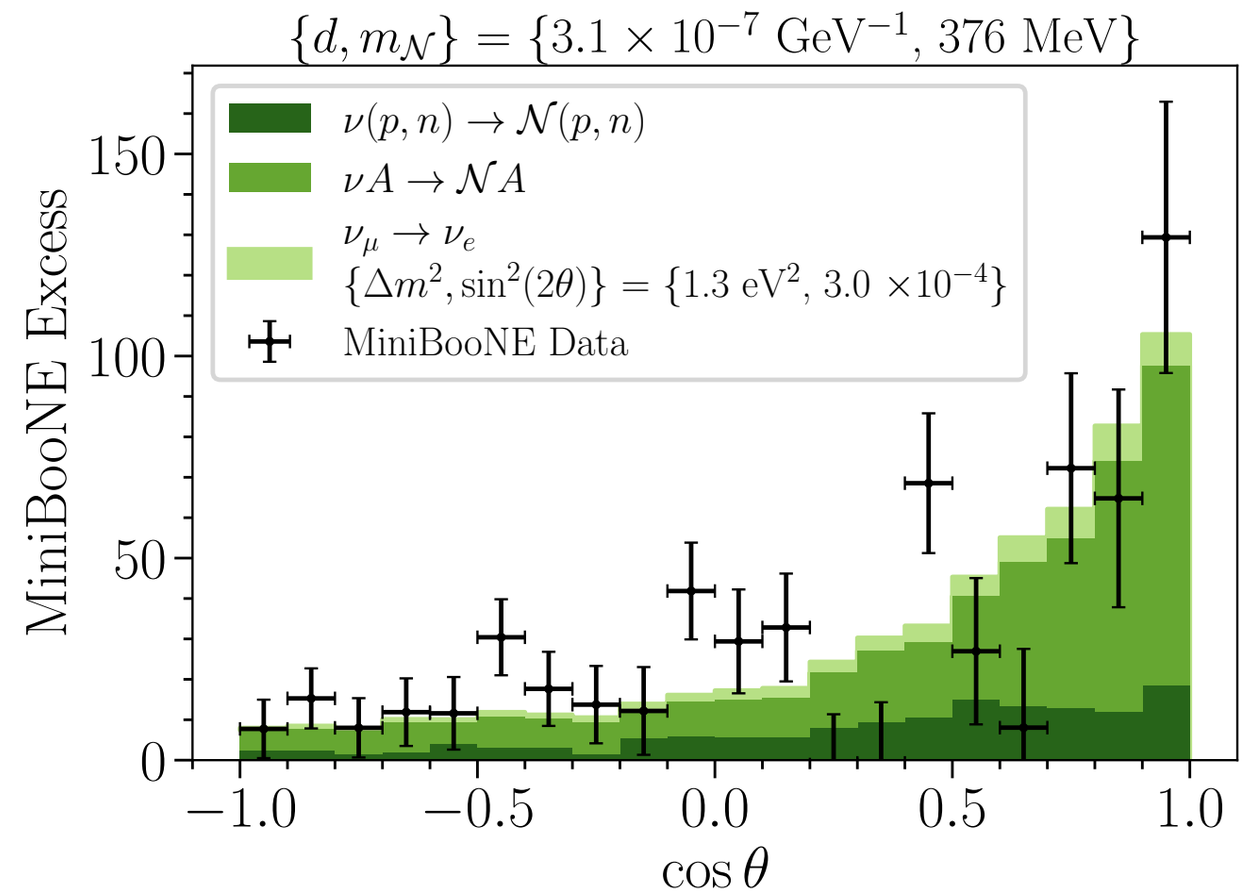




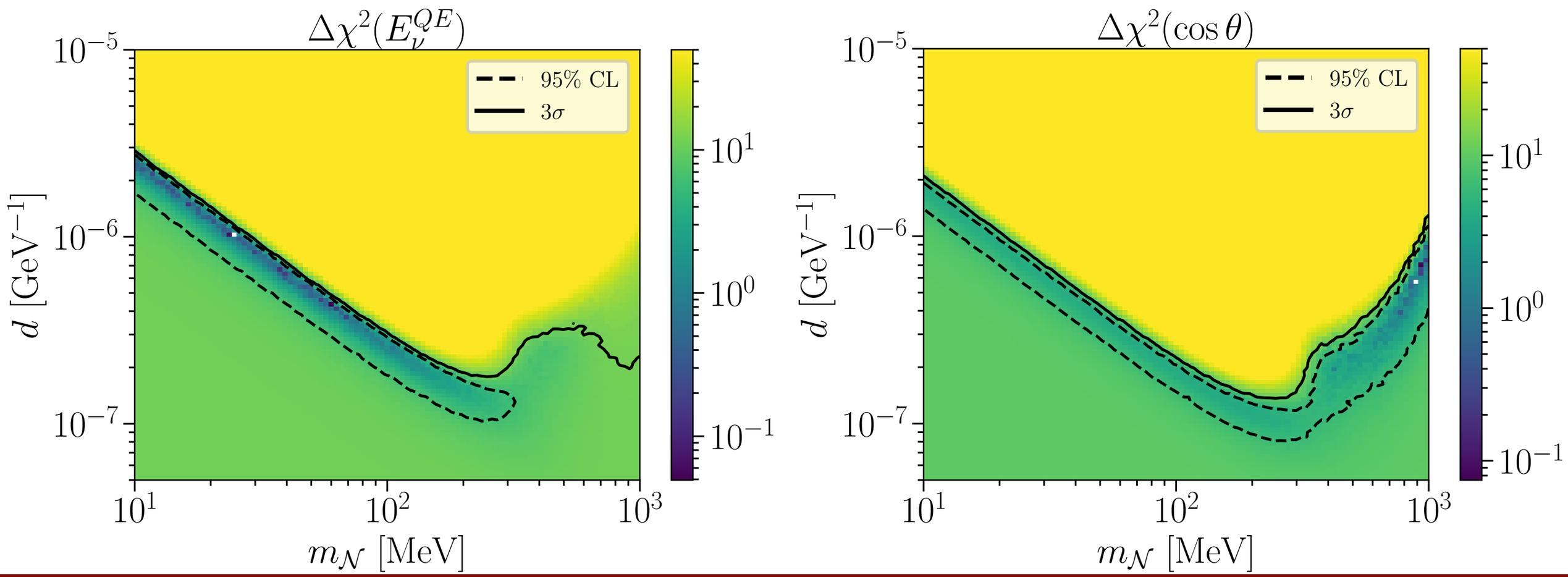
Slightly larger dipole coupling preferred compared to the best fit oscillation amplitude case

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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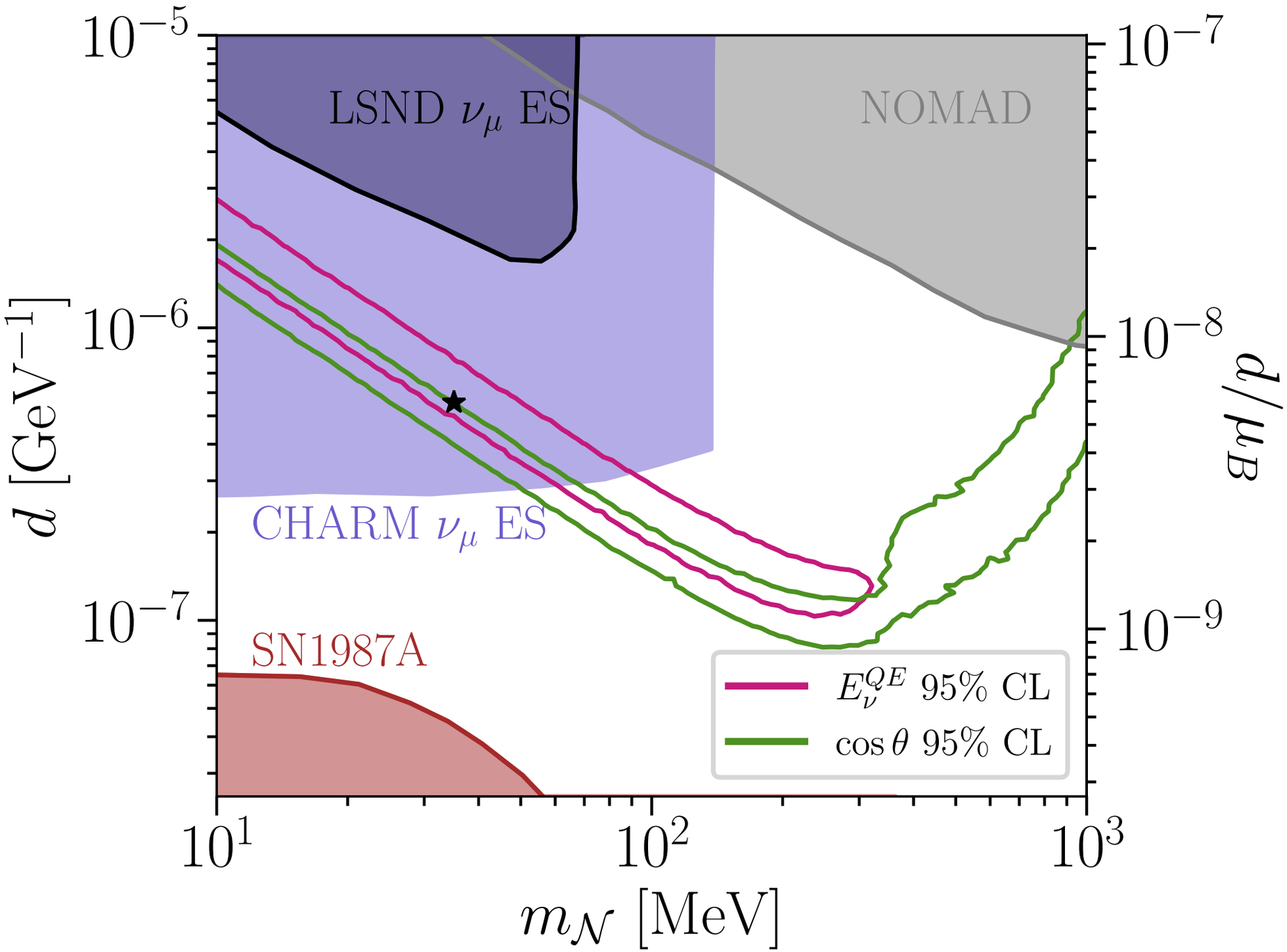

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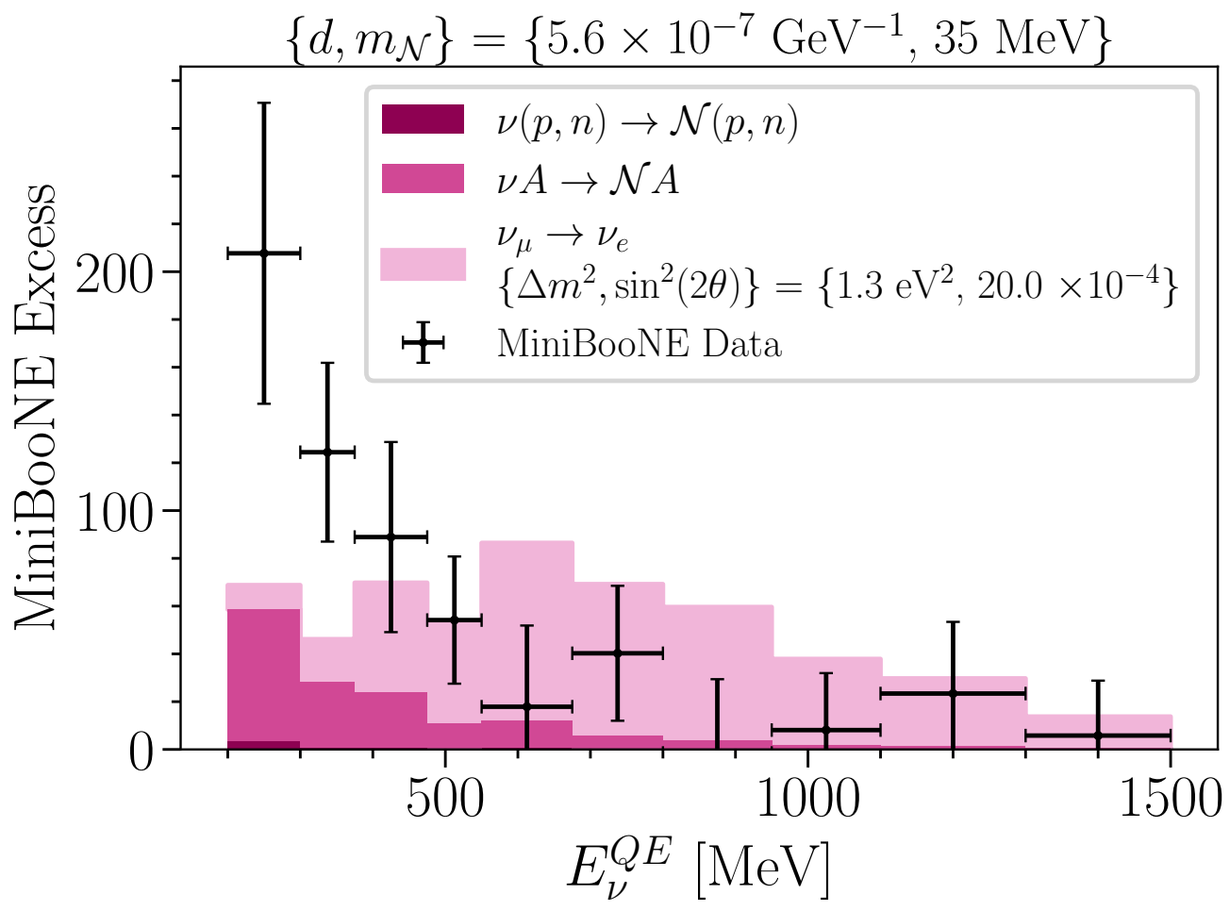
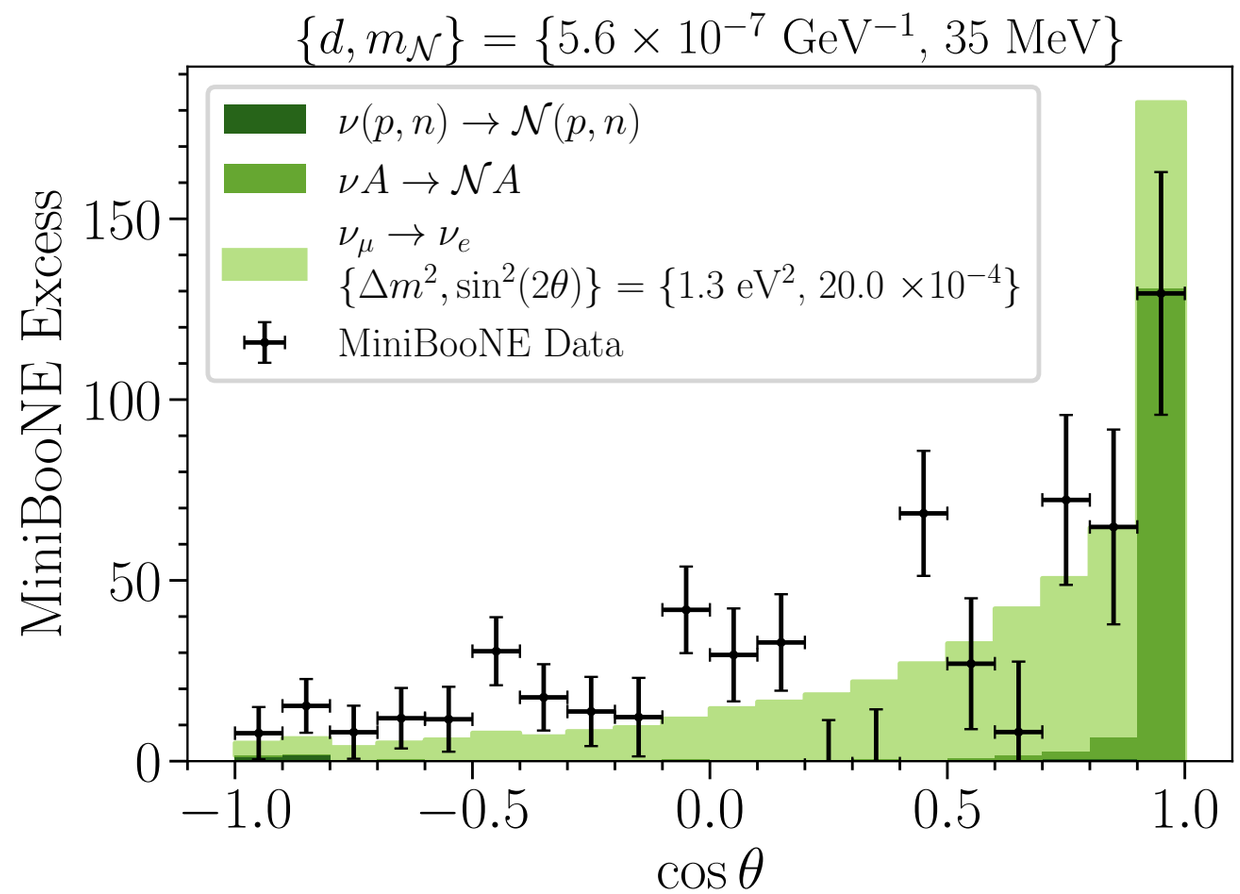
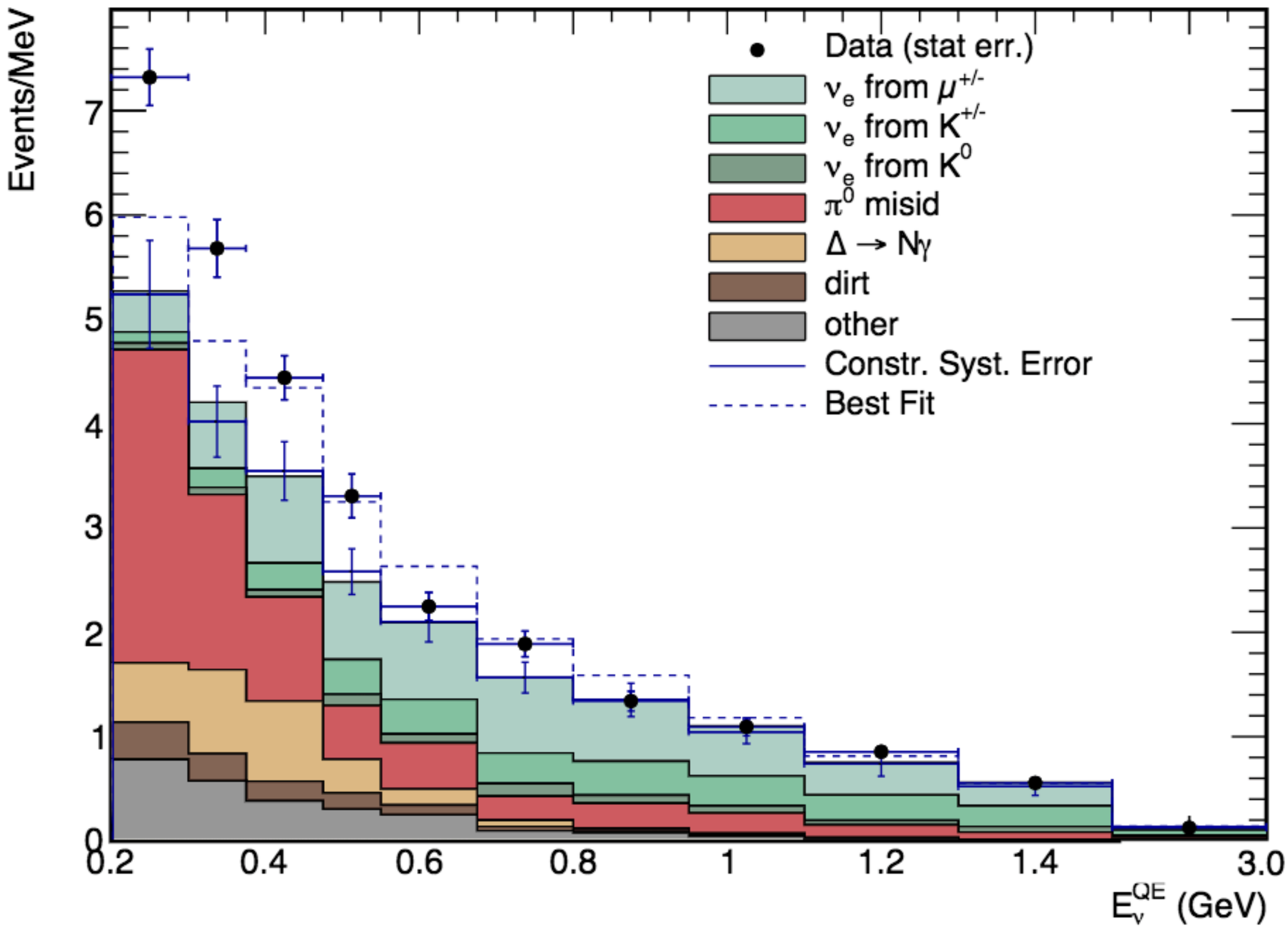
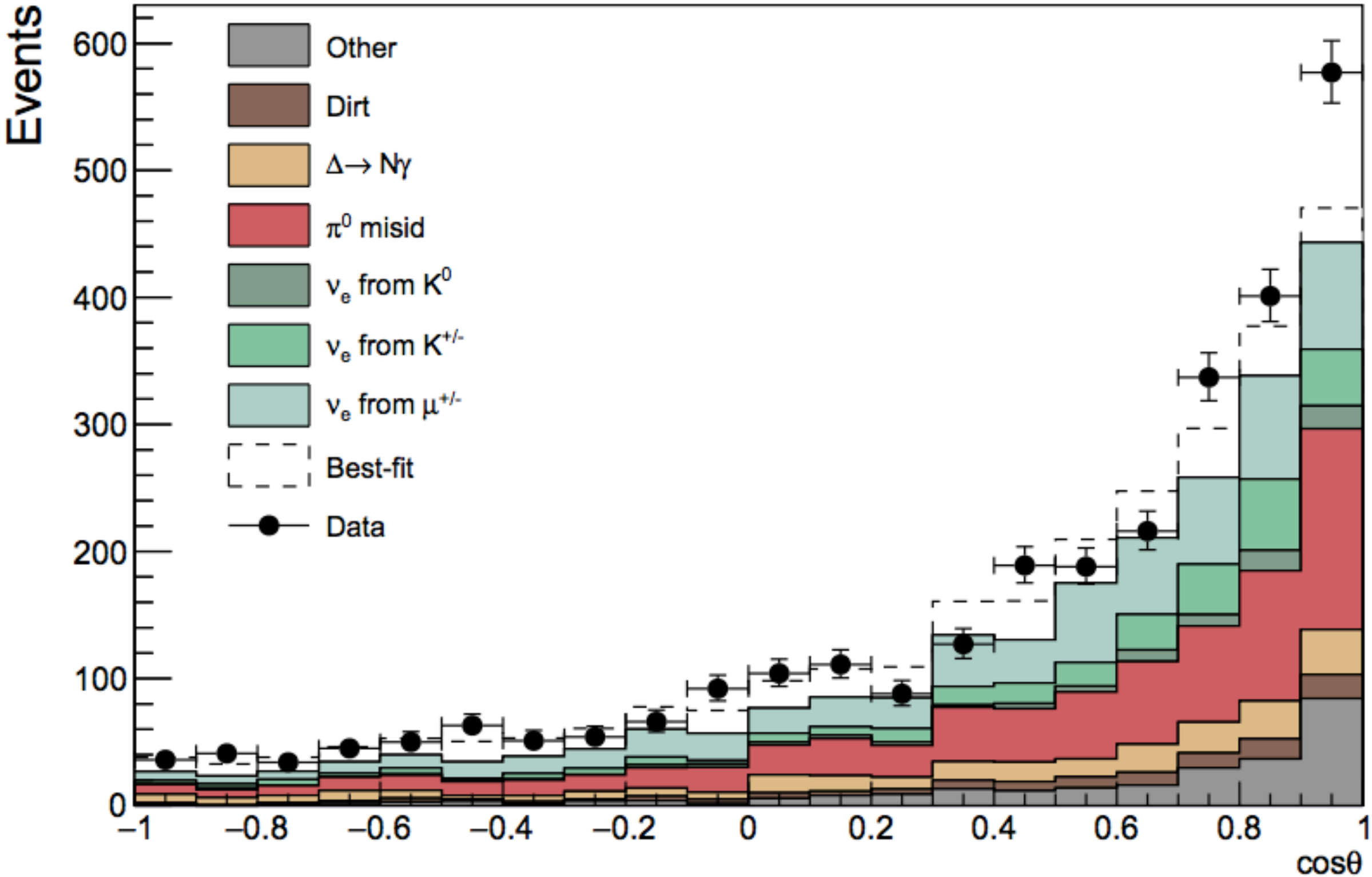
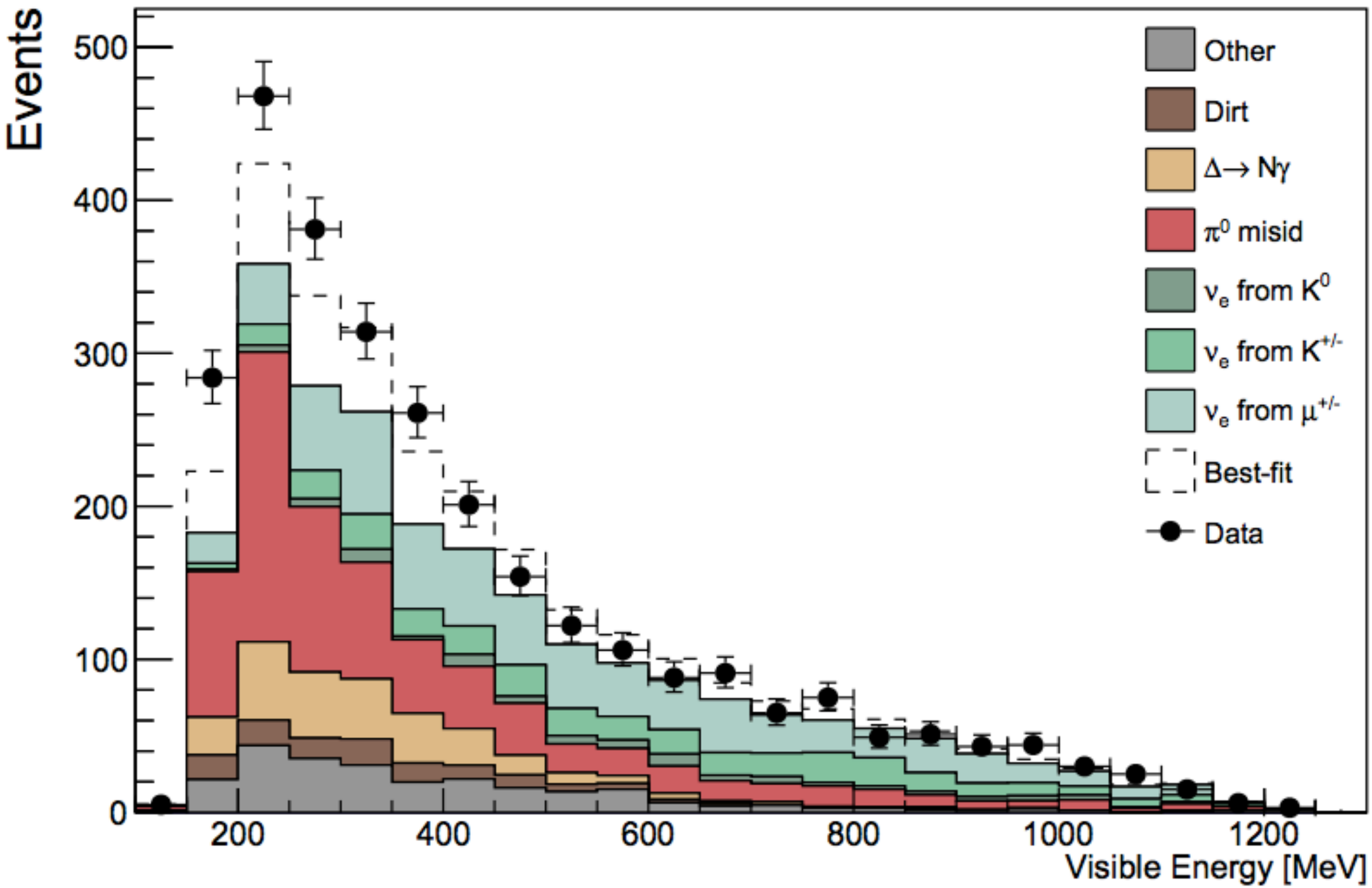




Preference for a smaller HNL mass here, but fits are worse in general


Events/MeV
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
0
1
2
3
4
5
6
7
0.2
0.4
0.6
0.8
1
1.2
1.4
3.0
E_ν^{QE} (GeV)


Events
600
500
400
300
200
100
0
Other
Dirt
Δ→ Nγ
π0 misid
νe from K0
νe from K+/-
νe from μ+/-
Best-fit
Data
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cosθ


Events
500
400
300
200
100
0
200
400
600
800
1000
1200
Visible Energy [MeV]
Other
Dirt
Δ→ Nγ
π0 misid
νe from K0
νe from K+/-
νe from μ+/-
Best-fit
Data

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