Heavy sterile neutrinos and the MiniBooNE anomaly

Based on O. Fischer et.al. arXiv:1909.09561

Alvaro Hernandez-Cabezudo, Oliver Fischer and Thomas Schwetz

Karlsruhe Institute of Technology (KIT)

alvaro.cabezudo@kit.edu

Neutrino Platform Week 2019: Hot Topics in Neutrino Physics

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elusives

Karlsruher Institut für Technologie

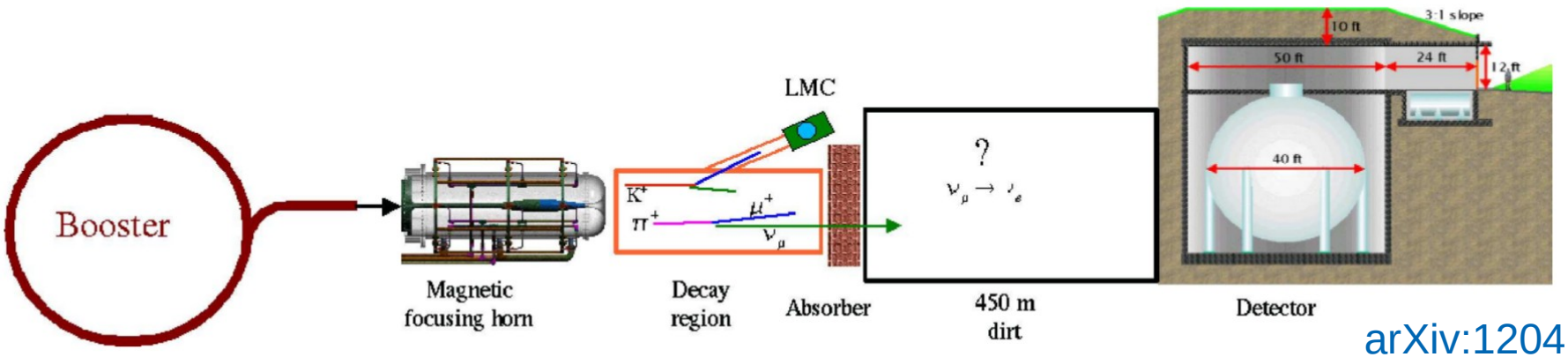
MiniBooNE excess explanation with a ~250 MeV heavy neutrino decaying into a photon

- Mixing: $10^{-11} \lesssim |U_{\ell 4}|^2 \lesssim 10^{-7}$
- Mass: $\sim 250\,\mathrm{MeV}$
- New physics scale: $10^4\,\mathrm{TeV} \lesssim \Lambda \lesssim 10^7\,\mathrm{TeV}$

Outline:

- MiniBooNE excess
- Model used in our work
  - Predictions
  - Time spectrum → Ultimate probe of the model
- Analysis
- Results
- Other searches

MiniBooNE

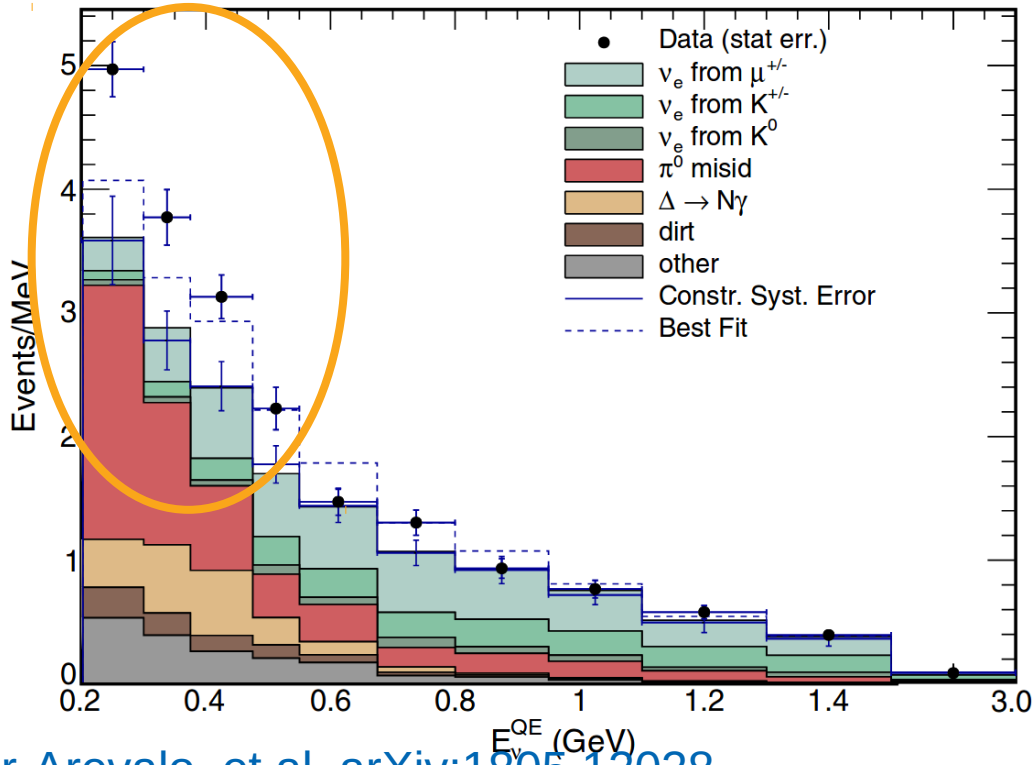


arXiv:1204.5379

ν_e appearance excess with respect to SM expectations

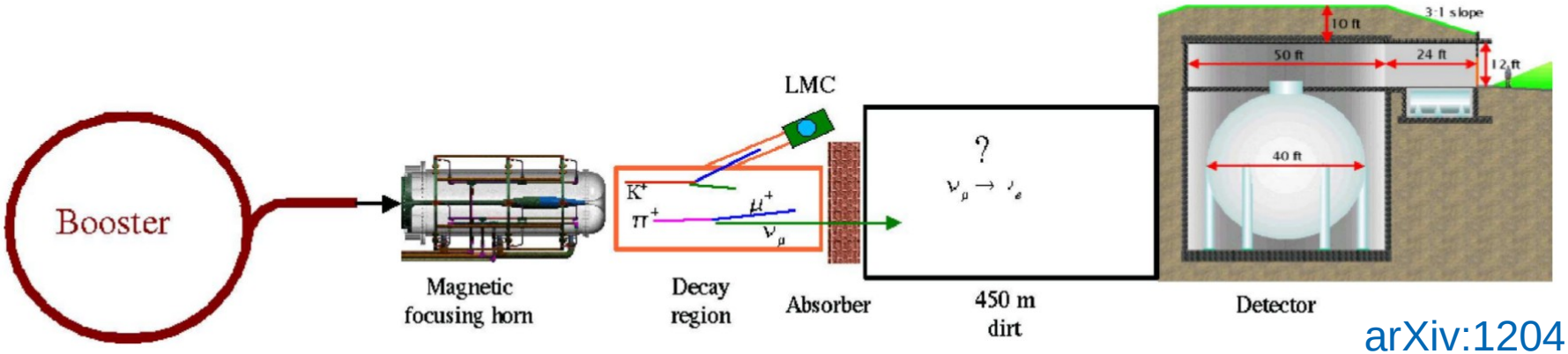
Low energy excess

4.5σ



A. A. Aguilar-Arevalo, et.al. arXiv:1805.12028

MiniBooNE



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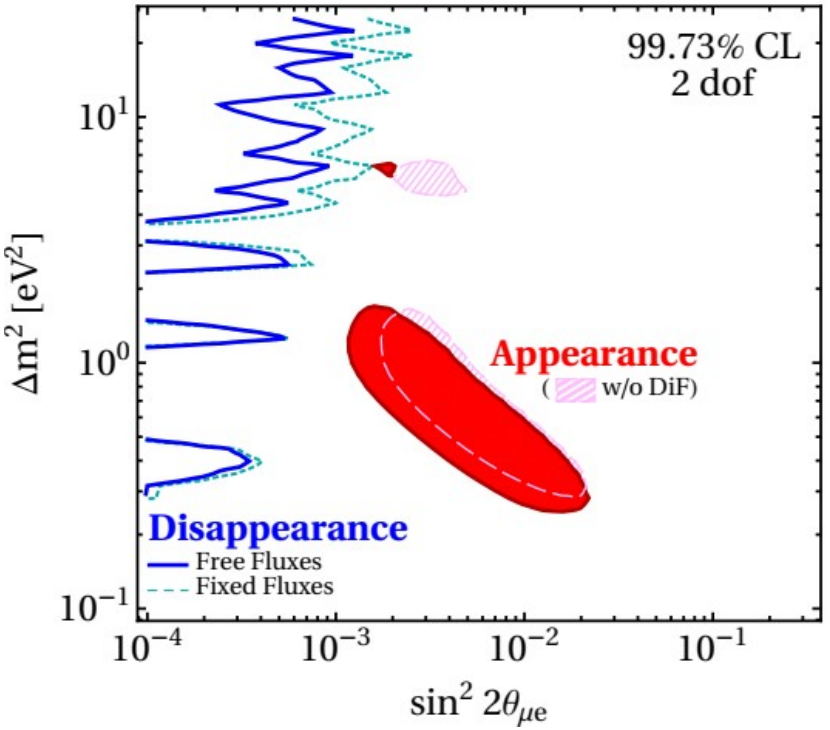
Strong tension with null results in $\bar{\nu}_\mu / \nu_\mu$ disappearance experiments



M.Dentler, et.al. arXiv:1803.10661

Within neutrino oscillations

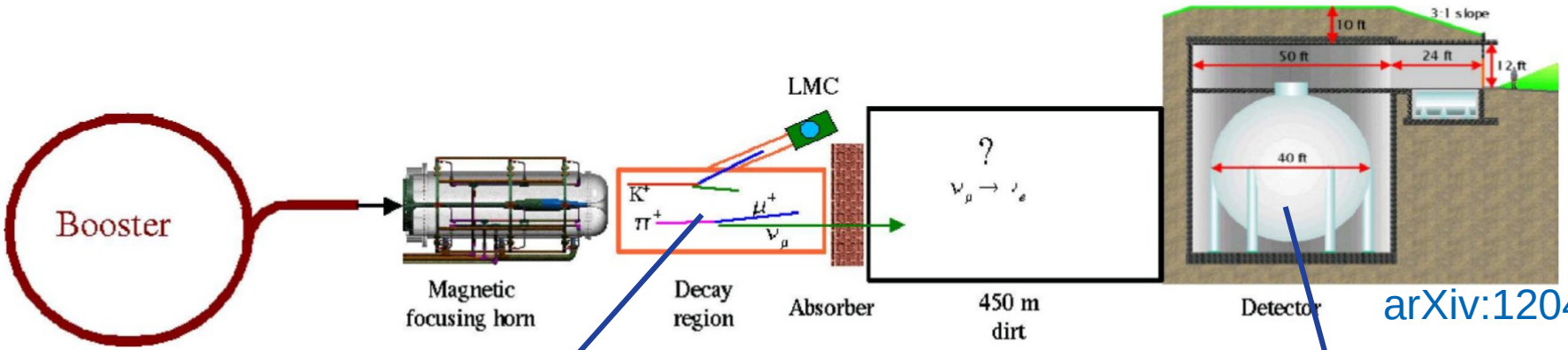
Appearance and Disappearance data sets are totally uncompatible

$$\sim 4 - 5\sigma$$

Need of alternative explanations

See also:
- S.N.Gininenko, arXiv:0902.3802
- S.N.Gininenko, arXiv:1009.5536
- E.Bertuzzo, et.al. arXiv:1807.09877
- P. Ballett, et.al. arXiv:1808.2915

MiniBooNE explanation



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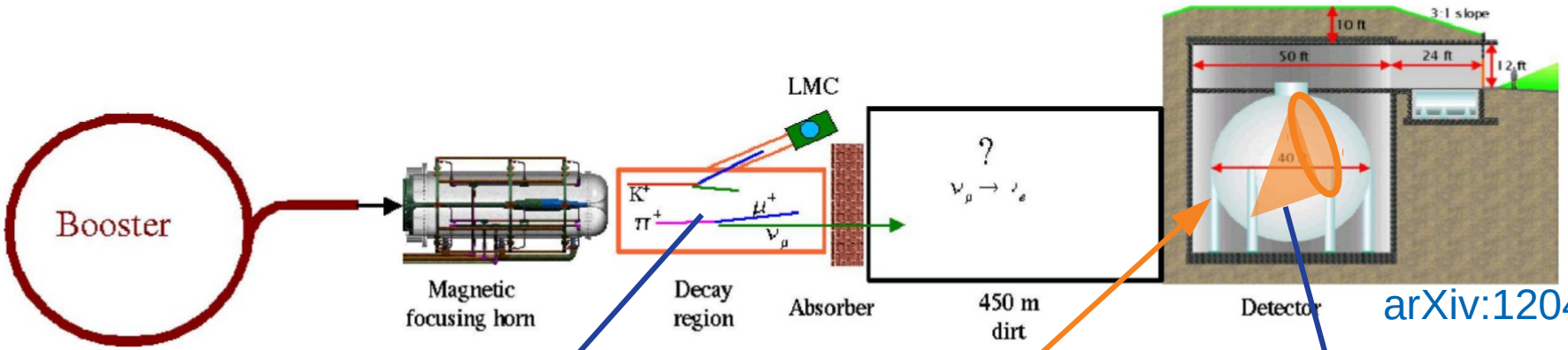
Production at the beam

$$K \to \ell N$$

Decay at the detector

$$N \to \gamma\nu$$

MiniBooNE explanation



arXiv:1204.5379

Production at the beam

$K \to \ell N$

Mimics the e-like signal

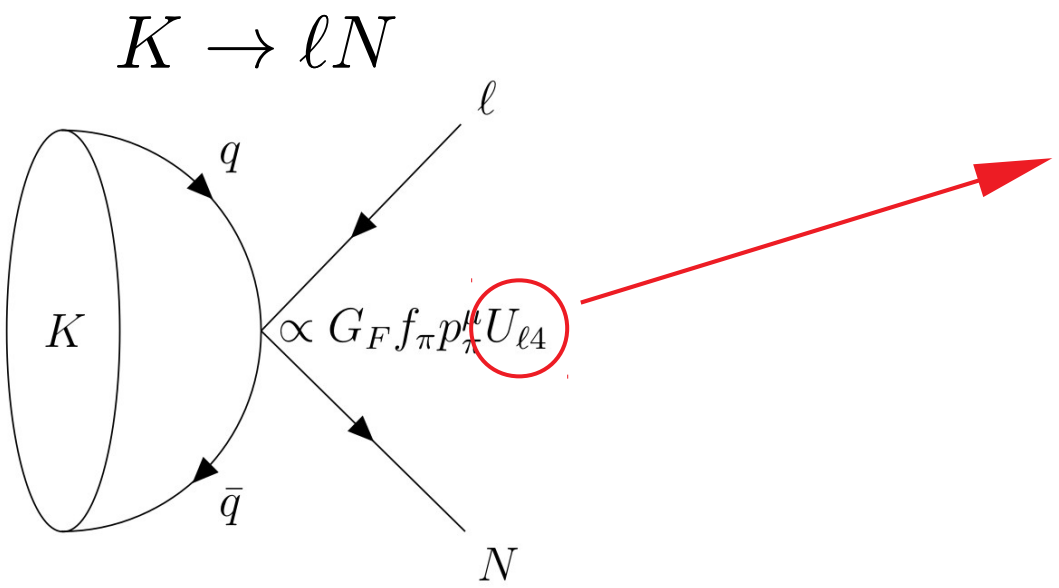
$E_\gamma \equiv E_{\rm vis}$

Decay at the detector

$N \to \gamma \nu$

The Model

Production at the beam



Dominant decay modes (mixing):

$N \to \ell^{\mp}\pi^{\pm}$

$N \to \nu\pi^0$

$$\Gamma_\pi \sim 3 \times 10^{-13}\mathrm{MeV}|U_{\ell 4}|^2 \left(\frac{m_N}{250\,\mathrm{MeV}}\right)^3$$

Production at the beam

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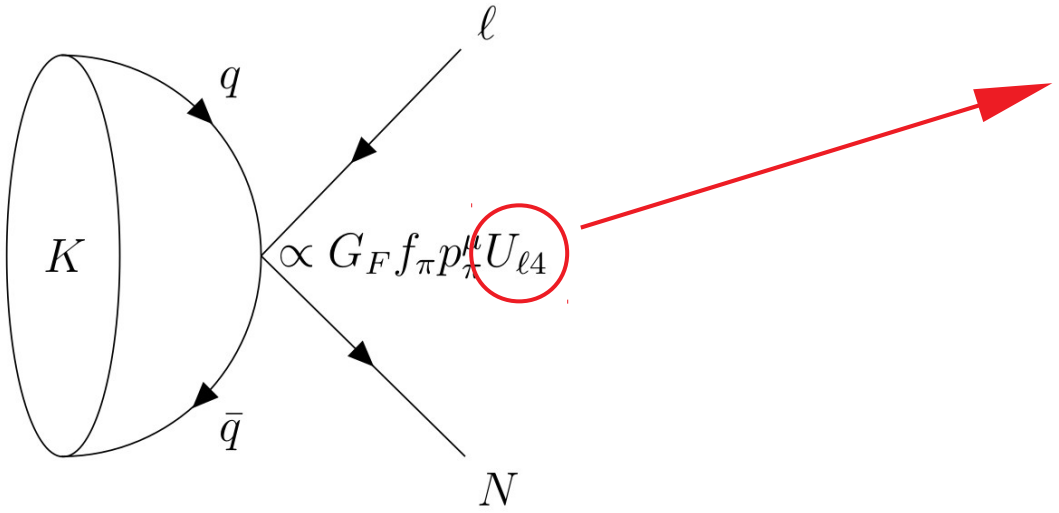

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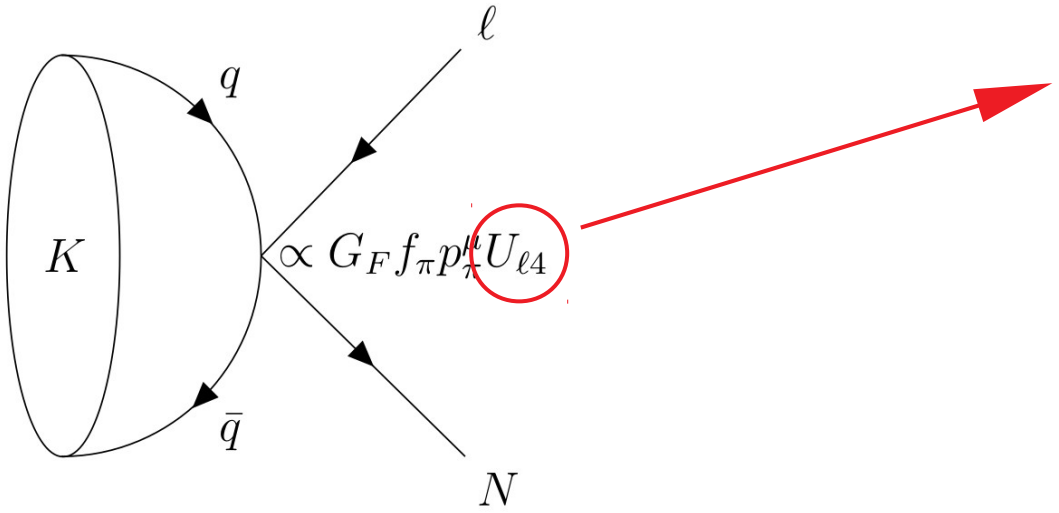

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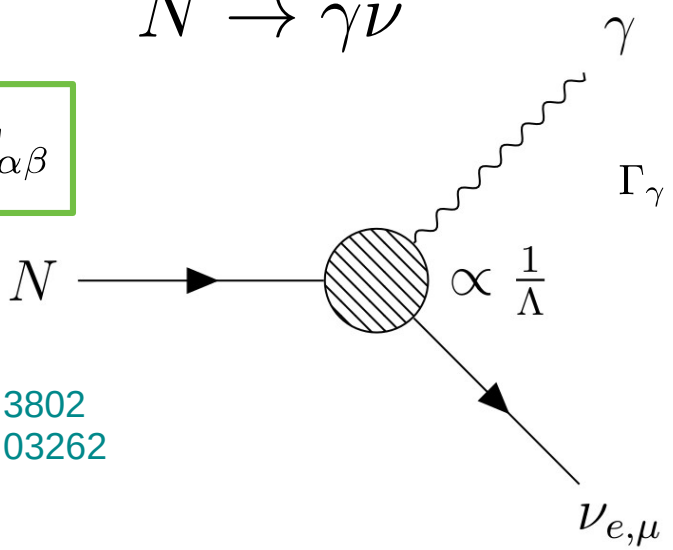
Decay at the detector

$$N \to \gamma\nu$$

$$\mathcal{O}_{N\to\gamma\nu} = \frac{1}{\Lambda}\bar{N}\sigma^{\alpha\beta}\nu F_{\alpha\beta}$$



$$\Gamma_\gamma \simeq 1.2 \times 10^{-16}\text{MeV}\left(\frac{10^5\,\text{TeV}}{\Lambda}\right)^2\left(\frac{m_N}{250\,\text{MeV}}\right)^3$$

See also:
- S.N.Gininenko: arXiv:0902.3802
- G.Margill, et.al: arXiv:1803.03262

Dominant decay channel

$$|U_{\ell 4}|^2 \downarrow\downarrow$$
$$\Gamma_{\text{tot}} = \Gamma_\gamma + \Gamma_\pi \simeq \Gamma_\gamma$$

Predictions

- Total excess
- Energy and angular spectra
- Time spectrum

Predictions

$$N_{\mathrm{decay}} = \mathrm{POT}\,\mathrm{Br}_{\gamma}\,A_{eff,\mathrm{MB}}\int \mathrm{d}p_N\,\phi_N(p_N,m_N)\,\hat{\epsilon}(p_N)\,P_{\mathrm{dec}}\,\omega_{time}(p_N,m_N)$$

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Protons on target

Predictions

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Protons on target

Branching ratio

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Effective area

Protons on target

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Protons on target

Branching ratio

Effective area

Heavy neutrino flux
(reconstructed from K induced ν_μ flux)

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Protons on target

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Decay probability

$$P_{\rm dec} = e^{-L_1 \Gamma_{tot} \frac{m_N}{p_N}} - e^{-L_2 \Gamma_{\rm tot} \frac{m_N}{p_N}} \simeq \Gamma_{\rm tot} \frac{m_N}{p_N} \Delta L$$

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Spectral predictions

$$\frac{1}{\Gamma^{\rm lab}_{N\to\gamma\nu}}\frac{{\rm d}\Gamma^{\rm lab}_{N\to\gamma\nu}}{{\rm d}p_\gamma}(p_\gamma) \Big/ \frac{1}{\Gamma^{\rm lab}_{N\to\gamma\nu}}\frac{{\rm d}\Gamma^{\rm lab}_{N\to\gamma\nu}}{{\rm d}\cos\theta}(\cos\theta)$$

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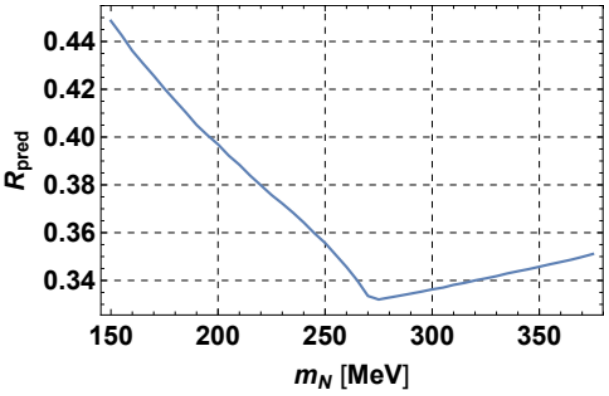
$\bar{\nu}/\nu$ predicted ratio

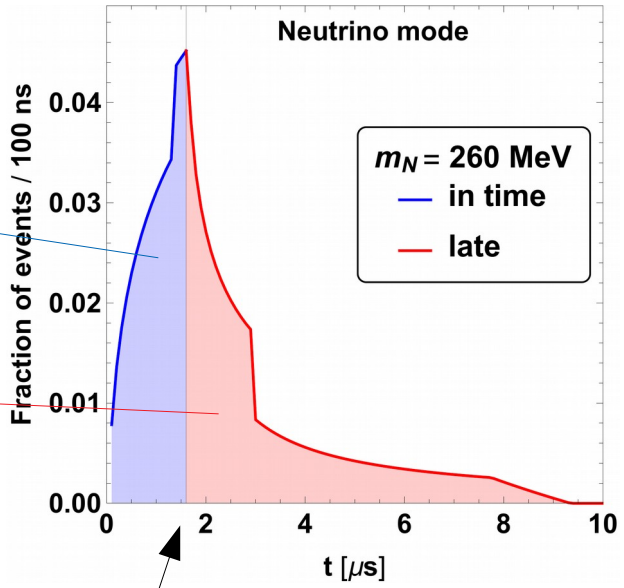


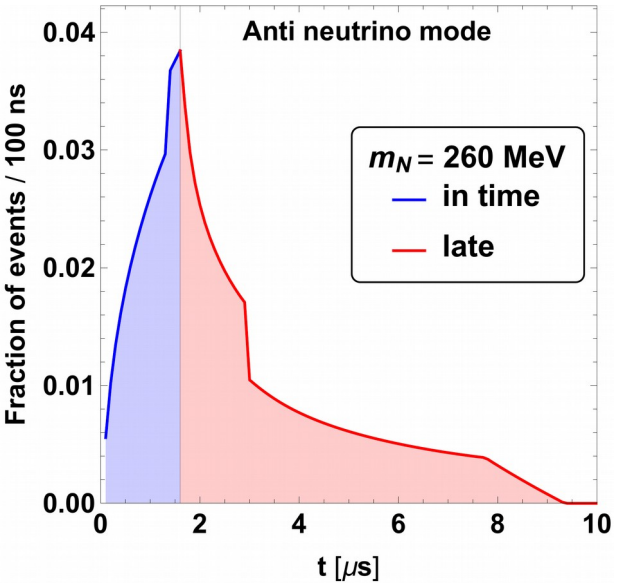
$$\phi_N(p_N, m_N) \rightarrow \phi(t)$$

Time shape: N are slower than ν

Inside the analyzed time window

Outside the analyzed time window



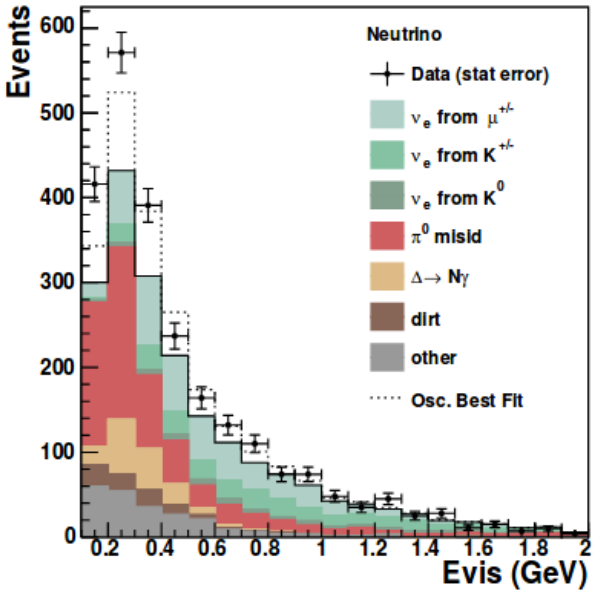


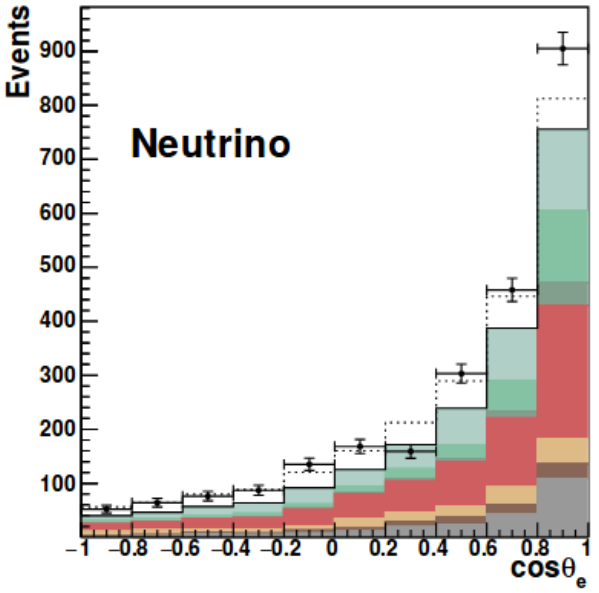
A **step-like** beam pulse of **1.6μs** is assumed

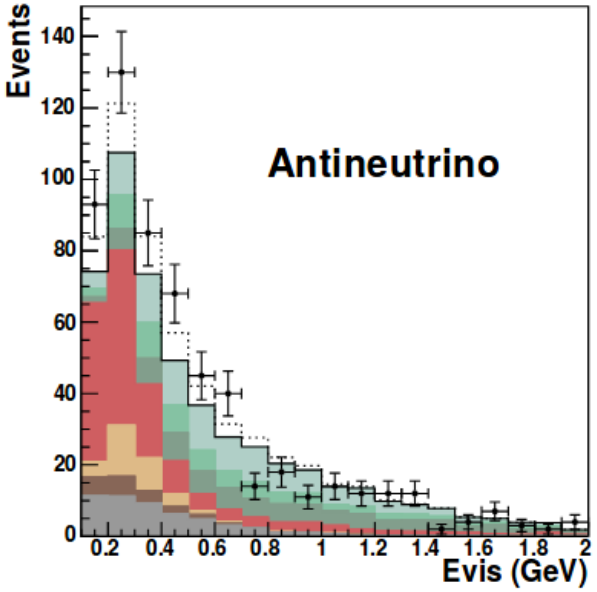
See also: P.Ballett, et.al. arXiv:1610.08512

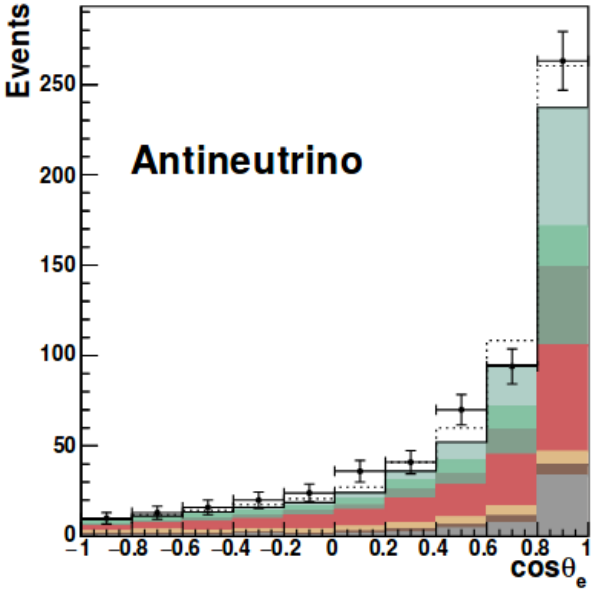
Analyses

Data used





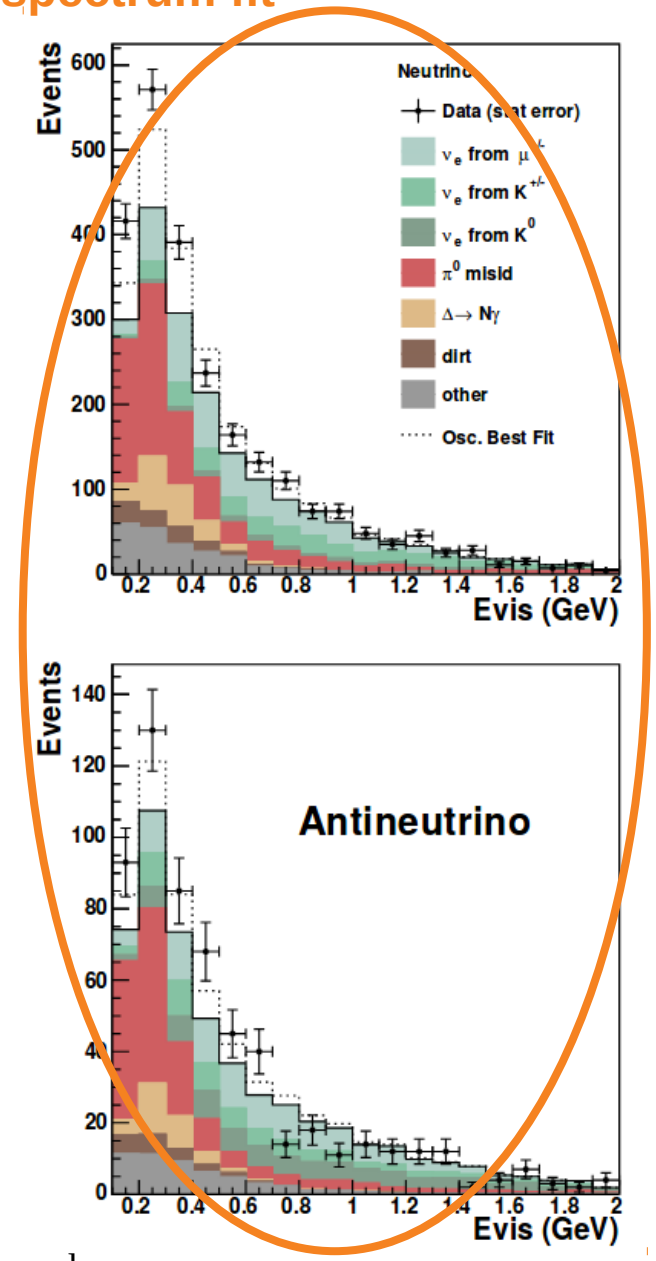


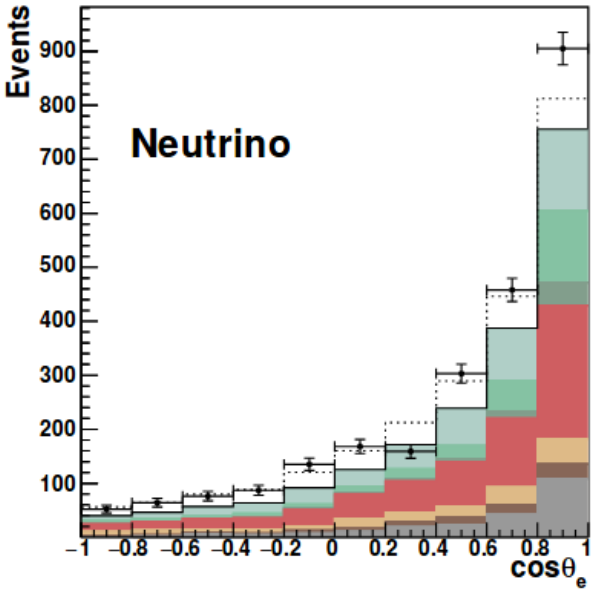


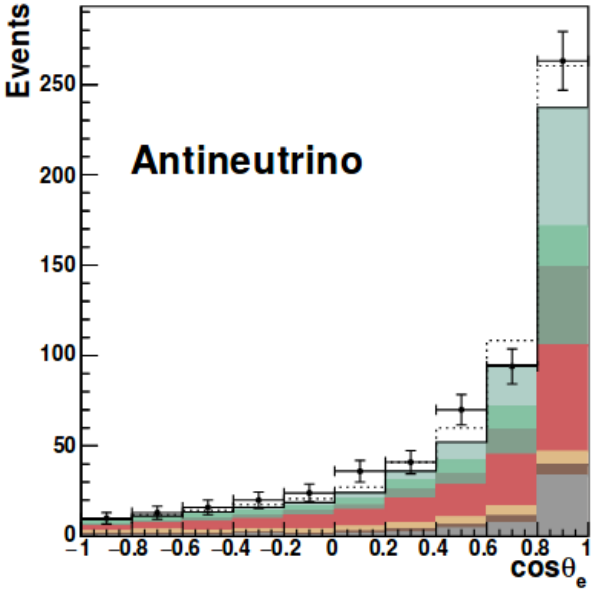
A. A. Aguilar-Arevalo, et.al. arXiv:1805.12028

Data used

Energy spectrum fit







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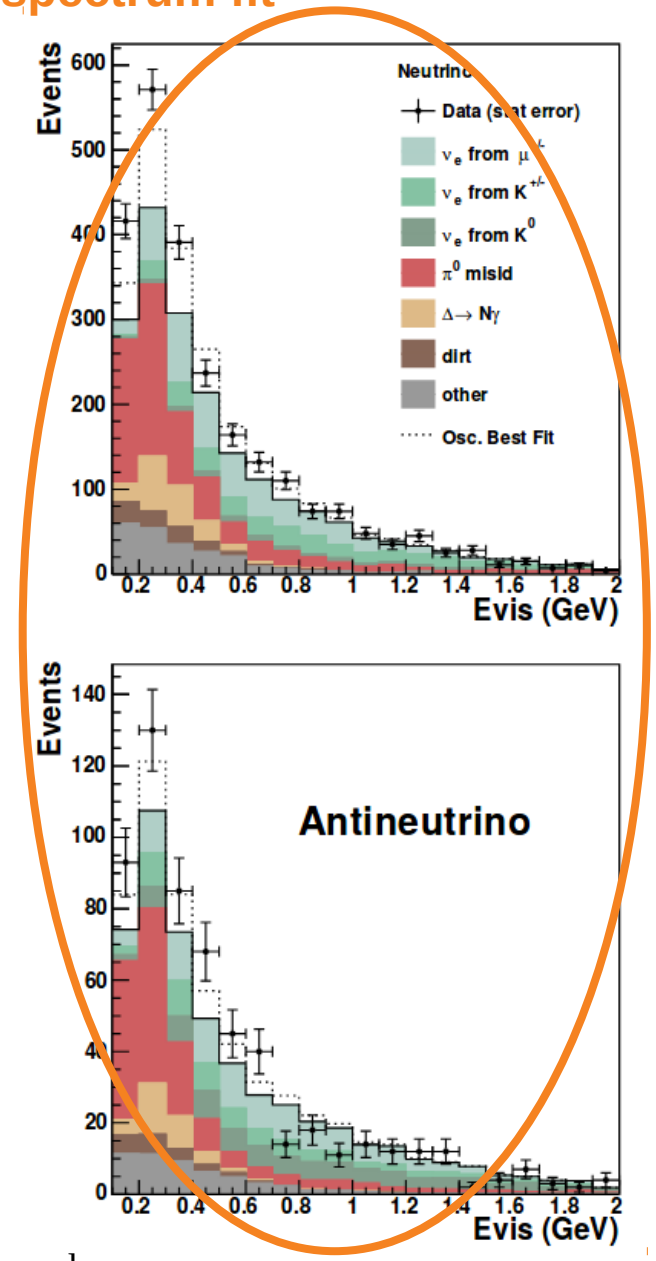
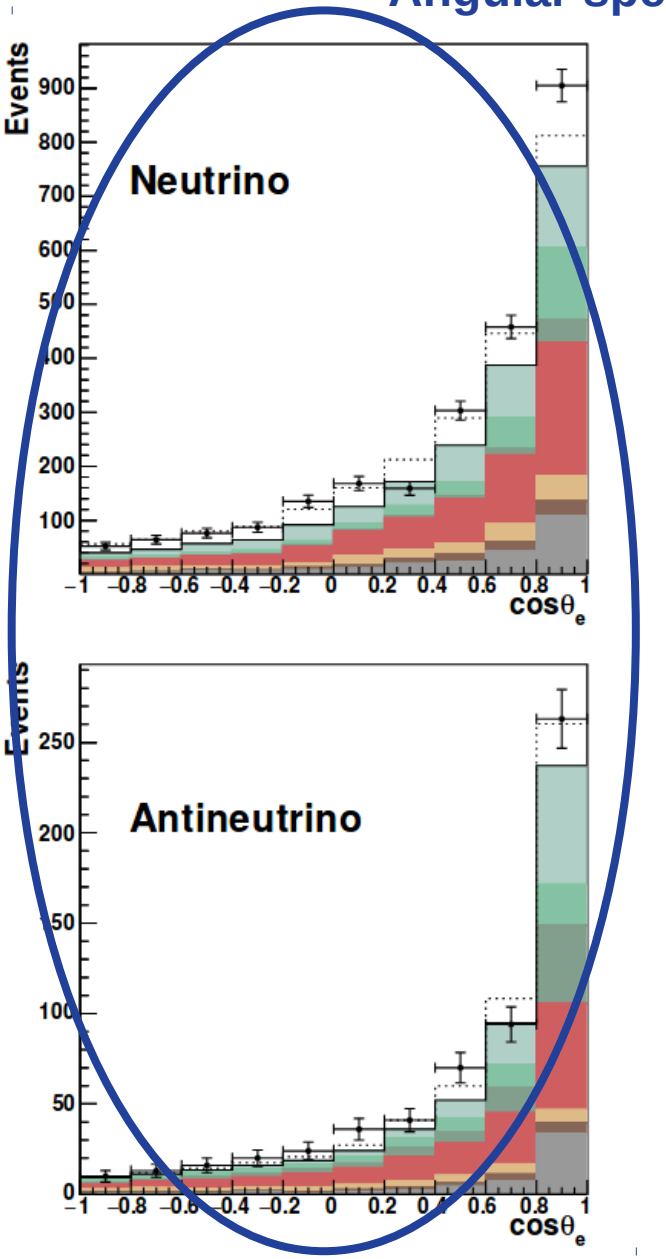
Energy spectrum fit

Angular spectrum fit





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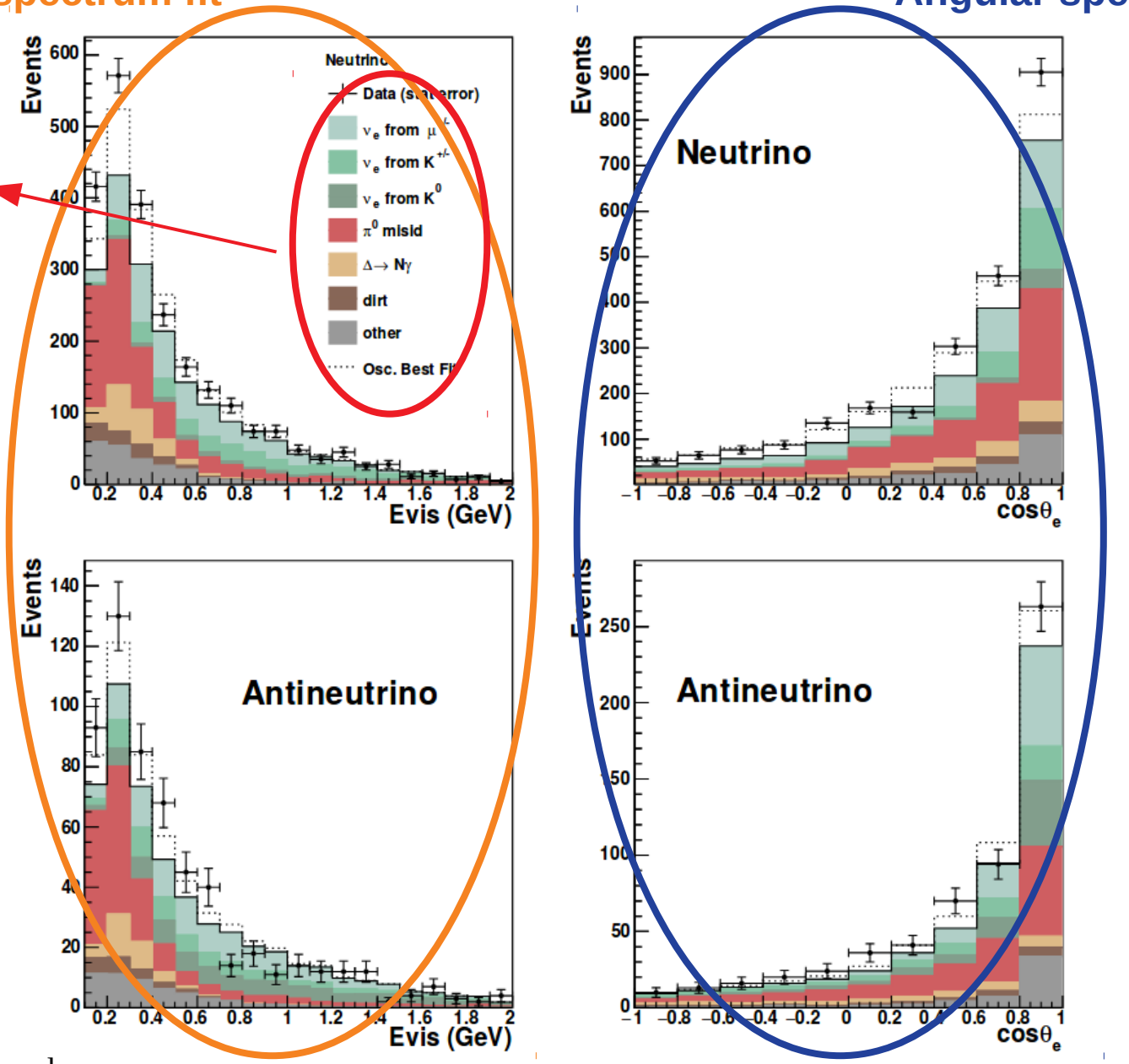
Data used

Energy spectrum fit

Angular spectrum fit

Uncorrelated



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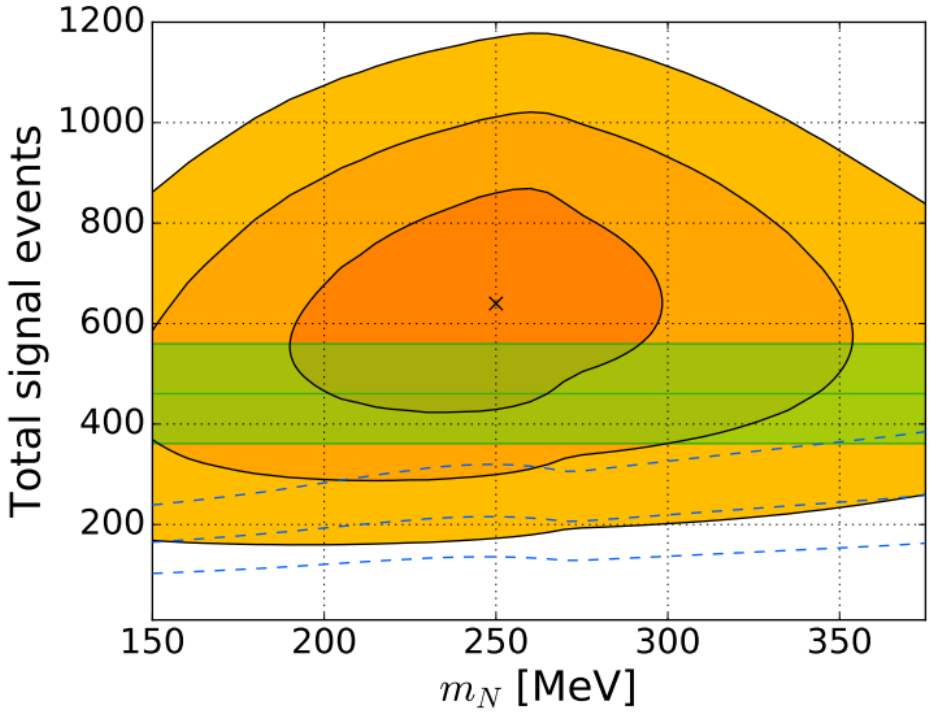
Energy and angular **spectra** fits



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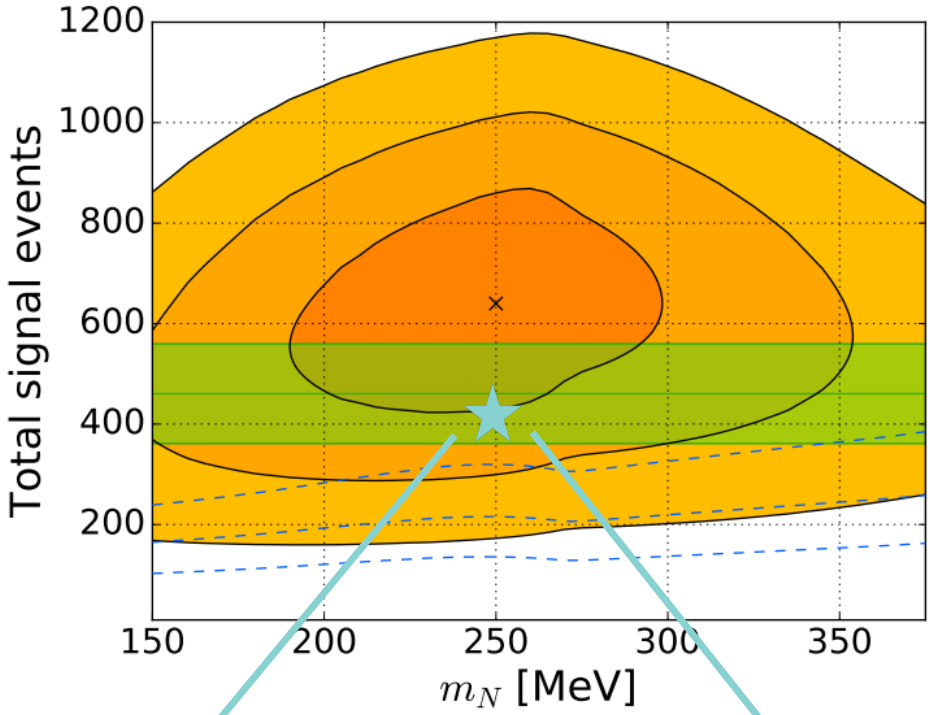
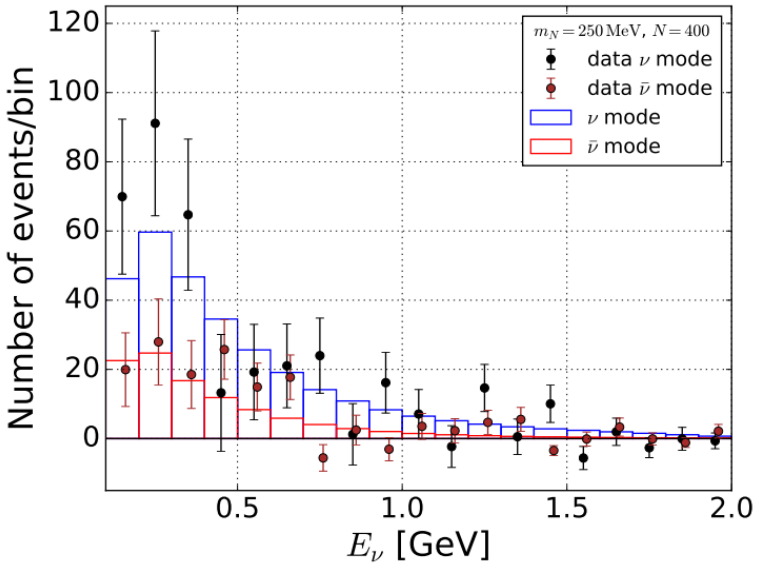
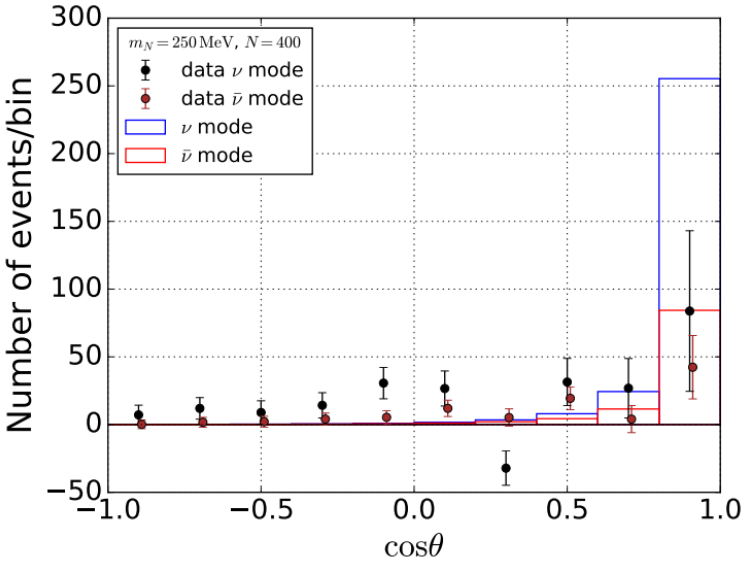


$\chi^2/\mathrm{dof} = 61/36$

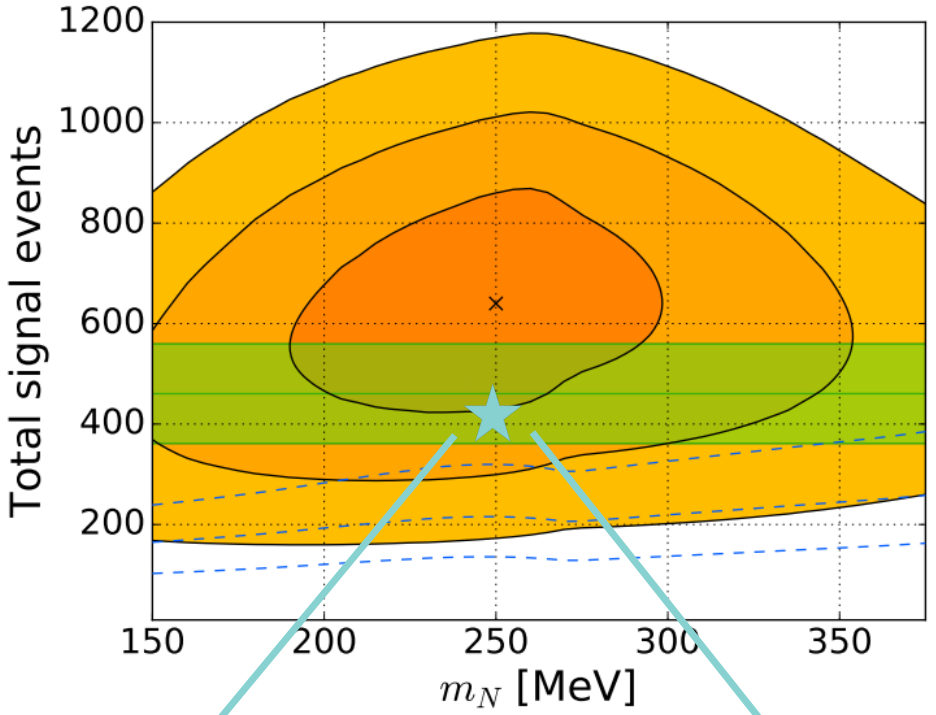


$\chi^2/\mathrm{dof} = 52/18$

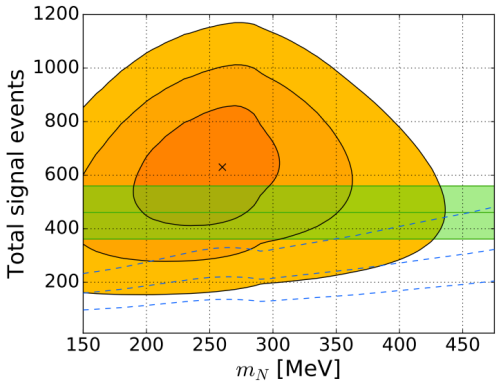


Energy and angular **spectra** fits

$K \to N\mu$



$K \to Ne$



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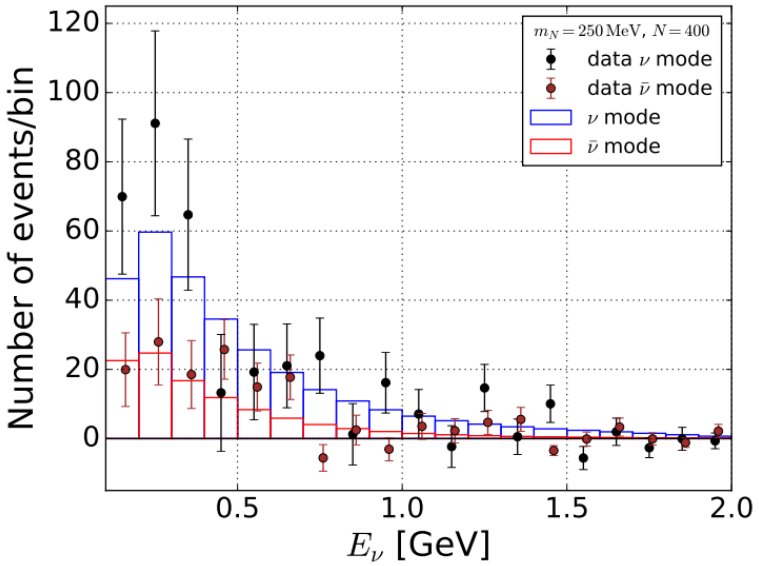

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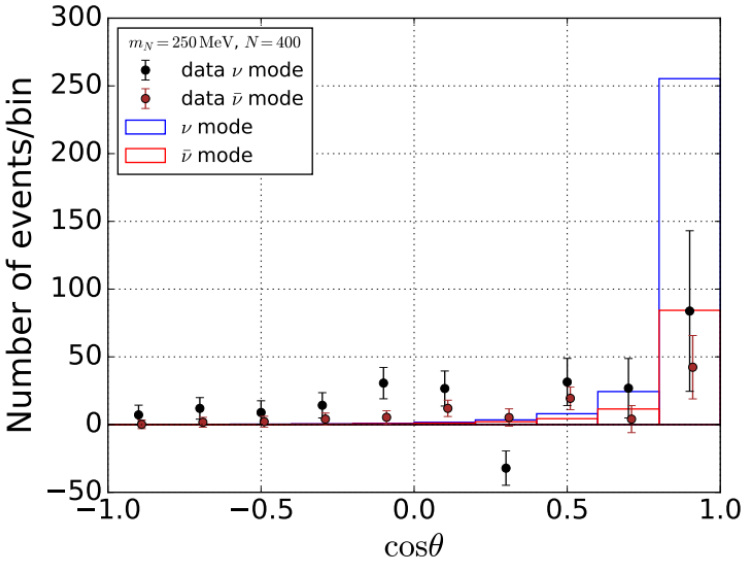
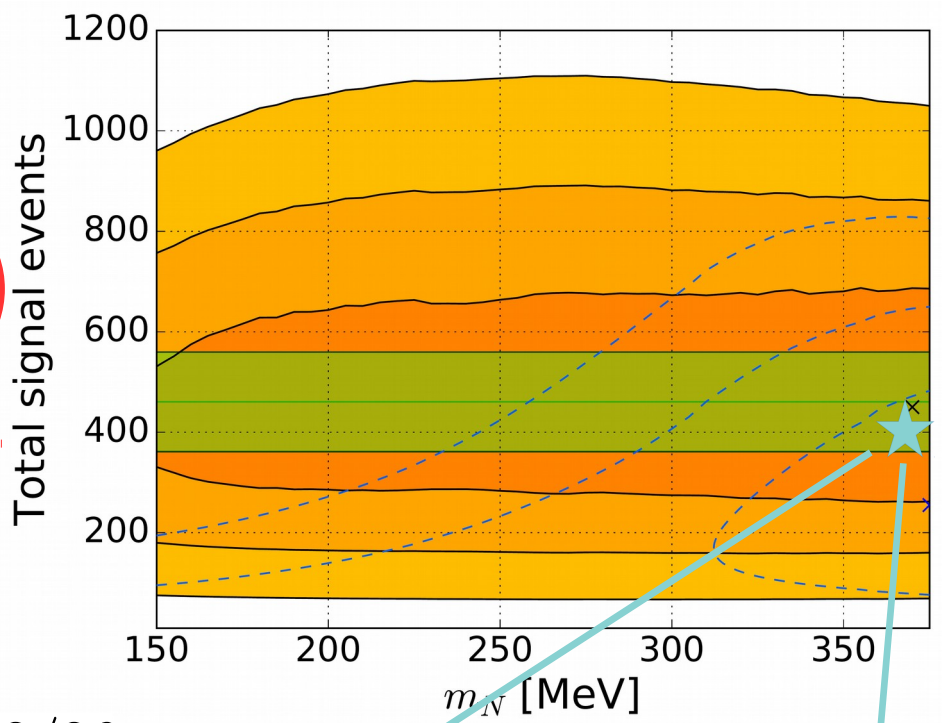


Energy and angular **spectra** fits

$K \to N\mu$

Without timing window



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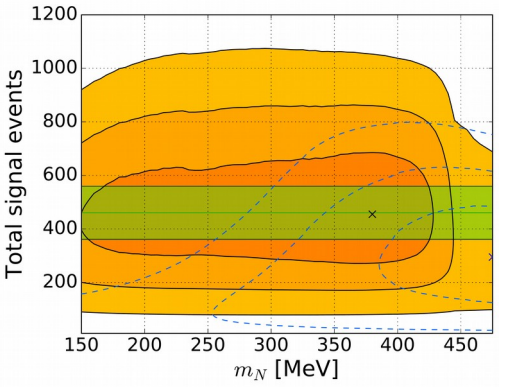

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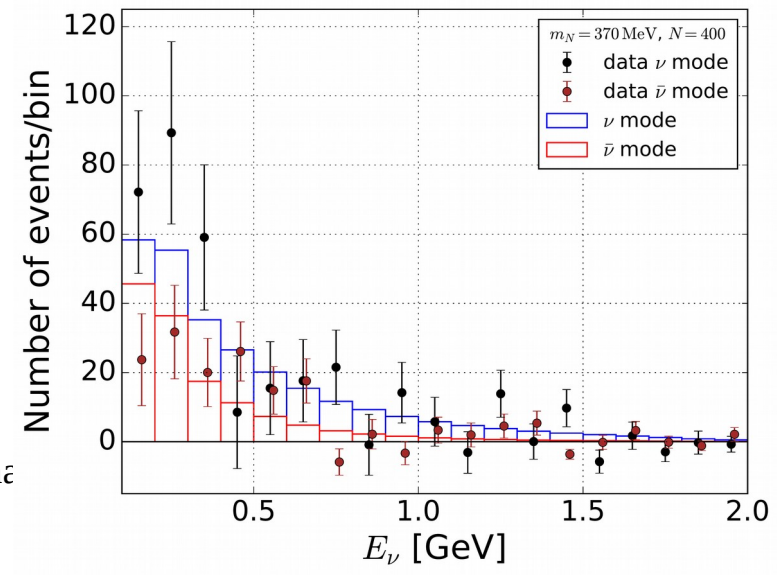

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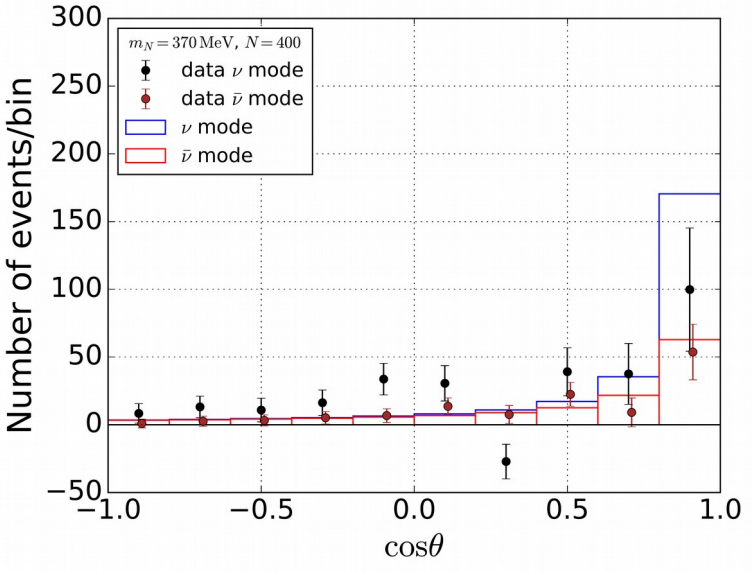

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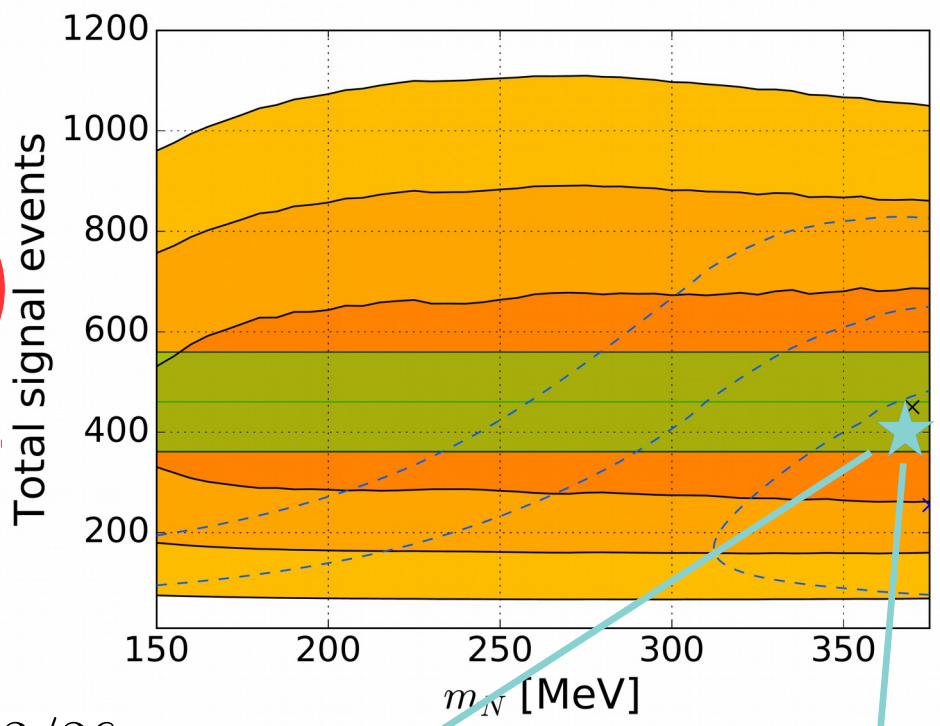

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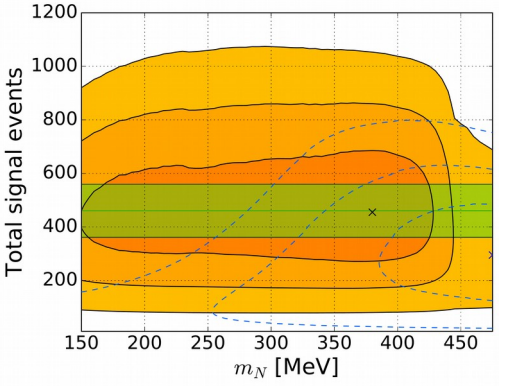

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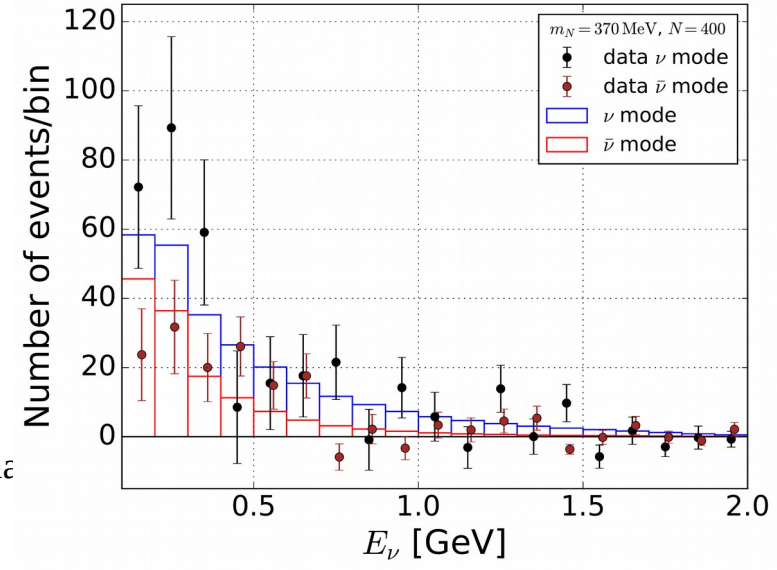
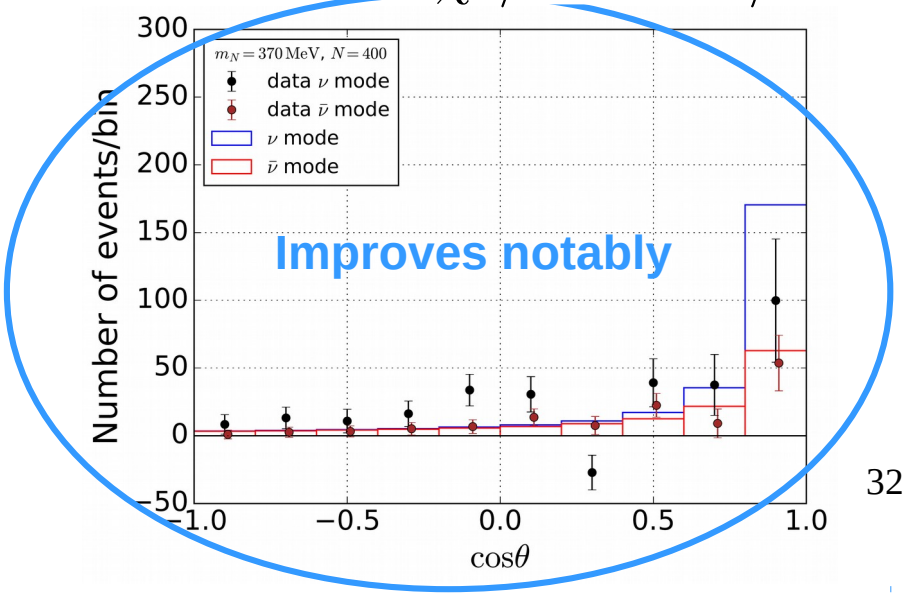
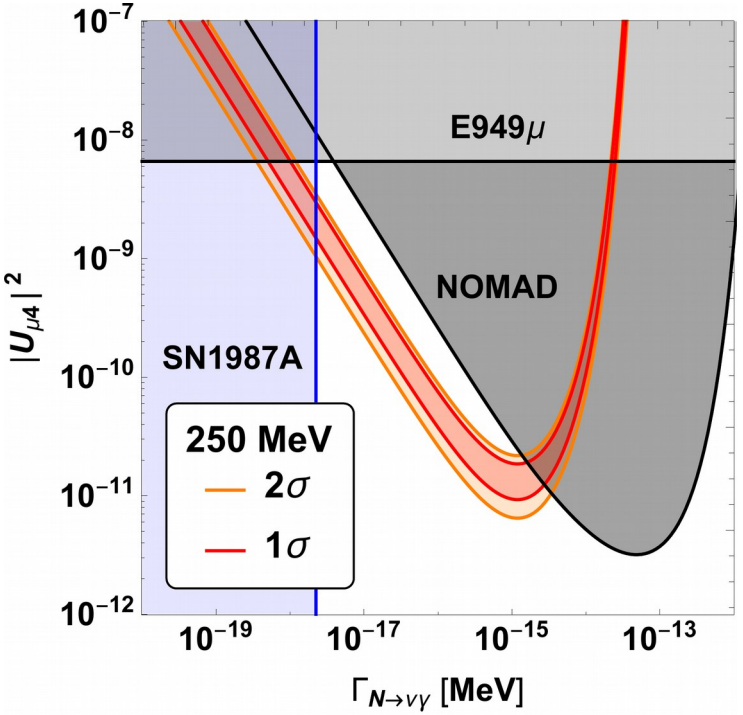
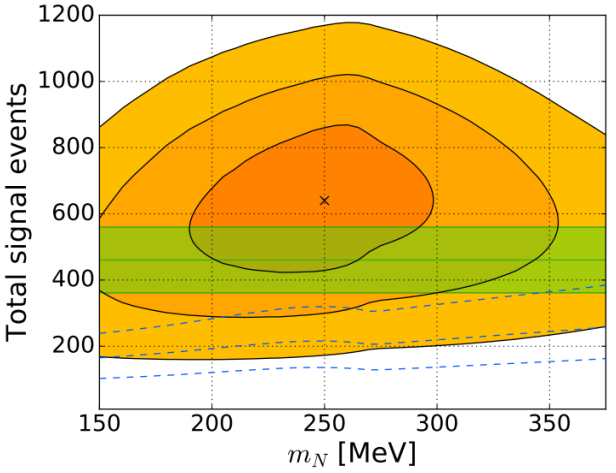


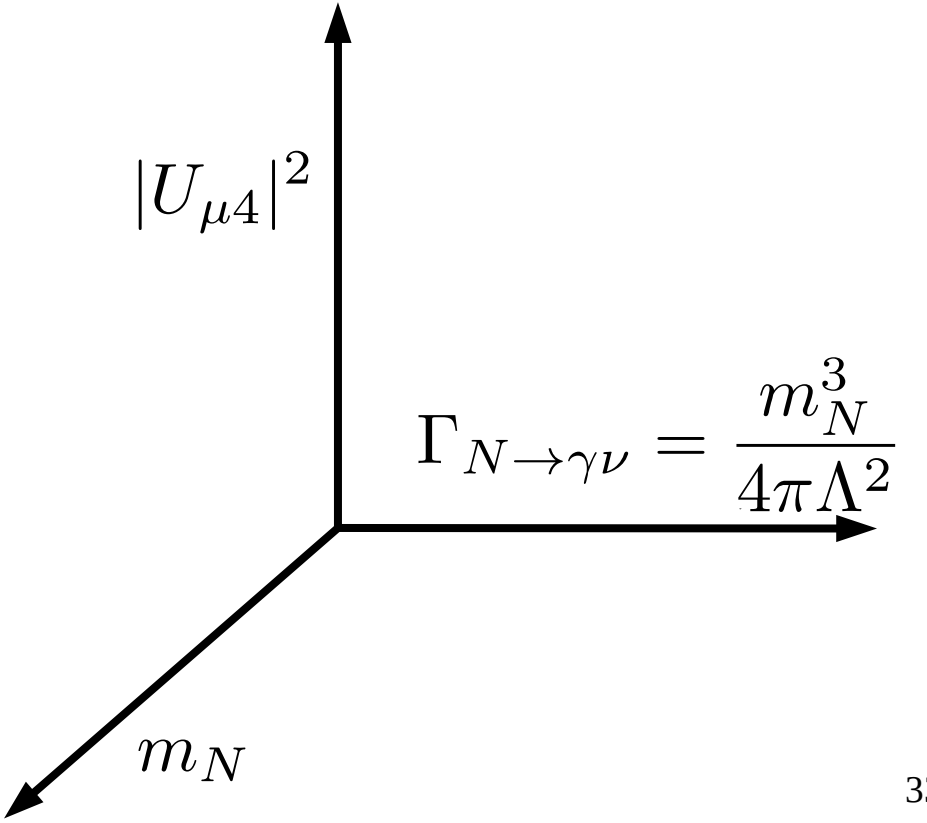
$\chi^2/\mathrm{dof} = 33/18$





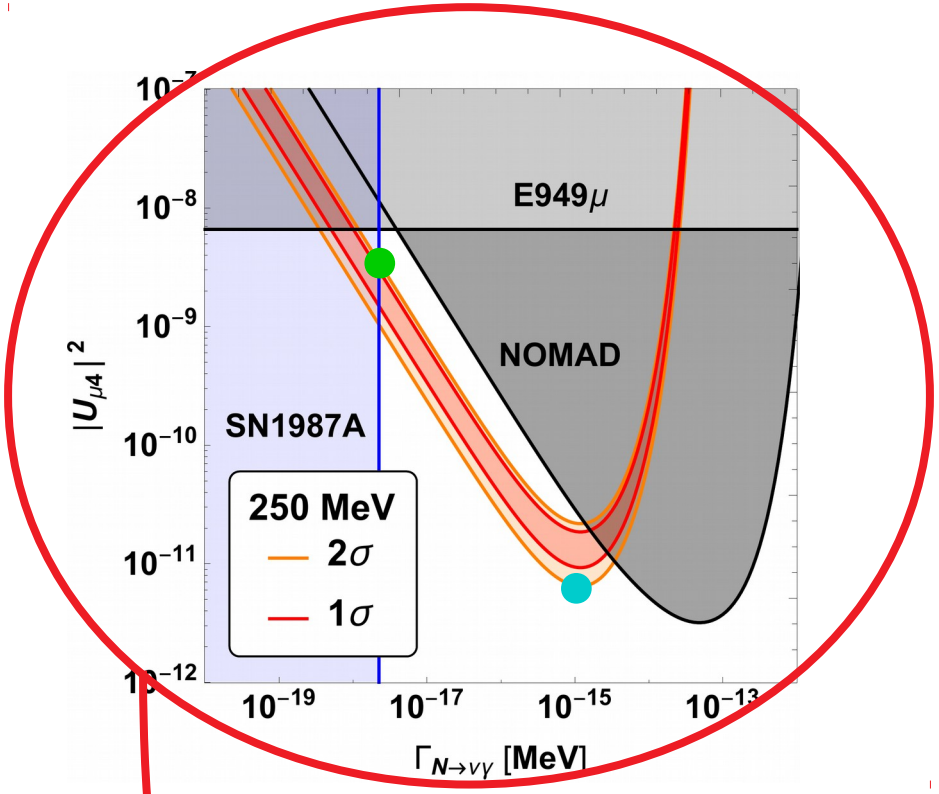


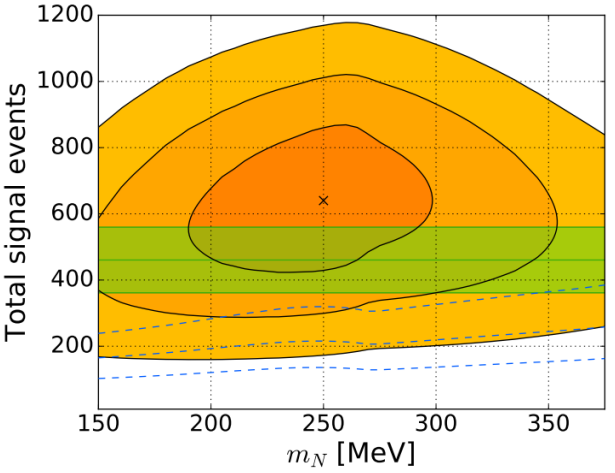
Parameters of the model



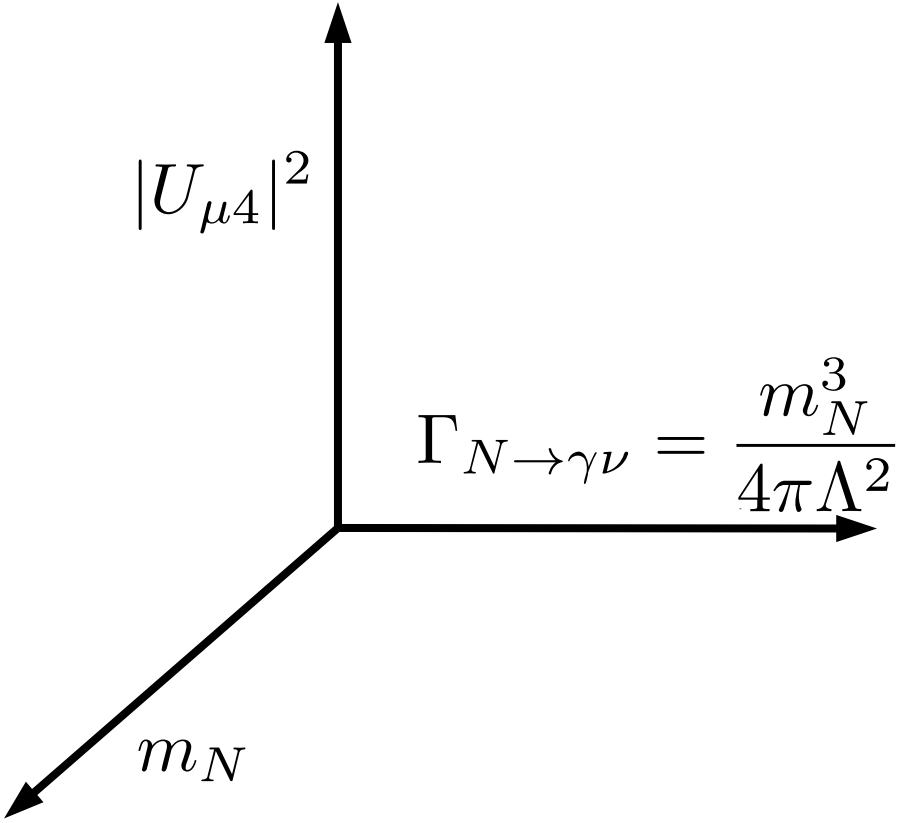
Supernova bound:

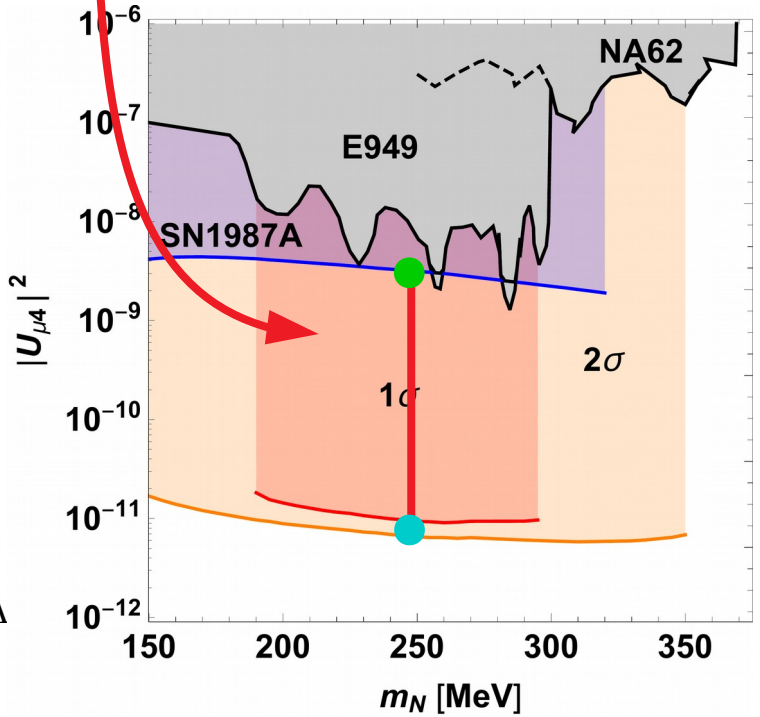
G.Magill et.al. arXiv:1803.0362



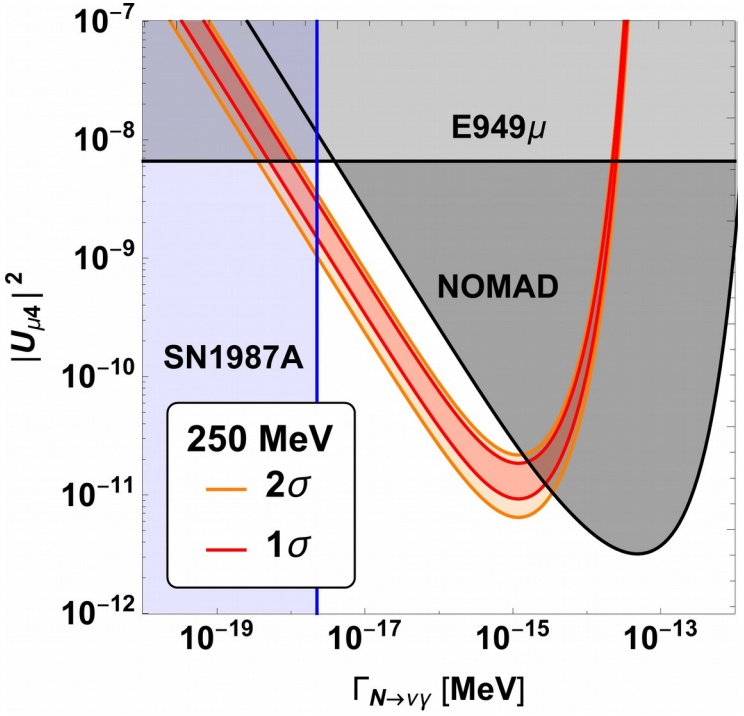


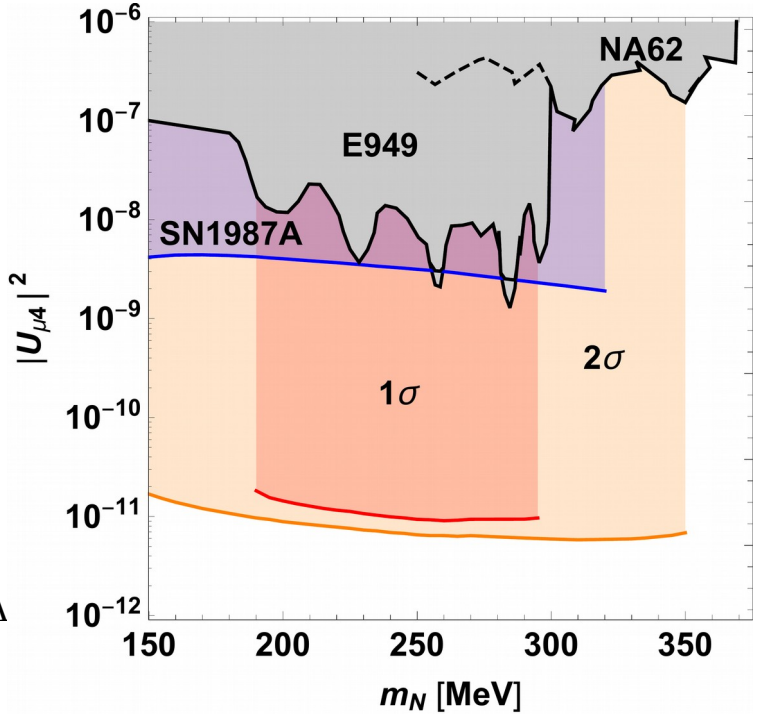
Parameters of the model



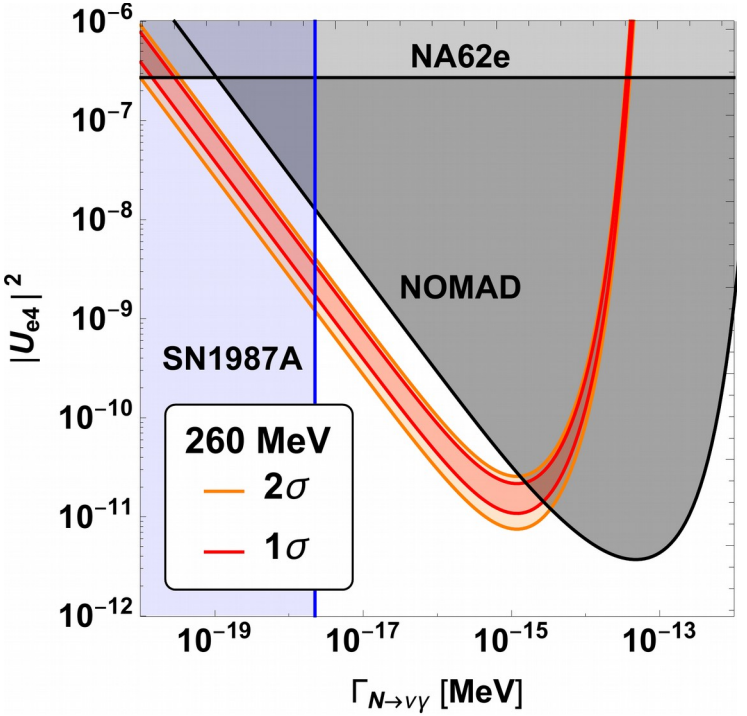


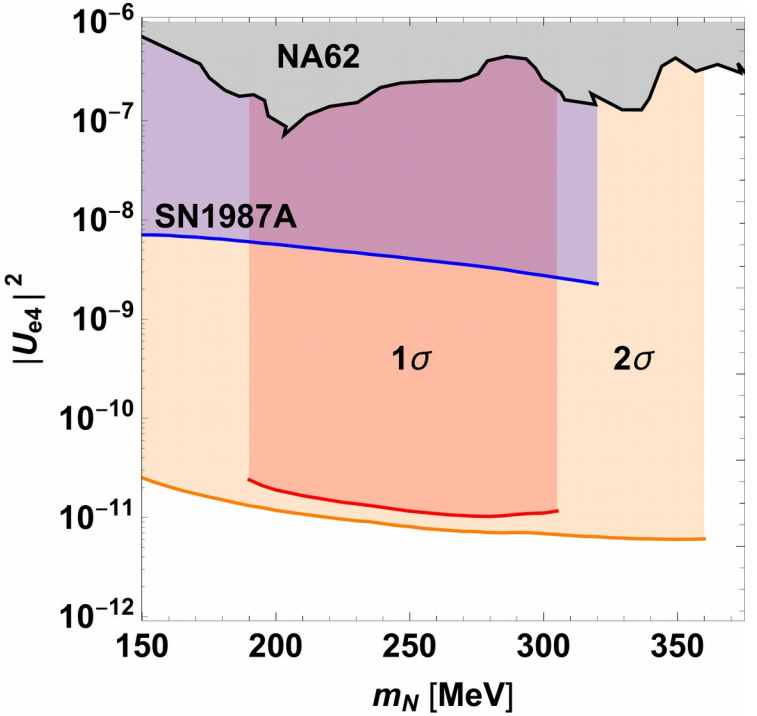
$K \to N\mu$





$K \to Ne$





More tests

- Fermilab Short-Baseline Neutrino Program

	MiniBooNE	SBND	MicroBooNE	Icarus
POT / 10^{20}	24	6.6	13.2	6.6
Volume / m^3	520	80	62	340
Baseline / m	540	110	470	600
Ratio		1	0.09	0.15
Events	400	400	35	58

See also: P.Ballett, et.al. arXiv:1610.08512

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$$\mathrm{POT} \times V/L^2$$

See also: P.Ballett, et.al. arXiv:1610.08512

Summary

MiniBooNE excess explanation with a ~250 MeV heavy neutrino decaying into a photon:

- Mixing: $10^{-11} \lesssim |U_{\ell 4}|^2 \lesssim 10^{-7}$
- Mass: $\sim 250\,\mathrm{MeV}$
- New physics scale: $10^4\,\mathrm{TeV} \lesssim \Lambda \lesssim 10^7\,\mathrm{TeV}$

Ingredients for the light neutrino masses via seesaw

- Timing shape: **Ultimate test** for the model
- More tests: Fermilab Short-Baseline Neutrino Program

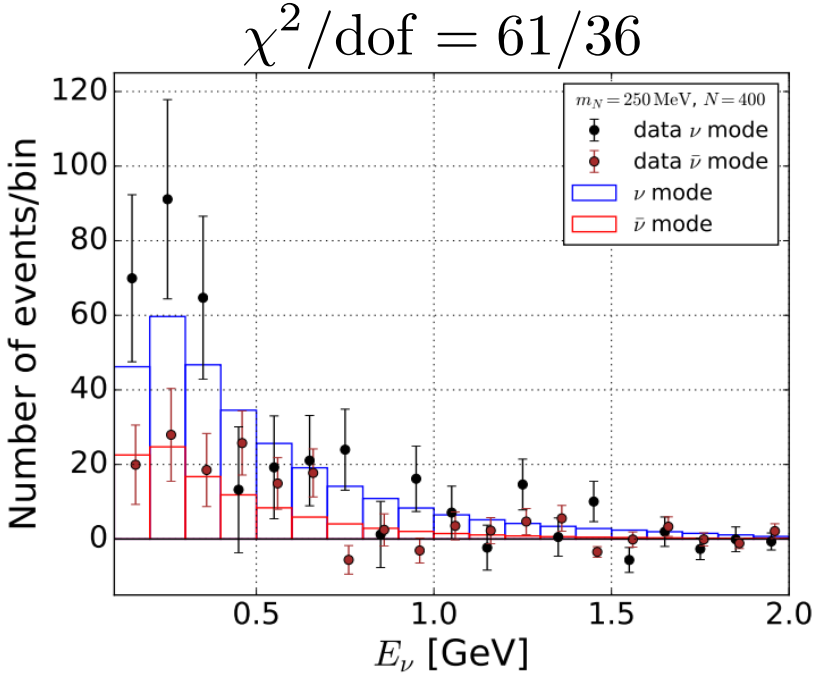
Thank you

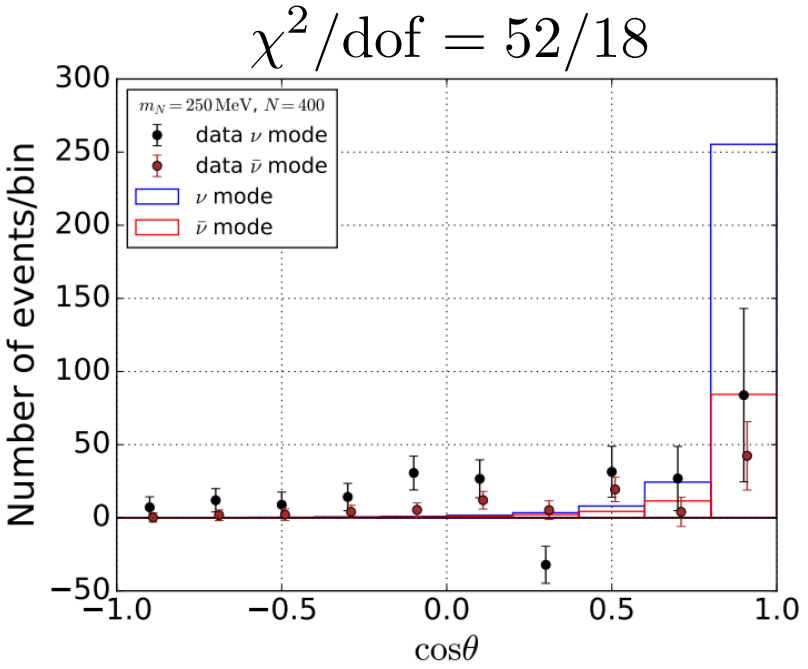
This project has received funding/support from the European Unions Horizon 2020 research and innovation programme under the Marie Sklodowska -Curie grant agreement No 674896

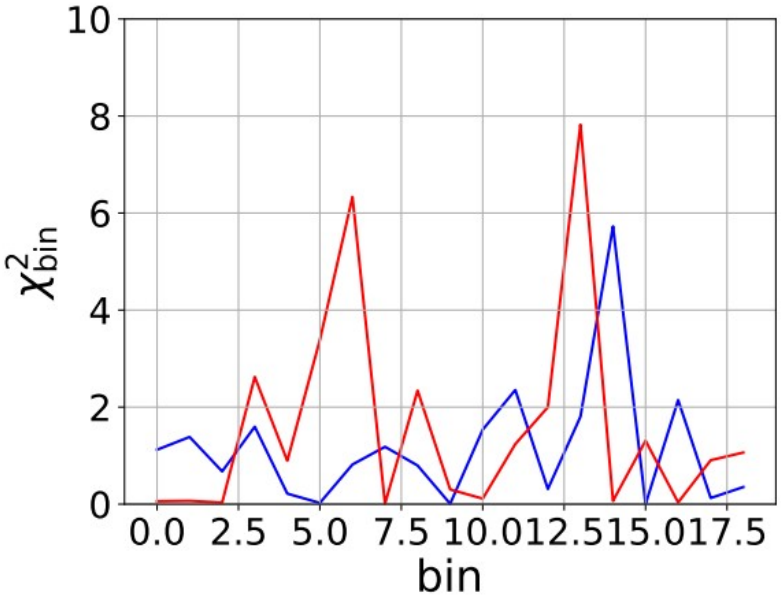
Back up slides

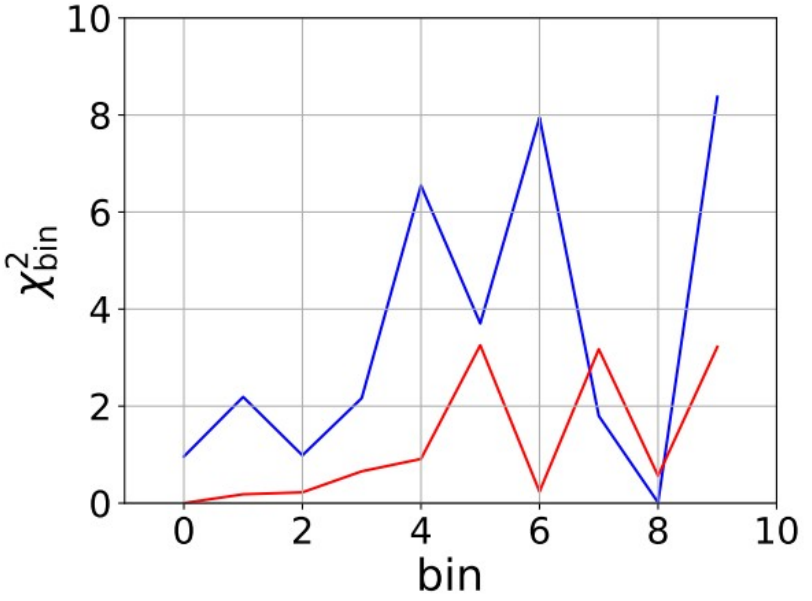
Spectral fits

Time window:





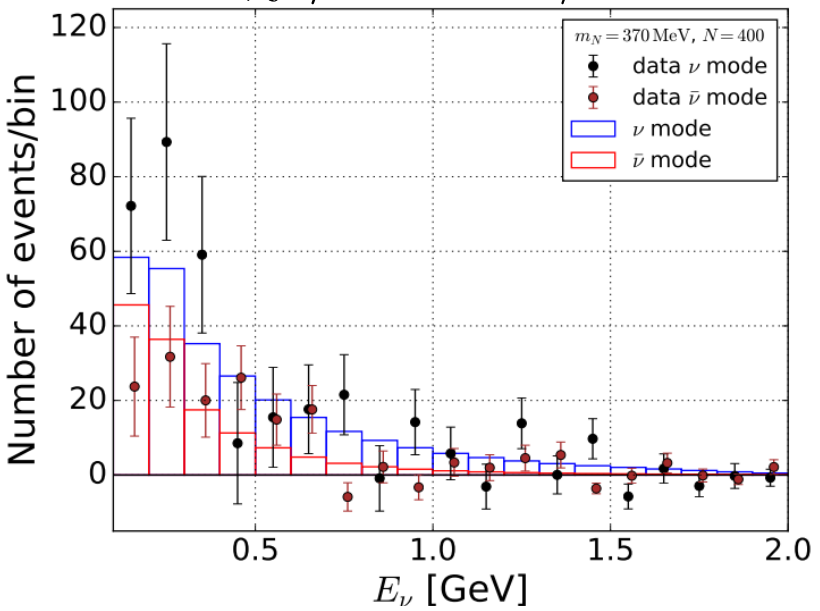




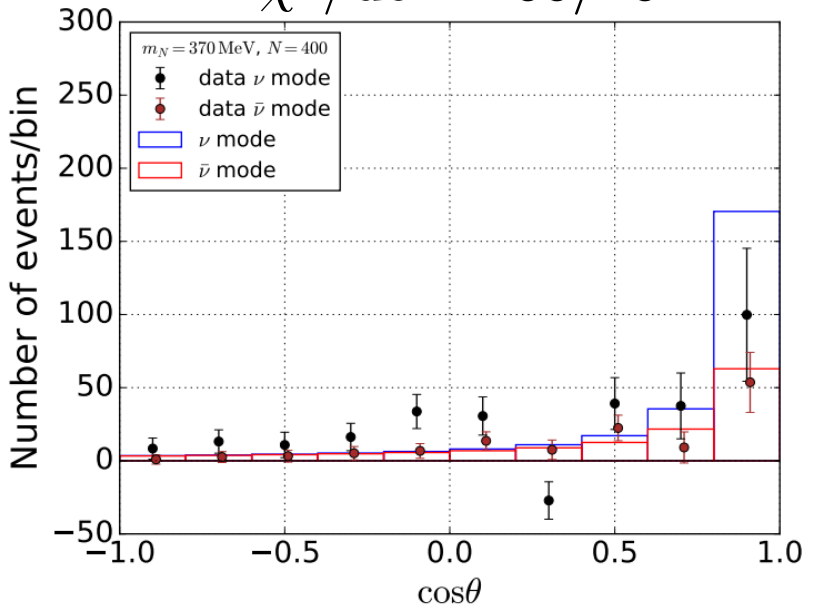
Spectral fits

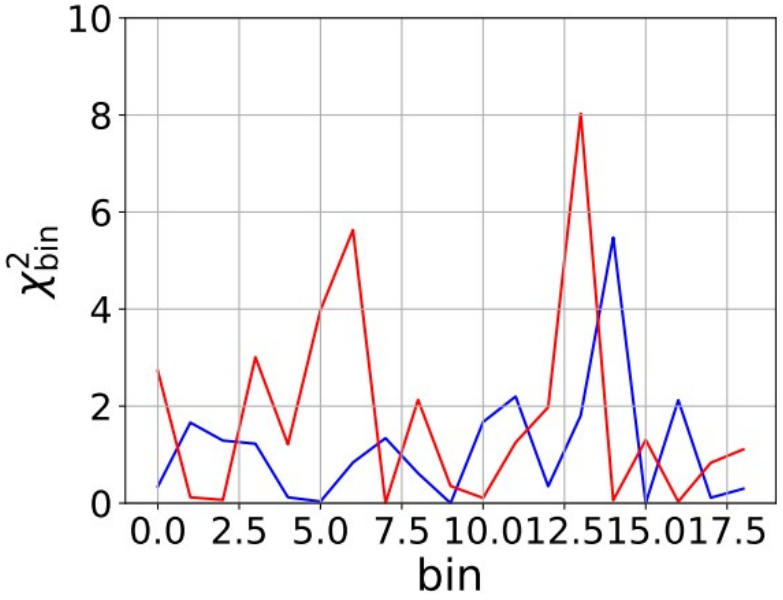
Without time window:

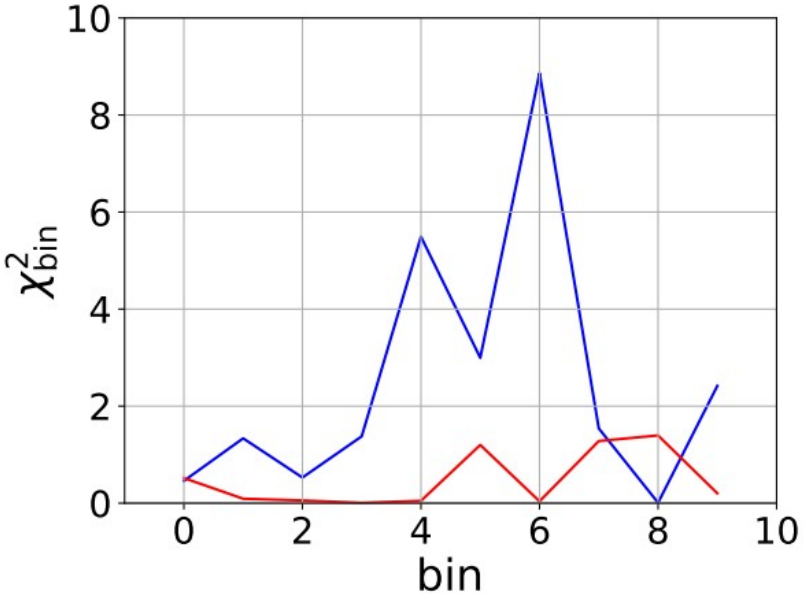
$\chi^2/\mathrm{dof} = 63/36$



$\chi^2/\mathrm{dof} = 33/18$

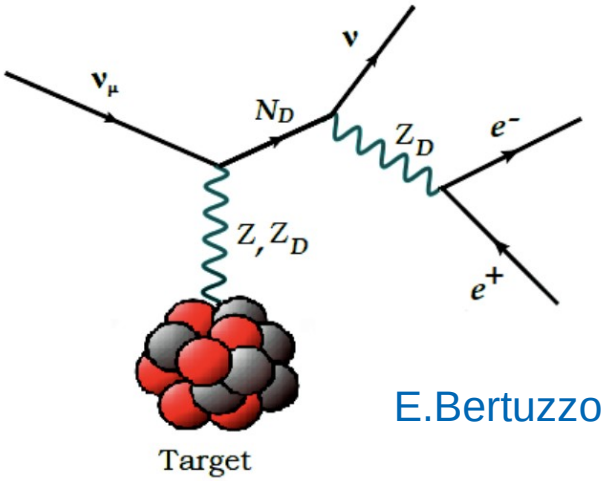




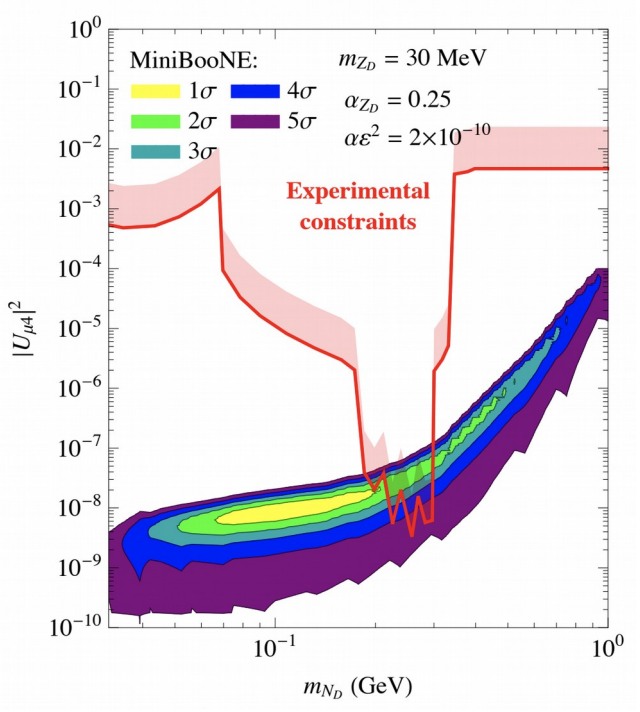


Further models

Nucleus scattering:

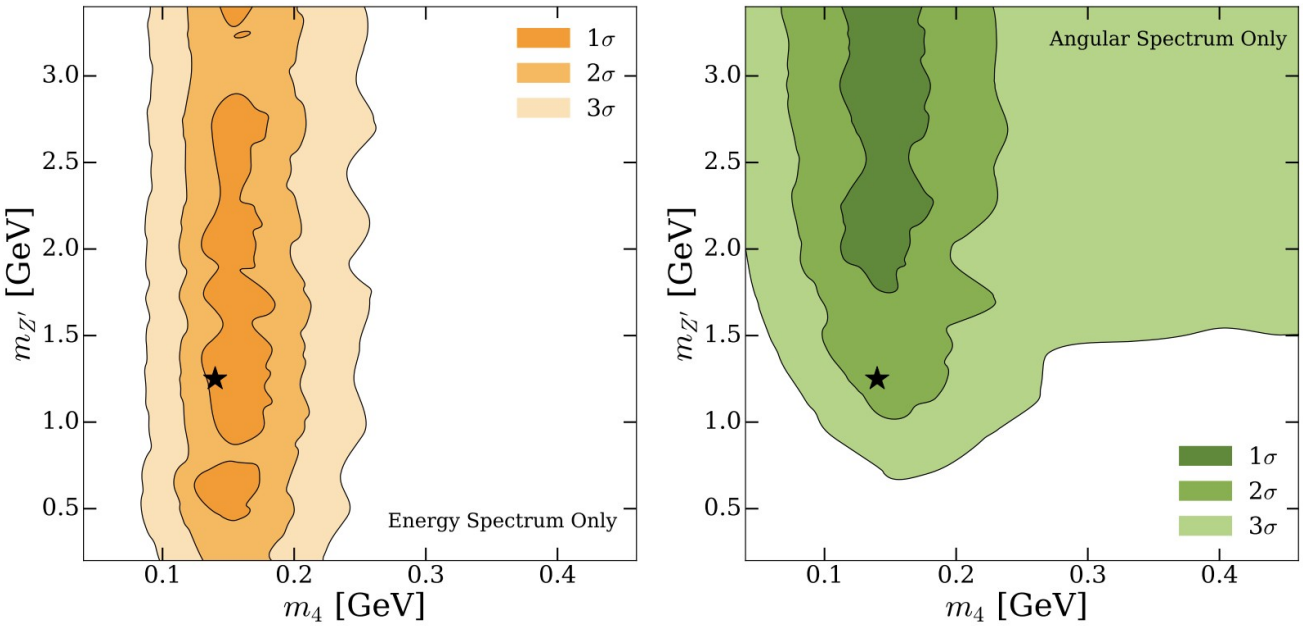


E.Bertuzzo et.al. arXiv:1807.09877



E.Bertuzzo et.al. arXiv:1807.09877

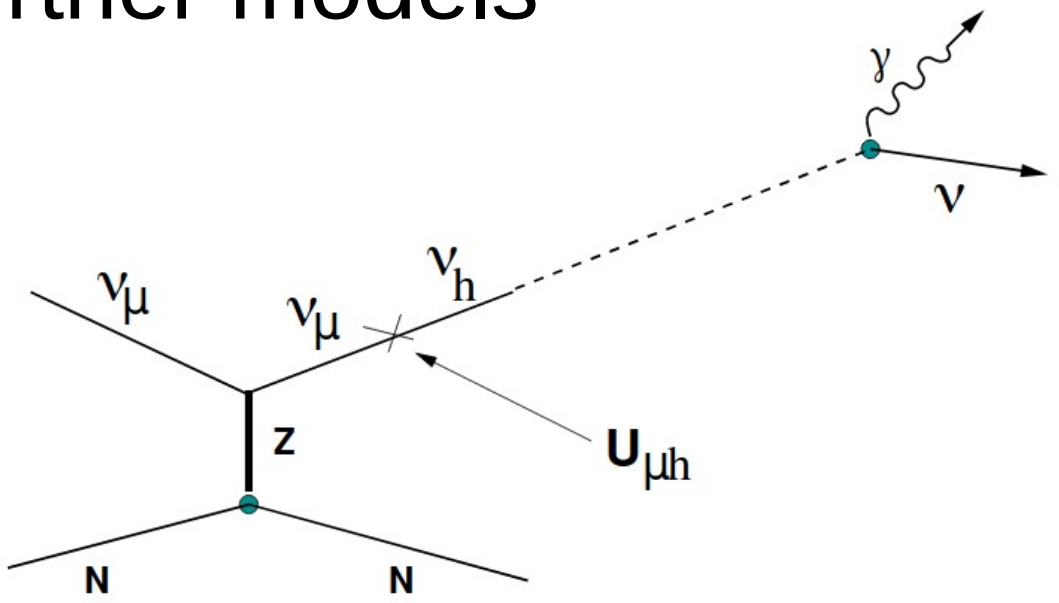
Different model, based on Nucleus scattering



P.Ballet et.al. arXiv:1808.02915

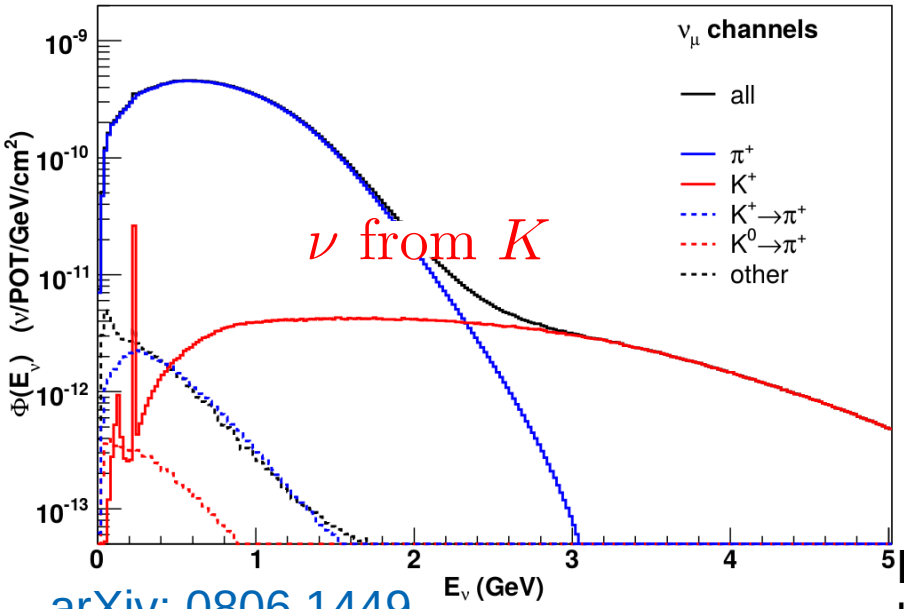
Further models

Nucleus scattering:



S.N.Gininenko arXiv: 0902.3802, arXiv: 1009.5536

Heavy neutrino flux

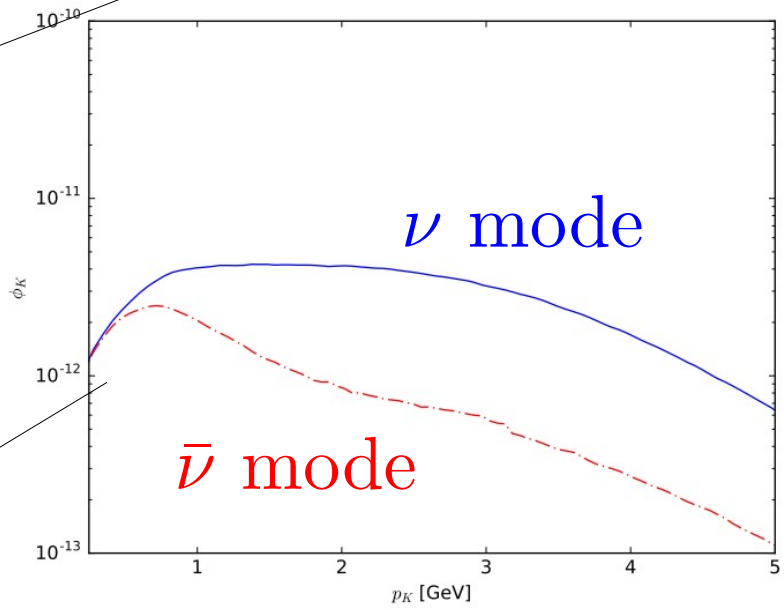


arXiv: 0806.1449

Inverse Boost

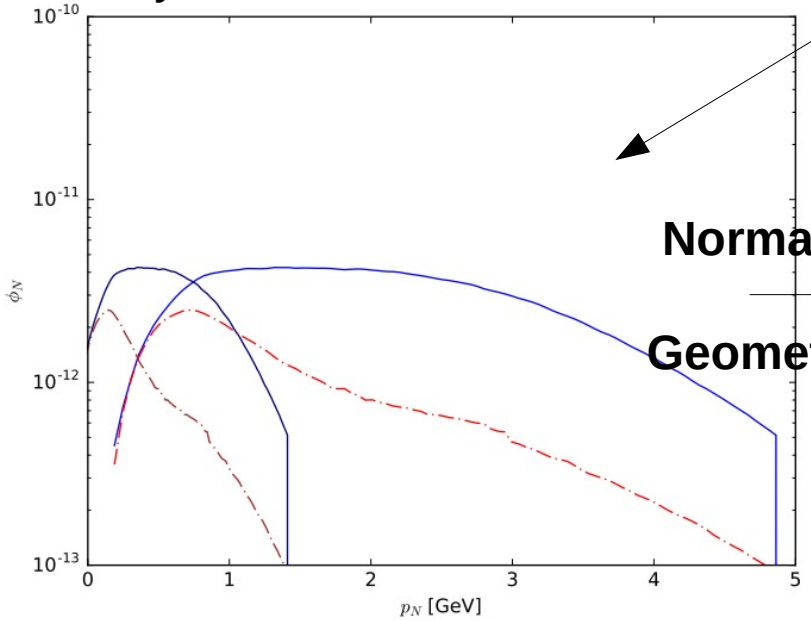
$K \to \ell\nu$

Kaon spectrum



Boost to the lab frame

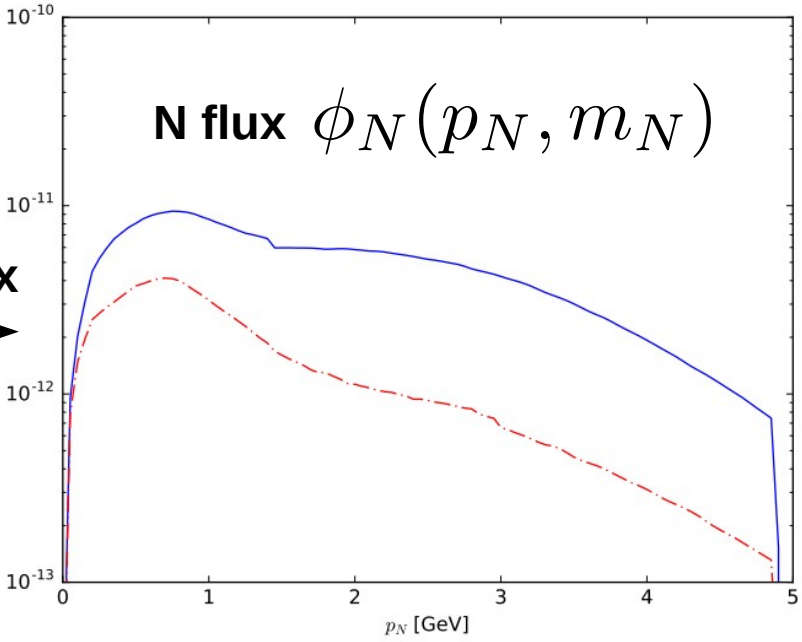
K decay at rest: backward & forward



Normalize to the total flux

Geometrical acceptance

N flux $\phi_N(p_N, m_N)$

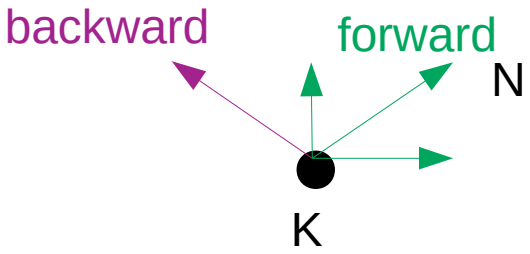


$\phi_N(p_N, m_N)$ from $\phi_\nu(p_\nu)$

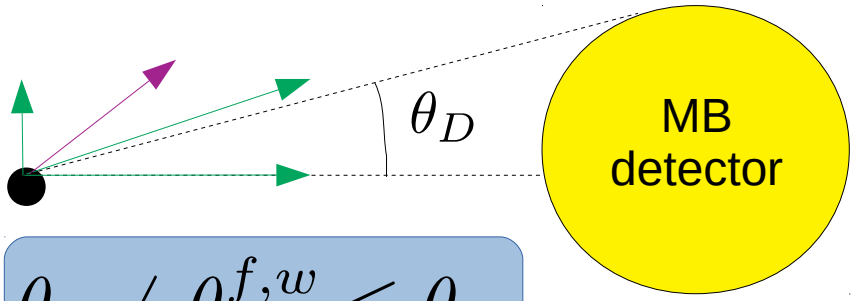
Branching ratio: $\dfrac{\mathrm{Br}(K \to \ell N)}{\mathrm{Br}(K \to \mu\nu)}$

- Mixing $|U_{\ell 4}|^2$
- Helicity enhancement
- Phase space suppression

Geometrical acceptance:



Boost to the lab frame



$$\theta_\nu \neq \theta_N^{f,w} \leq \theta_D$$