New Constraints on *New* Explanations of the *MiniBooNE* anomaly

Austin Schneider

Based on: 1812.08768, 2105.06470,
2109.03831, 2205.12273, 2206.07100

Neutrino Theory Network Workshop
Illinois, June 22, 2022

Carlos Argüelles

HARVARD UNIVERSITY

Alfred P. Sloan FOUNDATION

Starring:

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Nicolo Foppiani

Nicholas Kamp

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Outline

- Why go beyond vanilla sterile neutrinos?
- The garden of forking paths
- Focusing on two explanations:
  - Only Di-electron
  - Single photon + oscillations
- Future

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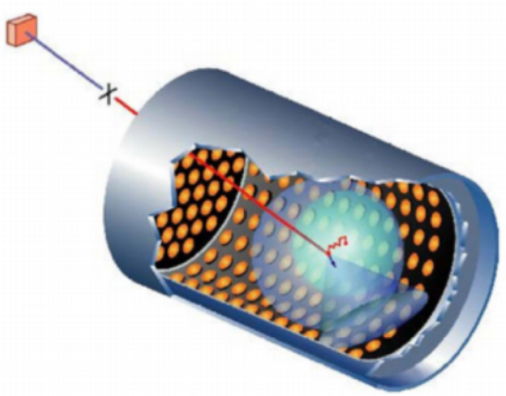
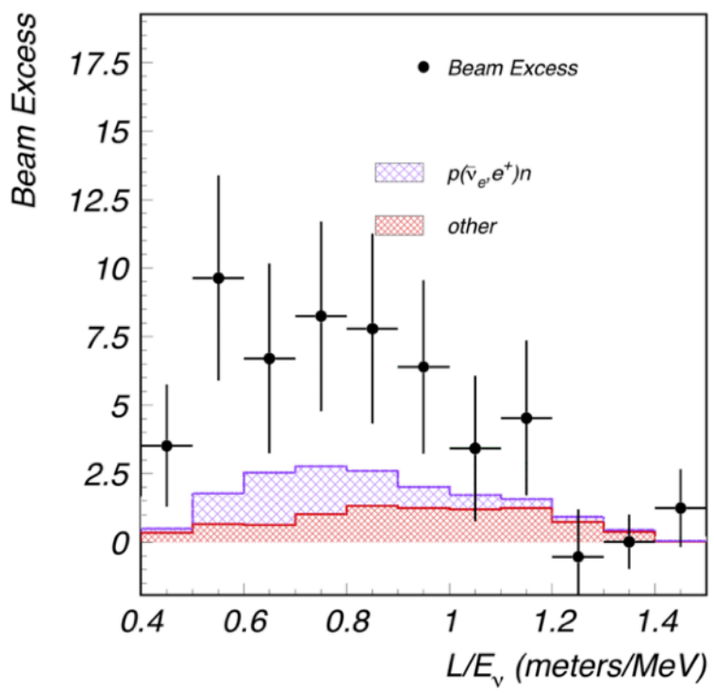
The pieces that do not fit: short-baseline anomalies

LSND

(3.8σ!)

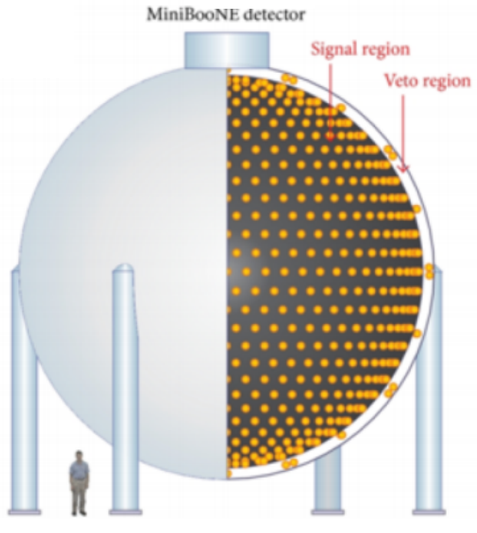


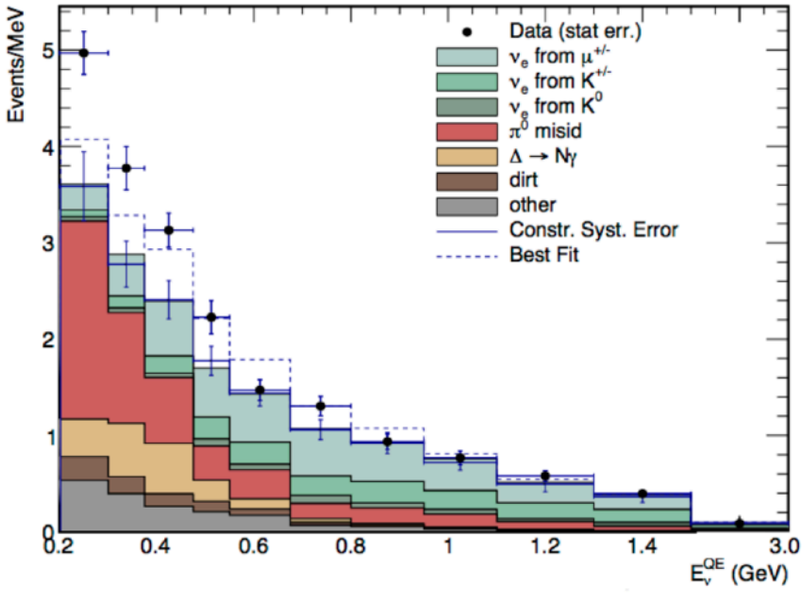


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

MiniBooNE

(4.8σ!)





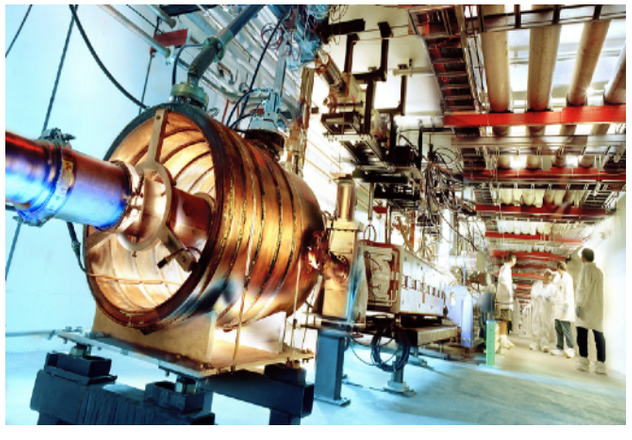
This points to $\Delta m^2 \sim 1 eV^2$

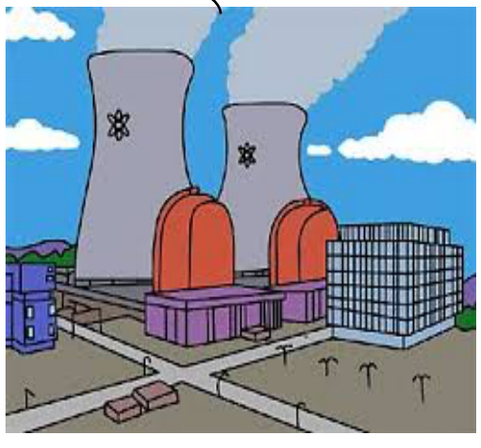
These are not alone, other interesting observations

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $*$	SciBooNE/MiniBooNE	KARMEN/LSND Cross Section
	MiniBooNE(NuMI)	CCFR	Gallium $*$
	NOMAD	CDHS	BEST $*$
	MicroBooNE (BNB) ($*$?)	MINOS IceCube	
Antineutrino	LSND $*$	SciBooNE/MiniBooNE	Bugey Daya Bay
	KARMEN	CCFR	NEOS PROSPECT
	MiniBooNE (BNB) $*$	MINOS	DANSS STEREO
		IceCube ($*$?)	Neutrino-4 $*$

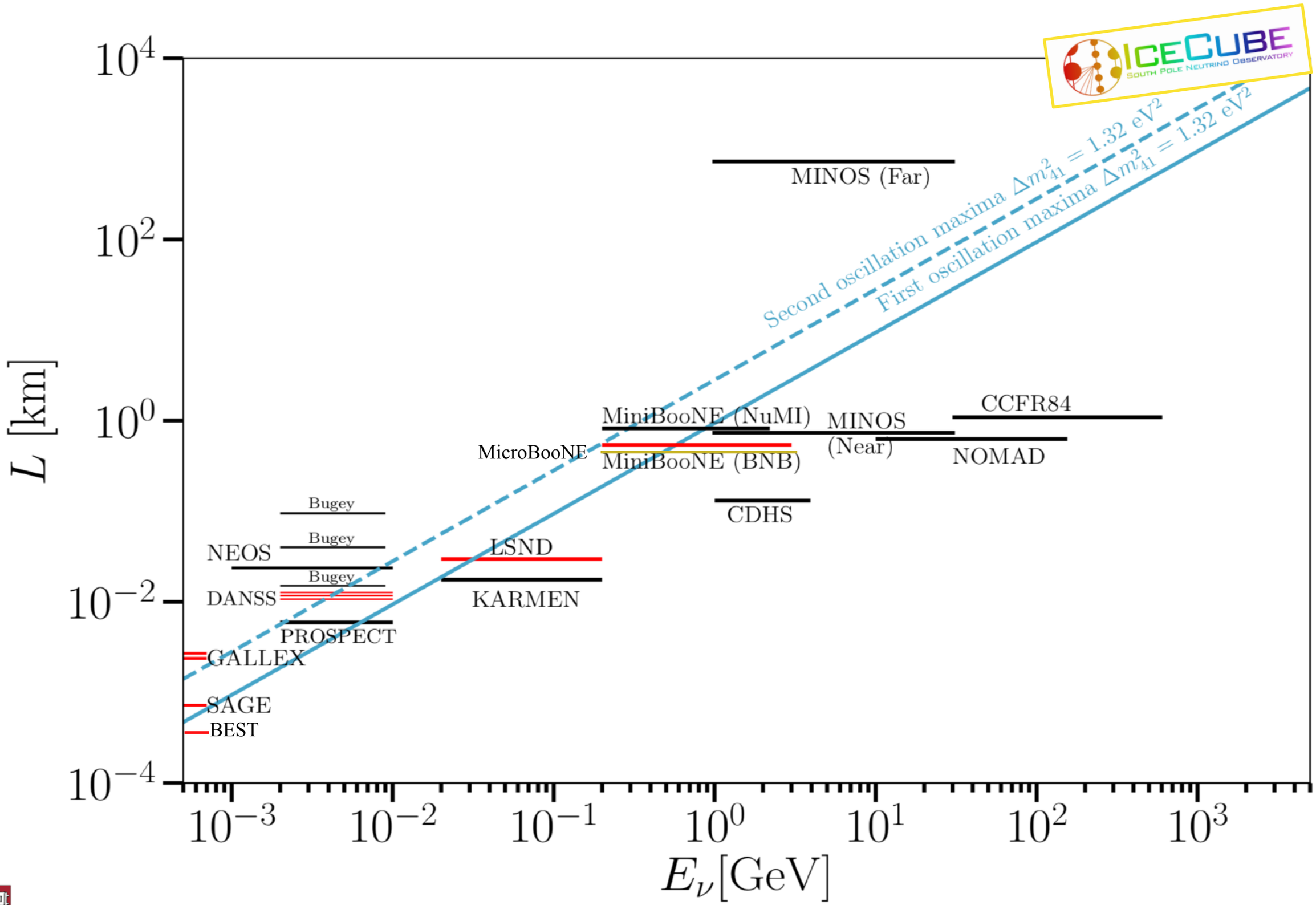
$\boxed{\ast} \implies$ >2σ “signal”

$\boxed{\ast} \implies$ unclear “signal”



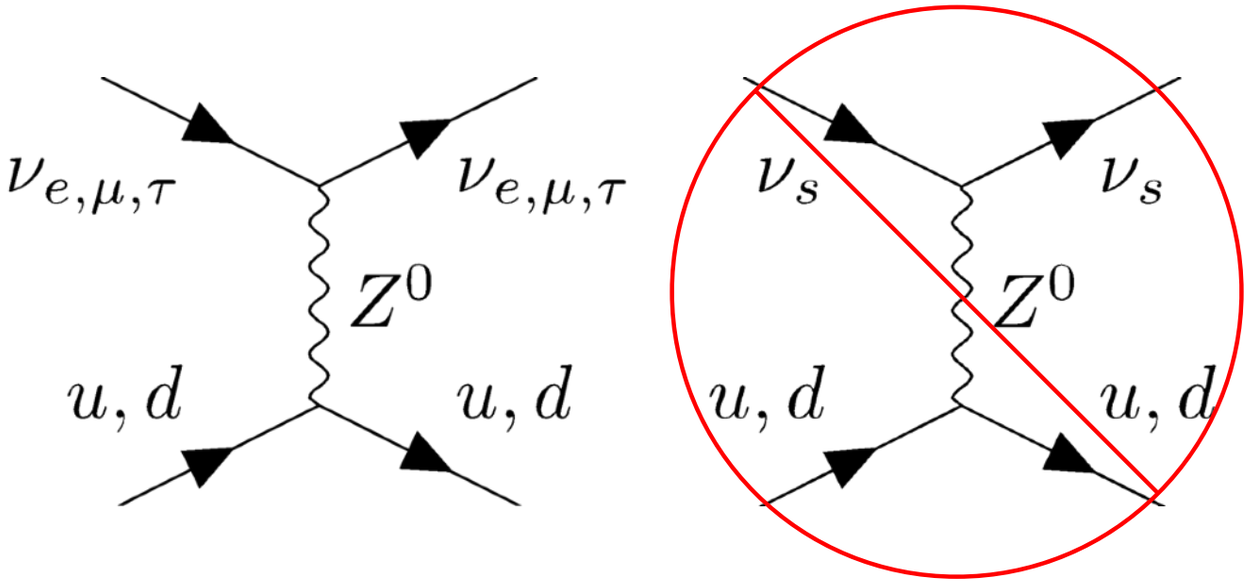


The anomalies lie ~ in a line

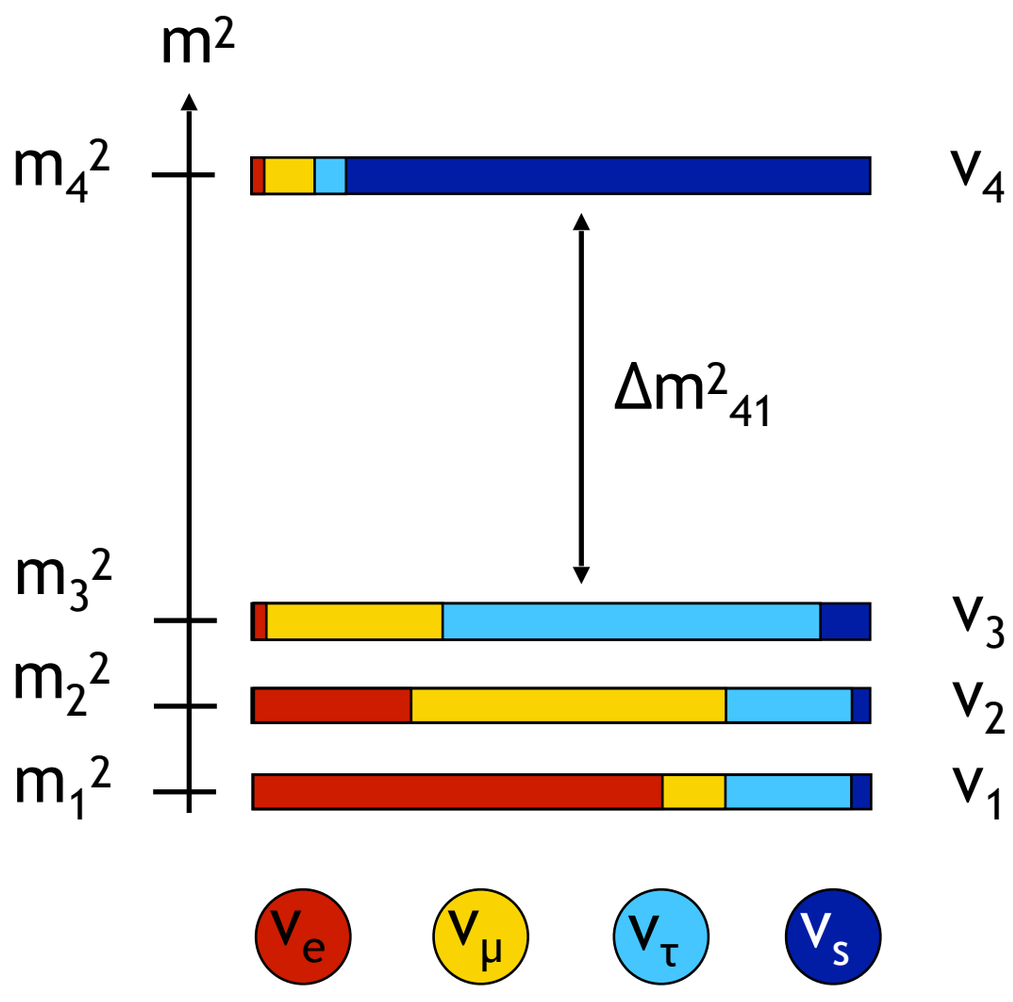


Diaz *et al.* arXiv:1906.00045

Introducing a sterile neutrino



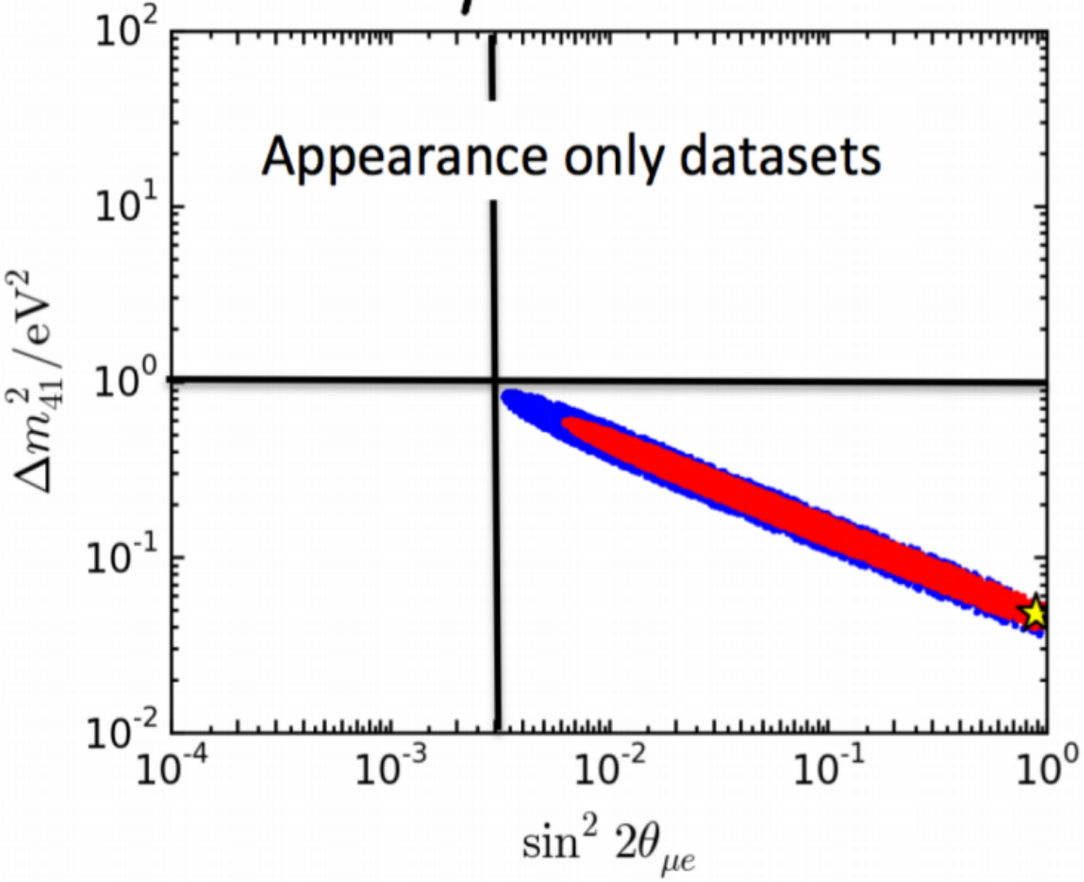
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



Assuming Normal Ordering

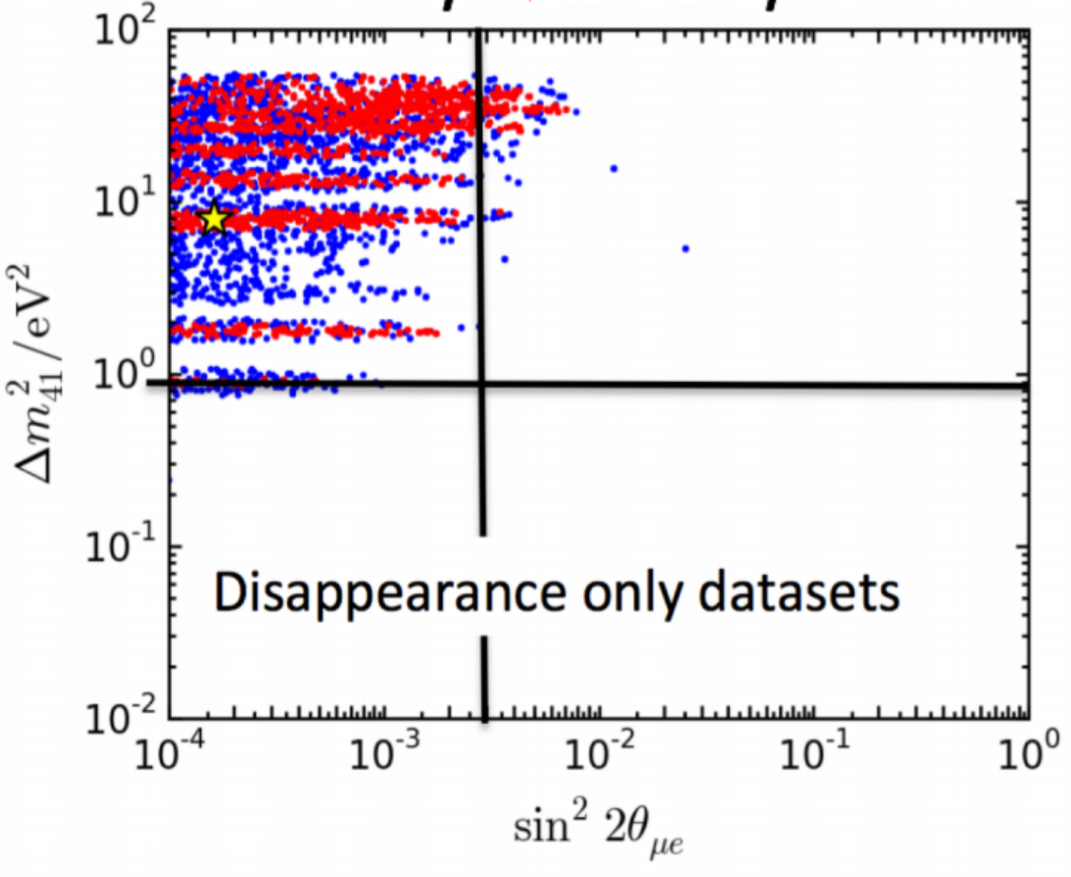
Appearance and disappearance "preference regions" don't overlap!

$\nu_\mu \rightarrow \nu_e$



LSND/MB Driven

$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\mu$



Reactor, Long-Baseline Driven

From Collin et al. 1602.00671, similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018). See Diaz et al. arXiv:1906.00045 for more discussion.

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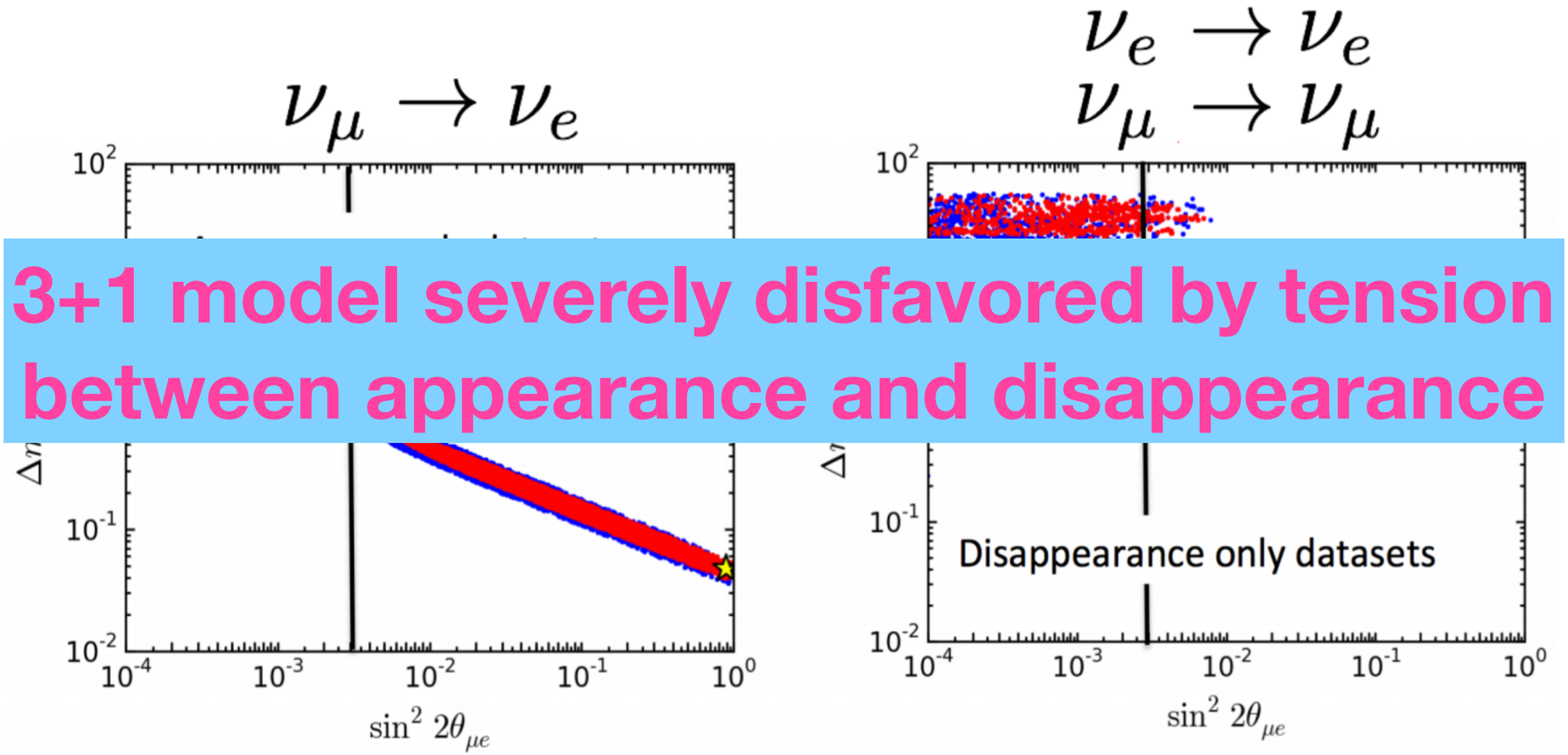

3+1 model severely disfavored by tension between appearance and disappearance

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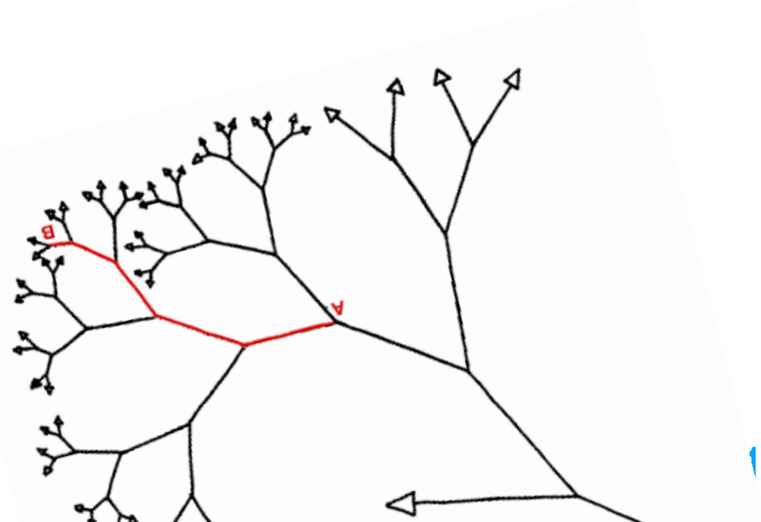
From here: The Garden of Forking Paths*

- Do we understand all SM background/process well enough?
- Do we understand how neutrino oscillations work?
- Are all the anomalies (MB, LSND, reactors) related? Or only some of them?
- Since null results are not scrutinized as carefully as anomalous ones
- Why is there a very significant signal for ν_e disappearance in sources, but not in reactors?
- How do we interpret MicroBooNE data? Electron-neutrino disappearance? Nothing?
- Is IceCube seeing hints of the missing muon-neutrino disappearance?
- If the anomalies are confirmed as new physics, in what theories are they embedded?



*Garden of Forking Paths is spy/mystery short story by Jorge Luis Borges

Stepping back: What do we know?

- LSND saw an excess of electron-antineutrino events.
- MiniBooNE saw an excess of electron-like events in neutrino and antineutrino modes.
- MicroBooNE saw no single photons; electron results need further discussion.
- Reactor experiments using ratios see hints of oscillations at large mass-square-differences.
- Source experiments see very significant deficit.
- Muon-neutrino disappearance has resulted in weak signals at large mass-square-differences.
- Anomalous observations are on a line on L/E.
- Standard cosmological scenarios disfavor an additional neutrino. Though tensions in the Hubble parameter indicate that something is missing.

Indications of new neutrino oscillations

Indications of additional new physics

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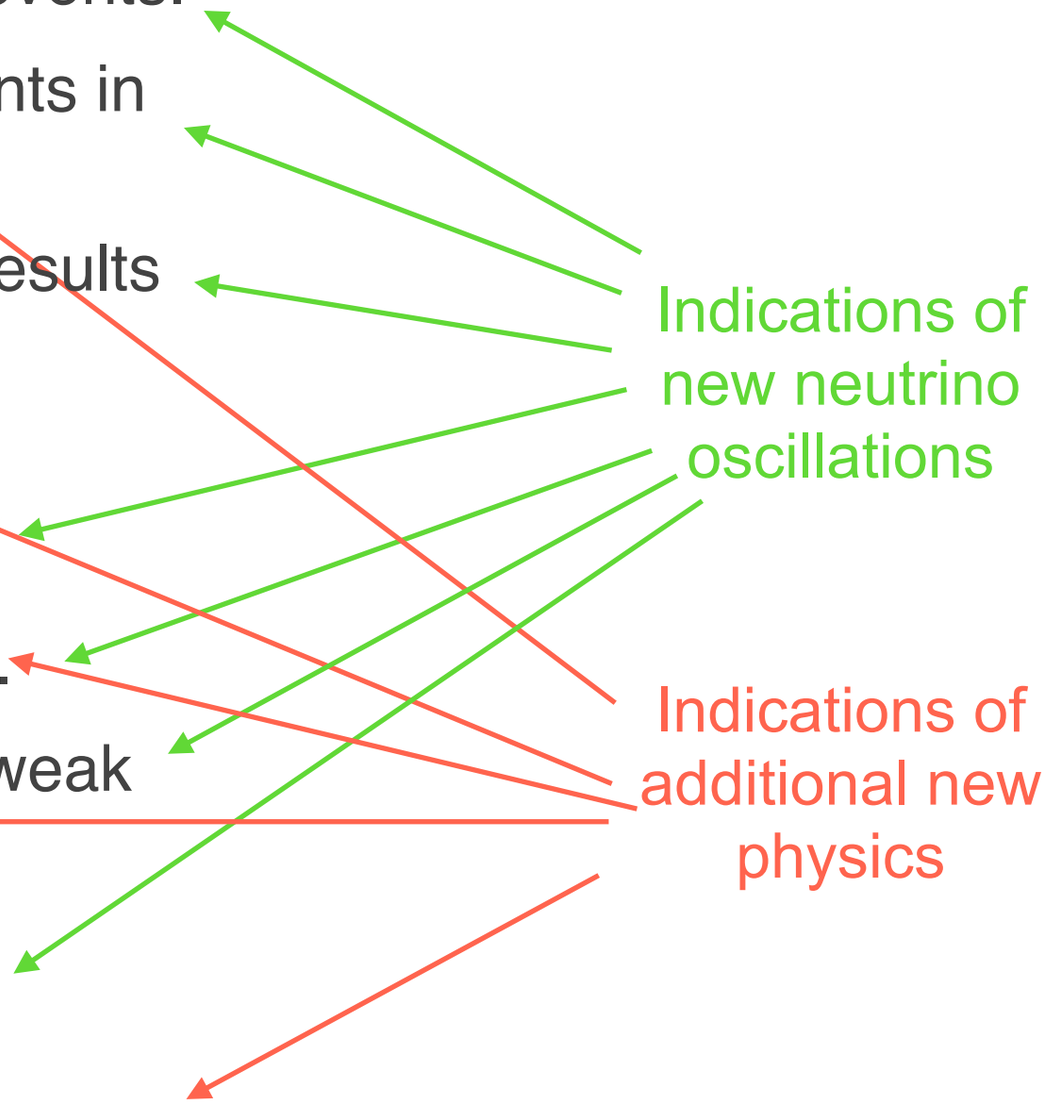

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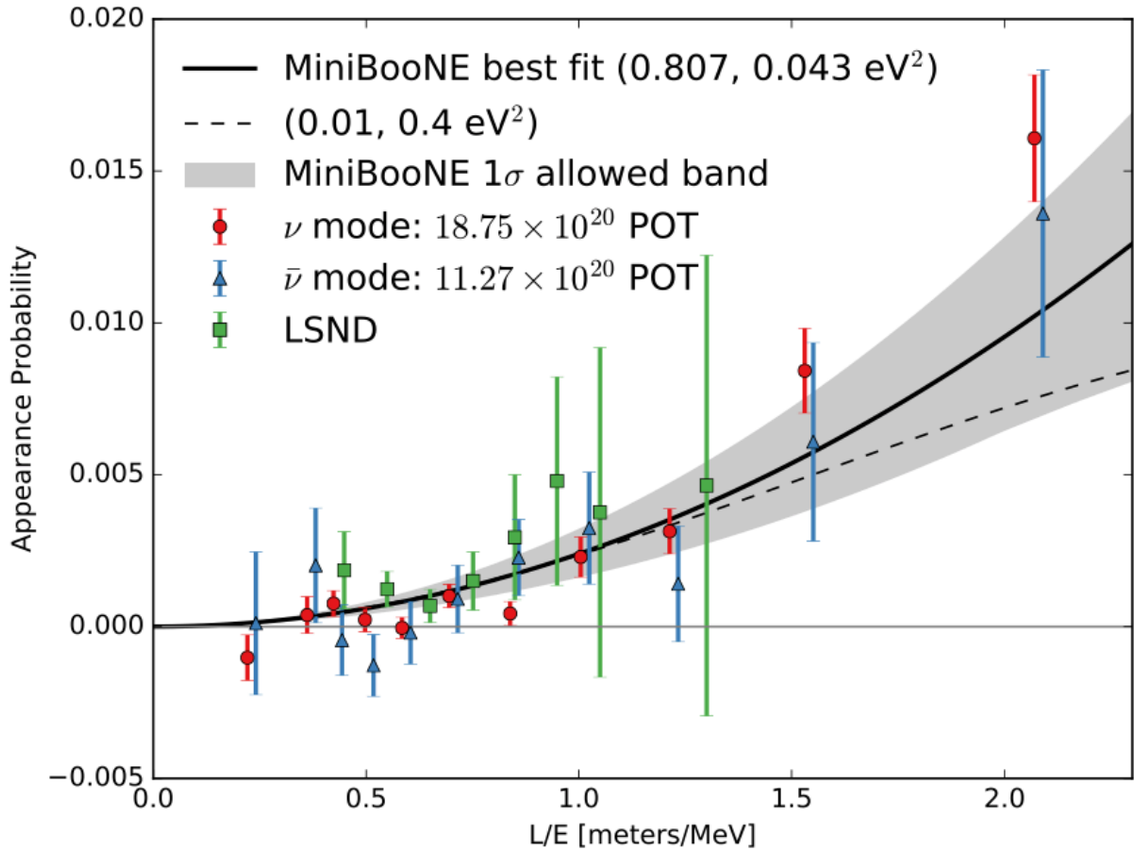
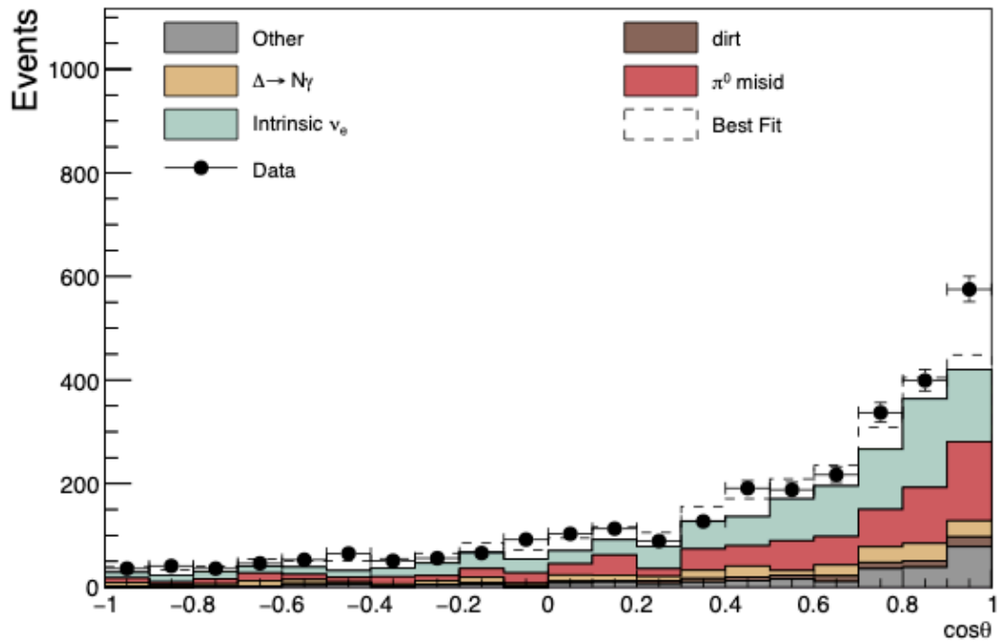
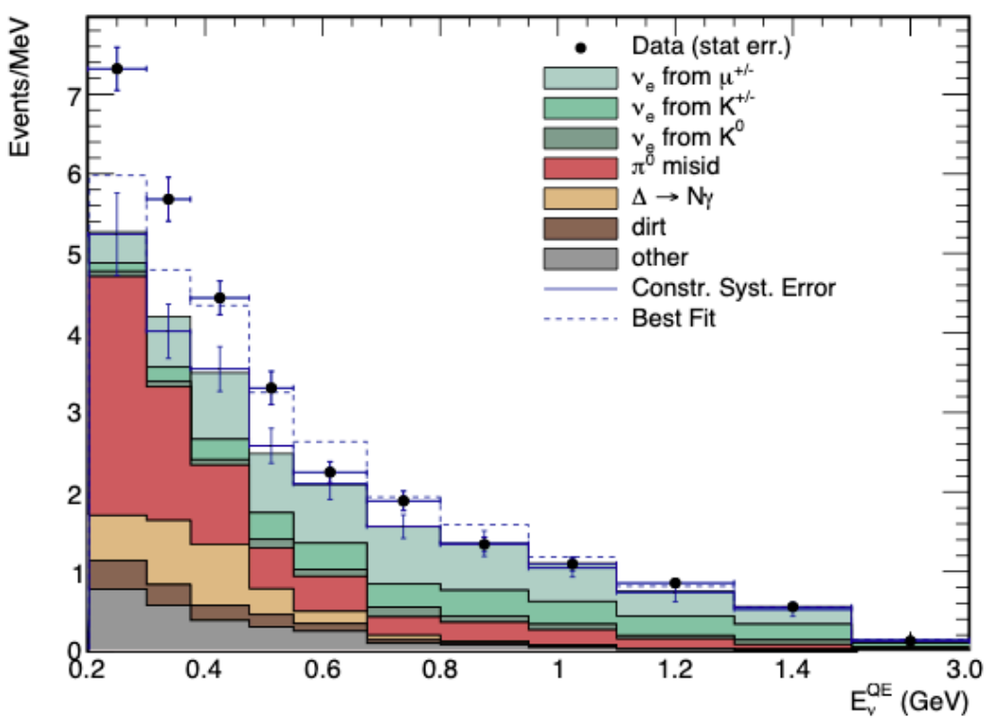
Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation





In other cases we need to fit these two!

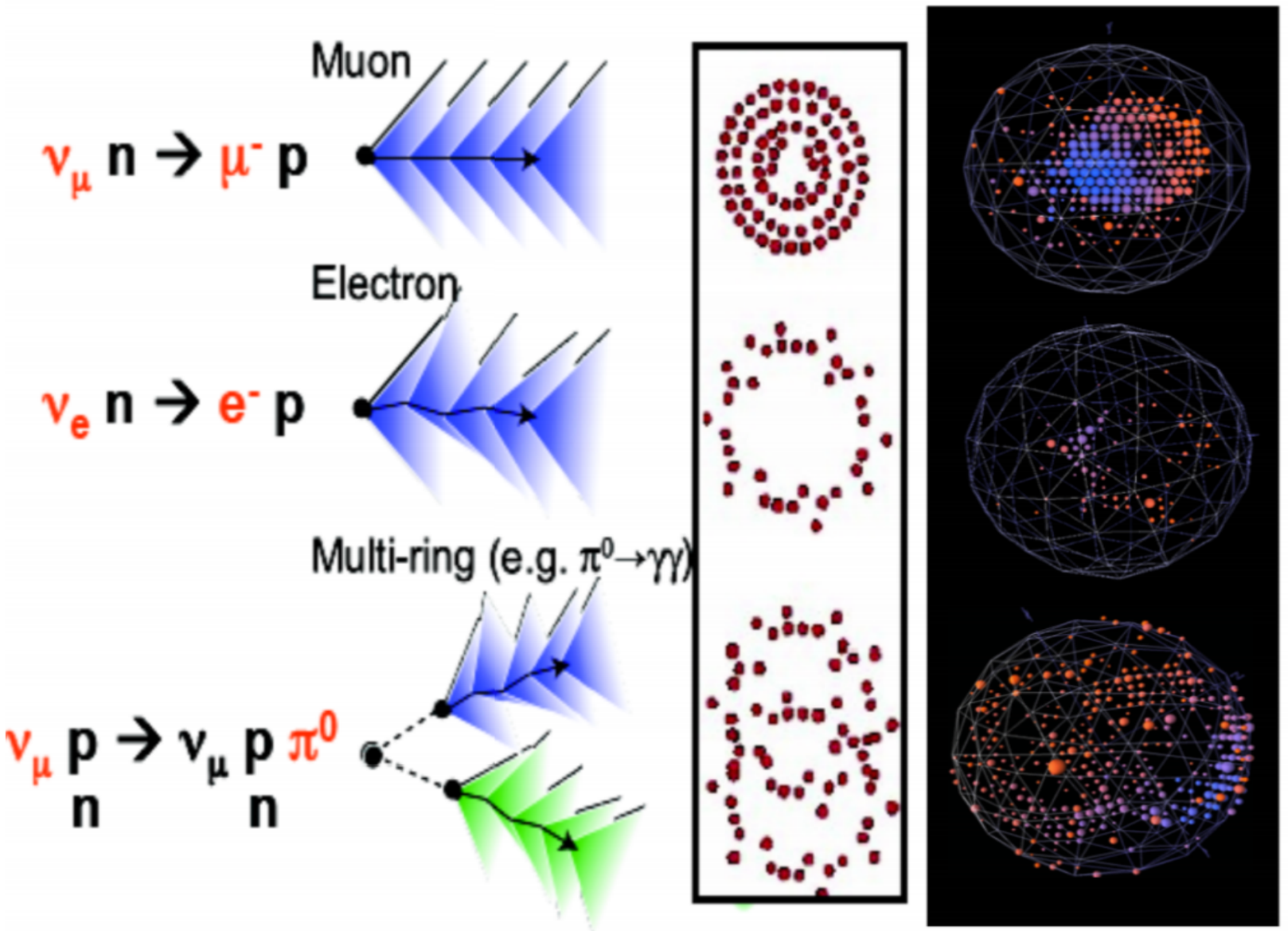


MiniBooNE Collaboration 2006.16883

MiniBooNE event identification

Three typical event signatures:

- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce π_0: two gammas -> two fuzzy rings.



Cannot distinguish between electrons and photons!

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Dark Neutrino

E. Bertuzzo et al., PhysRevLett.121.241801

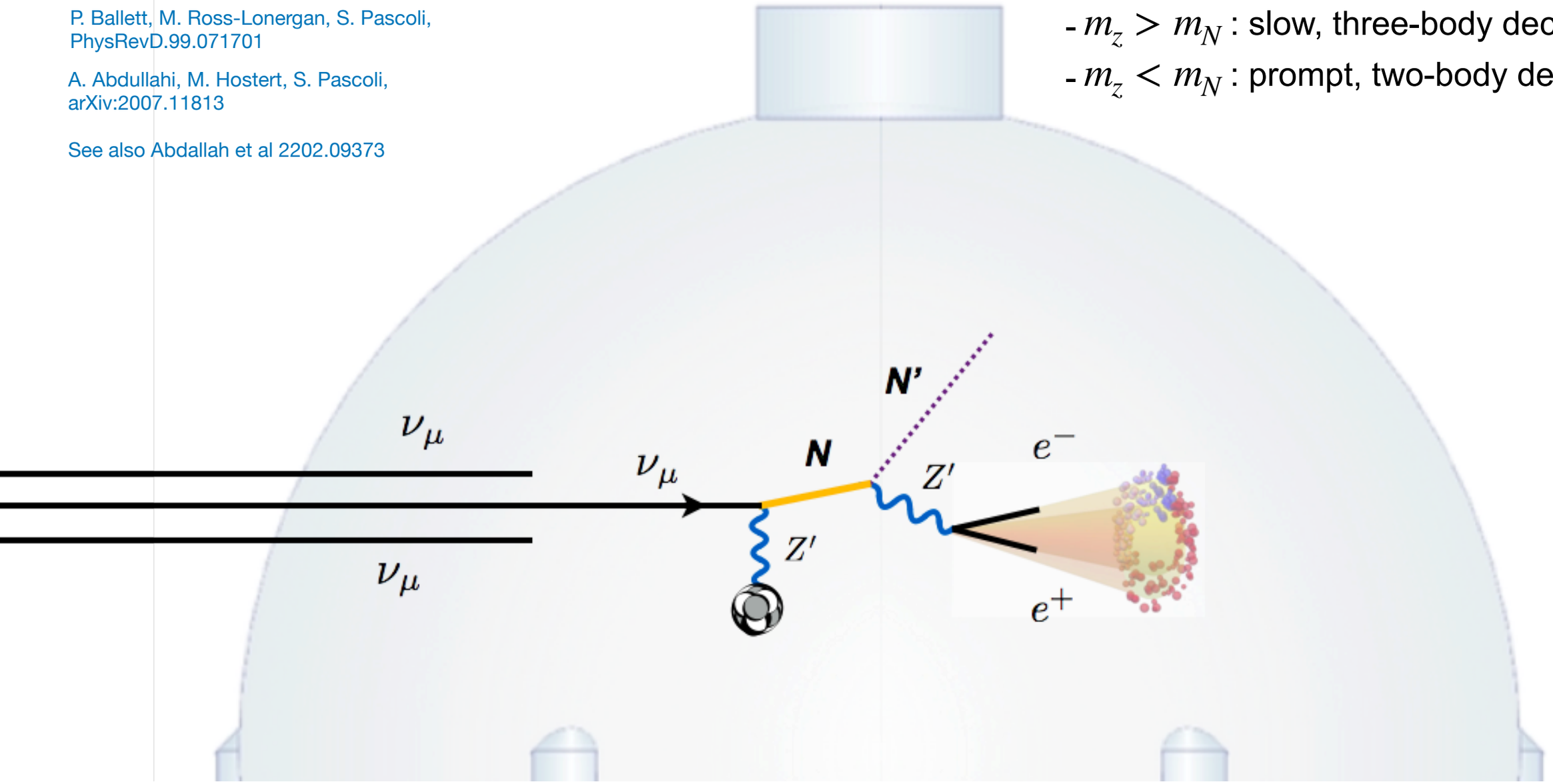
P. Ballett, M. Ross-Lonergan, S. Pascoli, PhysRevD.99.071701

A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813

See also Abdallah et al 2202.09373

Two phenomenologically distinct scenarios:

- $m_z > m_N$: slow, three-body decays.
- $m_z < m_N$: prompt, two-body decays.



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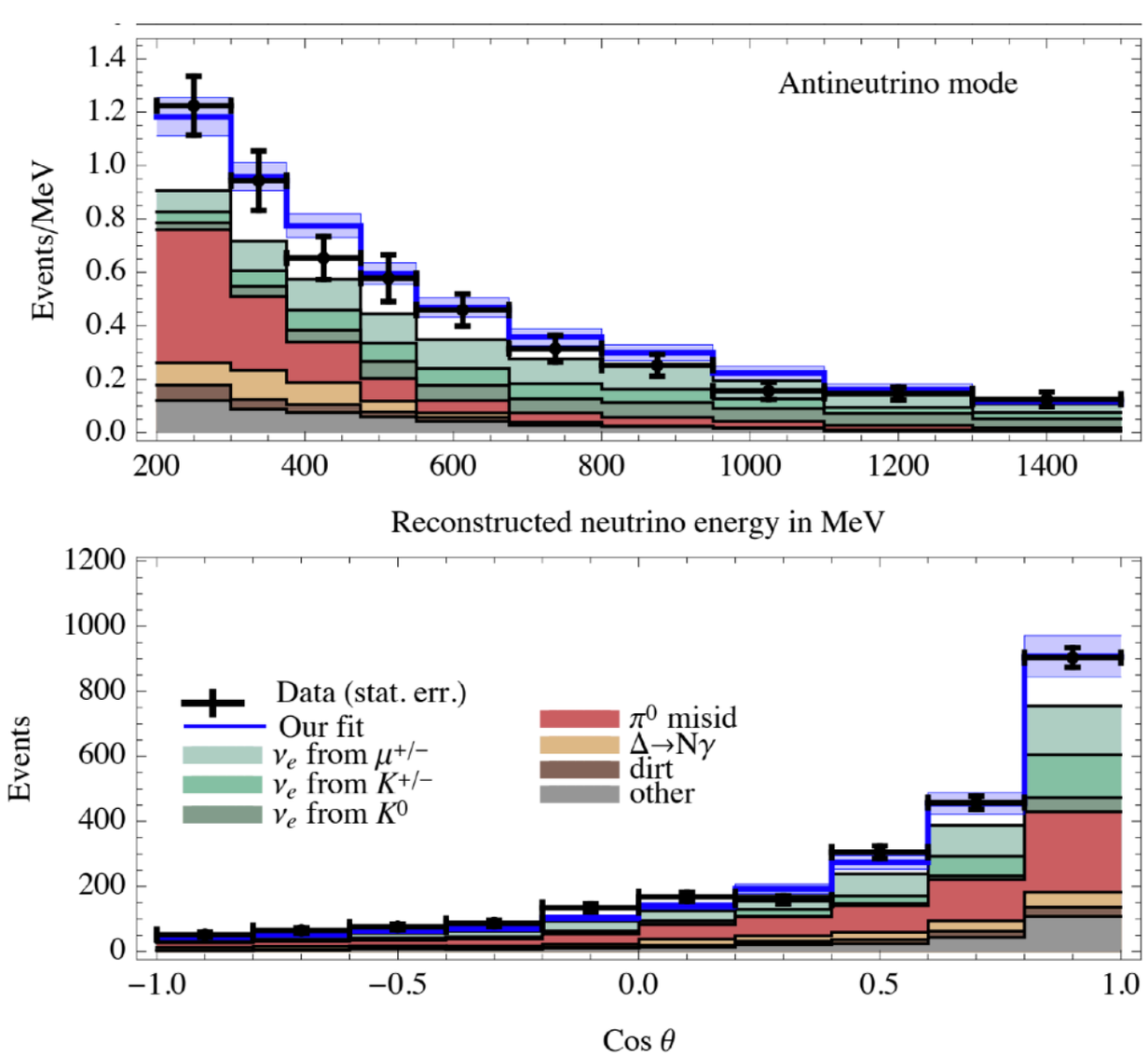

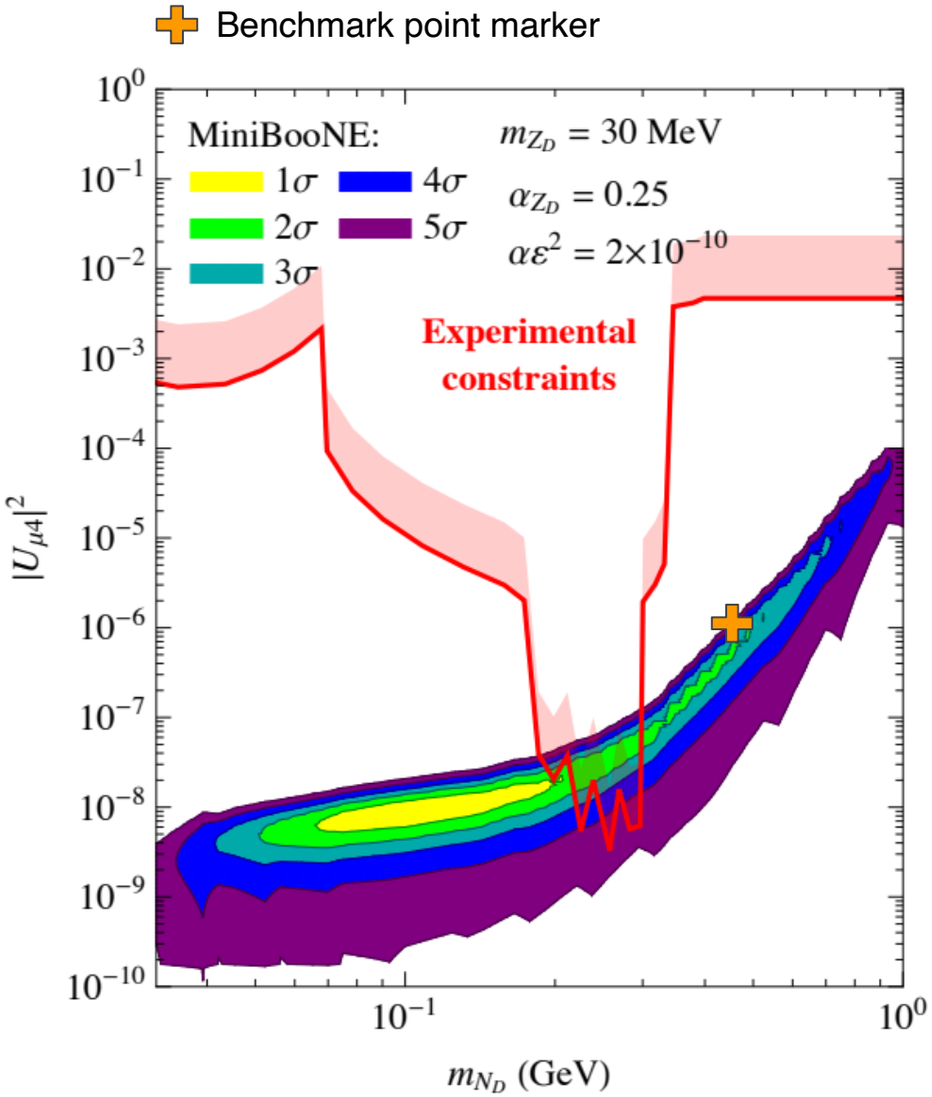

Good fit to the energy and angular distribution.

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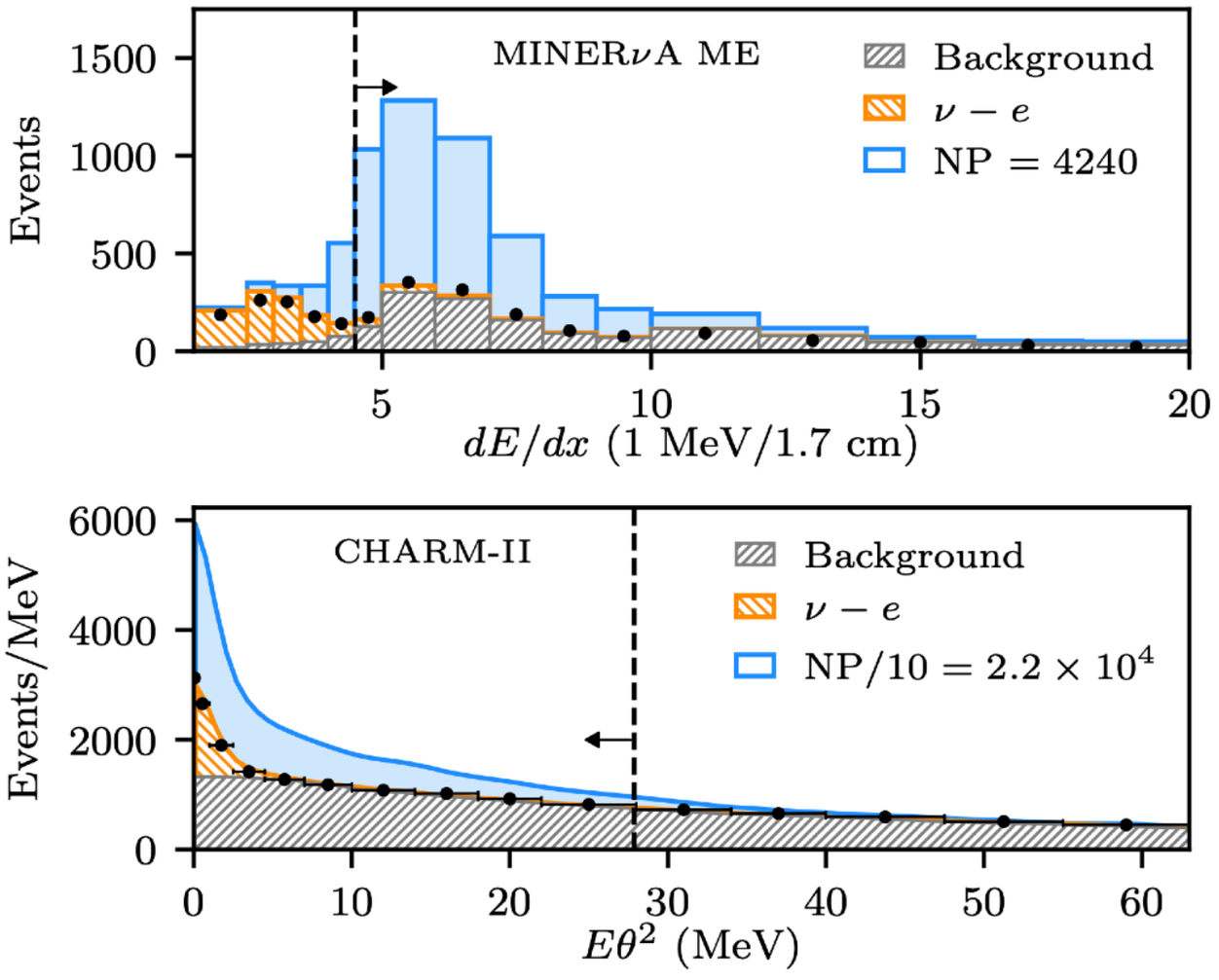
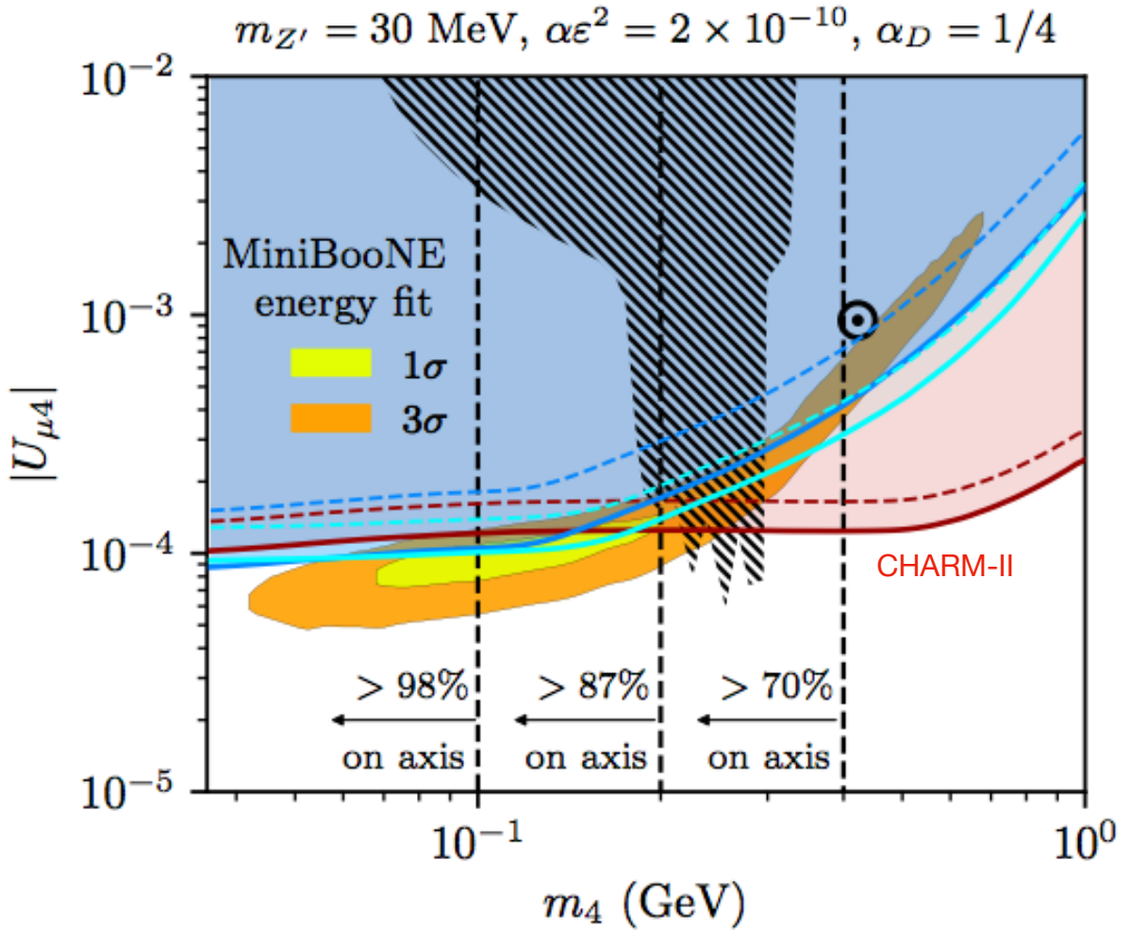
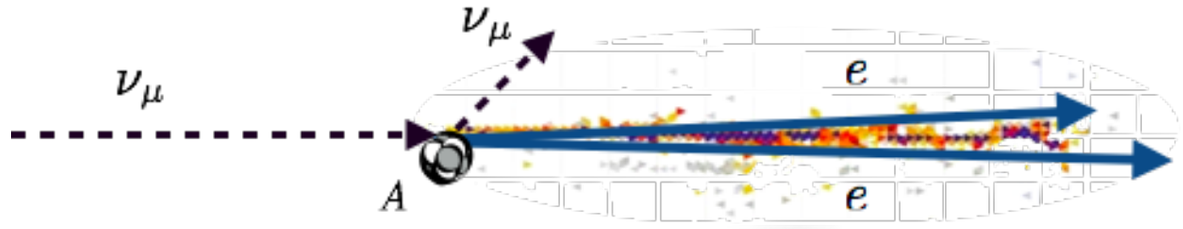
Dark Neutrino

This model can be constraint by Minerva electron-neutrino scattering data sets.



CA, M. Hostert, Y. Tsai, PhysRevLett. 123, 261801 (2019)





In tension with measurements of electron-neutrino scattering

Dark Neutrino

Sometime before the pandemic in a conference in the midwest …

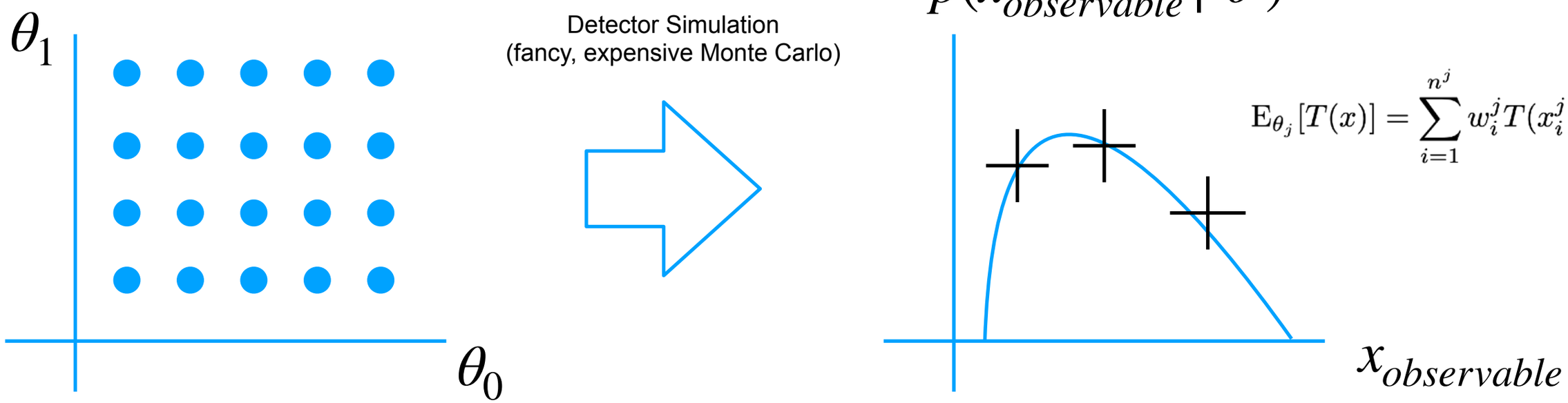
But
Carlos, you are fixing some parameters … how about a full parameter scan?

Good
point … so many parameters …. Let me think about it … ill be back …

Benchmark	(A) Light Z'	(B) Heavy Z'
m_N	100 MeV	100 MeV
$m_{Z'}$	30 MeV	1.25 GeV
$\|V_{\mu N}\|^2$	8×10^{-9}	2.2×10^{-7}
α_D	1/4	0.4
ϵ	1.7×10^{-4}	2×10^{-2}
$\|V_N\|^2$	$\|V_{\mu N}\|^2$	1

Addressing the High-Dimensionality Problem: Exploring New Parameter Space!

What do we normally do:



From this we can construct our test-statistic distribution (likelihood, χ^2, etc.) and obtain the test-statistic for each point on our parameter space grid.

Then we interpolate the test statistic on the grid and voila: we get our constraint plot.

See arXiv:2205.12273 for details

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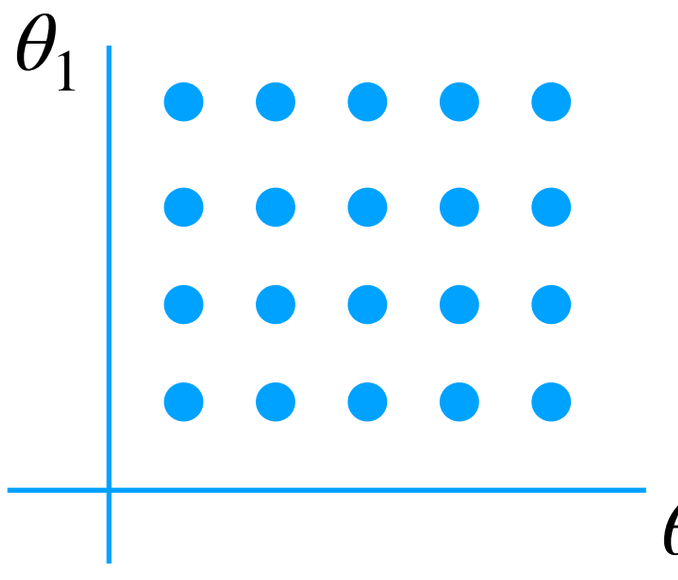
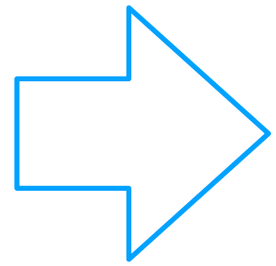
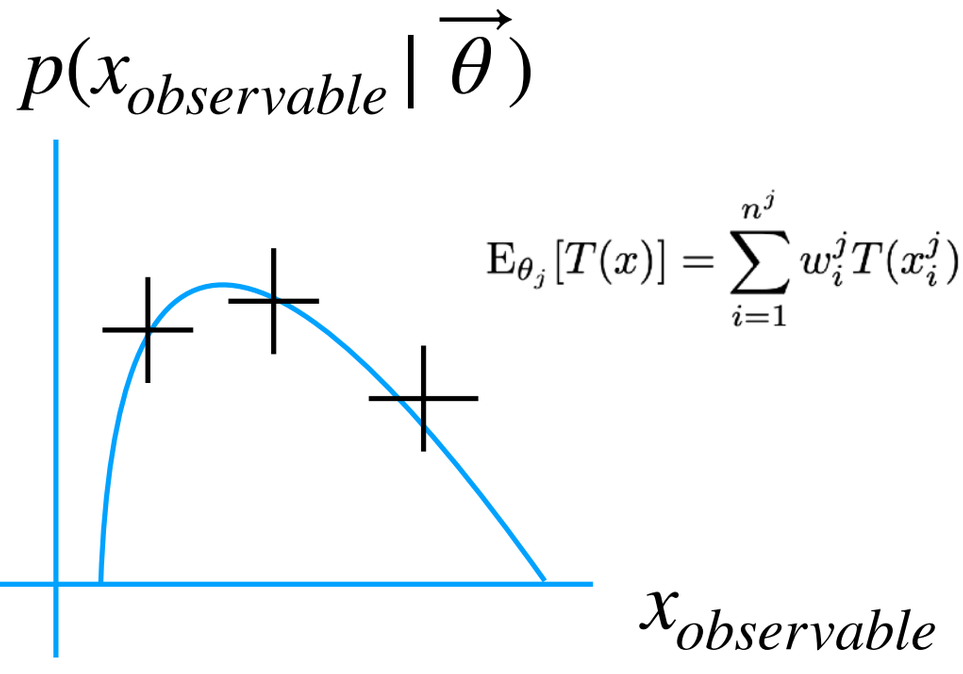


Detector Simulation
(fancy, expensive Monte Carlo)





From th tain the

Ther plot.

Idea: why don't we treat the physics parameters space variables like we do with the true kinematic distributions?

See arXiv:2205.12273 for details

Addressing the High-Dimensionality Problem: exploring new parameter space!

Instead of computing the test statistic on the sample this:

$$\mathrm{E}_{\theta_j}[T(x)] = \sum_{i=1}^{n^j} w_i^j T(x_i^j),$$

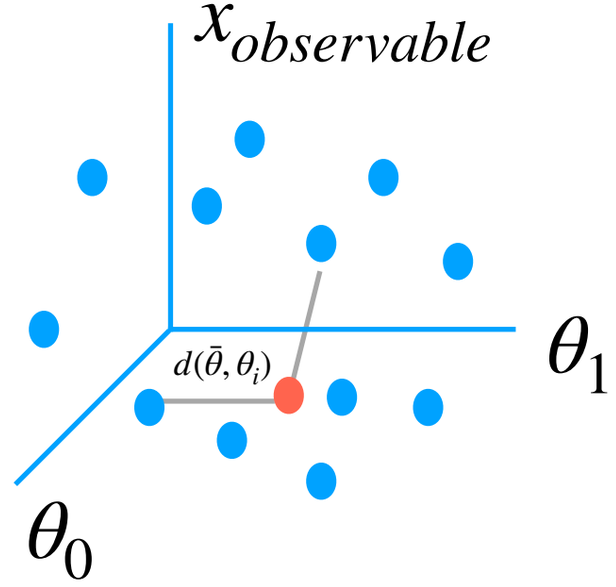
Test-statistic

$$p(x,\theta) = p(x|\theta)\mathcal{N}(\theta)q(\theta)$$

Promote $\vec{\theta}$ to a random variable and sample from that distribution too. In this case each Monte Carlo event has a different underlying physics parameter point.

$$\mathrm{E}_{\bar{\theta}}[T(x)] = \sum_i^n w_i T(x_i)\frac{w(\bar{\theta},\theta_i)}{q(\theta_i)}$$

$$= \sum_i w_i T(x_i)\frac{K(d(\bar{\theta},\theta_i),\delta)}{q(\theta_i)}$$

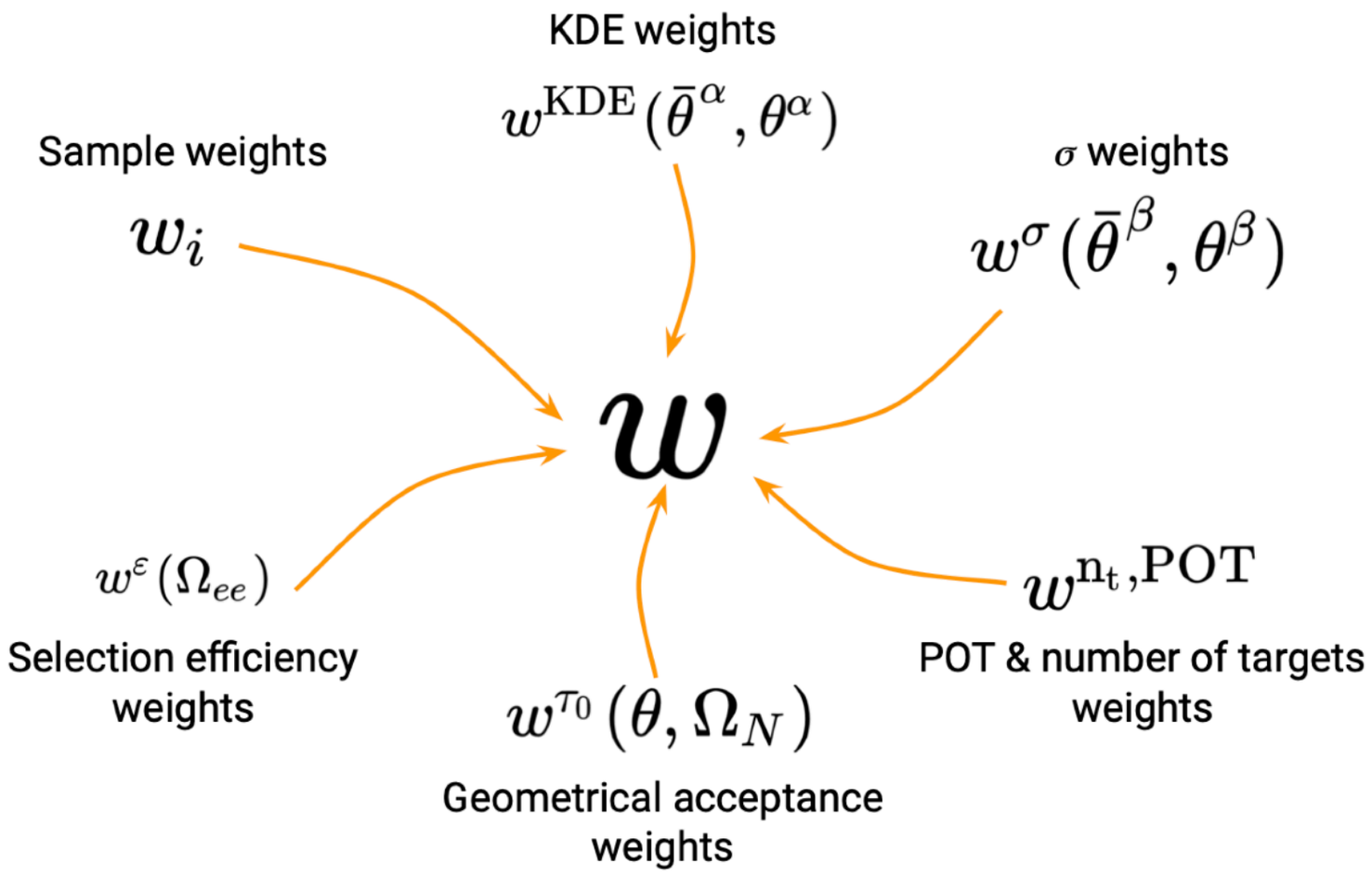


We can generate the points on the parameter space and the observable kinematic distributions efficiently by formulating this problem as a importance sampling problem. Namely computing this integral:

$$\int d\theta^\alpha q(\theta^\alpha)\int d\Omega_N \frac{d\sigma}{d\Omega_N}(\Omega_N|\theta)\int d\Omega_{ee}\frac{1}{\Gamma(\theta)}\frac{d\Gamma}{d\Omega_{ee}}(\Omega_{ee}|\Omega_N)$$

See arXiv:2205.12273 for details

Addressing the High-Dimensionality Problem: exploring new parameter space!



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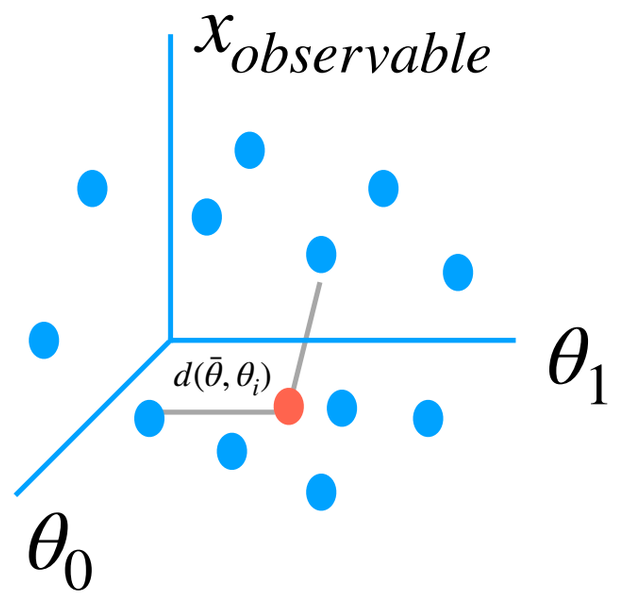

$$\mu(\theta) \simeq \sum_i^n w_i w_i^{\mathrm{KDE}}(\bar{\theta}^{\alpha}, \theta_i^{\alpha}) w_i^{\sigma}(\bar{\theta}^{\beta}, \theta_i^{\beta})$$
$$w_i^{\varepsilon}(\Omega_{ee,i}) w_i^{\tau_0}(\theta_i, \Omega_{N,i}) w_i^{\mathrm{n_t,POT}}$$

The trade off is that now you have to take into account the error on the prediction.

But that can be handled by either using the *Effective Likelihood* (1901.04645) in the poisson regime or adding an error to your χ^2 in the gaussian regime.

See arXiv:2205.12273 for details

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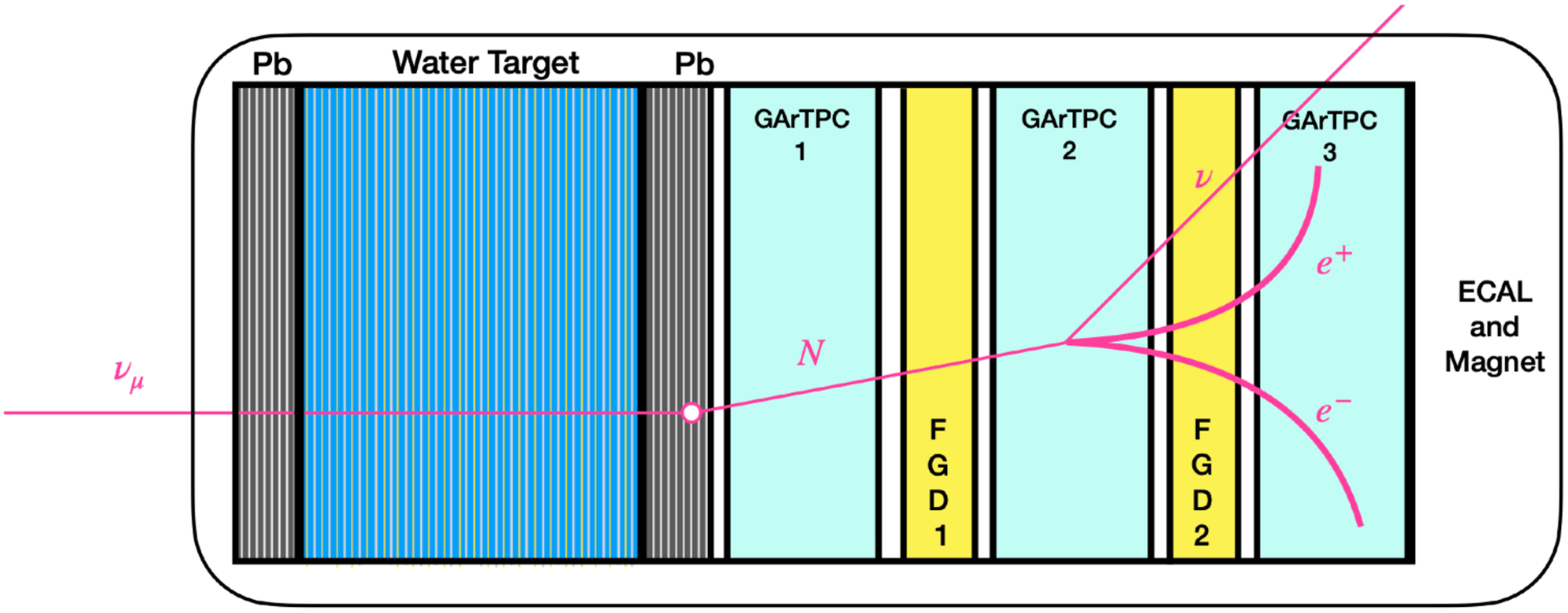
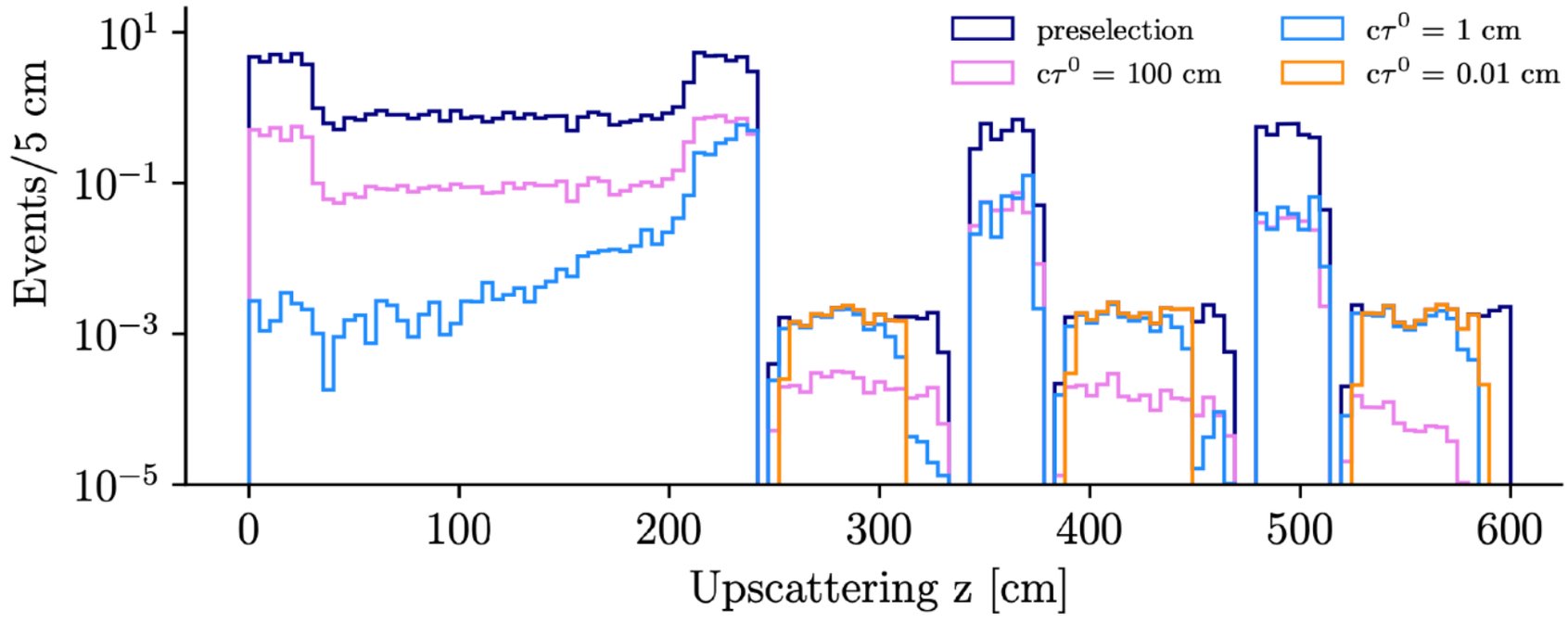
Dark Neutrino at T2K ND280

CA, Foppiani, Hostert 2205.12273





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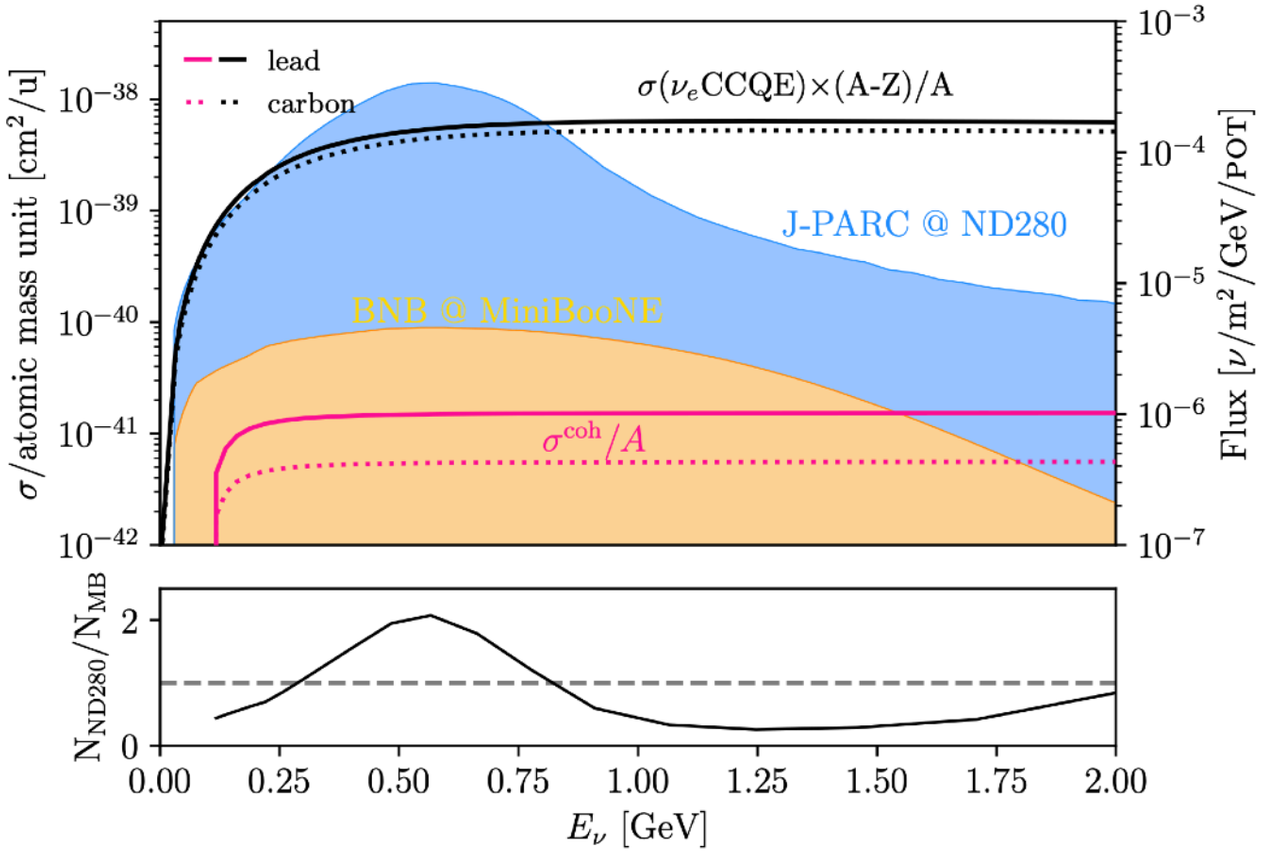
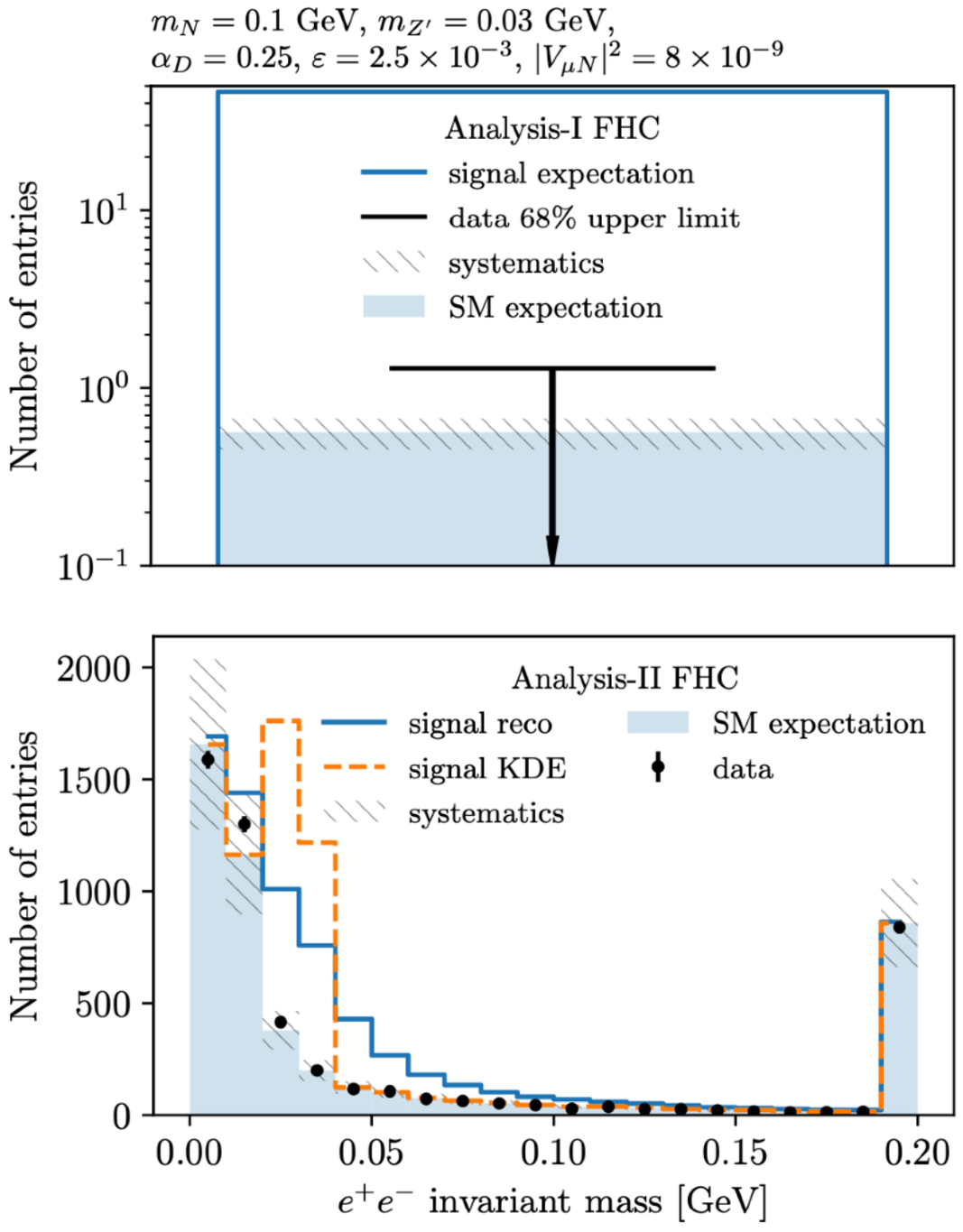
T2K ND280 detector is smaller, but flux at T2K
Is much more intense than at MB. Rates event out.



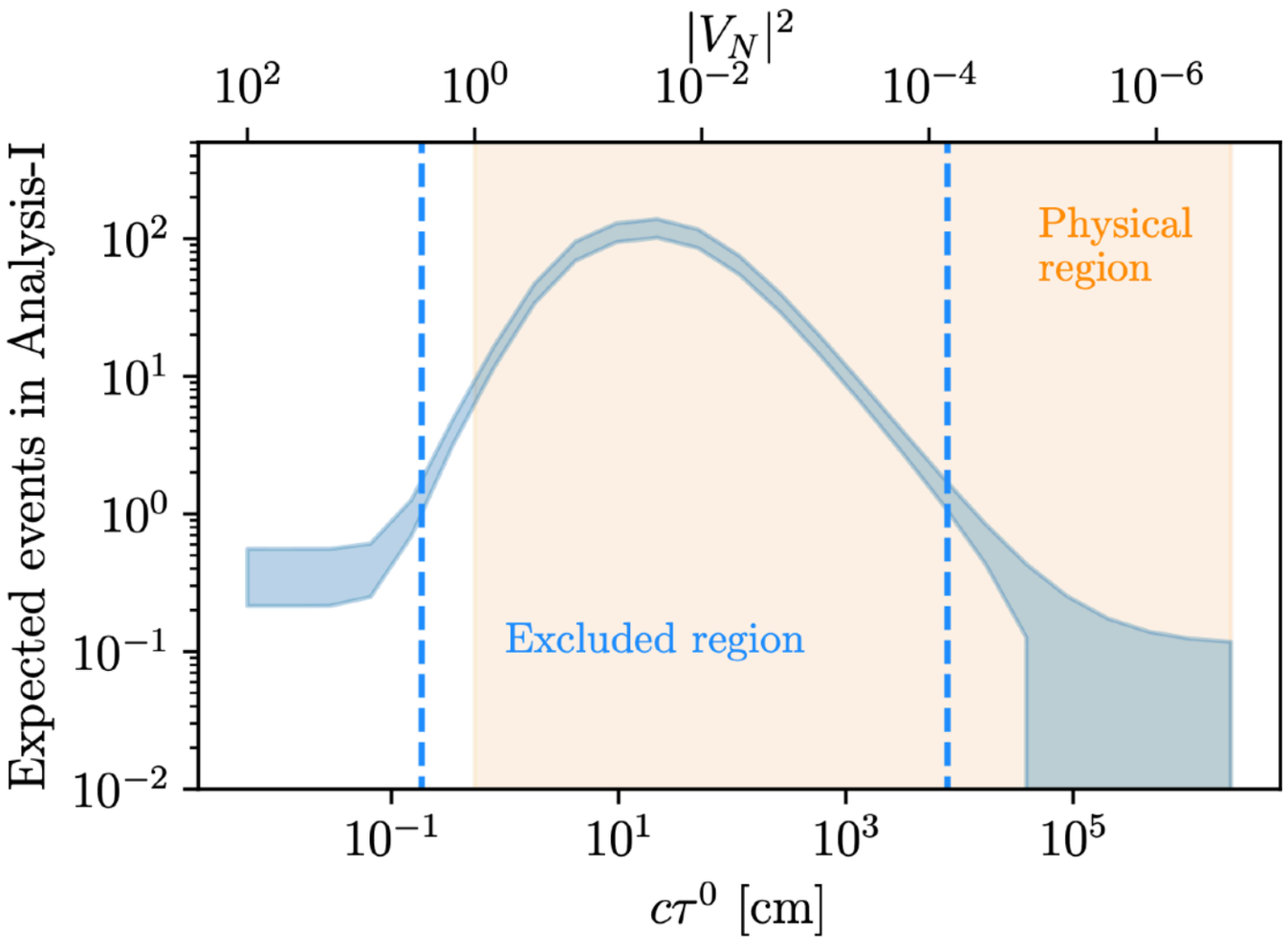


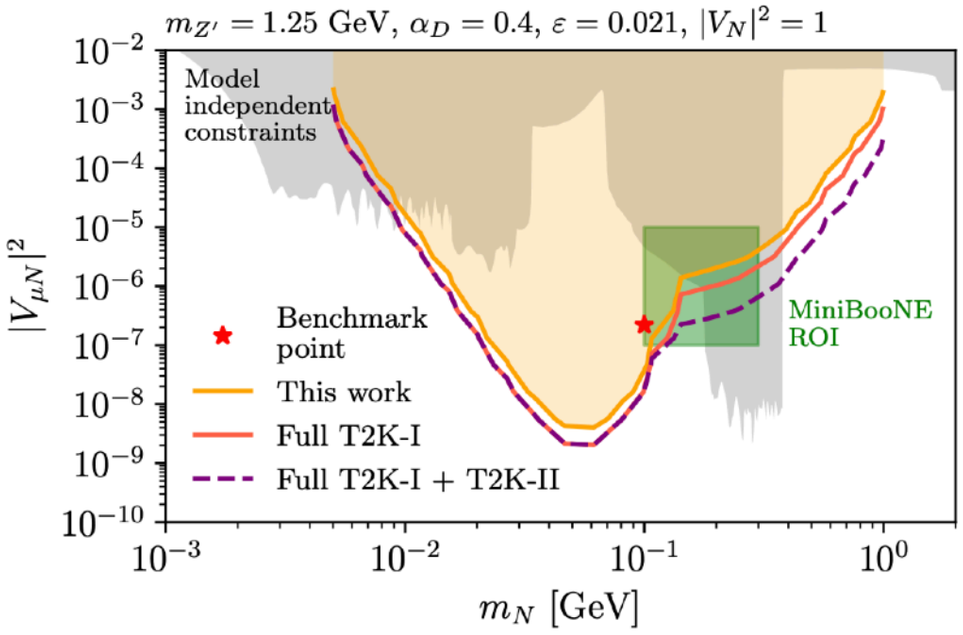
Dielectron

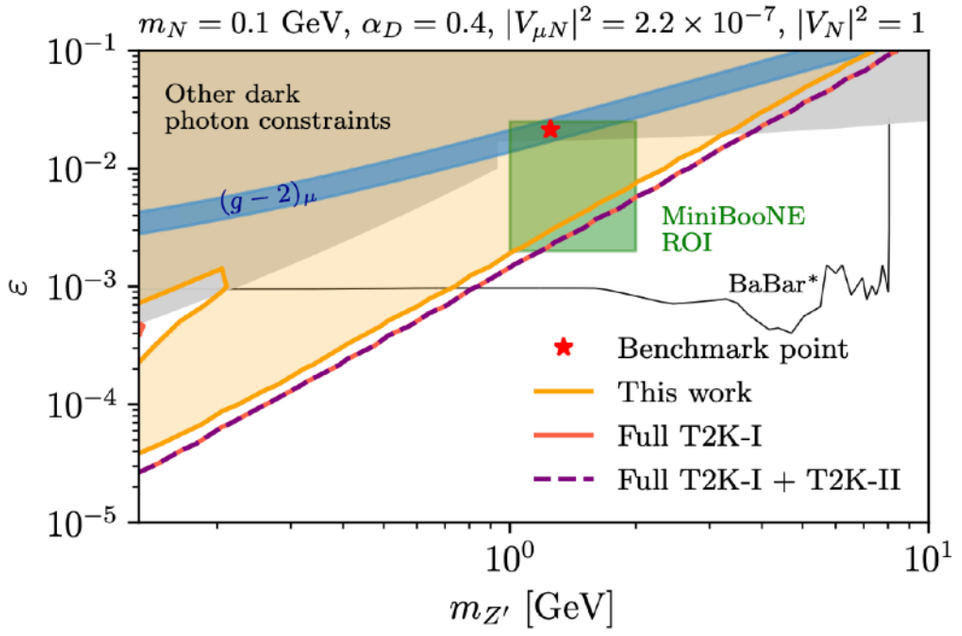
Dark Neutrino at T2K ND280

Constraints from T2K are powerful when the mediator is heavier, in the light case dominated by Minerva bounds.

CA, Foppiani, Hostert 2205.12273







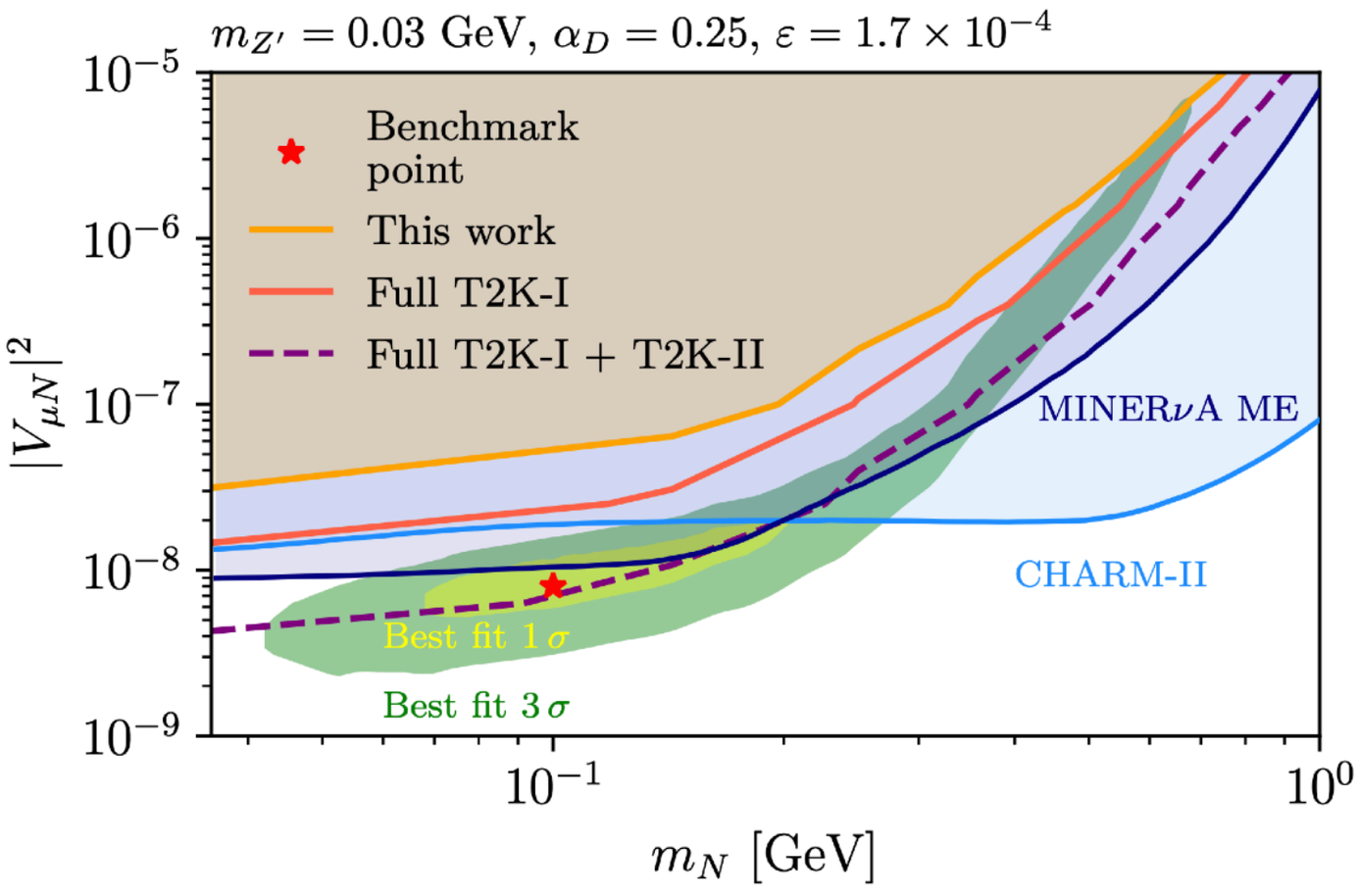
Dedicated T2K analysis should significantly improve these constraints.

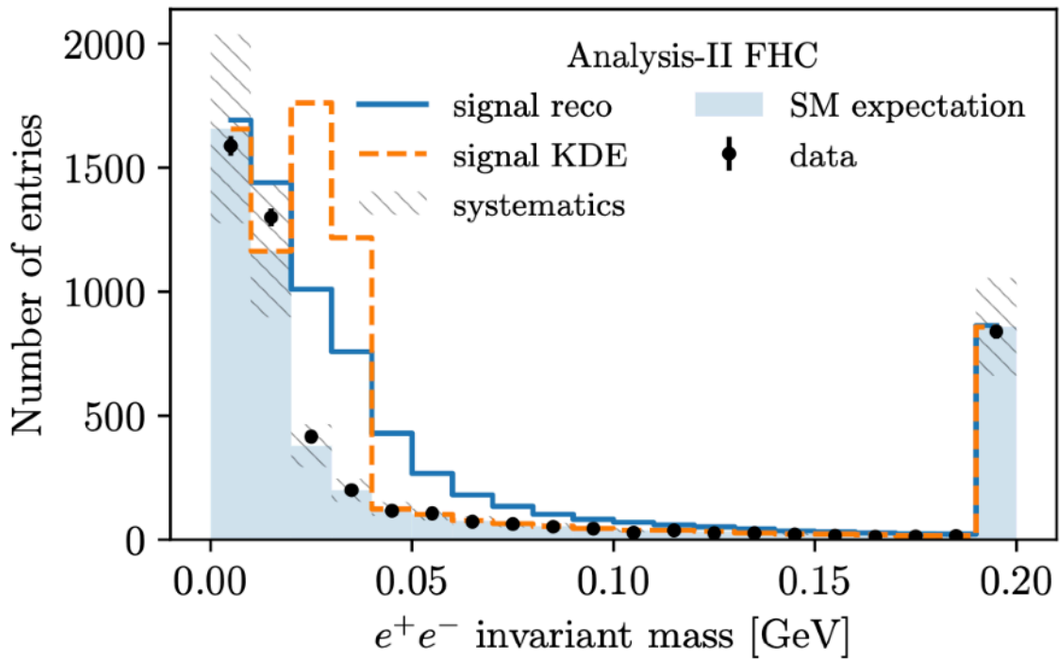
Dielectron

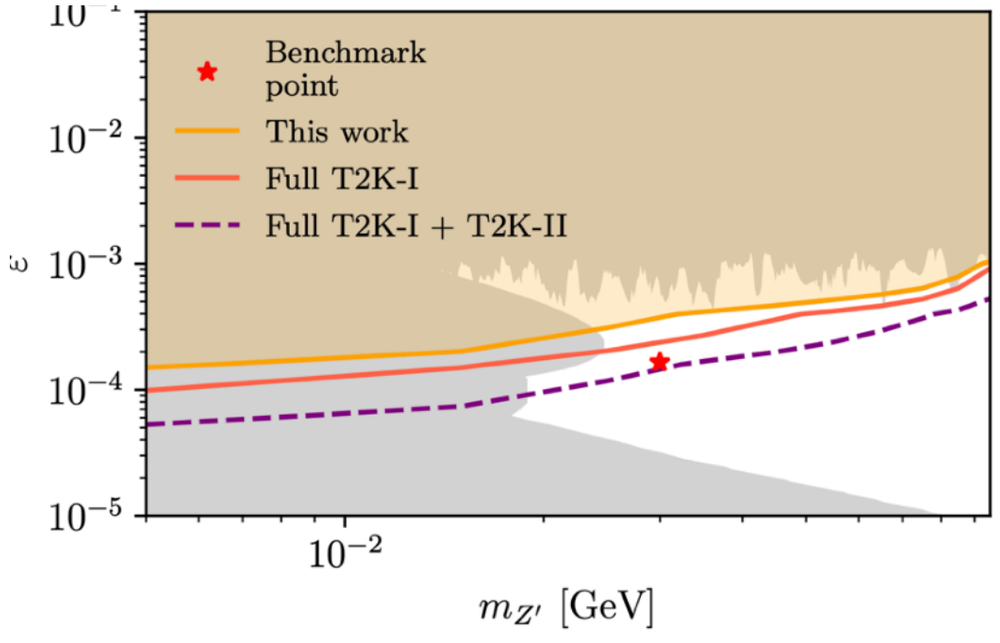
Dark Neutrino at T2K ND280

T2K light case constraints are dominated by quasi-elastic scattering photon side band. However, light case dominated by Minerva bounds.

CA, Foppiani, Hostert 2205.12273







Dedicated T2K analysis should significantly improve these constraints.

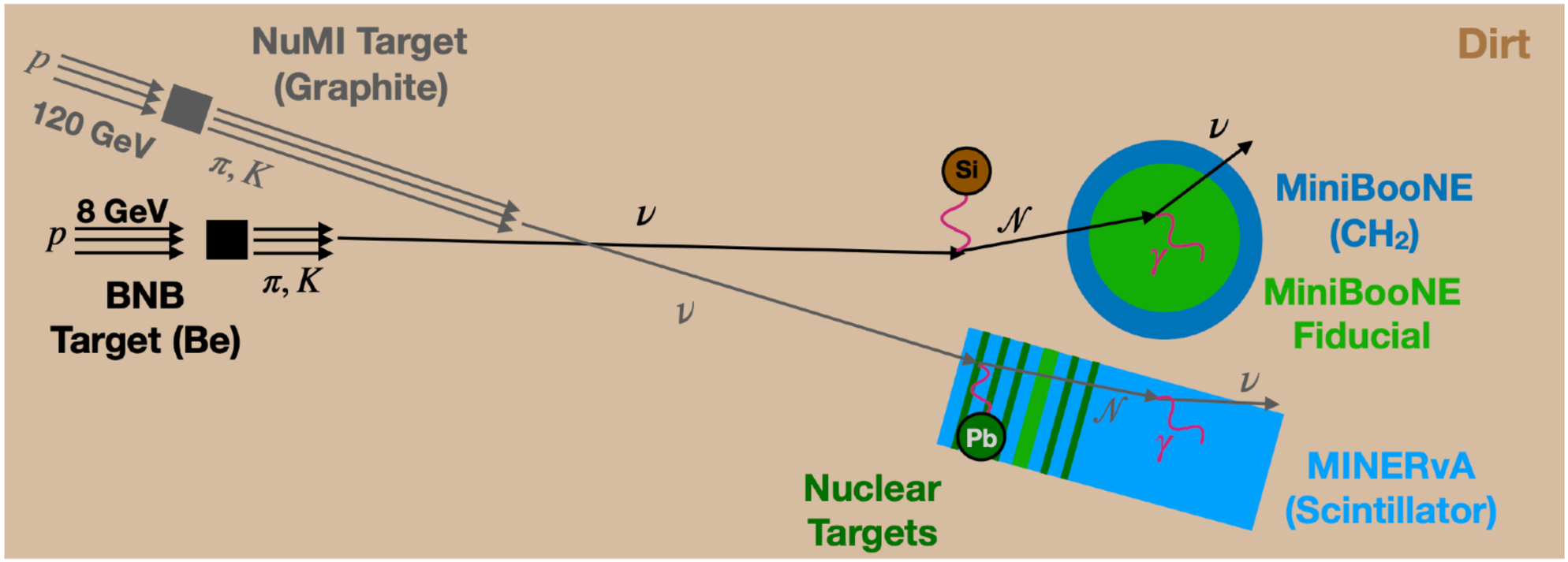
Outline

- Why go beyond vanilla sterile neutrinos?
- The garden of forking paths
- Focusing on two explanations:
  - Dark neutrino: Only Di-electron
  - Neutrissimo: Single photon + oscillations
- Future

Gamma

Neutrissimo Scenario

This scenario is predicated under the idea that there are oscillations, but *something else is going on* …



Neutrissimo: HNL with Transition Magnetic Moment

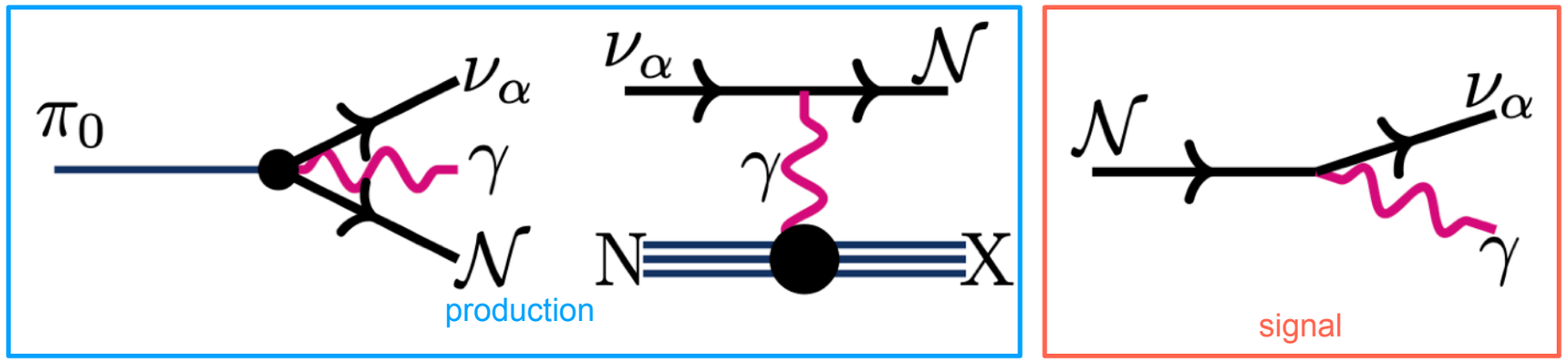
+

Light sterile neutrino explains:
-Reactors
-LSND
-Part of MiniBooNE

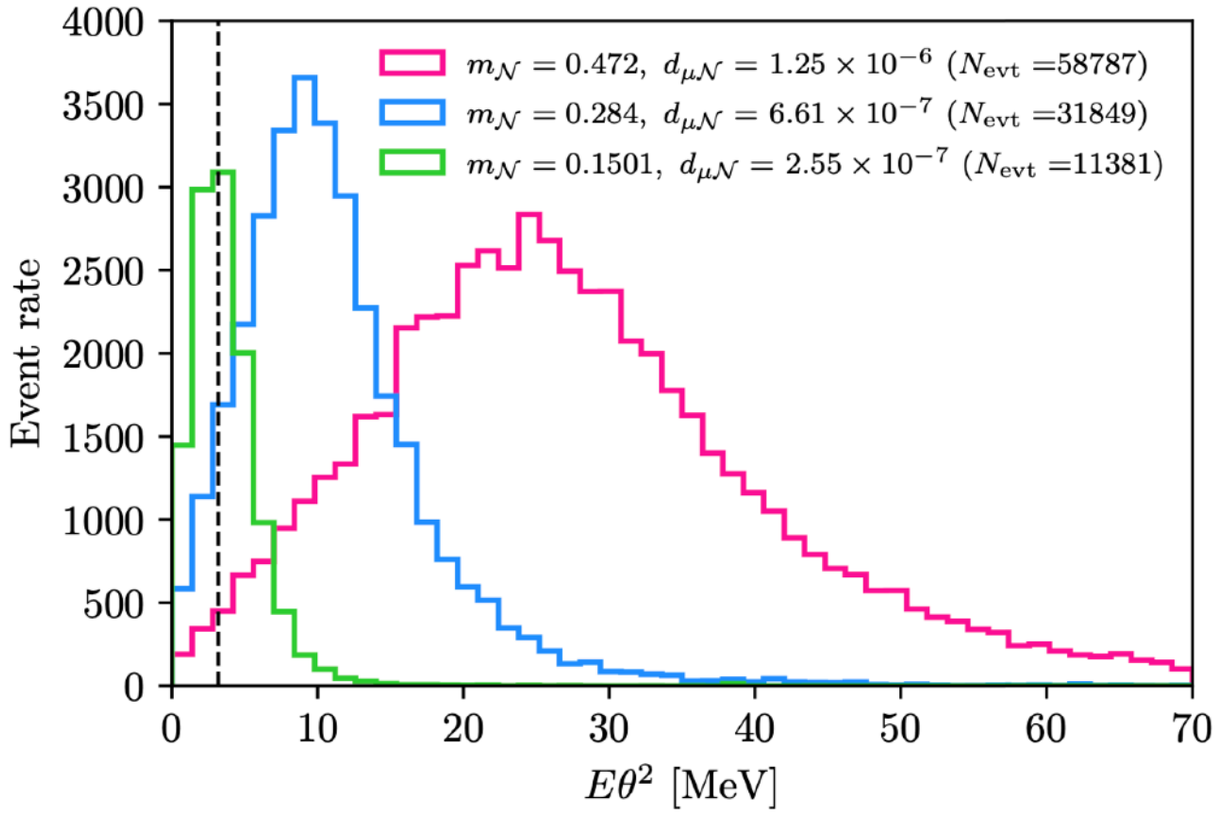
See arXiv: 2105.06470, 2206.07100

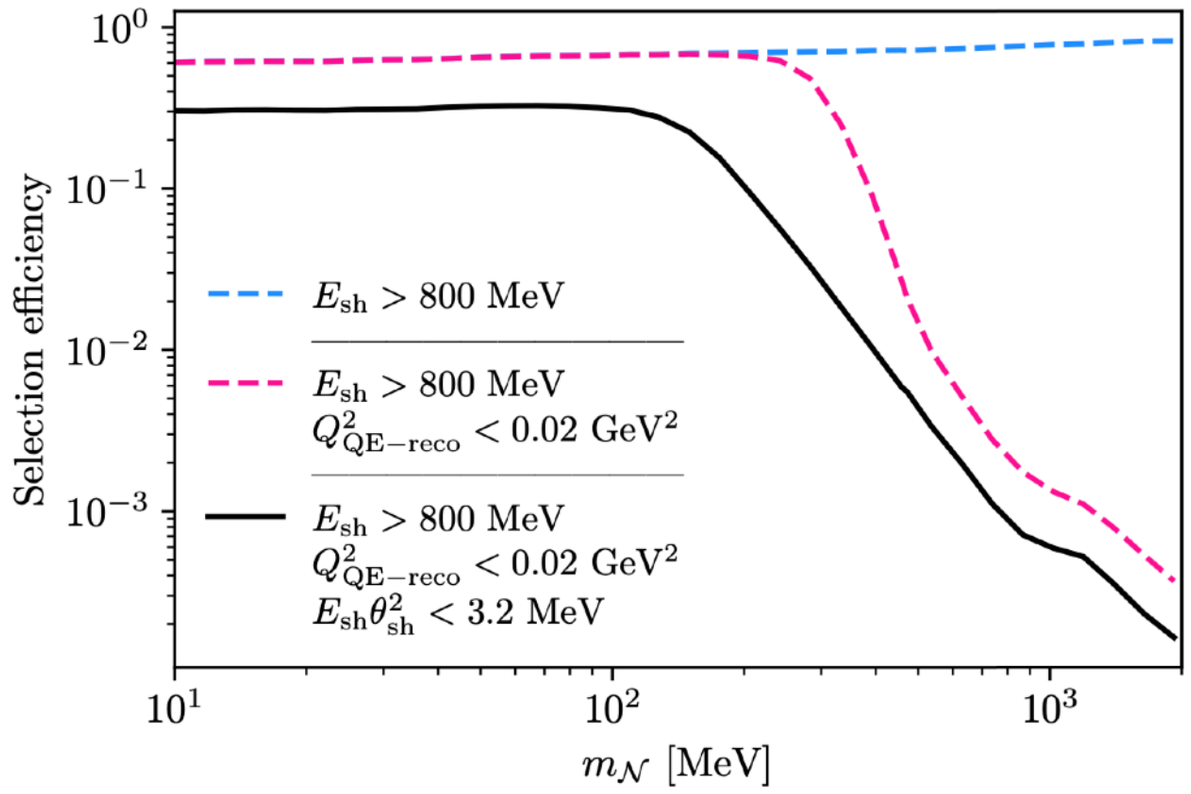
Gamma

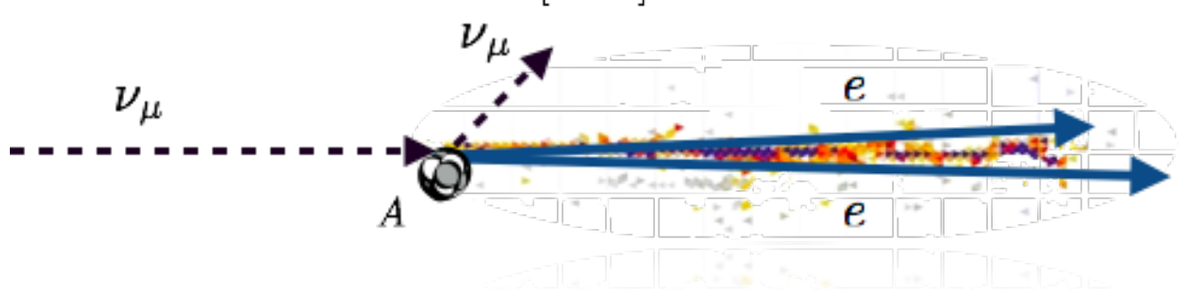
Neutrissimo Scenario

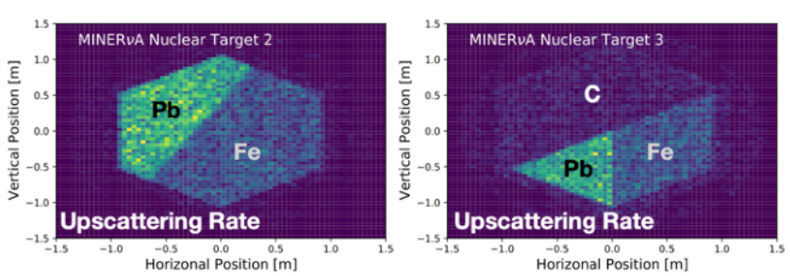


Minerva NUMI electron-neutrino scattering data selection efficiency.





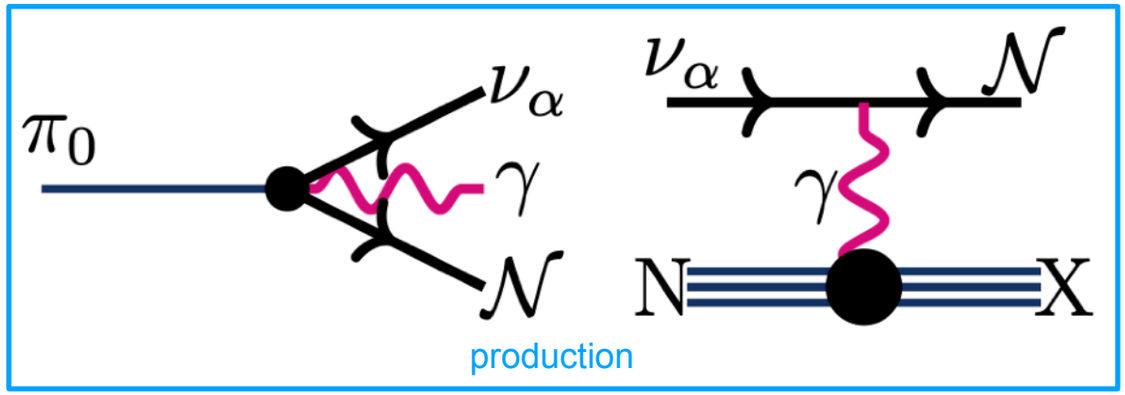


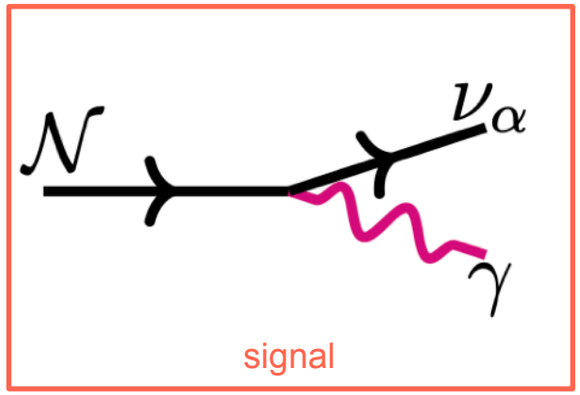


See arXiv: 2105.06470, 2206.07100

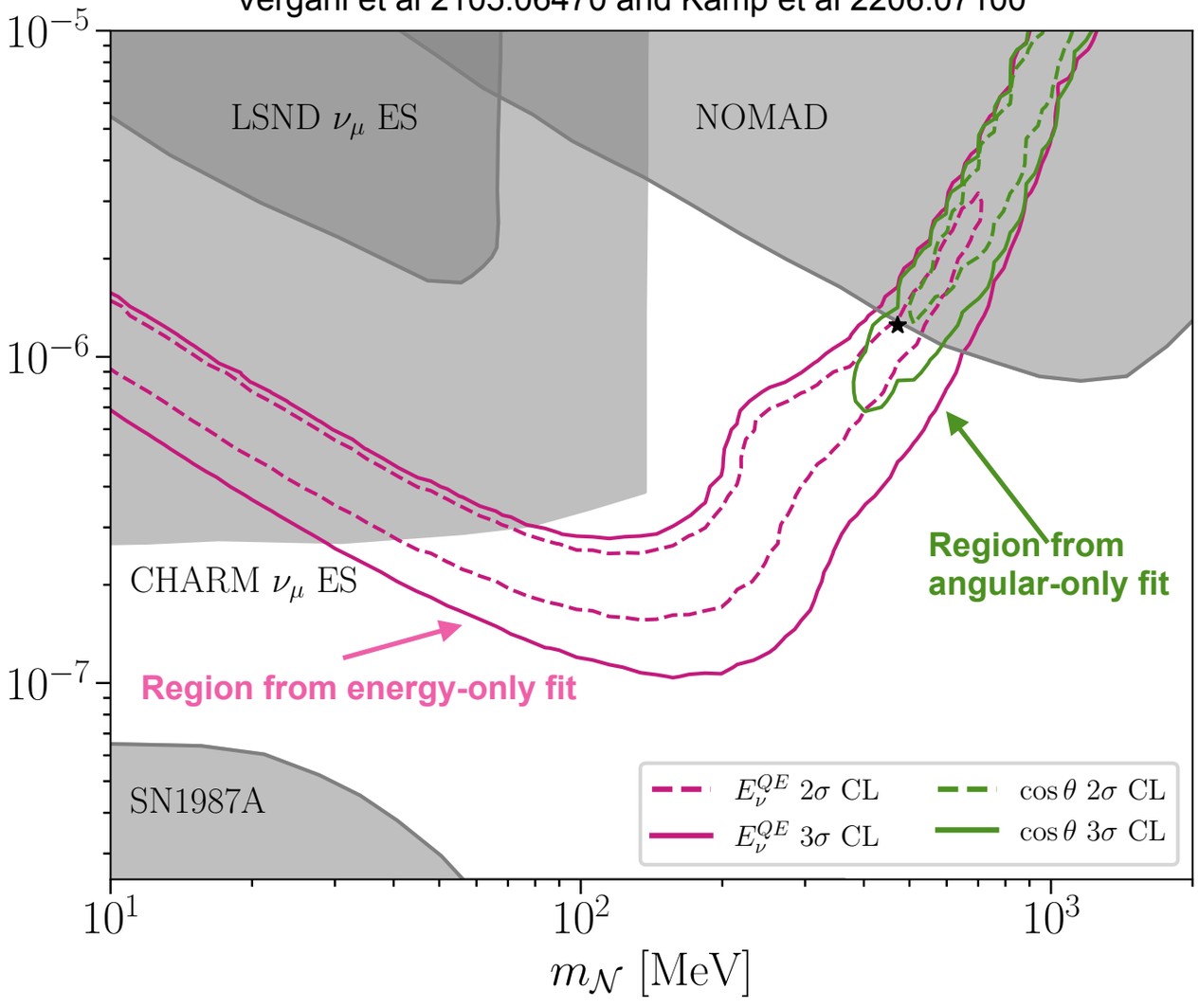
Gamma

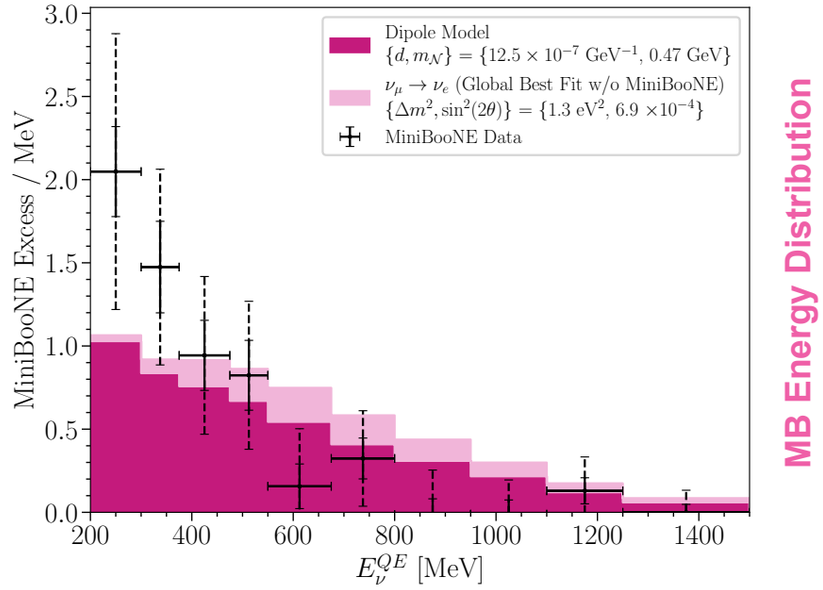
Neutrissimo Dominated

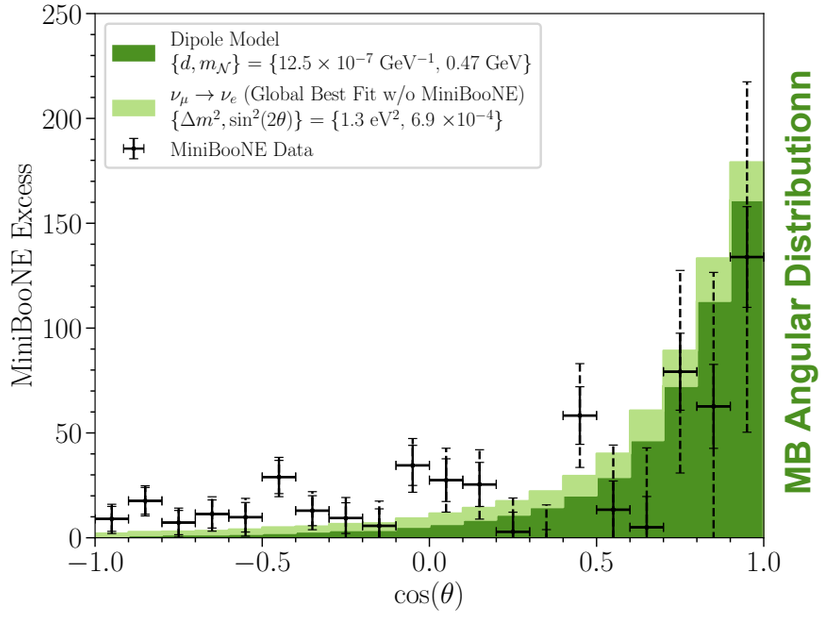




Vergani et al 2105.06470 and Kamp et al 2206.07100







See also Magill et al 1803.03262, and Brdar et al 2007.15563.

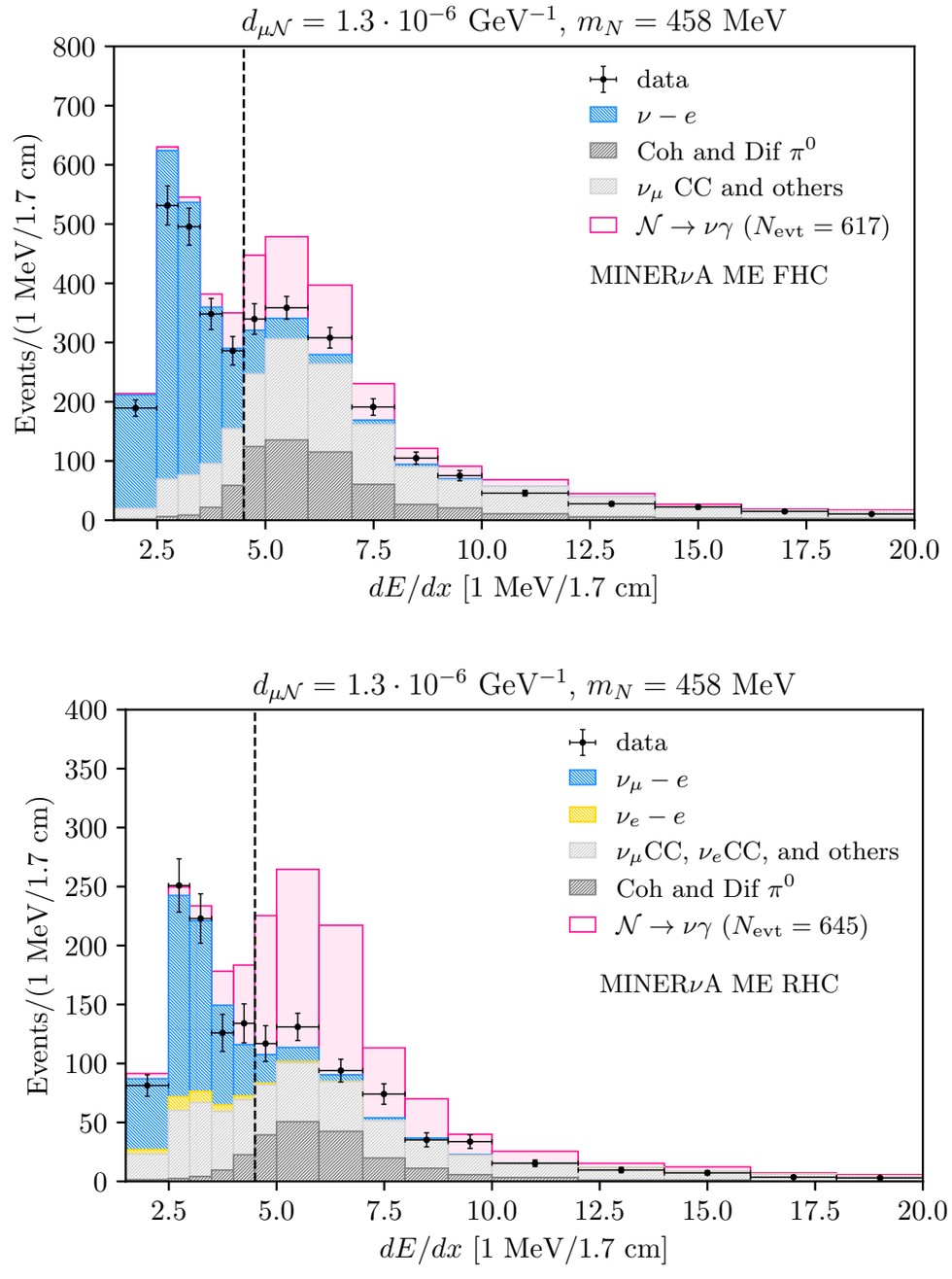
Gamma

Neutrissimo Dominated

This model can be constraint by Minerva neutrino-electron scattering data sets.

Medium Energy NuMI Beam

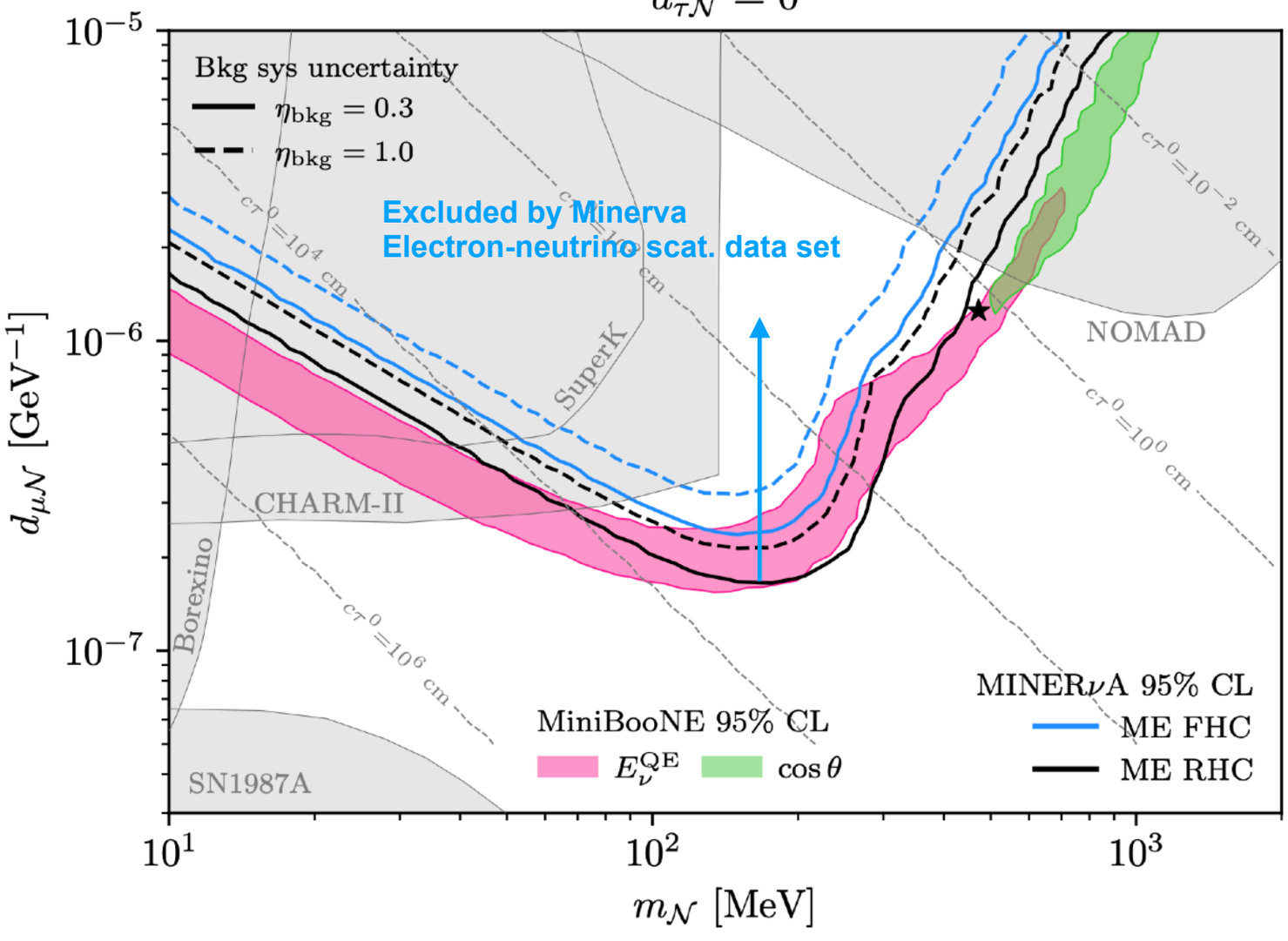
Neutrino mode



Antineutrino mode

Region from energy-only fit

Region from angular-only fit



See Kamp et al 2206.07100 for details

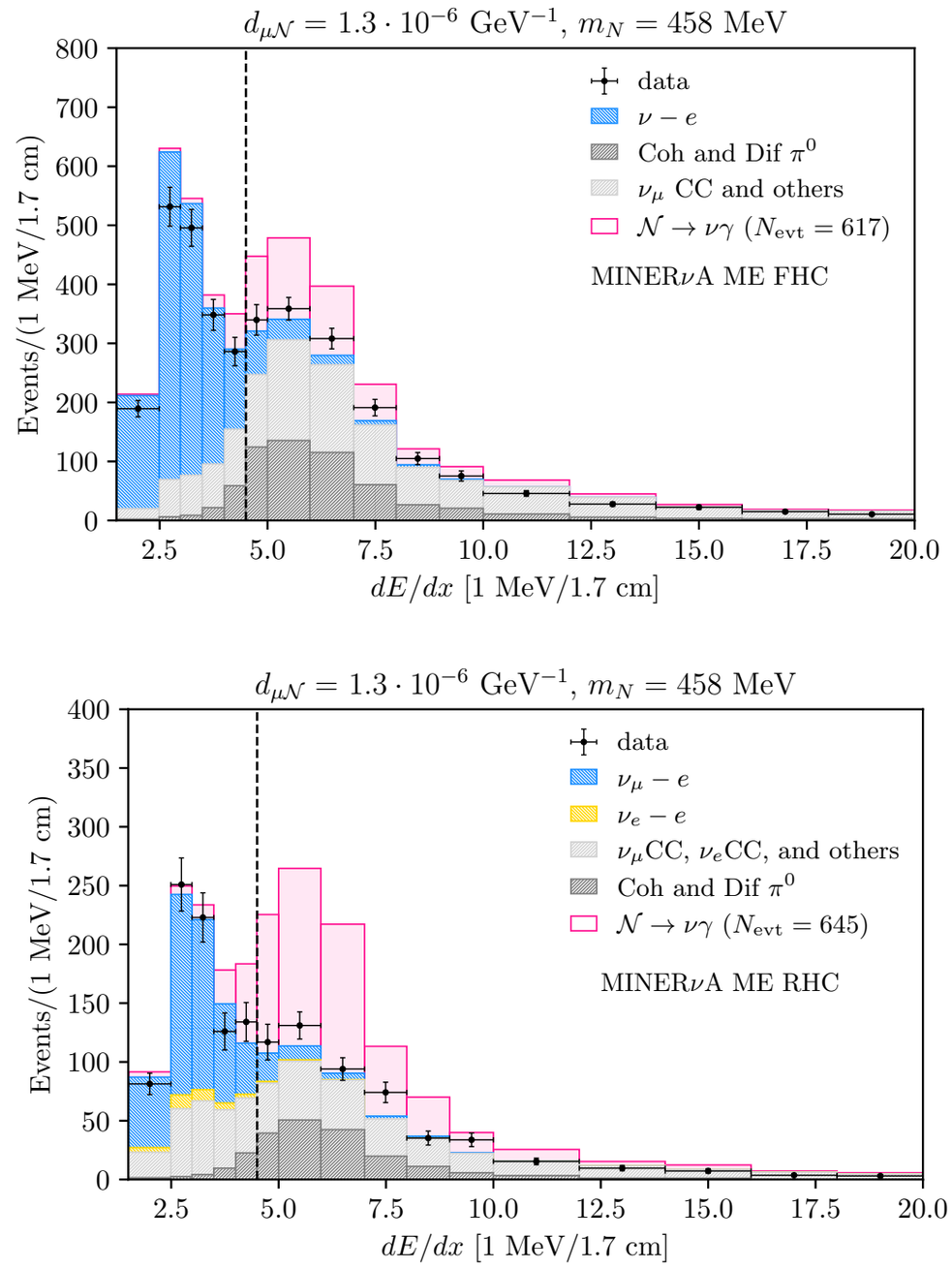
Gamma

Neutrissimo Dominated

This model can be constraint by Minerva neutrino-electron scattering data sets.

Medium Energy NuMI Beam

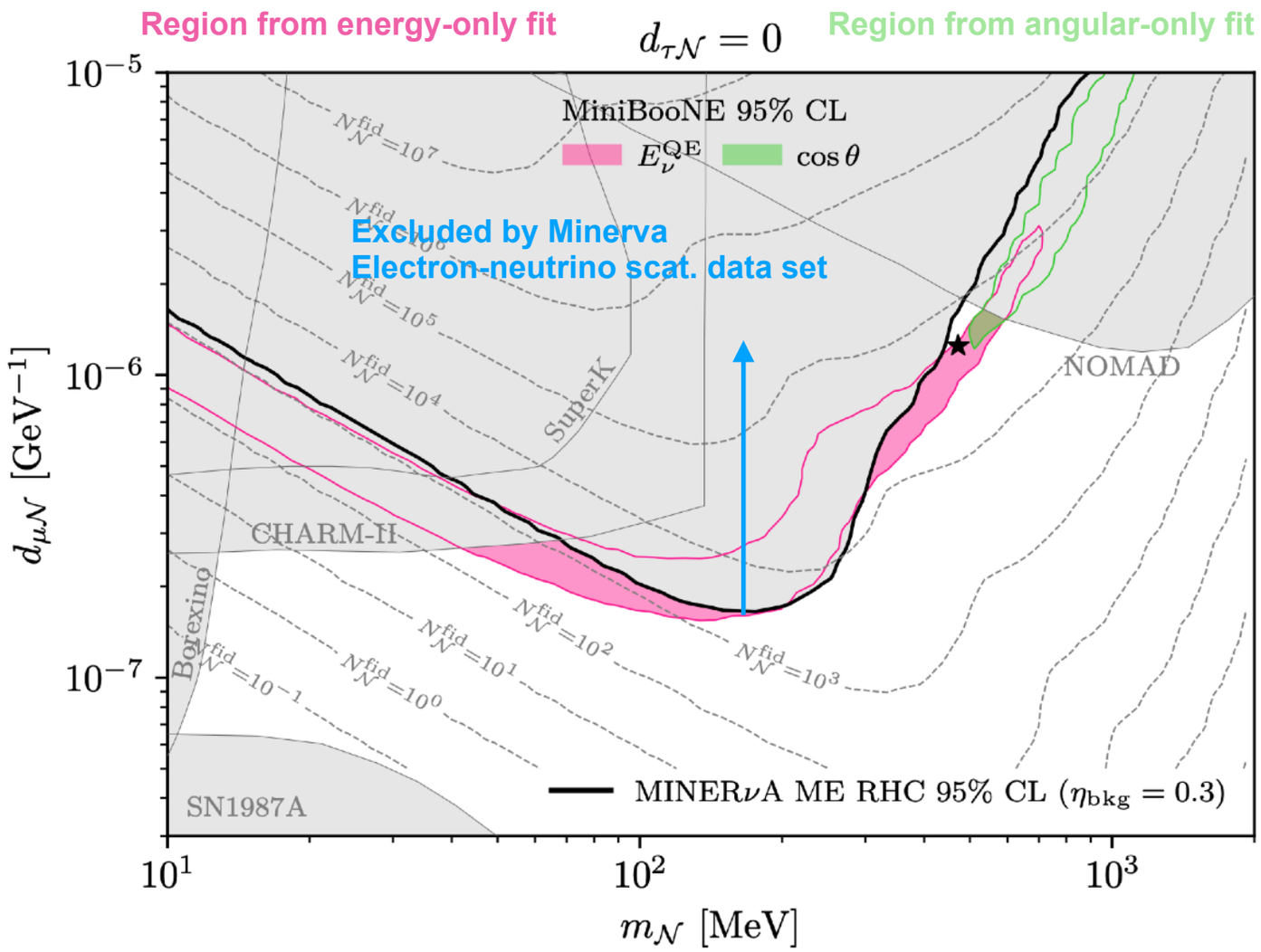
Neutrino mode



Antineutrino mode

Region from energy-only fit

Region from angular-only fit



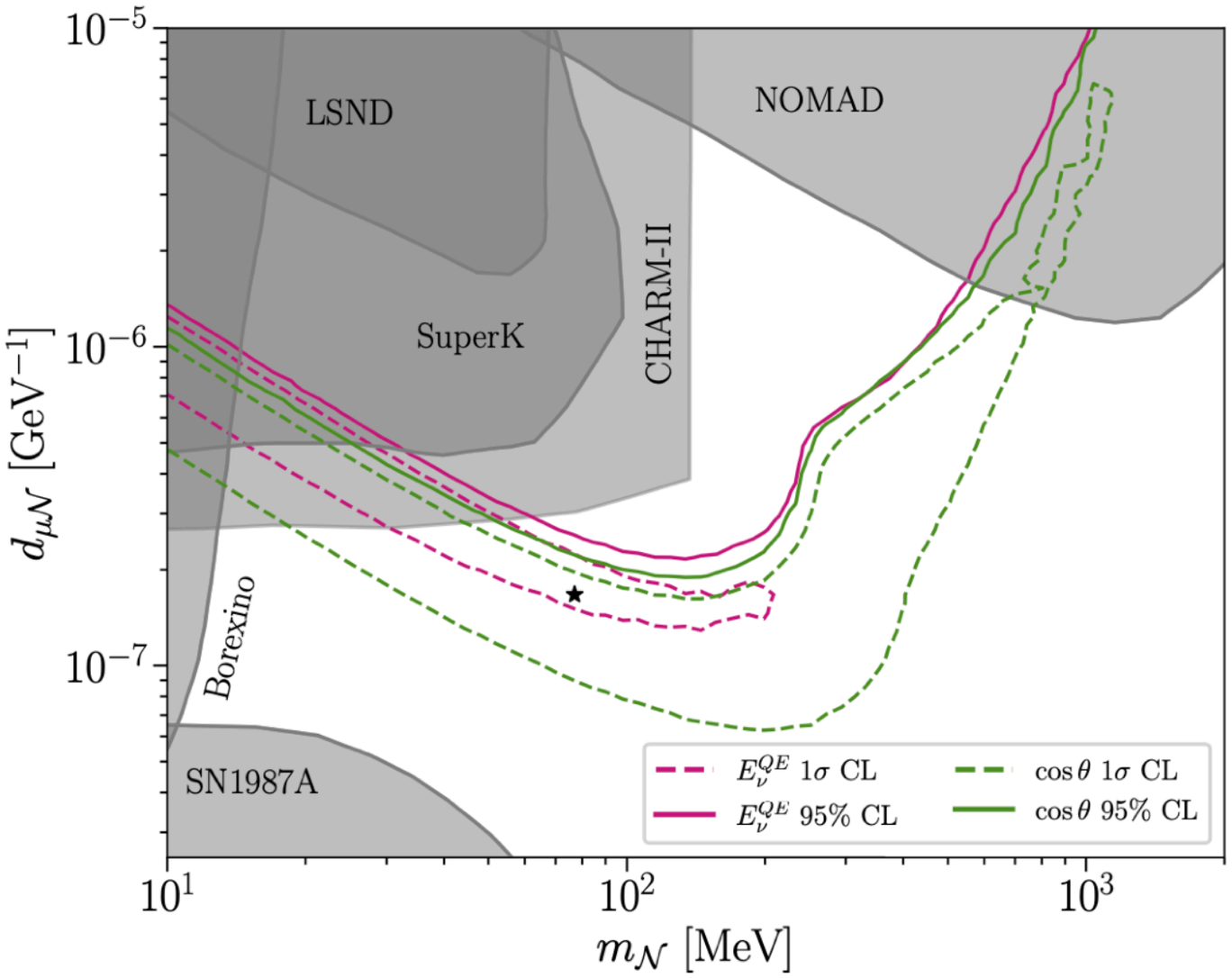
A dedicated Minerva analysis should be sensitive to the entire MiniBooNE a preferred region.

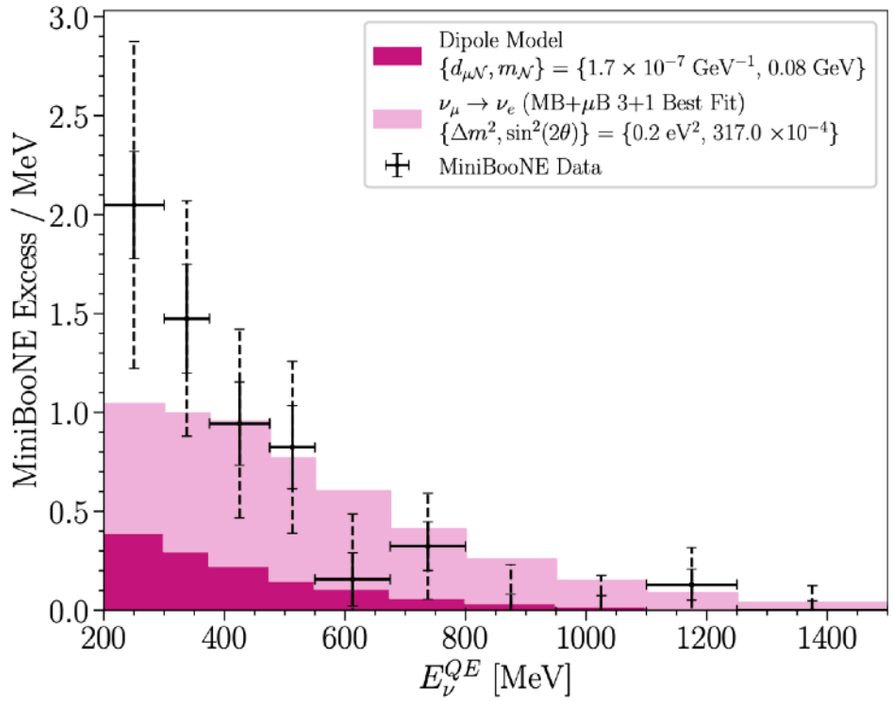
See Kamp et al 2206.07100 for details

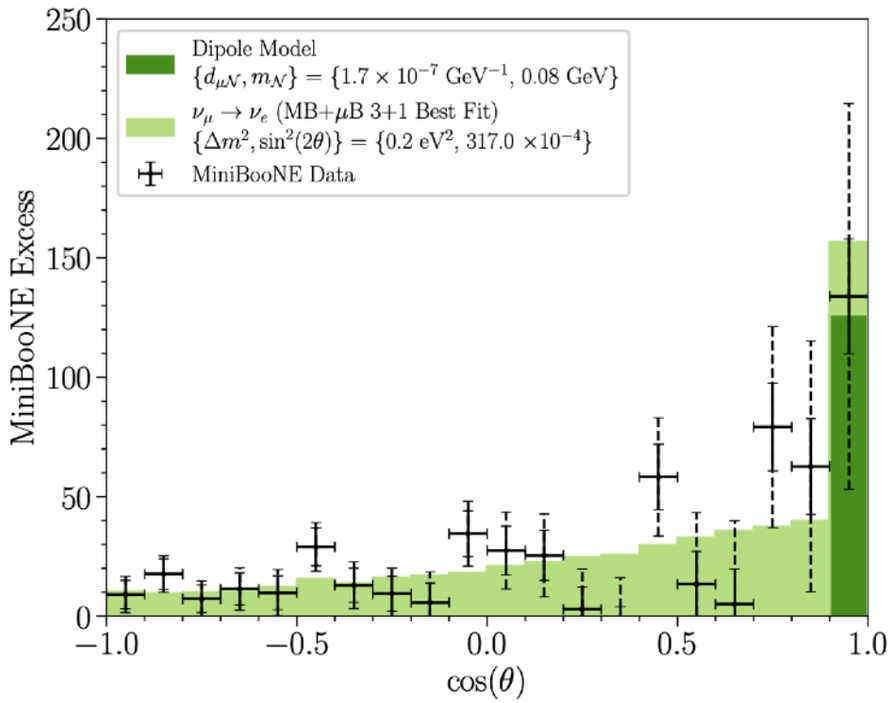
Gamma

Oscillation Dominated

Subleading Neutrissimo contribution avoids current constraints







See Kamp et al 2206.07100 for details

Outline

- Why go beyond vanilla sterile neutrinos?
- The garden of forking paths
- Non-vanilla sterile neutrinos
- Other explanations of MiniBooNE:
  - Single electron
  - Single photon
  - Di-electron
- Future

The MiniBooNE Lens

Single photon

Single electron

(3+1) + vis. decay

Dark sectors w/ pseudo -scalar

3+1 oscillations

Dark sectors w/ dark matter

Large Extra Dim

Neutrino dipole portal

(3+1) + inv-ν decay

Dark neutrinos

(3+1) + vis-ν decay

Lorentz Violation

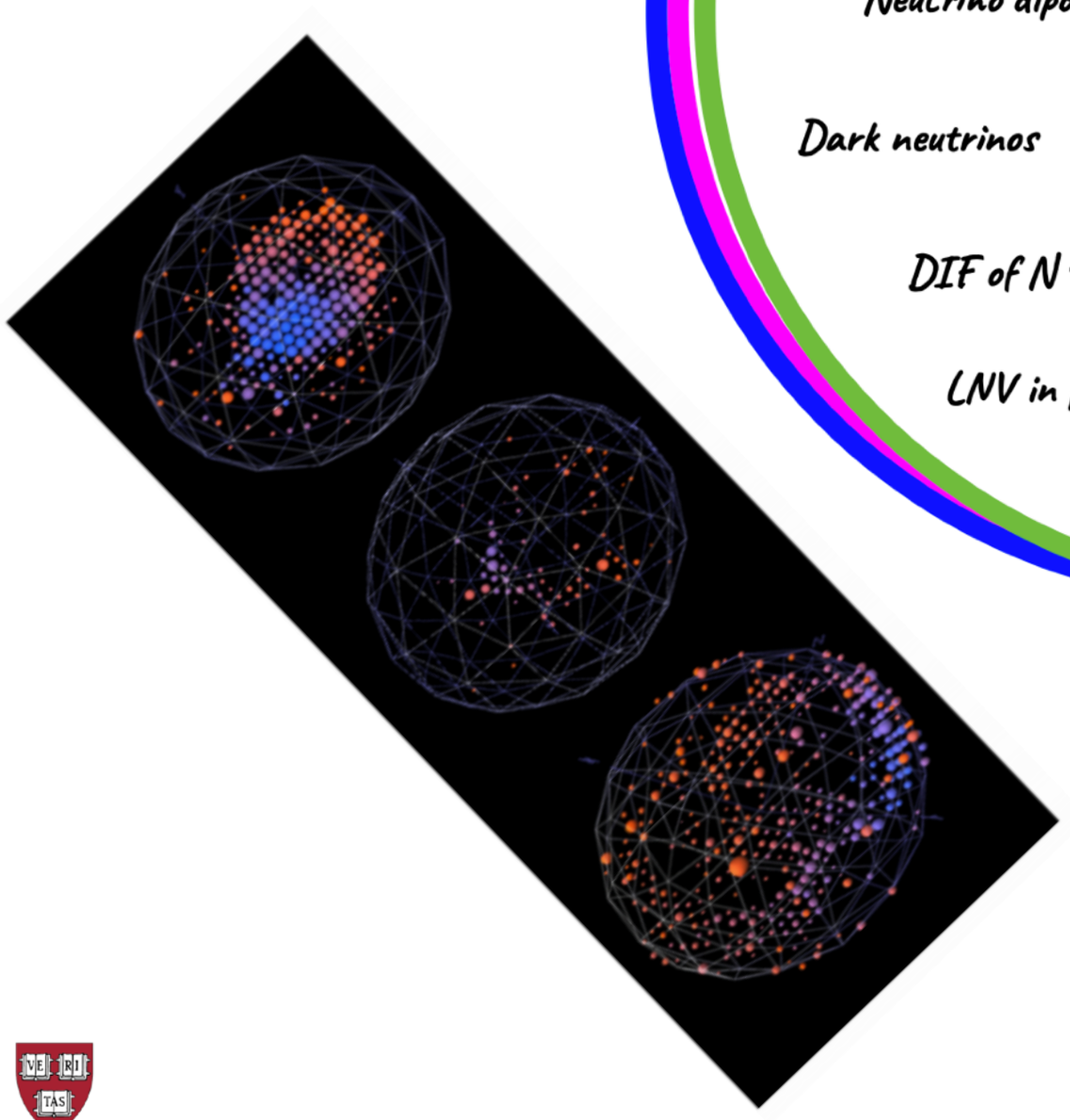
DIF of $N \rightarrow \nu\gamma$

Anomalous Matter

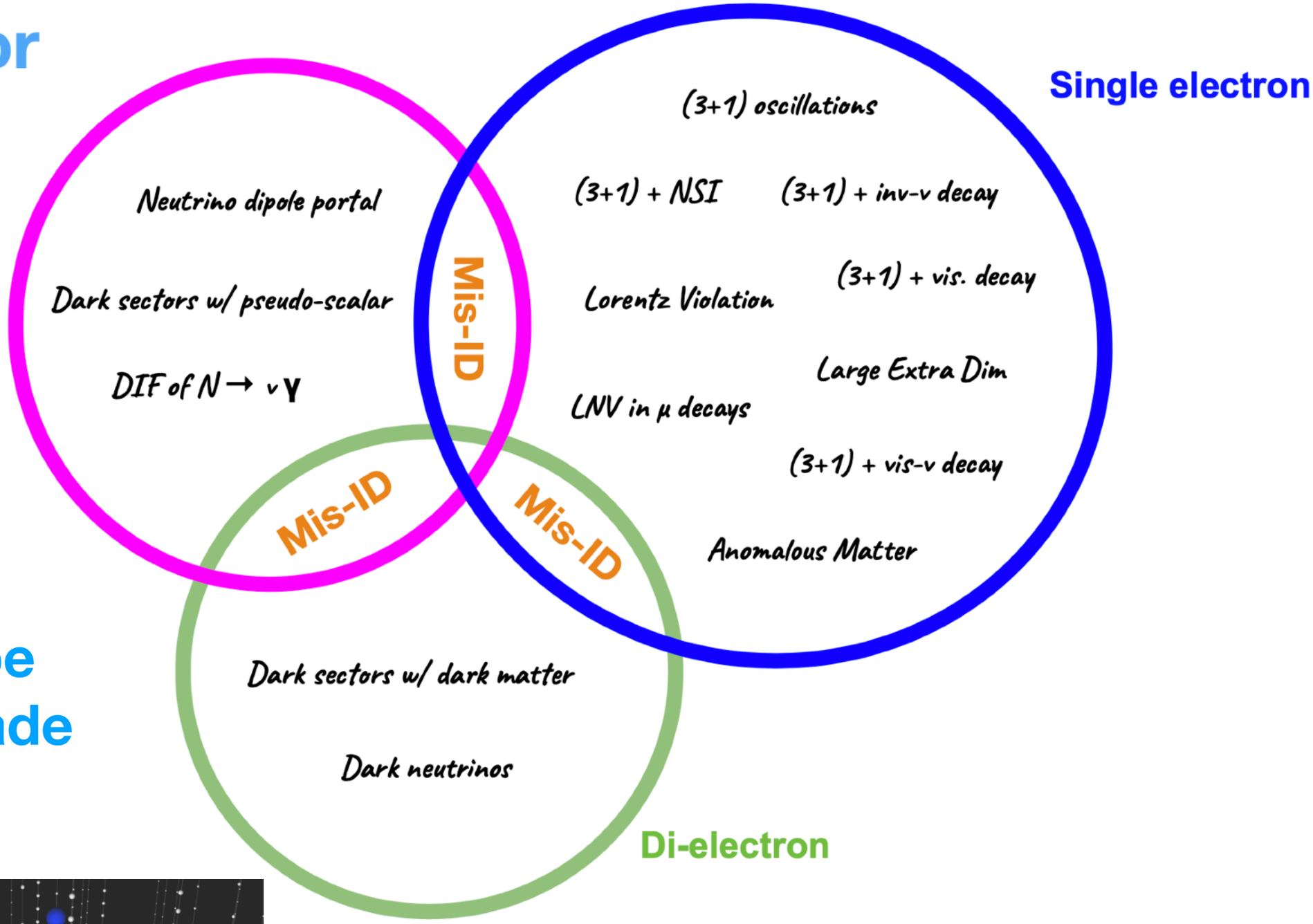
LNV in μ decays

(3+1) + NSI

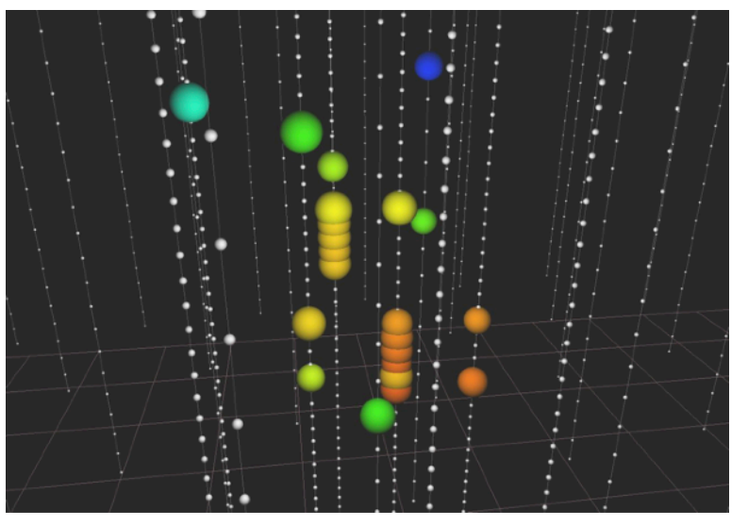
Di-electron

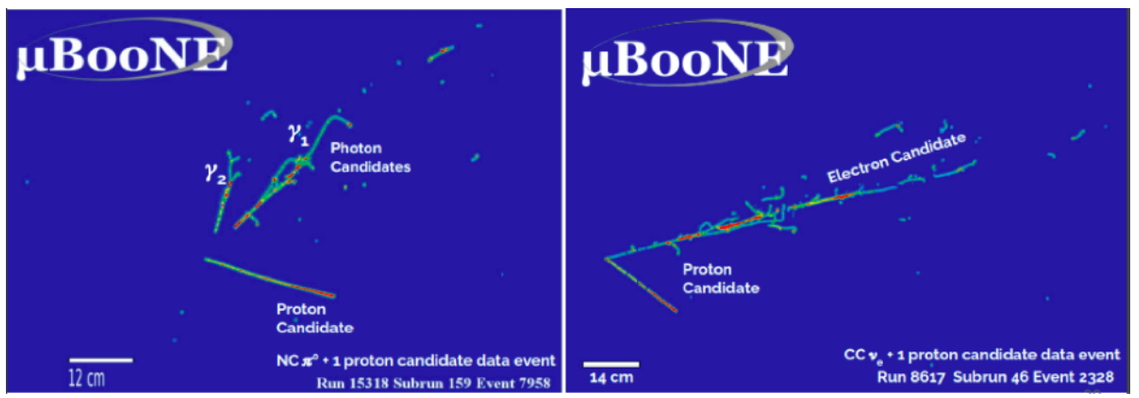


SBN Tricolor Lens



Also IceCube Double cascade search





Take home message

- The short-baseline anomalies are an unresolved puzzled in neutrino physics
- Minerva and T2K offer already important constraints on new models. Gas Argon TPC of T2K specially useful.
- Upcoming results from MicroBooNE, ICARUS, and others will help constraint these models.
- Current constraints only by phenomenologist. Need experiments to do these analyses!
- We need a combination of benchmark points of new models and full scans.

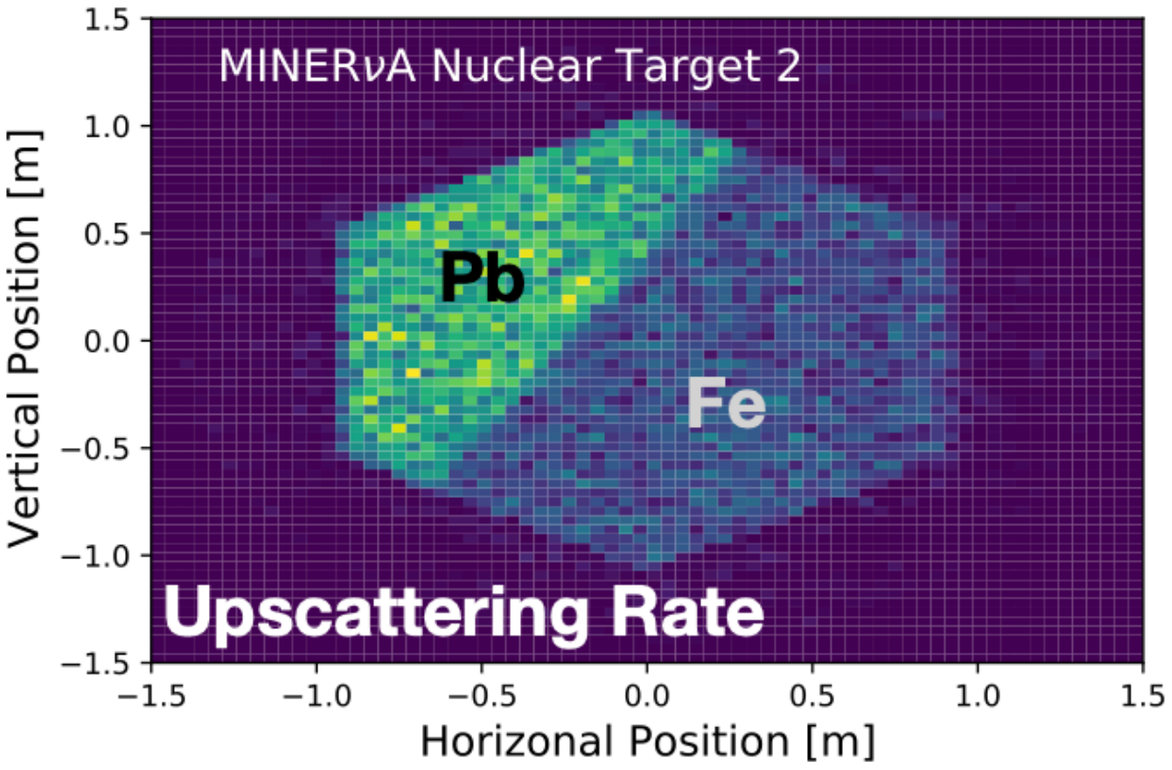
New Explanations: Not yet dead!

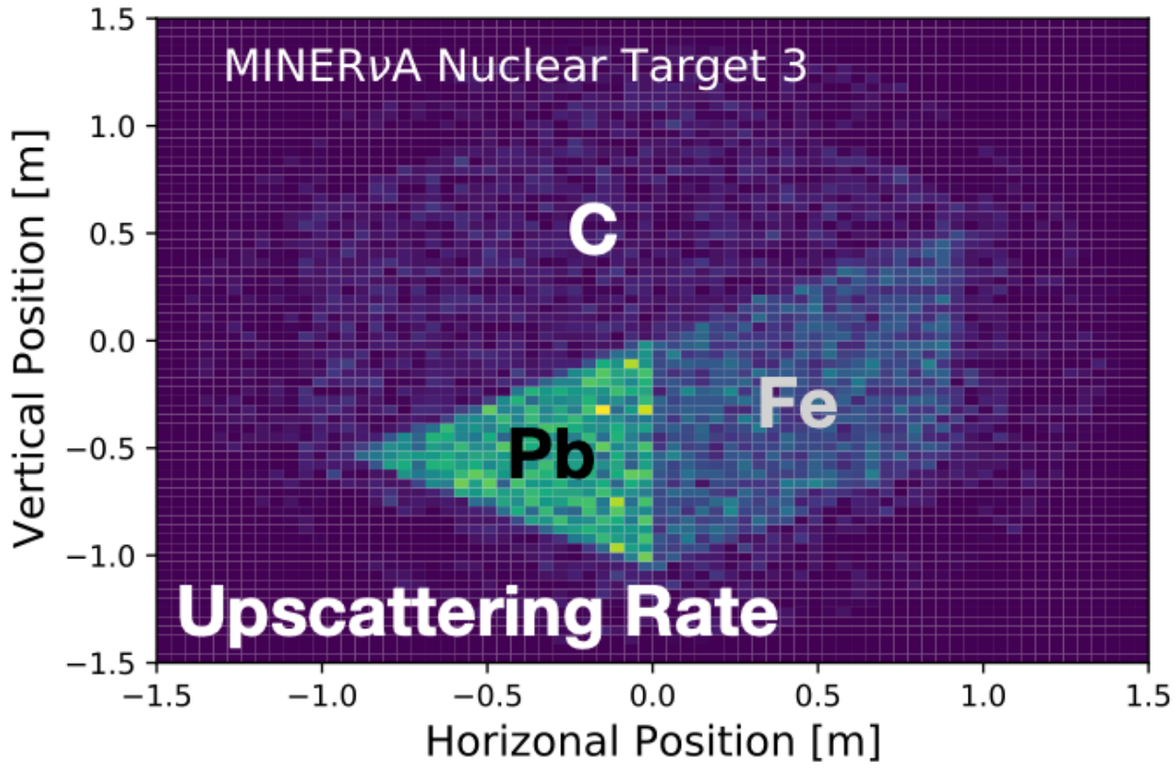
https://www.youtube.com/watch?v=uBxMPqxJGqI

Thank you!

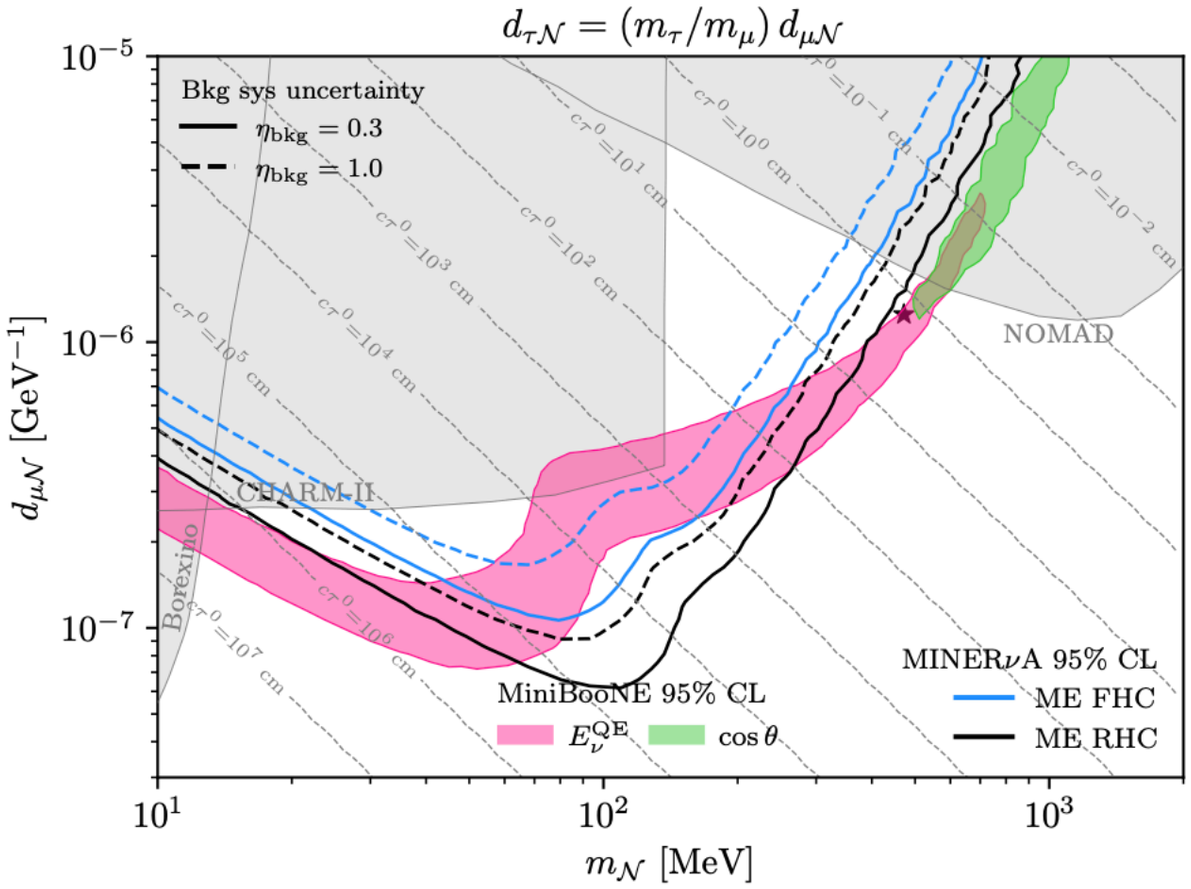
Bonus slides

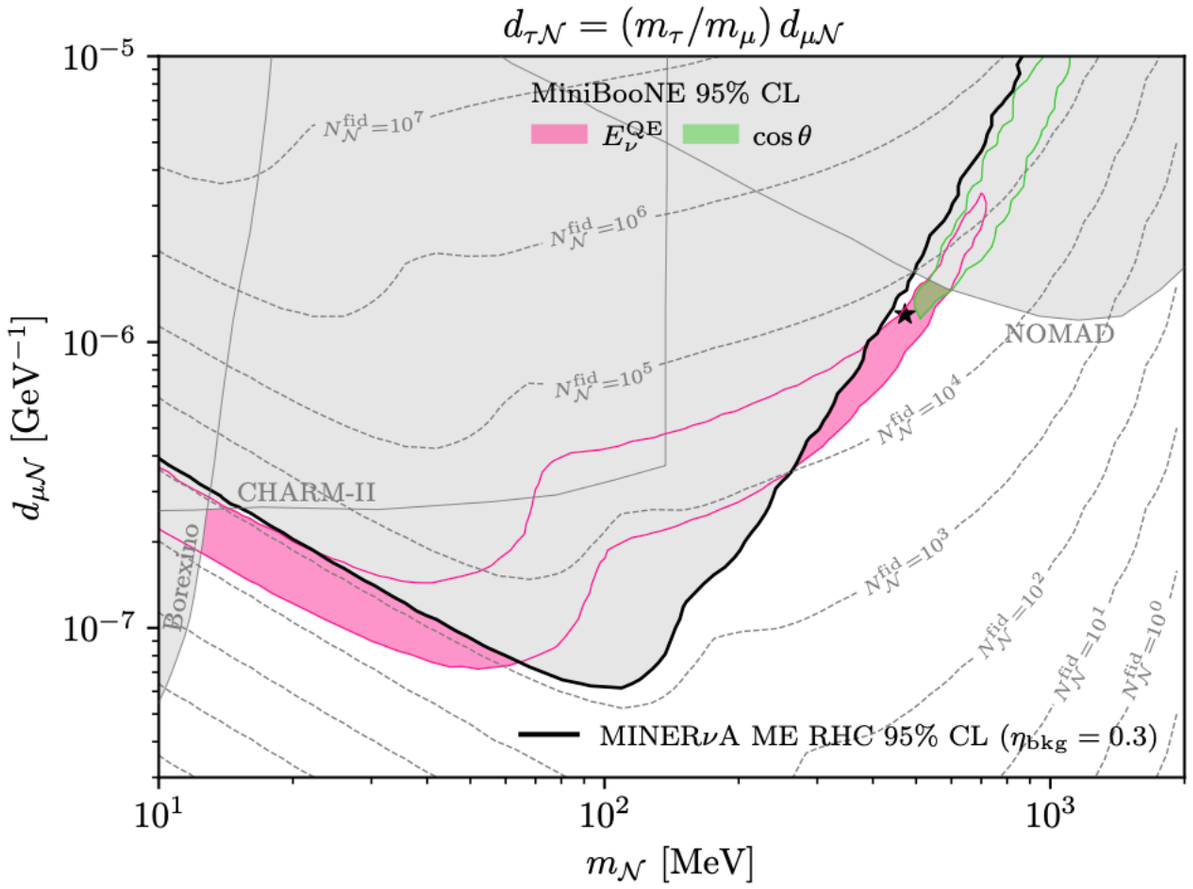
Minerva Neutrissimo Production





Neutrissimo with Tau Mixing

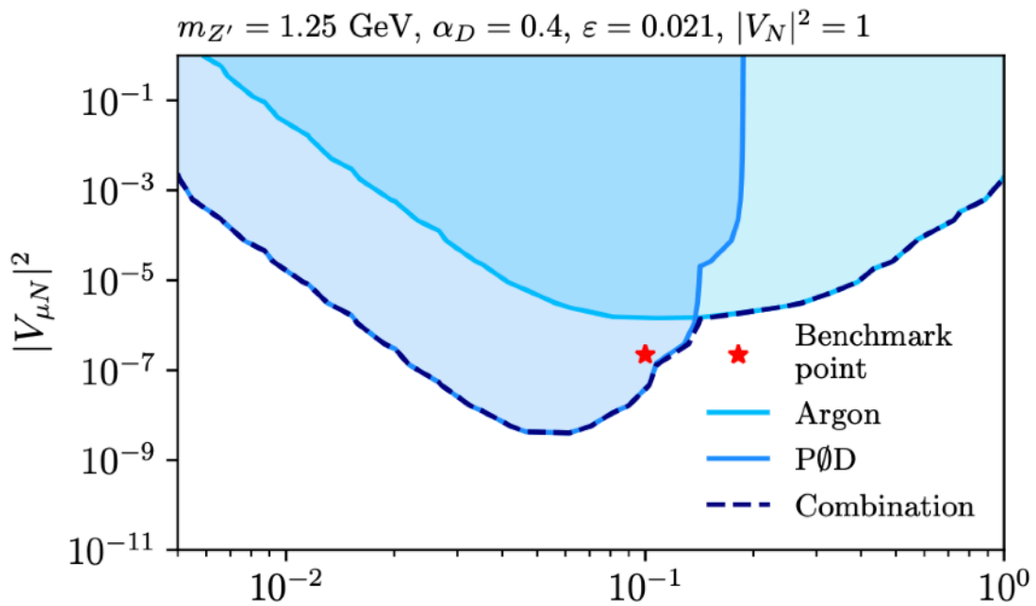


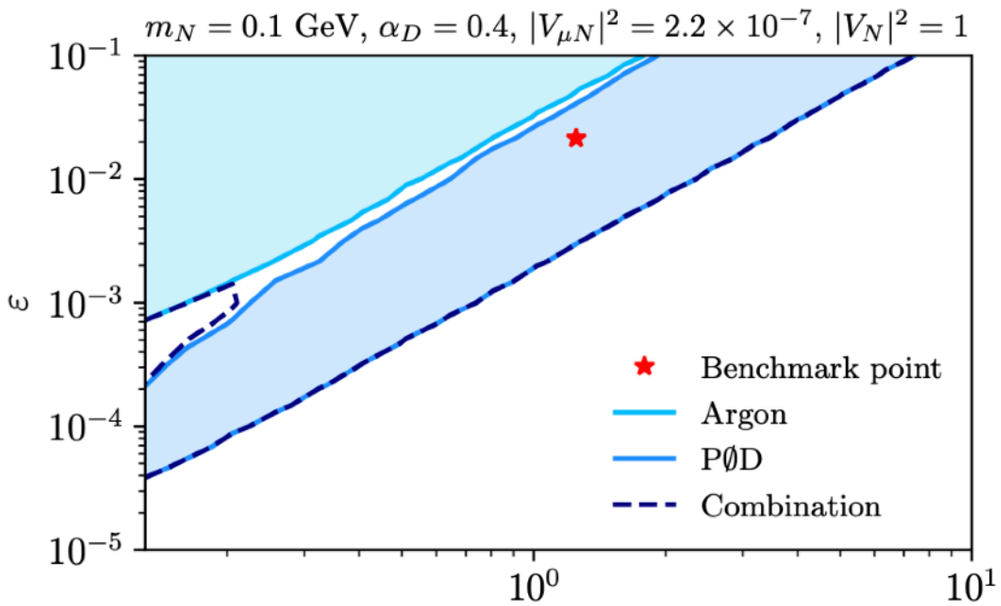


Dielectron

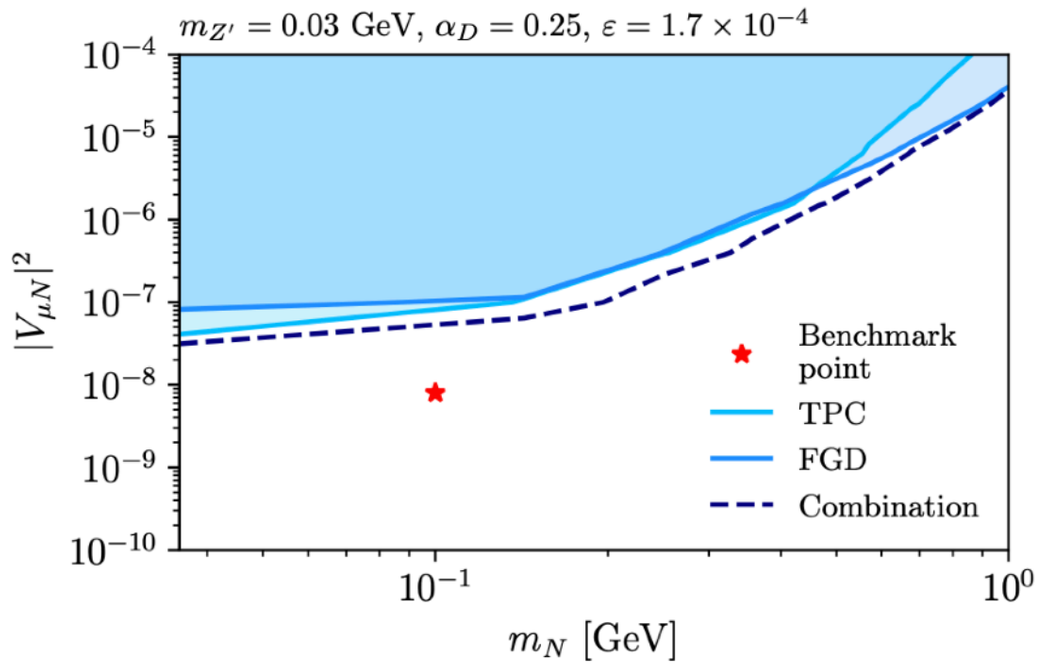
Dark Neutrino Production Regions

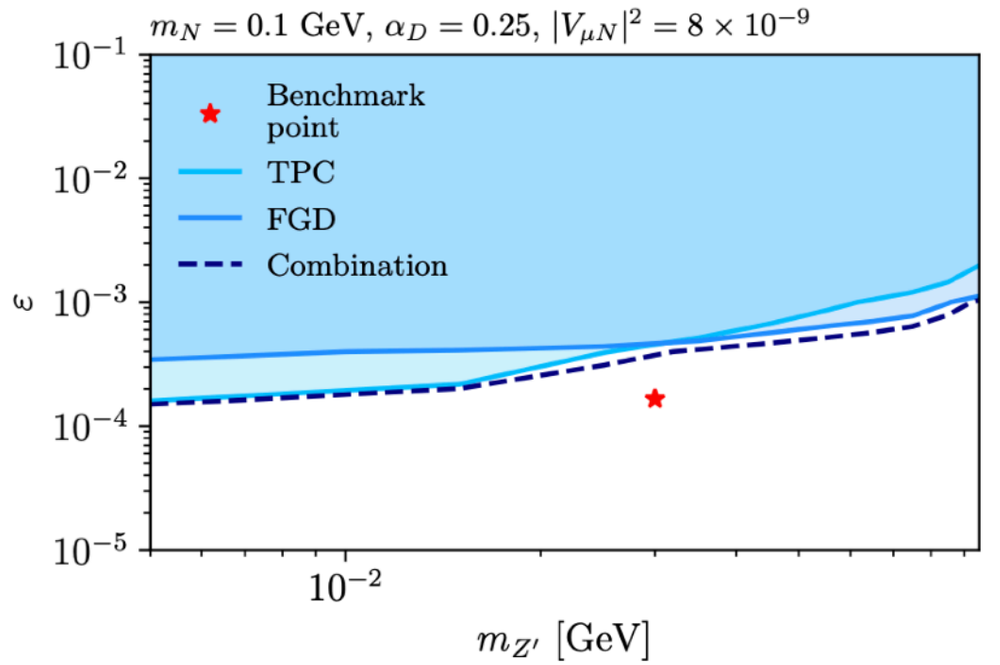
Heavy mediator scenario





Light mediator scenario



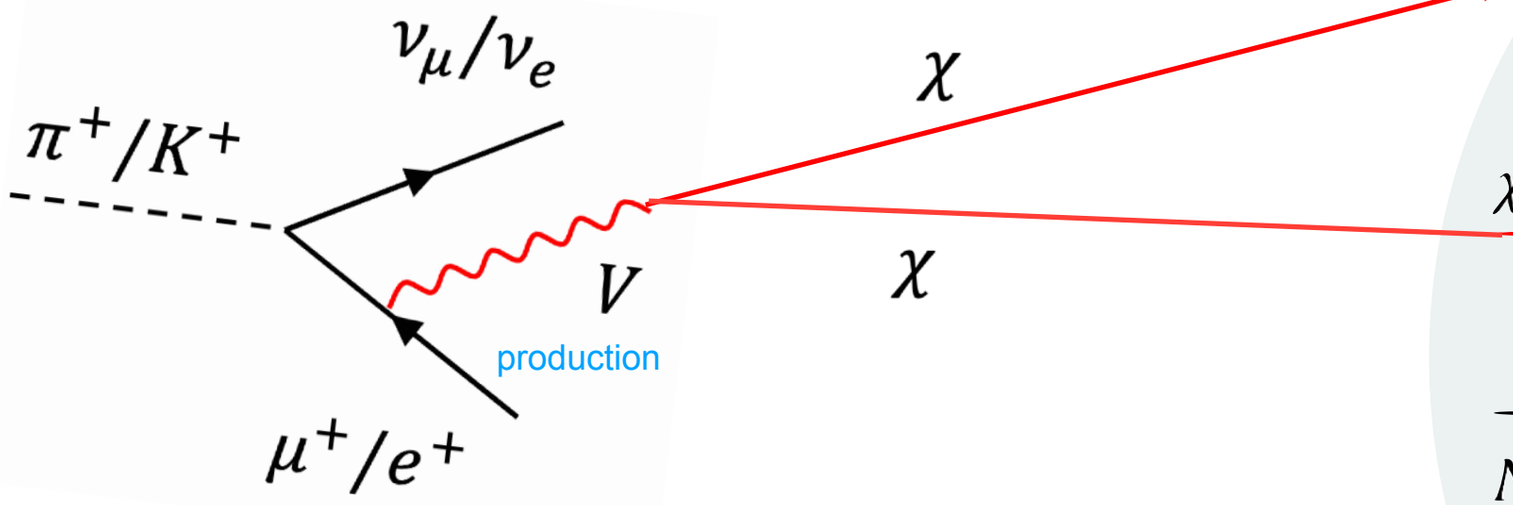


Dielectron

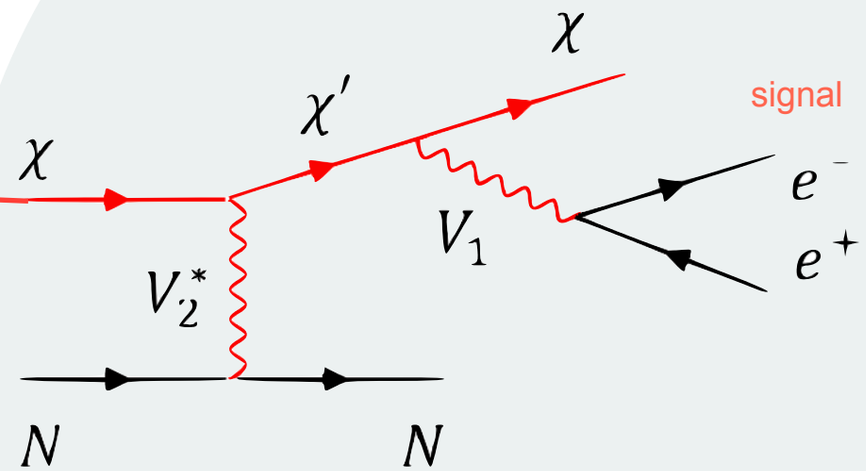
Dark Photon With Upscattering

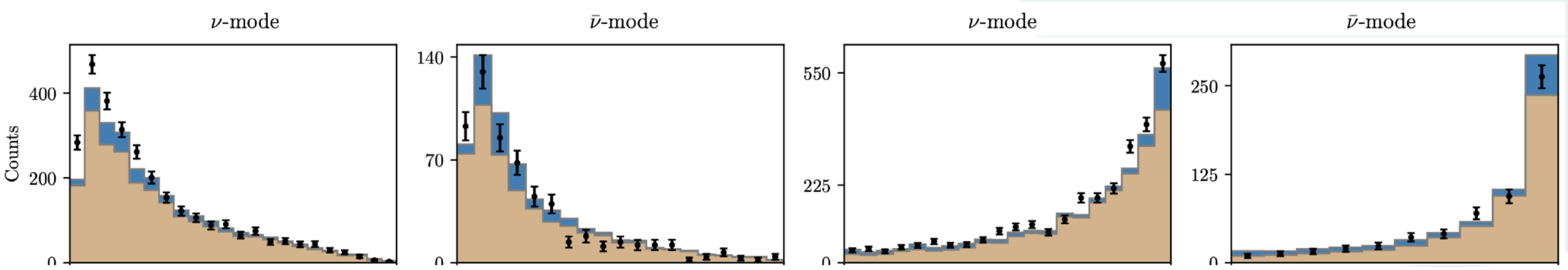
B. Dutta et al. 2110.11944

Booster Beam



MiniBooNE detector





Energy distribution

Angular distribution

χ Upscattering

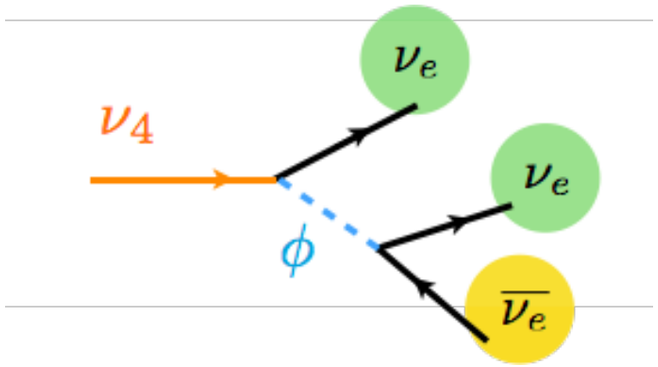
MiniBooNE Background

Vector-portal dark matter			
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$	χ^2/dof
Single	$(17, -, 8, 40)$	3.6×10^{-9}	2.5
Double	$(17, 200, 8, 50)$	1.3×10^{-7}	2.2

Electron

Visible Neutrino Decay in Beam

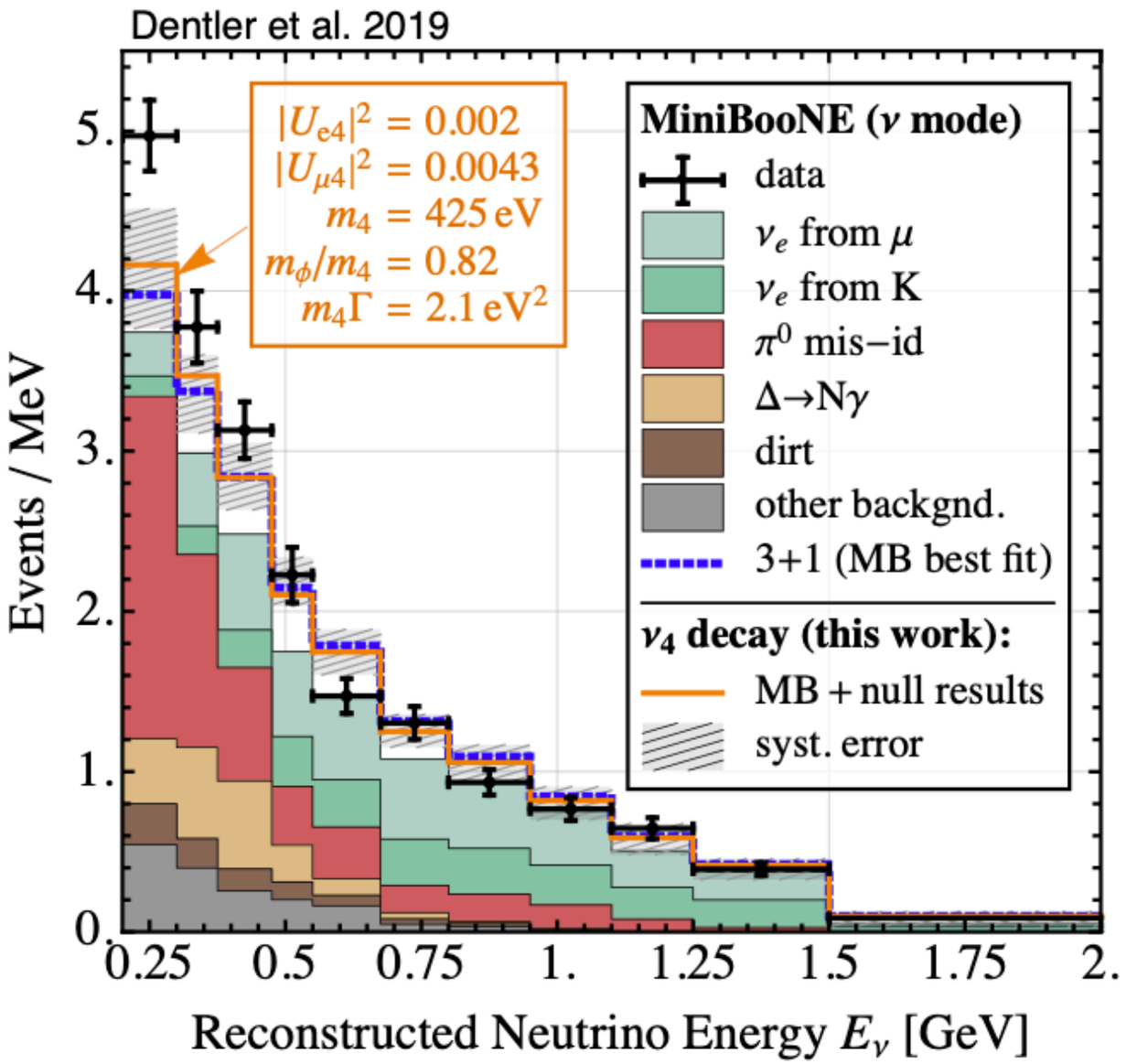
Dentler *et al* 1911.01427
Gouvea *et al* 1911.01447

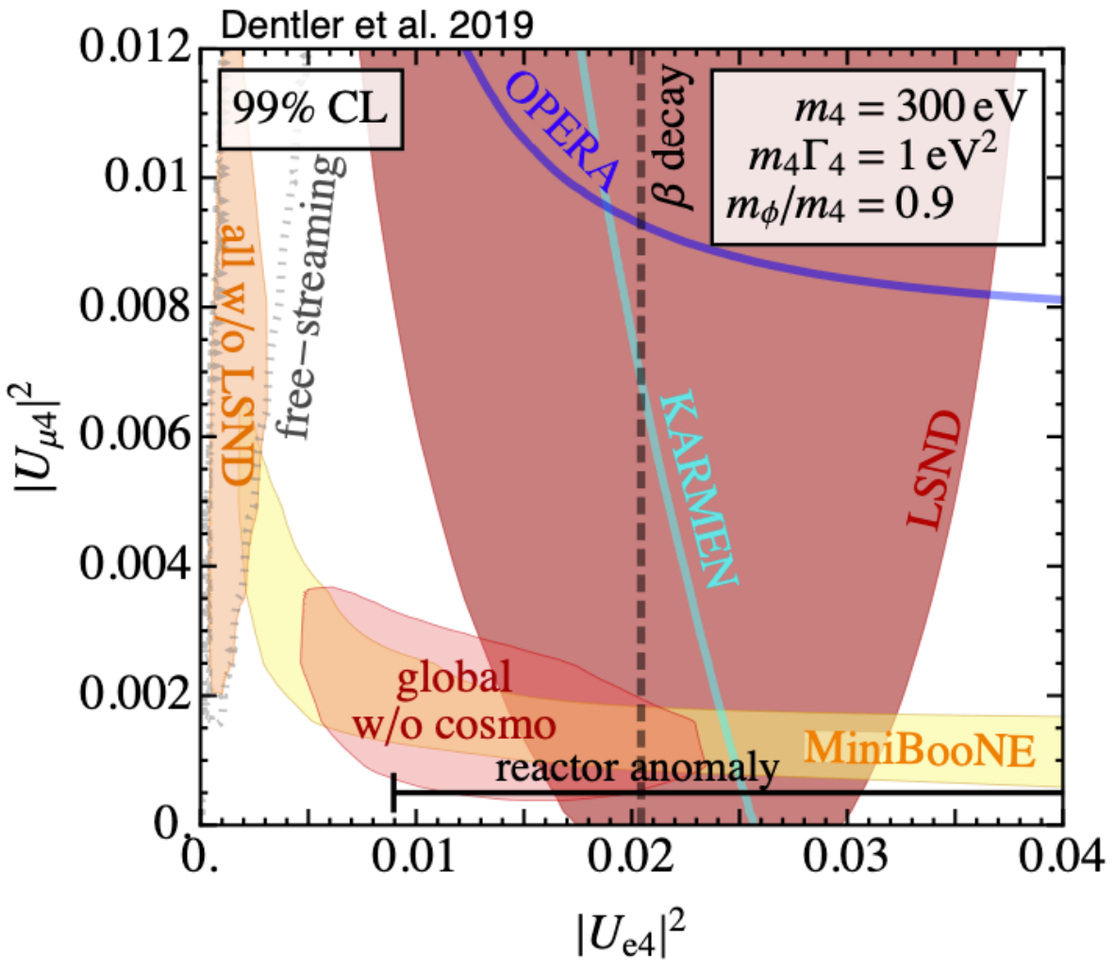


Heavy neutrino component in the neutrino beam decays into lighter less energetic neutrinos.

These neutrinos interact in the detector and produce the excess.

$$\mathcal{L} \supset -g\,\bar{\nu}_s \nu_s \phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha \nu_\beta$$



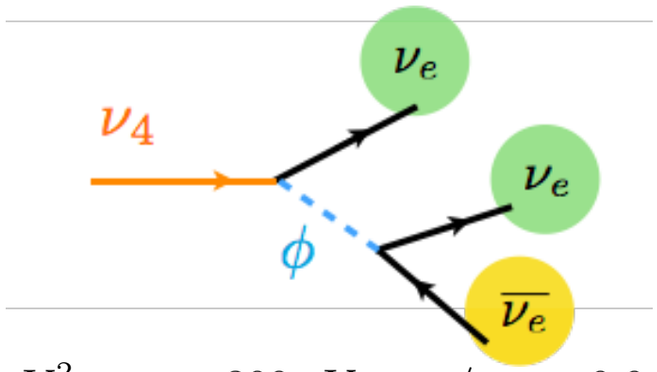


See also Fisher *et al* 1909.09561

Electron

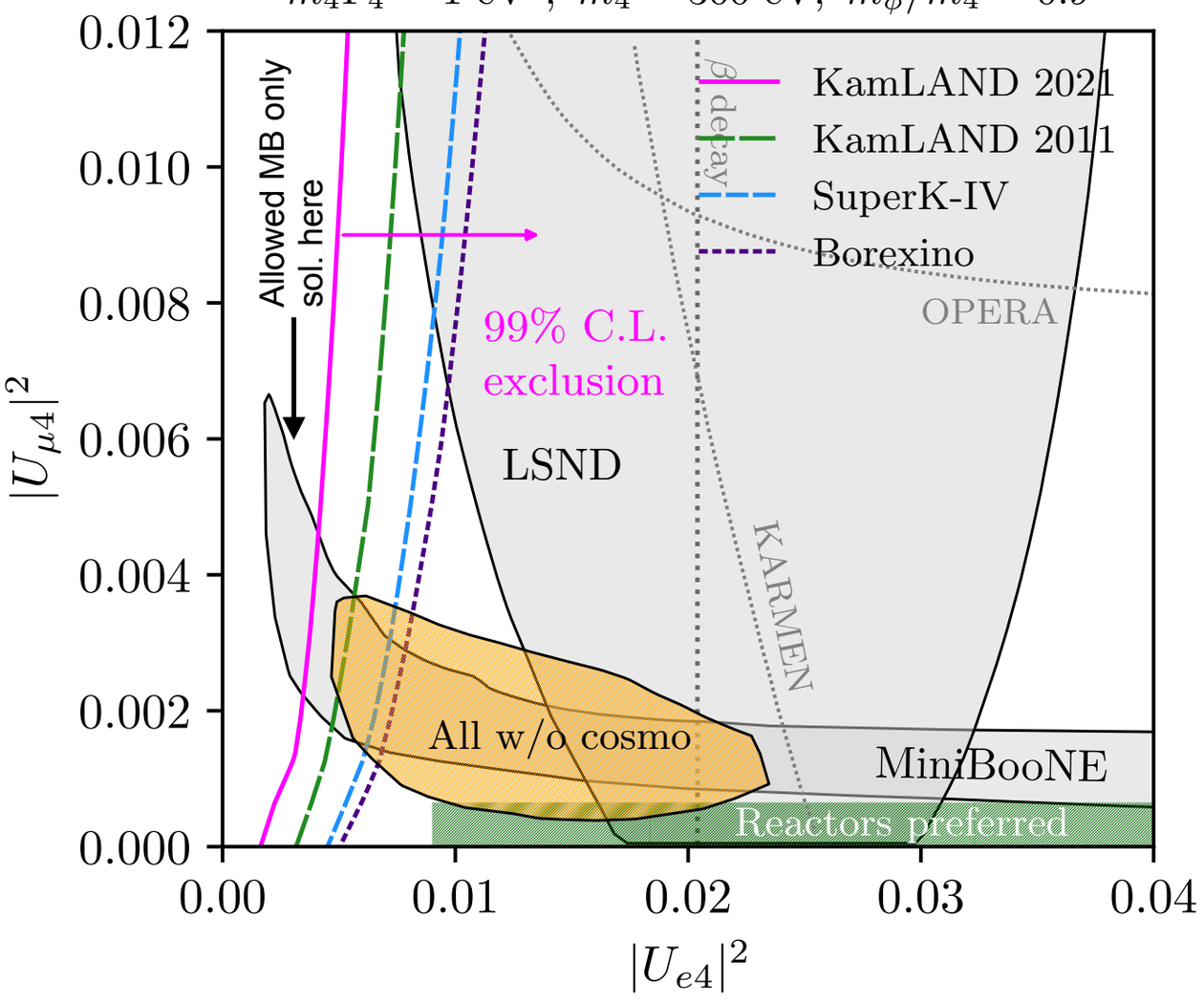
Visible Neutrino Decay in Beam

Dentler *et al* 1911.01427
Gouvea *et al* 1911.01447

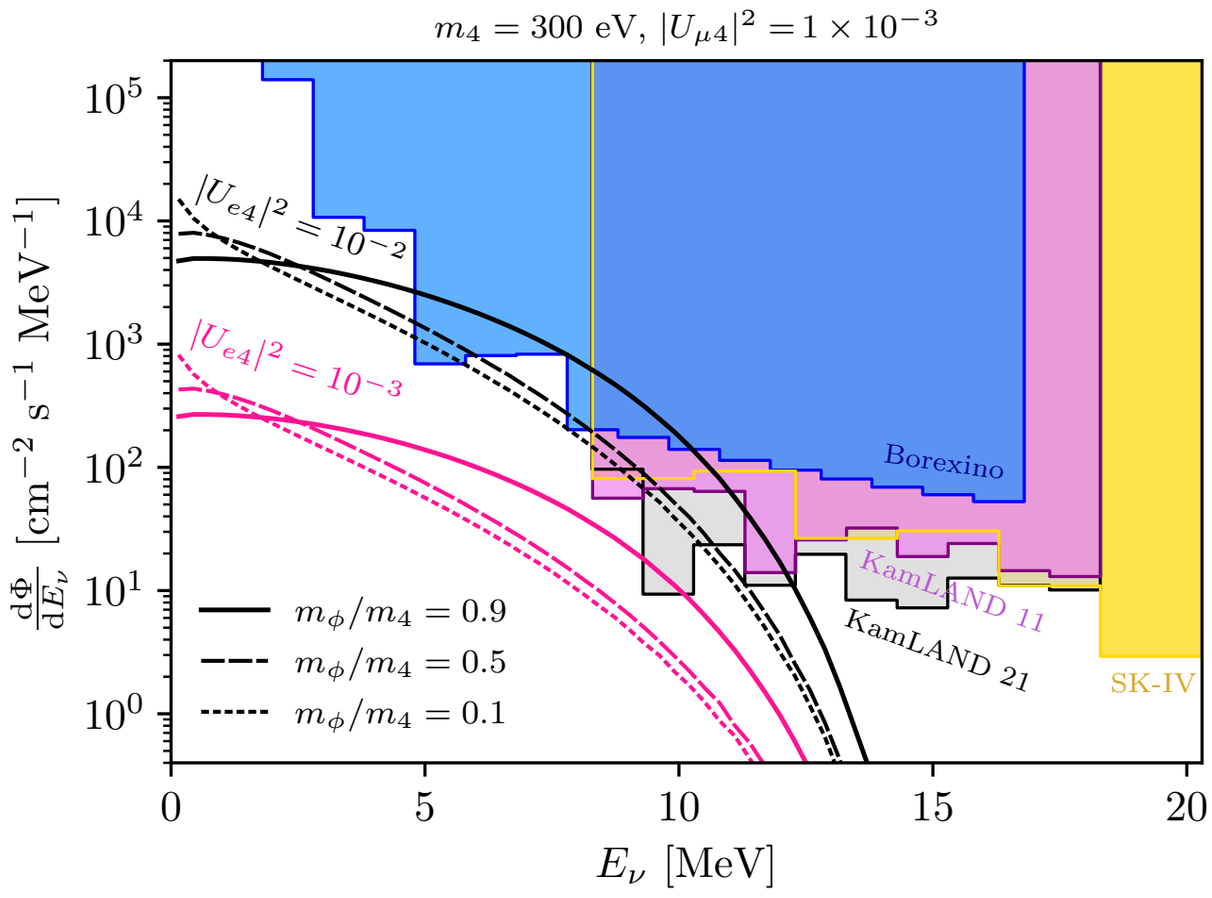


Constrains from antineutrinos from the Sun do not allow this to be a global solution of the anomalies.

MiniBooNE alone can be explained.



M. Hostert & M. Pospelov 2008.11851



Visible decay predicts emission of antineutrinos from the Sun!

Gamma

Idea 5: Scalar With "Primakoff" Upscattering

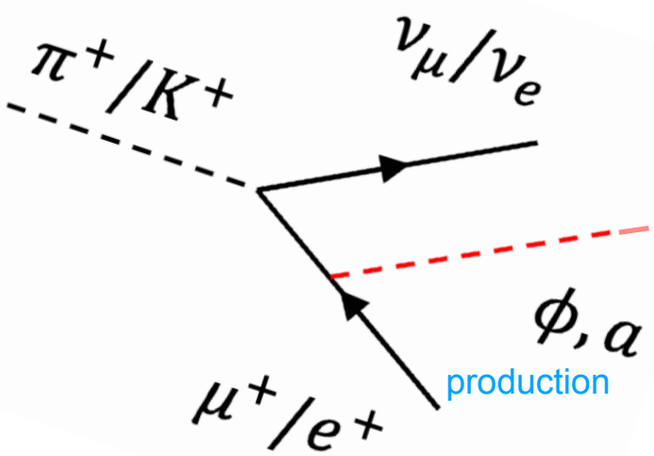
B. Dutta et al. 2110.11944
See also Abdallah et al 2202.09373

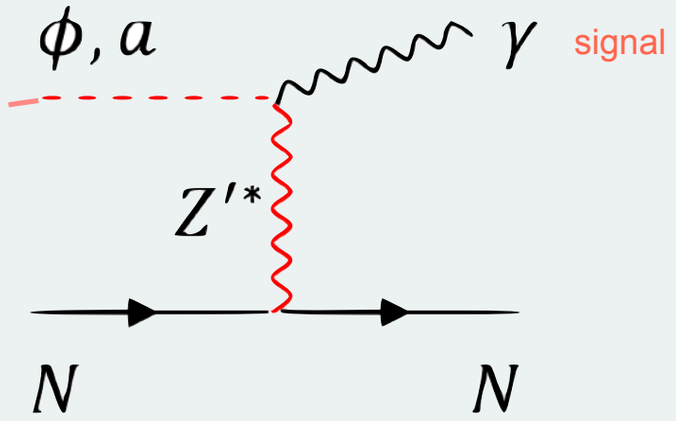
Booster Beam

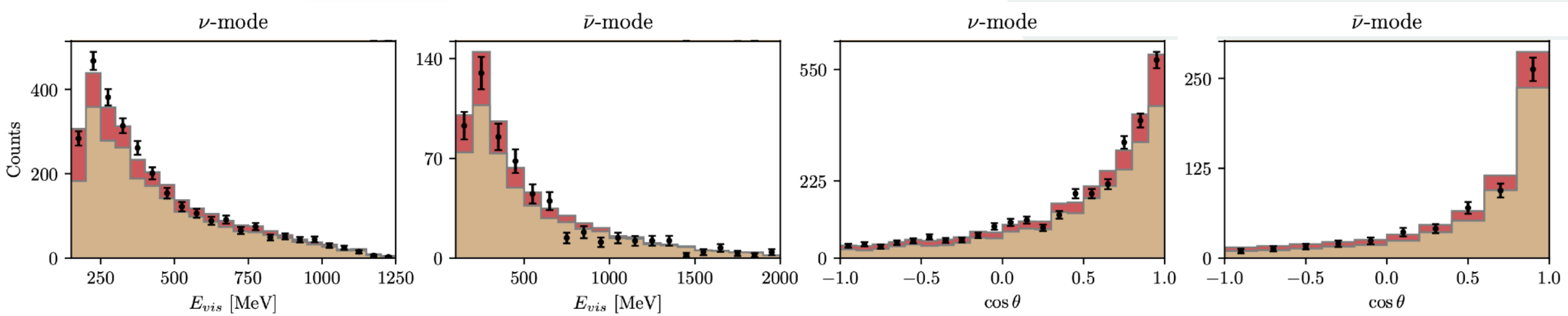
$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.},$$

$$\mathcal{L}_P \supset i g_\mu a \bar{\mu}\gamma^5\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + \text{h.c.}$$

MiniBooNE detector







Energy distribution

ϕ/a Dark Primakoff

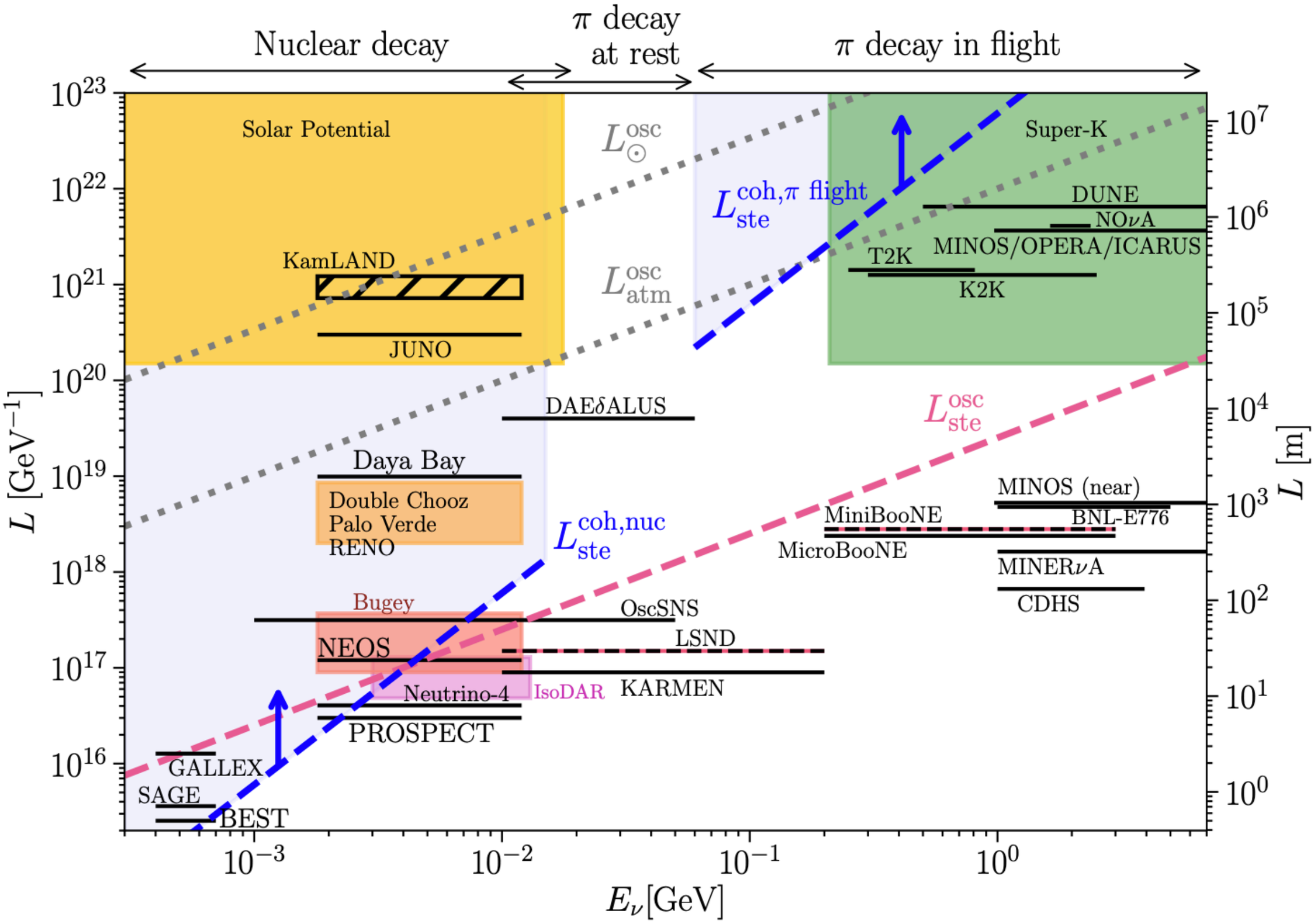
MiniBooNE Background

Angular distribution

Long-lived (pseudo)scalar

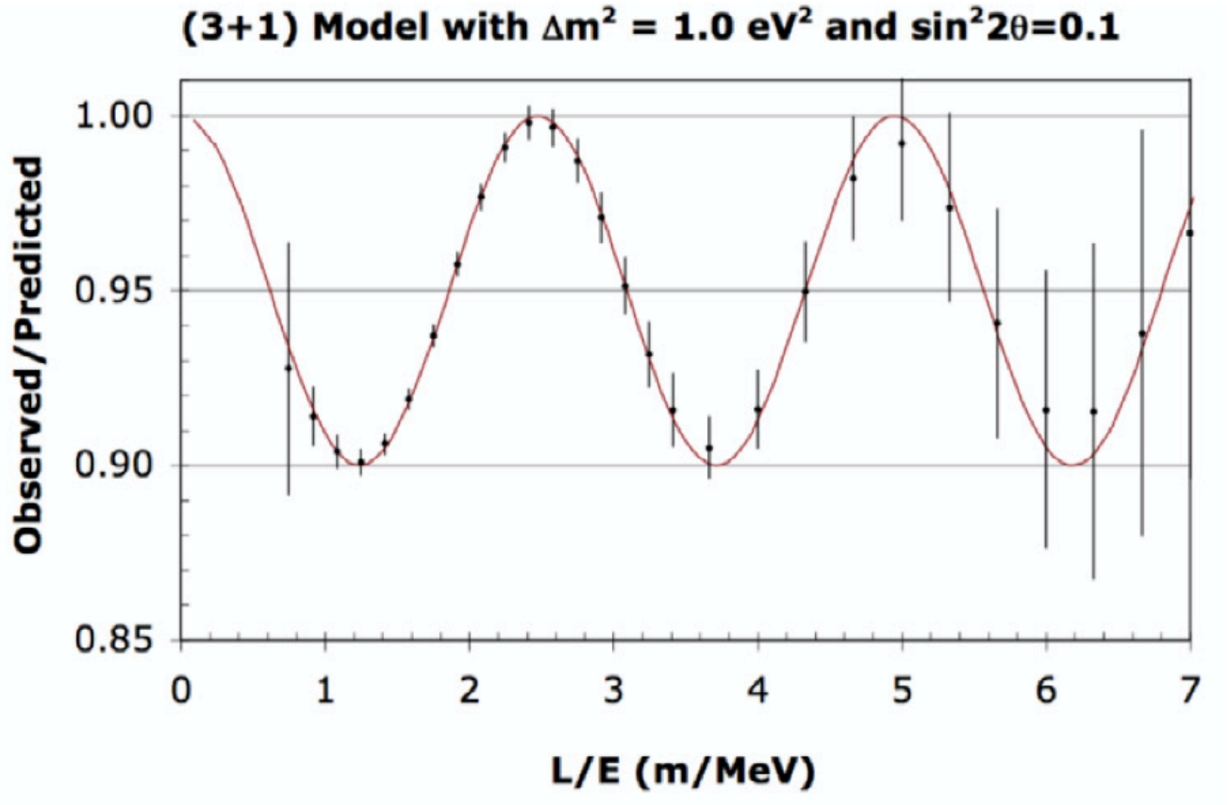
Scenario	$(m_{Z'}, m_{\phi/a})$	$(g_\mu g_n \lambda)$ [MeV^{-1}]	χ^2/dof
Scalar	$(49, 1)$	2.2×10^{-8}	1.6
Pseudoscalar	$(85, 1)$	5.9×10^{-7}	1.6

Where does it matter?

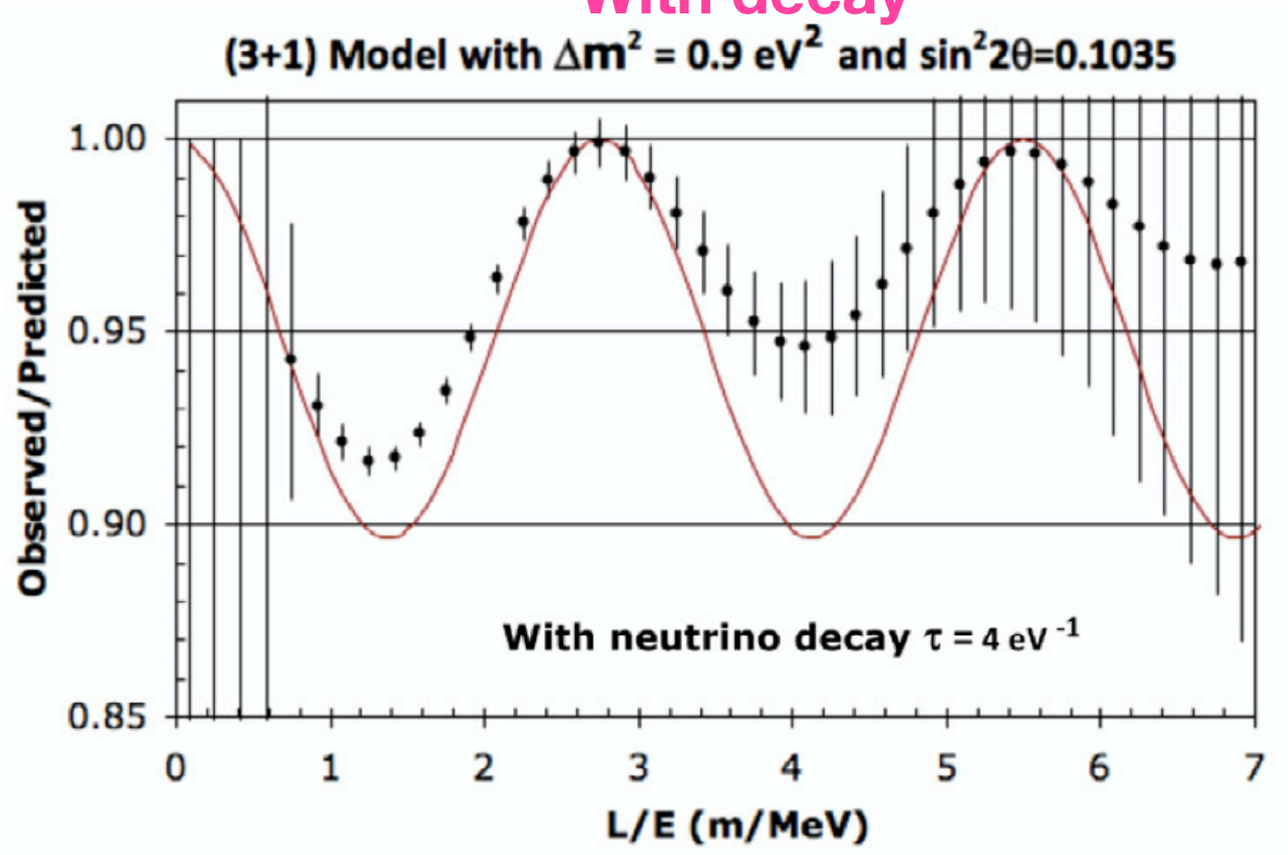


IsoDAR@Yemilab

No decay



With decay

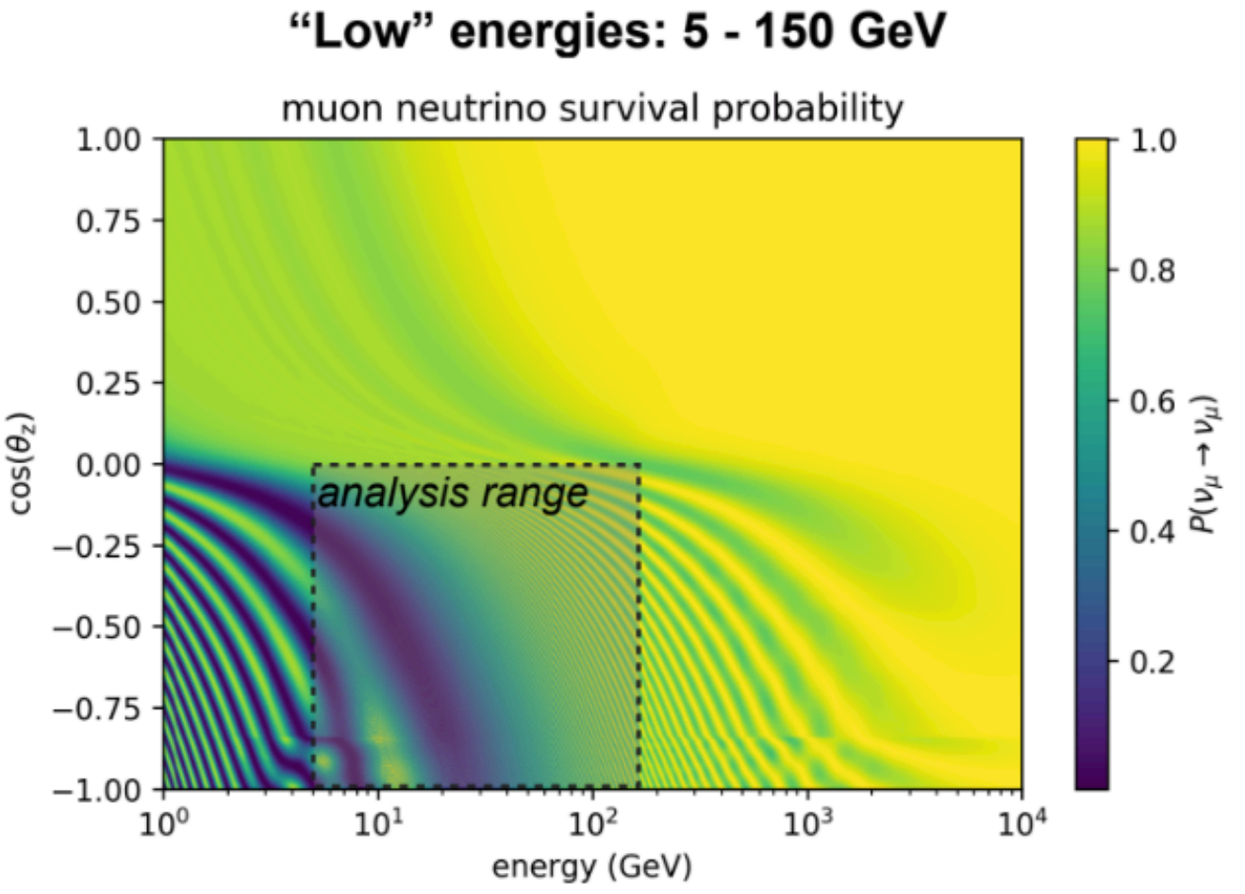


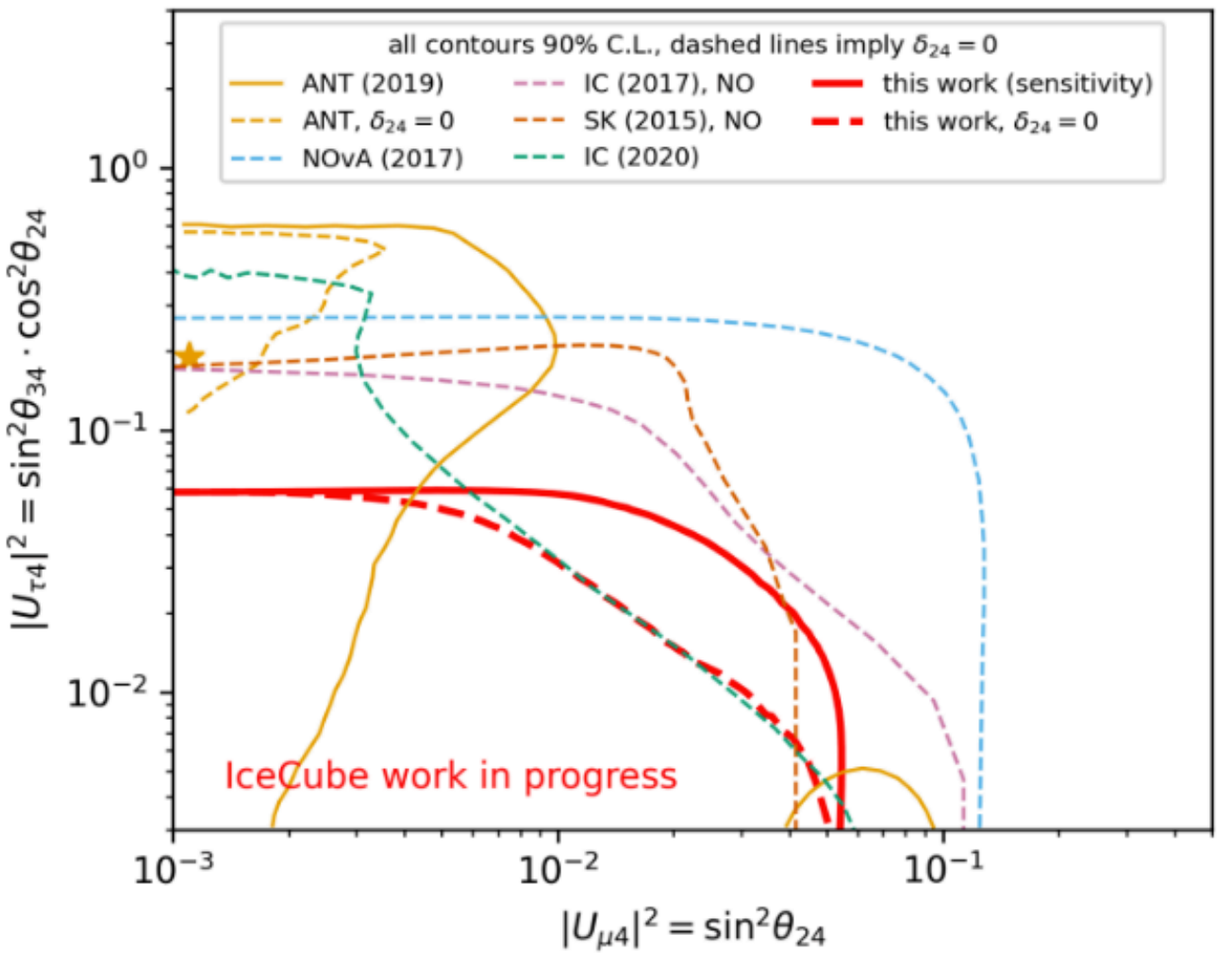
IsoDAR with O(1M) events

IsoDAR@Yemilab will conclusively rule out the 3+1 model, but also due to its ability to trace the oscillation wave see variants on this model such as 3+1+Decay

IceCube@Antartica

Talk by A. Trettin@PANIC2021





Projected sensitivity of sterile search with 8 years of DeepCore data

- very fast, unresolvable oscillations + distortion
- IceCube: World-leading limits on $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$!

IceCube will continue improving muon neutrino disappearance searches.
"Low energy" sample (<100 GeV) still not studied.

Menu of other explanations

New signatures

Gninenko 1107.0279
Magill et al 1803.03262
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
CA, Hostert, Tsai et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay

Heavy Neutrino Decay

Bai et al 1512.05357

Dentler et al 1911.01427,
de Gouvea et al 1911.01447,
Hostert & Pospelov 2008.11851

Heavy O(100MeV) decay to ν_e

Fisher et al 1909.0956,
CA, Foppiani, Hostert 2109.03831

Heavy O(100MeV) decay to photon

Oscillations+X

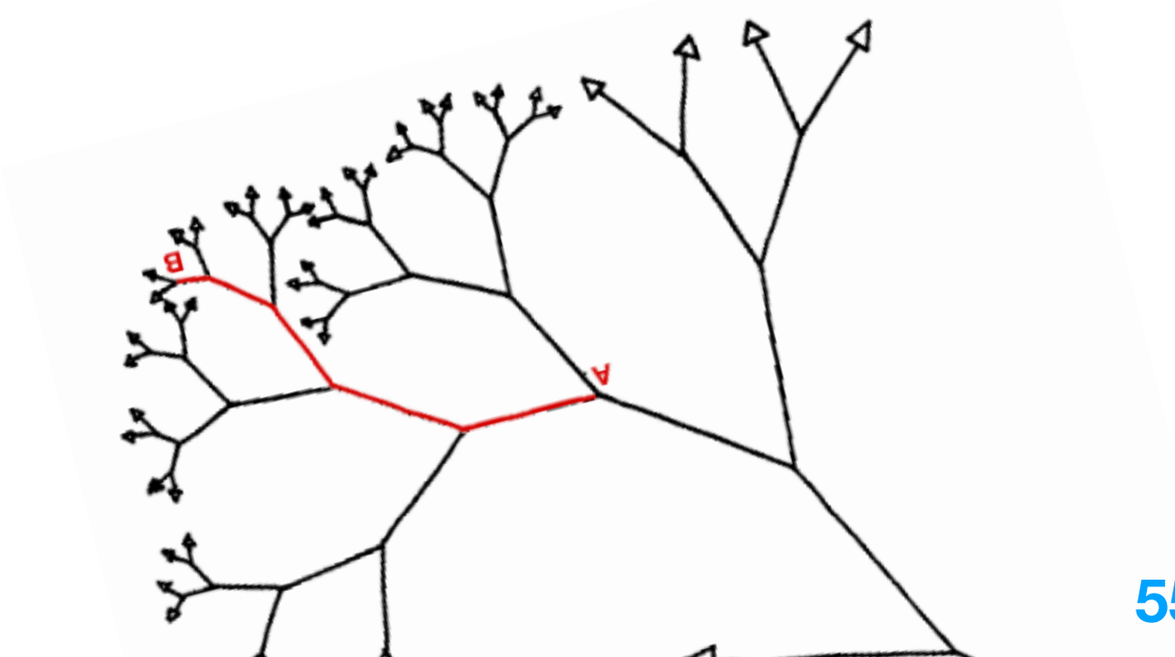
Assadi et al 1712.08019
Resonant matter effect

Moss et al 1711.05921, Moulai et al 1910.13456
Steriles +decay

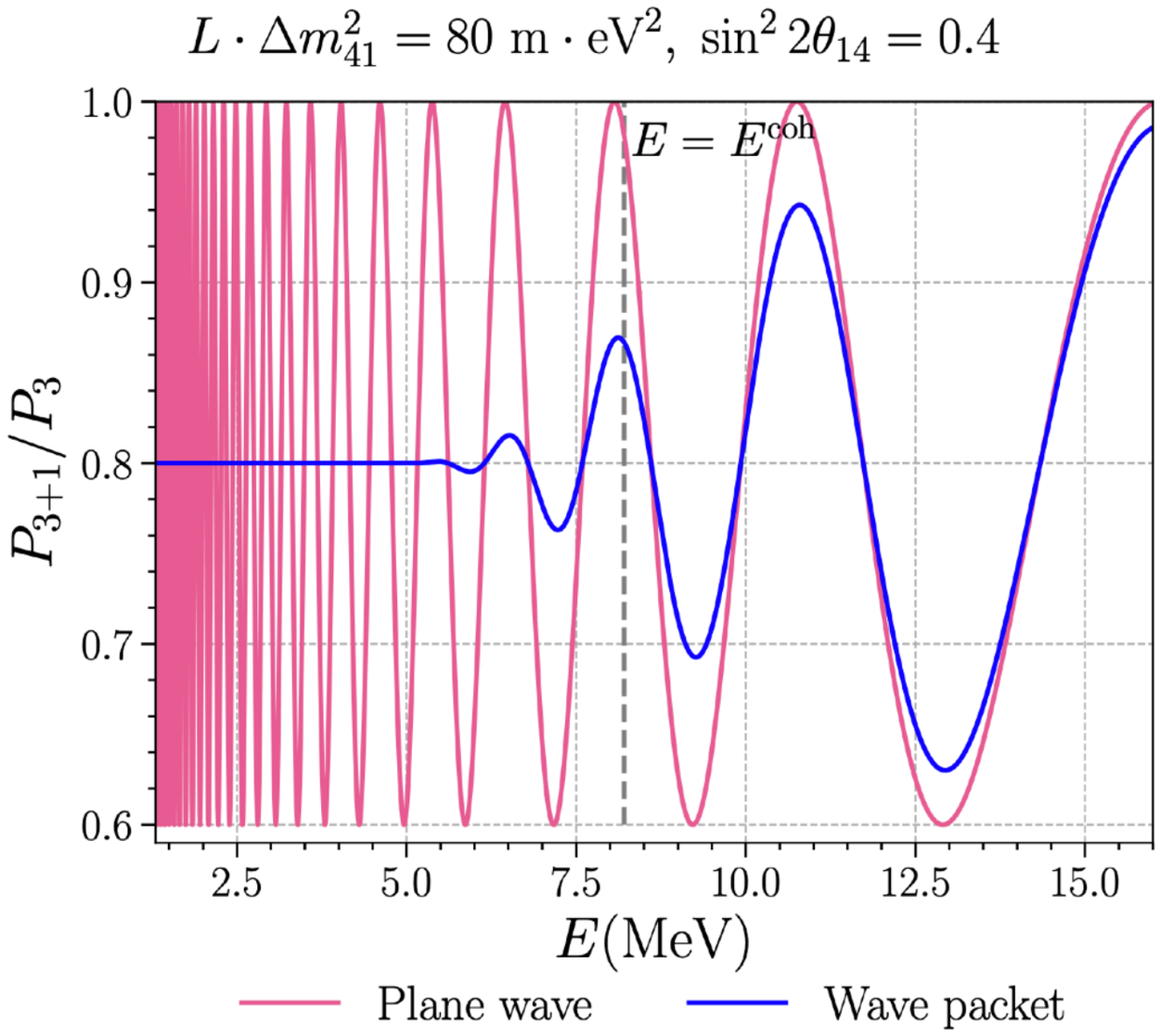
Liao et al 1810.01000
Steriles + NCNSI + CCNSI

More than one at a time

S. Vergani et al arXiv:2105.06470
Light Sterile + Heavy neutrino O(100MeV),
magnetic moment



Oscillation probability in the Wave Packet formalism



$$P_{\alpha\beta} = \sum_{i=1}^{n} |U_{\alpha i}|^2 |U_{\beta i}|^2 + 2\mathrm{Re} \sum_{j>i} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \times$$

$$\times \exp\left\{ -2\pi i \frac{L}{L^{ij}_{\mathrm{osc}}} - 2\pi^2 \left(\frac{\sigma_x}{L^{ij}_{\mathrm{osc}}} \right)^2 - \left(\frac{L}{L^{ij}_{\mathrm{coh}}} \right)^2 \right\}$$

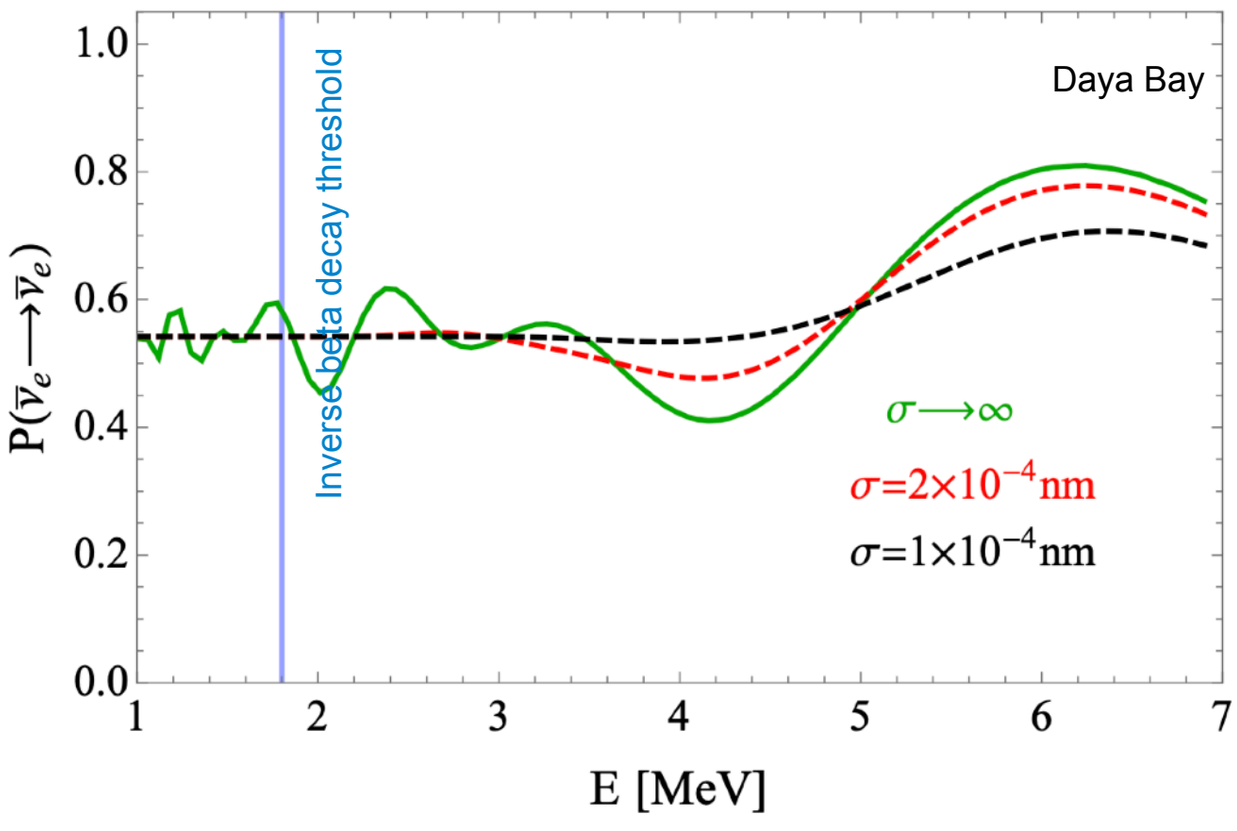
$$L^{ij}_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2_{ji}} \quad \text{and} \quad L^{ij}_{\mathrm{coh}} = \frac{4\sqrt{2} E^2 \sigma_x}{\Delta m^2_{ji}}$$

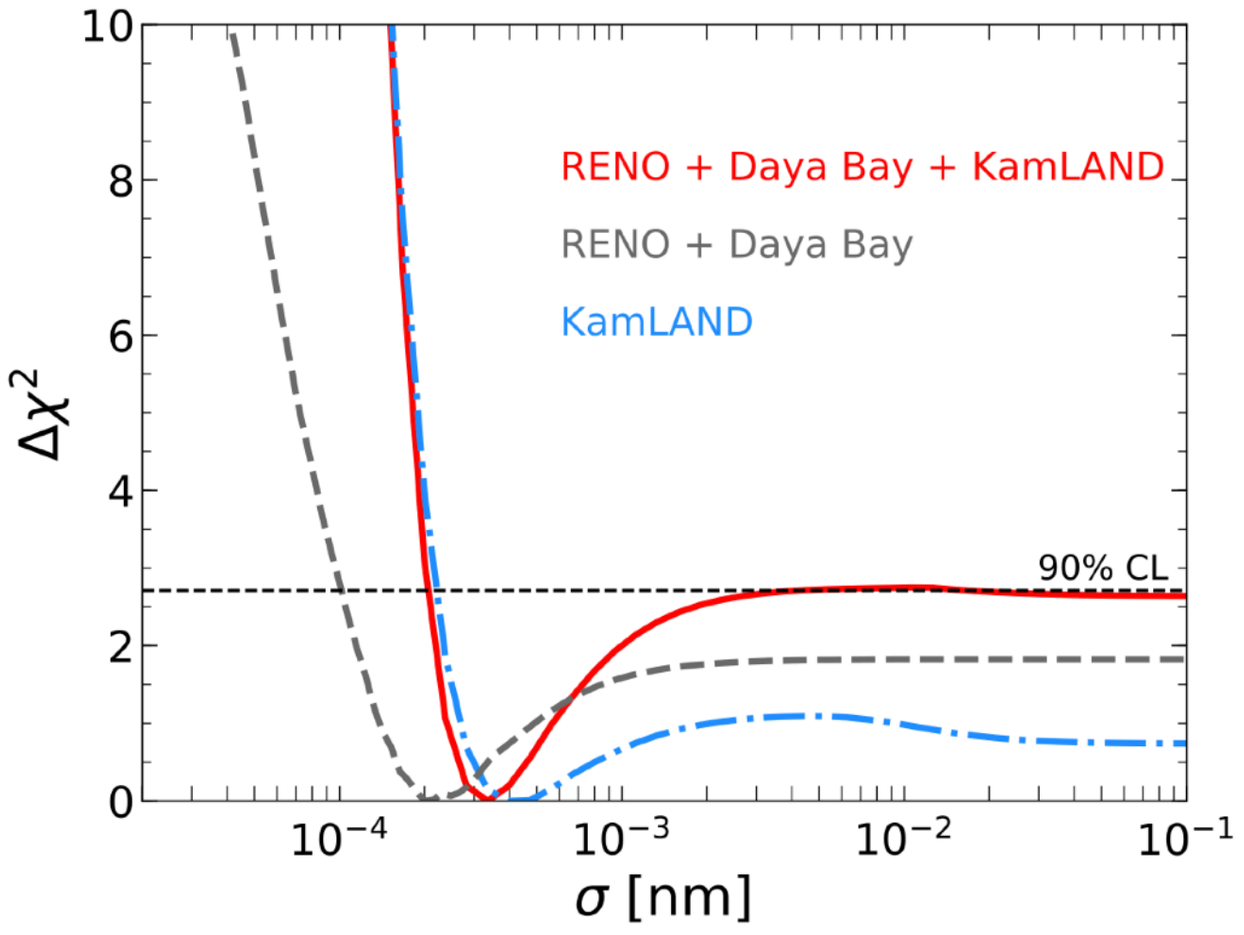
σ_x is the wave packet size

Oscillations are damped due to the added uncertainty in the neutrino energy

Can we measure/constraint its size?

Yes! We can look at the distortions on the reactor neutrino measurements of standard oscillations!





Reactor wave packet size to be constraint to be greater than 2.1×10^{-4}nm at 90% CL.

Gouvea arXiv:2104.05806 and Daya Bay Coll. 1608.01661

What is the size of the wave packet?

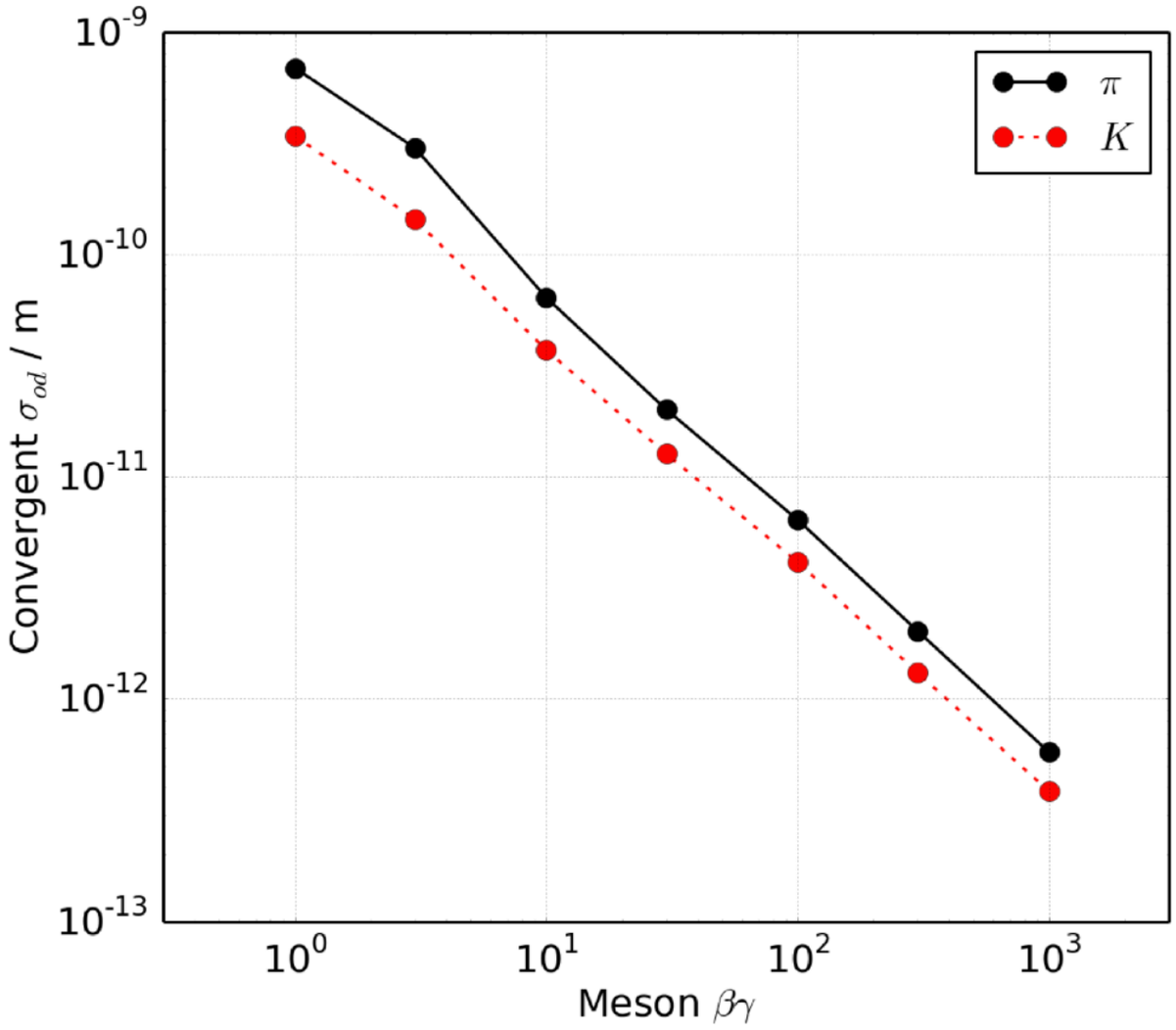
No detail calculation exists for neutrinos produced in reactors or radioactive sources. The following scales seem plausible:

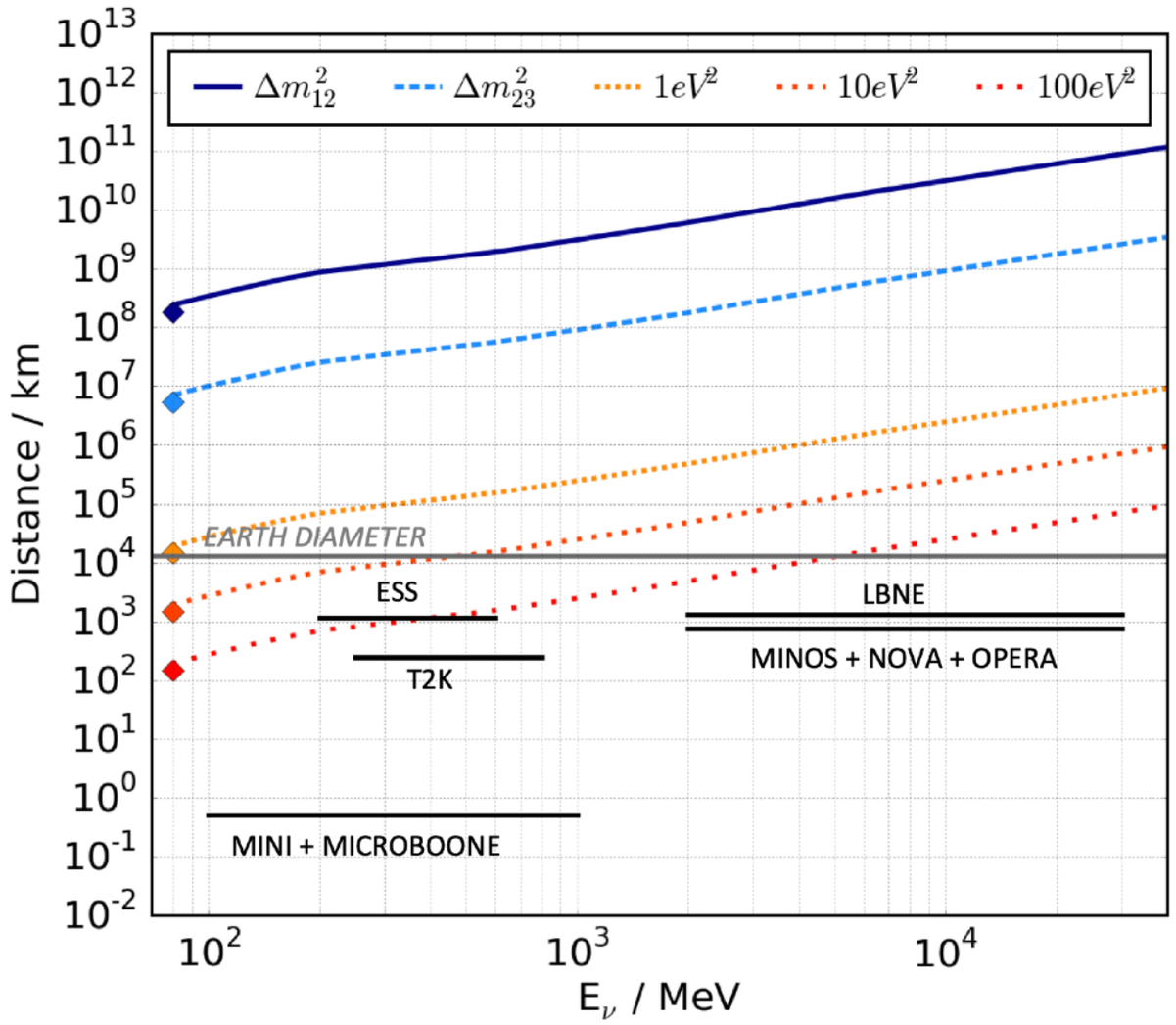
- Typical size of beta-decaying nuclei (10^{-5}nm)
- Interatomic spacing on reactor fuel ($0.1 - 1$nm for uranium)
- Inverse of the neutrino energy (10^{-4}nm)
- Inverse of detector energy resolution

The smaller the scale of the neutrino wave packet the larger the neutrino energy resolution effect.

What is the size of the wave packet?

Depends on production and detection process. This has been computed for pion decay in flight.

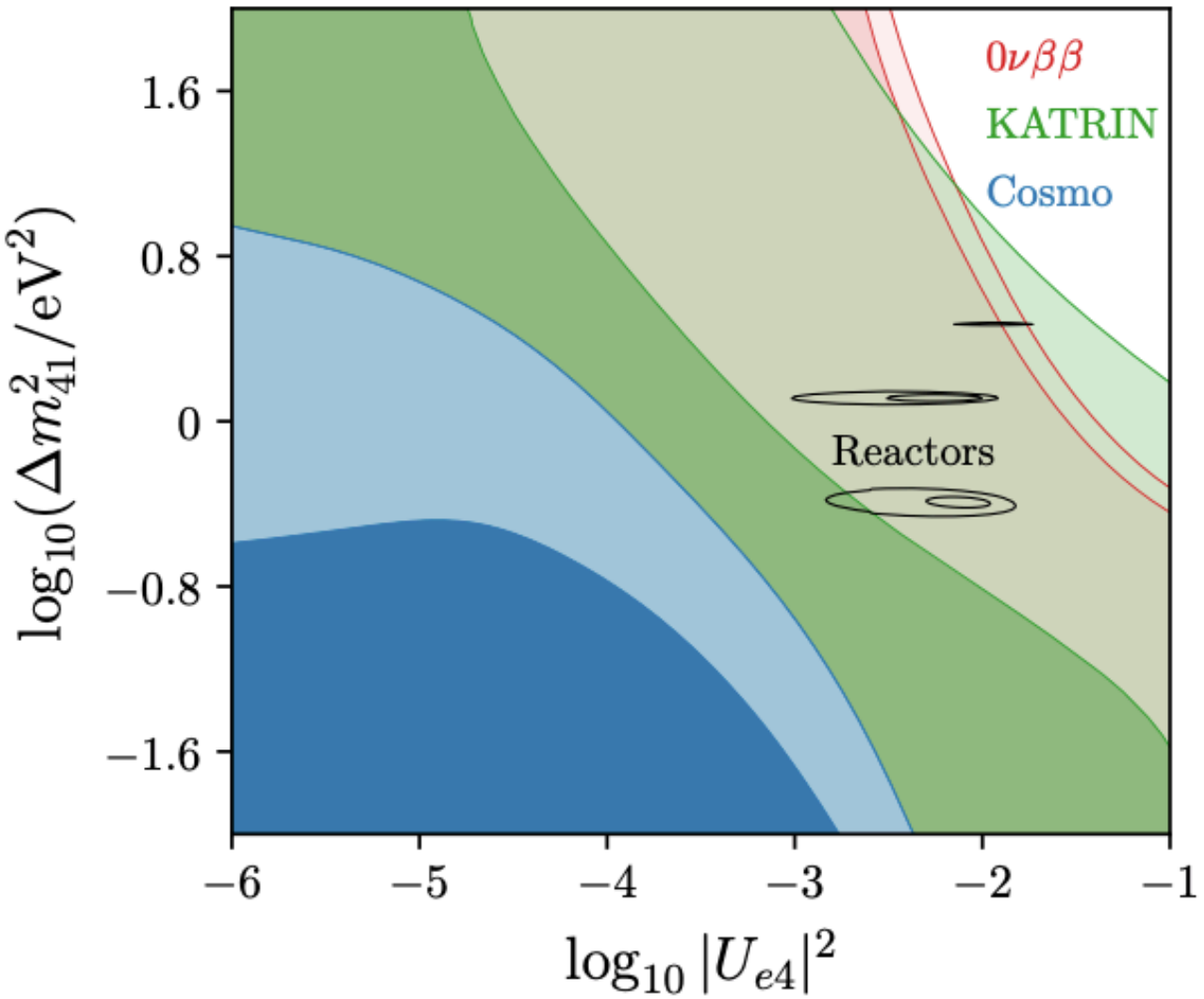




BJP Jones arXiv:1412.2264

Let's not forget cosmology!

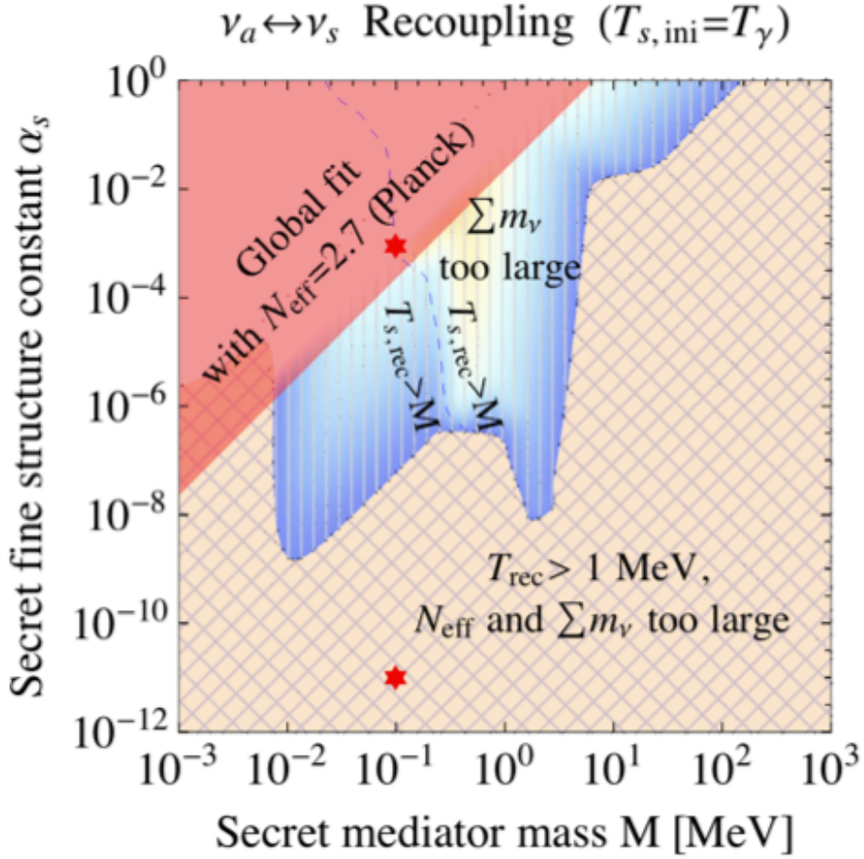
Hagztoz *et al* https://arxiv.org/pdf/2003.02289.pdf



Effective mixing → $\sin^2 2\theta_m = \dfrac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$ ← Vacuum mixing; ← Large

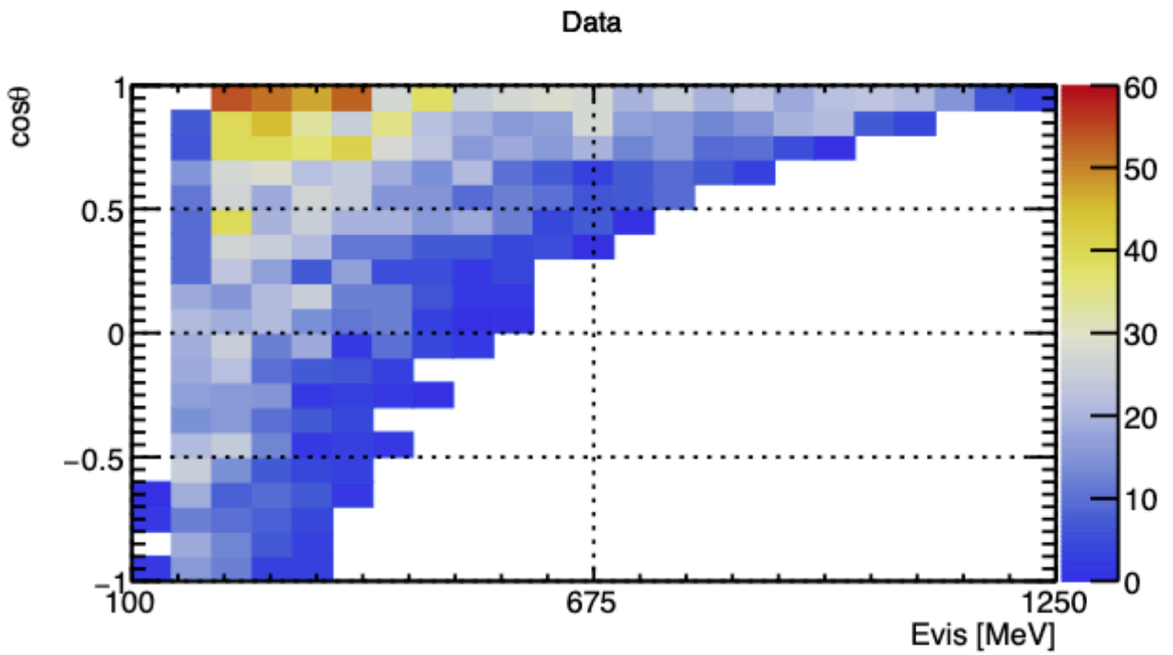
➡ Keeps N_{eff} at 3

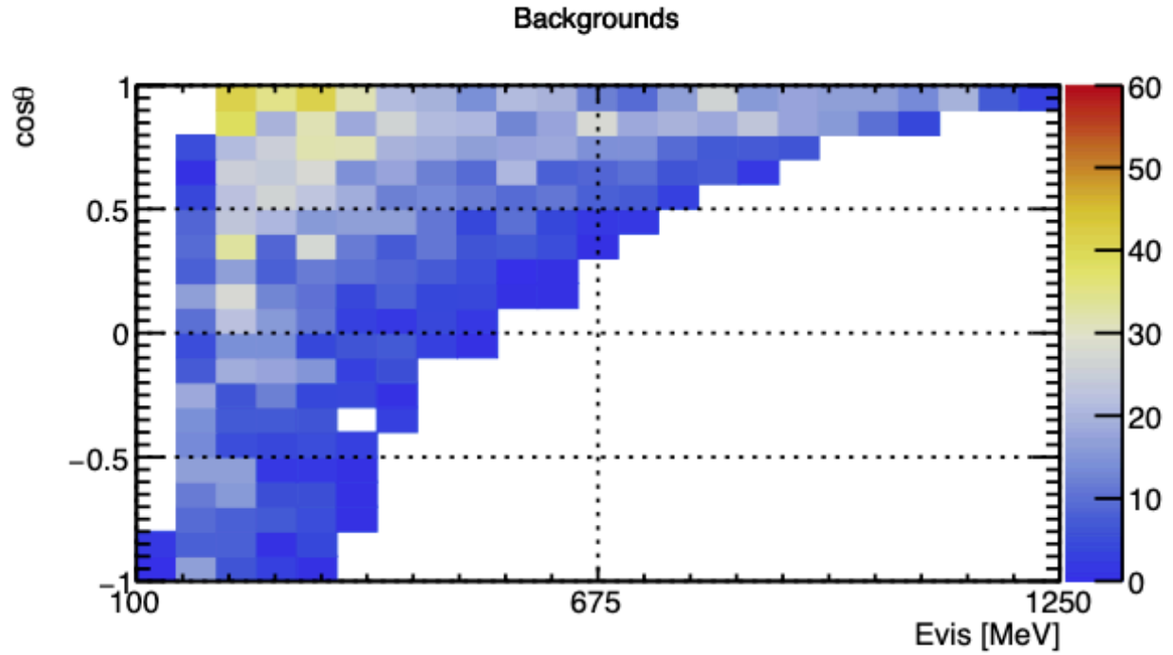
Chu et al. https://arxiv.org/pdf/1806.10629.pdf

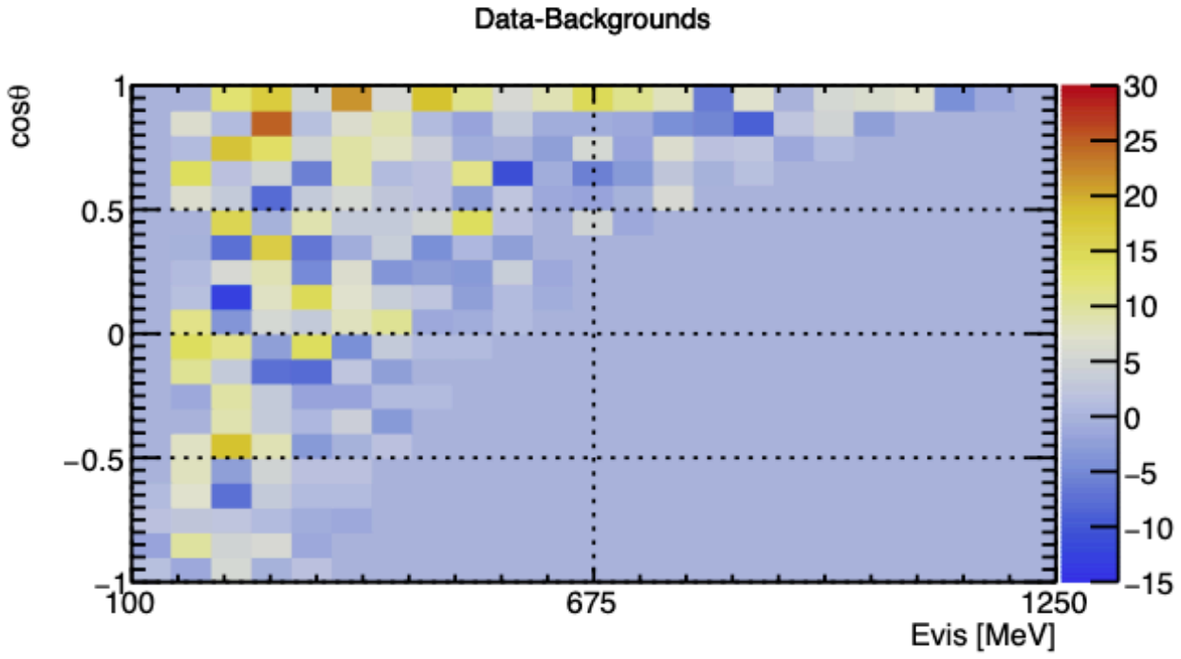


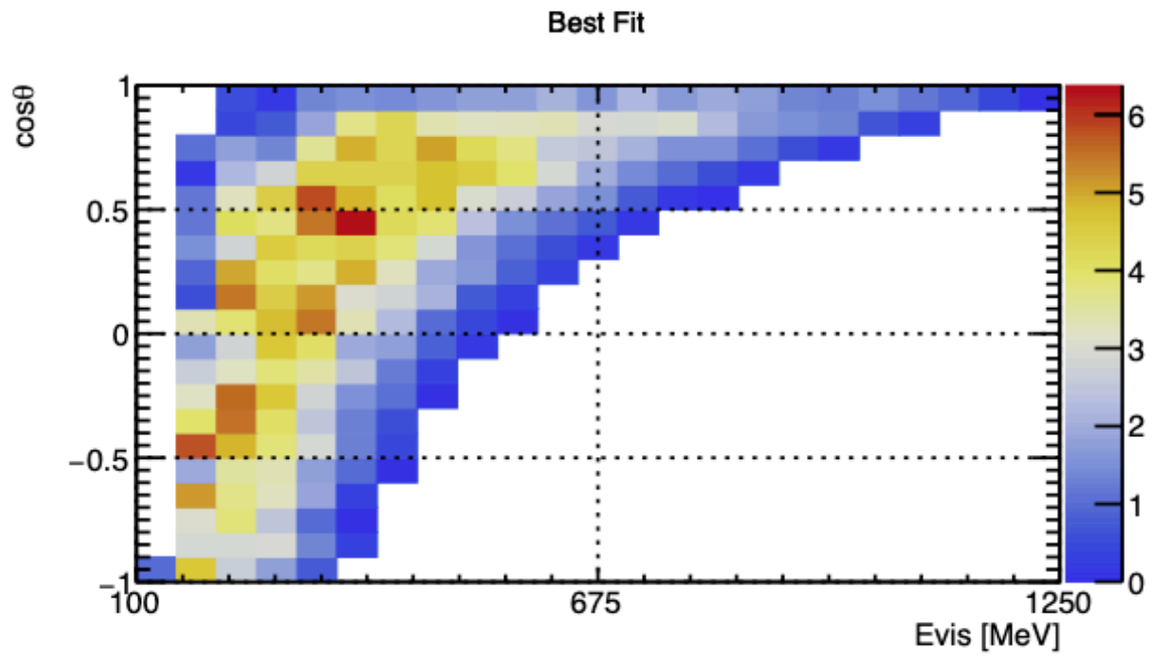
Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015 Saviano et al. 2014; Mirrizi et al. 2015;
Cherry, Friedland & Shoemaker 2016; Chu et al. 2018
See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary

More information & a new perspective!

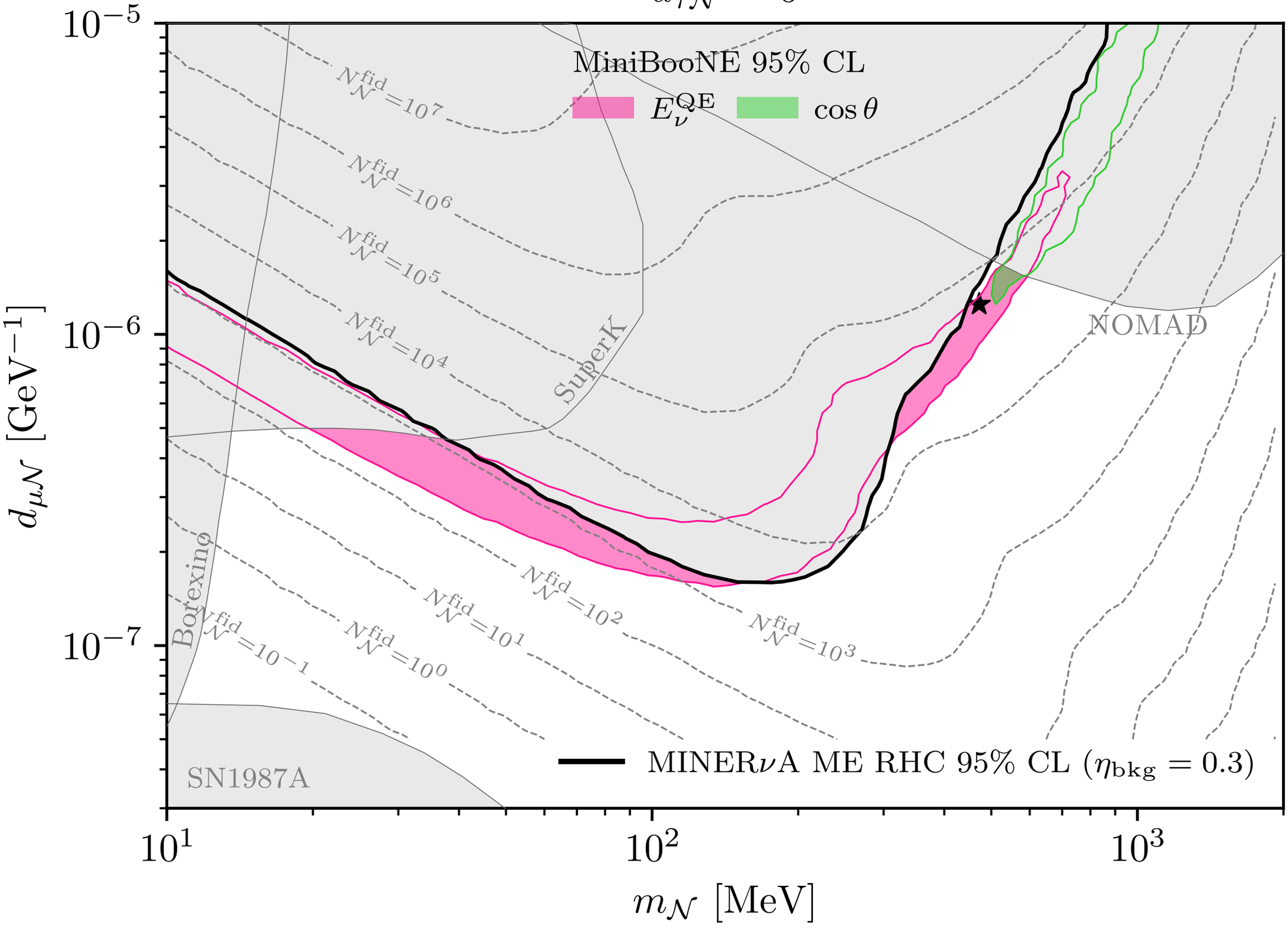


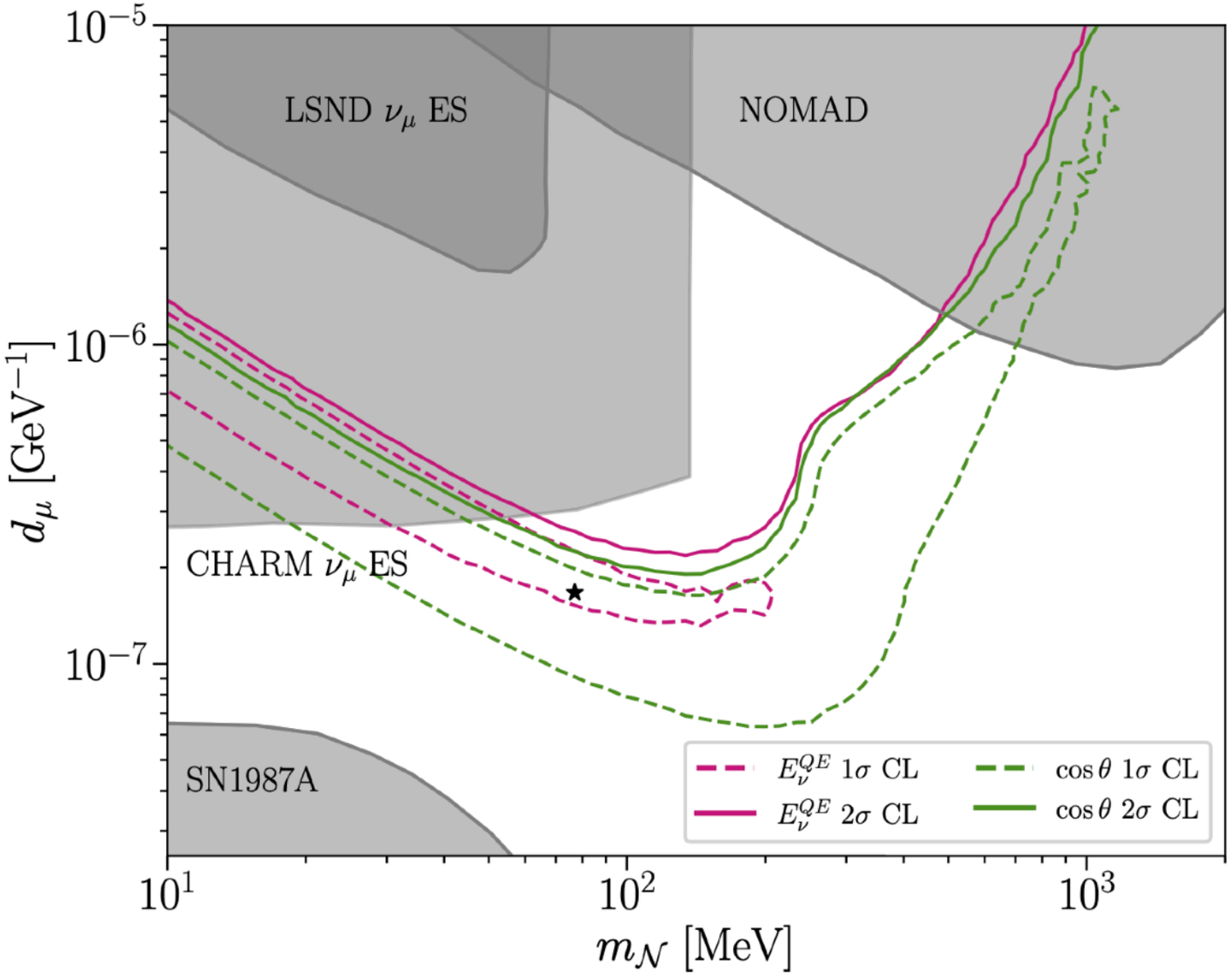


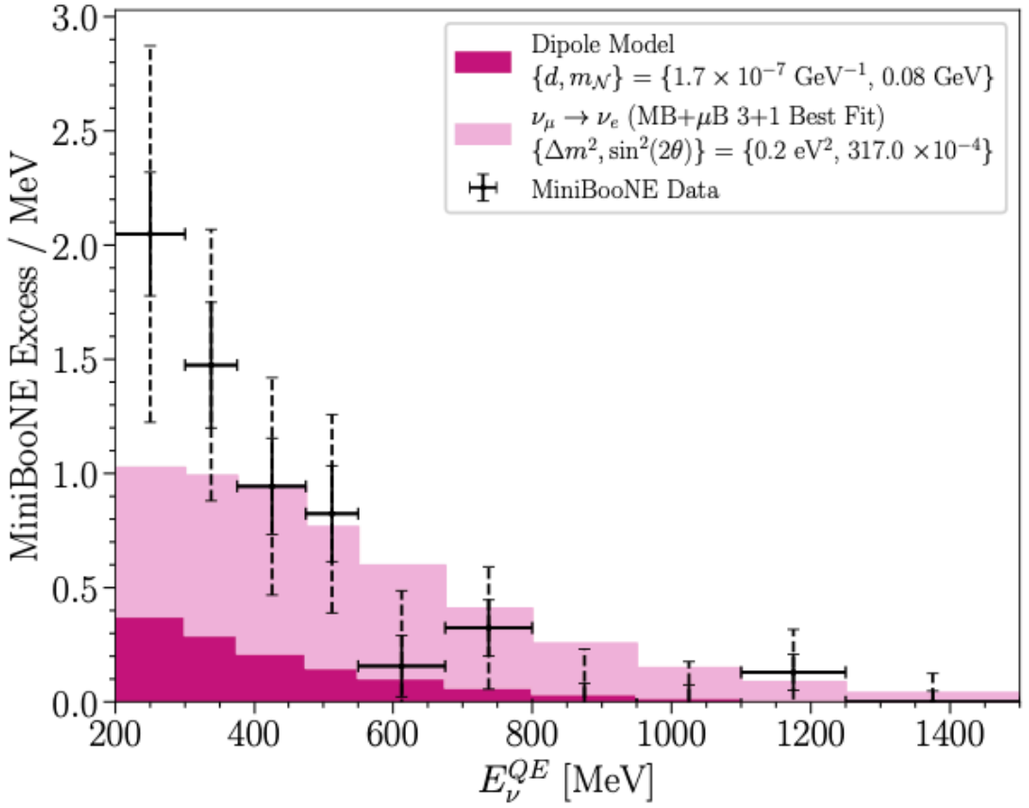


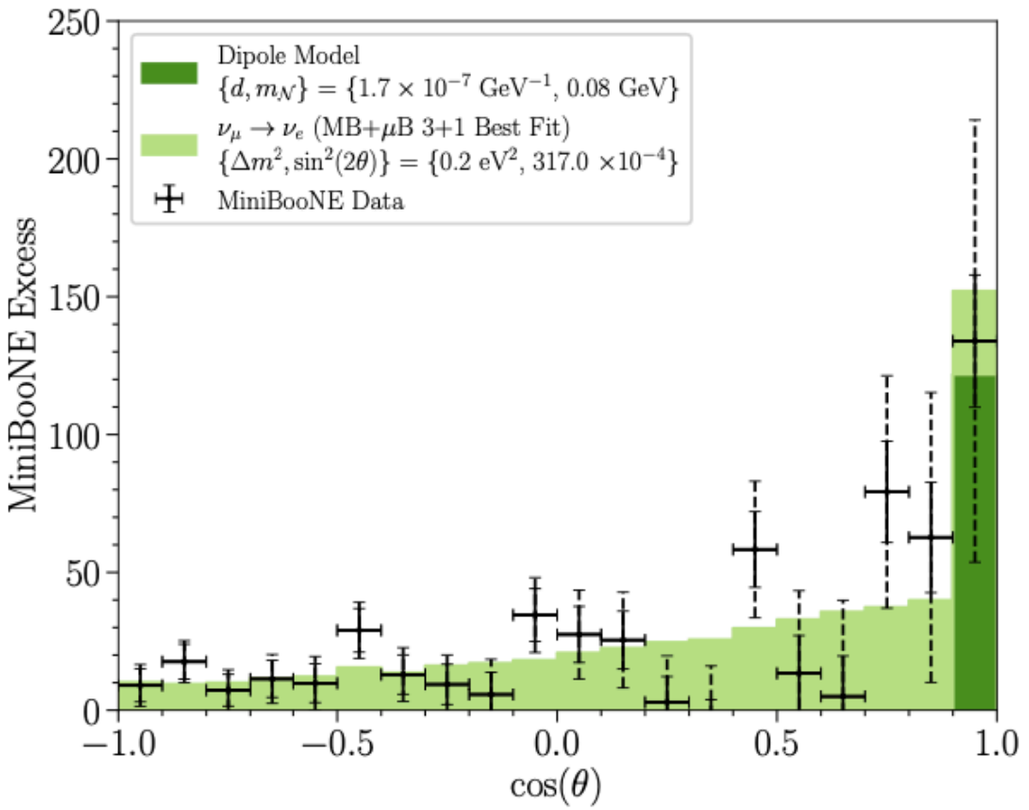


MiniBooNE Collaboration


$d_{\tau\mathcal{N}} = 0$
MiniBooNE 95% CL
$E_\nu^{\rm QE}$
$\cos\theta$
$N_{\mathcal{N}}^{\rm fid}=10^7$
$N_{\mathcal{N}}^{\rm fid}=10^6$
$N_{\mathcal{N}}^{\rm fid}=10^5$
$N_{\mathcal{N}}^{\rm fid}=10^4$
$N_{\mathcal{N}}^{\rm fid}=10^2$
$N_{\mathcal{N}}^{\rm fid}=10^1$
$N_{\mathcal{N}}^{\rm fid}=10^0$
$N_{\mathcal{N}}^{\rm fid}=10^{-1}$
$N_{\mathcal{N}}^{\rm fid}=10^3$
SuperK
NOMAD
Borexino
SN1987A
MINERνA ME RHC 95% CL ($\eta_{\rm bkg} = 0.3$)
10^{-5}
10^{-6}
10^{-7}
$d_{\mu\mathcal{N}}$ [GeV^{-1}]
10^1
10^2
10^3
$m_{\mathcal{N}}$ [MeV]


LSND ν_μ ES
NOMAD
CHARM ν_μ ES
SN1987A
E_ν^{QE} 1σ CL
E_ν^{QE} 2σ CL
$\cos\theta$ 1σ CL
$\cos\theta$ 2σ CL
d_μ [GeV^{-1}]
$m_\mathcal{N}$ [MeV]


Dipole Model
$\{d, m_\mathcal{N}\} = \{1.7 \times 10^{-7}$ GeV^{-1}, 0.08 GeV$\}$
$\nu_\mu \to \nu_e$ (MB+μB 3+1 Best Fit)
$\{\Delta m^2, \sin^2(2\theta)\} = \{0.2$ eV^2, 317.0 $\times 10^{-4}\}$
MiniBooNE Data
MiniBooNE Excess / MeV
E_ν^{QE} [MeV]


Dipole Model
$\{d, m_\mathcal{N}\} = \{1.7 \times 10^{-7}$ GeV^{-1}, 0.08 GeV$\}$
$\nu_\mu \to \nu_e$ (MB+μB 3+1 Best Fit)
$\{\Delta m^2, \sin^2(2\theta)\} = \{0.2$ eV^2, 317.0 $\times 10^{-4}\}$
MiniBooNE Data
MiniBooNE Excess
$\cos(\theta)$