New U(1)' Interactions and the MiniBooNE Low Energy Excess

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NEVIS LABORATORIES
COLUMBIA UNIVERSITY

Contents

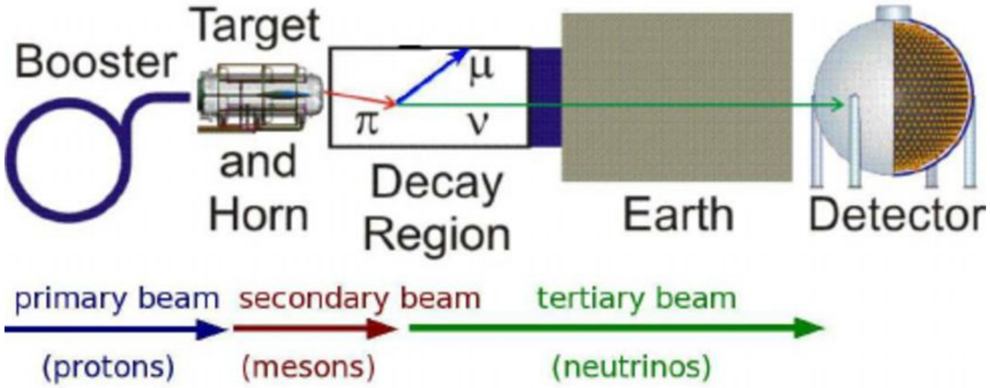
- Quick background on MiniBooNE
- A deep dive into what the Low-Energy Excess (LEE) looked like
- Introduce a U(1)' charged sterile neutrino to the mix
- Expectations at current Short-Baseline LArTPC experiments

Most of this talk is based on (with some updates);
"U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE"
Peter Ballett, Silvia Pascoli, M R-L
hep-ph/1808.02915

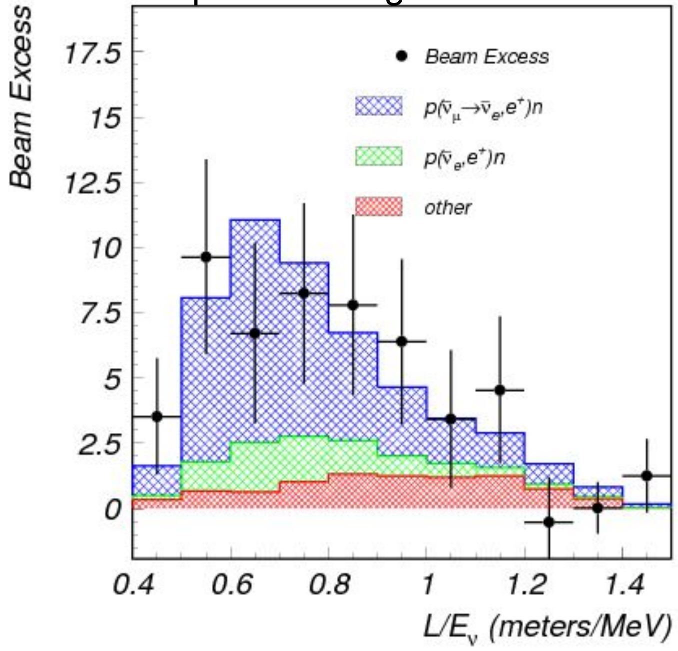
Why was MiniBooNE built?

MiniBooNE was built to prove or disprove the **~1eV² sterile** neutrino oscillation interpretation of the **LSND** experiment.

Sitting inside the Booster Neutrino beam at Fermilab, it probed the same L/E as LSND

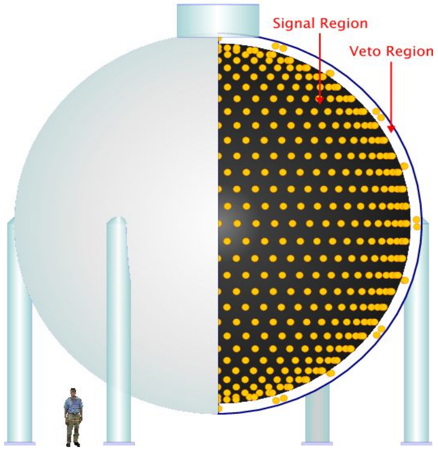


https://arxiv.org/abs/1306.6494



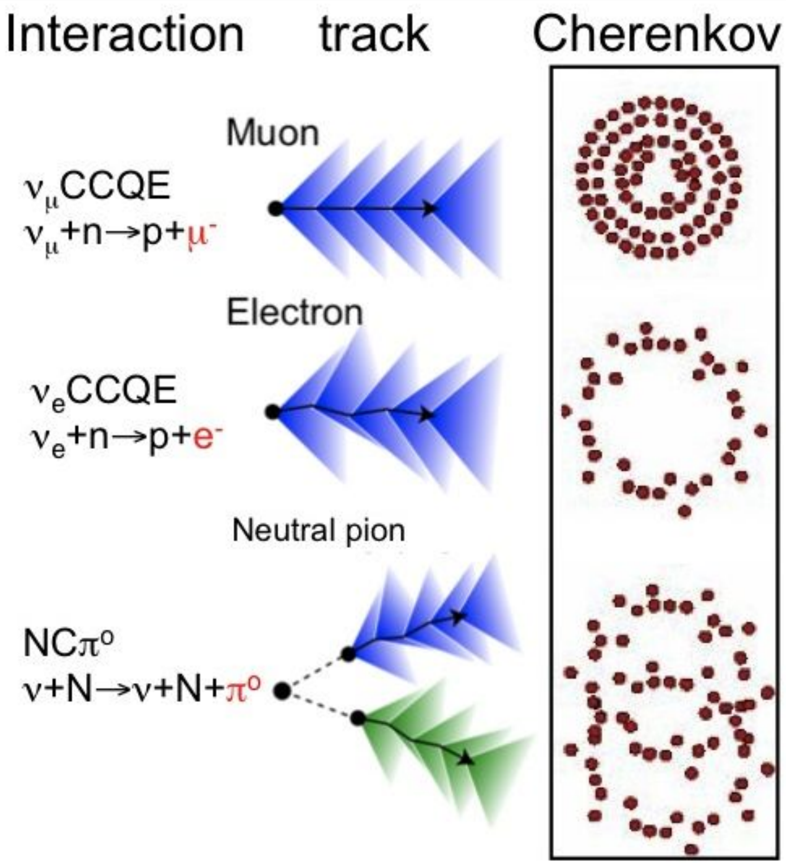
This is the last I will mention 1eV² oscillation in the talk

Mineral Oil Cherenkov Detector



MiniBooNE was a mineral oil Cherenkov detector.

Crucially, this technology could **not distinguish electron** induced cherenkov cones **from photon** induced cherenkov cones**.**



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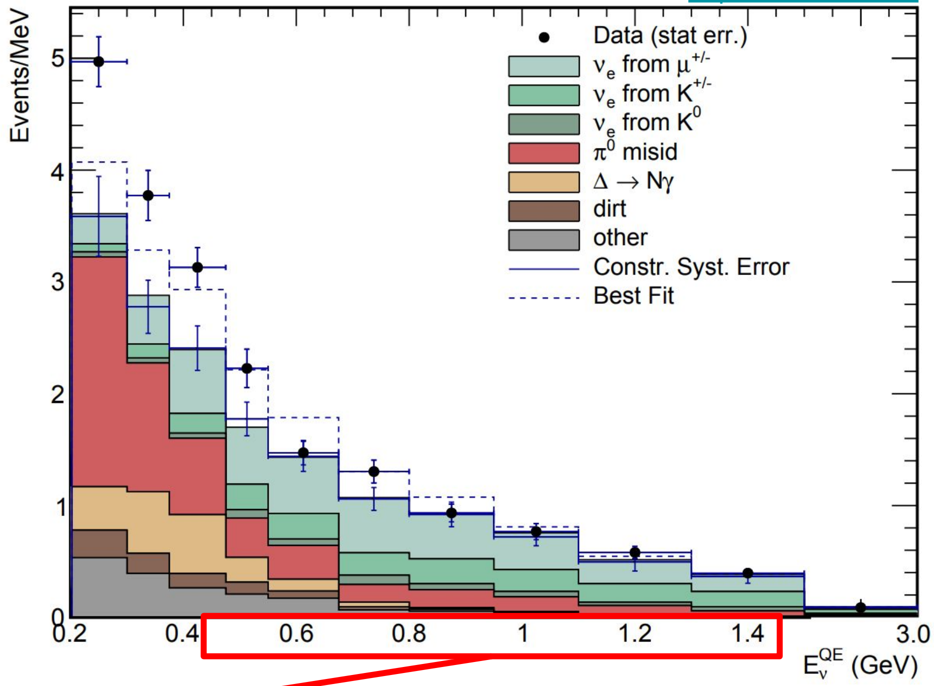
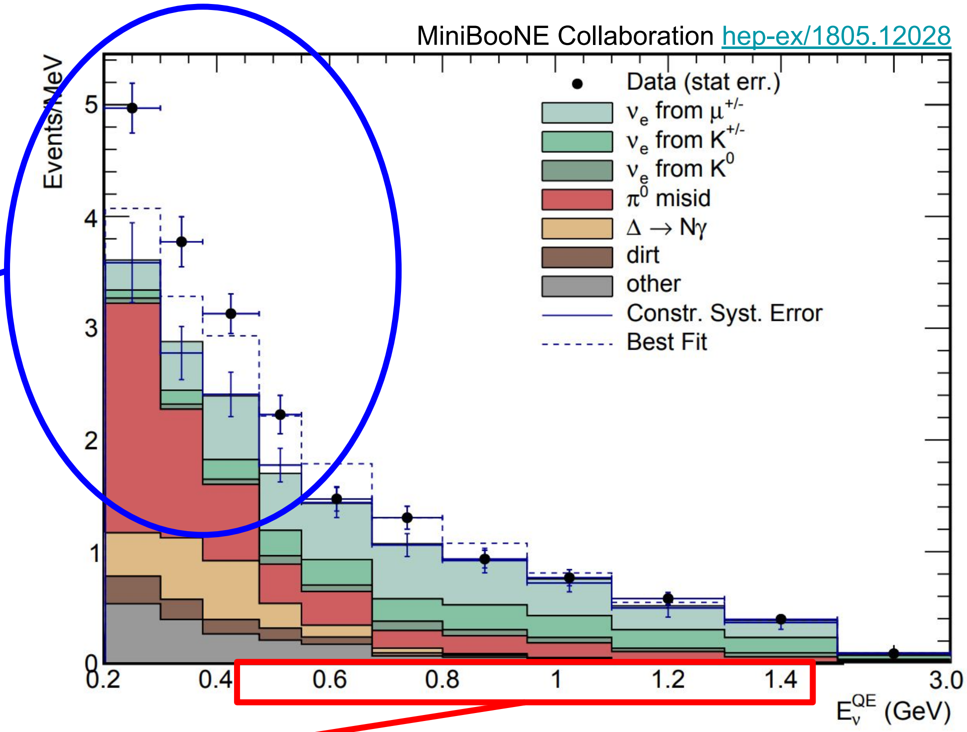
What did MiniBooNE observe?

MiniBooNE Collaboration [hep-ex/1805.12028](hep-ex/1805.12028)



This is the region that the LSND oscillation *should* have appeared

What did MiniBooNE observe?

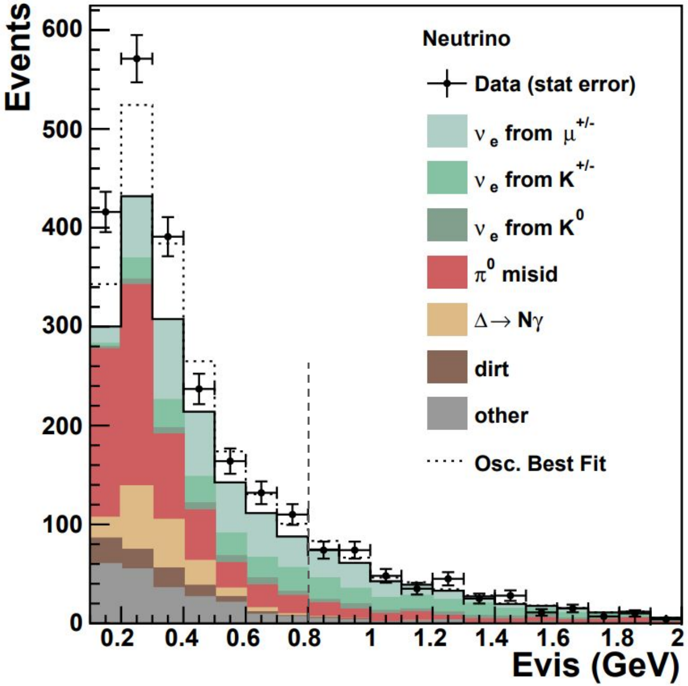


Instead MiniBooNE observed a large excess in the much **lower energy region** (hence the name LEE)

This is the region that the LSND oscillation *should* have appeared

The LEE is...

MiniBooNE Collaboration [hep-ex/1805.12028](hep-ex/1805.12028)

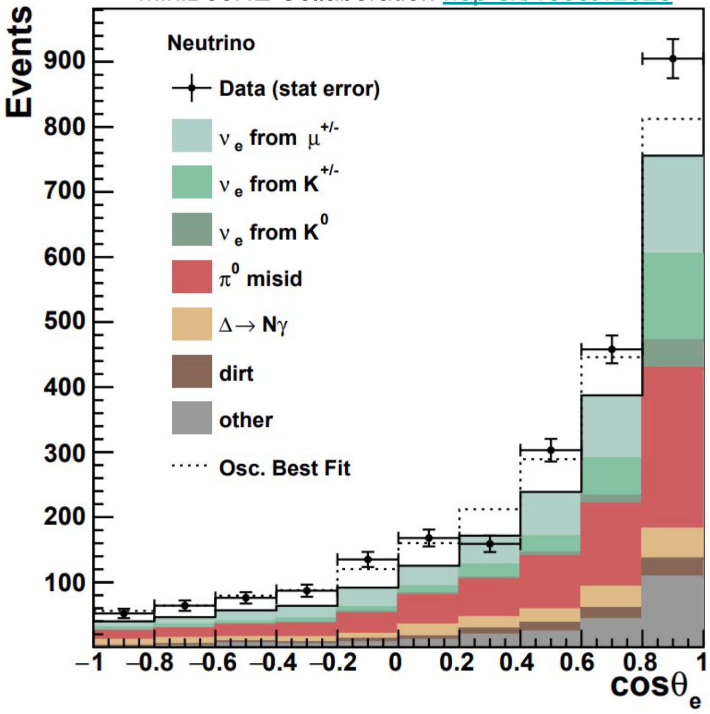


- **Contained below 800 MeV Visible energy. Majority below 400 MeV**

Note! The drop in the first bin relative to the second is an artifact of binning. An E_{vis} > 140 MeV cut had already been applied despite the fact that binning goes from 100-200 MeV

The LEE is...

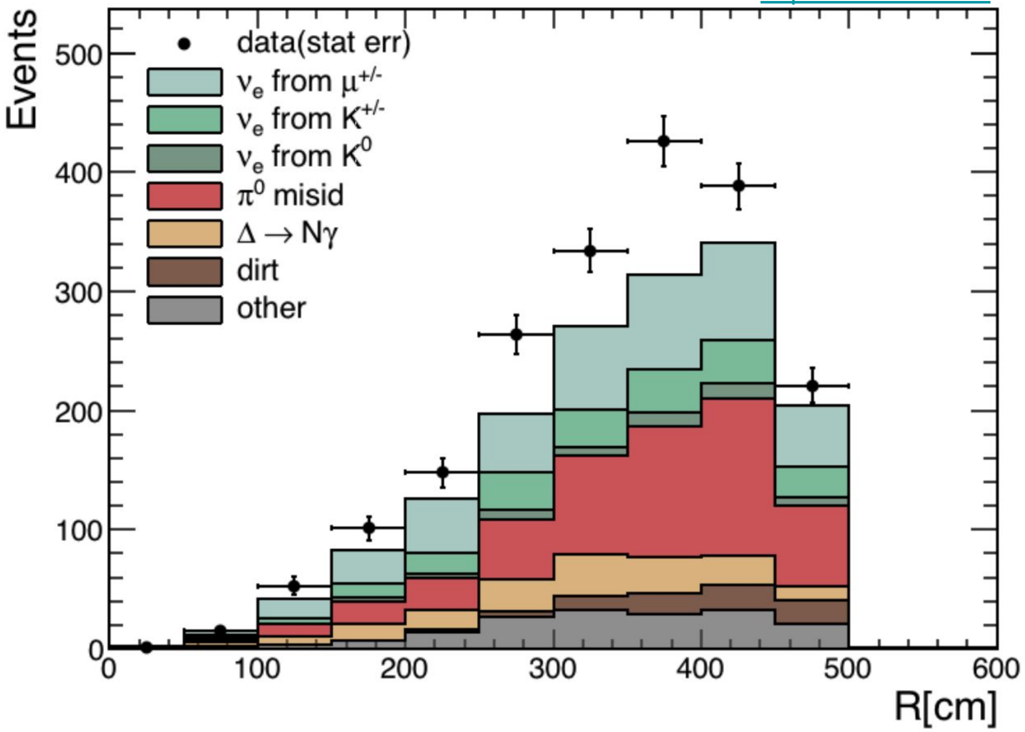
MiniBooNE Collaboration hep-ex/1805.12028



- Contained below 800 MeV Visible energy. Majority below 400 MeV
- **Not fully isotropic, but only a slight preference to forward pointing.**

The LEE is...

MiniBooNE Collaboration hep-ex/1805.12028



- Contained below 800 MeV Visible energy. Majority below 400 MeV
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- **Uniform in space (evenly distributed)**

The LEE is...

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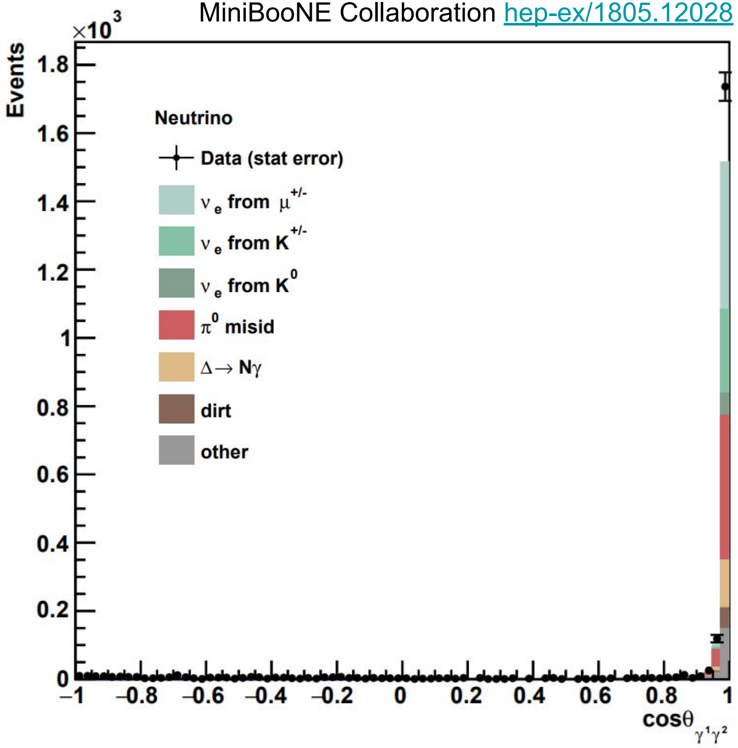

- Contained below 800 MeV Visible energy. Majority below 400 MeV
- Not fully isotropic, but only a slight preference to forward pointing.
- Uniform in space (evenly distributed)
- **If fit to two rings, opening angle between them < 10°**

The LEE is...

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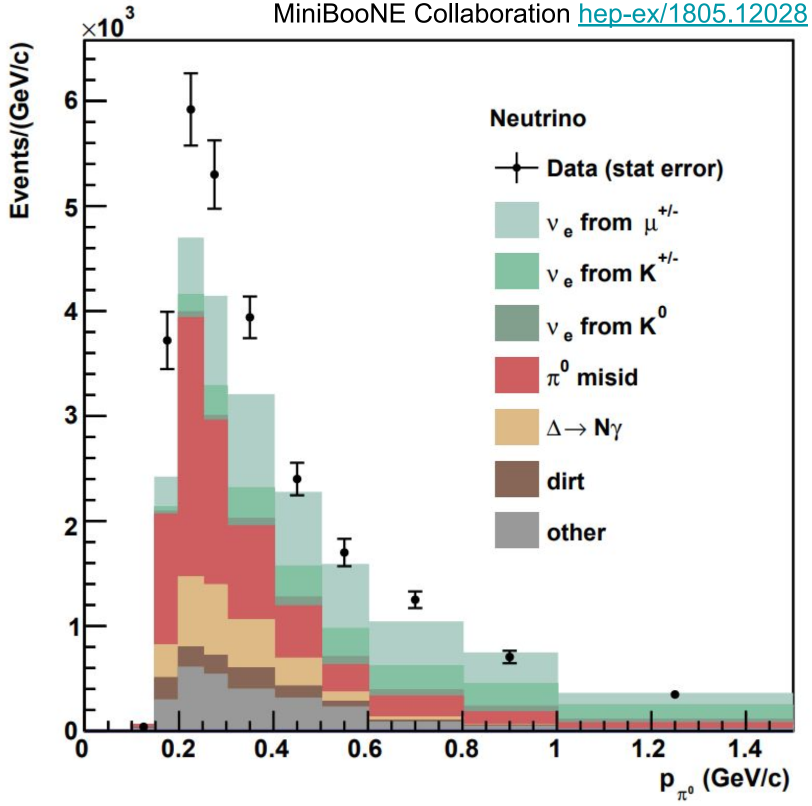


- Contained below 800 MeV Visible energy. Majority below 400 MeV
- Not fully isotropic, but only a slight preference to forward pointing.
- Uniform in space (evenly distributed)
- If fit to two rings, opening angle between them < 10°
- **If fit to two rings, the reconstructed π^0 tends to have low momentum**

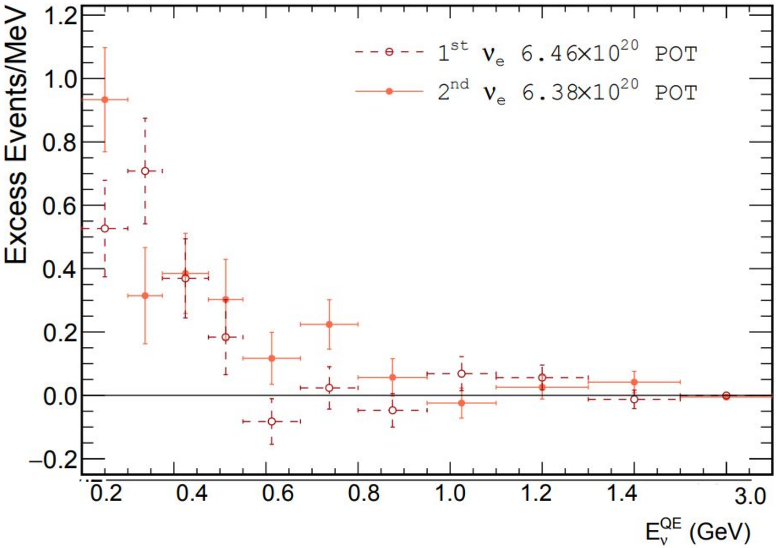
A note on the new MiniBooNE dataset

As of this summer MiniBooNE published an updated analysis containing twice the statistics

Impressively *"The neutrino mode event rate of 100 events per 10^{17} POT has been* ***stable*** *to* ***< 2% over the 15 year running period****."*

However, it must be mentioned that although the statistics were doubled, **no new Monte Carlo** or **improvements to the analysis were performed**.

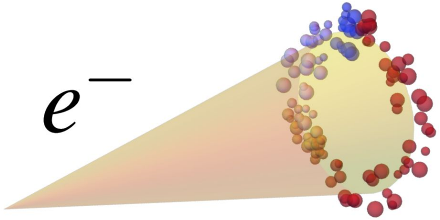
Everything you see in this talk will reference the combined new+old 12.84×10^{20} POT dataset.



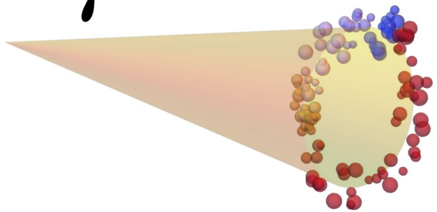
See: hep-ph/1805.12028 "Significant Excess of Electron like Events in the MiniBooNE Short-Baseline Neutrino Experiment" for more details.

What is the particle content of the LEE?

e^-

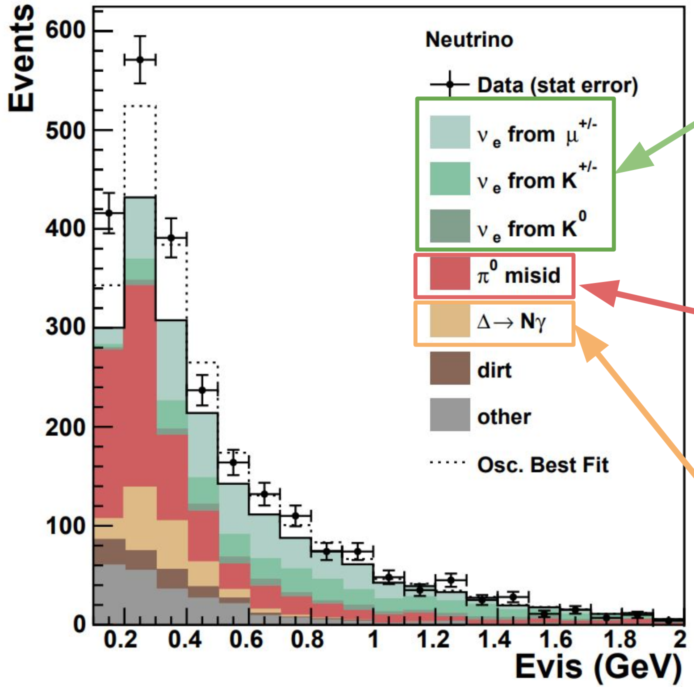


γ



Possible Explanations: Motivated by backgrounds

MiniBooNE Collaboration hep-ex/1805.12028



Intrinsic ν_e in the beam? Constrained by measuring ν_μ which come from the same π decay as the μ's that subsequently produce the ν_e.

π^0 misidentification? In which the second shower was missed or incorrectly reconstructed. MiniBooNE measured the largest sample of NC π^0 events ever collected and used this is constrain the exact rate of π^0's for the CCQE analysis.

Radiative Δ decay? This has never been observed in the neutrino sector. MiniBooNE bound it using their NC π^0 measurements which agrees well with best theoretical calculations. The biggest channel of interest to MicroBooNE's photon LEE analysis.

What is the particle content of the LEE?

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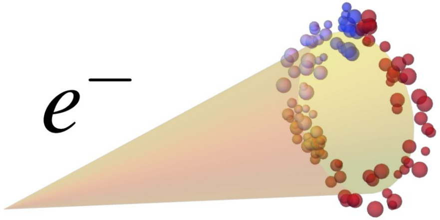
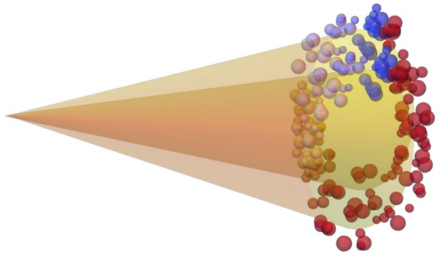


Overlapping e^+e^-



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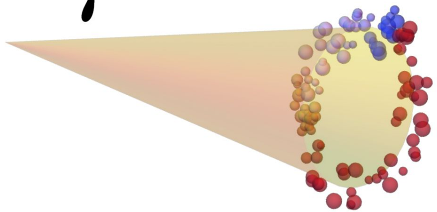
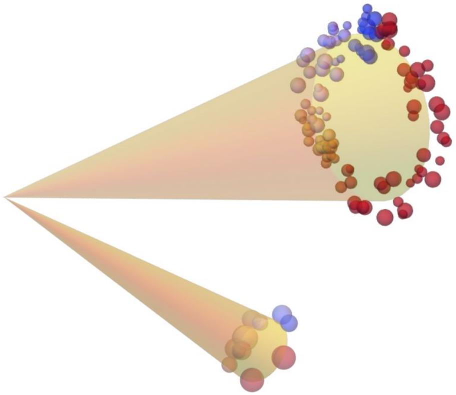


Highly Asymmetric e^+e^-



Quantify Overlapping and Asymmetric?

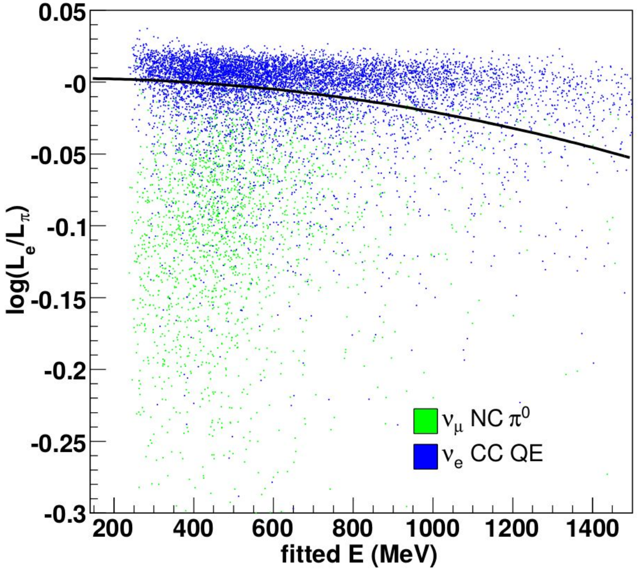
Two immediate questions....

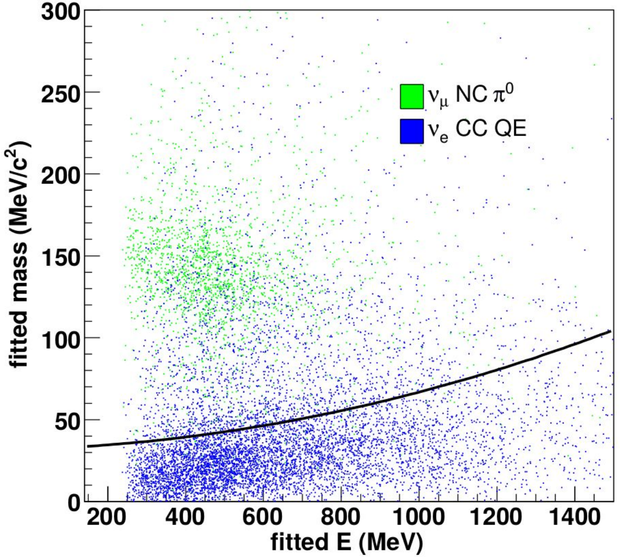
- How **low-energy** does the subleading electron have to be in an e^+e^- pair in order for an "**Asymmetric**" pair to look like a single ring?
- How **small an opening angle** does the e^+e^- pair have to have before it is "**Overlapping**" sufficiently to look like a single ring?

MiniBooNE has an advanced optical model to simulate exactly how particles looked in their detector [0806.4201] which complicated things..

Every event was fit under **both the single ring hypothesis (electron-like) and the two-ring hypothesis (π^0-like)** and used to build

MiniBooNE's CCQE analysis cuts





"Distinguish **one** fuzzy ring from **two** fuzzy rings"

"Force a fit to two rings and see if it looks π-like"

- These require detailed knowledge of the optical modeling that MiniBooNE utilized. **Exceptionally hard to approximate these with "simple" cuts…** but we will try anyway!

Quantify Overlapping and Asymmetric?

Our approximations:

- How **low-energy** does the subleading electron have to be in an e^+e^- pair in order for an "**Asymmetric**" pair to look like a single ring? $E_{True} < 30$ MeV
- How **small an opening angle** does the e^+e^- pair have to have before it is "**Overlapping**" sufficiently to look like a single ring? $\theta_{SEP} < 5^o$
- When forcing a two-ring fit to an event, the associated invariant mass should be sufficiently **non-π^0 like**: $m_{\gamma\gamma} < 80$ MeV

Are these a perfect approximation of the MiniBooNE Optical modelling and likelihood analysis? No of course not, but the final answer is relatively insensitive to the specifics.

Model Building

By now I hope I've convinced you that **sufficiently overlapping** or **asymmetric e^+e^- pairs** would potentially **mimic the MiniBooNE LEE events**, but I've not introduced a model in which such a scenario could happen..

U(1)' mediated sterile neutrino decays

We assume that the SM gauge group is extended by a new factor U(1)' which kinetically mixes with SM hypercharge with a mixing parameter **χ**.

$$\mathcal{L} = \mathcal{L}_{\nu\mathrm{SM}} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu} + \frac{\mu^2}{2}X_\mu X^\mu$$

With $\mathbf{B_\mu}$ and $\mathbf{X_\mu}$ denoting the $U(1)^Y$ and U(1)' gauge fields, respectively. At leading order in **χ** and in zeroth order in **μ/v** we can highlight the fields in the physical mass basis as:

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} c_\mathrm{W} & s_\mathrm{W} & c_\mathrm{W}\chi \\ -s_\mathrm{W} & c_\mathrm{W} & 0 \\ s_\mathrm{W}^2\chi & -s_\mathrm{W}c_\mathrm{W}\chi & 1 \end{pmatrix} \begin{pmatrix} B \\ W^3 \\ X \end{pmatrix}$$

Where A is the SM photon whose mass vanishes as usual, Z is the standard model Z and **Z'** is a **new "dark" gauge boson** with mass approx **μ**.

We assume that no SM particles hold a charge under this new U(1)' gauge symmetry.

Add a single sterile neutrino

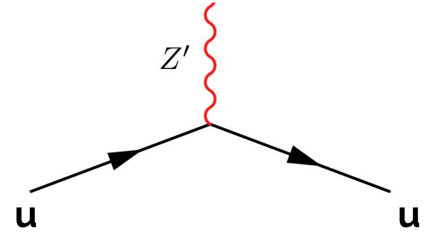
- We now introduce a new **SM-gauge singlets** which ***is*** charged under the new U(1)' , which naturally is **allowed to mix** with the **SM active** neutrinos.

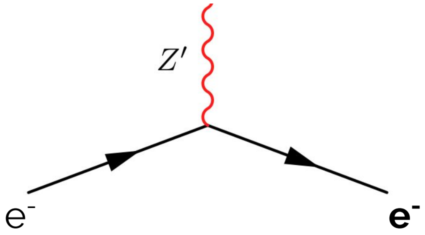
- Despite the fact no SM particles is charged under this new U(1)' gauge symmetry, post electroweak symmetry breaking and due to the **kinetic mixing** of the X and B bosons, **all SM particles pick up a small "effective" U(1)' charge**.

- This combination of gauge kinetic mixing and sterile-active neutrino mixing generates an interesting phenomenology at short baselines that can give rise of an LEE signature

Interaction Lagrangian:

$$\mathcal{L} \supset -eq_f c_{\mathrm{W}} \chi \overline{f} \gamma^\mu f Z'_\mu$$



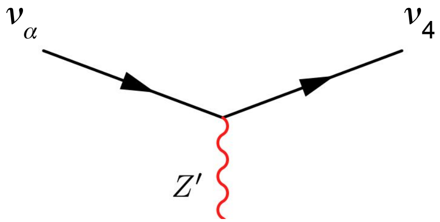


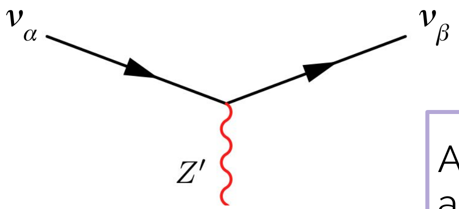
Gauge kinetic mixing

Interactions of Z' with charged fermions are purely vectorial

Active-Sterile mixing

$$U^*_{\alpha 4} g' \overline{\nu_\alpha} \gamma^\mu P_{\mathrm{L}} \nu_4 Z'_\mu \qquad + U^*_{\alpha 4} U_{\beta 4} g' \overline{\nu_\alpha} \gamma^\mu P_{\mathrm{L}} \nu_\beta Z'_\mu$$

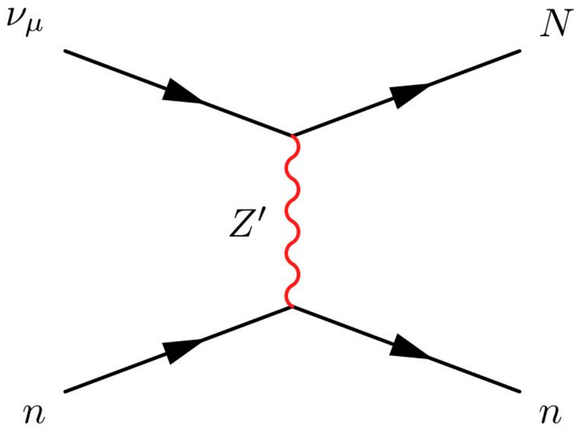




Active-Active vertices are doubly oppressed

Generating the LEE signal

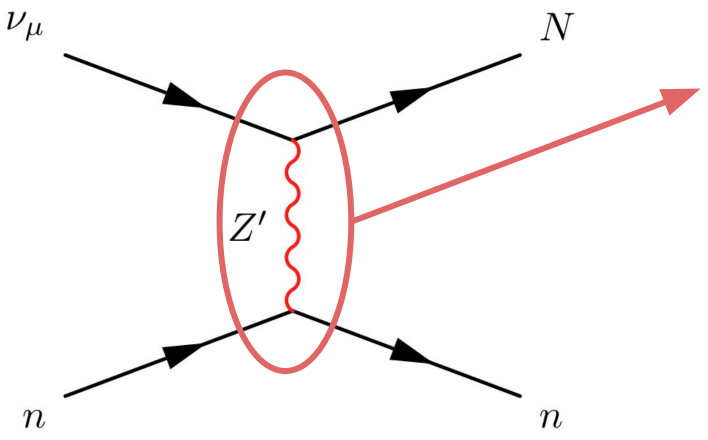
A muon-neutrino from
Booster Neutrino Beam..



Producing a heavy sterile
neutrino *in-situ* inside the
MiniBooNE detector

...Strikes a nucleon in the
MiniBooNE Mineral Oil

Generating the LEE signal



$$\propto |U_{\mu 4}|^2 \chi^2 \left(\frac{M_Z}{M_{Z'}} \right)^4$$

= ~ 0.01 x times the NC rate in MiniBooNE

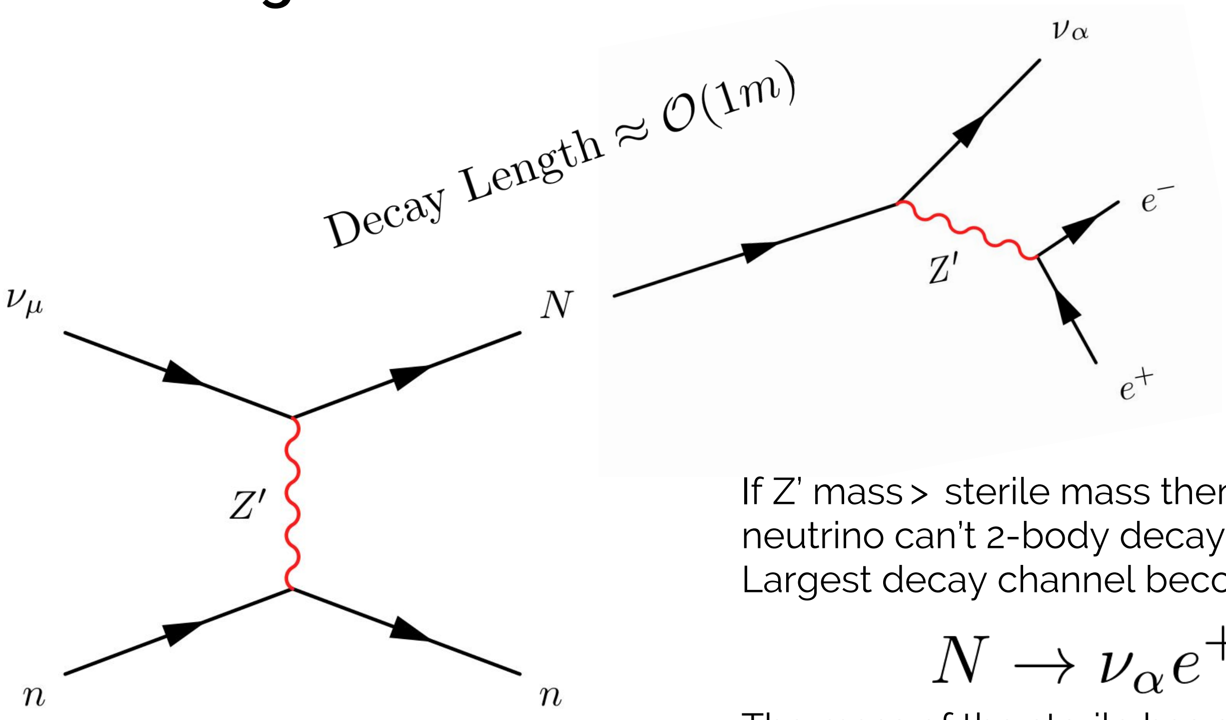
Smaller $M_{Z'}$ means:

- Larger cross-section
- Small momentum transfer (Q^2) thus very forward going sterile neutrinos

Larger $M_{Z'}$ means:

- Smaller cross-section
- Larger Q^2 and a **more isotropic distribution of sterile neutrinos**

Generating the LEE signal

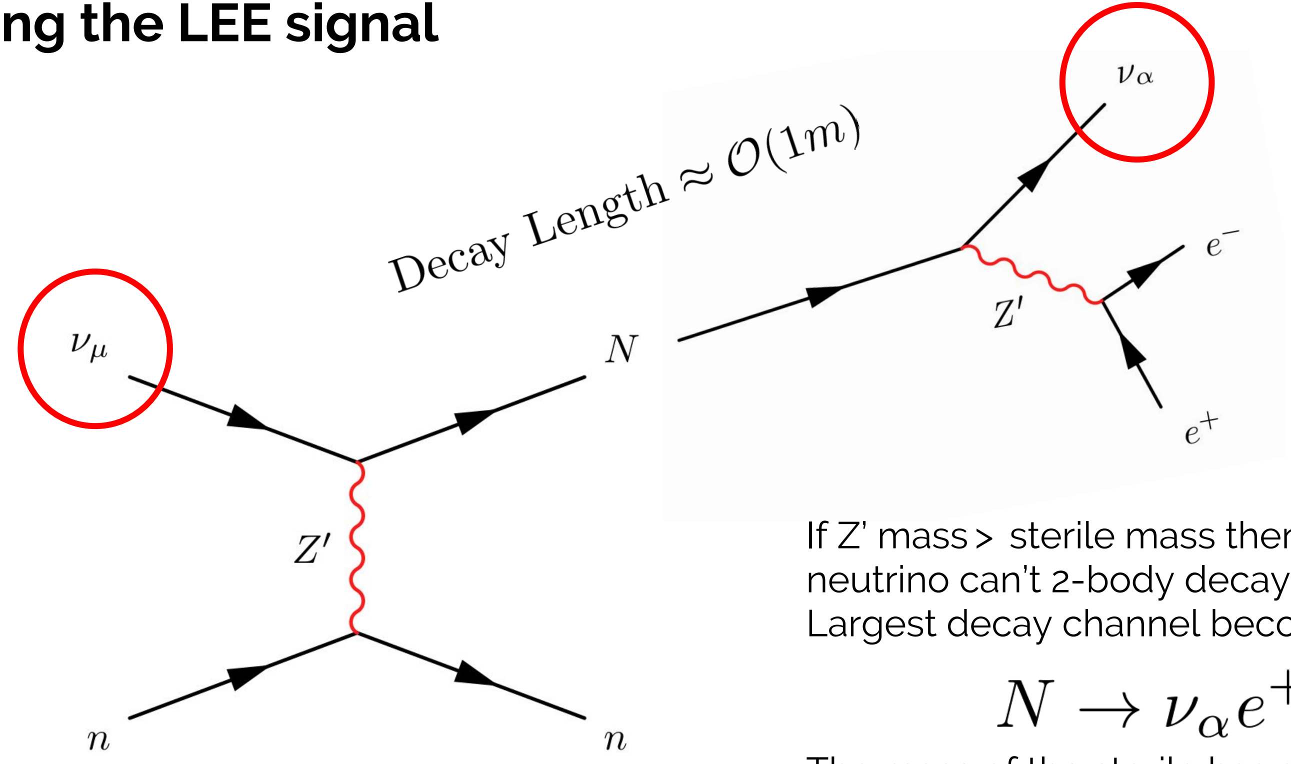


If Z' mass > sterile mass then the sterile neutrino can't 2-body decay to an on shell Z'. Largest decay channel becomes:

$$N \to \nu_\alpha e^+ e^-$$

The mass of the sterile has a large impact on the overall visible energy spectrum. Need sufficiently small mass to account for the "Low" aspect of the low-energy excess

Generating the LEE signal



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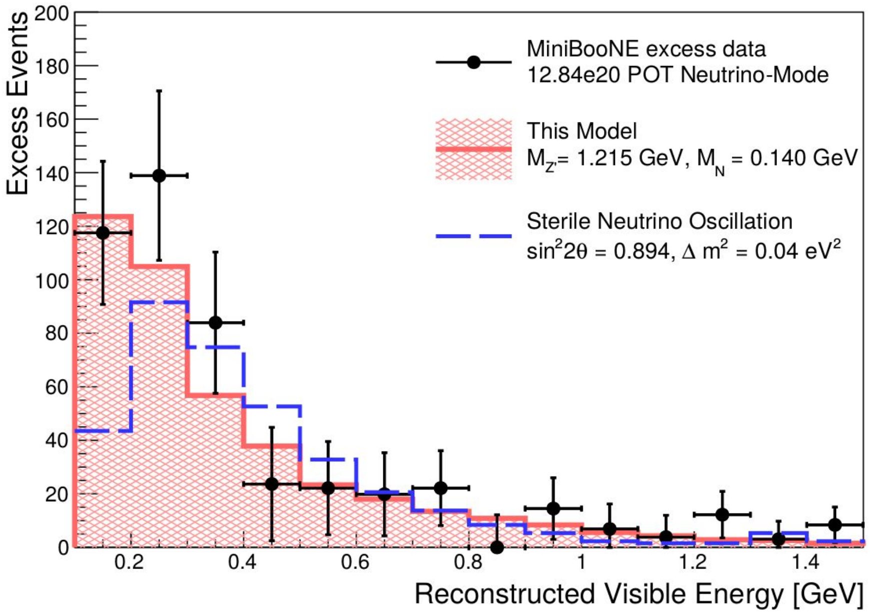
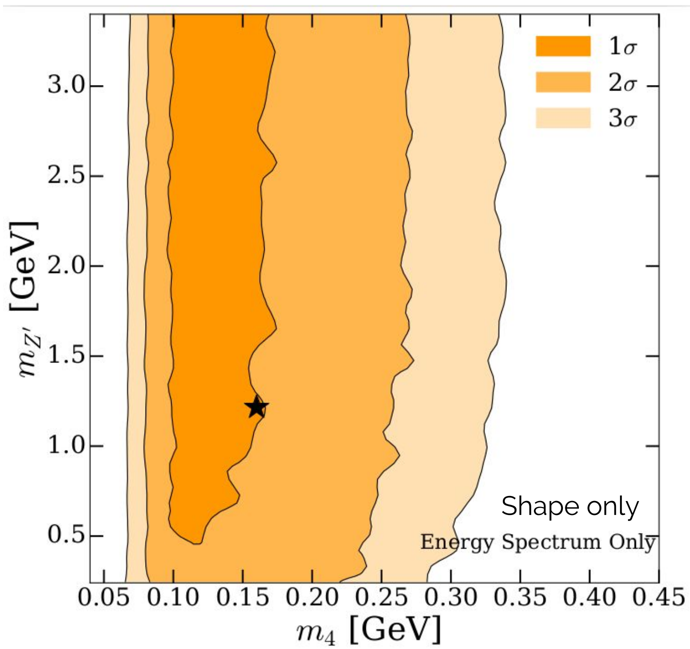
Results: Visible Energy Spectrum

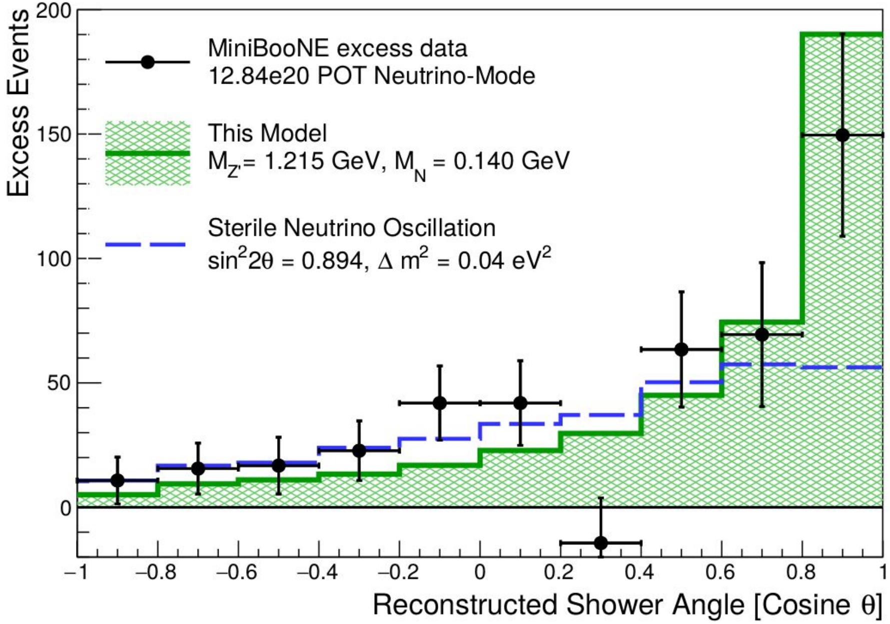


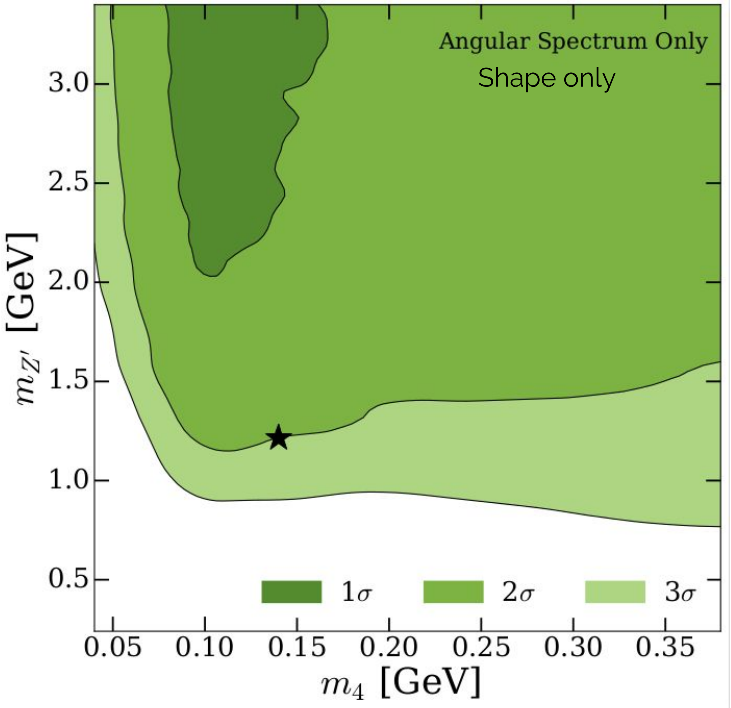


Excellent spectral agreement!
Generally insensitive to mass of the Z'.

- Too **large** a Sterile mass too many events at **high reconstructed energy**.
- Too **small** a sterile mass most events fall into **lowest bin only**

Results: Angular Spectrum





- Too **small** a Z' mass □ spectrum becomes **increasingly forward and non-isotropic**
- However, rate of scattering decreases as Z' mass grows too.

Concrete example

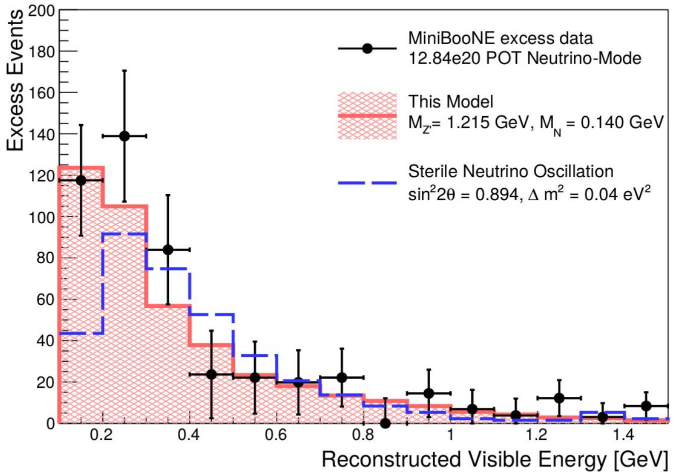
For this **minimal realization** we find that we can explain the MiniBooNE LEE with neutrino mixing angles of $|U_{\mu 4}|^2$ **= 1.5x10^{-6}** and $|U_{\tau 4}|^2$ **= 7.8x10^{-4}** , a kinetic mixing strength of χ^2 **= 5x10^{-6}**.

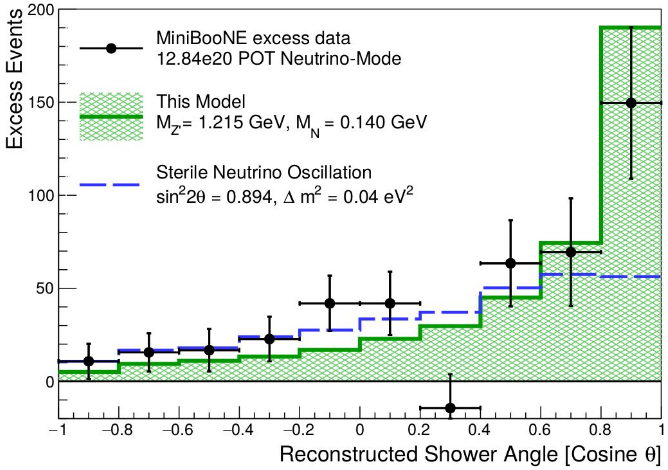
In this case, the hierarchy in mixing angles leads to a dominant visible decay of $N \to \nu_\tau e^+ e^-$ with a total decay length of O(1m)

If one extends the dark sector with additional sterile states one can trivially have the dominant visible decay modes being:

$$N \to \nu_5 e^+ e^-$$

Skirting the need for larger $U_{\tau 4}$ mixings





Bounds on Active-Sterile mixing, $U_{\alpha 4}$

- Bounds from beam dump style experiments on $U_{\mu 4}$ from **PS191** and **NuTeV** as well as $U_{\tau 4}$ from **NOMAD** and **CHARM** are exponentially weakened as the decay length of such a heavy sterile state is **O(1-10m)** meaning the flux of heavy steriles decay away before reaching the detectors.

- Bounds on mixing from **kinematic peak searches** at the end points of **meson decays** (e.g $\pi \to \mu\nu_\mu$) remain equally valid and provide the strongest bounds on the active-sterile mixing in the regime of interest and are satisfied by our model.

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Bounds on U(1)' kinetic mixing, χ

- Any experiment which looked for the visible decays of on-shell Z' particles must be reconsidered taking into account the invisible decays of the new boson which dominate and lead to a visible branching fraction which is **suppressed by a factor of χ**. e.g BABAR, KLOE, A1/MAMI.

- Bounds due to EW precision measurements of the SM Z-boson still apply but are well below the region of interest.

What fraction of heavy sterile decays are Asymmetric/Overlapping?

We have studied this via a dedicated Monte Carlo simulation of decay events, confirming that the percentage of e^+e^- decays in our model which are classified as asymmetric or overlapping events is mostly insensitive to the Z' mass

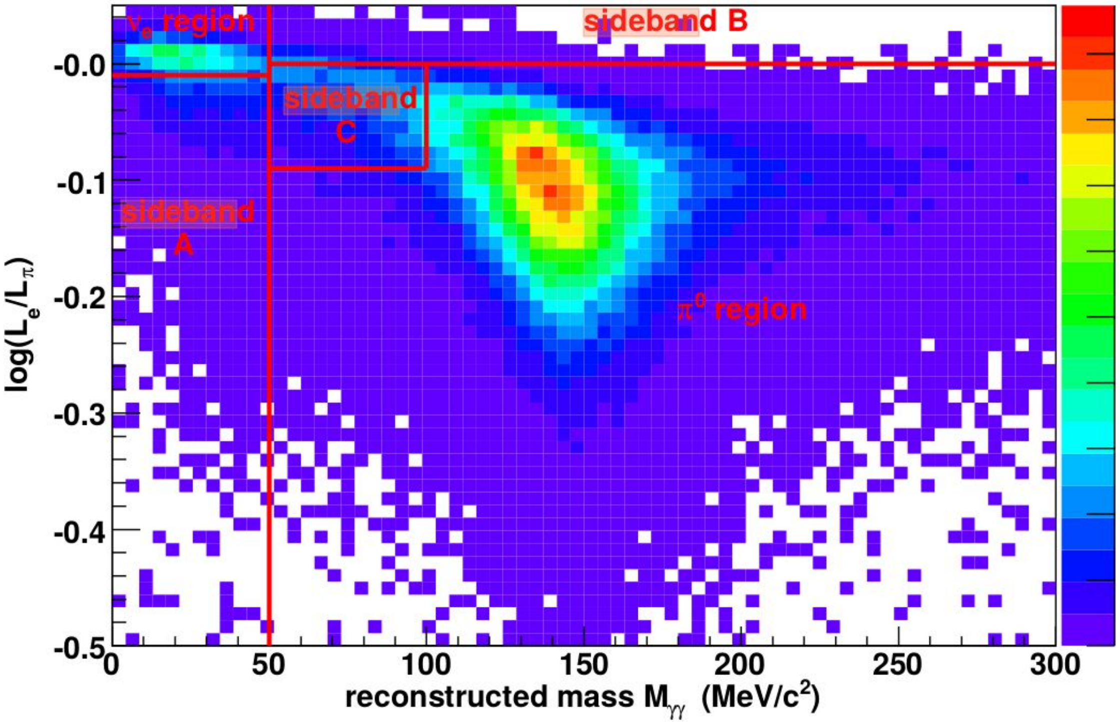
- Typical values ranging from **40%** (for **M_N of 50 MeV**) to below **10%** (for **M_N≥200 MeV).**

A natural question is thus

"What happens to the other events that have widely separable e^+e^- and are obviously two-ring events?"

Three sidebands and an NC π^0 measurement...

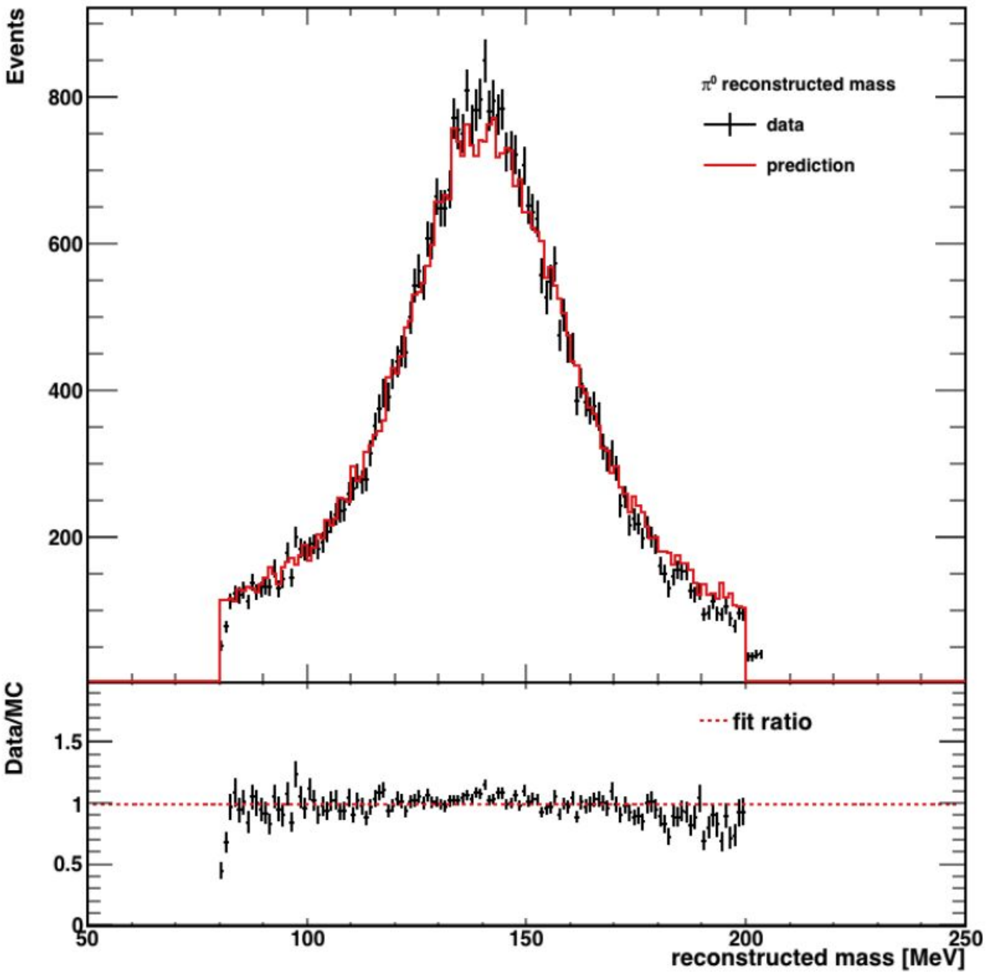
MiniBooNE Monte Carlo



A.A. Aguilar-Arevalo, Thesis

In-situ π^0 measurement

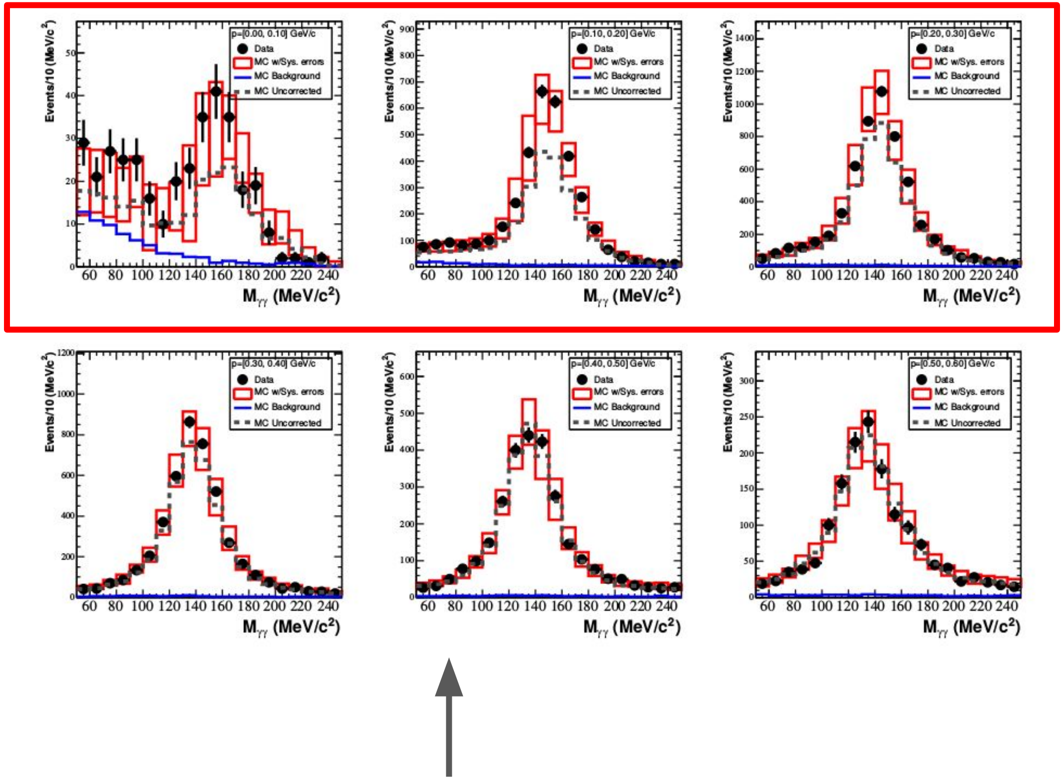
MiniBooNE Measured the π^0 *in-situ* and used this to *verify* their monte-carlo predictions.



Low energy π^0 Excess?

MiniBooNE Measured the π^0 *in-situ* and used this to *verify* their monte-carlo predictions.

MiniBooNE actually saw an **excess of low-momentum π^0 -like events**. (Look at the grey dashed uncorrected MC line)



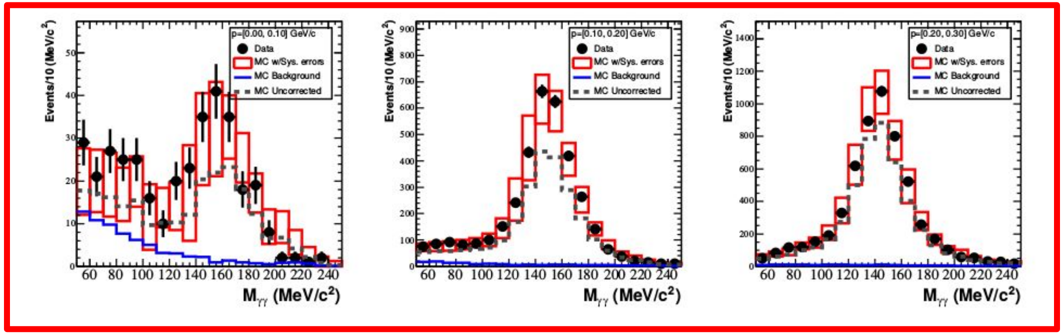
Same as π^0 invariant mass plot on last slide but split up in groups of π^0 -momentum

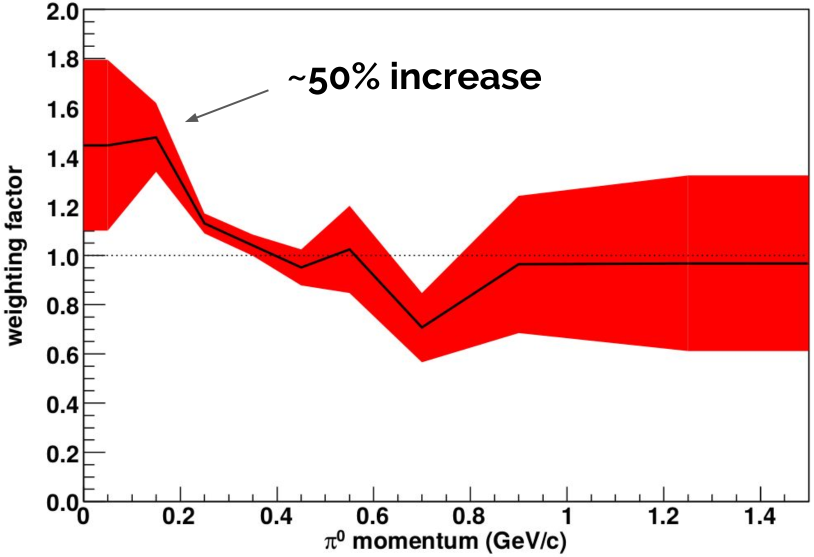
π^0 MC Correction

MiniBooNE Measured the π^0 *in-situ* and used this to *verify* their monte-carlo predictions.

MiniBooNE actually saw an **excess of low-momentum π^0 -like events**. [Look at the Gray dashed Uncorrected MC line]

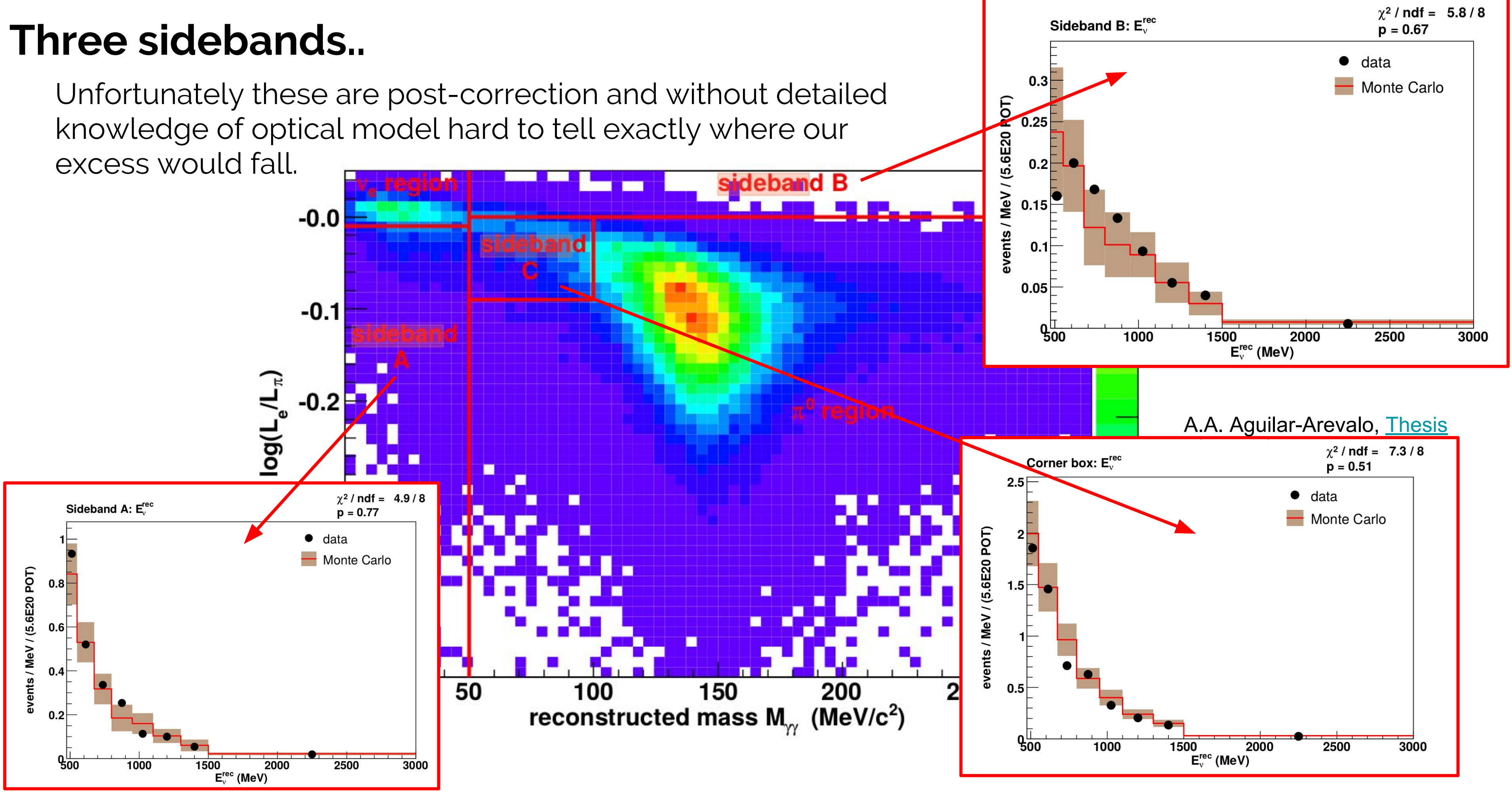
The Monte Carlo simulation was the "Corrected" by increasing the number of expected π^0 's with low momentum.





Three sidebands..

Unfortunately these are post-correction and without detailed knowledge of optical model hard to tell exactly where our excess would fall.



A.A. Aguilar-Arevalo, Thesis

"A Dark Neutrino Portal to Explain MiniBooNE" hep-ph/1807.09877

In the model presented here, in which $M_{Z'} > M_N$ the near-isotropic nature of the LEE is ensured by having a **heavy enough Z'** such that the momentum transfer in the upscattering is sufficient to guarantee the result sterile neutrino is not forward going.

An alternative approach was also put forward [*Enrico Bertuzzo, Sudip Jana, Pedro A. N. Machado, Renata Zukanovich Funchal*] in which $M_{Z'} < M_N$ and while the scattering tends to produce forward going sterile neutrinos, the resulting decay of the sterile (which is now governed by **two successive two-body decays** $N \to \nu_\mu Z'$ and $Z' \to e^+e^-$) gives the signal the necessary angular isotropy.

These two regimes are different phenomenological realizations of the same underlying generic model and highlight that if abstracted away from the LEE, these models can provide even more interesting studies.

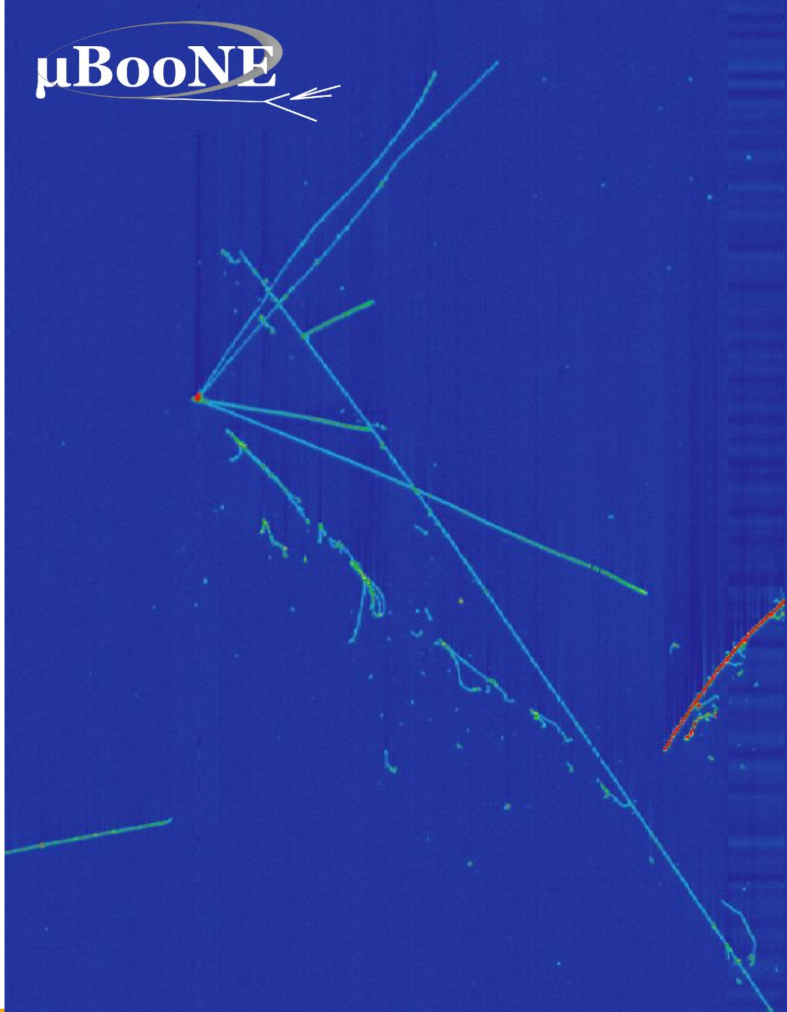
U(1)' models in Future and Current LArTPCs

This class of models has has incredibly **rich phenomenology** at LArTPCs such as **MicroBooNE**:

LArTPCs have the distinct advantage that one can tell photons and electron showers apart via two methods:

- Directly look for the **conversion gap**

- Use **Calorimetric measurements** to see rate of energy deposition (dE/dx). **Photons** that pair convert to e^+e^- **deposit x2 as much energy**.



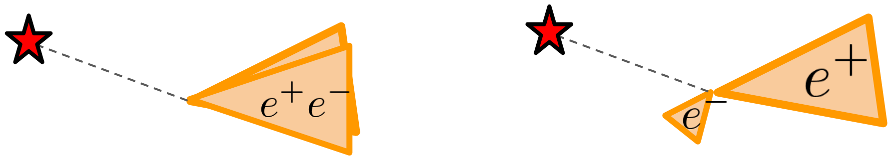
U(1)' models in Future and Current LArTPCs

Our Model: $M_{Z'} > M_N$

We estimate ~**150** LEE signal-like events in MicroBooNE that be split between an overlapping e^+e^- pair and an asymmetric e^+e^- (assuming 80% reco efficiency, 6.6e20 POT)

The overlapping sample would be indistinguishable from single photons.

Unlike MiniBooNE, MicroBooNE can use calorimetric measurements of the rate of energy deposition (dE/dx) in the initial few cm's of a shower to distinguish between asymmetric events.



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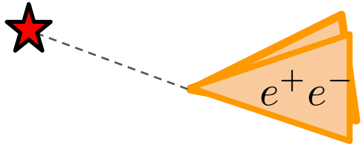
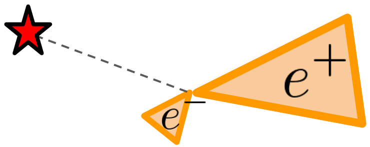
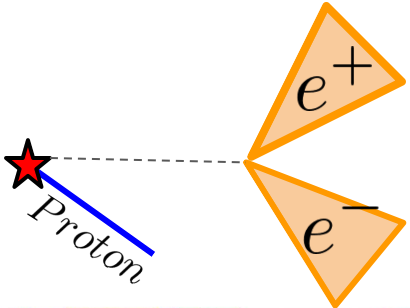




However, alongside this we predict ~**500** events that have **hadronic activity** as well as **distinguishable e^+e^- pairs**

However, depending on the exact decay rate this e^+e^- pair will not be attached to the proton, nor will it necessarily point back to the "vertex"

Low SM background but "vertexing" has never been optimized for such topological events.



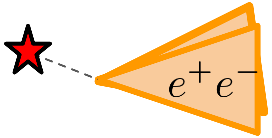
U(1)' models in Future and Current LArTPCs

Alternative regime of Bertuzzo et al. : $M_{Z'} < M_N$ **hep-ph/1807.09877**

Vast majority of events are (a) **coherently** produced and hence have no associated protons in the scattering (b) **extremely overlapping**.

This means the entire signal sample is indistinguishable from a lone photon shower, and without a proton to "tag" or locate the interaction vertex.

This is difficult to measure, but due to increases size of Argon nucleus over Carbon, rate is even larger in MiniBooNE than MiniBooNE due to coherent production.



Summary

- We proposed a novel solution for the MiniBooNE LEE based on **heavy sterile** neutrino (~100 MeV) **production and decay** inside the detector, both of which are **mediated by a new Z’** (~ 1 GeV)
- The explanation hinges on the mis-identification of the EM shower by a combination of **highly asymmetric** and **overlapping e^+e^-** pairs,
- We have given a concrete minimal realization that **evades current bounds**
- This class of models have a **very rich phenomenology** at short baselines

- If observed in LArTPCs such as MicroBooNe measuring the fraction of overlapping to asymmetric e+e- one can gain **distinguishing power between different hierarchies of models** ($M_{Z'} < M_N$ and $M_{Z'} > M_N$) as well as potentially resolve M_N and $M_{Z'}$ itself.

Thank you

The hadronic current in the neutrino-proton cross section is parameterized by the electromagnetic form factors of the proton, as the Z' only couples to SM particles via its electric charge vectorially.

We include both coherent scattering off of Carbon and incoherent scattering off the constituent protons of the detector medium. The coherent cross section is computed using an analytical approximation of a Woods-Saxon form factor based on the symmetrized Fermi function.

BooNE or MiniBooNE?

Original proposal for **BooNE (Booster Neutrino Experiment)** in 1997 put forward…

The BooNE (Booster Neutrino Experiment) program will have two phases. The first phase, MiniBooNE, is a single detector experiment designed to:

- Obtain $\sim$ 1000 events per year if the LSND signal is due to $\nu_\mu \to \nu_e$ oscillations. This establishes the oscillation signal at the $\sim 8\sigma$ level.

With a second near detector

The second phase of the experiment introduces a second detector, with the goal to:

- Accurately measure the Δm^2 and $\sin^2 2\theta$ parameters of observed oscillations.

Unfortunately it was never funded in its entirety with the **second near-detector not being built.**

https://www-boone.fnal.gov/publicpages/proposal.ps