# Testing New Physics Explanations Of The MiniBooNE Anomaly At Neutrino Scattering Experiments

## Based on arXiv:1812.08768

**Carlos A. Argüelles**

also starring

Matheus Hostert (Durham) and Yu-Dai Tsai (FNAL)

# The back story: LSND

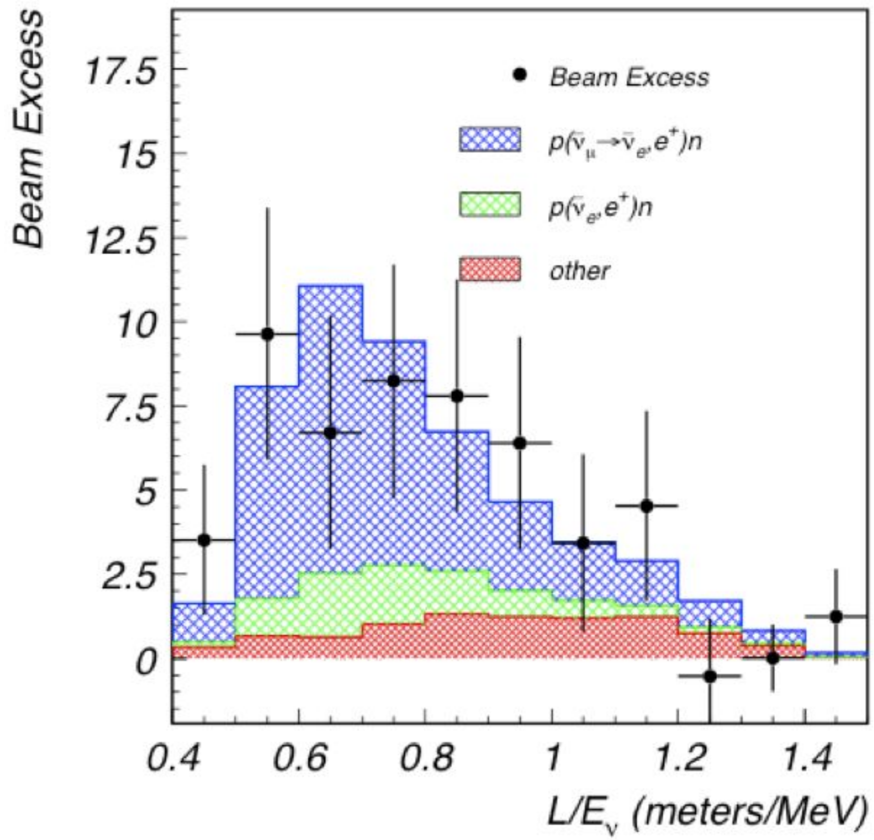
- LSND used an 800 MeV proton beam to produce pions which decay at rest.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

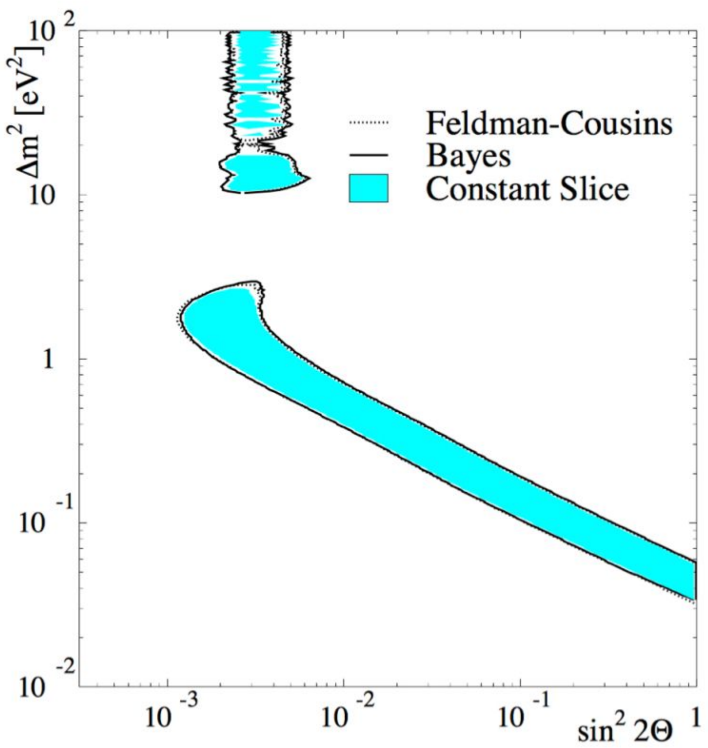
$$\mu^+ \rightarrow e^+ + \nu_e + \boxed{\bar{\nu}_\mu}$$

- Search for antineutrino-electron appearance

- Observed 3.8 sigma excess of events



# If interpreted as an appearance probability ...



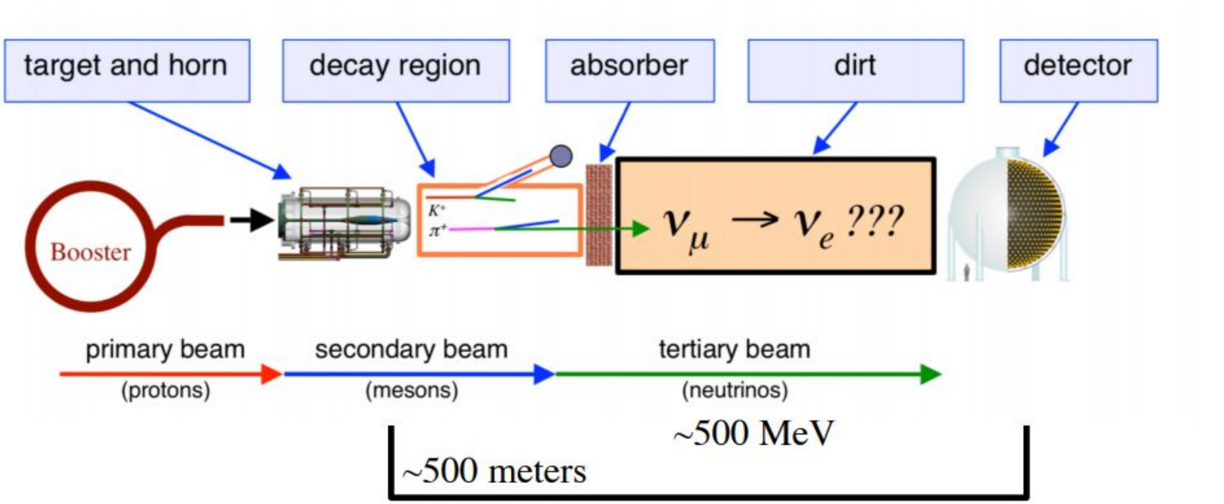

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E_\nu})$$

- The preferred parameter space of the LSND anomaly was not compatible with other known mass differences.
- If this is due to a new neutrino mass state, then we should observe a similar signal at different E and L, but same L/E!

A. Aguilar-Arevalo et al. [LSND Collaboration] Phys. Rev. D 64, 112007 (2001) [hep-ex/0104049].

# MiniBooNE@FNAL: proposed to test the LSND anomaly

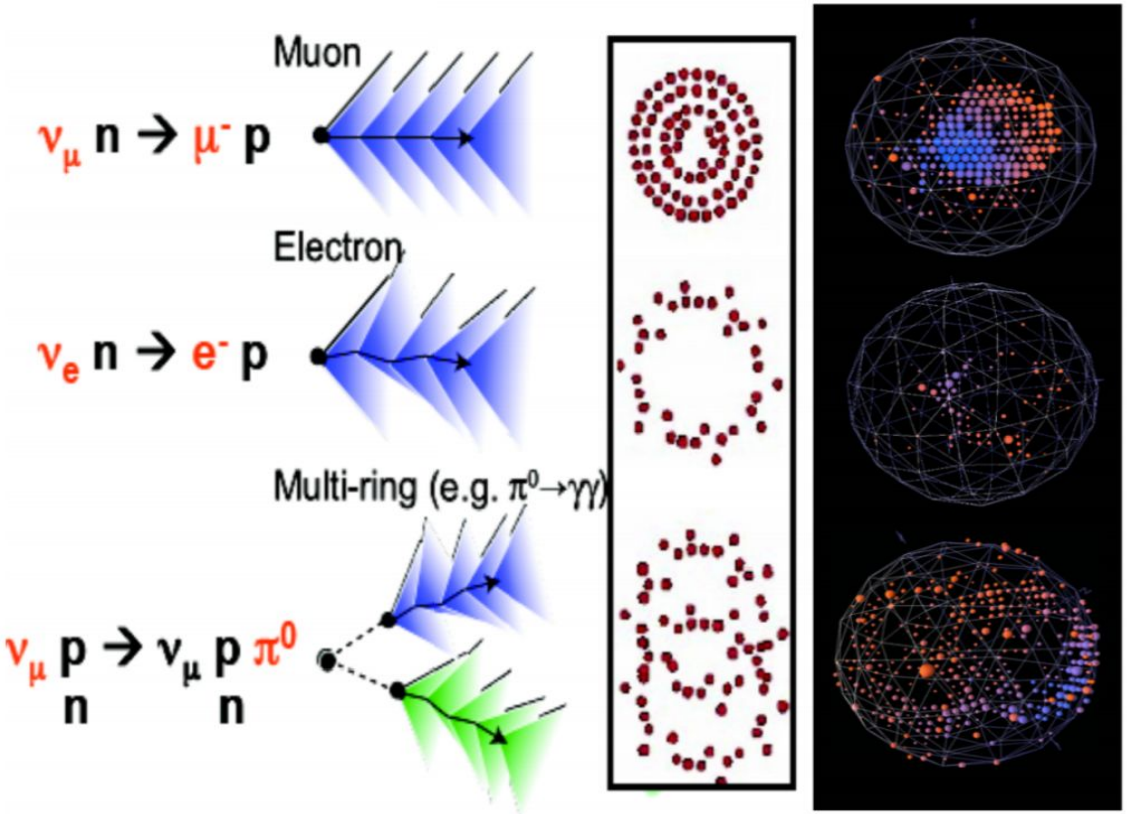
- Approximately same L/E, but ~15 x larger energy and baseline.
- Decay-in-flight pion source.
- Higher backgrounds than LSND, but more statistics!
- Neutrino and antineutrino mode available.



# MiniBooNE experimental signatures

Three typical event signatures:

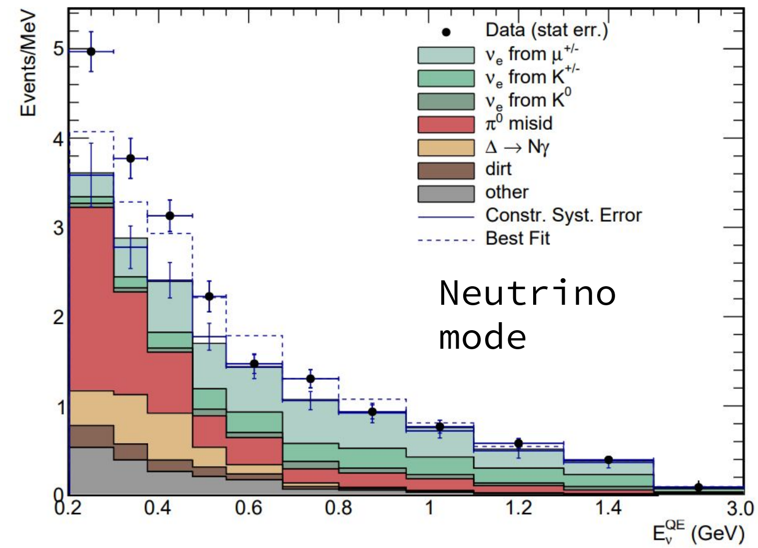
- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce pi0: two gammas -> two fuzzy rings.

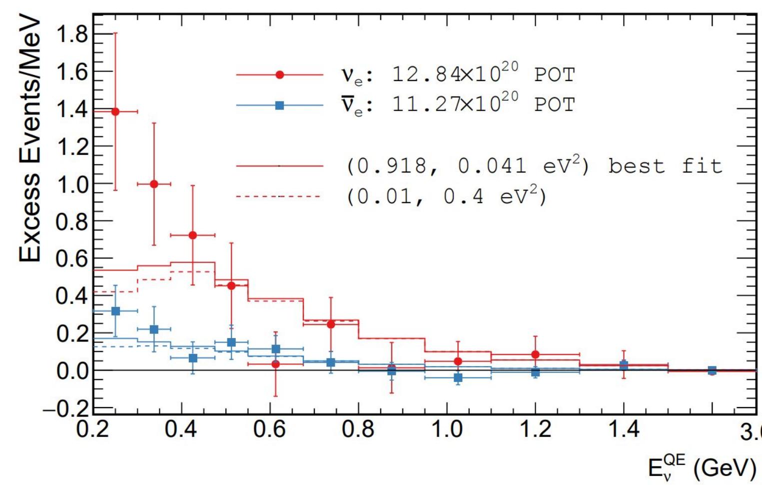



**Cannot distinguish between electrons and photons**

# Recent MiniBooNE excess of neutrino-electron-like events

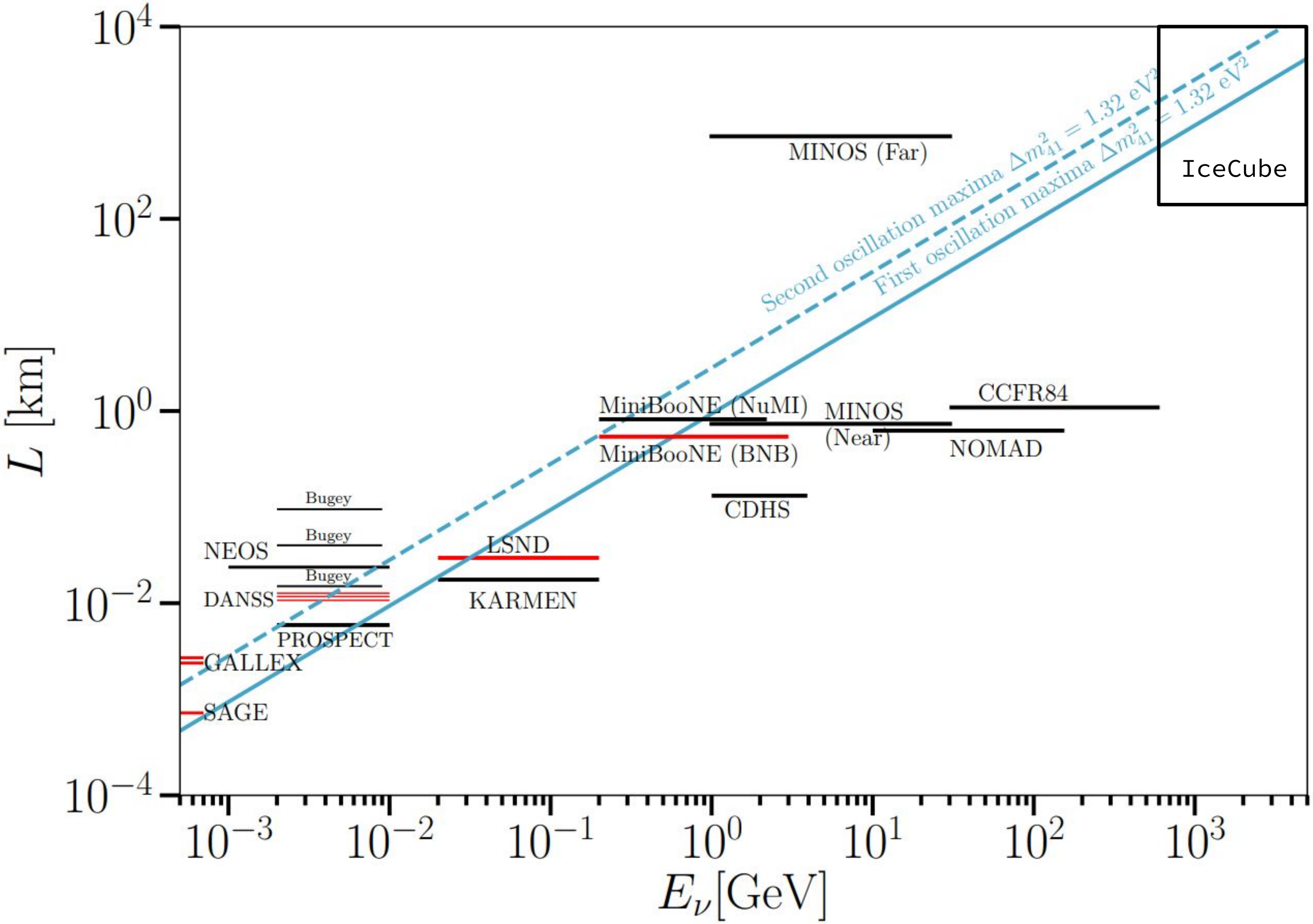
- MB has reported an excess in neutrino and antineutrino channels.
- They claim that this excess is compatible with LSND. (Previous results show tension with LSND in neutrino mode)
- Excess has remained after doubling the data: not statistical in nature.
- It has a significance of 4.7 sigma.




MiniBooNE Collaboration arXiv:1805.12028

# Sterile neutrino panorama




A. Diaz, CA, G.Collin, JM. Conrad, M. Shaevitz arXiv:1902.00517

# So … We have discover a new particle?!

# So ... We have discover a new particle!?



* R.I.P. grumpy cat.

# If it's a "vanilla" eV-scale sterile neutrino

$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

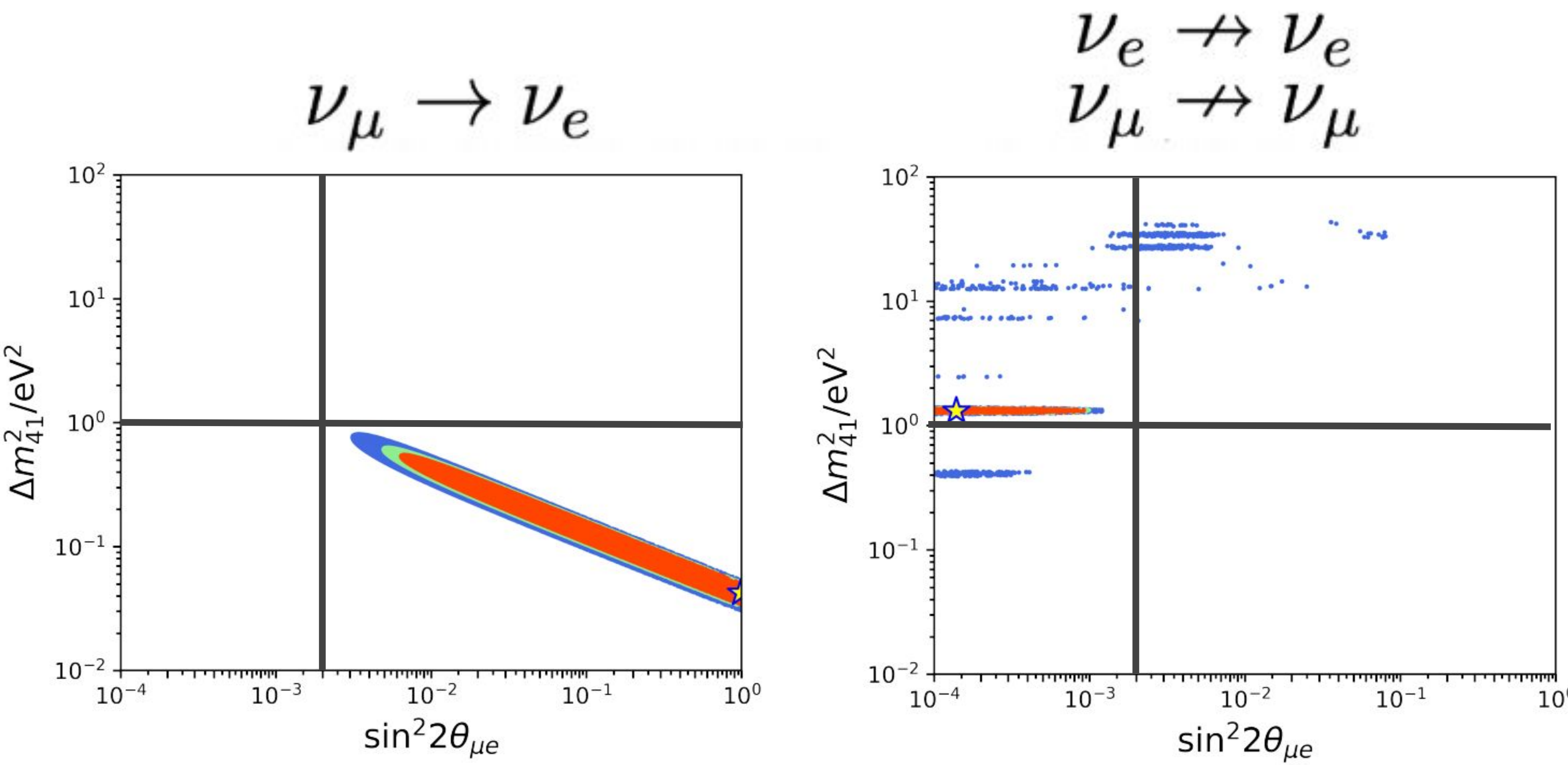
$$P_{\nu_\mu \to \nu_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

Oscillation probabilities among appearance and disappearance channels are related.

**Need to look in other channels for further confirmation!**

# App and Dis preference regions don't match!




A. Diaz, CA, G.Collin, JM. Conrad, M. Shaevitz arXiv:1902.00517

See also Collin et al 1602.00671, similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018)

# Tension in the global data!!!

PG: parameter goodness-of-fit.
Larger is better. Small is bad.
Very small is very bad.

| Analysis | $\chi^2_{\text{min,global}}$ | $\chi^2_{\text{min,app}}$ | $\Delta\chi^2_{\text{app}}$ | $\chi^2_{\text{min,disapp}}$ | $\Delta\chi^2_{\text{disapp}}$ | $\chi^2_{\text{PG}}/\text{dof}$ | PG |
|---|---|---|---|---|---|---|---|
| Global | 1120.9 | 79.1 | 11.9 | 1012.2 | 17.7 | 29.6/2 | $3.71 \times 10^{-7}$ |
| **Removing anomalous data sets** | | | | | | | |
| w/o LSND | 1099.2 | 86.8 | 12.8 | 1012.2 | 0.1 | 12.9/2 | $1.6 \times 10^{-3}$ |
| w/o MiniBooNE | 1012.2 | 40.7 | 8.3 | 947.2 | 16.1 | 24.4/2 | $5.2 \times 10^{-6}$ |
| w/o reactors | 925.1 | 79.1 | 12.2 | 833.8 | 8.1 | 20.3/2 | $3.8 \times 10^{-5}$ |
| w/o gallium | 1116.0 | 79.1 | 13.8 | 1003.1 | 20.1 | 33.9/2 | $4.4 \times 10^{-8}$ |
| **Removing constraints** | | | | | | | |
| w/o IceCube | 920.8 | 79.1 | 11.9 | 812.4 | 17.5 | 29.4/2 | $4.2 \times 10^{-7}$ |
| w/o MINOS(+) | 1052.1 | 79.1 | 15.6 | 948.6 | 8.94 | 24.5/2 | $4.7 \times 10^{-6}$ |
| w/o MB disapp | 1054.9 | 79.1 | 14.7 | 947.2 | 13.9 | 28.7/2 | $6.0 \times 10^{-7}$ |
| w/o CDHS | 1104.8 | 79.1 | 11.9 | 997.5 | 16.3 | 28.2/2 | $7.5 \times 10^{-7}$ |
| **Removing classes of data** | | | | | | | |
| $\overset{(-)}{\nu}_e$ dis vs app | 628.6 | 79.1 | 0.8 | 542.9 | 5.8 | 6.6/2 | $3.6 \times 10^{-2}$ |
| $\overset{(-)}{\nu}_\mu$ dis vs app | 564.7 | 79.1 | 12.0 | 468.9 | 4.7 | 16.7/2 | $2.3 \times 10^{-4}$ |
| $\overset{(-)}{\nu}_\mu$ dis + solar vs app | 884.4 | 79.1 | 13.9 | 781.7 | 9.7 | 23.6/2 | $7.4 \times 10^{-6}$ |

JHEP 08 (2018) 010, Dentler, M. et al.

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**A vanilla 3+1 sterile neutrino fails to explain all the data!**

JHEP 08 (2018) 010, Dentler, M. et al.

# This raises some more questions...

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Do we understand all SM background/process well enough?

Are all the anomalies related? Or only some of them?

E.g., are LSND and MiniBooNE observing the same physics?

Since null results are not scrutinized as carefully as anomalous ones. Are all null results reliable?

Is there a significant signal of electron-neutrino disappearance (e.g. reactors)?

If the anomalies are confirmed as new physics, in what theories are they embedded?

# Novel alternative explanations of the MiniBooNE anomaly

Assume that the SM gauge group is extended by a new U(1)' which mixes kinetically with the SM hypercharge

$$\mathscr{L}_{\text{kin}} \supset \frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{\sin\chi}{2}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \frac{m^2_{\hat{Z}'}}{2}\hat{Z}'^{\mu}\hat{Z}'_{\mu}$$

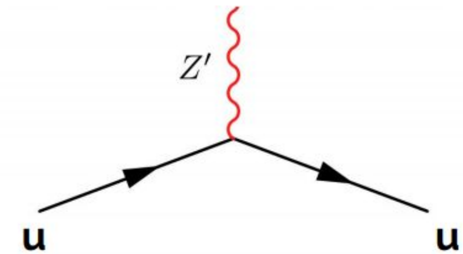
Also introduce a new SM-gauge singlet, charged under the new U(1)', which is allowed to mix with SM active neutrinos.

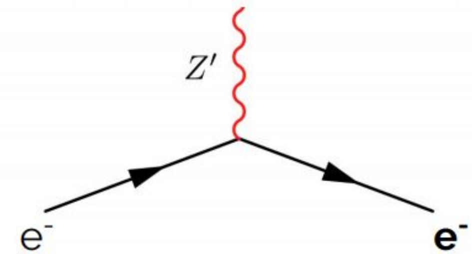
Bertuzzo et al. Phys. Rev. Lett. 121, 241801 (2018)

Ballett et al. arXiv:1808.02915

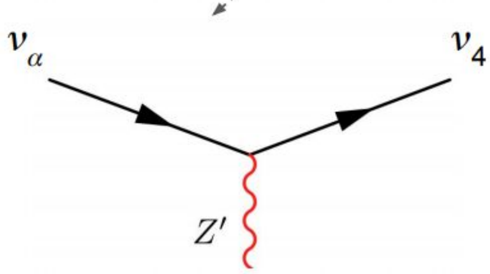
# Interaction Lagrangian

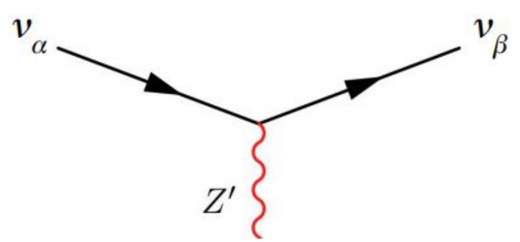
$$\mathcal{L} \supset -e q_f c_{\mathrm{W}} \chi \overline{f} \gamma^{\mu} f Z'_{\mu}$$



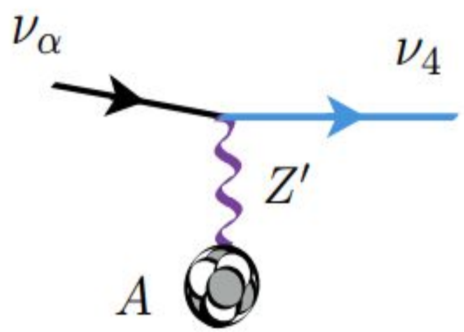

$$U^{*}_{\alpha 4} g' \overline{\nu_{\alpha}} \gamma^{\mu} P_{\mathrm{L}} \nu_4 Z'_{\mu} \quad + U^{*}_{\alpha 4} U_{\beta 4} g' \overline{\nu_{\alpha}} \gamma^{\mu} P_{\mathrm{L}} \nu_{\beta} Z'_{\mu}$$



# Producing the MiniBooNE signature

$$\alpha_D \alpha_{\text{QED}} \varepsilon^2 |U_{\alpha 4}|^2$$




Small Mz’:

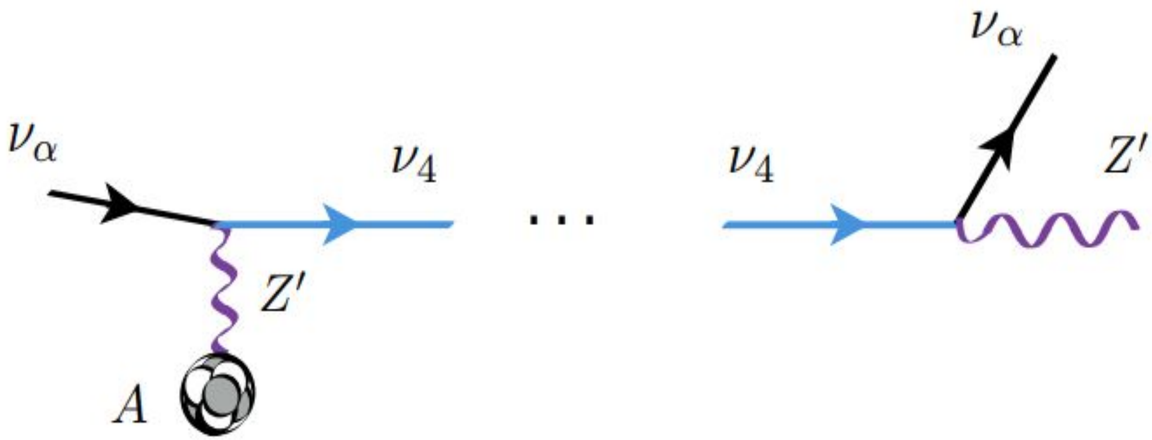
- Larger cross section
- Small Q^2: more forward nu_4, larger coherent to diffractive contributions

Large Mz’:

- Smaller cross section
- Larger Q^2: more isotropic nu_4 production, more diffractive contribution

# Producing the MiniBooNE signature

**Model from Bertuzzo et al.**
**Phys. Rev. Lett. 121, 241801 (2018)**

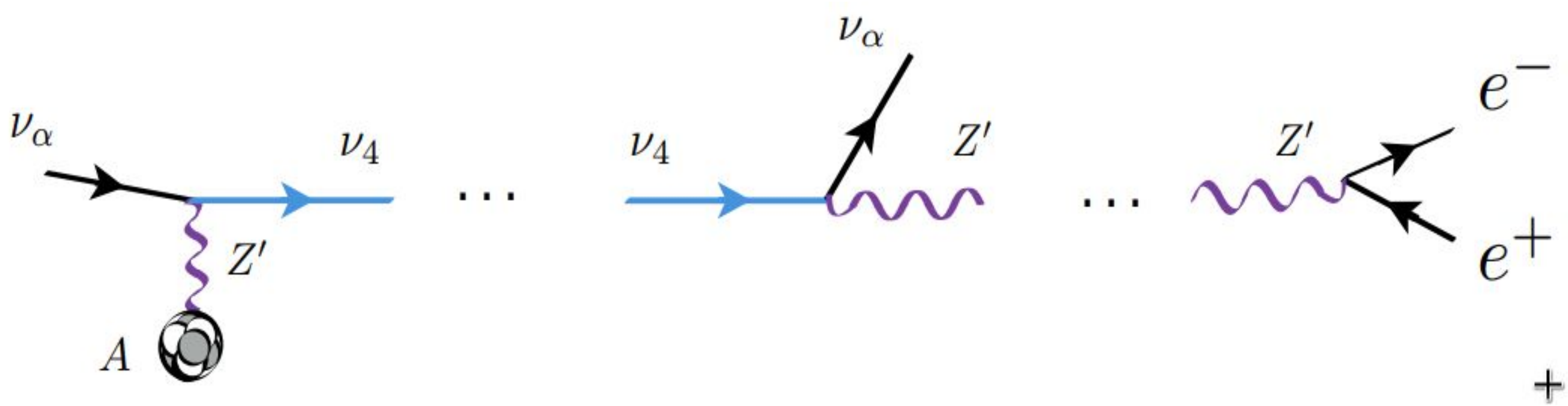



If M4 > MZ’, two body decay is the dominant decay channel.
M4 >~ 100 MeV so the decay products are not so boosted in order to reproduce angular distribution.

# Producing the MiniBooNE signature

**Model from Bertuzzo et al.**
**Phys. Rev. Lett. 121, 241801 (2018)**

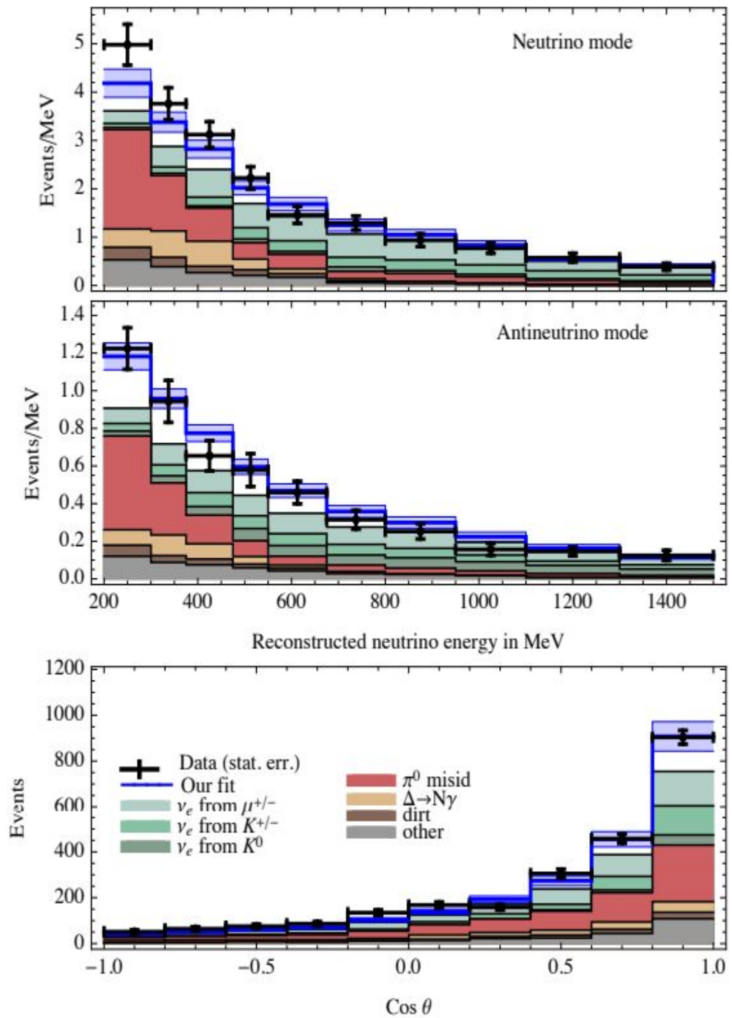
**Model from Ballett et al.**
**arXiv:1808.02915; see also 1903.07589.**



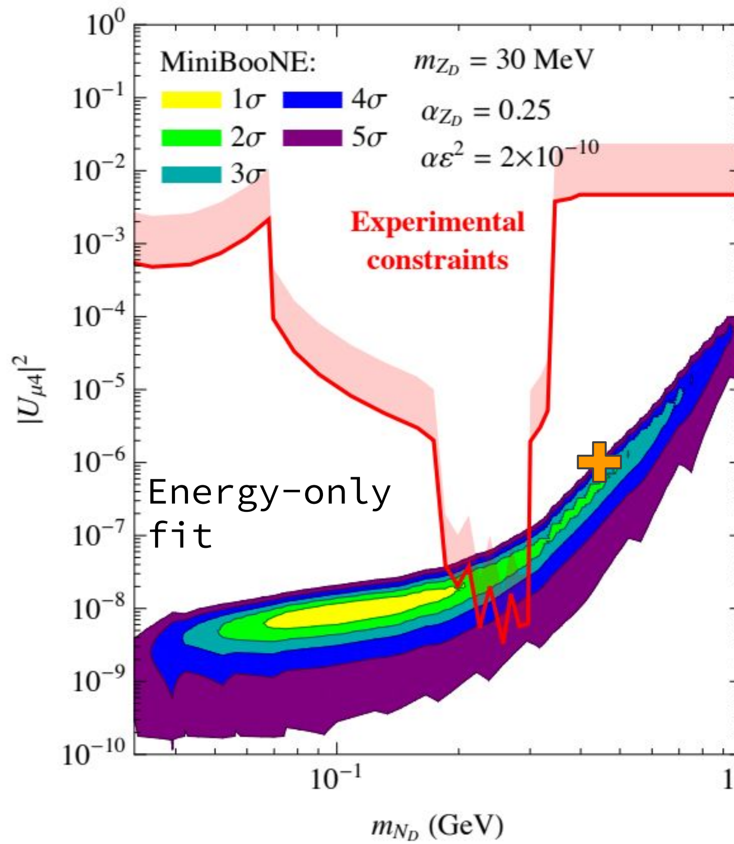

Mz should be light (< 60 MeV) so that the electron pair is collimated and can “fake” an electron-neutrino ring

# Model by Bertuzzo et al. parameter space

Distributions at benchmark point




Benchmark point marker



# Let’s focus on the realization by Bertuzzo et al.

- Production cross section is dominated by coherent processes; i.e. little/no hadronic activity at vertex.
- Products angular distribution is broad at Booster beam energies, but less so at higher energy beams.
- Electron pair produced by Z’ decay is very collimated.

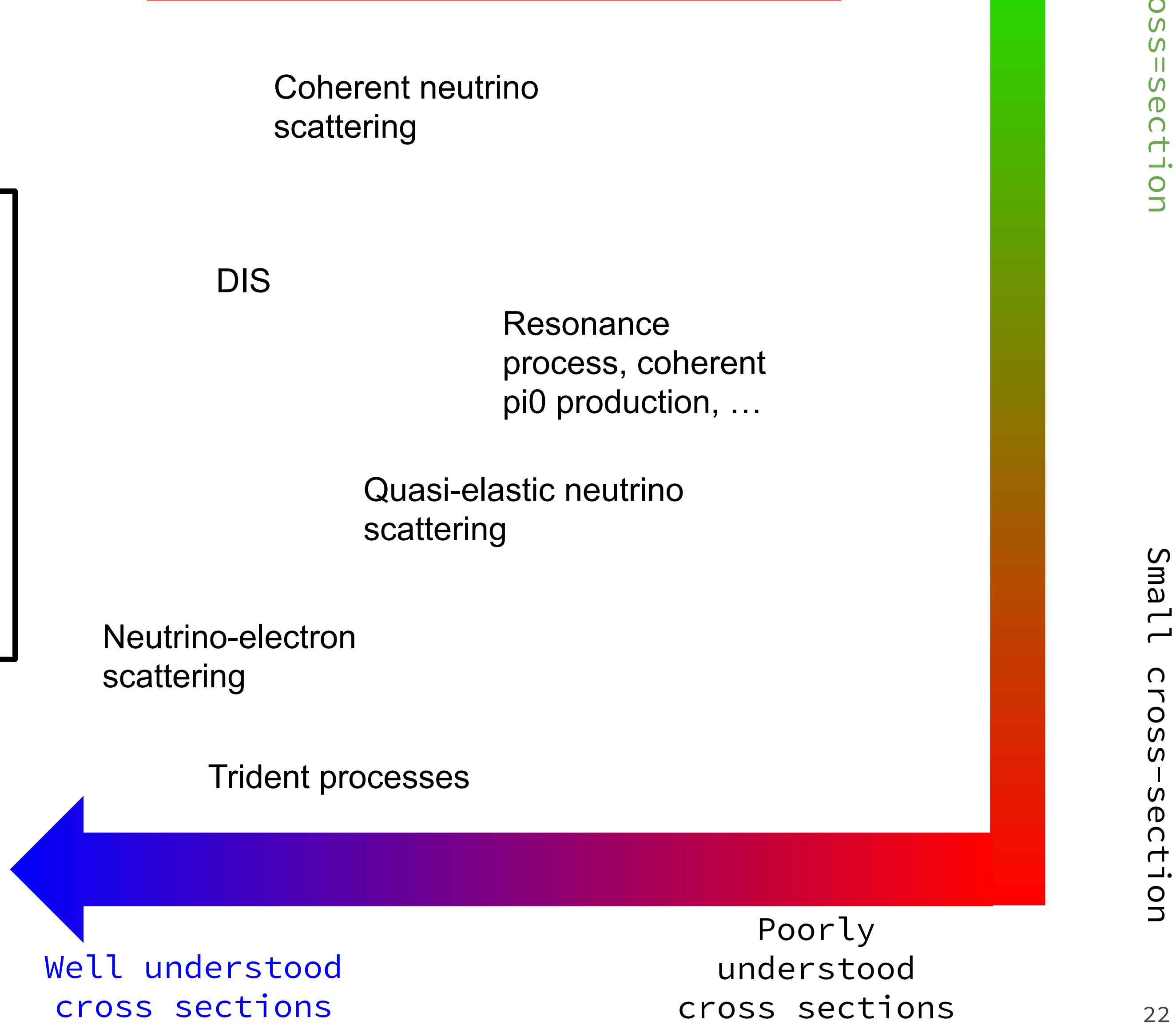
## How can we confirm or rule out a model like this?

### We **need** an strategy as in the eV-sterile one

# Strategy

NOTE that I am NOT putting scales in this diagram!

Looking for novel neutrino interactions requires understanding of our SM neutrino interactions. This is tough!



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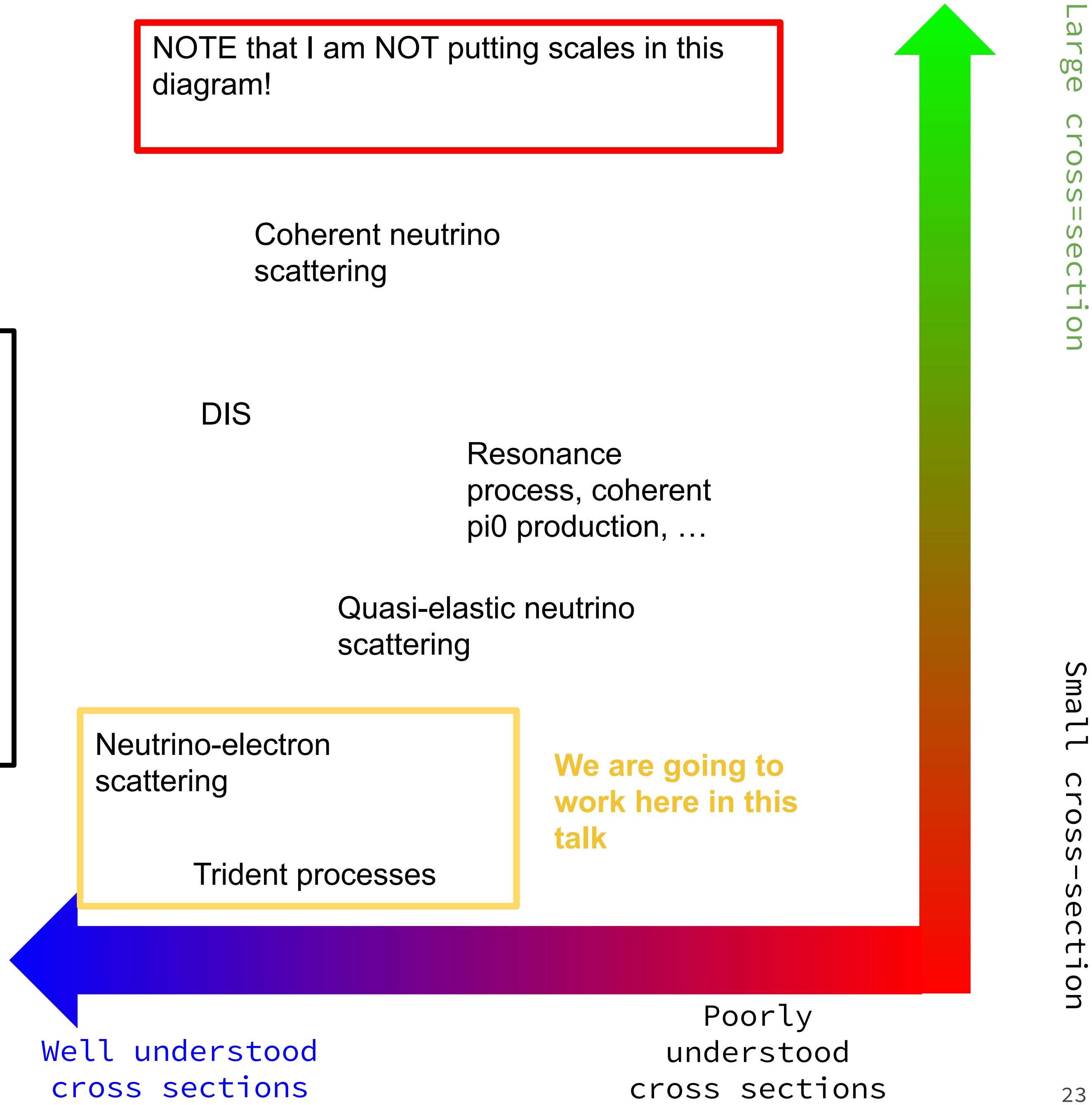
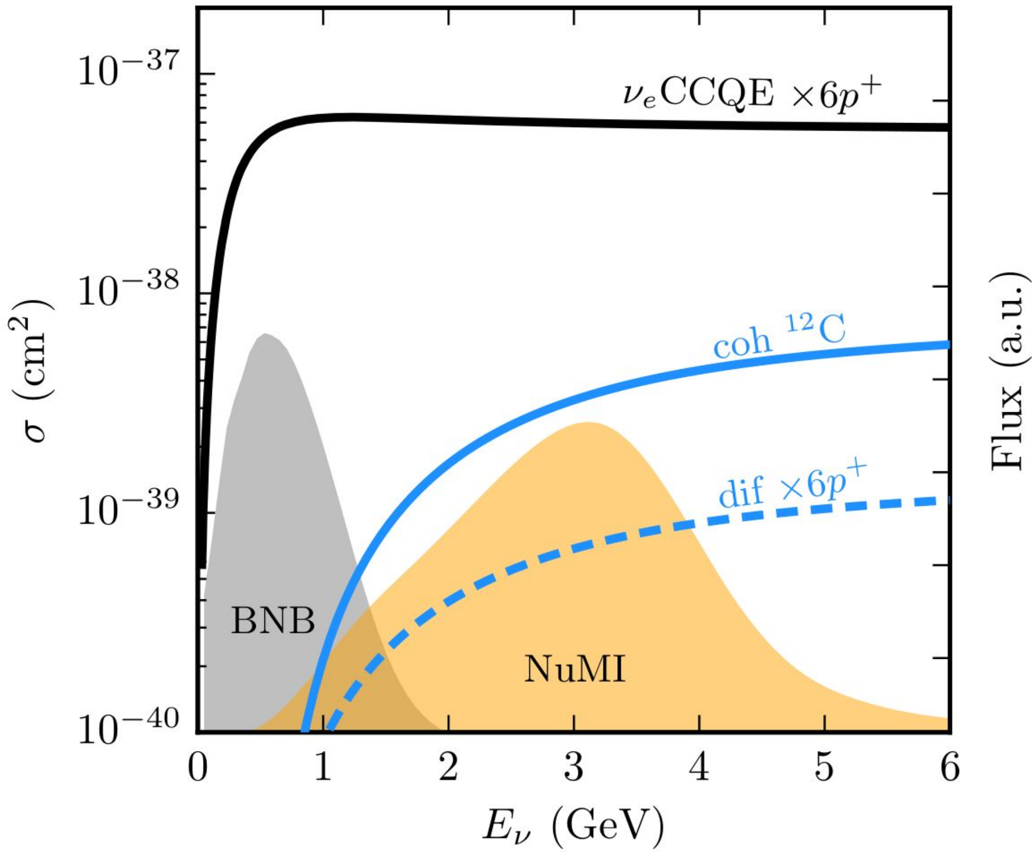


# How big of a cross section are we talking about?




Here we use benchmark (BP) point parameters reported by Bertuzzo et al. 1807.09877.

# Neutrino-electron scattering measurements

We have measured neutrino-electron scattering @:

- **LSND**
- **TEXONO**
- **Borexino**
- **SuperK**
- **MINERvA Low-Energy**
- **CHARM-II**

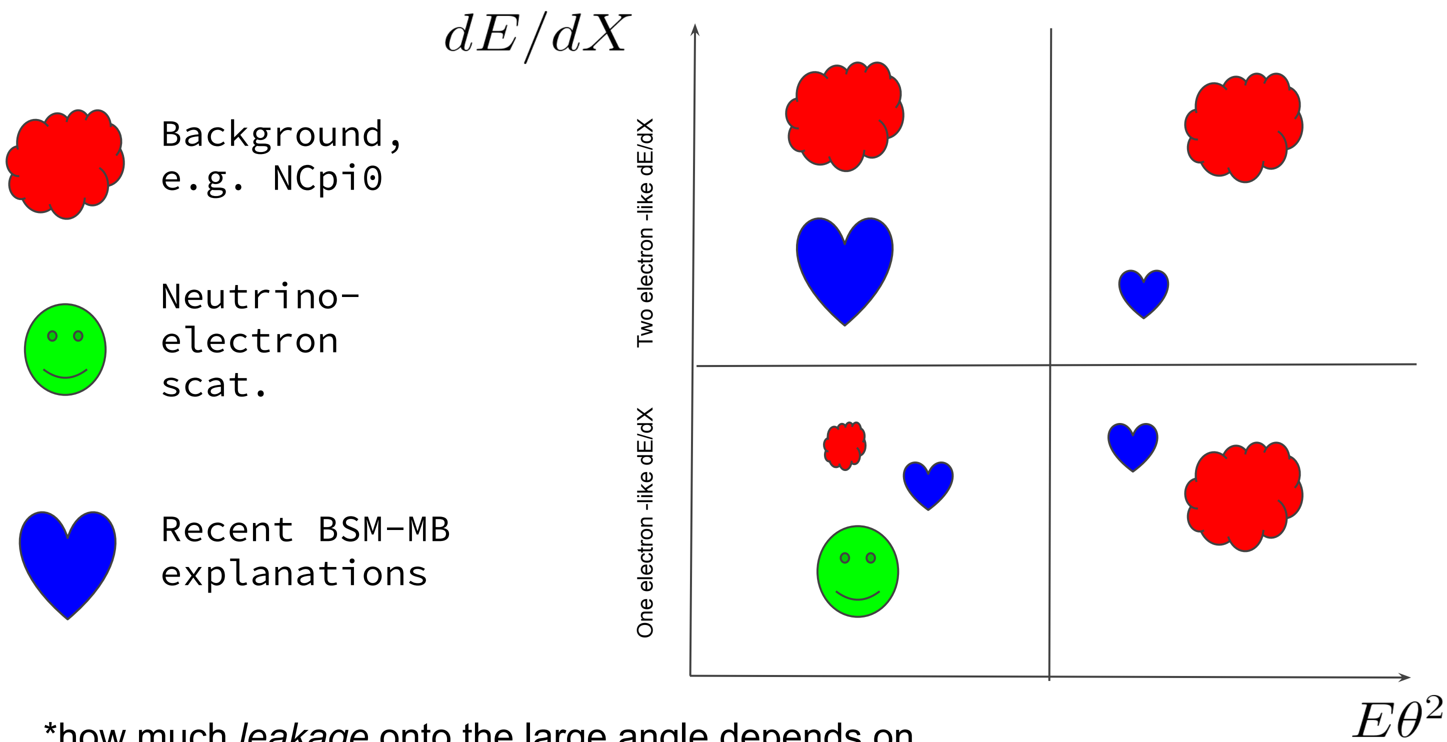
**Too low energies for BSM case of interest**

**We will focus on these experiments.**

Will measure it very soon @ **MINERvA Medium-Energy, NOvA,** and later @ **DUNE**.

# Analysis strategy

Electron-neutrino-like scattering search

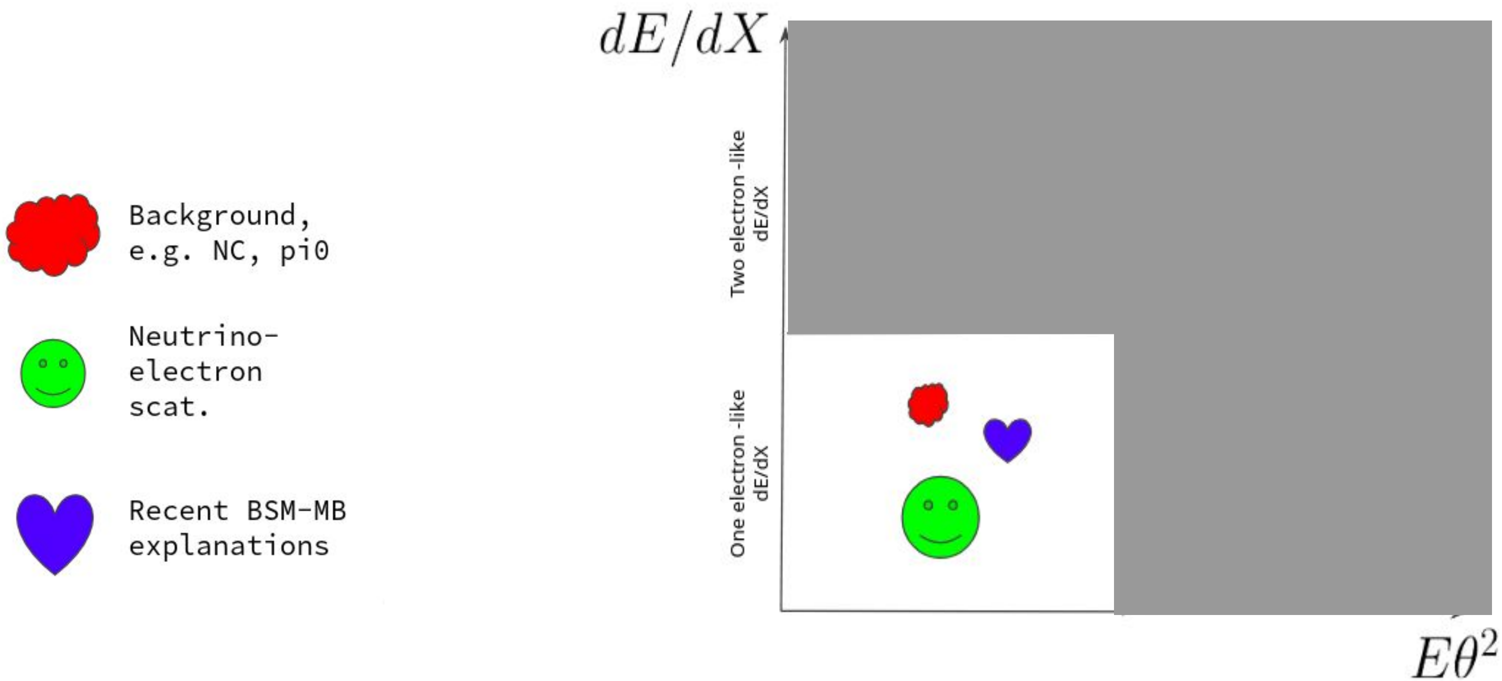



*how much *leakage* onto the large angle depends on model parameter and neutrino energy.

# Working around limited information!

By design at final cut level CHARM-II and Minerva measurements have small backgrounds: also means small amount of BSM-signal leaking in. We cannot use the final event samples to constrain the new models **:(!**

Would be great if we had access to the reconstructed electron energy and angular distributions at different cut levels.



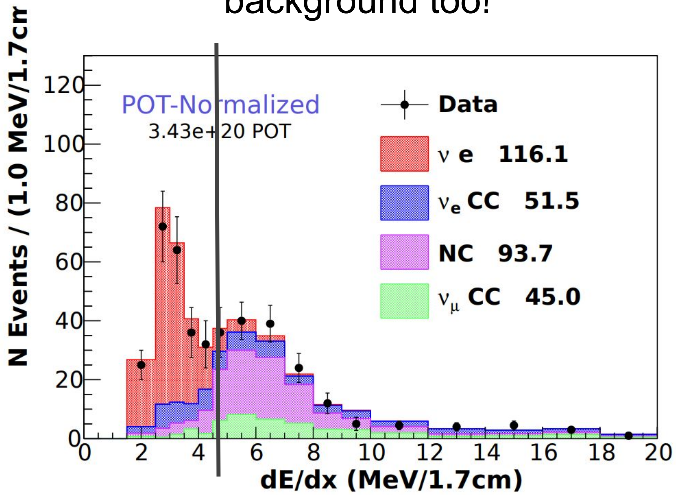
# MINERvA analysis strategy

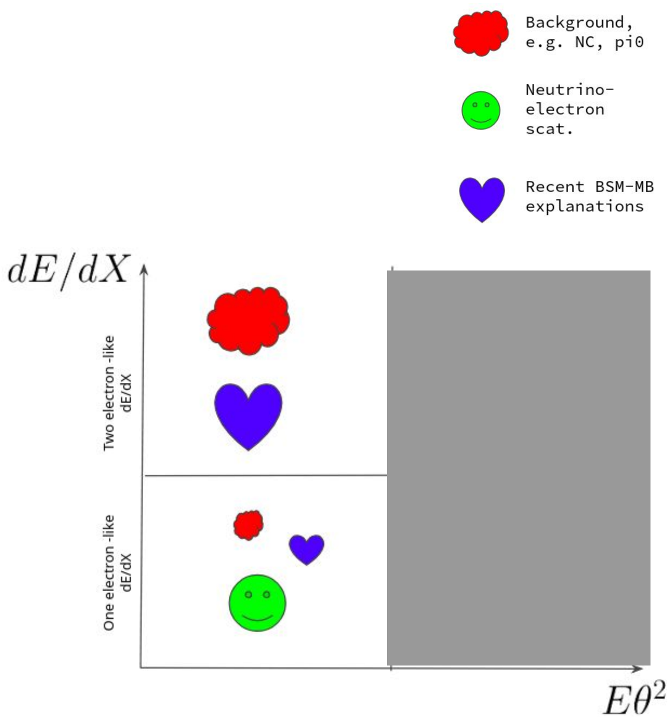
For MINERvA we are going to use the dE/dX distribution of candidate electron-neutrino scattering events.

BSM signal lives here, but background too!

**All MINERvA cuts applied, except for the final dE/dX cut!**

**Note that backgrounds have been tuned here!**




Minerva Collaboration
Phys. Rev. D 93, 112007 (2016)

# MINERvA analysis strategy

| Parameter | Tuned value |
|---|---|
| $\nu_e$ | $0.76 \pm 0.03$ |
| $\nu_\mu$ NC | $0.64 \pm 0.03$ |
| $\nu_\mu$ CC | $1.00 \pm 0.02$ |

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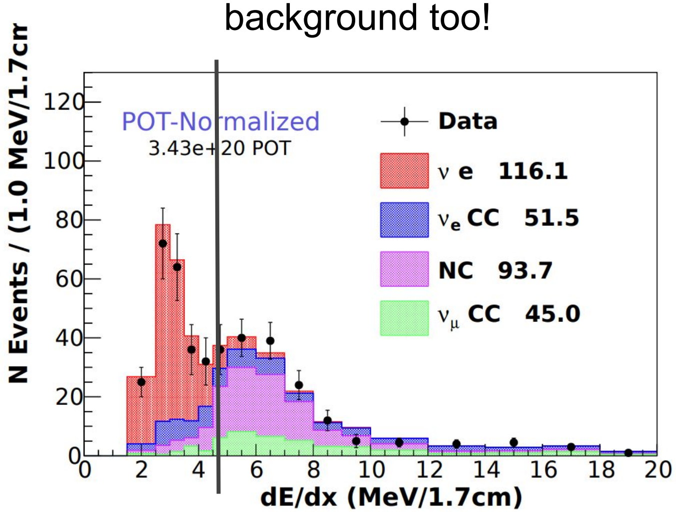
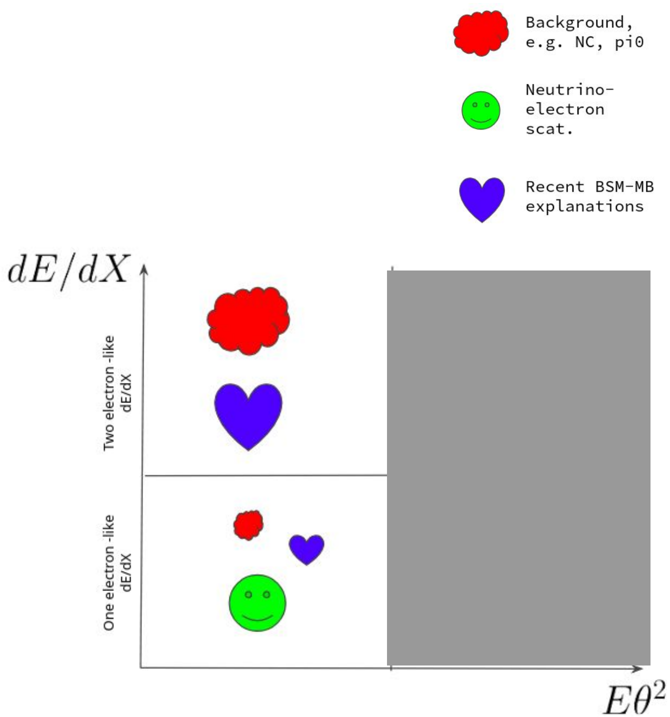



Minerva Collaboration
Phys. Rev. D 93, 112007 (2016)

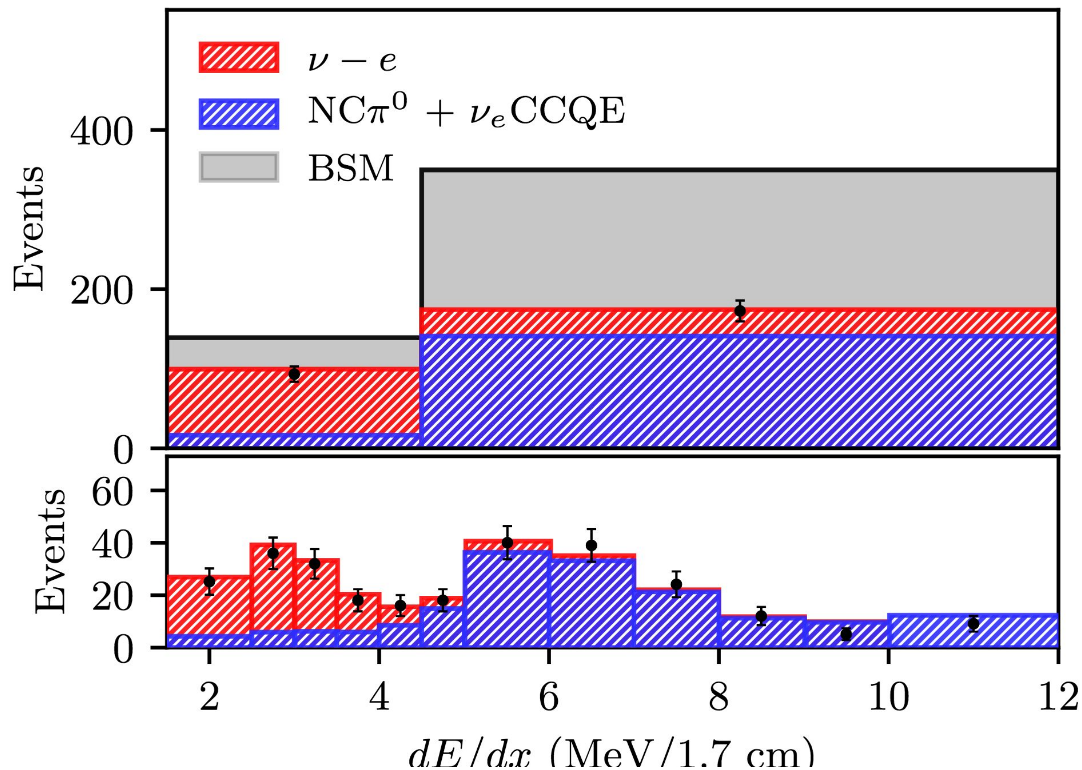
Tunning parameters table from J. Park thesis:
http://lss.fnal.gov/archive/thesis/2000/fermilab-thesis-2013-36.pdf

# MINERvA: Our Analysis setup

- We do a rate-only analysis on the single bin with

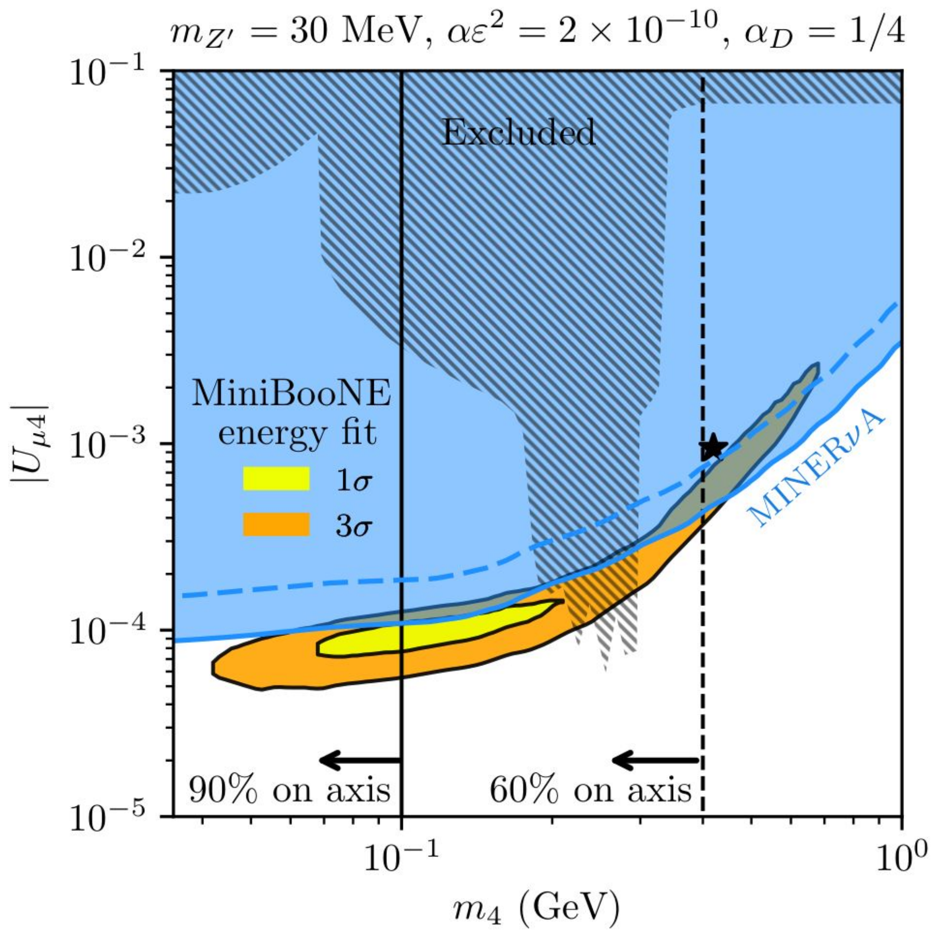
dE/dX > 4.5MeV/(1.7cm)

- We use 3.43e20 POTs, Assume fiducial mass of 6.10 tons.

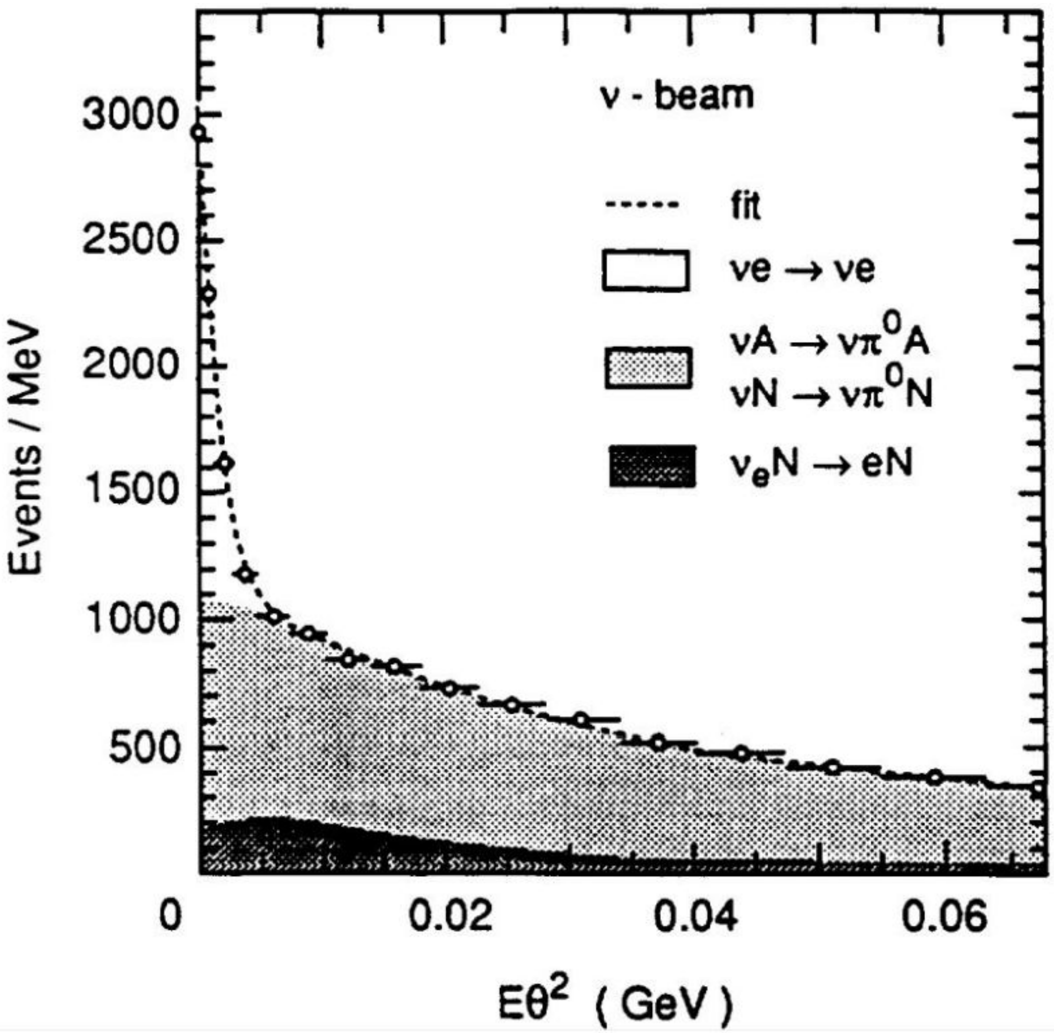


# MINERvA result

We checked that changing the background uncertainty from 30% to 100% changes the result by no more than a factor of two. The constraint power is coming from the BSM signal overshooting the data.

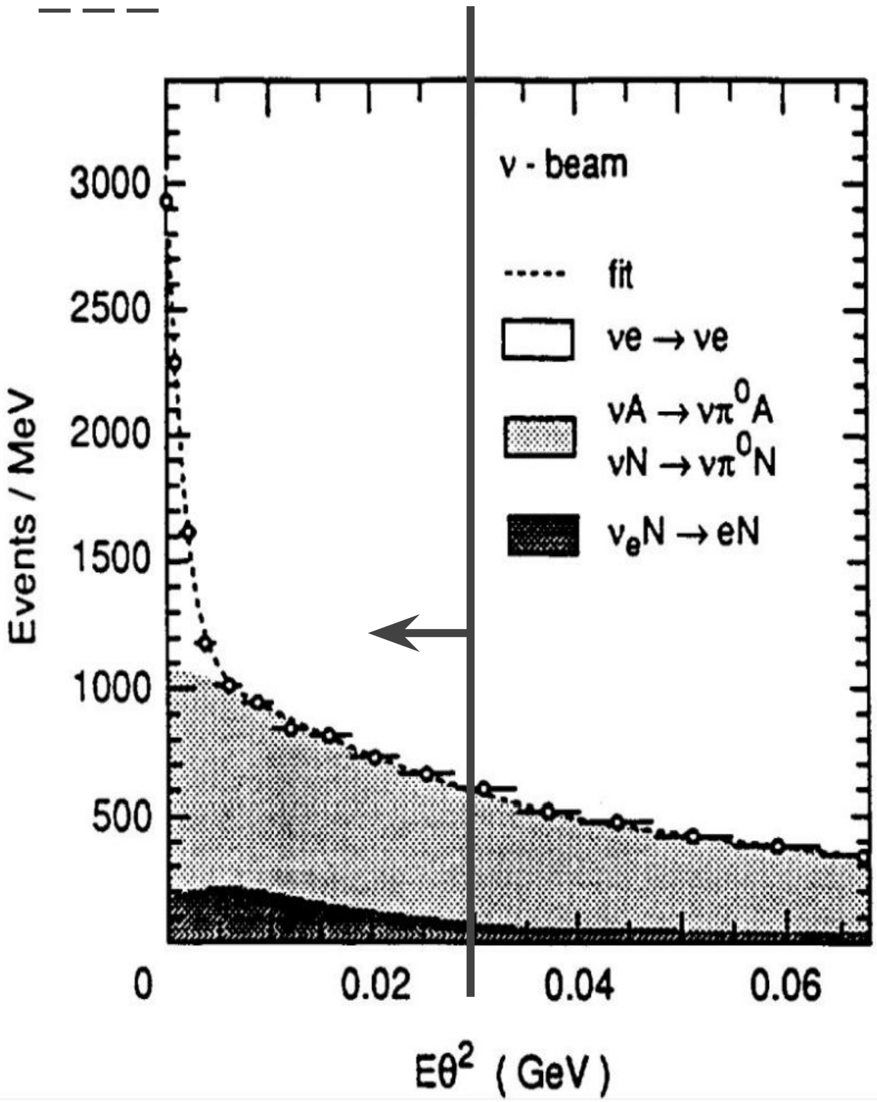


# CHARM-II: complementary measurement

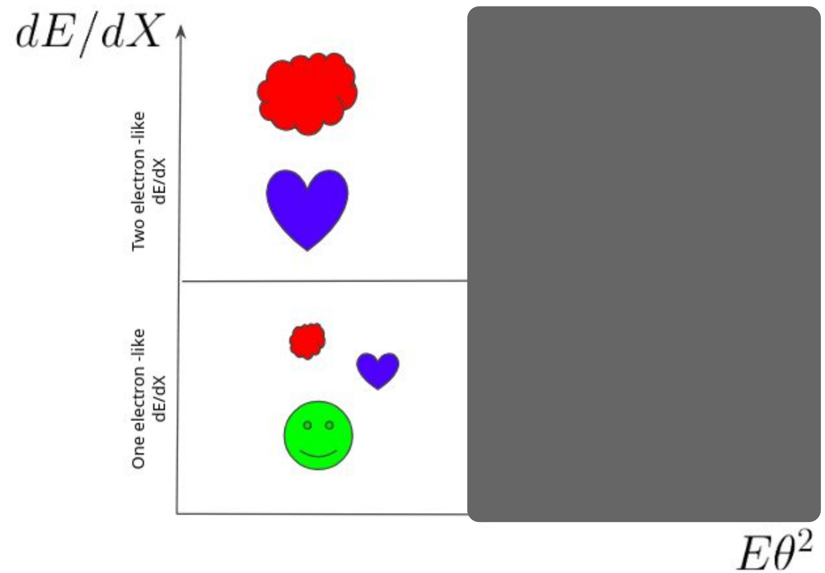



For CHARM-II we are going to use the E\theta^2 distribution before the final dE/dX cut is applied.

# CHARM-II: complementary measurement

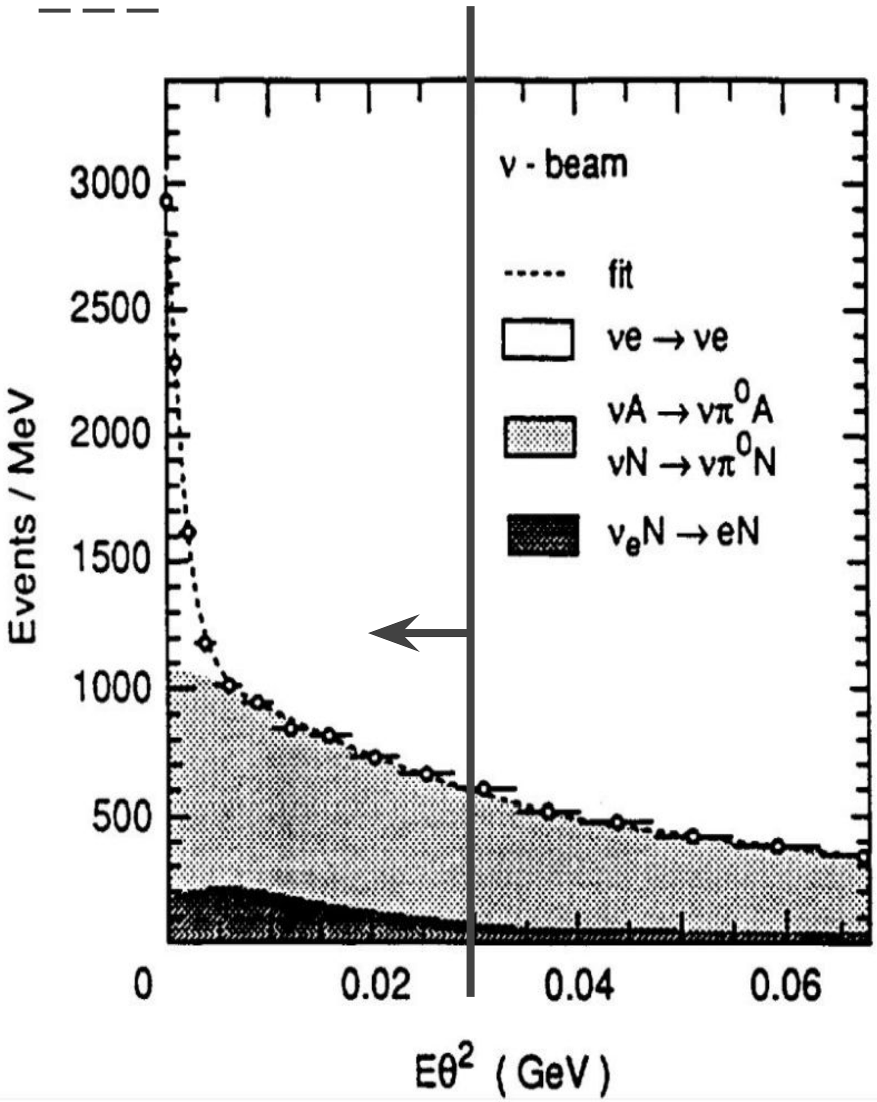



For CHARM-II we use the distribution before the angular cut and dE/dX were applied

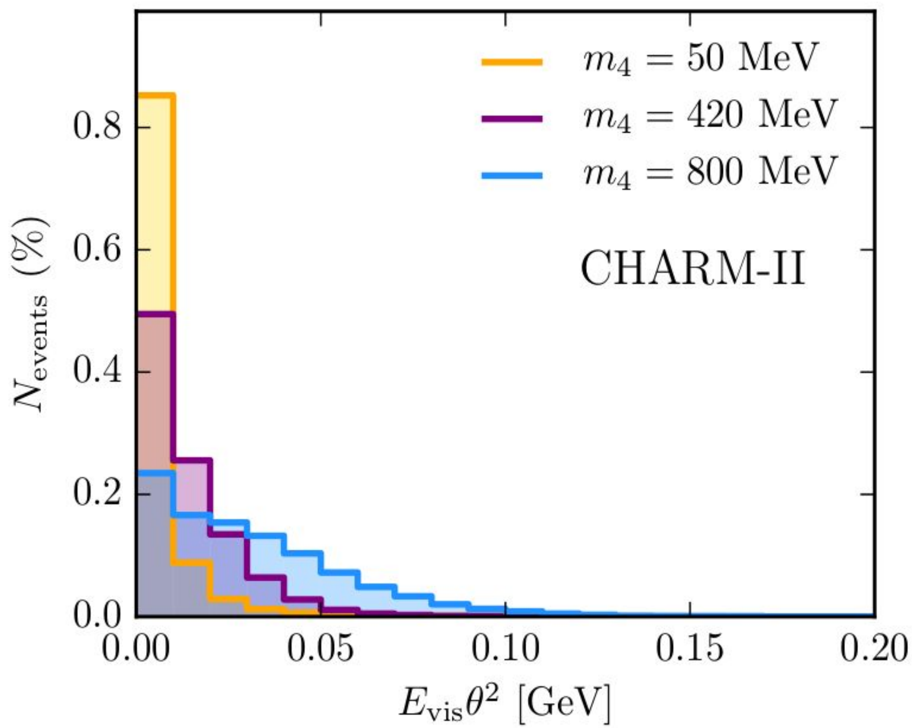



Use the region with E\theta^2>0.03 to obtain the background uncertainty.
Allow for rate/slope to change; with this we estimate its rate to be constrain to be ~3%.

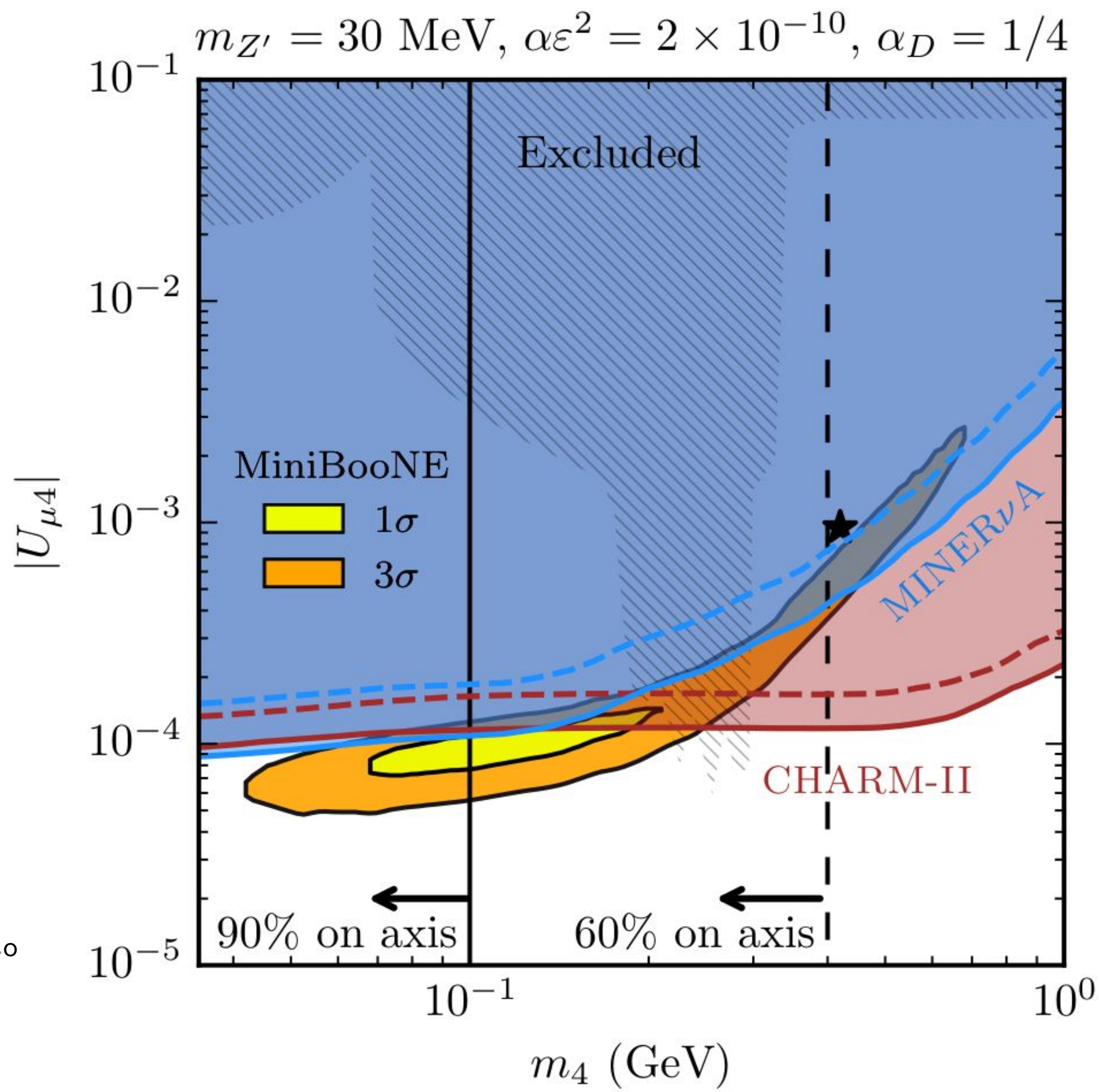
# Finding “BSM-safe” sideband to measure background




Angular distribution of BSM-signal



# Putting it all together: the money plot



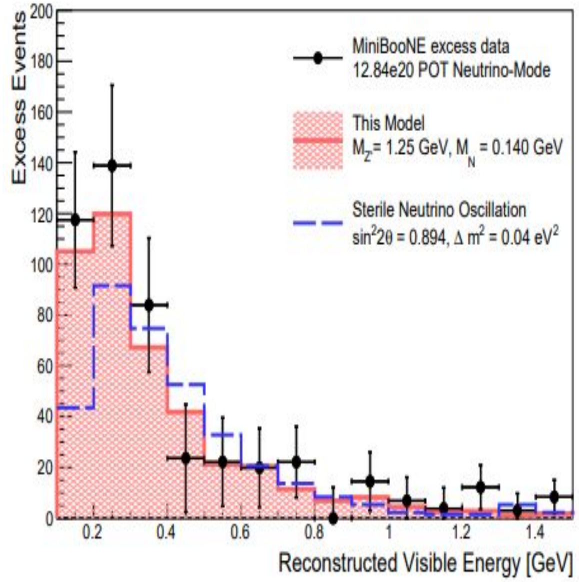

Here for CHARM-II we also consider 3 times larger background uncertainty (dashed)

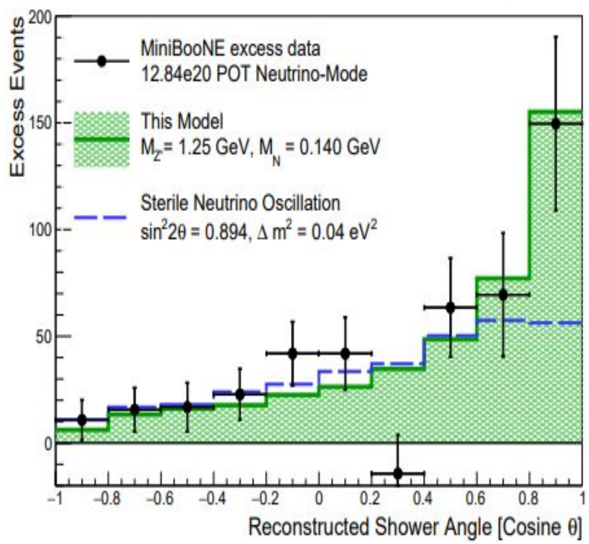
# Take home message: lessons learned

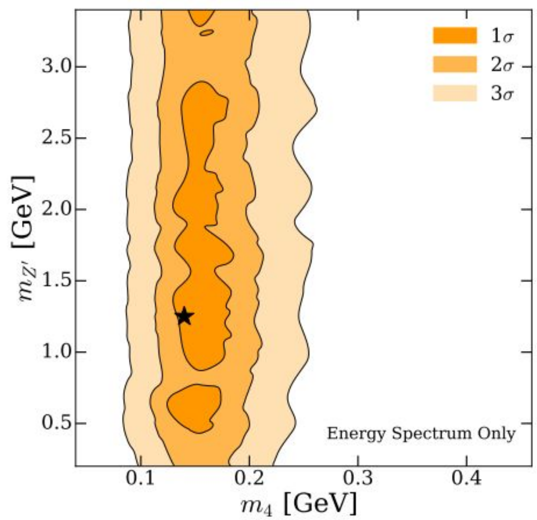
- ➔ We are really excited to see upcoming neutrino-electron scattering analyses by Minerva-ME and NOvA!
- ➔ We have used two different experiments to constrain recent MiniBooNE explanations. Tensions are large with the proposed models.
- ➔ If the MiniBooNE anomaly is due to some new neutrino-dominant interaction: how do we confirm it? We need a new strategy that allow us to overcome neutrino experimental uncertainties.
- ➔ Neutrino electron scattering is a powerful tool to constraint new physics interactions. Our constraints can also be adapted to other MB explanations, such as the dipole portal.

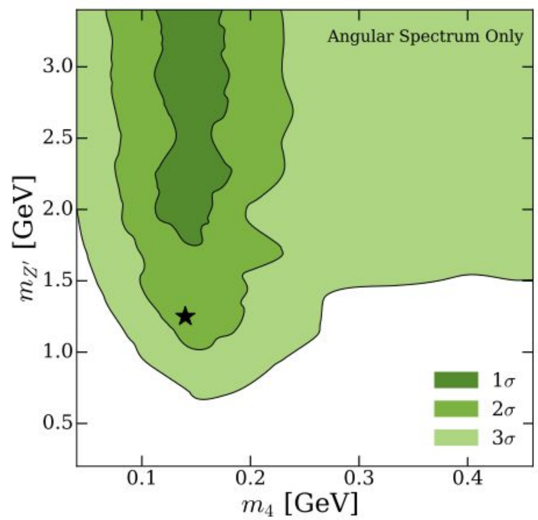
# Bonus slides!

# Model by Ballett et al. parameter space



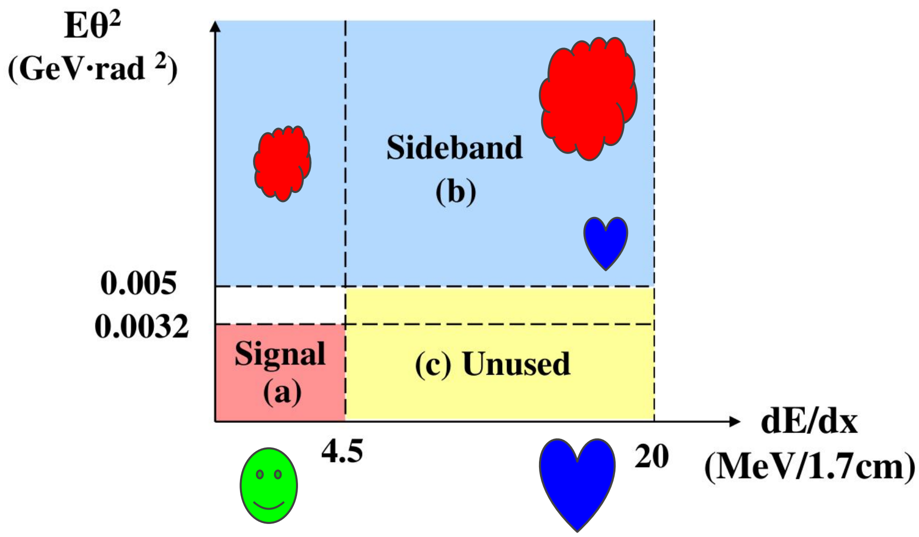



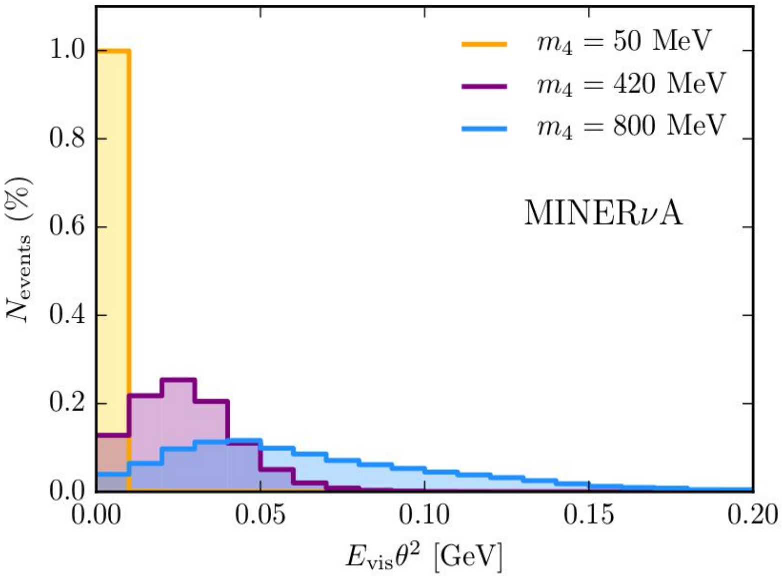



# Sidebans used for tuning background on MINERvA

Tunning parameters diagram from J. Park thesis:
http://lss.fnal.gov/archive/thesis/2000/fermilab-thesis-2013-36.pdf

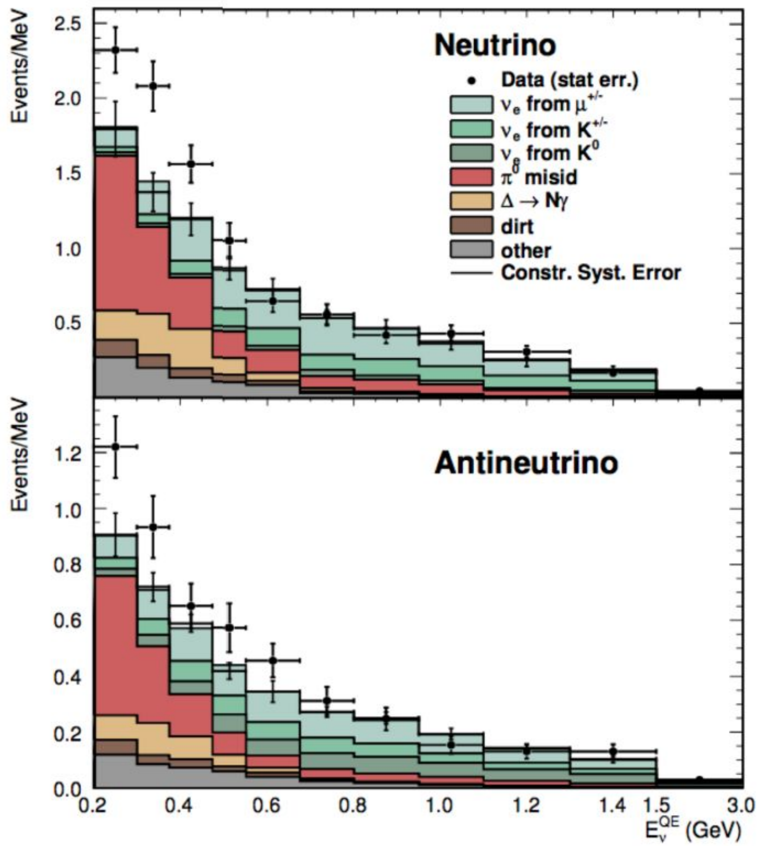


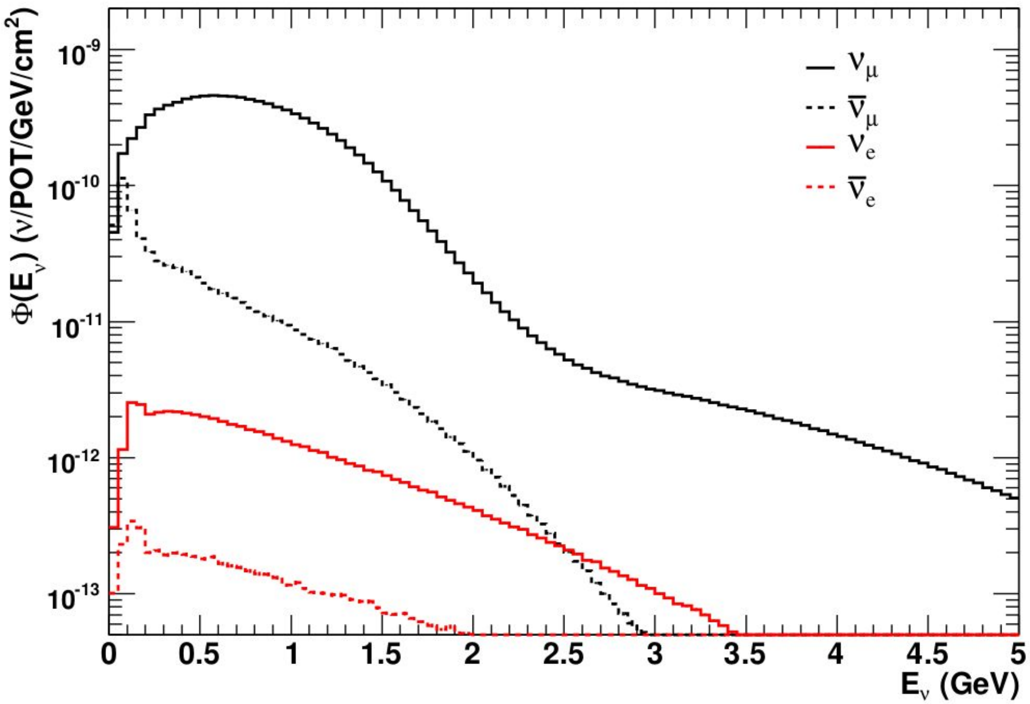

For large heavy neutrino masses the BSM contribution leaks the sideband used to constrain the background on the neutrino electron scattering region.

# MiniBooNE previous results

- Neutrino mode excess above the null primarily under 475 MeV. This is not expected given the LSND signal.
- Antineutrino mode saw excess above and below 475 MeV.
- Antineutrino mode was consistent with LSND, neutrino mode had tension.



# Booster beam

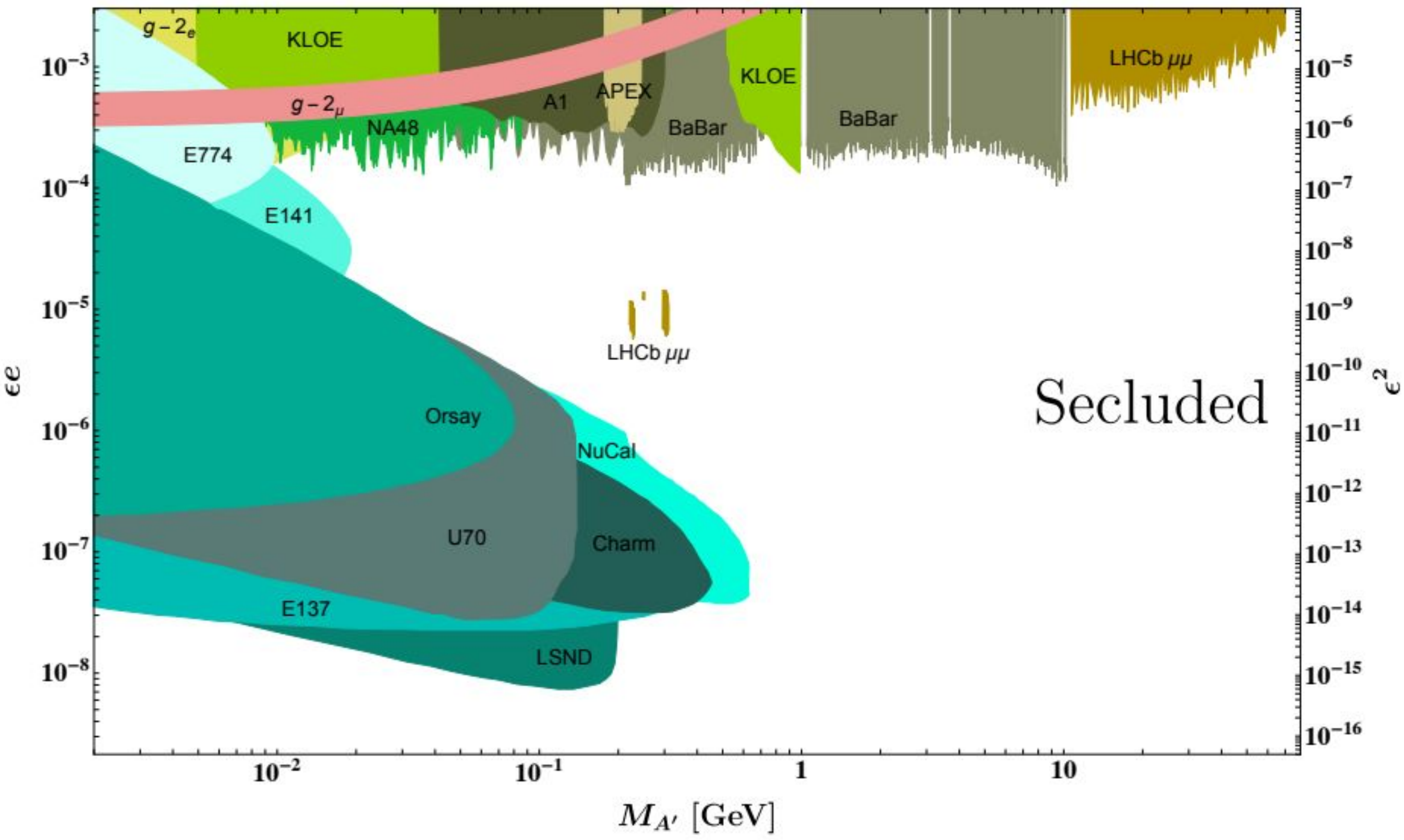



- Maxima < 1 GeV neutrino energy
- Production of heavy states via neutrino interaction: hard.
- Heavier BSM physics look like “effective”-interactions; then angular distribution of excess wont work.

Recent proposals:
Light new physics ~< GeV.

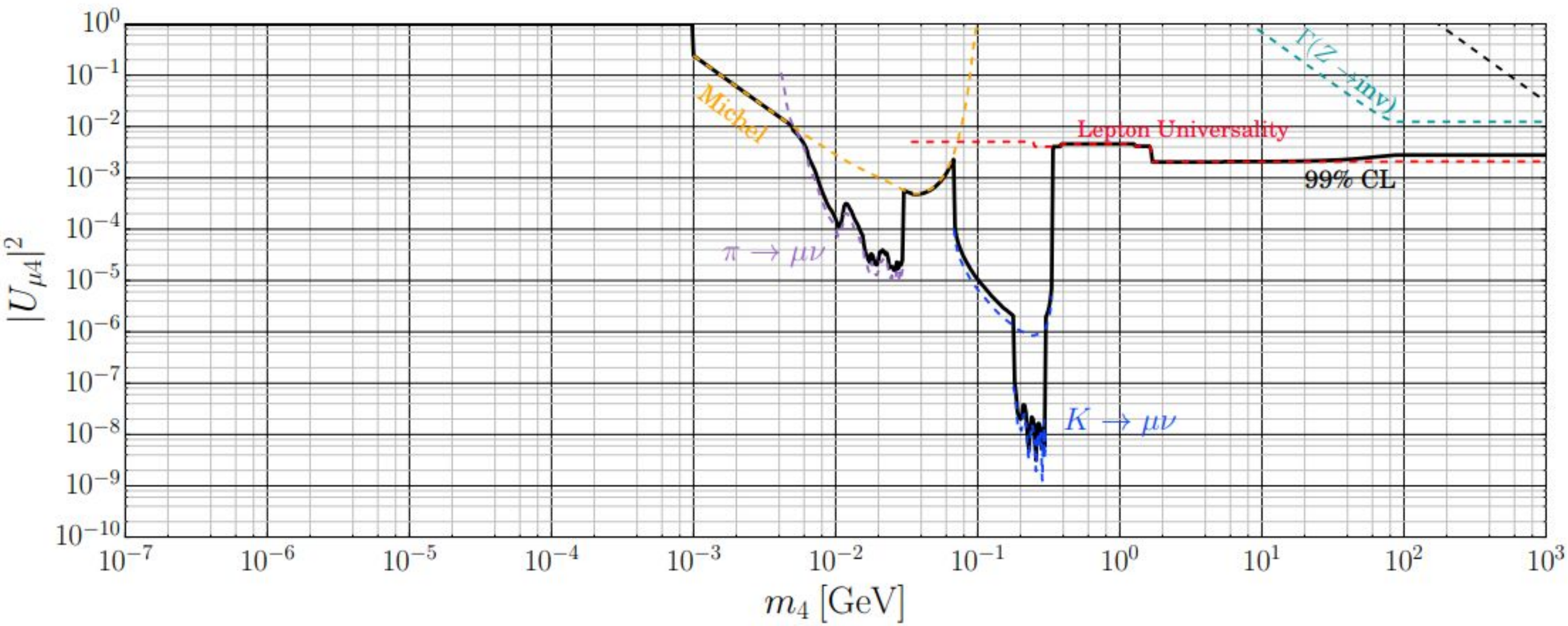
see arXiv:0806.1449

# Dark Photon Searches




see arXiv:1803.05466

# Heavy Neutrino Limits




See arXiv:1511.00683

# MINERvA: Our Analysis setup

We use the following \chi^2 definition:

$$\chi^2_{\alpha\beta} = \frac{(N_{\rm data} - (1+\alpha+\beta)\mu_{\rm MC}^{\rm BKG} - (1+\alpha)\mu_{\rm MC}^{nu-e} - (1+\alpha)\mu_{\rm BSM})^2}{N_{\rm data}} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

- We set \sigma_\alpha = 10% account for beam uncertainties.
- We set \sigma_\beta = 30% motivated by the amount of tuning; conservative with respect to tune normalization uncertainty.
- We include only coherent contribution to the BSM signal to avoid hadronic activity cuts.

# Our CHARM-II analysis setup details

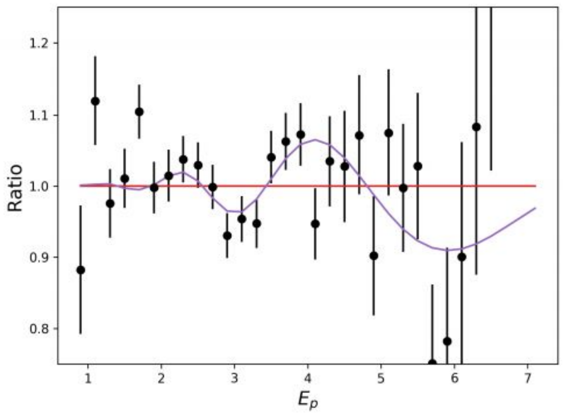
- Rate-only analysis on a single bin with E\theta^2 < 0.03 GeV.

- Same \chi^2 definition as in MINERvA, but updated uncertainties.

- Background norm. from sideband ~ 3%; flux uncertainty ~ 4%.

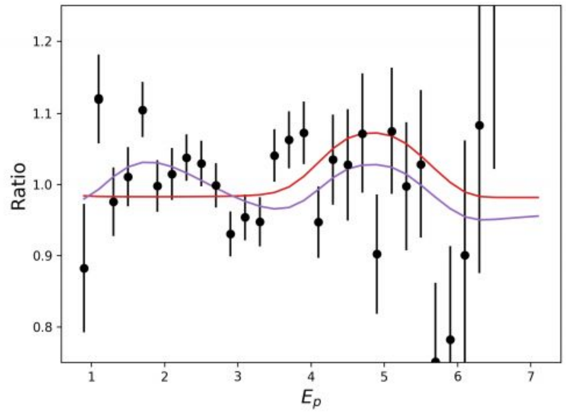
- We assume a fiducial mass of 547tons, <A>~20.7, and 2.5e19 POT.

# Reactor bump and eV-sterile neutrinos



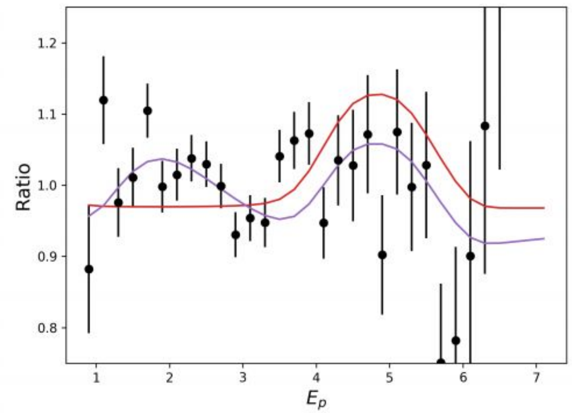

(a) No 5 MeV excess flux model.

chi^2: 62 ->50




(b) An equal 5 MeV excess for all fuel components.

chi^2: 69 ->58




(c) A 5 MeV excess for $^{235}$U only.

chi^2: 84 ->61

| Experiment | Average $L$ | Observation | Core Type | Detector Size | n-capture | Ref. |
|---|---|---|---|---|---|---|
| PROSPECT | 8 m | No Excess | HEU | $< 10$ t | Li | [81] |
| ILL | 9 m | No Excess | HEU | $< 1$t | He | [82] |
| STEREO | 10 m | No Excess | HEU | $< 10$ t | Gd | [86] |
| Bugey | 15, 40, and 90 m | No Excess at any position | HEU | $< 10$ t | Li | [56] |
| ROVNO | 18 m | Excess | LEU | $< 10$ t | Gd | [84] |
| Savannah River | 18 and 24 m | No Excess and Unclear | LEU | $< 1$ t | Gd | [83] |
| NEOS | 24 m | Excess | LEU | $< 1$ t | Gd | [57] |
| Goesgen | 38, 46 and 65 m | Excess | LEU | $< 1$ t | He | [85] |
| RENO | 294 m | Excess | LEU | $> 10$ t | Gd | [40] |
| Daya Bay | 512 and 561 m | Excess | LEU | $> 10$ t | Gd | [87] |
| Double Chooz | 1050 m | Excess | LEU | $> 10$ t | Gd | [88] |

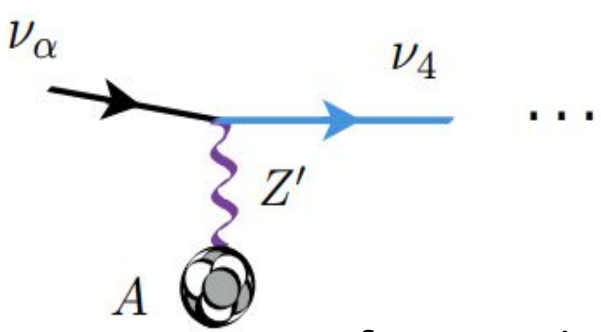
A. Diaz, CA, G.Collin, JM. Conrad, M. Shaevitz arXiv:1902.00517

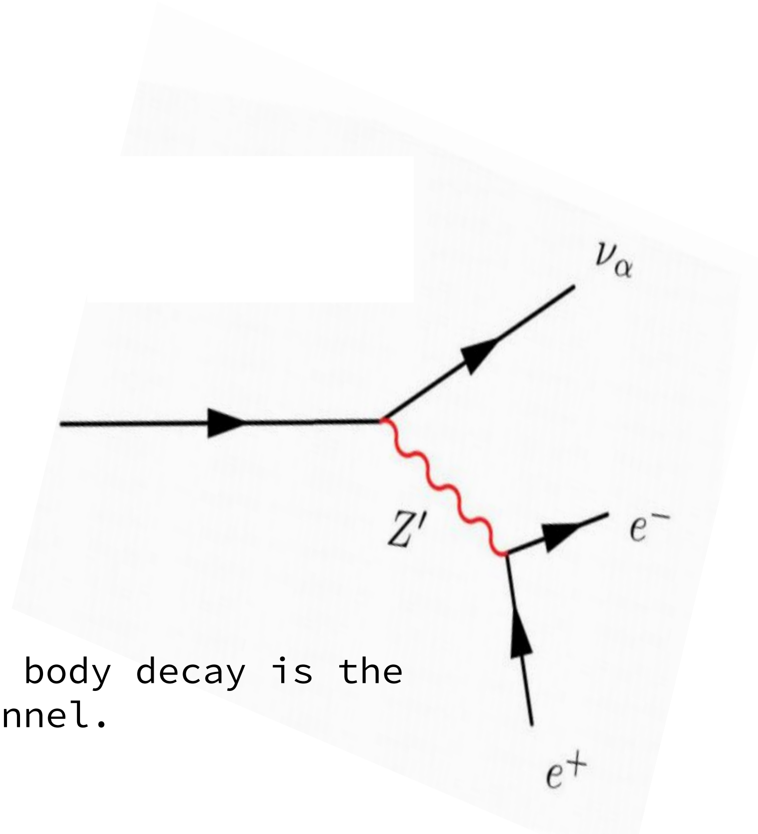
# Best-fits

| Fit type: | $3\nu$ (null) | 3+1 | 3+2 | 3+1+decay |
|---|---|---|---|---|
| Best Fits | | | | |
| $\chi^2$ | 493 | 458 | 449 | 450 |
| $dof$ | 509 | 506 | 502 | 505 |
| $p$-value | 0.687 | 0.938 | 0.957 | 0.962 |
| (Null vs Sterile) | | | | |
| $\Delta\chi^2$ | | 35 | 44 | 43 |
| $\Delta dof$ | | 3 | 7 | 4 |
| $p$-value | | 1.2E-07 | 2.1E-07 | 1.0E-08 |
| $N\sigma$ | | 5.2 | 5.1 | 5.6 |
| (3+1 vs Other) | | | | |
| $\Delta\chi^2$ | | | 9 | 8 |
| $\Delta dof$ | | | 4 | 1 |
| $p$-value | | | 0.0611 | 0.0047 |
| $N\sigma$ | | | 1.5 | 2.6 |
| (PG Test) | | | | |
| $\chi^2_{app}$ | | 77 | 69 | 77 |
| $N_{app}$ | | 2 | 5 | 3 |
| $\chi^2_{dis}$ | | 356 | 350 | 356 |
| $N_{dis}$ | | 3 | 6 | 4 |
| $\chi^2_{glob}$ | | 458 | 449 | 450 |
| $N_{glob}$ | | 3 | 7 | 4 |
| $\chi^2_{PG}$ | | 25 | 30 | 17 |
| $N_{PG}$ | | 2 | 4 | 3 |
| $p$-value | | 3.7E-06 | 4.9E-06 | 7.1E-04 |
| $N\sigma$ | | 4.5 | 4.4 | 3.2 |

# Producing the MiniBooNE signature

**Model from Ballett et al.**
**arXiv:1808.02915; see also 1903.07589.**




If M4 < MZ’, three body decay is the dominant decay channel.

M4 ~> 300 MeV: large too many high-energy events
M4 ~< 50 MeV most events in lowest energy bin.

MZ’ ~< 1 GeV: spectrum is too forward.