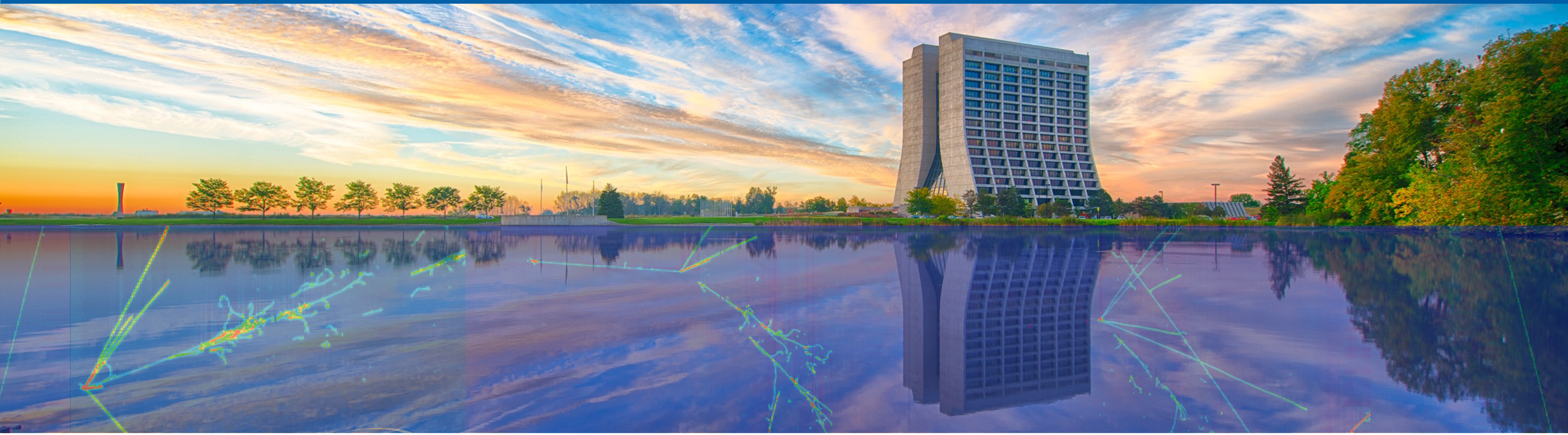


Big Questions in Particle Physics: The Low Energy Excess

Bonnie Fleming and Pedro Machado

January, 2022

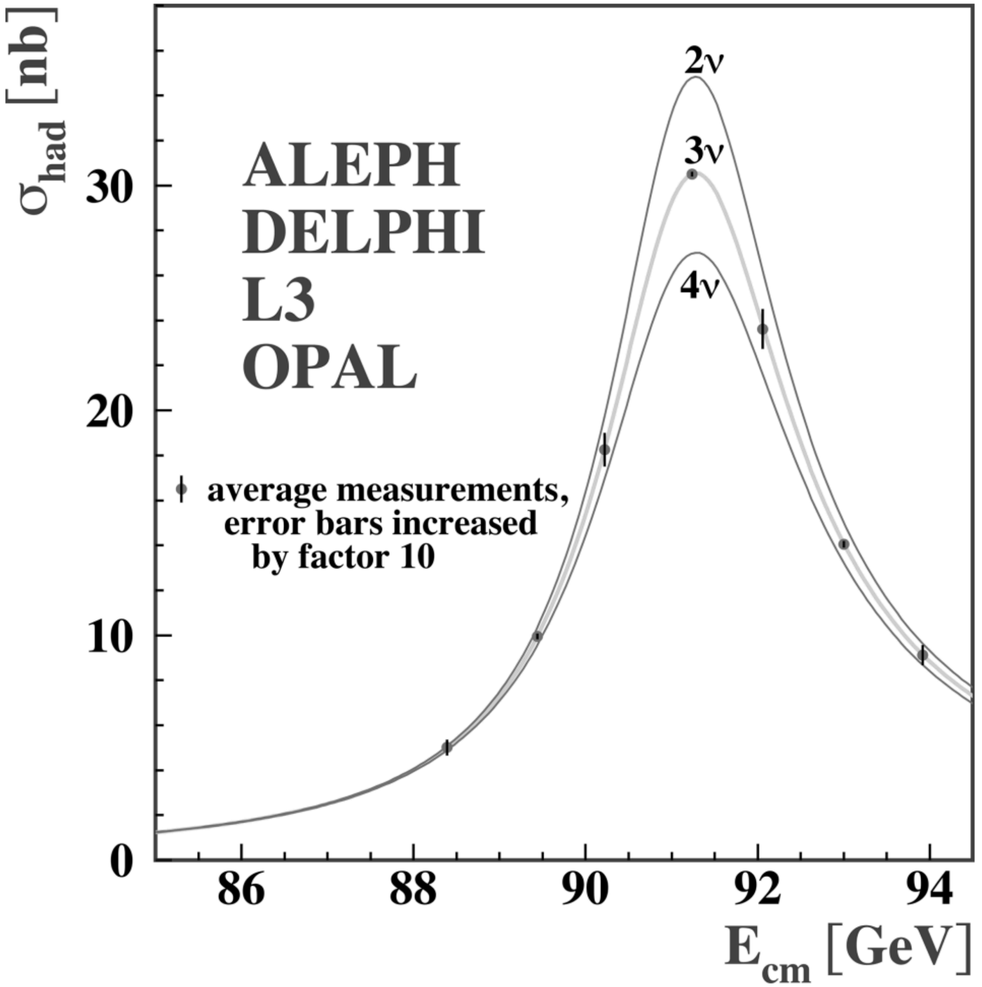
Interpretation of MicroBooNE results in terms of sterile neutrinos

Neutrinos have no strong interactions and no electric charge

Neutrino weak interactions affect the decays of the Z boson

We have measured directly and indirectly the decay of Z bosons to “invisible” particles

All is consistent with 3 neutrinos, as predicted in the standard model



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Interpretation of MicroBooNE results in terms of sterile neutrinos

But there could be neutrinos without weak interactions: **sterile neutrinos**

These could have no known interaction with usual matter

But they could still affect neutrino oscillations

Can the MiniBooNE excess of ν_e coming from ν_μ oscillations be due to sterile neutrinos?

$$P_{\text{app}} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2[\text{eV}^2] L[\text{m}]}{E[\text{MeV}]} \right)$$

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Interpretation of MicroBooNE results in terms of sterile neutrinos

Within the sterile neutrino framework,
ν_μ to ν_e appearance
should be accompanied by both
ν_e and ν_μ disappearance

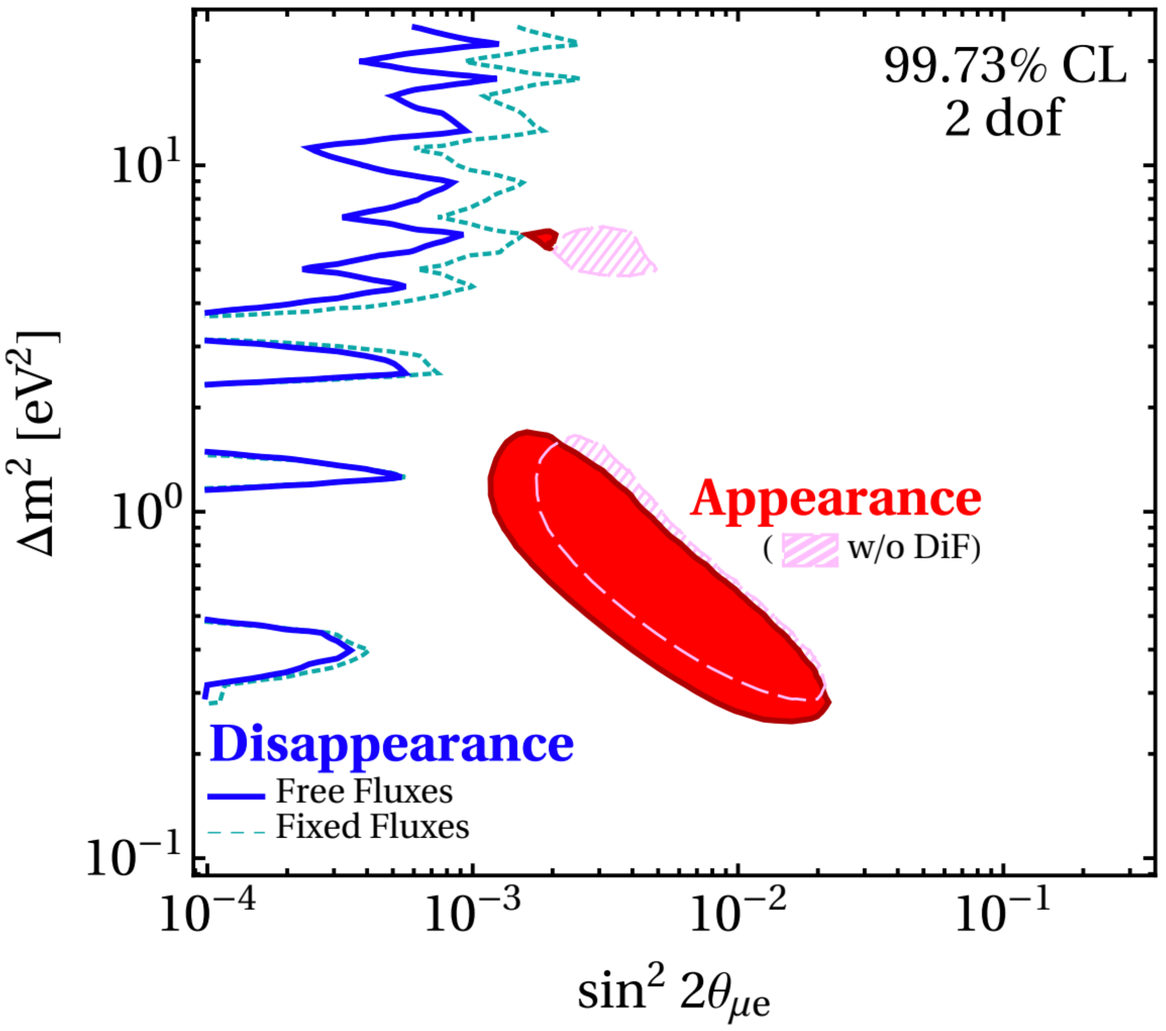
There is tension in this interpretation of all experimental data, particularly due to disappearance data

But check out last night's paper on how **wave packet considerations could change the overall sterile neutrino landscape** by Arguelles Bertoléz-Martínez Salvado 2201.05108

Situation is highly unclear

We need MicroBooNE

Dentler **PM** et al 1803.10661



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Interpretation of MicroBooNE results in terms of sterile neutrinos

We performed a detailed simulation of MicroBooNE, following the official data releases and accounting carefully for neutrino energy reconstruction, systematic uncertainties, …

Here is what we get

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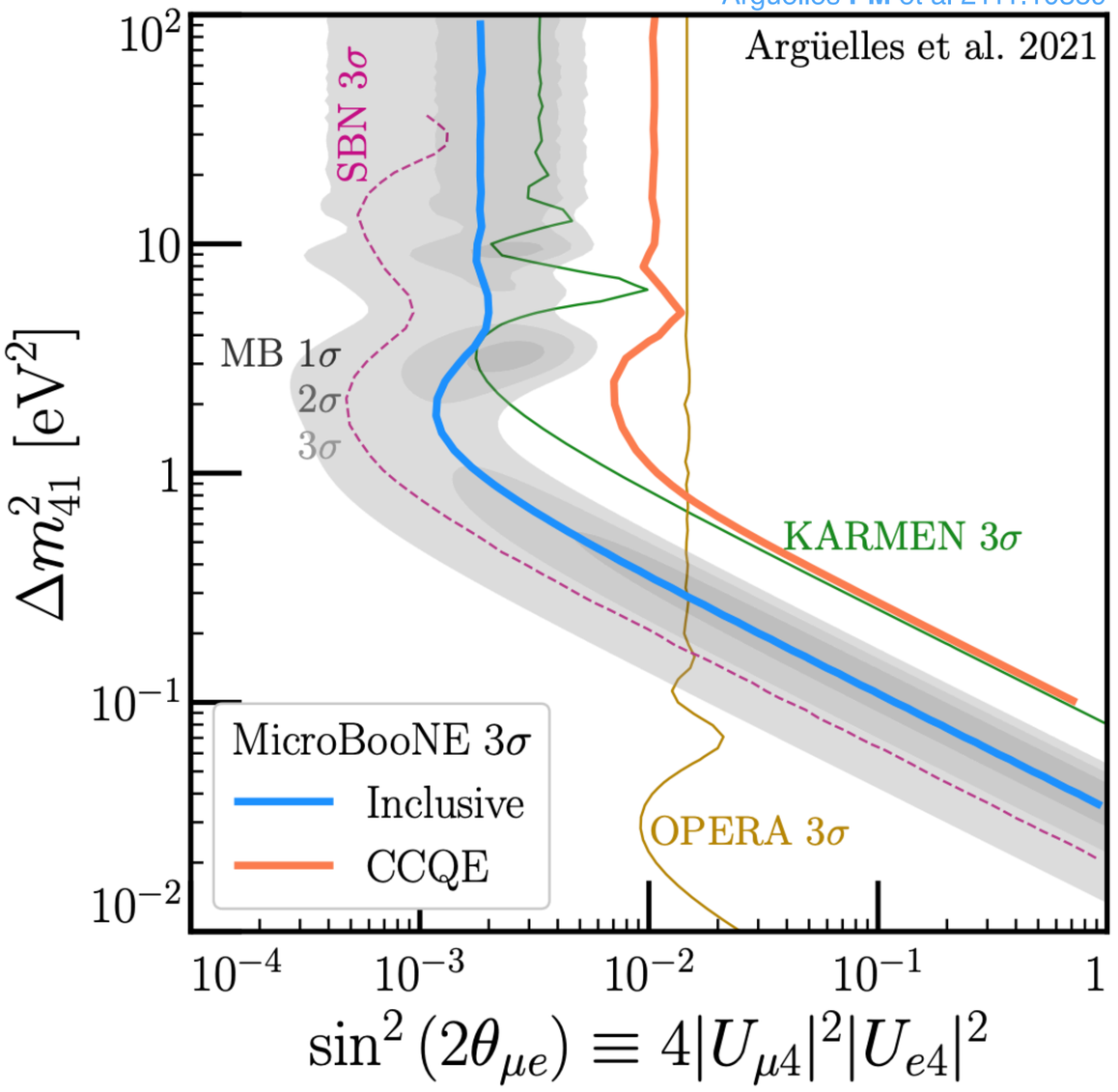
Interpretation of MicroBooNE results in terms of sterile neutrinos

MicroBooNE inclusive analysis is cutting right through the MiniBooNE preferred region!

MicroBooNE currently provides the **most stringent constrain to date** on ν_e appearance

Future SBN combined analysis (SBND + μB + ICARUS) could essentially rule out the MB sterile neutrino interpretation with excellent significance

Arguelles **PM** et al 2111.10359



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Interpretation of MicroBooNE results in terms of sterile neutrinos

This result is a landmark on neutrino physics and it motivates the question:

If not sterile neutrinos, then what?

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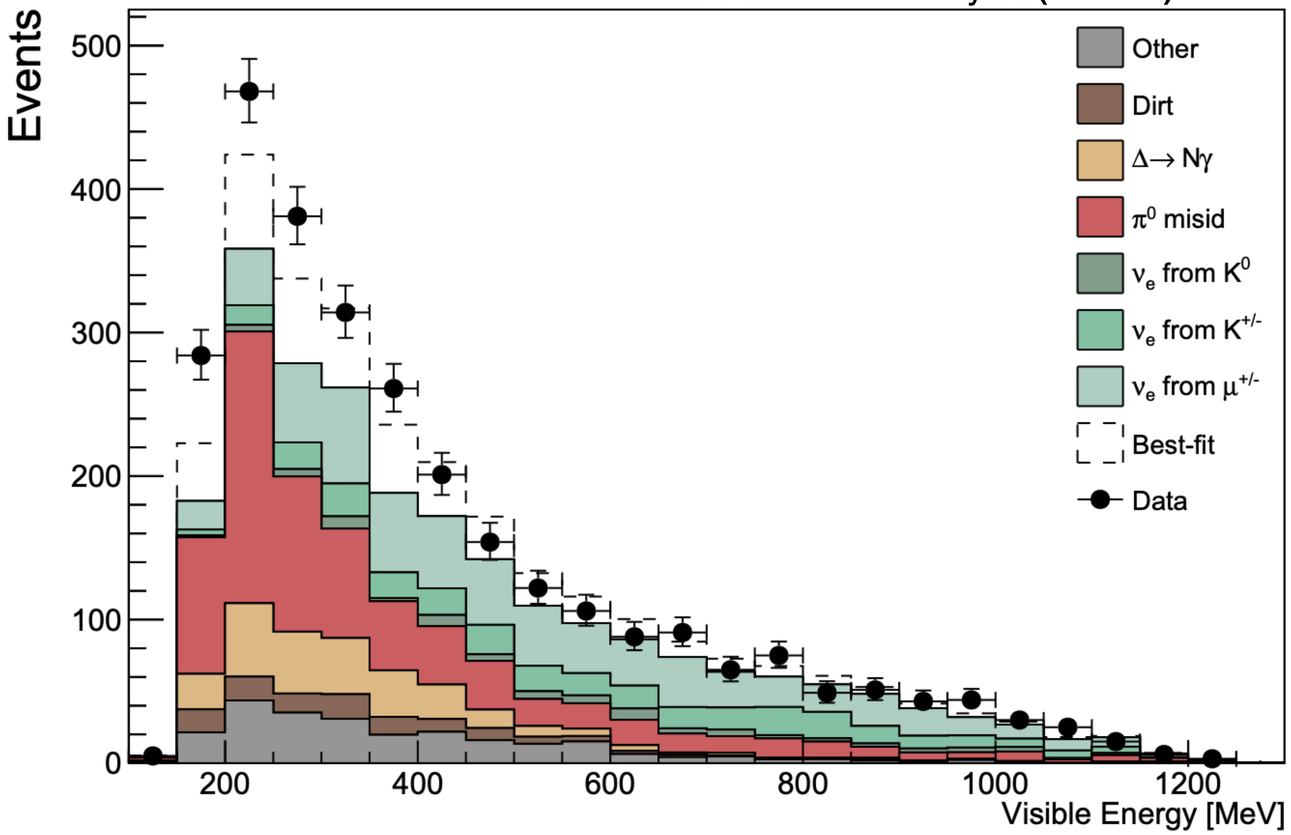
Dark neutrinos and other explanations of the MiniBooNE anomaly

arXiv:2006.16883v3 [hep-ex] 8 Mar 2021

Updated MiniBooNE neutrino oscillation results with increased data and new background studies

Excess: $638 \pm 52.1_{stat} \pm 122.2_{syst}$ (4.8σ)



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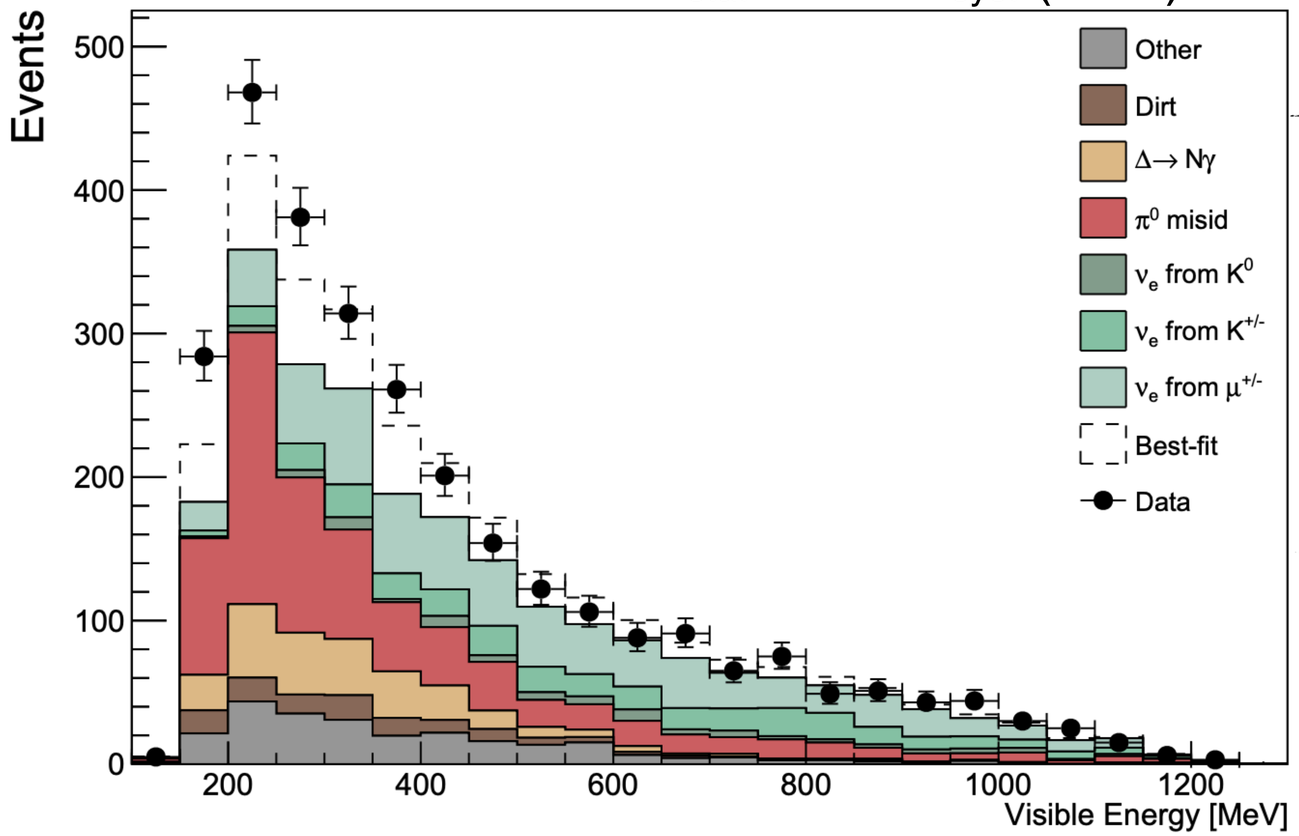

If the obvious explanations don't work, how do we explain this data?

Take a step back a look at the experiment again

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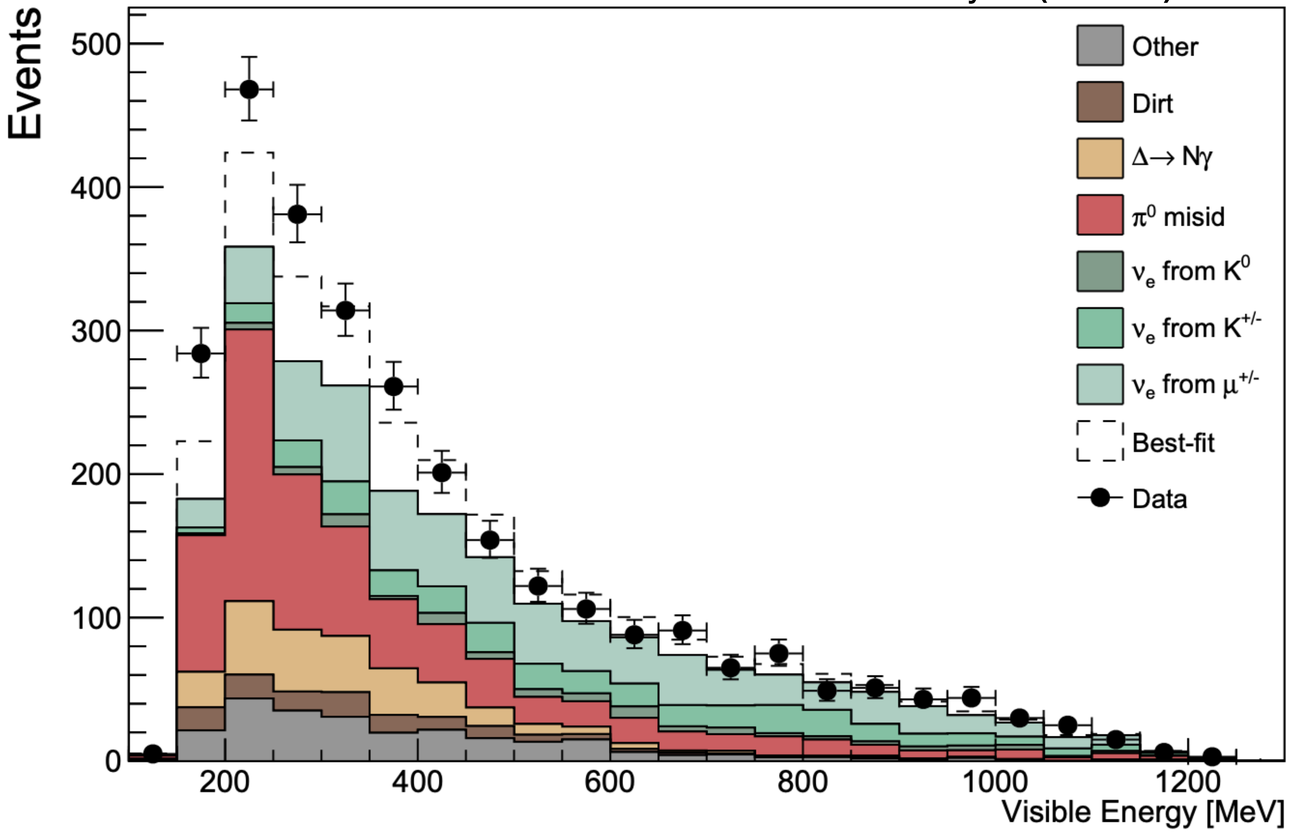

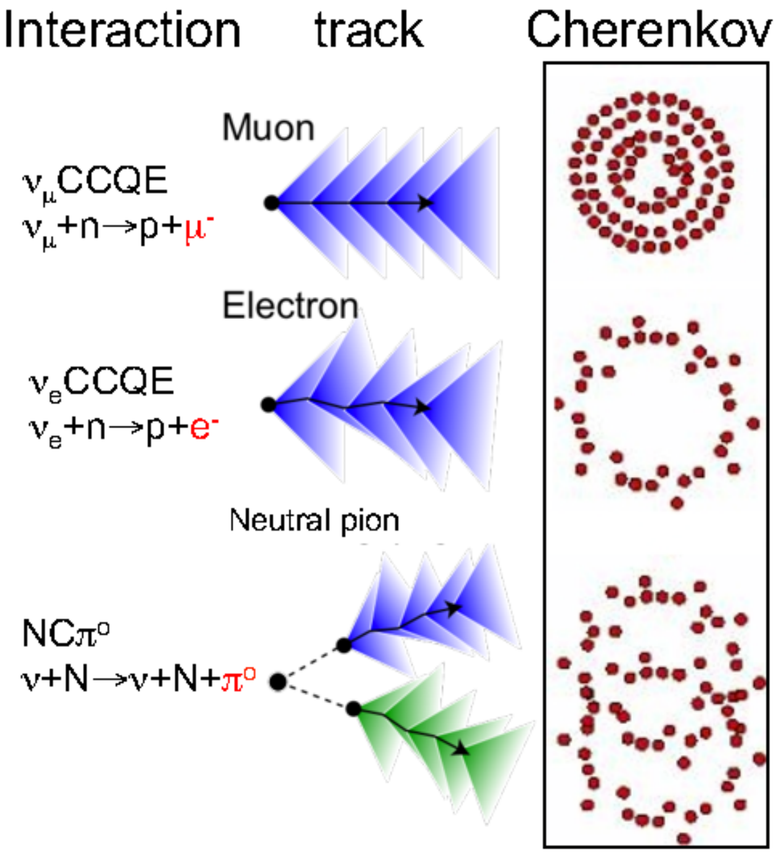

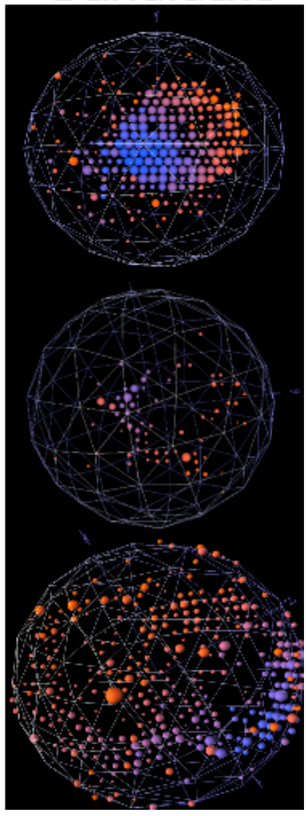

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Dark neutrinos and other explanations of the MiniBooNE anomaly

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801
Bertuzzo, **PM** et al Phys.Lett.B 791 (2019) 210-214

Can we explain this data in an ultraviolet complete model?

UV complete as opposed to an effective theory (it needs to be renormalizable, to respect gauge symmetries, anomaly free, …)

Can we relate it to any of the outstanding questions of the standard model, for instance to the **origin of neutrino masses**?

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Yes!

Let me show you how

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Dark neutrinos and other explanations of the MiniBooNE anomaly

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801
Bertuzzo, **PM** et al Phys.Lett.B 791 (2019) 210-214

Right handed neutrinos are part of a dark sector, with their own interactions

This forbids neutrino masses just like SM fermions are massless without the Higgs

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Dark neutrinos and other explanations of the MiniBooNE anomaly

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801
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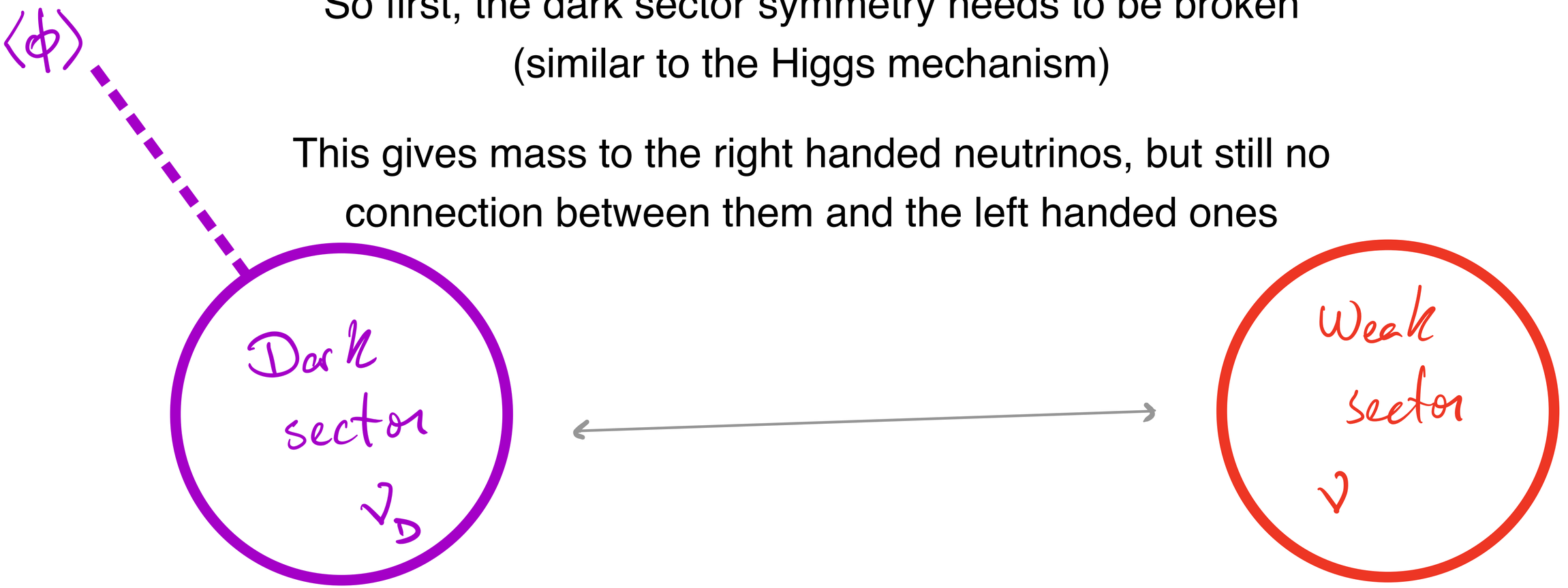
So first, the dark sector symmetry needs to be broken (similar to the Higgs mechanism)

This gives mass to the right handed neutrinos, but still no connection between them and the left handed ones



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Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801
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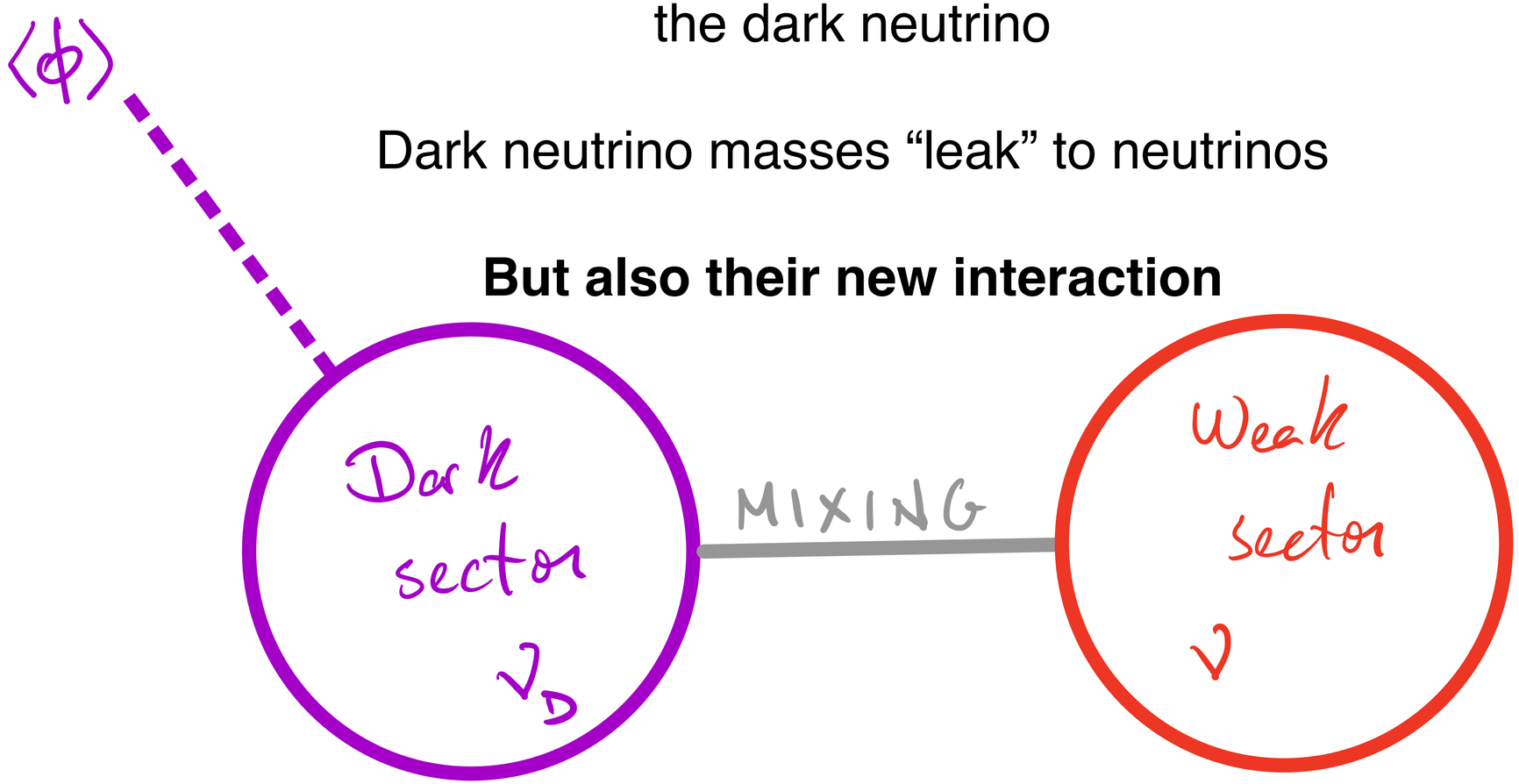
The last ingredient is mixing between the neutrino and the dark neutrino

Dark neutrino masses “leak” to neutrinos

But also their new interaction



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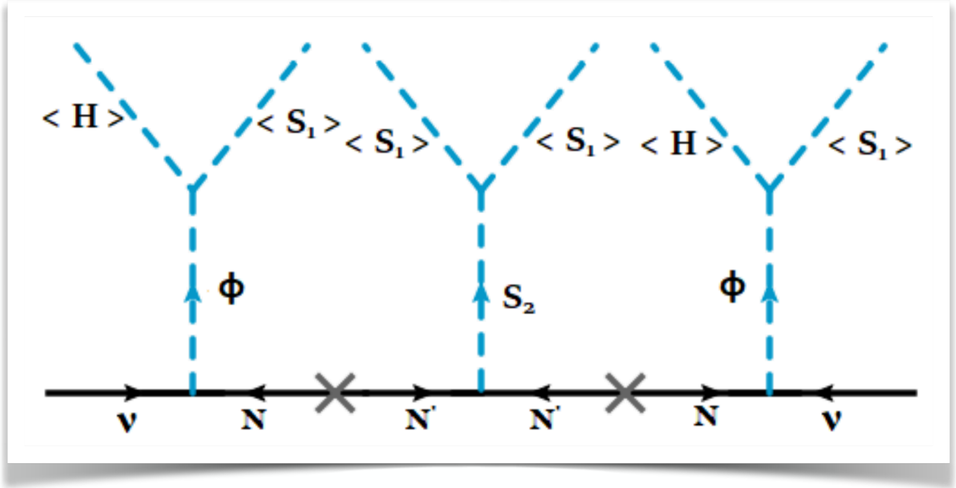
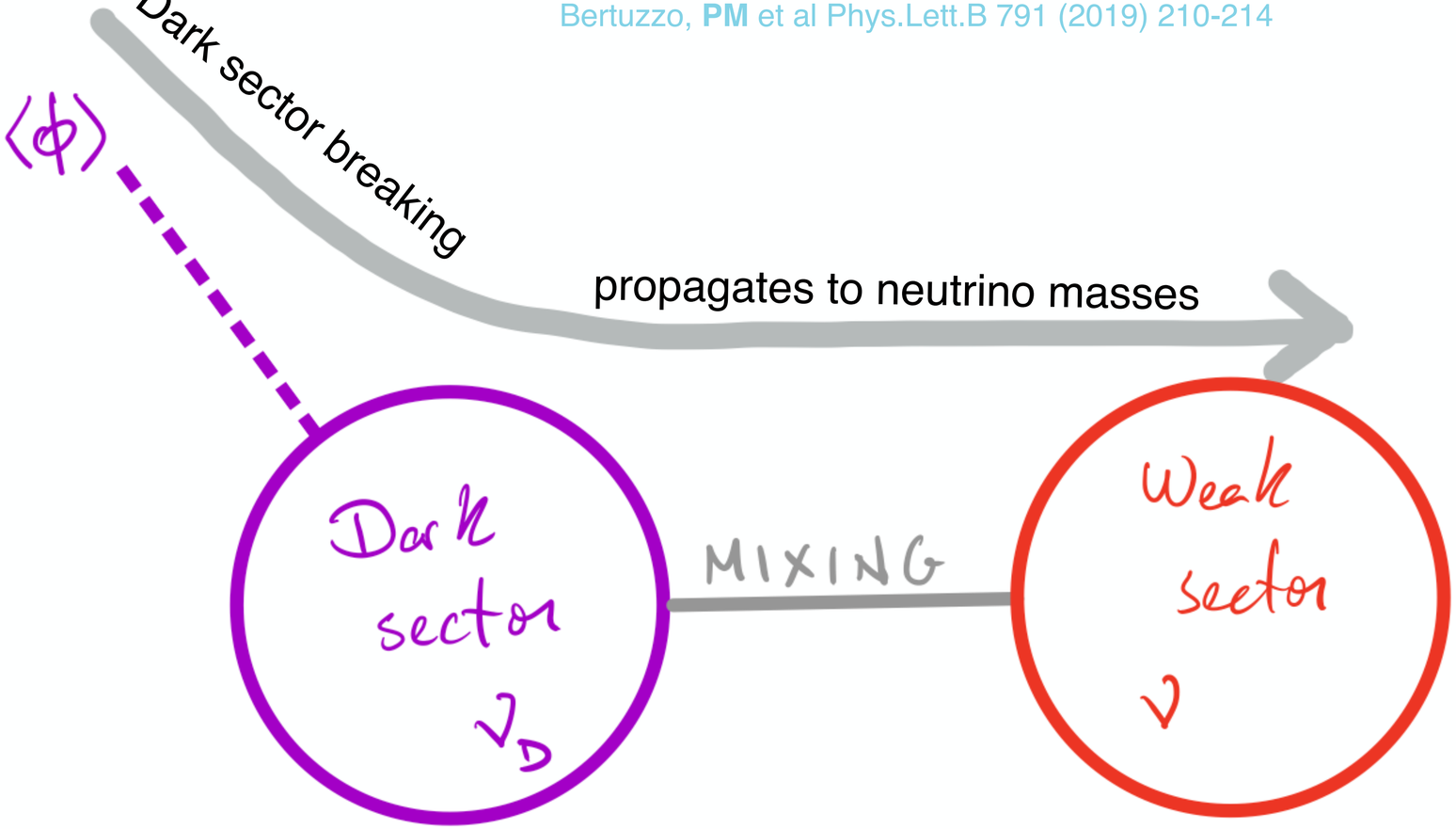
Dark neutrinos and other explanations of the MiniBooNE anomaly

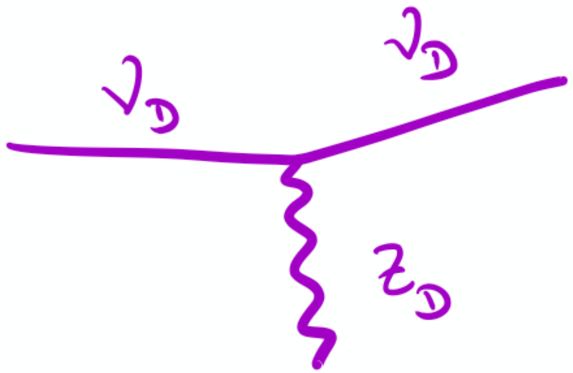
Because of mixings in the neutrino sector and between dark forces and the photon,

neutrinos would be a portal to new physics

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801
Bertuzzo, **PM** et al Phys.Lett.B 791 (2019) 210-214







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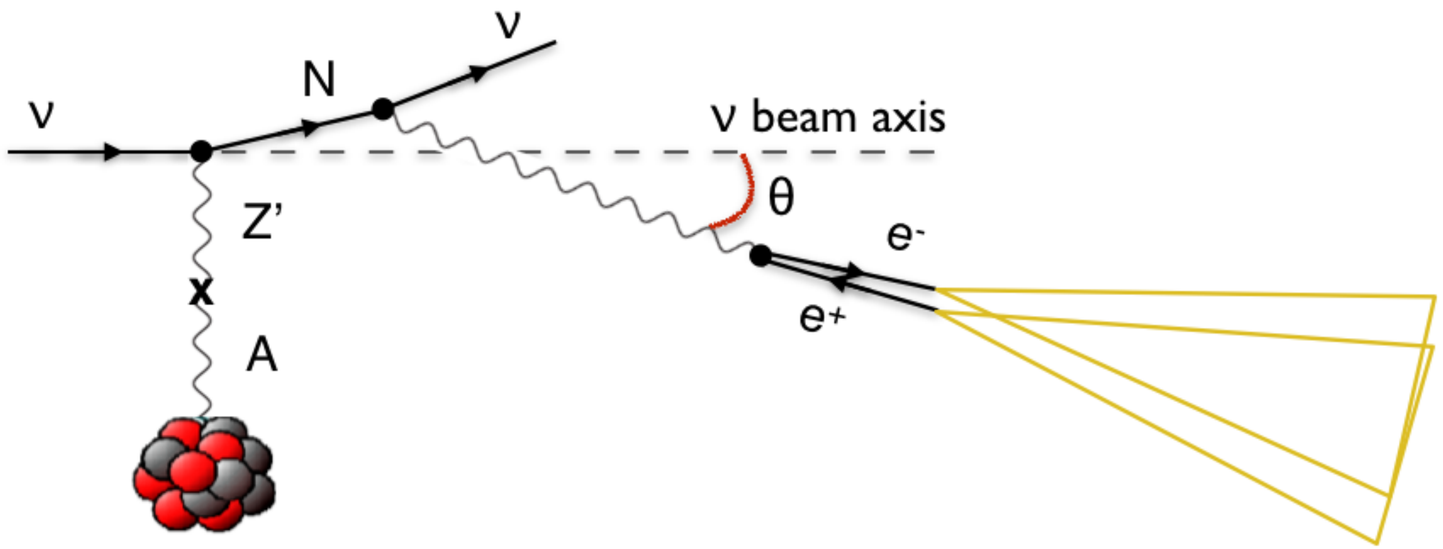
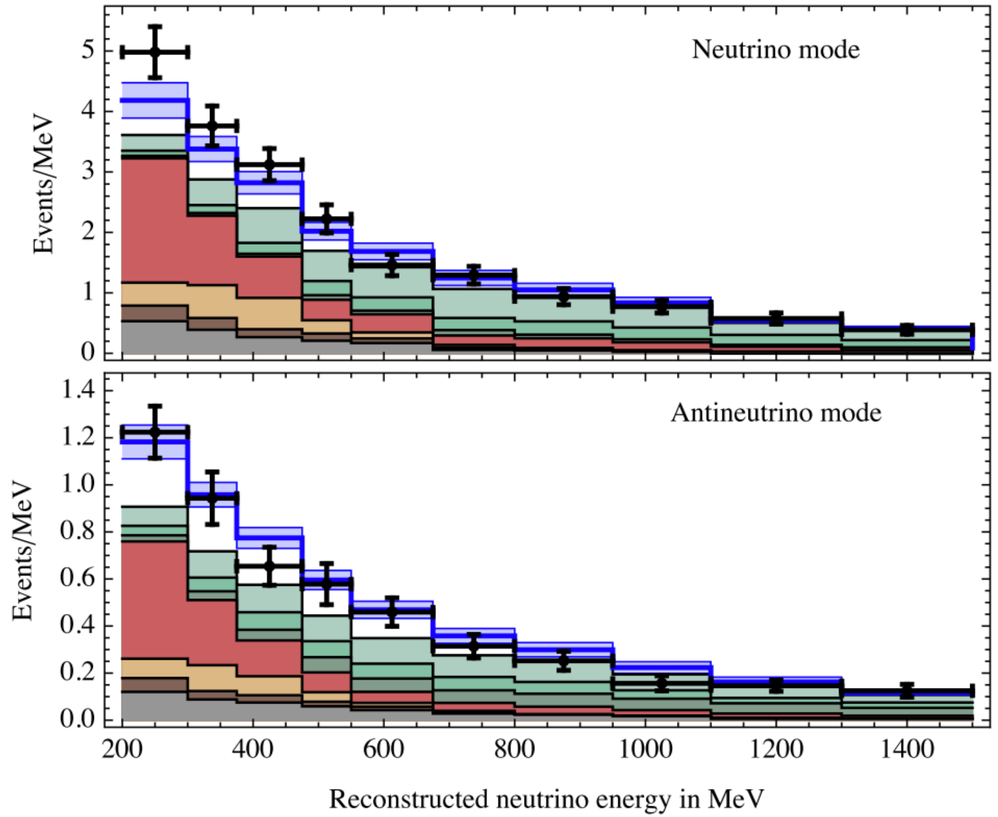
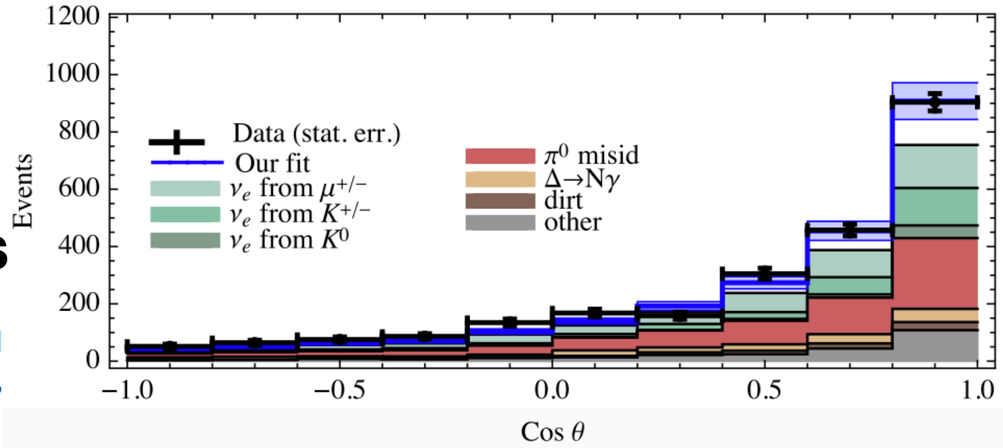


1. Neutrinos up-scatter to *dark neutrinos*
2. *Dark neutrinos* have new interaction
3. N_D decays to collimated e^+e^- pair
4. MiniBooNE classifies that as electron-like event

UV completion is related to origin of neutrino masses





Dark neutrinos and other explanations of the MiniBooNE anomaly

MiniBooNE cannot distinguish among electrons, collimated e^+e^- pairs and photons

Therefore, several models involving oscillations or not
may explain the MiniBooNE excess

But they could look fairly different in LArTPCs…

Interestingly, MicroBooNE's proposal had nothing about e^+e^- pairs,
but the technology allows you to leverage it for distinguishing models

Bertuzzo et al 1807.09877; Arguelles et al 1812.08768; Ballett et al 1808.02915, 1903.07589; Abdullahi et al 2007.11813; Dutta et al 2006.01319; Gninenko 0902.3802, 1201.5194; Vergani et al 2105.06470; Brdar et al 2007.14411; …

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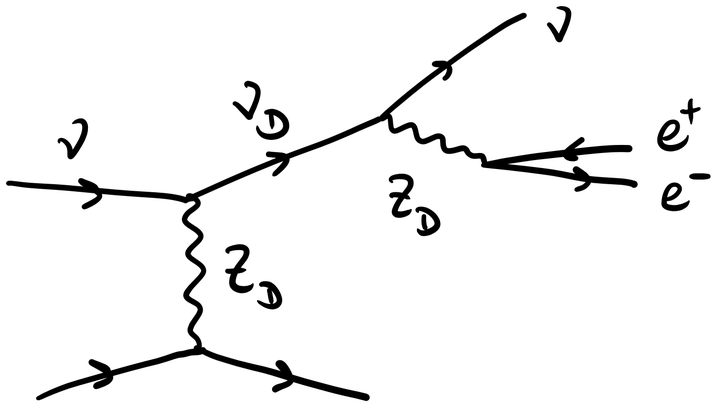
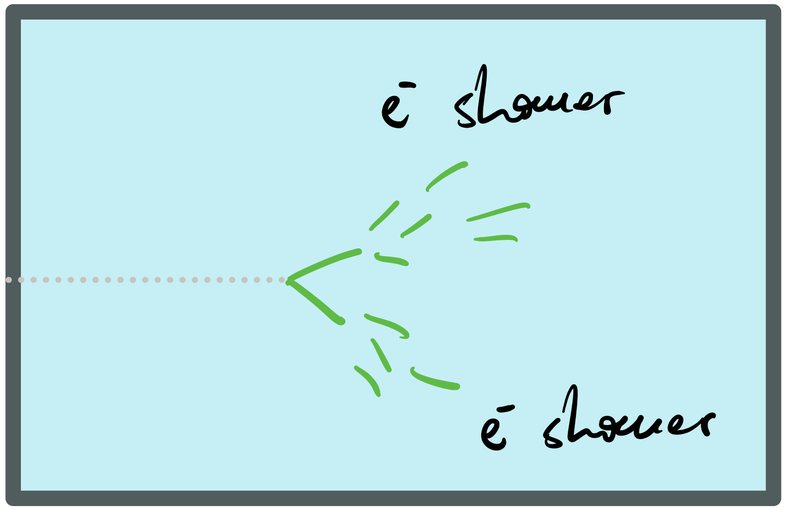
Dark neutrino, light Z’





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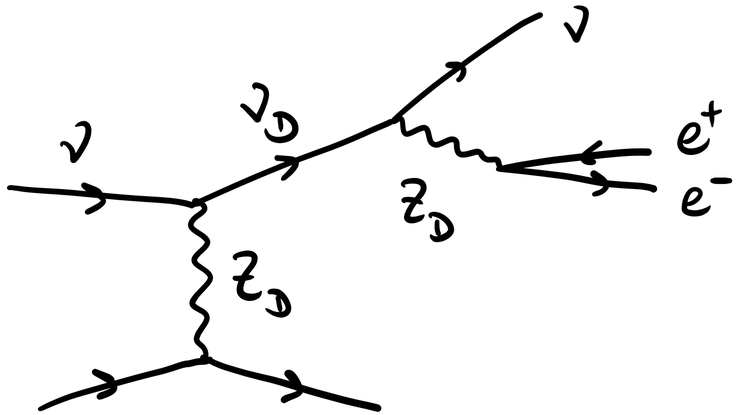
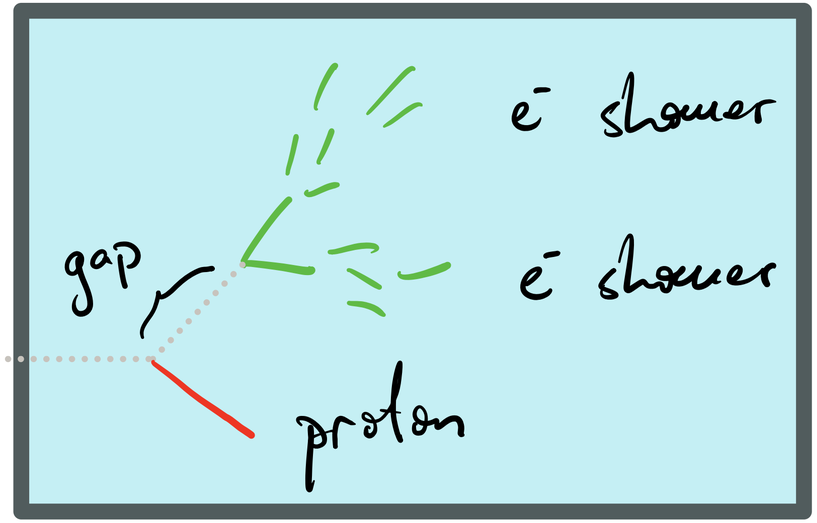
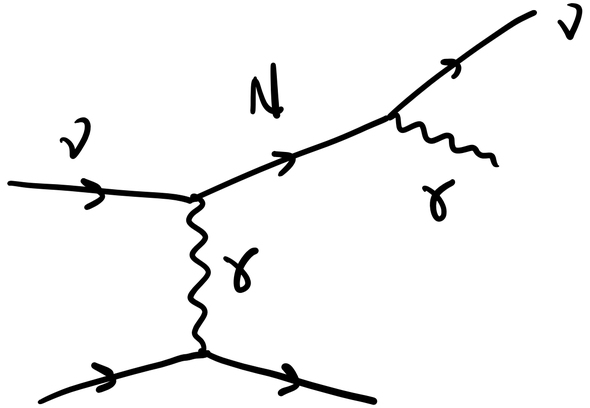
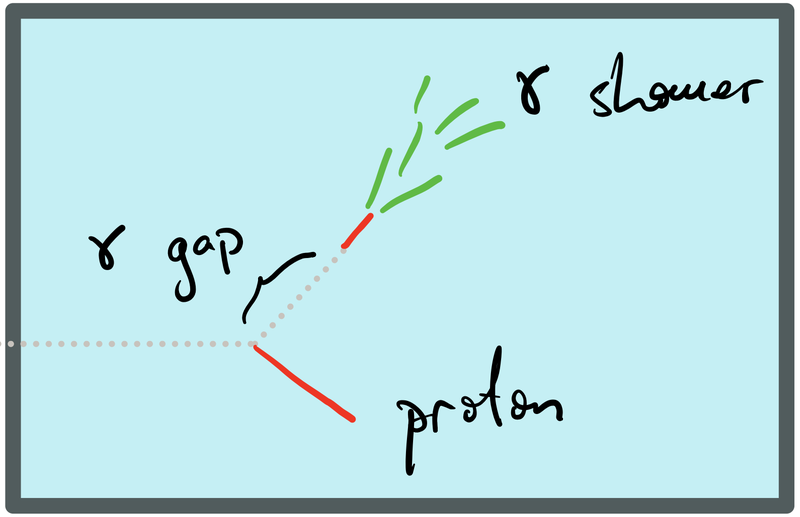




Transition magnetic moment





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Dark neutrinos and other explanations of the MiniBooNE anomaly

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801

Several possibilities

Model related: $M_N > M_{Z'}$ or $M_{Z'} > M_N$; transition magnetic moment; scalar mediator; …

Pheno related: single photon versus e^+e^- pair; different e^+e^- opening angles; different amount of hadronic activity; coherent enhancement (more events in ^{40}Ar compared to ^{12}C); …

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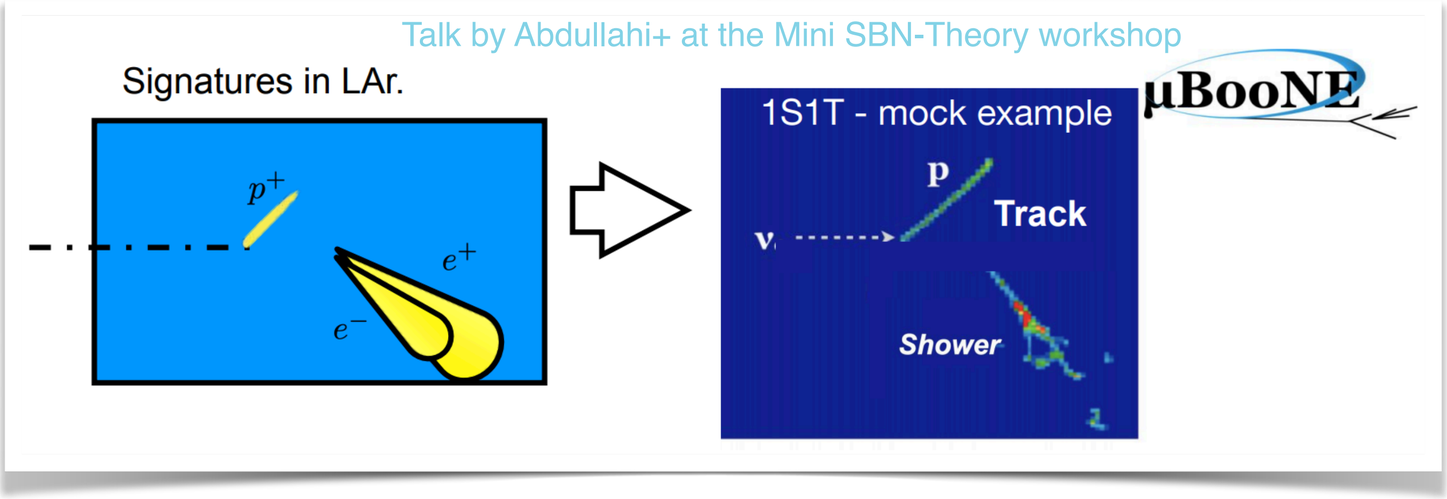
Signature driven searches could efficiently cover most, if not all, of the model parameter space

Talk by Abdullahi+ at the Mini SBN-Theory workshop



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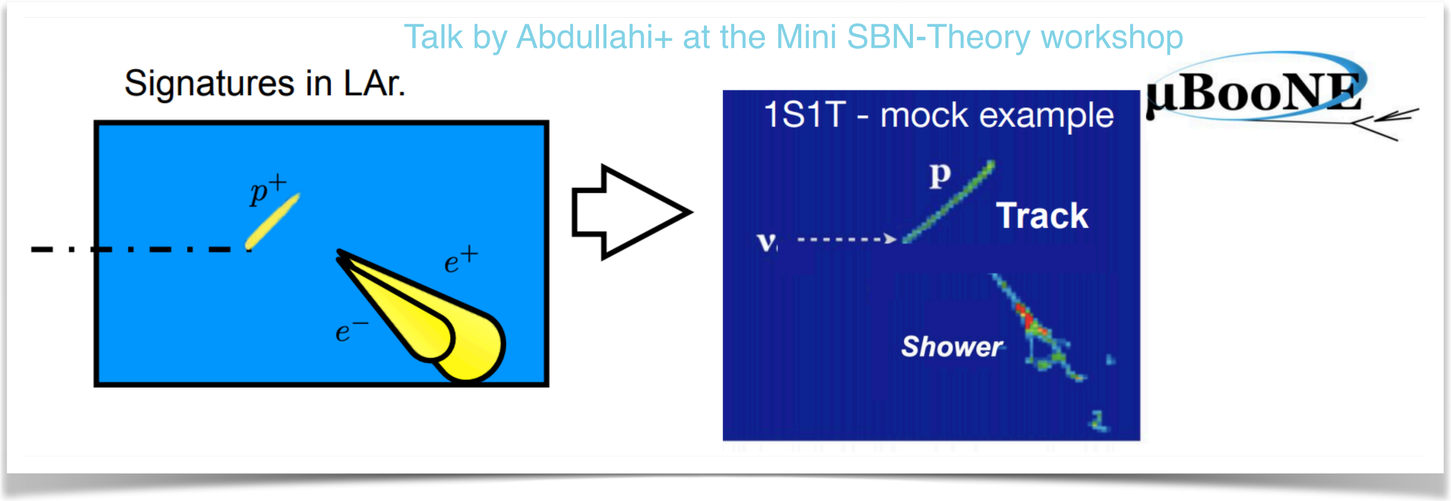

Backgrounds and experimental handles depend on experiment itself and the model realization

- MicroBooNE
- ICARUS
- SBND
- T2K near detector
- IceCube
- …

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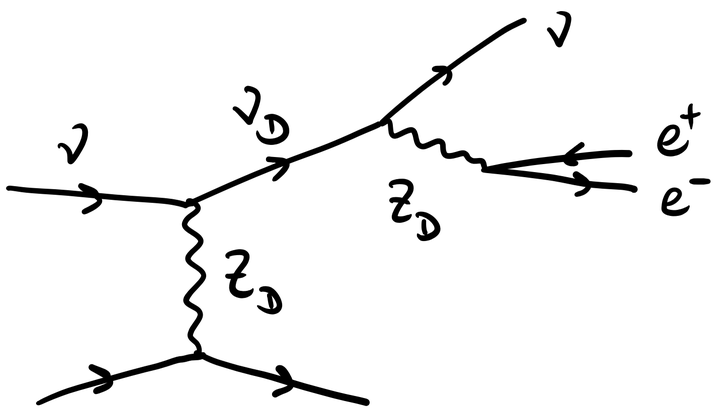
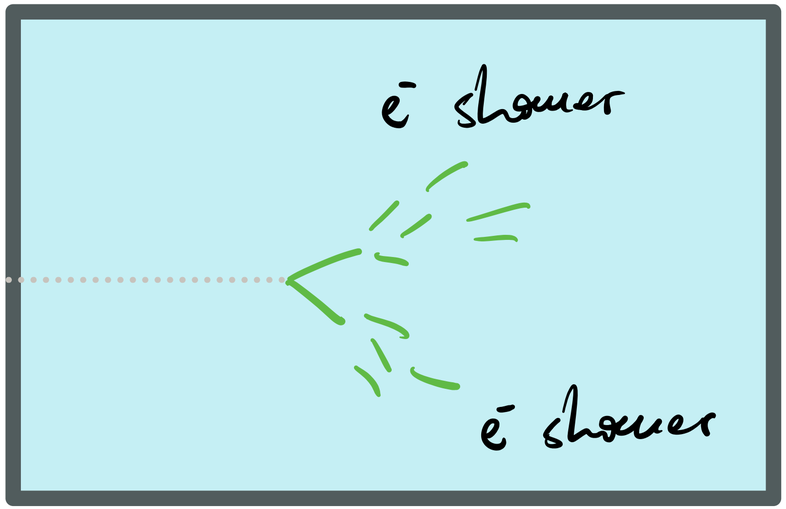


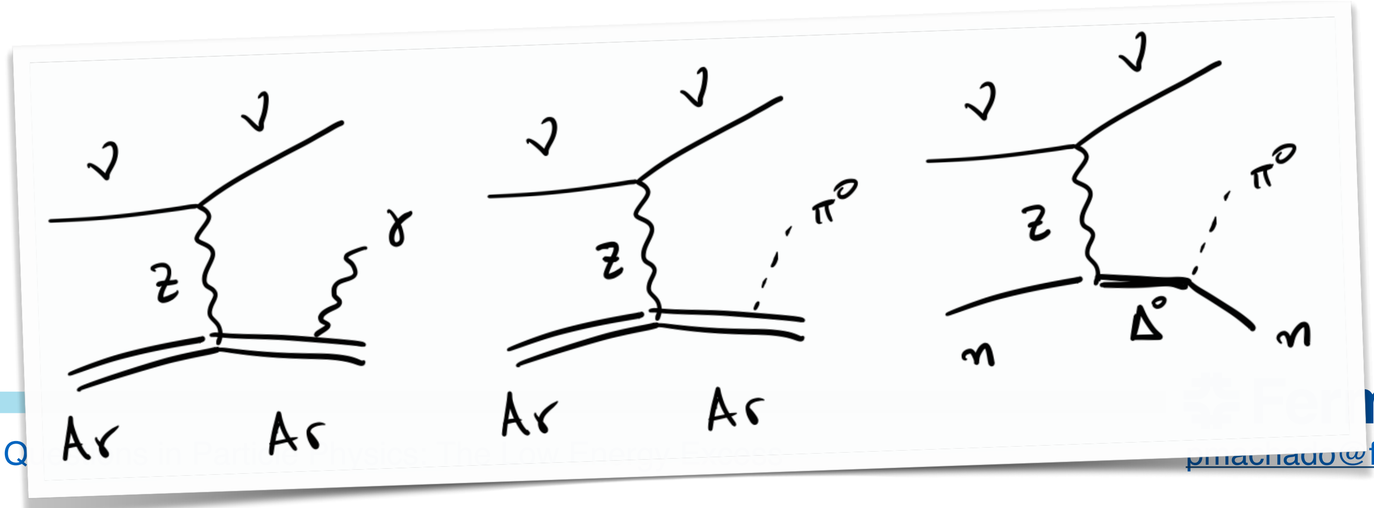


Experimental signatures

- Excellent fit to MB energy spectrum
- Angular spectrum of e^+e^- pair tends to be forward
- Somewhat collimated e^+e^- pair (could be mistaken by a photon)
- No hadronic activity
- A bit of missing transverse momentum (but nuclear physics…)
- Z_D invariant mass may be hard to reconstruct (too light)

Backgrounds

- Any shower mis-id (at these energies, electrons don't shower much)
- Coherent photon production
- mis-id π^0, e.g. from Δ to π^0 neutron or coherent π^0 production



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Dark neutrinos and other explanations of the MiniBooNE anomaly

To probe these models we need to understand the nontrivial interplay among
the physics of neutrino-nuclei interactions
the smoking gun signatures of the models themselves
and the experimental capabilities

That is, we need deep understanding of theory and experiment

I don’t think anyone can do it alone

Let’s talk, brainstorm, and collaborate more!

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Conclusions

Let's finish with a reflection

We are living an era of precision neutrino physics

Precision = novel opportunities, e.g. probing the mechanism of neutrino masses in μBooNE

To benefit from these opportunities we need to leverage the unique capabilities of neutrino detectors and to explore the model signatures in great detail

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Conclusions

Let's finish with a reflection

The technology that we pushed in the last Snowmass is now here and available

In the EXP side, it is much more capable than what we thought

In the TH side, it has spurred an urge of creativity on both model building and search proposals

To me, we can fully explore this with a vibrant collaboration between THs and EXPs

This will expand the physics of the neutrino program and push both TH and EXP to their fullest

Easier said than done

Are you up for the challenge?

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