Confronting Neutrino Mass Generation Mechanism with MiniBoone Anomaly

Sudip Jana

Phenomenology Symposium 2019

University of Pittsburgh

Based on

1. arXiv: 1807.09877 , Phys.Rev.Lett. 121 (2018) no.24, 241801

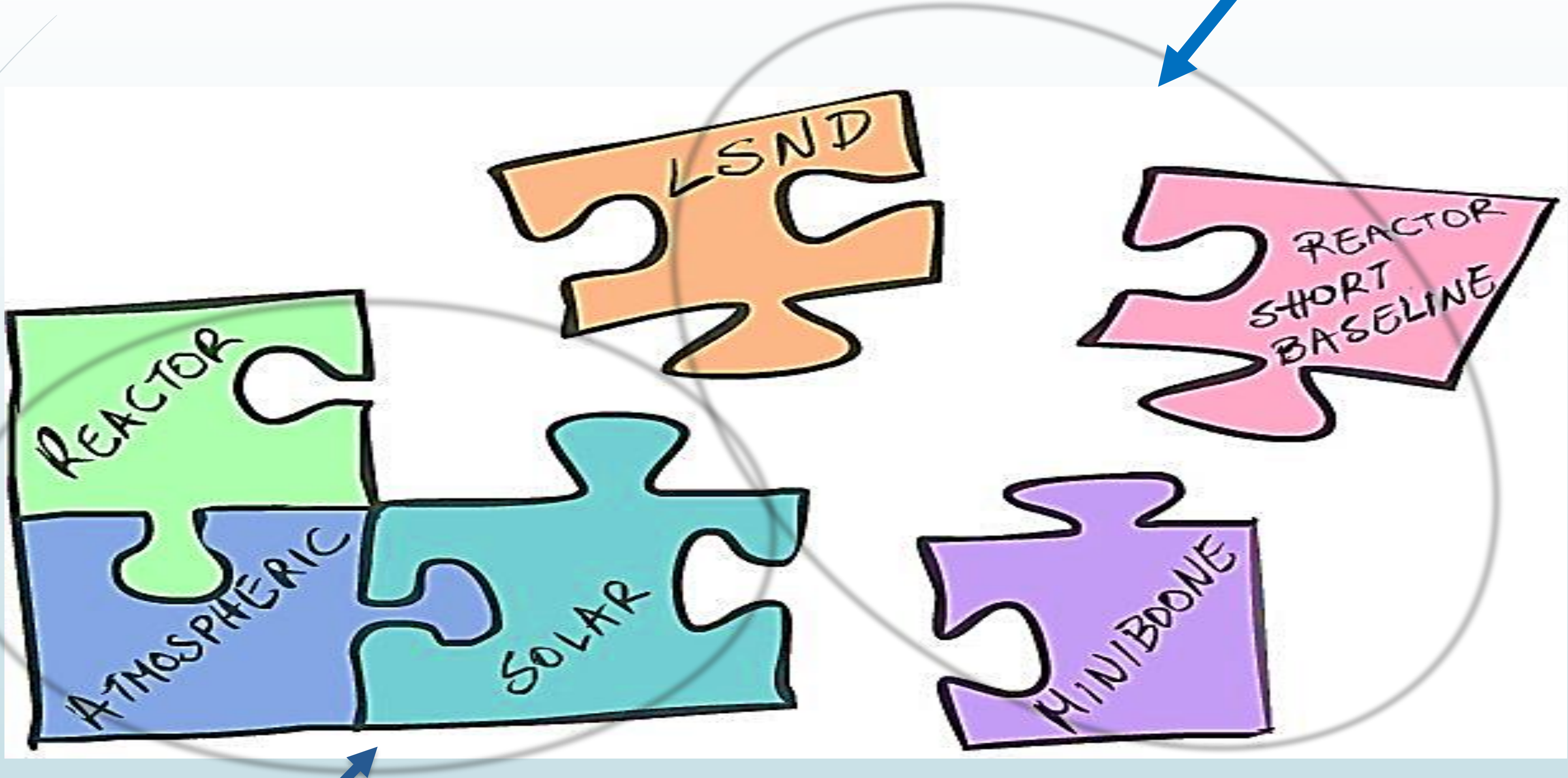
2. arXiv: 1808.02500, Phys.Lett.B791 (2019) 210-214

in collaboration with

E. Bertuzzo, Pedro A. N. Machado and R. Zukanovich-Funchal

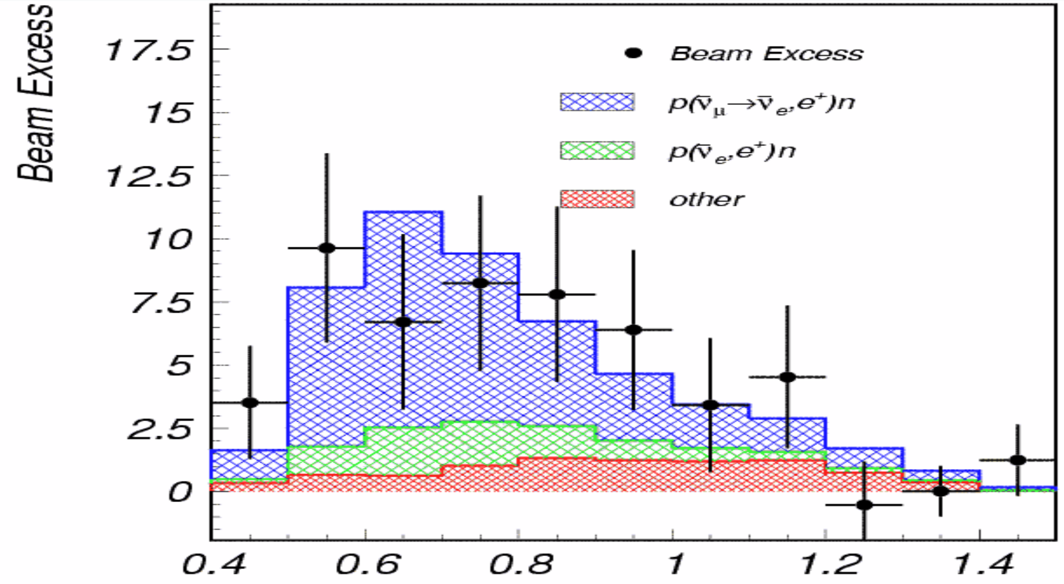
OKLAHOMA STATE UNIVERSITY

Three-neutrino oscillation: Not the full picture?

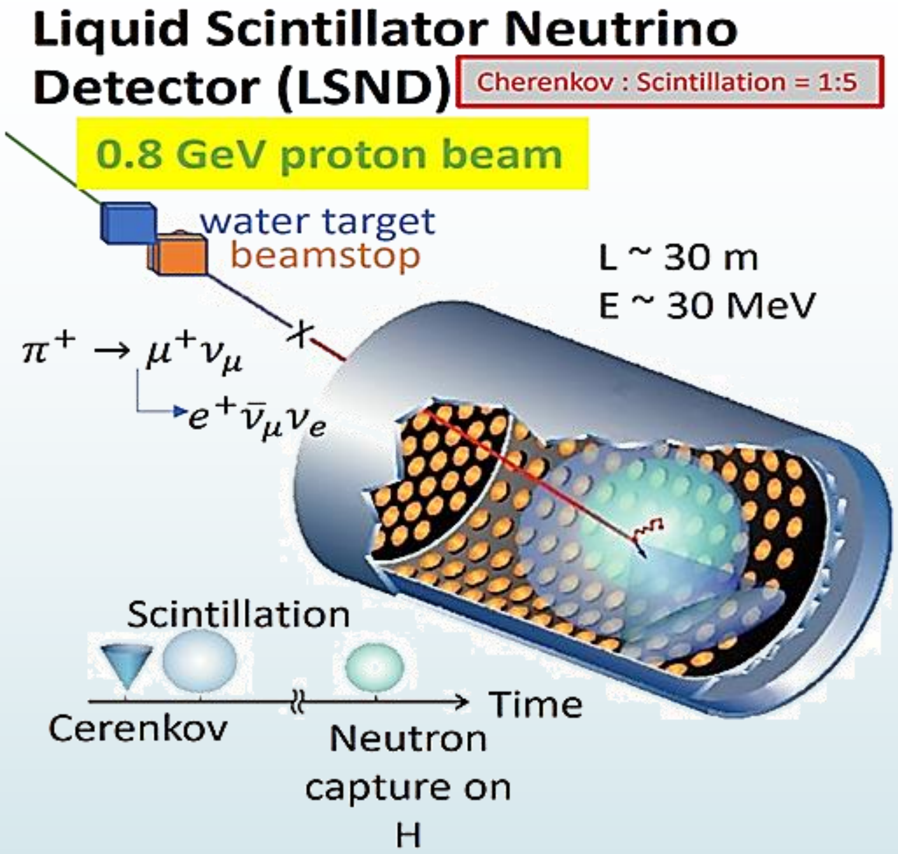


Short Baseline Anomalies

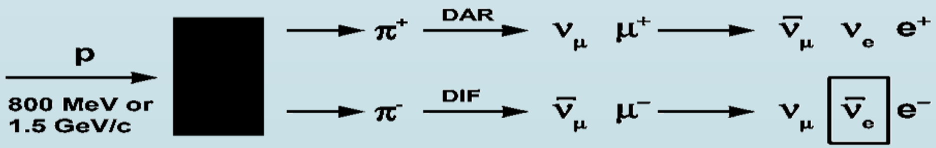
Long and Medium Baseline



hep-ex/0104049



LSND neutrino source

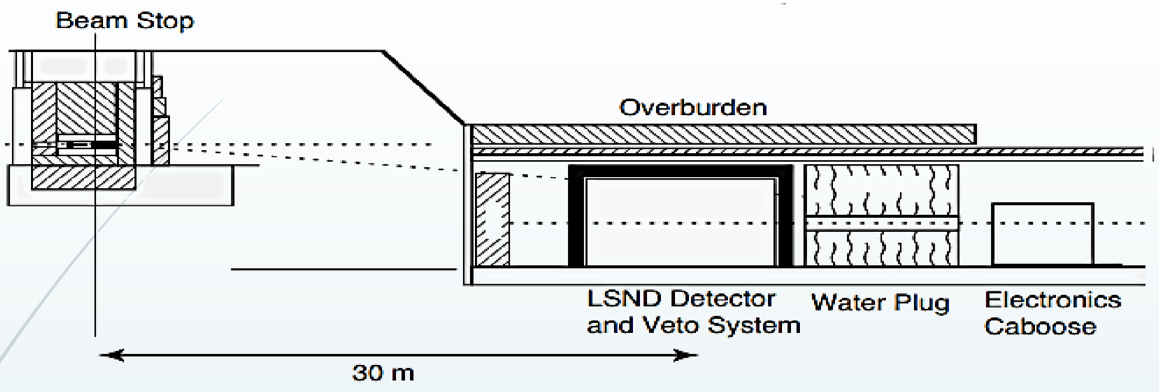


DAR of μ^- competes with $\mu^- + (A,Z) \rightarrow \nu_\mu + (A, Z-1)$

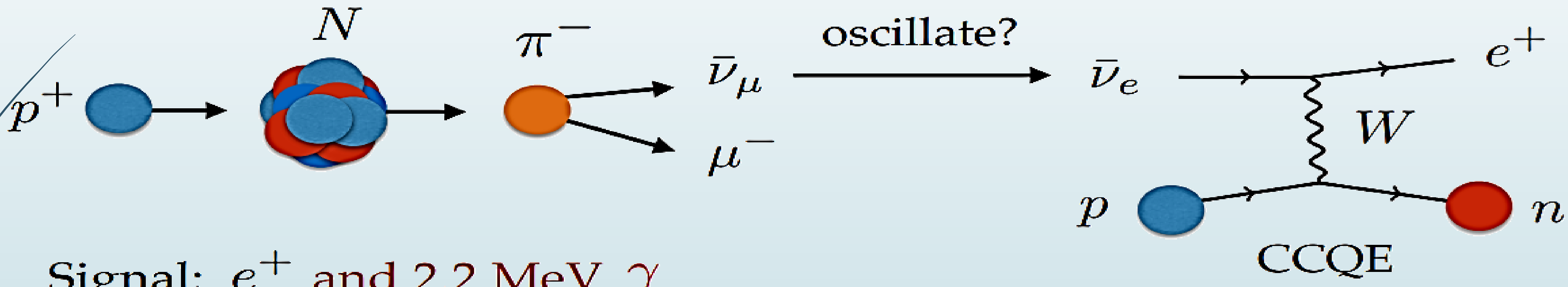
LSND detected more $\bar{\nu}_e$ than expected :

87.9 ± 22.4 ± 6.0 events

3.8 σ excess



$$10^{22}\ \mathrm{POT}, E_p = 800\ \mathrm{MeV}$$

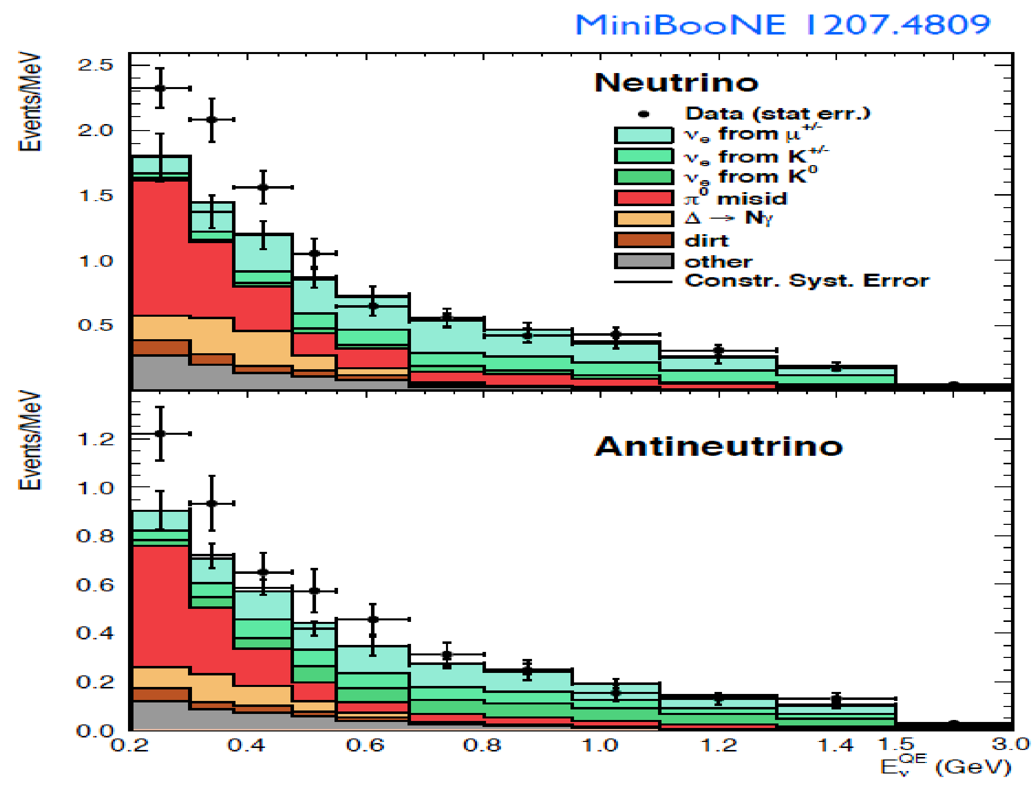


Signal: e^+ and 2.2 MeV γ
Scatter + neutron absorption

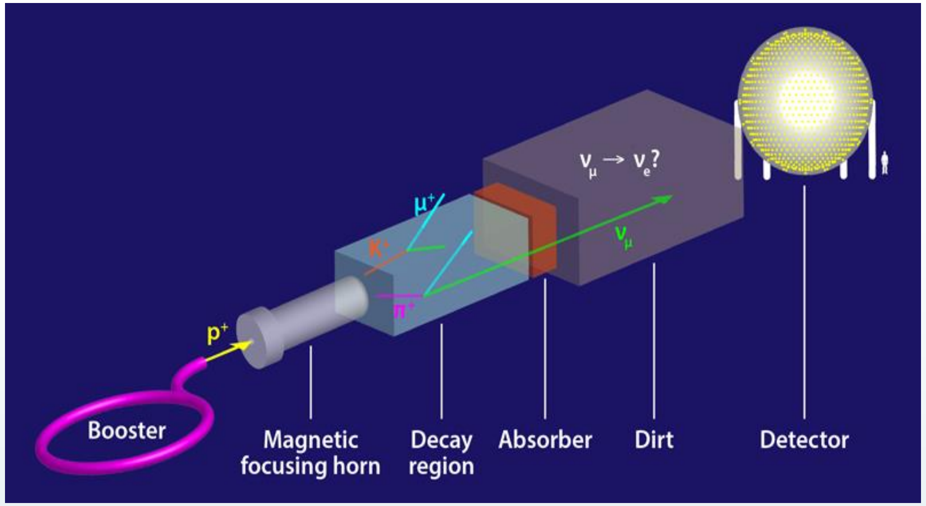
Observed 90 events
Expectation of 0 events
3.8σ significance

$$P_{\mathrm{osc}} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

LSND Collaboration hep-ex/0104049

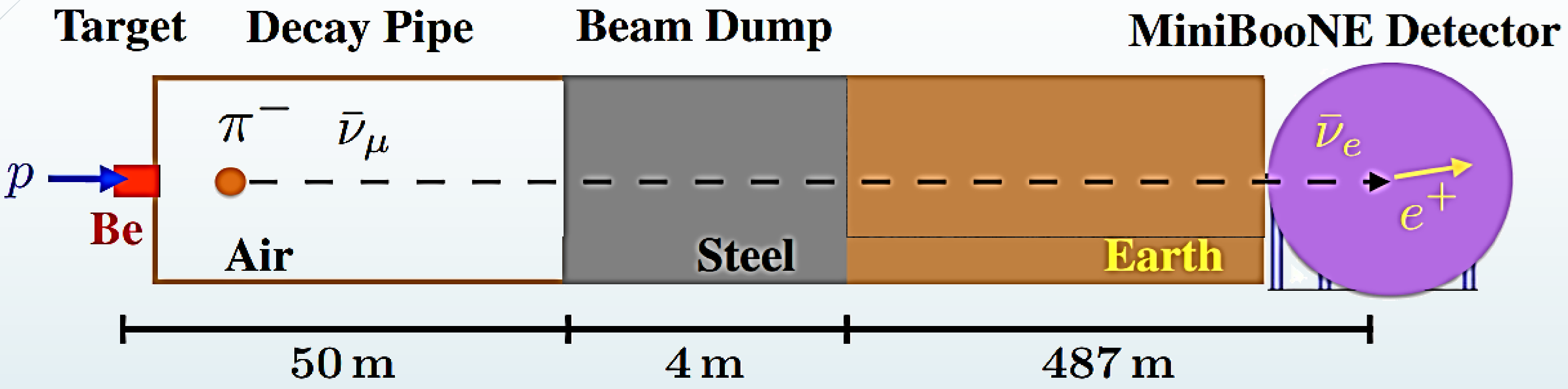


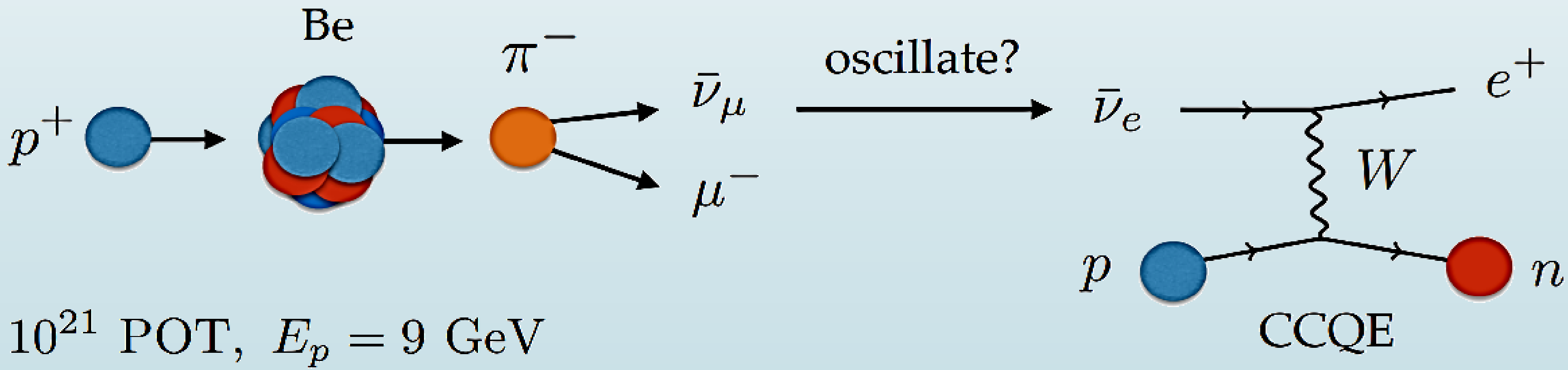
•Neutrino and anti neutrino modes see excesses of ν_e and $\bar{\nu}_e$ (Combined is also 3.8 **σ** excess)



- **To test the LSND indication of anti-electron neutrino oscillations**
- **Keep L/E same, change beam, energy, and systematic errors**
- **Baseline: L = 540 meters, ~ x 15 LSND**
- **Neutrino Beam Energy: E ~ x (10-20) LSND**
- **Different systematics: event signatures and backgrounds different from LSND High statistics: ~ x 6 LSND**
- **Perform experiment in both neutrino and anti-neutrino modes.**

MiniBooNE's Low Energy Excess





10^{21} POT, $E_p = 9$ GeV

Energy and baseline chosen to test LSND

Comparable oscillation probabilities

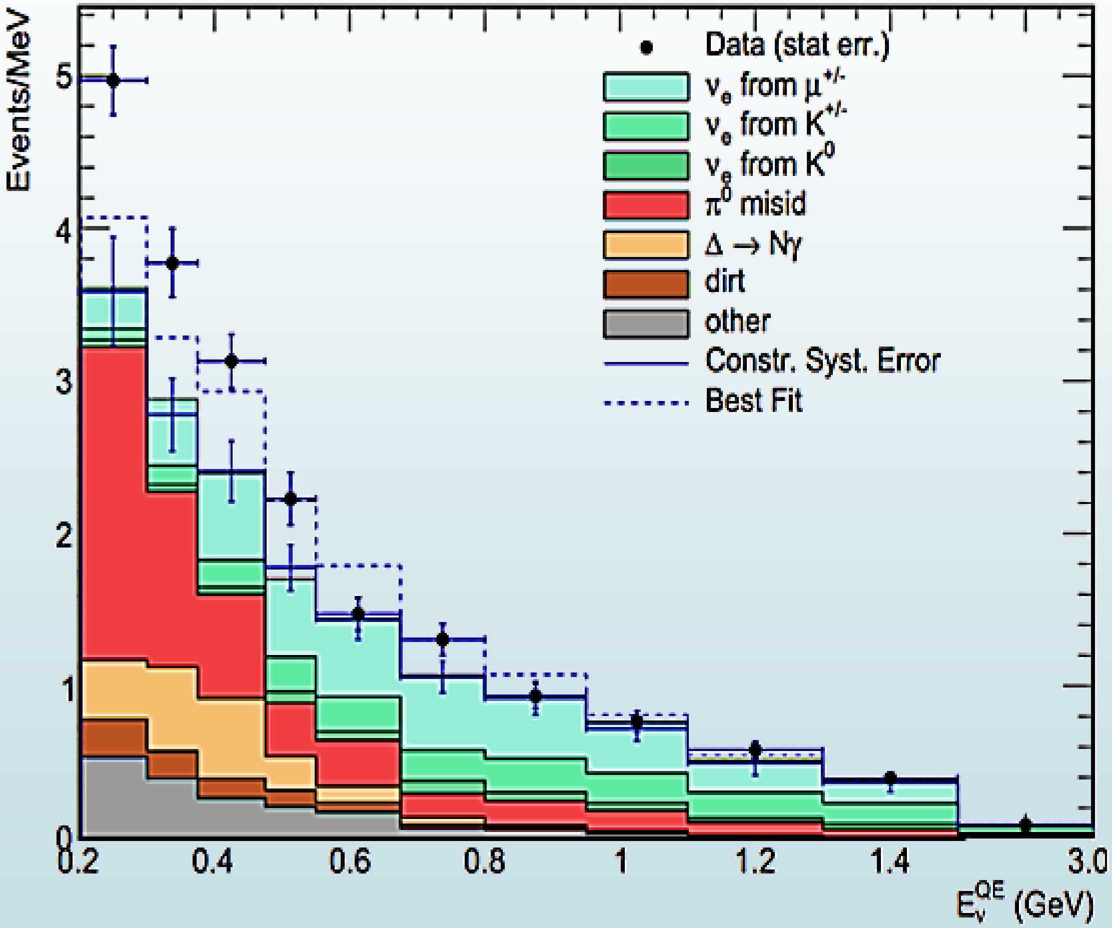
MiniBooNE Collaboration 1805.12028

MiniBooNE’s Low Energy Excess

- Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short Baseline Neutrino Experiment
- Double neutrino-mode data in

  2016-2017 (6.46×10^{20} + 6.38×10^{20} POT)
- Event excess: 381.2 ± 85.2 (4.5σ)

MiniBooNE Collaboration hep-ex/1805.12028



What is going on???

- What is the nature of the excess?
- Possible detector anomalies or reconstruction problems?
- Incorrect estimation of the background?
- New sources of background?
- New physics including/excluding exotic oscillation scenarios?

The origin of such excess is unclear – it could be the presence of new physics, or a large background mismodeling. However, the MiniBooNE result, if due to new physics, would revolutionize the field of particle physics.

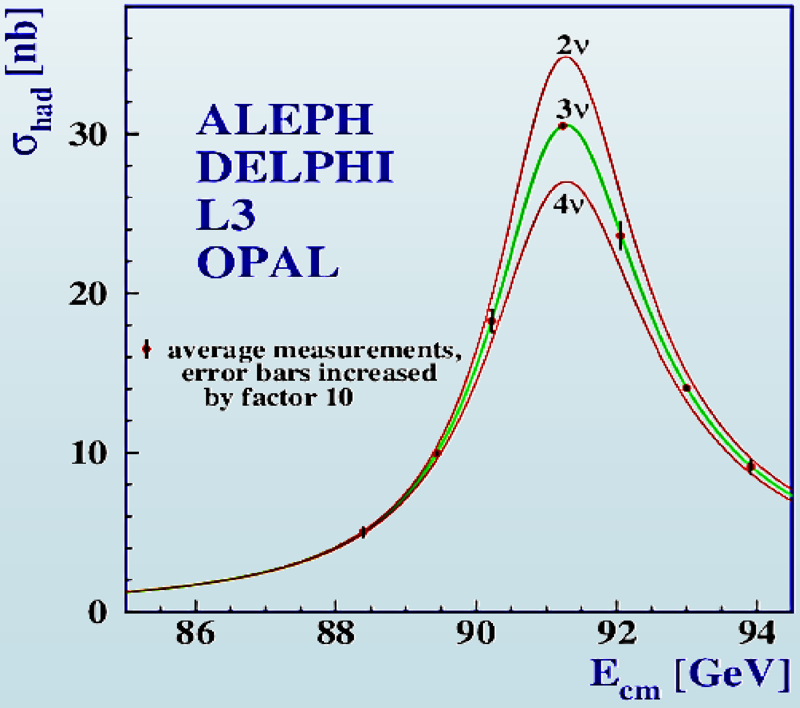
What sort of new physics can explain these anomalies?

❖ What about eV Sterile Neutrino Interpretation ???

Beyond three-neutrino oscillations

- We can add a forth neutrino
- This neutrino must be sterile, which means it is a singlet under all standard model gauge groups
- A forth active neutrino is excluded by observations of invisible Z-decays

$$e^+e^- \to Z \to \sum_{j=e,\mu,\tau} \nu_j$$



Phys. Rept. 427 (2006) 257, LEP

❖ *What about eV Sterile Neutrino Interpretation ???*

Effective 3+1 oscillations

We extend the mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

APPearance

$$P^{\mathrm{SBL}}_{\alpha\beta} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\nu_\mu \to \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu 4}|^2$$

@LSND, Karmen, MiniBoone, Opera

DISappearance

$$P^{\mathrm{SBL}}_{\alpha\alpha} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

$$\nu_e \to \nu_e : |U_{e4}|^2 = \sin^2\theta_{14}$$

@Reactors and **Gallium**

$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

@atmospherics and **accelerators**

❖ *What about eV Sterile Neutrino Interpretation ???*

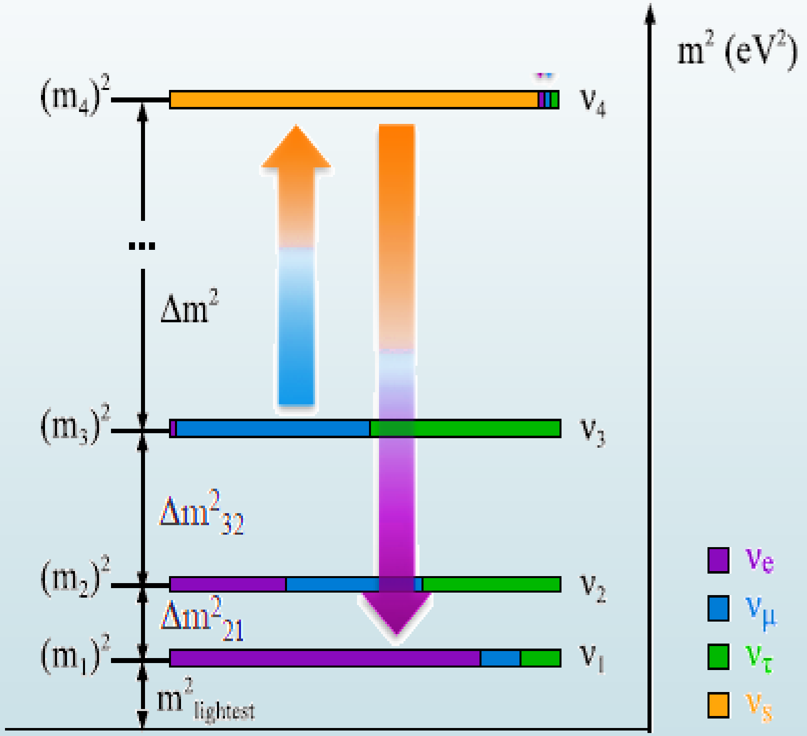
$$P^{\mathrm{SBL}}_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P^{\mathrm{SBL}}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right).$$

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\;U_{\mu 4}|^2$$

Leads to ν_e disappearance

Leads to ν_μ disappearance



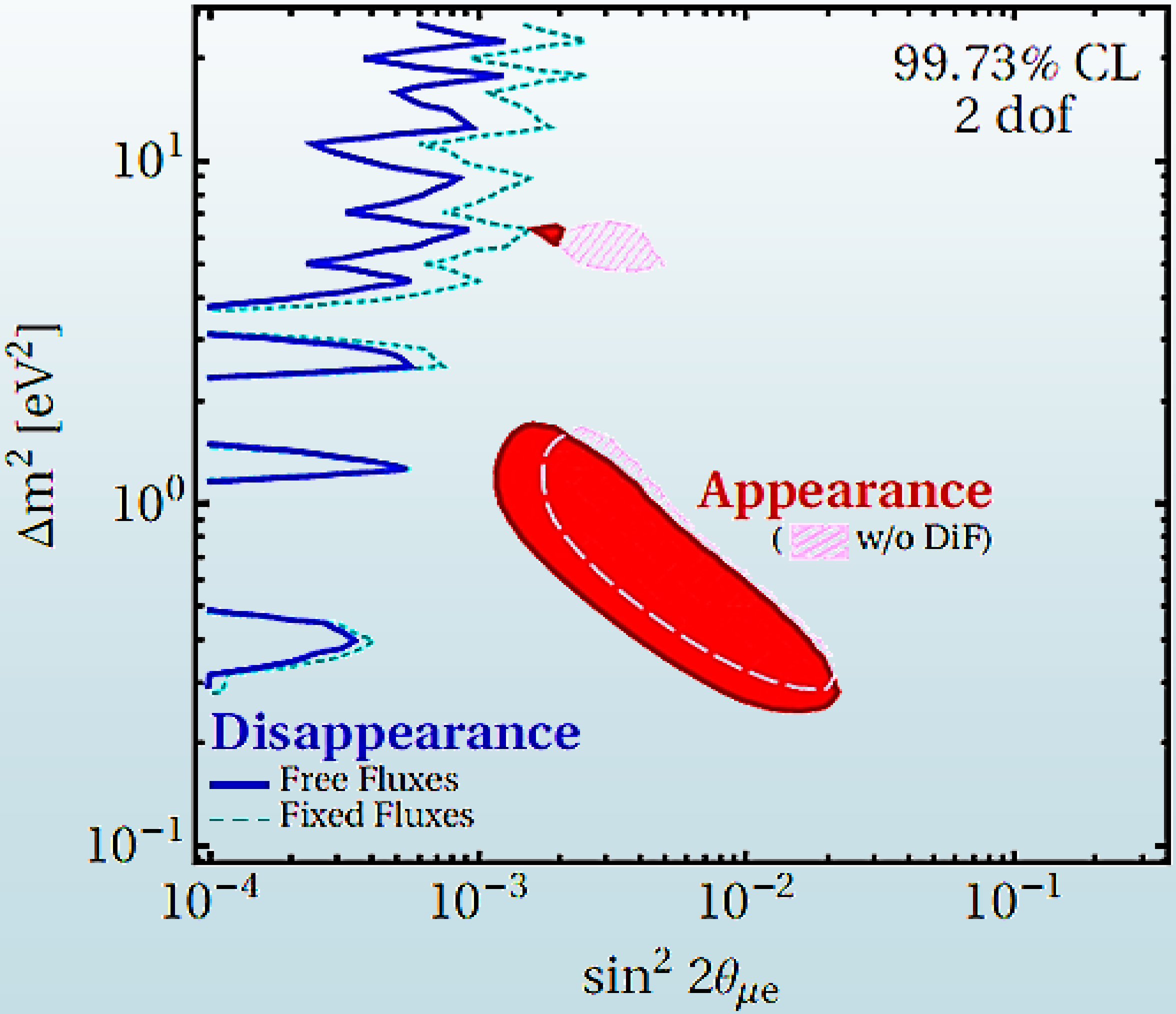
❖ *What about eV Sterile Neutrino Interpretation ???*

$$\sin^2 2\theta_{\mu e} = 4\,|\underbrace{U_{e4}\,U_{\mu 4}}|^2$$

Leads to ν_μ to ν_e disappearance

- 2 variables: U_{e4}, $U_{\mu 4}$
- 3 data sets: ν_e- Disappearance
  ν_μ- Disappearance
  ν_e- Appearance

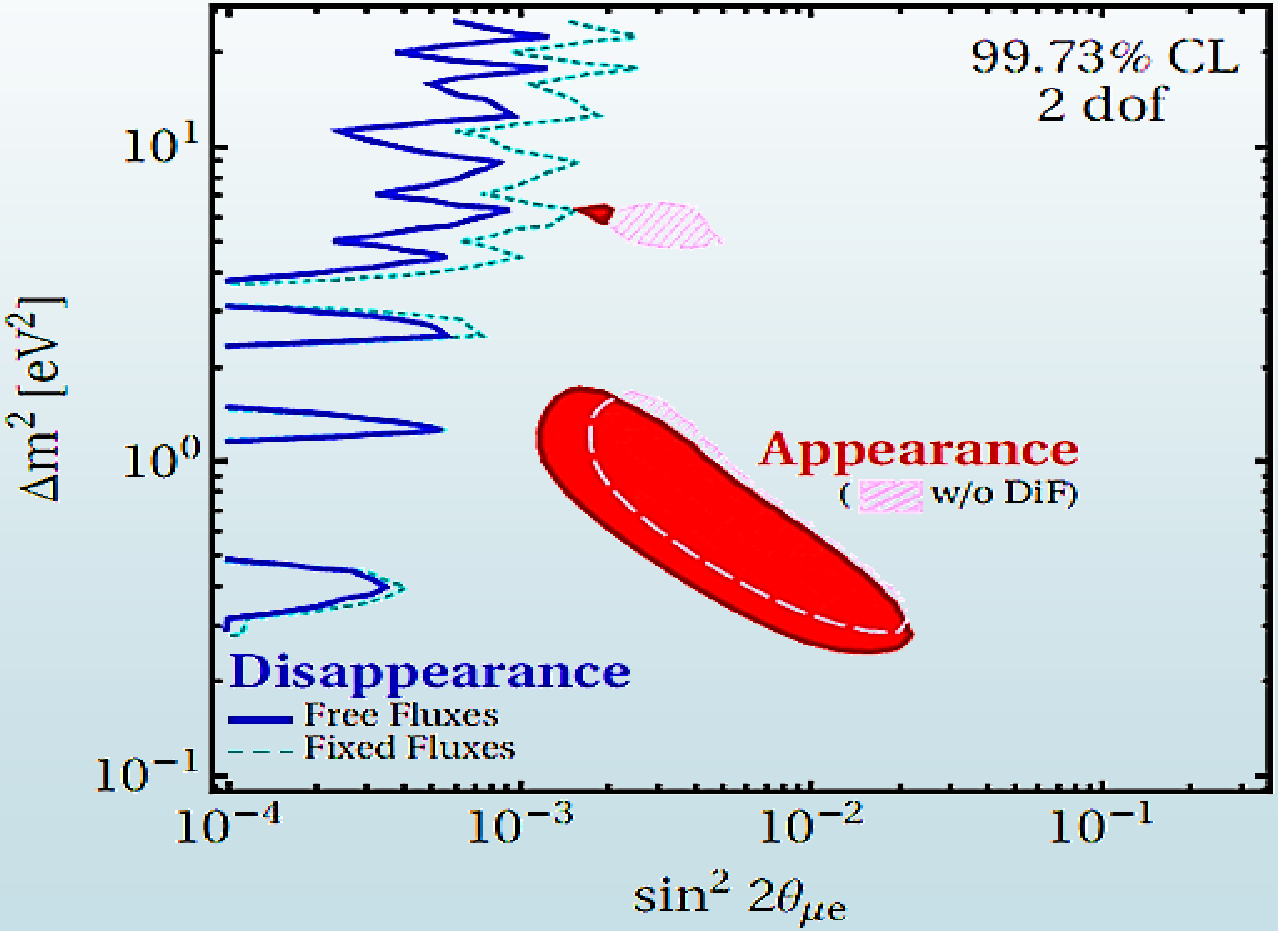
Mona Dentler et al. JHEP 1808 (2018) 010



❖ *What about eV Sterile Neutrino Interpretation ???*

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\,U_{\mu 4}|^2$$

4.7 σ tension between Appearance and Disappearance data sets under eV sterile interpretation

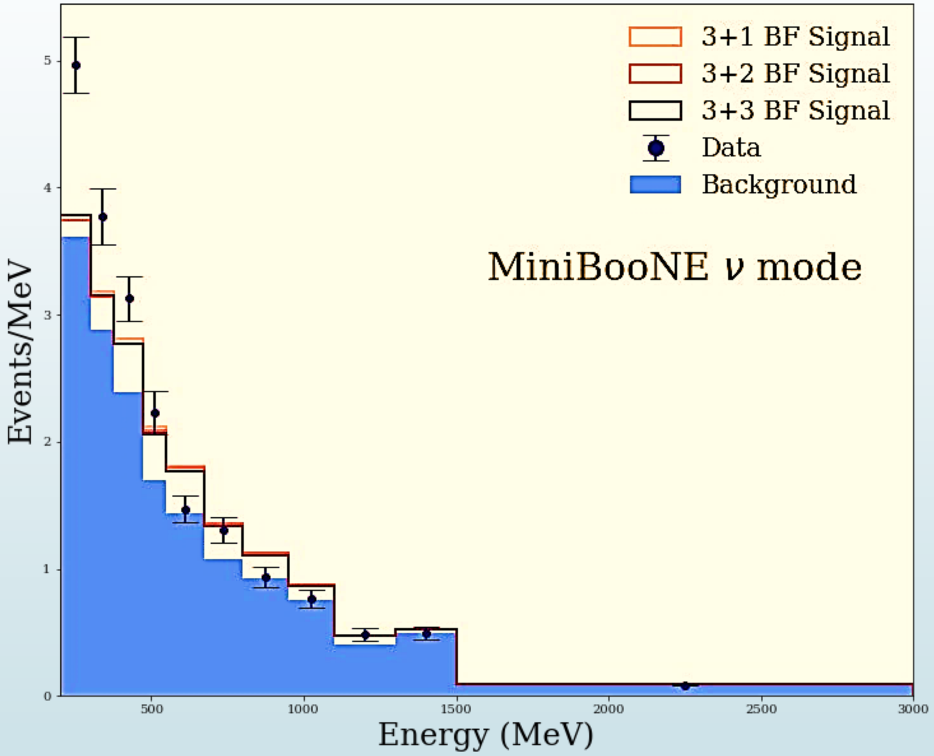


Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860

➢ 3+N GLOBAL FITS

Shortcoming:
Failure to accommodate
MiniBooNE low-energy excess.

"3+N STANDARD STERILE NEUTRINOS": INSUFFICIENT



D. Cianci, et al. (Talk presented at Applied Antineutrino Physics Workshop 2018)

❖ What about eV Sterile Neutrino Interpretation ???

Sterile neutrinos require $\sin^2 2\theta_{\mu e} > 10^{-3}\ ,\ m_4 < \text{few eV}$

Generic early universe thermalization

$$\Gamma > H \implies \sin^2 2\theta_{\mu e} G_F^2 T^5 > \sqrt{g_*}\frac{T^2}{m_{\rm Pl}} \implies n_4 \sim n_\nu$$

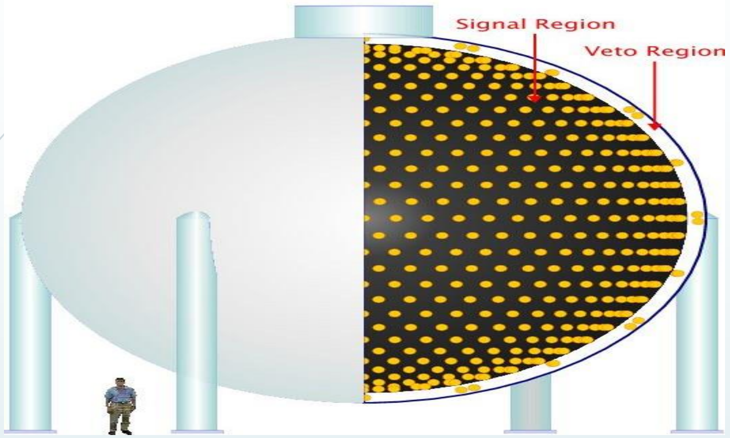
Excluded by BBN/CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

Unless max temperature satisfies $T_{\rm max} \lesssim 15 \text{ MeV} \left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

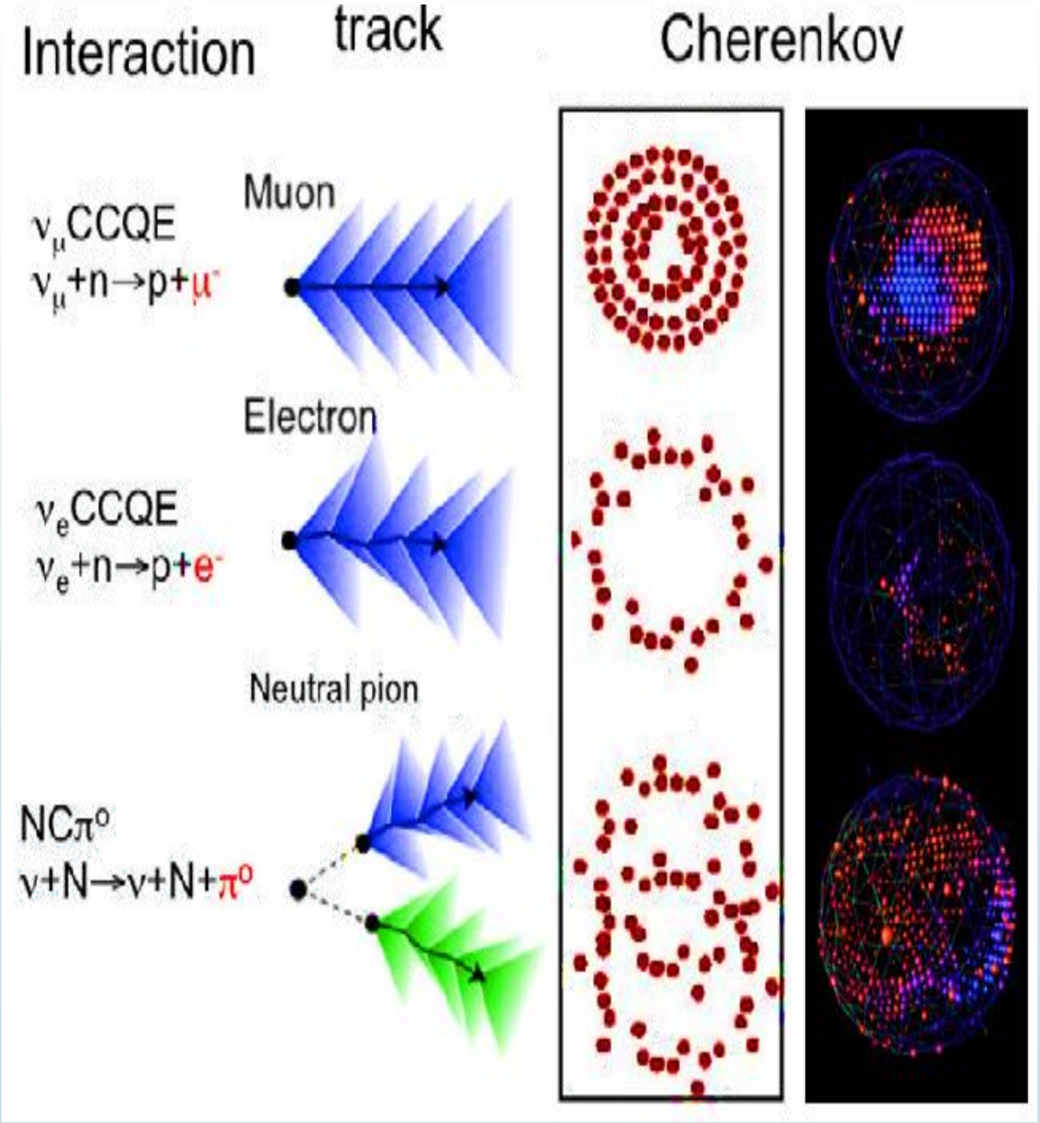
❑ *Explanation of MiniBooNE's low energy excess*

- Sterile ν at the eV scale present strong tension between data sets
- Cosmological bounds further threat the eV sterile ν hypothesis
- Is there an explanation that is not ruled out?
- Is there a "real model" for these explanations?
- Can this relate to any of the theoretical problems of the SM?

❖ *Explanation of MiniBooNE's low energy excess*

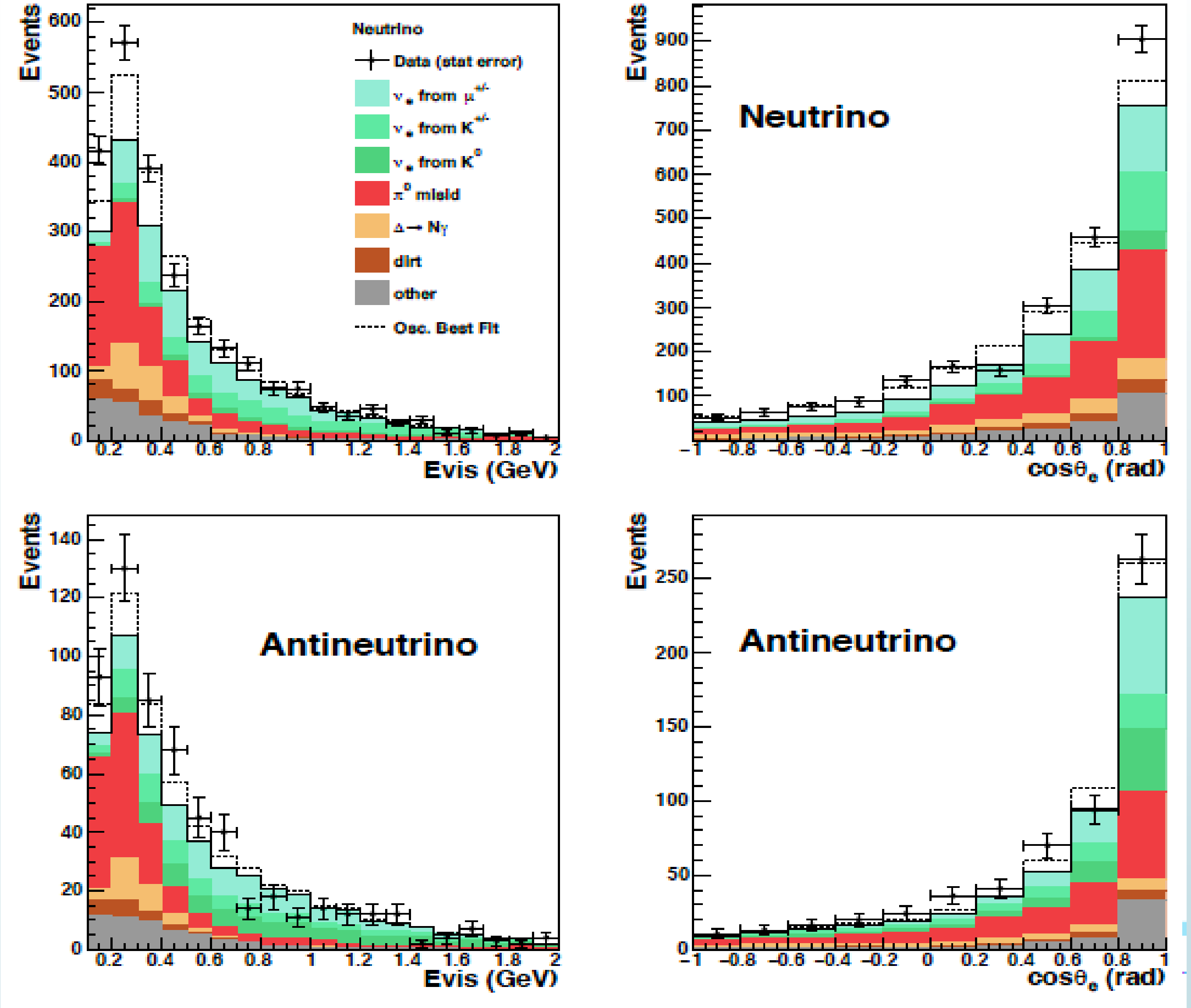


- MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles.
- Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.
- Excess is correlated with beam in power, angle and timing. It is present in positive and negative horn polarities. It is not present in beam dump configuration



❖ *Explanation of MiniBooNE's low energy excess*

- ➢ Angular spectrum is forward, but not that much
- ➢ Scattering on electrons would typically lead to $\cos\theta > 0.99$
- ➢ Decays of invisible light (<10 MeV) particles produced in the beam would also lead to forward spectrum



arxiv : 1805.12028 [hep-Ex]

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

❖ *Explanation of MiniBooNE's low energy excess*

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- There is a dark sector with a novel interaction
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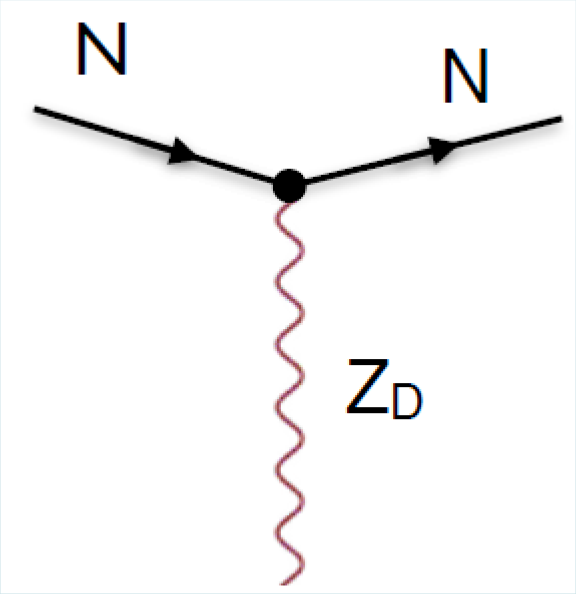

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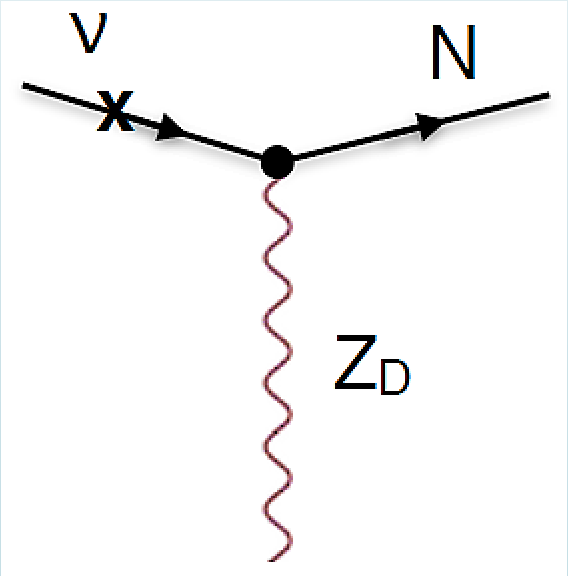

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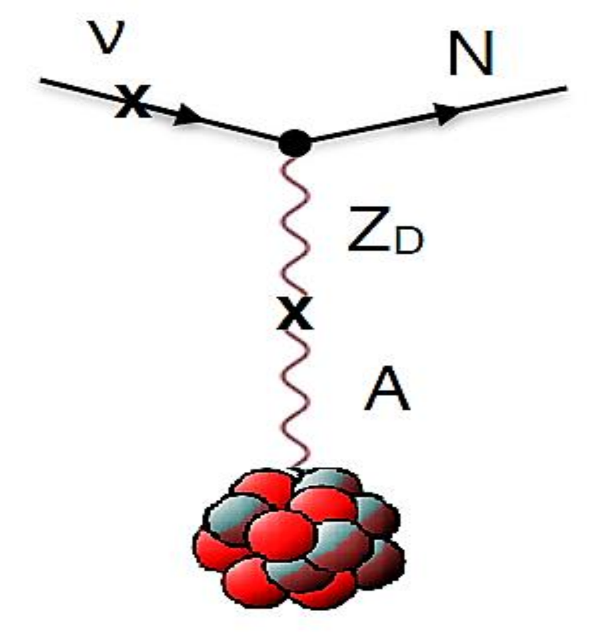

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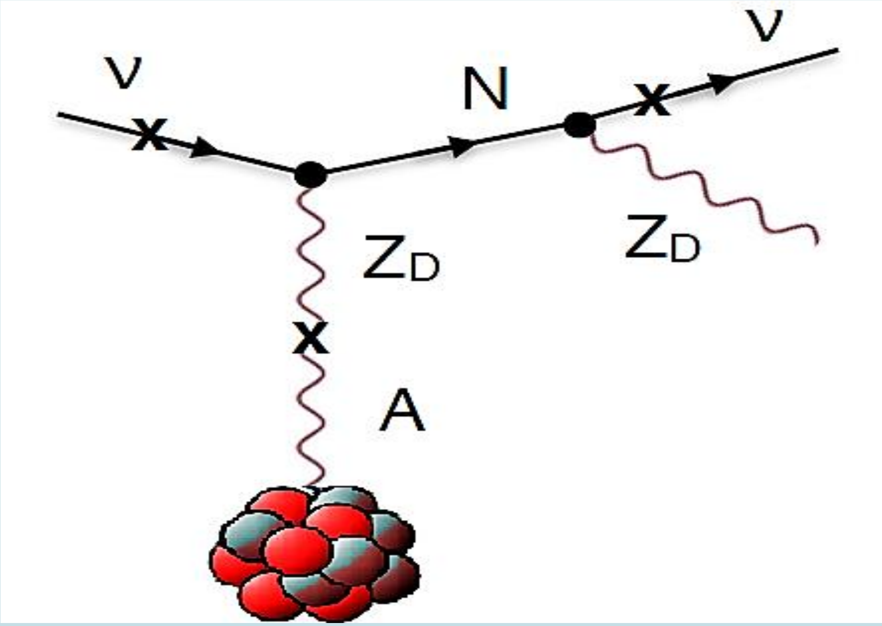

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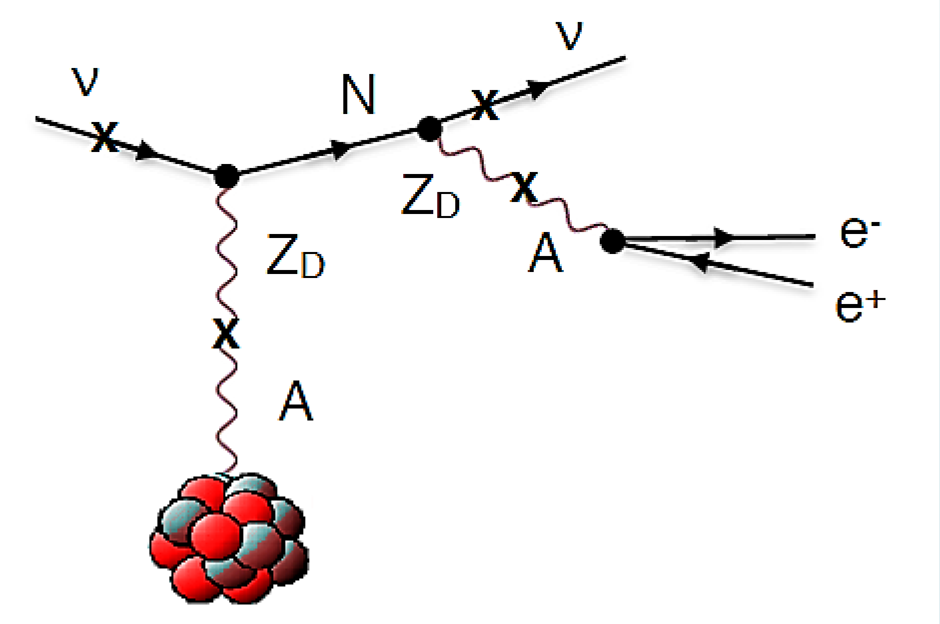

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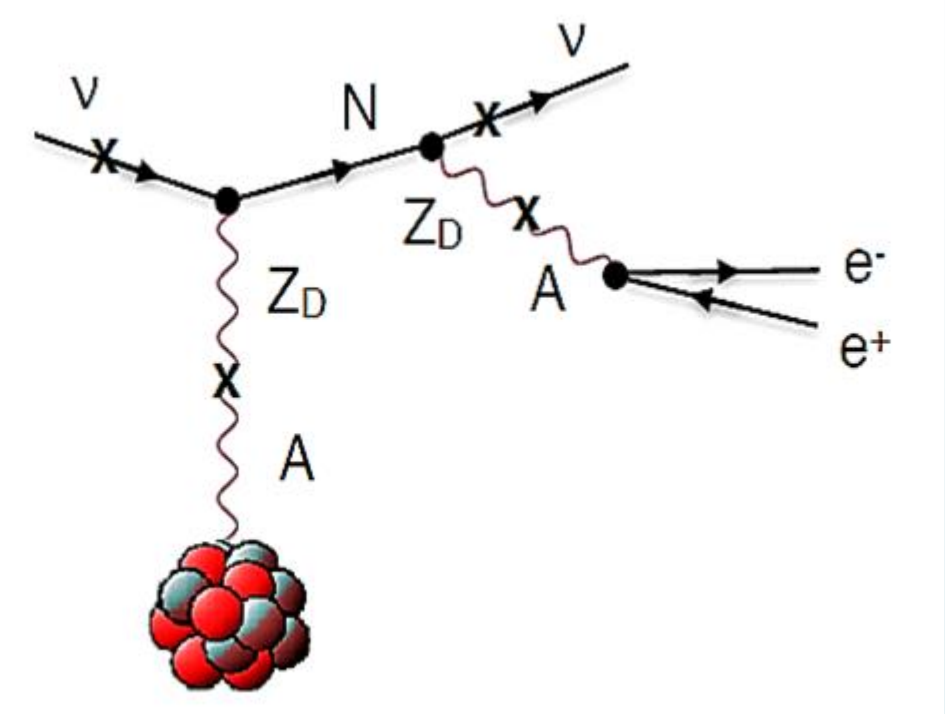
- Relevant part of the Lagrangian :



Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

$$\mathcal{L}_D \supset \frac{m_{Z_D}^2}{2} Z_{D\mu} Z_D^\mu + g_D Z_D^\mu J_{D\mu} + e\epsilon Z_D^\mu J_\mu^{\text{em}} + \frac{g}{c_W}\epsilon' Z_D^\mu J_\mu^Z$$

❖ *Explanation of MiniBooNE's low energy excess*

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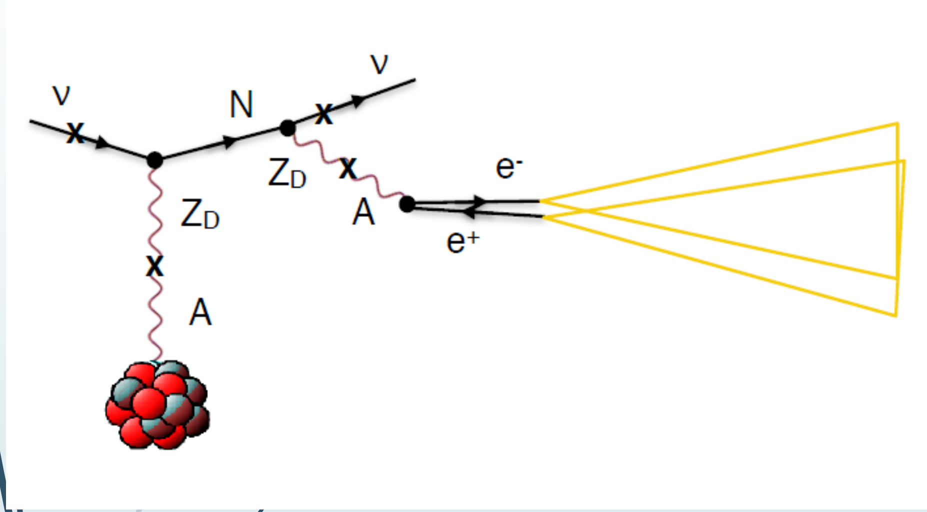
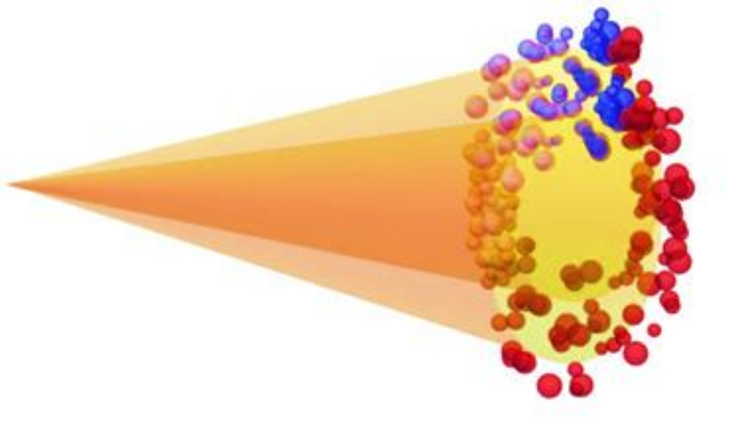
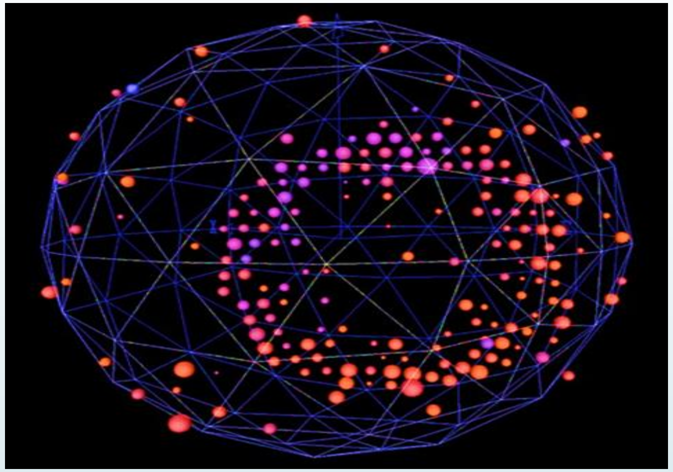
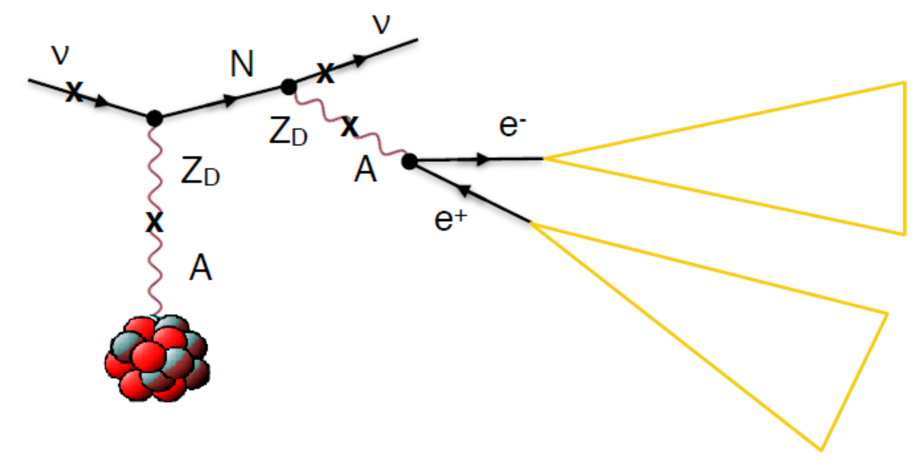
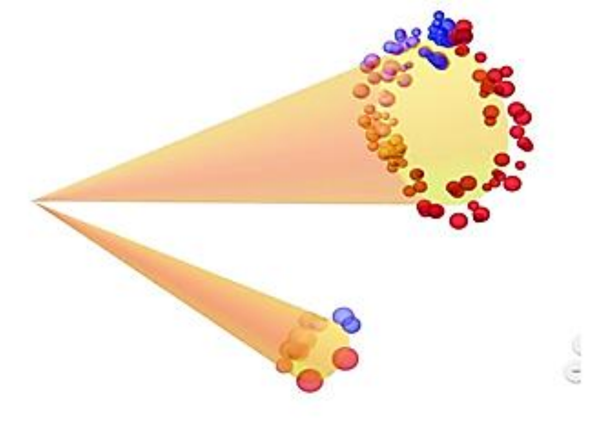
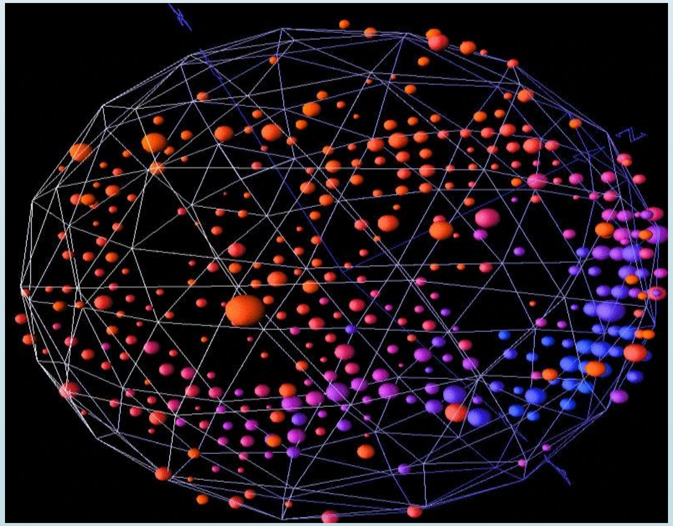






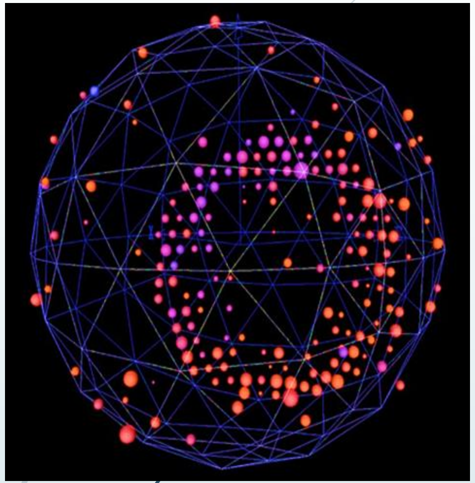


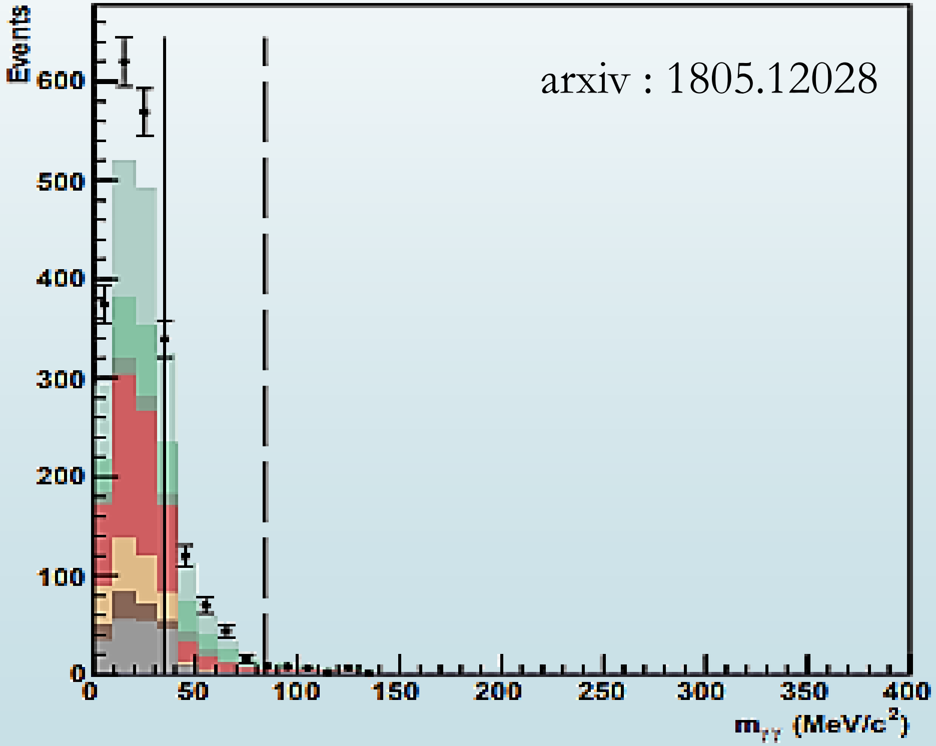


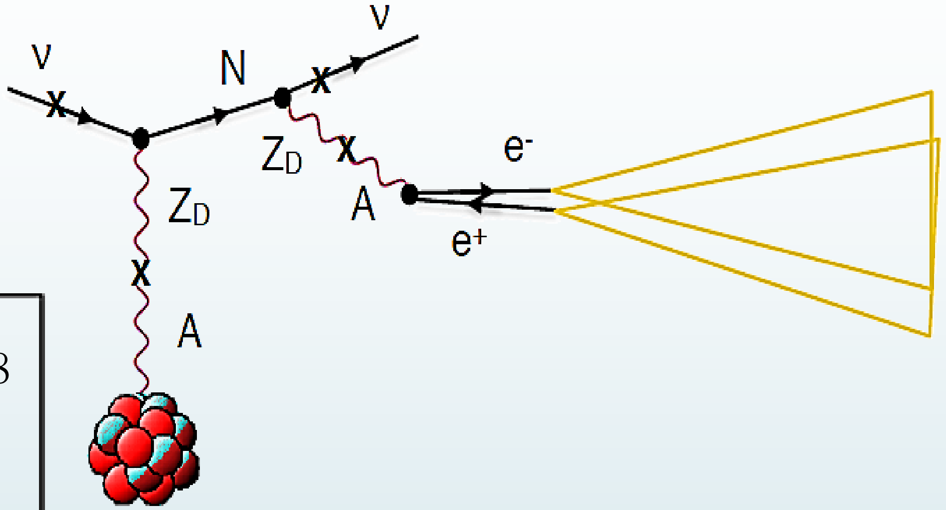


❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



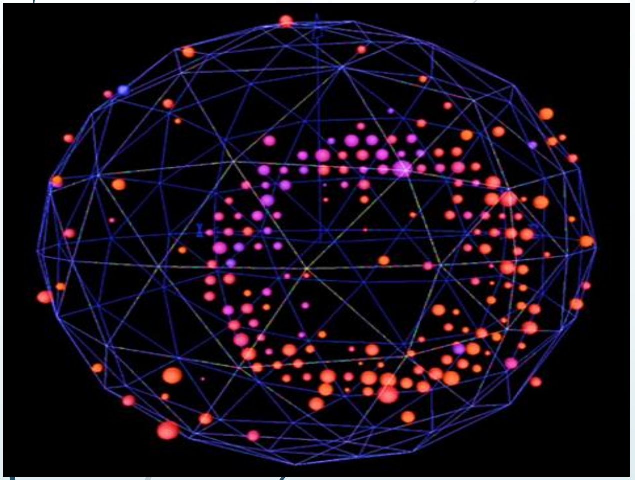


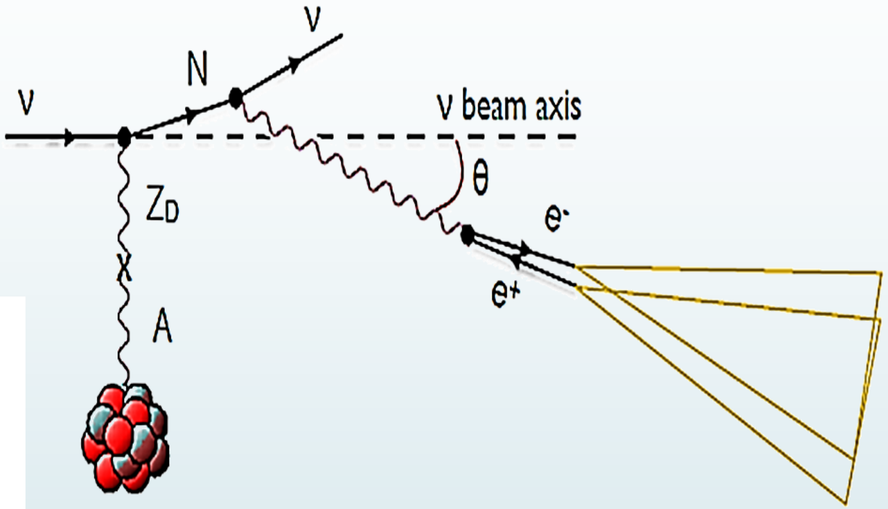


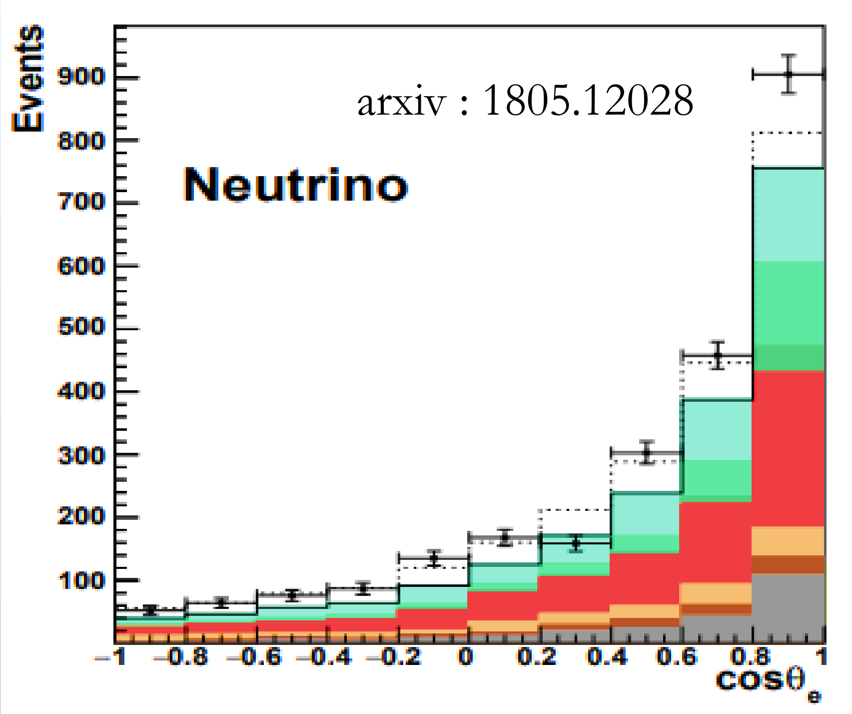
If e^+e^- pair is collimated ($\cos\theta_{ee} > 0.99$-ish), it will be classified as e-like

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



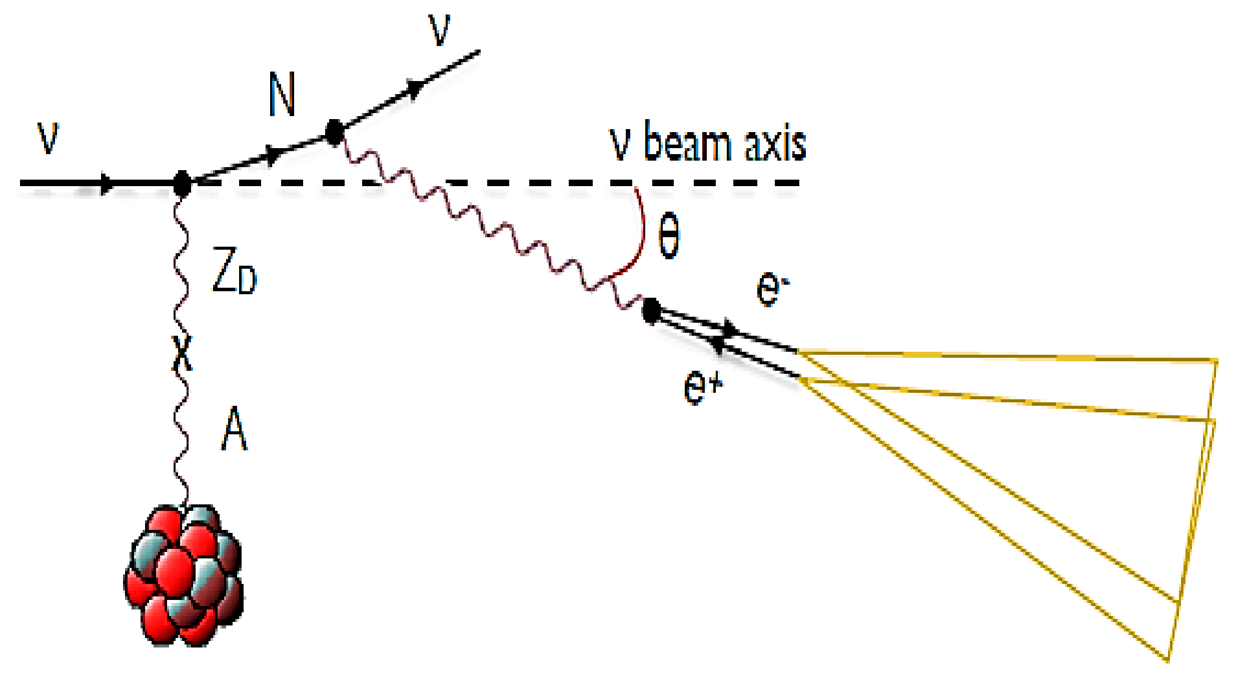


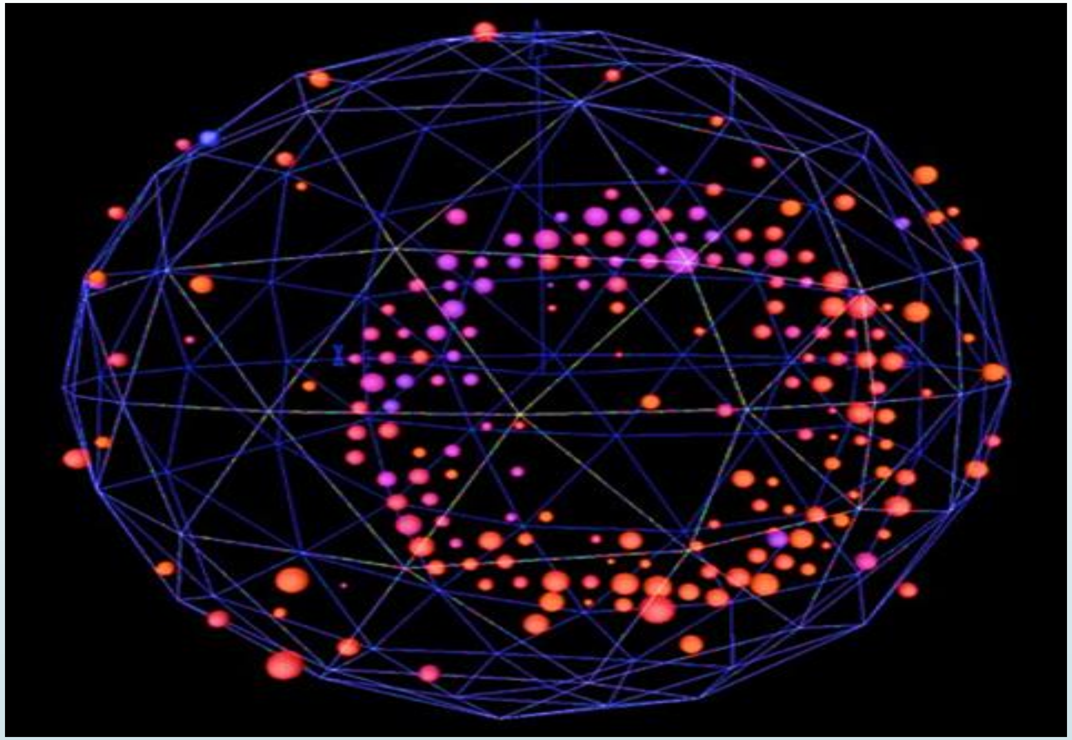


We have to get this angular spectrum

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA





(1) N_D should be heavy (> 100 MeV) so its decay products are not so boosted

(2) Z_D should be light (< 60 MeV) so that the e^+e^- pair is collimated

❖ Explanation of MiniBooNE's low energy excess

Fit to energy spectrum only

(Official MB data release)

Benchmark Points :

$m_N = 420$ MeV

$m_{ZD} = 30$ MeV

$|U_{\mu 4}|^2 = 9 \times 10^{-7}$

$\alpha_D = 0.25$

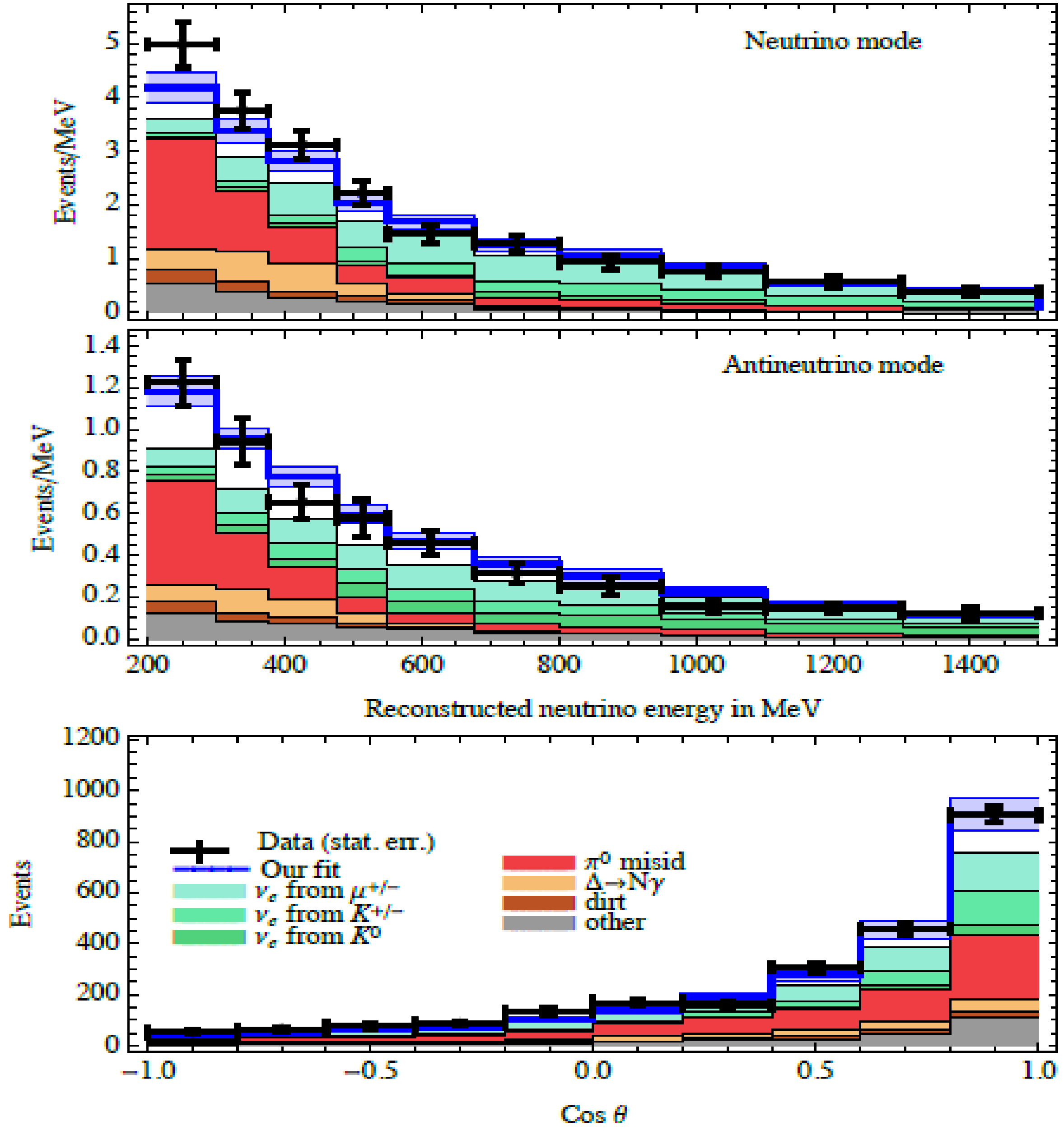
$\alpha\varepsilon^2 = 2 \times 10^{-10}$

$\chi^2/\text{dof} = 33.2/36$

Bertuzzo et al 1807.09877

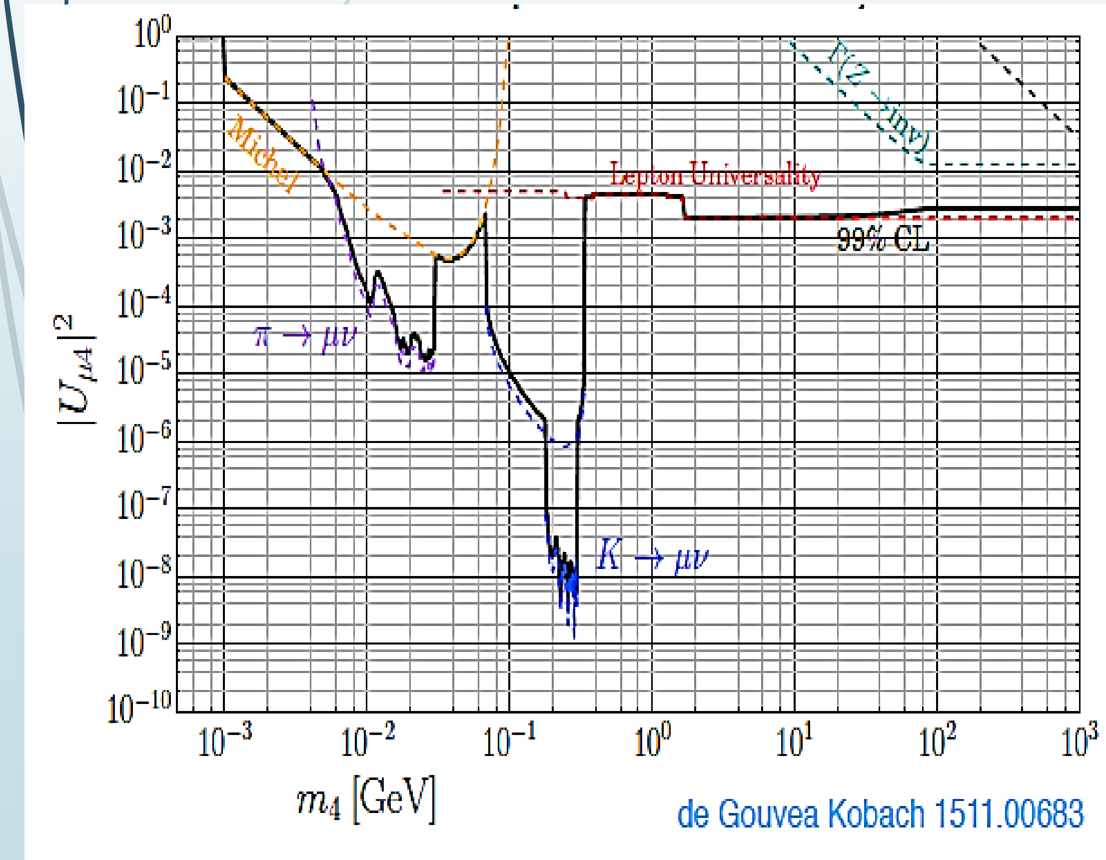
See also Ballett et al 1808.02915

for different realization of the mechanism

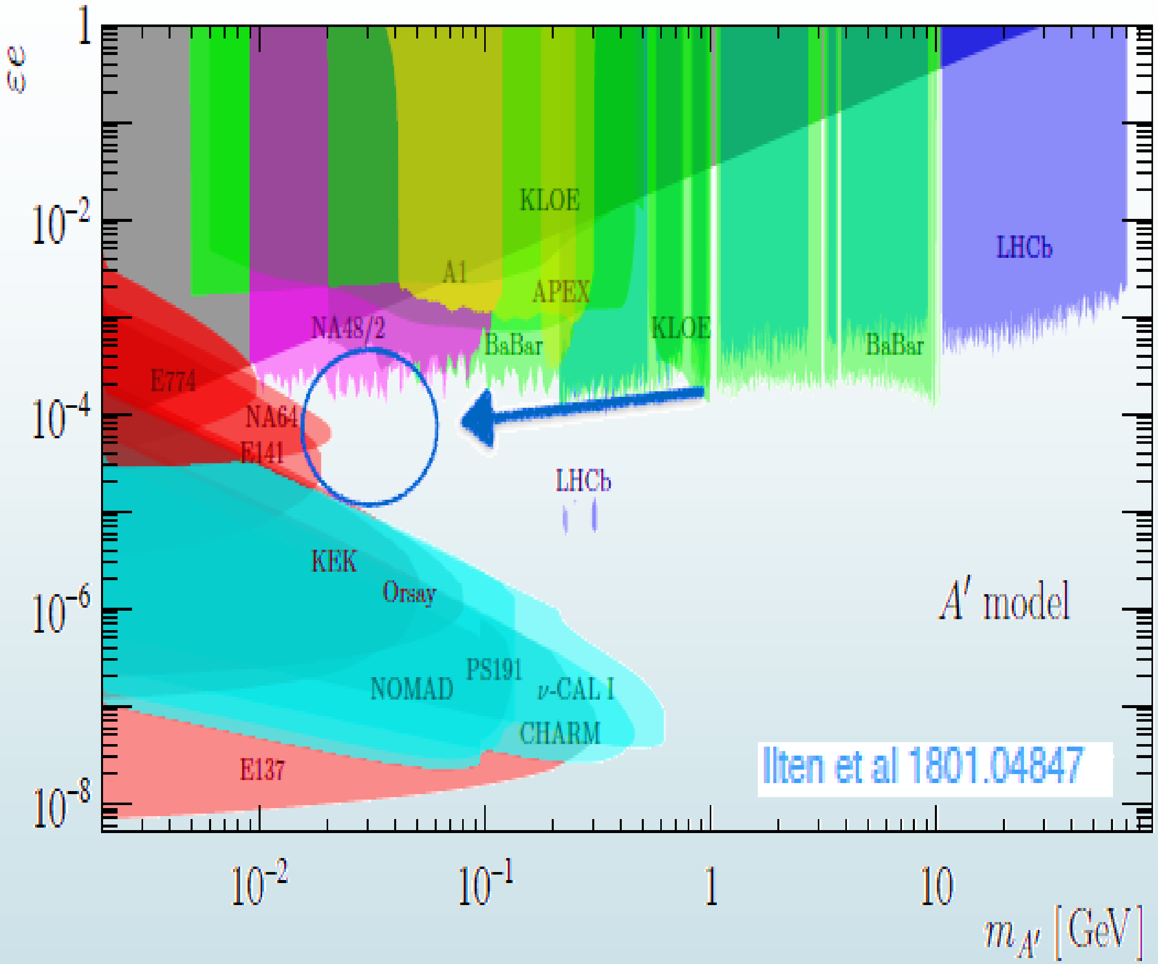


❖ Constraint on Light Dark Sector

Model Independent Constraint on Heavy Sterile Neutrino



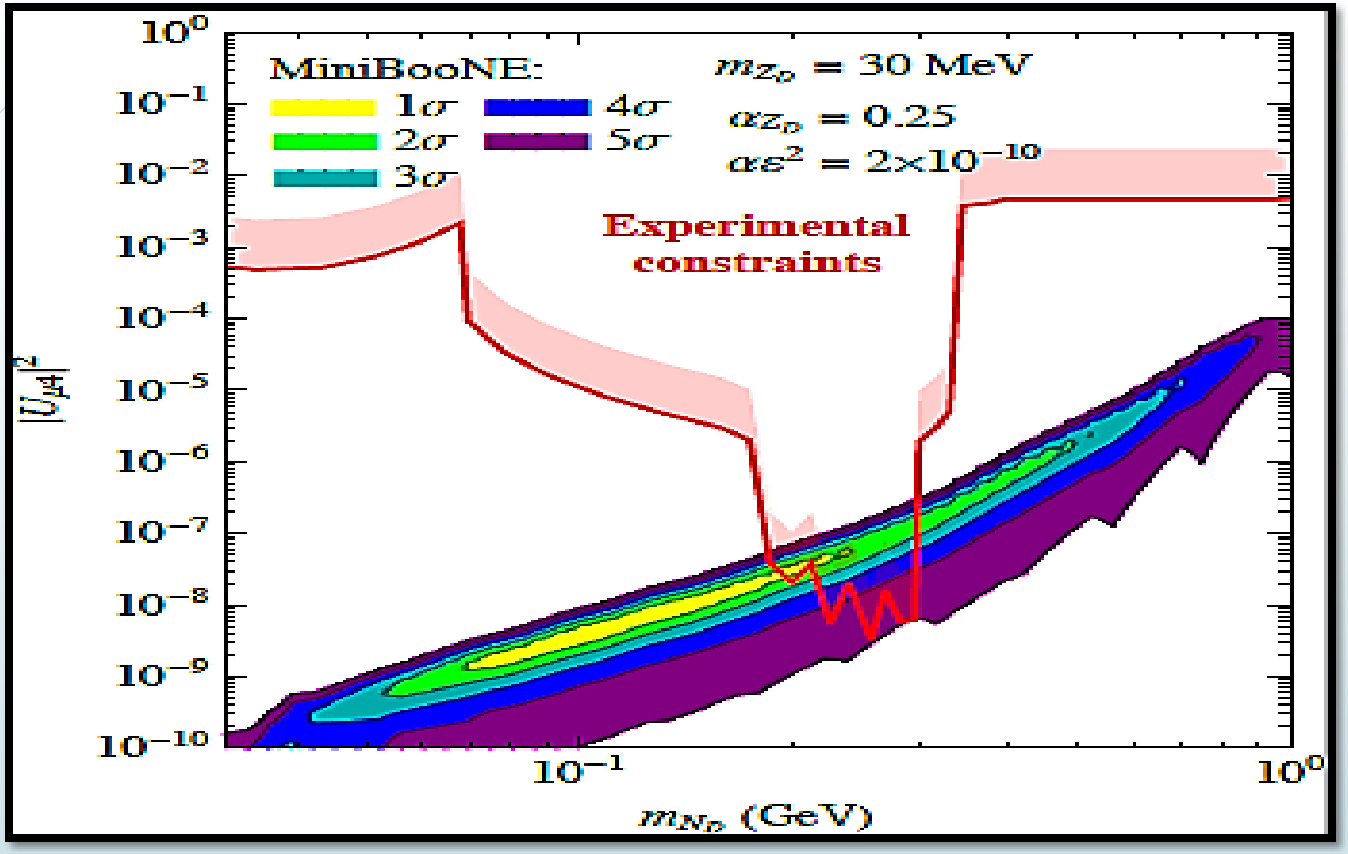
de Gouvea Kobach 1511.00683



Ilten et al 1801.04847

- ➢ Z_D phenomenology is similar to dark photon case
- ➢ LHC constraints are not expected to be stringent below 1 GeV

❖ Explanation of MiniBooNE's low energy excess



Region of our model in the $|U_{\mu 4}|^2$ versus m_{N_D} plane satisfying MiniBooNE data at 1σ to 5σ CL, for the hypothesis $m_{Z_D} = 30$ MeV, $\alpha_{Z_D} = 0.25$ and $\alpha\epsilon^2 = 2\times 10^{-10}$. The region above the red curve is excluded at 99% CL by meson decays, the muon decay Michel spectrum and lepton universality

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Connection to Neutrino Mass Generation Mechanism

Scale of Seesaw Mechanism

- **Despite numerous searches for neutrino mass models (at TeV scale) at high-energy colliders, no compelling evidence has been found so far.**

- **Is it really sufficient to search for new physics scale behind neutrino mass generation mechanism at LHC only ?**

- **The new physics scale behind neutrino mass generation mechanism might be at low scale and which is less sensitive to high energy collider experiments**

- **It may show up at low energy neutrino experiments at near future.**

Scale of Seesaw Mechanism

- **Despite numerous searches for neutrino m**
  models (at TeV scale) at high-energy
  compelling evidence has been

- **Is it really sufficient to**
  ics scale
  behind neutrin
  echanism at

Can neutrino masses come from light physics ?

cale behind neutrino mass
chanism might be at low scale and
less sensitive to high energy collider
experiments

- **It may show up at low energy neutrino experiments at near future.**

Neutrino masses from light physics

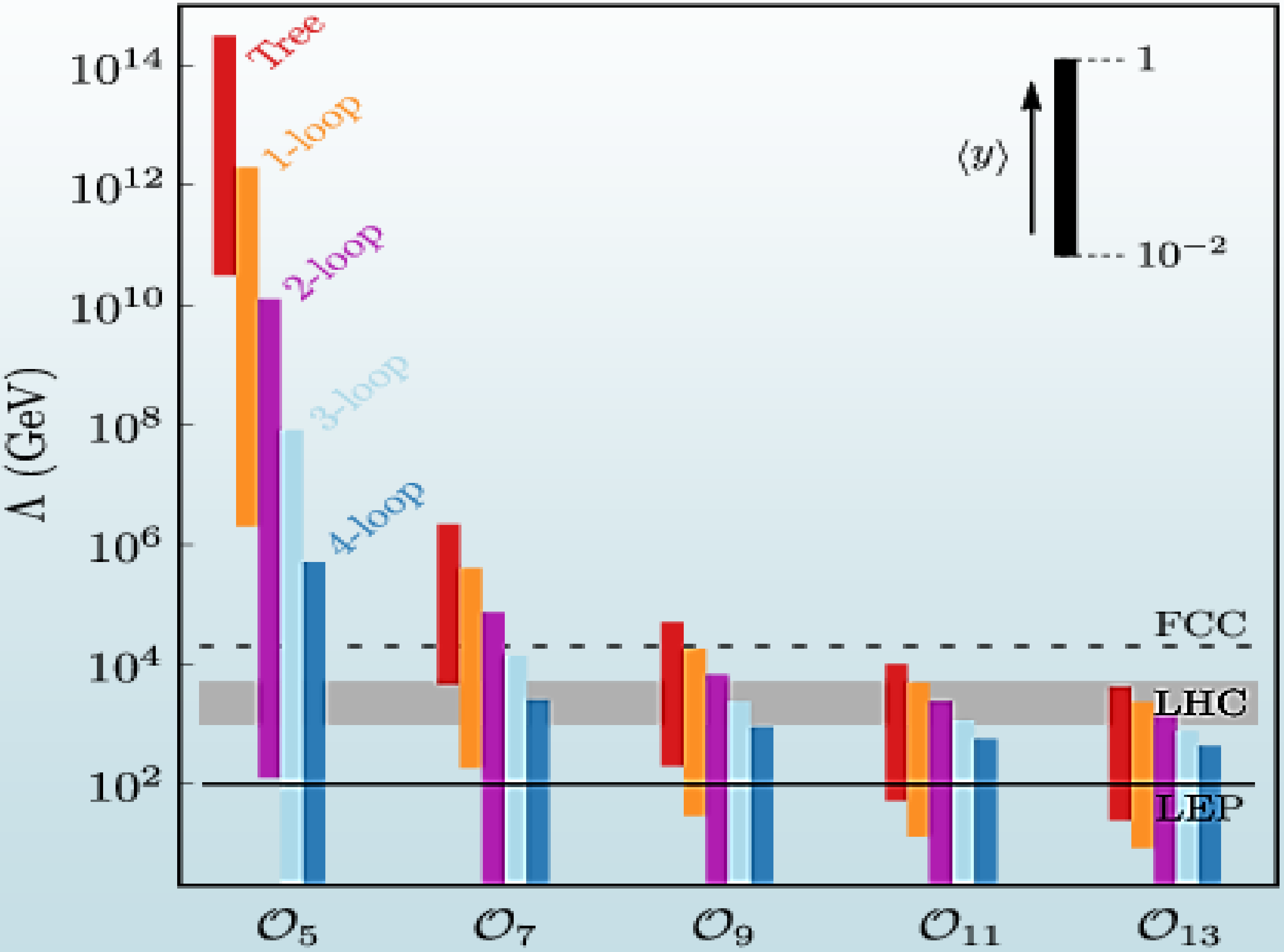
In an effective theory, the Lagrangian should be described as

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}}\mathscr{O}^{d=5} + \frac{1}{\Lambda_{\text{NP}}^2}\mathscr{O}^{d=6} + \frac{1}{\Lambda_{\text{NP}}^3}\mathscr{O}^{d=7} + \cdots$$

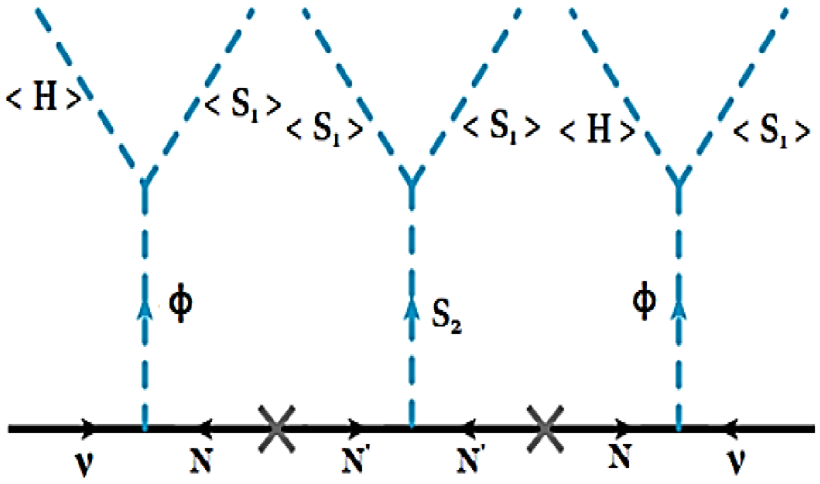
Neutrino masses from a n-loop-induced dim-d operator

$$m_\nu = v \times \left(\frac{1}{16\pi^2}\right)^n \times \left(\frac{v}{\Lambda_{\text{NP}}}\right)^{d-4}$$

Scale of Seesaw Mechanism



Neutrino masses from light physics



$$\mathcal{L}_\nu^{d=9} \sim y_\nu^2\, y_N \frac{\mu^2}{M_{H_D}^2} \frac{\mu'}{M_{S'_D}^4} \frac{(\overline{L^c} H)(H^T L)}{m^2} (S_1^* S_1)^2$$

Neutrino masses from D=9 operator

All scales involved may be below electroweak

Light Z_D, ν-N mixing, Z_D-ν-N coupling, kinetic mixing unavoidable

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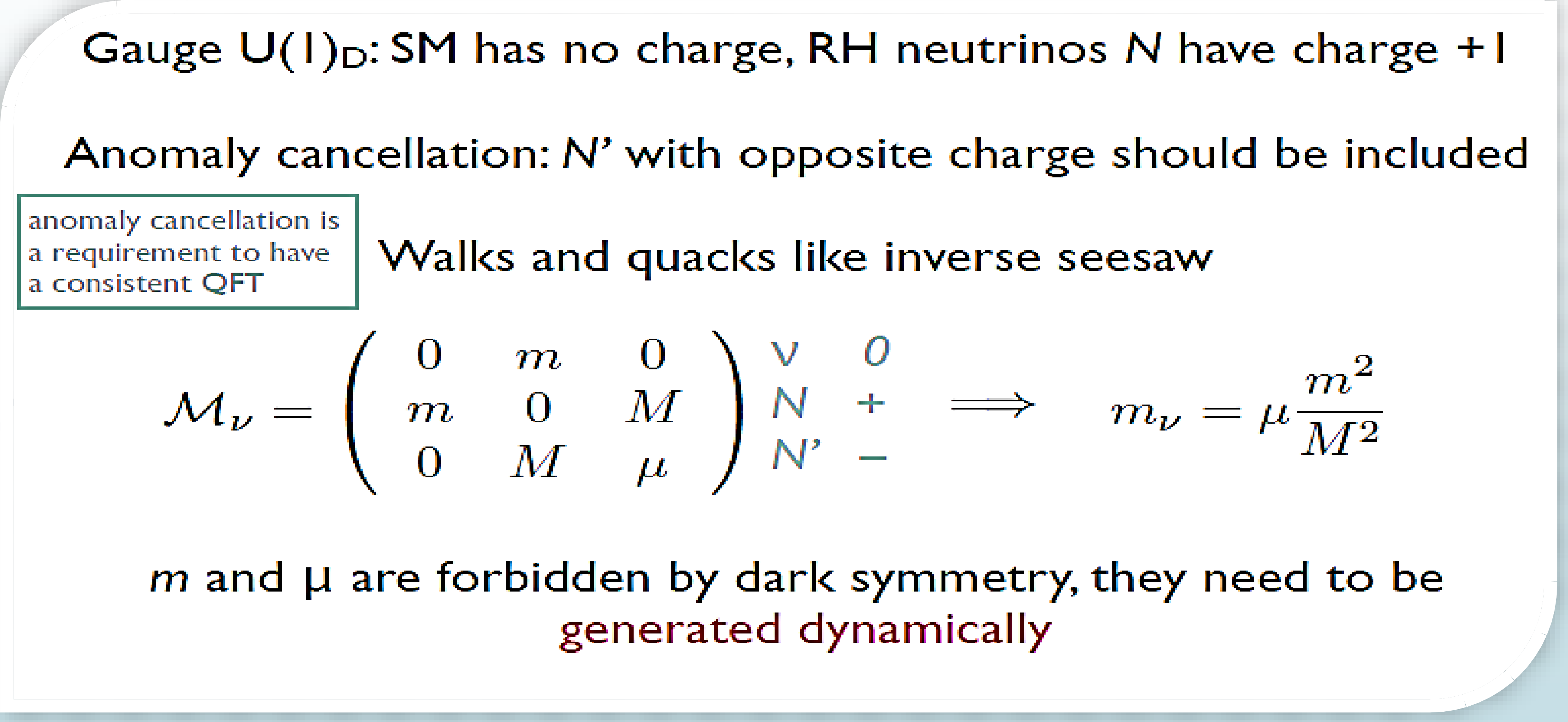
Neutrino masses from light physics



Gauge $U(1)_D$: SM has no charge, RH neutrinos *N* have charge +1

Anomaly cancellation: *N'* with opposite charge should be included

anomaly cancellation is a requirement to have a consistent QFT

Walks and quacks like inverse seesaw

$$\mathcal{M}_\nu = \left(\begin{array}{ccc} 0 & m & 0 \\ m & 0 & M \\ 0 & M & \mu \end{array}\right) \begin{array}{cc} \nu & 0 \\ N & + \\ N' & - \end{array} \quad \Longrightarrow \quad m_\nu = \mu \frac{m^2}{M^2}$$

m and μ are forbidden by dark symmetry, they need to be generated dynamically

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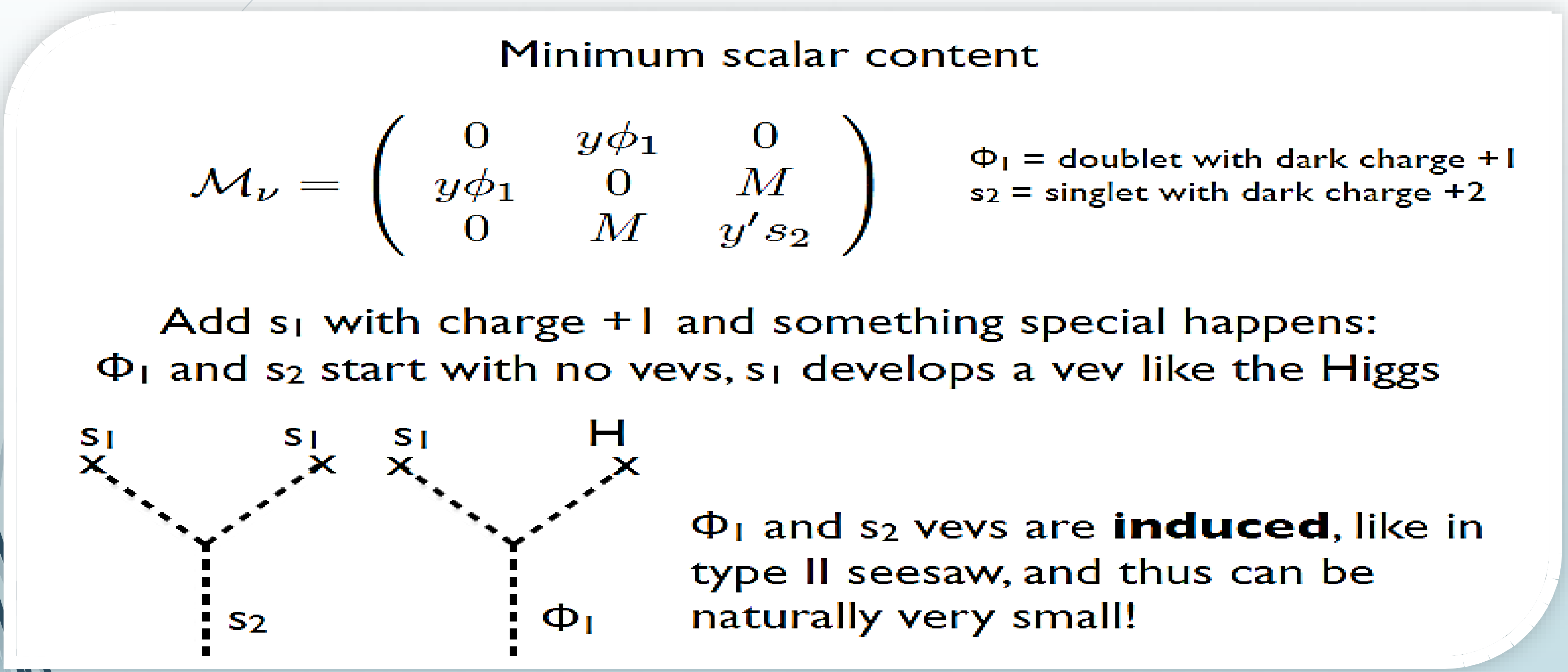
Neutrino masses from light physics



Minimum scalar content

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & y' s_2 \end{pmatrix}$$

Φ_1 = doublet with dark charge +1
s_2 = singlet with dark charge +2

Add s_1 with charge +1 and something special happens:
Φ_1 and s_2 start with no vevs, s_1 develops a vev like the Higgs

Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

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Neutrino masses from light physics

Minimum scalar content

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & \boxed{y' s_2} \end{pmatrix}$$

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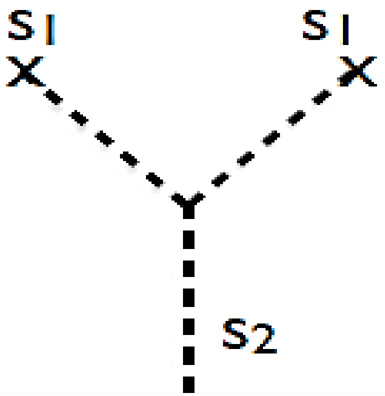

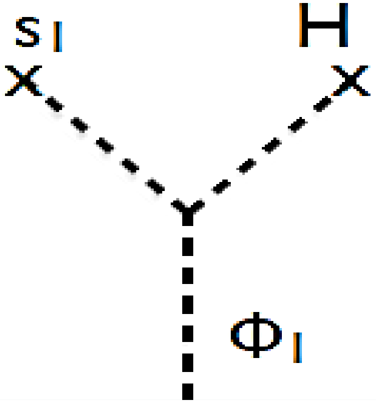

Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

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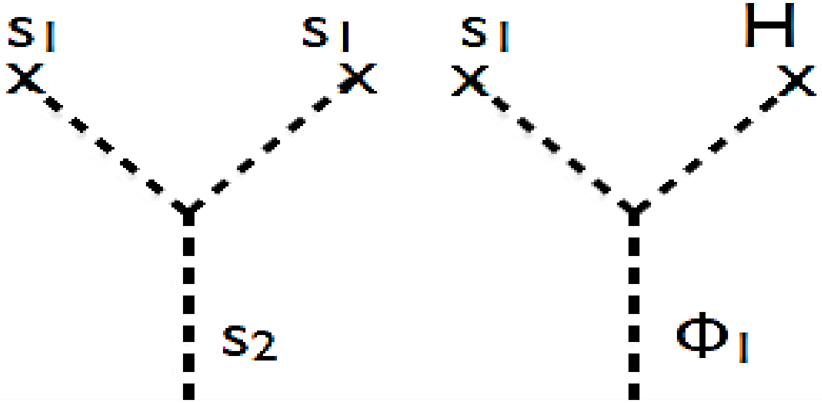
Neutrino masses from light physics

Minimum scalar content

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & \boxed{y' s_2} \end{pmatrix}$$

$$\mathcal{L}_\nu = -\,y_\nu\,\overline{L}\widetilde{\phi}N + y_N\,S_2\,\overline{N}N^c + y_{N'}\,S_2^*\,\overline{N'}N'^c + m\,\overline{N'}N^c + \text{h.c.}$$

Add s_1 with charge +1 and something special happens:
Φ_1 and s_2 start with no vevs, s_1 develops a vev like the Higgs



Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

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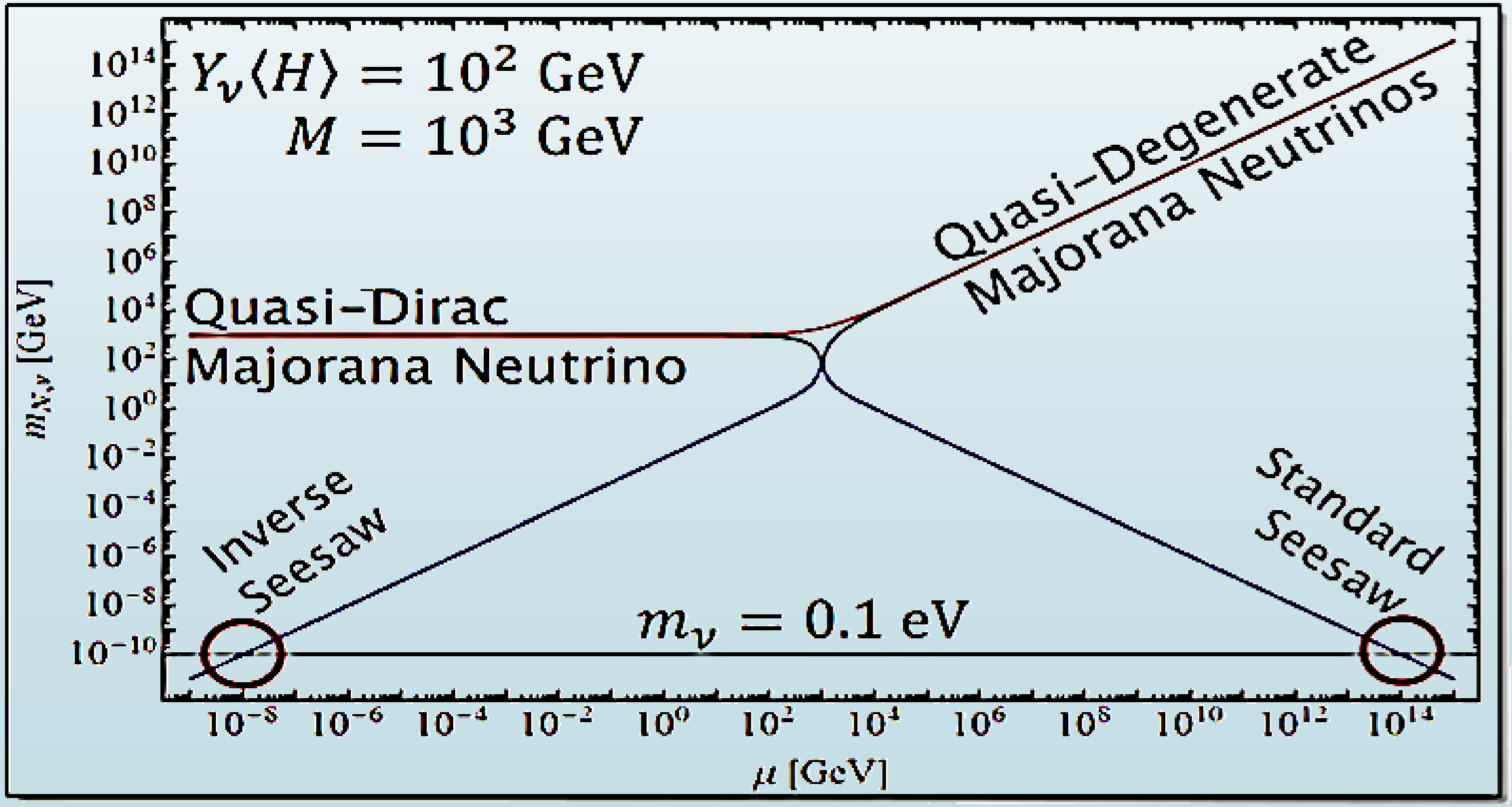
Scale of Seesaw Mechanism

- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $\boxed{Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}}$
  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\boxed{\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}}$$

    - Large Yukawa couplings $\approx 10^{-2}$
    - Quasi–Dirac heavy neutrino



❖Inverse Seesaw

[Mohapatra, 86]
[Mohapatra,Valle, 86]

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$

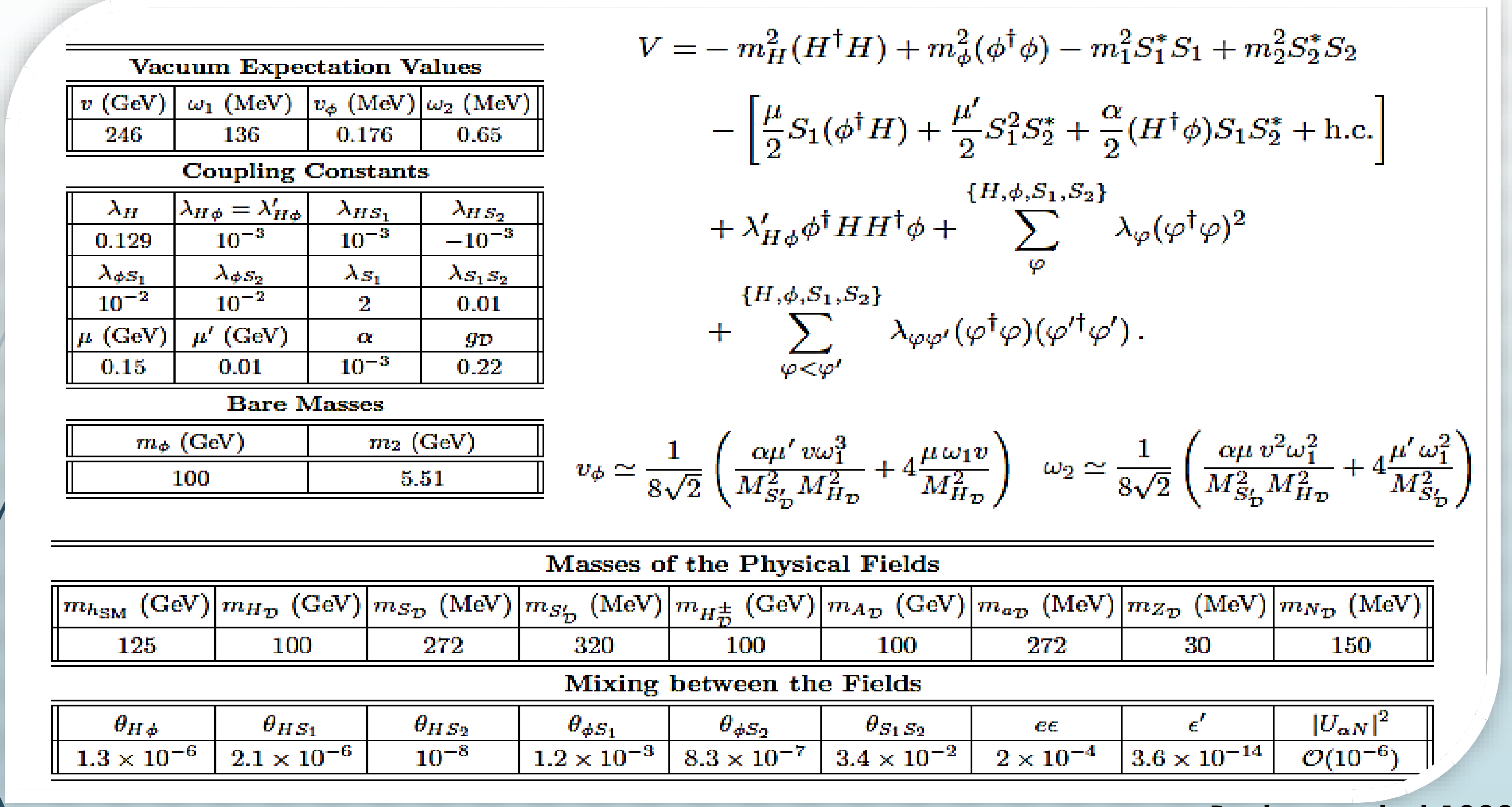
Ψ, Ψ^c **Pseudo-Dirac**

$$m_\nu \sim \frac{y^2v^2}{m_\Psi^2}\boxed{\mu}$$

$$y \sim 0.1 \quad m_\Psi \sim 1\mathrm{TeV} \quad \boxed{\mu \sim 1\mathrm{keV}}$$

- Why μ is much smaller than TeV scale?

Neutrino masses from light physics



Vacuum Expectation Values

v (GeV)	ω_1 (MeV)	v_ϕ (MeV)	ω_2 (MeV)
246	136	0.176	0.65

Coupling Constants

λ_H	$\lambda_{H\phi} = \lambda'_{H\phi}$	λ_{HS_1}	λ_{HS_2}
0.129	10^{-3}	10^{-3}	-10^{-3}
$\lambda_{\phi S_1}$	$\lambda_{\phi S_2}$	λ_{S_1}	$\lambda_{S_1 S_2}$
10^{-2}	10^{-2}	2	0.01
μ (GeV)	μ' (GeV)	α	$g_{\mathcal{D}}$
0.15	0.01	10^{-3}	0.22

Bare Masses

m_ϕ (GeV)	m_2 (GeV)
100	5.51

$$V = - m_H^2 (H^\dagger H) + m_\phi^2 (\phi^\dagger \phi) - m_1^2 S_1^* S_1 + m_2^2 S_2^* S_2$$

$$- \left[\frac{\mu}{2} S_1 (\phi^\dagger H) + \frac{\mu'}{2} S_1^2 S_2^* + \frac{\alpha}{2} (H^\dagger \phi) S_1 S_2^* + \text{h.c.} \right]$$

$$+ \lambda'_{H\phi} \phi^\dagger H H^\dagger \phi + \sum_{\varphi}^{\{H,\phi,S_1,S_2\}} \lambda_\varphi (\varphi^\dagger \varphi)^2$$

$$+ \sum_{\varphi < \varphi'}^{\{H,\phi,S_1,S_2\}} \lambda_{\varphi\varphi'} (\varphi^\dagger \varphi)(\varphi'^\dagger \varphi') \, .$$

$$v_\phi \simeq \frac{1}{8\sqrt{2}} \left(\frac{\alpha \mu' \, v \omega_1^3}{M_{S'_{\mathcal{D}}}^2 M_{H_{\mathcal{D}}}^2} + 4 \frac{\mu \, \omega_1 v}{M_{H_{\mathcal{D}}}^2} \right) \quad \omega_2 \simeq \frac{1}{8\sqrt{2}} \left(\frac{\alpha \mu \, v^2 \omega_1^2}{M_{S'_{\mathcal{D}}}^2 M_{H_{\mathcal{D}}}^2} + 4 \frac{\mu' \, \omega_1^2}{M_{S'_{\mathcal{D}}}^2} \right)$$

Masses of the Physical Fields

$m_{h_{\rm SM}}$ (GeV)	$m_{H_{\mathcal{D}}}$ (GeV)	$m_{S_{\mathcal{D}}}$ (MeV)	$m_{S'_{\mathcal{D}}}$ (MeV)	$m_{H^\pm_{\mathcal{D}}}$ (GeV)	$m_{A_{\mathcal{D}}}$ (GeV)	$m_{a_{\mathcal{D}}}$ (MeV)	$m_{Z_{\mathcal{D}}}$ (MeV)	$m_{N_{\mathcal{D}}}$ (MeV)
125	100	272	320	100	100	272	30	150

Mixing between the Fields

$\theta_{H\phi}$	θ_{HS_1}	θ_{HS_2}	$\theta_{\phi S_1}$	$\theta_{\phi S_2}$	$\theta_{S_1 S_2}$	$e\epsilon$	ϵ'	$\lvert U_{\alpha N}\rvert^2$
1.3×10^{-6}	2.1×10^{-6}	10^{-8}	1.2×10^{-3}	8.3×10^{-7}	3.4×10^{-2}	2×10^{-4}	3.6×10^{-14}	$\mathcal{O}(10^{-6})$

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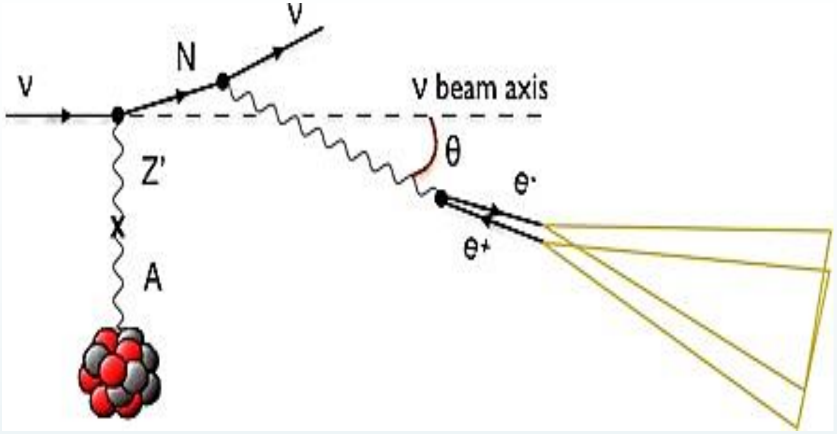
❖ Phenomenology on other neutrino experiment

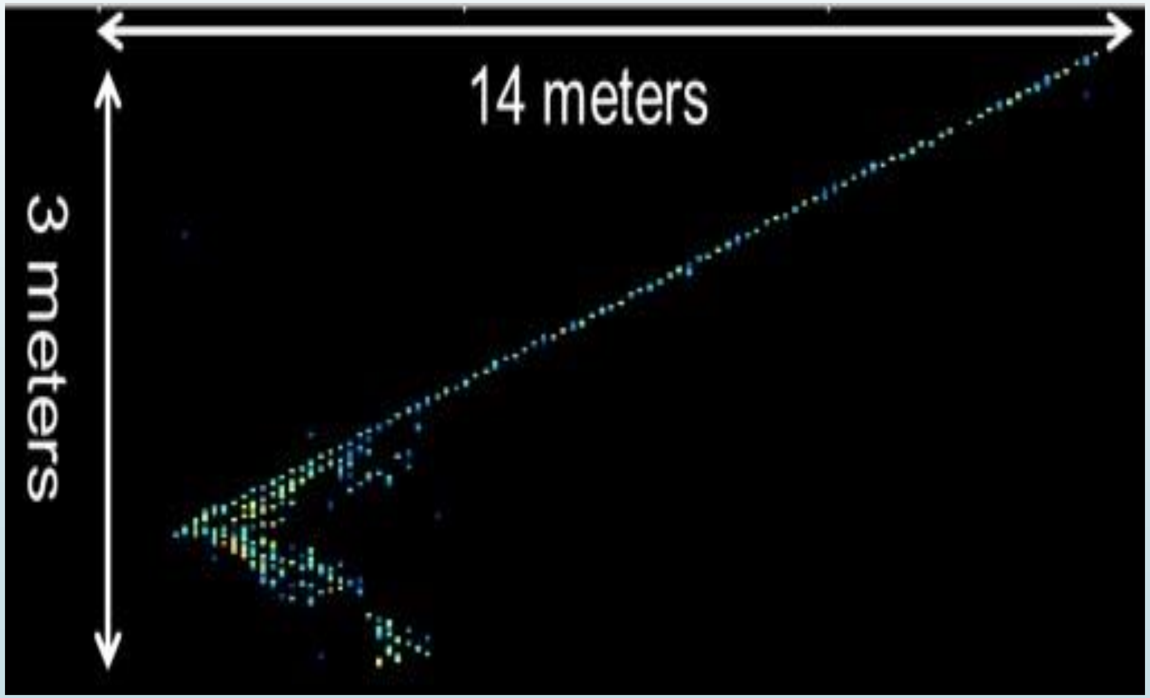
MiniBooNE's signature: Collimated e^+e^- pair in MINOS+, NOvA, or T2K is likely be tagged as ν_e event

General signature:

Heavy enough Z_D can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized…)

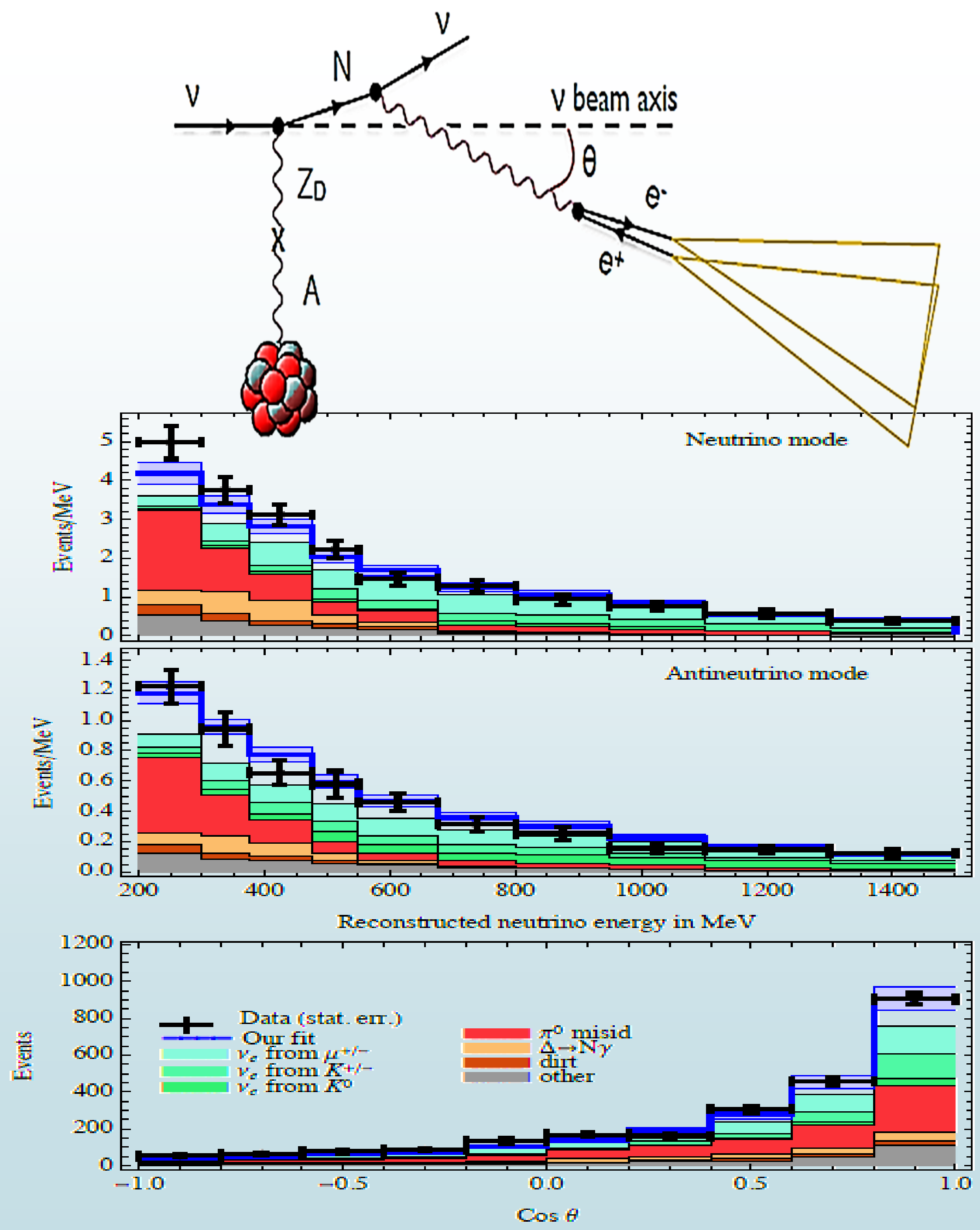
Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N





Conclusions :

- *Novel explanation of MiniBooNE*
- *Agreement with all EXP data*
- *Novel, simple frameworks*
- *Deep connection to neutrino mass generation mechanism*
- *A realistic "complete" model below EW scale to explain neutrino mass generation*
- *Solves the hierarchy of Inverse Seesaw*
- *Rich phenomenology*



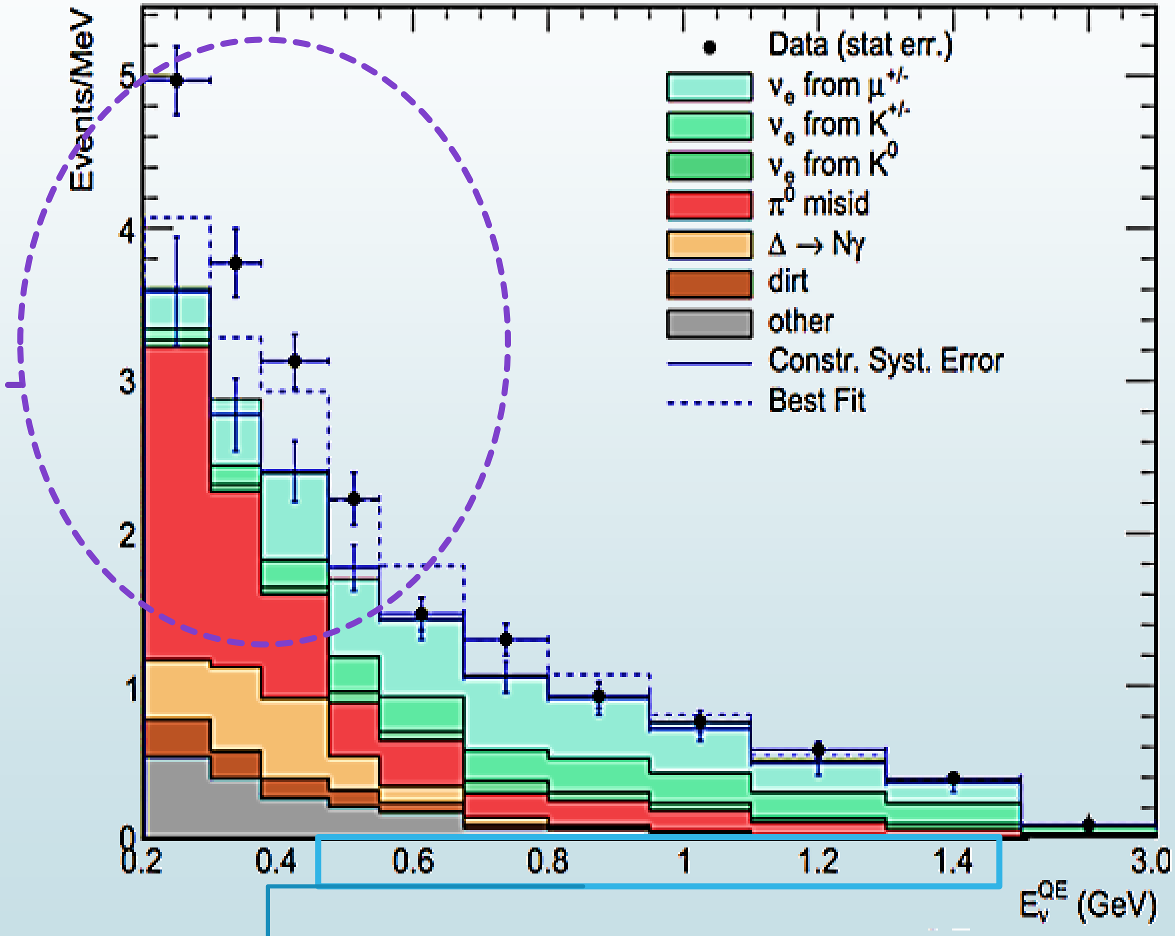

DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
V
TOP SECRET


DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
ν
MiniBooNE


Thank you!

MiniBooNE's Low Energy Excess

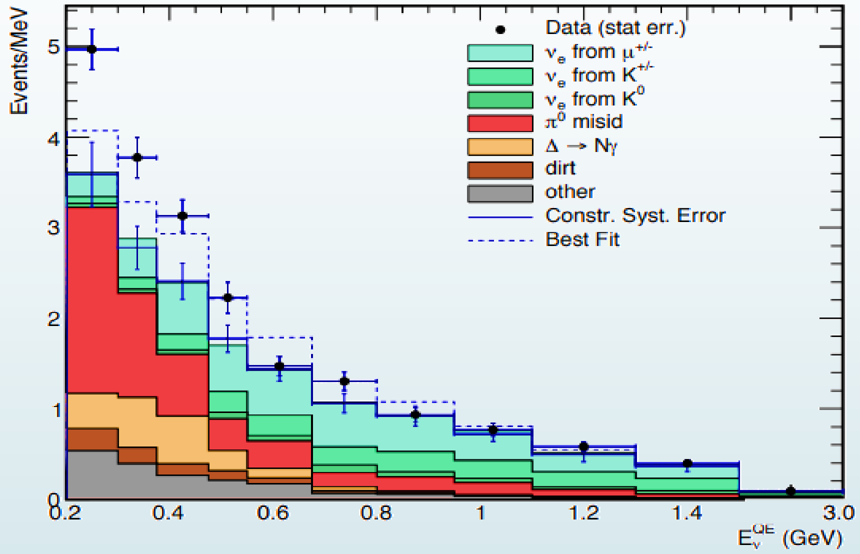
MiniBooNE Collaboration [hep-ex/1805.12028]()

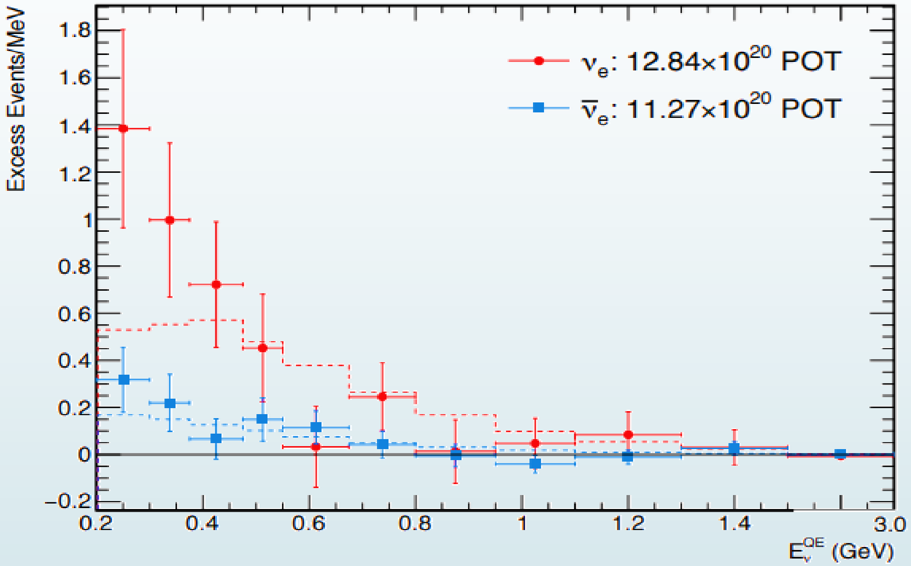


MiniBooNE observed a large excess in the much lower energy region

This is the region that the LSND oscillation should have appeared

MiniBooNE’s Low Energy Excess


Neutrino mode only


Both excesses, BG subtracted

$$E_\nu^{(\text{reconst.})} = \frac{2m_n E_e + m_p^2 - m_n^2 - m_e^2}{2(m_n - E_e + \cos\theta_e \sqrt{E_e^2 - m_e^2})}$$

Measure charged lepton energy/angle

Observed ~ 400 events, PMNS predicts 0

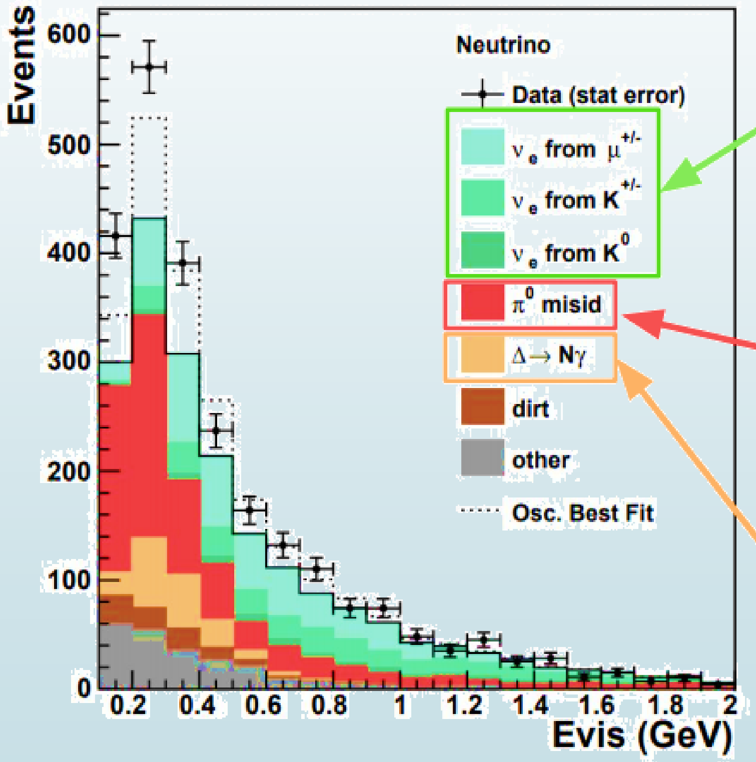
Combined $\nu/\bar{\nu}$ modes : 4.8σ excess

MiniBooNE Collaboration 1805.12028

MiniBooNE's Low Energy Excess

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.

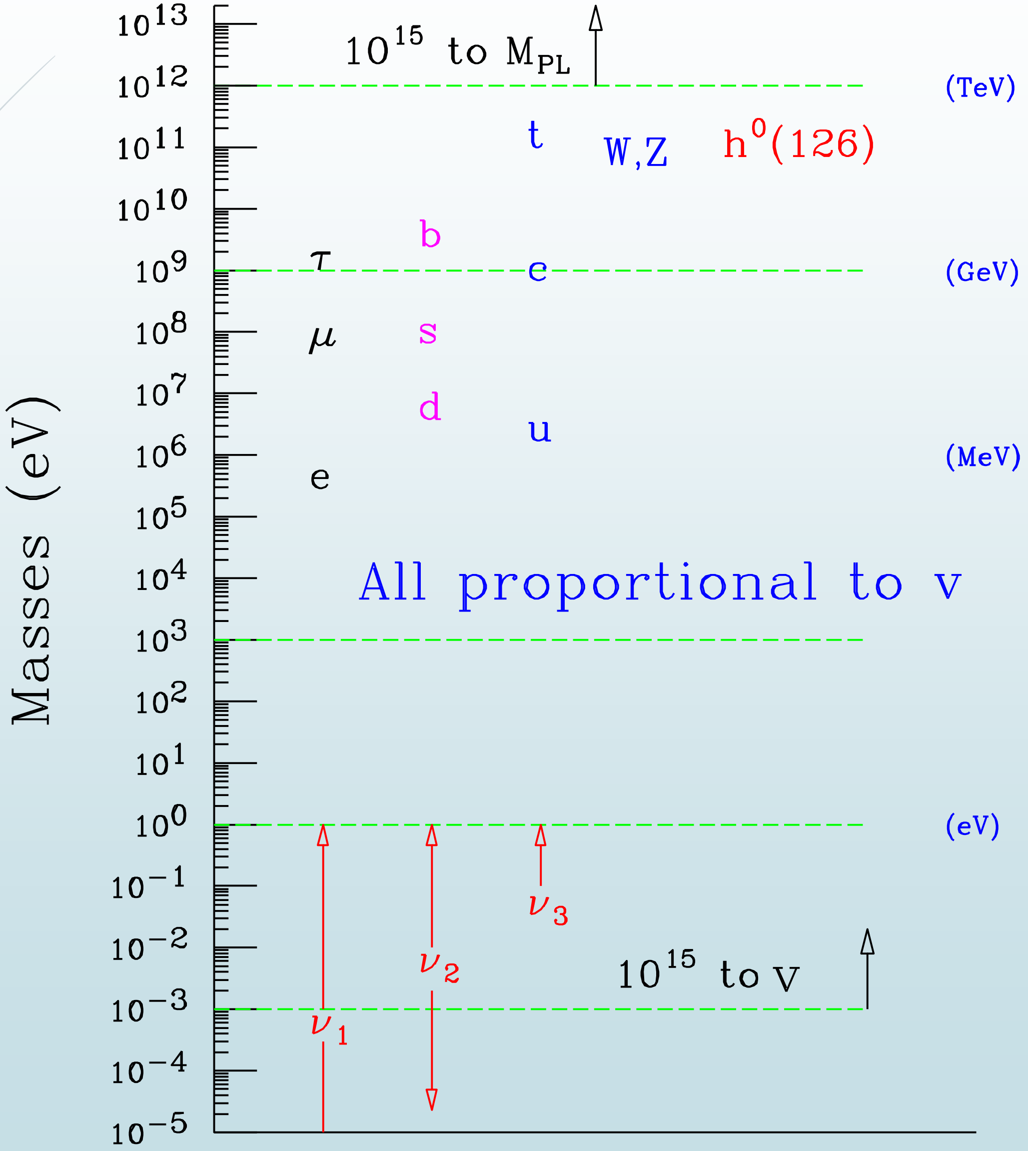
Radiative Δ decay? This has never been observed in the neutrino sector. MiniBooNE bound it using their NC π^0 measurements which agrees well with best theoretical calculations. The biggest channel of interest to MicroBooNE's photon LEE analysis.

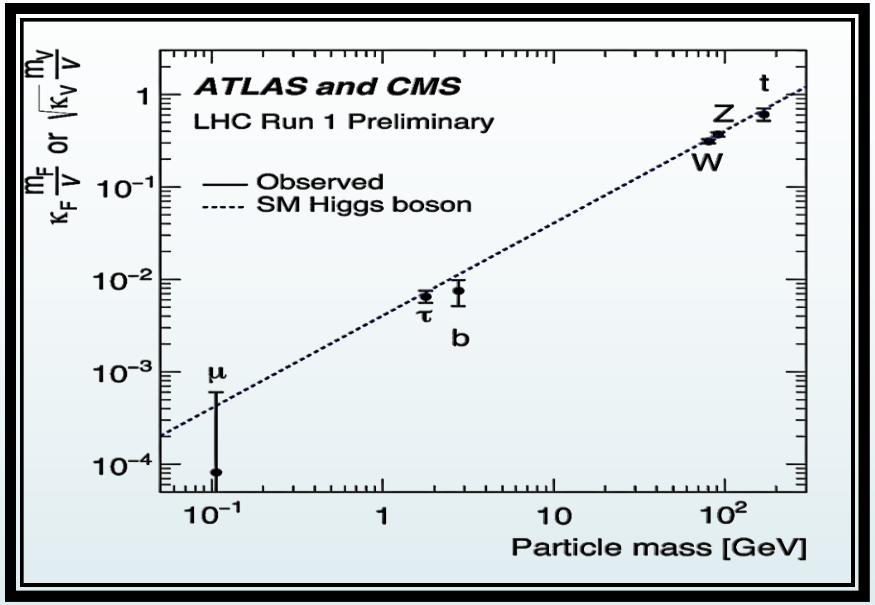
❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE PRESCRIPTION

- 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? $\theta_{SEP} < 5^0$
- 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

Neutrino Mass ⇨ New physics beyond SM:





$$m_\nu \sim y_\nu^{eff}\ v$$

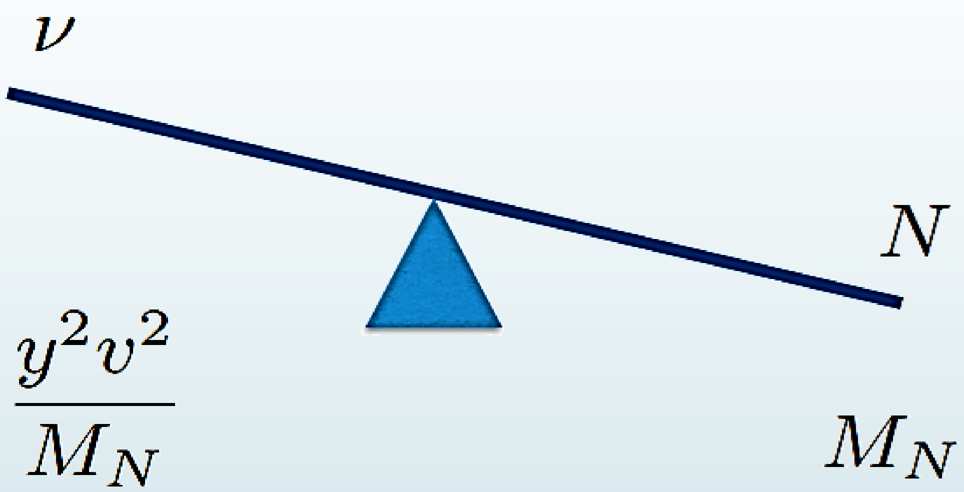
$$y_\nu^{eff} < 10^{-12}$$

❖ Standard/Type I Seesaw

$$yNH\ell + M_N NN$$

$$\frac{y^2 \ell H \ell H}{M_N}$$

$$m_\nu \sim \frac{y^2 v^2}{M_N}$$



$$\boxed{m_\nu \sim 0.1\text{eV} \qquad y \sim 0.1 \qquad M_N \sim 10^{12}\text{GeV}}$$

Lepton number is broken at very high scale M_N

❖ Phenomenology on other neutrino experiment

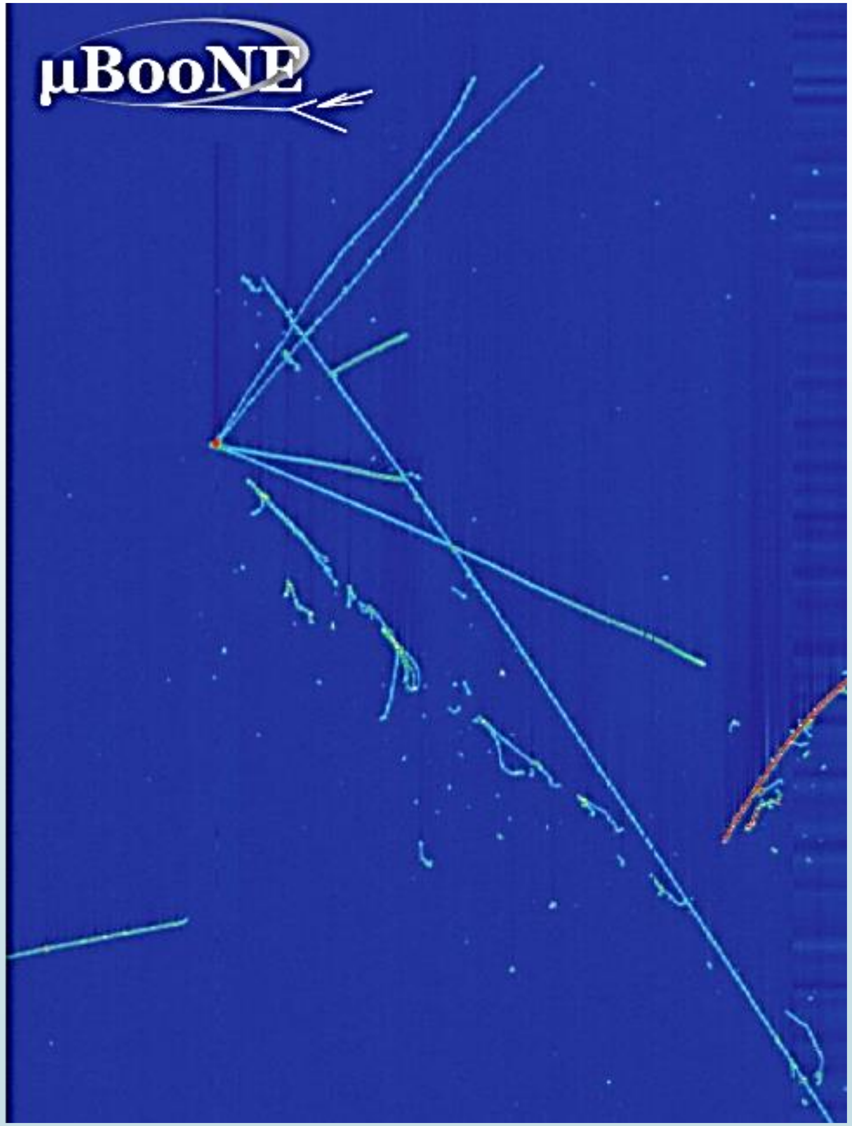
U(1)' models in Future and Current LArTPCs

This class of models has has incredibly **rich phenomenology** at LArTPCs such as **MicroBooNE, SBND or the DUNE near detector**:

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

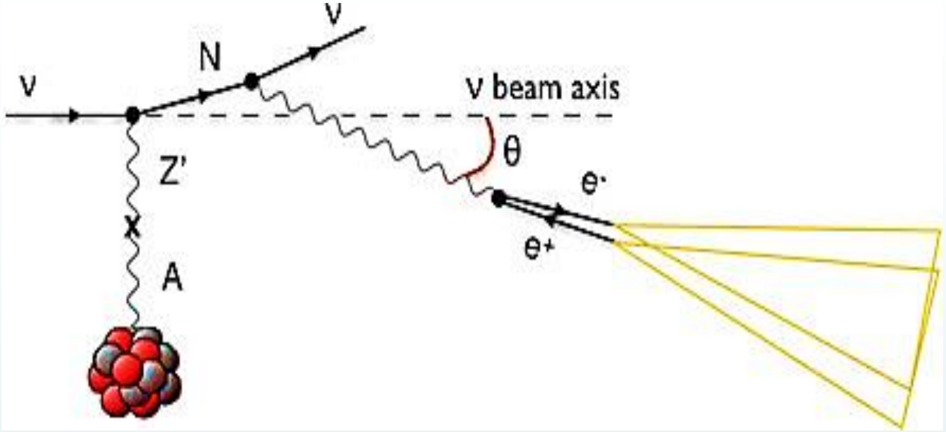
- Directly look for the **conversion gap**

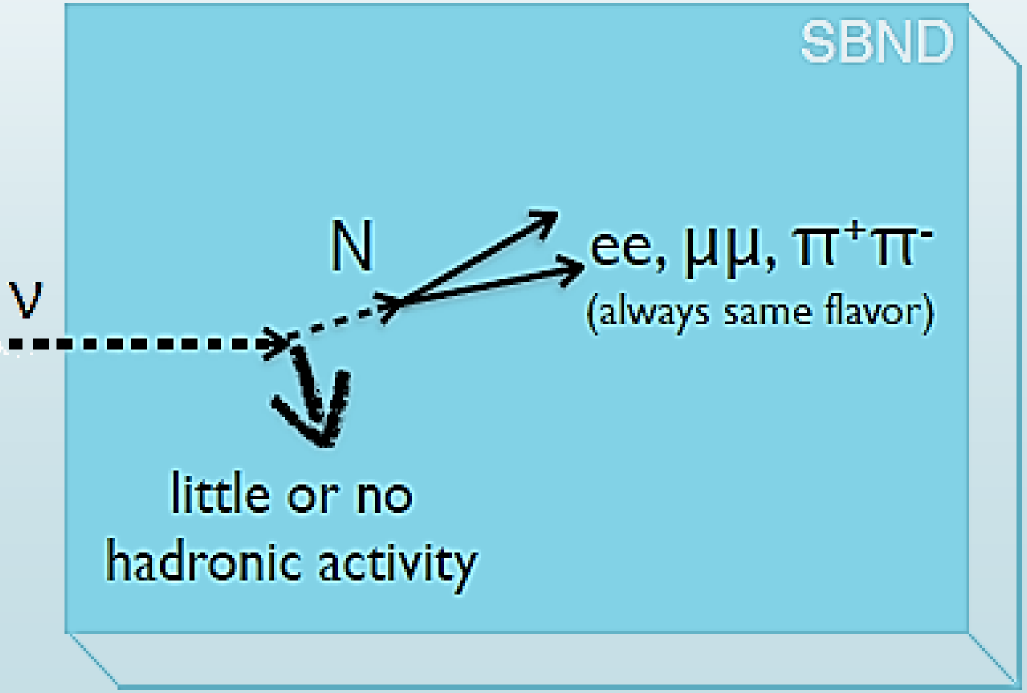
- Use **Calorimetric measurements** to see rate of energy deposition (dE/dx). **Photons** that pair convert to e^+e^- **deposit x2 as much energy**.

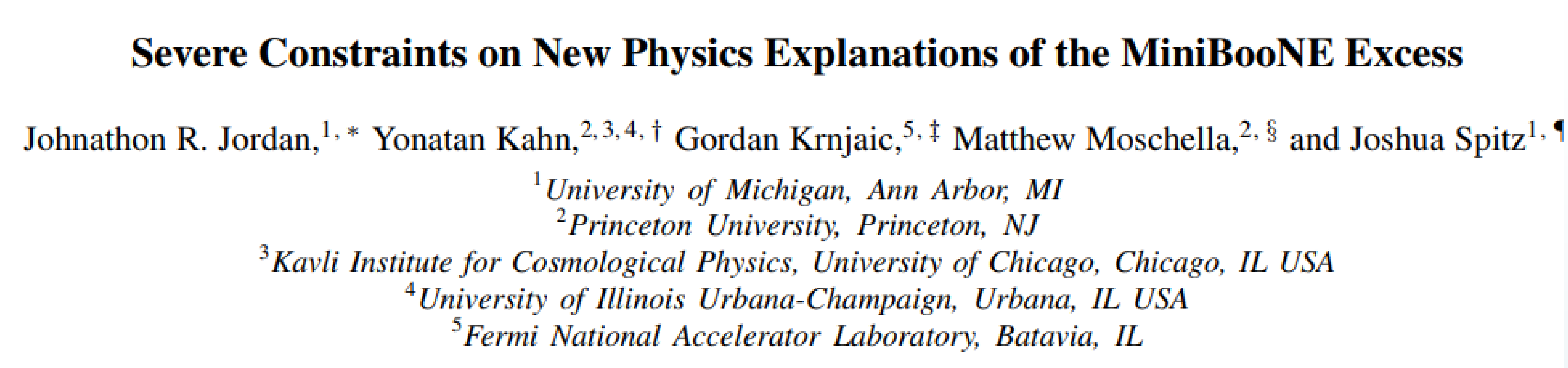


❖ What happens at the SBN program?

- ✓ **No baseline dependence**
- ✓ **Almost no hadronic activity to tag interaction vertex**
- ✓ Decays to collimated e^+e^- pairs
- ✓ More events due to coherence:
- ✓ $_6$C vs $_{18}$Ar ~ 3 times more events for same exposure
- ✓ Hard to probe !!!







Severe Constraints on New Physics Explanations of the MiniBooNE Excess

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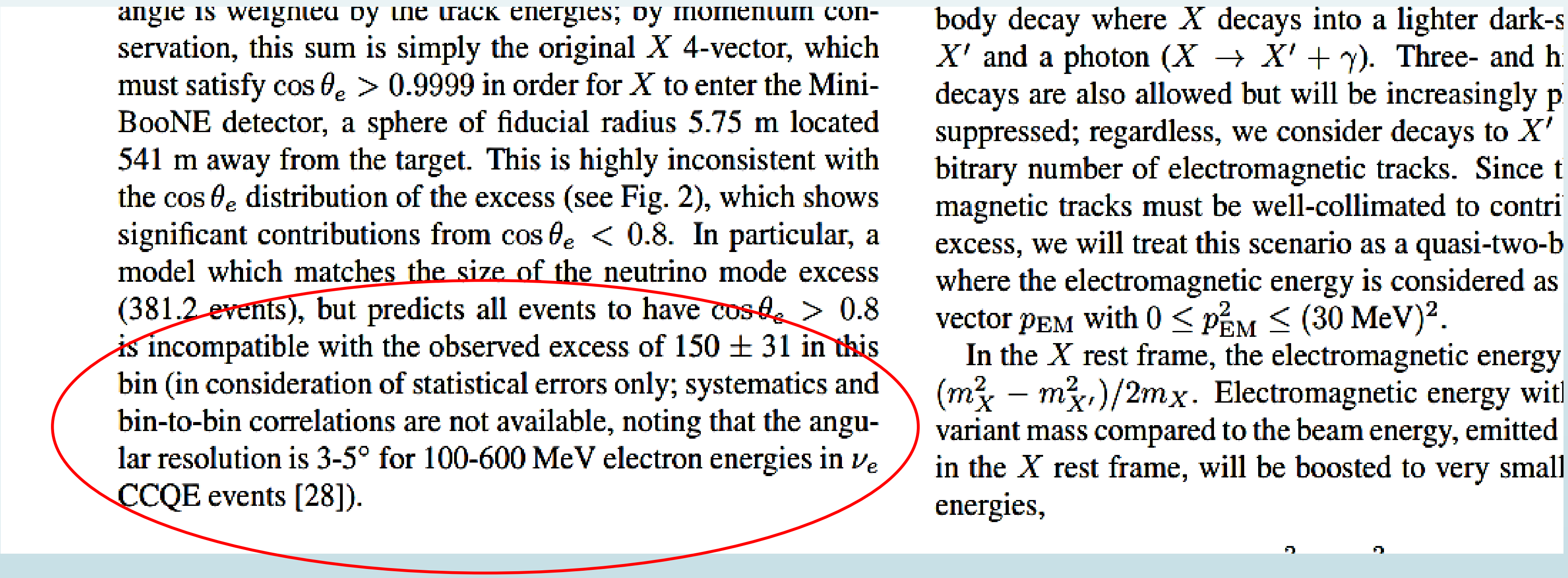
[3]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL USA*
[4]*University of Illinois Urbana-Champaign, Urbana, IL USA*
[5]*Fermi National Accelerator Laboratory, Batavia, IL*



angle is weighted by the track energies; by momentum conservation, this sum is simply the original X 4-vector, which must satisfy $\cos\theta_e > 0.9999$ in order for X to enter the MiniBooNE detector, a sphere of fiducial radius 5.75 m located 541 m away from the target. This is highly inconsistent with the $\cos\theta_e$ distribution of the excess (see Fig. 2), which shows significant contributions from $\cos\theta_e < 0.8$. In particular, a model which matches the size of the neutrino mode excess (381.2 events), but predicts all events to have $\cos\theta_e > 0.8$ is incompatible with the observed excess of 150 ± 31 in this bin (in consideration of statistical errors only; systematics and bin-to-bin correlations are not available, noting that the angular resolution is 3-5° for 100-600 MeV electron energies in ν_e CCQE events [28]).

body decay where X decays into a lighter dark-s
X' and a photon ($X \to X' + \gamma$). Three- and h
decays are also allowed but will be increasingly p
suppressed; regardless, we consider decays to X'
bitrary number of electromagnetic tracks. Since t
magnetic tracks must be well-collimated to contri
excess, we will treat this scenario as a quasi-two-b
where the electromagnetic energy is considered as
vector p_{EM} with $0 \leq p_{\mathrm{EM}}^2 \leq (30\ \mathrm{MeV})^2$.

In the X rest frame, the electromagnetic energy
$(m_X^2 - m_{X'}^2)/2m_X$. Electromagnetic energy wit
variant mass compared to the beam energy, emitted
in the X rest frame, will be boosted to very small
energies,