Confronting Neutrino Mass Generation Mechanism with MiniBooNE Anomaly

Sudip Jana

NTN Workshop on Neutrino Non-Standard Interactions

29-31 May 2019

Washington University in St Louis

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

BSM Motivations

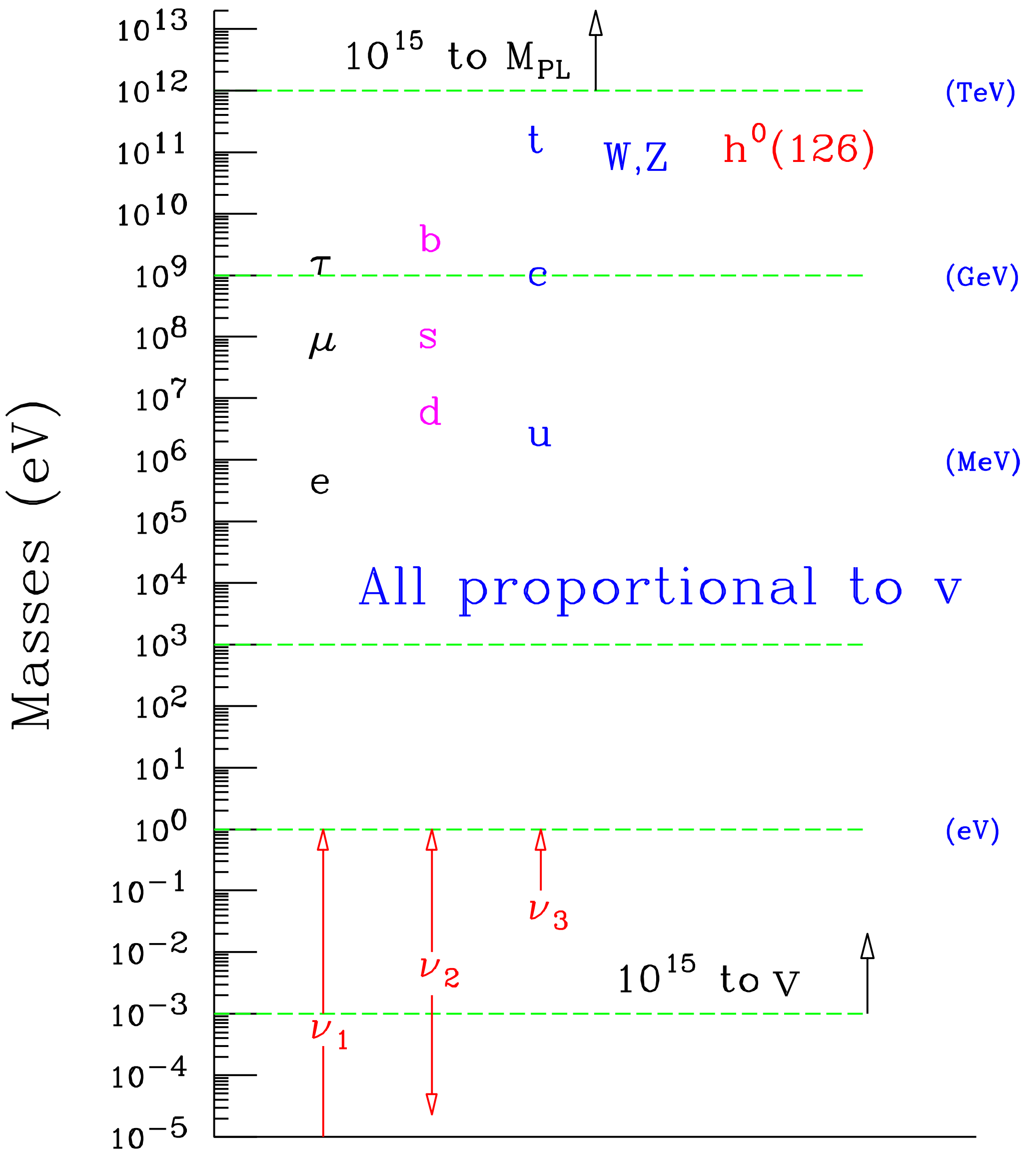
Experimental Evidences

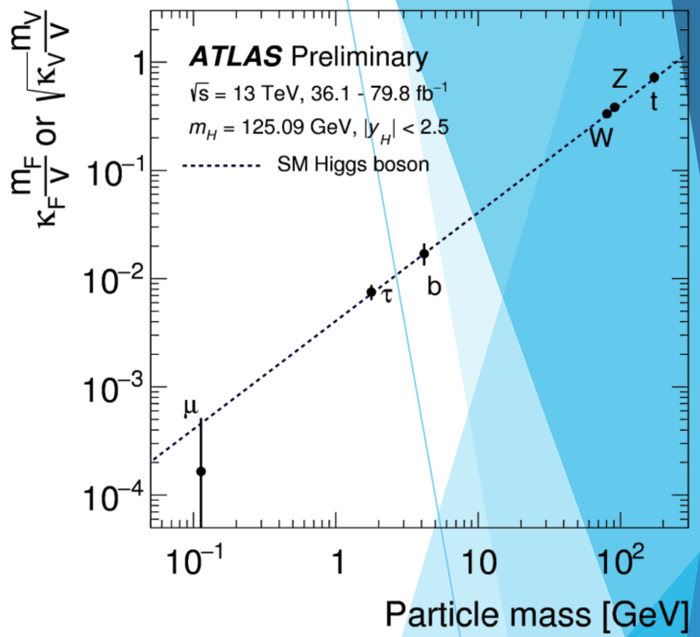
- Neutrino Masses and Mixing
- Dark Matter and Dark Energy
- Matter-antimatter Asymmetry
- Anomalies

Theoretical Motivations

- Naturalness Problem
- Strong CP Problem
- Grand Unification
- Flavor Puzzle

❖ Neutrino Masses and Mixings > New physics beyond SM





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

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

❖ Small Neutrino Masses

- "Technically natural" in t'Hooft sense. Small values are protected by symmetry. At a cut-off scale Λ :
  "natural" - $\delta m_f \sim g^2/(16\pi^2)\, m_f \ln(\Lambda^2/m_f^2)$
  "unnatural" - $\delta m_H^2 \sim -\, y_t^2/(8\pi^2)\, \Lambda^2$

- Two ways to generate small values naturally :

- Suppression by integrating out heavy states :
  the higher dimension $1/\Lambda^n$, the lower Λ can be.

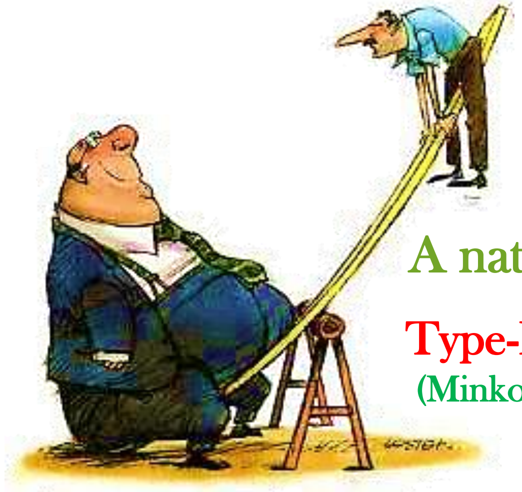
- Suppression by loop radiative generation:
  the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

Neutrino Mass Models

- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (79) 1566

- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ★ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ★ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ★ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ★ Linear, Inverse, etc ...
  - Loop-induced:
    - ★ 1-loop Zee (80), Ma (99)
    - ★ 2-loop Babu (88)

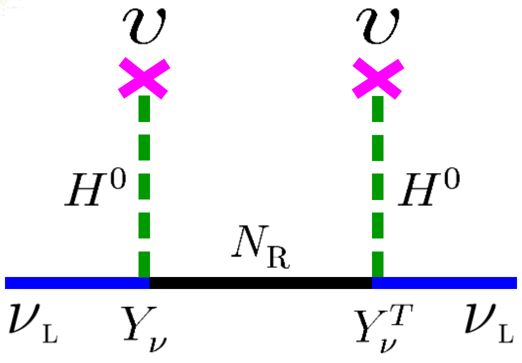


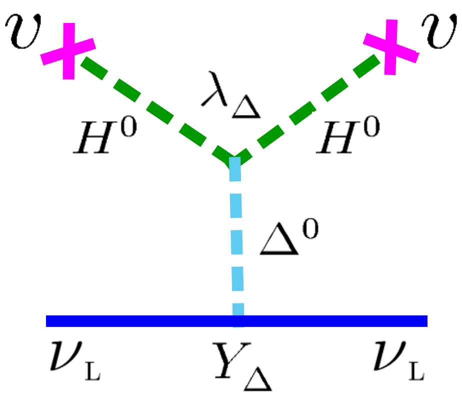
❖ Seesaw Models

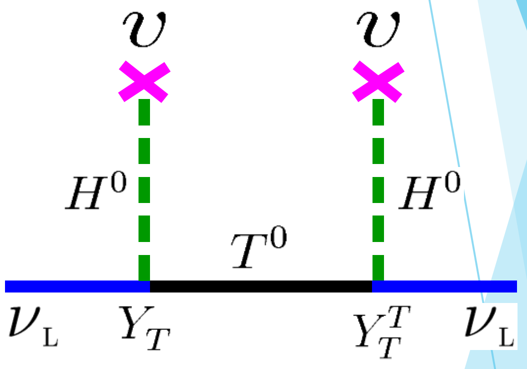
A natural theoretical way to understand why 3 ν-masses are very small.

Type-I: SM + 3 right-handed Majorana ν's

(Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)







$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

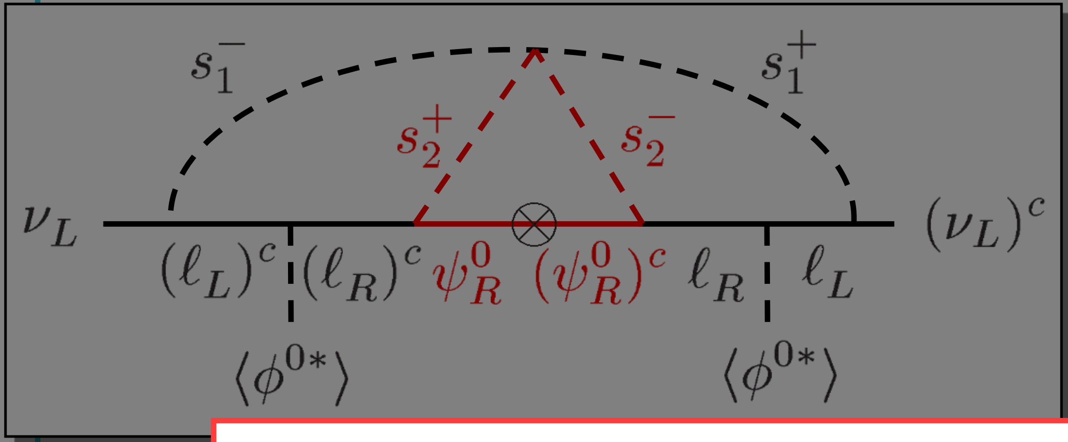
Type-II: SM + 1 Higgs triplet

(Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

Type-III: SM + 3 triplet fermions

(Foot, Lew, He, Joshi 89)

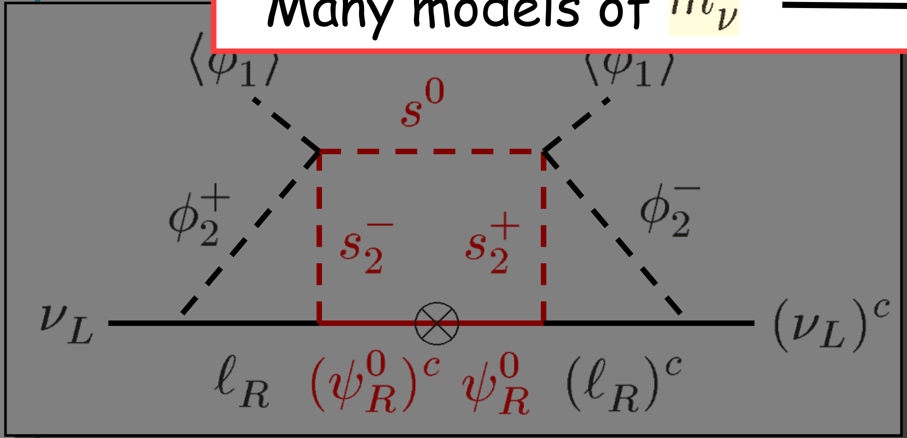
Higher-loop models with DM



Krauss-Nasri-

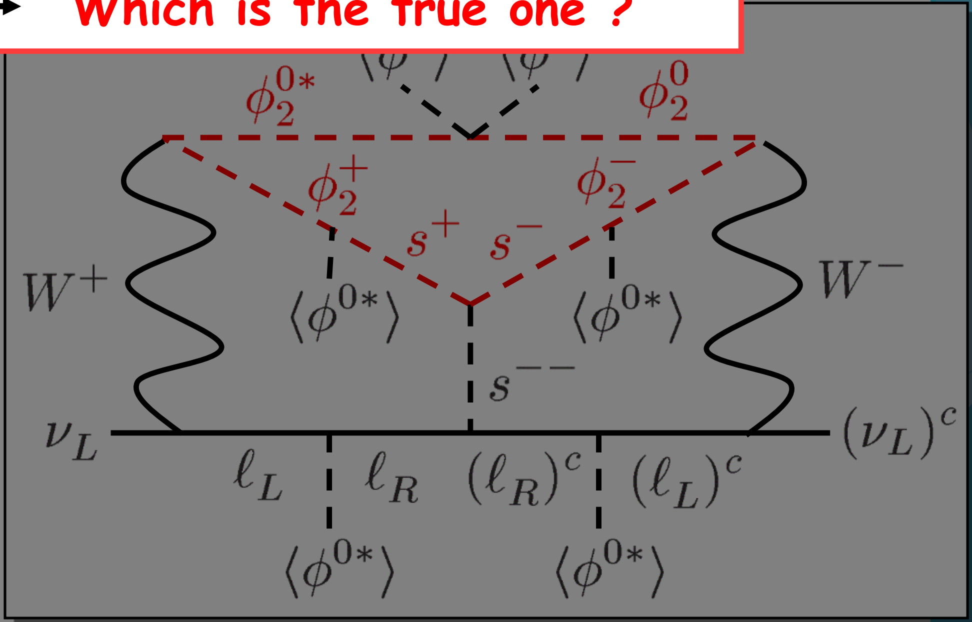
M.L. Krauss, S. N

Many models of m_ν → **Which is the true one ?**



Aoki-Kanemura-Seto model

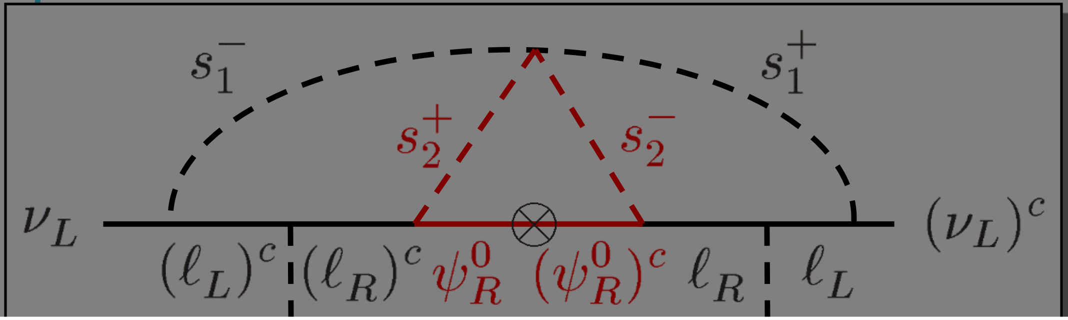
M. Aoki, S. Kanemura and O. Seto, PRL**102**, 051805 (2009)



Gustafsson-No-Rivera model

M. Gustafsson, J.M. No, and M.A. Rivera, PRL**110**, 21802 (2013)

Higher-loop models with DM



Krauss-Nasri-

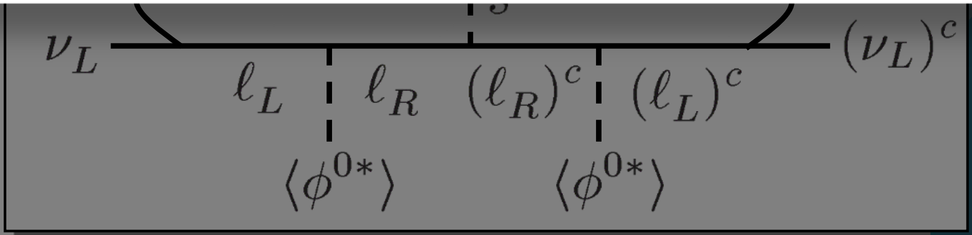
M.L. Krauss, S. N

1. Can we test / falsify these models at the experiments ?

2. Can we explore the new Physics Scale M ?

Aoki-Kanemura-Seto model

M. Aoki, S. Kanemura and O. Seto, PRL**102**, 051805 (2009)



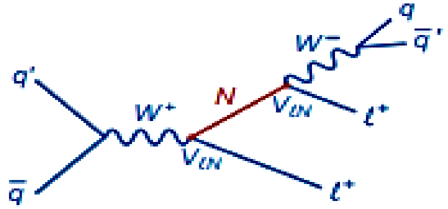
Gustafsson-No-Rivera model

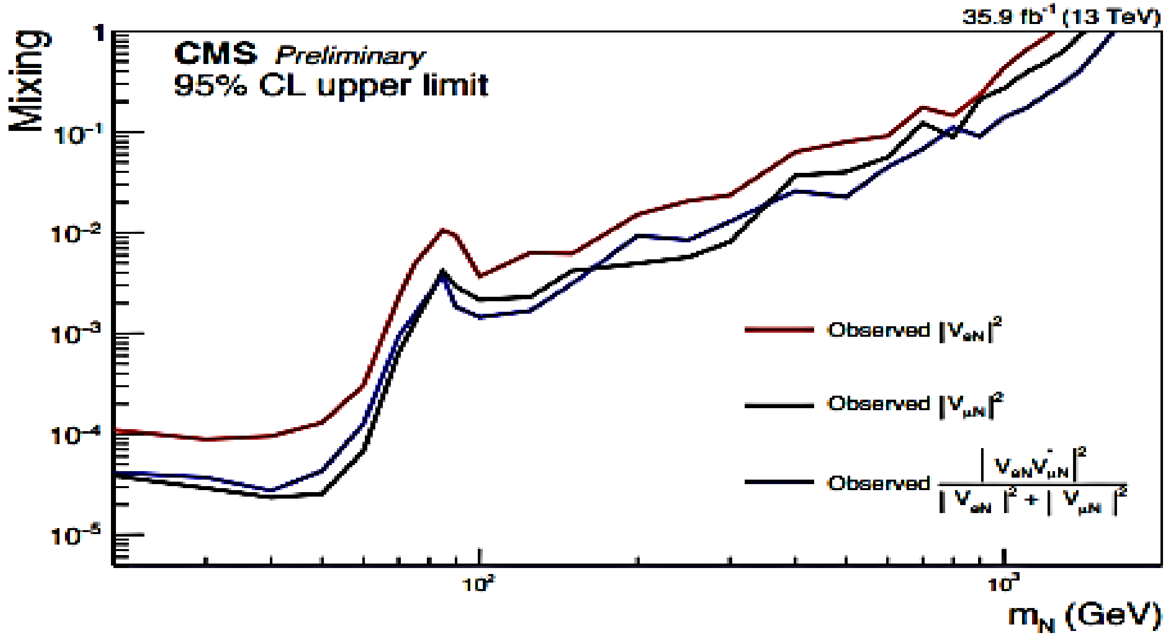
M. Gustafsson, J.M. No, and M.A. Rivera, PRL**110**, 21802 (2013)

❖ Testing Type-I Seesaw Experimentally

[Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Panella, Cannoni, Carimalo, Srivastava (PRD '02); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); Atre, Han, Pascoli, Zhang (JHEP '09)]

Same-sign dilepton plus jets (without $\not{E}_T$)





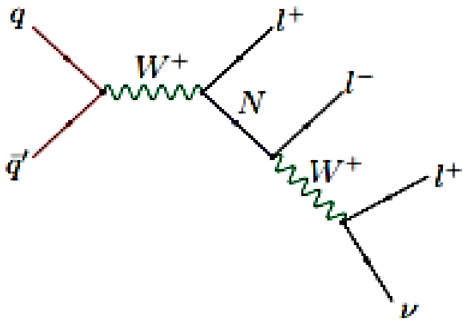
[CMS PAS EXO-17-028]

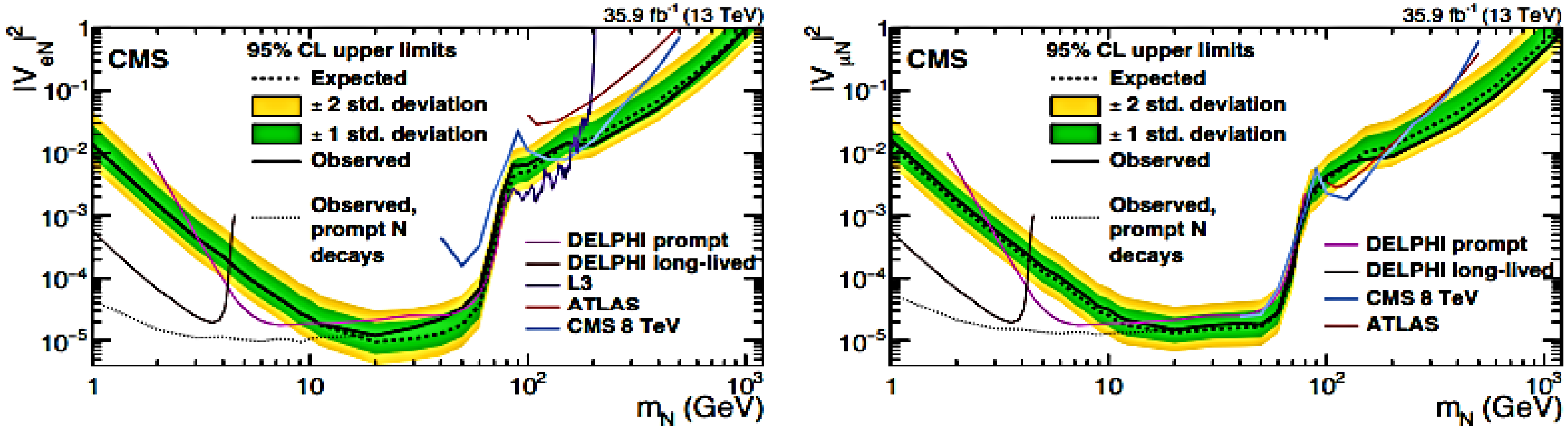
❑ Need (sub)-TeV scale heavy neutrinos with 'large' mixing with active neutrinos.

Testing Inverse Seesaw Experimentally

[del Aguila, Aguilar-Saavedra (PLB '09; NPB '09); Chen, BD (PRD '12); Das, Okada (PRD '13); Das, BD, Okada (PLB '14); Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang (PRD '17; CPC '17); Dube, Gadkari, Thalapillil (PRD '17)]

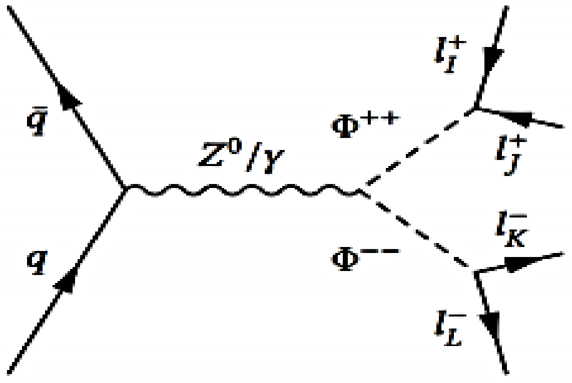
Trilepton plus $\not{E}_T$



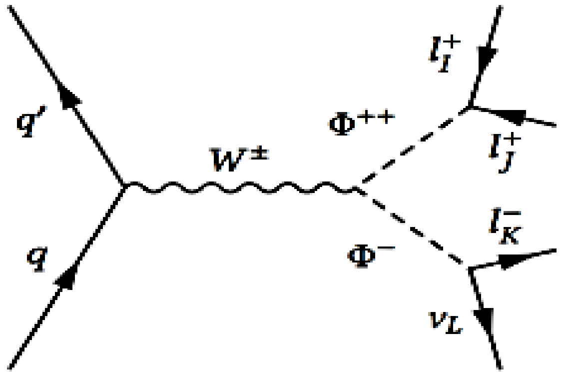


[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

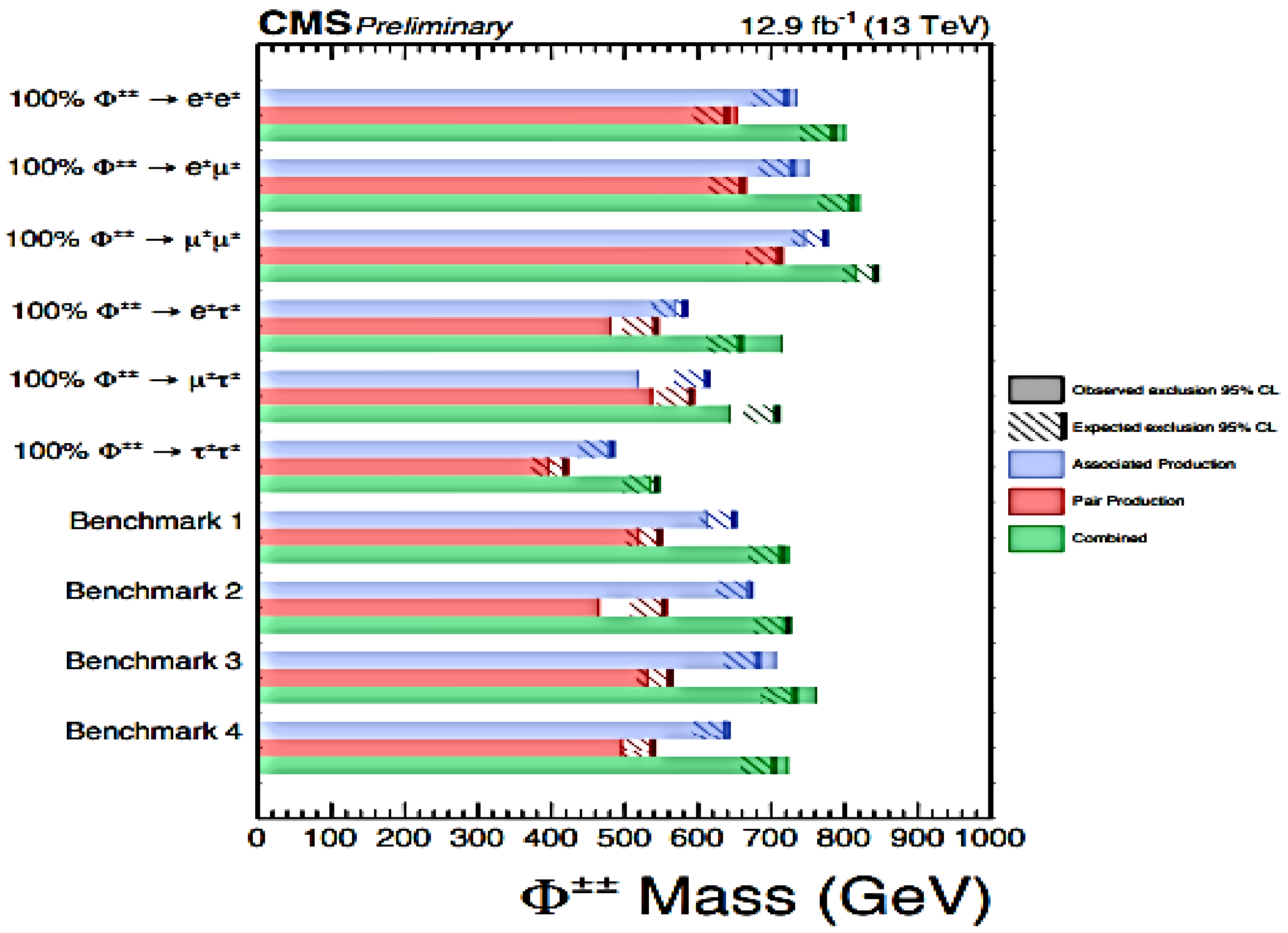
Testing Type-II Seesaw at the LHC



(a) 4ℓ



(b) 3ℓ



[CMS-PAS-HIG-16-036]

Rizzo (1982); Huitu, Maalampi, Pietila, Raidal (1997); Gunion, Loomis, Pitts (1996); Akeryod, Aoki (2005); Han, Mukhopadhyaya, Ci, Wang (2005), N. Sahu, Uma Sankar (2005); Sarma, Devi, Singh (2007); Chao, Luo, Xing, Zhao (2007); Perez, Han, Huang, Li, Wang (2008); McDonald, Sahu, Sarkar (2008); Chiang, Nomura, Tsumura (2012); Dev, D. Ghosh, Okada, Saha (2013); Nayak, Parida (2015); Cai, Han, Ruiz (2017), Babu , Jana (2017)……

❖ Doubly Charged Higgs Phenomenology

- Doubly Charged Scalars appear in neutrino mass models :

1 • **Radiative Neutrino Mass Model** (Babu 88; Zee 80)

2 • **Type II Seesaw Model** (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

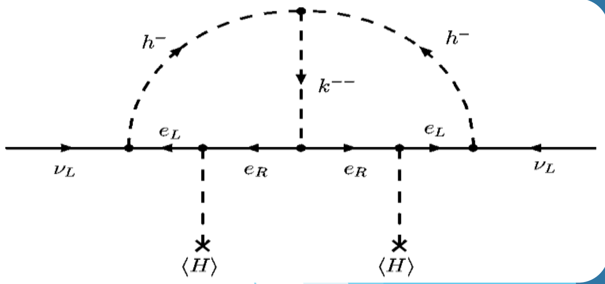
3 • **Left Right Symmetric Model** (Pati, Jogesh C. et al. (74), Mohapatra (75), Senjanovic, (75))

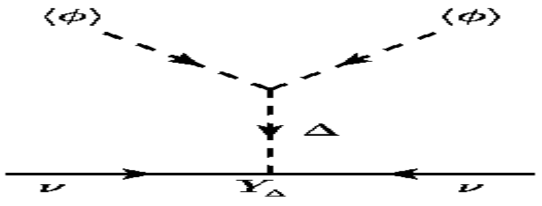
4 • **Little Higgs Model** (Arkani-Hamed, N. (2002))

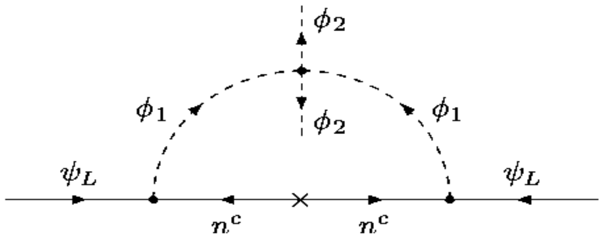
5 • **Dimension 7 Neutrino Mass Model** (Babu, Nandi (2009))

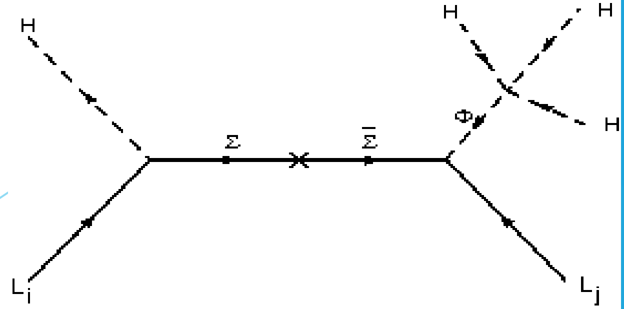
6 • **Georgi-Machacek Model** (Georgi, Howard et al.(85))

7 • **Other Models** (Gunion (90), etc.)



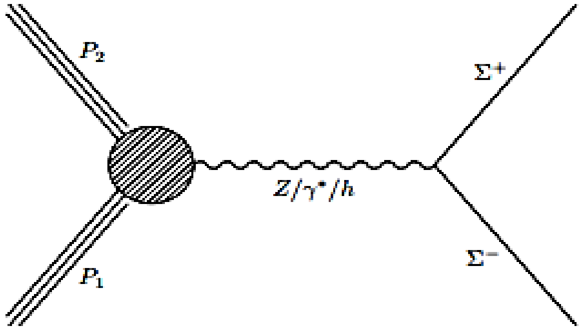


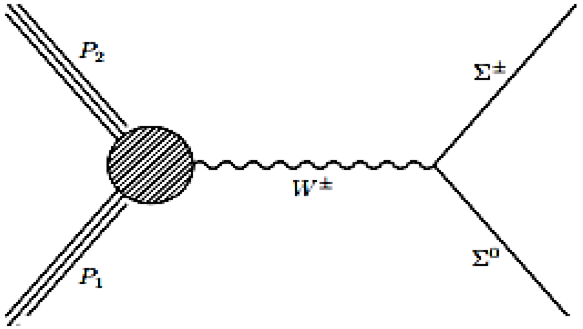


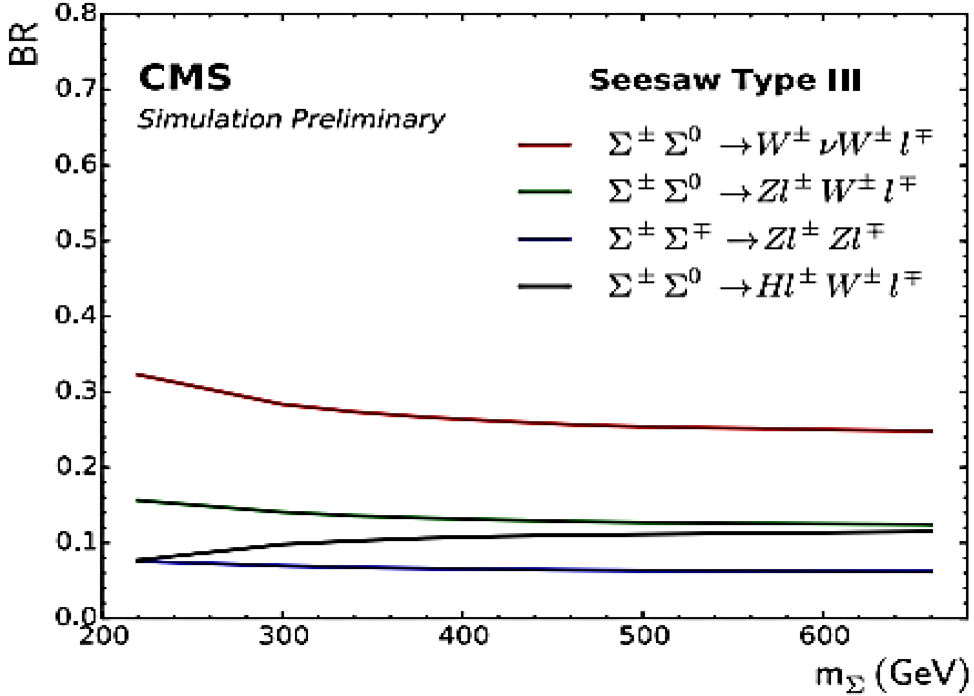


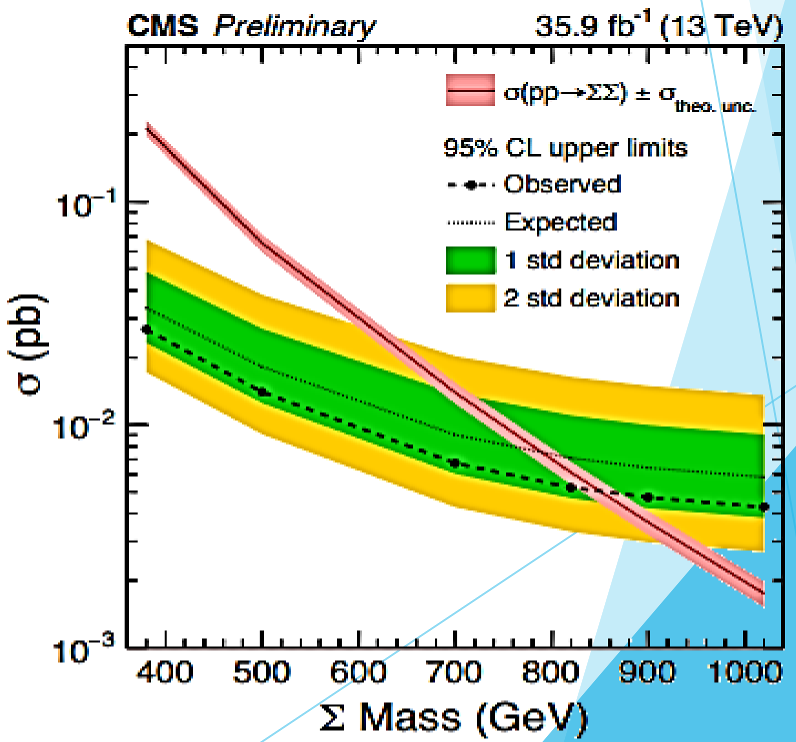
❖ Testing Type-III Seesaw at the LHC

- Multi-lepton signatures. [Franceschini, Hambye, Strumia (PRD '08); Li, He (PRD '09); Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović (PRD '10); Ruiz (JHEP '15)]

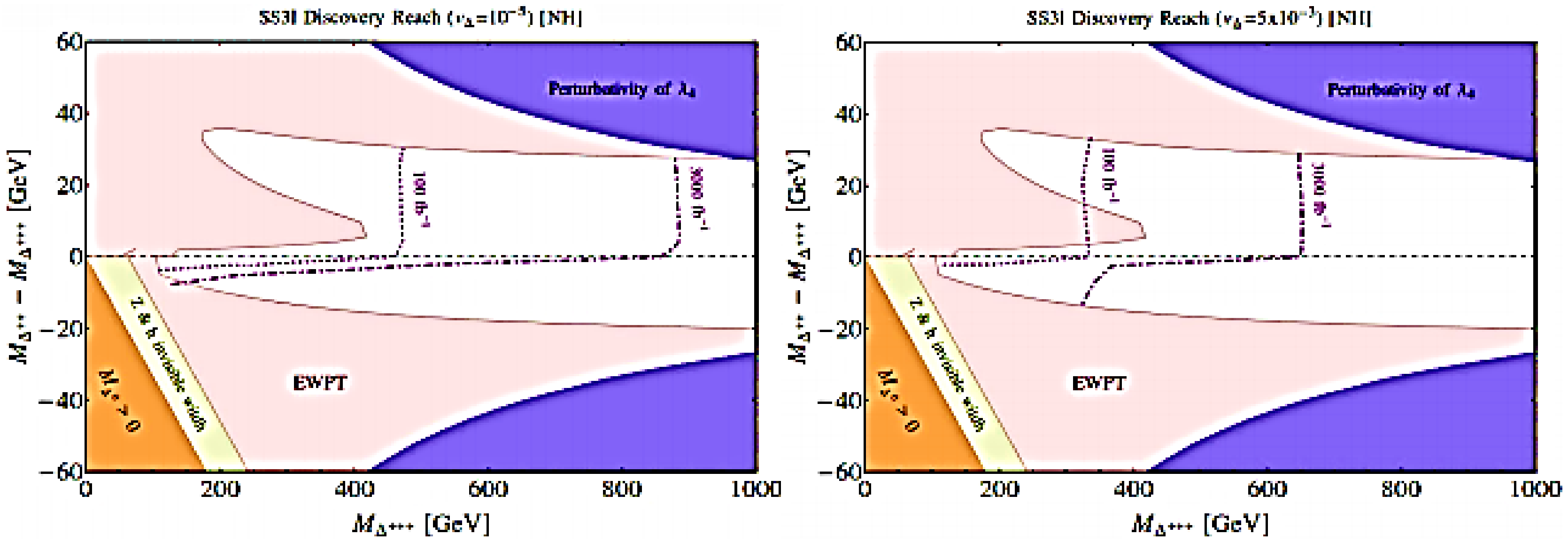








Testing Seesaw with dim=7 operator at the LHC



- Discovery potential upto 450 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region Discovery potential upto 500 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region
- Discovery potential upto 350 (700) GeV at 100 (3000) fb^{-1} for *WWW* dominated region
- Covers the whole area available for $\Delta M > 0$ scenarios
- Similar results for NH and IH

T. Ghosh, Jana, Nandi (2018)
K. Ghosh, Jana, Nandi (2017)

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 c compelling evidence has been**

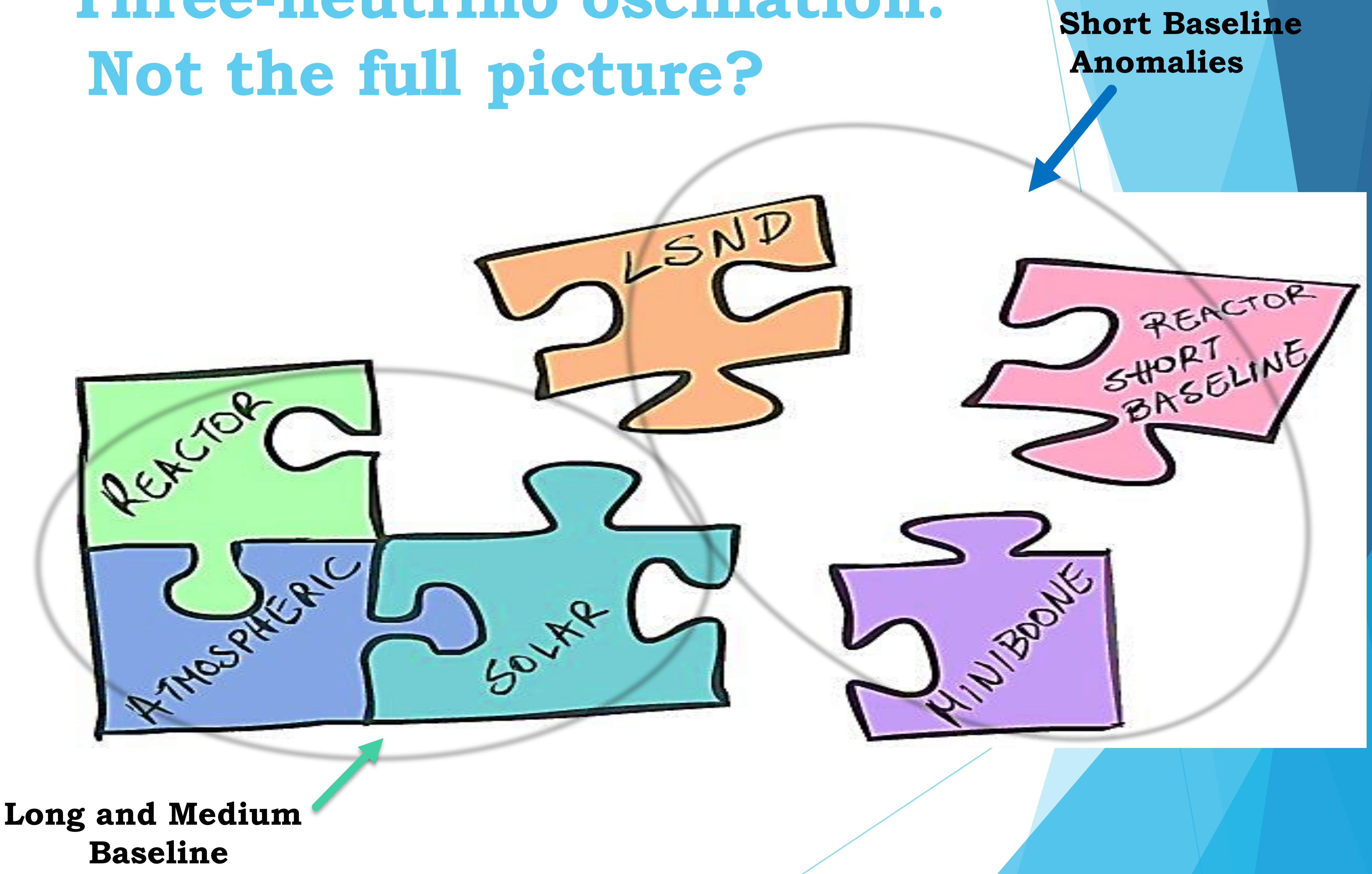
- **Is it really sufficient to ics scale behind neutrino echanism at**

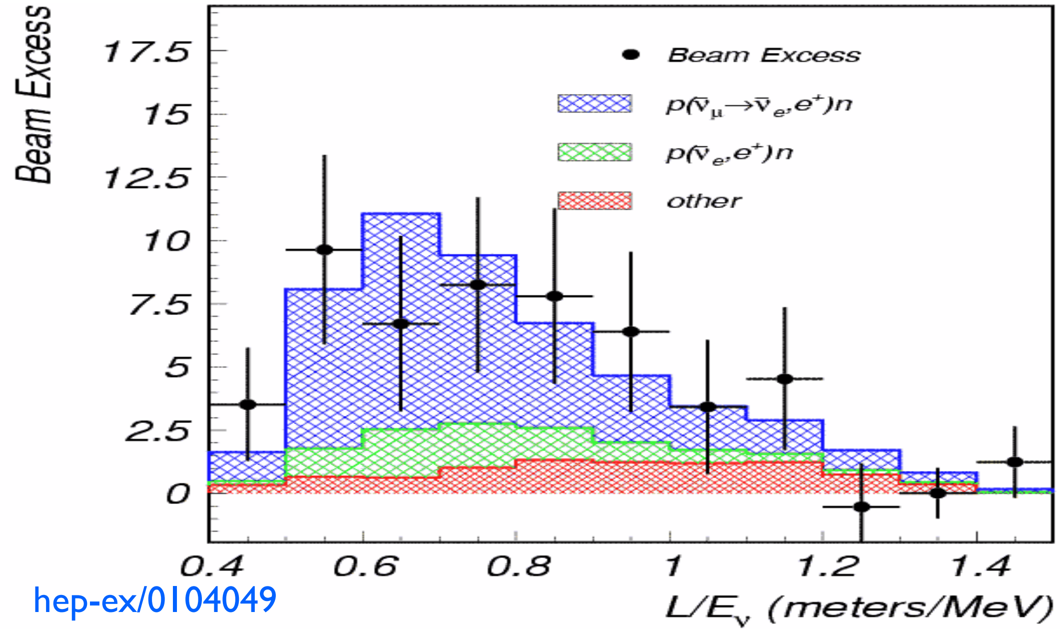
Can neutrino masses come from light physics ?

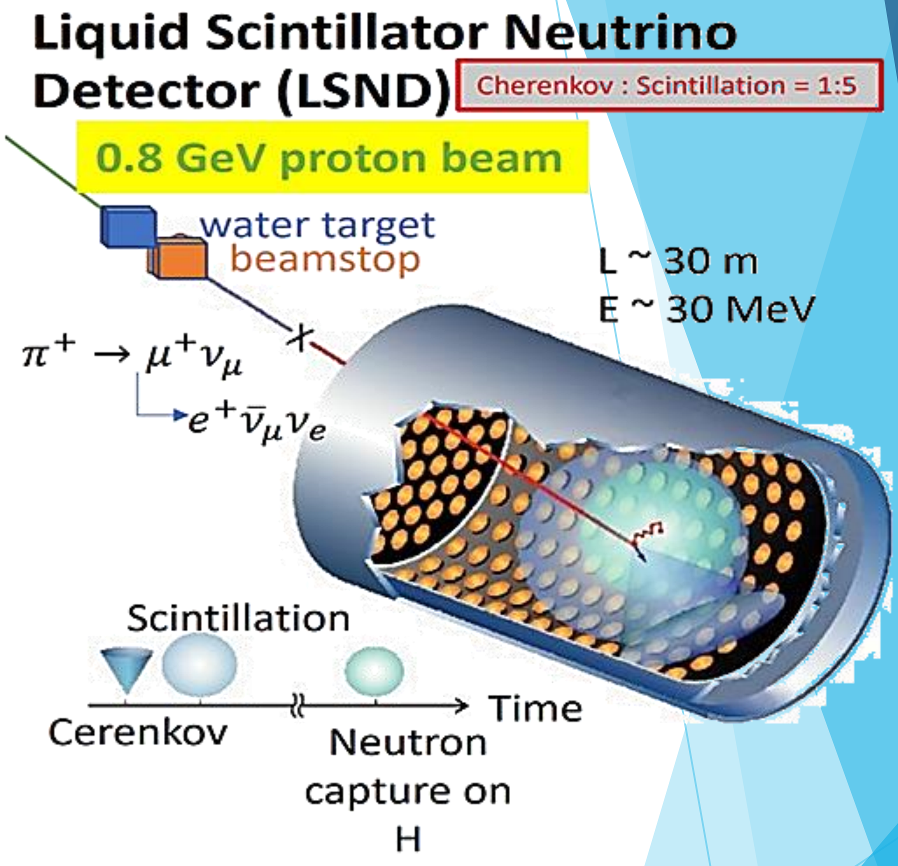
- **scale behind neutrino mass chanism might be at low scale and s less sensitive to high energy collider experiments**

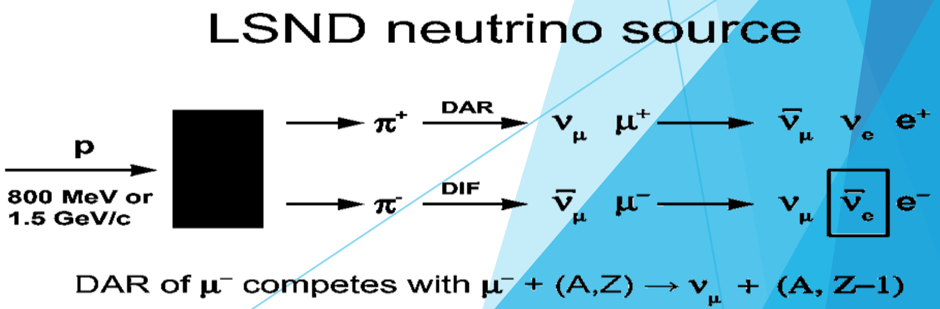
- **It may show up at low energy neutrino experiments at near future.**

Three-neutrino oscillation: Not the full picture?





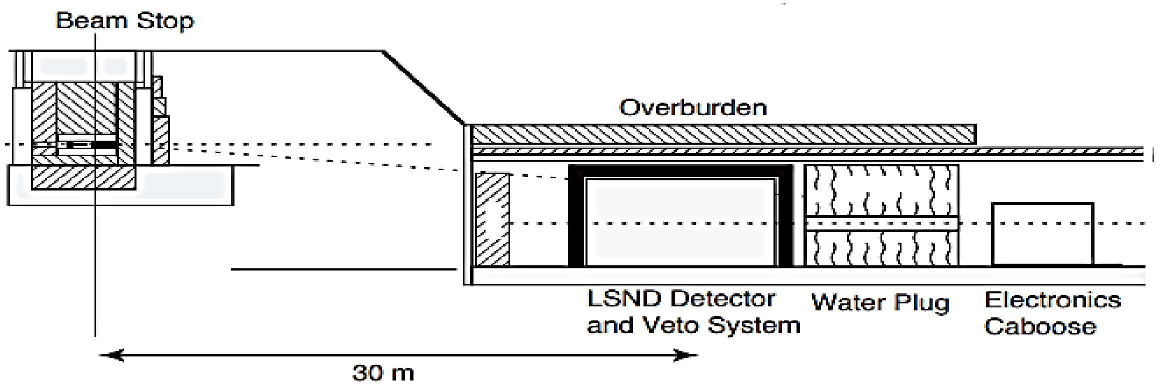




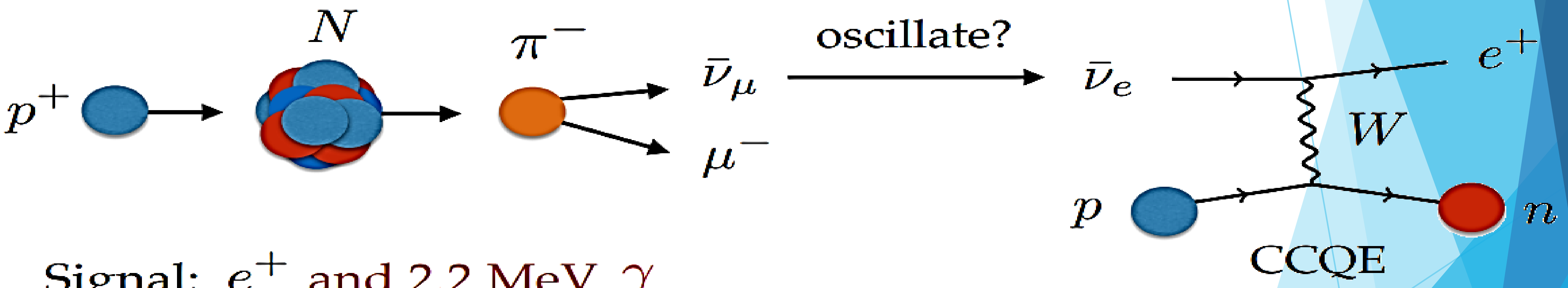
LSND detected more $\bar{\nu}_e$ than expected :

87.9 ± 22.4 ± 6.0 events

3.8 σ excess



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

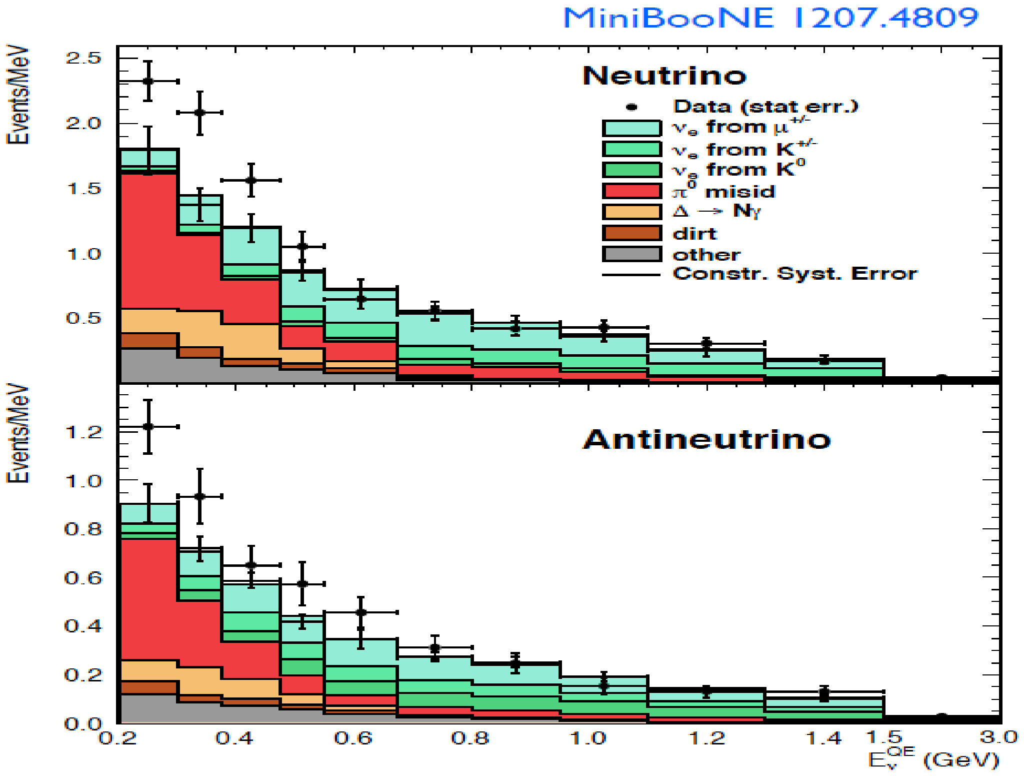


Signal: e^+ and 2.2 MeV γ
Scatter + neutron absorption

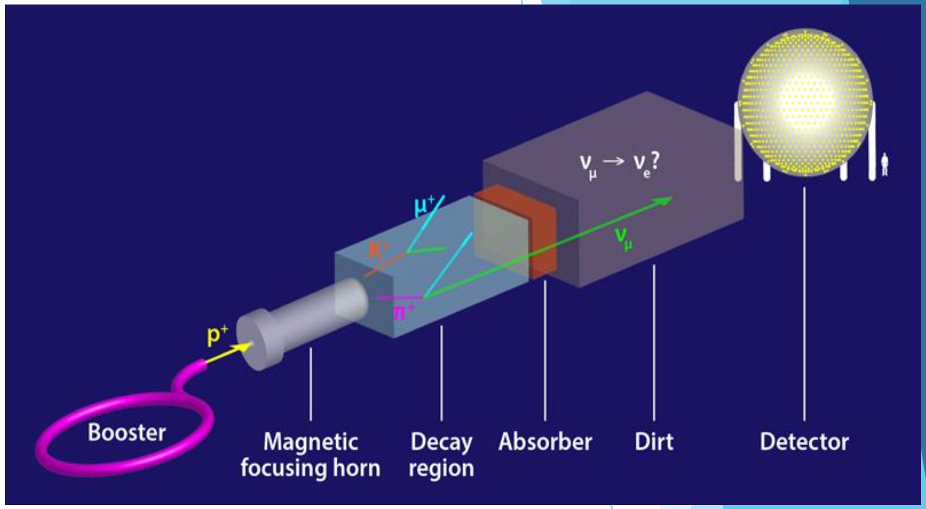
Observed 90 events
Expectation of 0 events
3.8σ significance

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

LSND Collaboration hep-ex/0104049

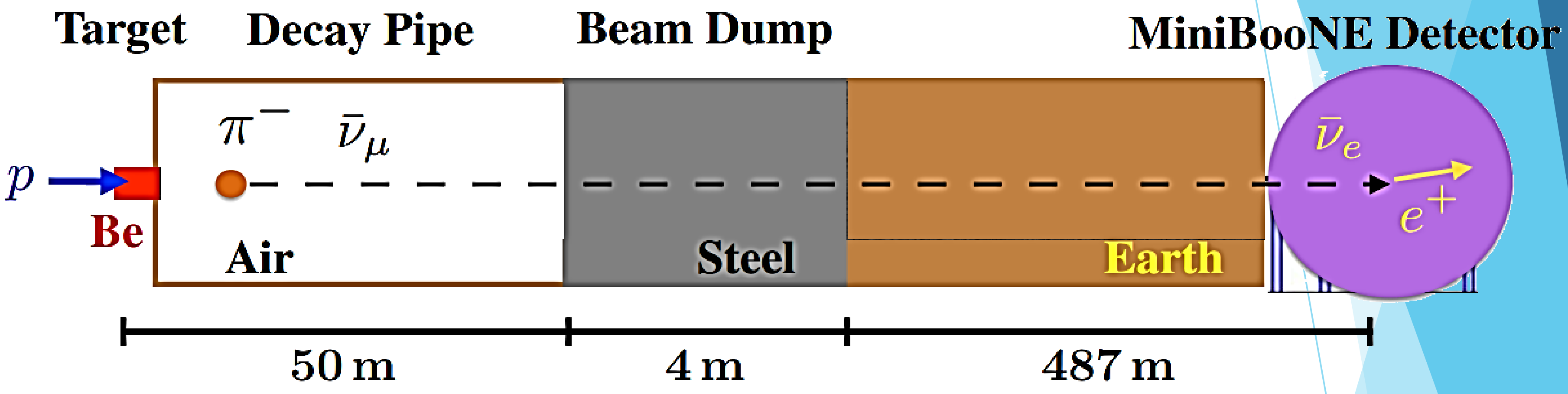


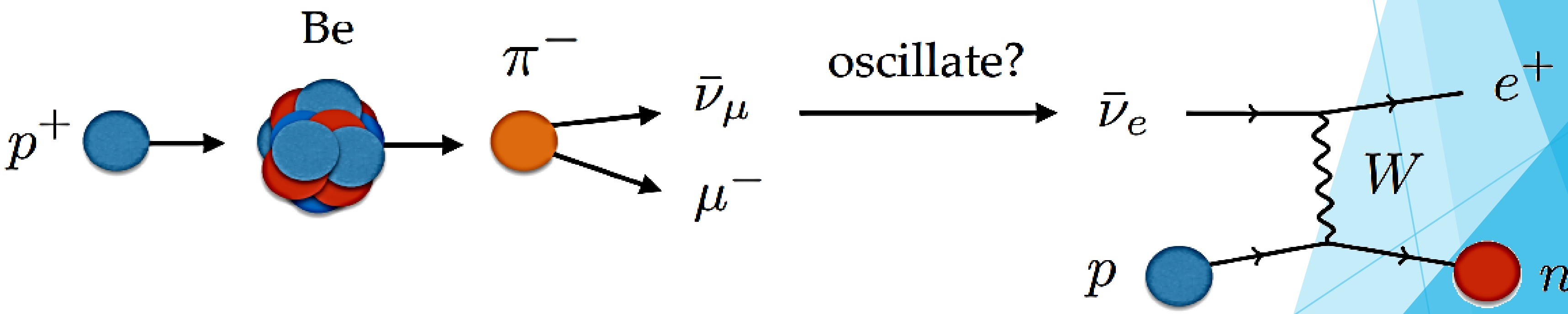
•Neutrino and anti neutrino modes see excesses of ν_e and $\overline{\nu}_e$ (Combined is also 3.8 σ excess)



- 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

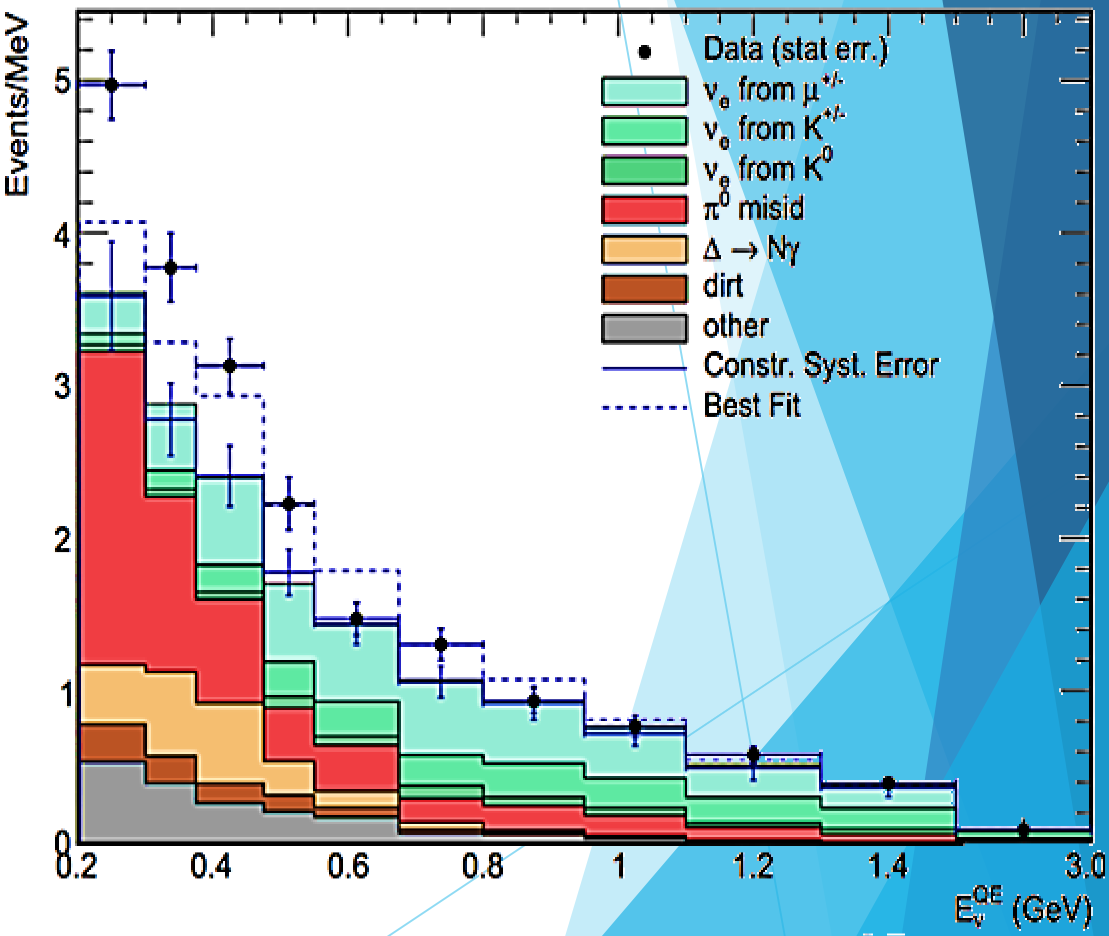
Energy and baseline chosen to test LSND

Comparable oscillation probabilities

MiniBooNE Collaboration 1805.12028

MiniBooNE's Low Energy Excess

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



- 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)

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.

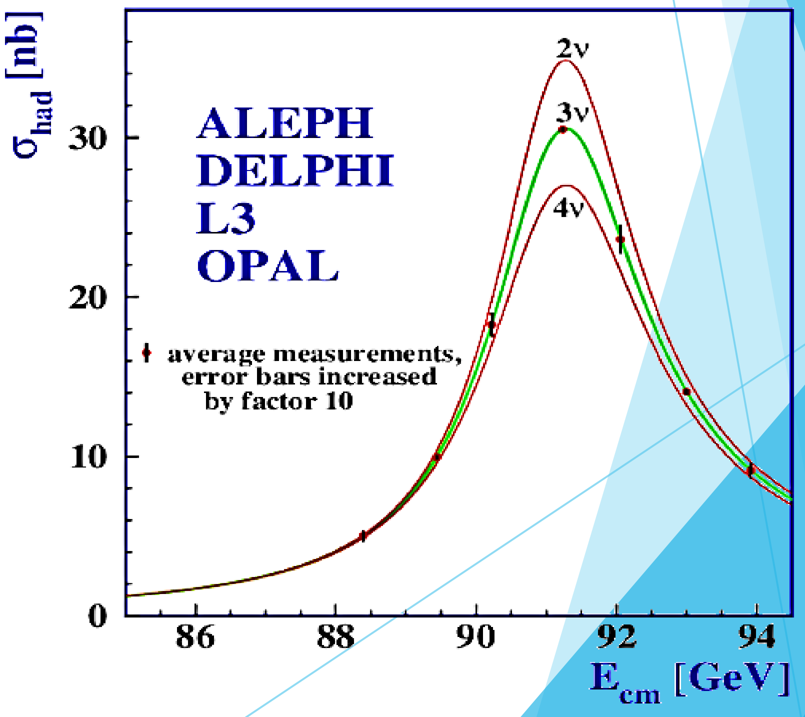
What sort of new physics can explain these anomalies?

❖ *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

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

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

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

@LSND, Karmen, MiniBoone, Opera

DISappearance

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

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

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

@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 ???*

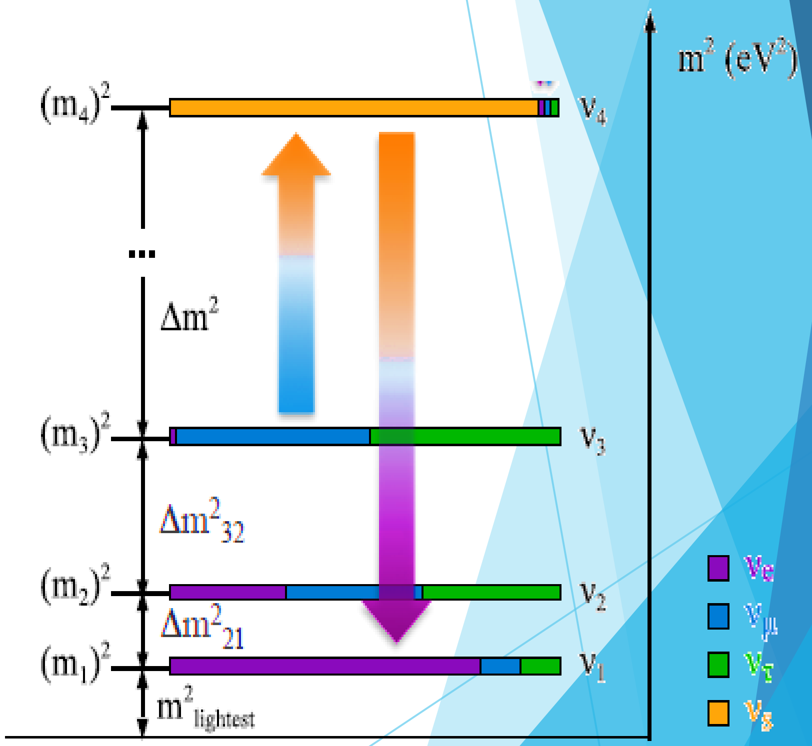
$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\alpha\beta}^{\rm SBL} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right).$$

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

Leads to ν_e disappearance

Leads to ν_μ disappearance



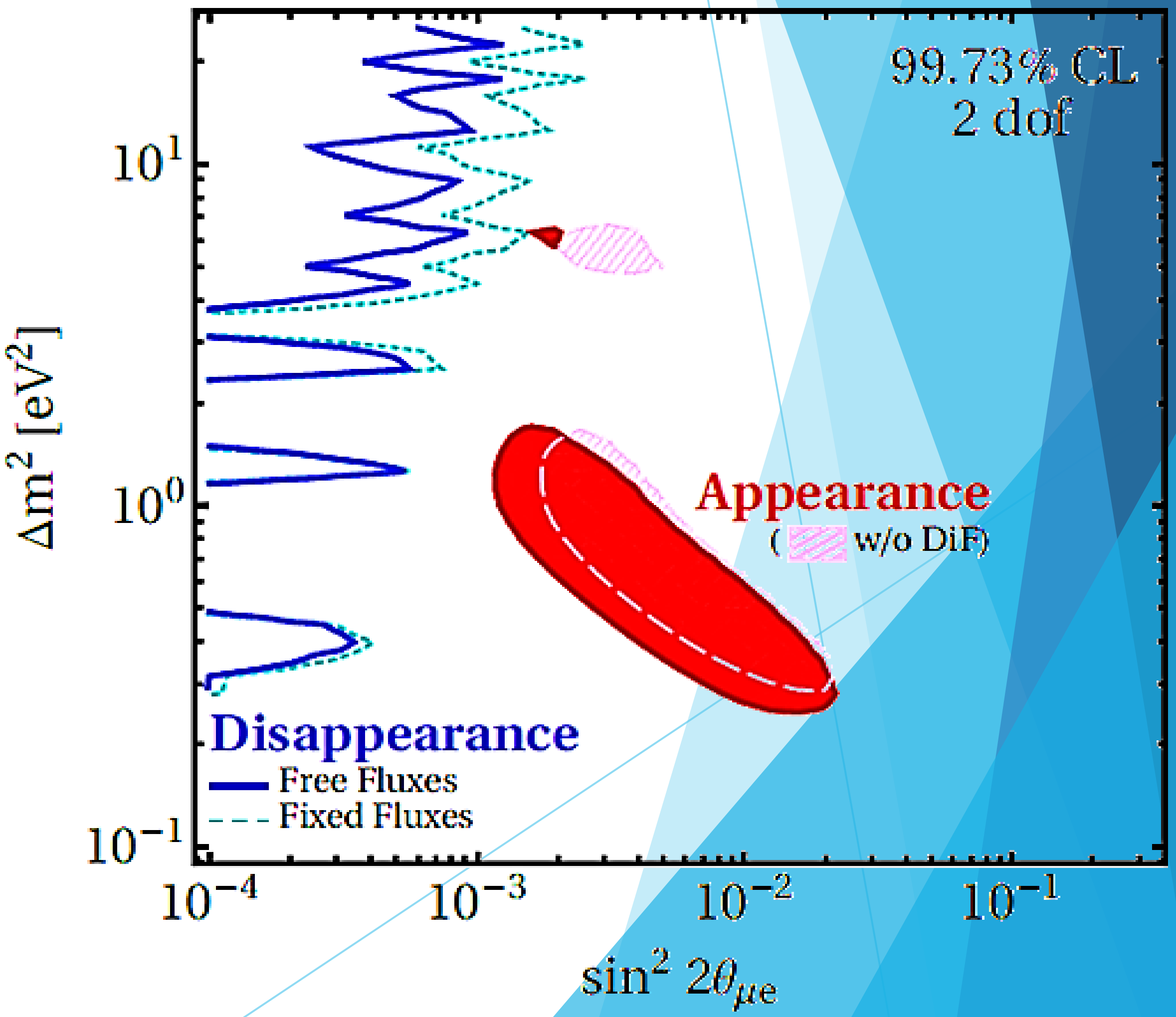
❖ *What about eV Sterile Neutrino Interpretation ???*

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

Leads to ν_μ to ν_e disappearance

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

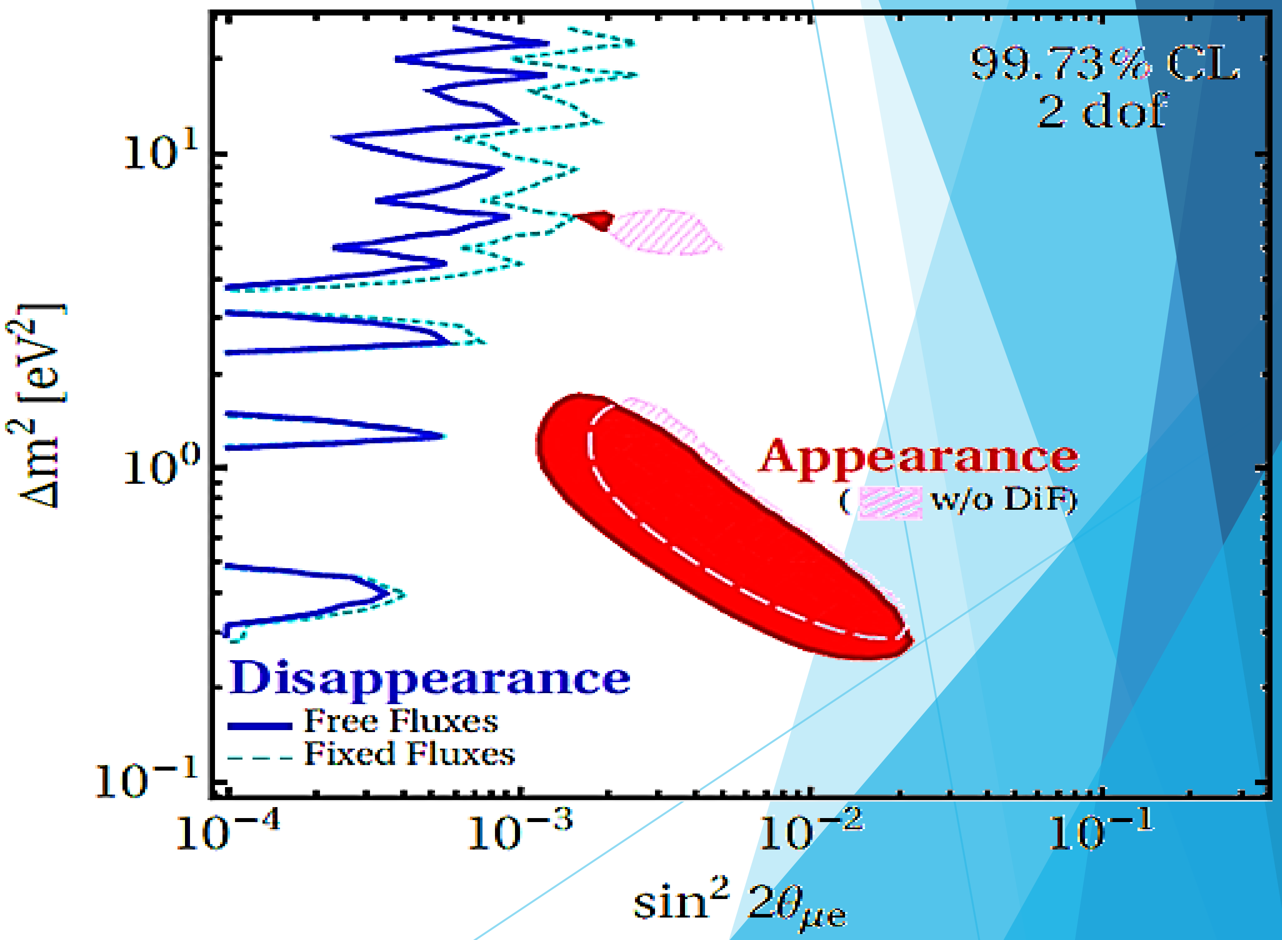
Mona Dentler et al. JHEP 1808 (2018) 010



❖ *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

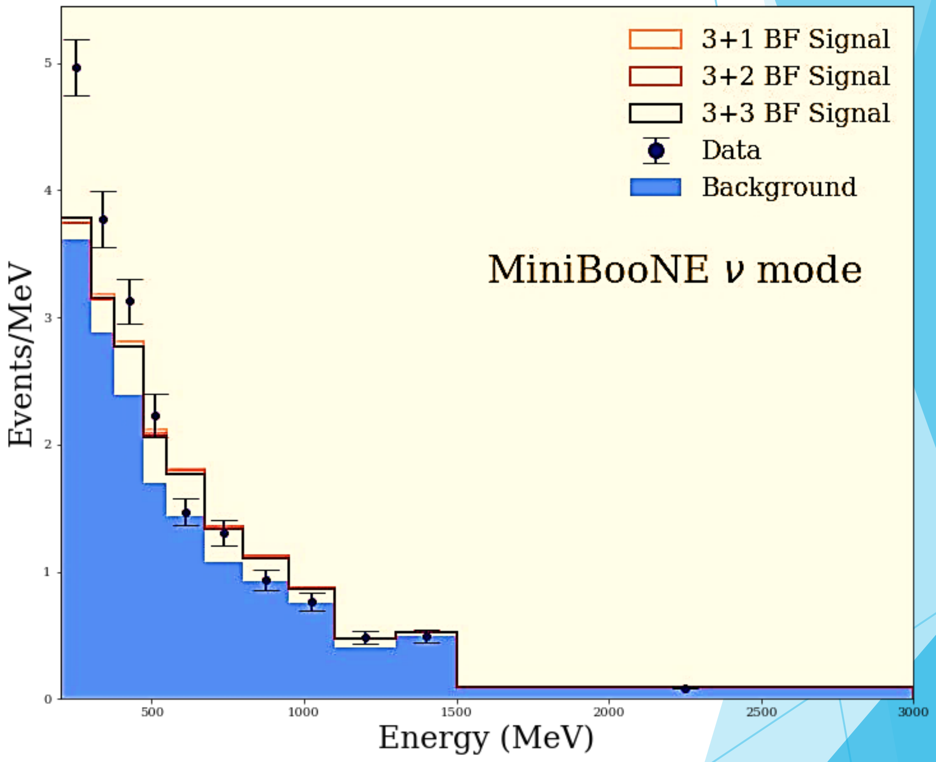


Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860

➢ 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 $\sin^2 2\theta_{\mu e} > 10^{-3}$, $m_4 <$ few eV

Generic early universe thermalization

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

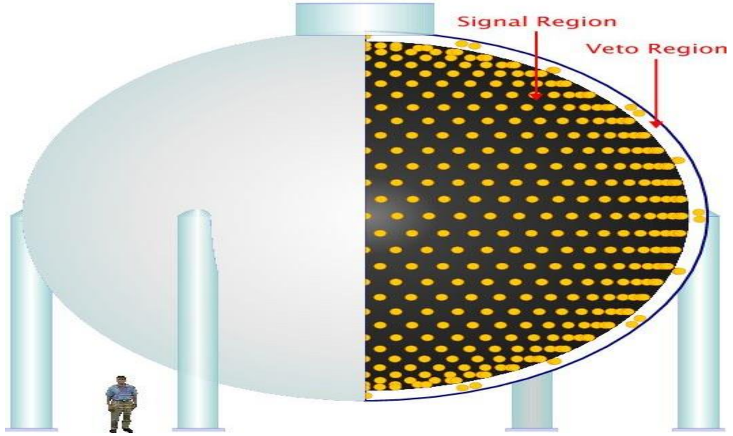
Excluded by BBN/CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

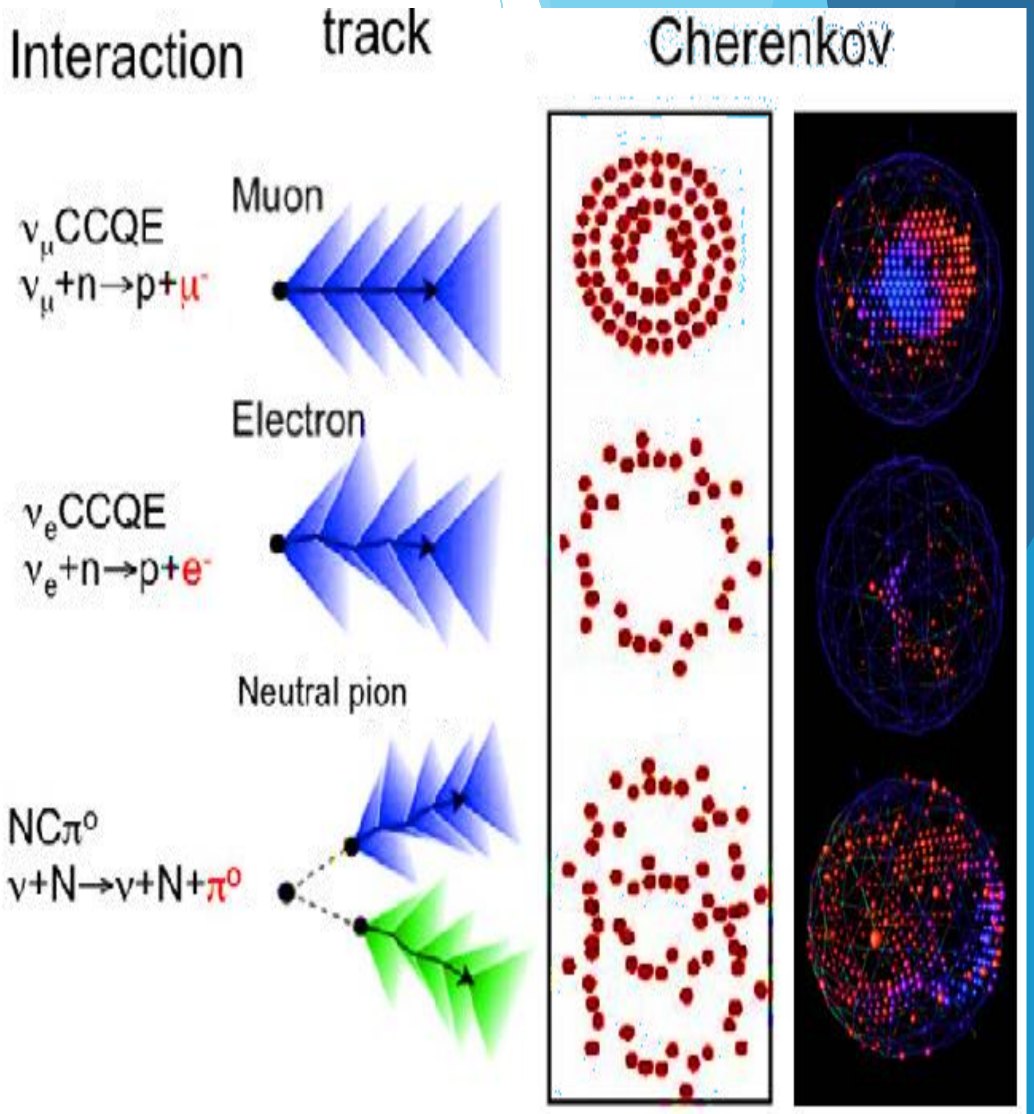
Unless max temperature satisfies $T_{\rm max} \lesssim 15\ {\rm MeV}\left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

❑ *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 hyp
- ❖ 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*

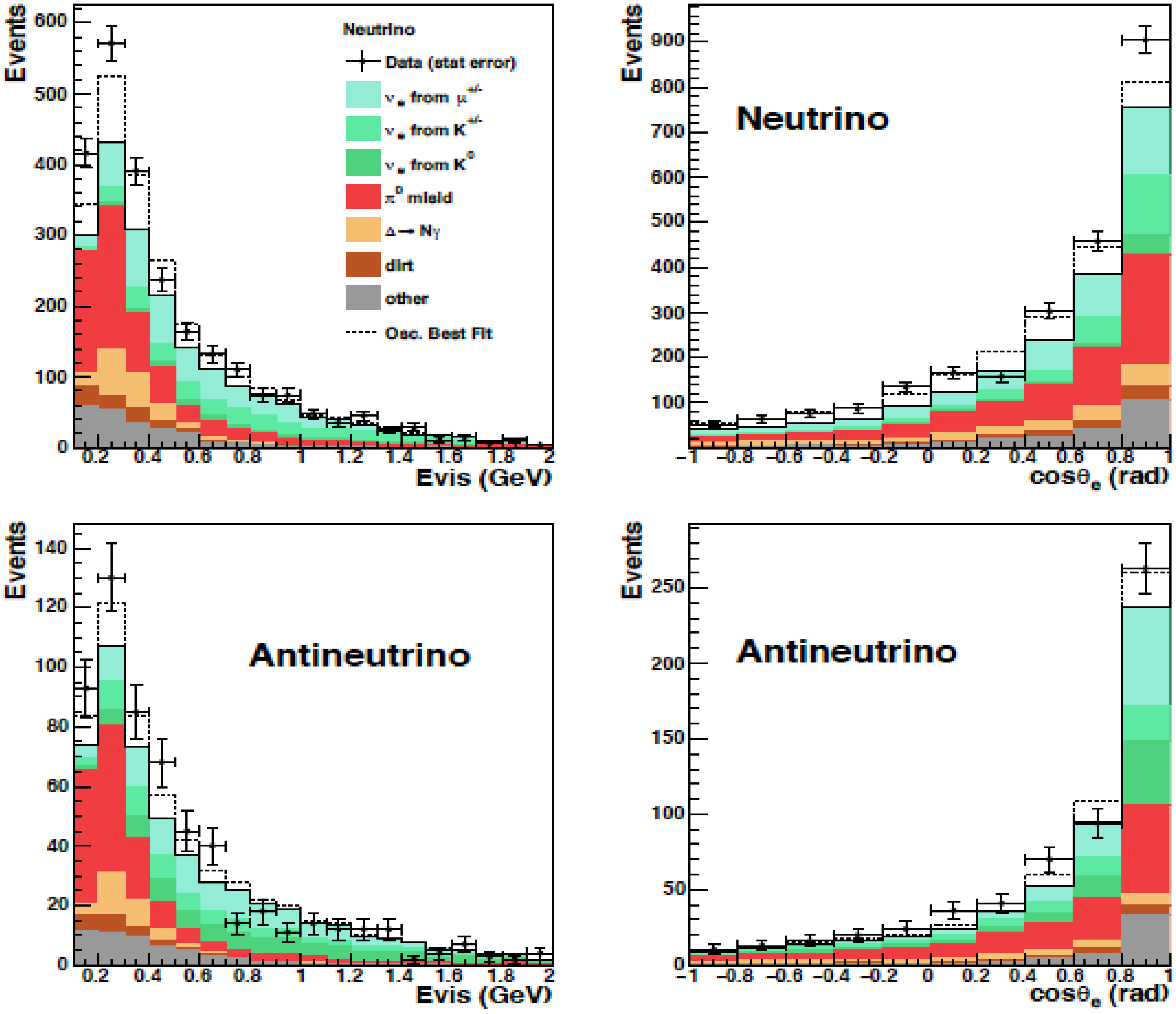




- MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles.
- Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.
- Excess is correlated with beam in power, angle and timing. It is present in positive and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

❖ *Explanation of MiniBooNE's low energy excess*

arxiv : 1805.12028 [hep-Ex]

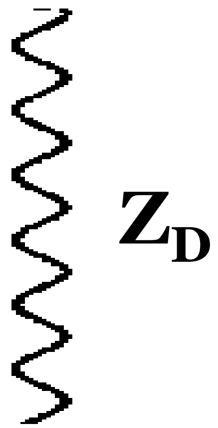


- ➢ Angular spectrum is forward, but not that much
- ➢ Scattering on electrons would typically lead to $\cos\theta > 0.99$
- ➢ Decays of invisible light (<10 MeV) particles produced in the beam would also lead to forward spectrum

❖ *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*

A LIGHT DARK SECTOR – THE IDEA

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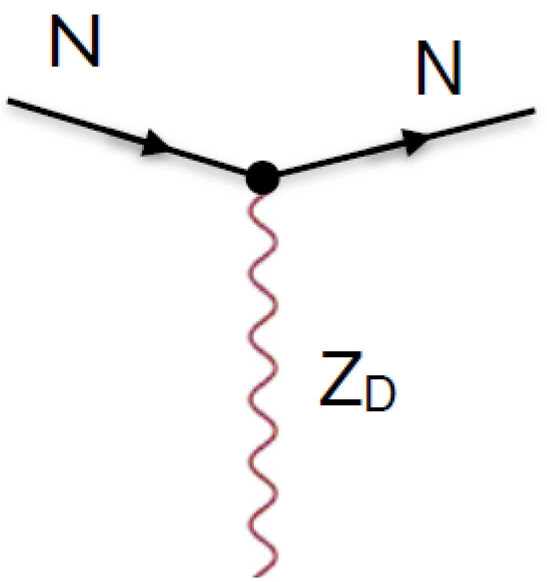
- Right-handed neutrinos are part of the dark sector and are subject to new interaction



Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

❖ *Explanation of MiniBooNE's low energy excess*

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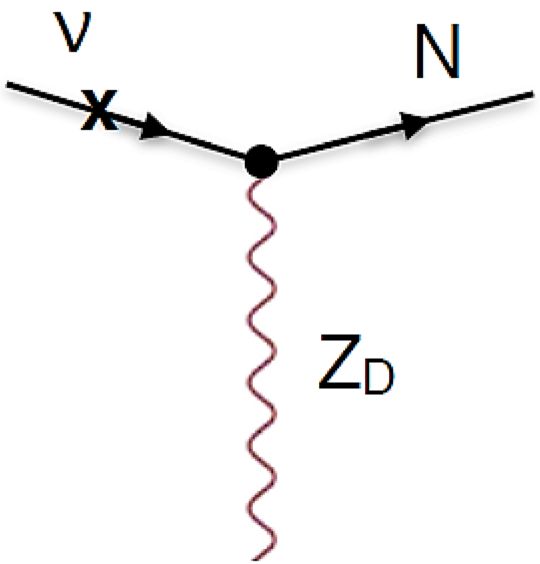

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

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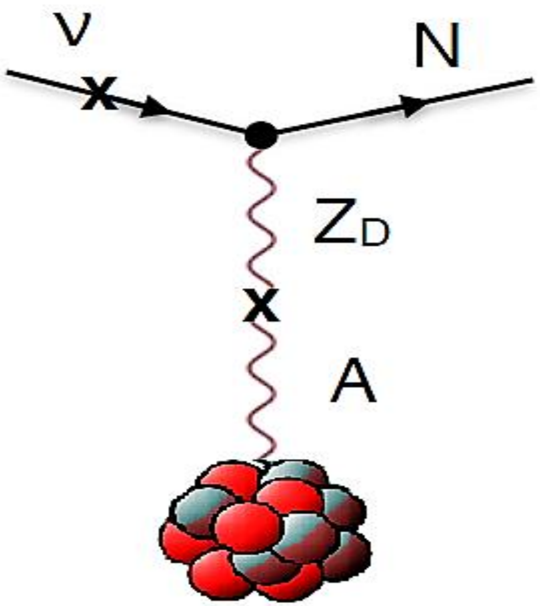
- Mixing between Z_D and photon leads to interaction with protons



Bertuzzo et al 1807.09877
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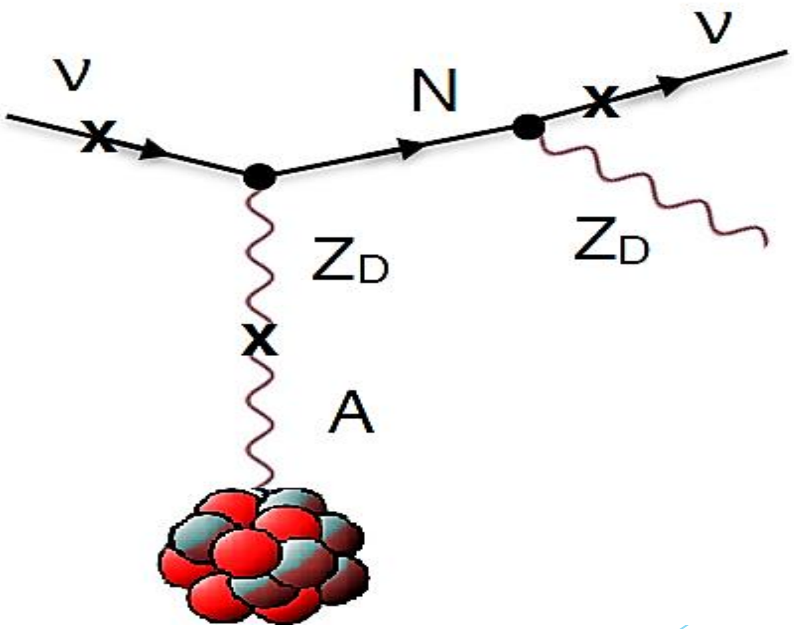

Bertuzzo et al 1807.09877
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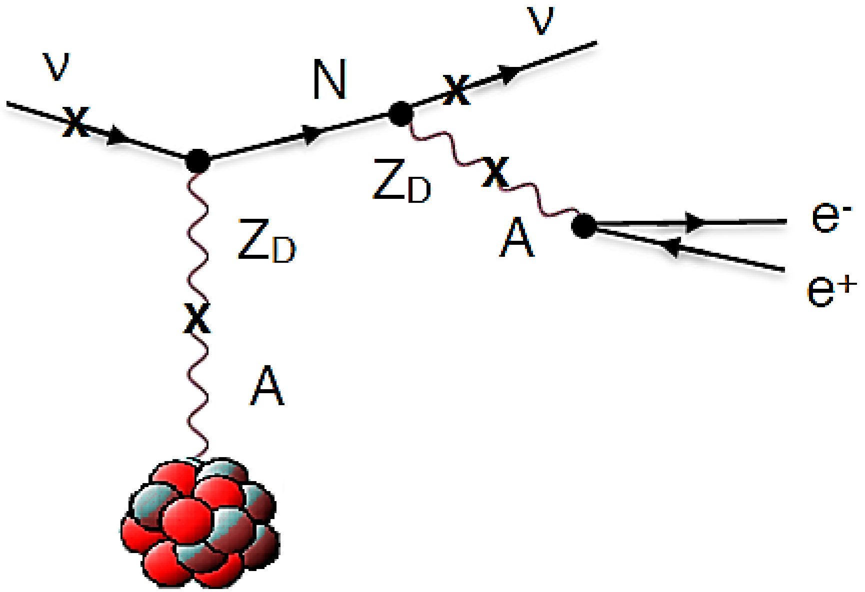

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

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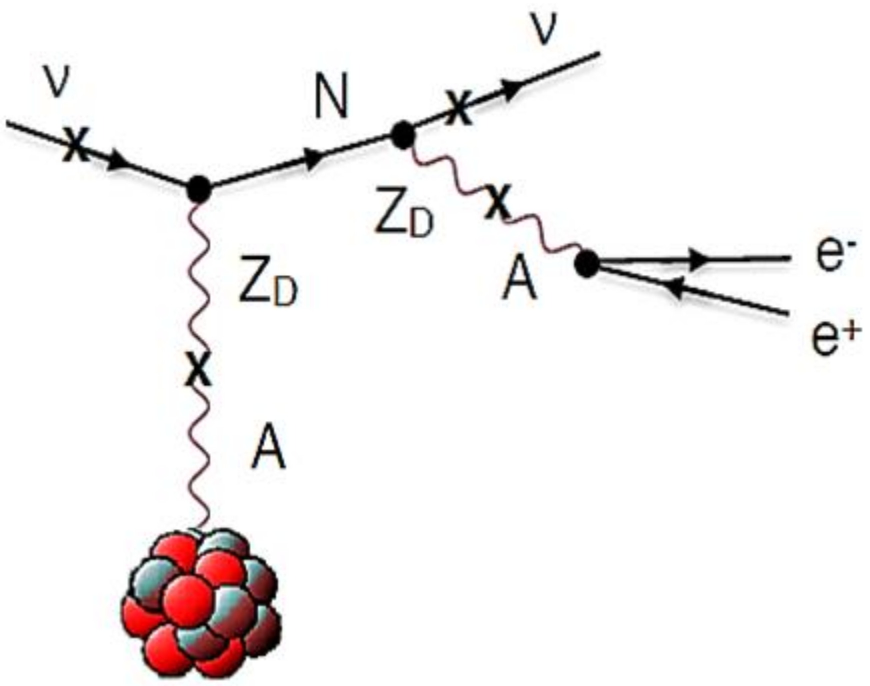
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons
- Relevant part of the Lagrangian :

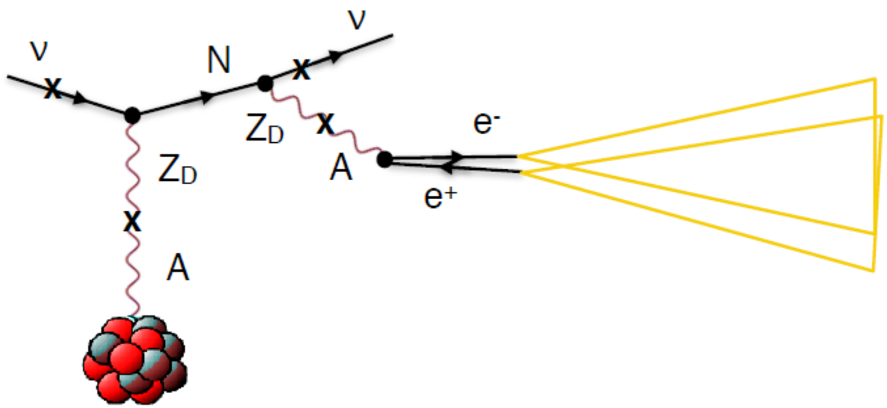


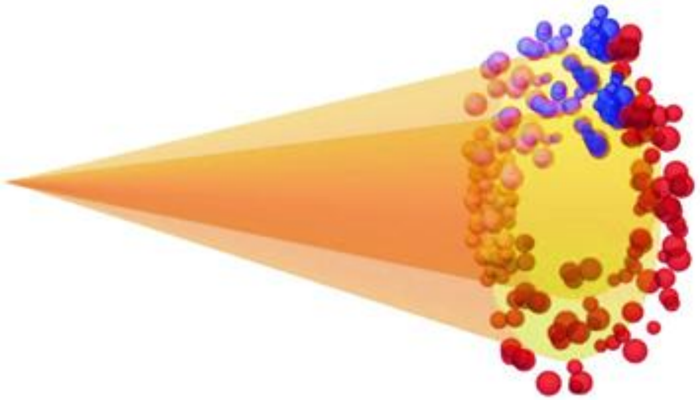
Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

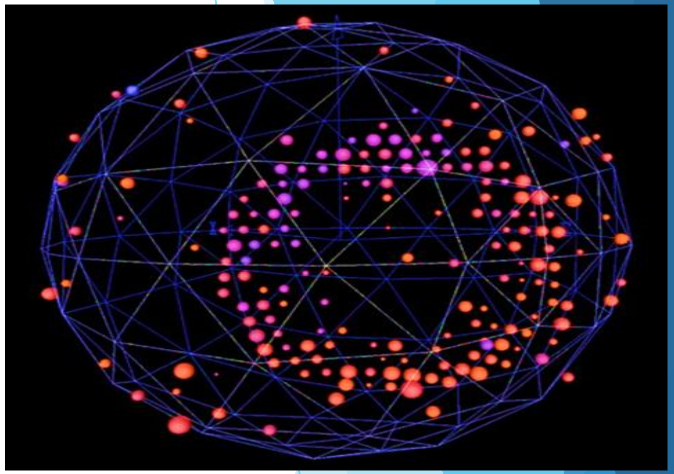
$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} J_{\mathcal{D}\mu} + e\epsilon Z_{\mathcal{D}}^{\mu} J_{\mu}^{\text{em}} + \frac{g}{c_W} \epsilon' Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z}$$

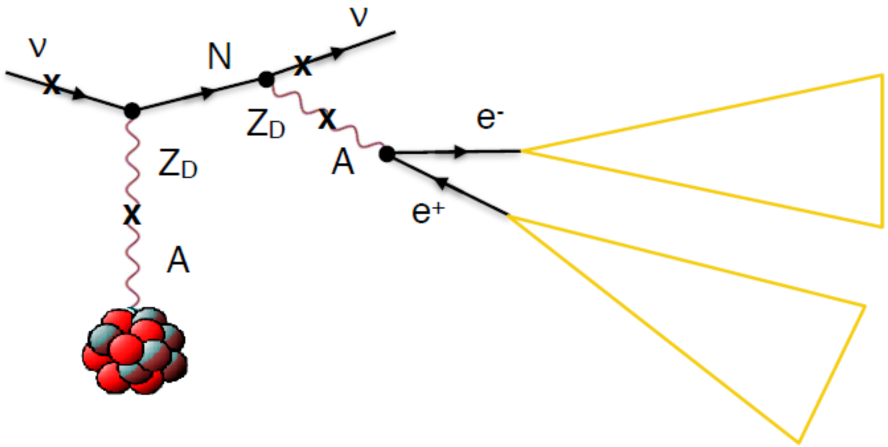
❖ *Explanation of MiniBooNE's low energy excess*

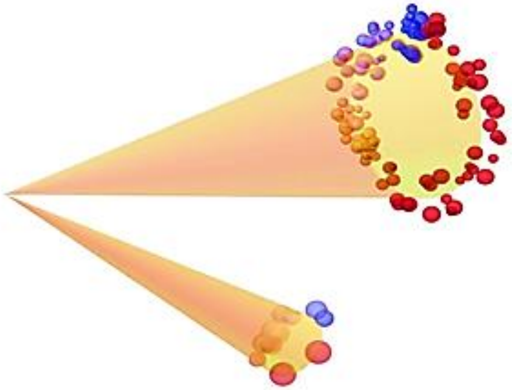
A LIGHT DARK SECTOR – THE IDEA

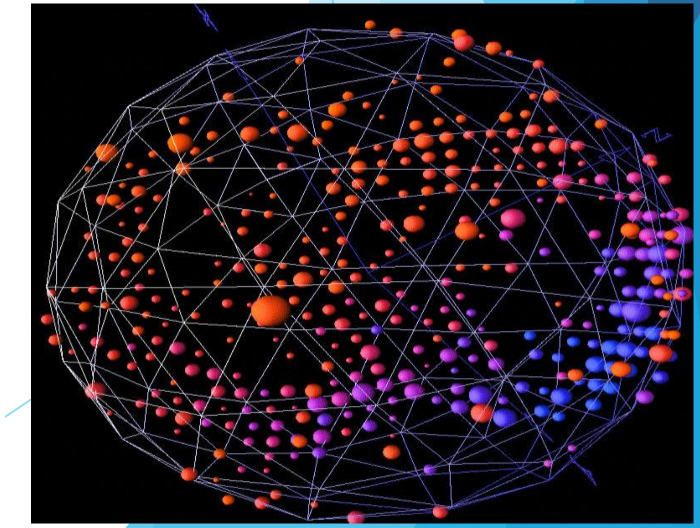






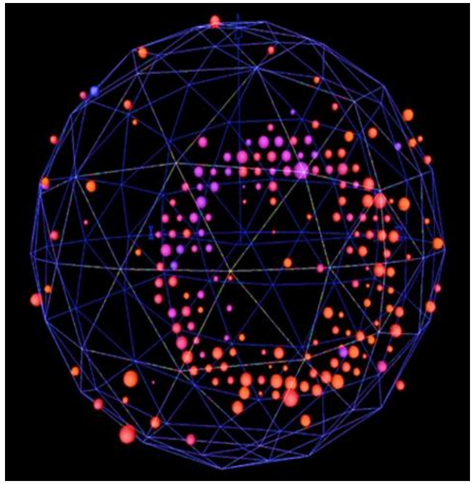


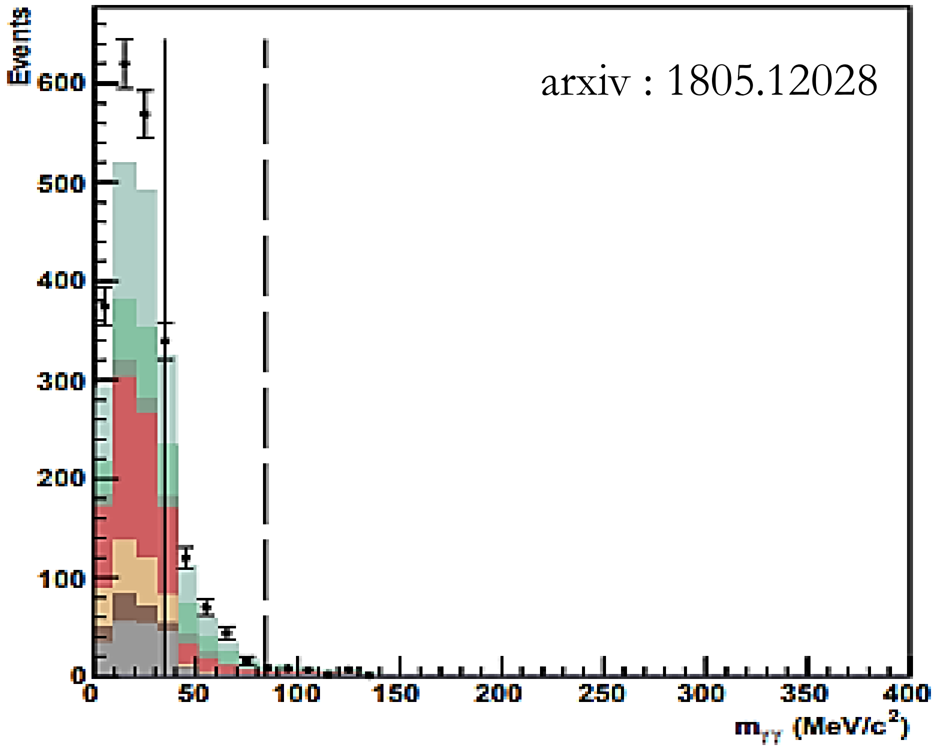


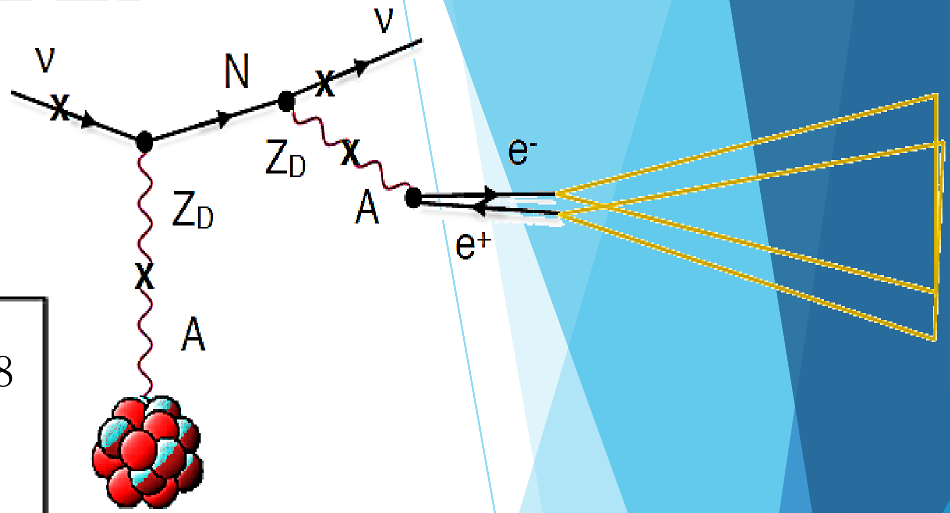


❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



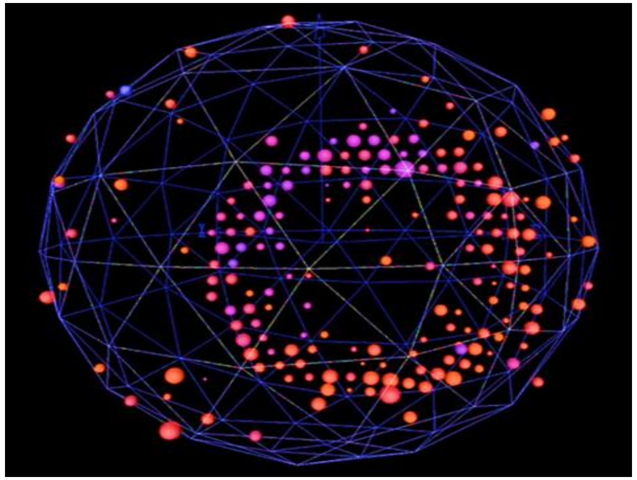


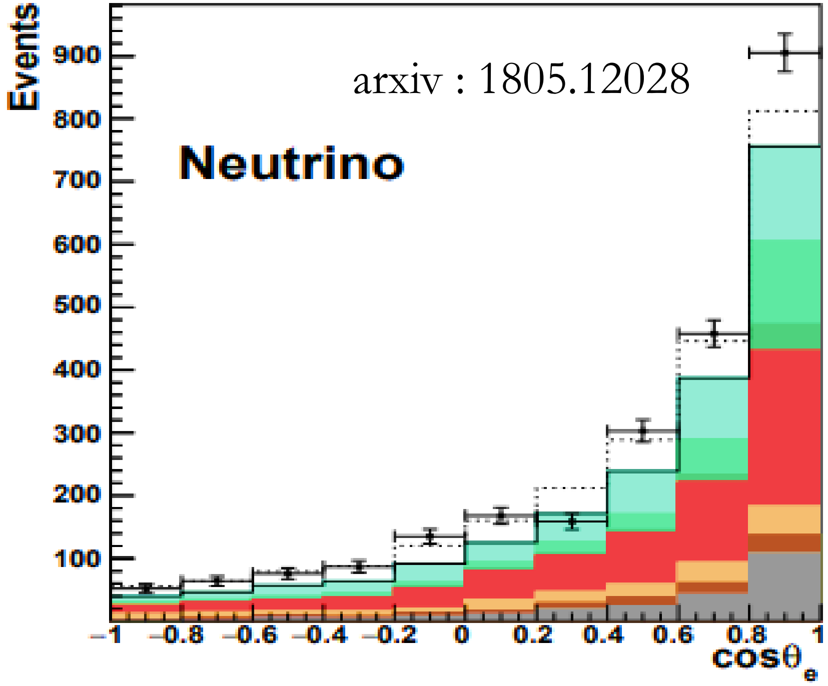


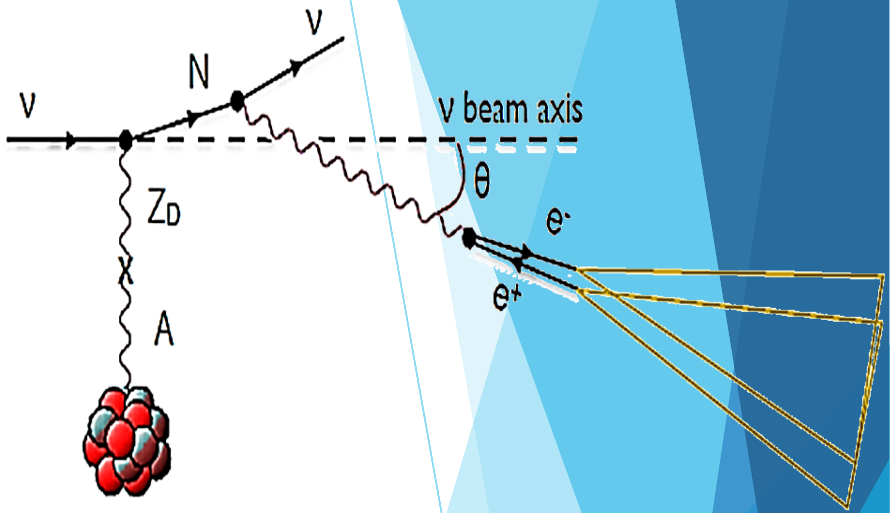
If e^+e^- pair is collimated ($\cos\theta_{ee}$ > 0.99-ish), it will be classified as e-like

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



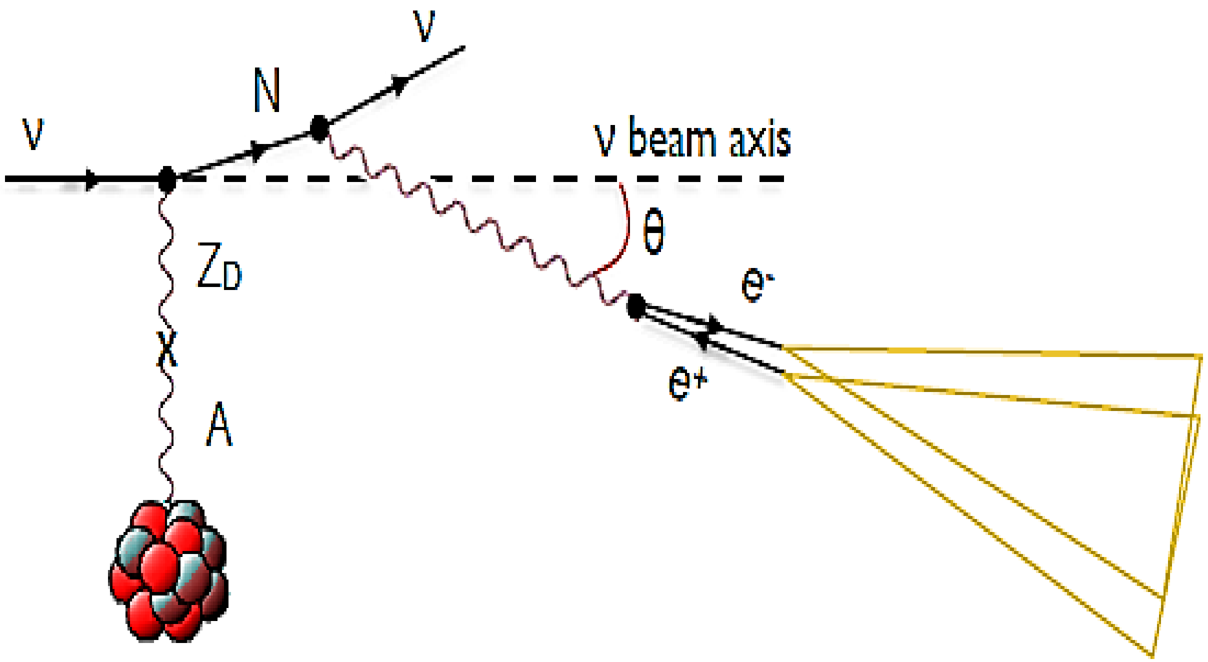


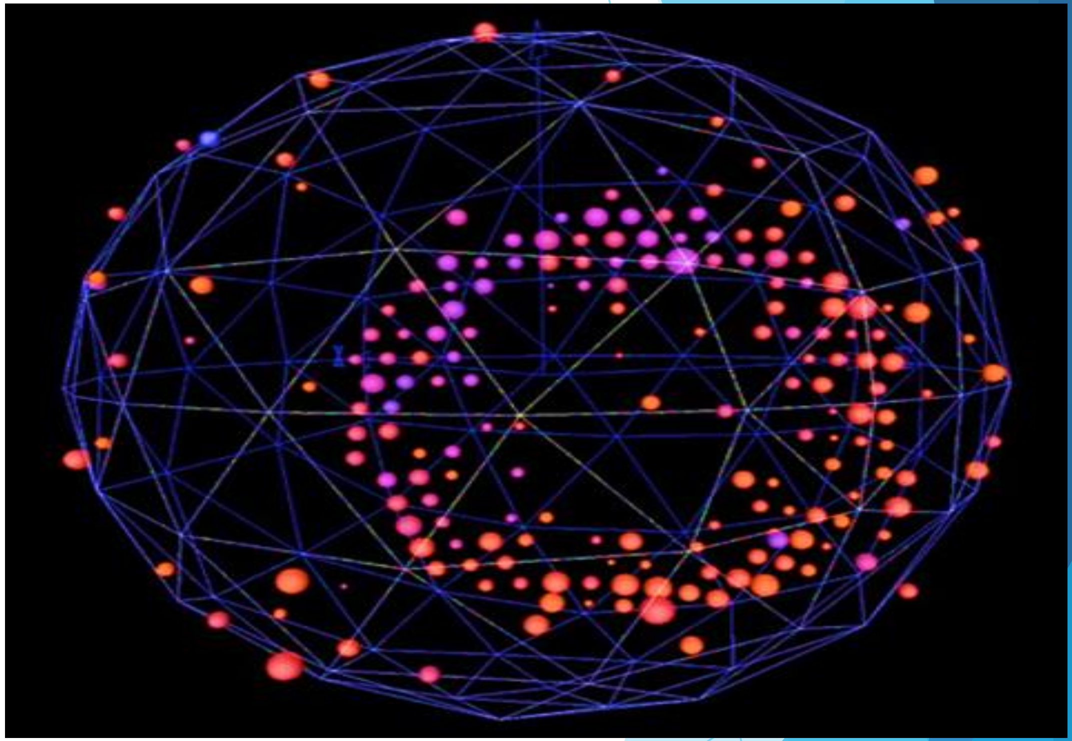


We have to get this angular spectrum

❖ *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

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

$\alpha_D = 0.25$

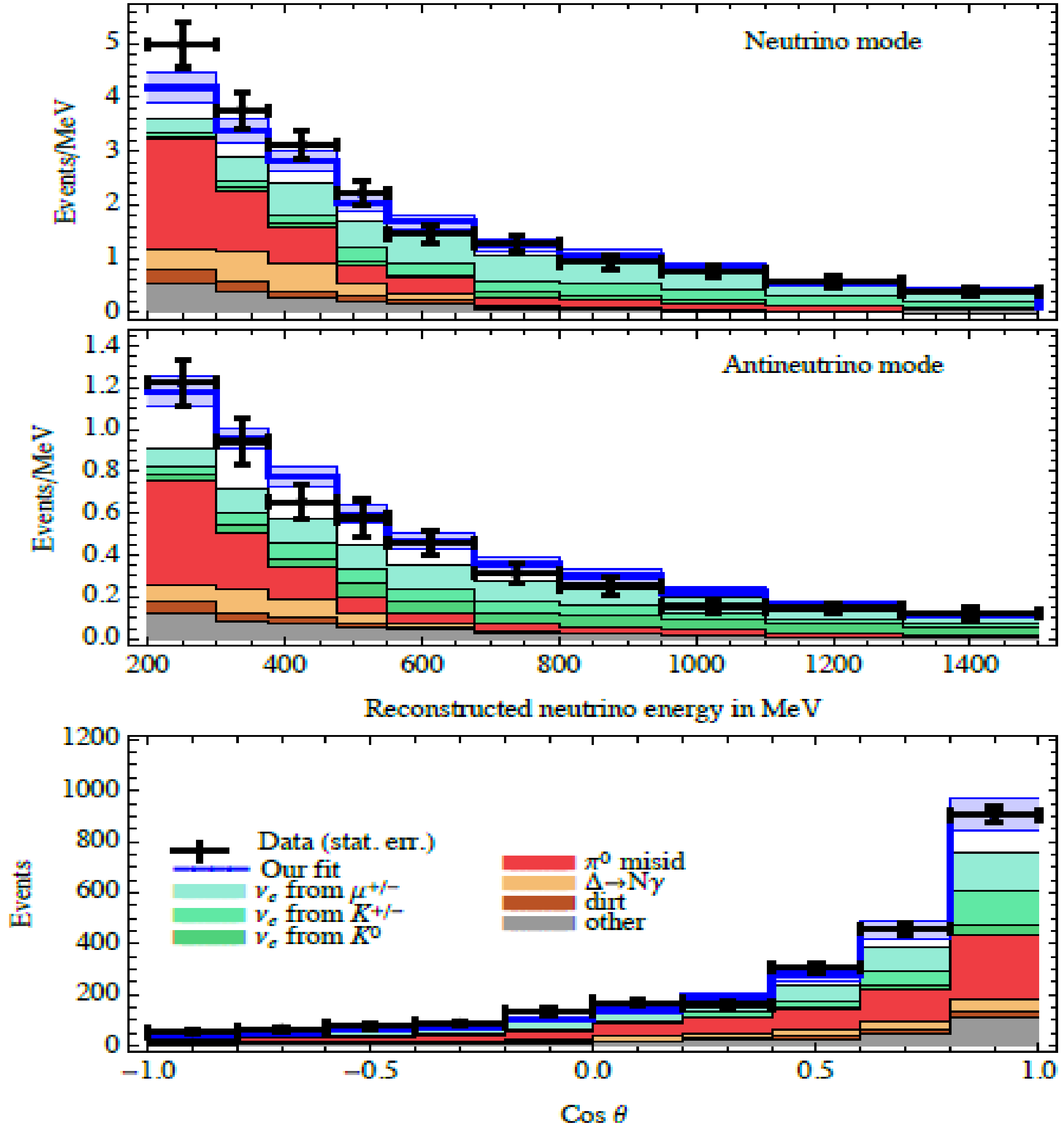
$\alpha\varepsilon^2 = 2 \times 10^{-10}$

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

Bertuzzo et al 1807.09877

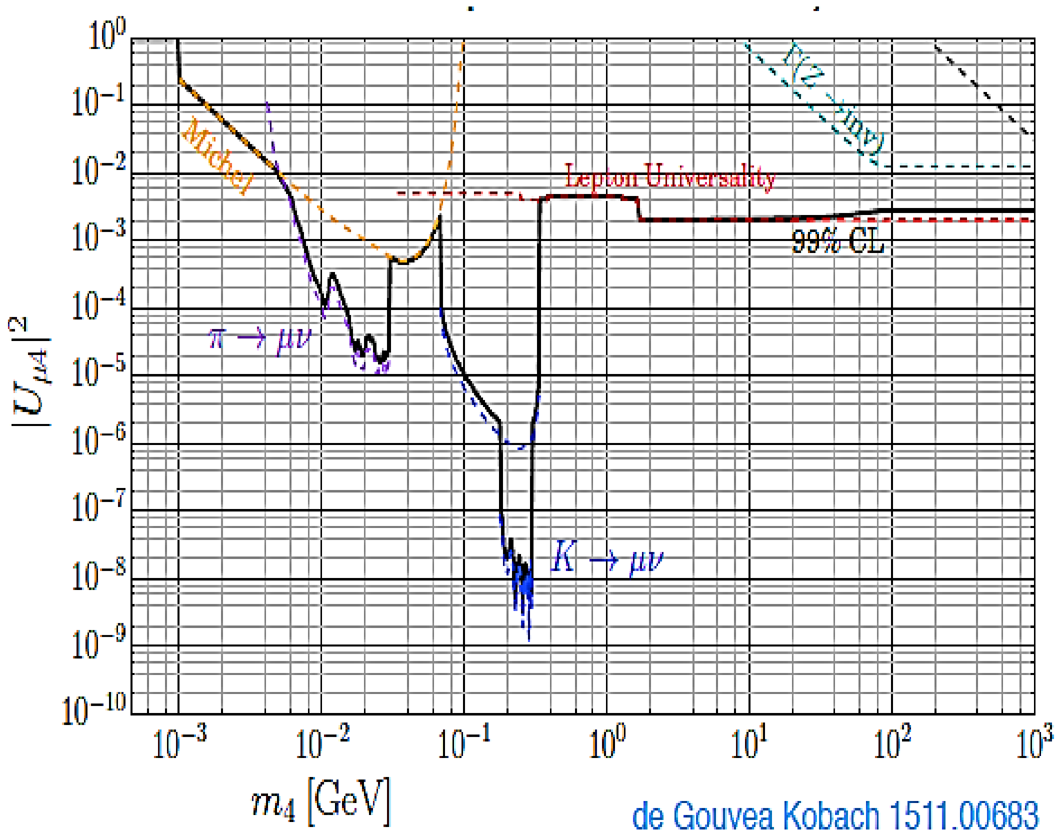
See also Ballett et al 1808.02915

for different realization of the mechanism

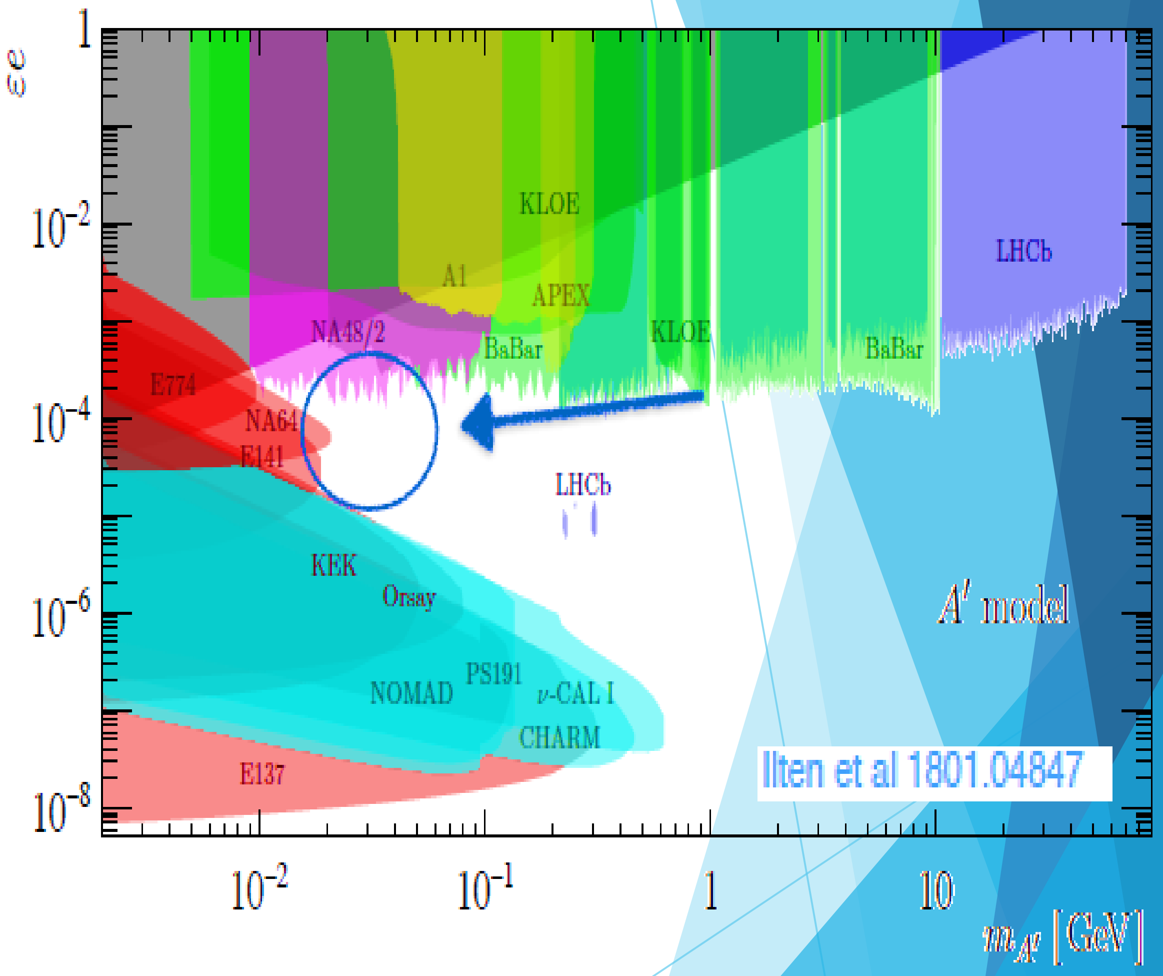


❖ Constraint on Light Dark Sector

Model Independent Constraint on Heavy Sterile Neutrino



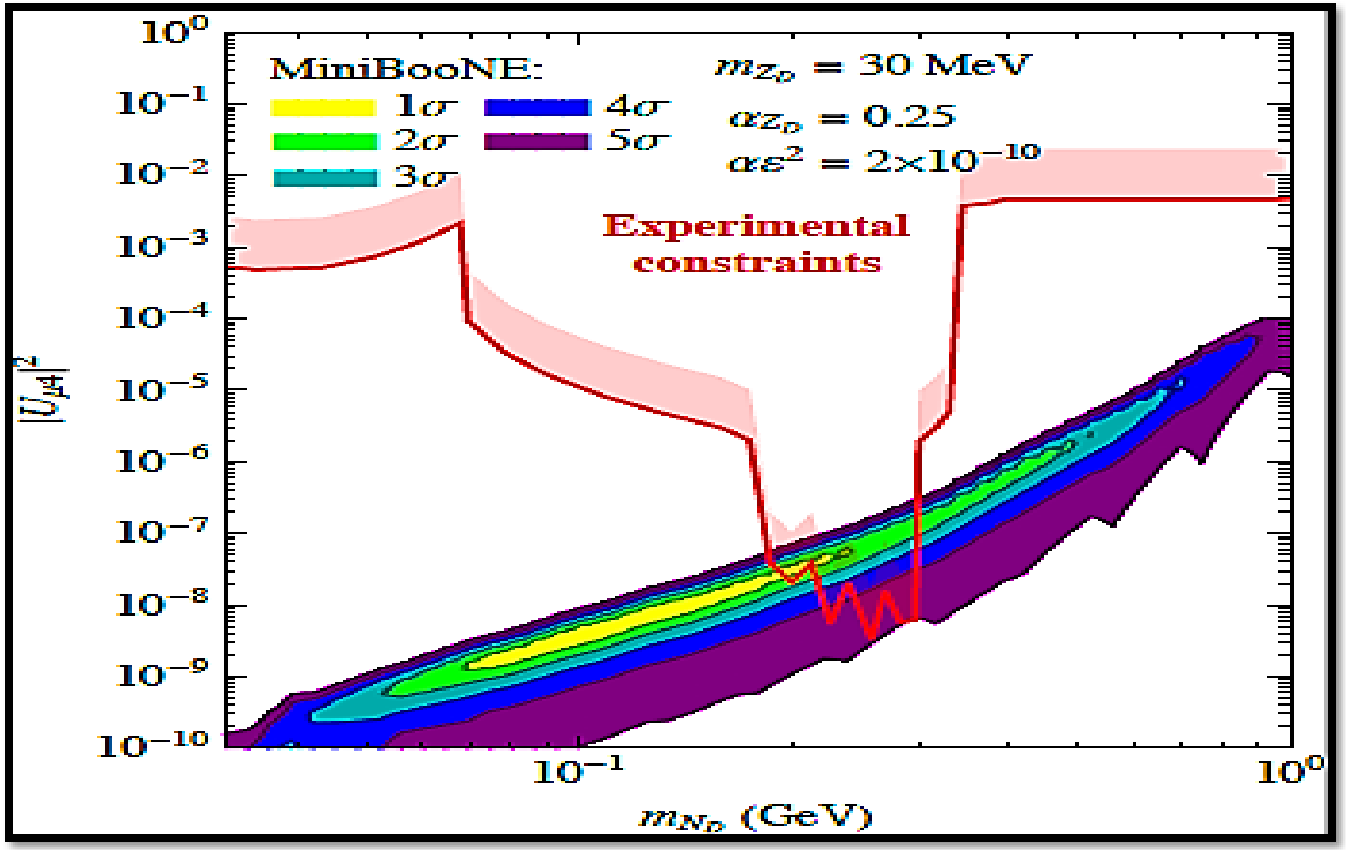
de Gouvea Kobach 1511.00683



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

Bertuzzo et al 1807.09877

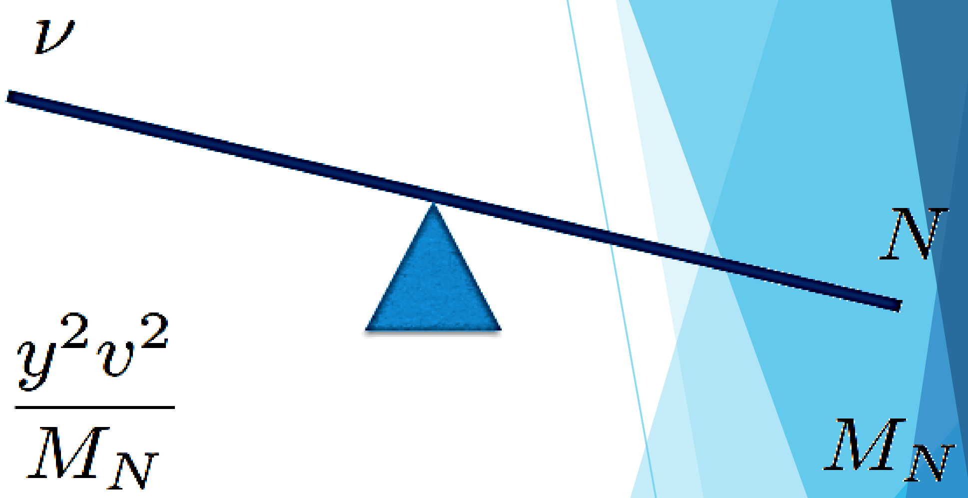
Connection to Neutrino Mass Generation Mechanism

❖ Standard/Type I Seesaw

$$yNH\ell + M_N NN$$

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

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



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

Lepton number is broken at very high scale M_N

❖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**

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

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

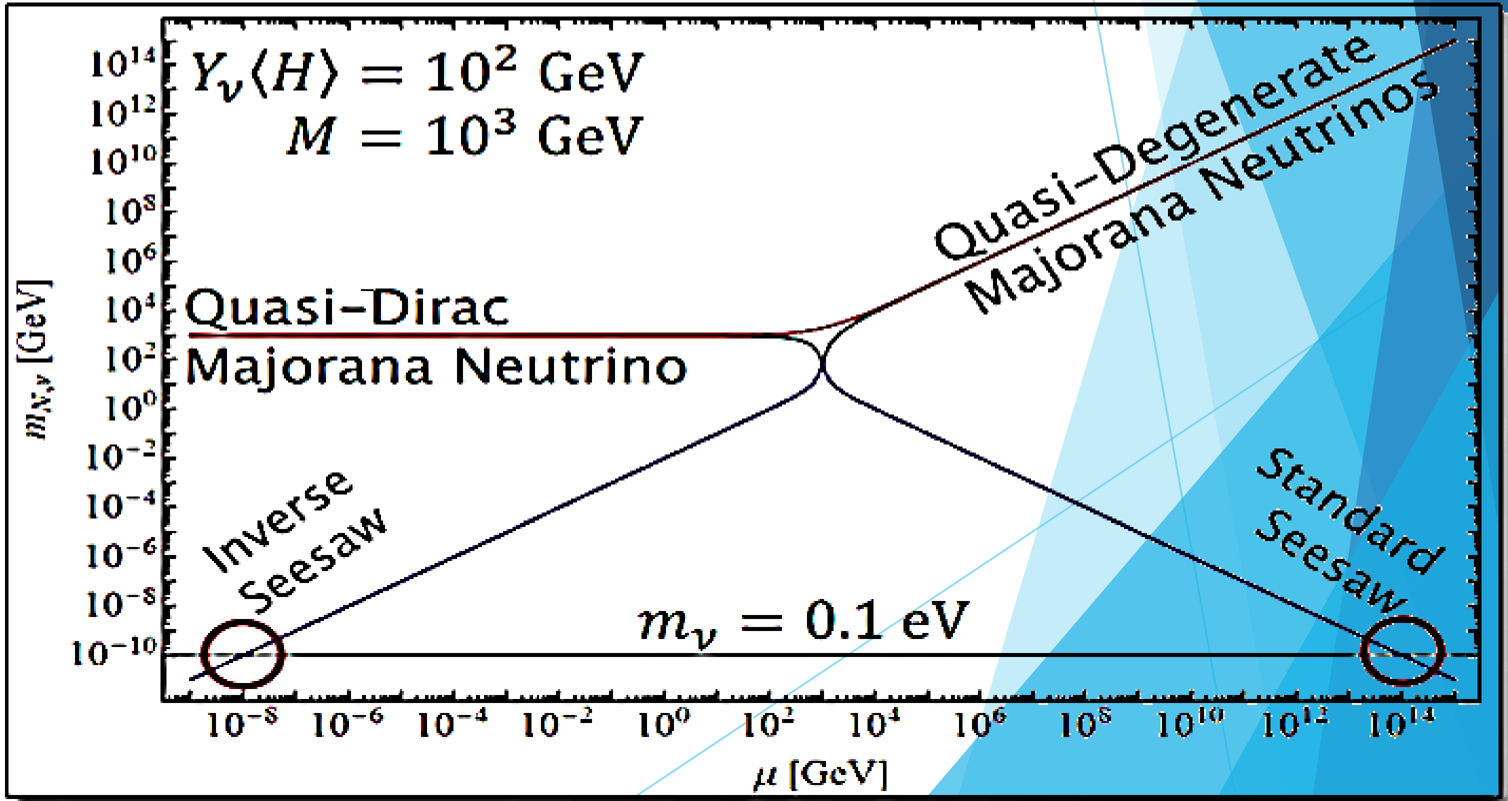
- Why μ is much smaller than TeV scale?

Scale of Seesaw Mechanism

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

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

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



Scale of Seesaw Mechanism

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

❖ Is it really sufficient to ics scale
behind neutrin echanism at

Can neutrino masses come from light physics ?

scale 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

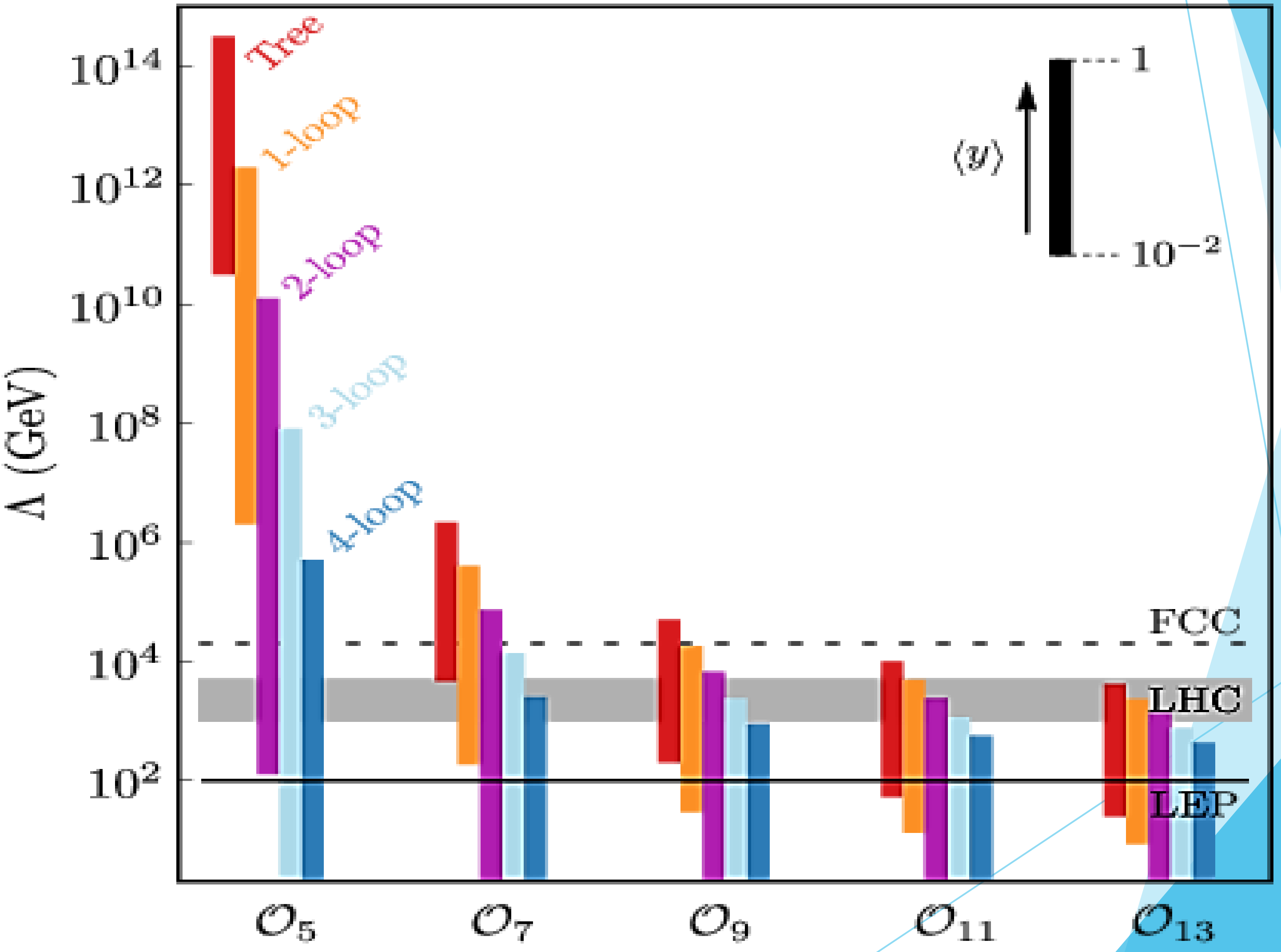
In an effective theory, the Lagrangian should be described as

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

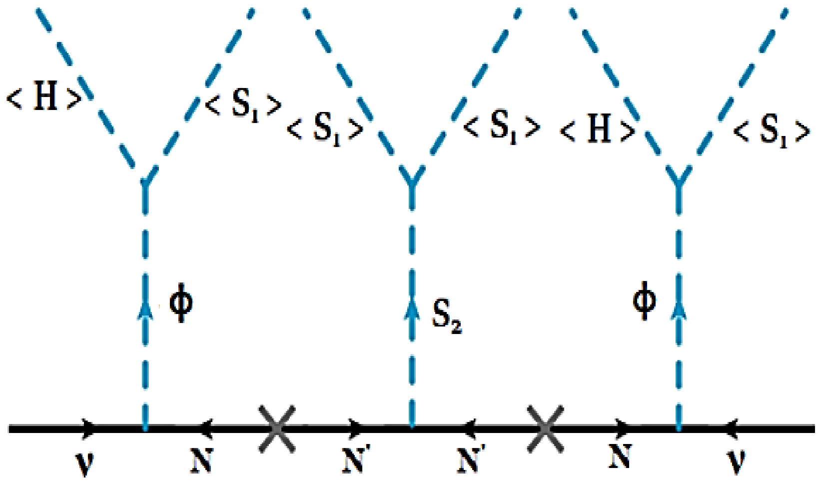
Neutrino masses from a n-loop-induced dim-d operator

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

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

Bertuzzo et al 1808.02500

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

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m & 0 \\ m & 0 & M \\ 0 & M & \mu \end{pmatrix} \begin{matrix} \nu & 0 \\ N & + \\ N' & - \end{matrix} \implies m_\nu = \mu \frac{m^2}{M^2}$$

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

Bertuzzo et al 1808.02500

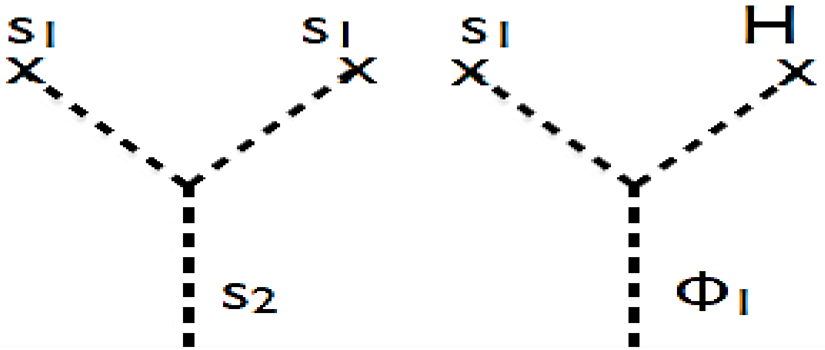
Neutrino masses from light physics

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!

Bertuzzo et al 1808.02500

Neutrino masses from light physics

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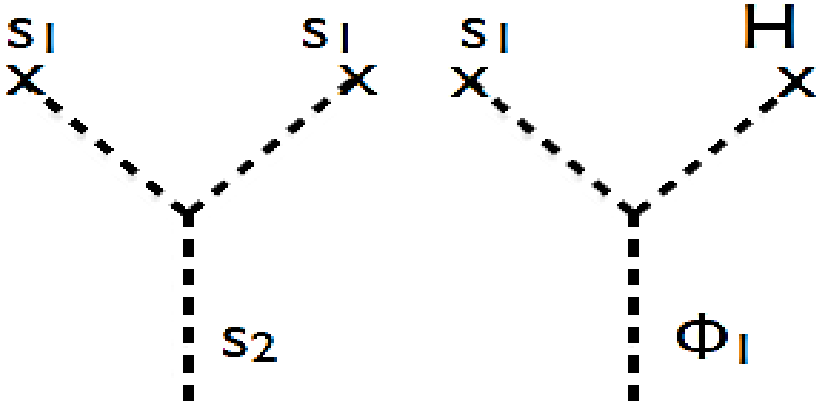

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Bertuzzo et al 1808.02500

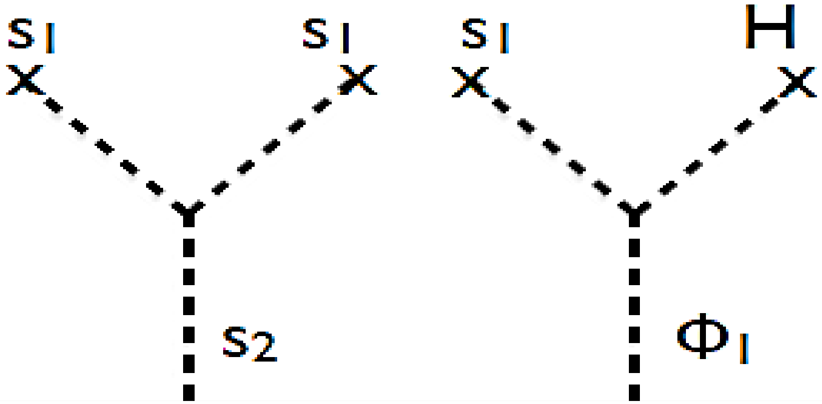
Neutrino masses from light physics

Minimum scalar content

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

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

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



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Bertuzzo et al 1808.02500

❖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**

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

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

- 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

$$V = -m_H^2(H^\dagger H) + m_\phi^2(\phi^\dagger\phi) - m_1^2 S_1^* S_1 + m_2^2 S_2^* S_2 - \left[\frac{\mu}{2} S_1(\phi^\dagger H) + \frac{\mu'}{2} S_1^2 S_2^* + \frac{\alpha}{2}(H^\dagger\phi) S_1 S_2^* + \text{h.c.}\right] + \lambda'_{H\phi}\phi^\dagger H H^\dagger \phi + \sum_{\varphi}^{\{H,\phi,S_1,S_2\}} \lambda_\varphi(\varphi^\dagger\varphi)^2 + \sum_{\varphi<\varphi'}^{\{H,\phi,S_1,S_2\}} \lambda_{\varphi\varphi'}(\varphi^\dagger\varphi)(\varphi'^\dagger\varphi') .$$

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

Masses of the Physical Fields								
$m_{h_{SM}}$ (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}	$\mathcal{O}(10^{-6})$

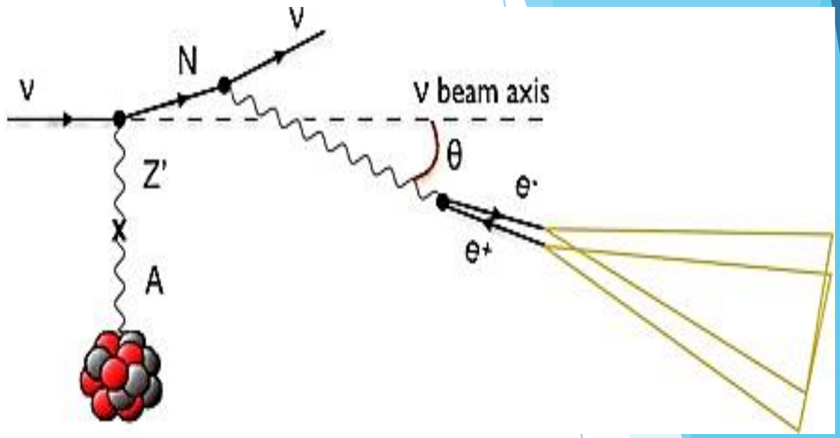
Bertuzzo et al 1808.02500

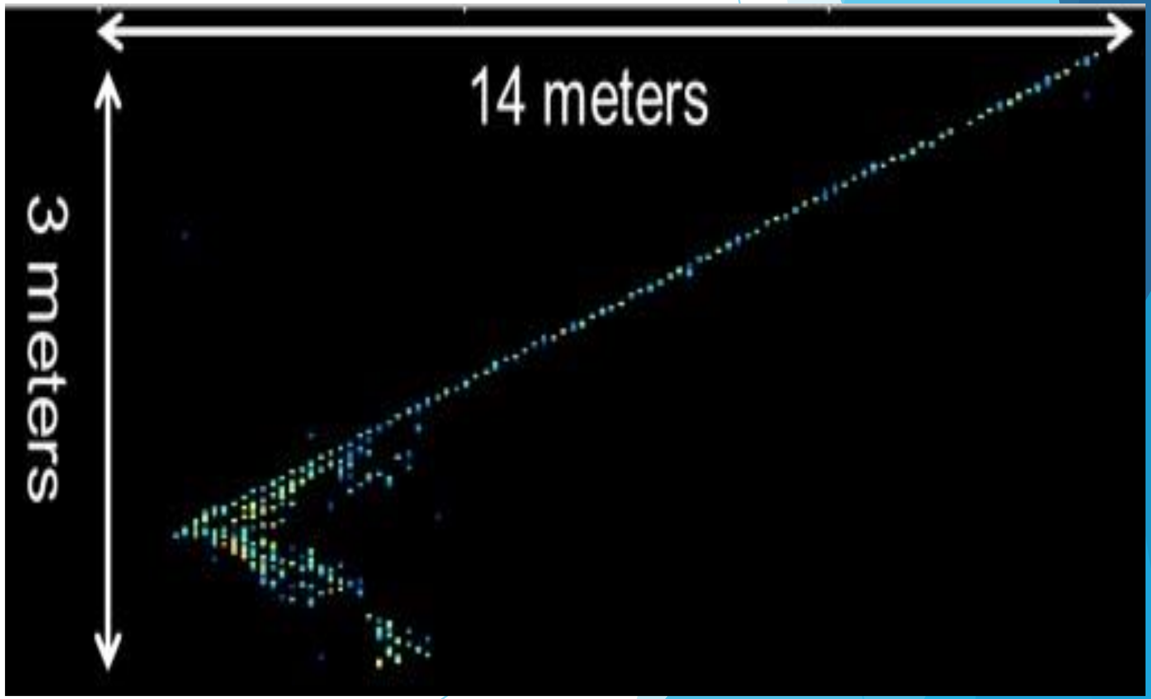
❖ Phenomenology on other neutrino experiment

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…)

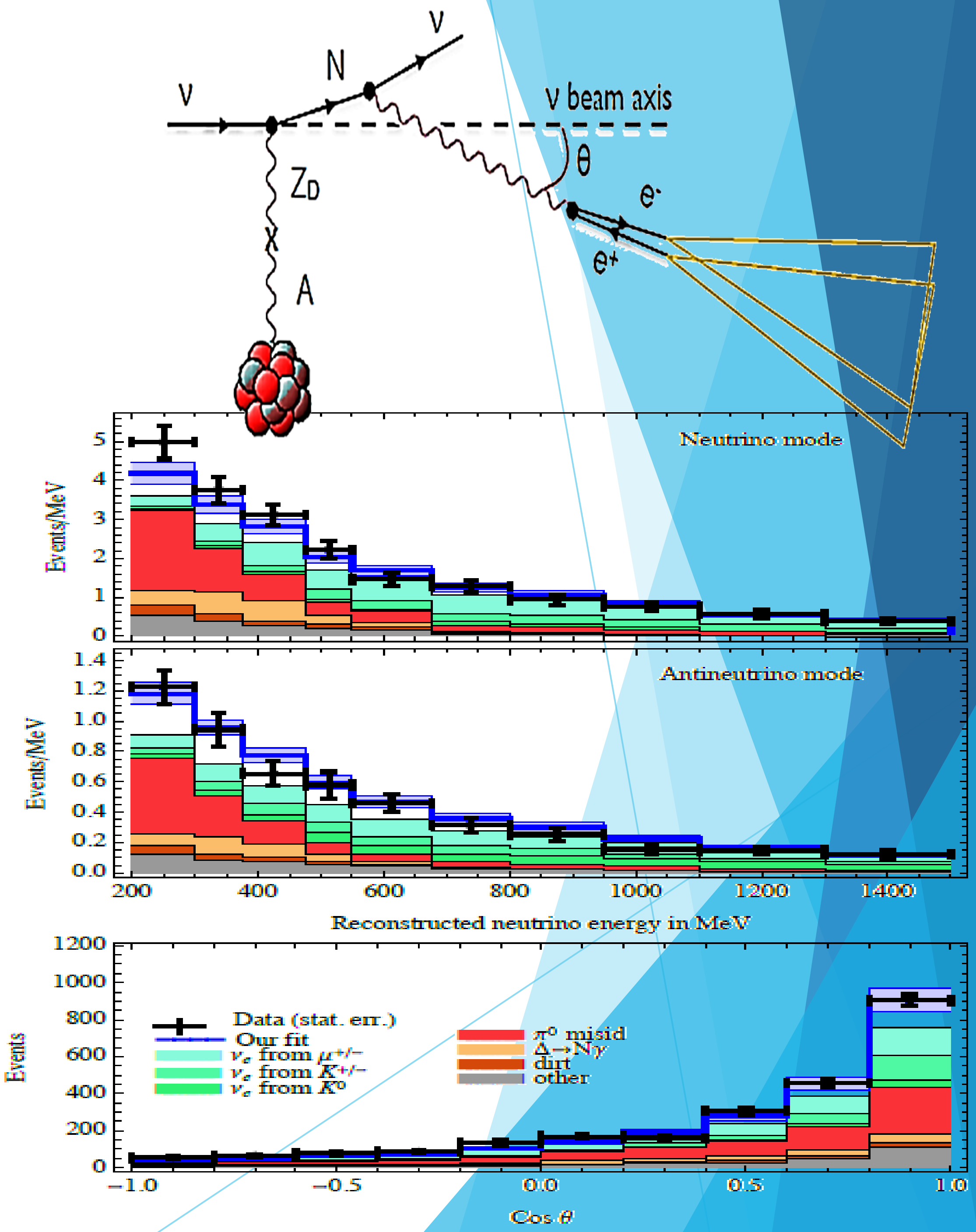
Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N



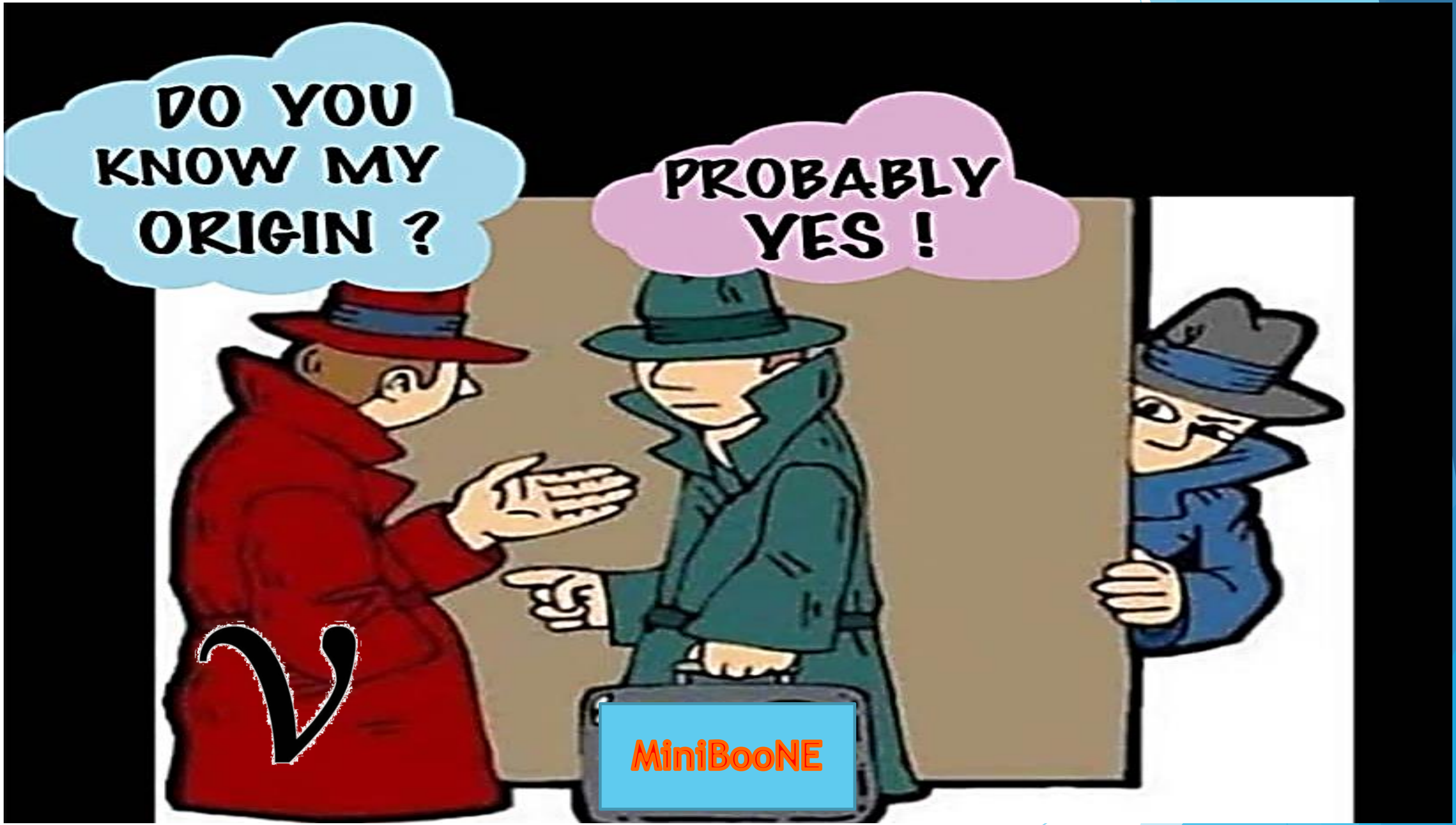


Conclusions :

- *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*



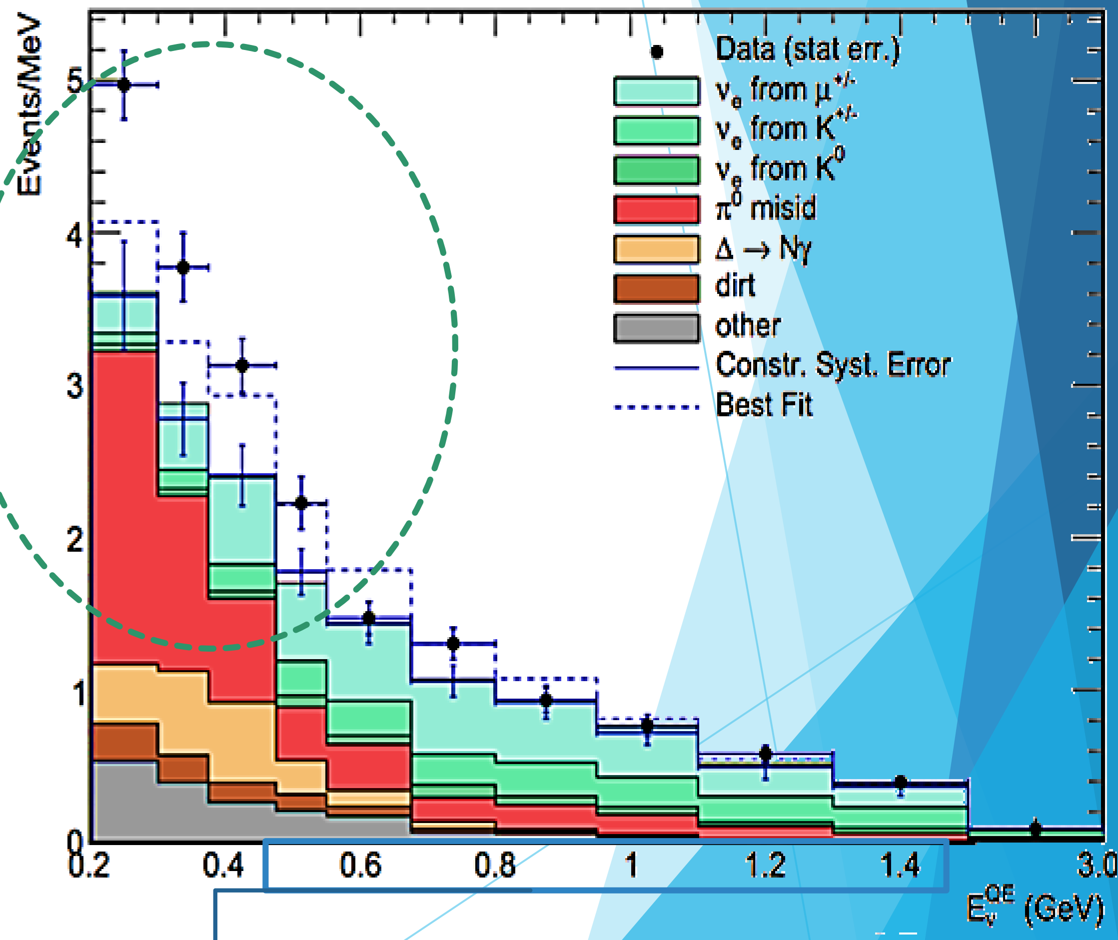

DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
TOP SECRET
V


DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
ν
MiniBooNE


Thank you!

MiniBooNE's Low Energy Excess

MiniBooNE Collaboration hep-ex/1805.12028

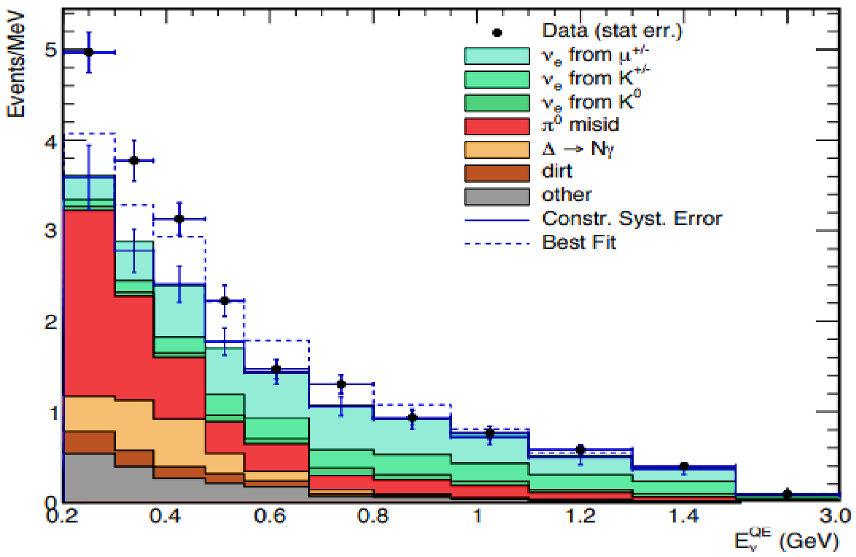


MiniBooNE observed a large excess in the much lower energy region

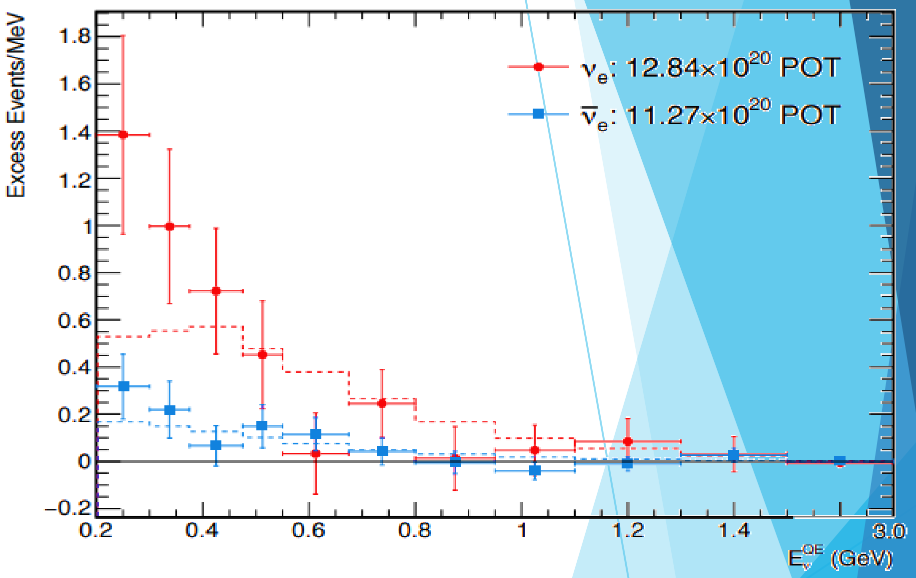
This is the region that the LSND oscillation should have appeared

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

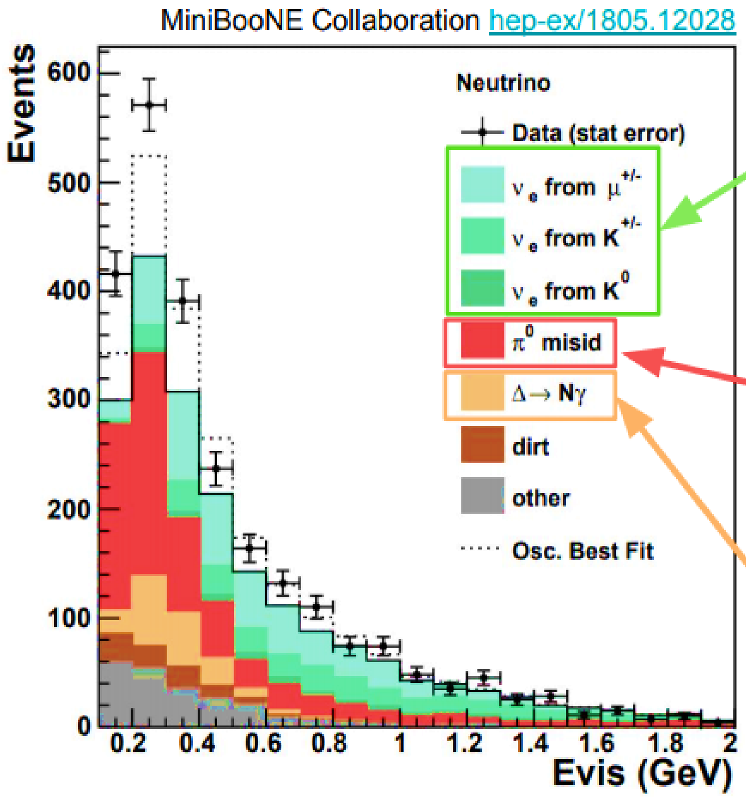
Observed ~ 400 events, PMNS predicts 0

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

MiniBooNE Collaboration 1805.12028

MiniBooNE's Low Energy Excess

Possible Explanations: Motivated by backgrounds



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.

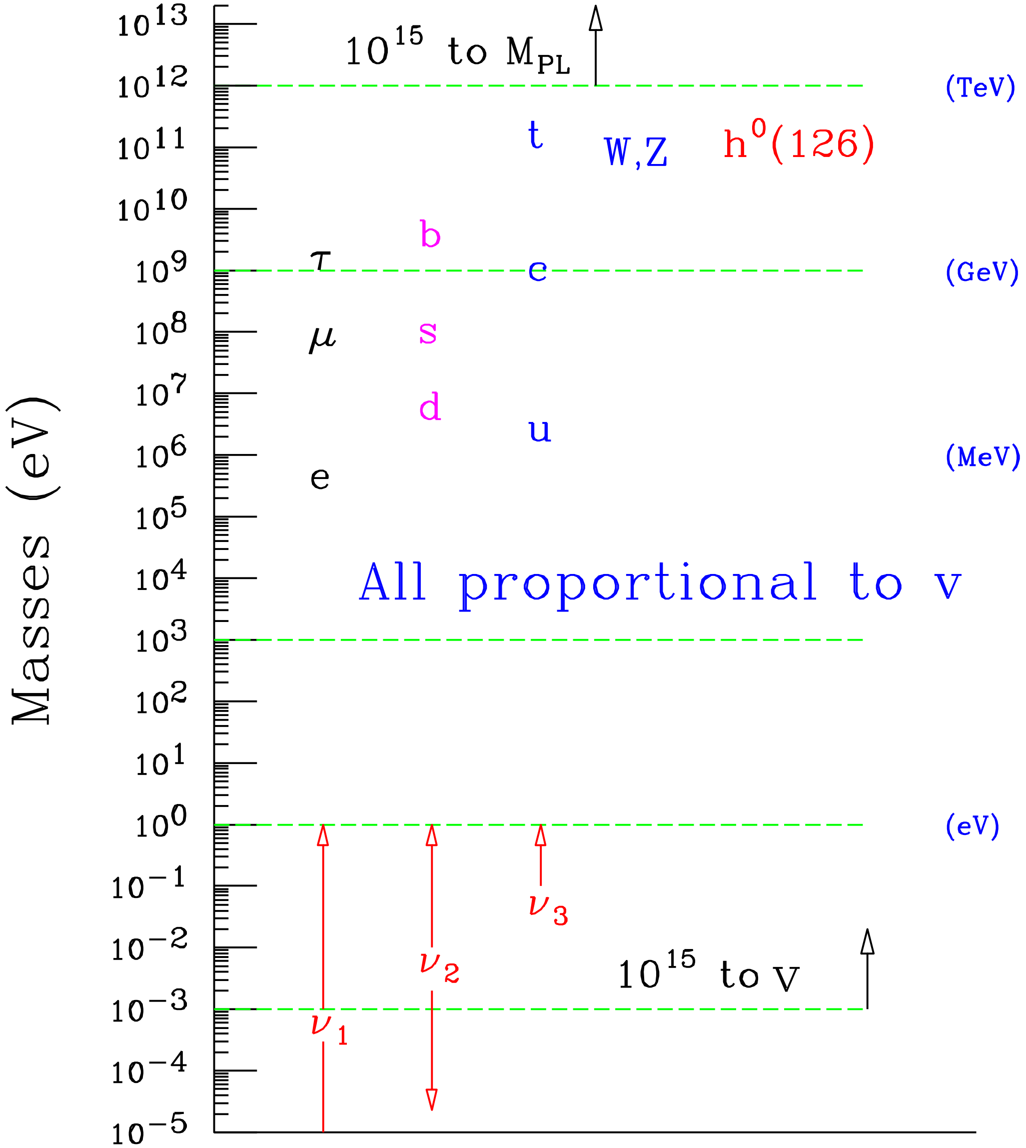
Radiative Δ decay? This has never been observed in the neutrino sector. MiniBooNE bound it using their NC π^0 measurements which agrees well with best theoretical calculations. The biggest channel of interest to MicroBooNE's photon LEE analysis.

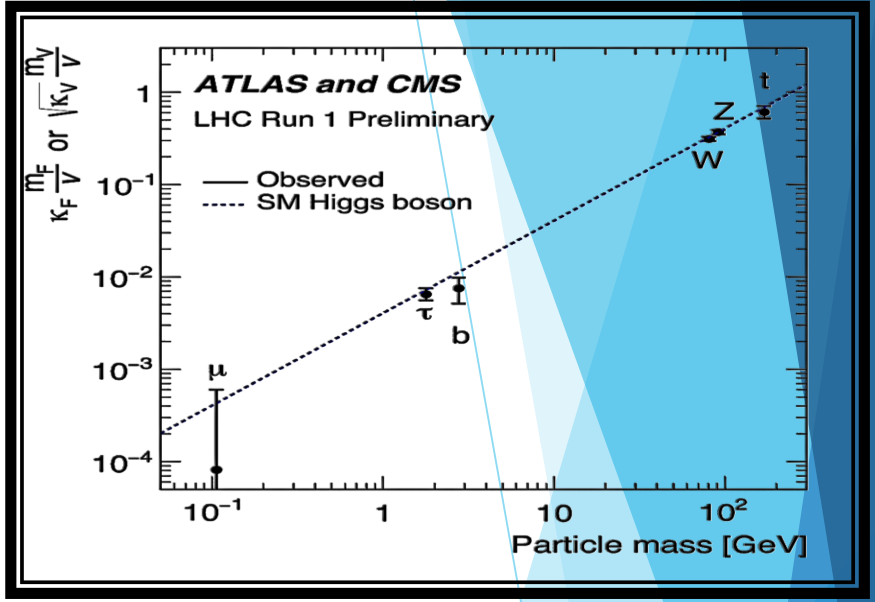
❖ *Explanation of MiniBooNE's low energy excess*

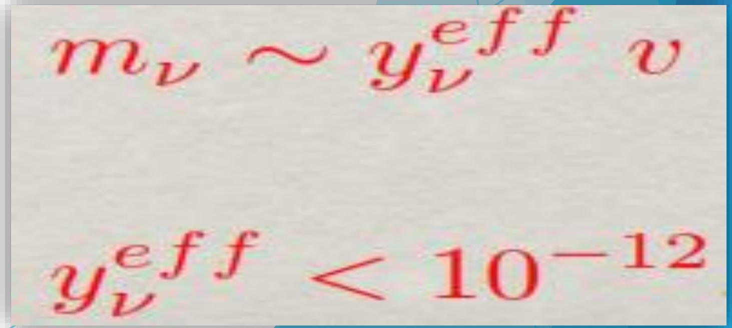
A LIGHT DARK SECTOR – THE PRESCRIPTION

- 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:







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

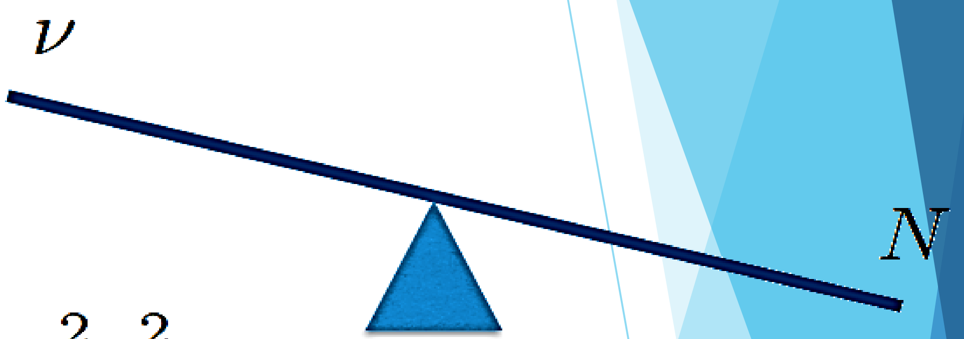
$$y_\nu^{eff} < 10^{-12}$$

❖ Standard/Type I Seesaw

$$yNH\ell + M_N NN$$

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

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



$$\frac{y^2 v^2}{M_N} \qquad M_N$$

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

Lepton number is broken at very high scale M_N

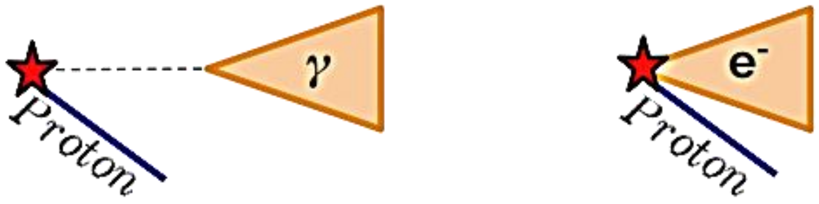
❖ Phenomenology on other neutrino experiment

U(1)' models in Future and Current LArTPCs

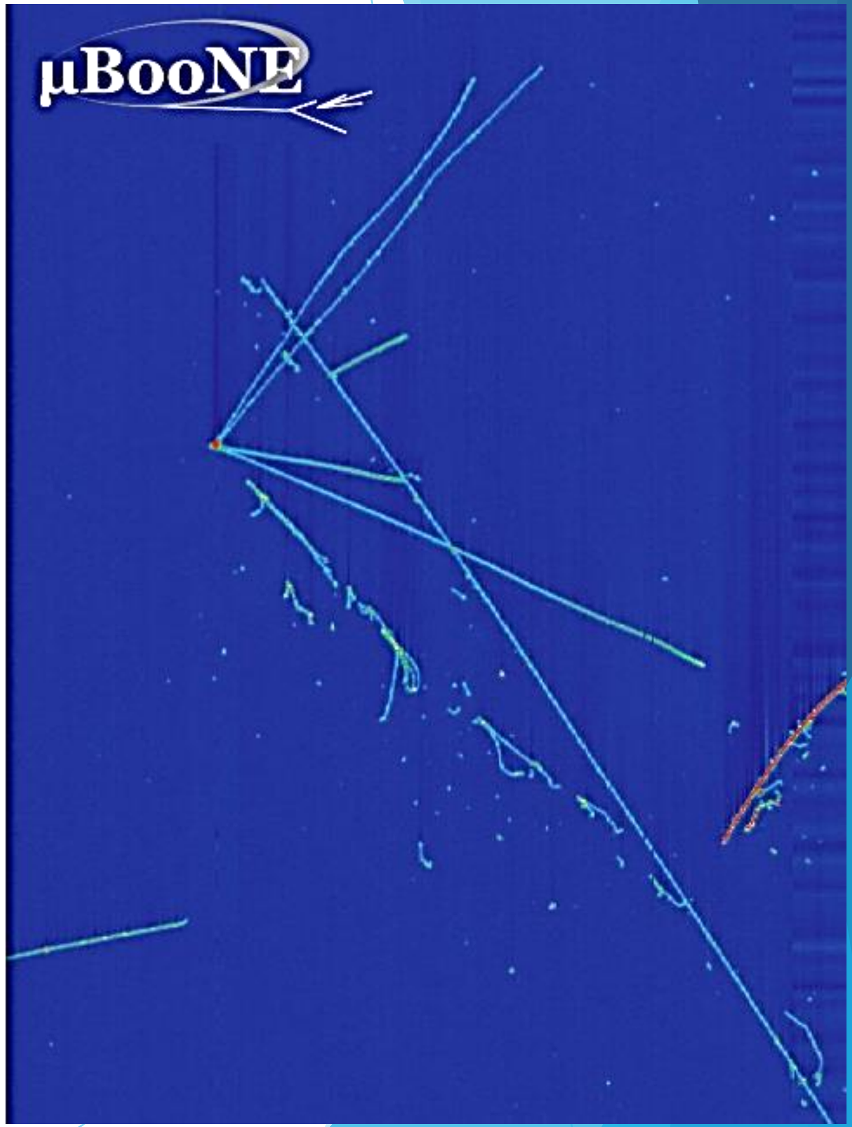
This class of models has has incredibly **rich phenomenology** at LArTPCs such as **MicroBooNE, SBND or the DUNE near detector**:

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**

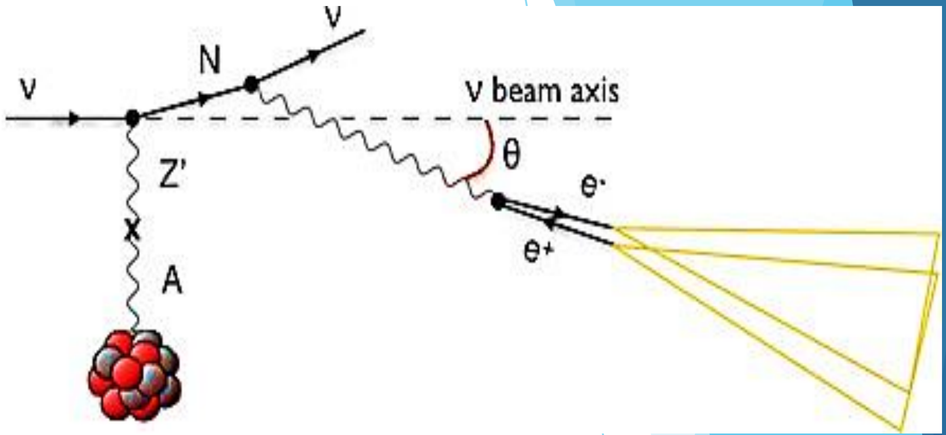
✓ **Almost no hadronic activity to tag interaction vertex**

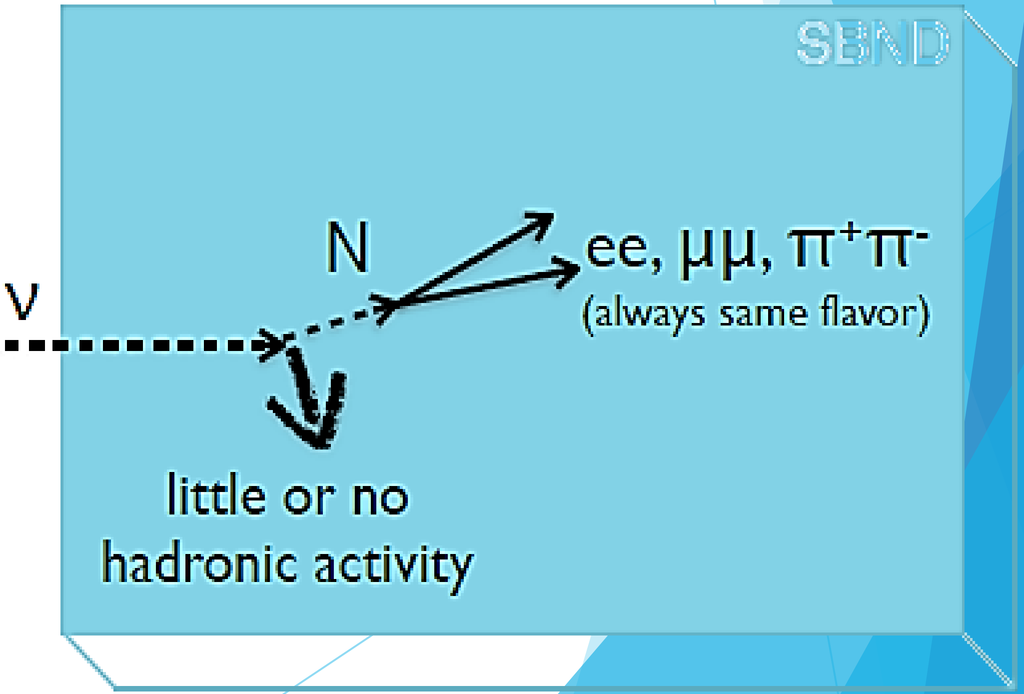
✓ Decays to collimated e^+e^- pairs

✓ 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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[5] Fermi National Accelerator Laboratory, Batavia, IL

$m_X < 30$ MeV. As described above, the reconstructed track 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]).

B. Semi-Visibly Decaying Particles

Since new particles with fully visible decays necessarily give forward-peaked energy depositions in conflict with the angular distribution of the measured excess, we now consider the possibility that a new unstable particle X decay signature

... analysis [30]. Thus, the dominant allowed channel is a two-body decay where X decays into a lighter dark-sector state X' and a photon ($X \to X' + \gamma$). Three- and higher-body decays are also allowed but will be increasingly phase-space suppressed; regardless, we consider decays to X' plus an arbitrary number of electromagnetic tracks. Since the electromagnetic tracks must be well-collimated to contribute to the excess, we will treat this scenario as a quasi-two-body decay, where the electromagnetic energy is considered as a single 4-vector $p_{\rm EM}$ with $0 \le p^2_{\rm EM} \le (30\ {\rm MeV})^2$.

In the X rest frame, the electromagnetic energy is $E_{\rm EM} = (m_X^2 - m_{X'}^2)/2m_X$. Electromagnetic energy with small invariant mass compared to the beam energy, emitted backwards in the X rest frame, will be boosted to very small lab-frame energies,

$$E_{\rm EM,\,lab} \approx \frac{m_X^2 - m_{X'}^2}{2m_X}\gamma(1-\beta), \quad (4)$$

where γ and β are the boost and velocity of X, respectively. This will make it difficult for such an event to pass the $E_e > 140$ MeV selection for the ν_e-like excess unless the mass splitting between dark states $m_X^2 - m_{X'}^2$ is large to make up for the (typically very small) $1-\beta$ factor.