Confronting Neutrino Mass Generation Mechanism with MiniBooNE Anomaly

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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IIT Guwahati, India

MAX-PLANCK-GESELLSCHAFT

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

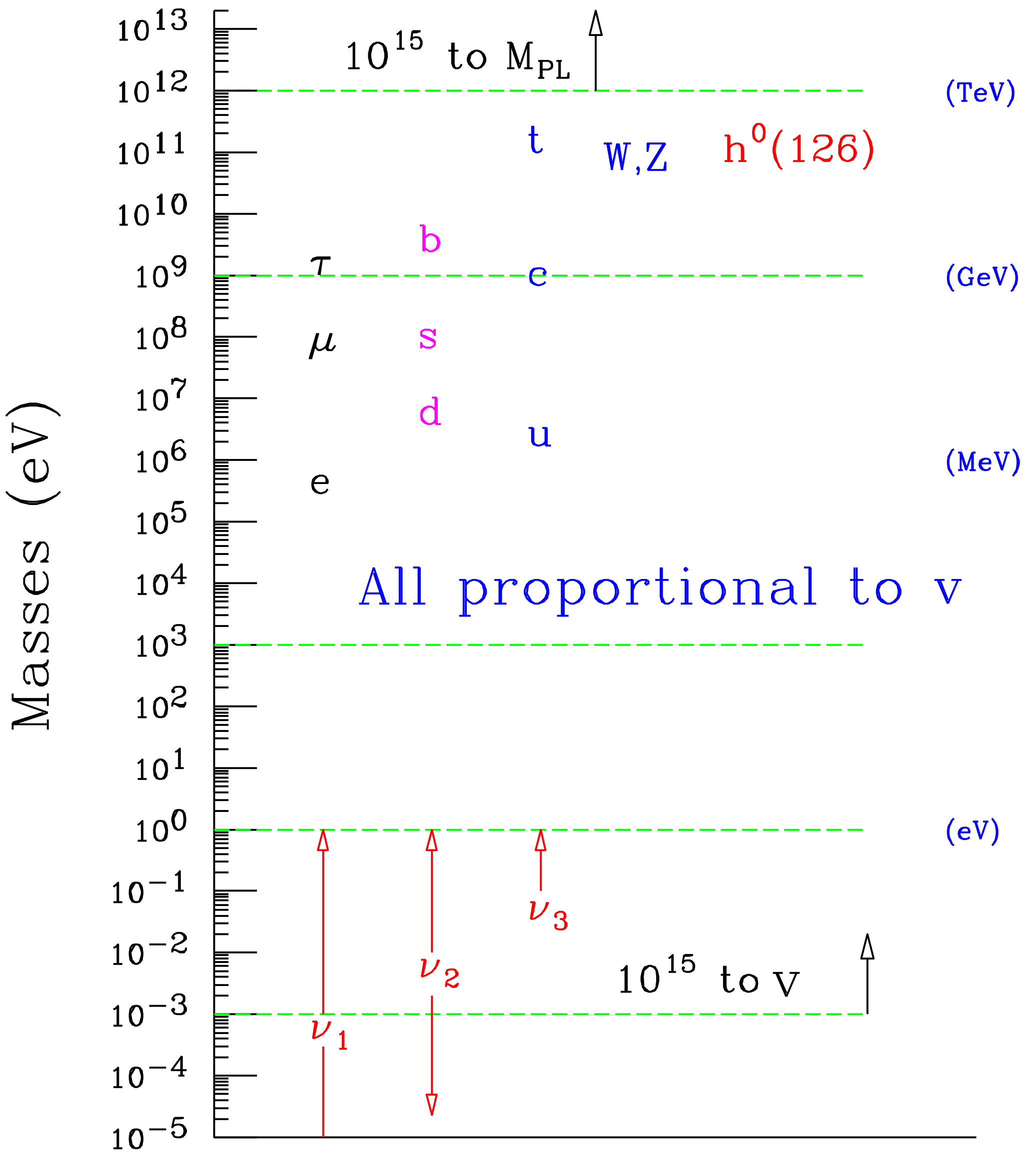
Experimental Evidences

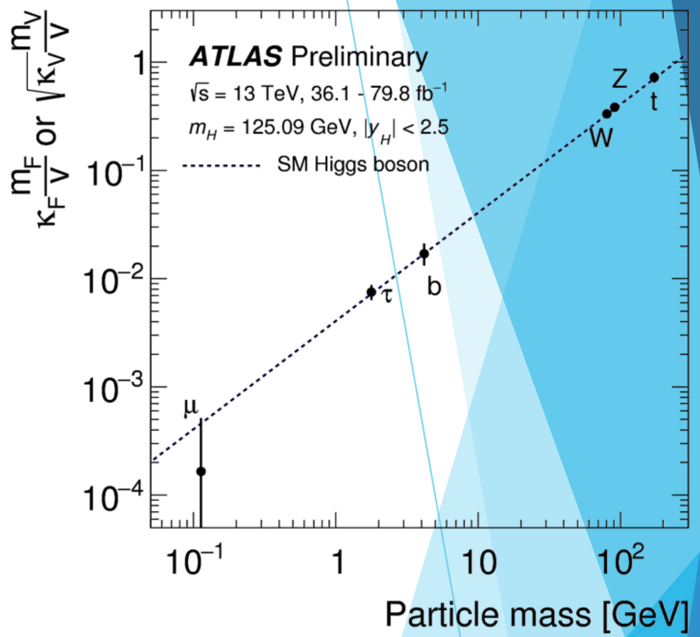
- Neutrino Masses and Mixing
- Dark Matter and Dark Energy
- Matter-antimatter Asymmetry
- Anomalies

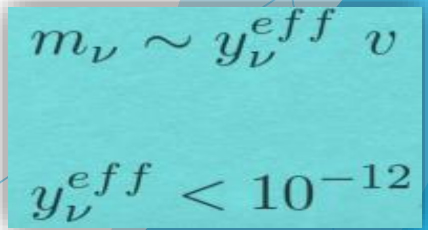
Theoretical Motivations

- 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.

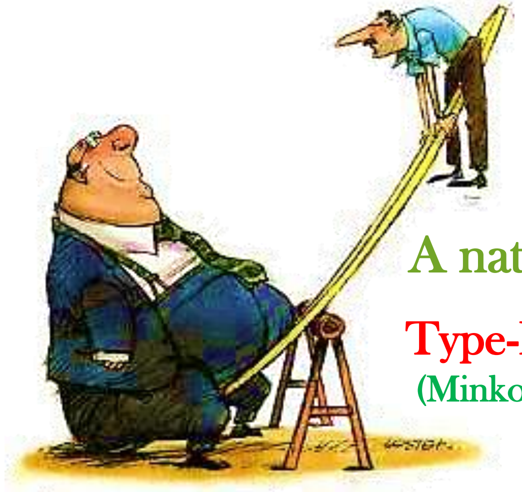
❖ Suppression by loop radiative generation: the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

❖ 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)

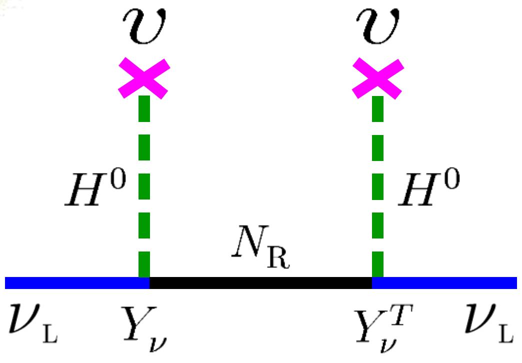


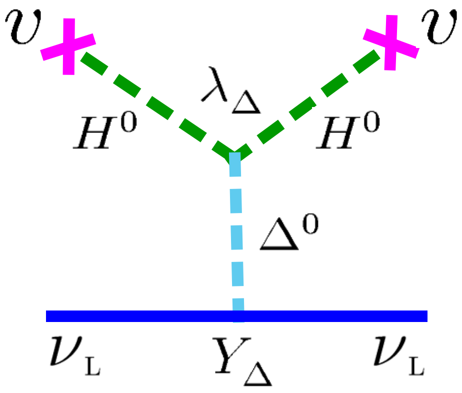
Seesaw Models

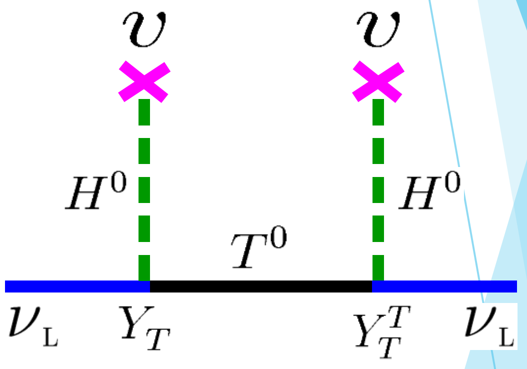
A natural theoretical way to understand why 3 ν-masses are very small.

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

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







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

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

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

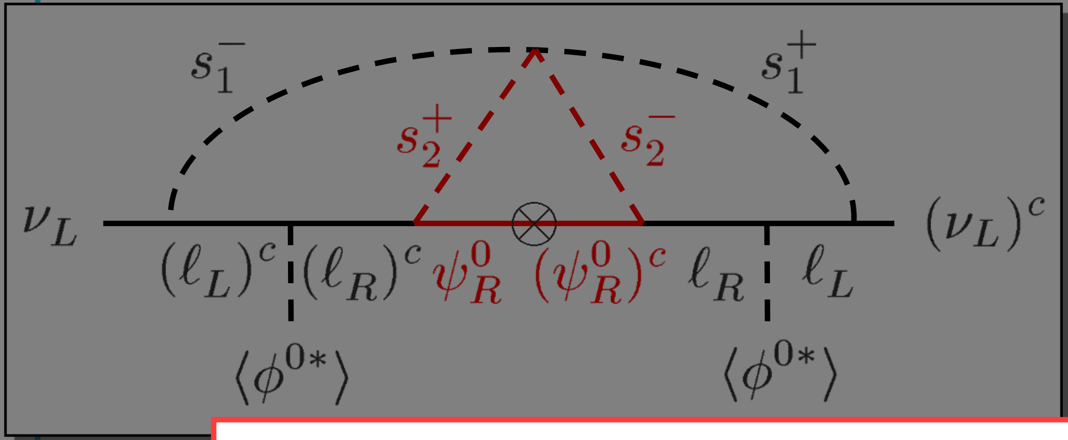
Type-II: SM + 1 Higgs triplet

(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)

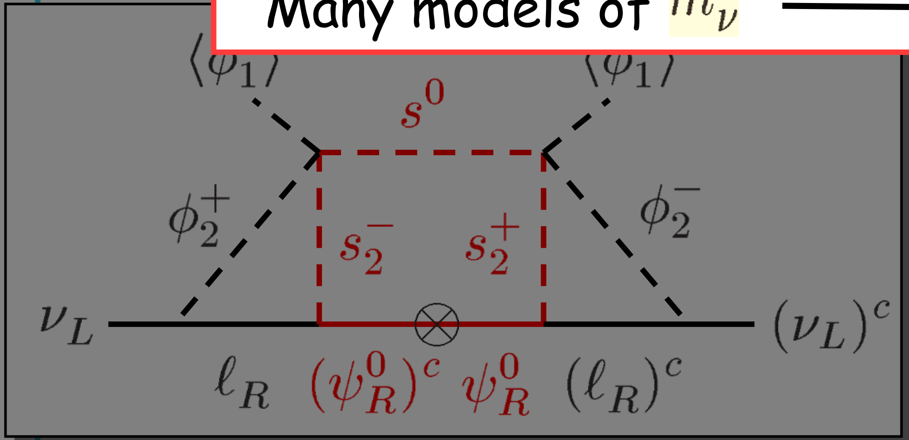
Higher-loop models with DM



Krauss-Nasri-

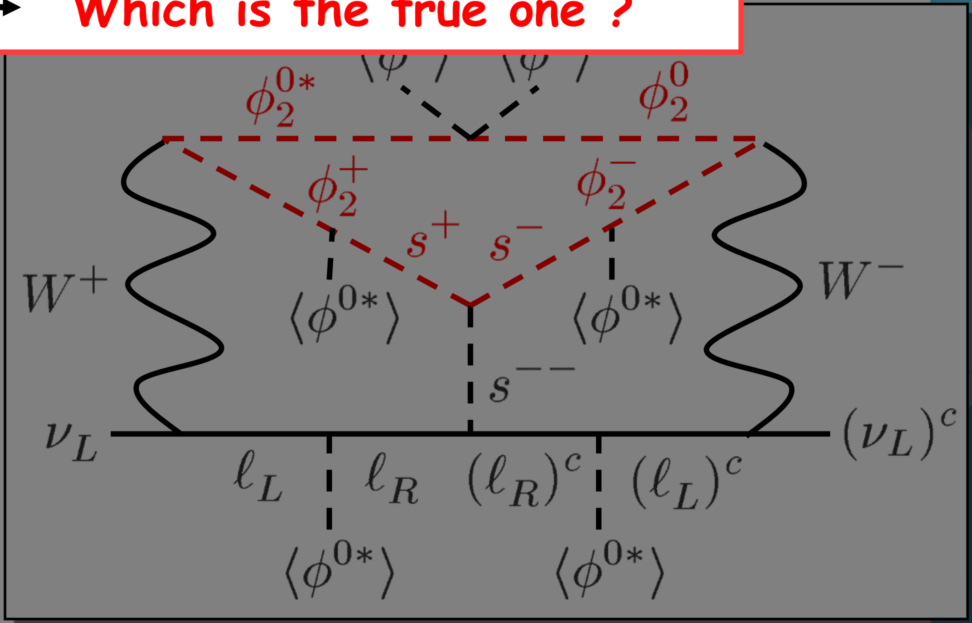
M.L. Krauss, S. N

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



Aoki-Kanemura-Seto model

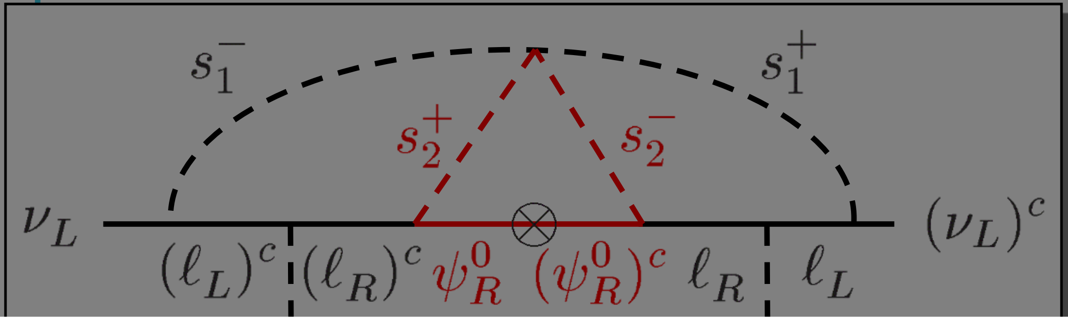
M. Aoki, S. Kanemura and O. Seto, PRL**102**, 051805 (2009)



Gustafsson-No-Rivera model

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

Higher-loop models with DM



Krauss-Nasri-

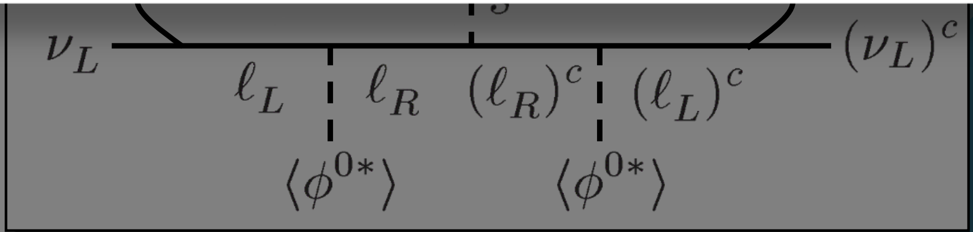
M.L. Krauss, S. N

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)



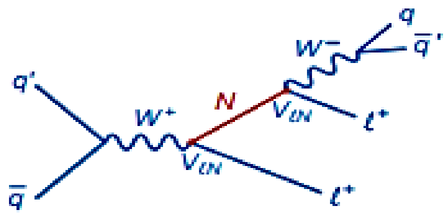
Gustafsson-No-Rivera model

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

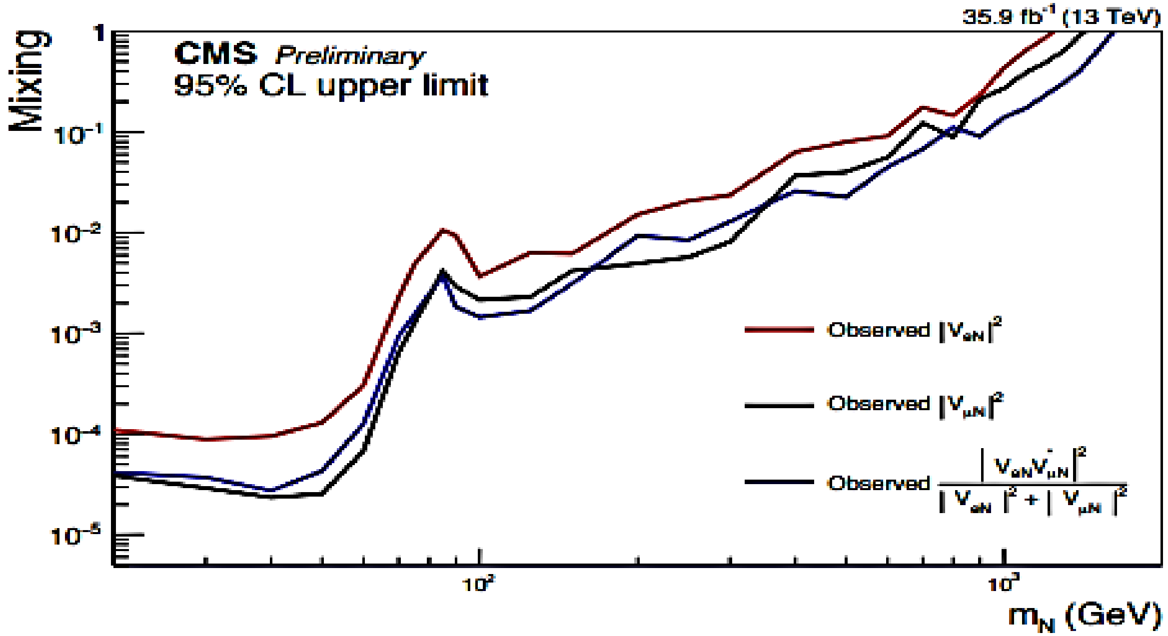
Testing Type-I Seesaw Experimentally

[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 $\not{E}_T$)



Chun, Das



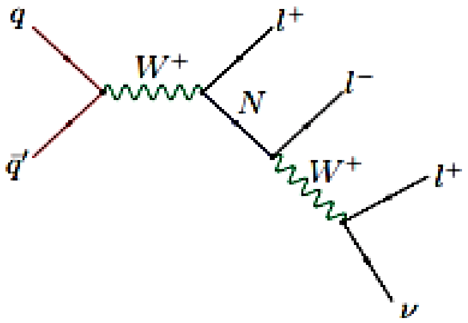
[CMS PAS EXO-17-028]

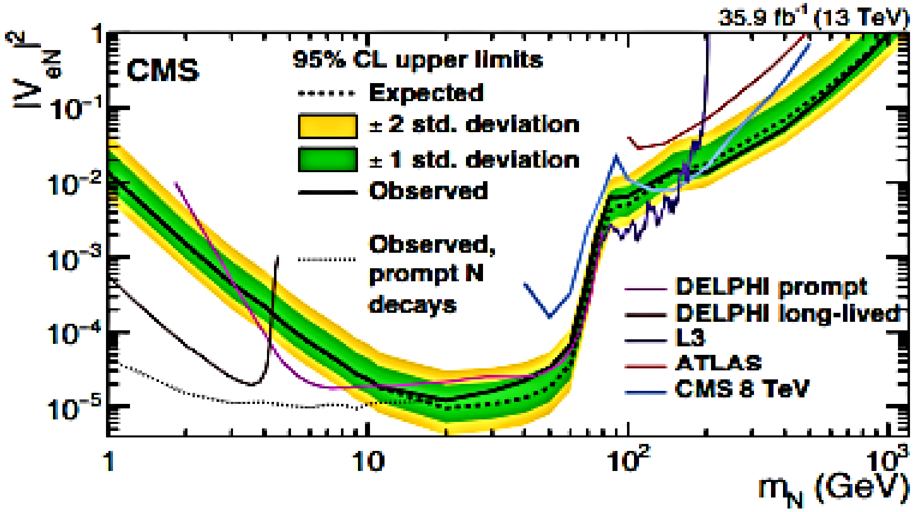
- ❑ Need (sub)-TeV scale heavy neutrinos with 'large' mixing with active neutrinos.

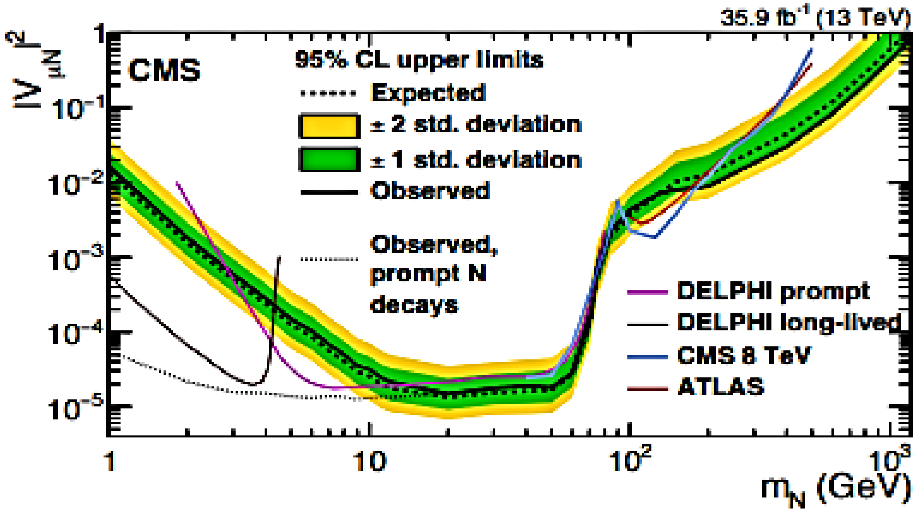
Testing Inverse Seesaw Experimentally

[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 $\not{E}_T$

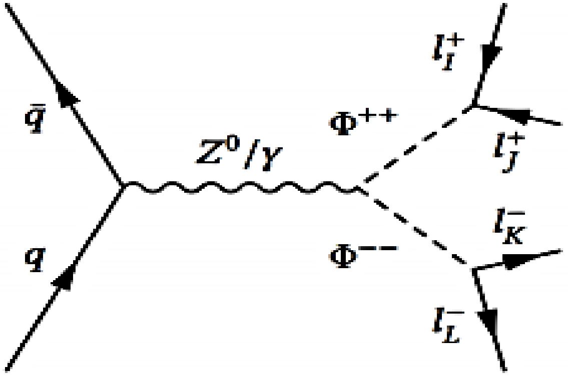




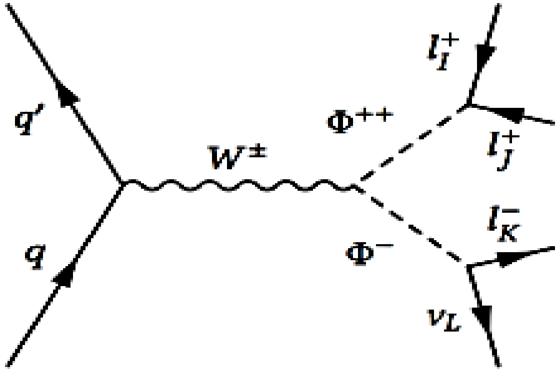


[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

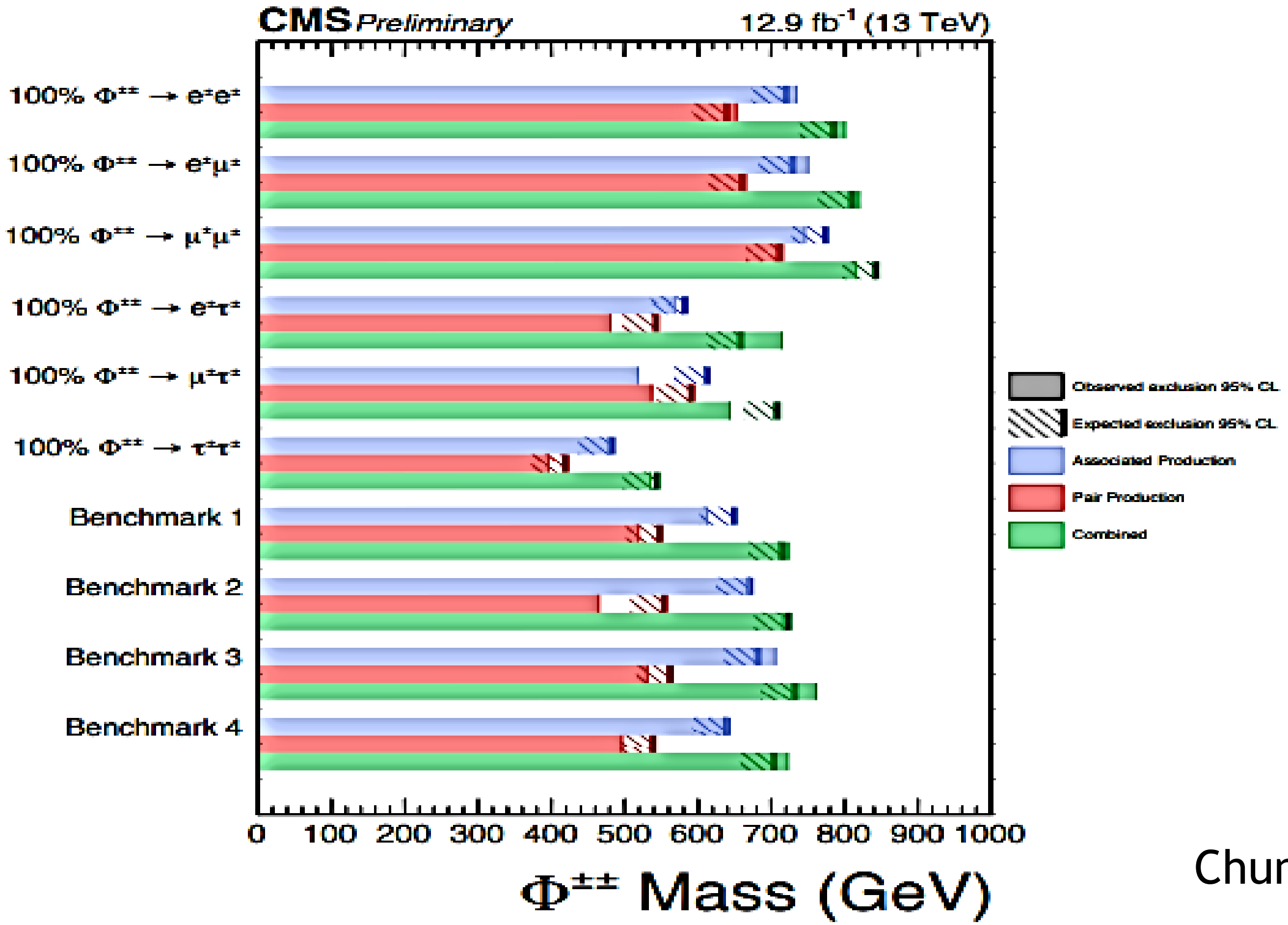
Testing Type-II Seesaw at the LHC



(a) 4ℓ



(b) 3ℓ



[CMS-PAS-HIG-16-036]

Chun

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)

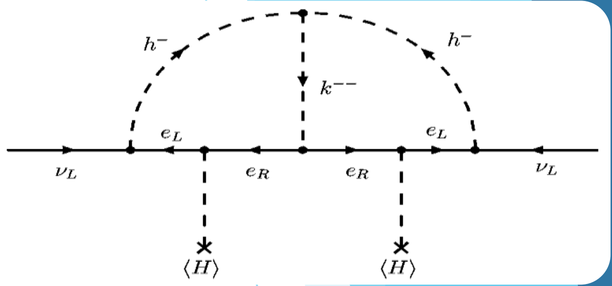
3 **• Left Right Symmetric Model**
(Pati, Jogesh C. et al. (74), Mohapatra (75), Senjanovic, (75))

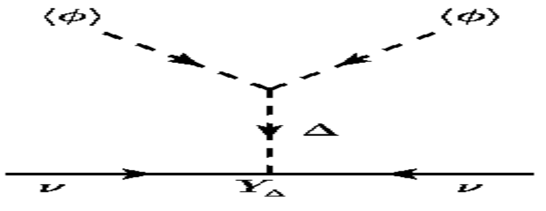
4 **• Little Higgs Model**
(Arkani-Hamed, N. (2002))

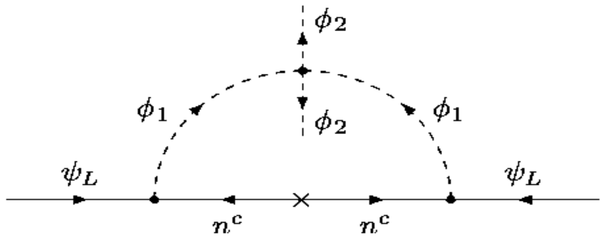
5 **• Dimension 7 Neutrino Mass Model**
(Babu, Nandi (2009))

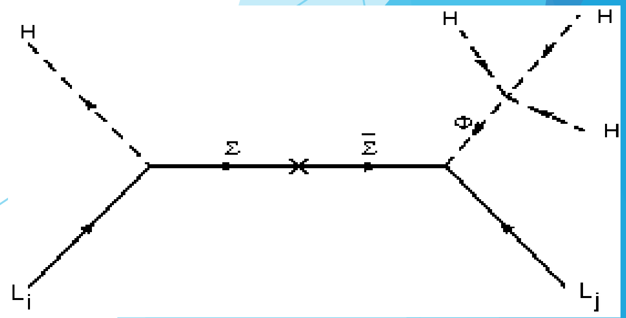
6 **• Georgi-Machacek Model**
(Georgi, Howard et al.(85))

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



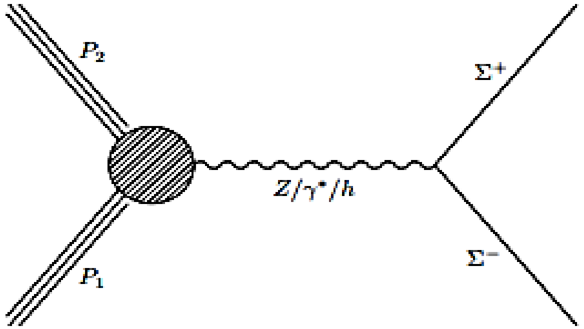


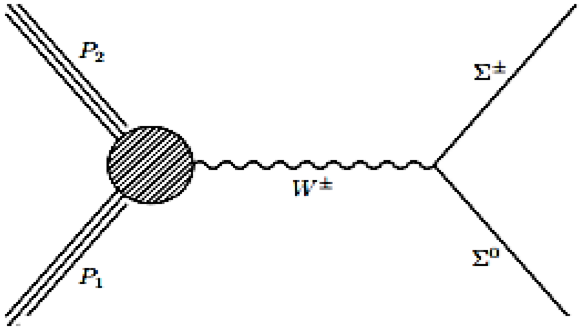


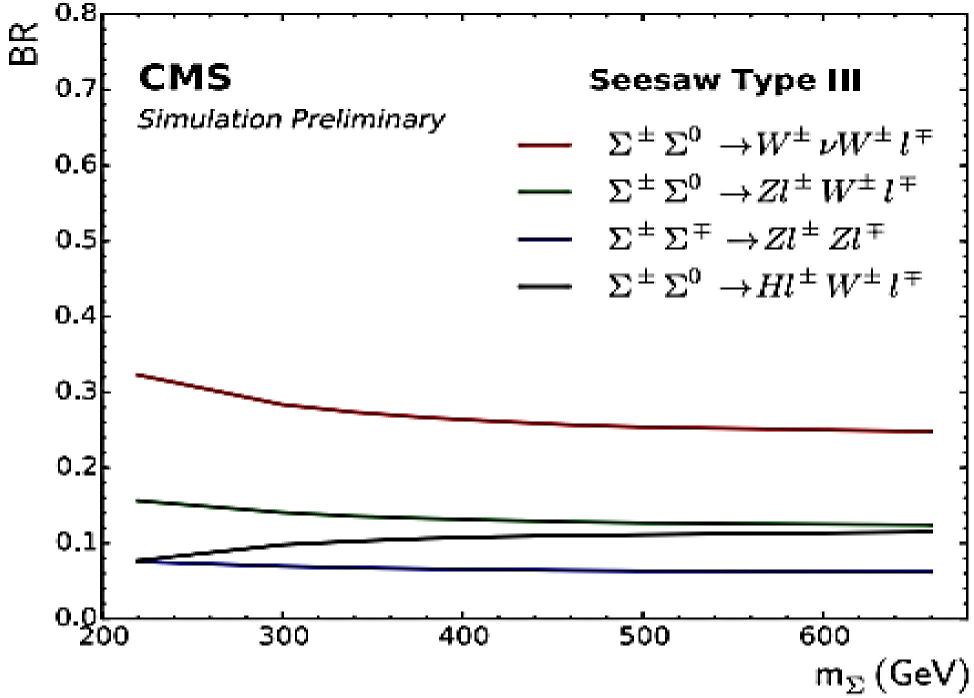


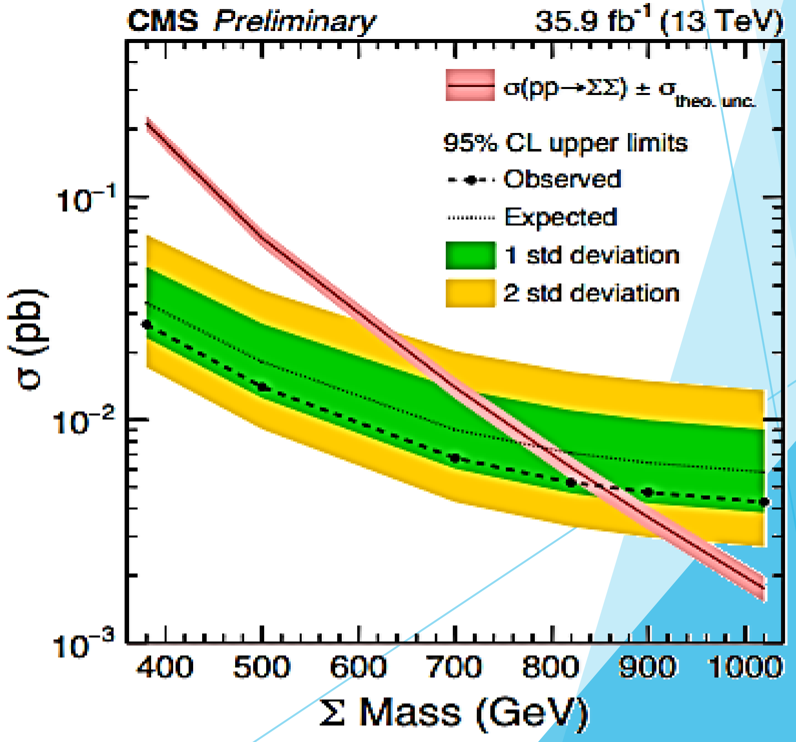
❖ Testing Type-III Seesaw at the LHC

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

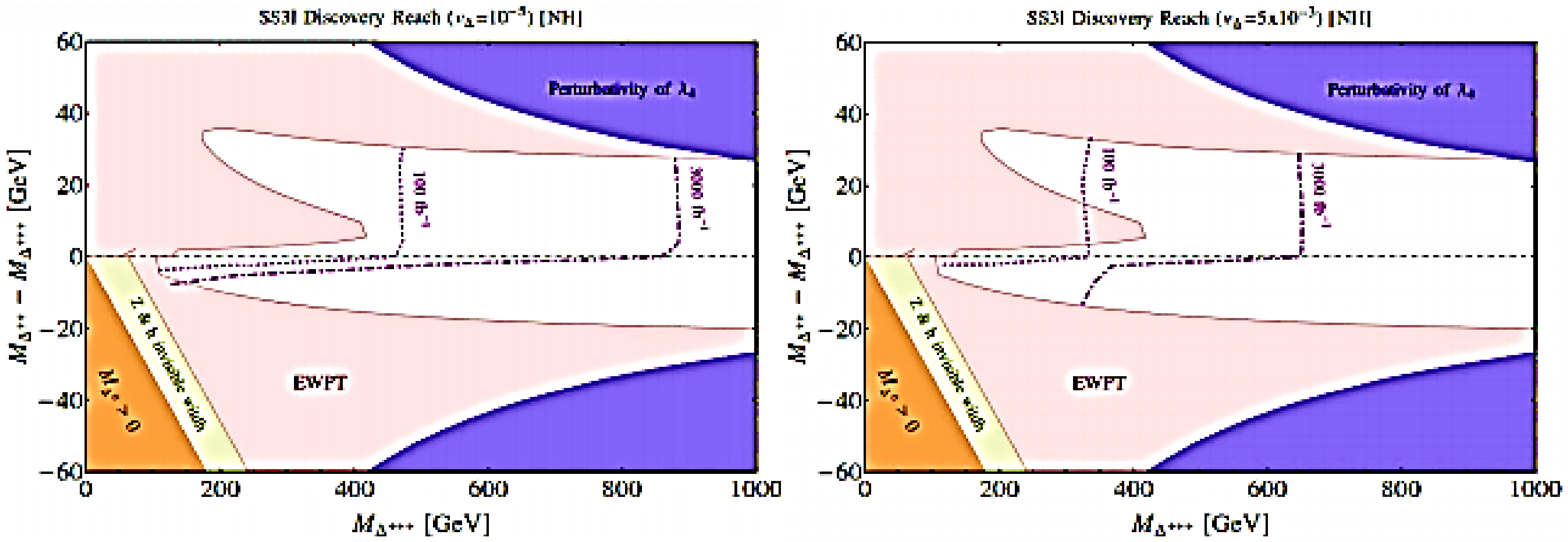








Testing Seesaw with dim=7 operator at the LHC

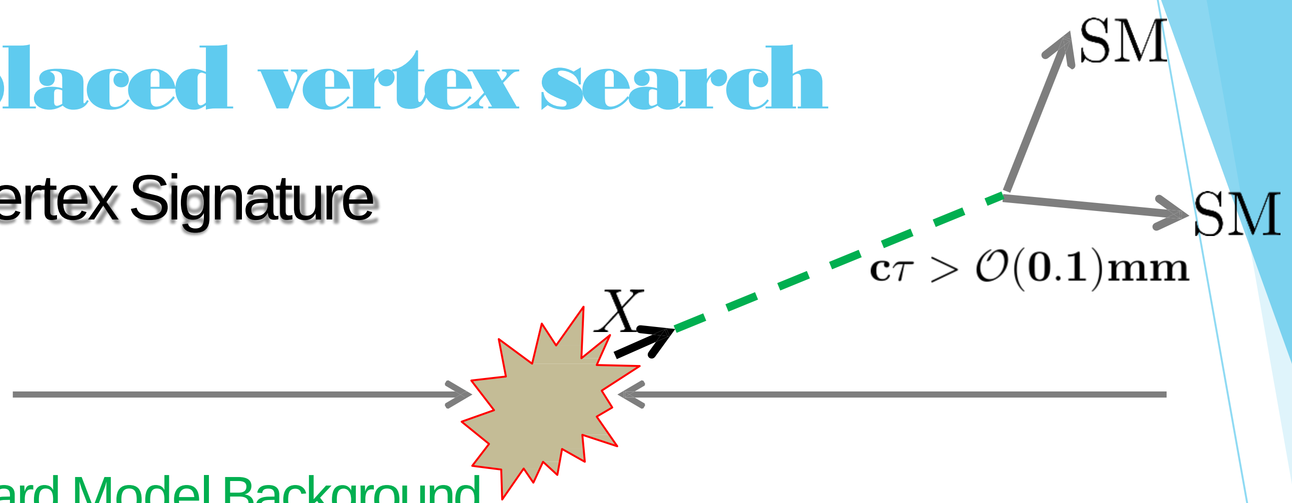


- Discovery potential upto 450 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region Discovery potential upto 500 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region
- Discovery potential upto 350 (700) GeV at 100 (3000) fb^{-1} for *WWW* dominated region
- Covers the whole area available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

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

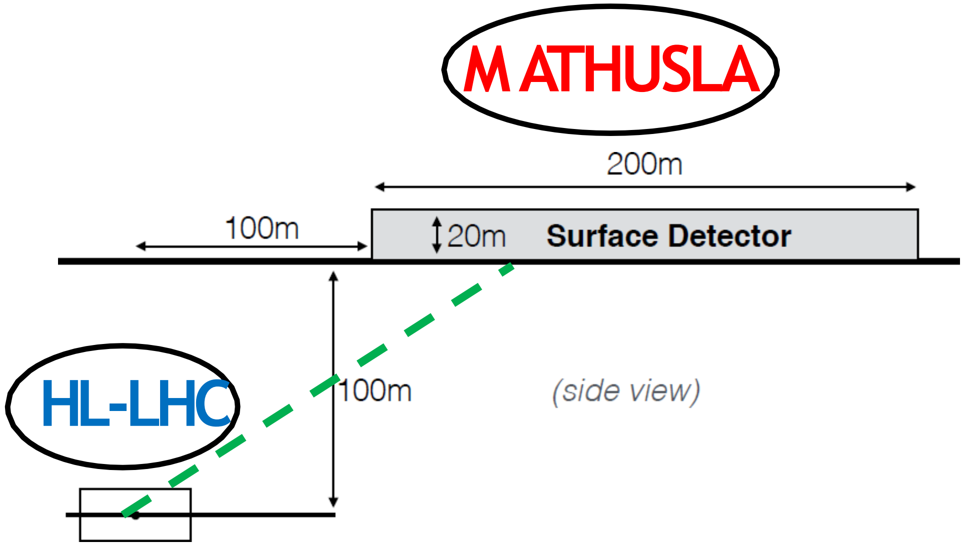
Future displaced vertex search

- Displaced Vertex Signature

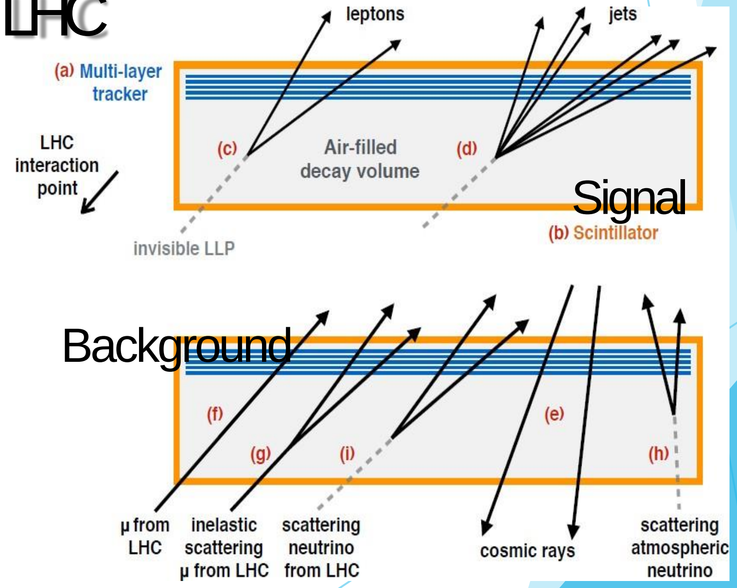


  - ➢ Low Standard Model Background
  - ➢ Ideal for new physics searches

- Future Displaced Vertex Searches at LHC



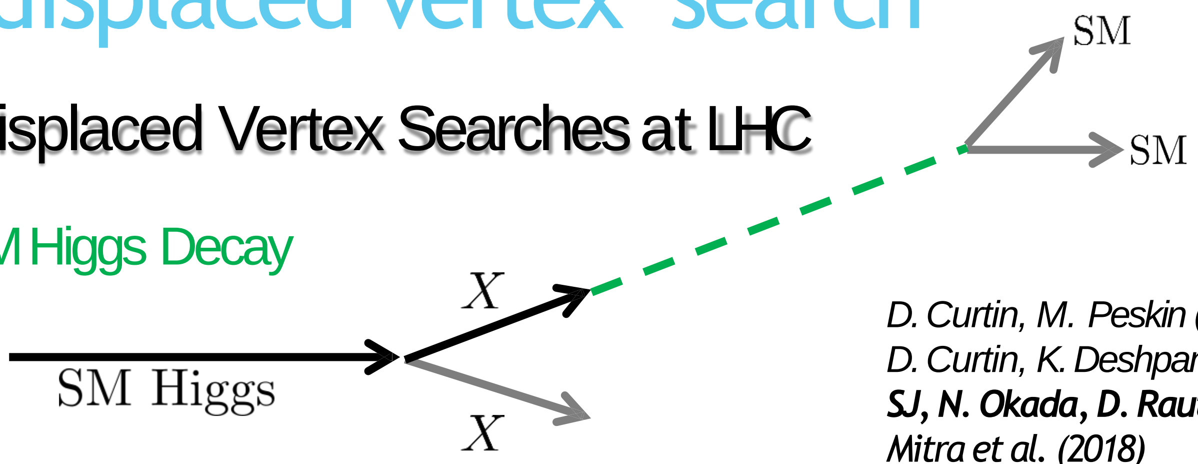
J. Chou, D. Curtin, H. Lubatti
arXiv: 1606.06298



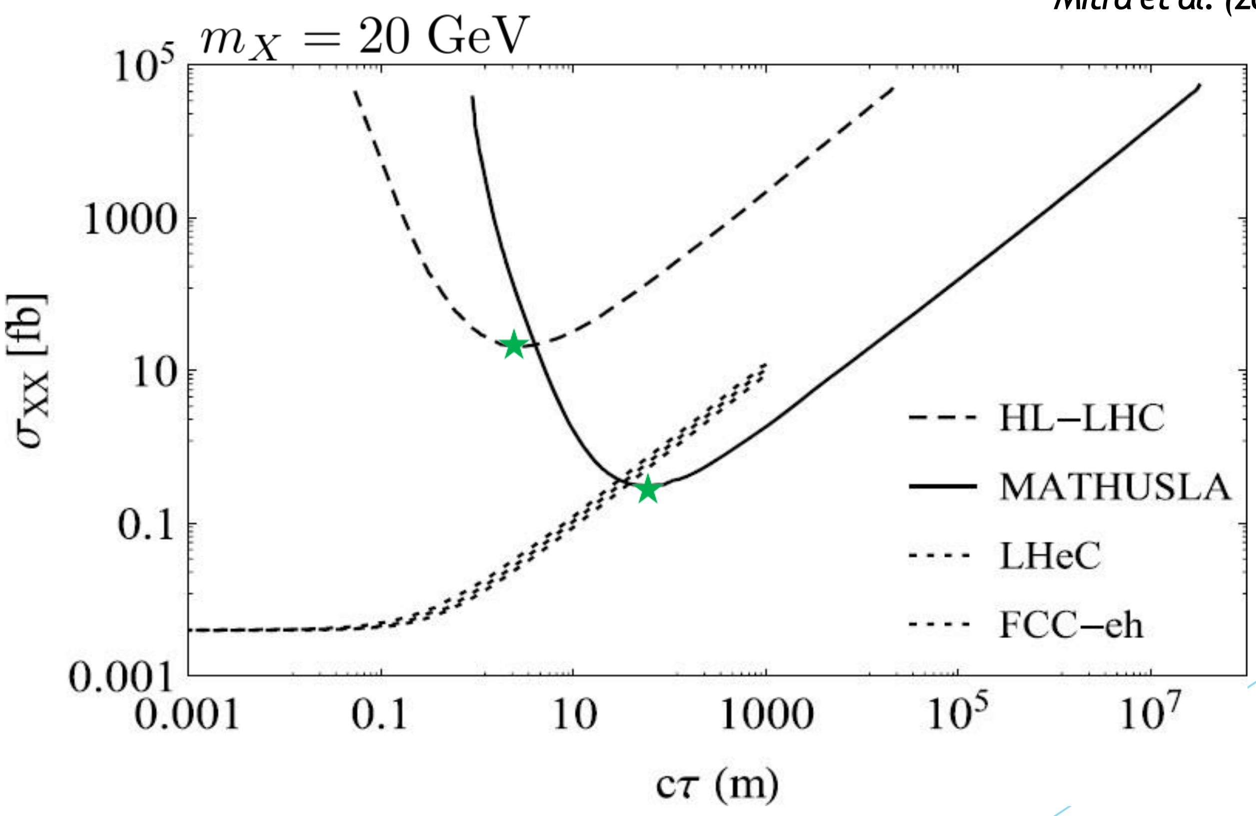
MATHUSLA

Future displaced vertex search

- Future Displaced Vertex Searches at LHC
  - Rare SM Higgs Decay

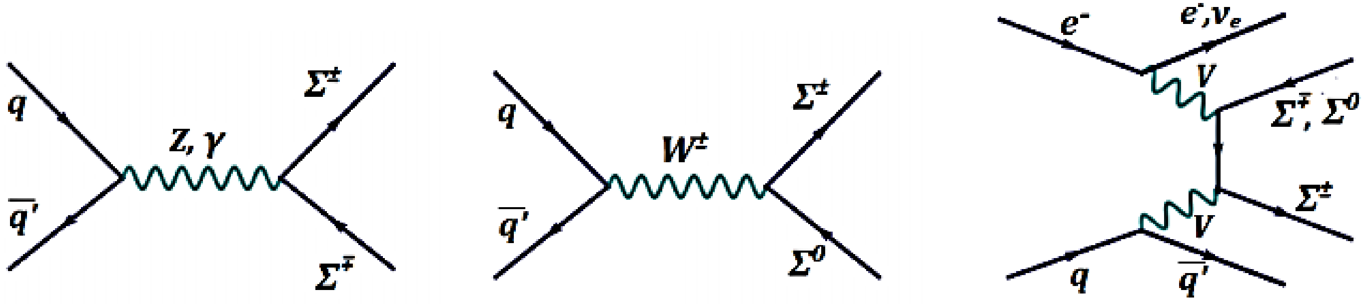


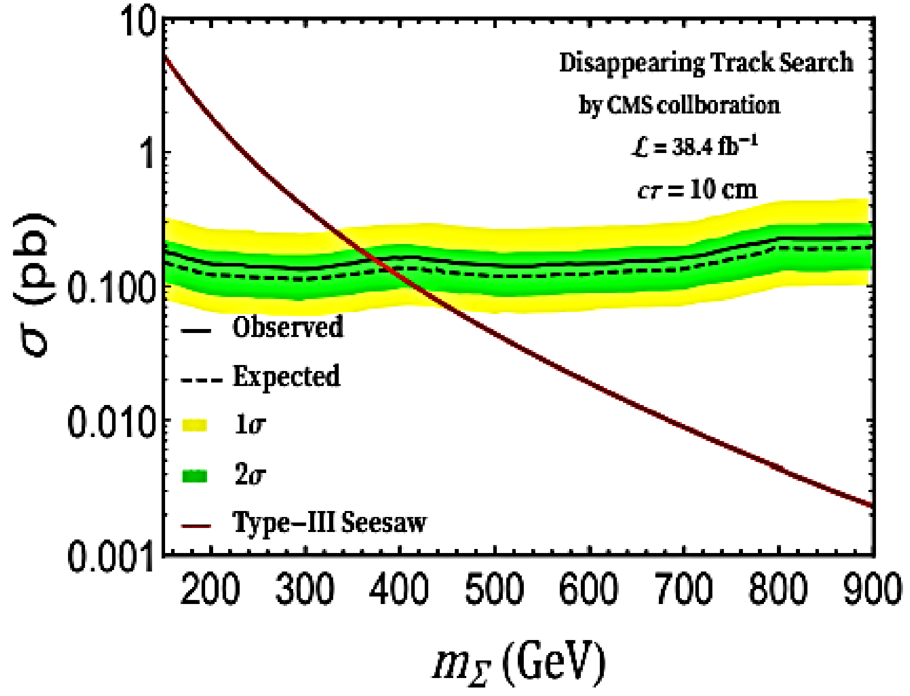
D. Curtin, M. Peskin ***(2017)***
D. Curtin, K. Deshpande, et.al ***(2017)***
SJ, N. Okada, D. Raut (2018)
Mitra et al. (2018)

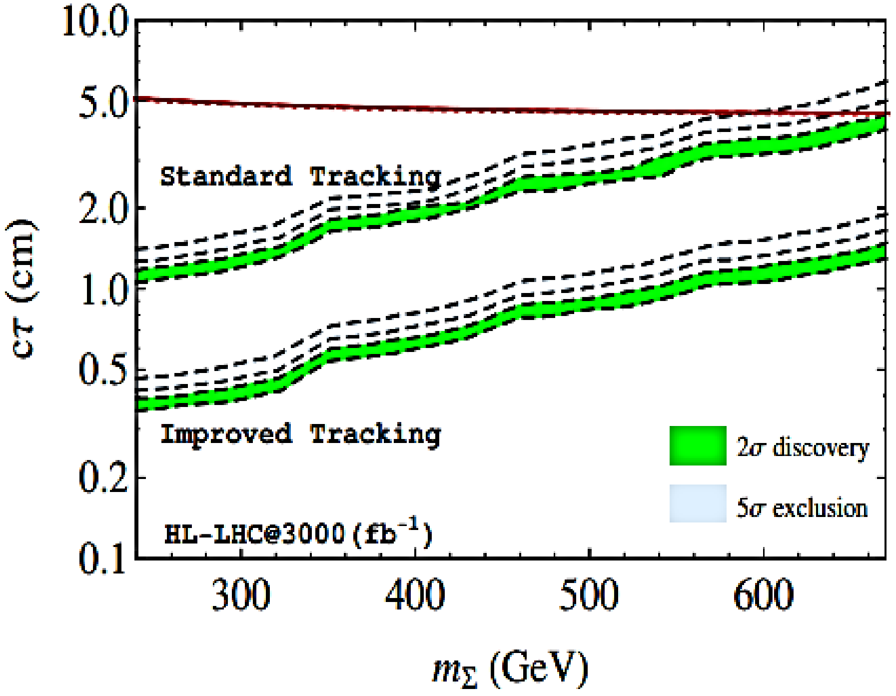


Displaced vertex search for type III seesaw

SJ, SJ,N. Okada, D. Raut (2019)

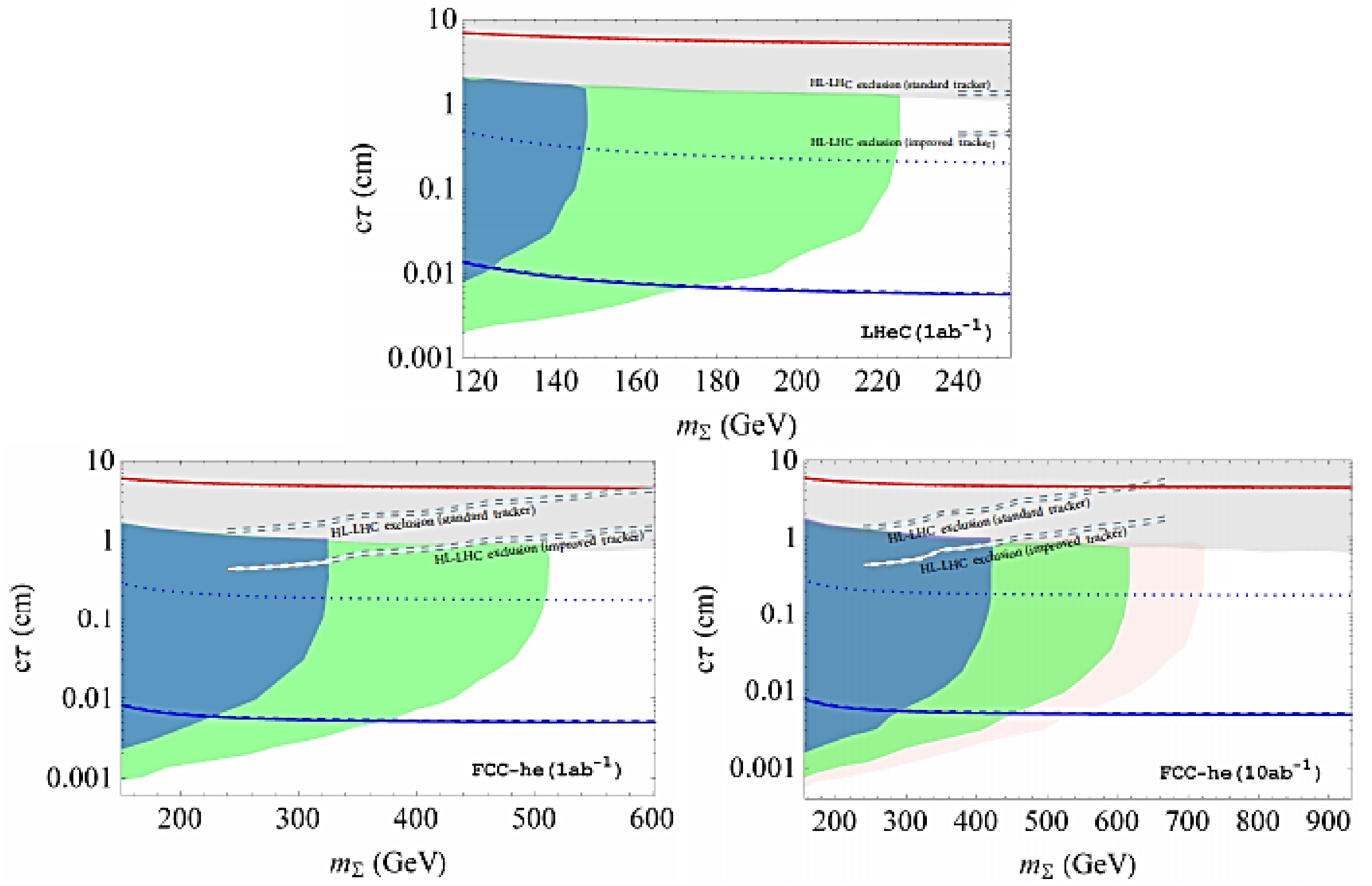






Displaced vertex search for type III seesaw

SJ, N. Okada, D. Raut (2019)



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 neutrin ... echanism at

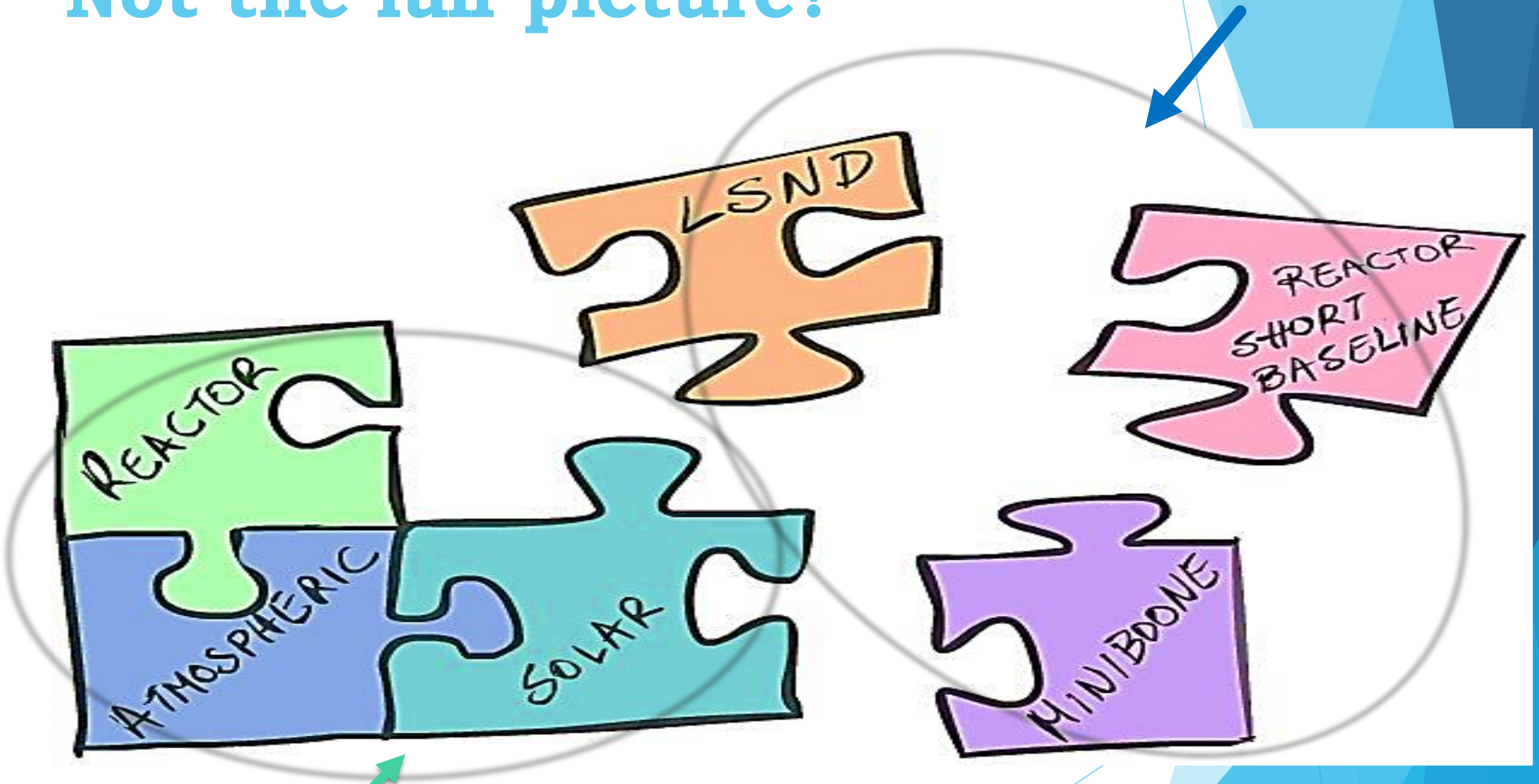
Can neutrino masses come from light physics ?

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

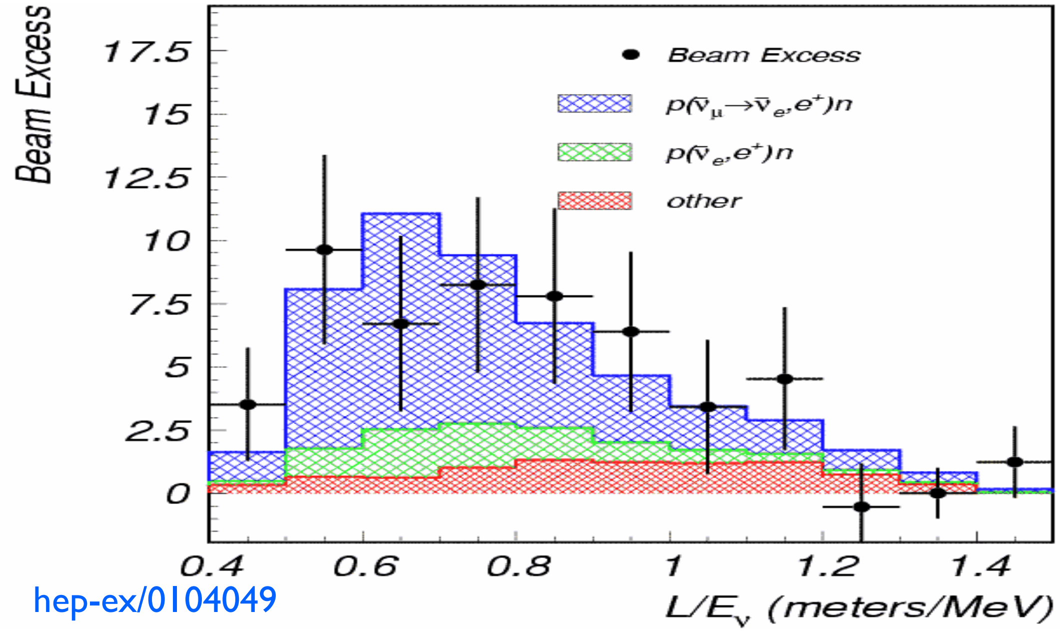
❖ It may show up at low energy neutrino experiments at near future.

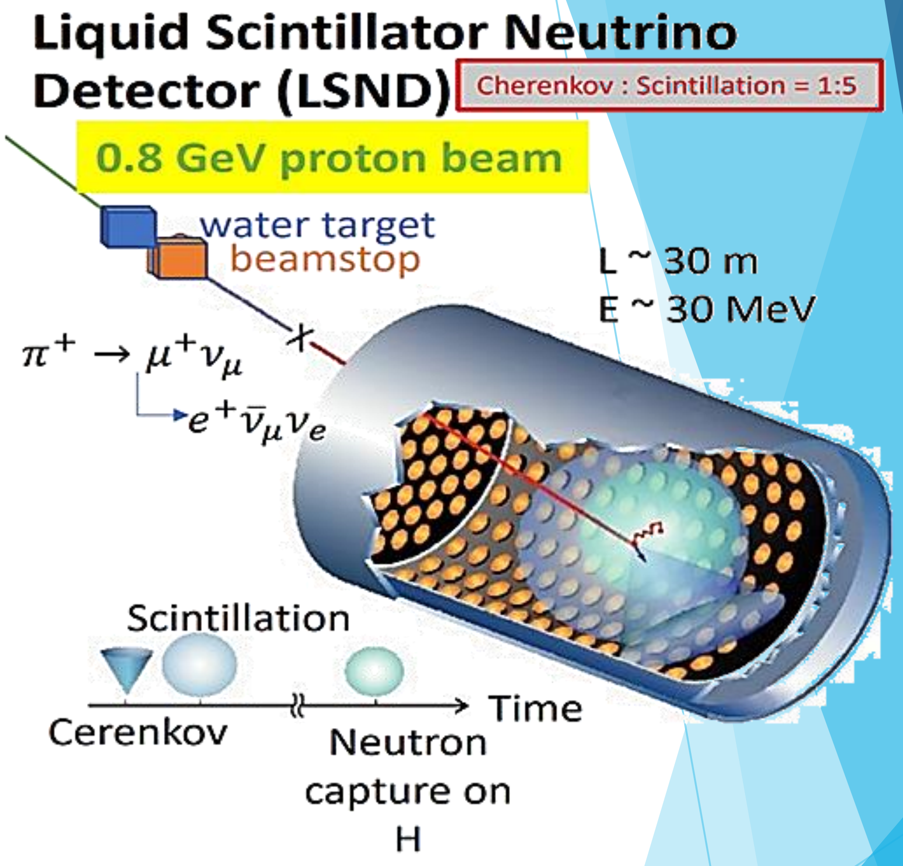
Three-neutrino oscillation: Not the full picture?

Short Baseline Anomalies

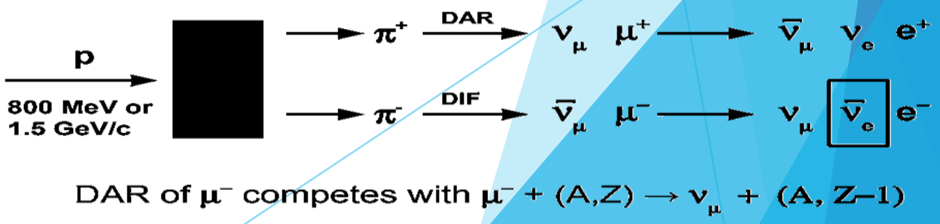


Long and Medium Baseline





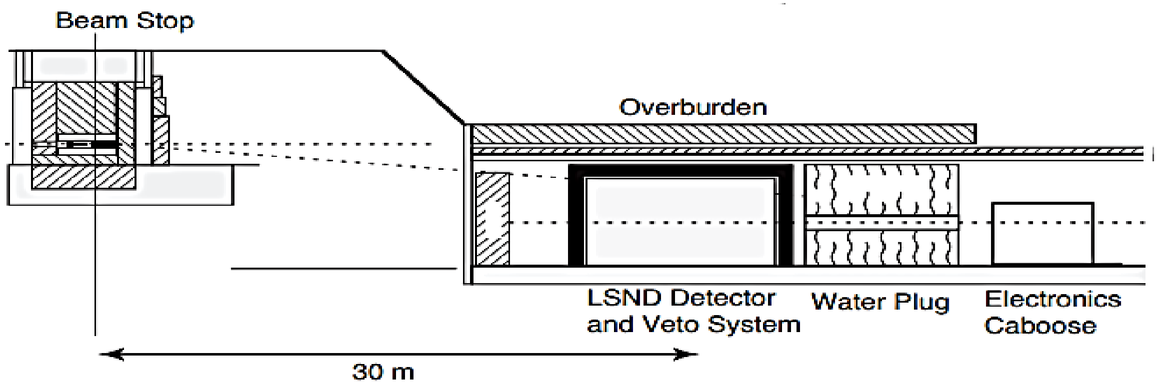
LSND neutrino source



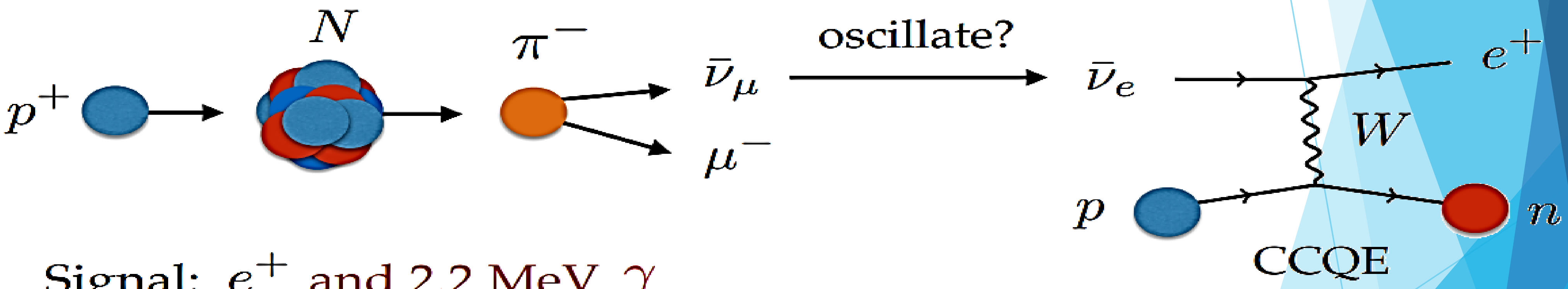
LSND detected more $\bar{\nu}_e$ than expected :

87.9 ± 22.4 ± 6.0 events

3.8 σ excess



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

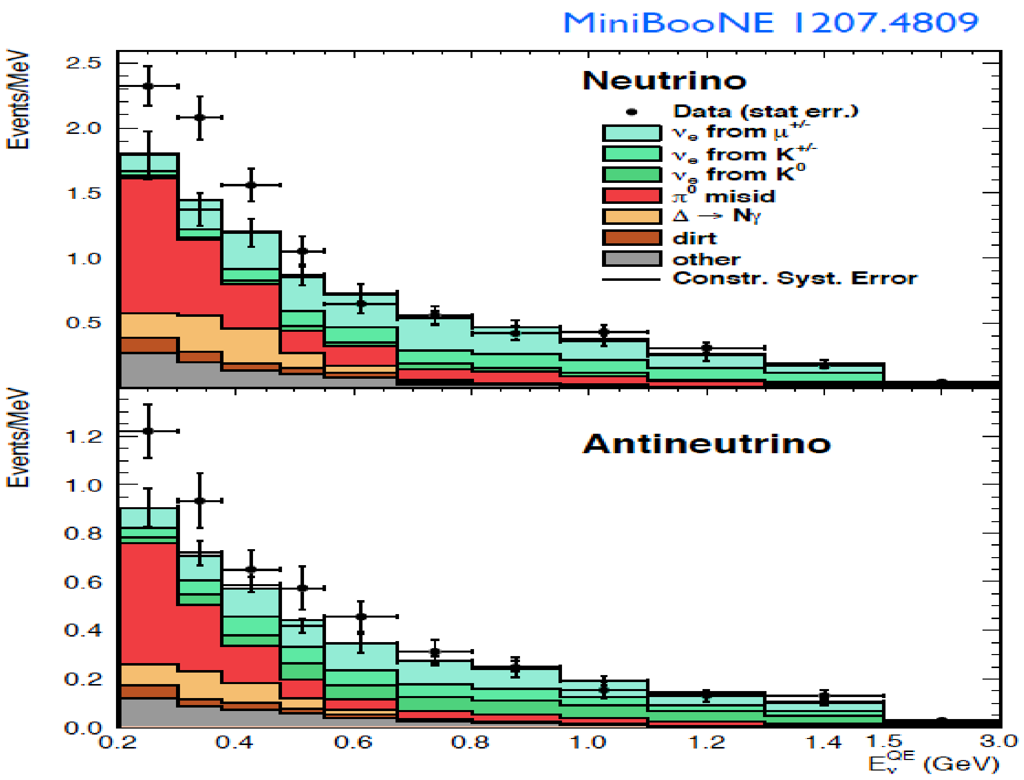


Signal: e^+ and 2.2 MeV γ
Scatter + neutron absorption

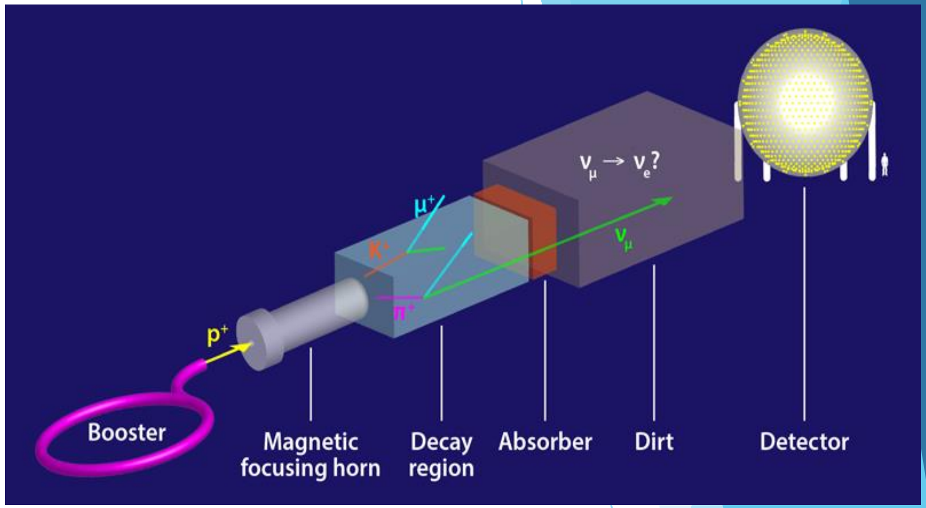
Observed 90 events
Expectation of 0 events
3.8σ significance

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

LSND Collaboration hep-ex/0104049

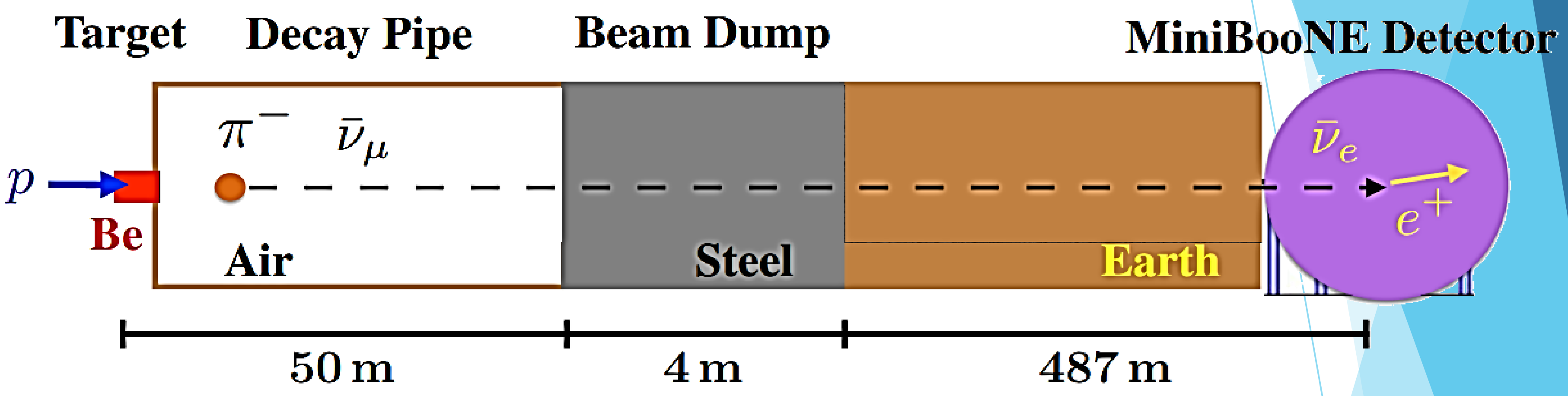


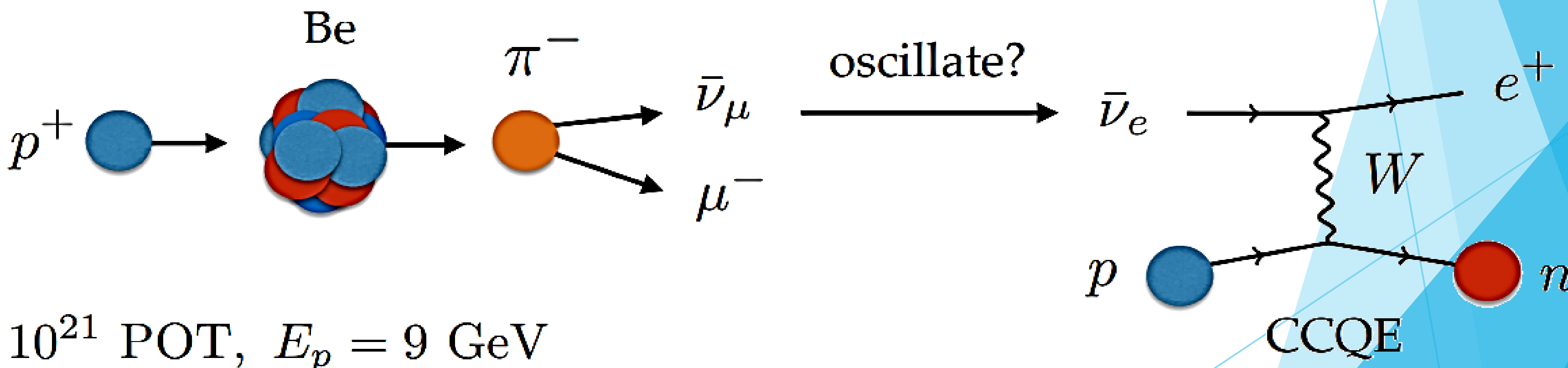
•Neutrino and anti neutrino modes see excesses of ν_e and $\overline{\nu}_e$ (Combined is also 3.8 σ excess)



- 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

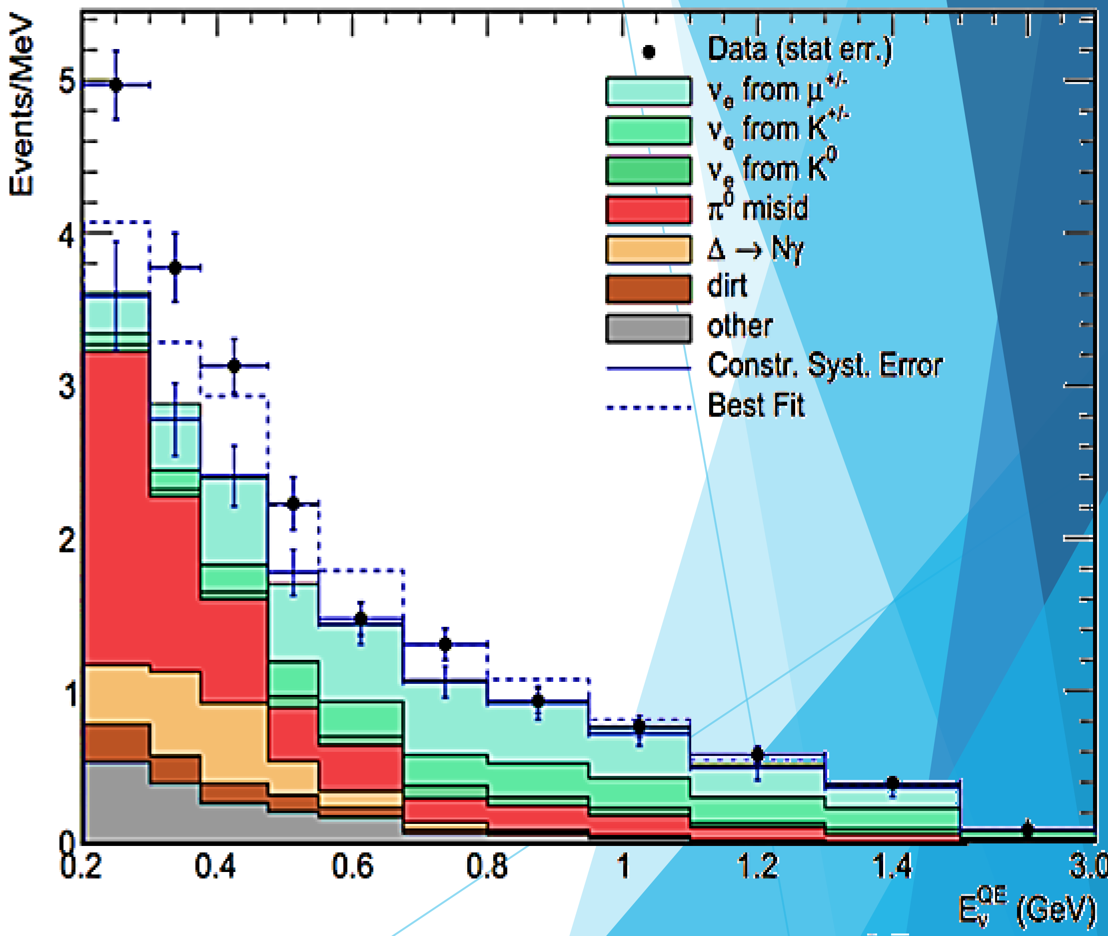
MiniBooNE Collaboration 1805.12028

MiniBooNE's Low Energy Excess

- 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.

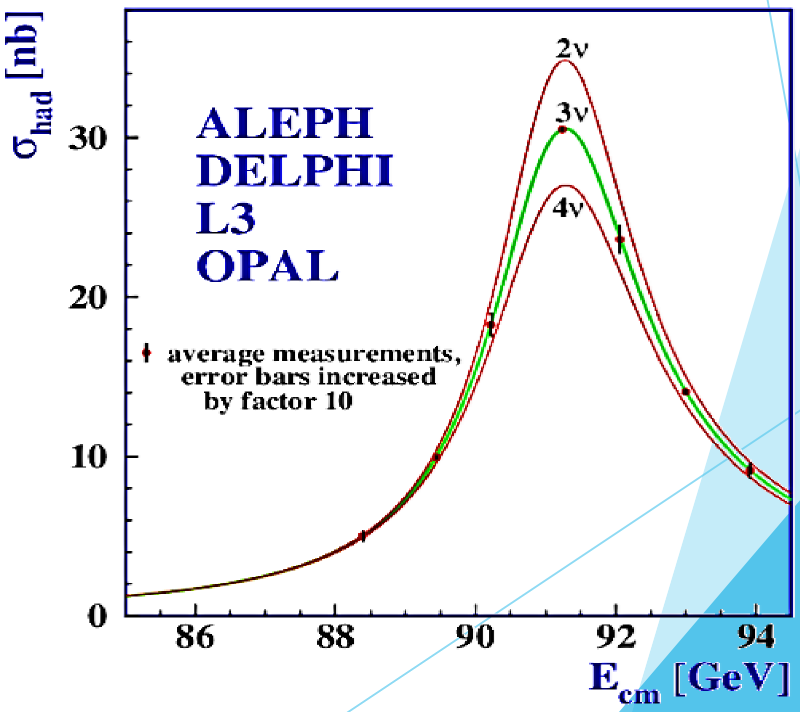
What sort of new physics can explain these anomalies?

❖ *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

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

APPearance

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

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$$\nu_\mu \to \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu4}|^2$$

@LSND, Karmen, MiniBoone, Opera

DISappearance

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

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

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

@Reactors and **Gallium**

$$\nu_\mu \to \nu_\mu : |U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

@atmospherics and **accelerators**

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

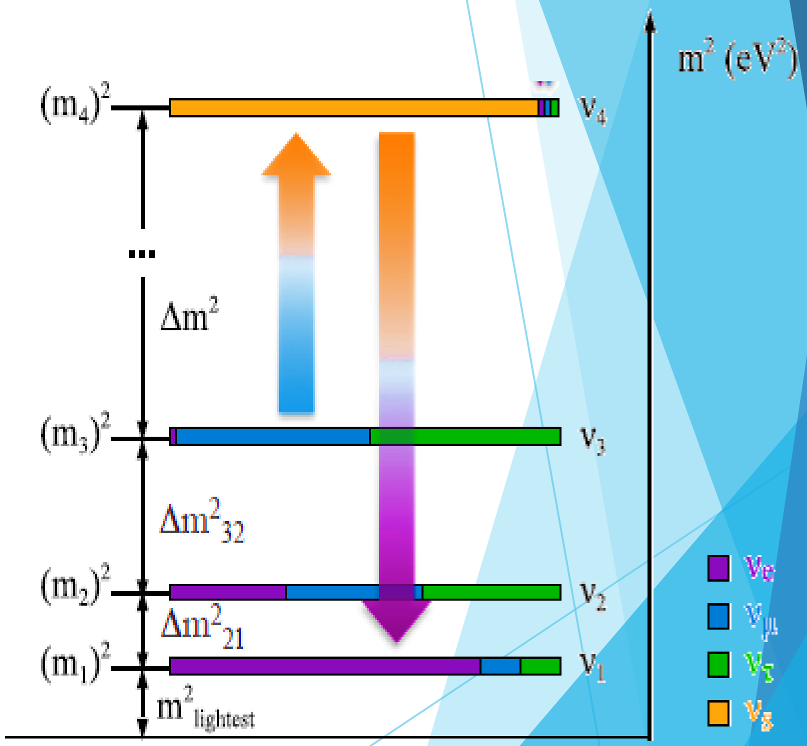
$$P_{\alpha\alpha}^{\text{SBL}} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

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

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

Leads to ν_e disappearance

Leads to ν_μ disappearance



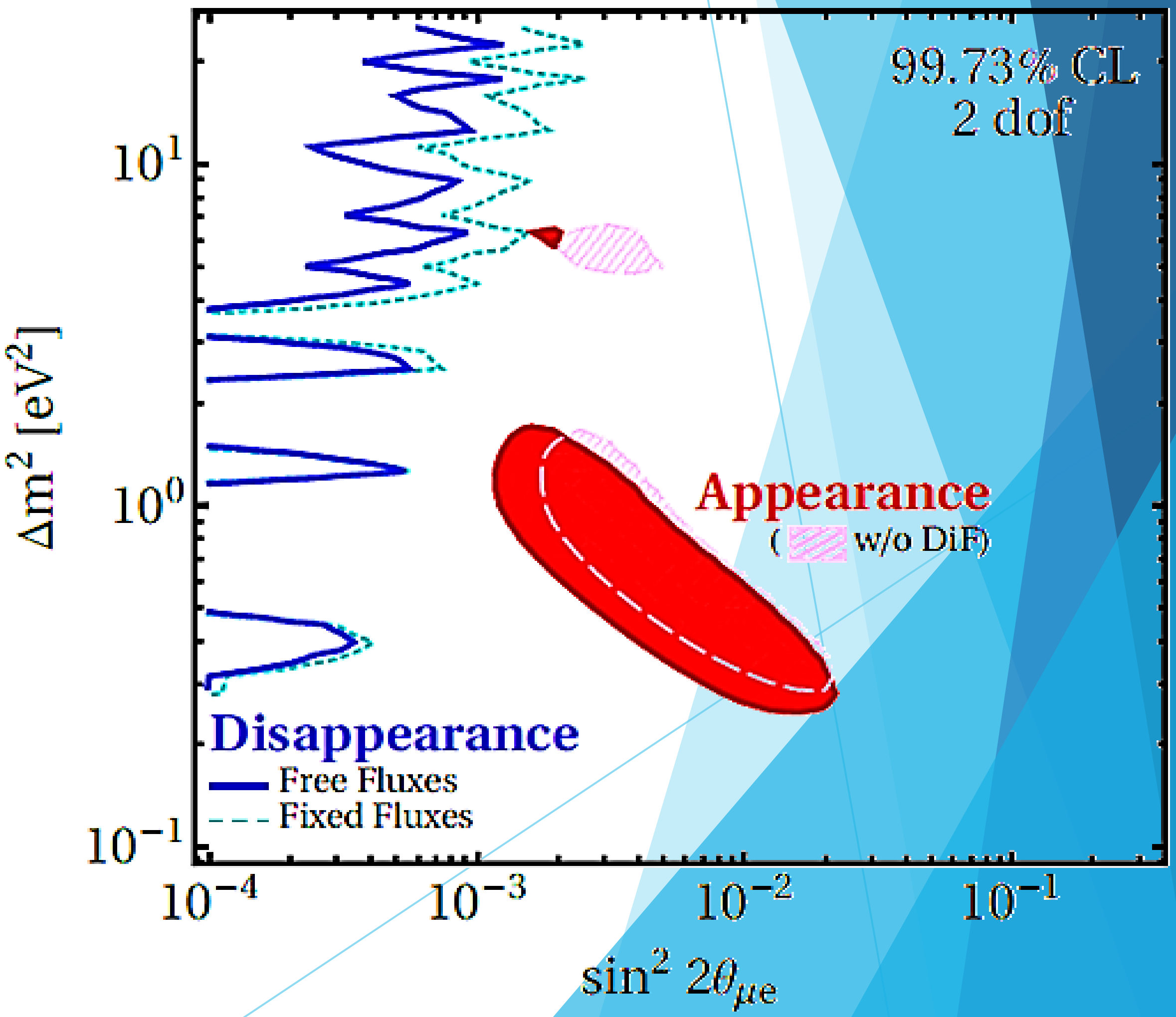
❖ *What about eV Sterile Neutrino Interpretation ???*

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

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

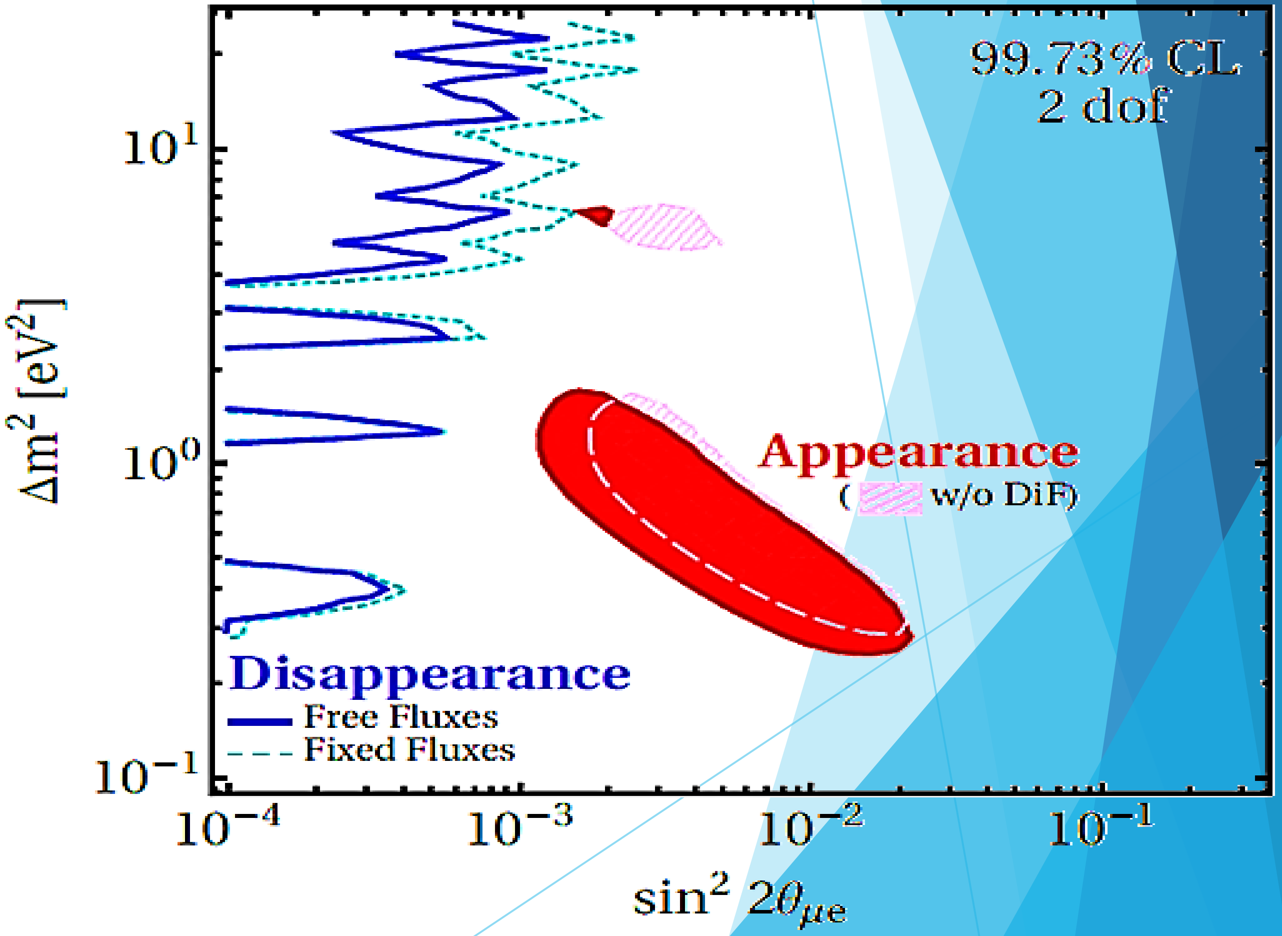
Mona Dentler et al. JHEP 1808 (2018) 010



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

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\,U_{\mu4}|^2$$

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

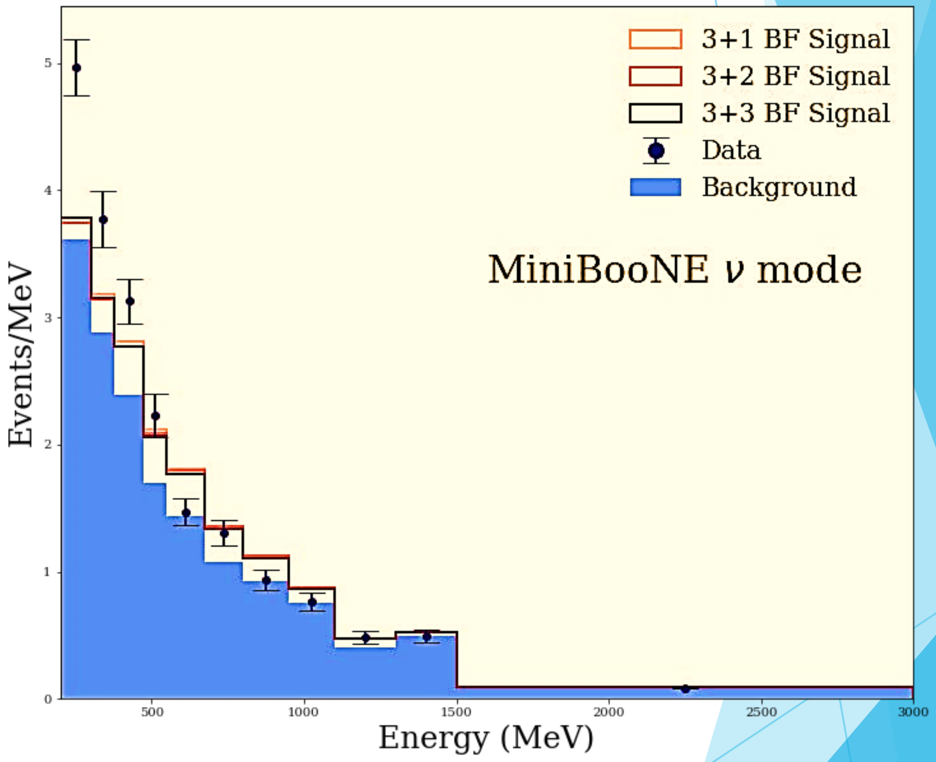


Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860

➢ 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

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

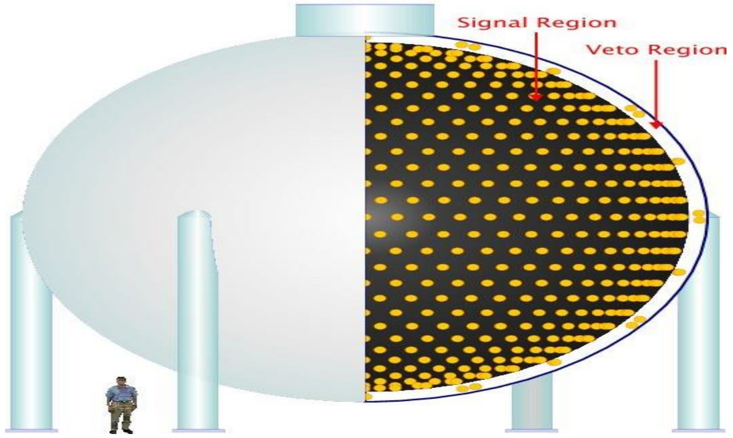
Excluded by BBN / CMB $N_{\rm eff} = 2.99 \pm 0.17$ Planck 1807.06209

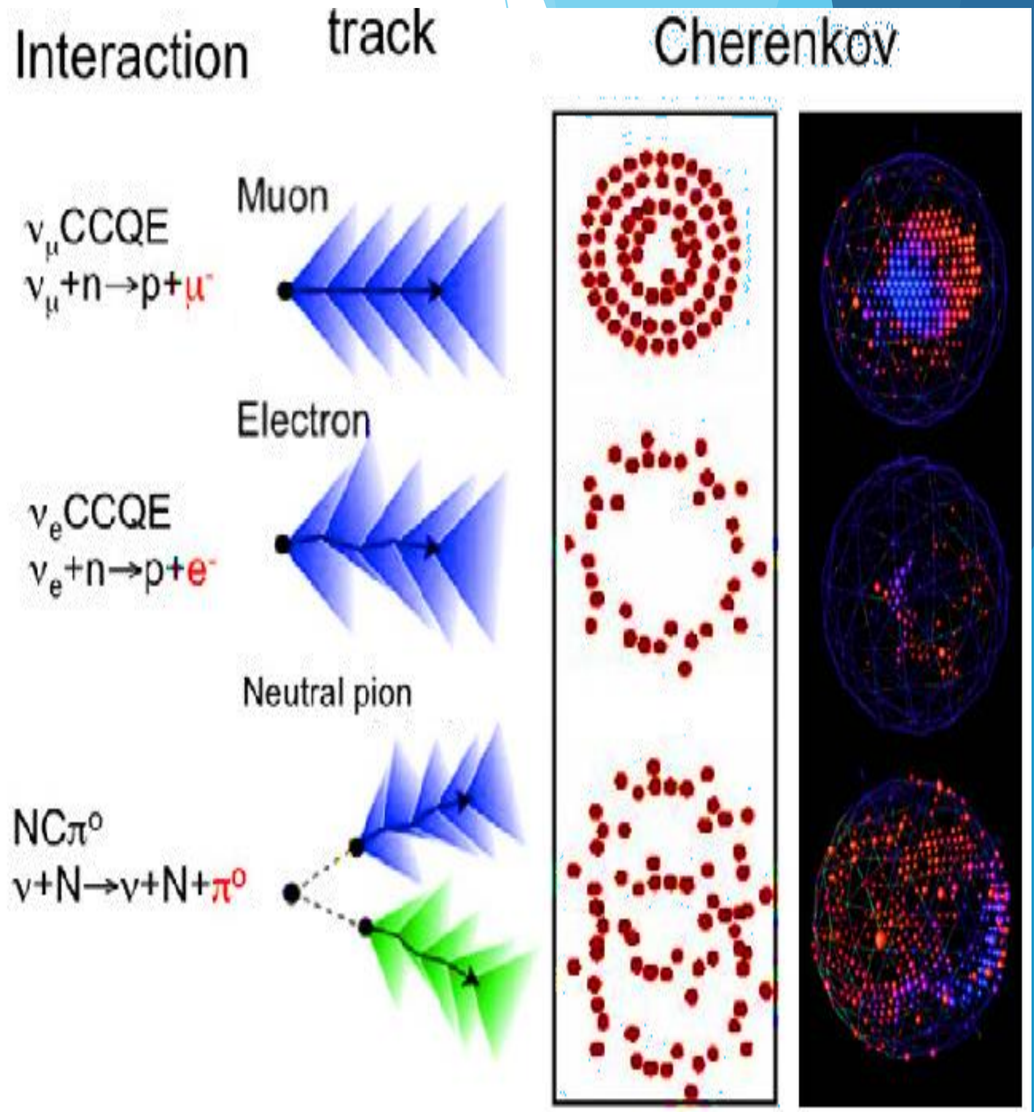
Unless max temperature satisfies $T_{\rm max} \lesssim 15\ {\rm MeV}\left(\frac{10^{-3}}{\sin^2 2\theta_{\mu e}}\right)^{1/3}$

❑ *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*

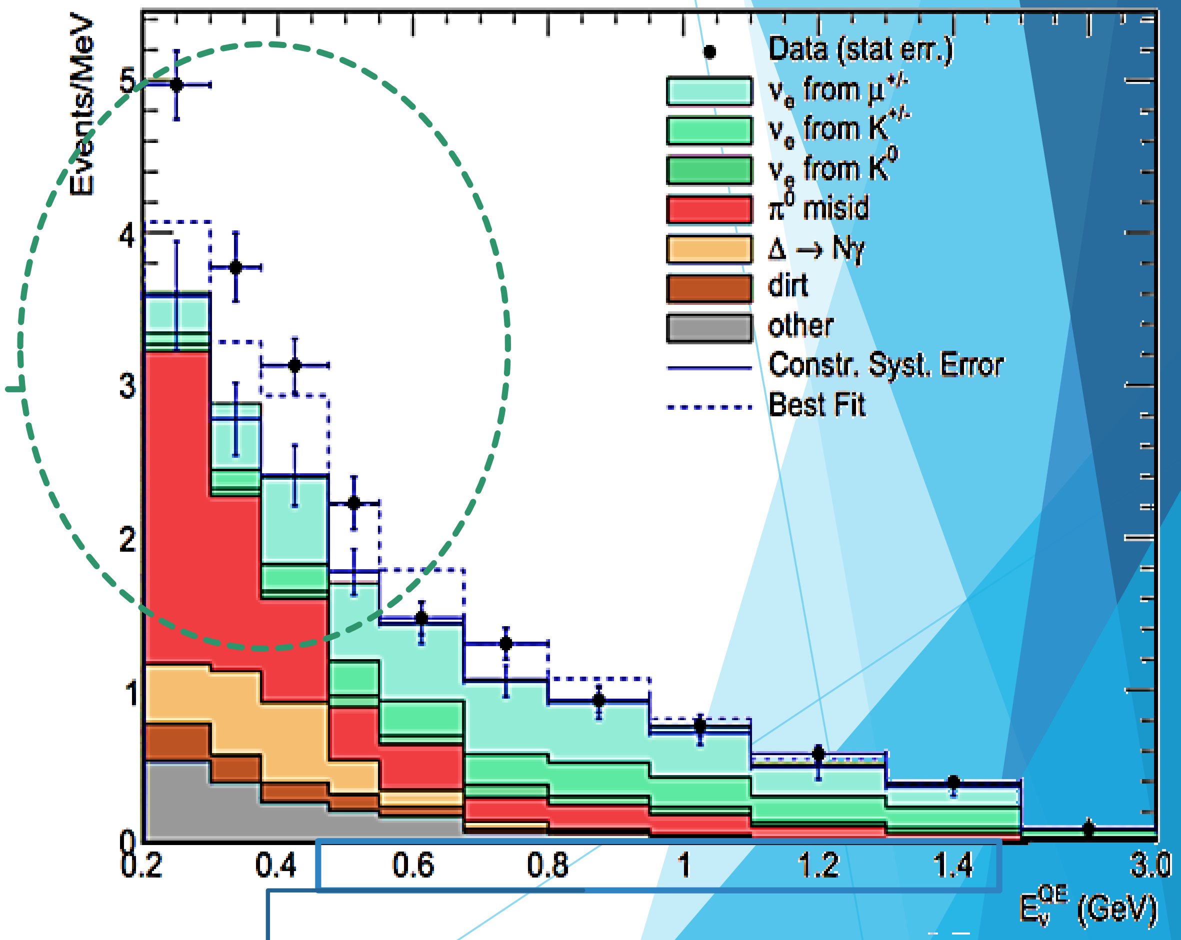




- MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles.
- Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.
- Excess is correlated with beam in power, angle and timing. It is present in positive and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

MiniBooNE's Low Energy Excess

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



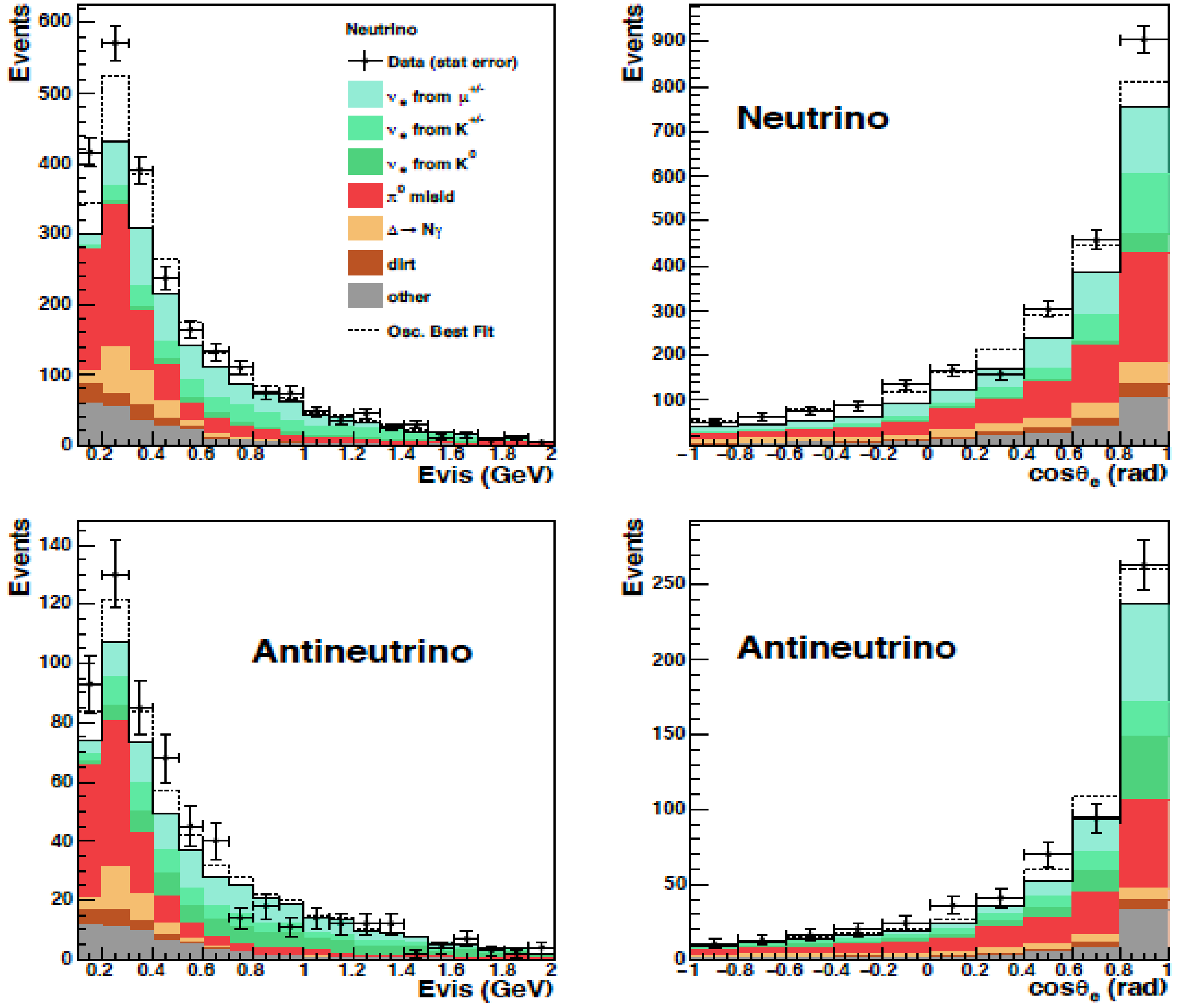
MiniBooNE observed a large excess in the much lower energy region

This is the region that the LSND oscillation should have appeared

❖ *Explanation of MiniBooNE's low energy excess*

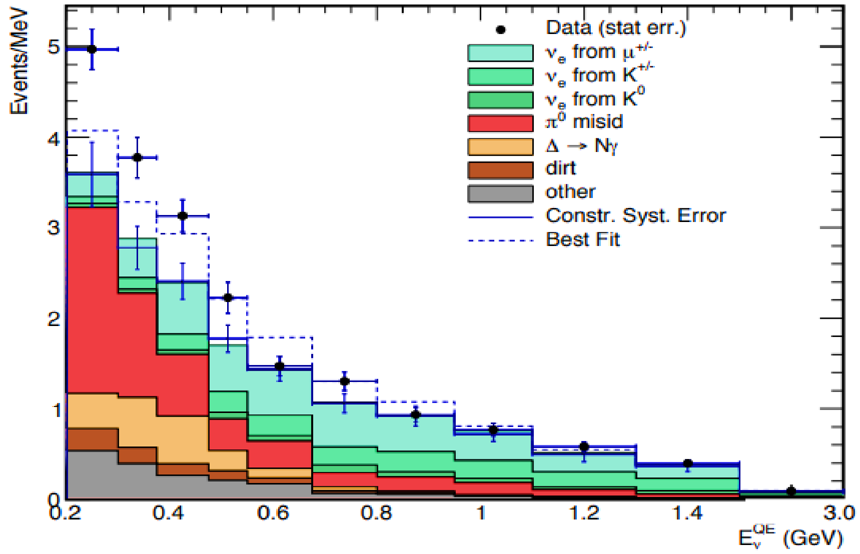
- Angular spectrum is forward, but not that much
- Scattering on electrons would typically lead to $\cos\theta > 0.99$
- Decays of invisible light (<10 MeV) particles produced in the beam would also lead to forward spectrum
- The Cherenkov and scintillation light emitted by charged particles traversing the detector are used for particle identification and neutrino energy reconstruction, assuming the kinematics of CCQE scattering.

arxiv : 1805.12028 [hep-Ex]

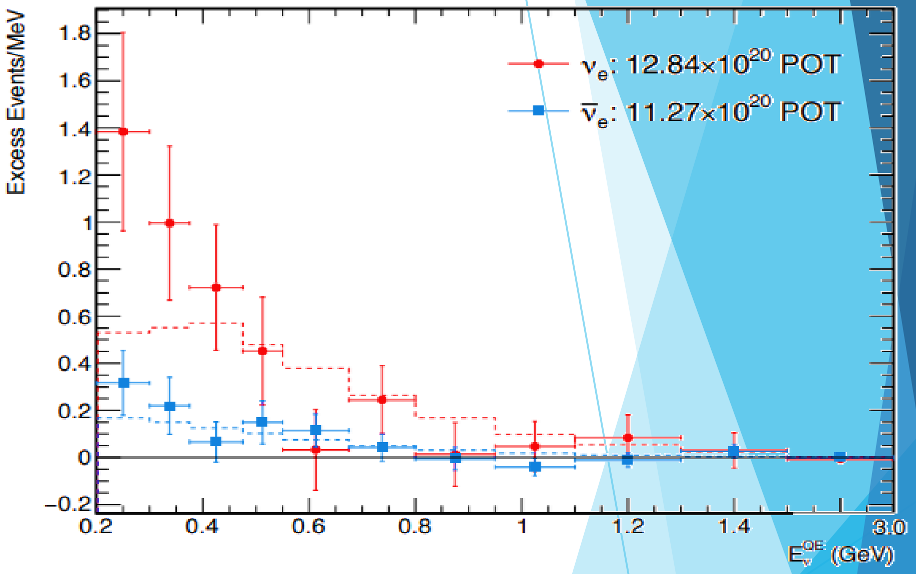


MiniBooNE's Low Energy Excess

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

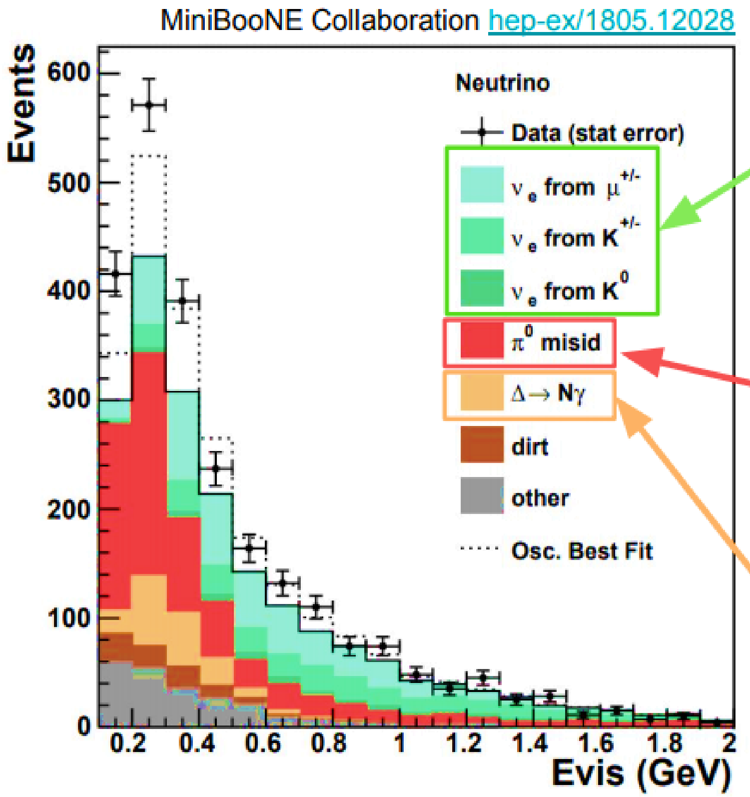
Observed ~ 400 events, PMNS predicts 0

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.

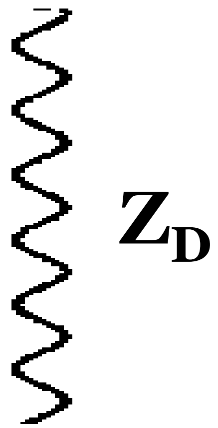
π^0 misidentification? In which the second shower was missed or incorrectly reconstructed. MiniBooNE measured the largest sample of NC π^0 events ever collected and used this is constrain the exact rate of π^0's for the CCQE analysis.

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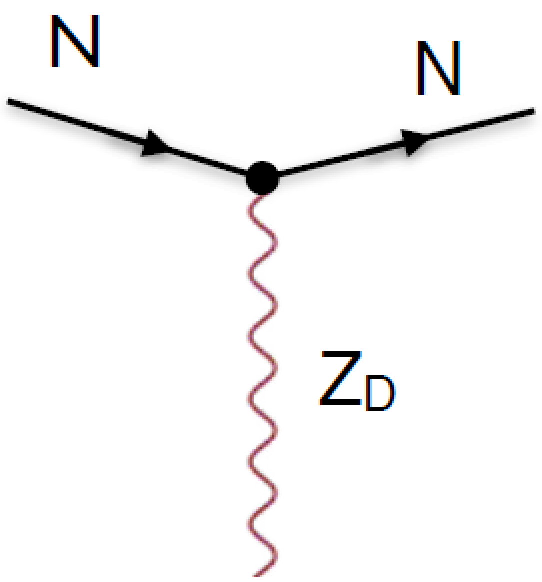
- Right-handed neutrinos are part of the dark sector and are subject to new interaction



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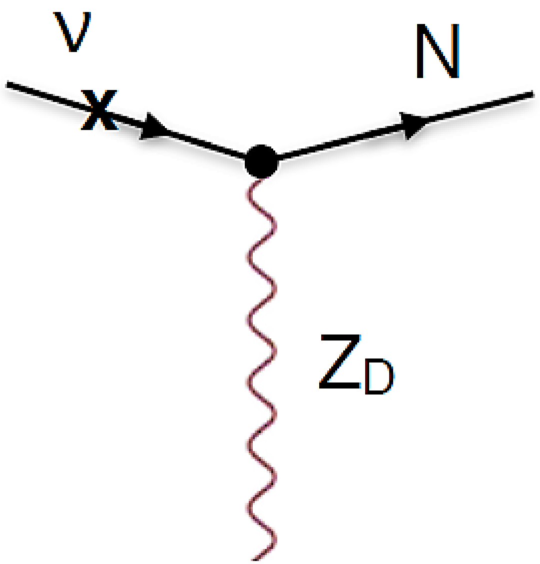
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector



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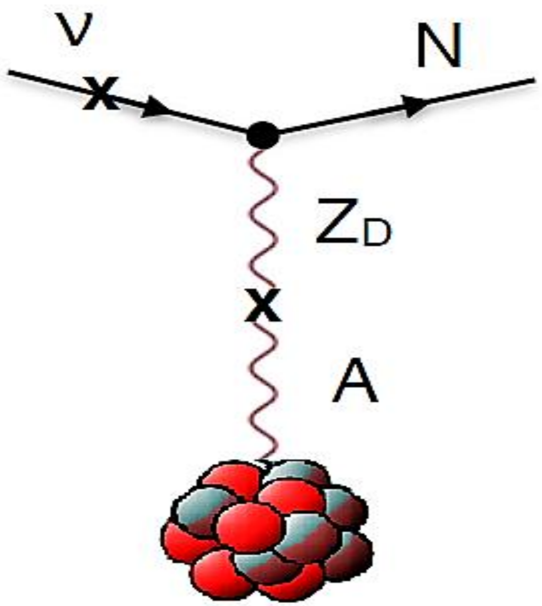

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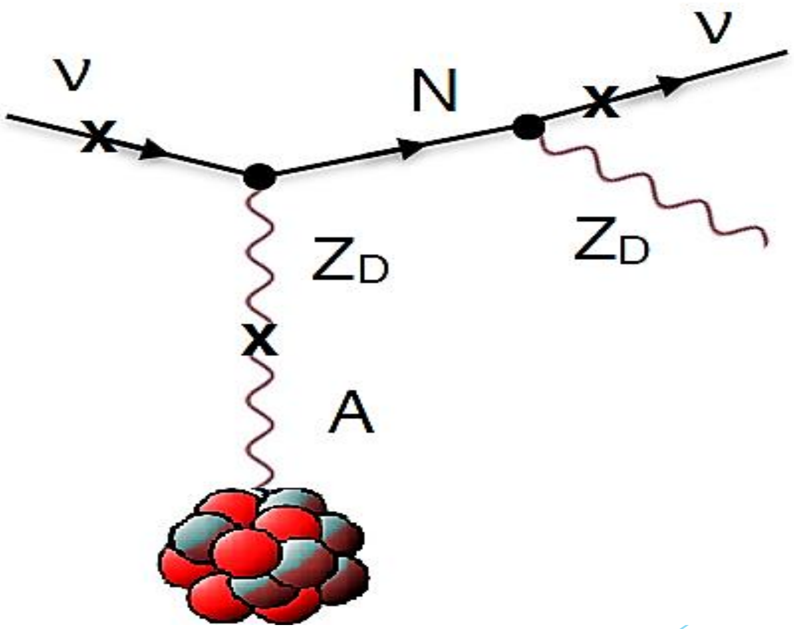

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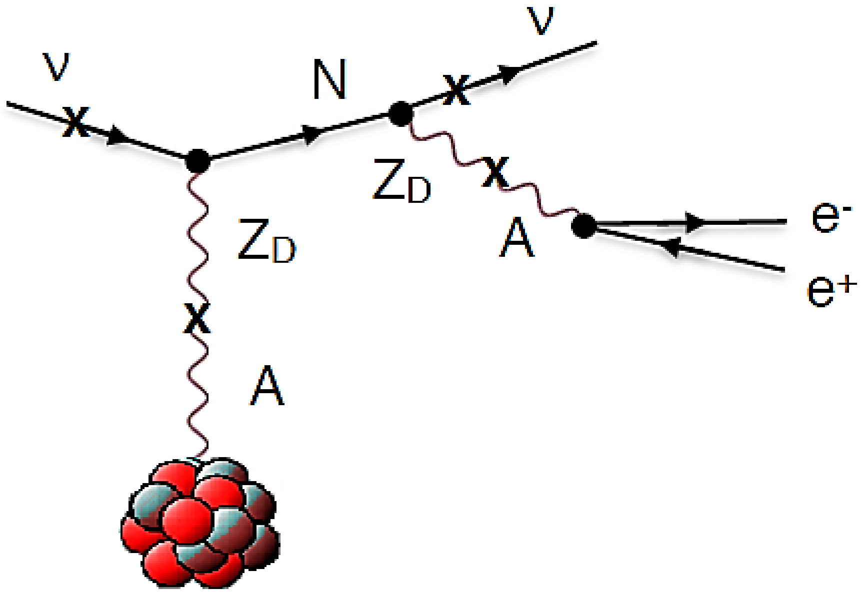

Bertuzzo et al 1807.09877
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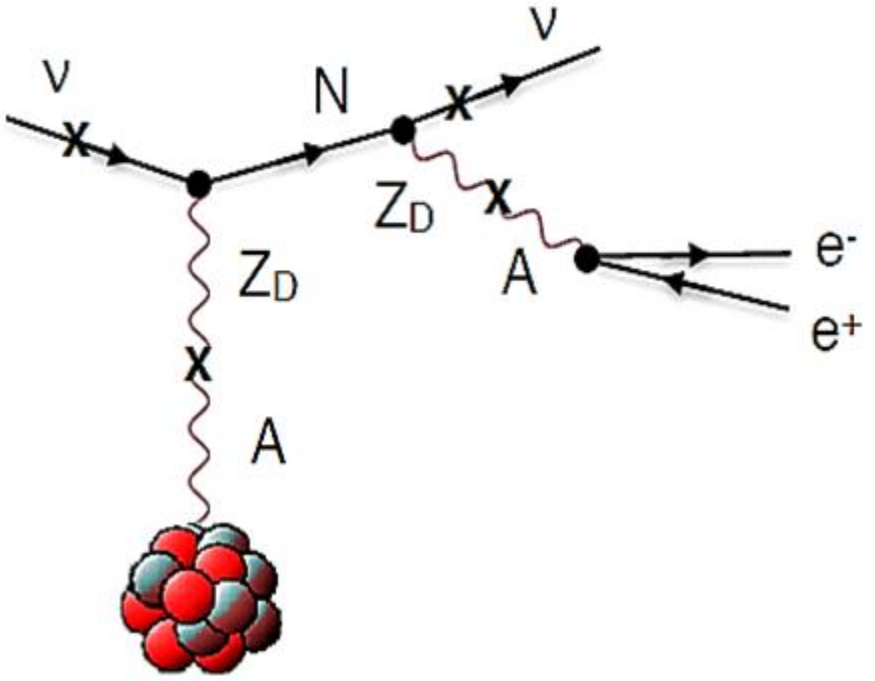

- Relevant part of the Lagrangian :

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

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

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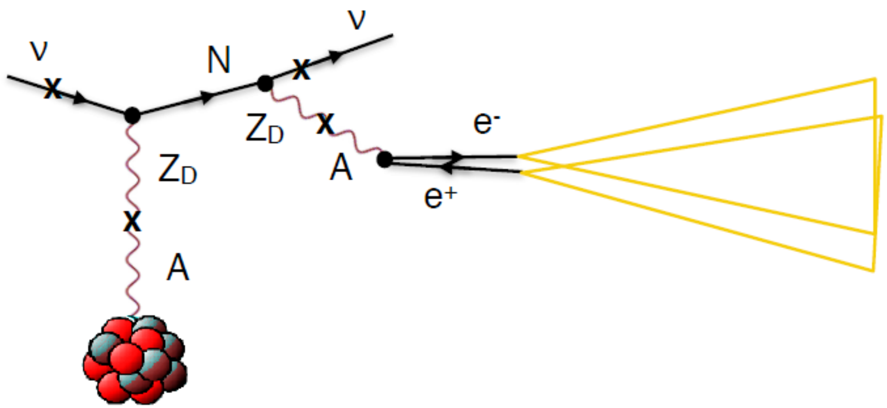
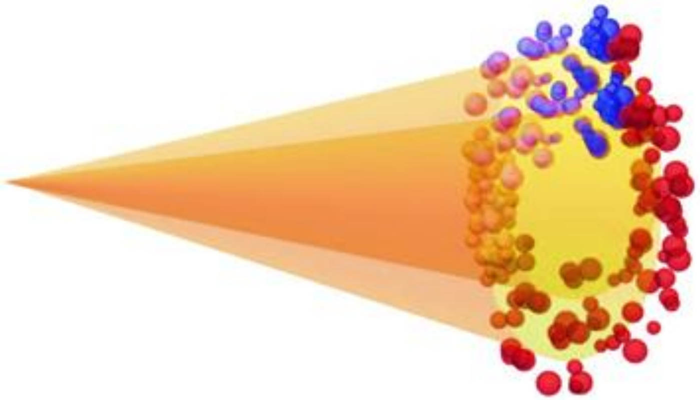
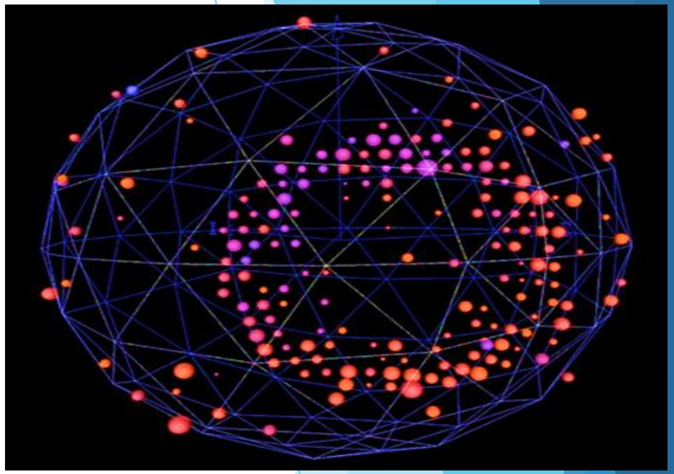
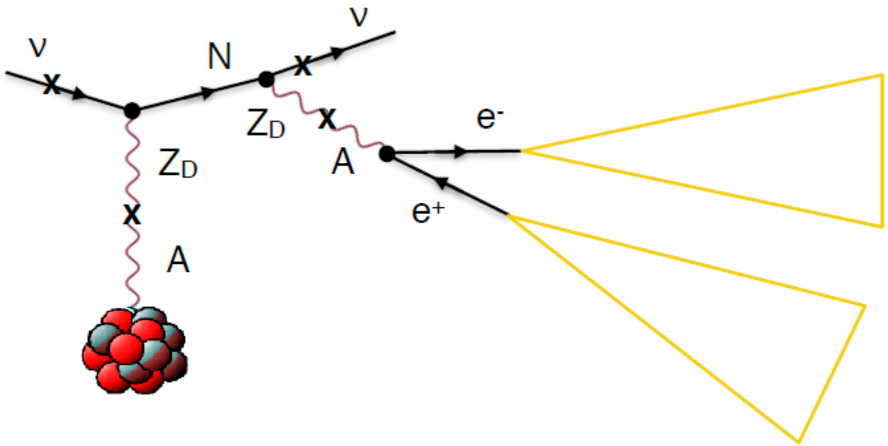
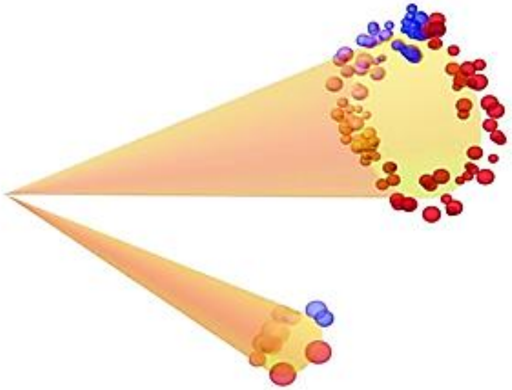
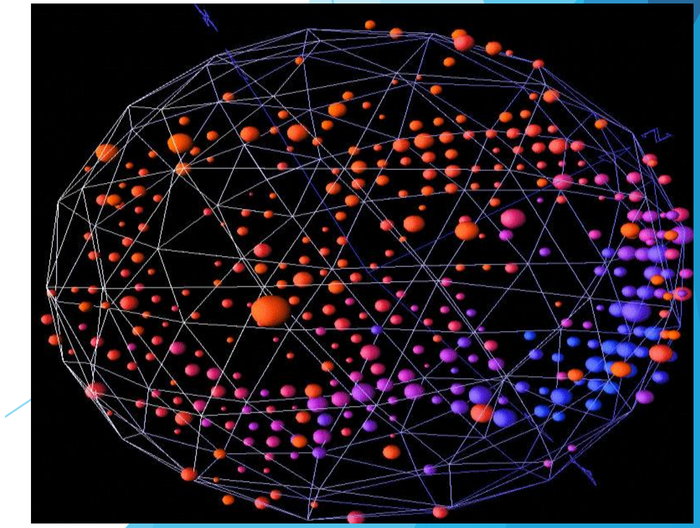






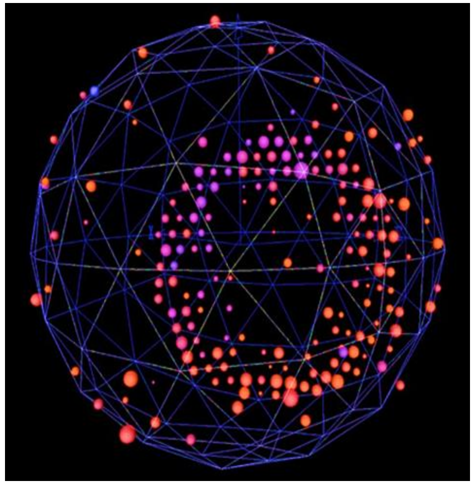


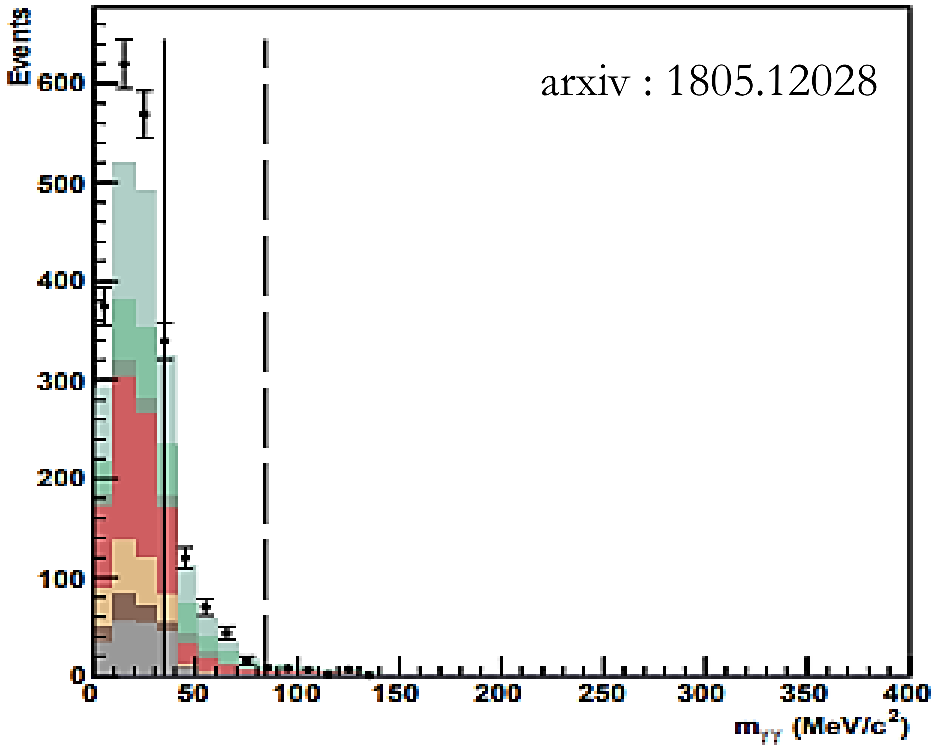


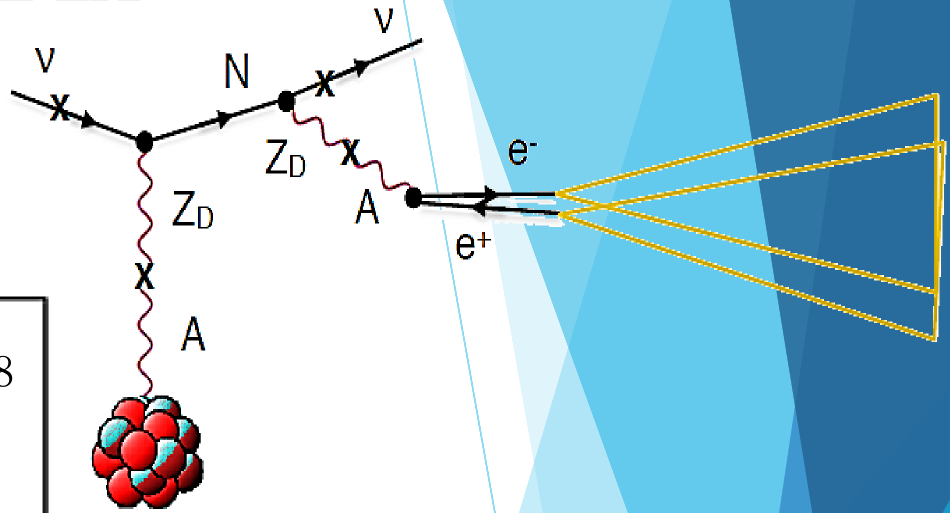


❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



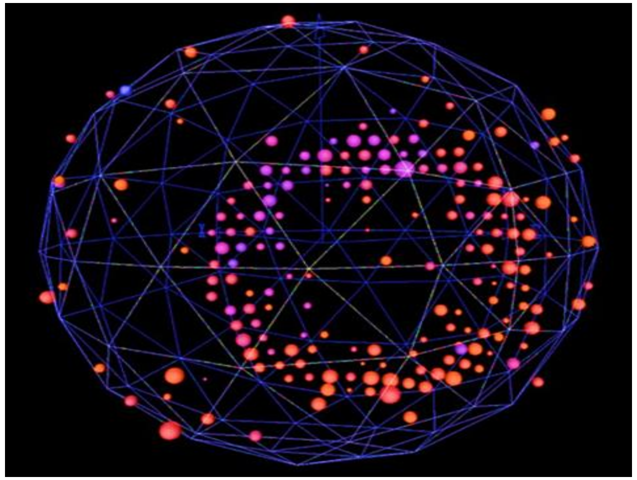


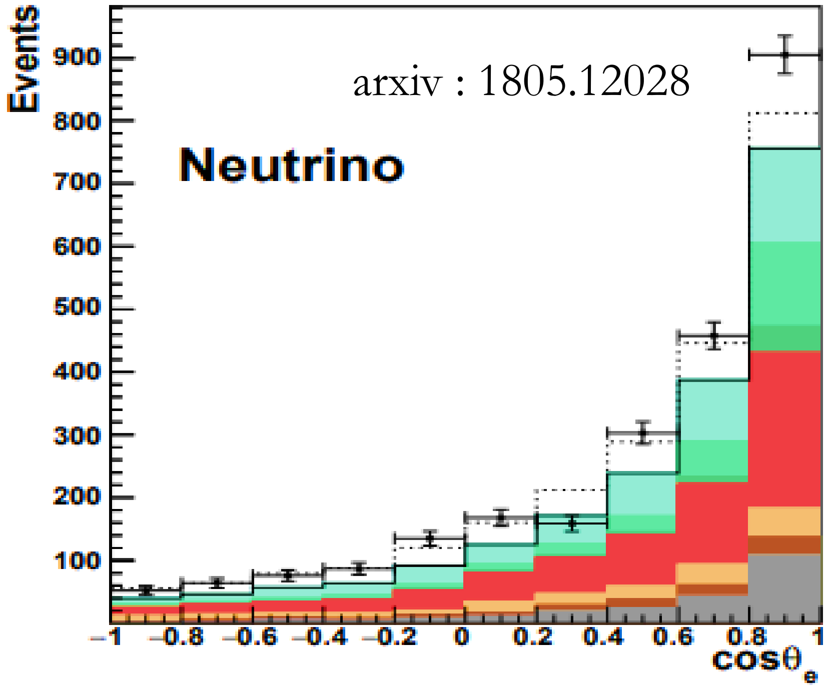


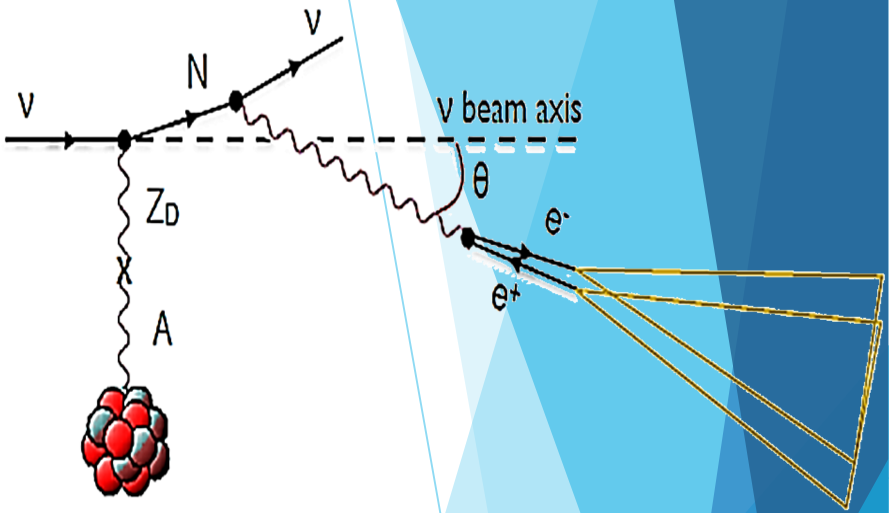
If e^+e^- pair is collimated ($\cos\theta_{ee}$ > 0.99-ish), it will be classified as e-like

❖ *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*

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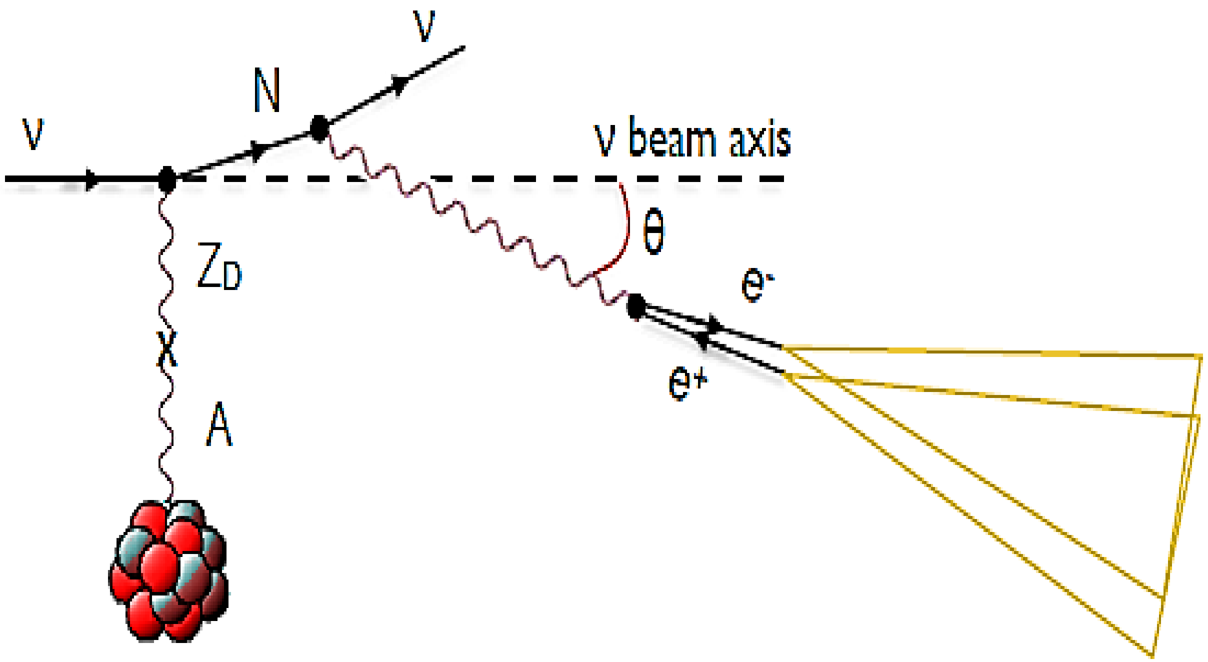
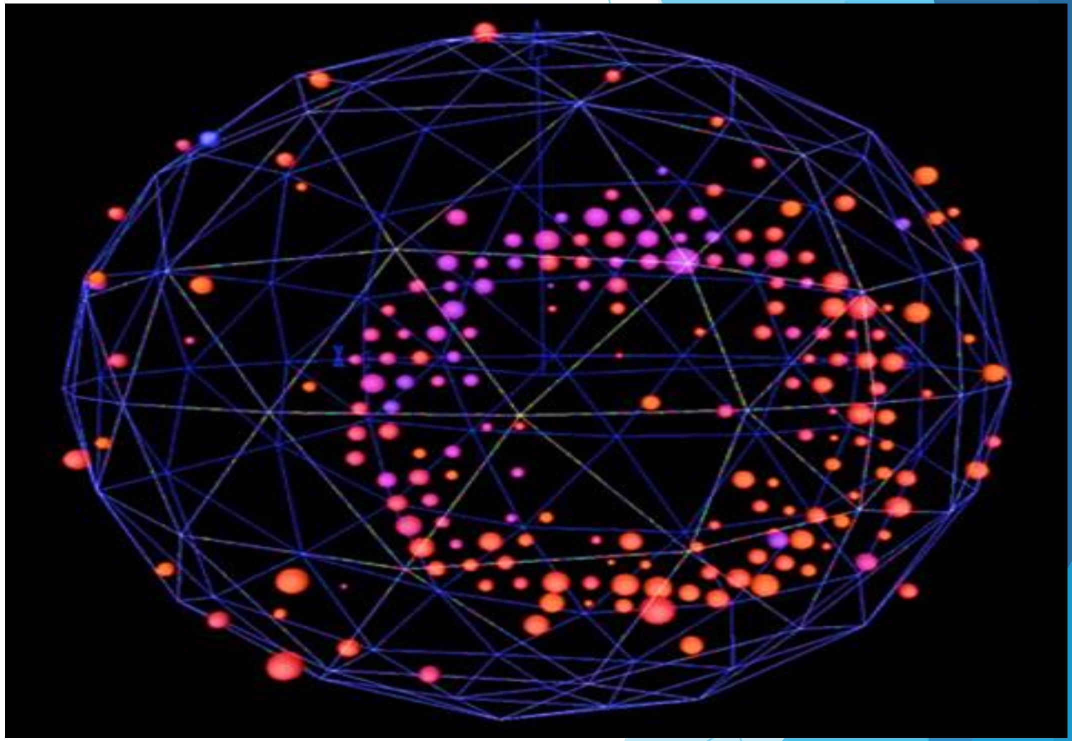




(1) N_D should be heavy (> 100 MeV) so its decay products are not so boosted

(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

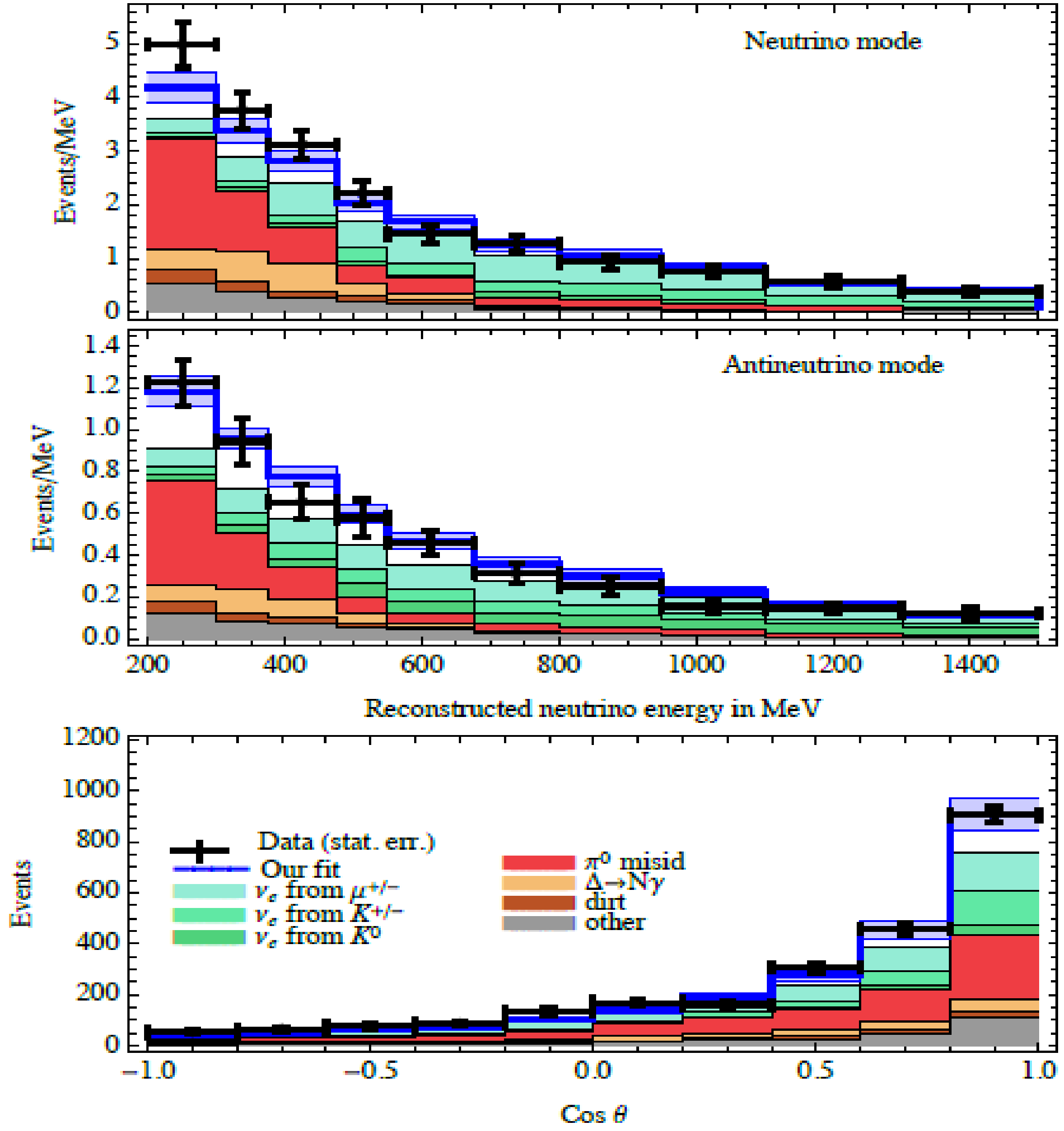
$m_{ZD} = 30$ MeV

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

$\alpha_D = 0.25$

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

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



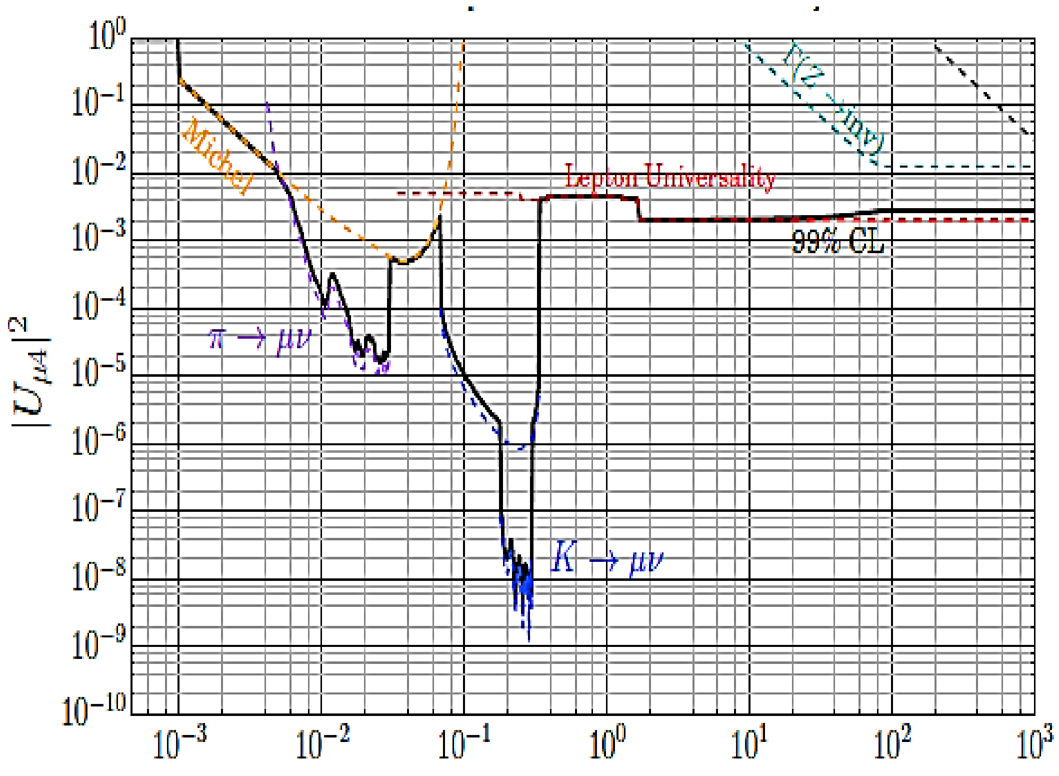
Bertuzzo et al 1807.09877

See also Ballett et al 1808.02915

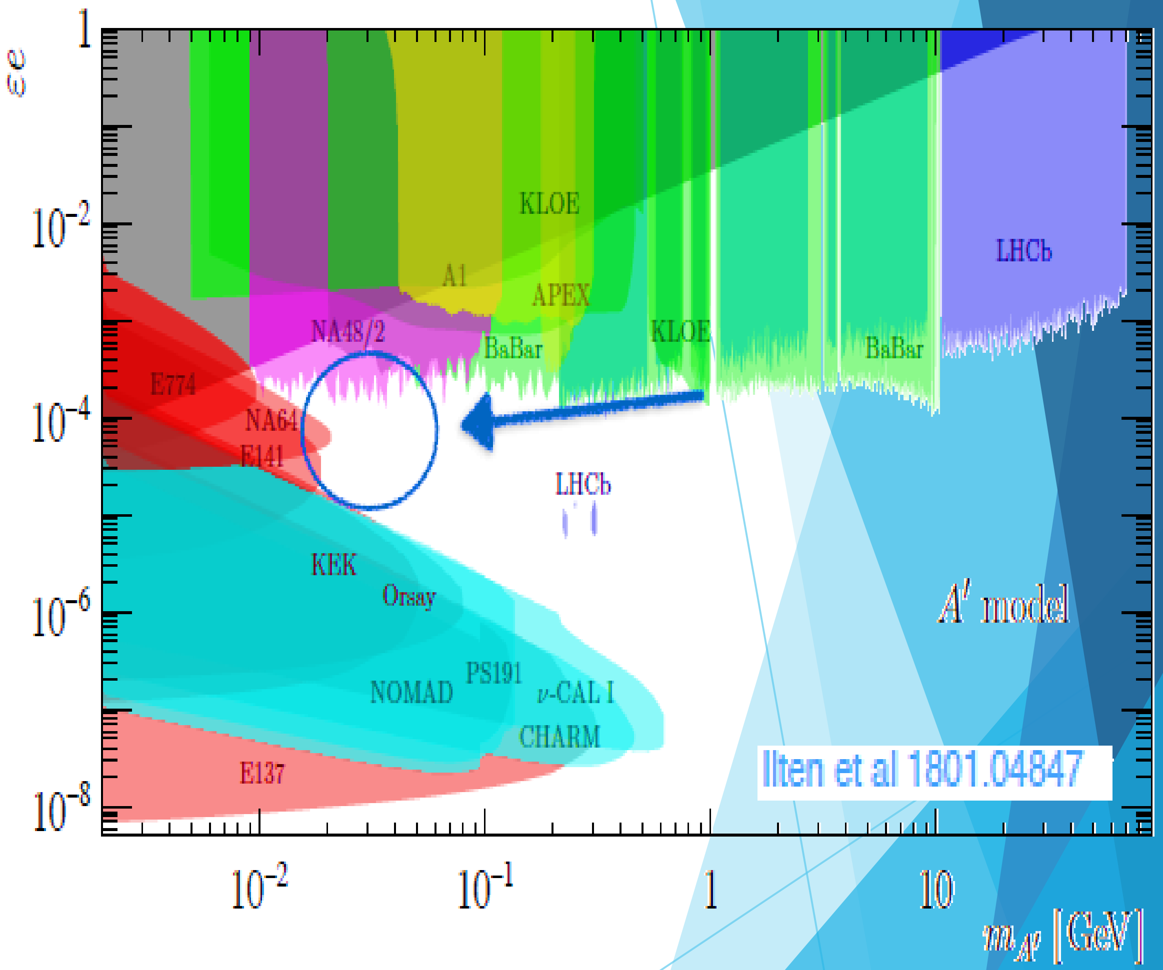
for different realization of the mechanism

❖ Constraint on Light Dark Sector

Model Independent Constraint
on Heavy Sterile Neutrino



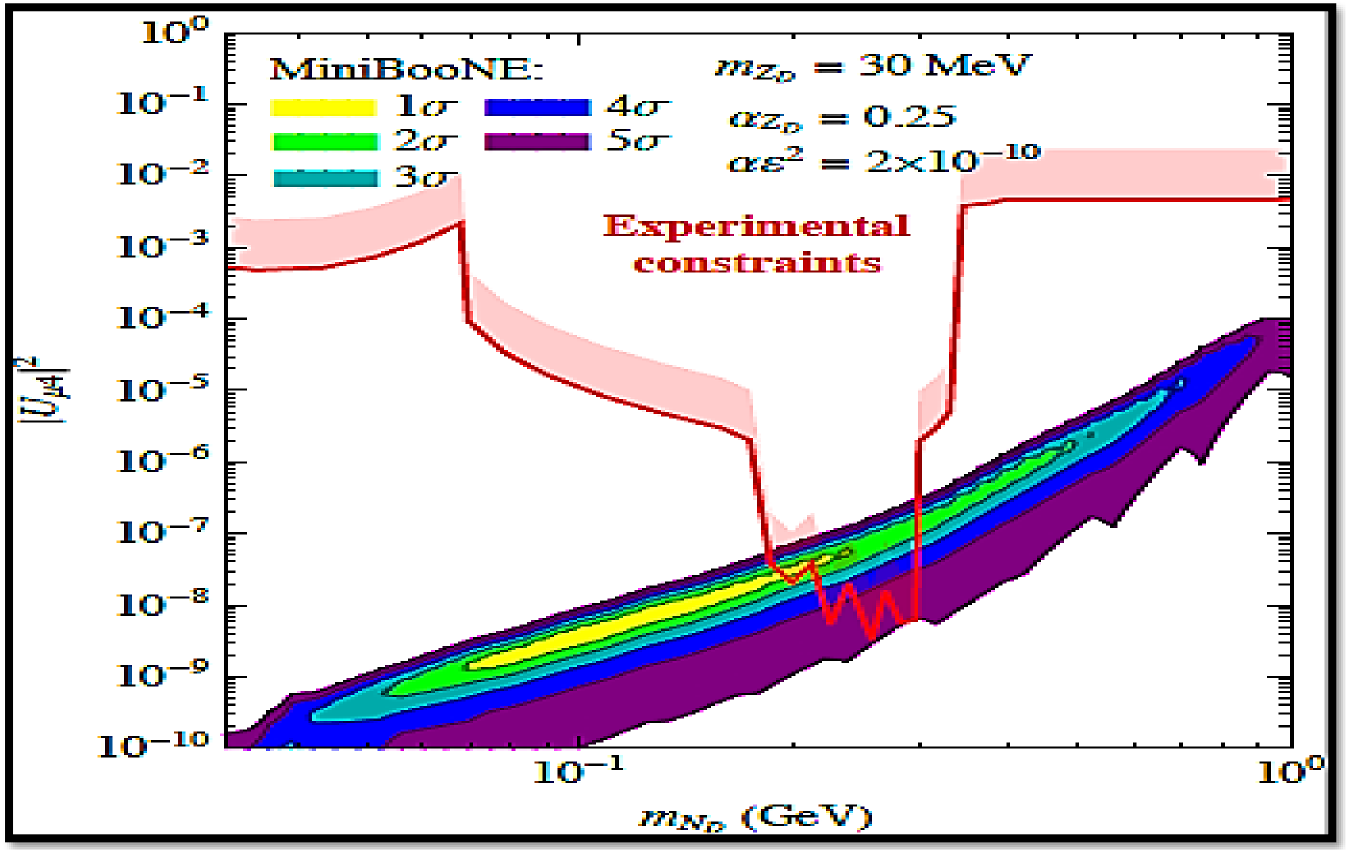
de Gouvea Kobach 1511.00683



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

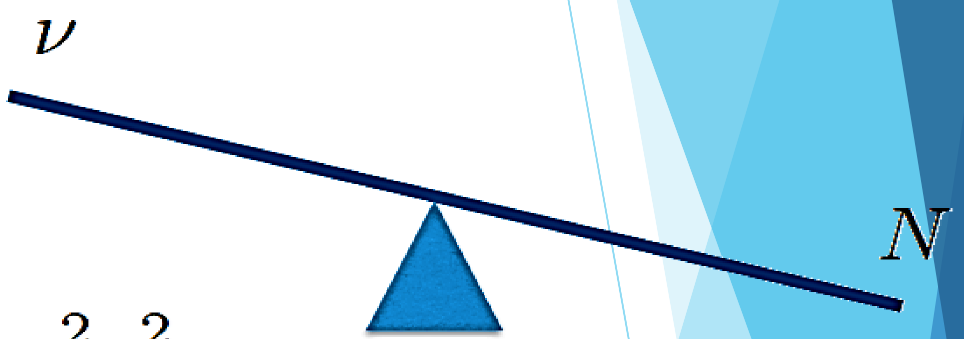
Connection to Neutrino Mass Generation Mechanism

❖ Standard/Type I Seesaw

$$yNH\ell + M_N NN$$

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

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



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

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

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**

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

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

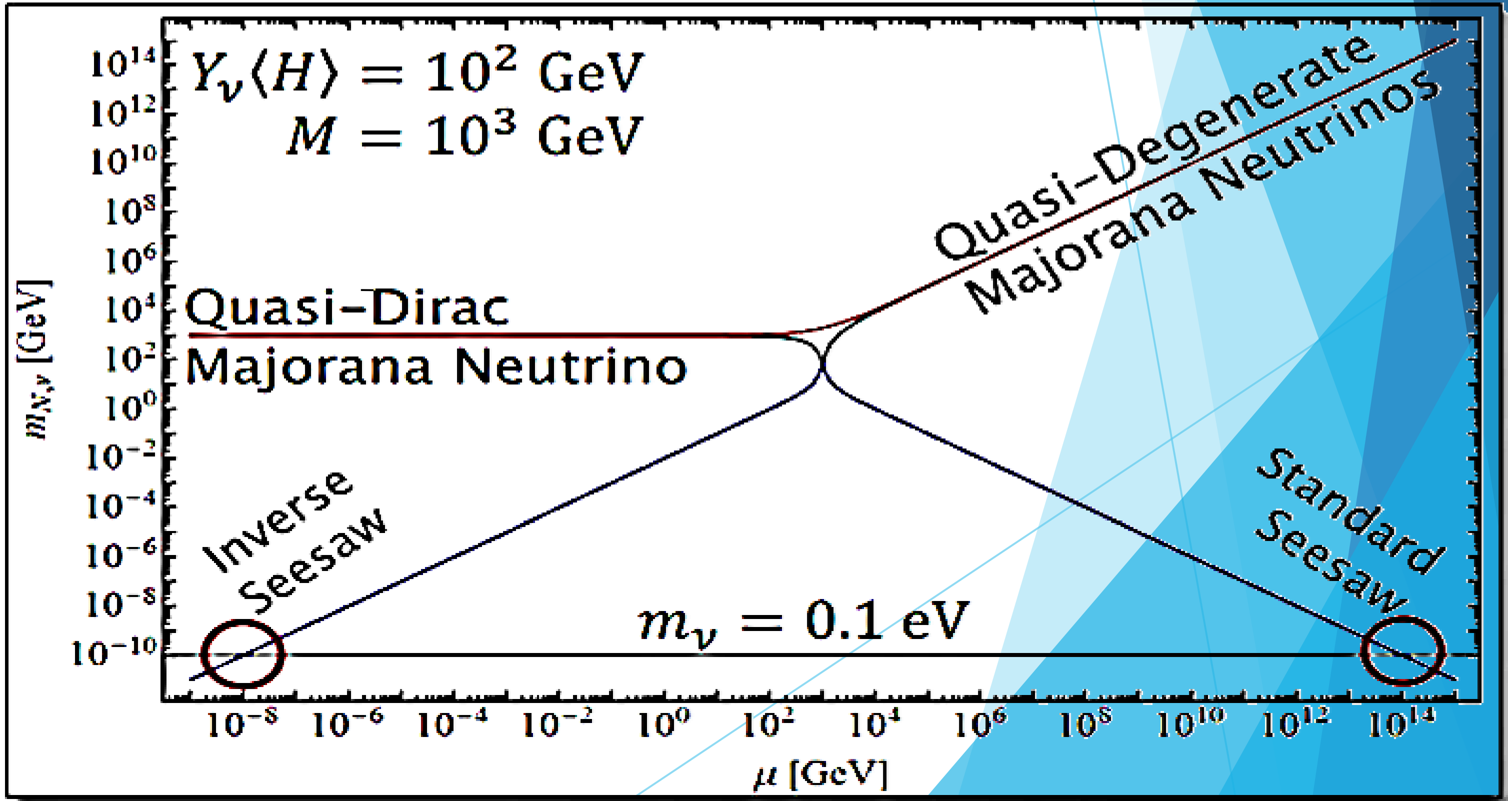
- Why μ is much smaller than TeV scale?

Scale of Seesaw Mechanism

- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$
  - "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 …

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

Can neutrino masses come from light physics ?

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

Neutrino masses from light physics

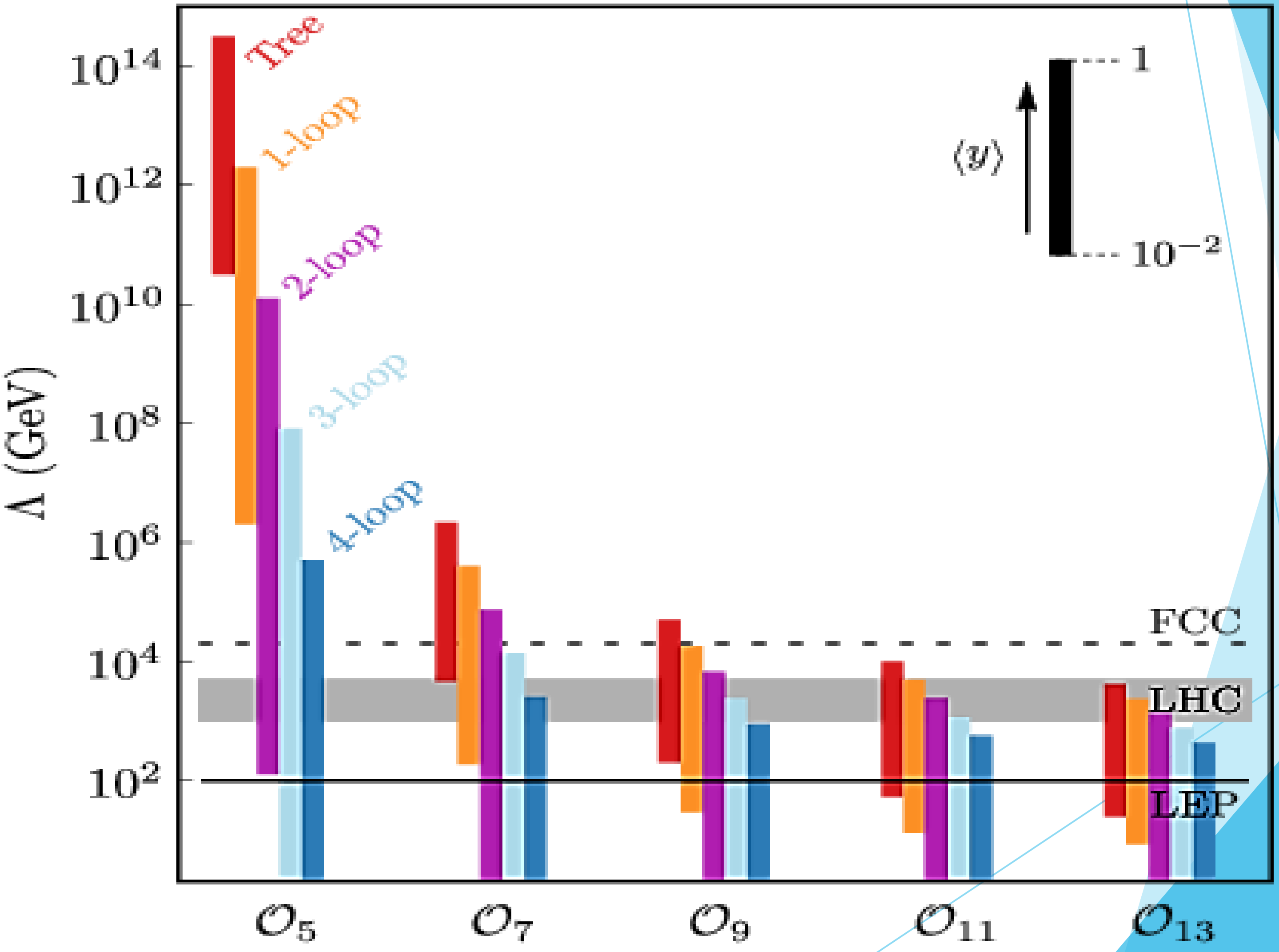
In an effective theory, the Lagrangian should be described as

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

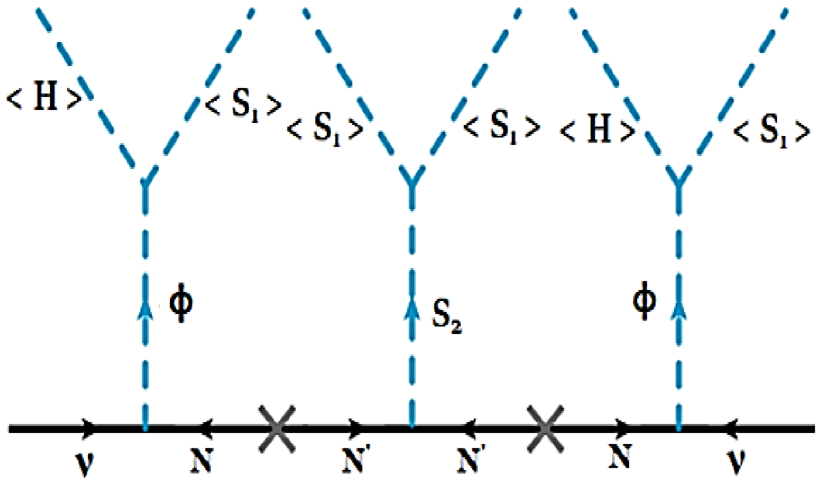
Neutrino masses from a n-loop-induced dim-d operator

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

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

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

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

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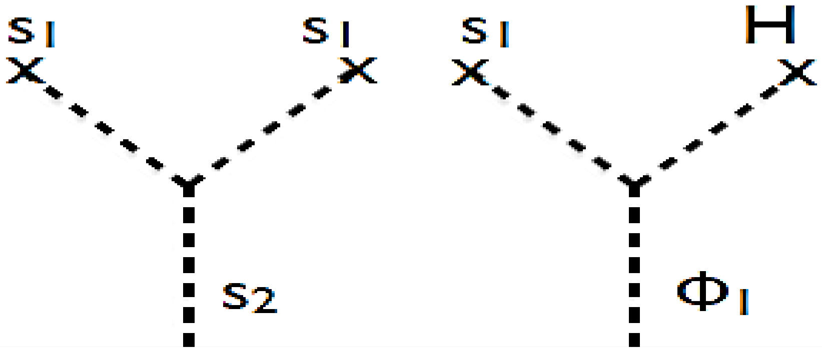
Neutrino masses from light physics

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

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

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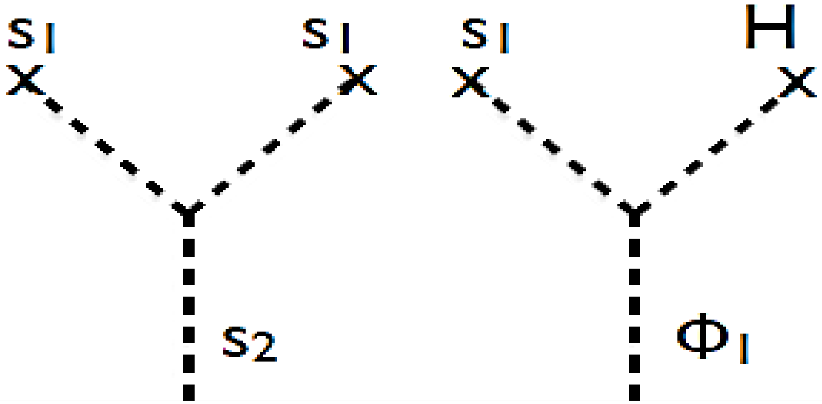

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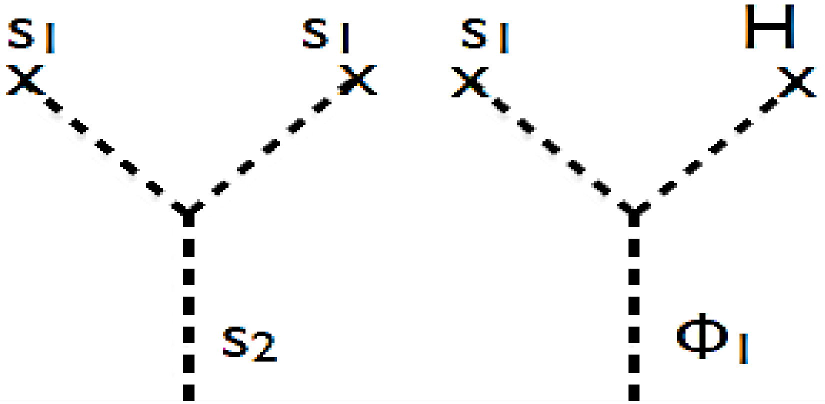
Neutrino masses from light physics

Minimum scalar content

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

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

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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❖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?

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

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

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

Masses of the Physical Fields								
$m_{h_{\rm SM}}$ (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'	$\|U_{\alpha N}\|^2$
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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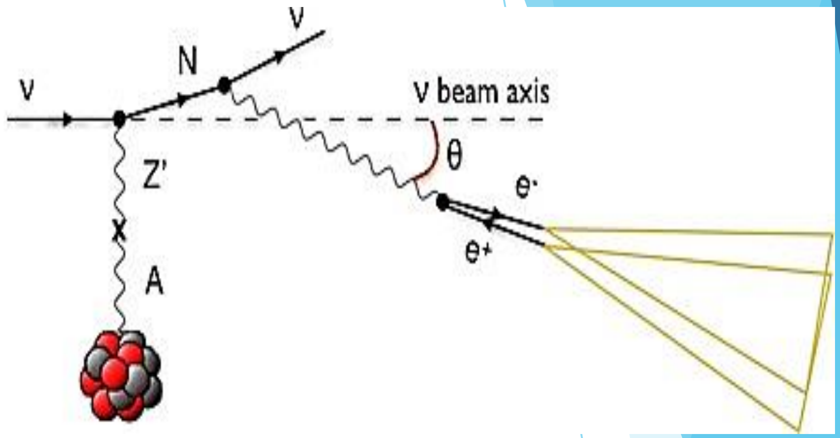
❖ Phenomenology on other neutrino experiment

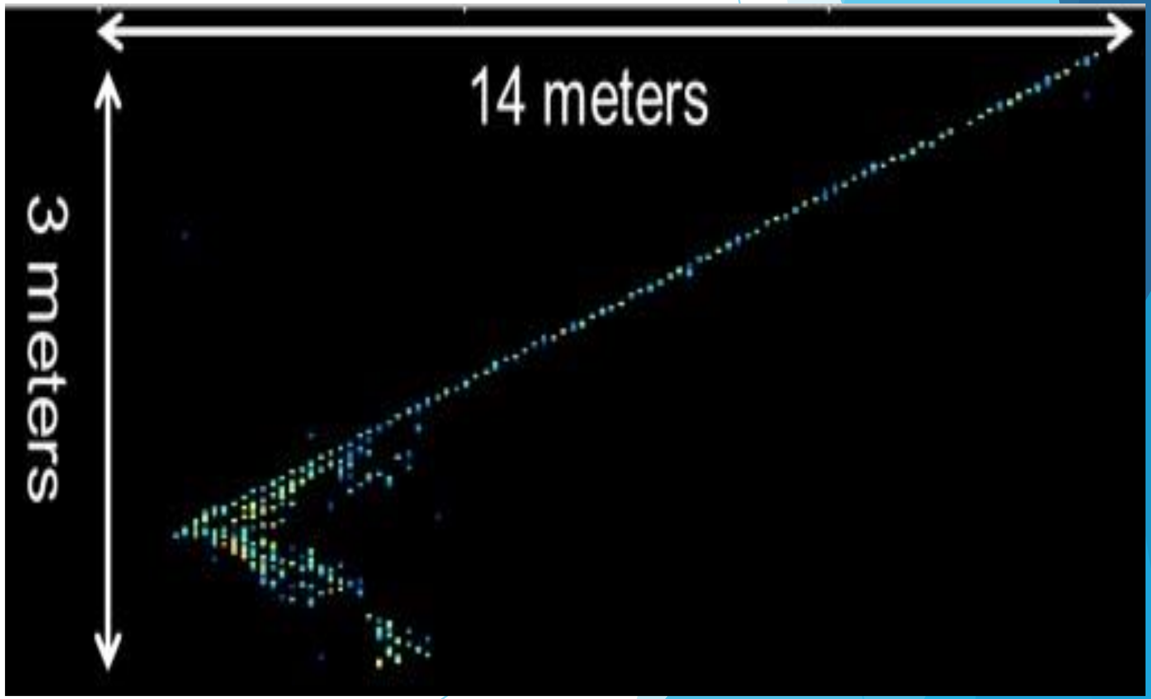


MiniBooNE's signature: Collimated e^+e^- pair in MINOS+, NOvA, or T2K is likely be tagged as ν_e event

General signature:

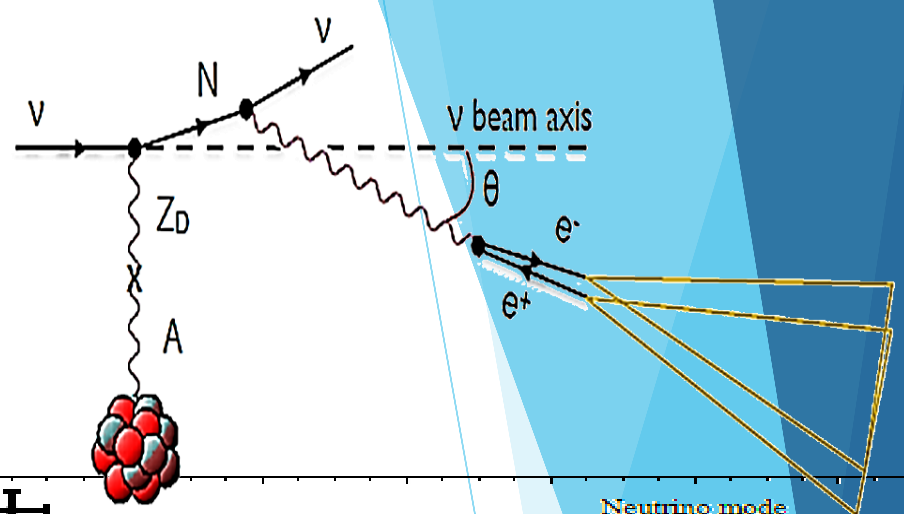
Heavy enough Z_D can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized…)

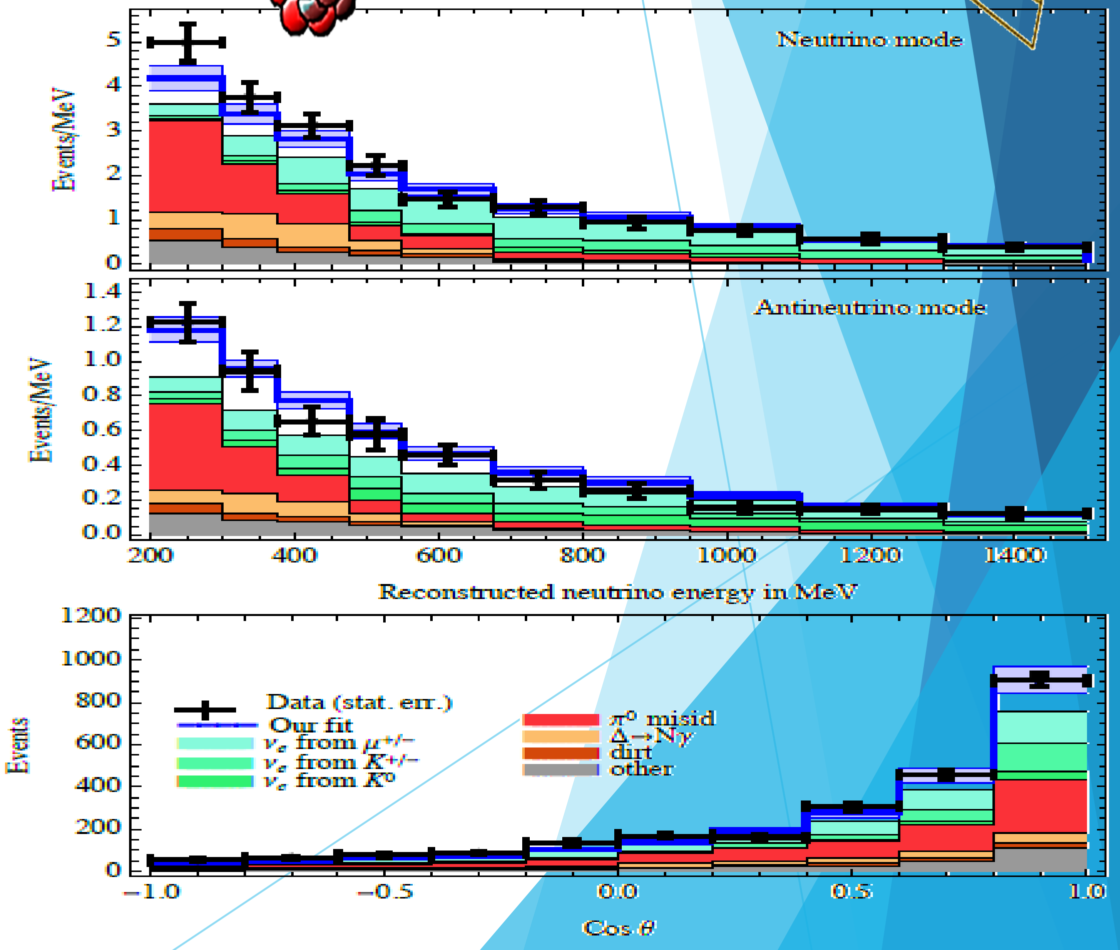
Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N



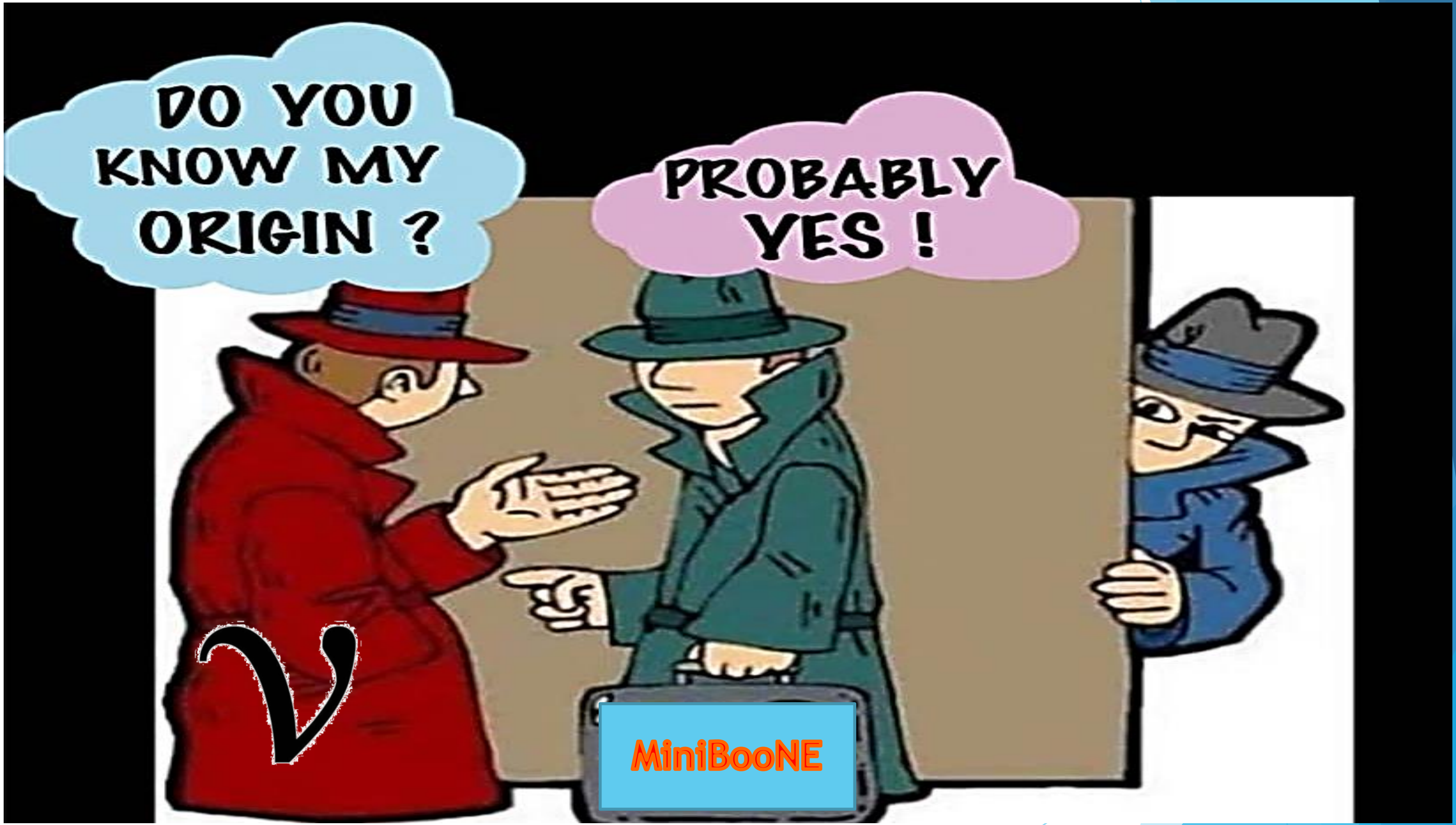
Conclusions :

- *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*





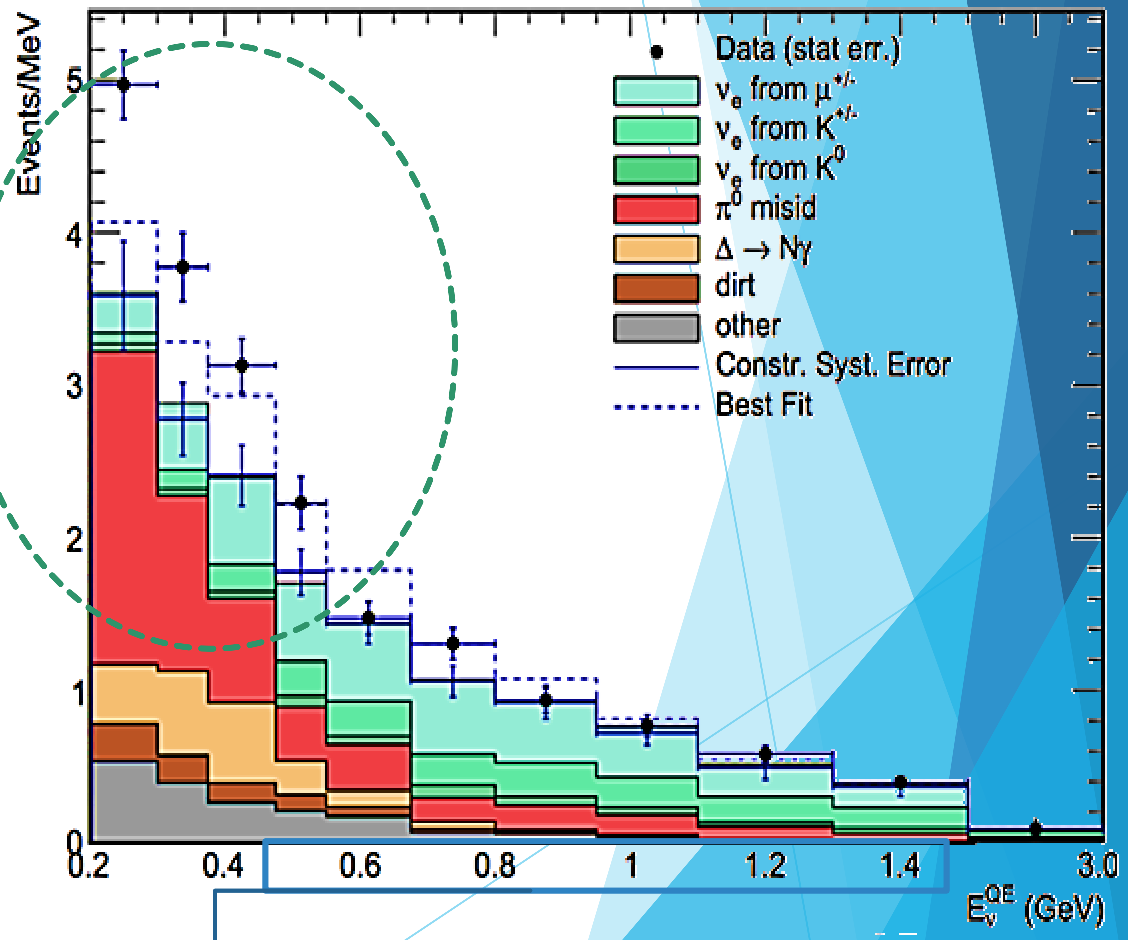

DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
V
TOP SECRET


DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
ν
MiniBooNE


Thank you!

MiniBooNE's Low Energy Excess

MiniBooNE Collaboration hep-ex/1805.12028

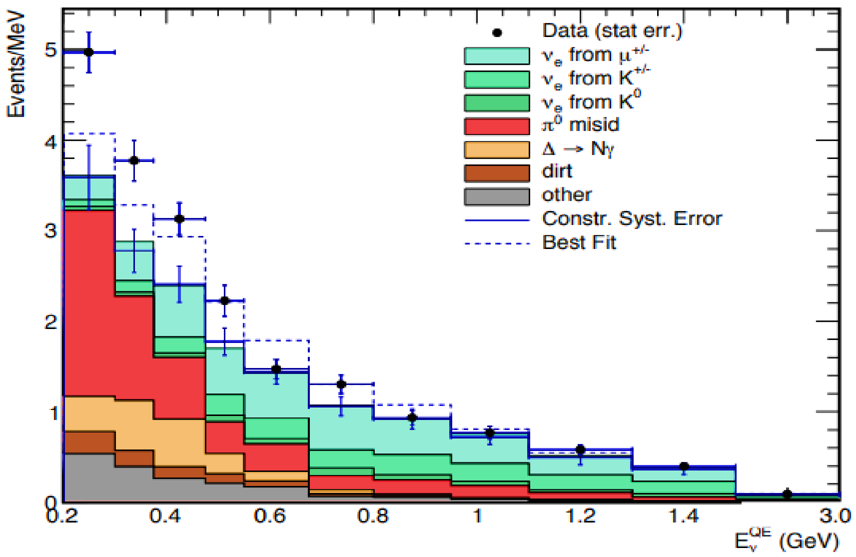


MiniBooNE observed a large excess in the much lower energy region

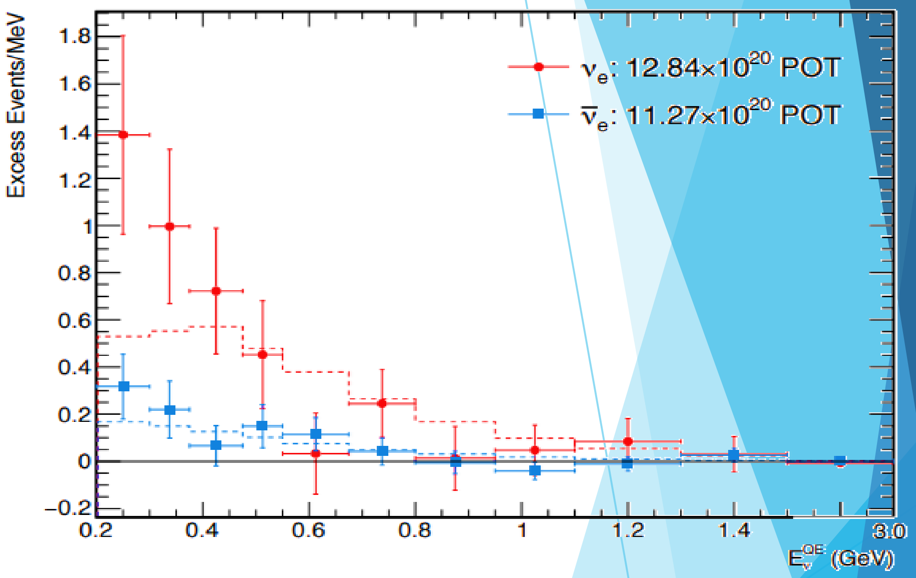
This is the region that the LSND oscillation should have appeared

MiniBooNE's Low Energy Excess

Neutrino mode only



Both excesses, BG subtracted



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

Measure charged lepton energy/angle

Observed ~ 400 events, PMNS predicts 0

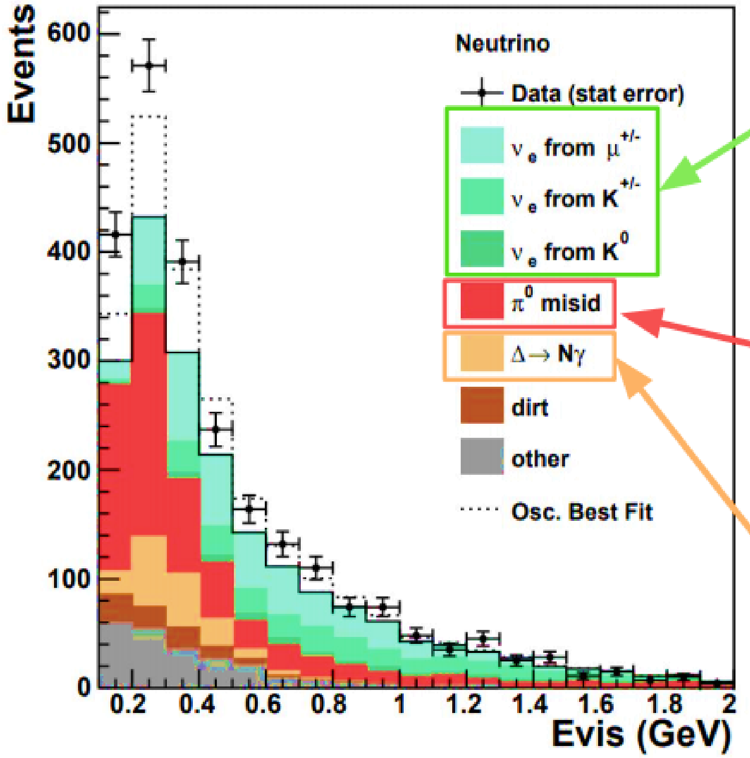
Combined $\nu/\bar{\nu}$ modes : 4.8σ excess

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.

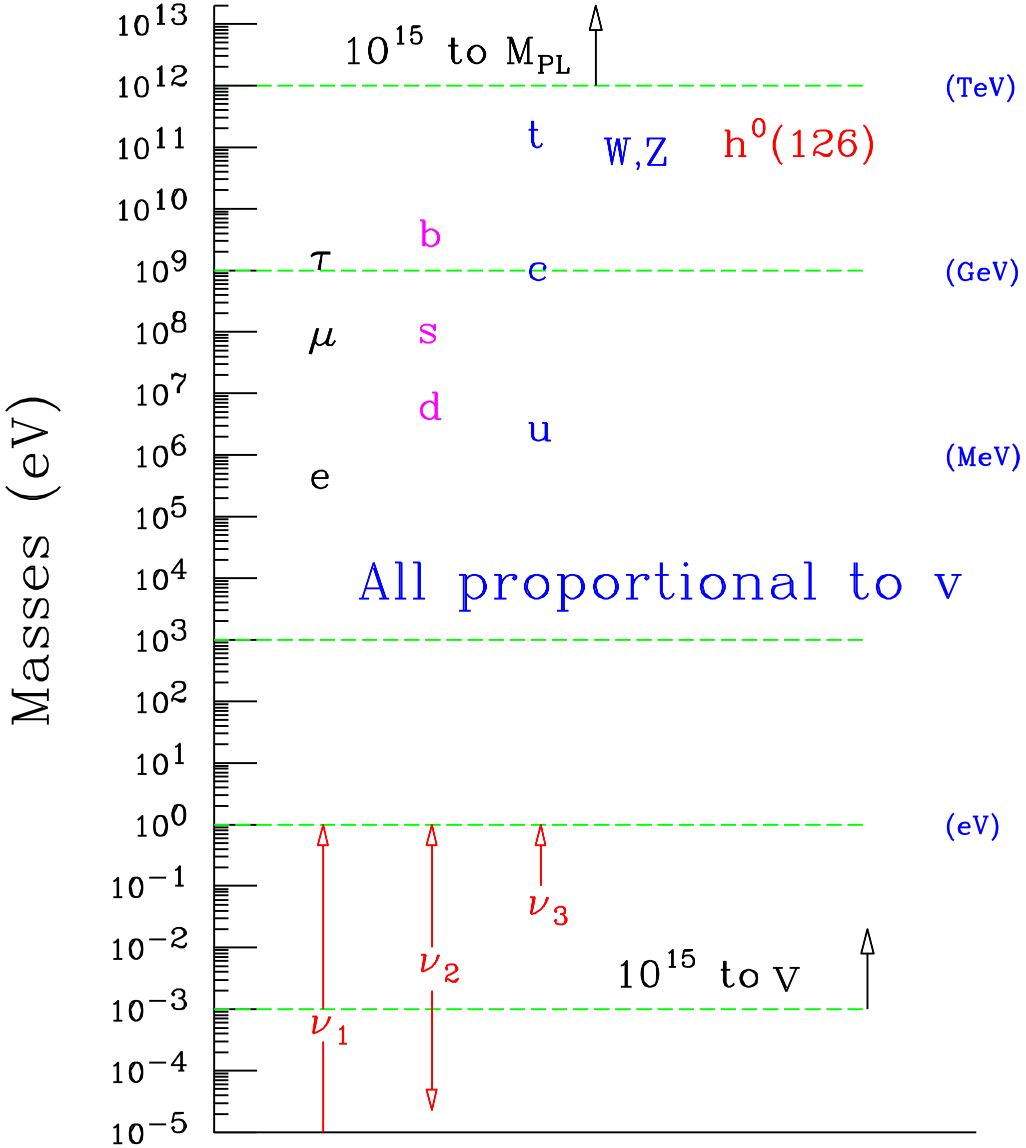
Radiative Δ decay? This has never been observed in the neutrino sector. MiniBooNE bound it using their NC π^0 measurements which agrees well with best theoretical calculations. The biggest channel of interest to MicroBooNE's photon LEE analysis.

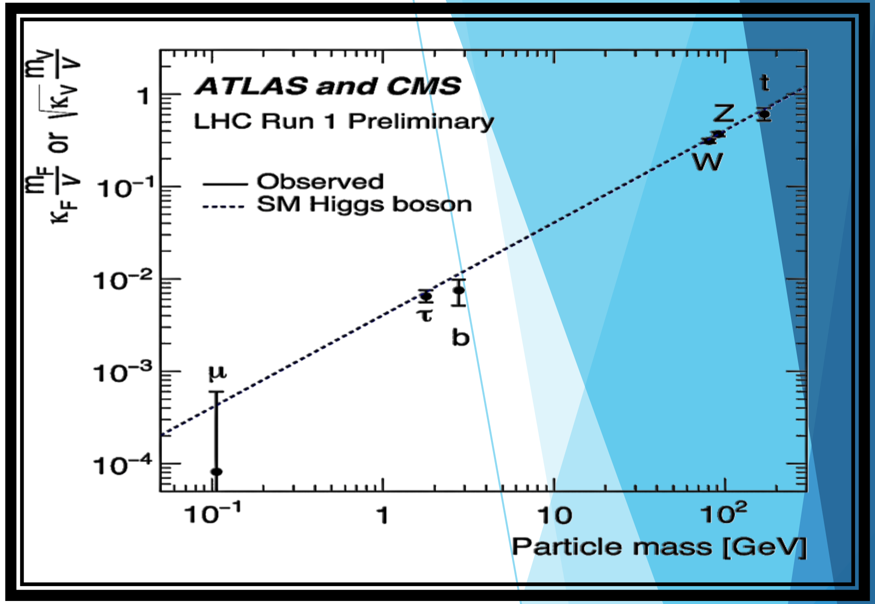
❖ *Explanation of MiniBooNE's low energy excess*

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:





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

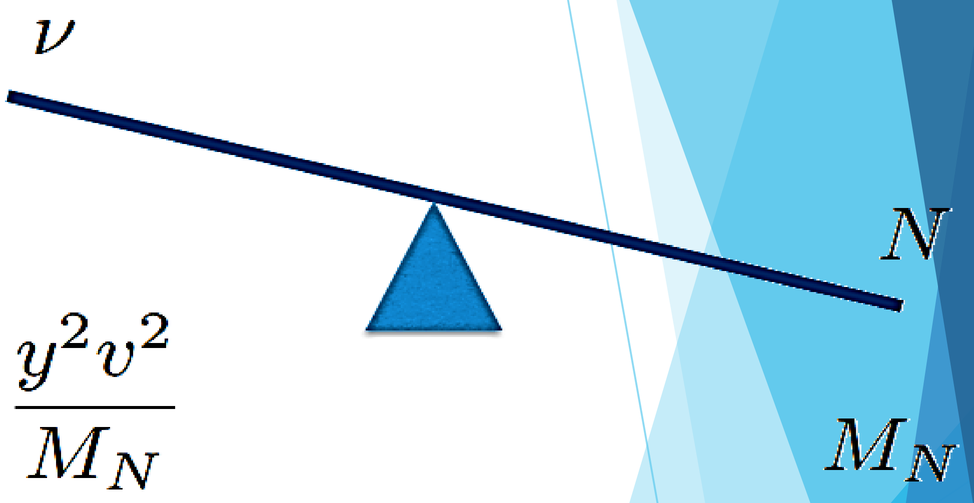
$$y_\nu^{eff} < 10^{-12}$$

❖ Standard/Type I Seesaw

$$yNH\ell + M_N NN$$

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

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



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

Lepton number is broken at very high scale M_N

❖ Phenomenology on other neutrino experiment

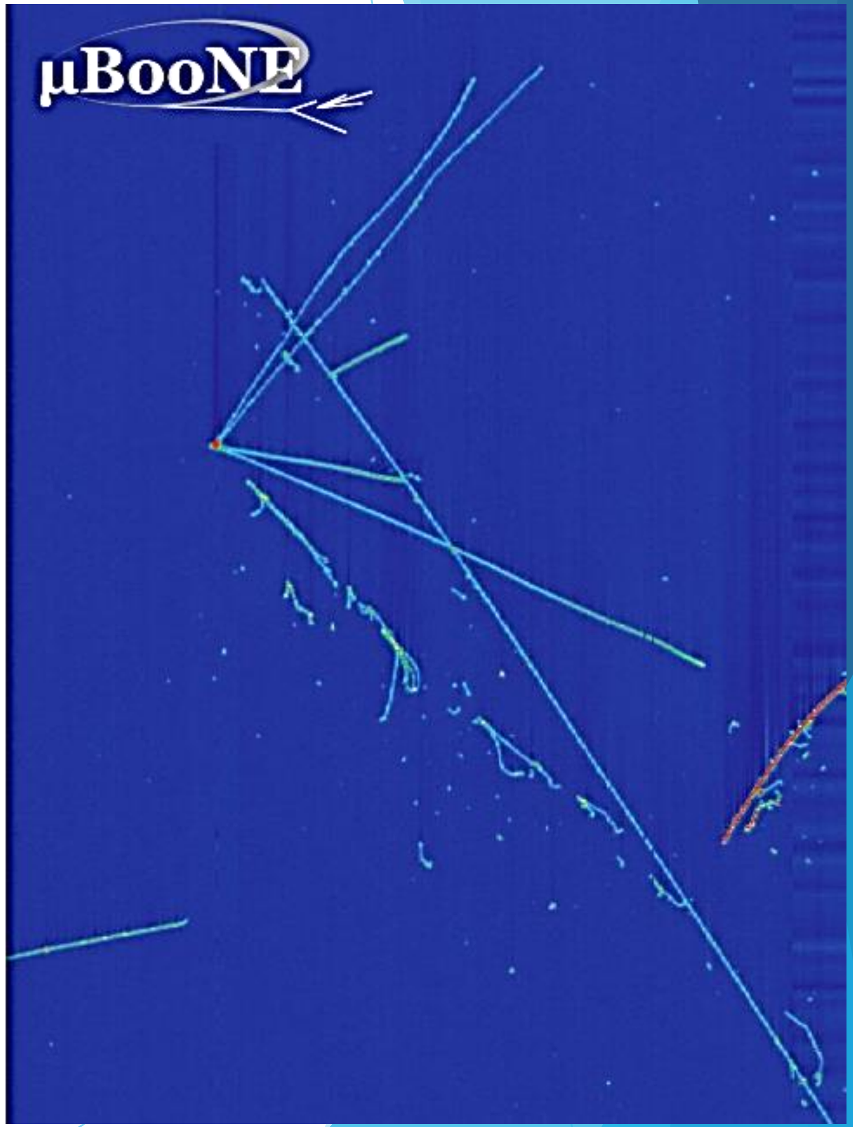
U(1)' models in Future and Current LArTPCs

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:

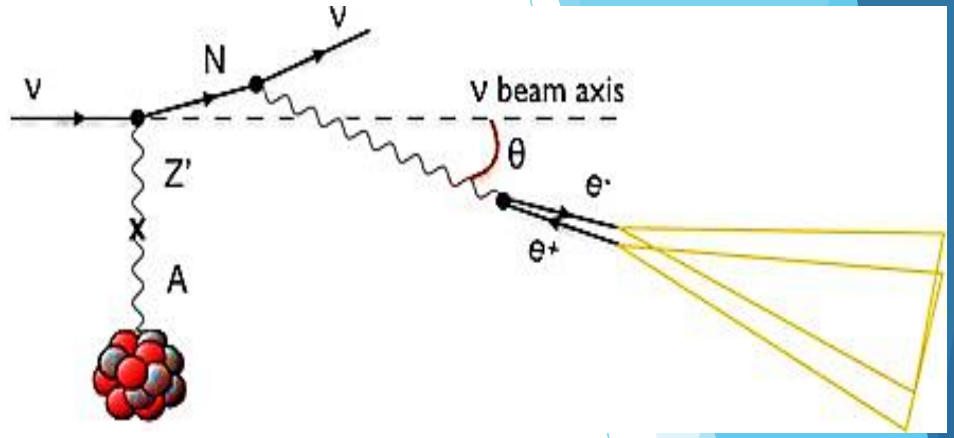
- Directly look for the **conversion gap**

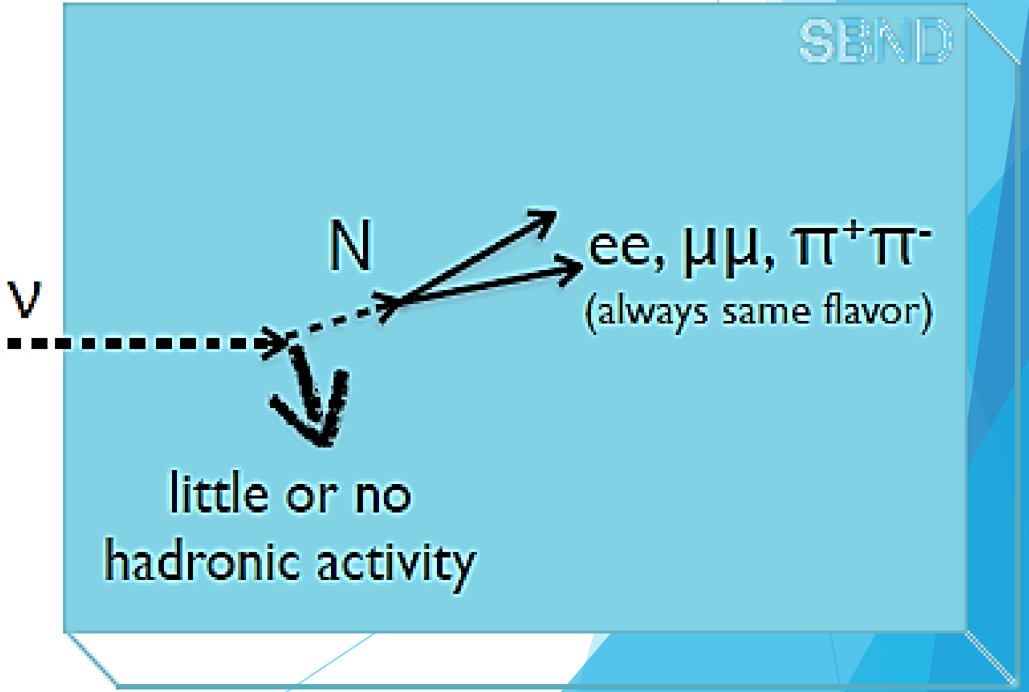
- Use **Calorimetric measurements** to see rate of energy deposition (dE/dx). **Photons** that pair convert to e^+e^- **deposit x2 as much energy**.



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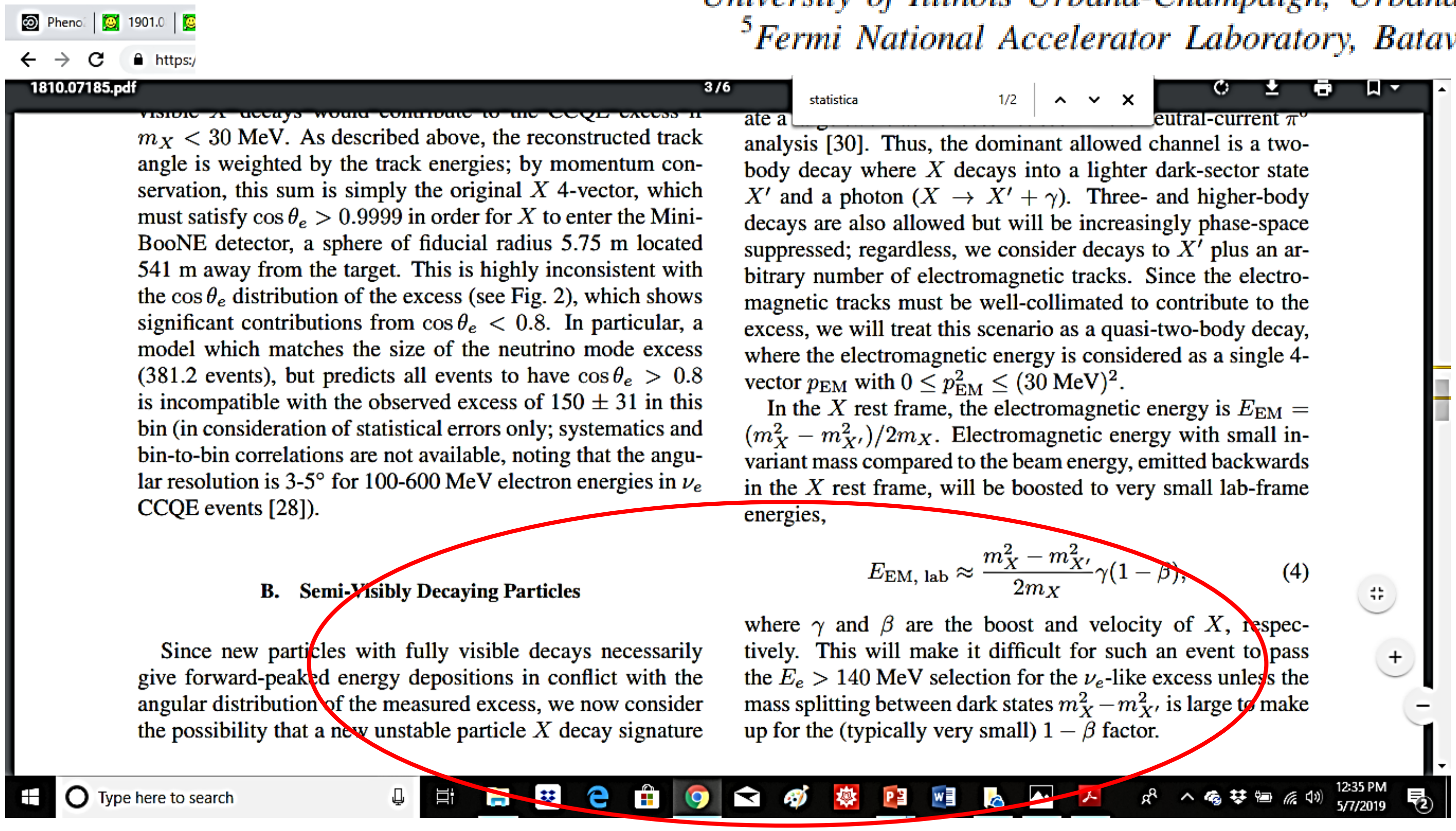
[3] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL USA*
[4] *University of Illinois Urbana-Champaign, Urbana, IL USA*
[5] *Fermi National Accelerator Laboratory, Batavia, IL*



$m_X < 30$ 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

ate a ... neutral-current π^0 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 $0 \le p_{\rm EM}^2 \le (30\ {\rm MeV})^2$.

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,

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

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.