Confronting Neutrino Mass Generation Mechanism with MiniBooNE Anomaly

POND^2

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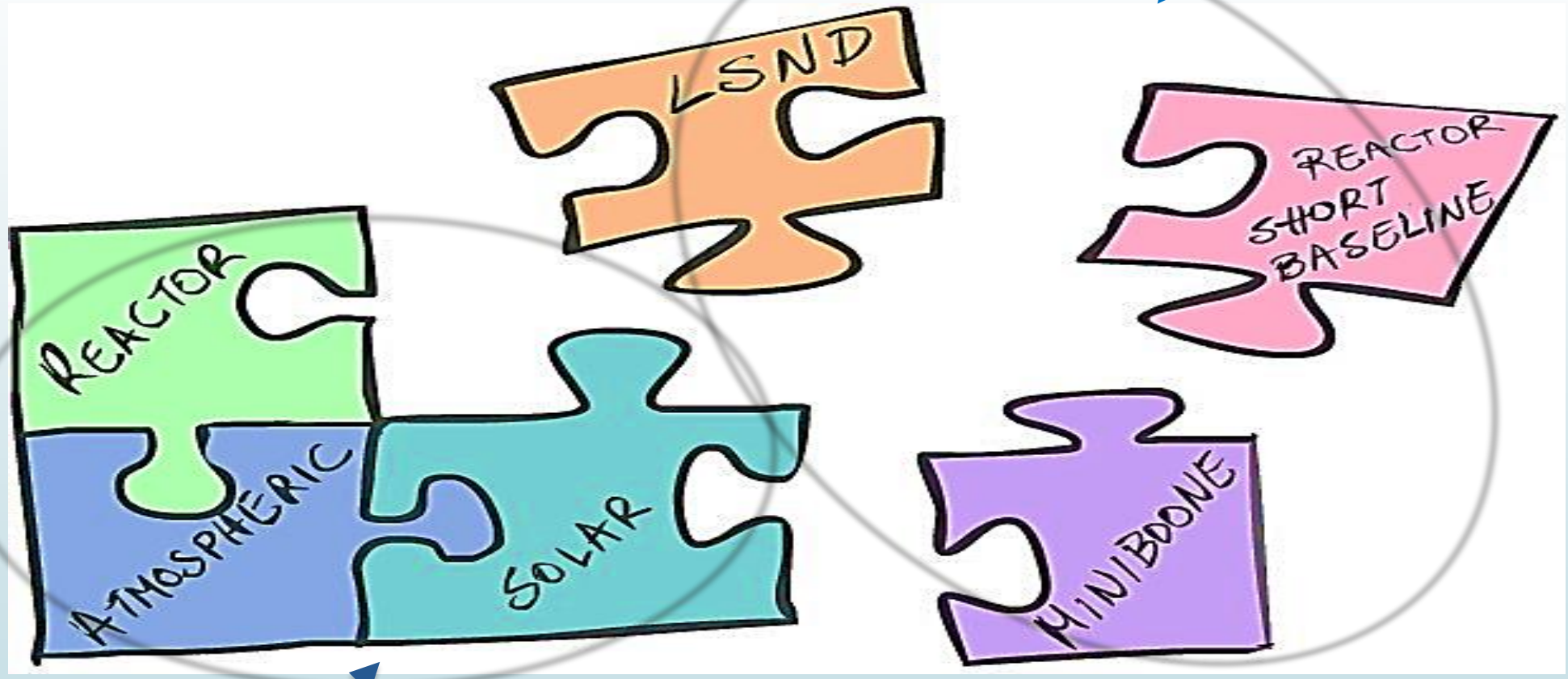
Fermilab 2018

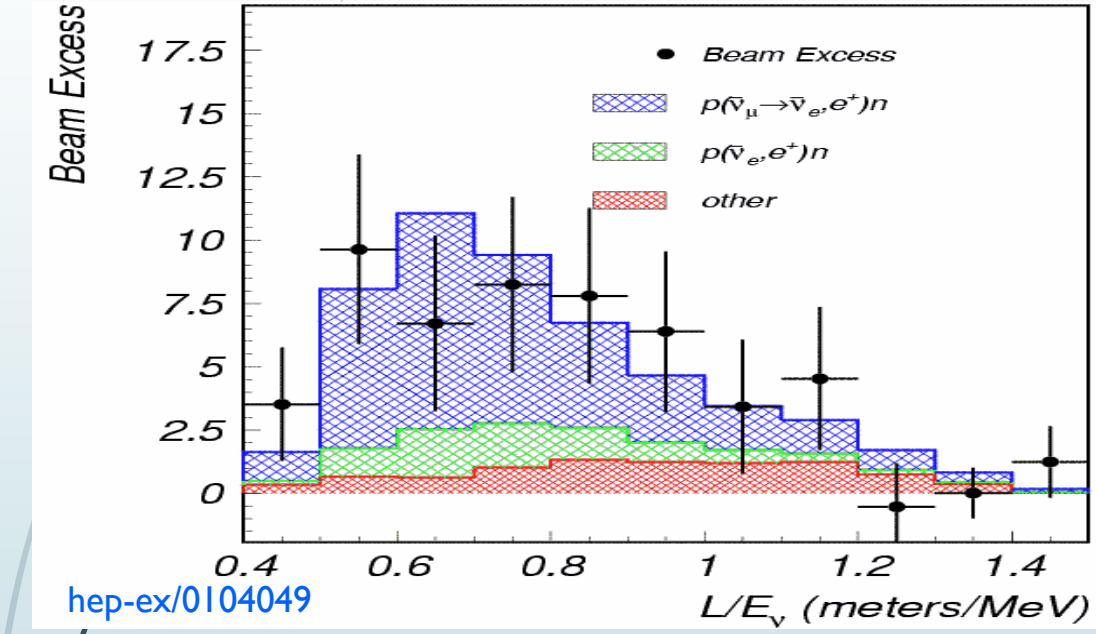
Based on *arXiv:1807.09877* and *arXiv:1808.02500*
in collaboration with
E. Bertuzzo, Pedro A. N. Machado and R. Zukanovich-Funchal

Three-neutrino oscillation: Not the full picture?

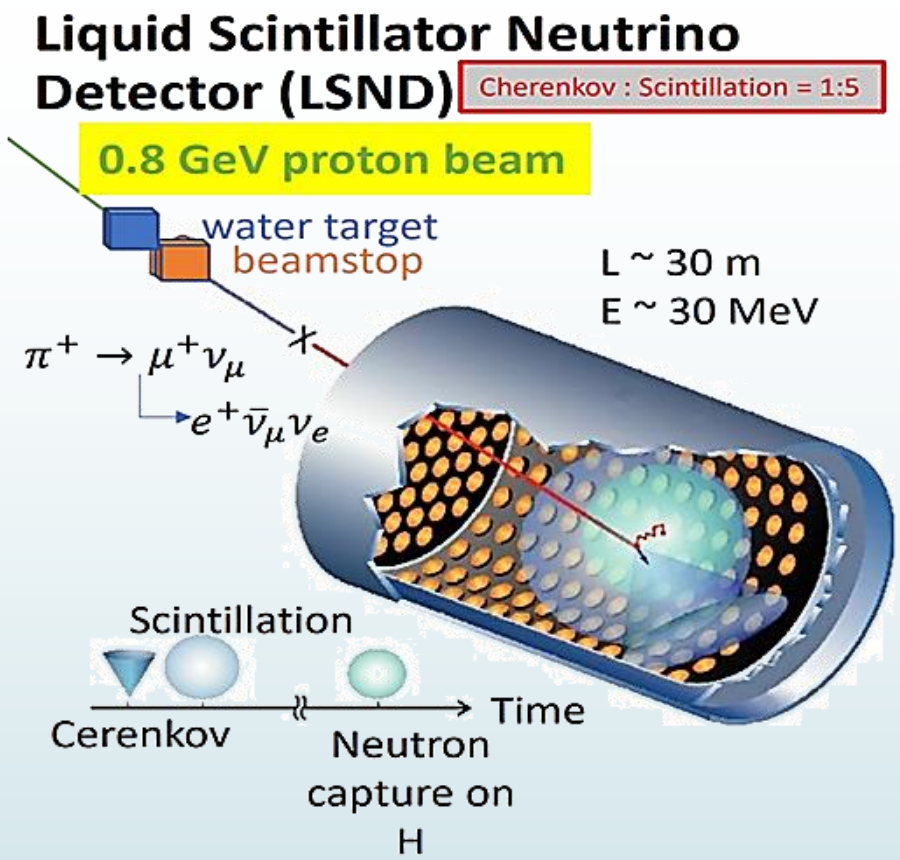
Short Baseline Anomalies



Long and Medium Baseline



hep-ex/0104049



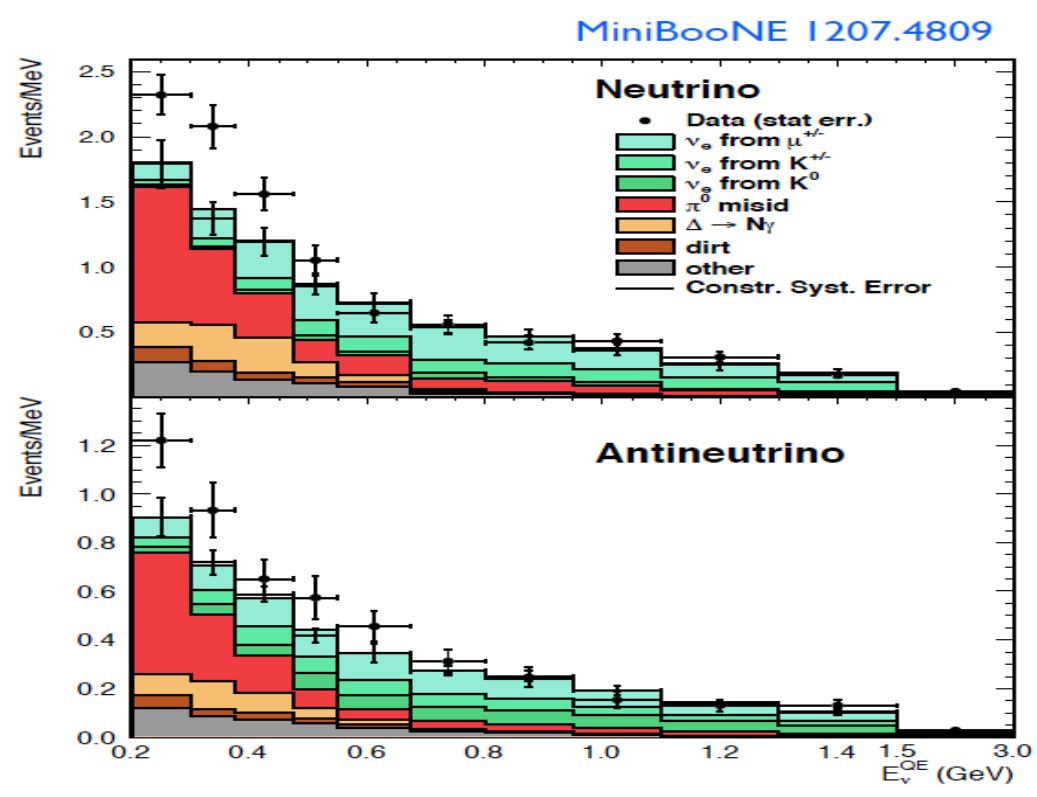
LSND neutrino source

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

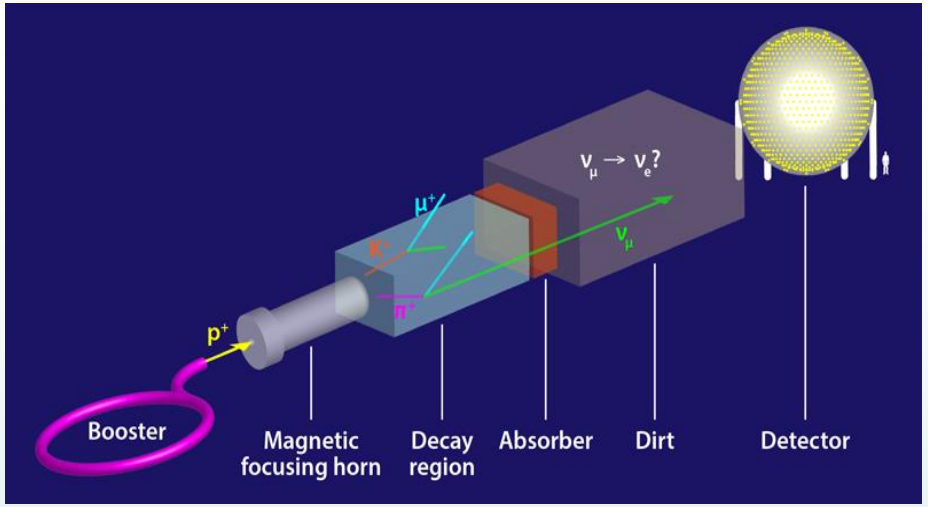
LSND detected more $\bar{\nu}_e$ than expected :

87.9 ± 22.4 ± 6.0 events

3.8 σ excess



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

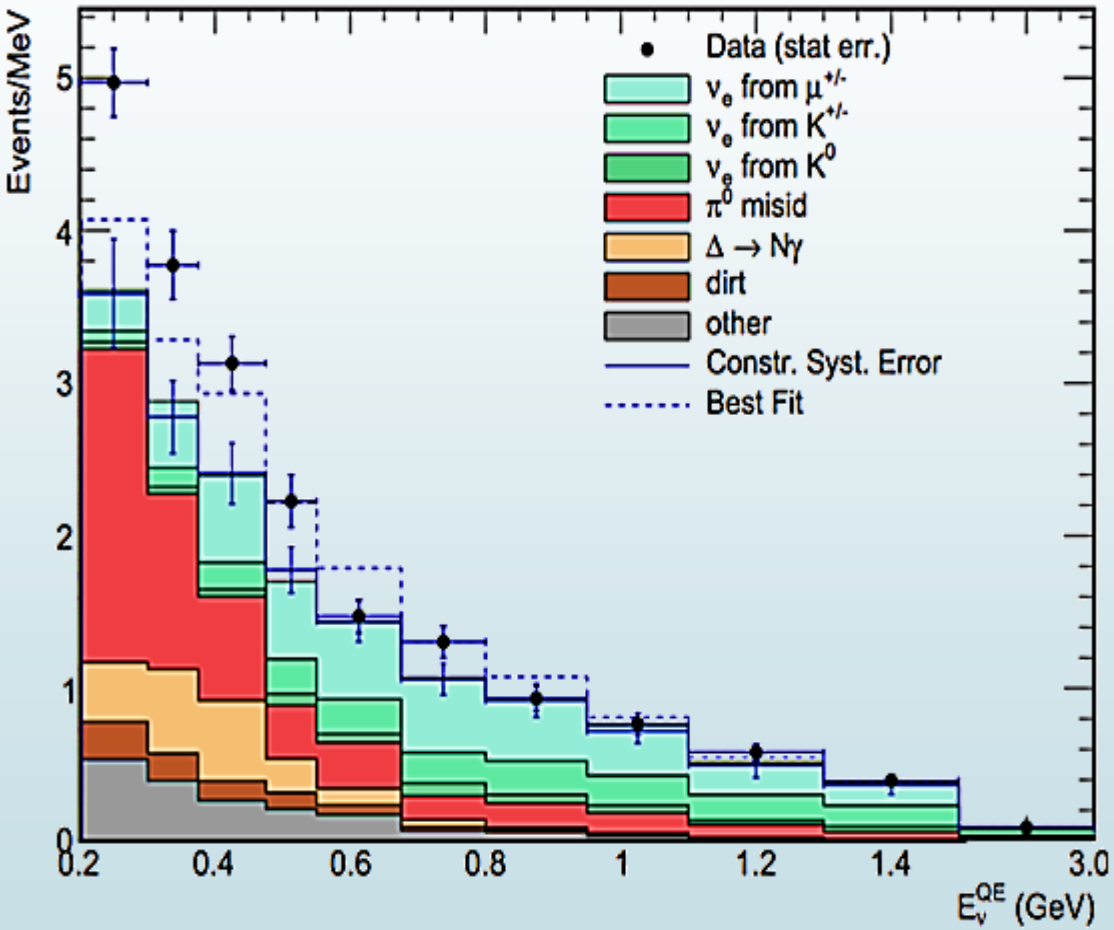


- To test the LSND indication of anti-electron neutrino oscillations
- Keep L/E same, change beam, energy, and systematic errors
- Baseline: L = 540 meters, ~ x 15 LSND
- Neutrino Beam Energy: E ~ x (10-20) LSND
- Different systematics: event signatures and backgrounds different from LSND High statistics: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

MiniBooNE's Low Energy Excess

- Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short Baseline Neutrino Experiment
- Double neutrino-mode data in 2016-2017 ($6.46\times10^{20} + 6.38\times10^{20}$ POT)
- Event excess: **381.2 ± 85.2 (4.5σ)**

MiniBooNE Collaboration hep-ex/1805.12028



MiniBooNE's Low Energy Excess

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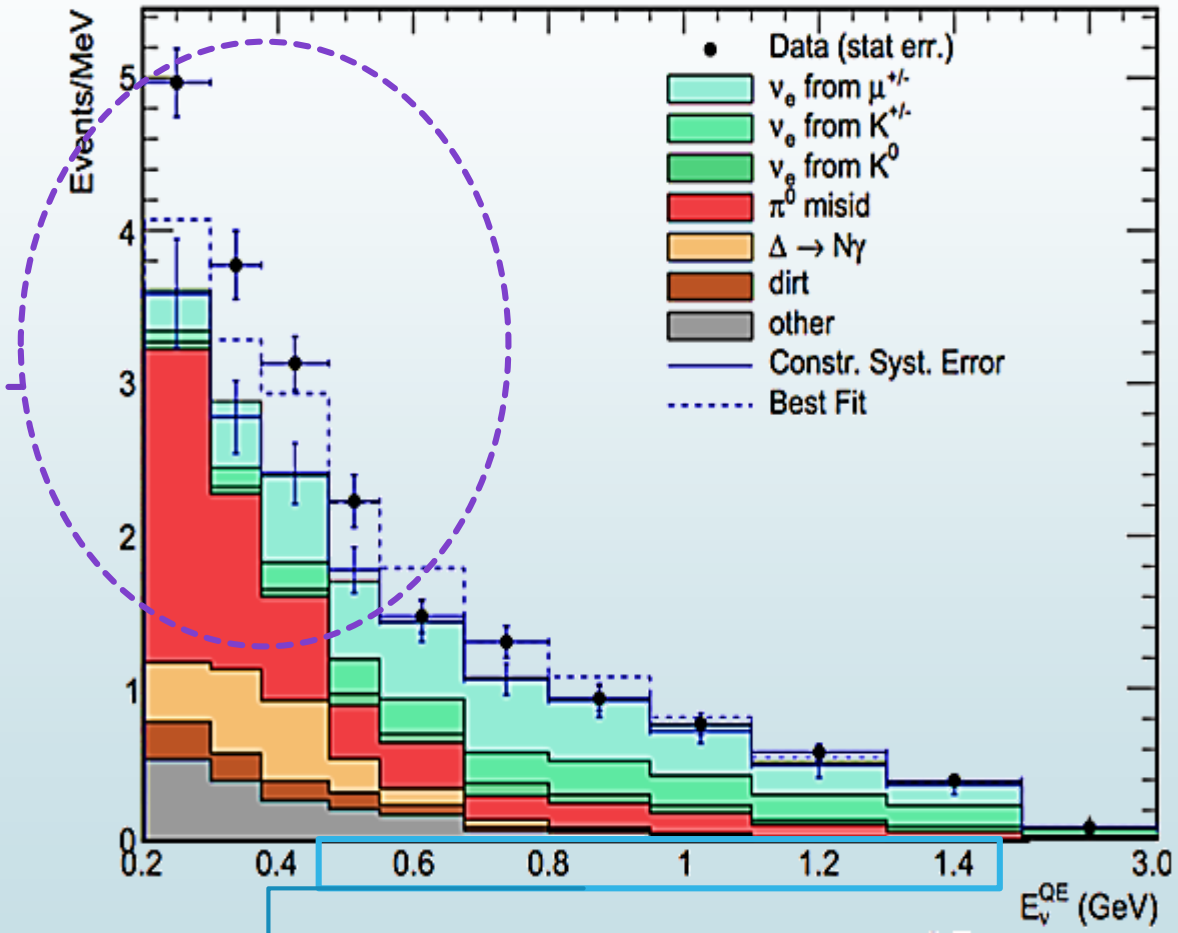


MiniBooNE observed a large excess in the much lower energy region

This is the region that the LSND oscillation should have appeared

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 ???

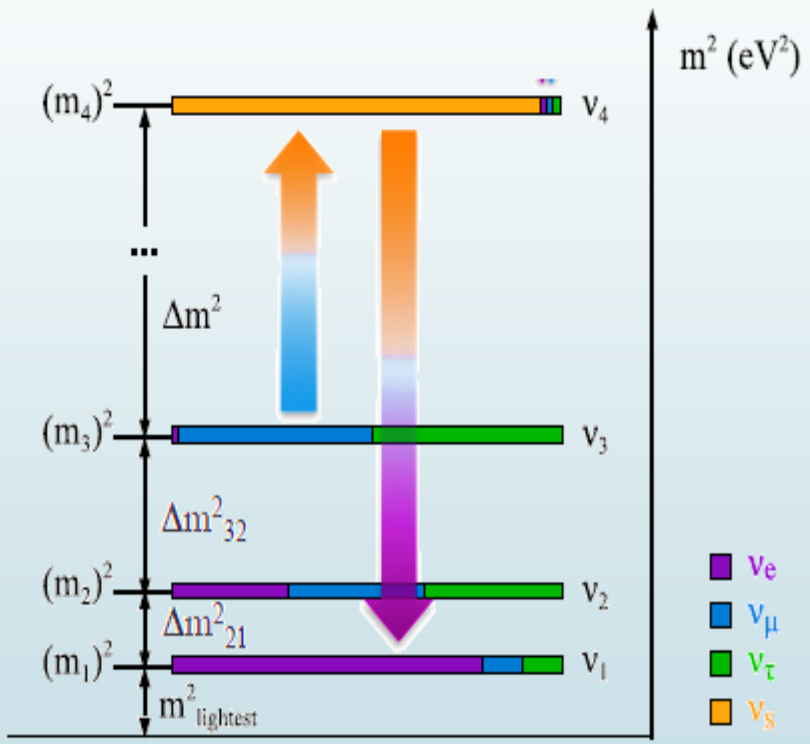
$$P^{\mathrm{SBL}}_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

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

Leads to ν_e disappearance

Leads to ν_μ disappearance

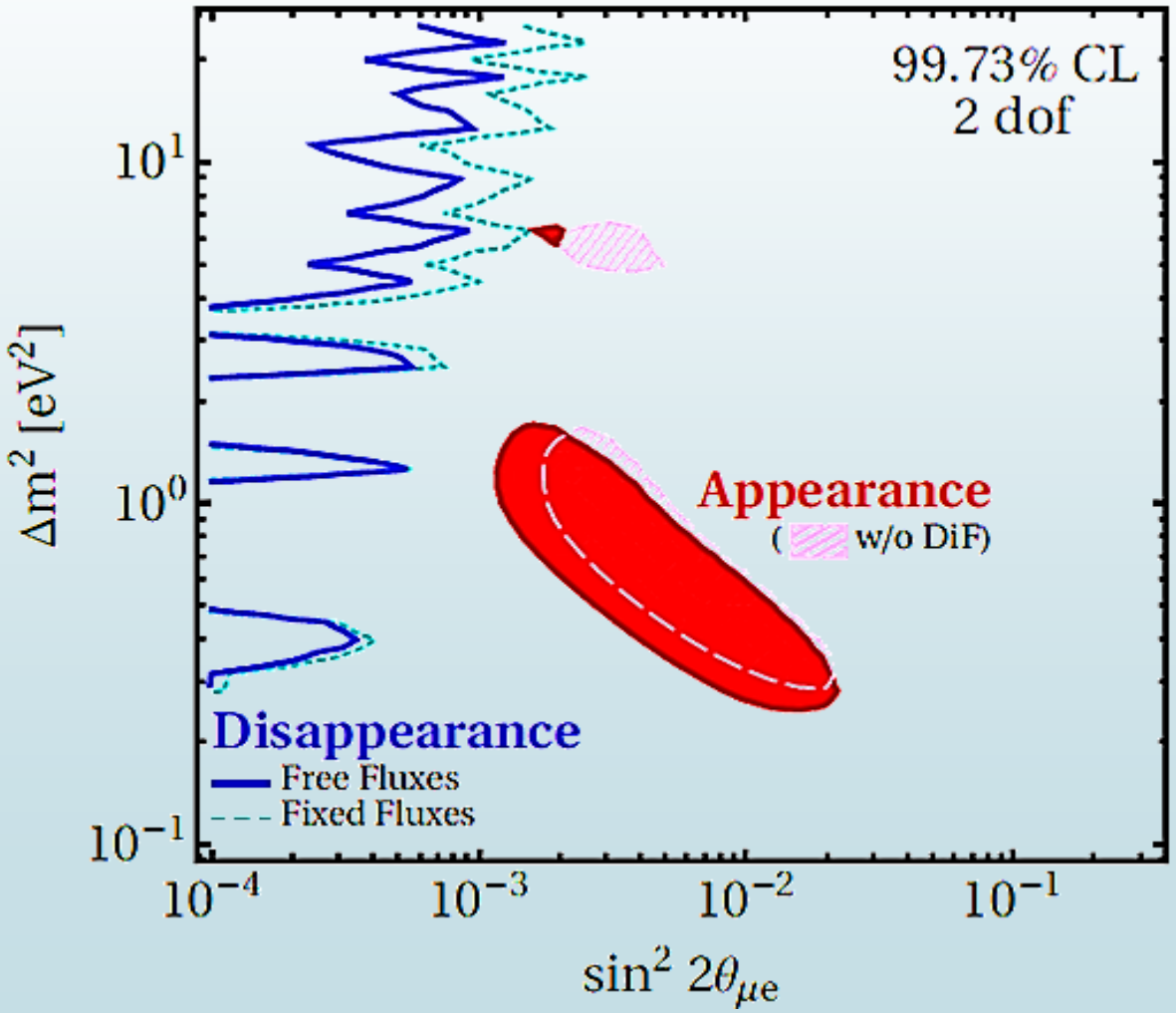


❖ What about eV Sterile Neutrino Interpretation ???

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

Leads to ν_μ to ν_e disappearance

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

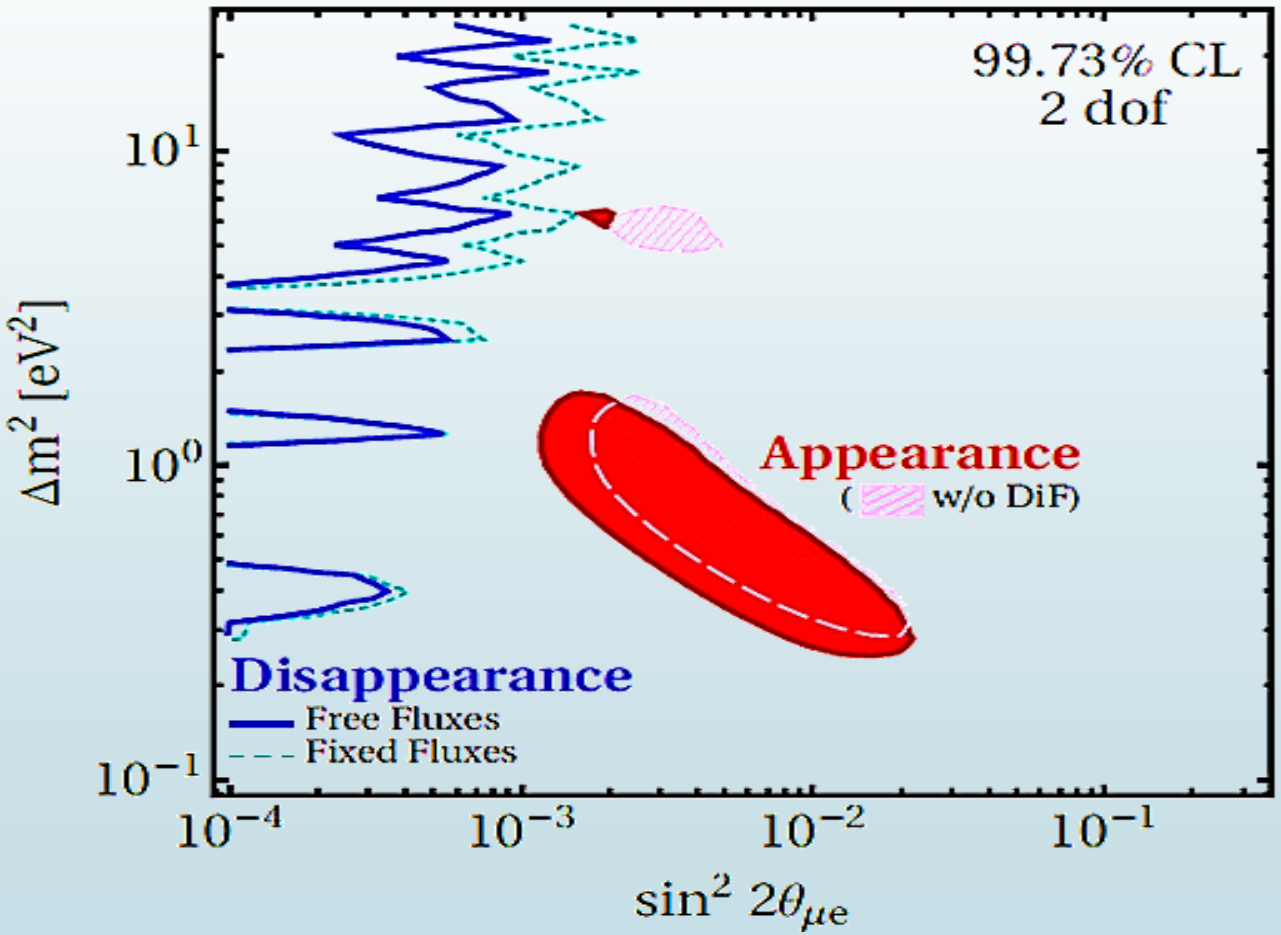


Mona Dentler et al. JHEP 1808 (2018) 010

❖ What about eV Sterile Neutrino Interpretation ???

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

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

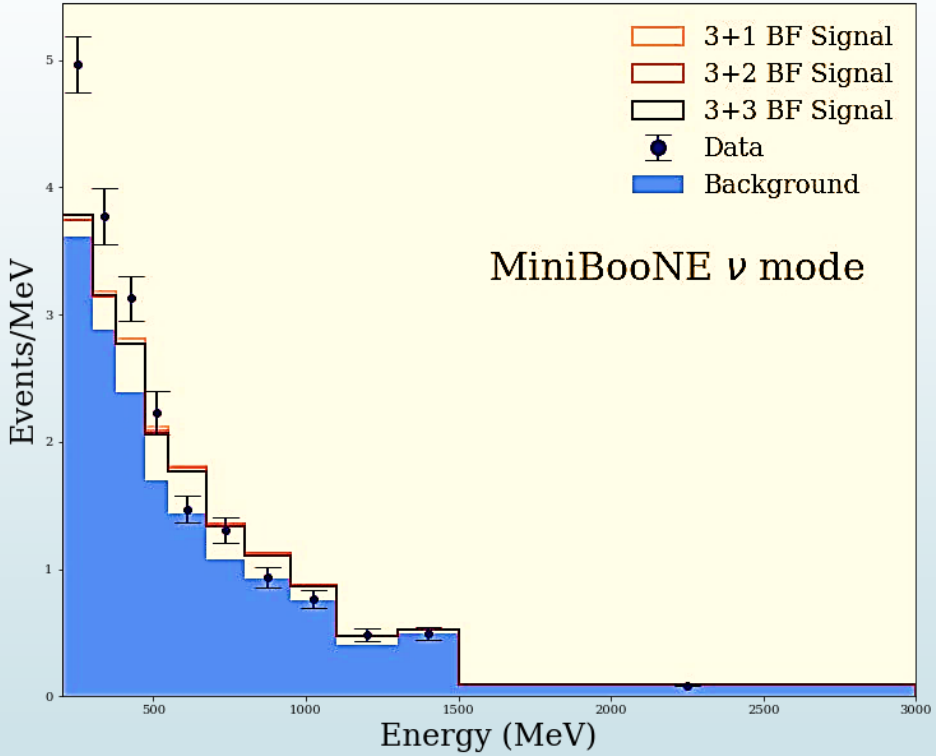


Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860

➢ 3+N GLOBAL FITS

Shortcoming:
Failure to accommodate MiniBooNE low-energy excess.

"3+N STANDARD STERILE NEUTRINOS": INSUFFICIENT

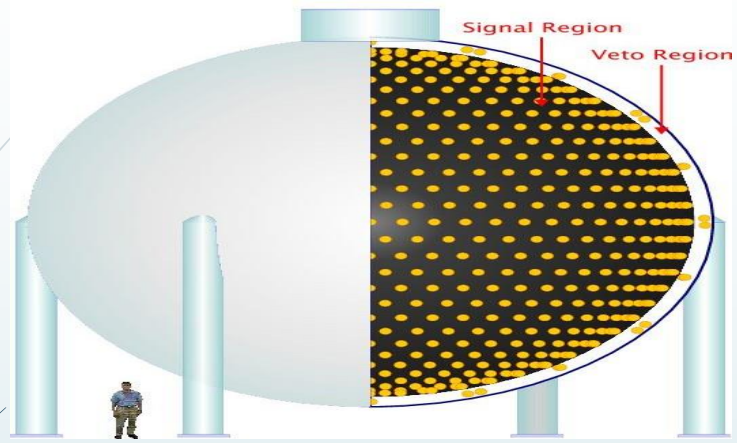


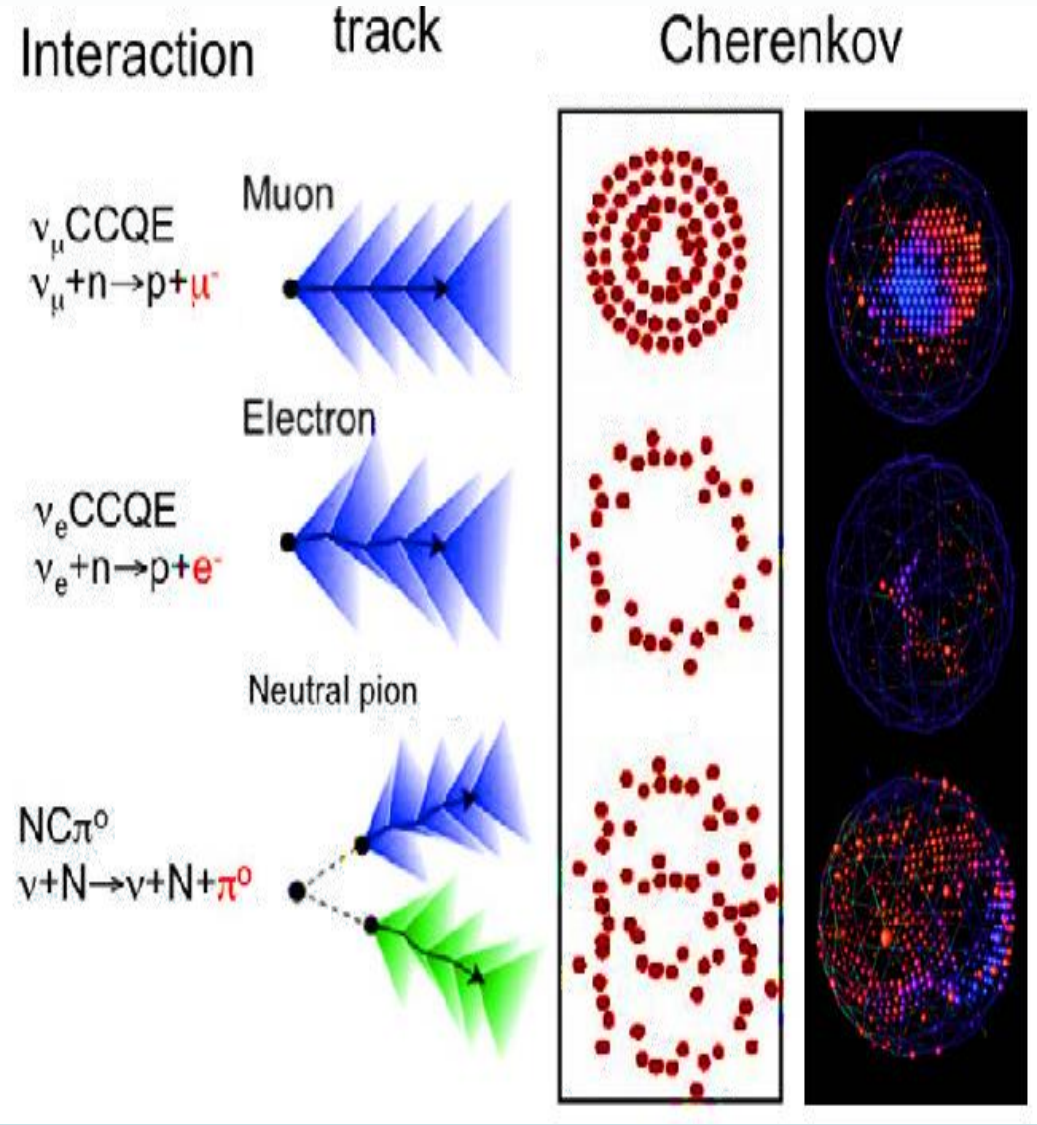
D. Cianci, et al. (Talk presented at Applied Antineutrino Physics Workshop 2018)

❑ Explanation of MiniBooNE's low energy excess

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

❖ Explanation of MiniBooNE's low energy excess



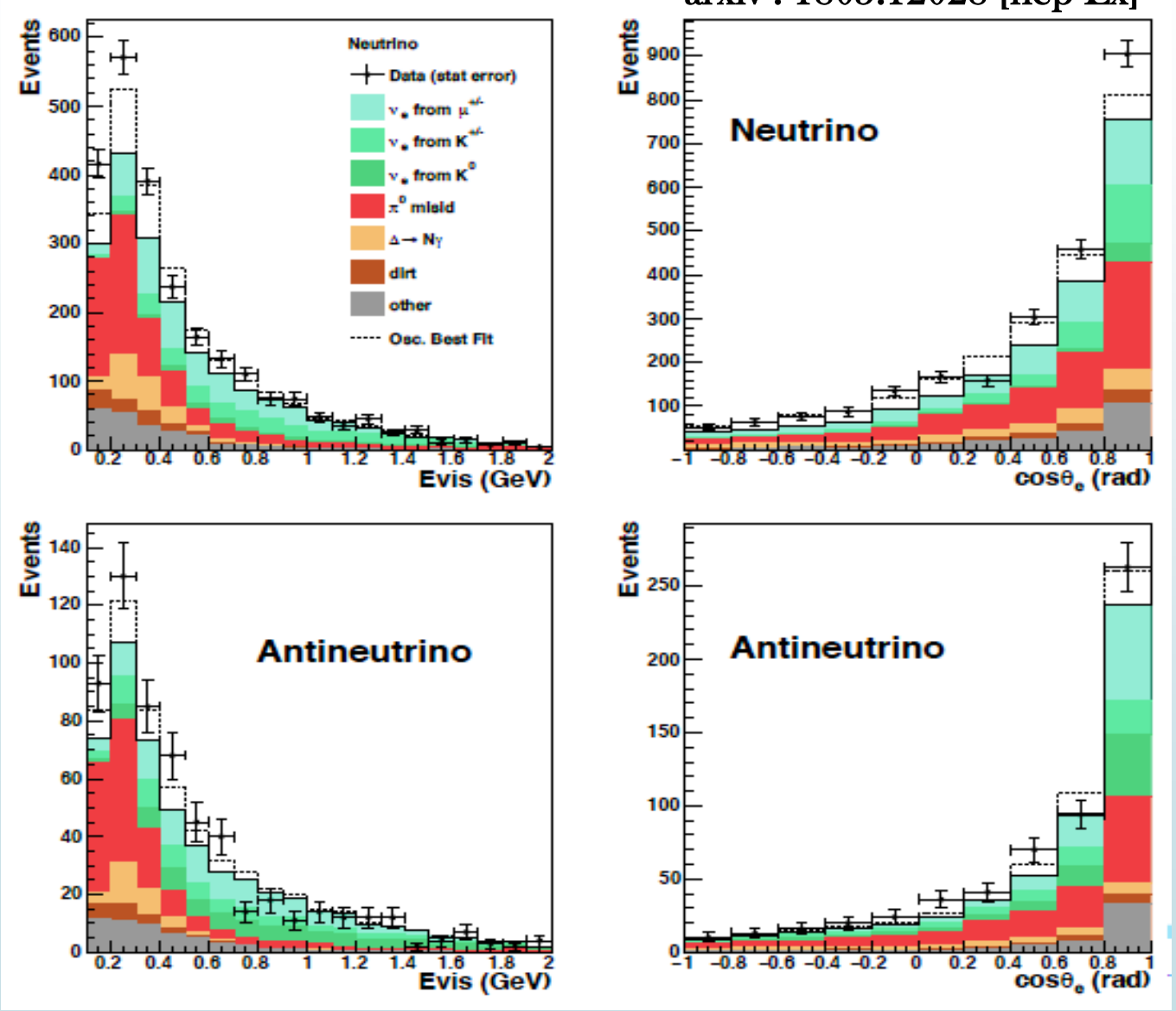


- MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles.
- Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.
- Excess is correlated with beam in power, angle and timing. It is present in positive and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

❖ Explanation of MiniBooNE's low energy excess

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

Z_D

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

❖ Explanation of MiniBooNE's low energy excess

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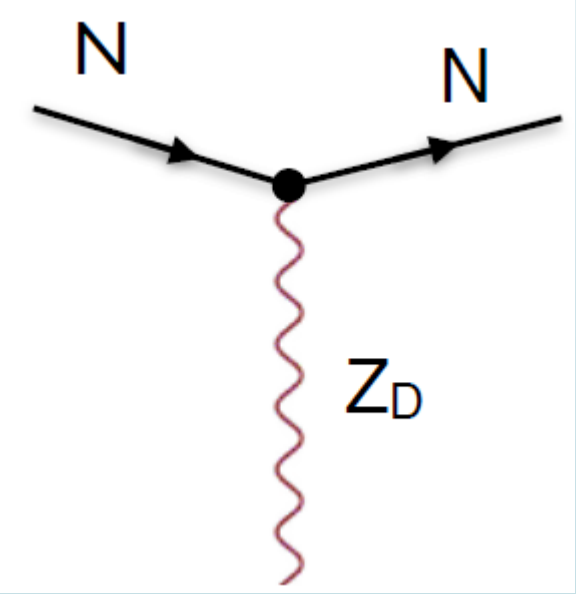

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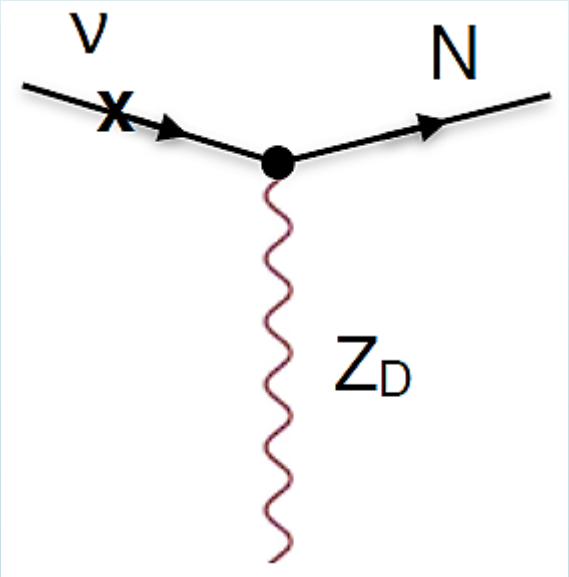

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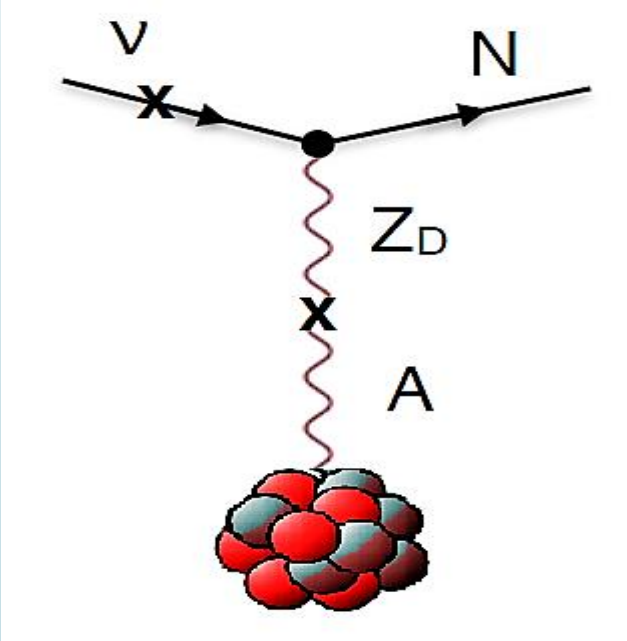

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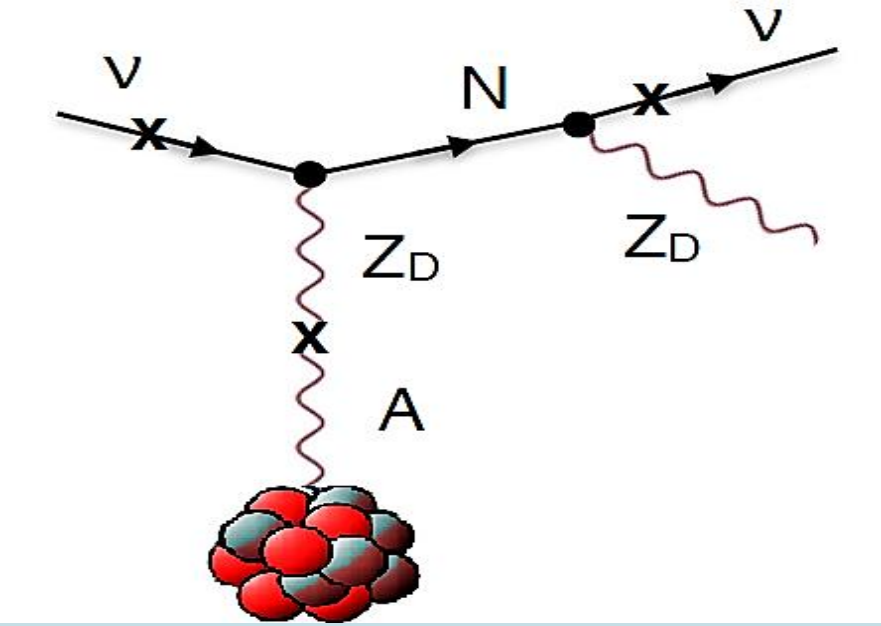

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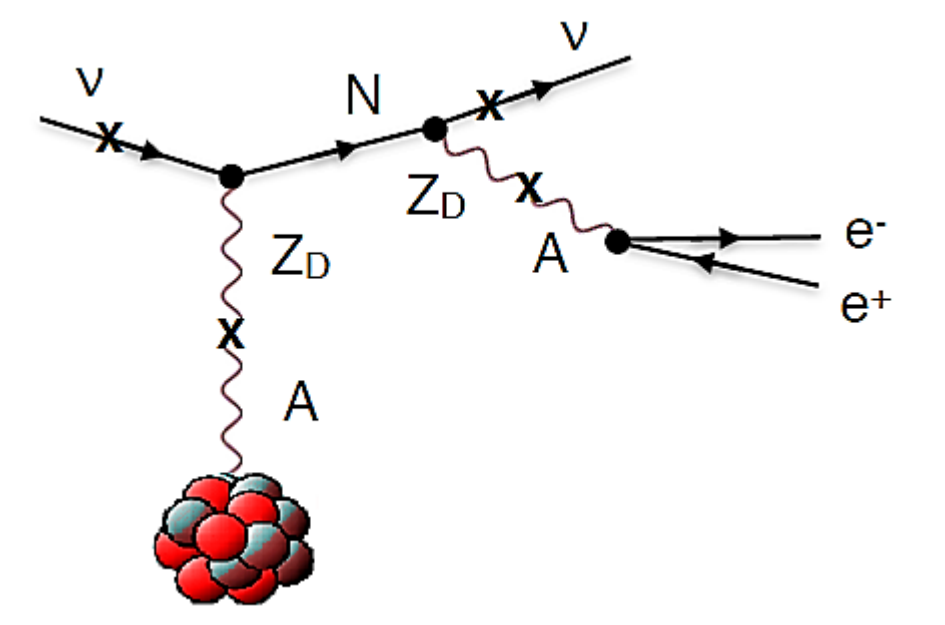

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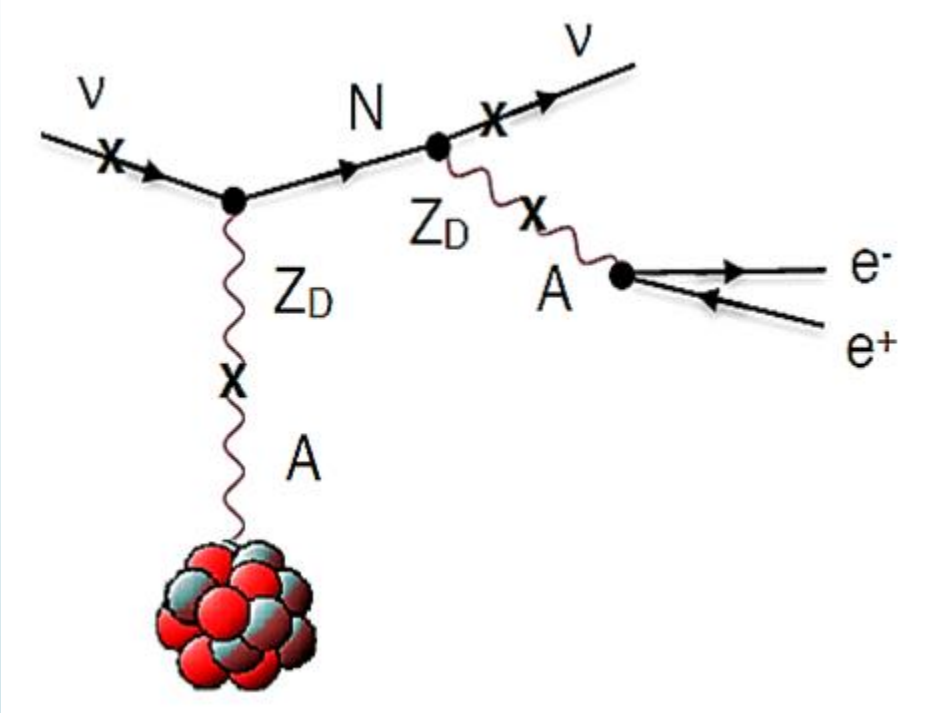
- Relevant part of the Lagrangian :



Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500

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

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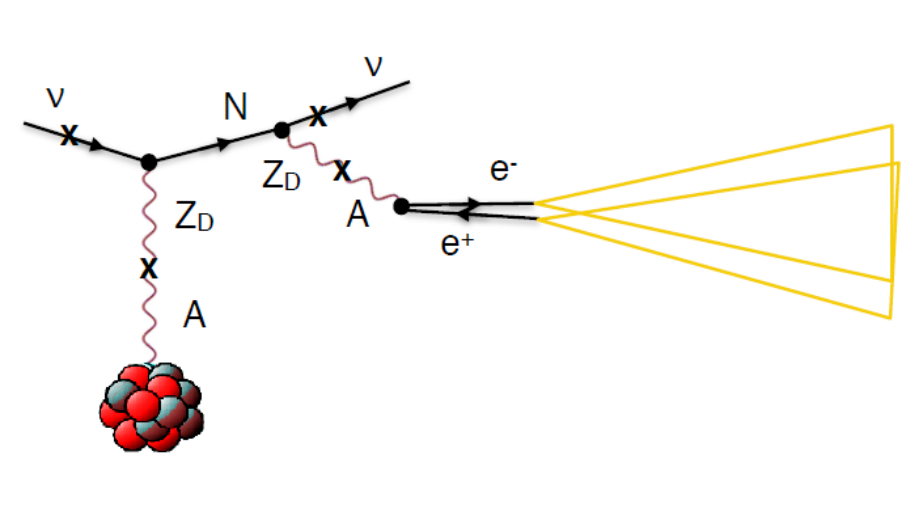

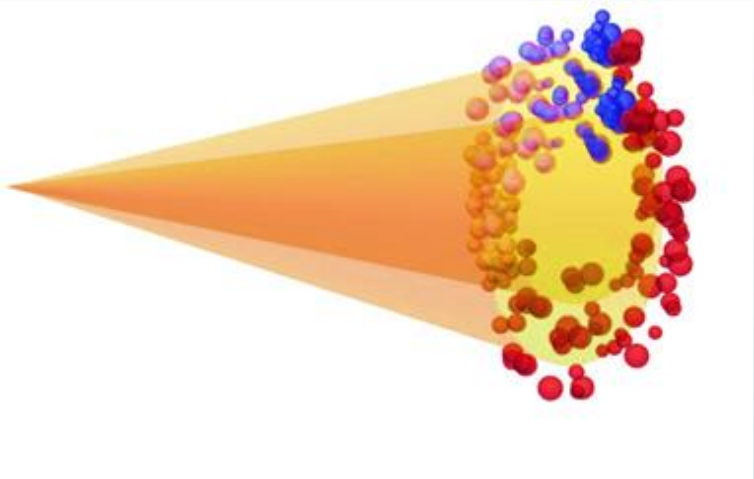

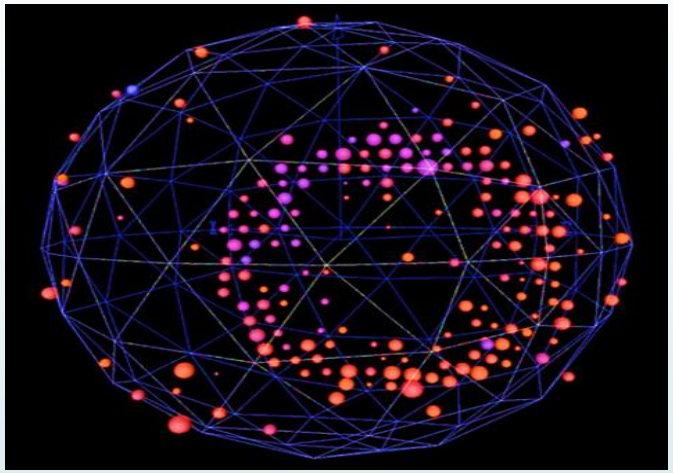

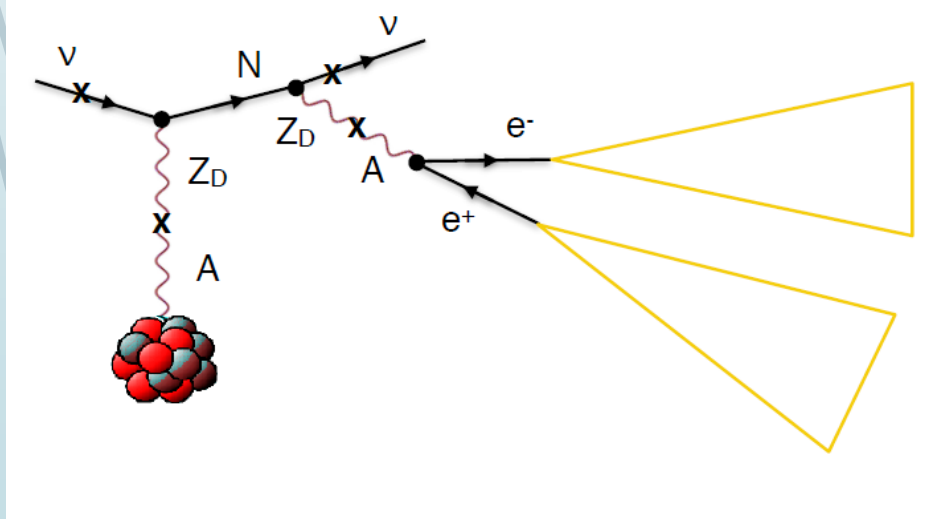

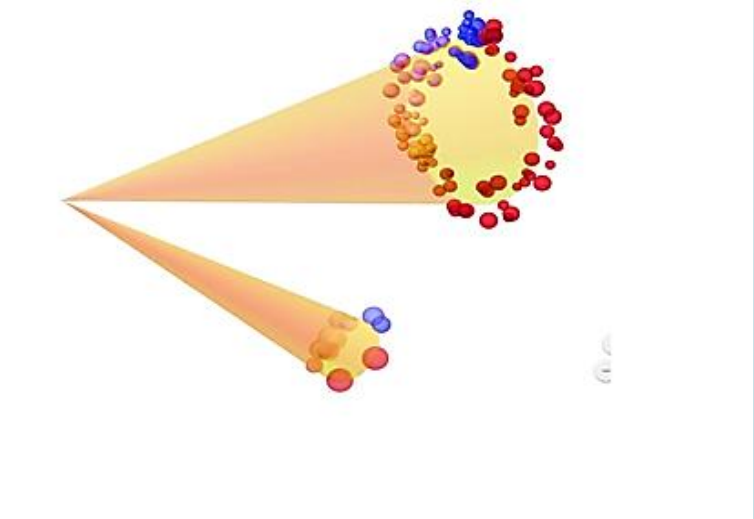

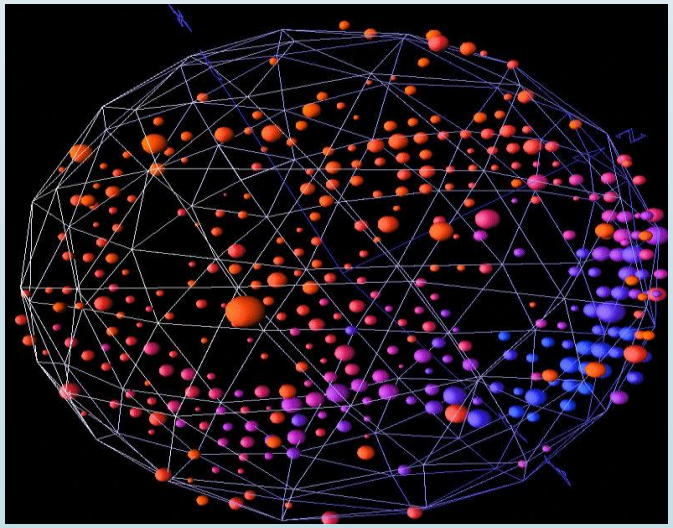

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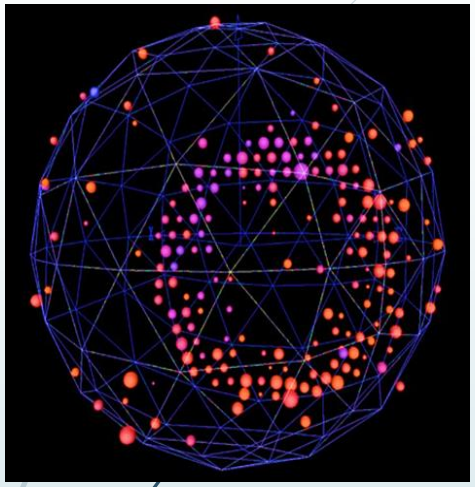
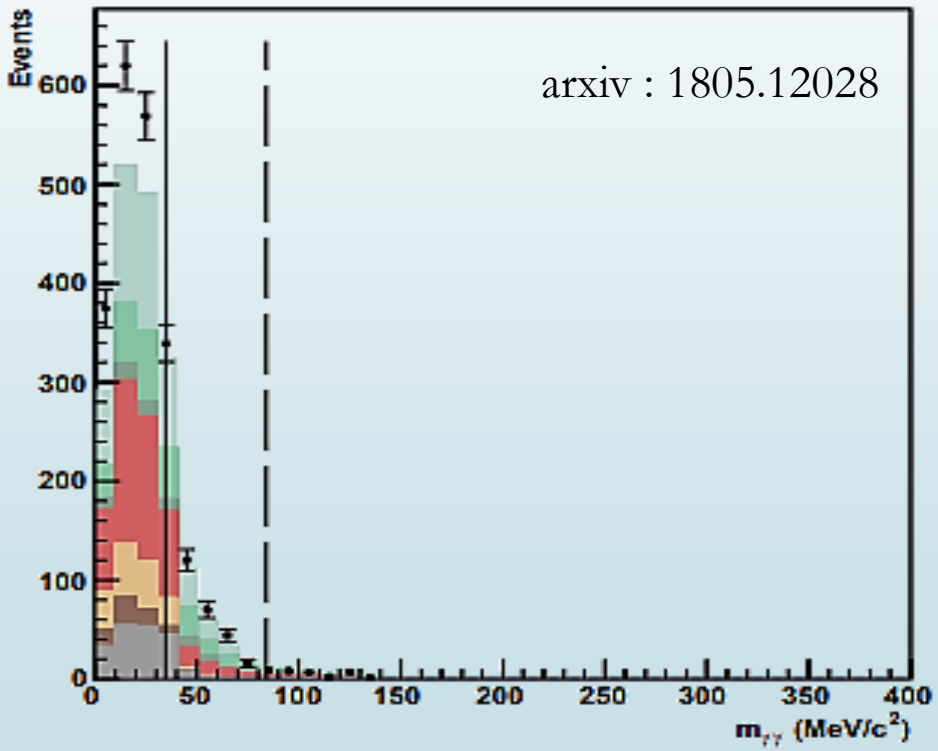
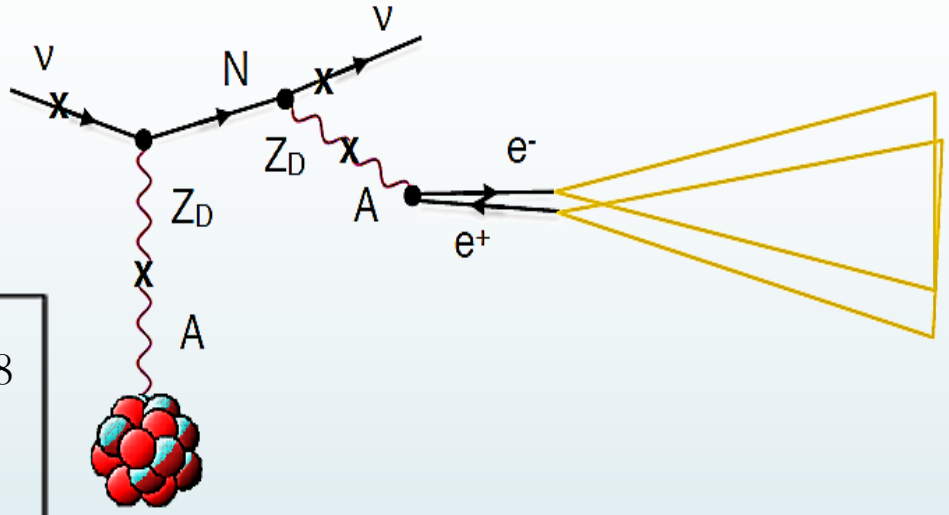


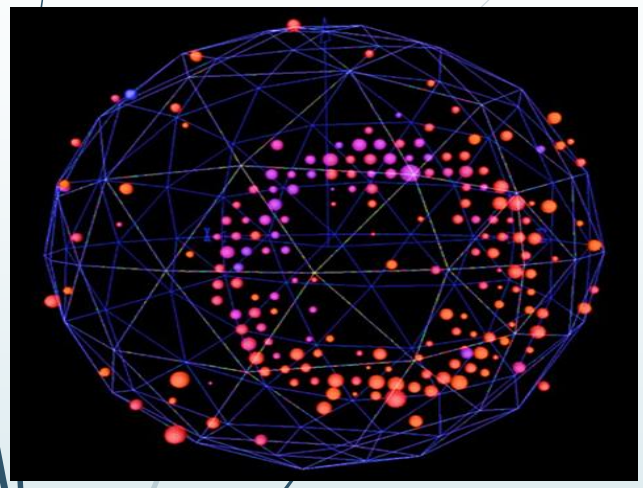


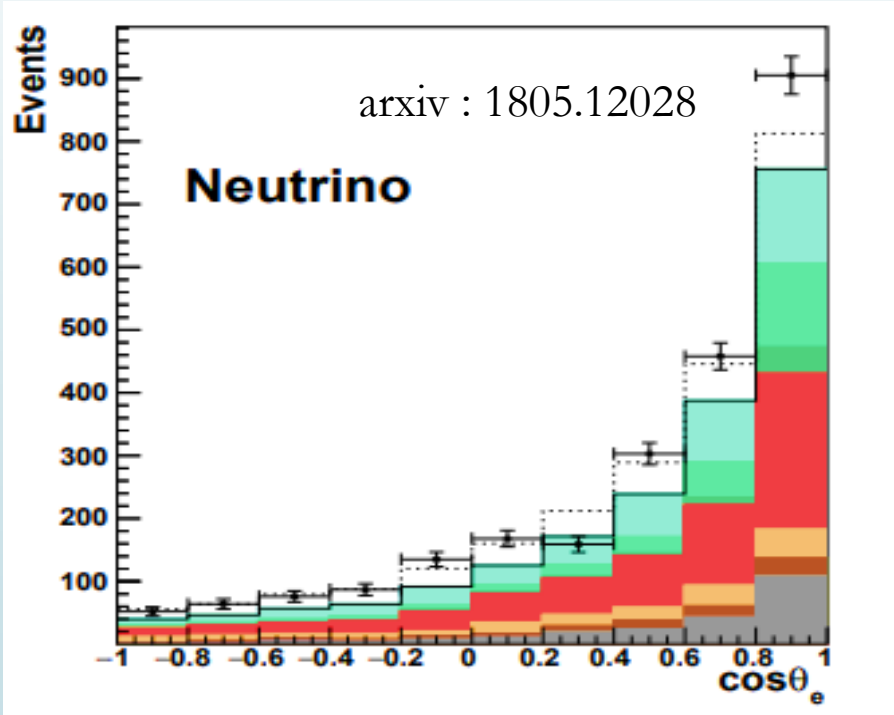


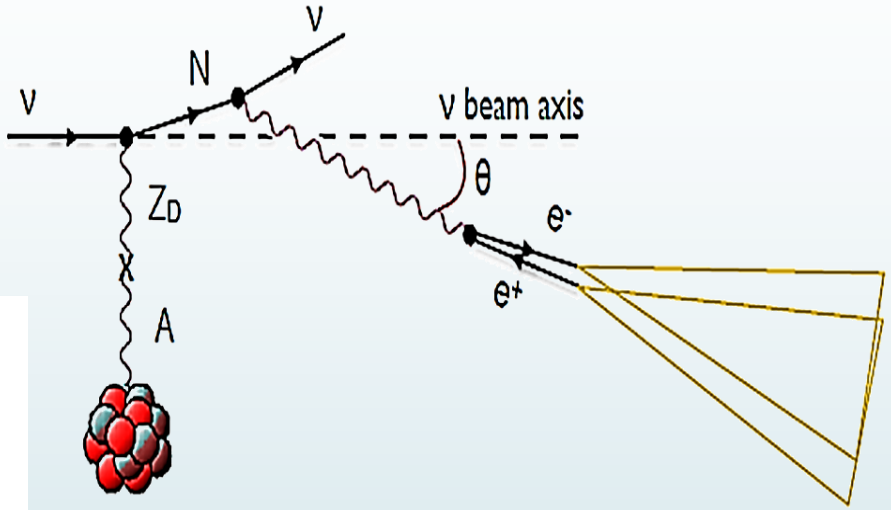
If e^+e^- pair is collimated ($\cos\theta_{ee}$ > 0.99-ish), it will be classified as e-like

❖ 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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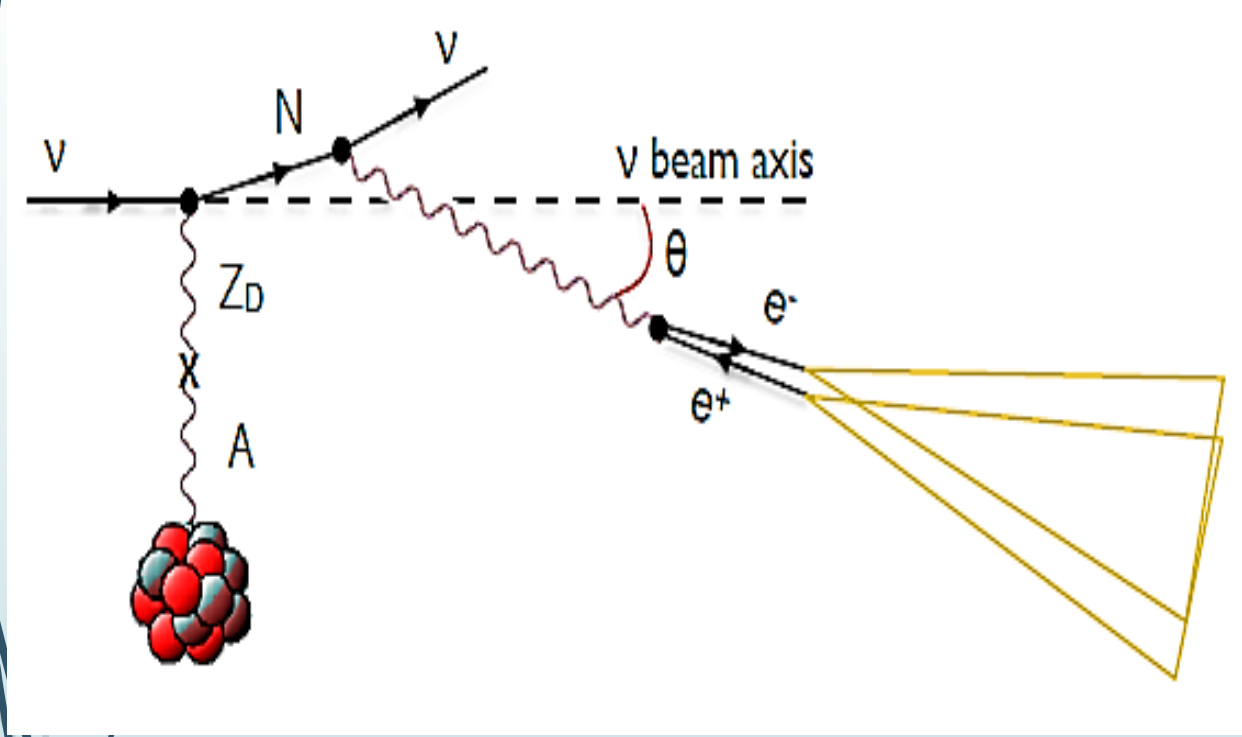
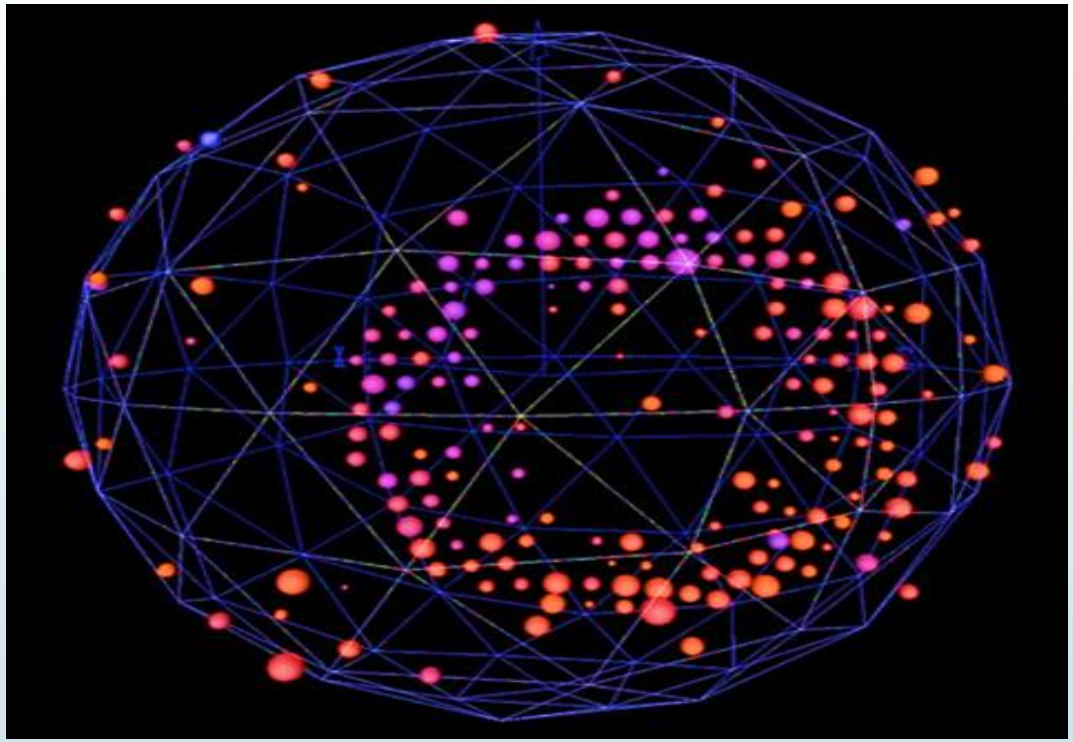




(1) N_D should be heavy (> 100 MeV) so its decay products are not so boosted

(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

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

$\alpha_D = 0.25$

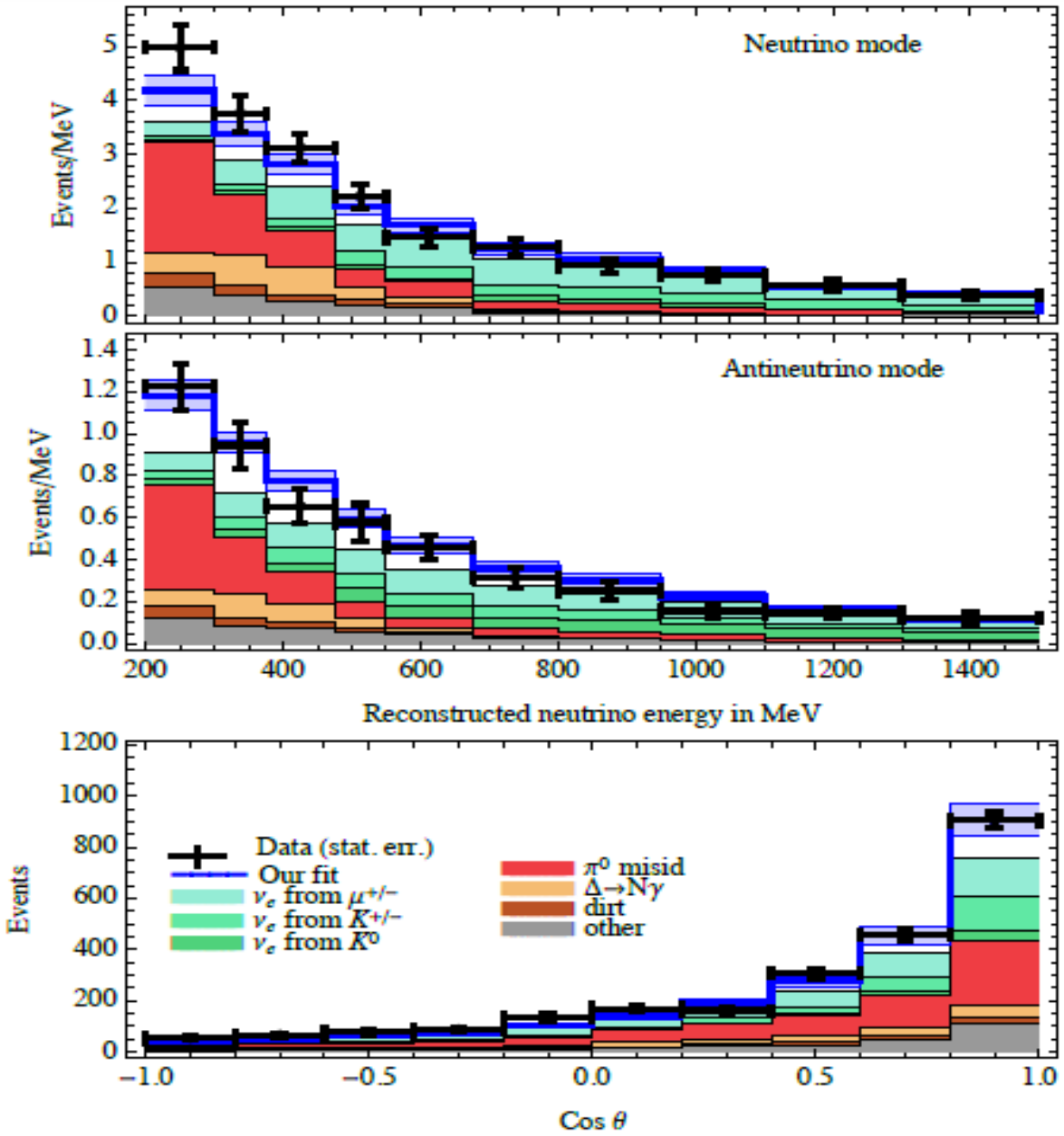
$\alpha\varepsilon^2 = 2 \times 10^{-10}$

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

Bertuzzo et al 1807.09877

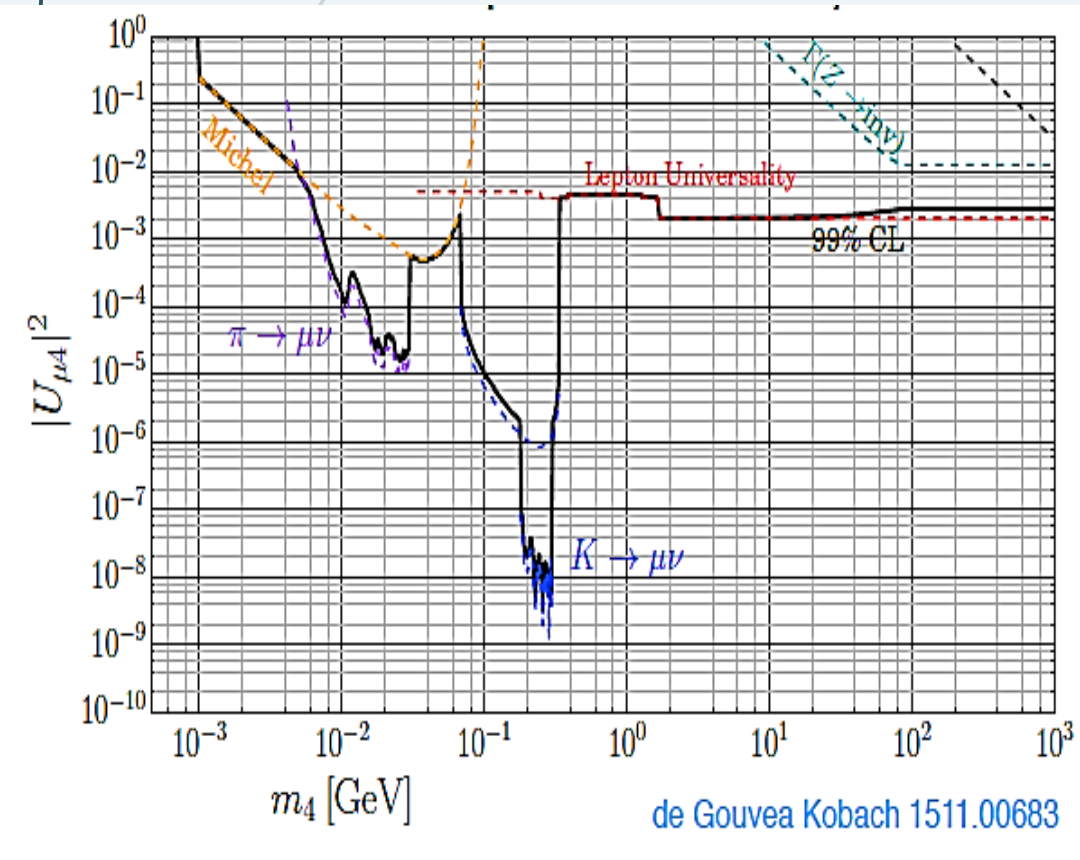
See also Ballett et al 1808.02915

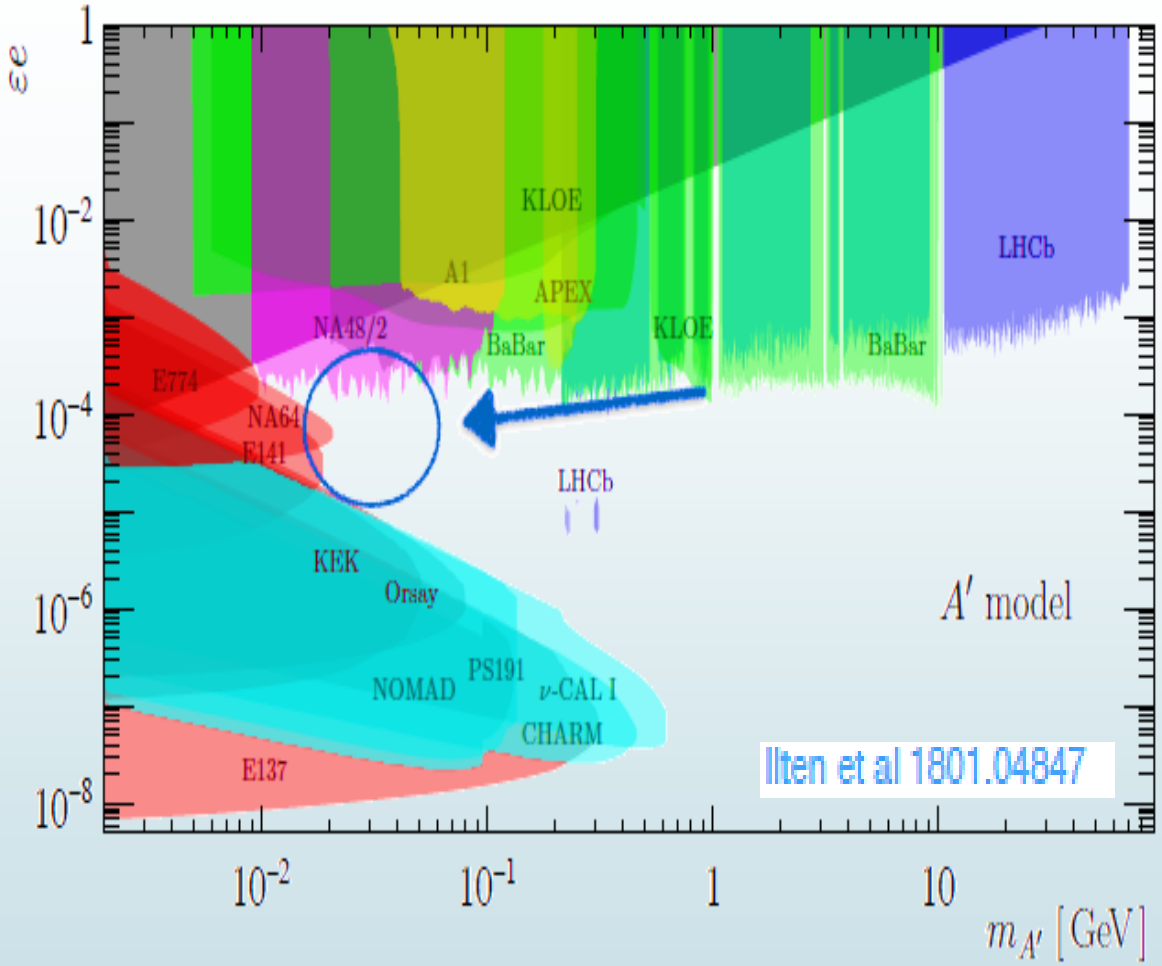
for different realization of the mechanism



❖ Constraint on Light Dark Sector

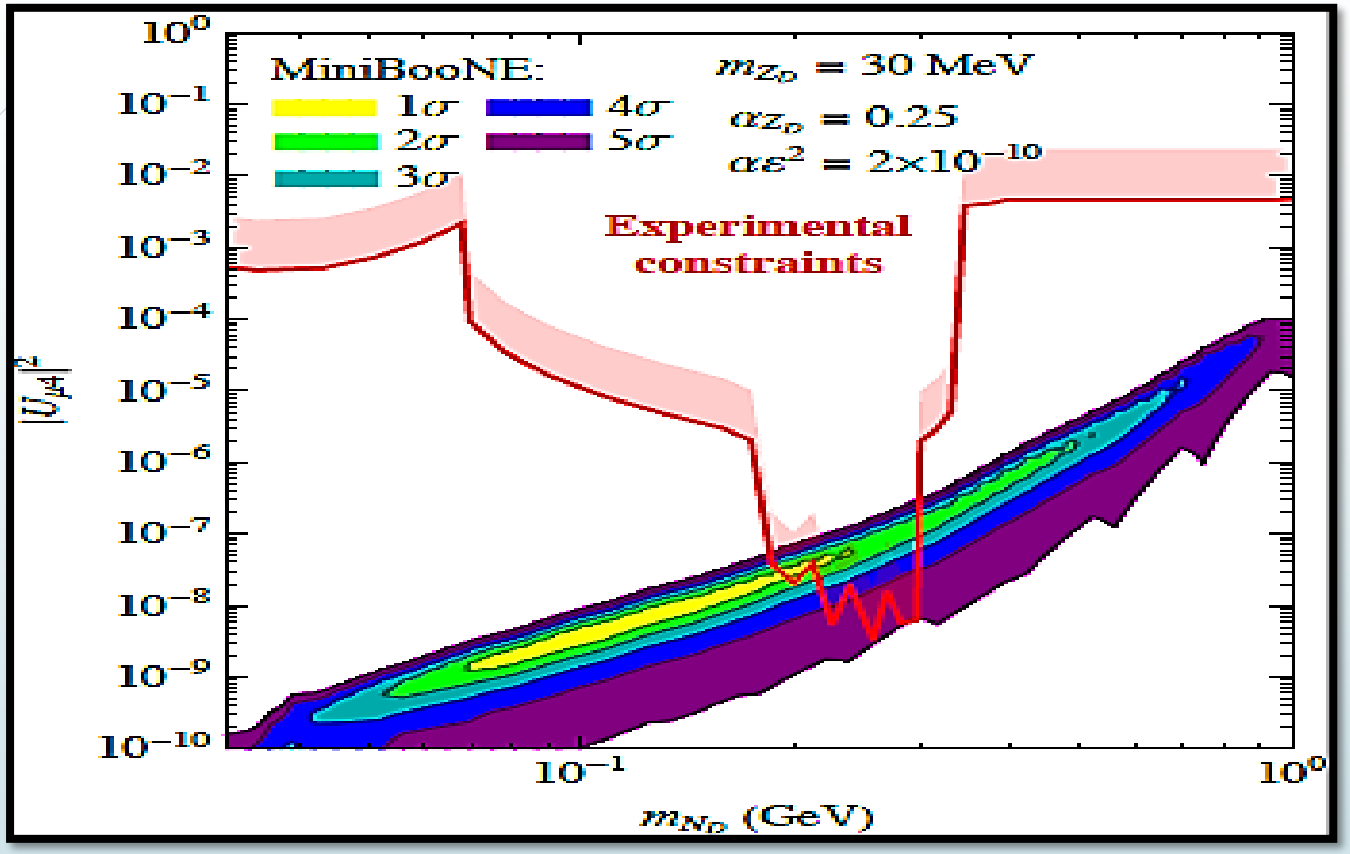
Model Independent Constraint on Heavy Sterile Neutrino





- 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

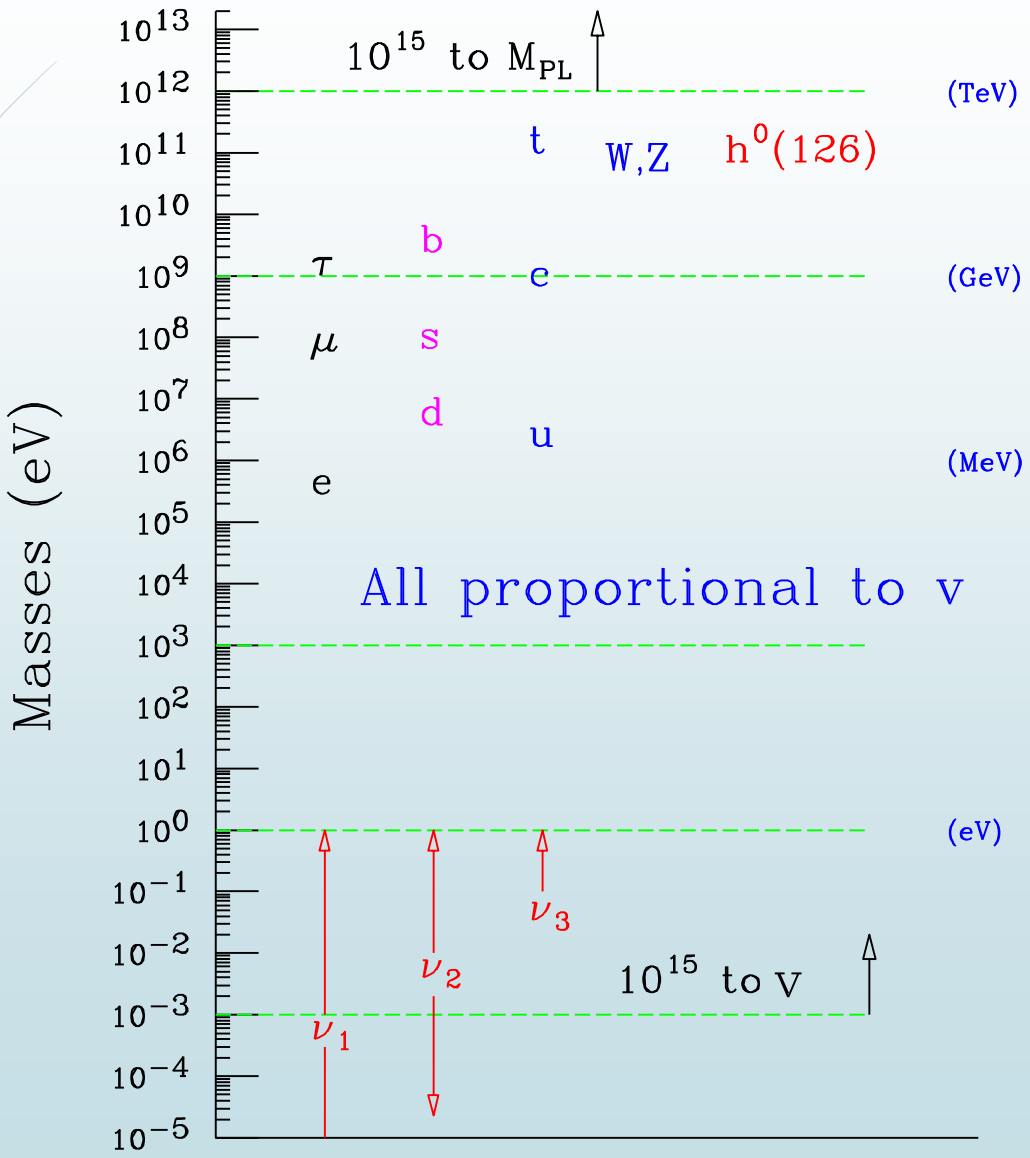


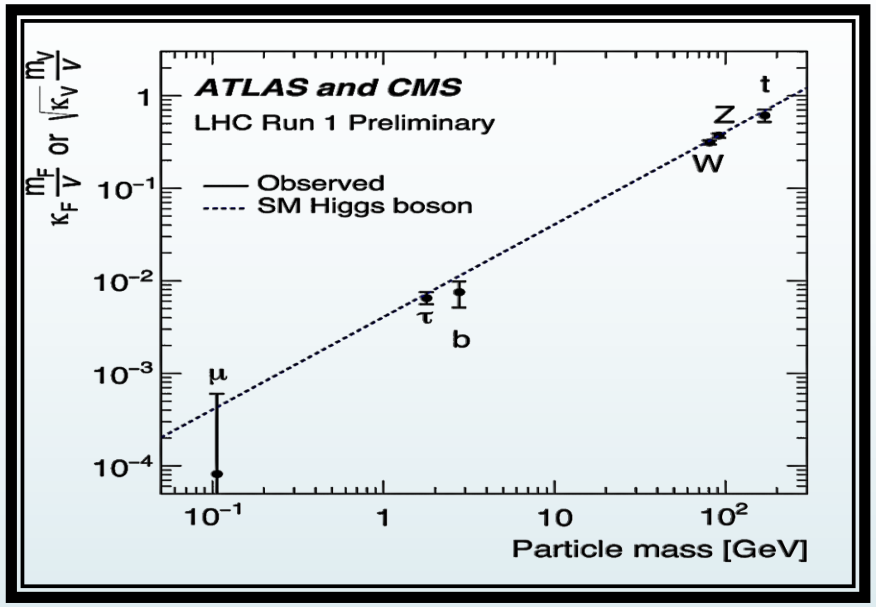
Bertuzzo et al 1807.09877

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

Connection to Neutrino Mass Generation Mechanism

Neutrino Mass → 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

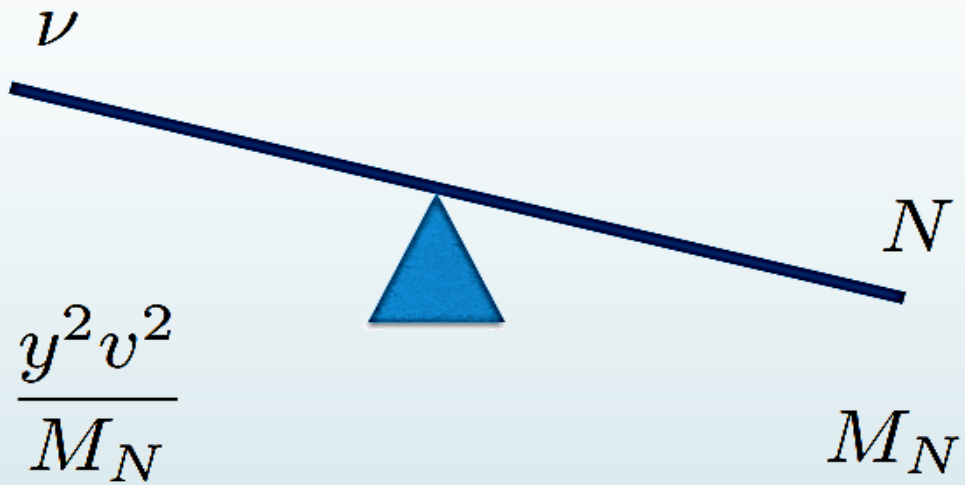
- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ⋆ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ⋆ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ⋆ Type-III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

❖ 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

❖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**

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

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

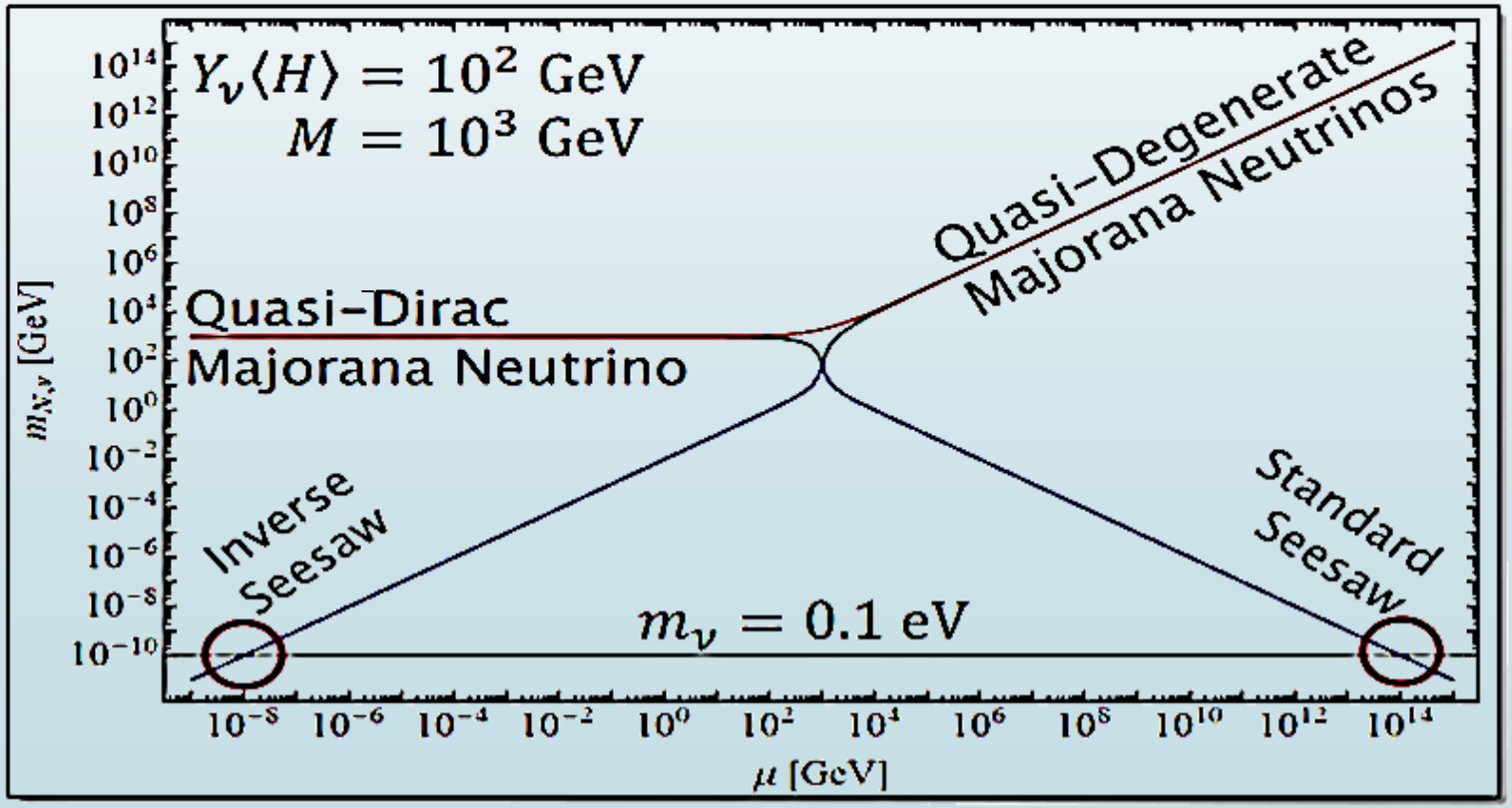
- Why μ is much smaller than TeV scale?

Scale of Seesaw Mechanism

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

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

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



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**
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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

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

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

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

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

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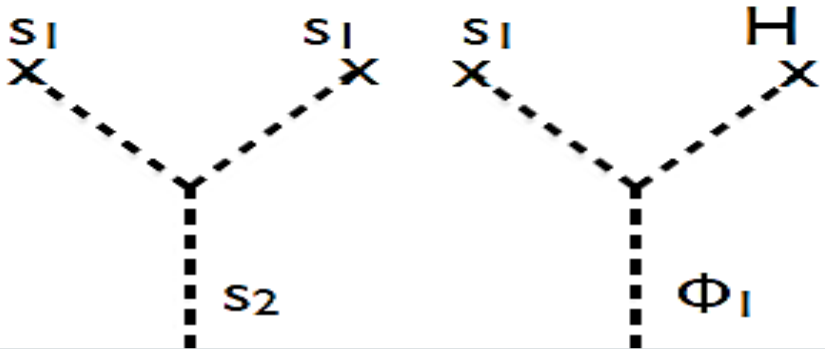
Neutrino masses from light physics

Minimum scalar content

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

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

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



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

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❖Inverse Seesaw

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

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

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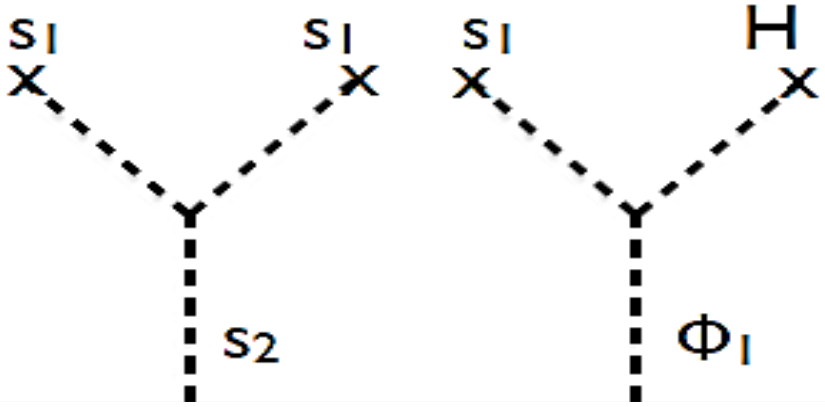

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Neutrino masses from light physics

Minimum scalar content

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

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

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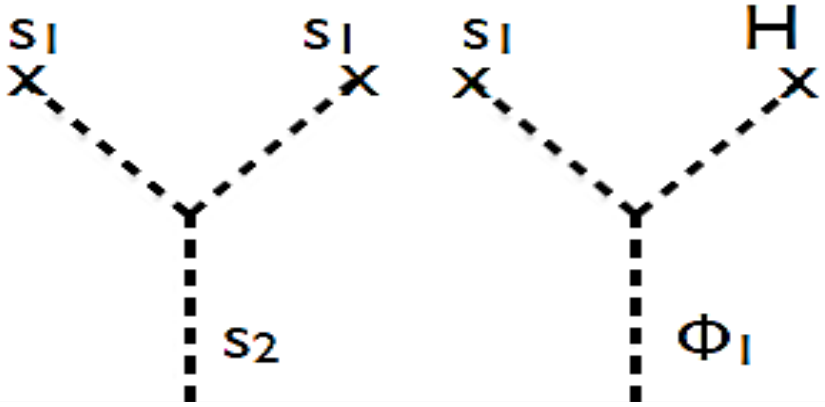

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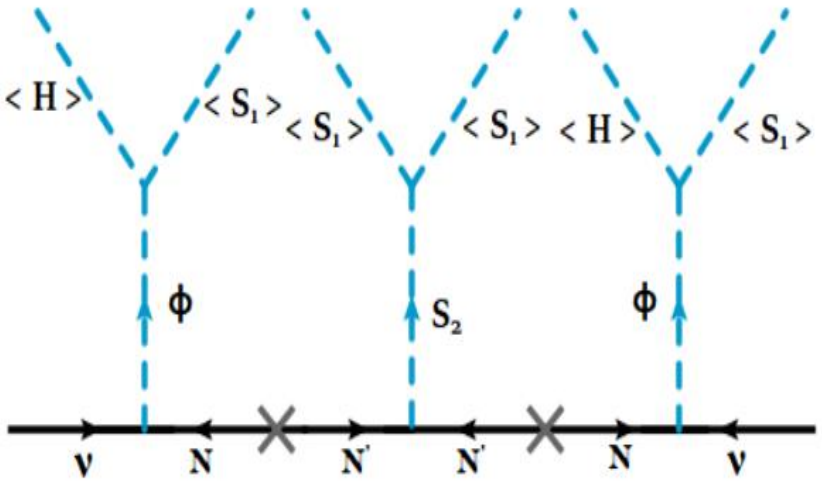
Neutrino masses from light physics



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

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

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}	$\mathcal{O}(10^{-6})$

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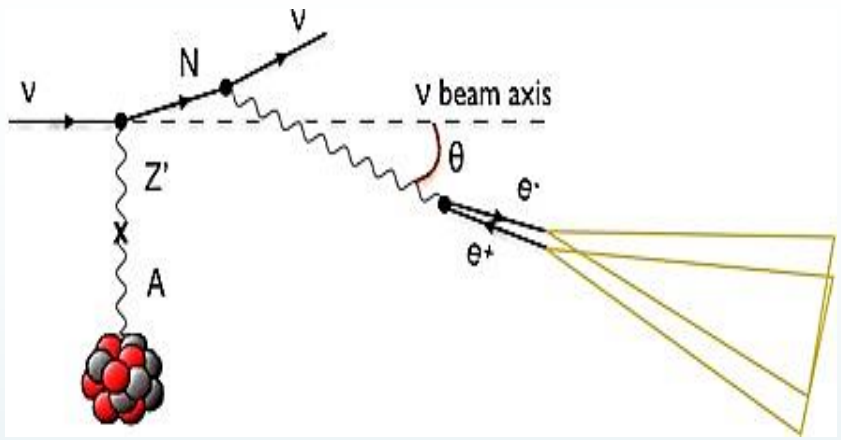
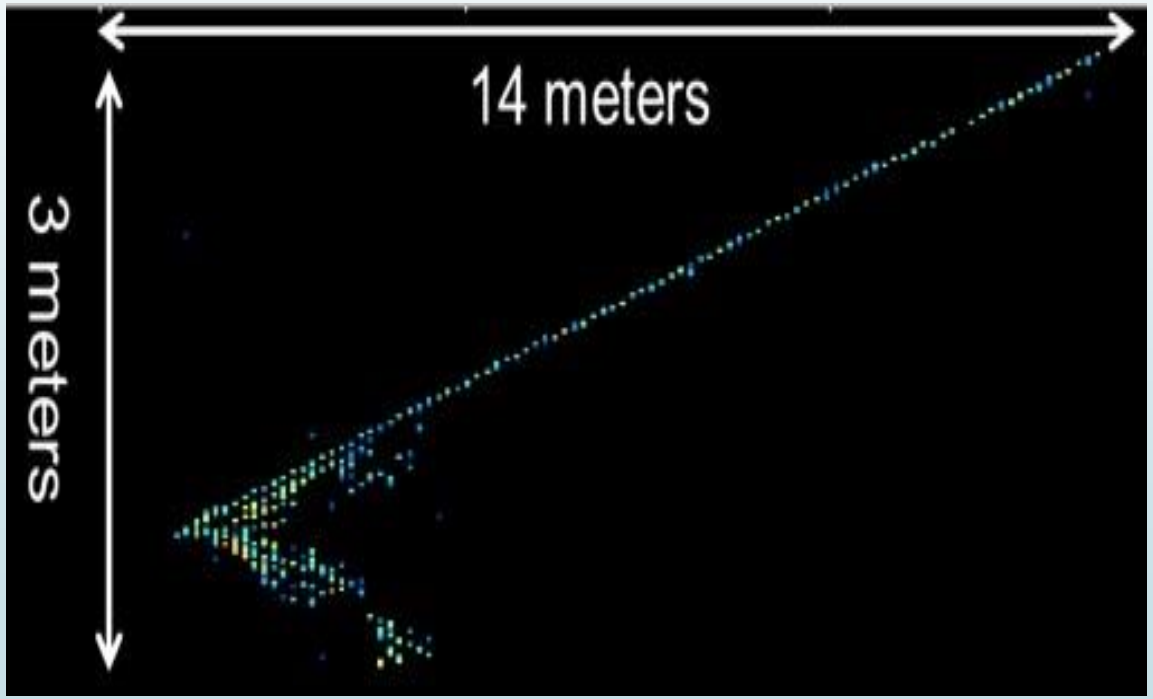
❖ Phenomenology on other neutrino experiment

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



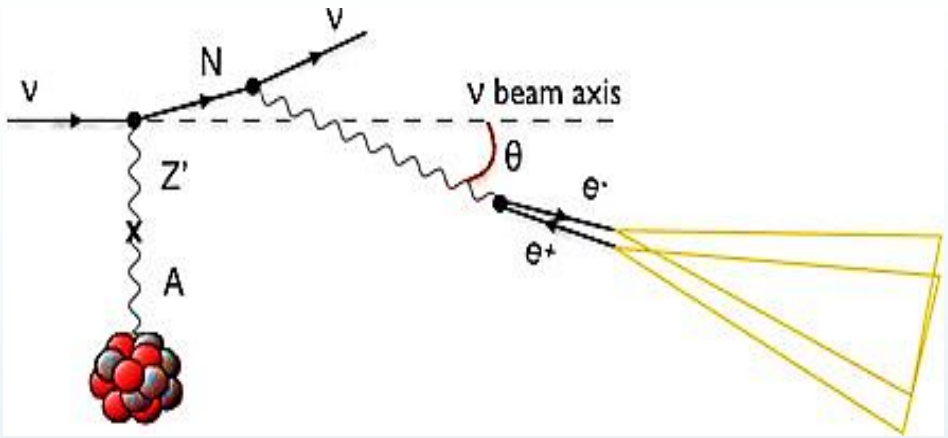
General signature:
Heavy enough Z_D can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized…)

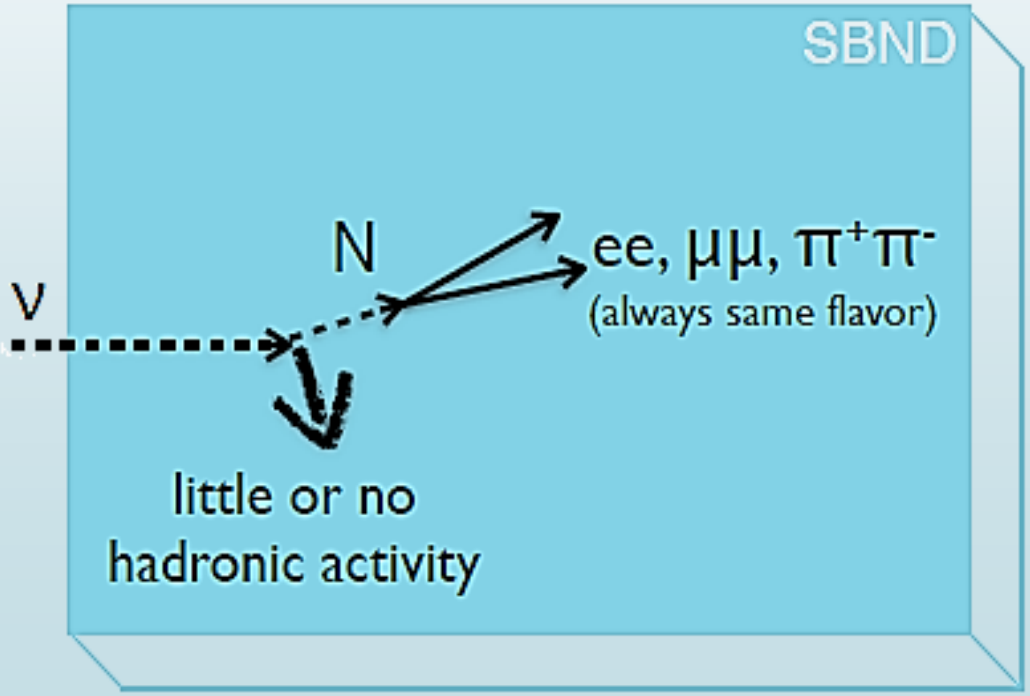


Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N

❖ What happens at the SBN program?

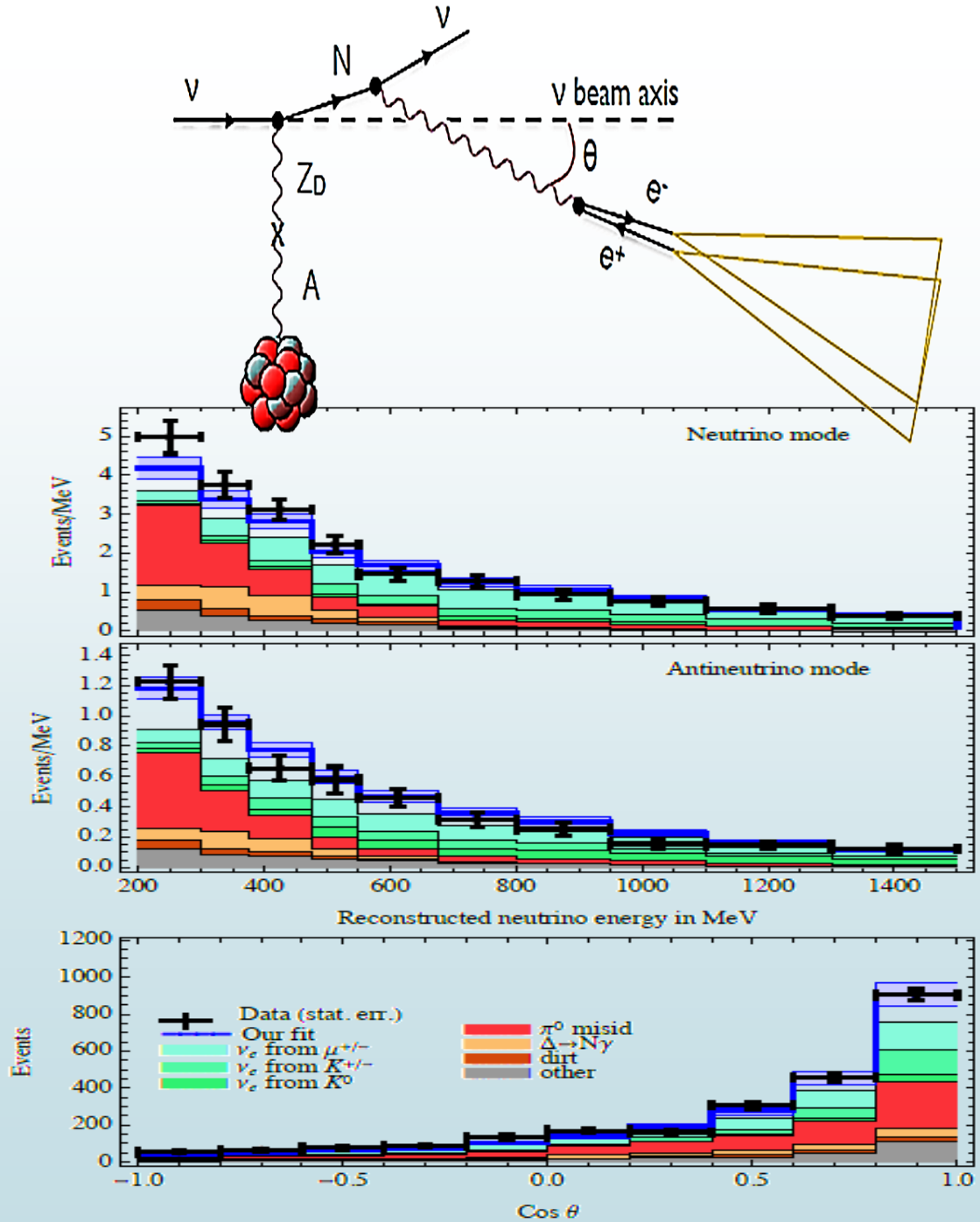
- ✓ **No baseline dependence**
- ✓ **Almost no hadronic activity to tag interaction vertex**
- ✓ Decays to collimated e^+e^- pairs
- ✓ More events due to coherence:
- ✓ ${}_{6}C$ vs ${}_{18}Ar$ ~ 3 times more events for same exposure
- ✓ Hard to probe !!!





Conclusions :

- Novel explanation of MiniBooNE
- Agreement with all EXP data
- Novel, simple framework
- 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
ν


DO YOU KNOW MY ORIGIN ?
PROBABLY YES !
ν
MiniBooNE


thank you!