A light dark sector to explain MiniBooNE's low energy excess
or
Has MiniBooNE observed the mechanism behind ν masses?

Pedro A. N. Machado

October 2018

Based on 1807.09877 and 1808.02500 in collaboration with E. Bertuzzo, S. Jana and R. Zukanovich-Funchal

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Short baseline anomalies

Many anomalies in short baseline neutrino experiments

Explanation is a challenge - tensions, *ad hoc* models, etc

LSND experiment

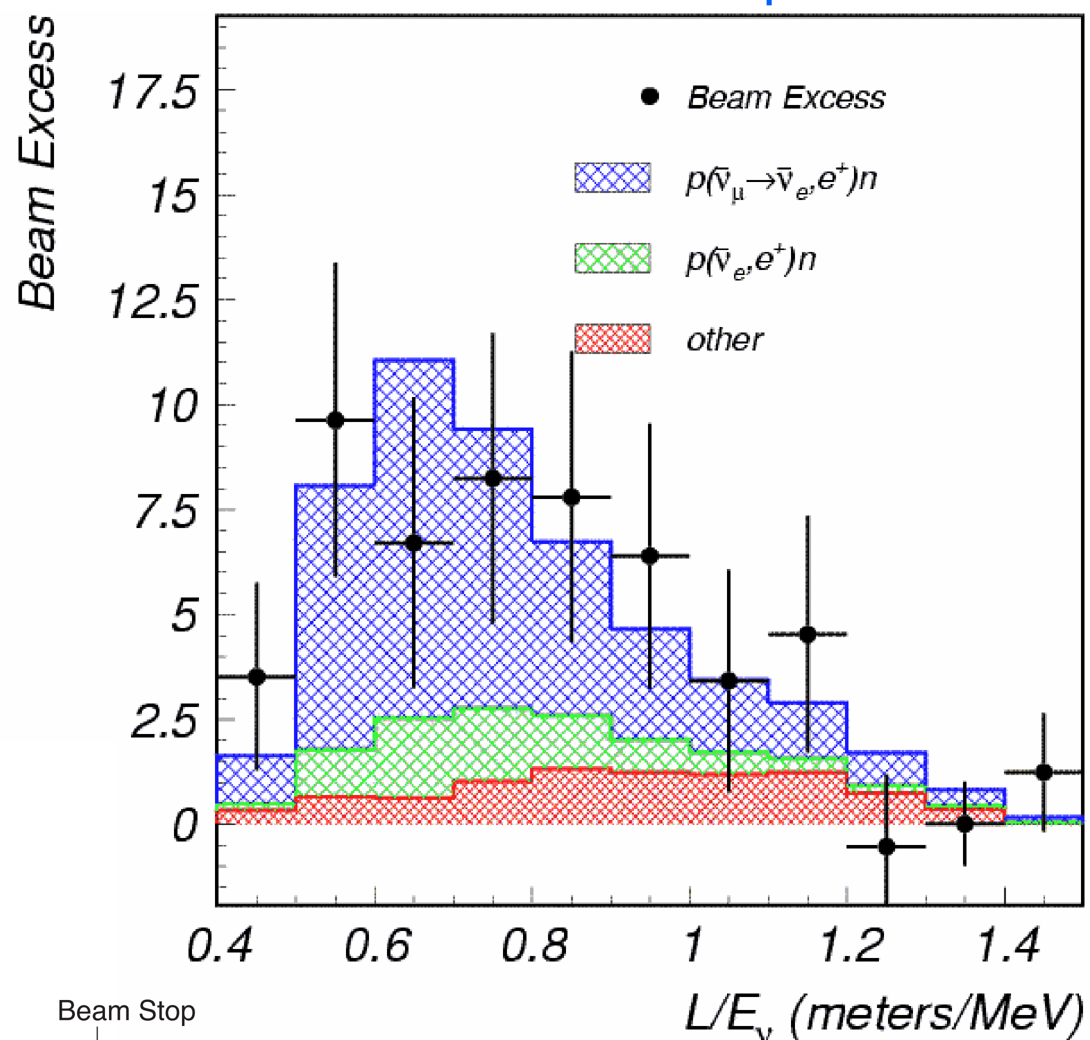
@Los Alamos

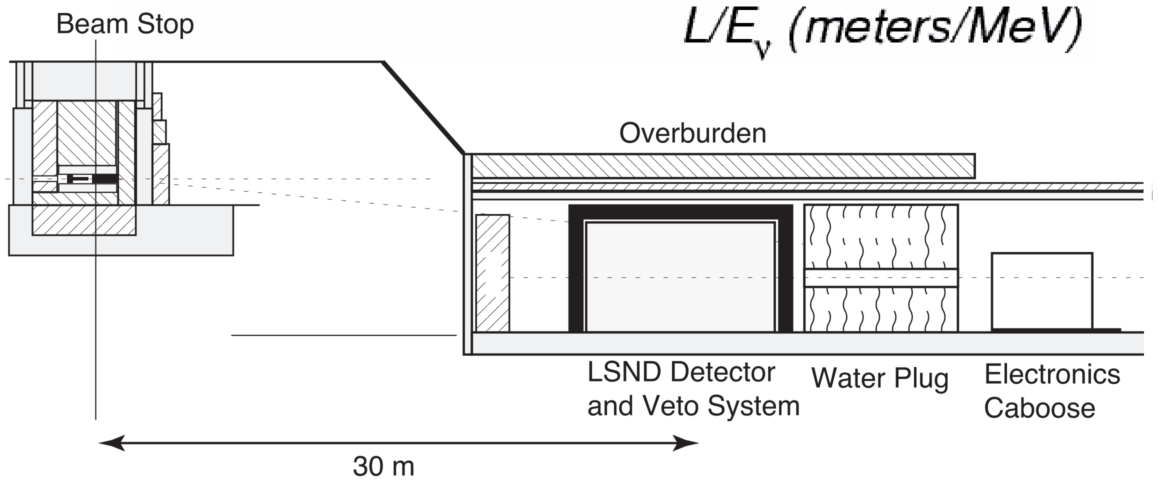
Intense proton beam

$$p + X \rightarrow \pi^+ + X'$$
$$\hookrightarrow \mu^+ \nu_\mu \text{ (DAR)}$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

LSND detected more $\bar{\nu}_e$ than expected (3.8σ excess)

hep-ex/0104049





MiniBooNE Experiment

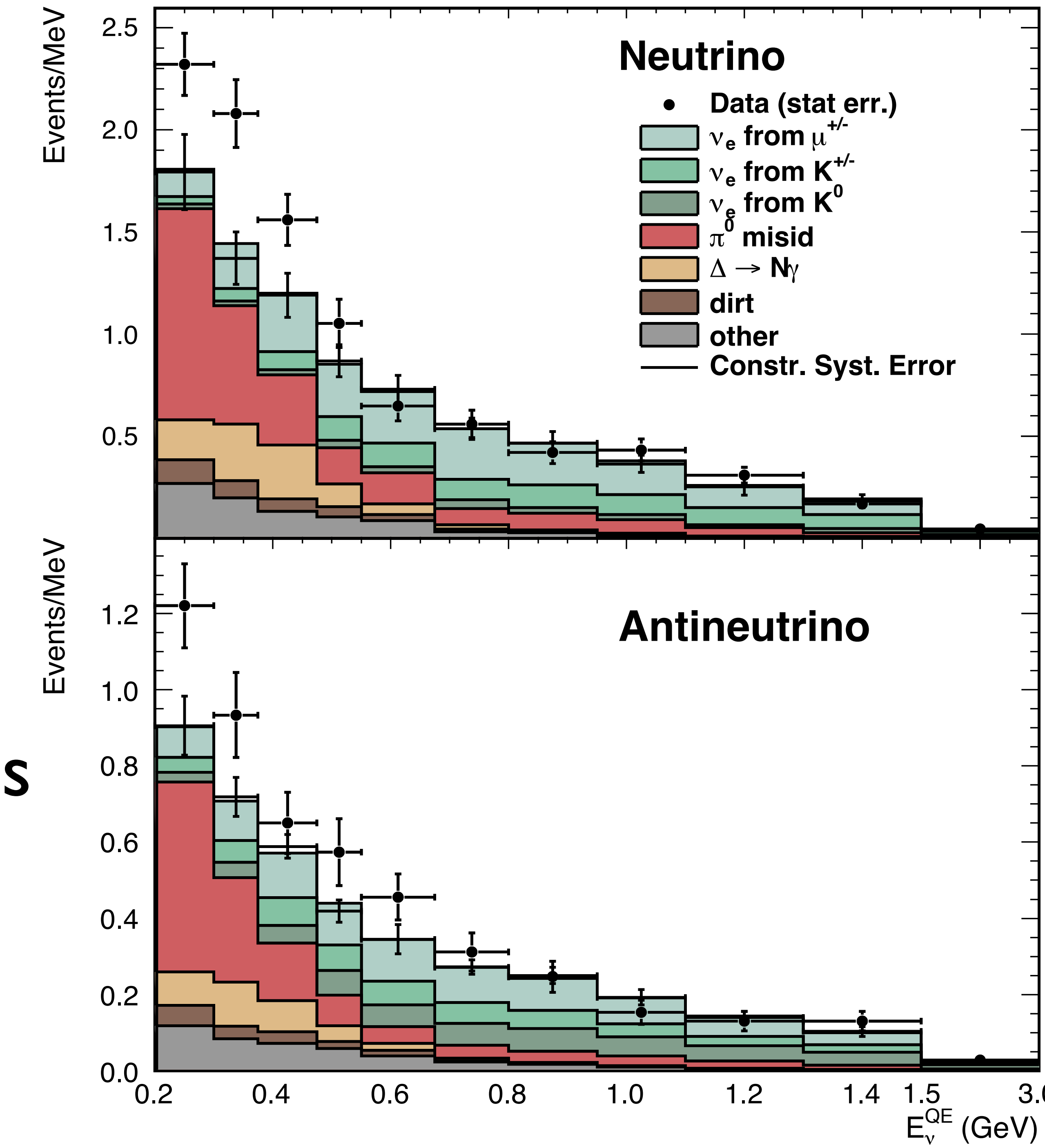
@Fermilab

Intense proton beam

$$p + X \to \pi^+, \pi^-, \cdots + X'$$
$$\hookrightarrow \mu^+ \nu_\mu$$

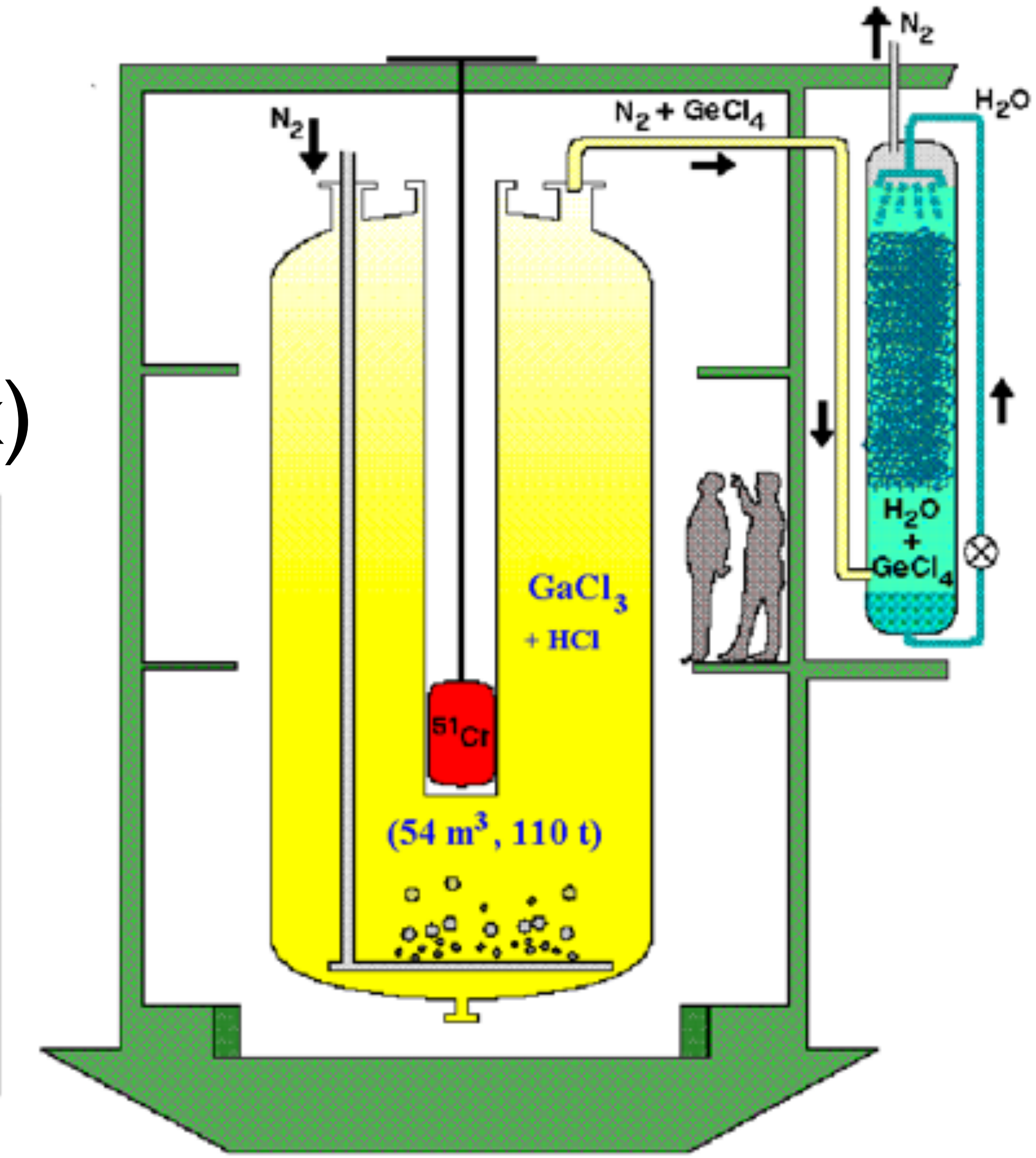
Neutrino and antineutrino modes see excesses of ν_e and $\bar{\nu}_e$ (combined is also a 3.8σ excess)

MiniBooNE 1207.4809



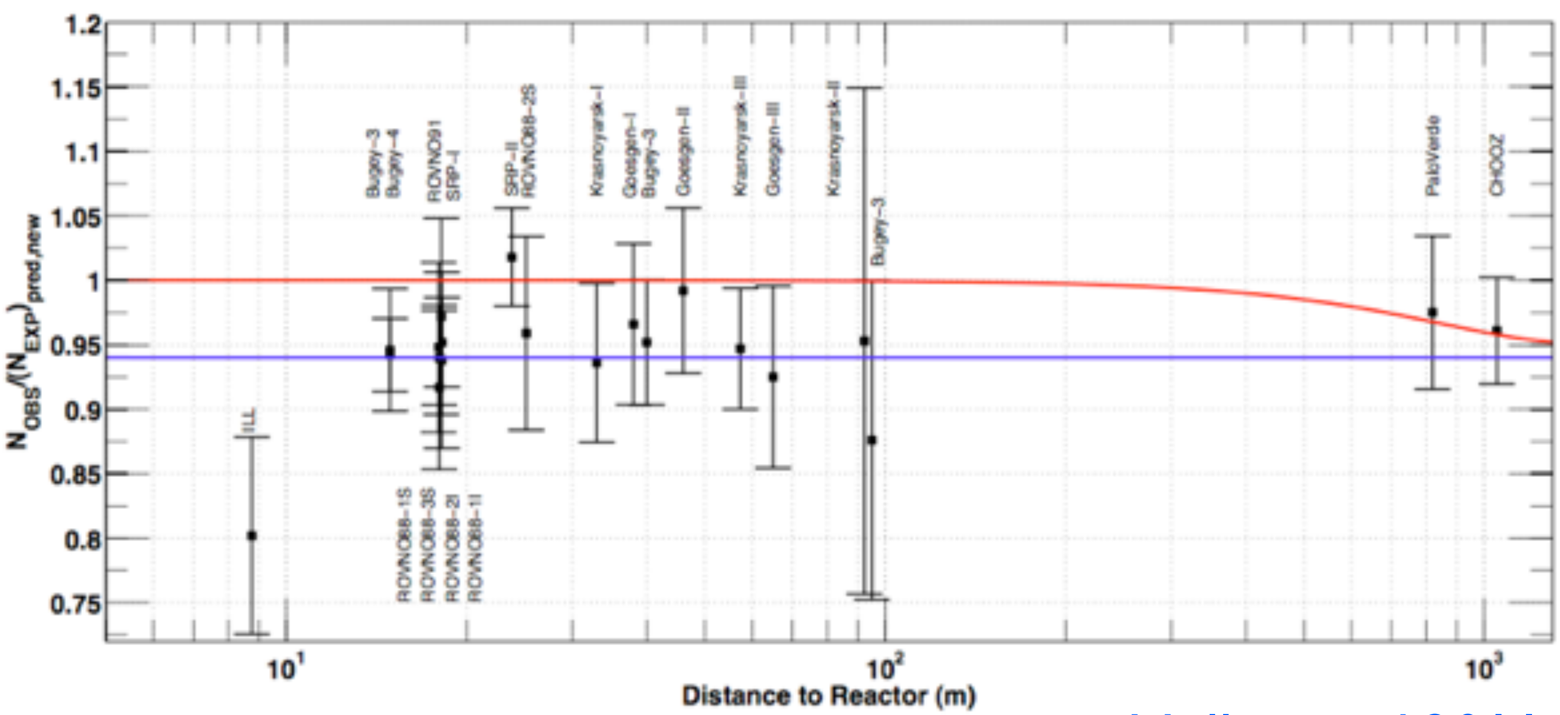
Other anomalies

Gallium calibration experiments and theoretical cross sections



Hampel *et al* 1998
Kaether *et al* 2010
Abdurashitov *et al* 1998
Abdurashitov *et al* 2005

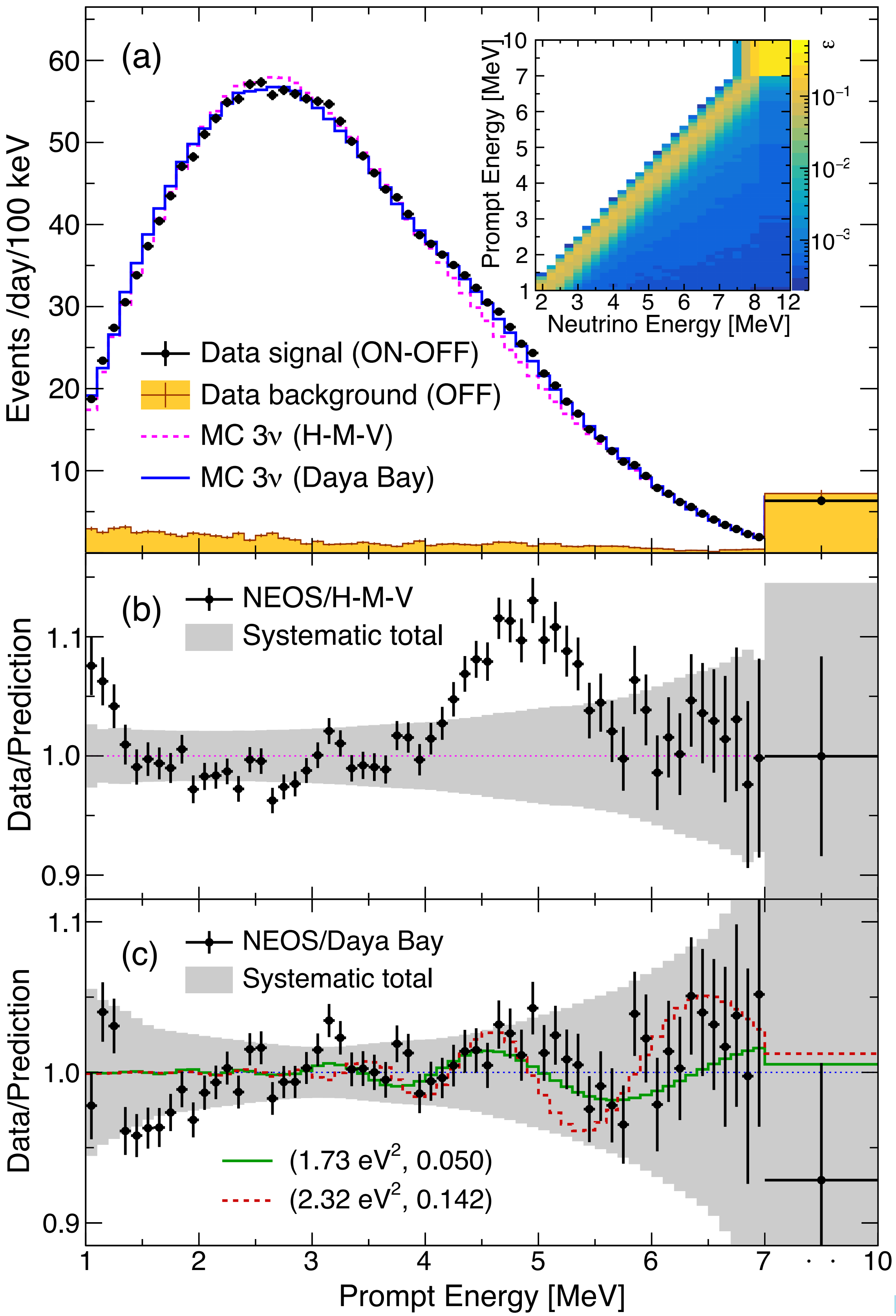
Reactor anomaly (reevaluation of expected neutrino flux)



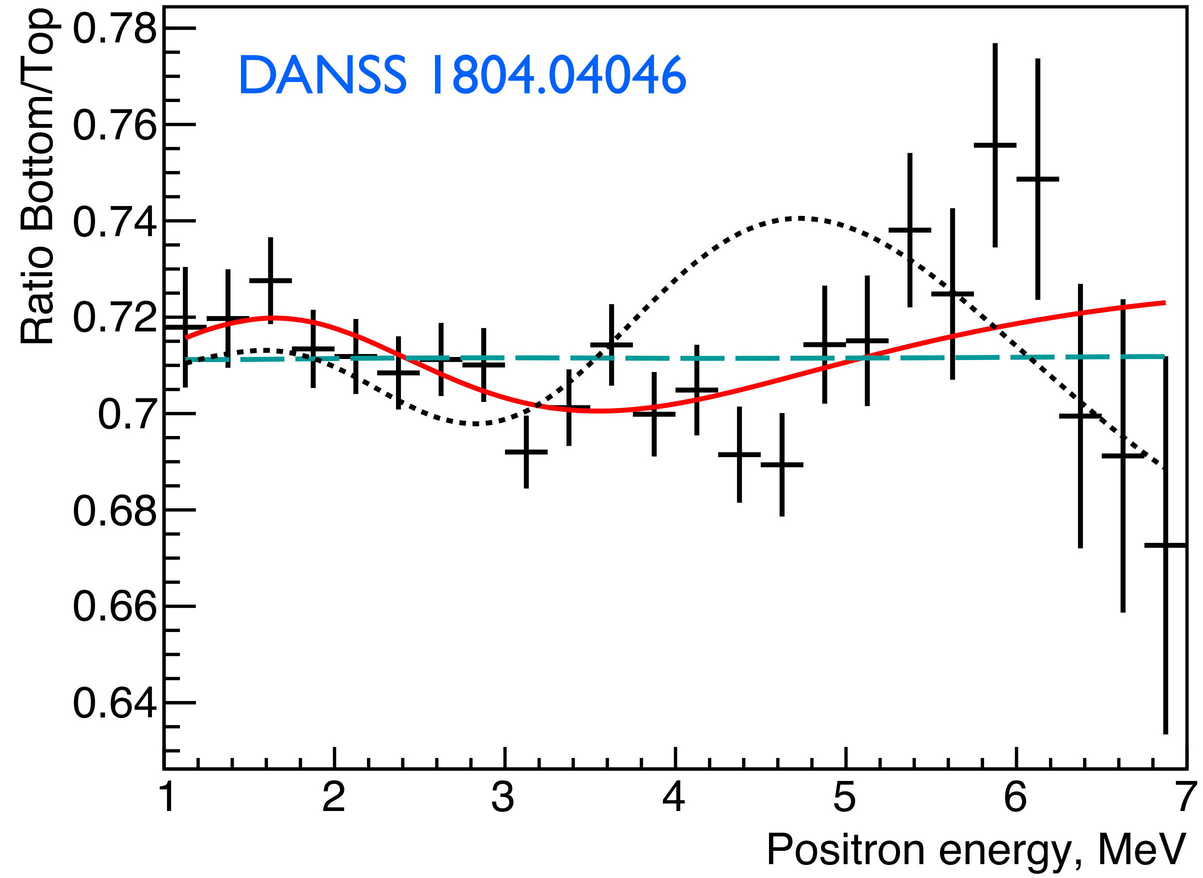
Müller *et al* 2011
Huber 2011

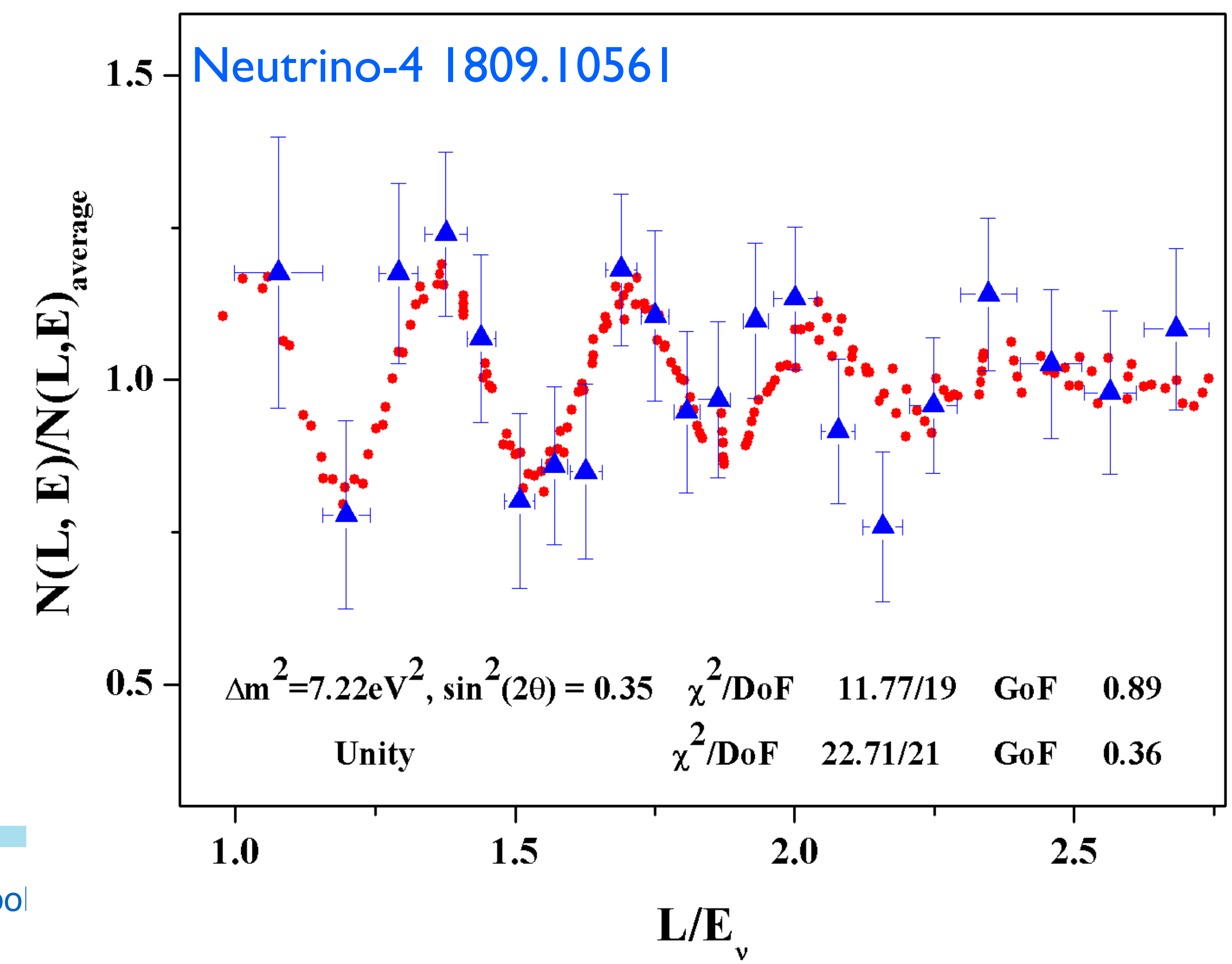
Fermilab

Other anomalies



NEOS 1610.05134





arXiv:1805.12028v1 [hep-ex] 30 May 2018

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Double neutrino-mode data in 2016-2017
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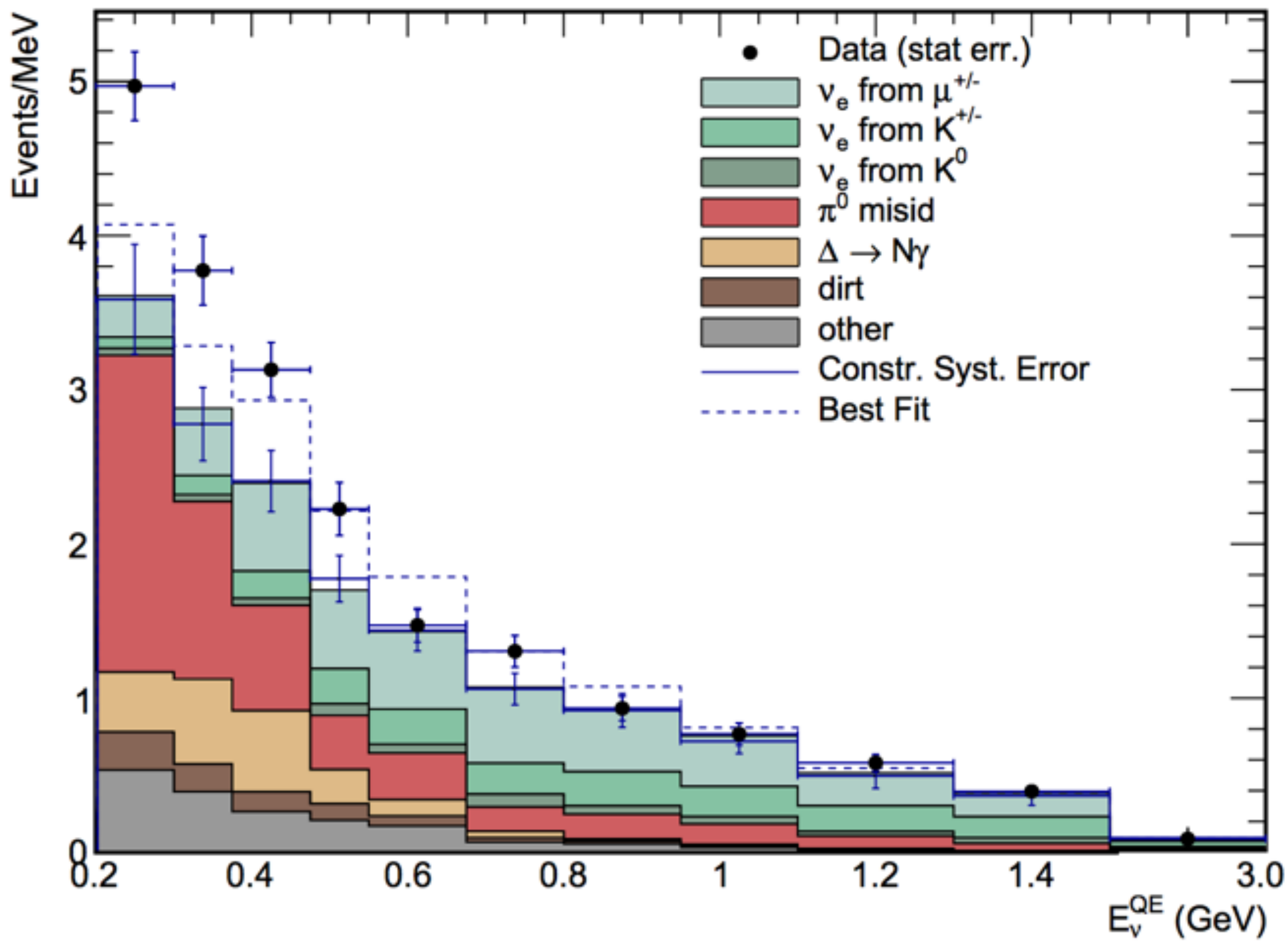

What is going on???

Translating to *theorist language*:

What sort of new physics can explain these anomalies?

Published for SISSA by Springer
Received: *April 12, 2018*

Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos

Mona Dentler,[a] Álvaro Hernández-Cabezudo,[b] Joachim Kopp,[a,c] Pedro Machado,[d] Michele Maltoni,[e] Ivan Martinez-Soler[e] and Thomas Schwetz[b]

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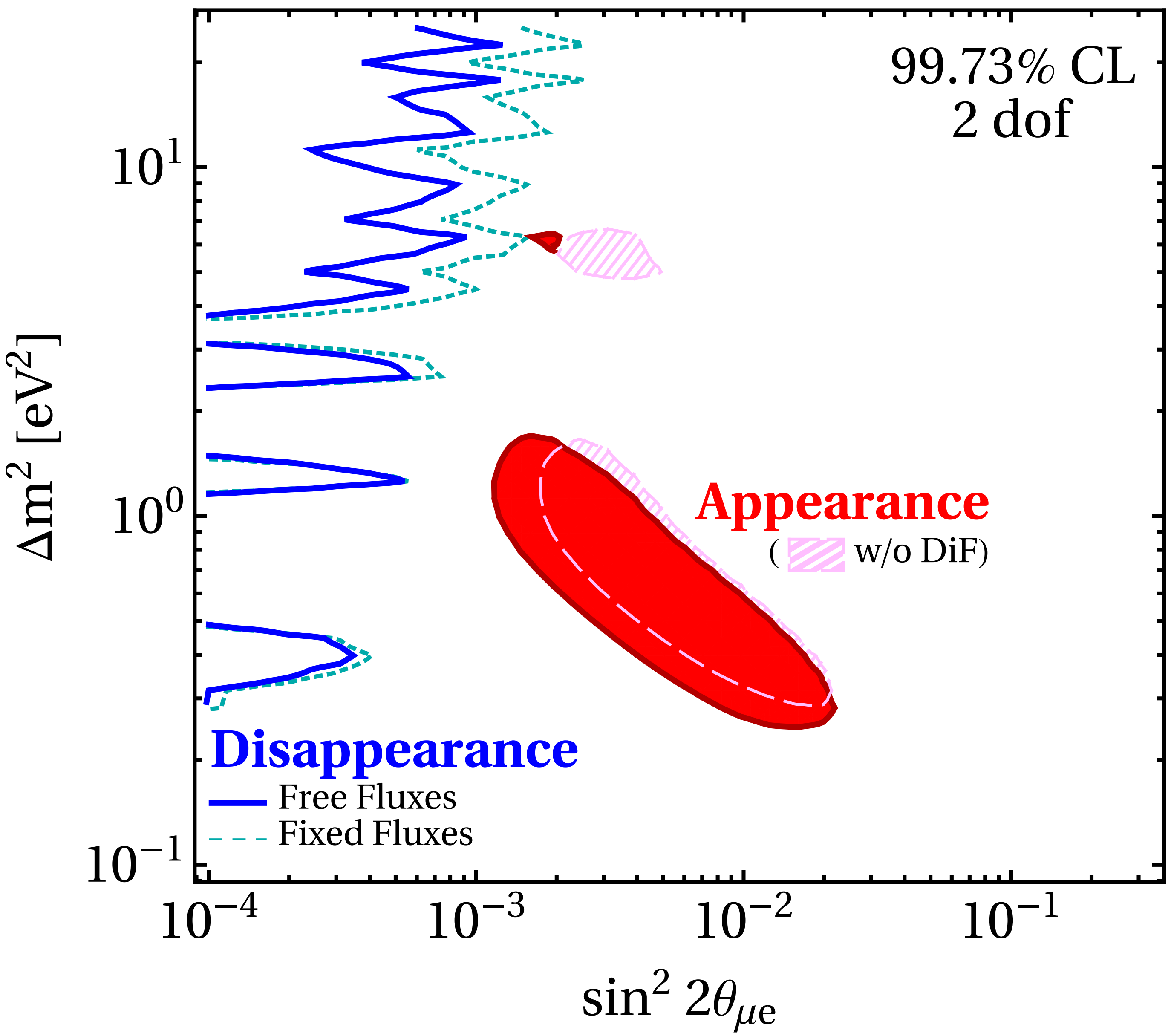

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\,U_{\mu 4}|^2$$

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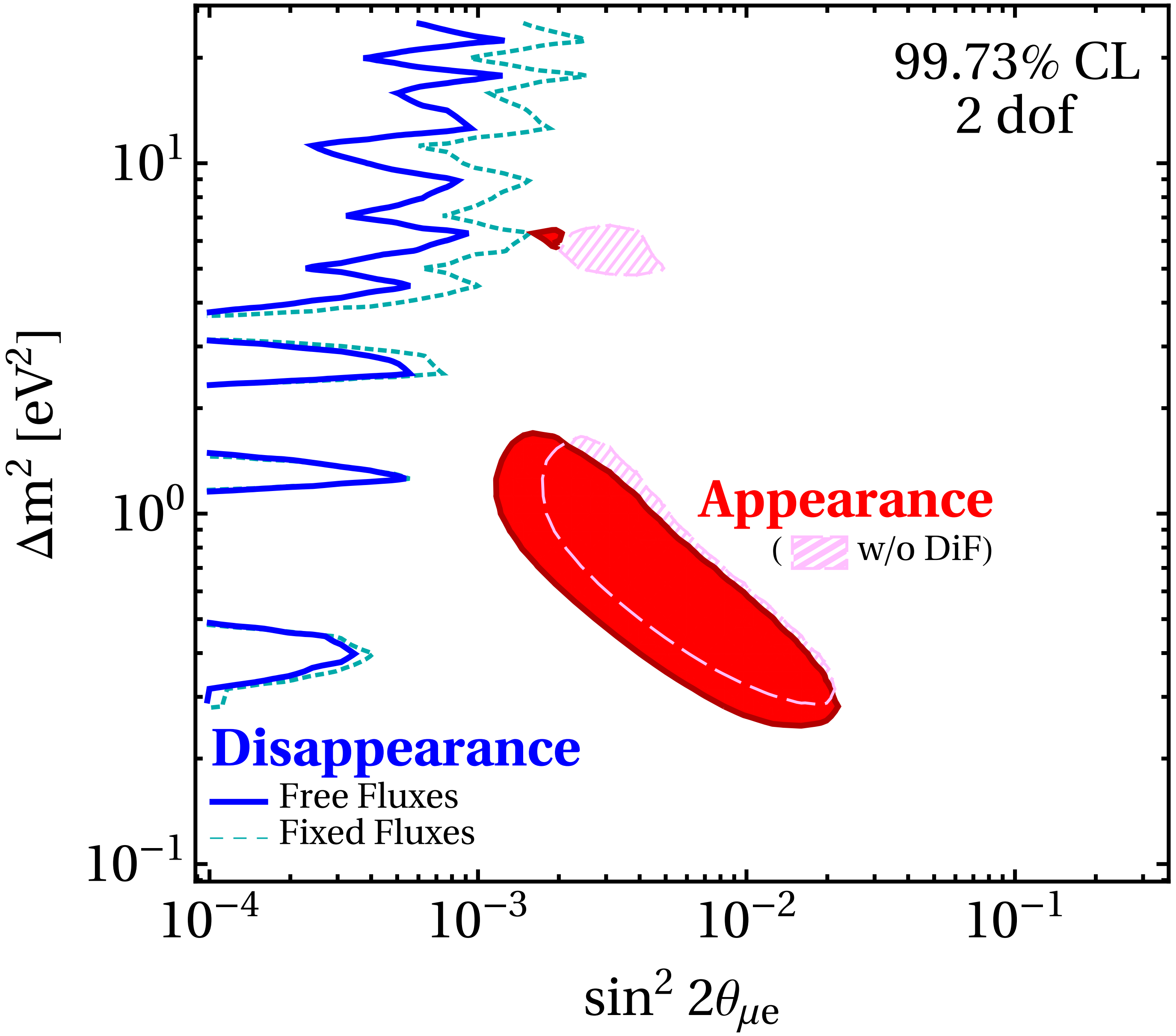

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Leads to ν_e disappearance

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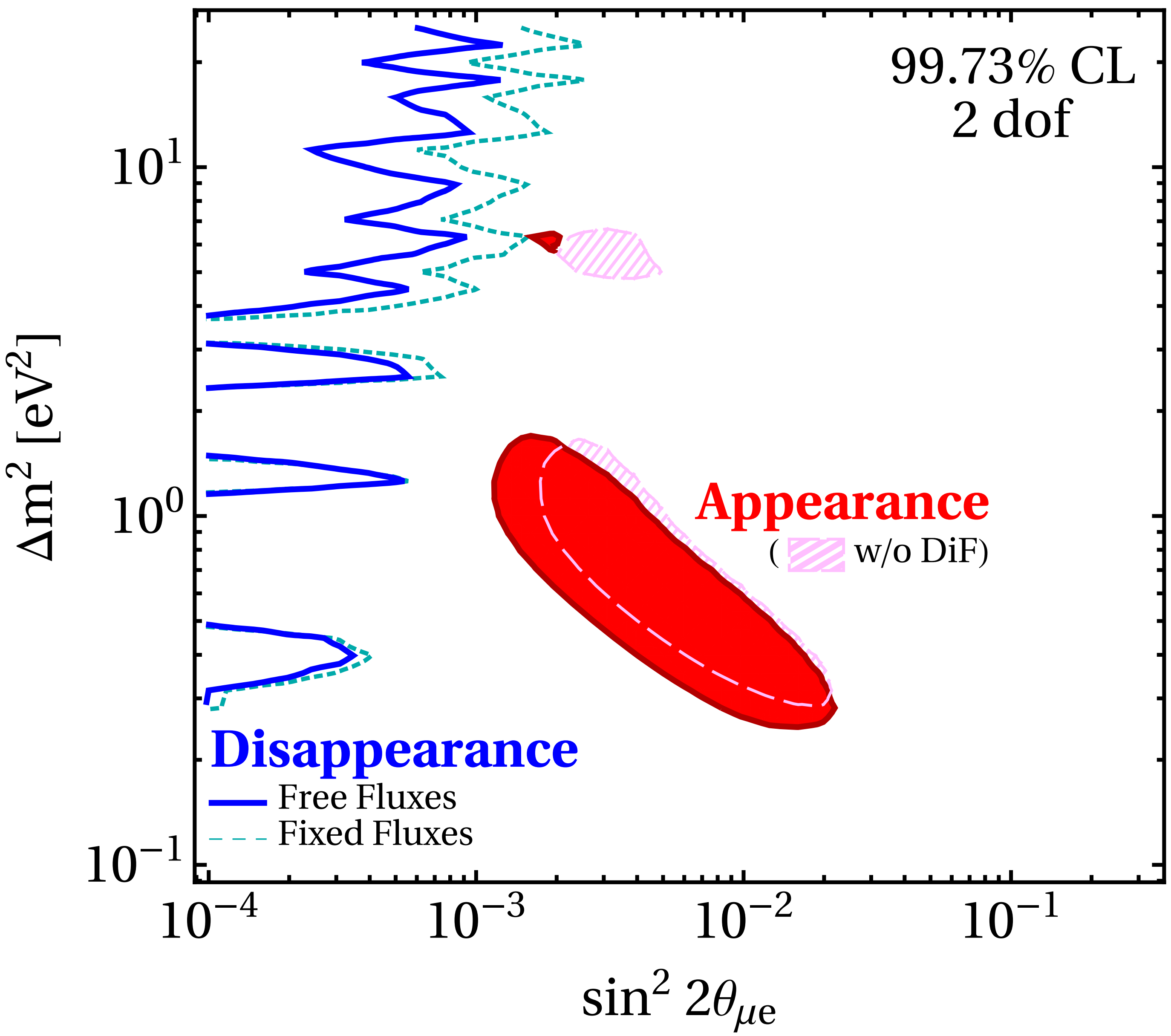

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\boxed{U_{\mu 4}}|^2$$

Leads to ν_μ disappearance

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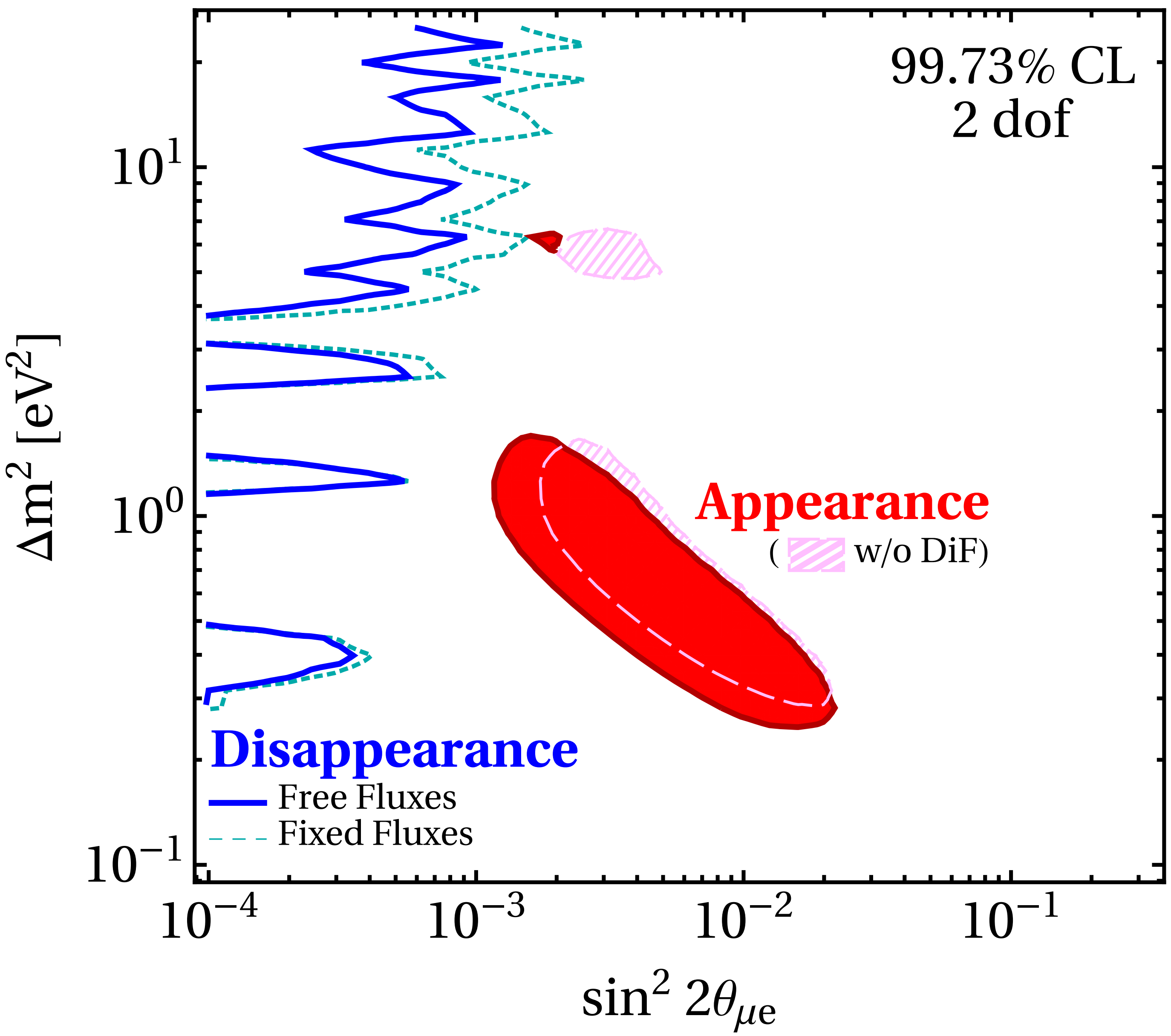

$$\sin^2 2\theta_{\mu e} = 4\,\boxed{|U_{e4}\,U_{\mu 4}|^2}$$

Leads to ν_μ to ν_e appearance

2 variables:

U_{e4}, $U_{\mu 4}$

3 data sets:

ν_e-DIS, ν_μ-DIS, ν_e-APP

JHEP
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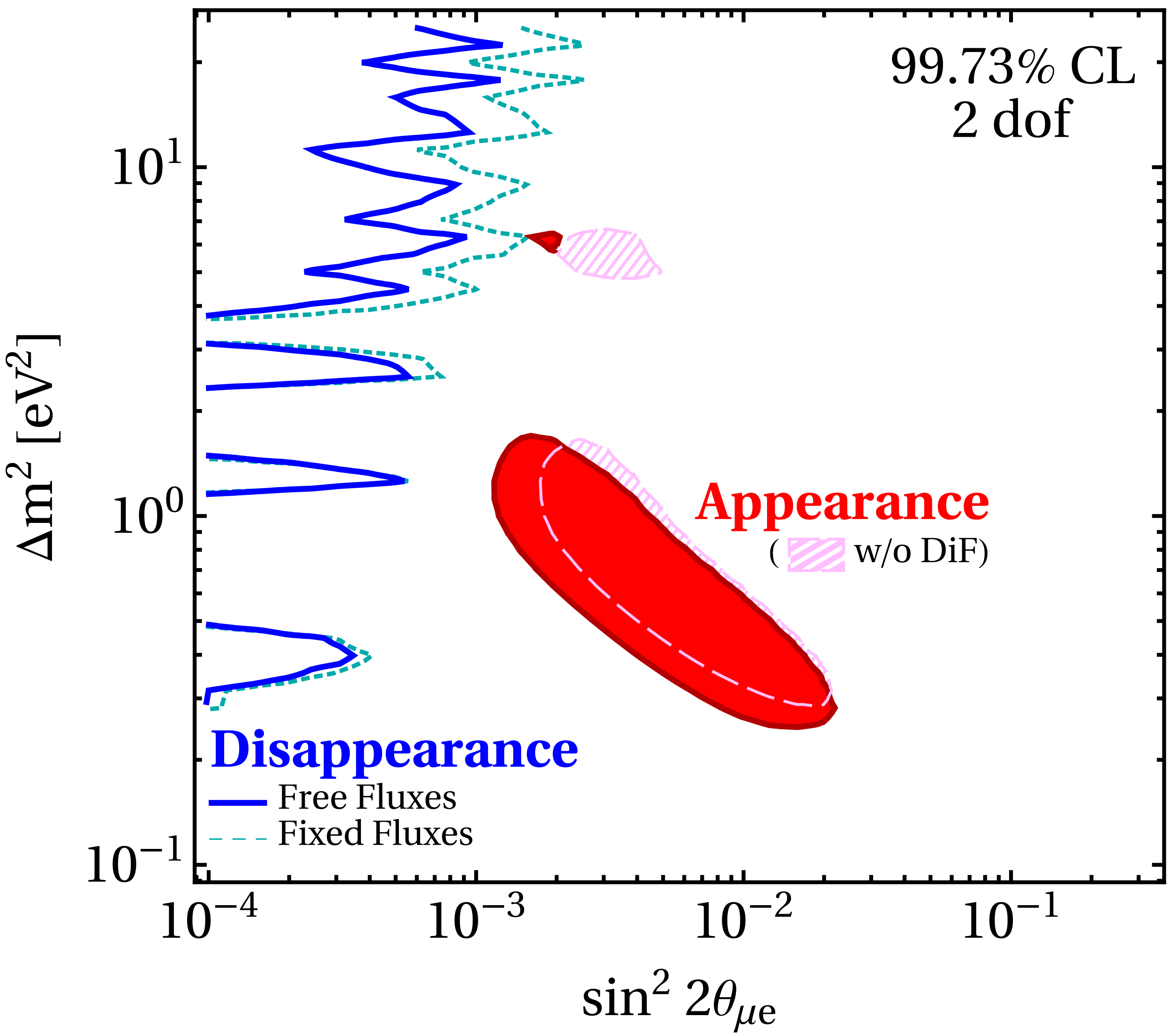

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\,U_{\mu 4}|^2$$

4.7 σ tension between APP and DISAPP data sets under eV sterile interpretation

Exercise: remove each experiment and see if agreement improves

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Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global							3.71×10^{-7}
Removing anomalous data sets							
w/o LSND							1.6×10^{-3}
w/o MiniBooNE							5.2×10^{-6}
w/o reactors							3.8×10^{-5}
w/o gallium							4.4×10^{-8}
Removing constraints							
w/o IceCube							4.2×10^{-7}
w/o MINOS(+)							4.7×10^{-6}
w/o MB disapp							6.0×10^{-7}
w/o CDHS							7.5×10^{-7}

MiniBooNE 2012 data set

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MiniBooNE 2012 data set

Results in agreement with other global analysis
Collin et al 1602.00671
Gariazzo et al 1703.00860

What is going on?

Sterile ν at the eV scale present strong tension between data sets

Cosmological bounds further threat the eV sterile hypothesis

Is there an explanation that is not ruled out?

Adding more ingredients may alleviate the case for light steriles
Too ad hoc?

Is there a real model for these explanations?

Can this relate to any of the theoretical problems of the SM?

What is going on?

Gninenko 1107.0279
MeV sterile, magnetic moment, and decays

Bai et al 1512.05357
keV steriles decaying to active neutrinos

Asaadi et al 1712.08019
eV sterile, new light Higgs boson and resonant matter effect

Doring et al 1808.07460
eV steriles and extra dimensional shortcuts
...

Sterile ν at the eV scale present stro

Cosmological bounds further threa ... hypothesis

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Part I

(and possibly the only one…)

Explaining MiniBooNE’s low energy excess

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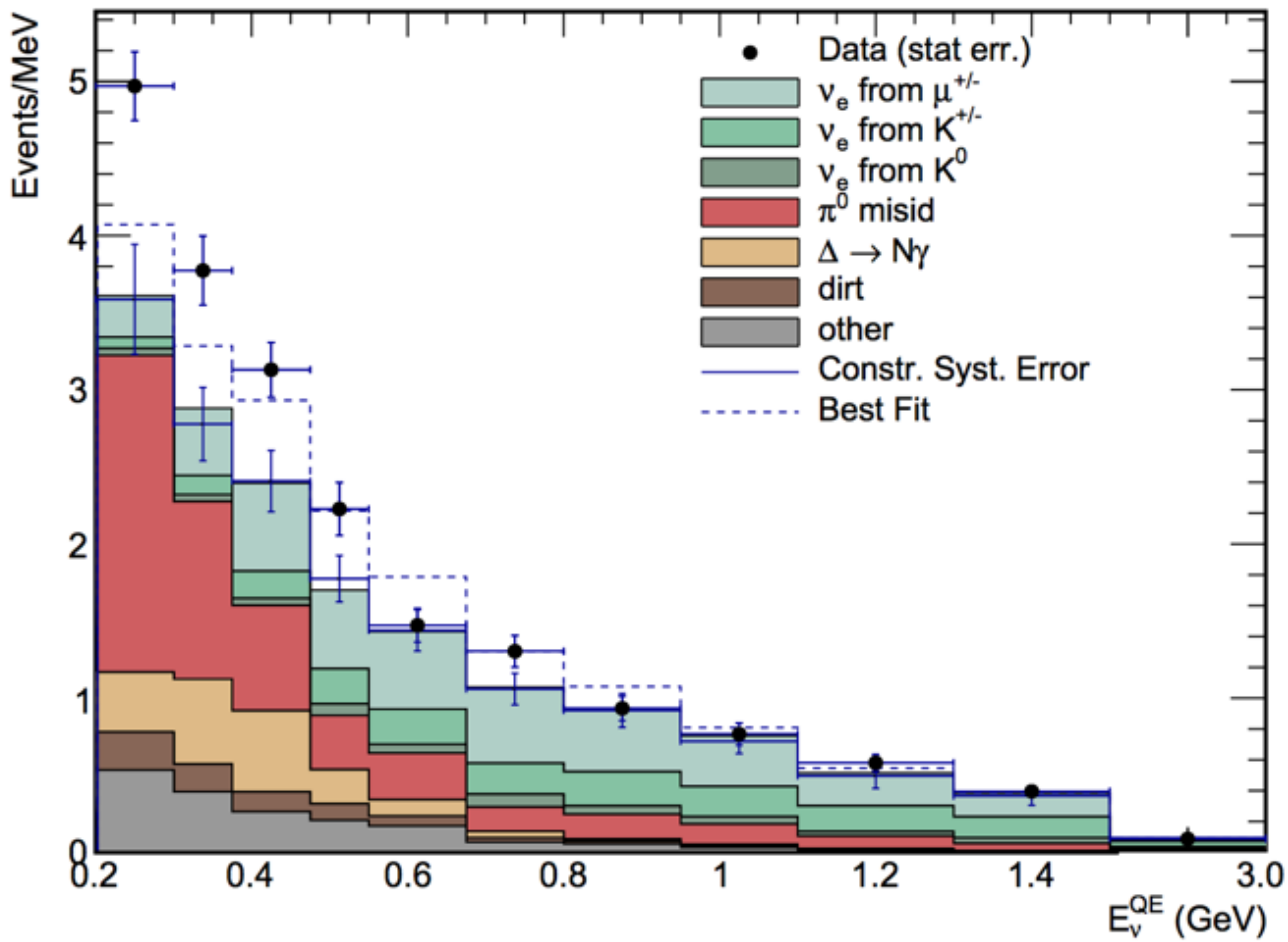

MiniBooNE's low energy excess

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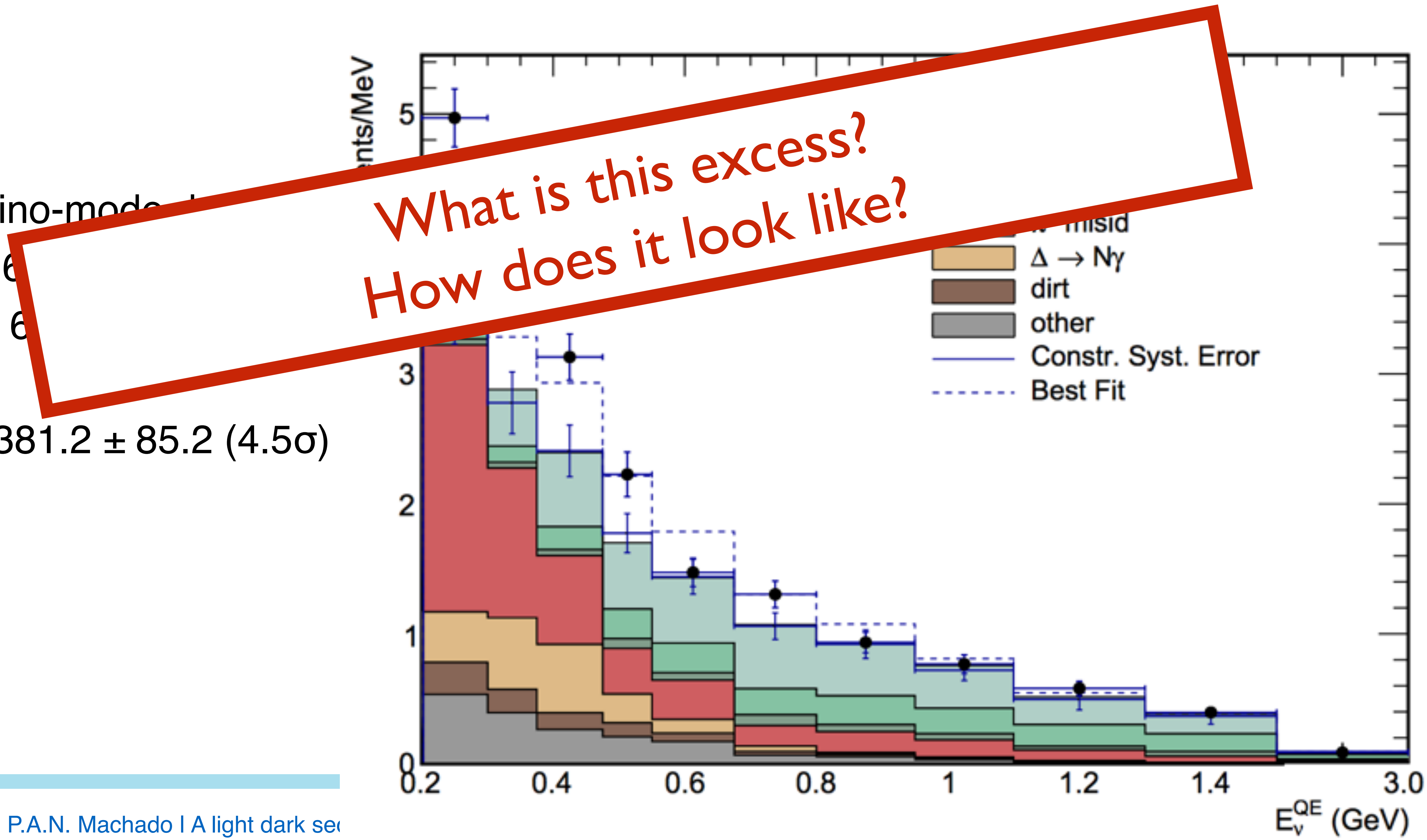
Double neutrino-mode

2016

(6.46×10[20] + 6

Event excess: 381.2 ± 85.2 (4.5σ)



MiniBooNE's low energy excess

8 GeV proton beam

$$p + X \to \pi^+, \pi^-, \cdots + X'$$
$$\hookrightarrow \mu^+ \nu_\mu$$

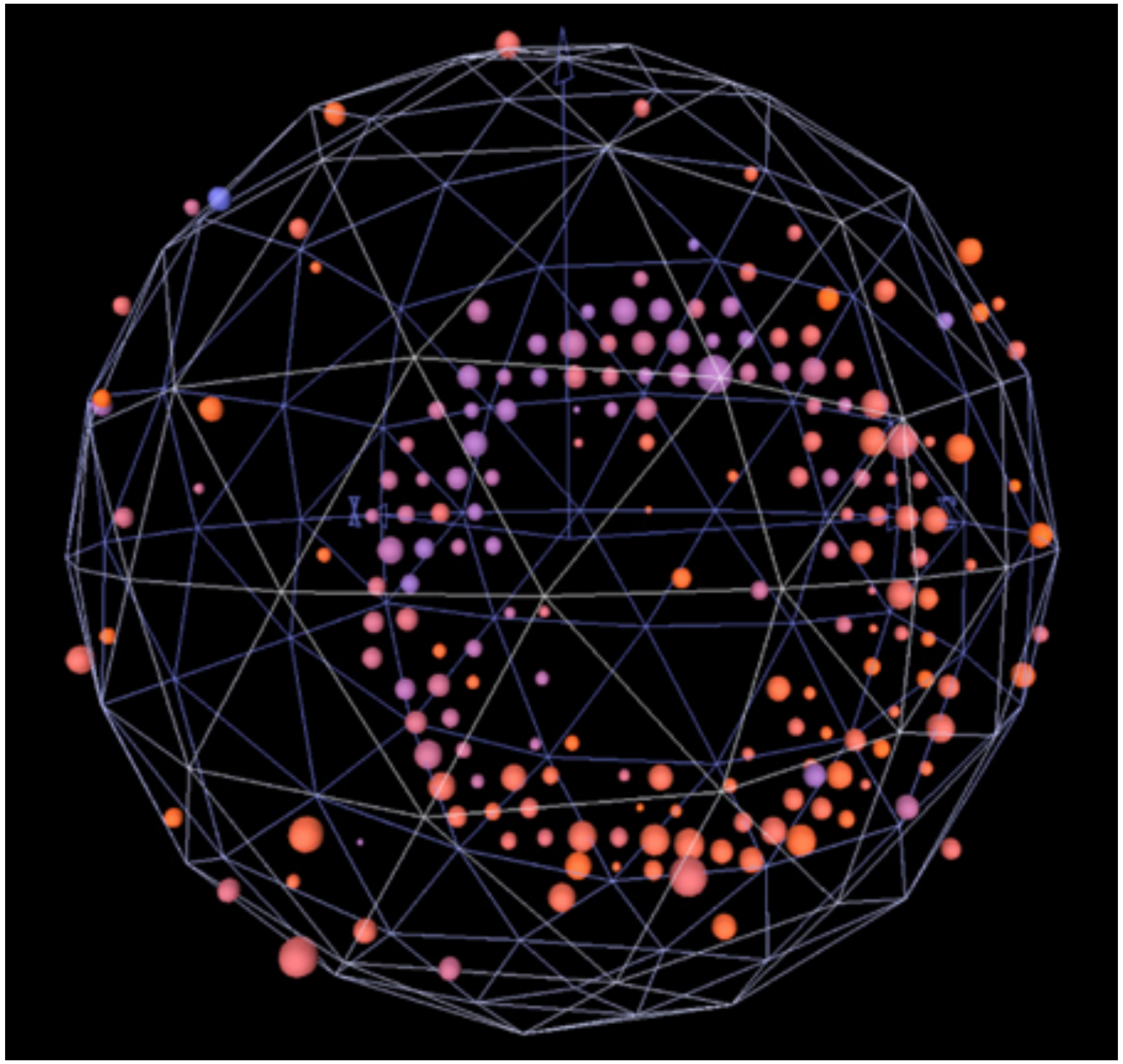
Signal consists of electron-like ring

Excess is correlated with beam in power, angle and timing

It is present in positive and negative horn polarities

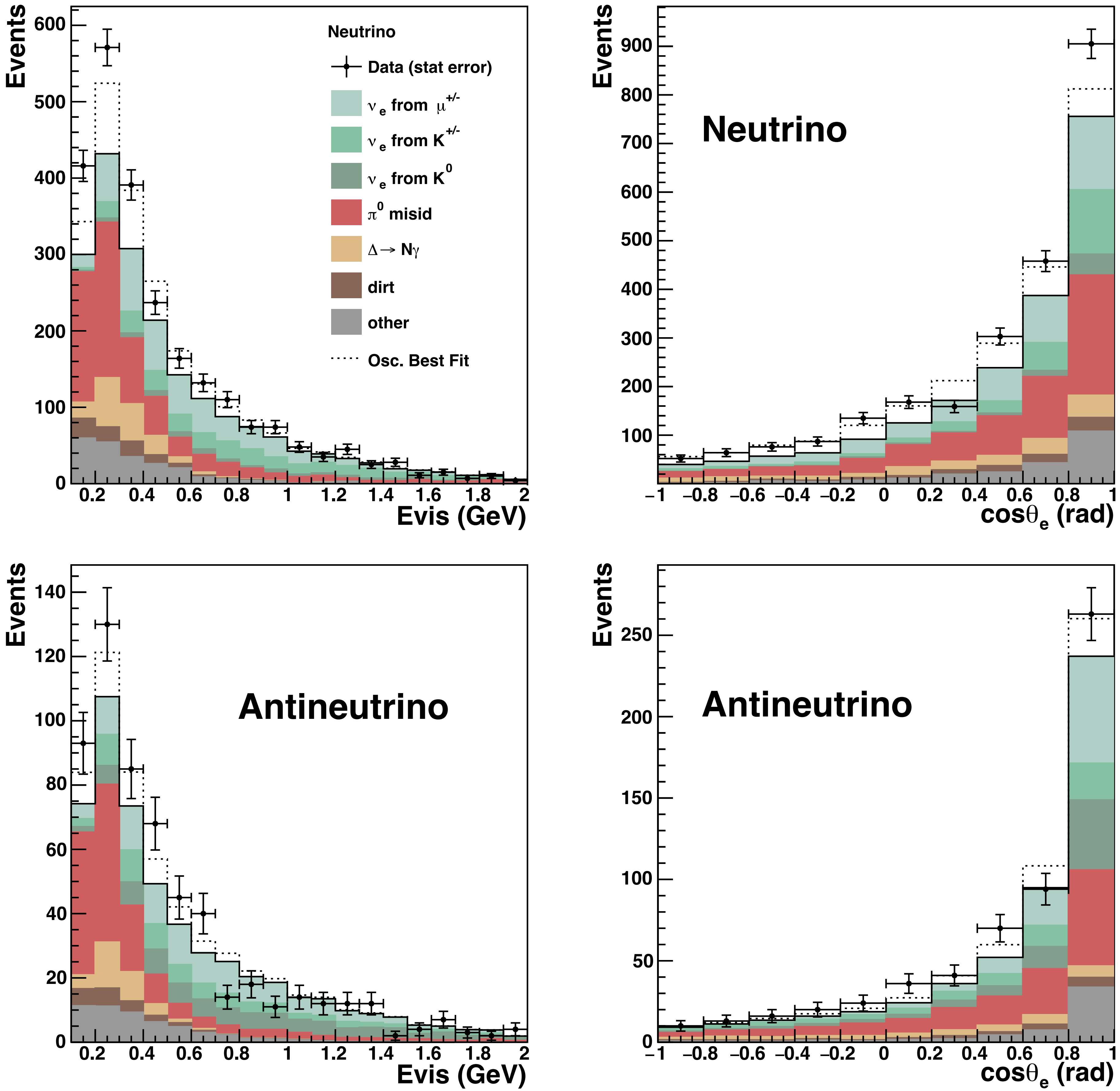
It is not present in beam dump configuration

MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles



It looks like it comes from neutrinos

MiniBooNE's low energy excess



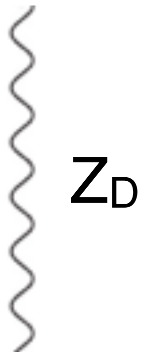
Angular spectrum is forward, but not that much

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

A light dark sector - the idea

There is a dark sector with a novel interaction



Bertuzzo et al 1807.09877

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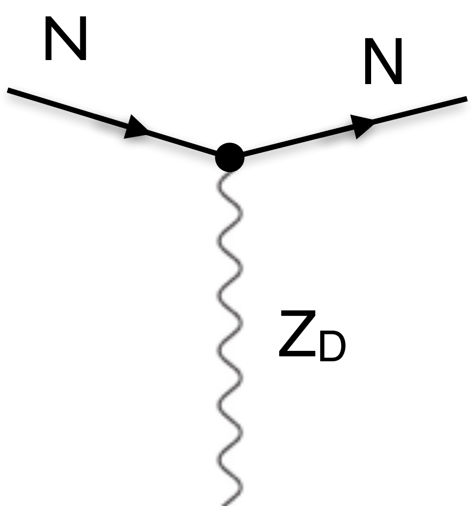
Right-handed neutrinos are part of the dark sector and are subject to new interaction



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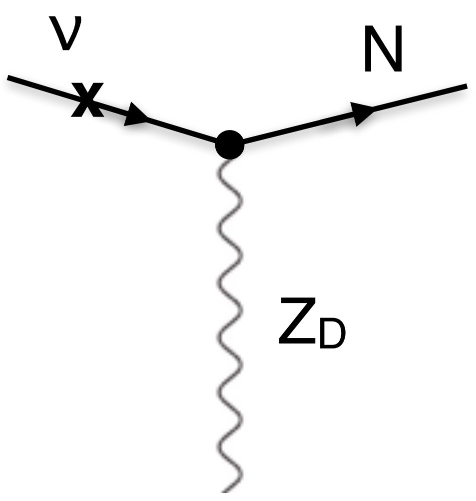
Mixing between RH and LH neutrinos leads to interaction in active neutrino sector



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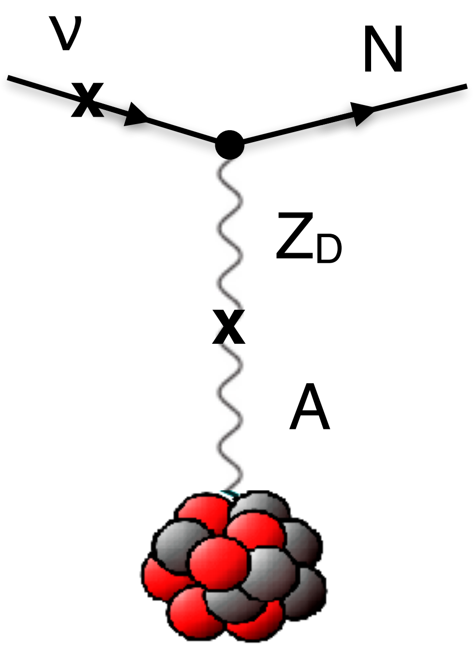

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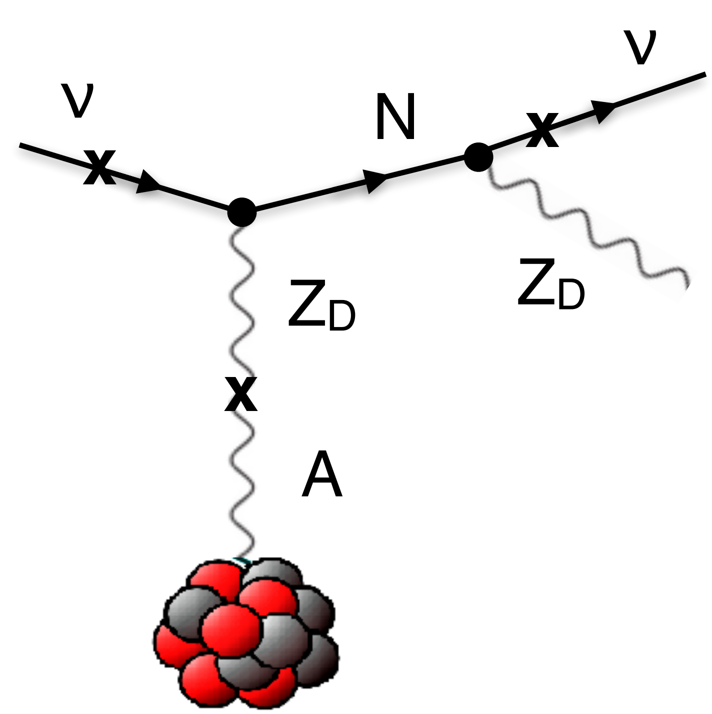

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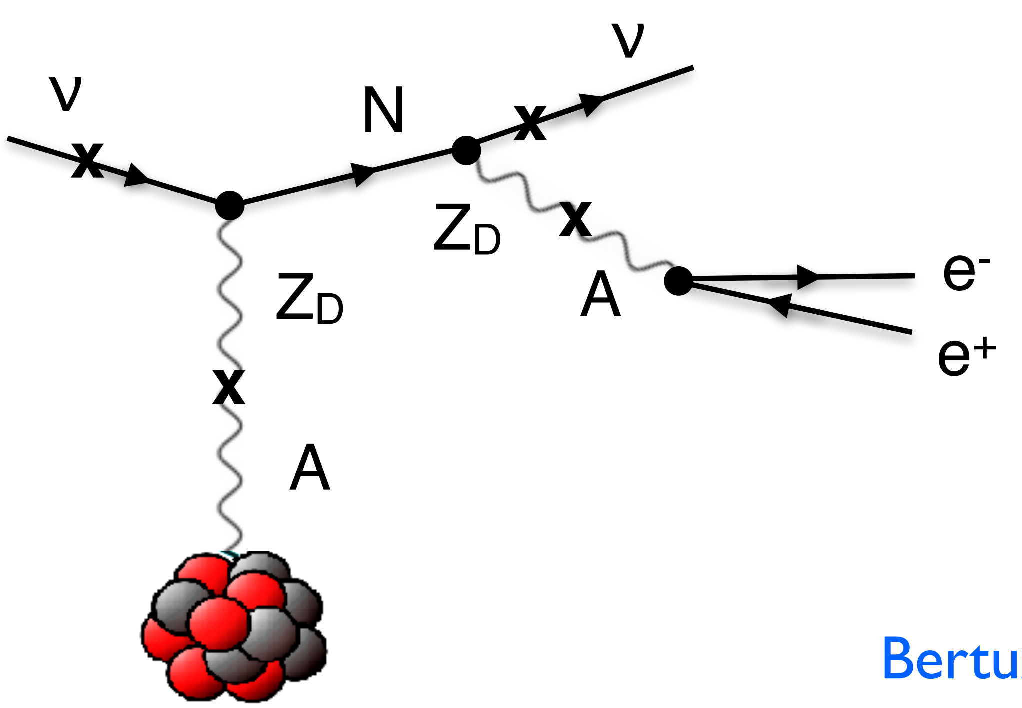

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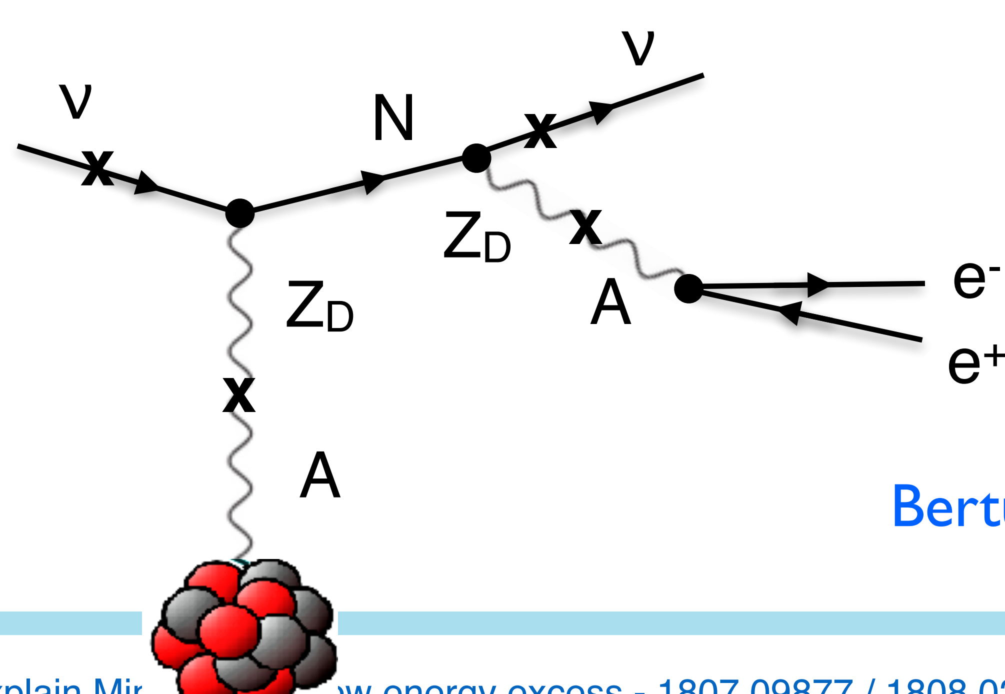
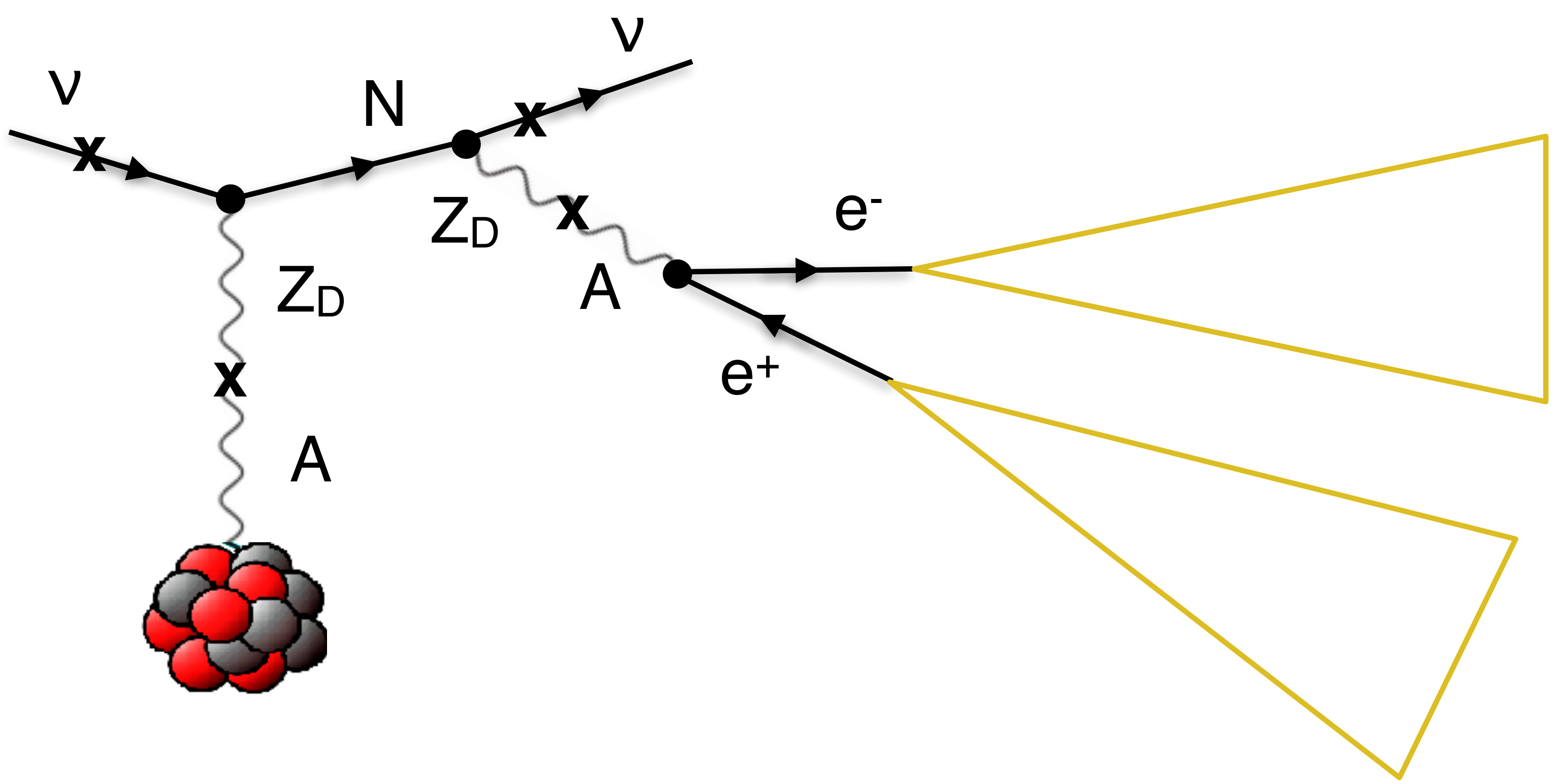
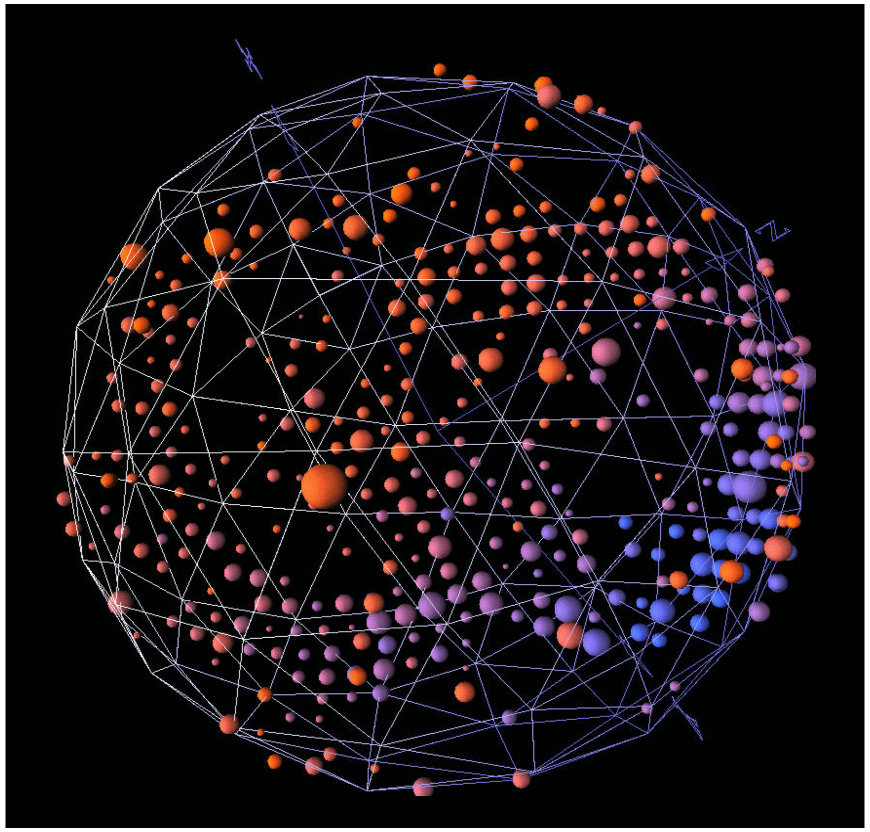
$$\mathcal{L}_\mathcal{D} \supset \frac{m_{Z_\mathcal{D}}^2}{2} Z_{\mathcal{D}\mu} Z_\mathcal{D}^\mu + g_\mathcal{D} Z_\mathcal{D}^\mu J_{\mathcal{D}\mu} + e\epsilon\, Z_\mathcal{D}^\mu J_\mu^{\rm em} + \frac{g}{c_W}\epsilon'\, Z_\mathcal{D}^\mu J_\mu^{\rm Z}$$



Bertuzzo et al 1807.09877

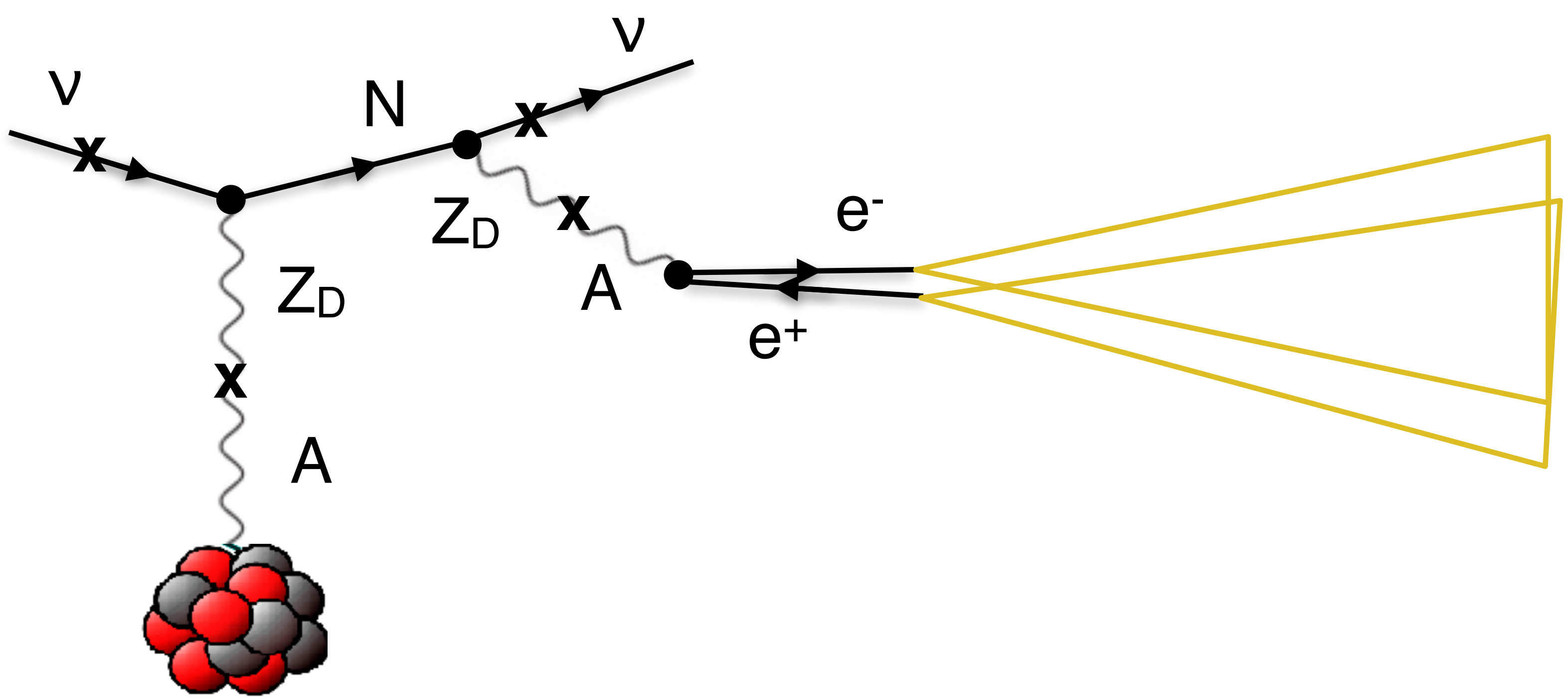
A light dark sector phenomenology

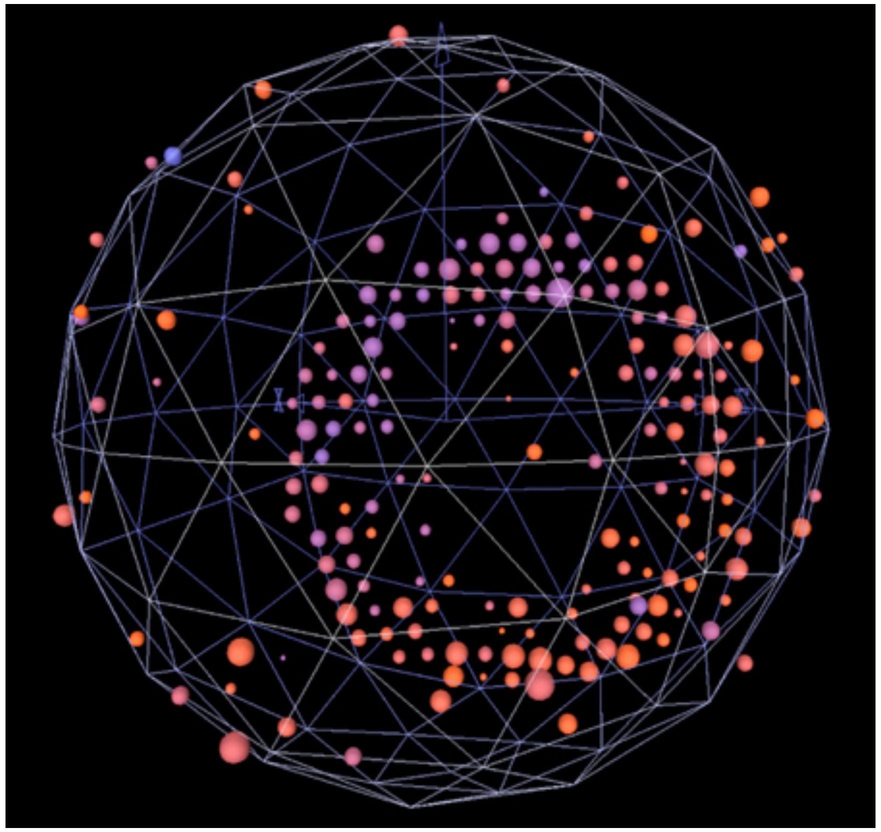




If e^+e^- pair is not collimated, event will not look e-like

A light dark sector phenomenology





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

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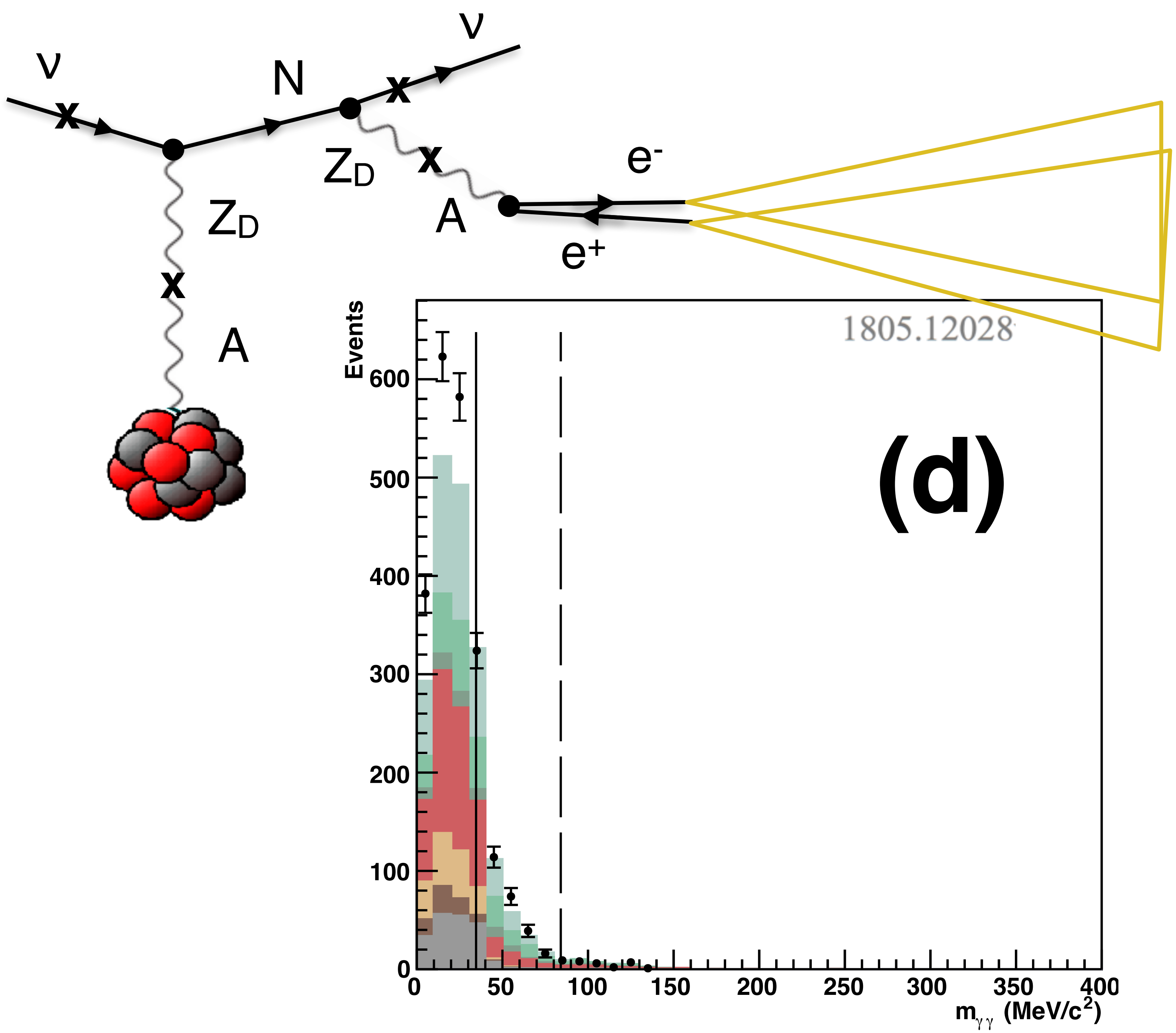

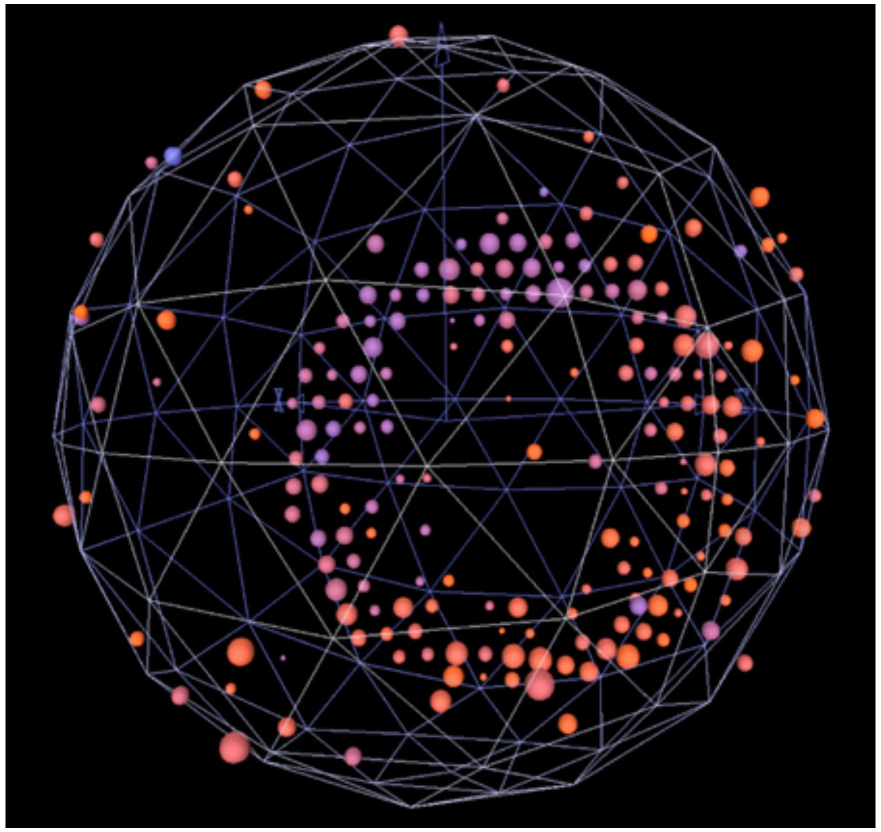

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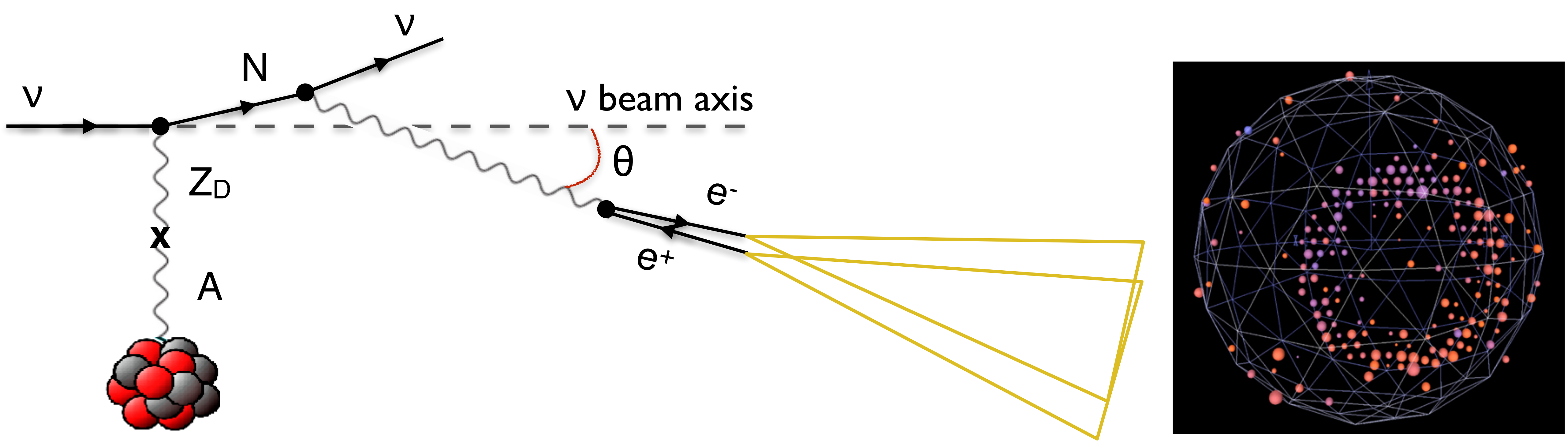

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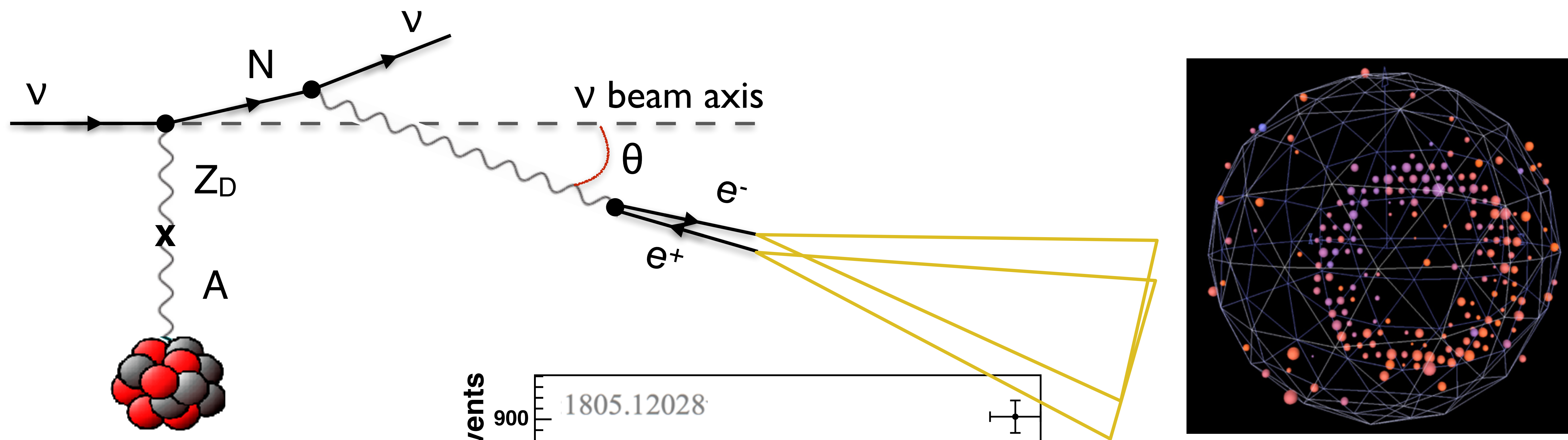
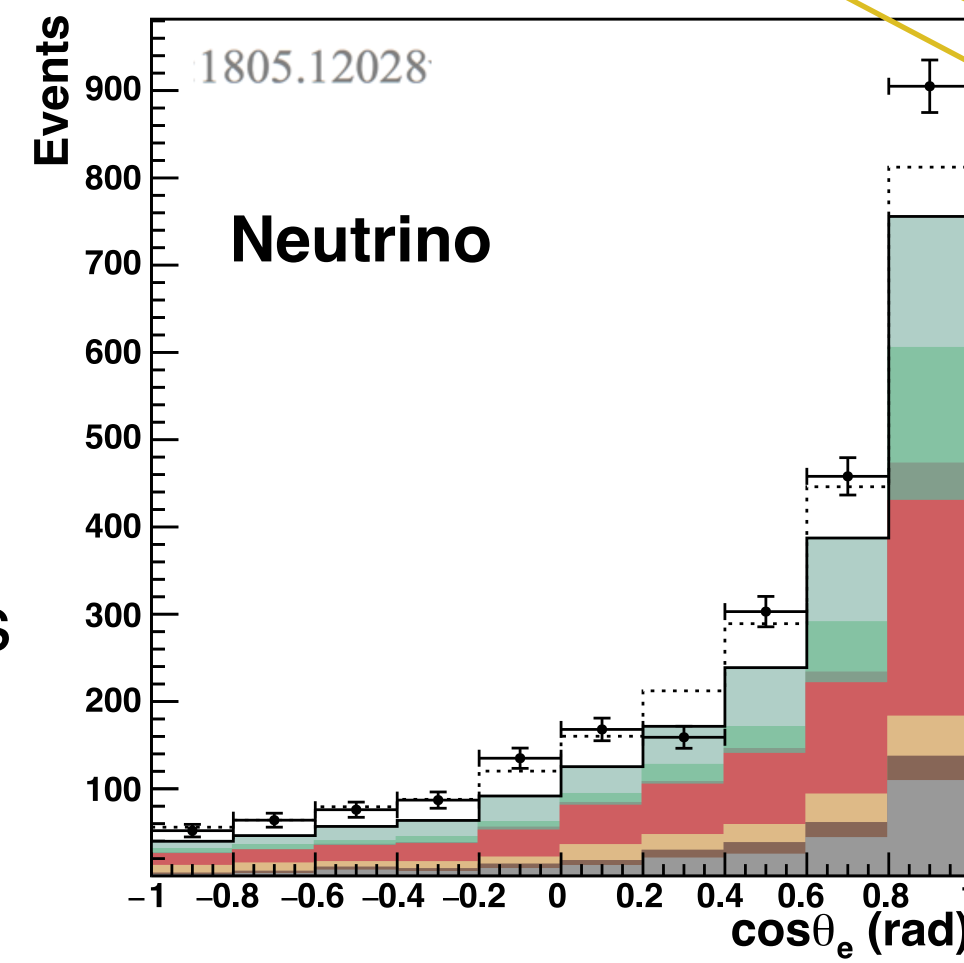


We have to get this angular spectrum



Fermilab

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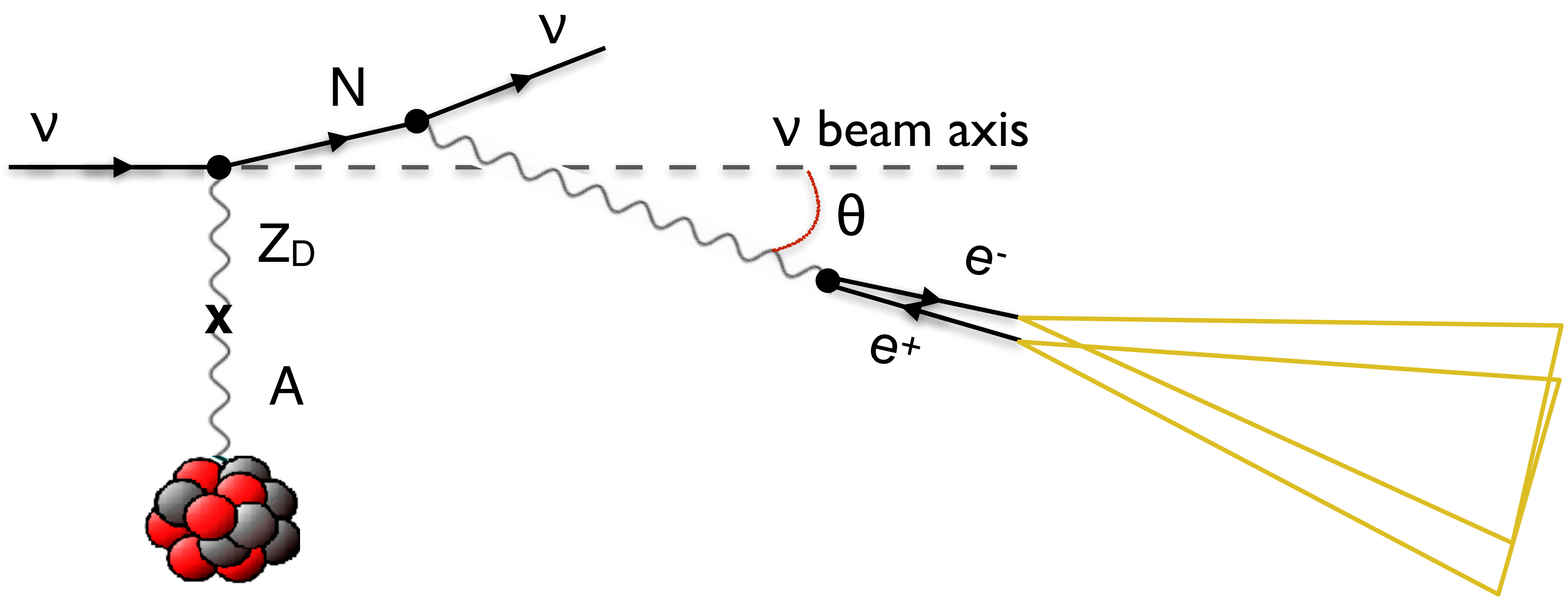
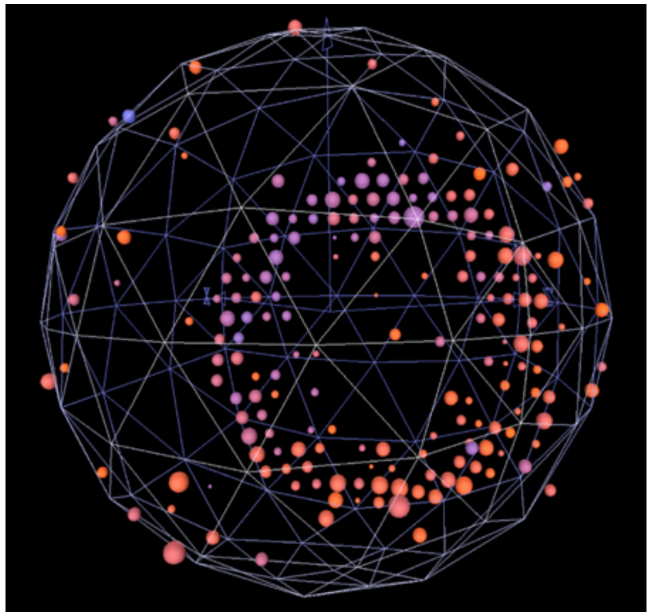
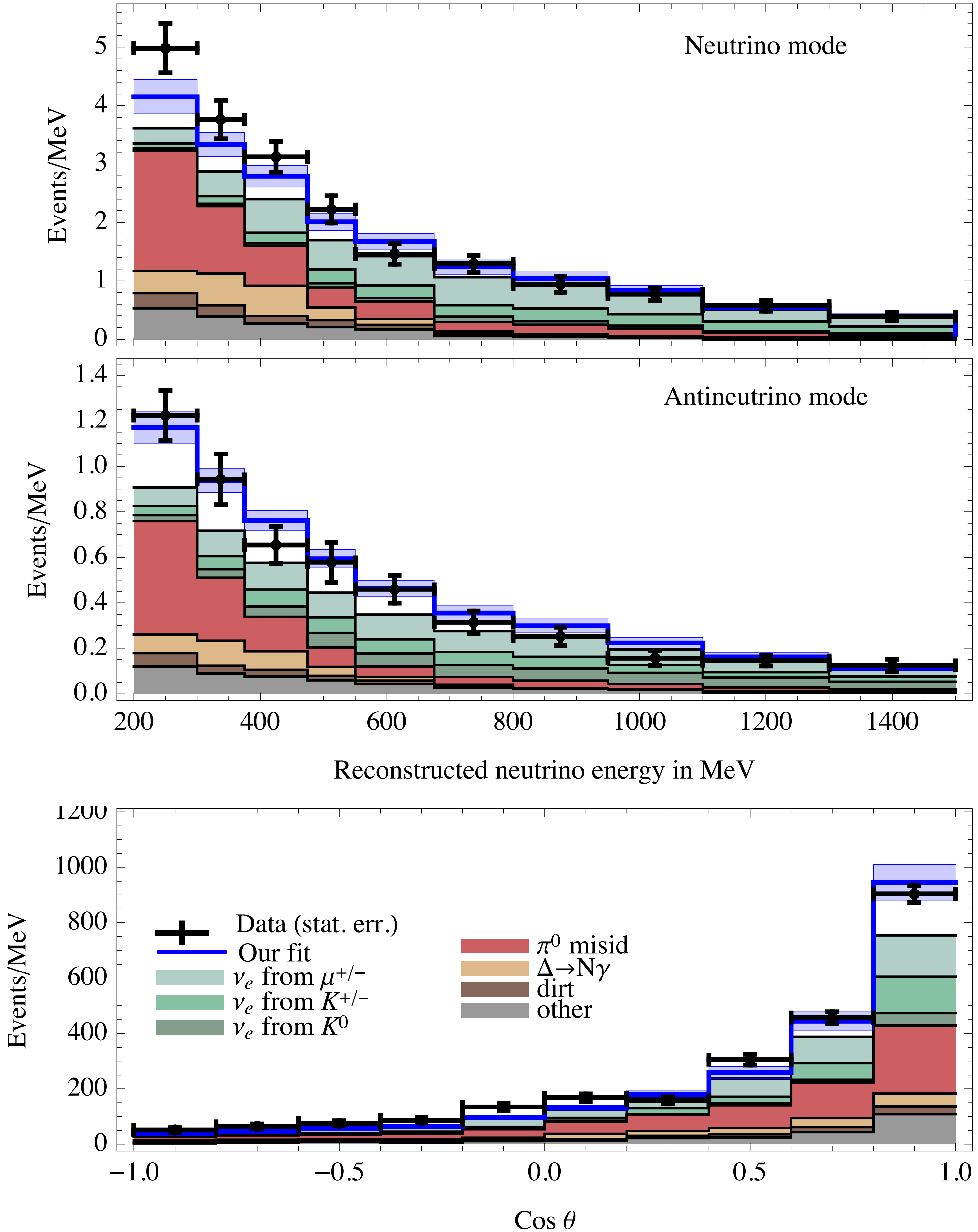
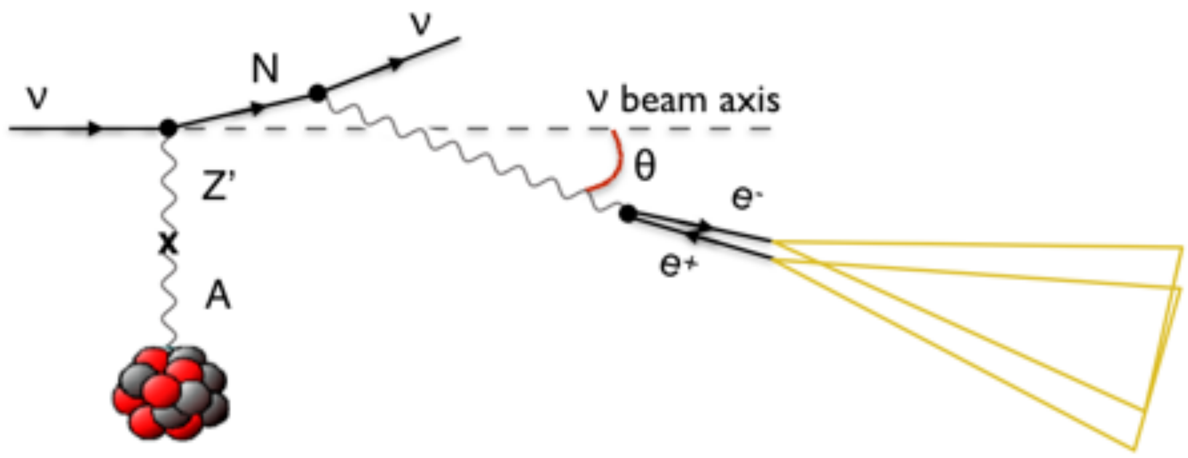




1) N should be heavy (> 100 MeV) so its decay products are not so boosted
2) Z_D should be light (< 60 MeV) so that the e^+e^- pair is collimated

A light dark sector pheno





Fit to energy spectrum only

(Official MB data release)

Benchmark

$m_N = 320$ MeV

$m_{Z'} = 60$ MeV

$|U_{\mu 4}|^2 = 10^{-6}$

$\alpha_D = 0.25$

$\alpha\varepsilon^2 = 3 \times 10^{-9}$

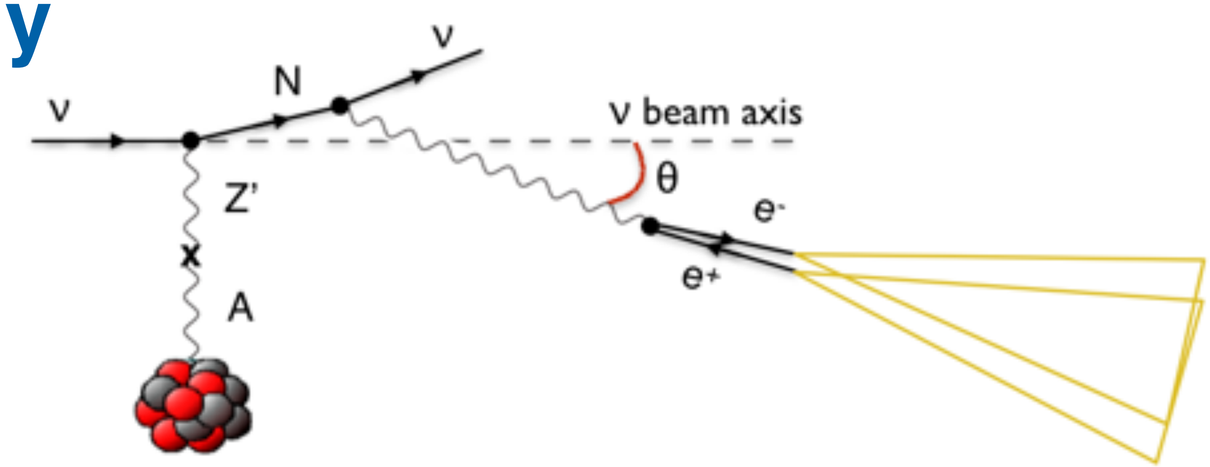
$\chi^2/\mathrm{dof} = 31.2/36$

Bertuzzo et al 1807.09877

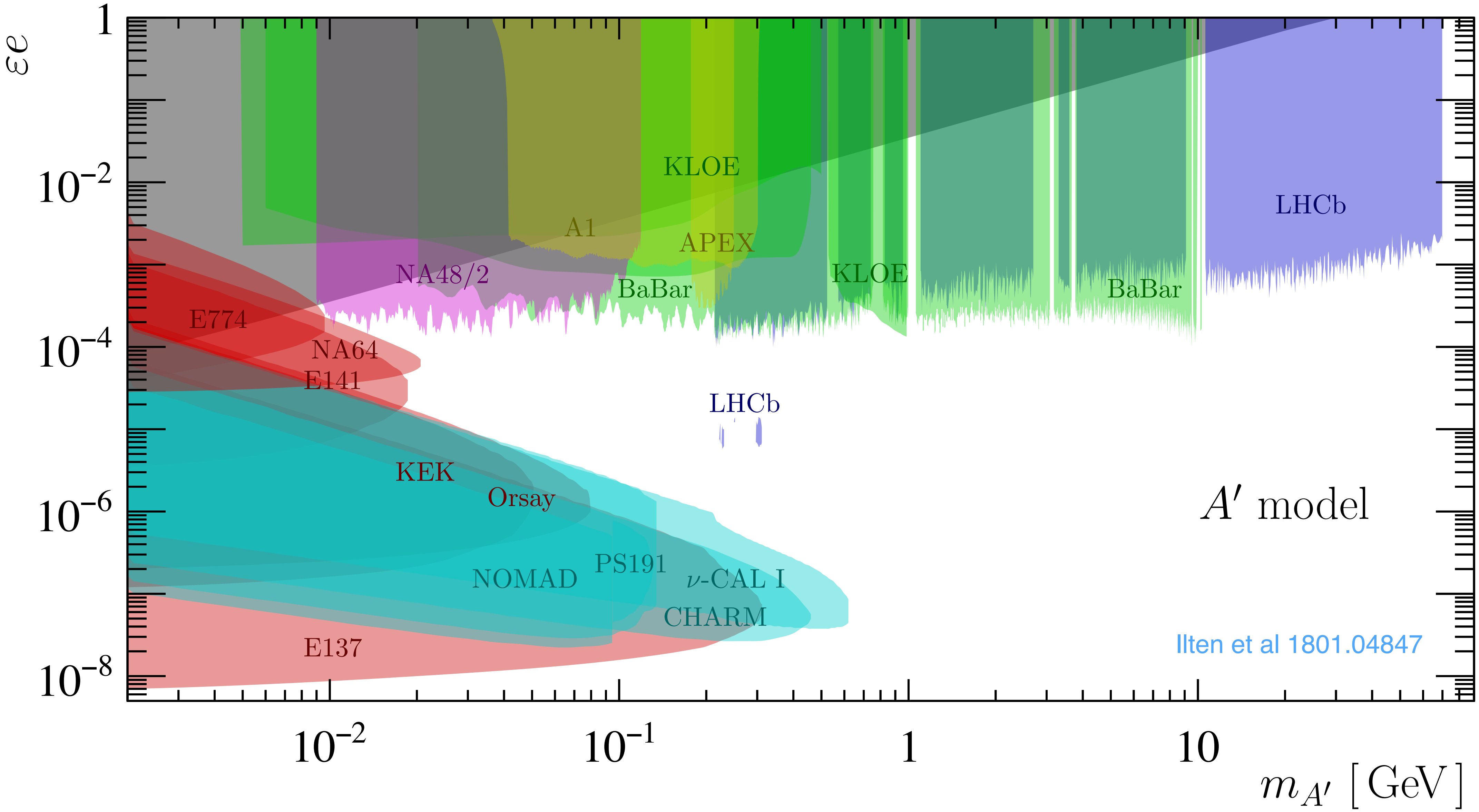
See also Ballett et al 1808.02915

for different realization of the mechanism

A light dark sector phenomenology



Z_D pheno is similar to dark photon case



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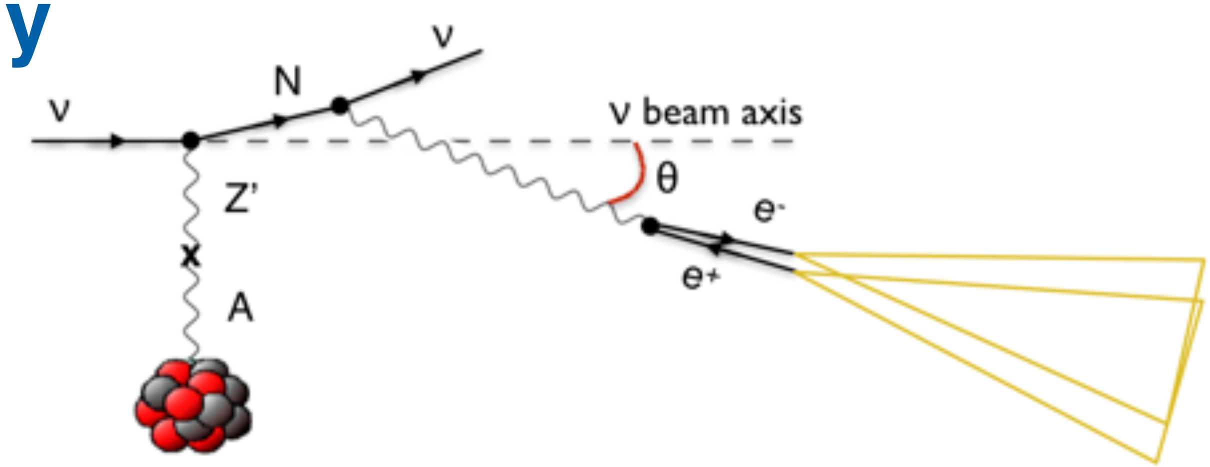
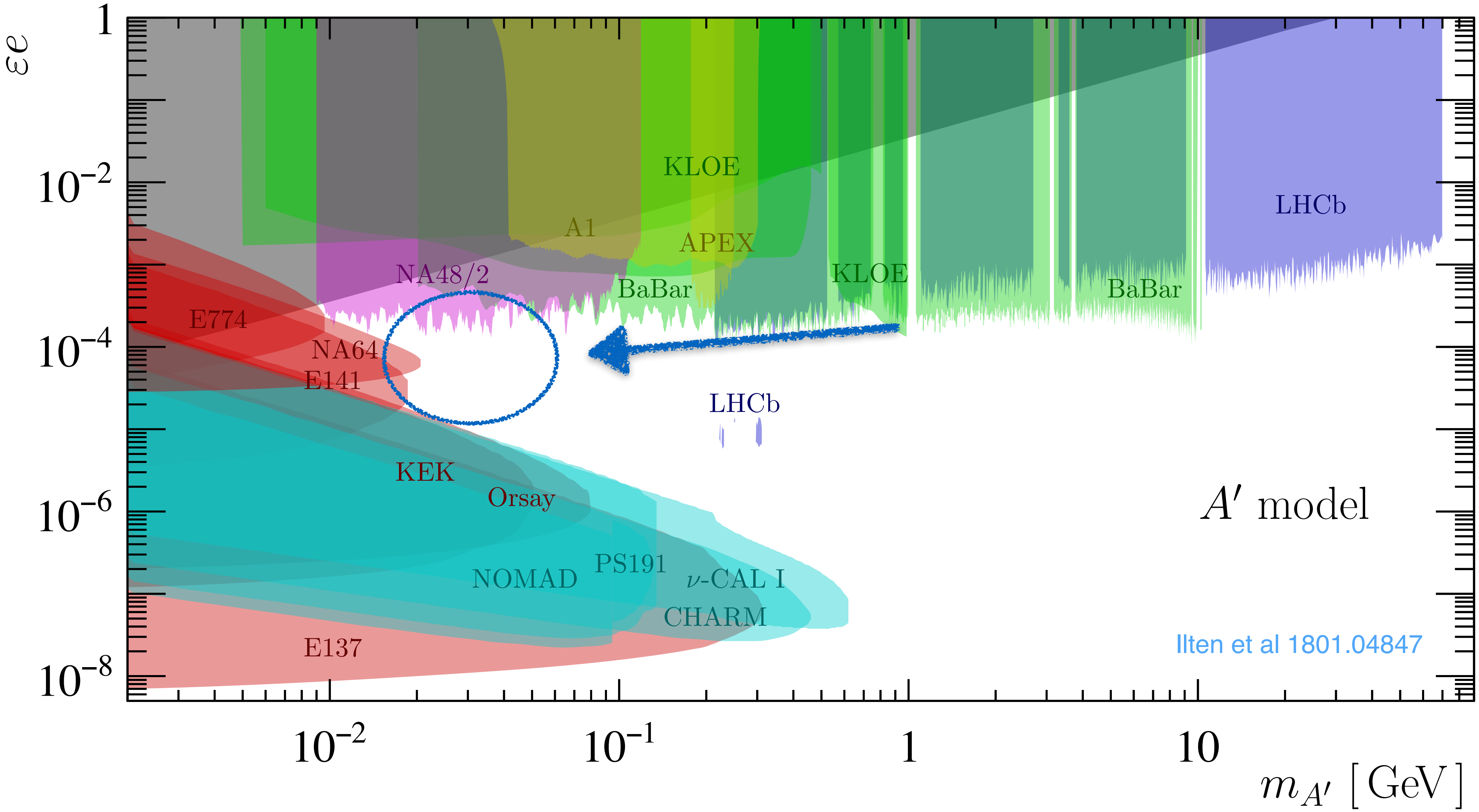


Z_D pheno is similar to dark photon case



Benchmark

m_N = 320 MeV

$m_{Z'}$ = 60 MeV

$|U_{\mu 4}|^2 = 10^{-6}$

α_D = 0.25

$\alpha\varepsilon^2 = 3 \times 10^{-9}$

χ^2/dof = 31.2/36

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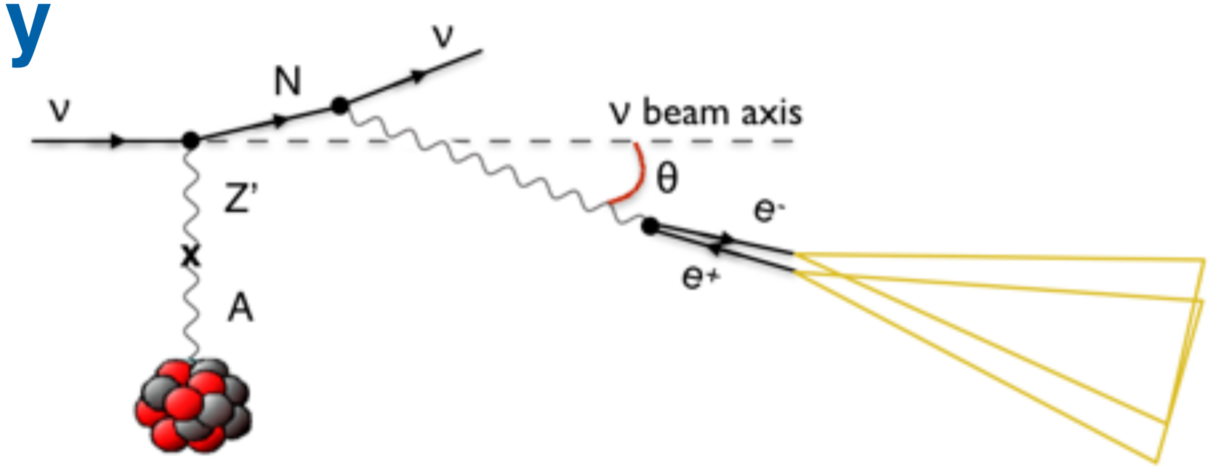


N pheno is novel, we are working on it

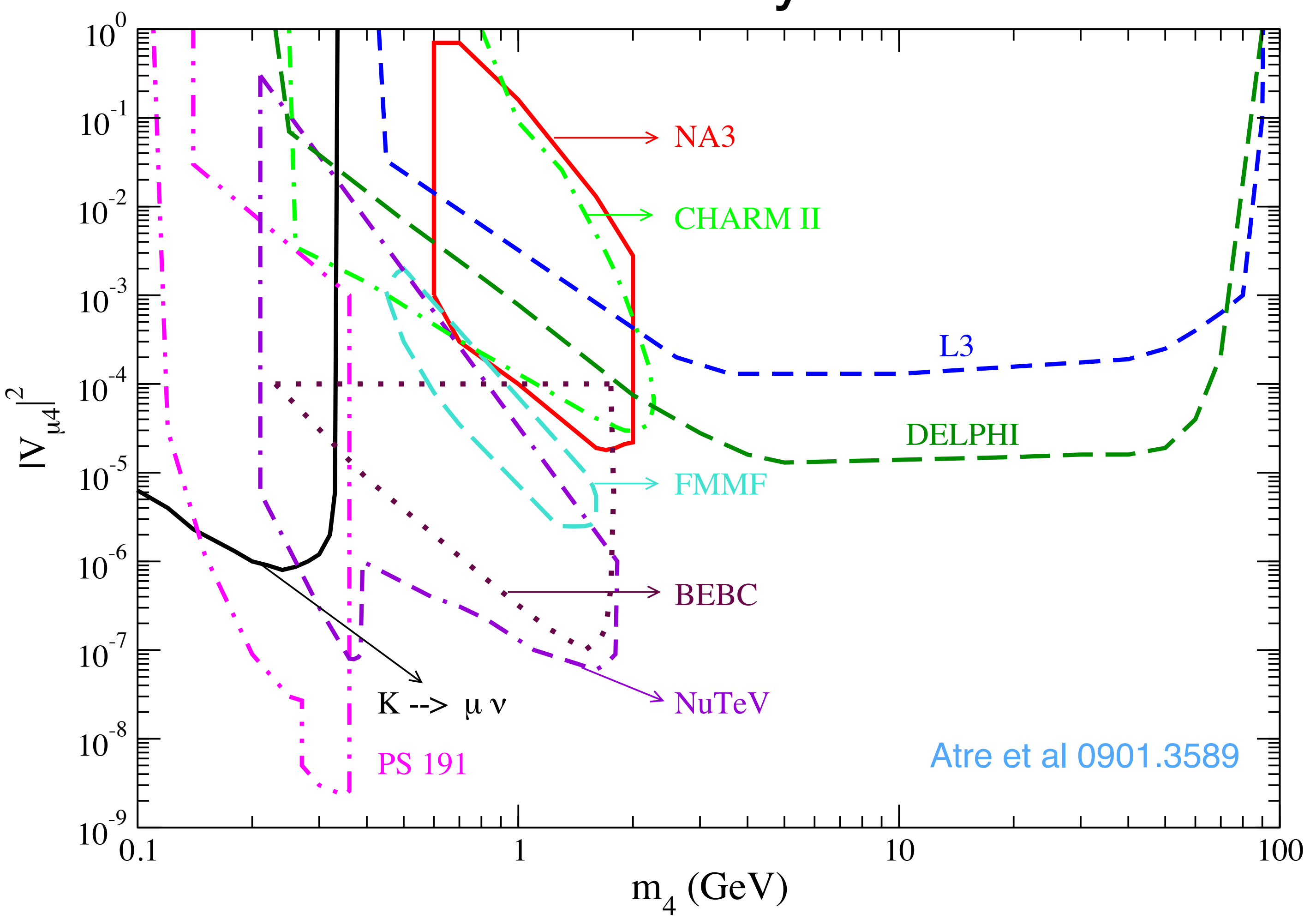
Many constraints depend on lifetime

Ex: PS 191, BEBC, NuTeV, …

In many experiments, sensitivity depends crucially on *N* **not** decaying promptly

Due to parameters, our *N* always decay promptly!

“Vanilla” heavy sterile



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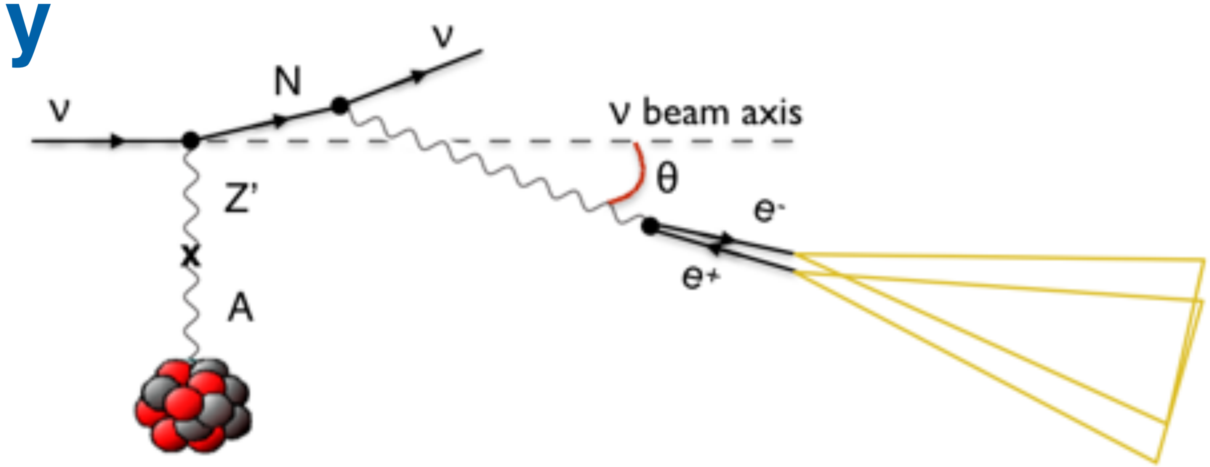

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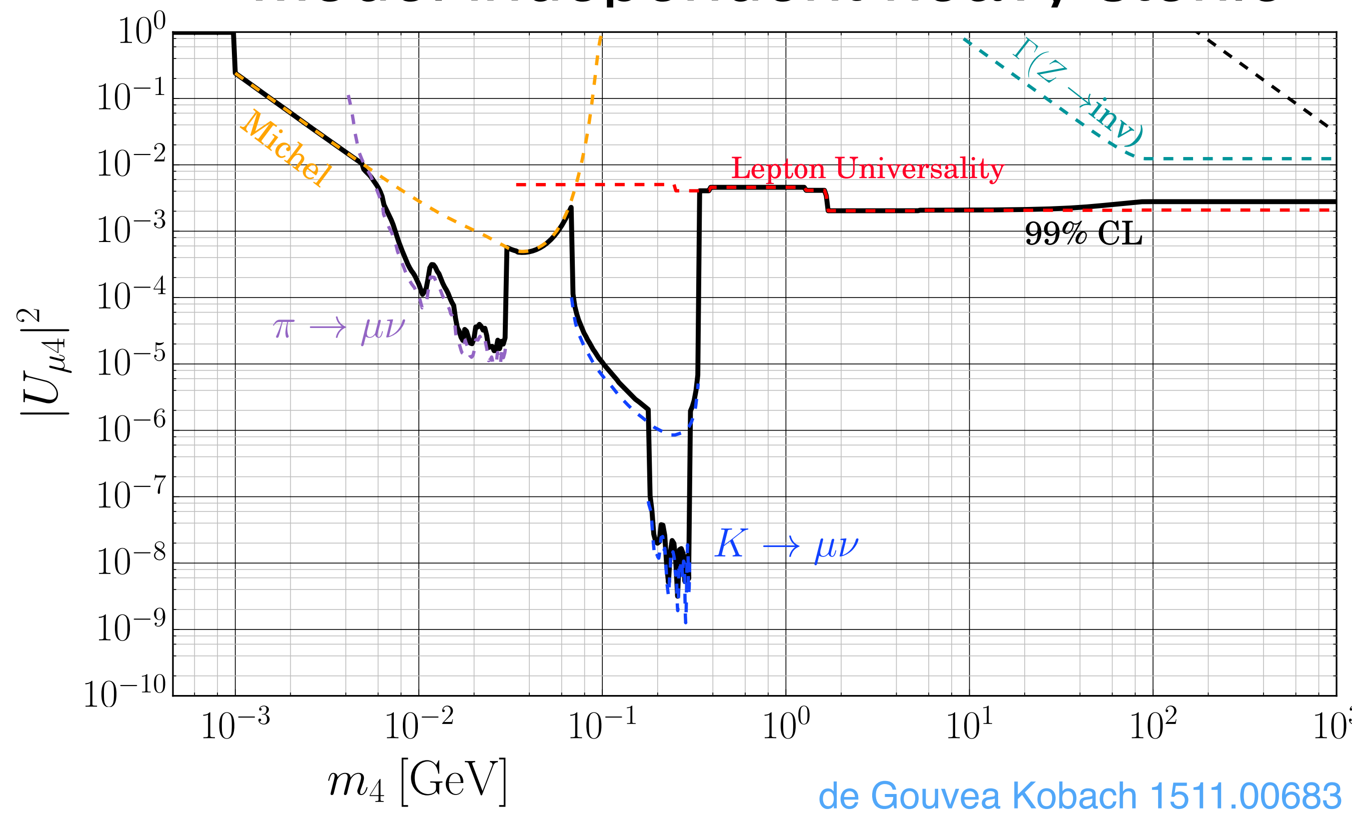

de Gouvea Kobach 1511.00683

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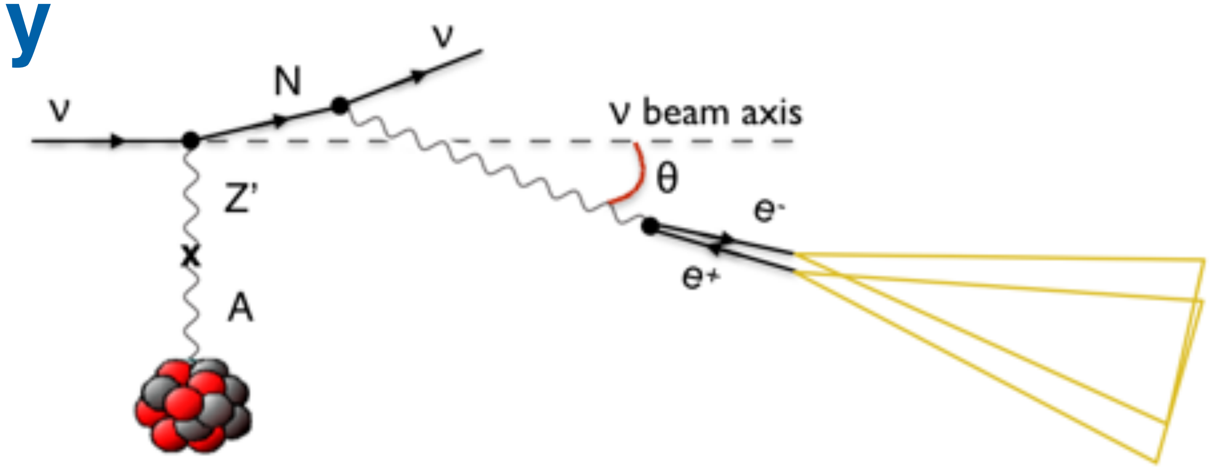

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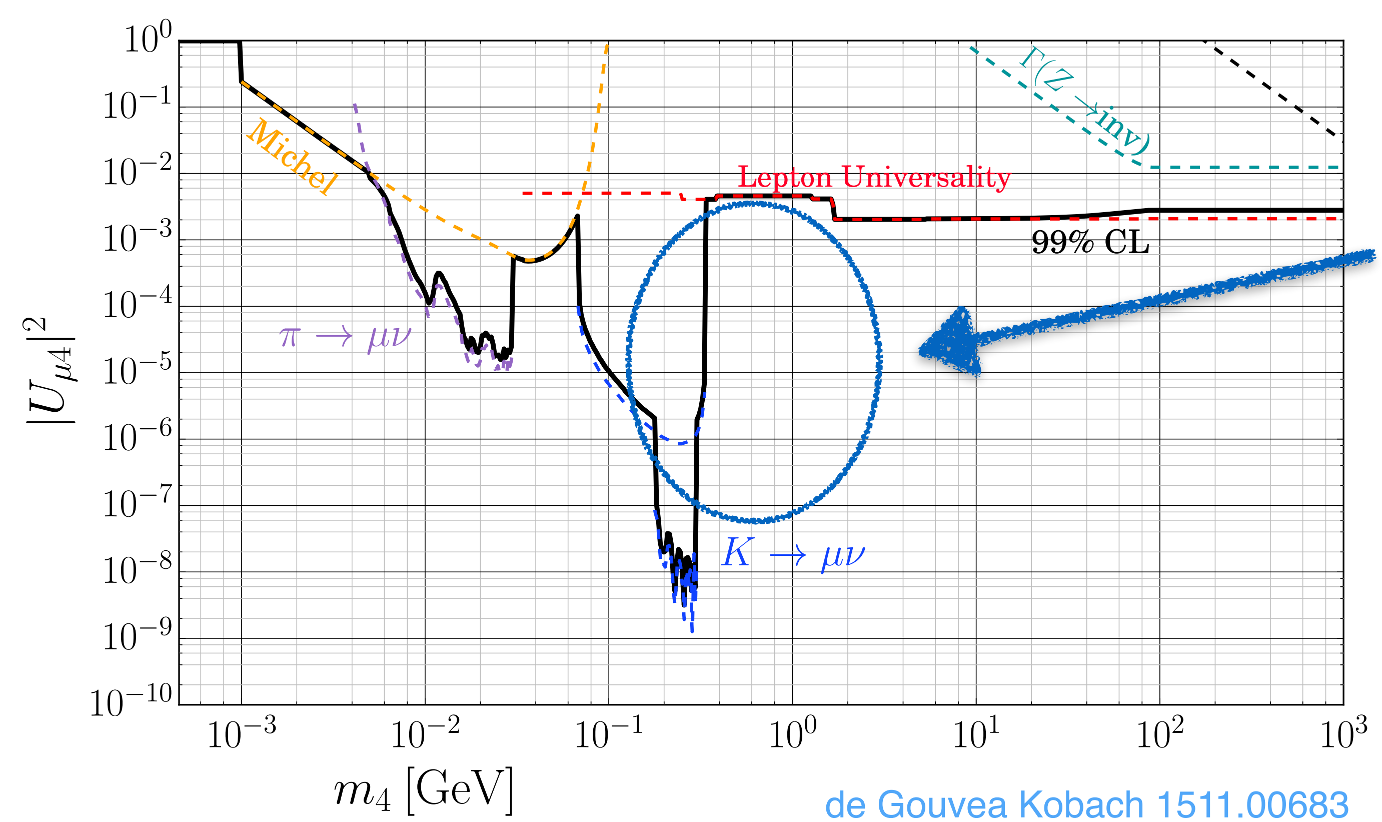

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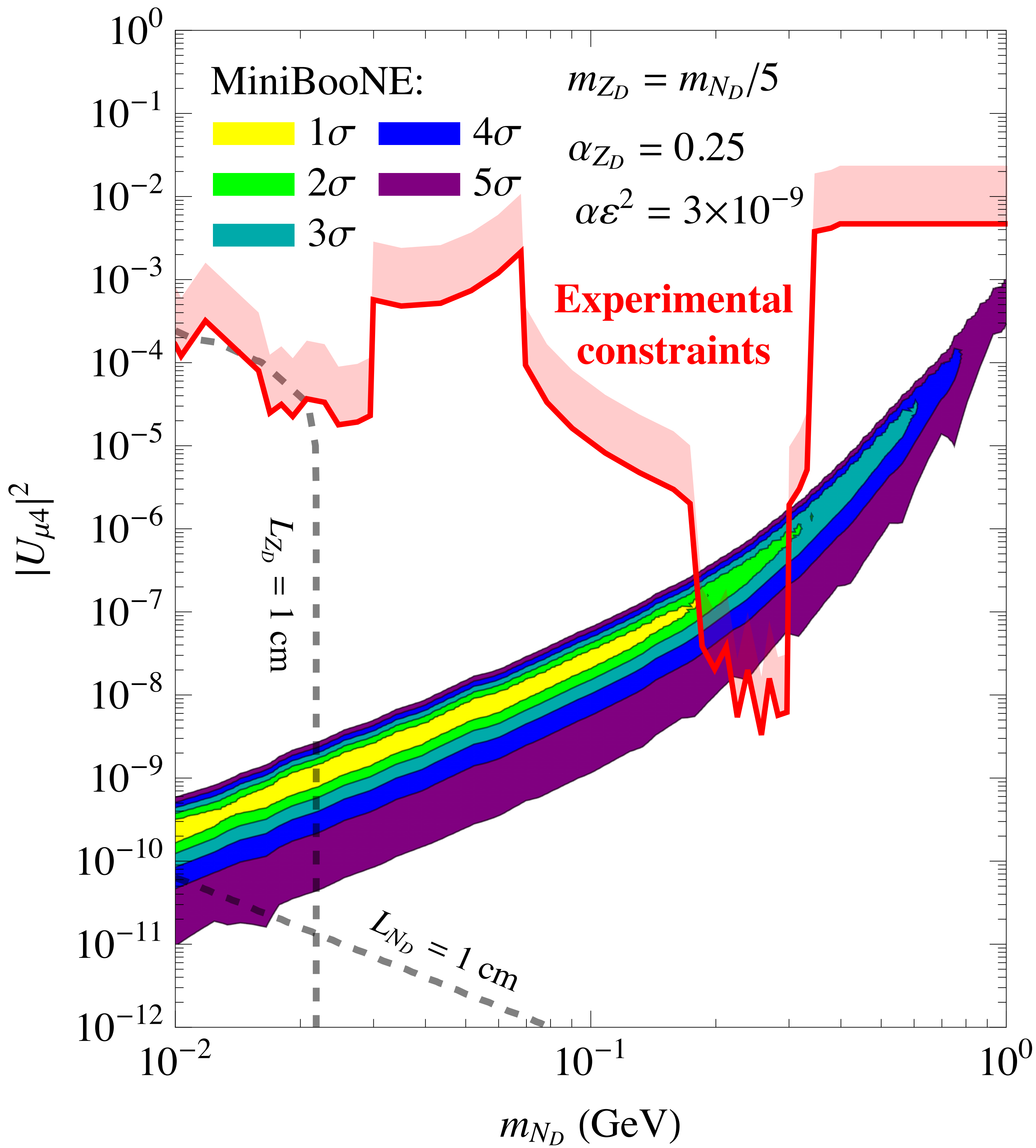

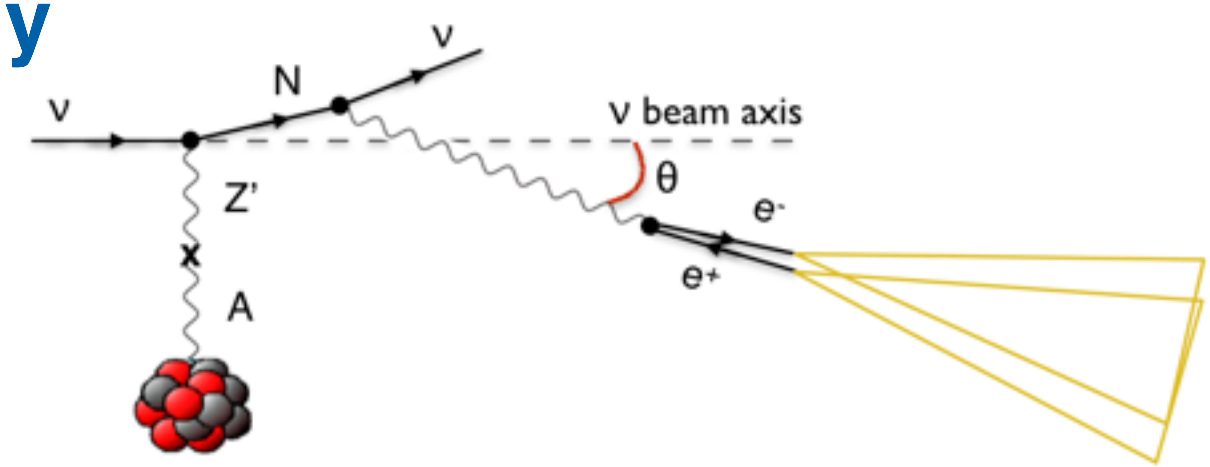

Bertuzzo et al 1807.09877

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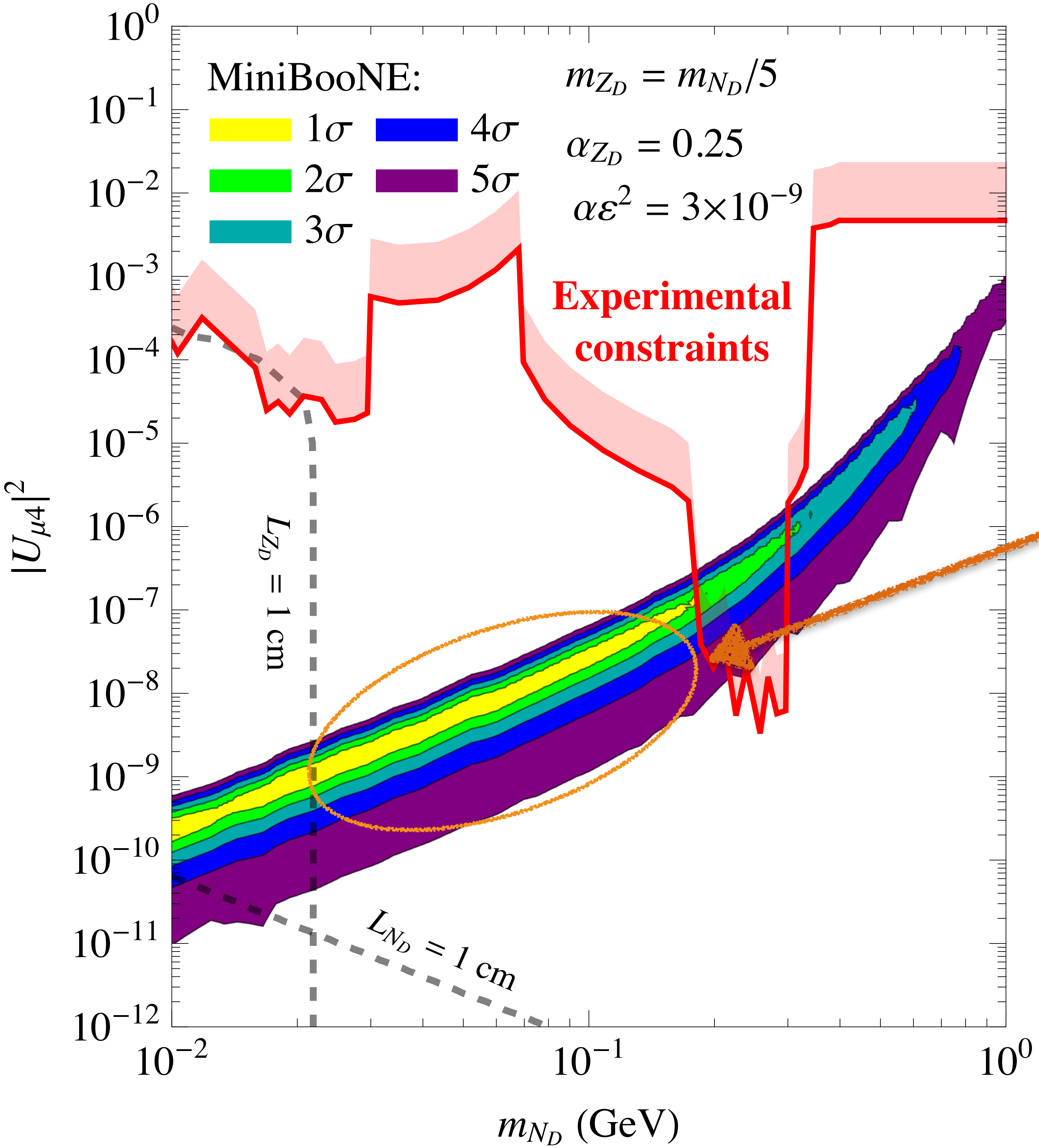

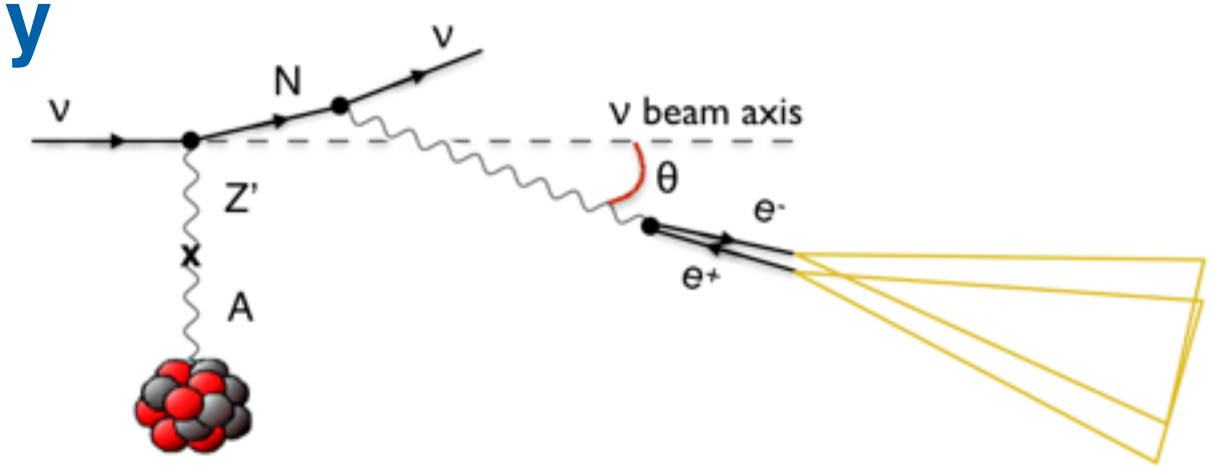

Angular spectrum not great here

Bertuzzo et al 1807.09877

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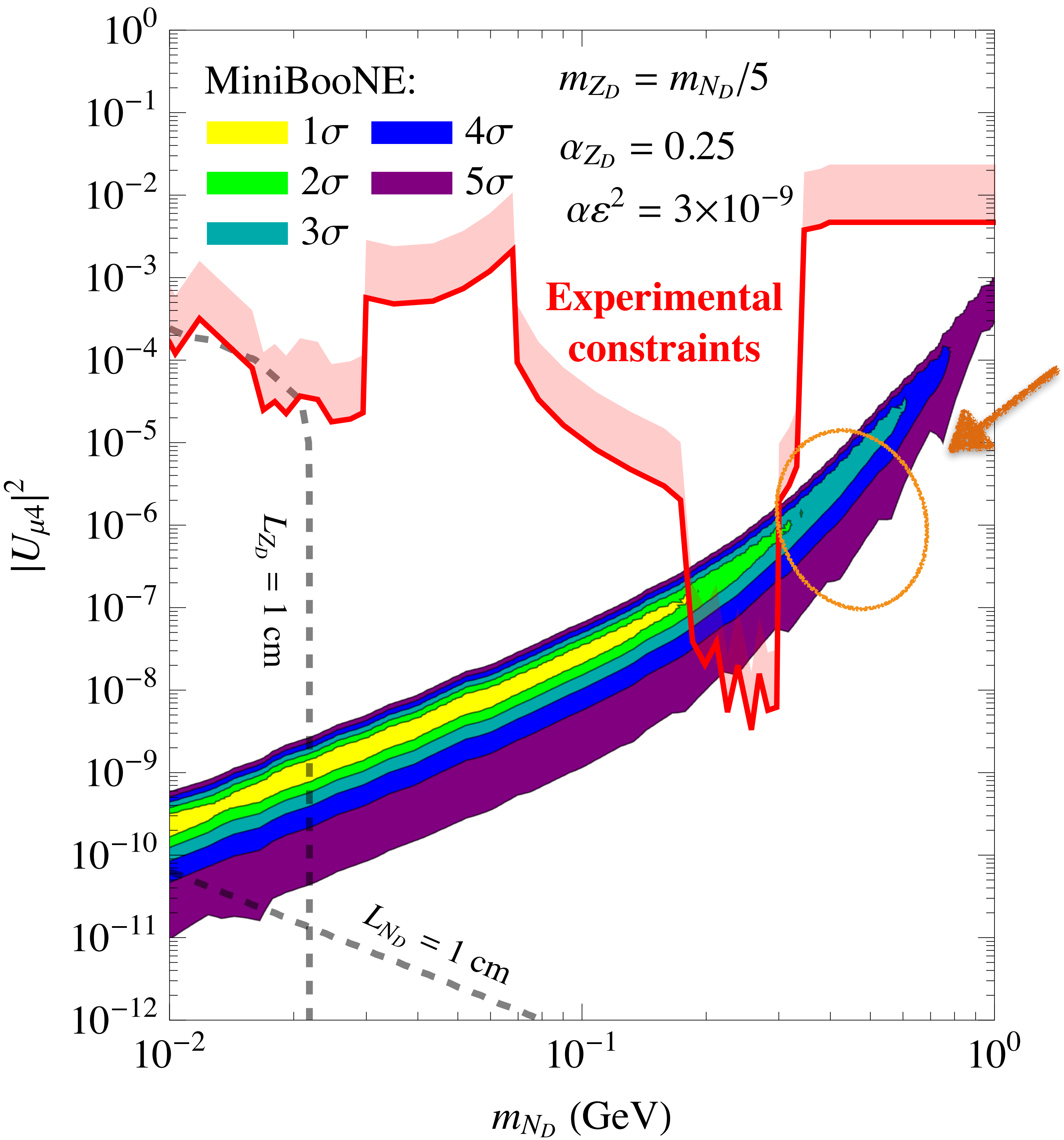

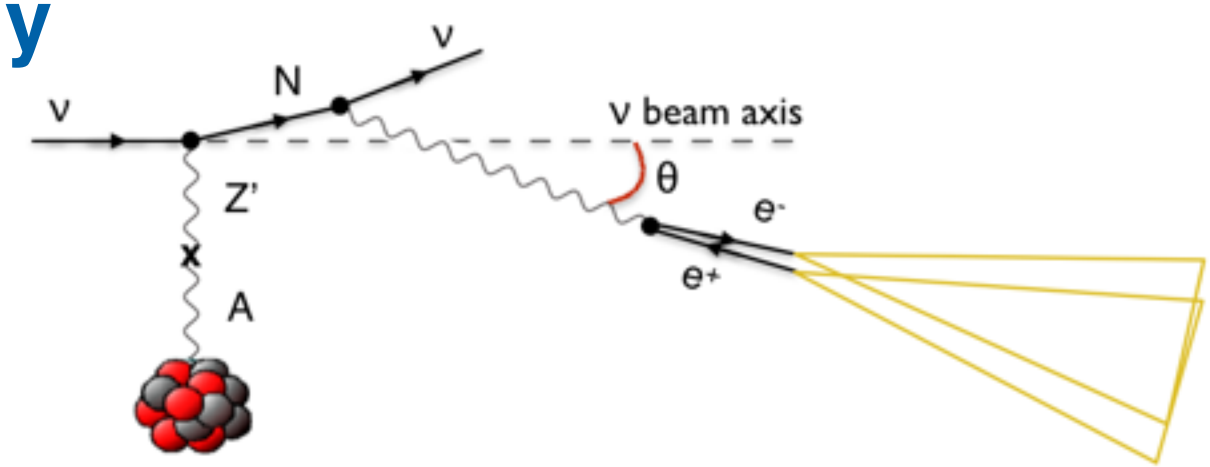

Angular spectrum quite good!

Bertuzzo et al 1807.09877

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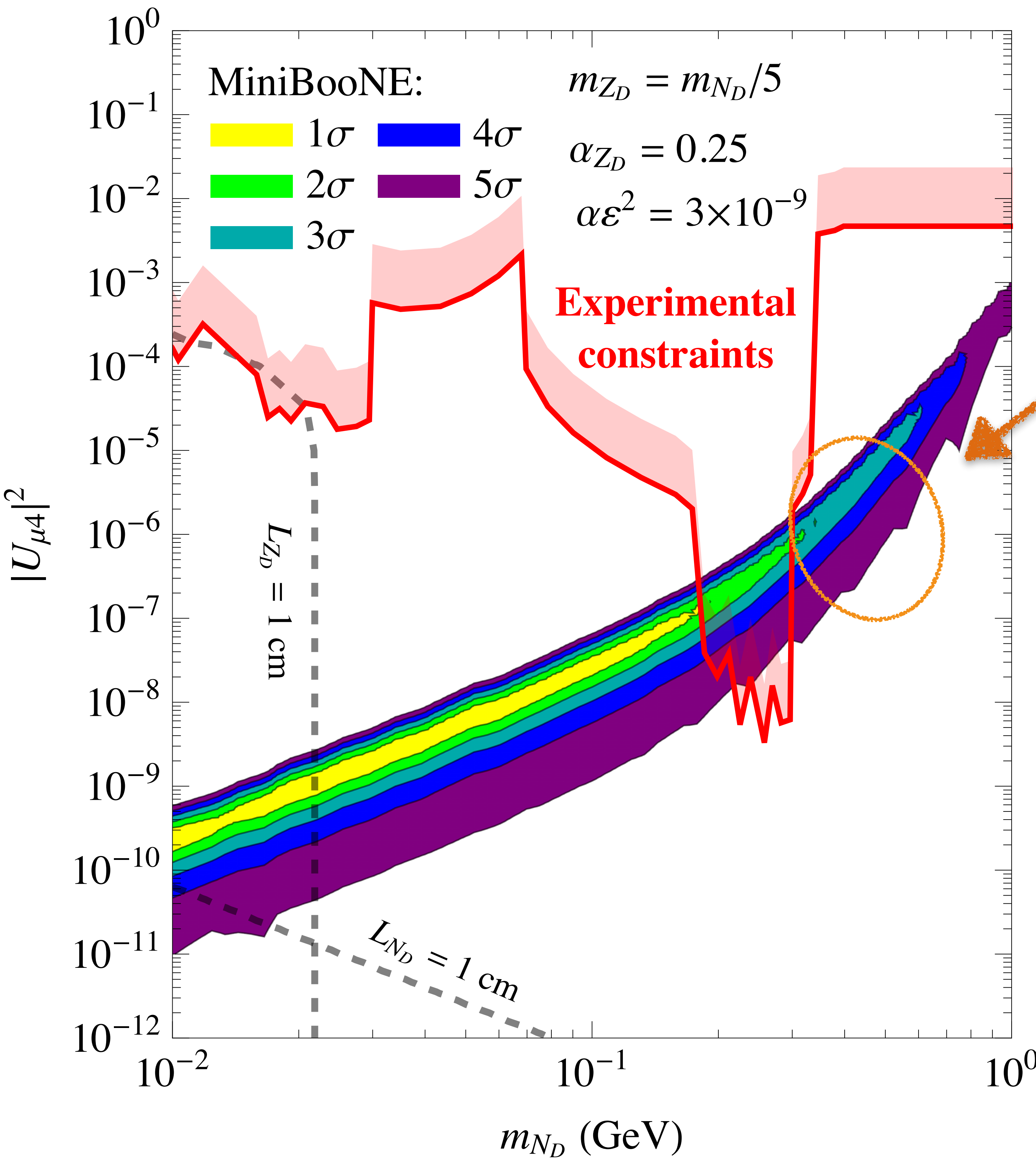

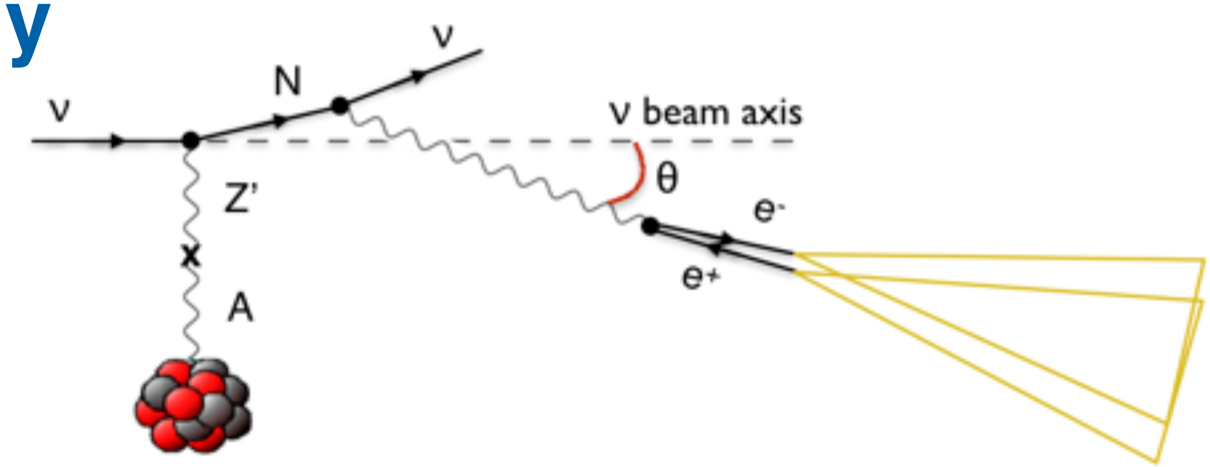

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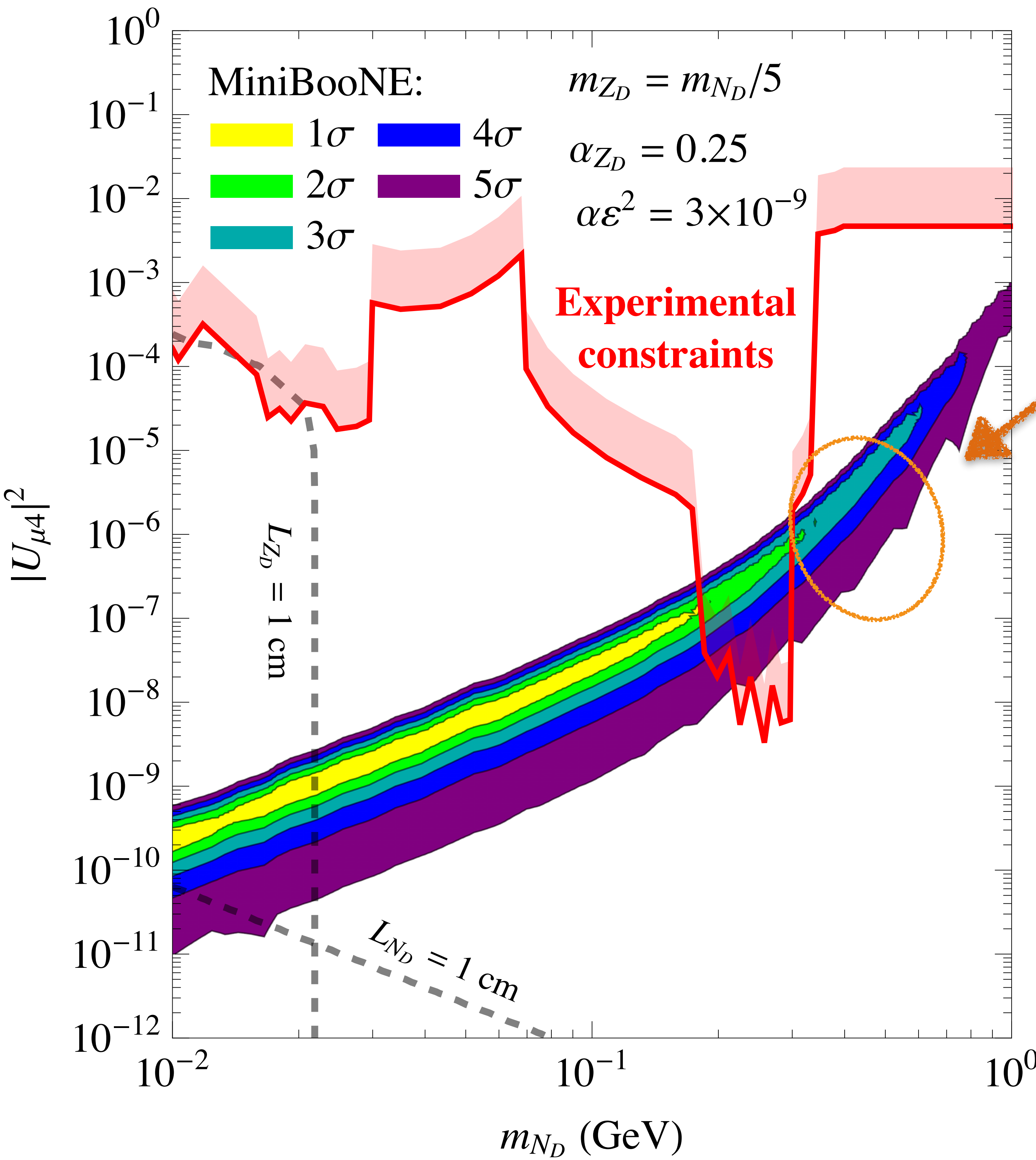

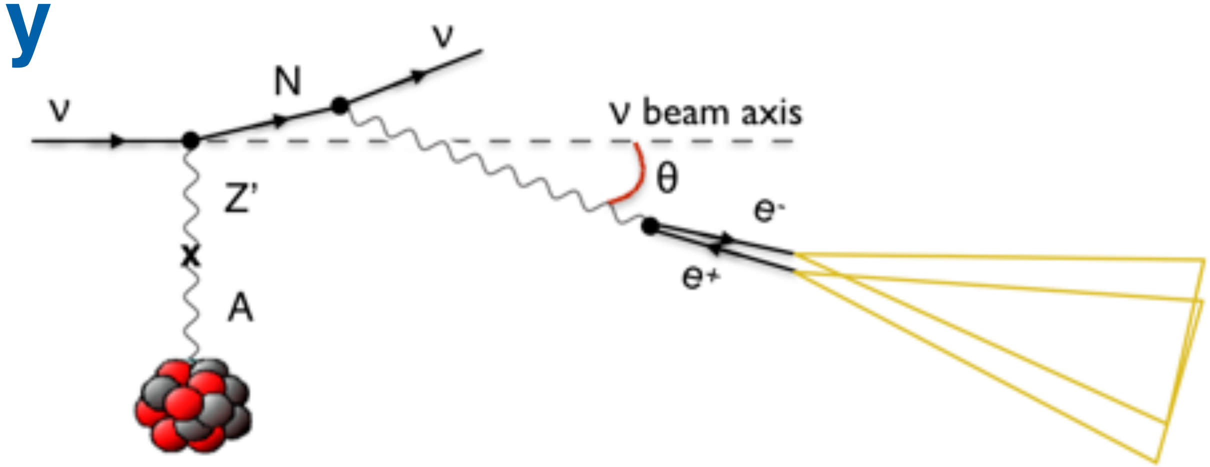

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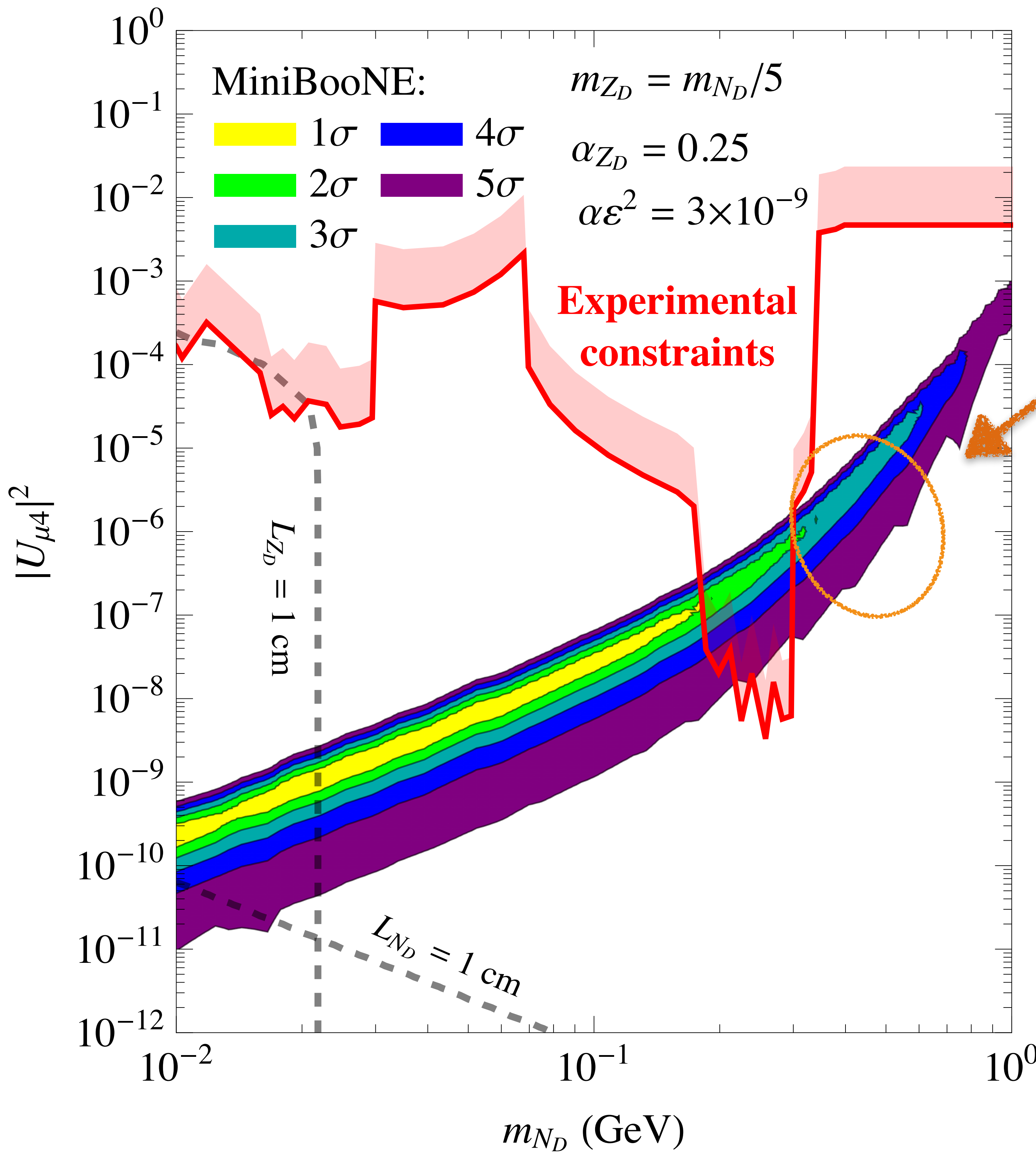

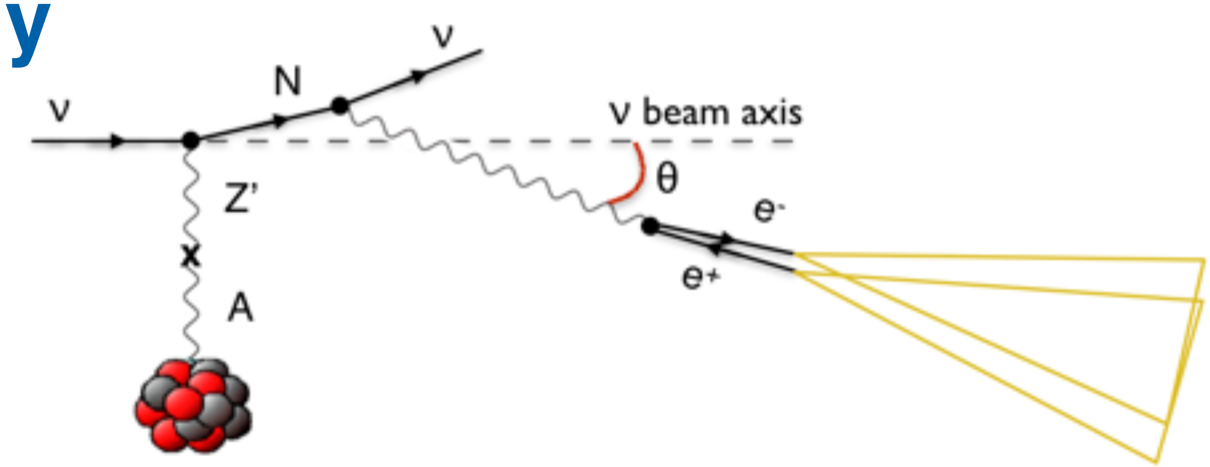

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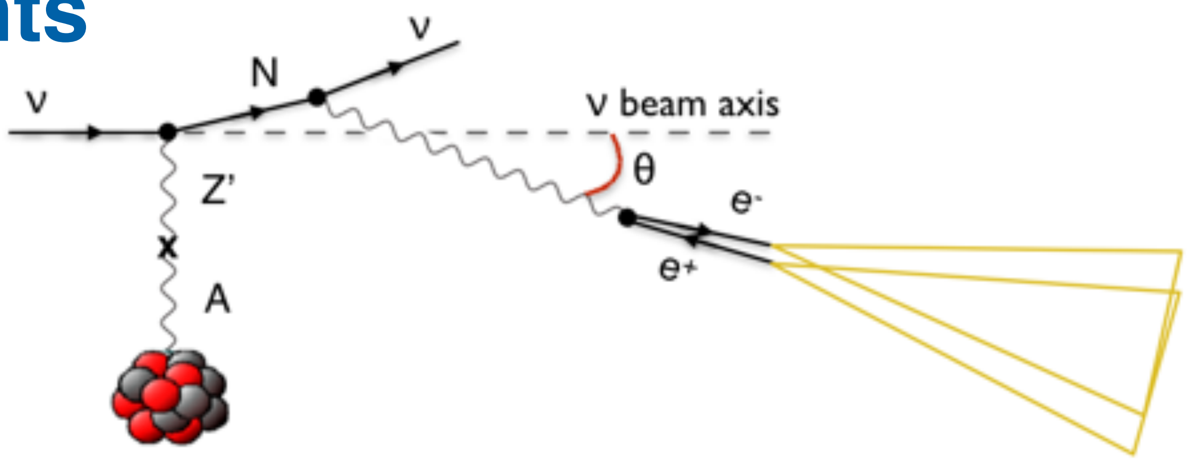
Light Z_D = partially coherent scattering

LHC constraints are not expected to be stringent below 1 GeV

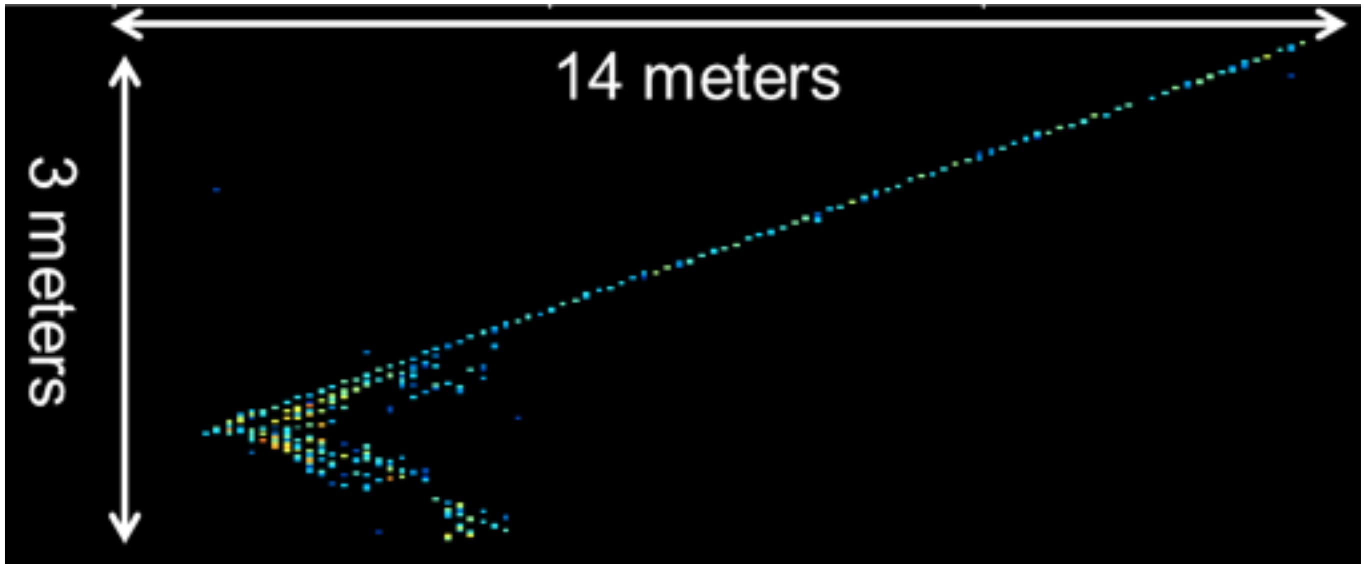
Bertuzzo et al 1807.09877

Pheno in other neutrino experiments



MiniBooNE's signature:

Collimated e^+e^- pair in MINOS+, NOvA, or T2K is likely be tagged as ν_e event



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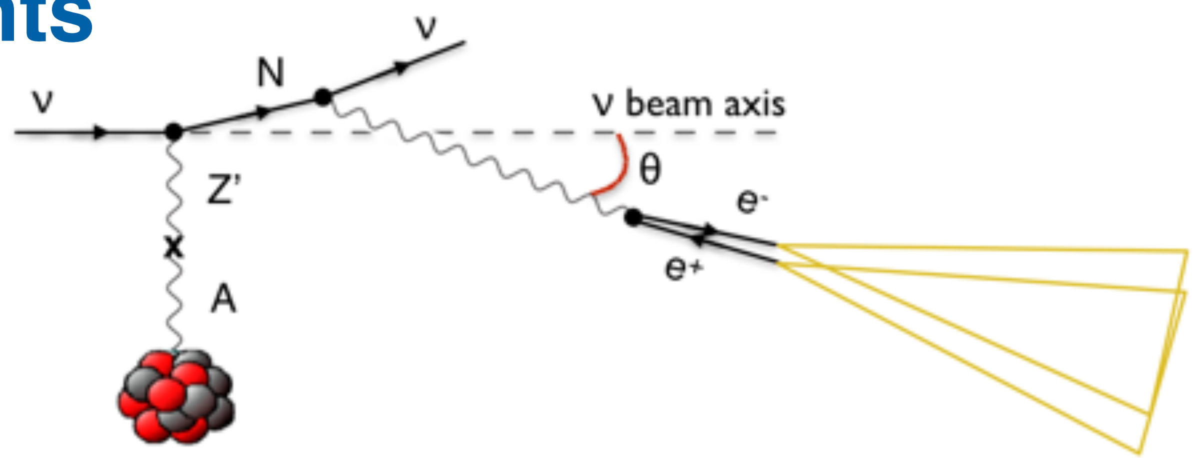

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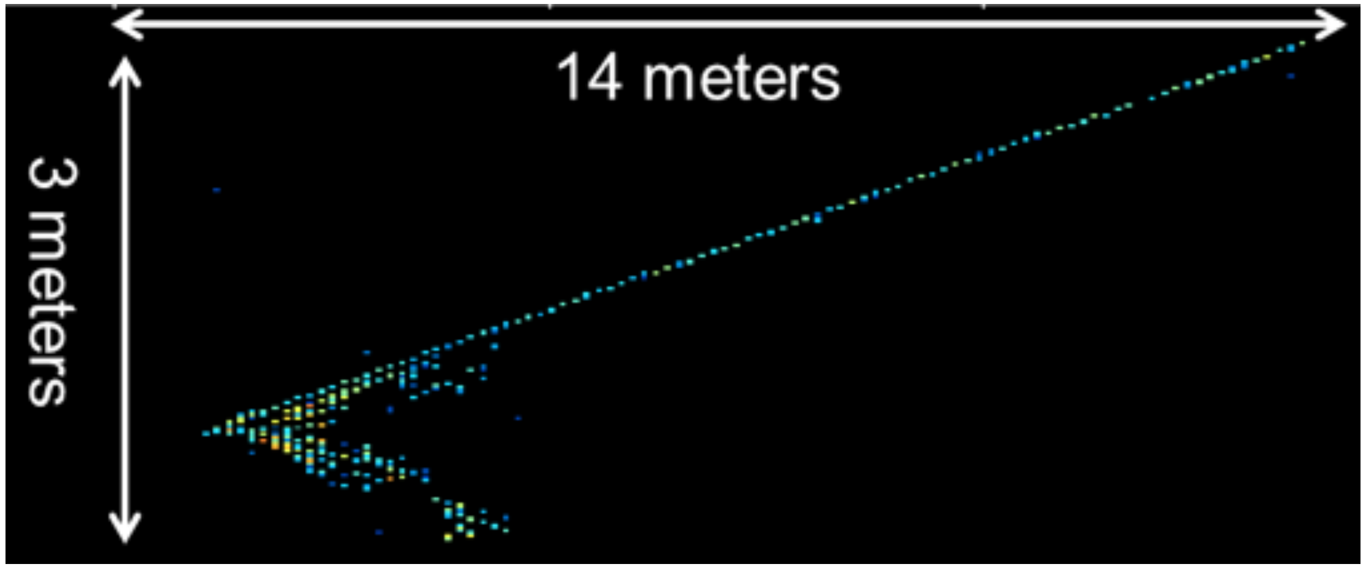
Heavy enough Z_D can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized…)



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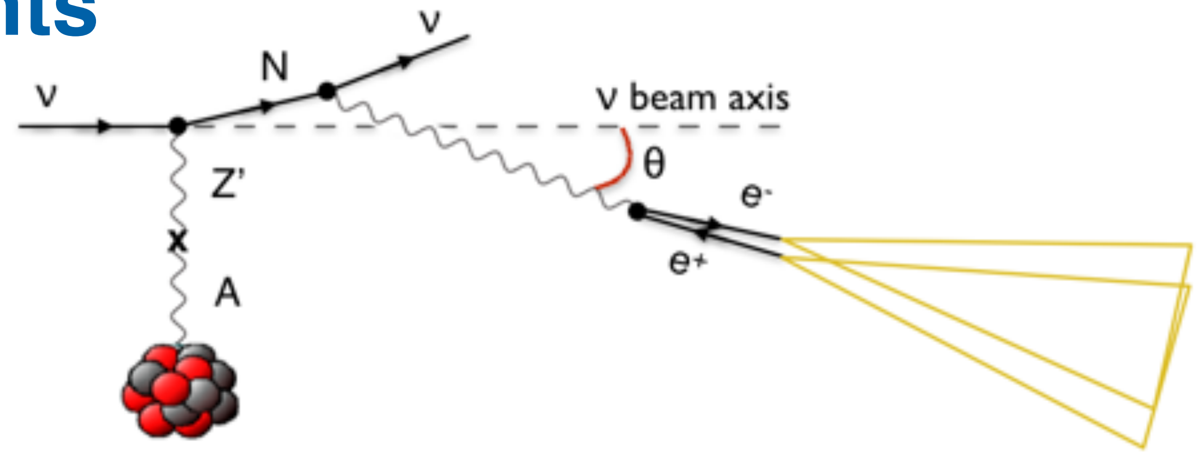

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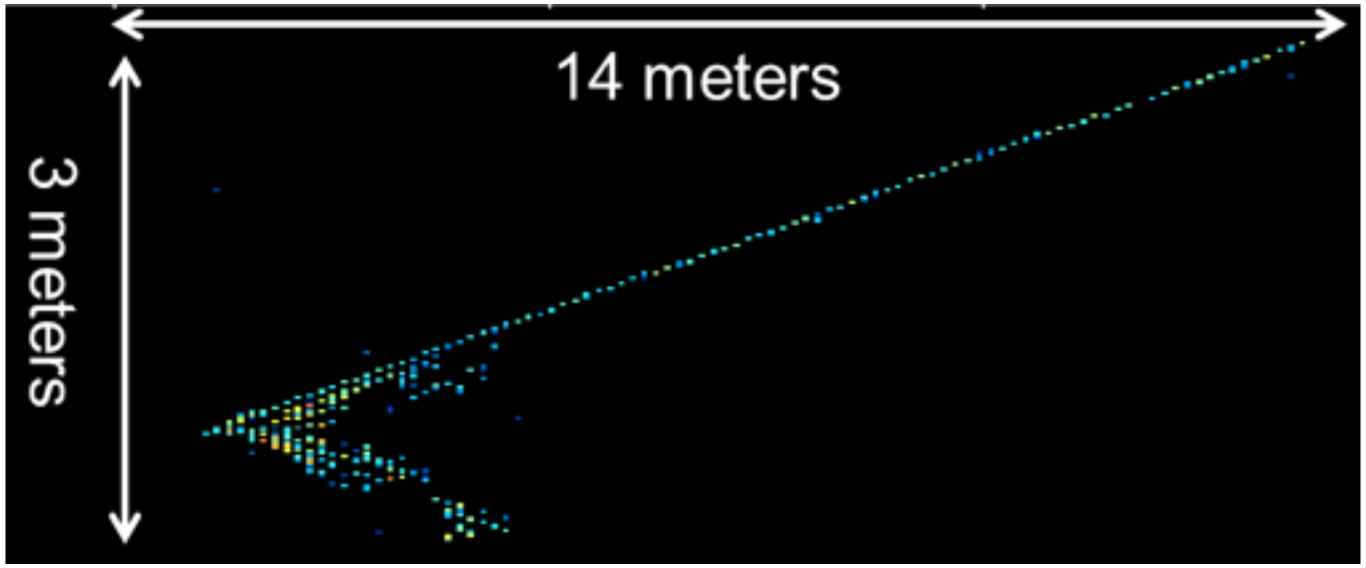
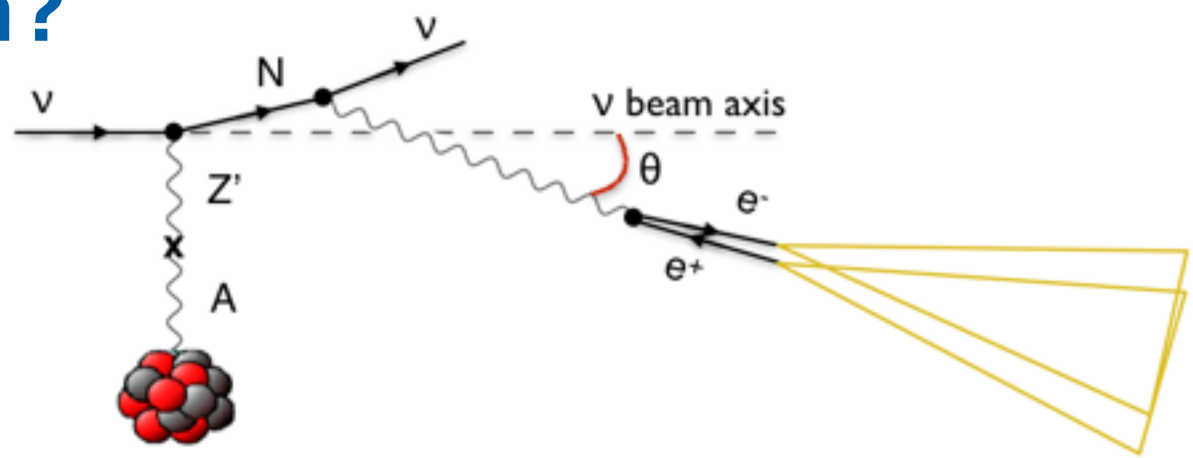
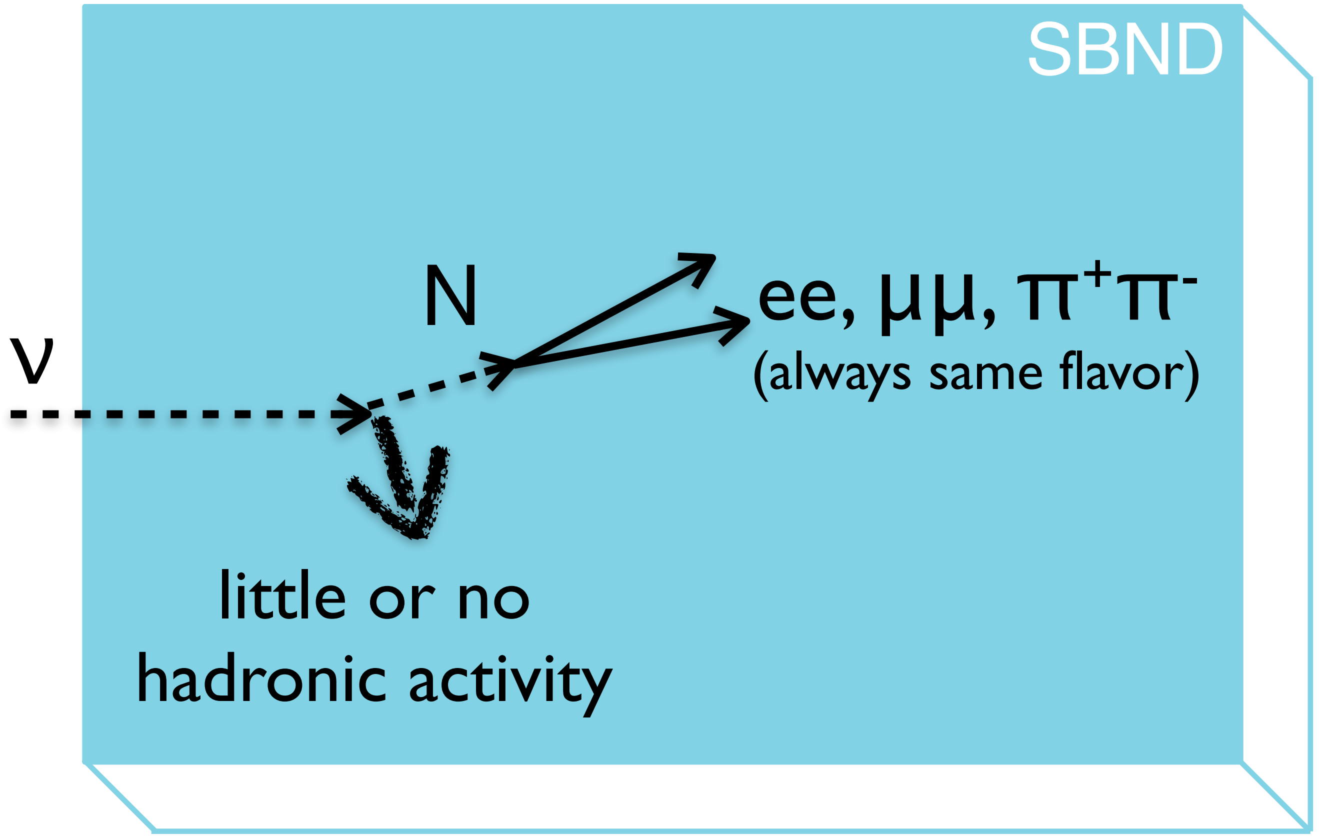


Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N

What happens at the SBN program?



No baseline dependence



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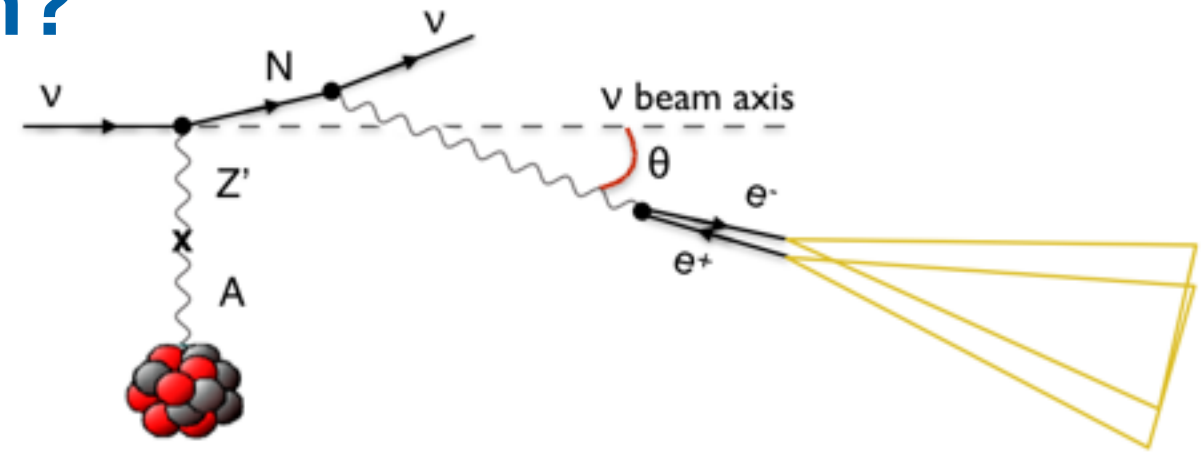

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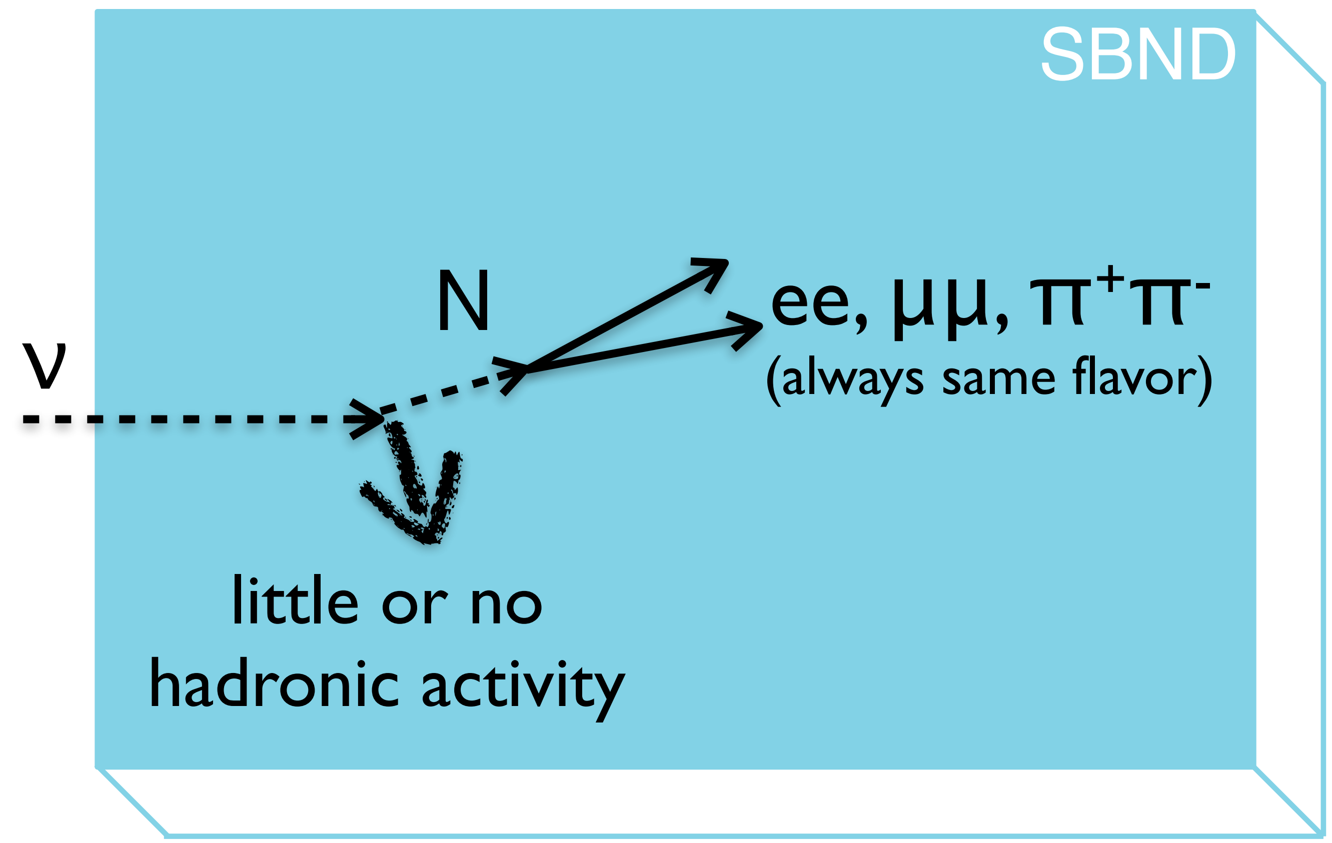

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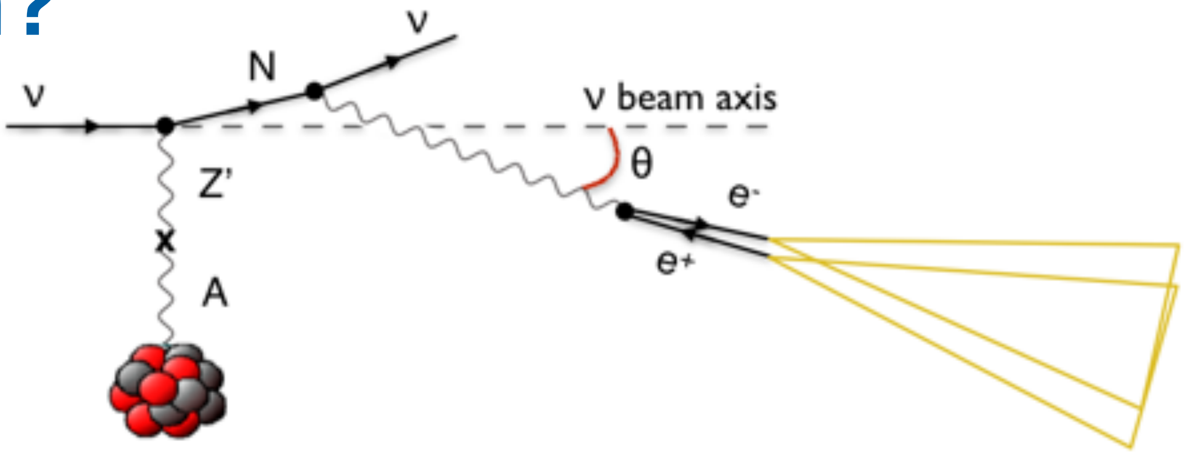

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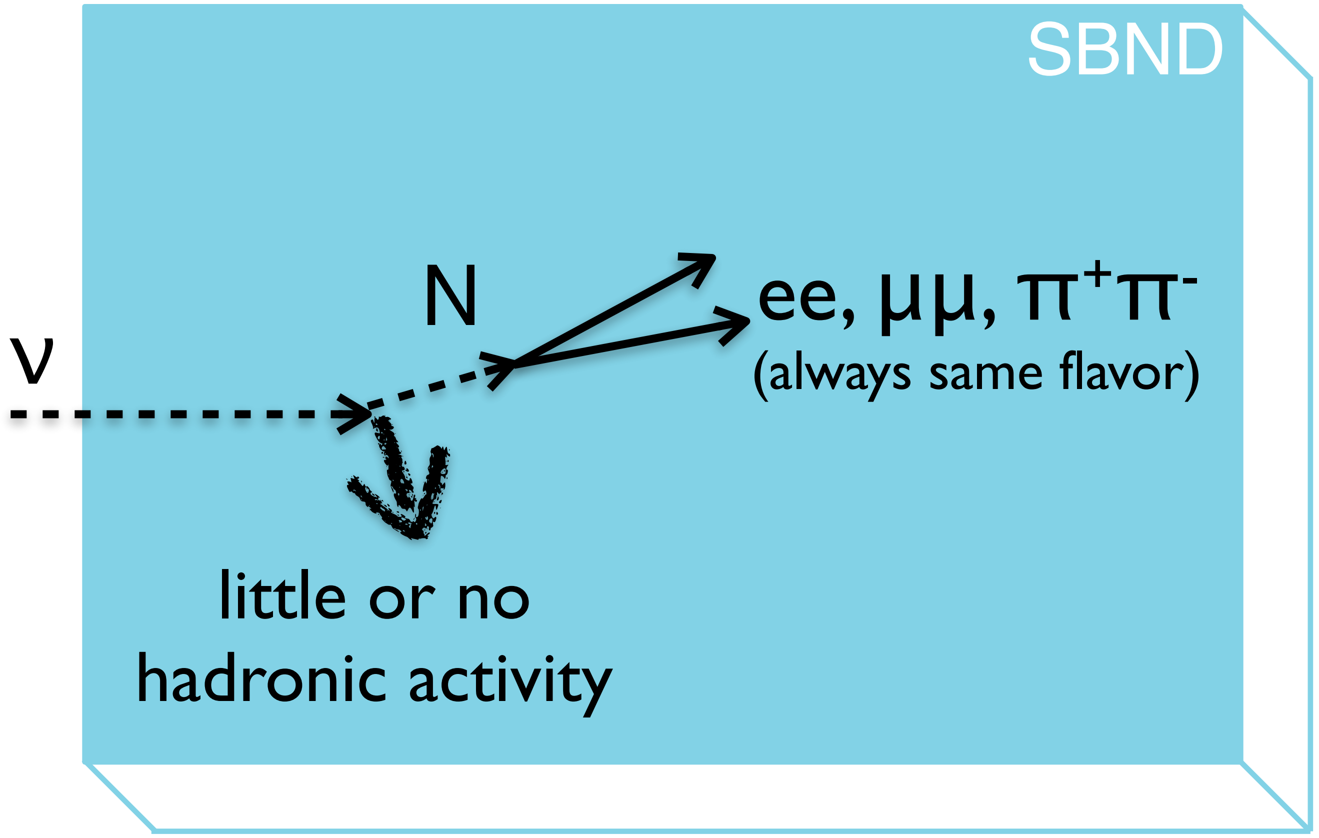

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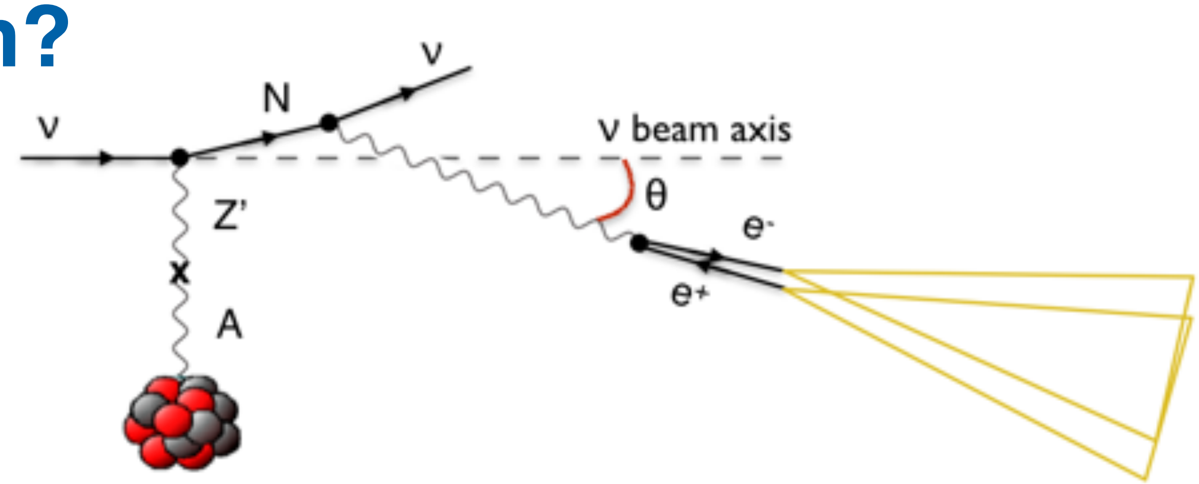

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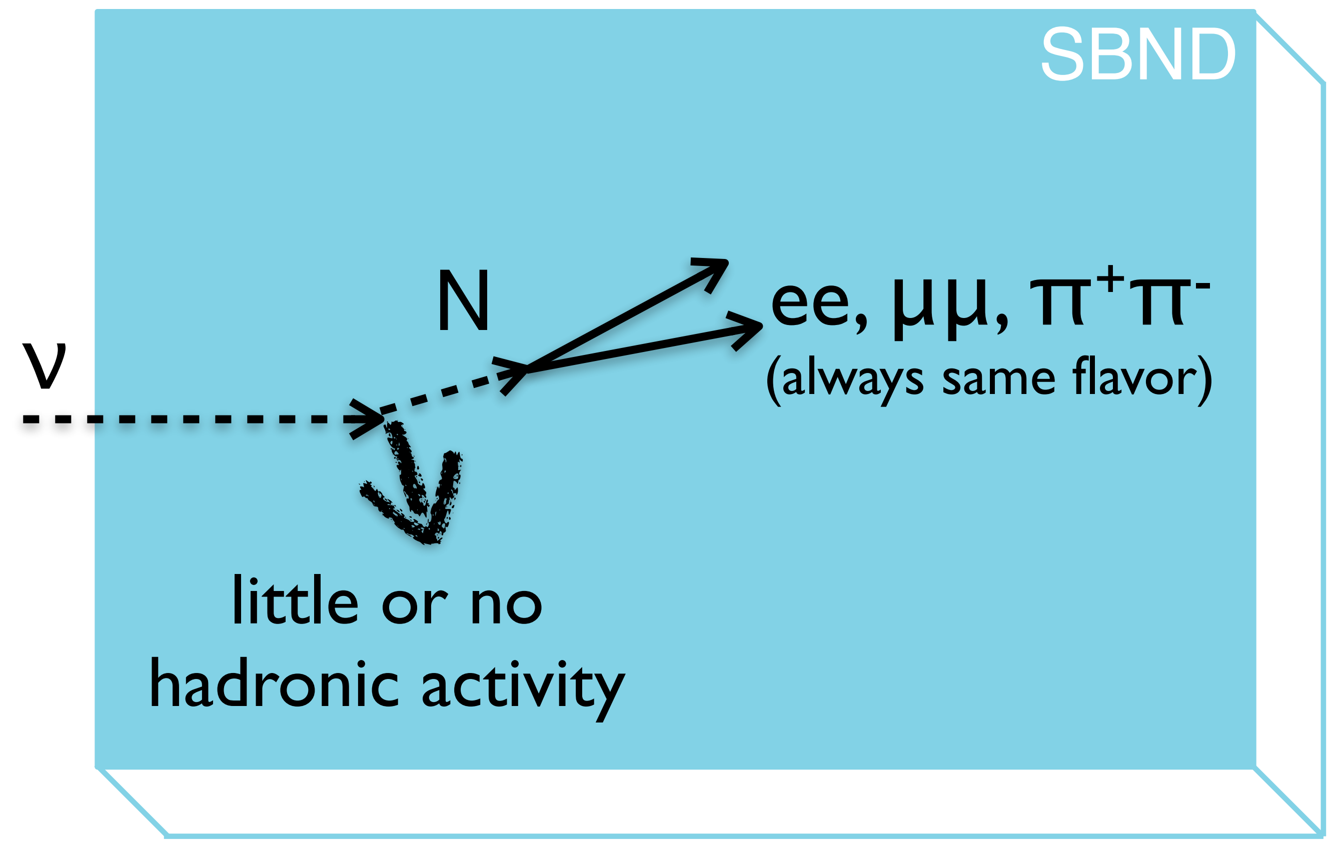

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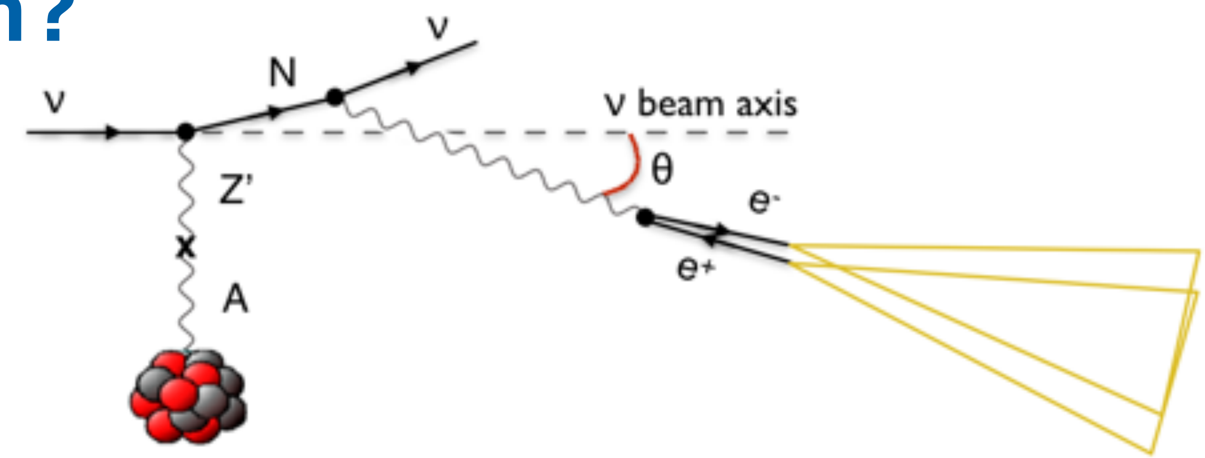

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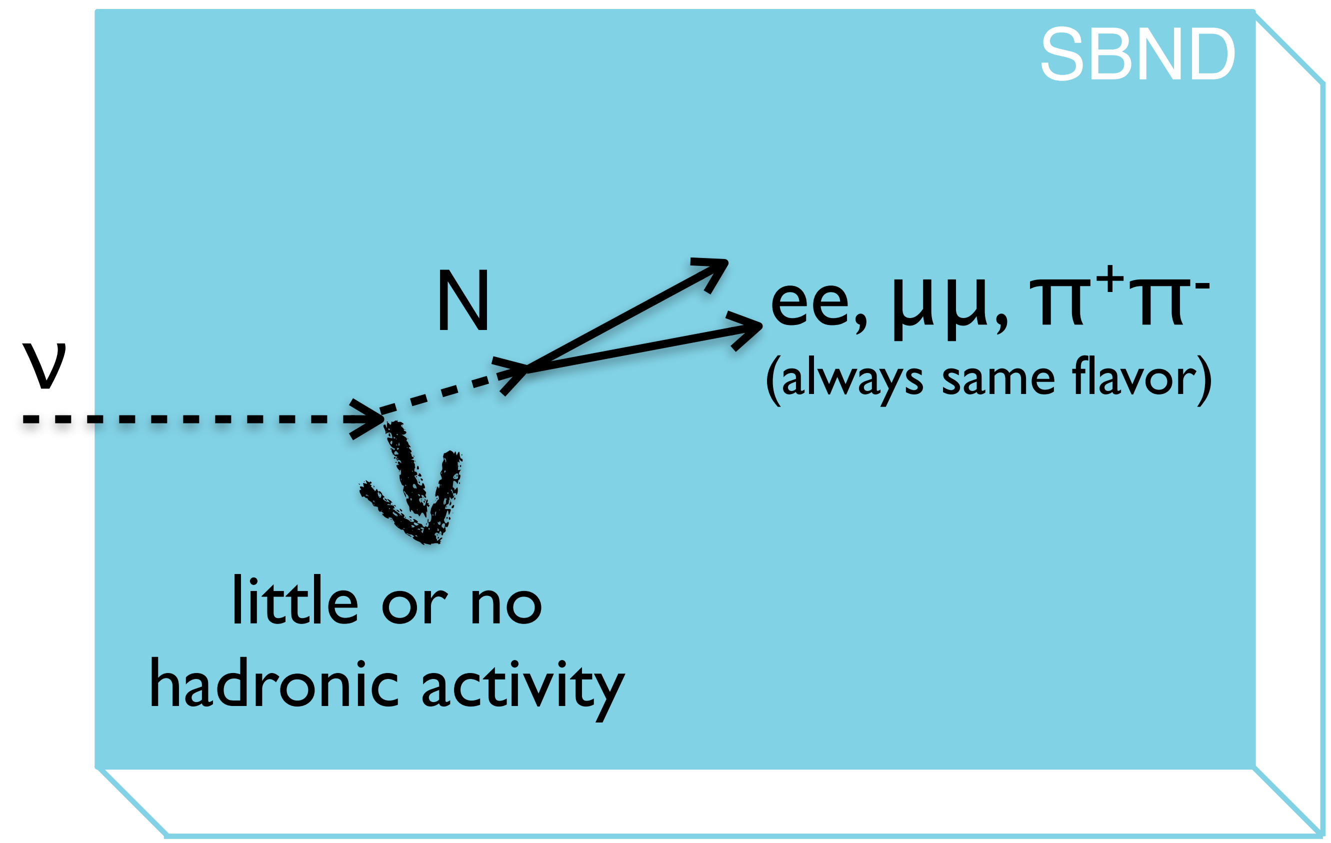

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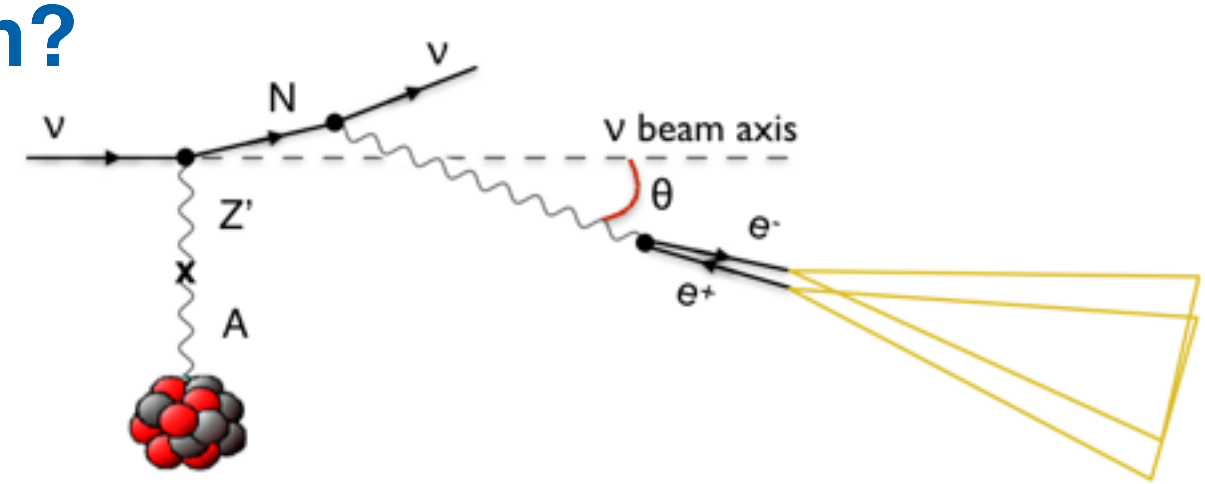

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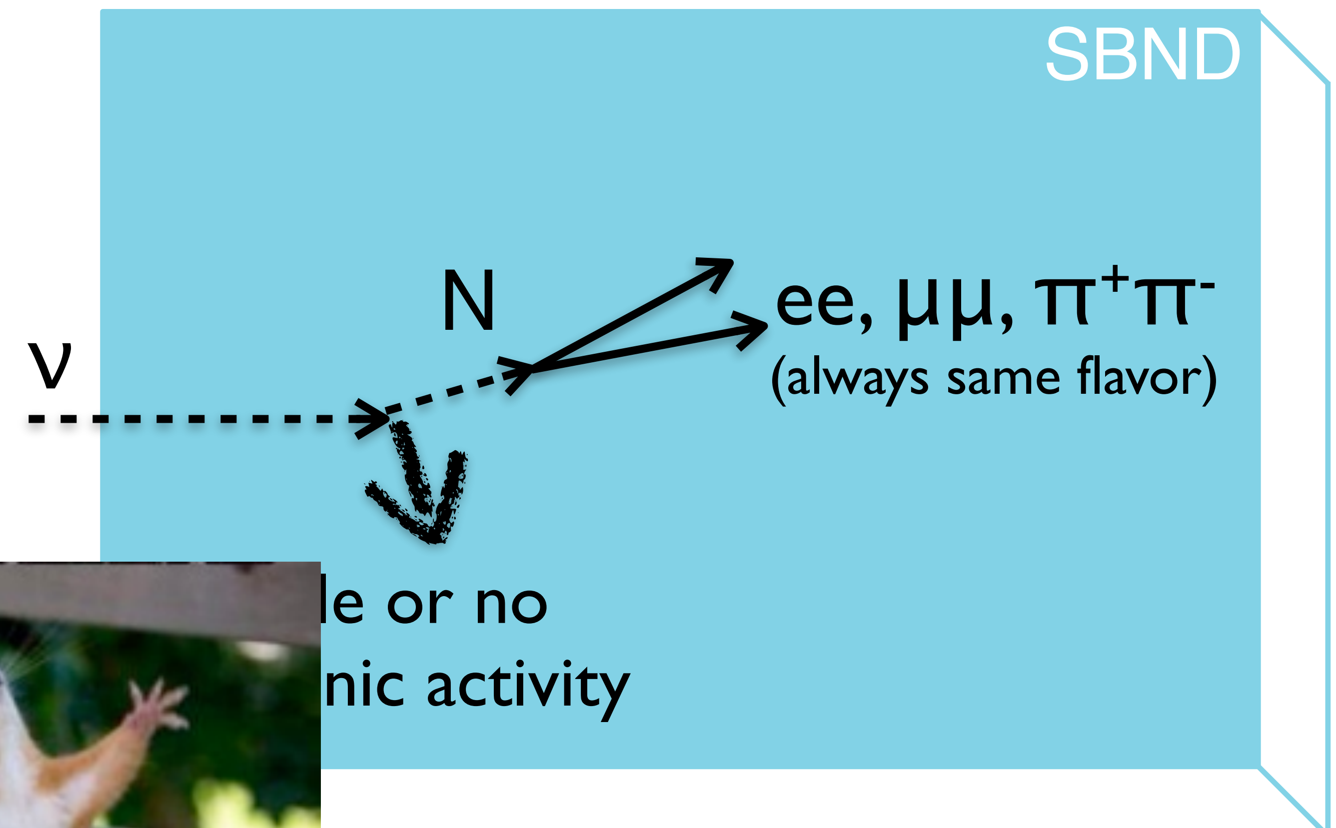

Part II

(if I still have 10 mins)

The connection to neutrino masses

pmachado@fnal.gov

Why are neutrino masses so small?

$$\bar{L}\tilde{H}N$$

Neutrino masses are very special

Just repeating the Higgs mechanism leads to
RH neutrino *N* with no conserved quantum number

Majorana mass allowed, leading to Weinberg operator

$$\mathcal{O}_5 = \frac{c}{\Lambda} LLHH$$

Very large Λ, very high scales involved

Can neutrino masses come from light physics?

Neutrinos and the dark sector

RH neutrinos:
no conserved quantum number, no SM interactions = dark sector

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Neutrino masses are a natural portal to the dark sector

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All this + new dark Z = MiniBooNE explanation!

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Neutrinos and the dark sector

RH neutrinos:
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Neutrino masses are a natural portal to the dark sector

All this + new dark Z = MiniBooNE explanation!

Maybe a low scale dark sector can give rise to neutrino masses and explain the MiniBooNE excess

Starting point:

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

Neutrinos and the dark sector

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Walks and quacks like inverse seesaw

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

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

Neutrinos and the dark sector

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
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Neutrinos and the dark sector

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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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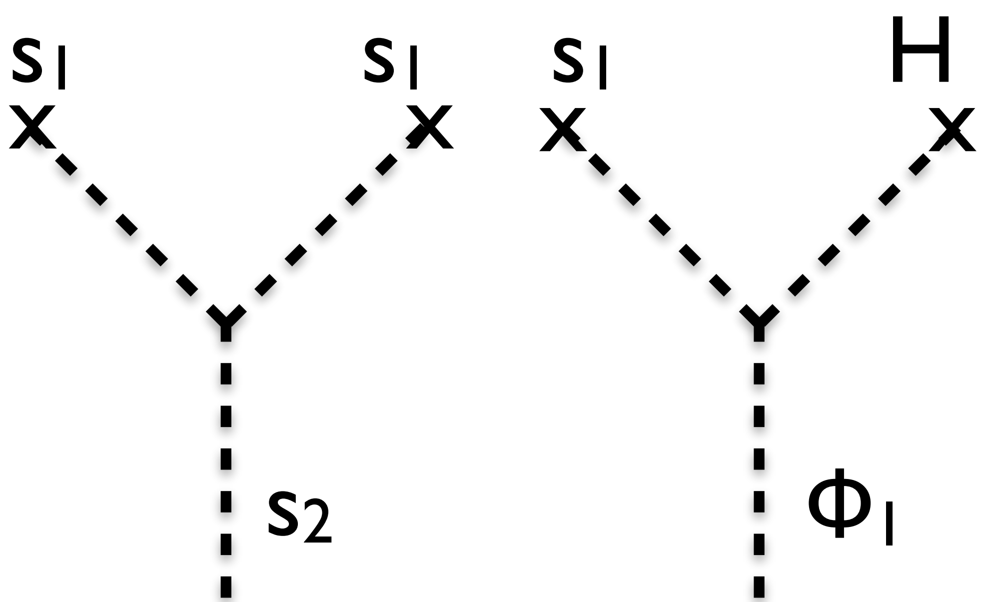

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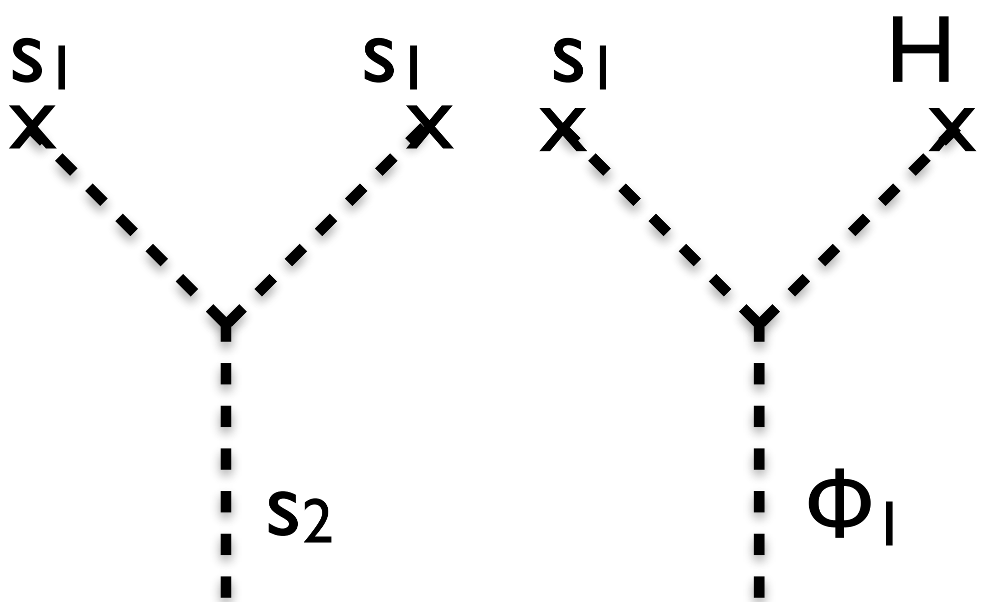
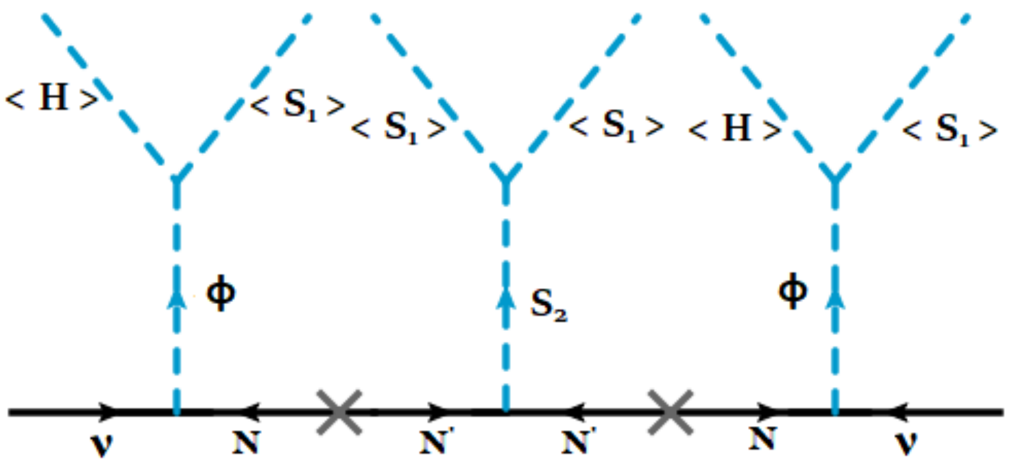


Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

Neutrinos and the dark sector

Consequences:



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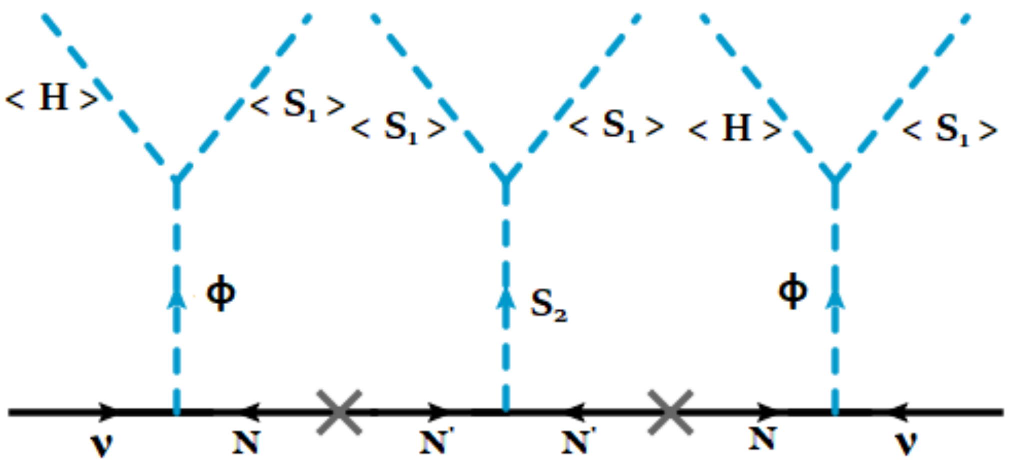

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Neutrino masses from D=9 operator

Neutrinos and the dark sector

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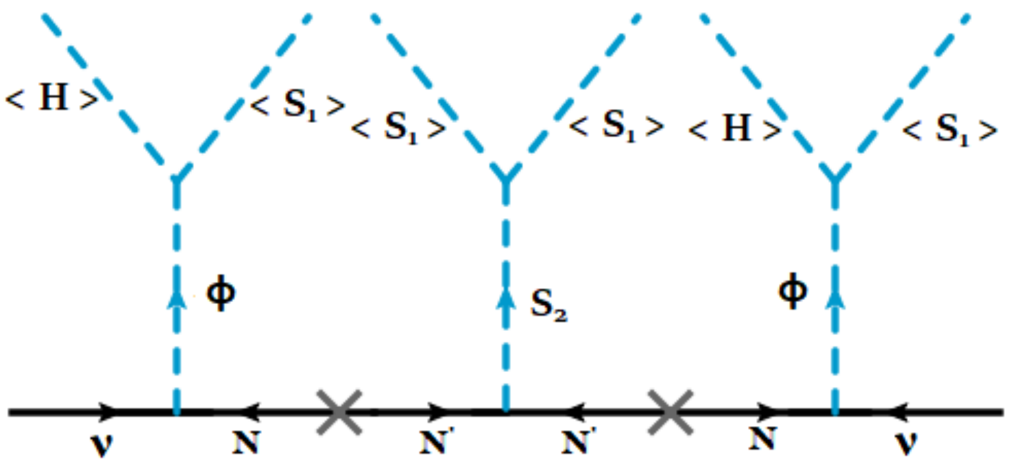

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All scales involved may be below electroweak

Neutrinos and the dark sector

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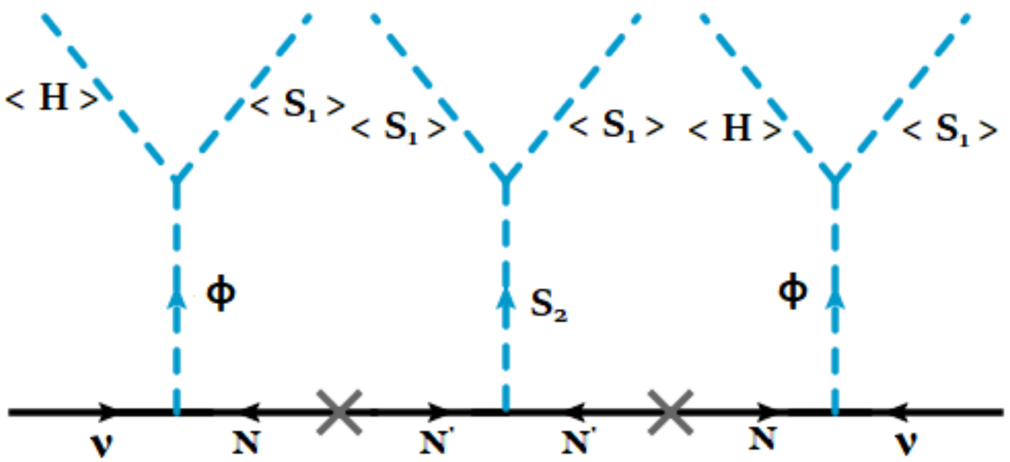

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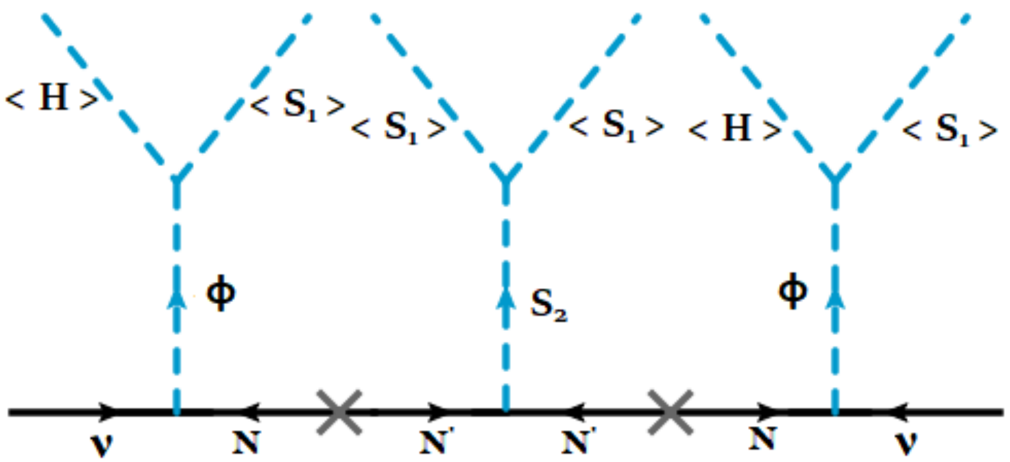

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We can simultaneously explain the smallness of neutrino masses dynamically and the MiniBooNE excess!

Conclusions

Novel explanation of MiniBooNE

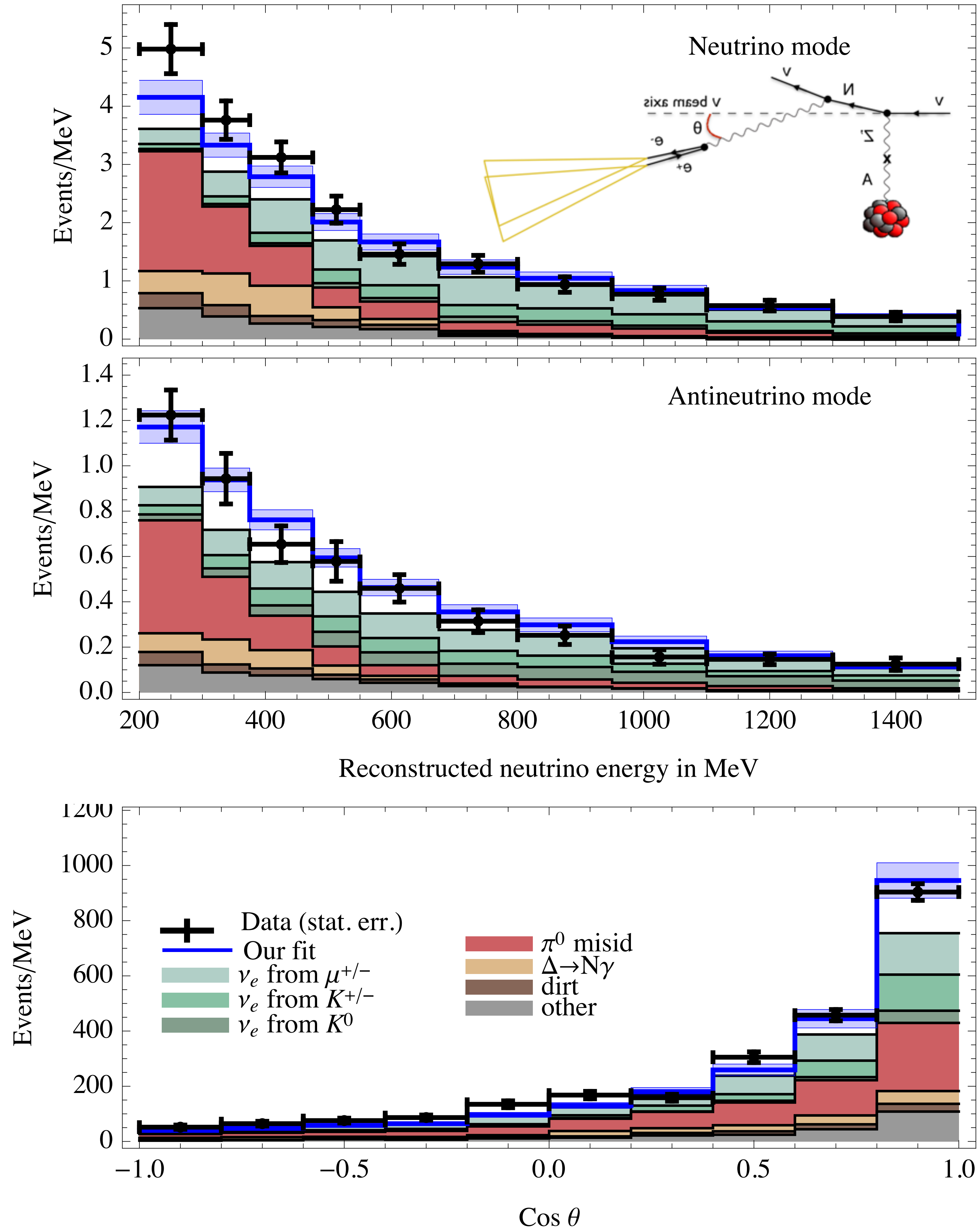
Agreement with all EXP data

Novel, simple framework

Rich phenomenology

Deep connection to m_ν

Has MiniBooNE observed the mechanism behind neutrino masses???



Neutrinos and the dark sector

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

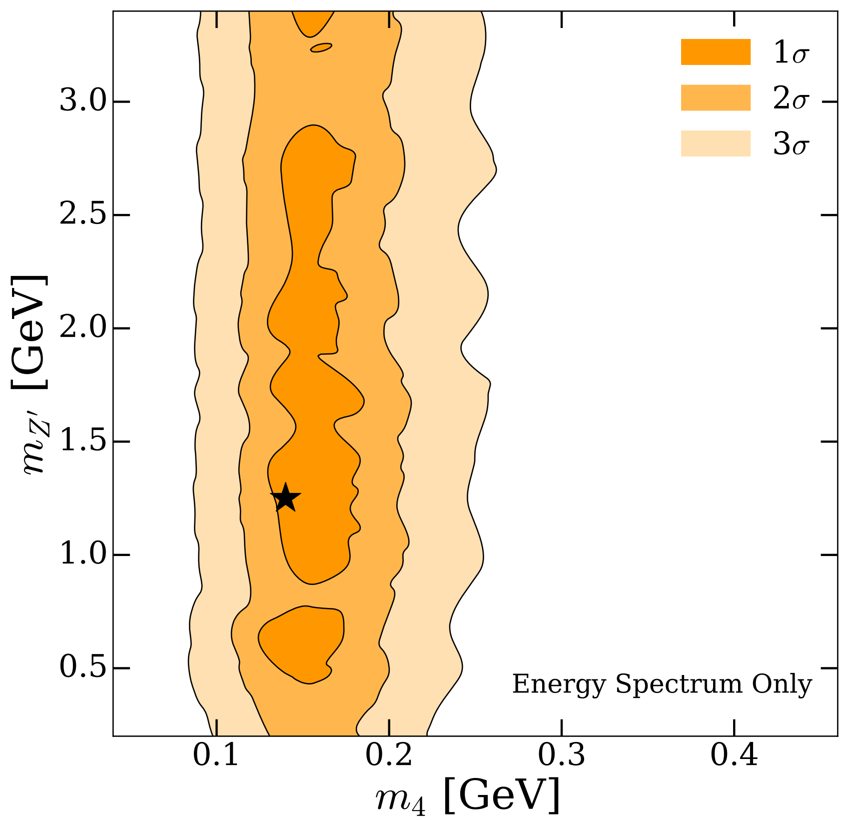
$m_{h_{\rm SM}}$ (GeV)	$m_{H_{\mathcal{D}}}$ (GeV)	$m_{S_{\mathcal{D}}}$ (MeV)	$m_{S'_{\mathcal{D}}}$ (MeV)	$m_{H^\pm_{\mathcal{D}}}$ (GeV)	$m_{A_{\mathcal{D}}}$ (GeV)	$m_{a_{\mathcal{D}}}$ (MeV)	$m_{Z_{\mathcal{D}}}$ (MeV)	$m_{N_{\mathcal{D}}}$ (MeV)
125	100	272	320	100	100	272	30	150

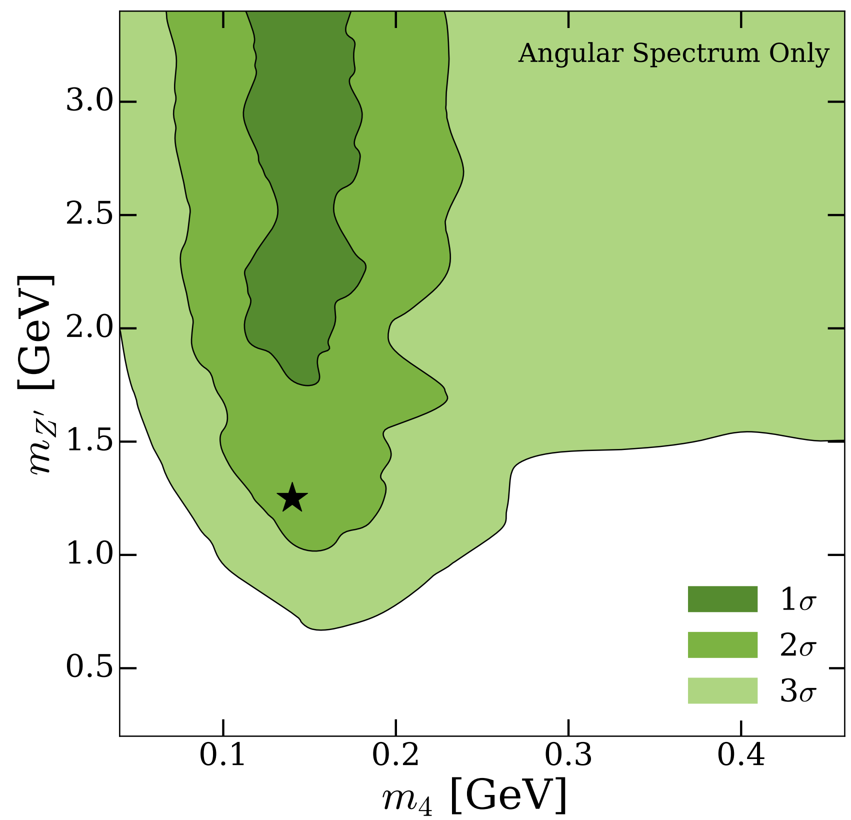
Mixing between the Fields

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

$M_Z > M_N$

Ballett et al 1808.02915





Rich pheno!
Lots of potential!