Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

BSM in the Neutrino Sector

Pedro Machado

March 27th, 2023

Outline

In this talk, I will discuss three broad classes of BSM

(1) BSM in neutrino oscillations

(2) BSM in neutrino interaction

(3) BSM in neutrino experiments

I will *not* review all work that has been done in the last years

but I will discuss some recent developments which are new and exciting

Hopefully these will inspire some of us to think about

how to fully exploit neutrino experiments

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BSM in neutrino oscillations

Why should we care about measuring neutrino oscillations precisely?

Oscillation physics provides a highly nontrivial probe of new physics

Let me give you some examples

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BSM in neutrino oscillations: nonstandard interactions

$$\mathcal{L} = 2\sqrt{2}G_F\epsilon^{\psi}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma_\mu\nu_\beta\right)\left(\bar{\psi}\gamma^\mu\psi\right)$$

NSIs can affect neutrino propagation in matter

Oscillations look differently from standard

Several criticisms on gauge invariance, UV

Can these actually exist?

Let’s take a UV complete model that predicts the existence of large NSIs that can be probed at neutrino experiments

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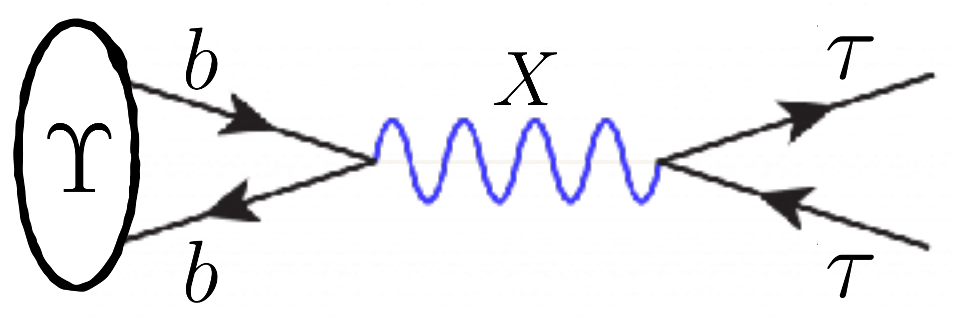
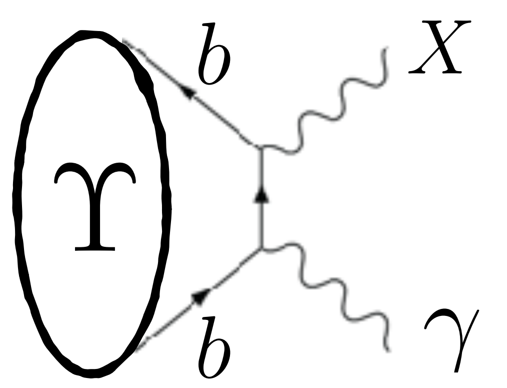
Gauge 3rd family $B-L$

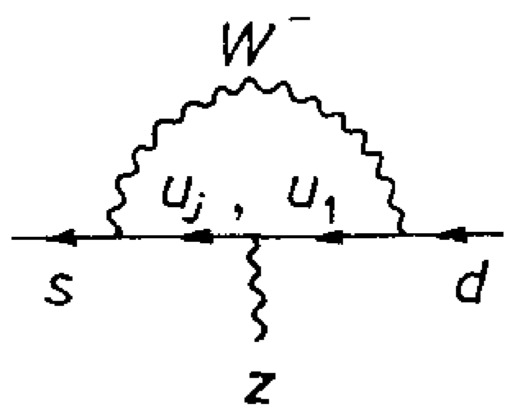
Maybe this is why V_{ub} and V_{cb} are so small

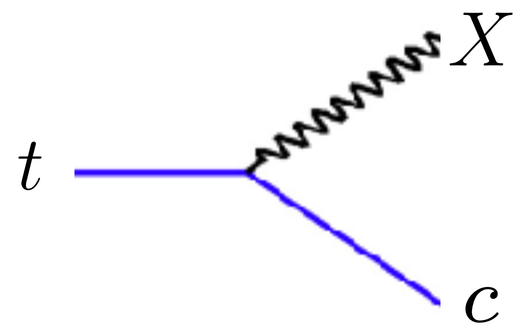
$$\mathcal{L}^q_{yuk} = \overline{\mathbf{Q}}_L \begin{pmatrix} y^u_{11}\widetilde{\phi}_2 & y^u_{12}\widetilde{\phi}_2 & y^u_{13}\widetilde{\phi}_1 \\ y^u_{21}\widetilde{\phi}_2 & y^u_{22}\widetilde{\phi}_2 & y^u_{23}\widetilde{\phi}_1 \\ 0 & 0 & y^u_{33}\widetilde{\phi}_2 \end{pmatrix} \mathbf{u}_R + \overline{\mathbf{Q}}_L \begin{pmatrix} y^d_{11}\phi_2 & y^d_{12}\phi_2 & 0 \\ y^d_{21}\phi_2 & y^d_{22}\phi_2 & 0 \\ y^d_{31}\phi_1 & y^d_{32}\phi_1 & y^d_{33}\phi_2 \end{pmatrix} \mathbf{d}_R$$

Realize it below the Fermi scale









$D^0 - \overline{D^0}$ and …

Babu Friedland **M** Mocioiu 1705.01822

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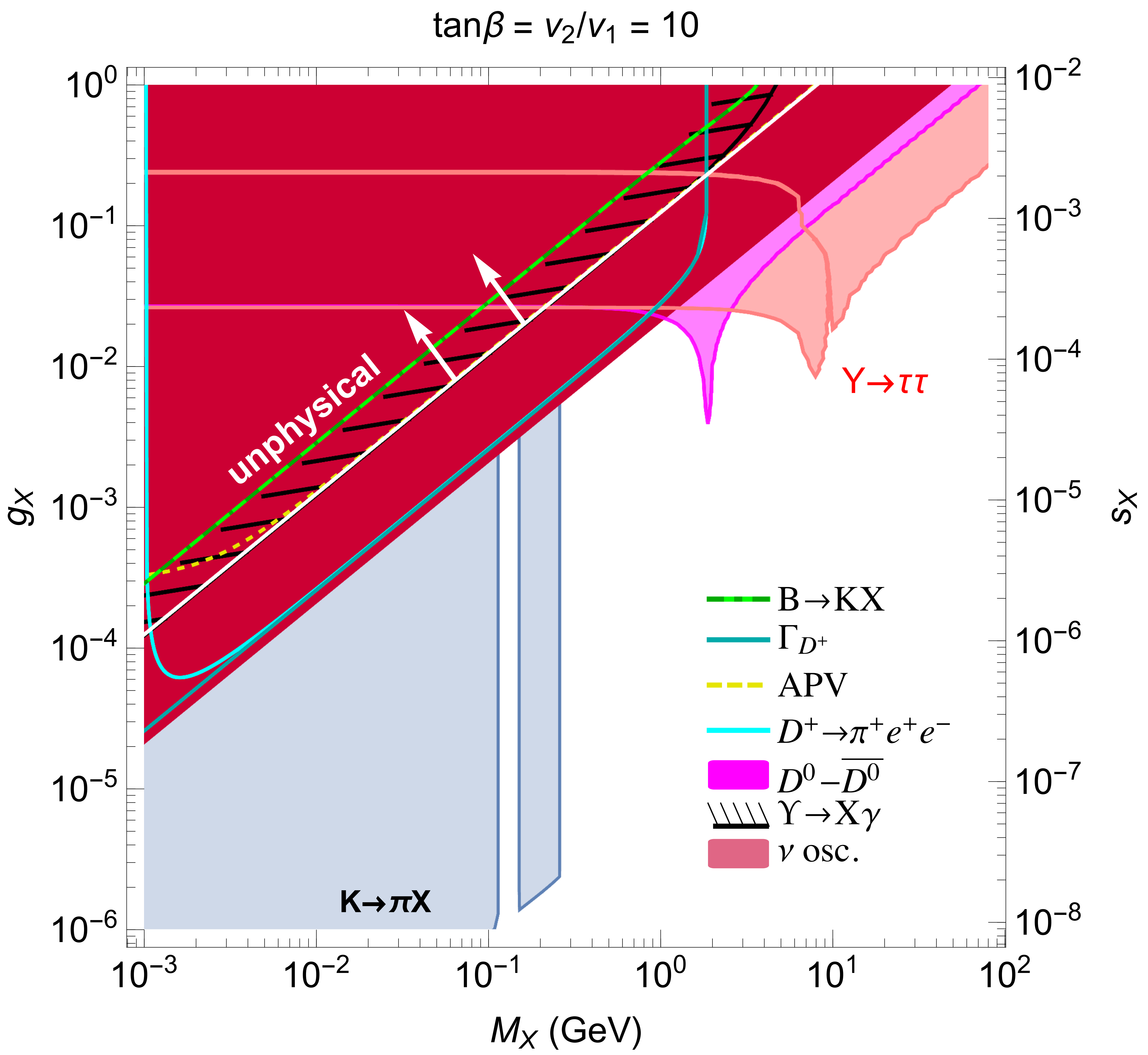
BSM in neutrino oscillations: nonstandard interactions



This model predicts large $\varepsilon_{\tau\tau}$ NSI

Neutrino oscillations are competitive with other low energy constraints

Nontrivial probe of low scale models

How does that relate to high energy probes?

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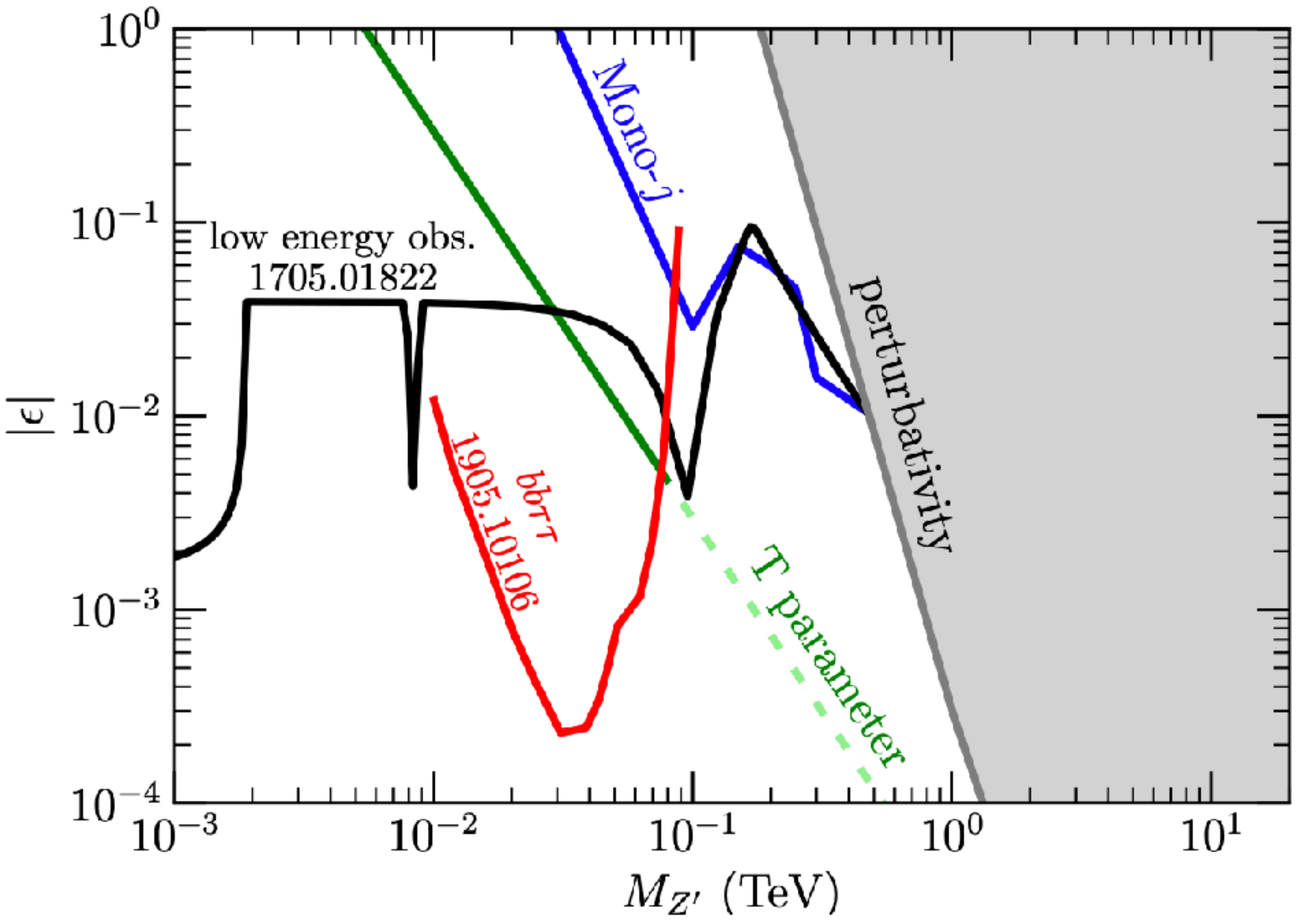
BSM in neutrino oscillations: nonstandard interactions



Babu Gonçalves Jana **M** 2003.03383

We can only ask these questions when we have a UV complete model at hand

The scales for different experiments can be wildly different: neutrino oscillations, LHC, …

For this specific UV completion, LHC, neutrinos, EWPT, and other low energy observables are all complementary

See Tao's talk for neutrinos @ LHC

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BSM in neutrino oscillations

Can the mechanism of neutrino masses show up in oscillation physics?

While oscillations are not sensitive to the absolute neutrino mass, or to the nature of neutrinos, the mechanism of neutrino masses could leave imprints in neutrino oscillation phenomenology, specially if the scales involved are low

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BSM in neutrino oscillations: scale dependent PMNS

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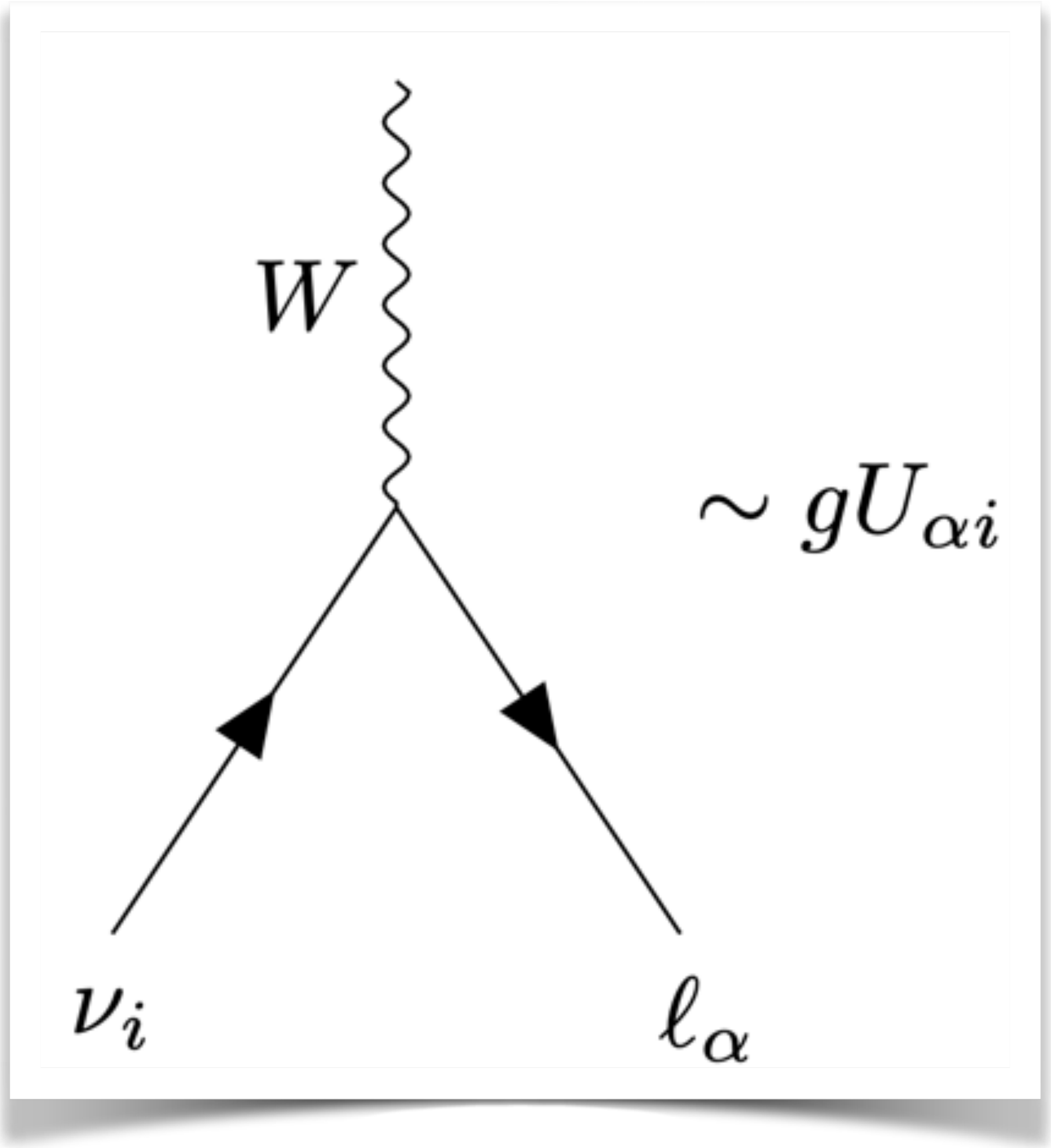
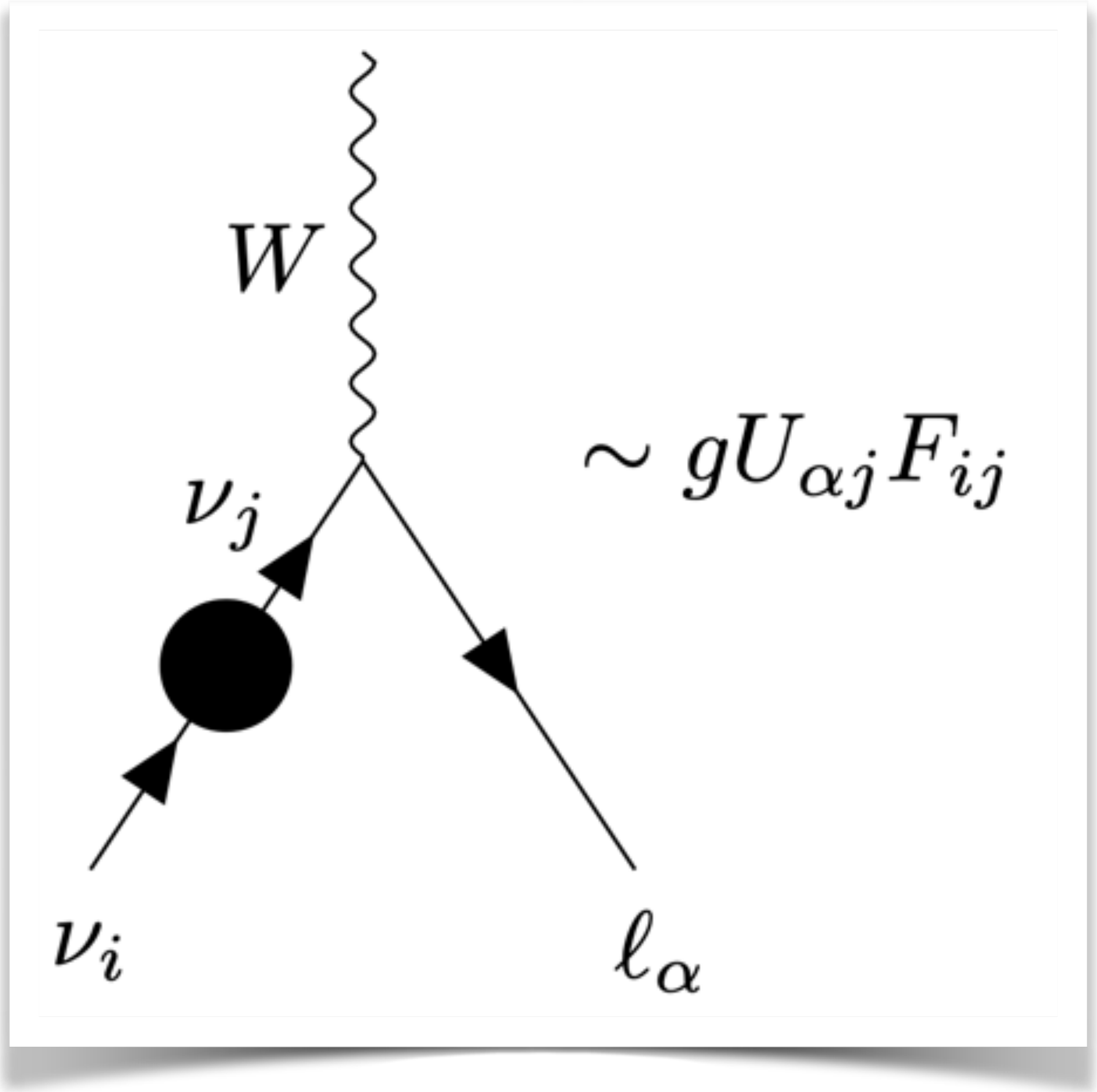
While oscillations are not sensitive to the absolute neutrino mass, or to the nature of neutrinos, the mechanism of neutrino masses could leave imprints in neutrino oscillation phenomenology, specially if the scales involved are low



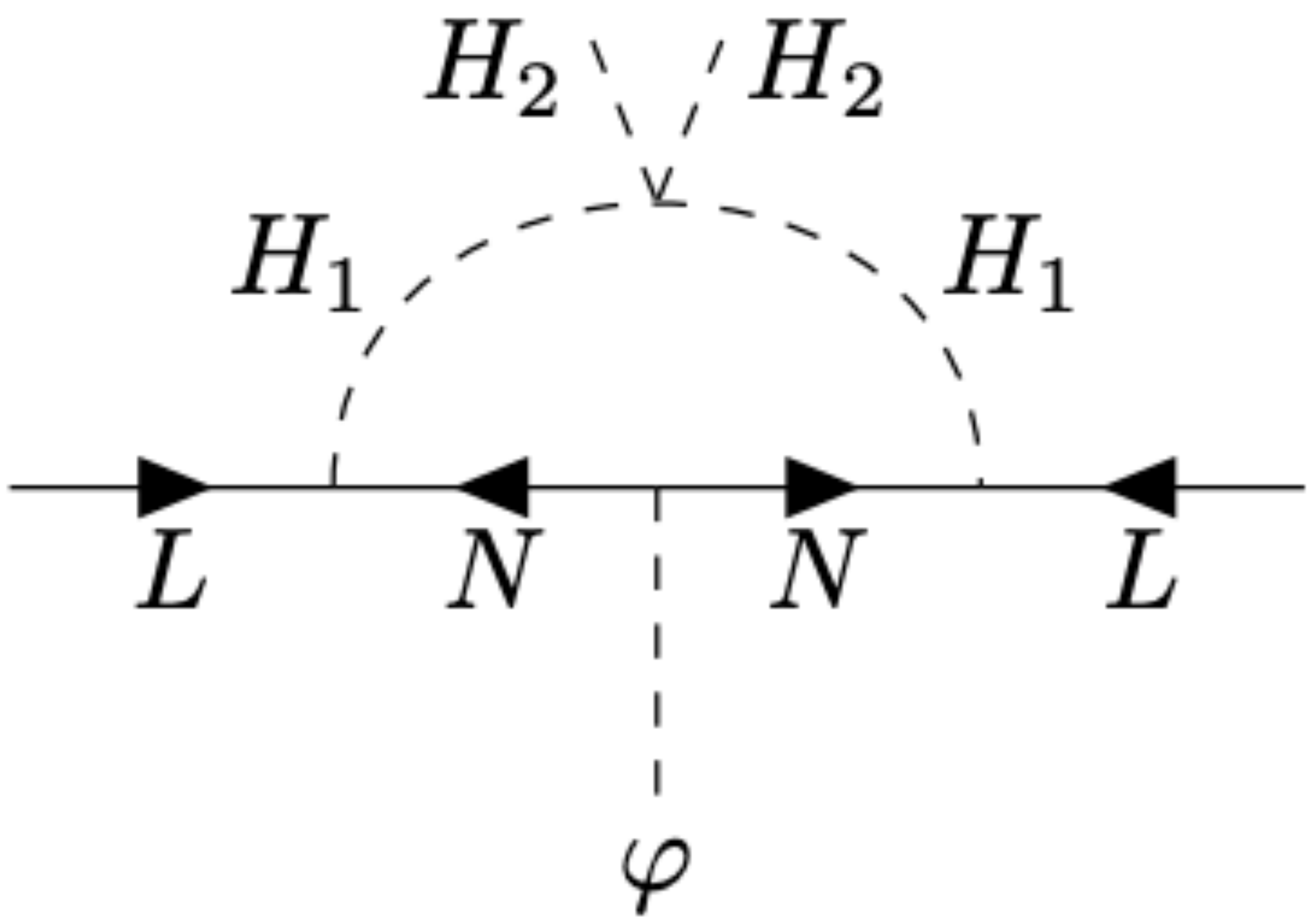


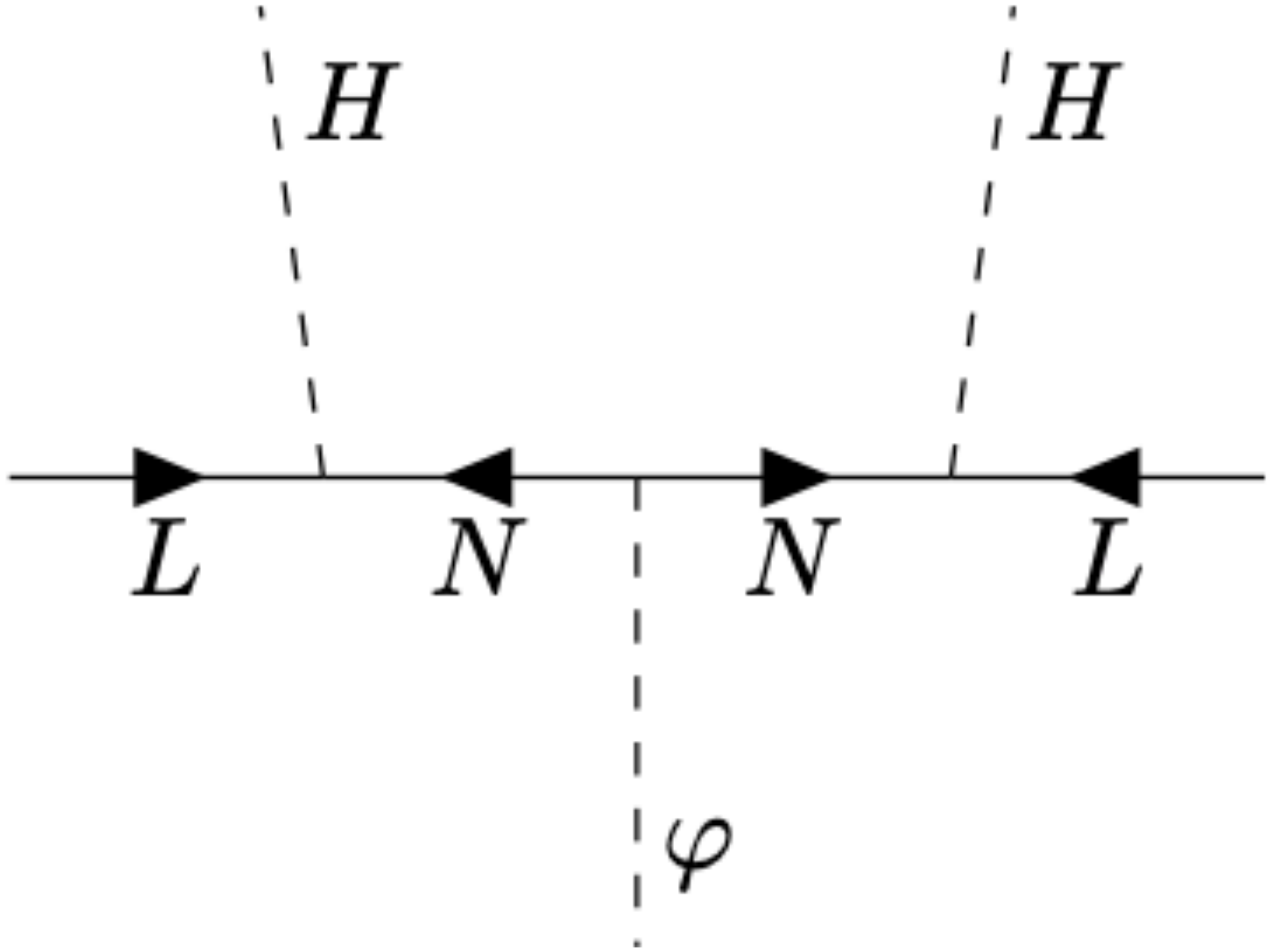
If there are significant quantum corrections to the neutrino mass matrix at low scales, the PMNS matrix becomes scale dependent.

This means that production and detection of neutrinos may not go via the same PMNS matrices.

Babu Brdar de Gouvêa **M** 2108.11961, 2209.00031

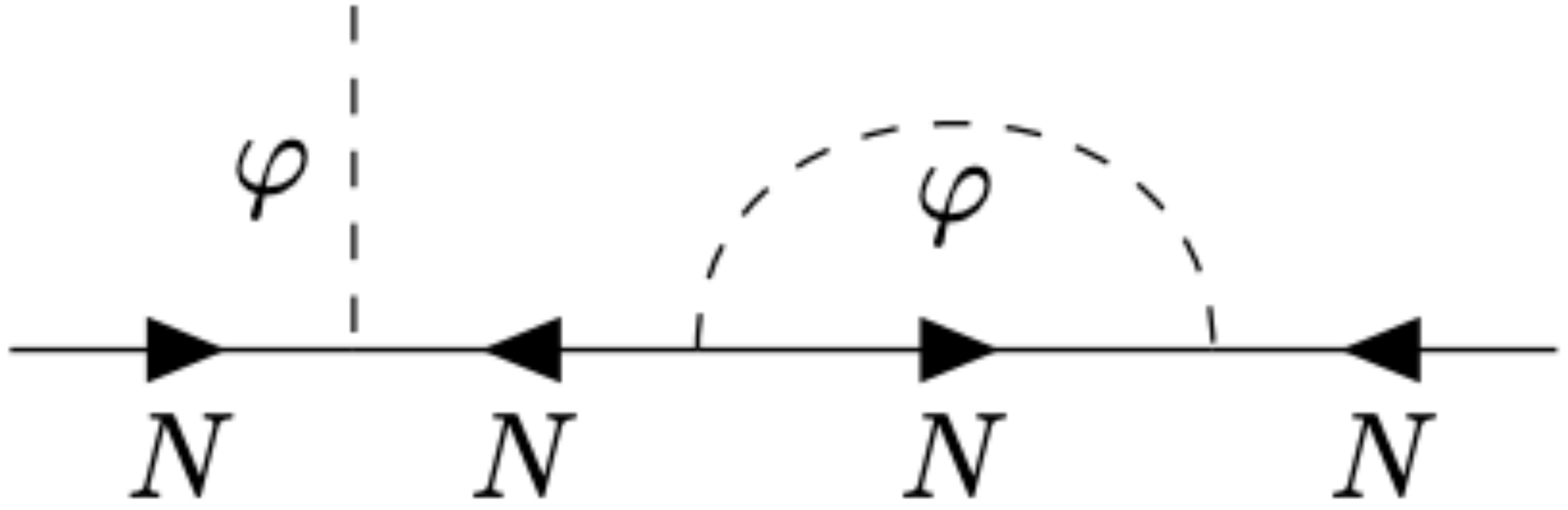
UV completion is actually quite simple





$$M_\nu \simeq \frac{v_\varphi}{16\sqrt{2}\pi^2} Y_\nu Y_N Y_\nu^T \ln \frac{M_H^2}{M_A^2}$$

$$16\pi^2 \frac{dY_N}{d\ln|Q|} = 4Y_N\left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2)\right]$$



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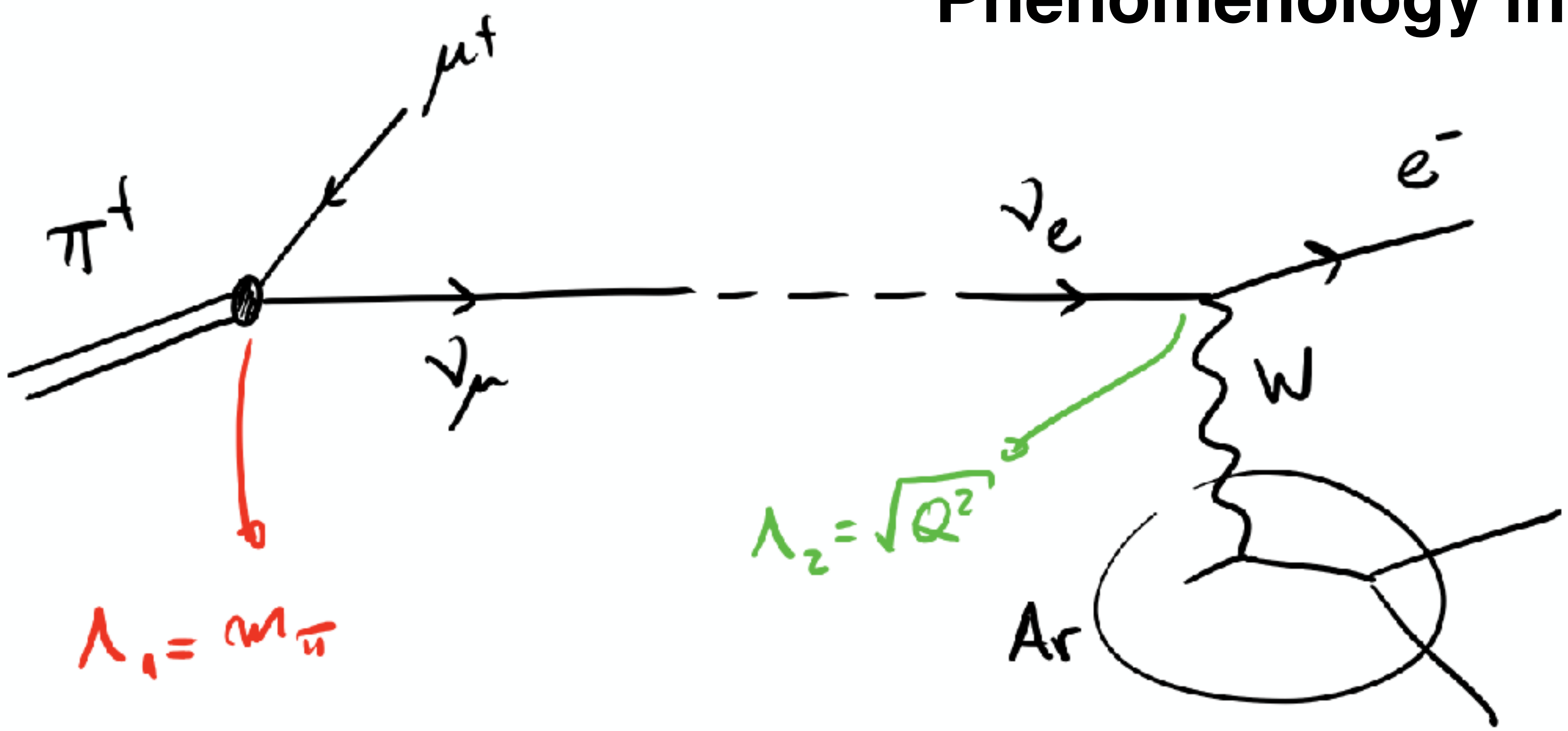
Phenomenology in a nutshell



Standard case

$$\mathcal{A}(\nu_\mu \to \nu_e) = \langle \nu_e | \exp(-iHL) | \nu_\mu \rangle = \sum_i U_{ei} U^*_{\mu i} \exp\left(-\frac{i m_i^2 L}{2E}\right)$$

With scale dependent effects:

$$\mathcal{A}(\nu_\mu \to \nu_e) = \langle \nu_e, Q_2^2 | \exp(-iHL) | \nu_\mu, Q_1^2 \rangle = \sum_i U_{ei}(Q_2^2)\, U^*_{\mu i}(Q_1^2) \exp\left(-\frac{i m_i^2 L}{2E}\right)$$

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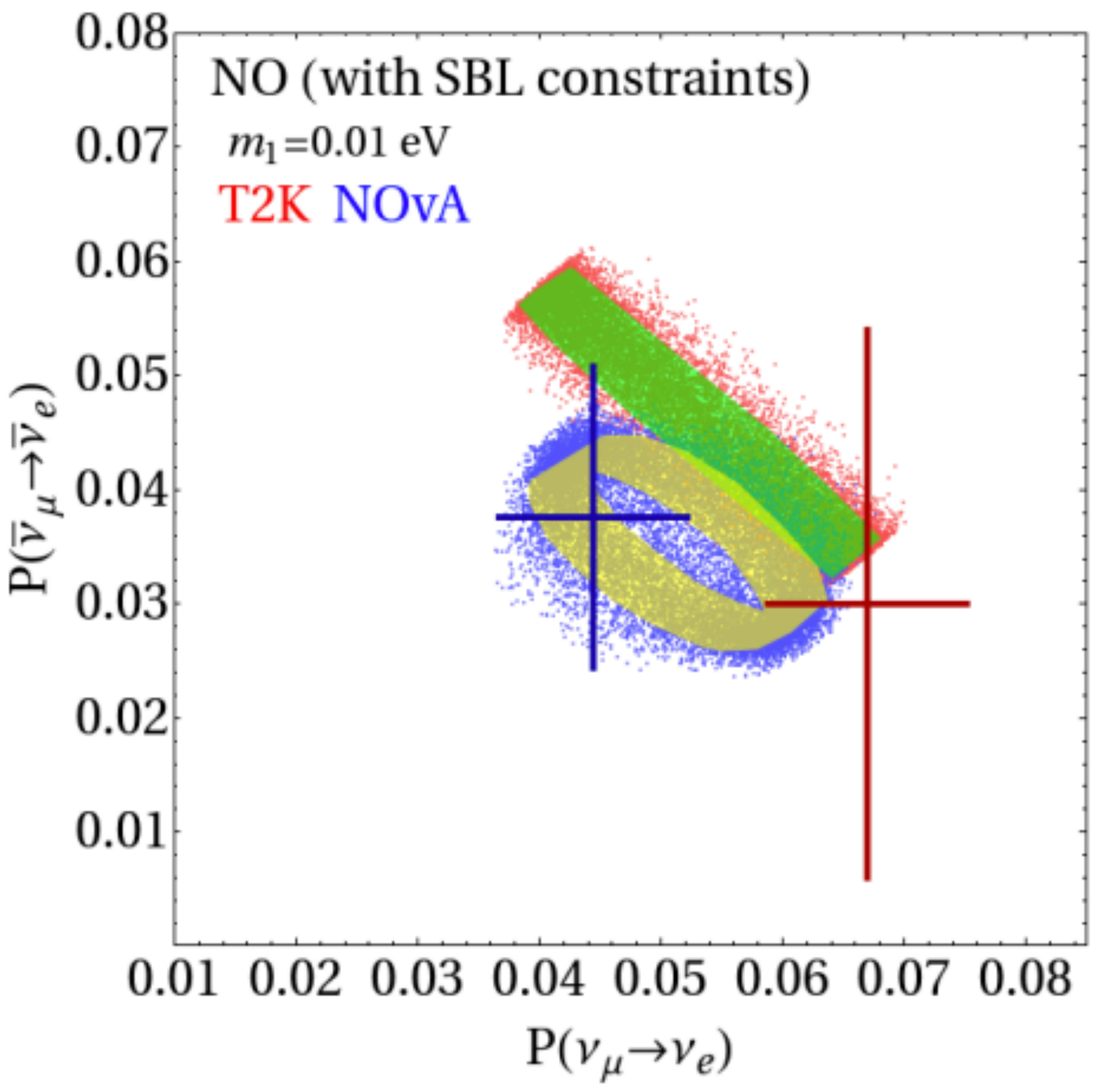
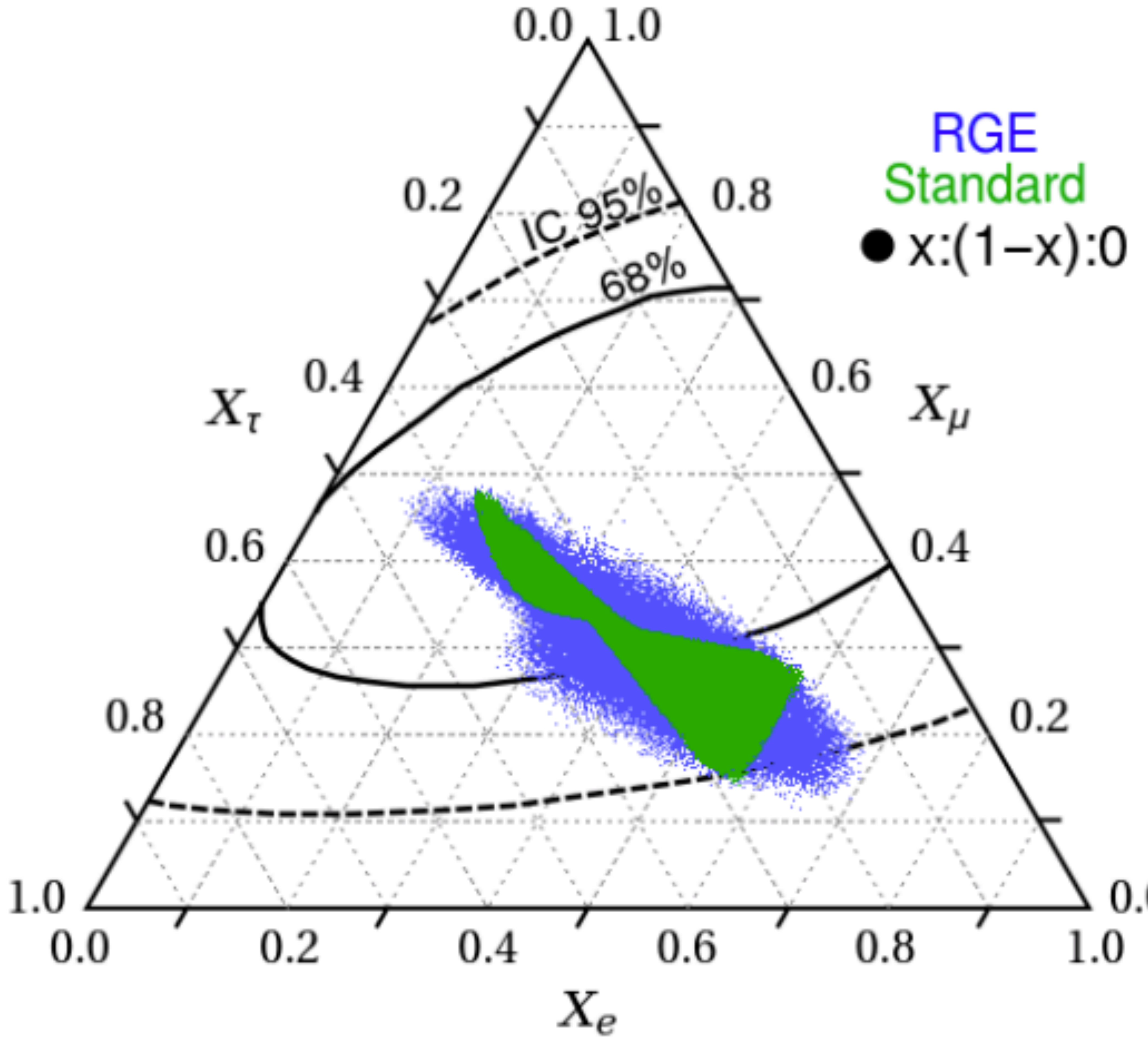
BSM in neutrino oscillations: scale dependent PMNS

Phenomenology in a nutshell





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Last example: ultralight dark matter and neutrino oscillations

Say DM is an ultralight scalar field ($m_\phi \ll$ eV)

$$\rho_\phi = \frac{m_\phi^2 \phi^2}{2}$$

It behaves as a classical field, its vev is related to its occupation number

The vev can modulate on time

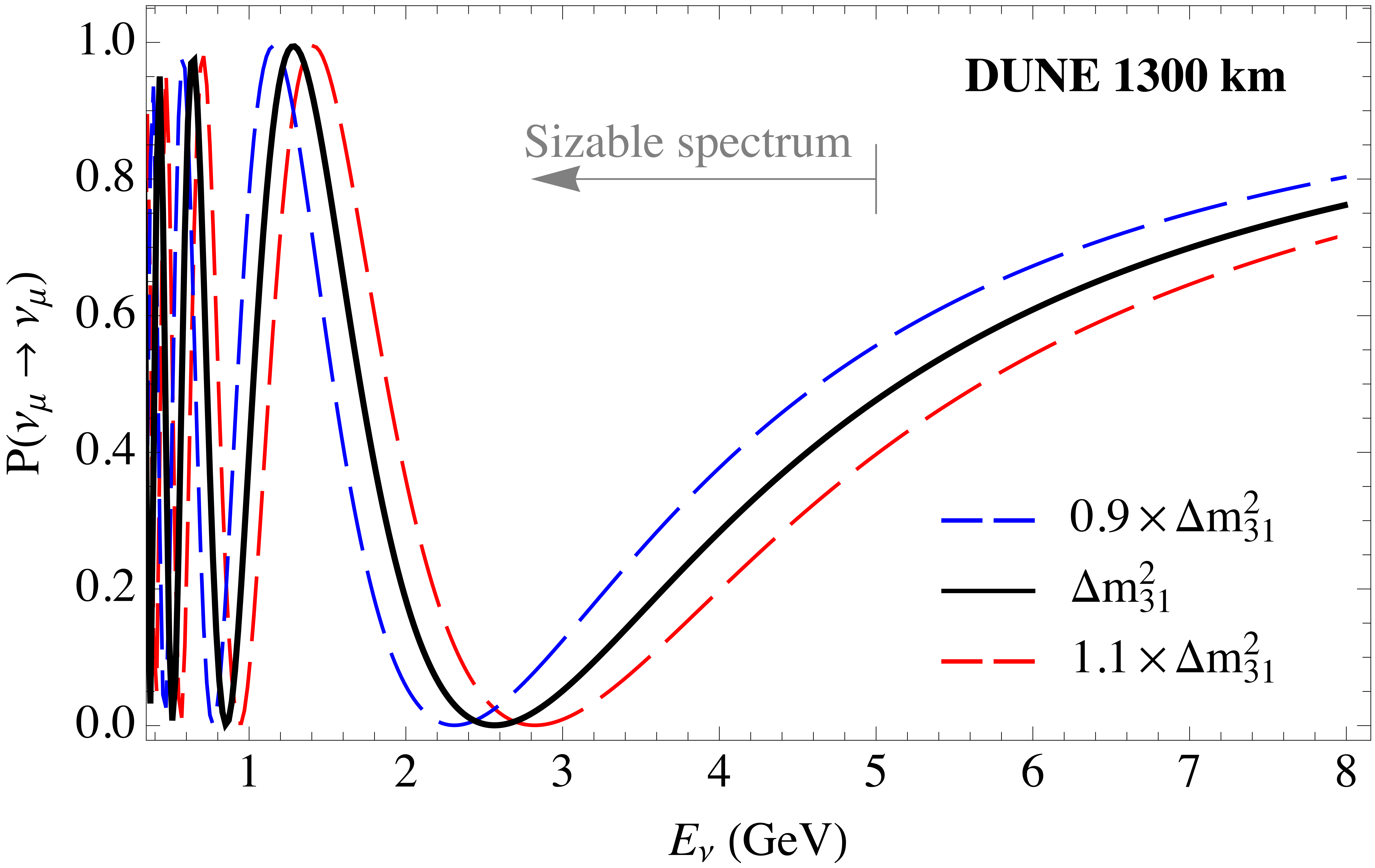
$$\phi(x,t) \simeq \frac{\sqrt{2\rho_\phi^\odot}}{m_\phi} \cos[m_\phi(t - \vec{v}\cdot\vec{x})]$$

If it couples to SM, we can have particle masses or other “constants" modulating on time

What if it couples to neutrinos or to anything in the neutrino mass mechanism (e.g. N_R)?

Berlin 2017; Krnjaic M Necib 2017; Brdar et al 2017; Dev M Martinez-Mirave 2020

BSM in neutrino oscillations: ultralight dark matter



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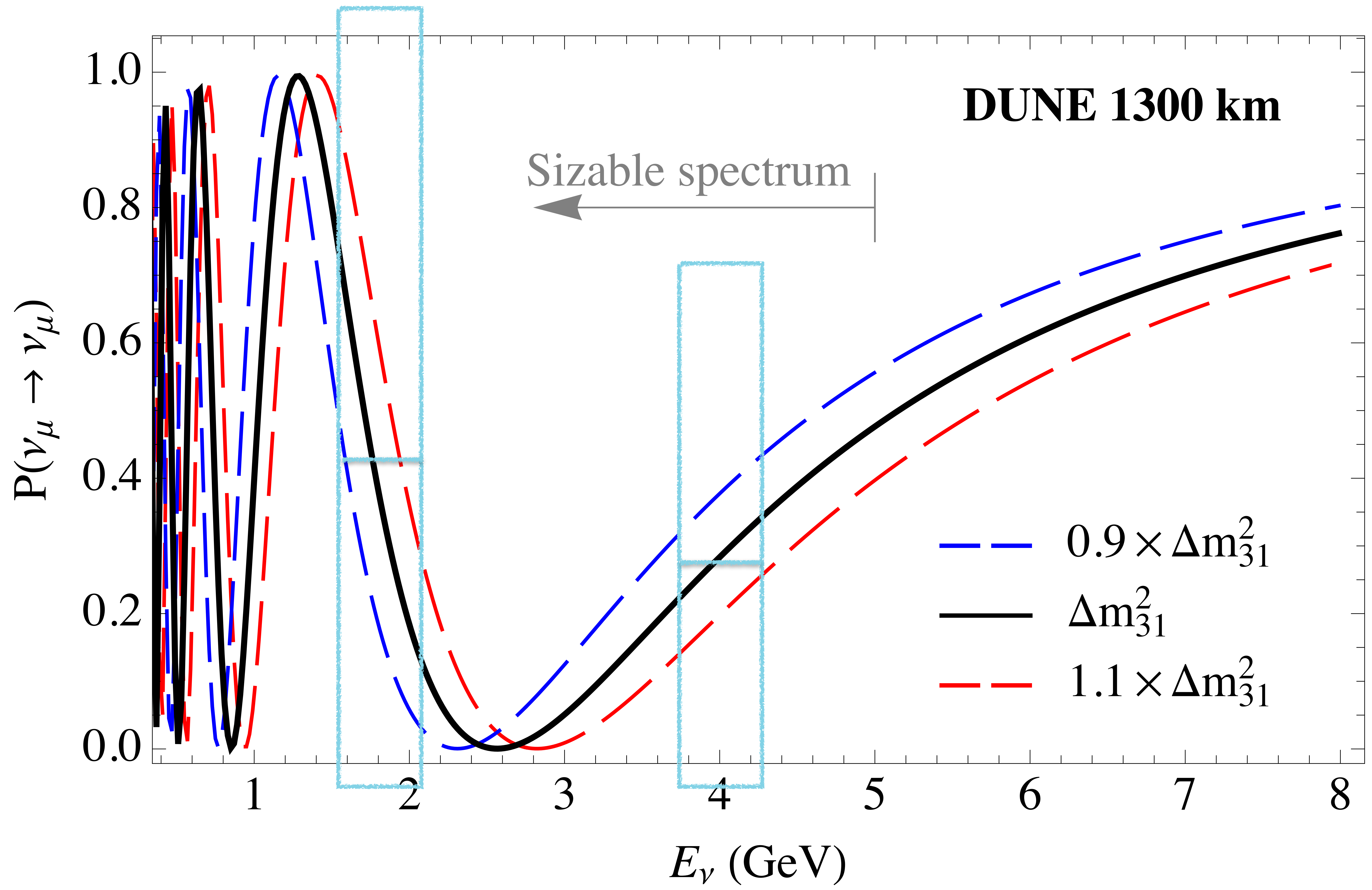
BSM in neutrino oscillations: ultralight dark matter



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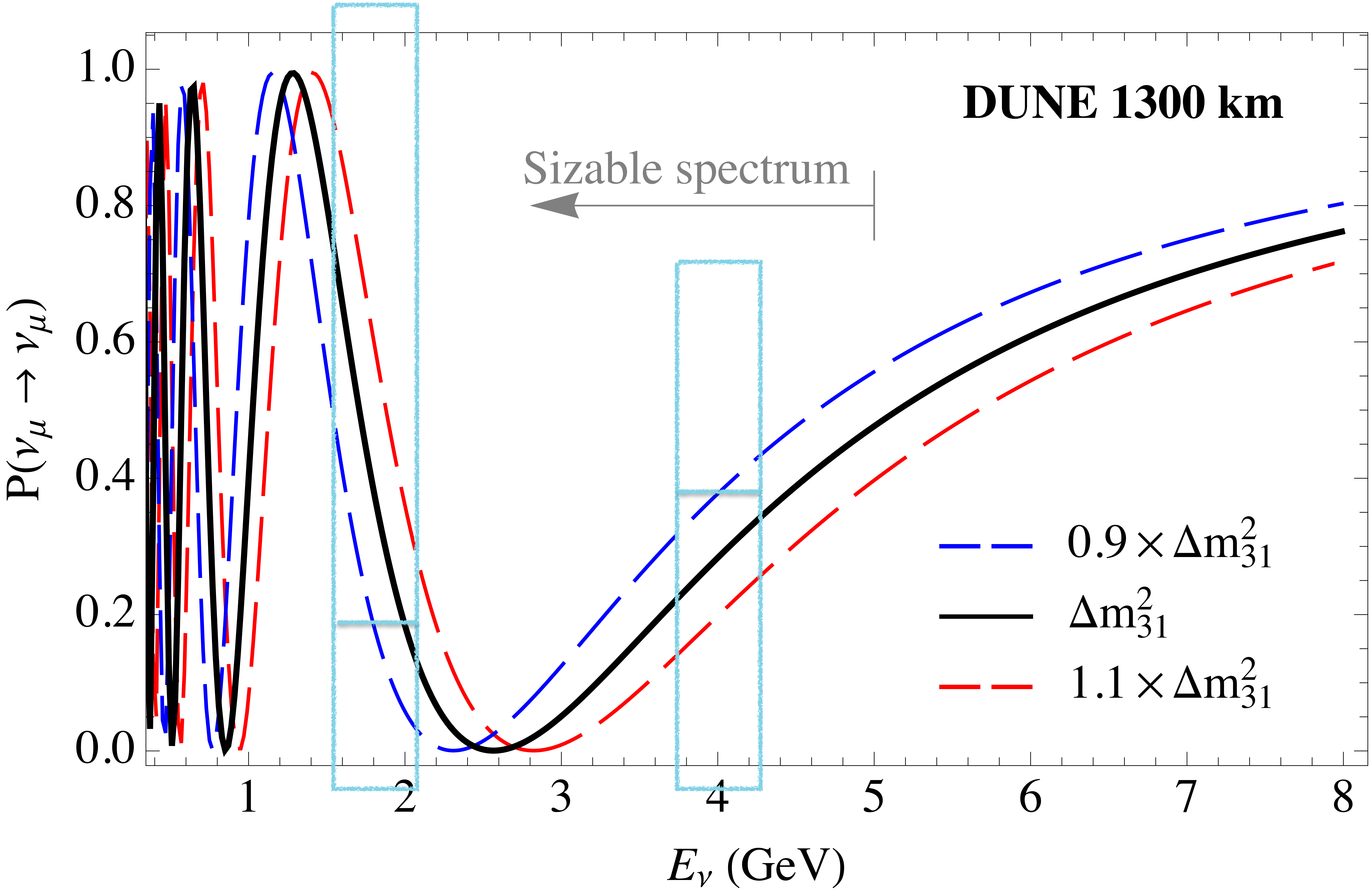
BSM in neutrino oscillations: ultralight dark matter



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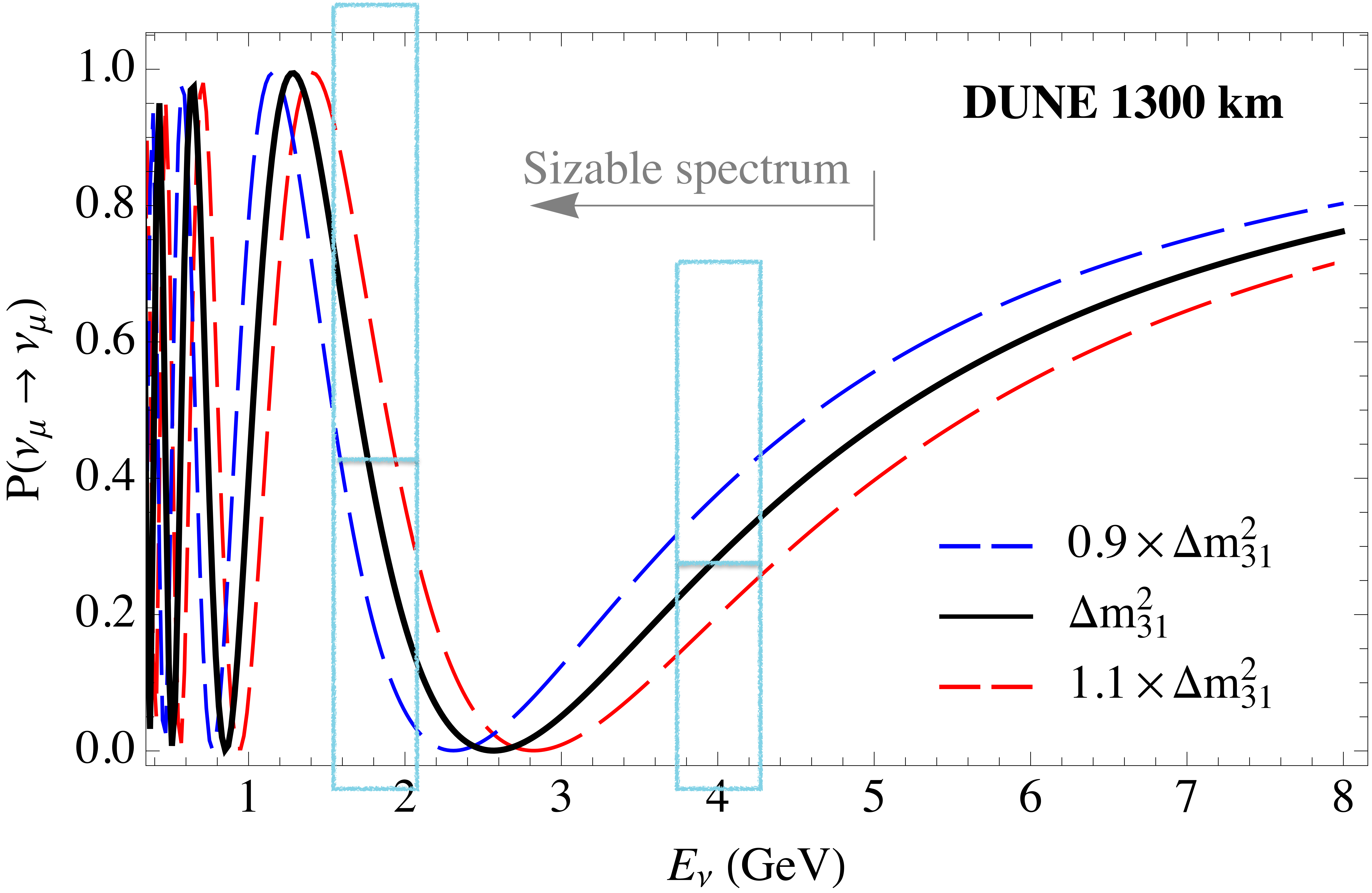

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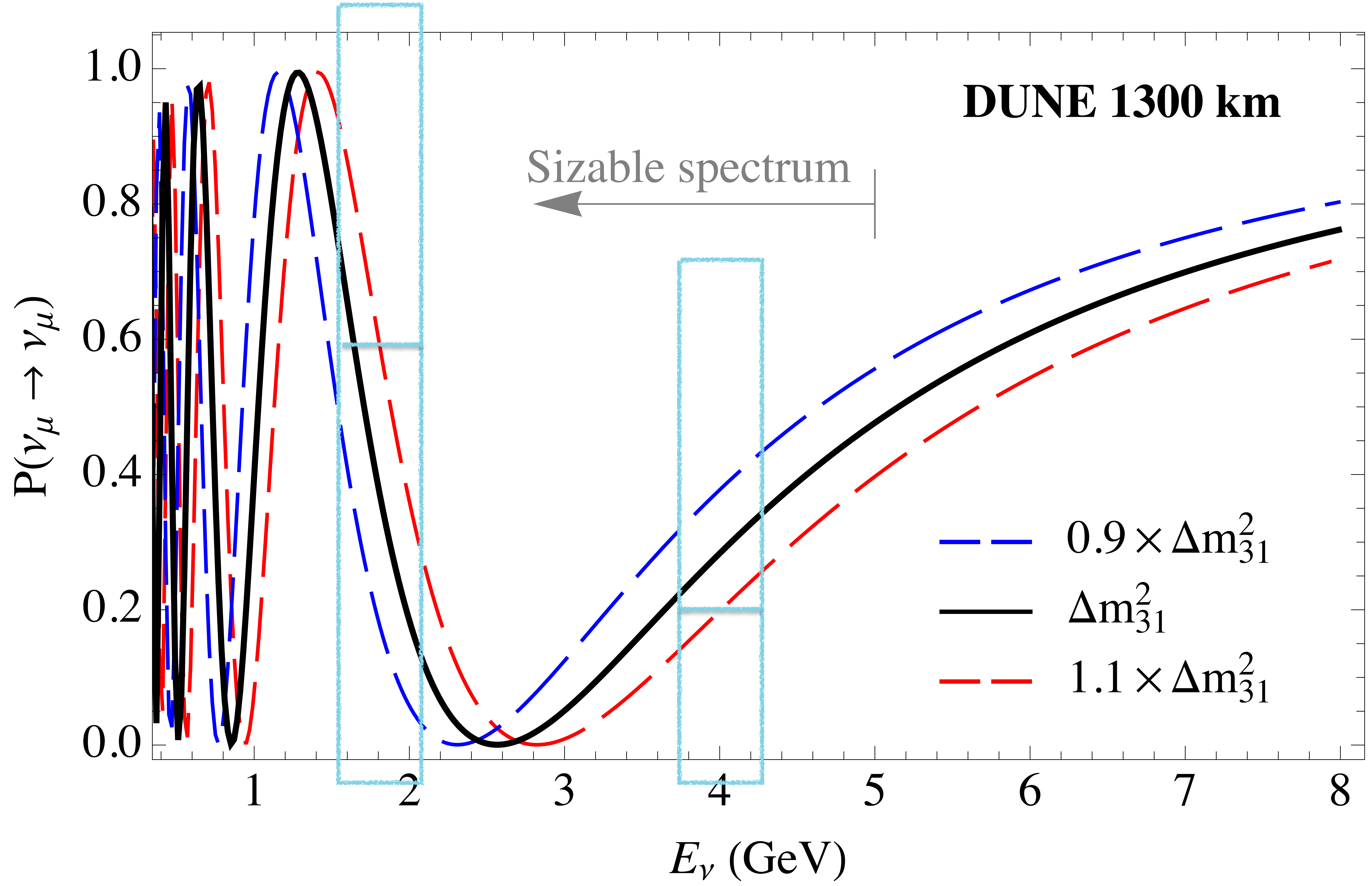

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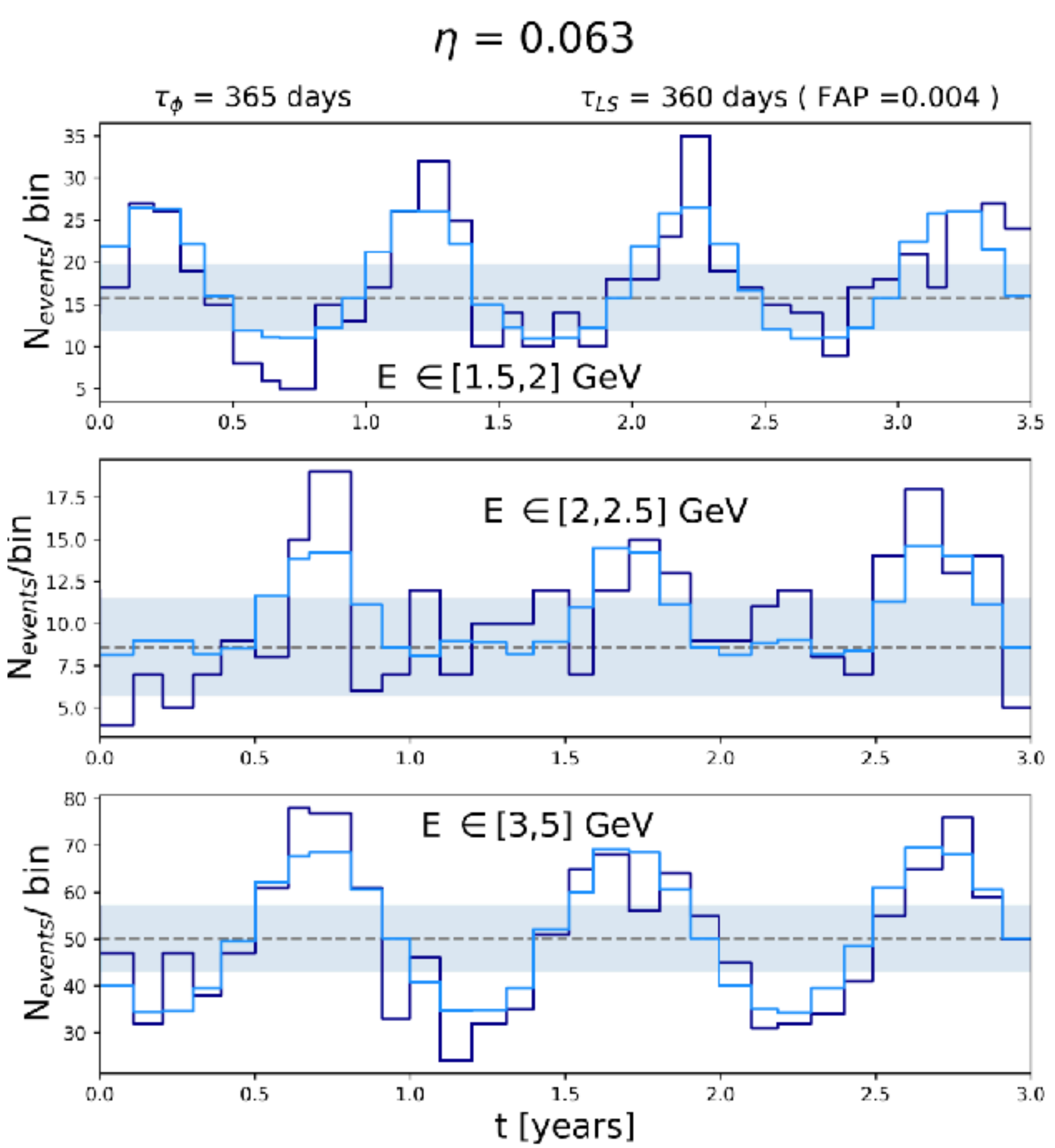
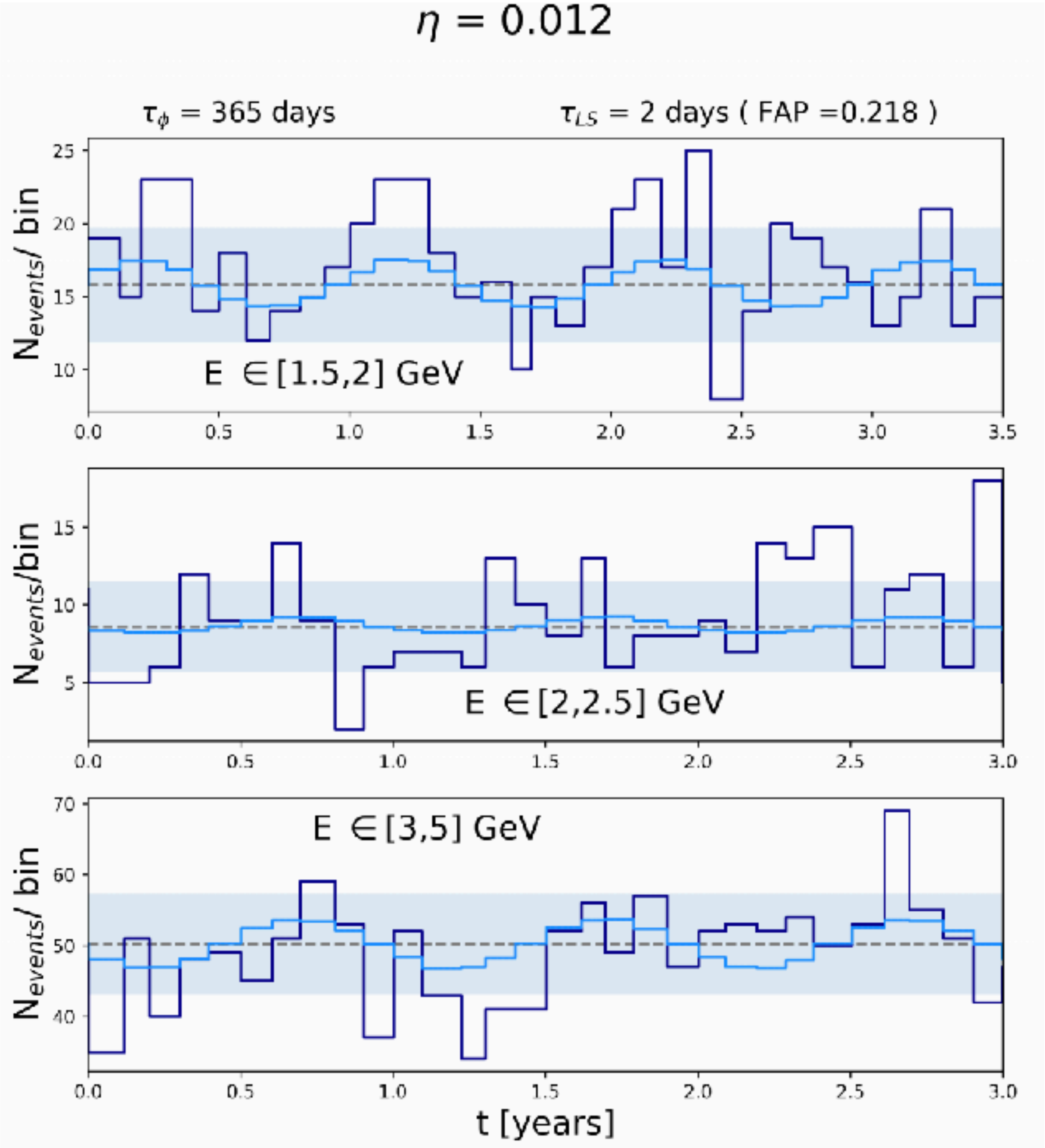
BSM in neutrino oscillations: ultralight dark matter





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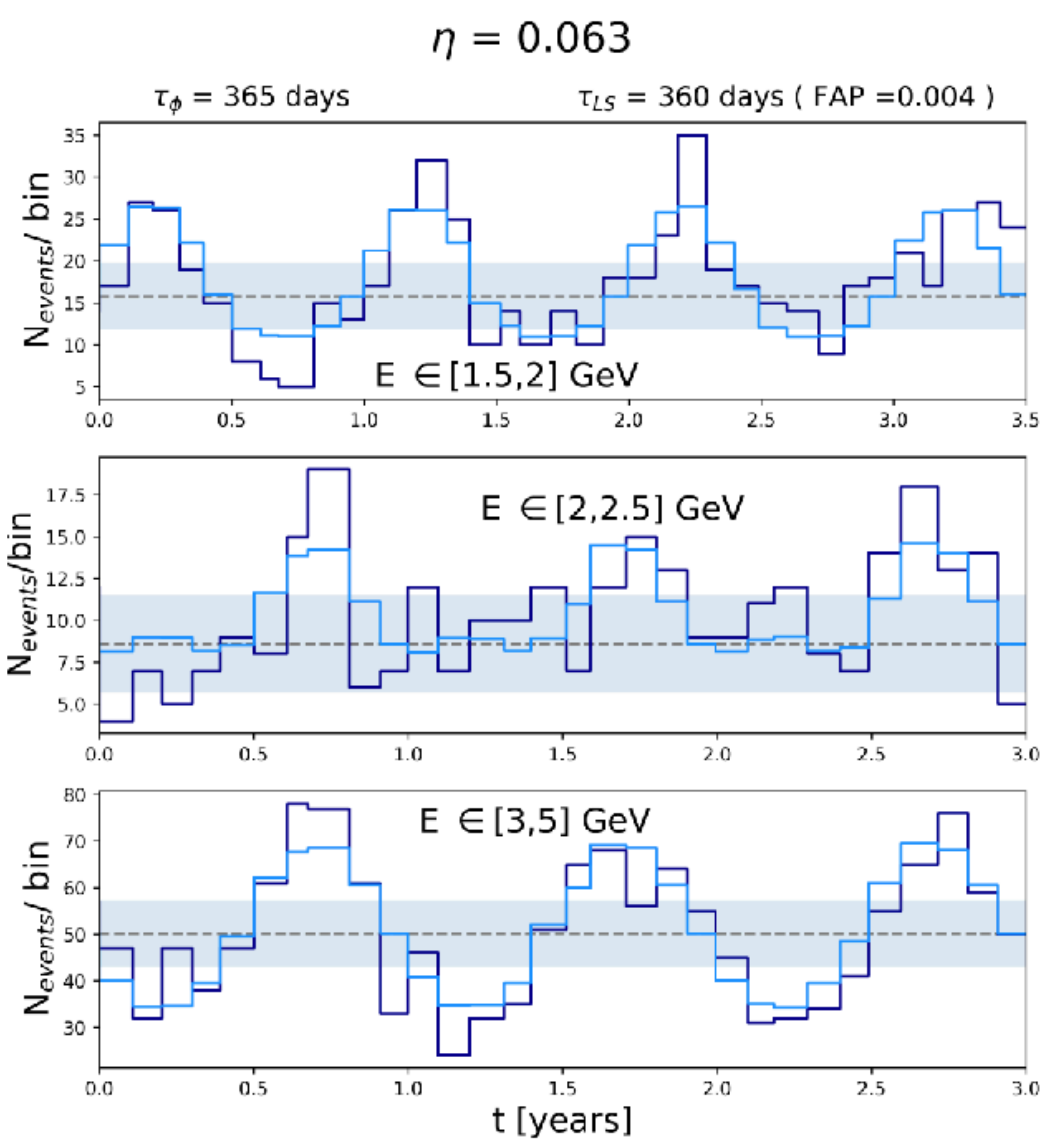

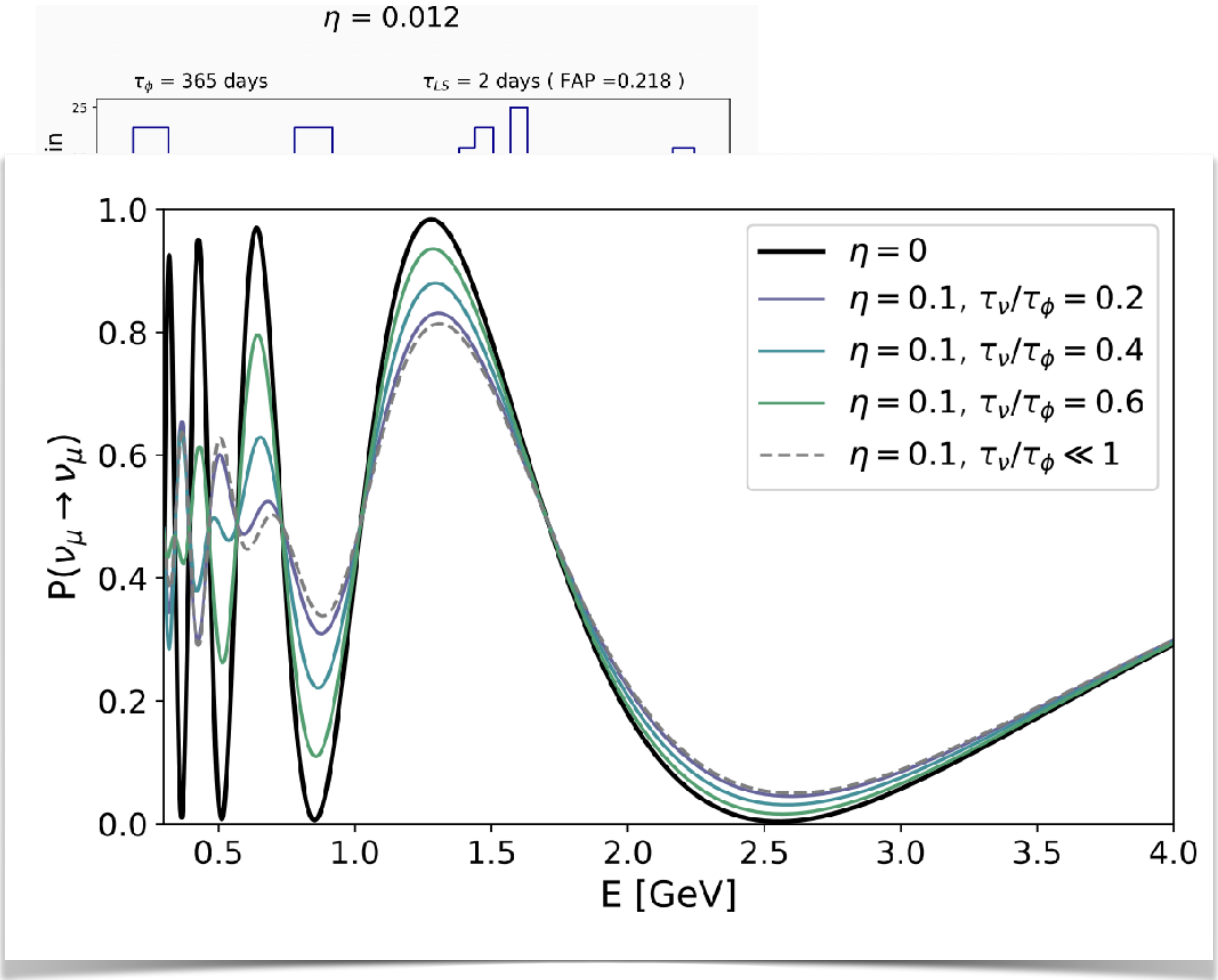

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BSM in neutrino oscillations

Neutrino oscillations provide a nontrivial probe of physics beyond the standard model

It is well geared towards light, weakly coupled physics

The mechanism of neutrino masses could leave imprints in oscillations

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BSM in neutrino interactions and at neutrino experiments

Neutrino mass mechanism and BSM,

a brief review (with uncensored comments) of the MiniBooNE anomaly,

and some remarks on exotic searches at neutrino experiments

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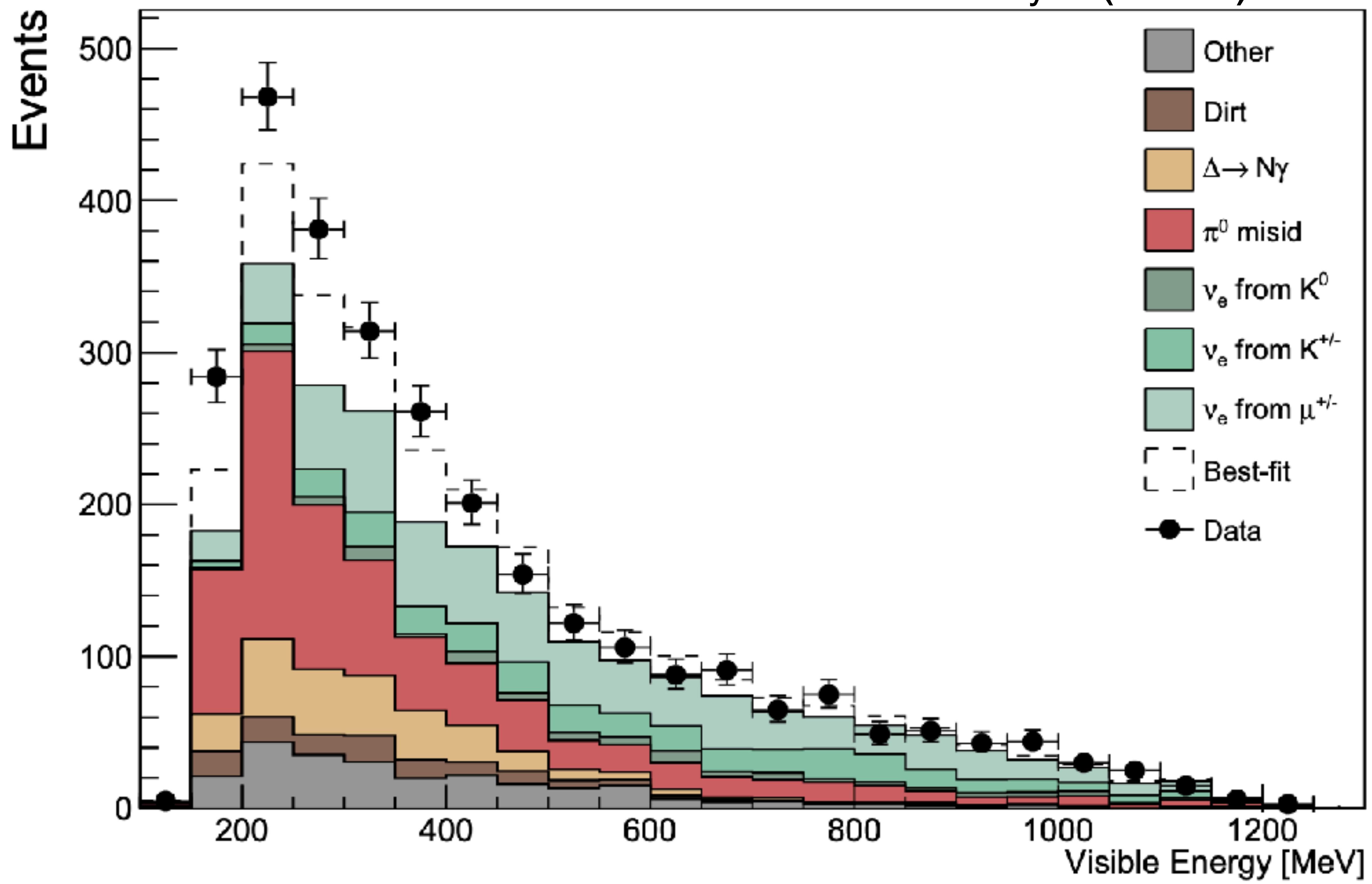
The MiniBooNE anomaly

Updated MiniBooNE neutrino oscillation results with increased data and new background studies

arXiv:2006.16883v3 [hep-ex] 8 Mar 2021

Excess: $638 \pm 52.1_{stat} \pm 122.2_{syst}$ (4.8σ)



MiniBooNE's anomaly is dominated by systematic uncertainties, particularly on the background

ν_e contamination has large flux uncertainty, pion and delta backgrounds depend on ν-A modeling

Theory uncertainties play an important role in interpreting this

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The MiniBooNE anomaly

Updated MiniBooNE neutrino oscillation results with increased data and new background studies

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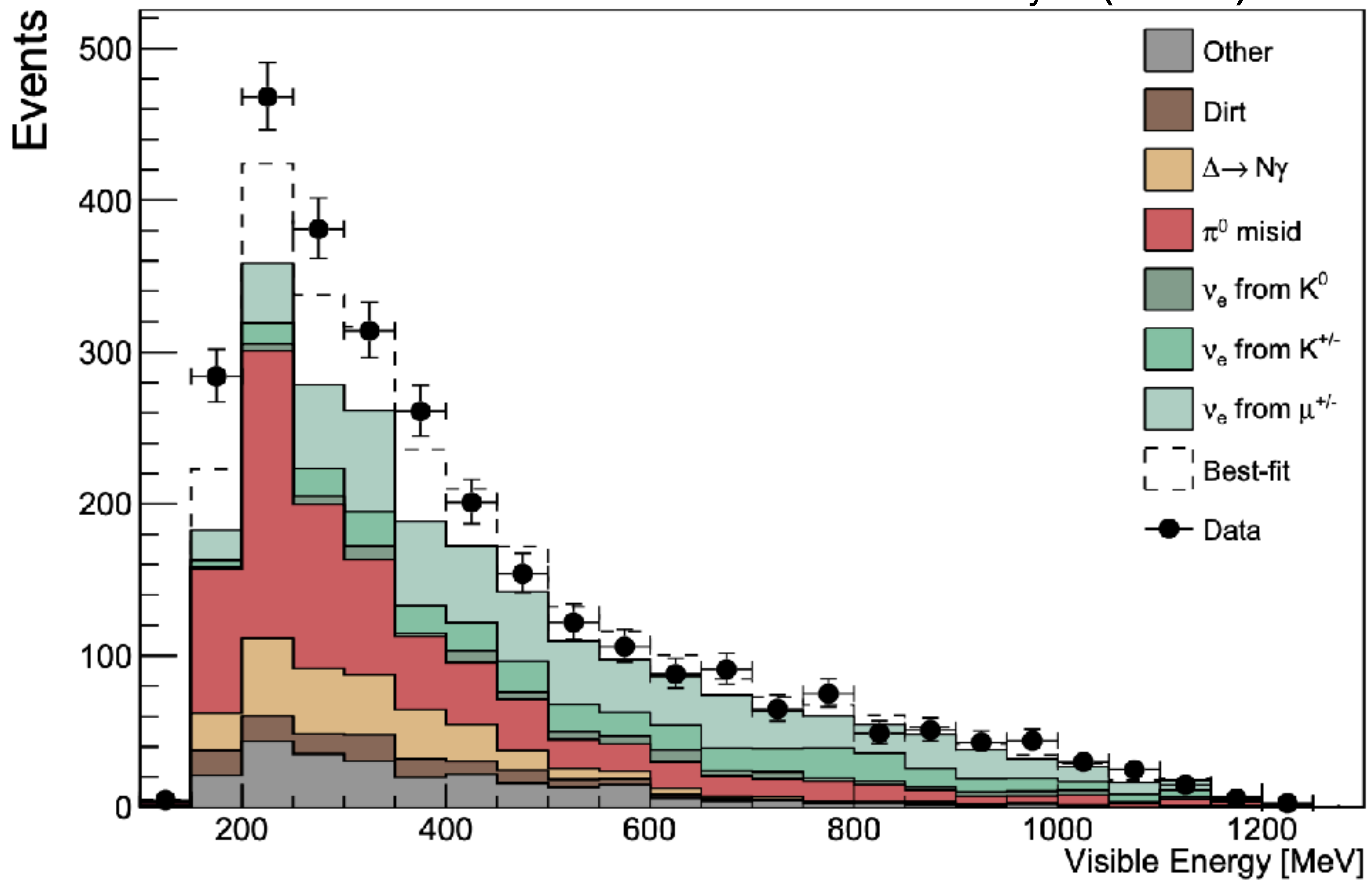

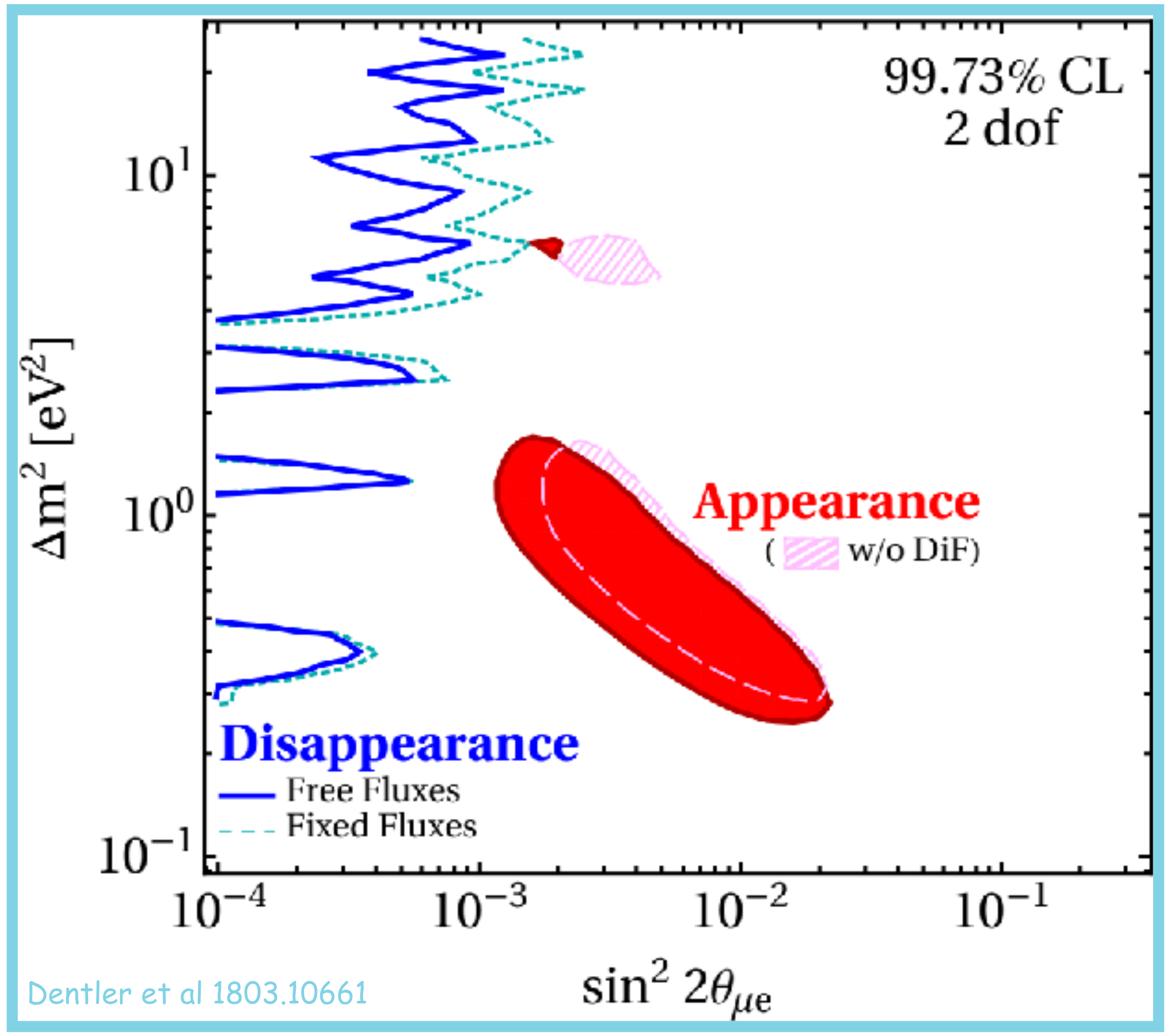

Sterile neutrinos do not really work: experimental tension, cosmology, …

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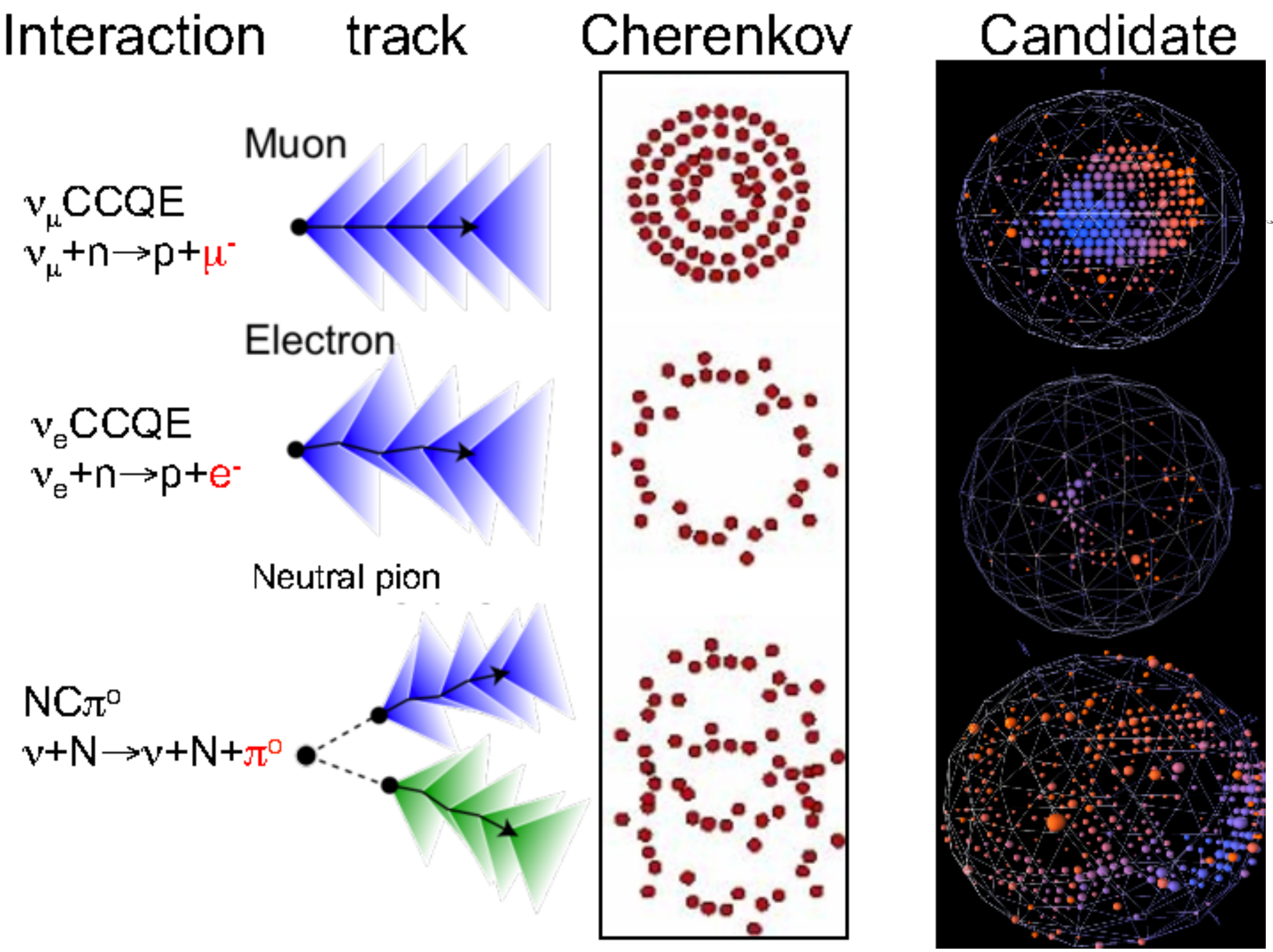
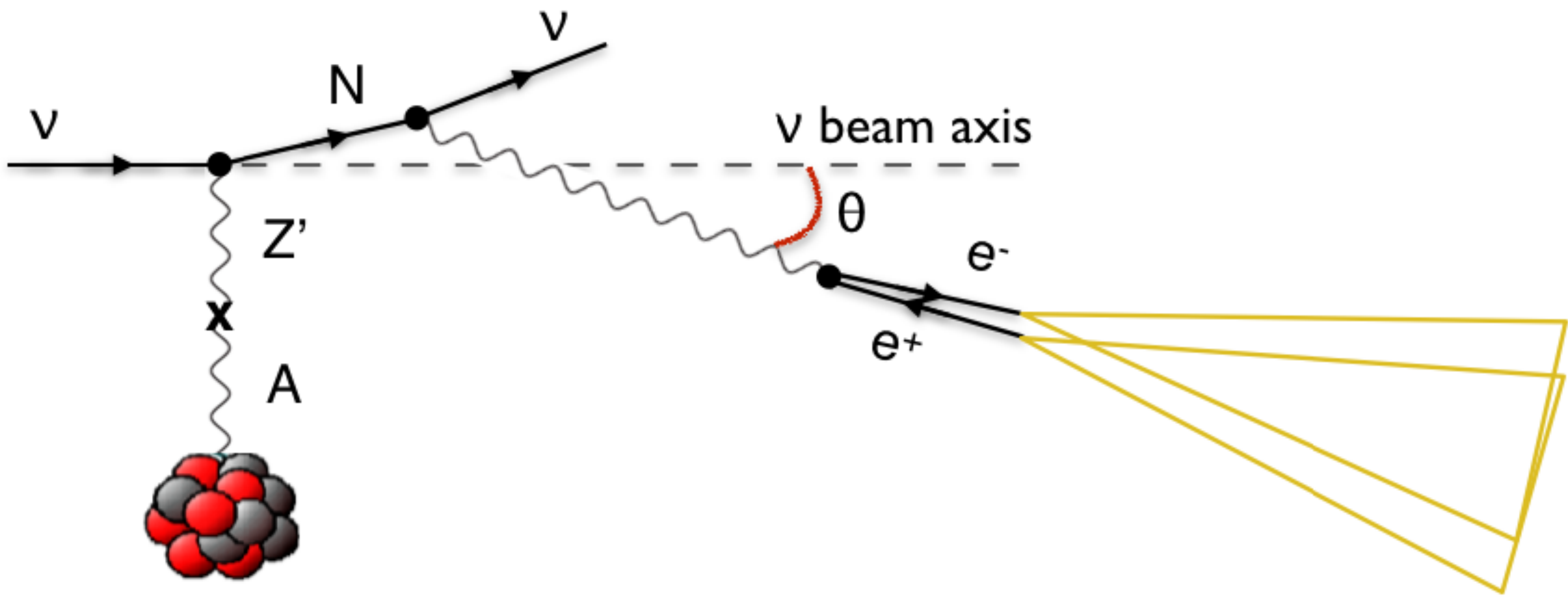
Updated MiniBooNE neutrino oscillation results with increased data and new background studies



Alternative explanations:
collimated e^+e^- pairs or photons



Bertuzzo **PM** et al 1807.09877; Bertuzzo **PM** et al 1808.02500; Arguelles et al 1812.08768; Ballett et al 1808.02915, 1903.07589; Abdullahi et al 2007.11813; Dutta et al 2006.01319; Gninenko 0902.3802, 1201.5194; Vergani et al 2105.06470; Brdar et al 2007.14411; …

The MiniBooNE anomaly

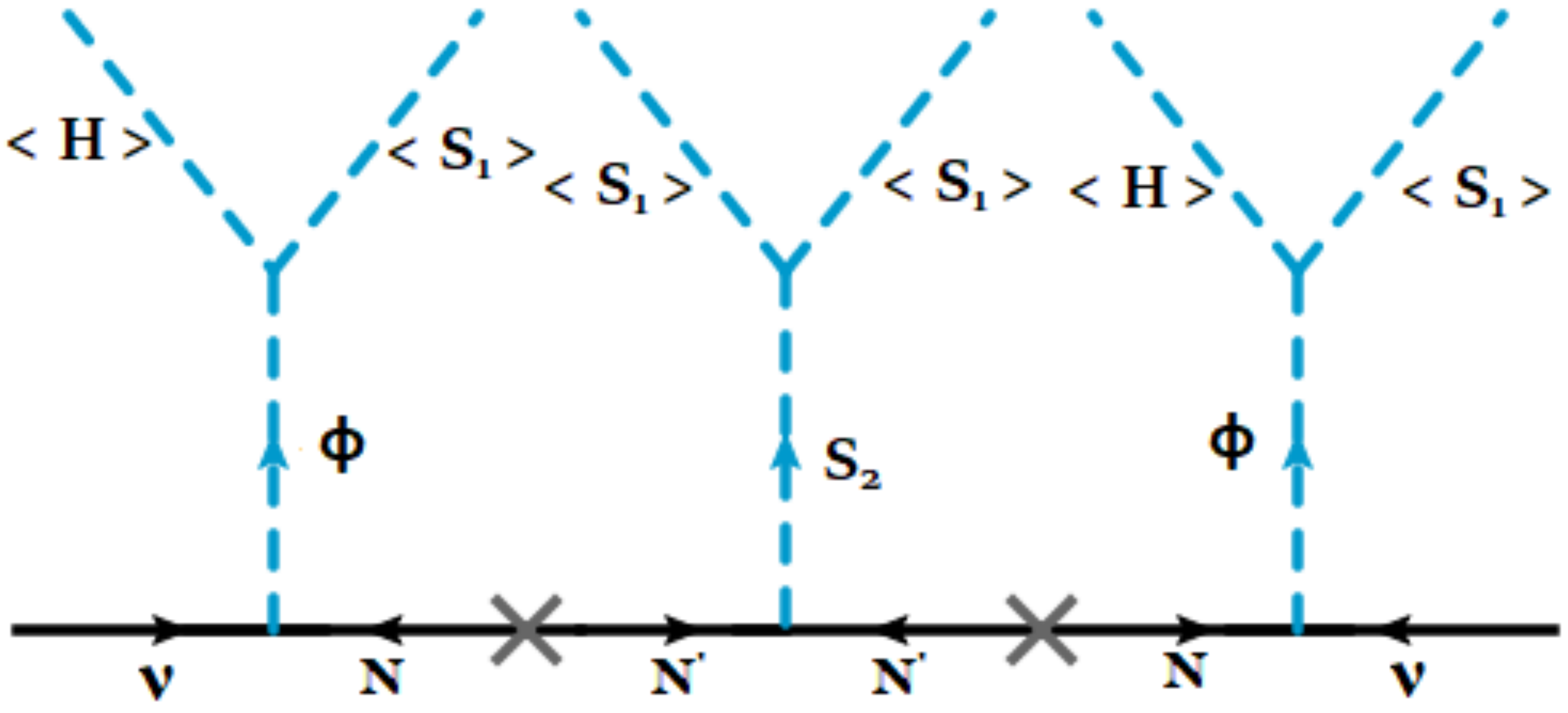
The model in one slide

U(1)$_D$

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

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

Neutrino masses from D=9 operator



Bertuzzo **PM** et al 1807.09877, 1808.02500

Neutrino masses come from new symmetry breaking

Entire model lives below the EW scale

Correlates neutrino mass with new interactions

Mixings are everywhere: Higgs, $F_{\mu\nu}$, neutrinos

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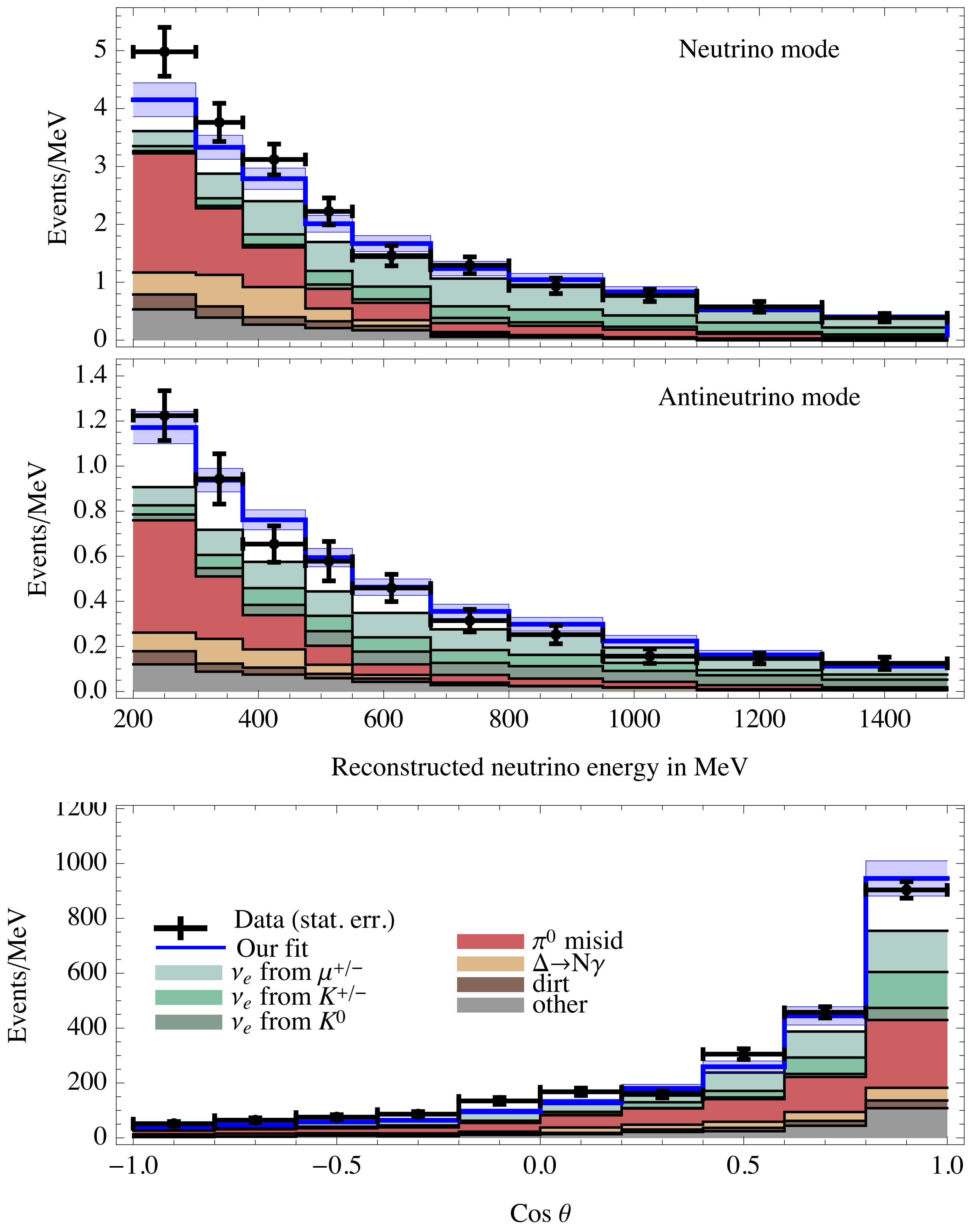
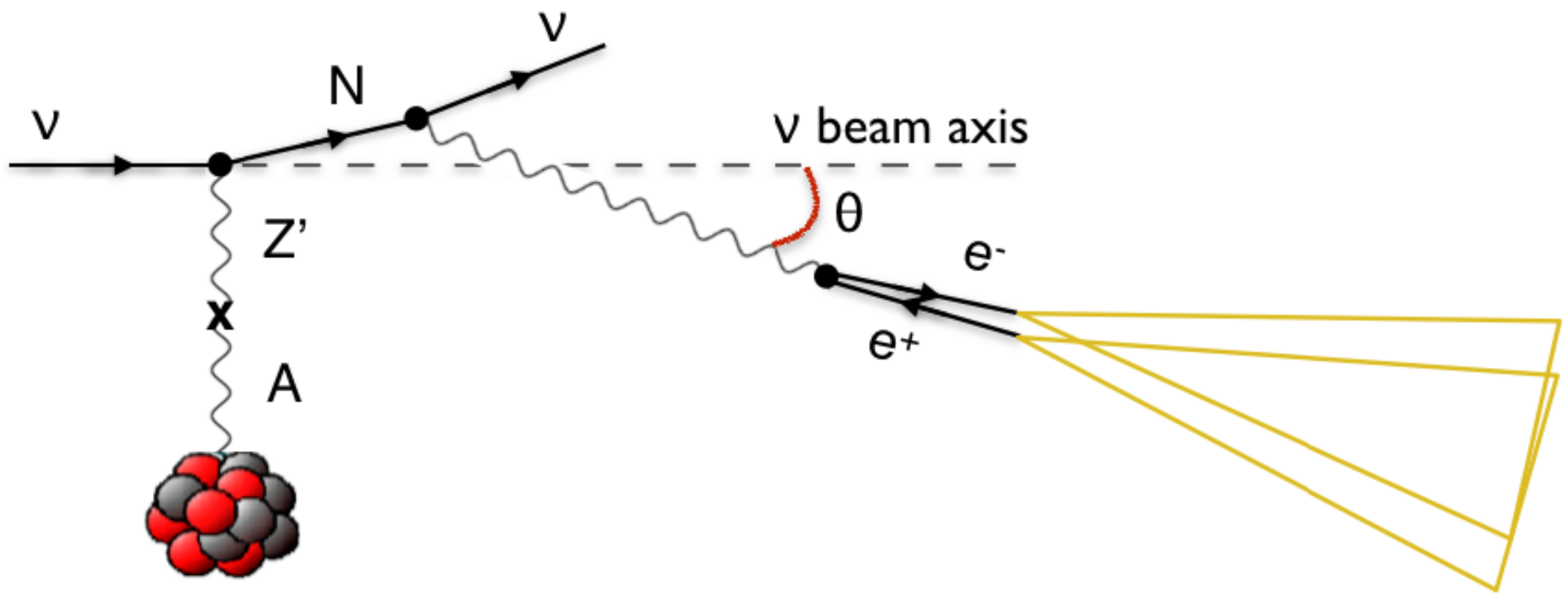
The MiniBooNE anomaly





Pretty good fit to energy and angular spectra

New connection between neutrino mass model and novel interactions at low scales

New connection between anomalies and neutrino masses

Does not explain LSND, Gallium or Reactor* anomalies

(but then again, do all of them need BSM explanations?)

Bertuzzo **PM** et al 1807.09877, 1808.02500

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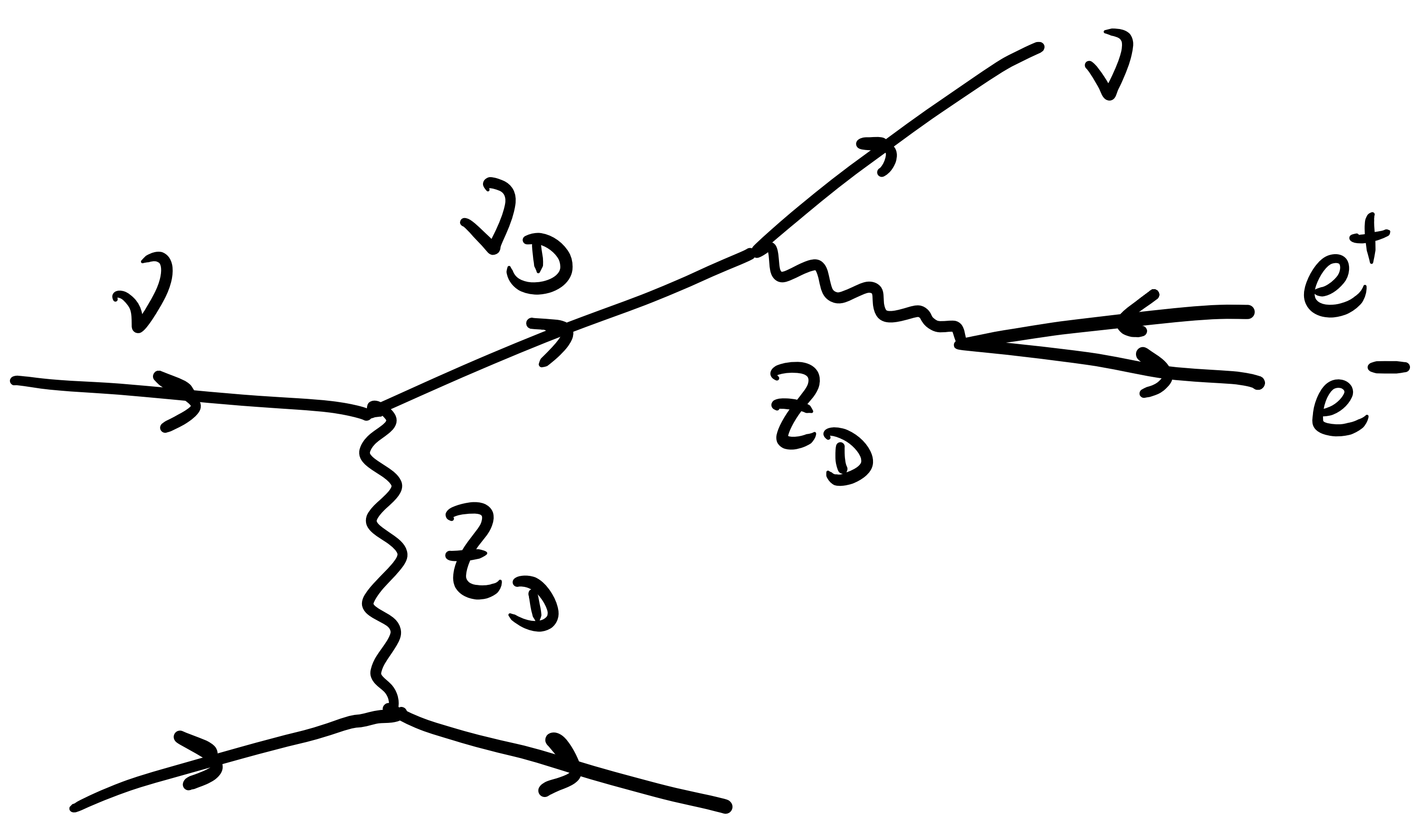
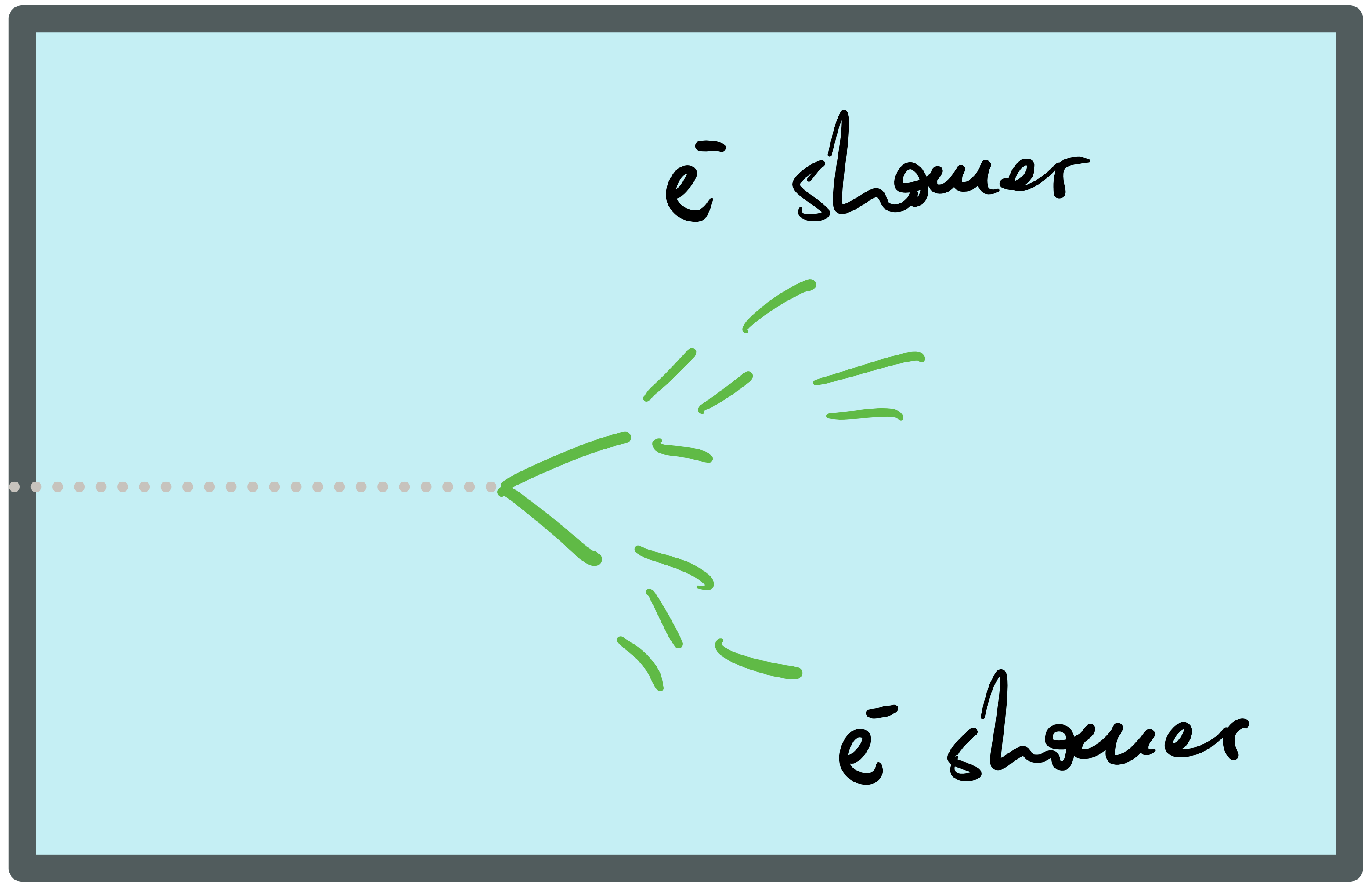
Leveraging future experiments

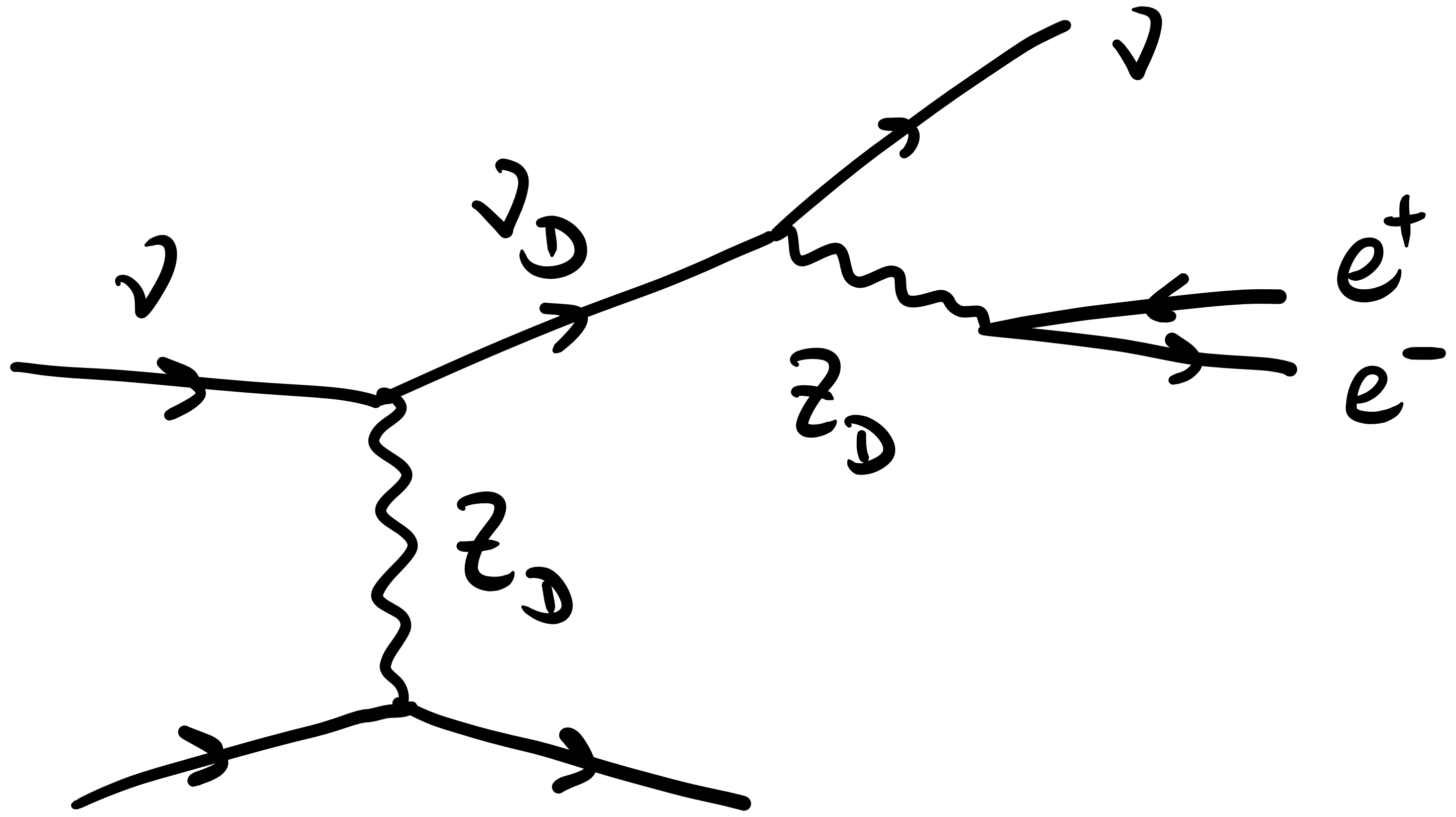
LArTPCs solving anomalies

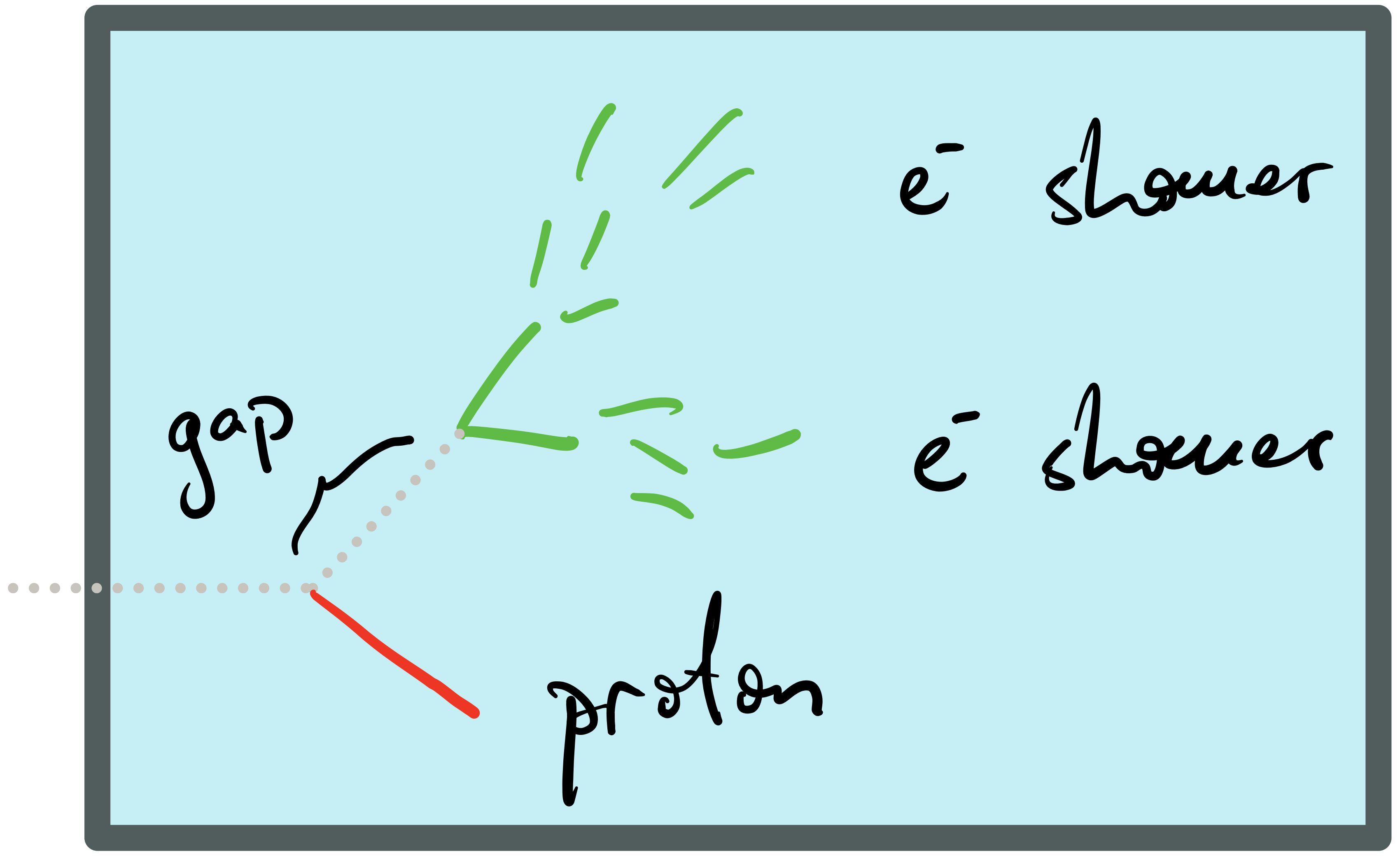
Dark neutrino, light Z_D



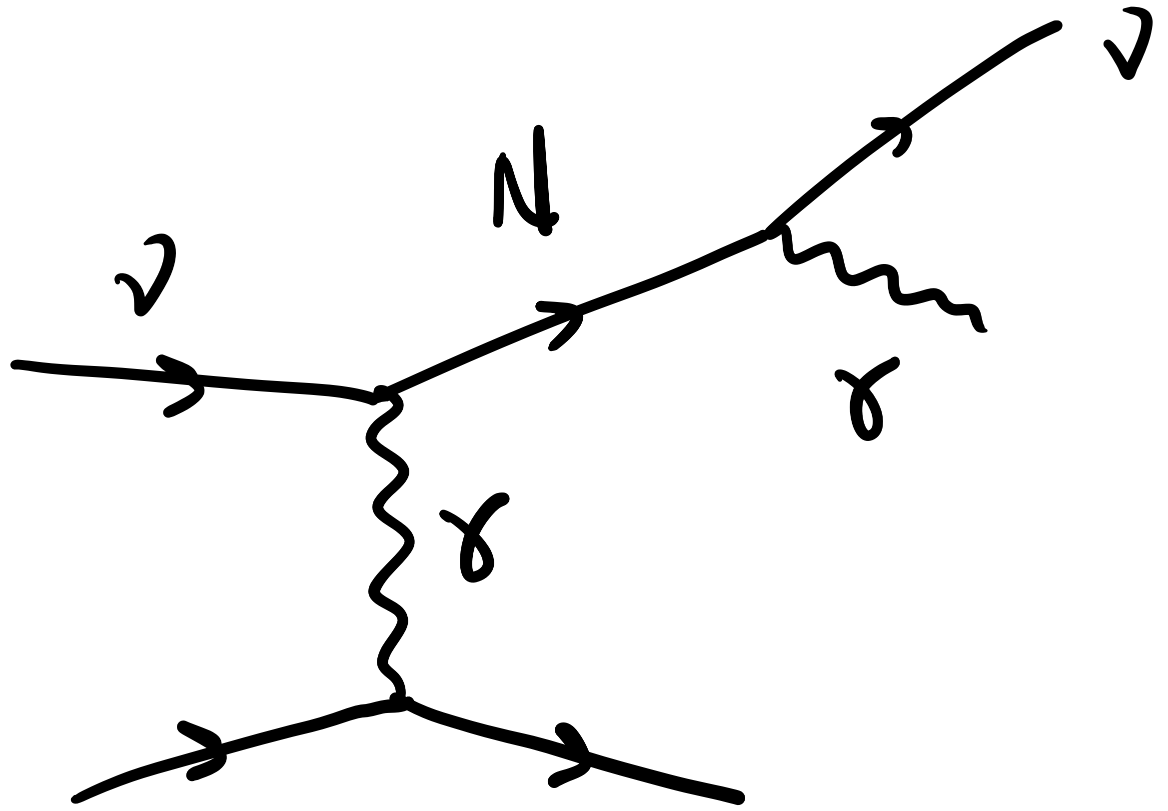


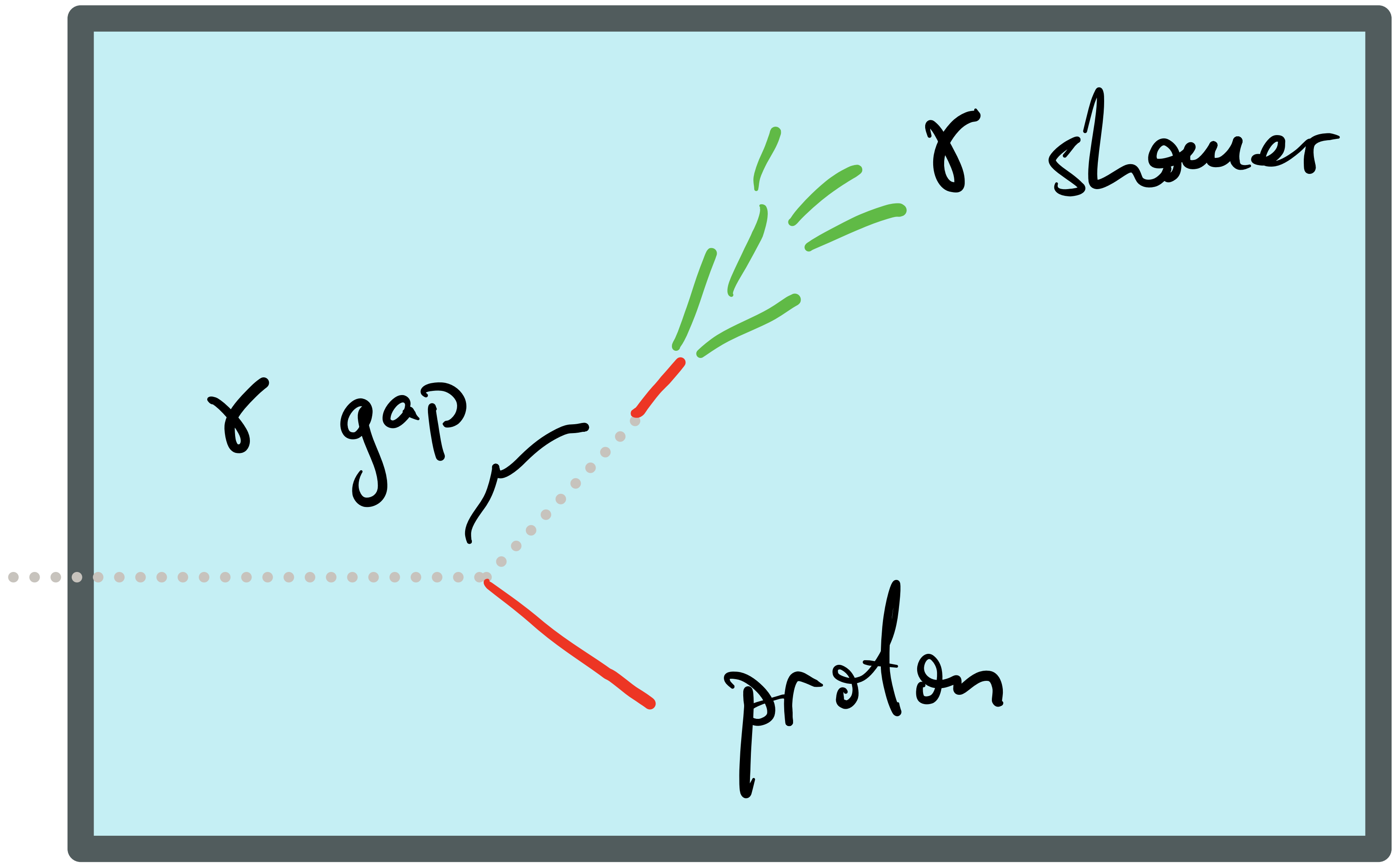
Dark neutrino, heavy Z_D





Transition magnetic moment





*See Ornella's talk for more on LArTPCs

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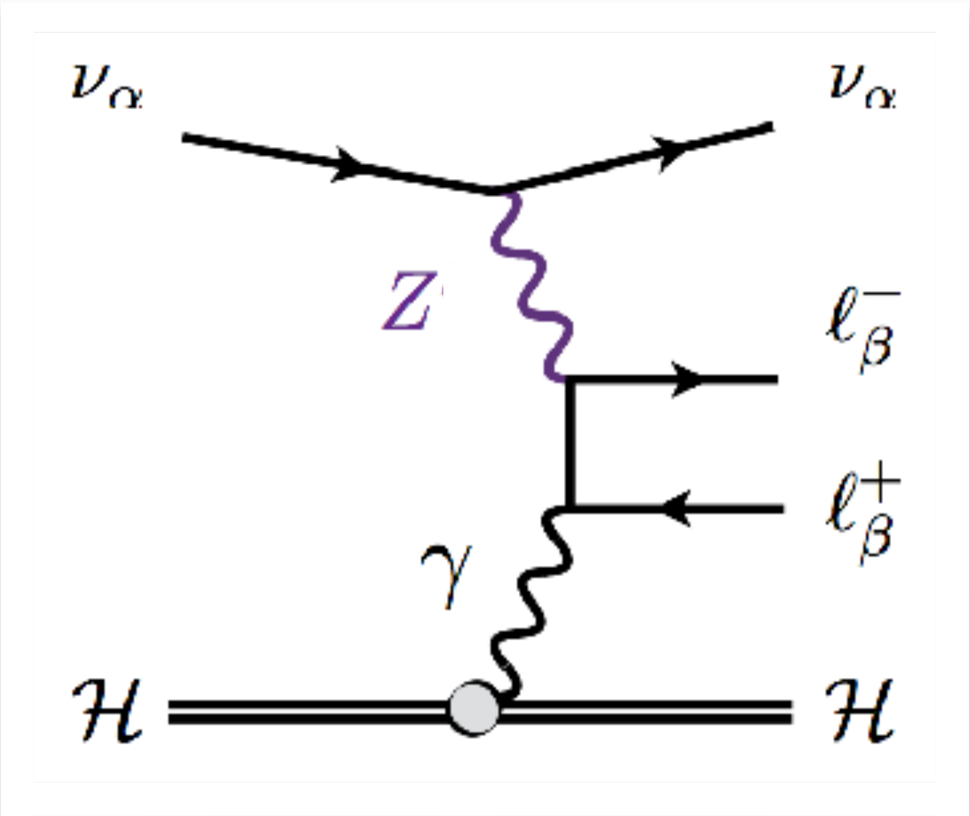
Exotic searches at LArTPCs: dark sectors

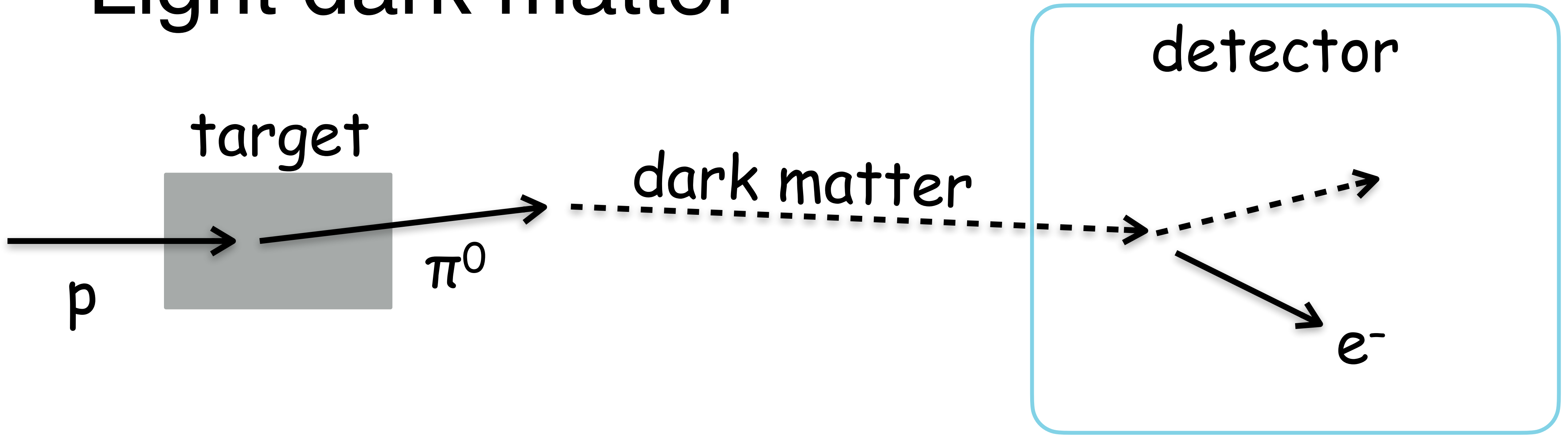
*See Berryman et al 1912.07622 for an extensive study in DUNE-ND

Neutrino tridents



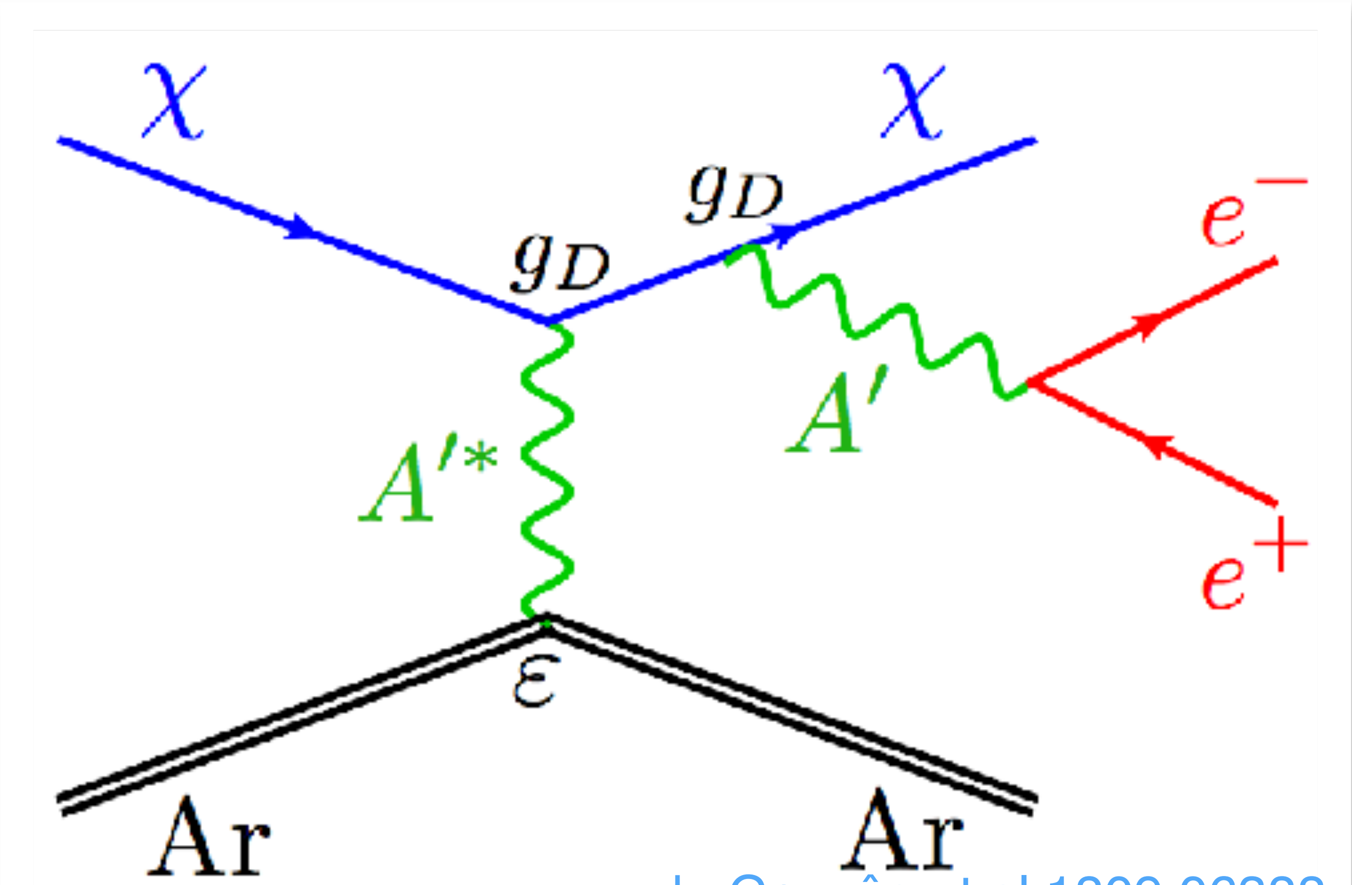
Ballett et al 1807.10973, 1902.08579
Altmannshofer et al 1902.06765

Light dark matter



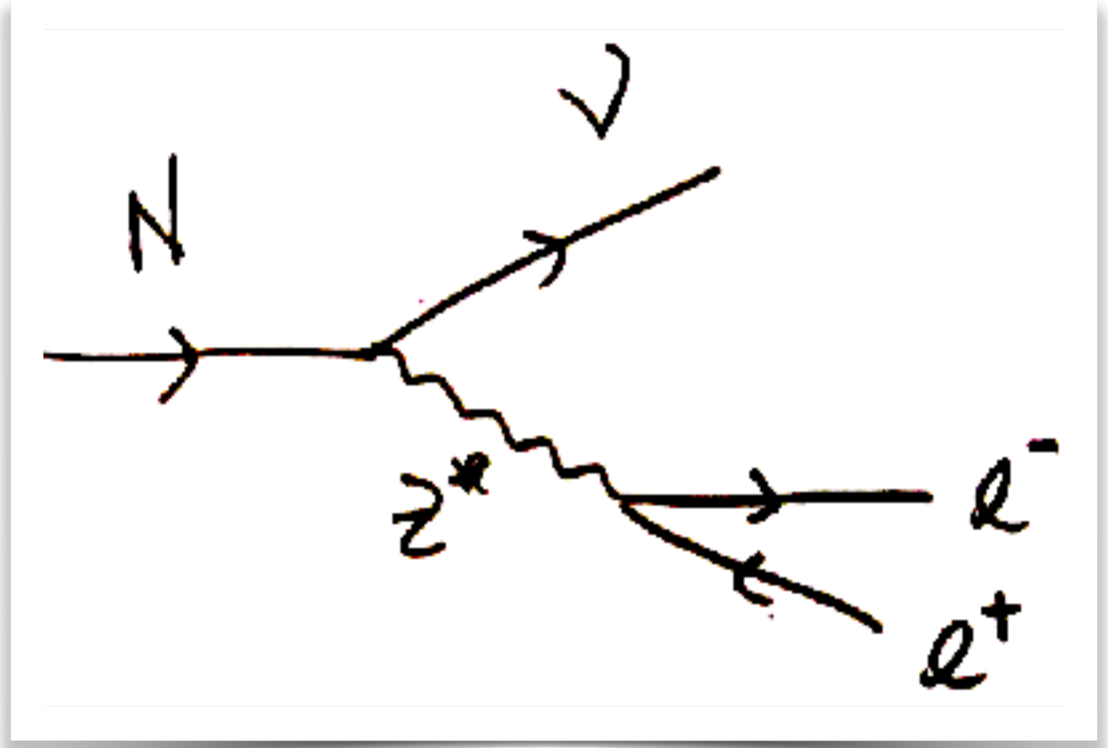
see de Romeri Kelly M 1903.10505 for DUNE constraints

Dark tridents



de Gouvêa et al 1809.06388

Heavy neutral leptons



And axions, weak mixing angle, other dark matter models, light scalars, …

*See Brian's and Maxim's talks for more on dark sectors

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Exotic searches at LArTPCs: the challenge

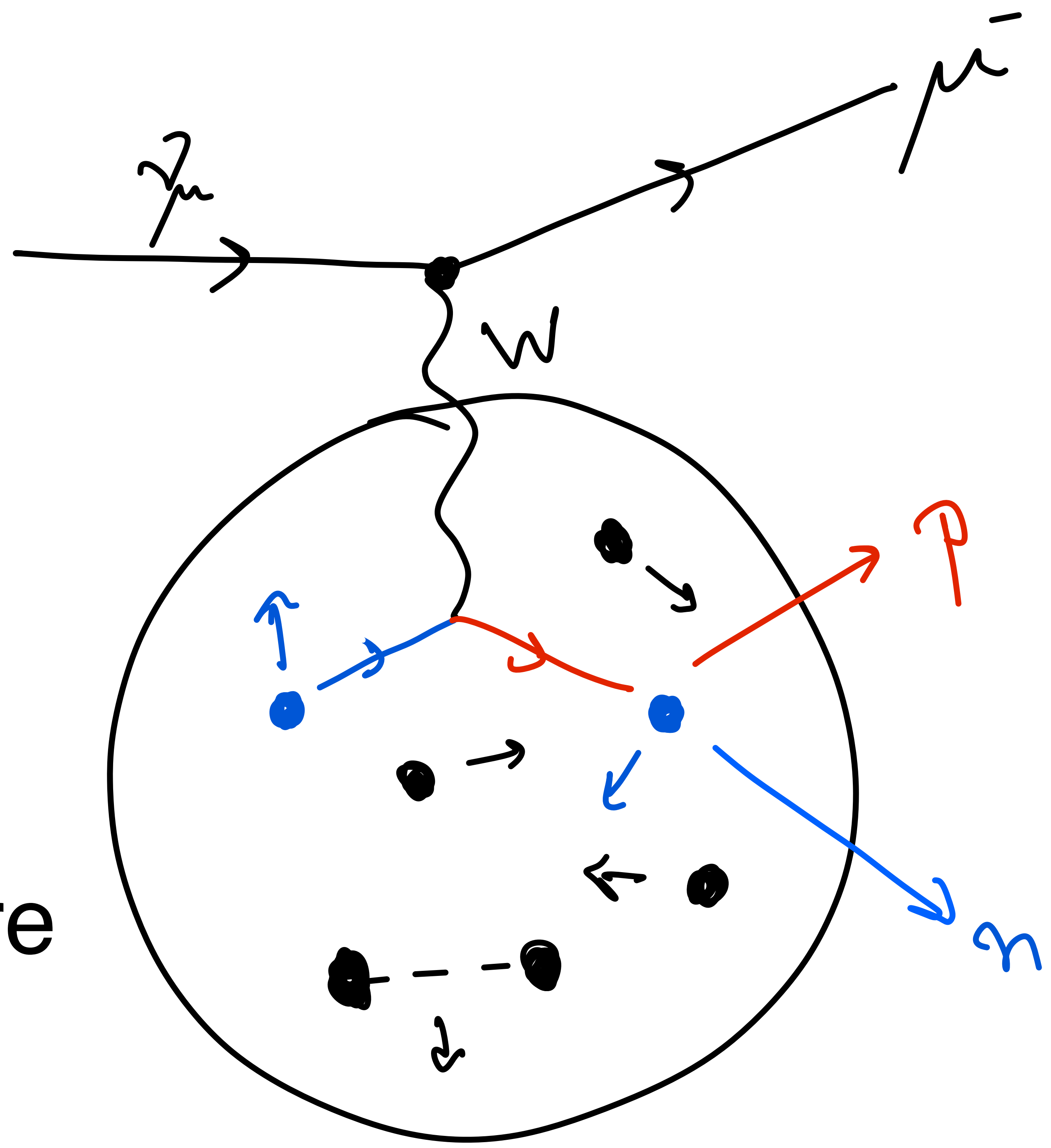
The main challenge to these searches is the modeling of neutrino-nucleus interactions

What is the problem?

The detector response depends on it

How many neutrons? How many protons?
At which energy? In which direction?

It is likely to have BSM << SM, so cuts on kinematics or signature will be necessary to enhance signal-to-background ratios



These will have a nontrivial dependence on the modeling of neutrino-nucleus interactions

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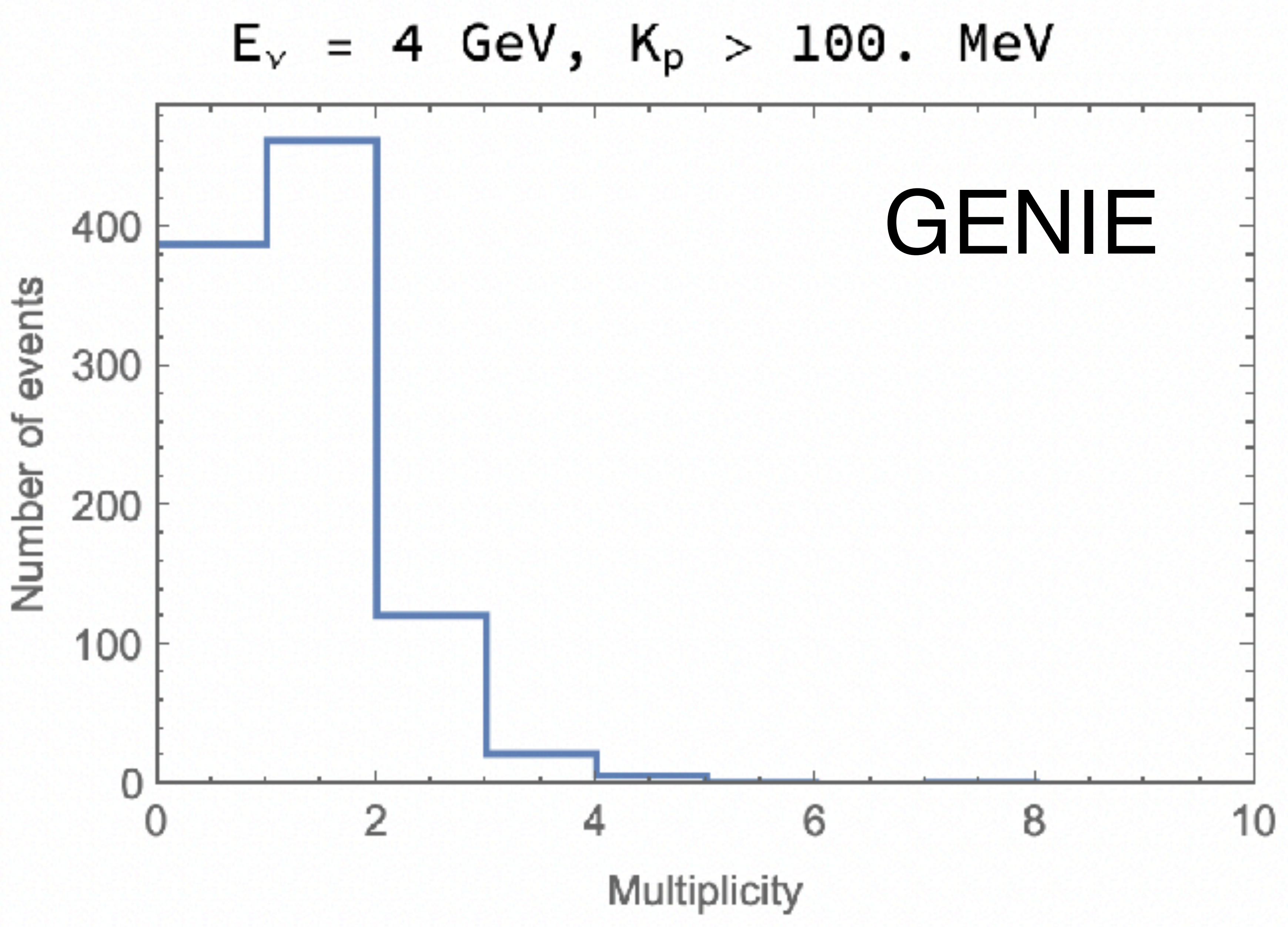
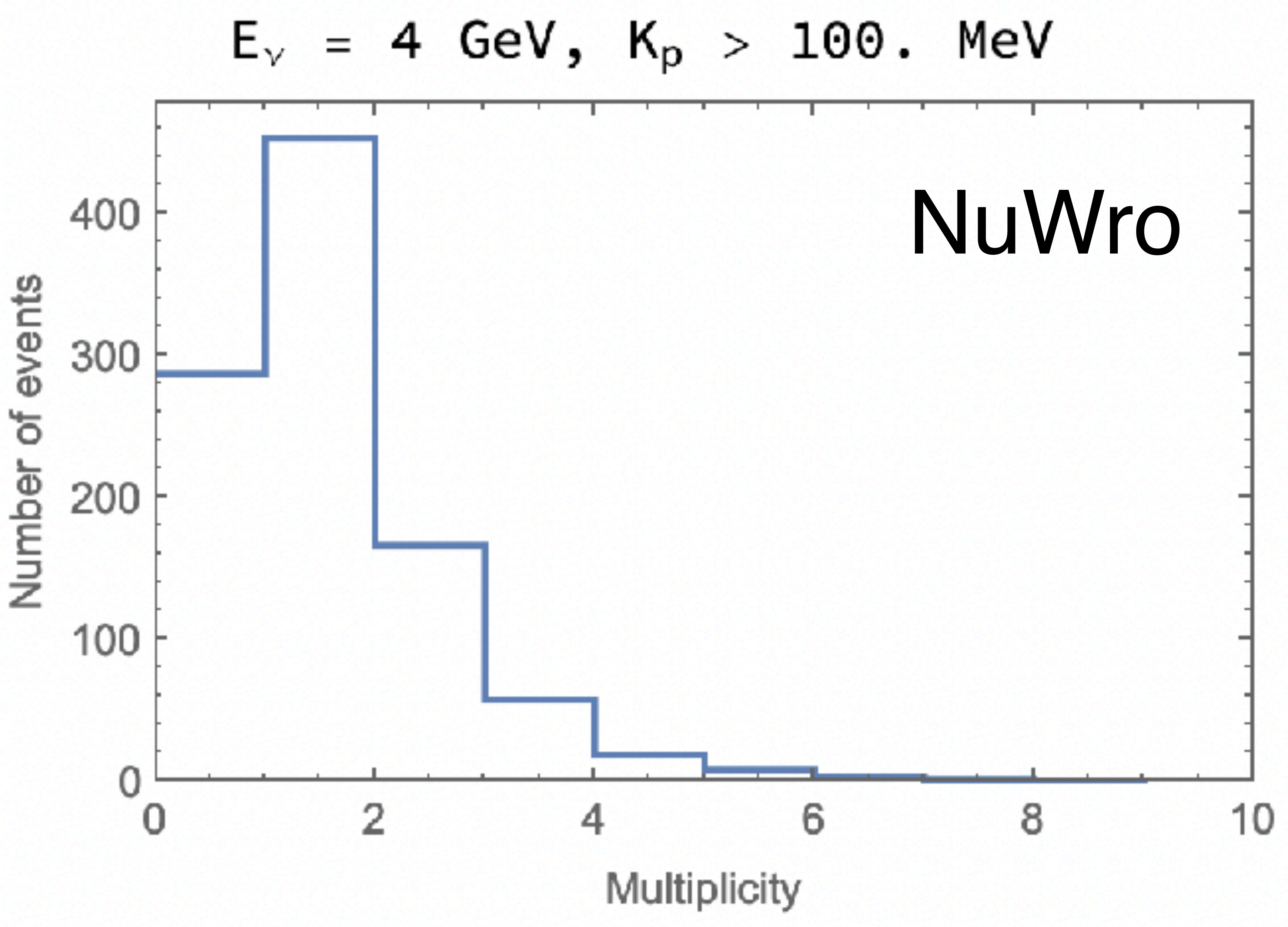
Different generators still yield wildly different results



Multiplicity:

0	=	388
1	=	462
2	=	121
3	=	22
4	=	6
5	=	1
6	=	0
7	=	1
8	=	0
9	=	0



Multiplicity:

0	=	288
1	=	454
2	=	167
3	=	58
4	=	19
5	=	9
6	=	4
7	=	2
8	=	0
9	=	0

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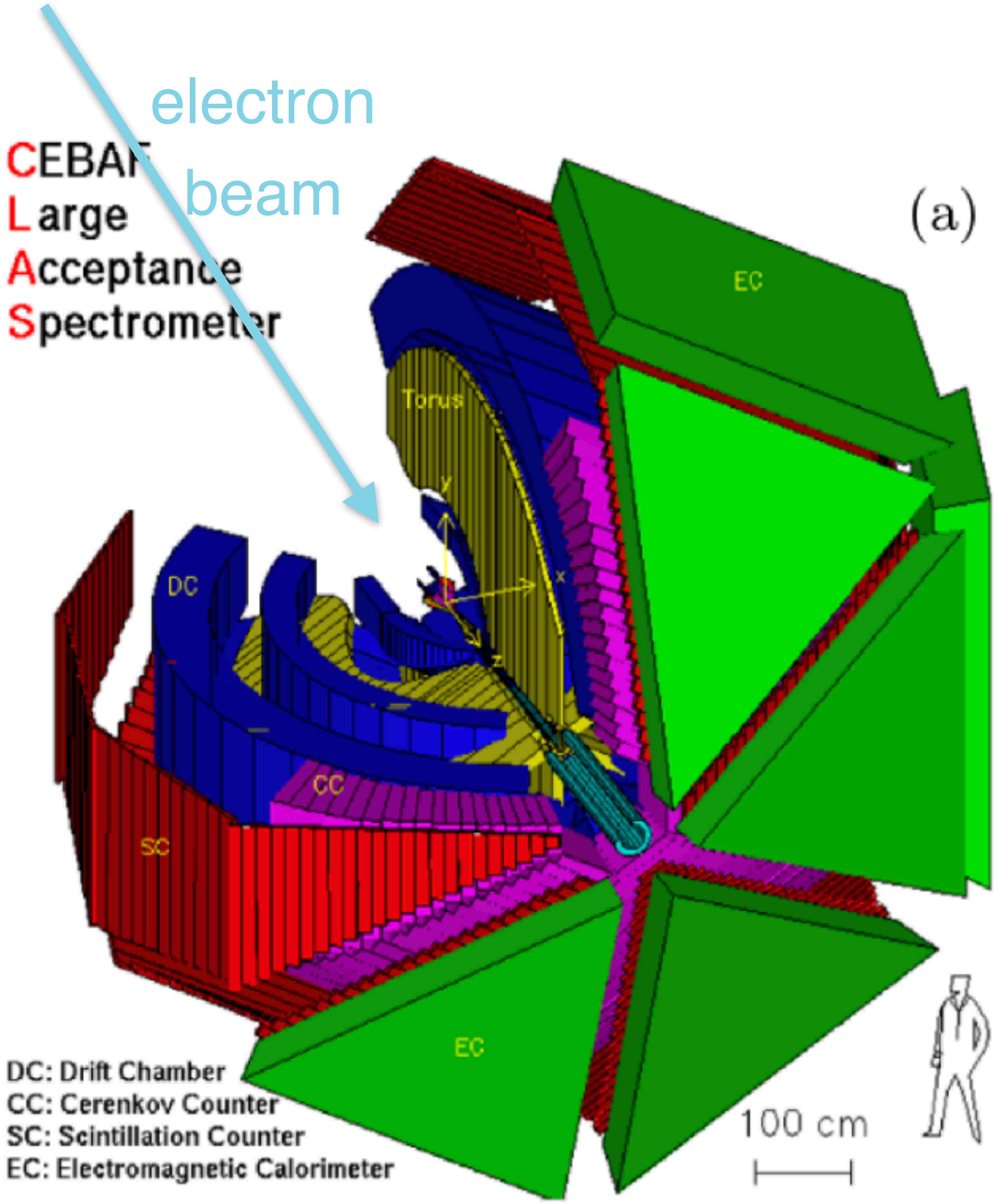
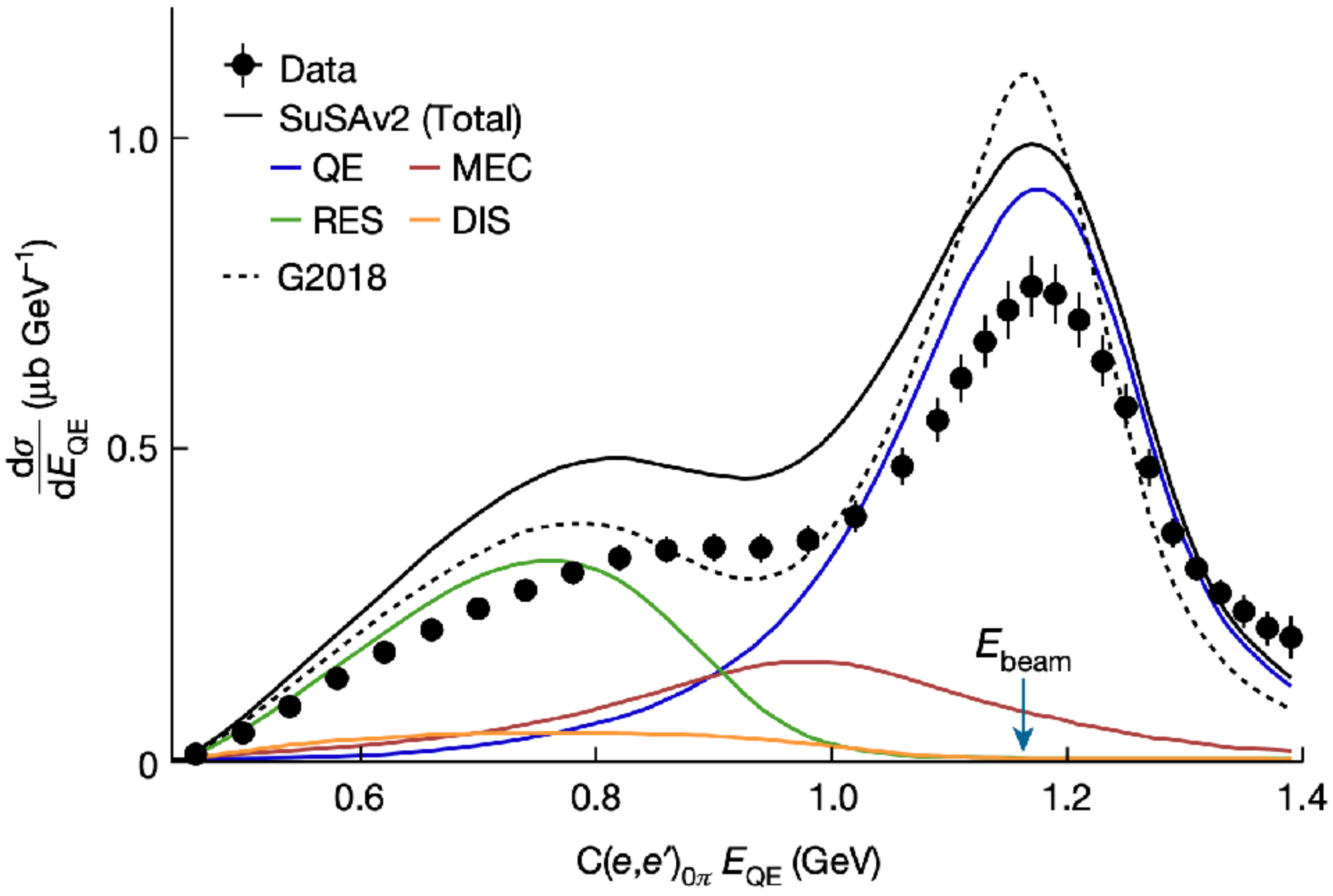
Exotic searches at LArTPCs: the challenge

Right now, theory predictions are just not good enough



CLAS/E4v Nature 599 (2021) 7886, 565-570



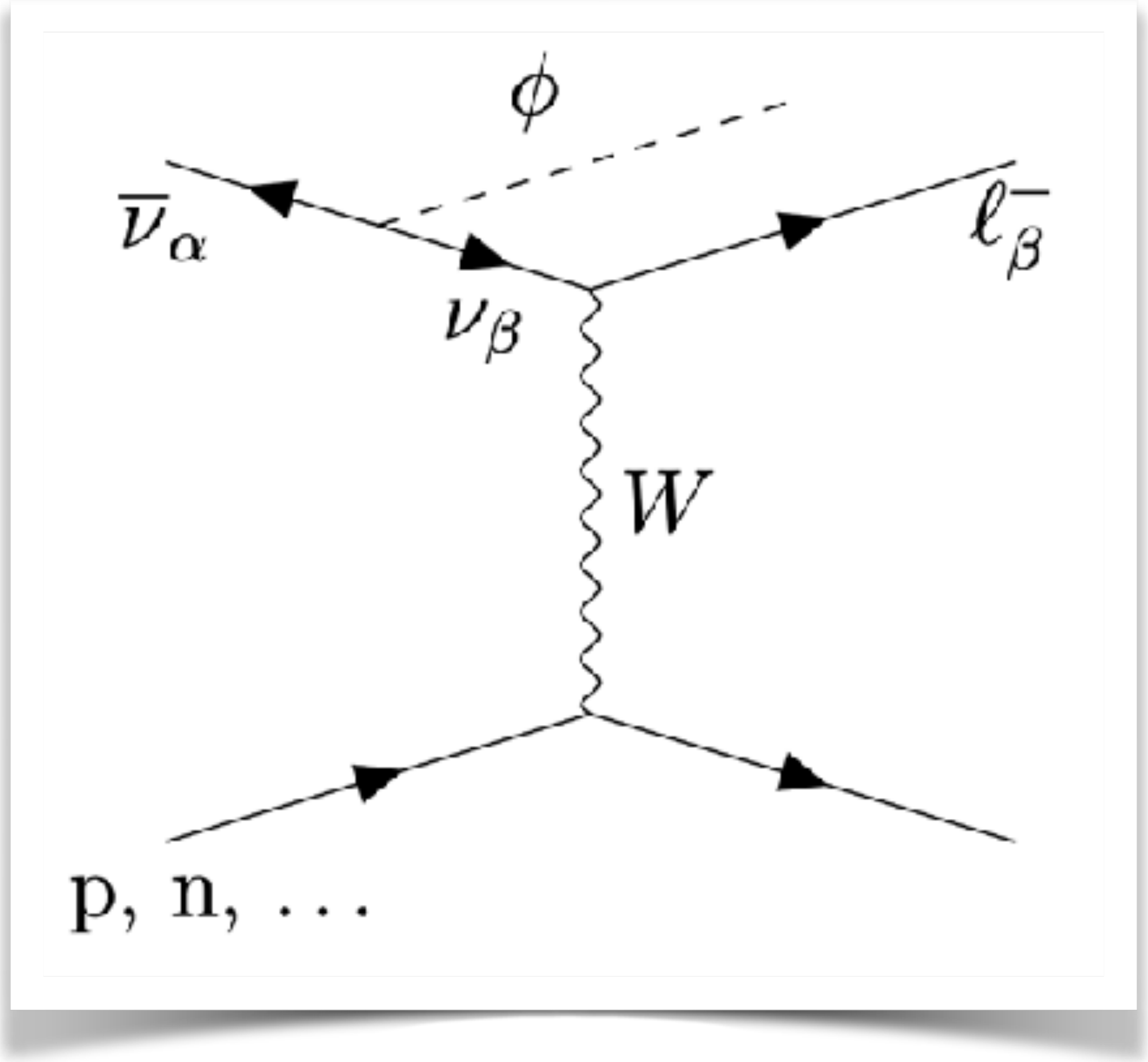
pmachado@fnal.gov

NOvA 2006.08727
Nina Coyle, Shirley Li and PM 2210.03753

Generator (GENIE) does not describe well NOvA data
NOvA reweights the MEC component of the cross section

Exotic searches at LArTPCs: the challenge

New physics leads to small effects
Experimental cuts increase signal-to-background
These cuts can make ν-A mis-modeling worse



Coyle Li **M** 2210.03753

pmachado@fnal.gov

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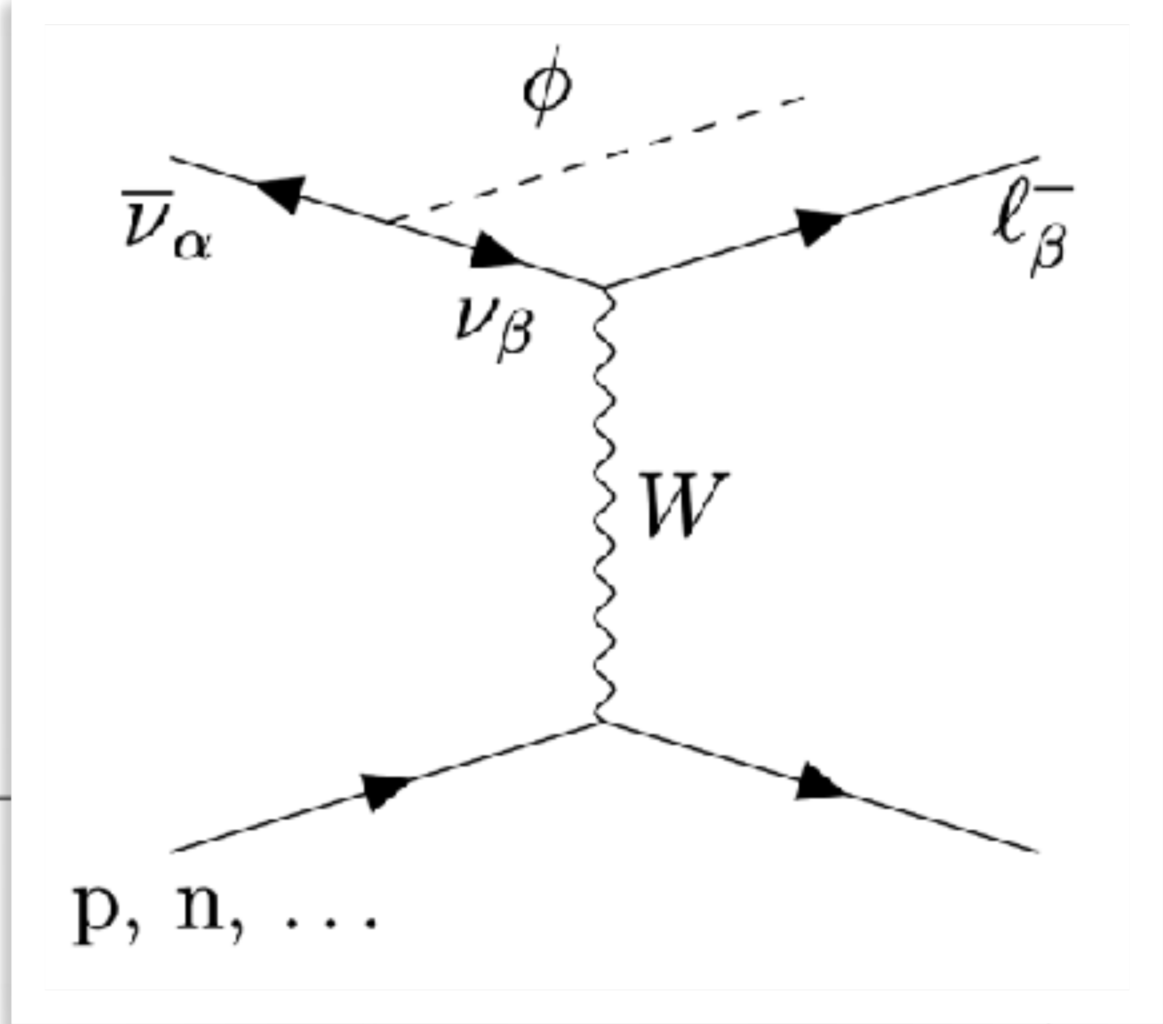
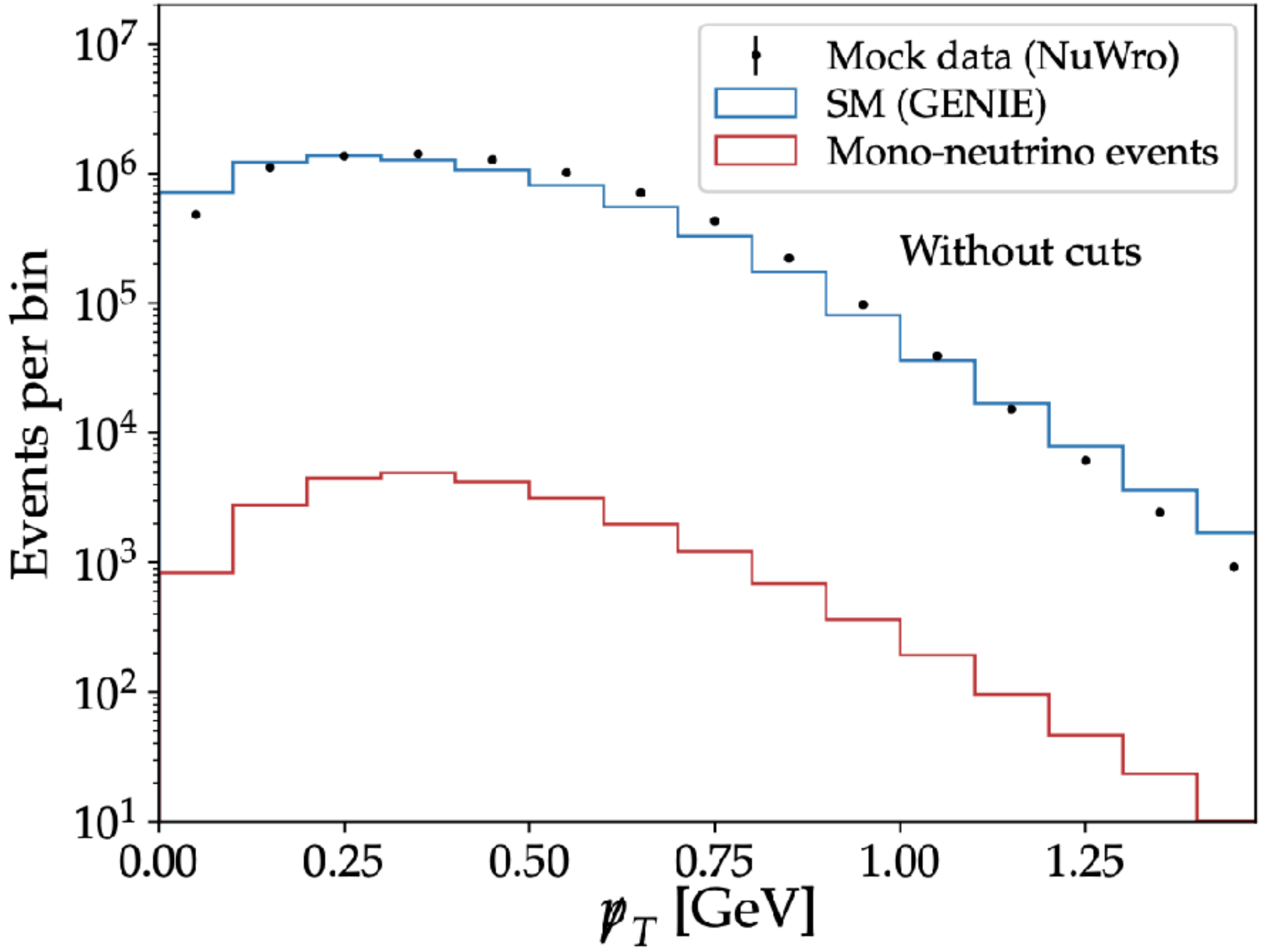
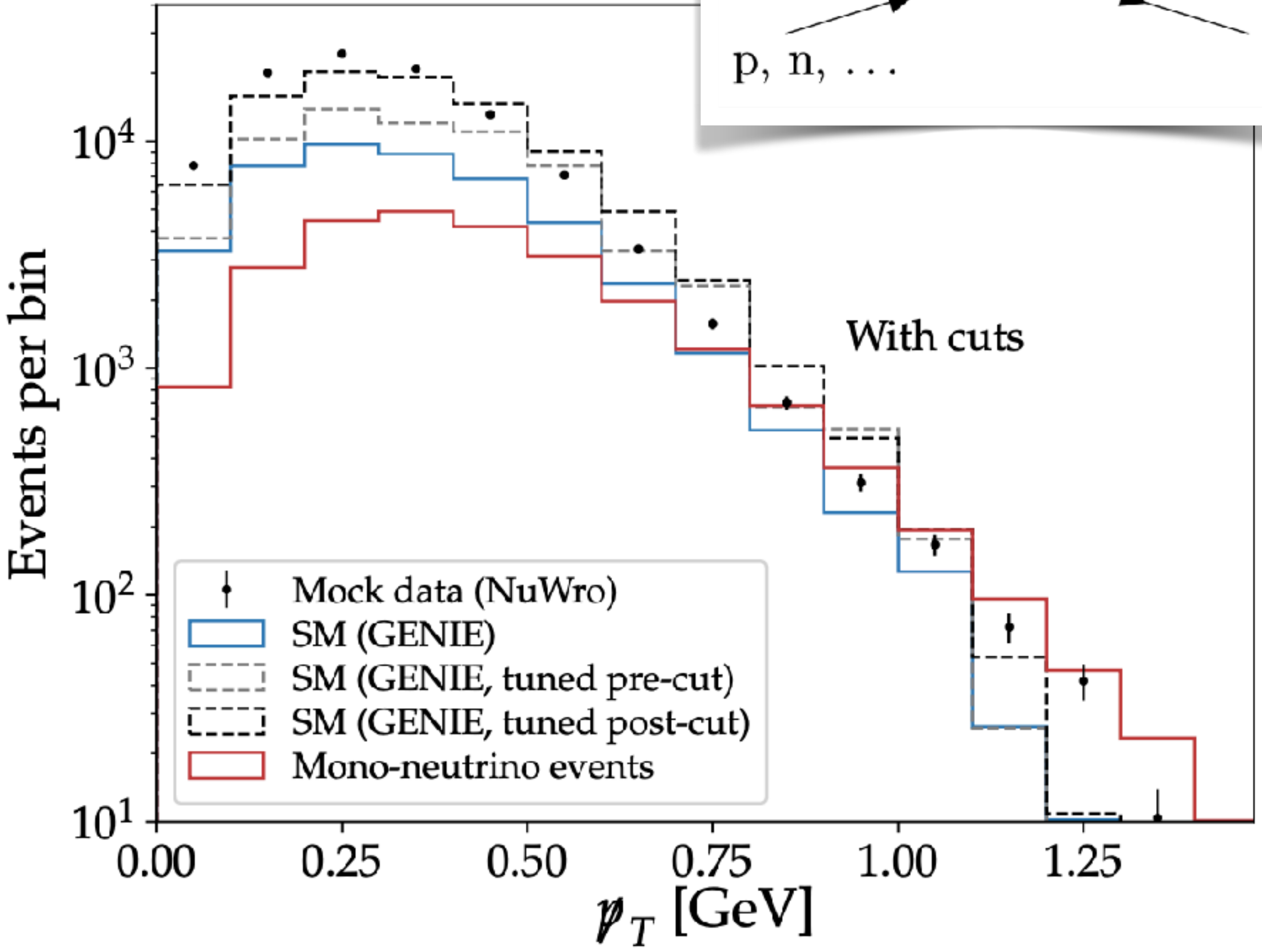


Coyle Li M 2210.03753





Exotic searches at LArTPCs: the challenge

We need better modeling of neutrino-nucleus interactions,
and easy interfaces with BSM scenarios

Achilles: **A CHI**cago**L**and **L**epton **E**vent **S**imulator

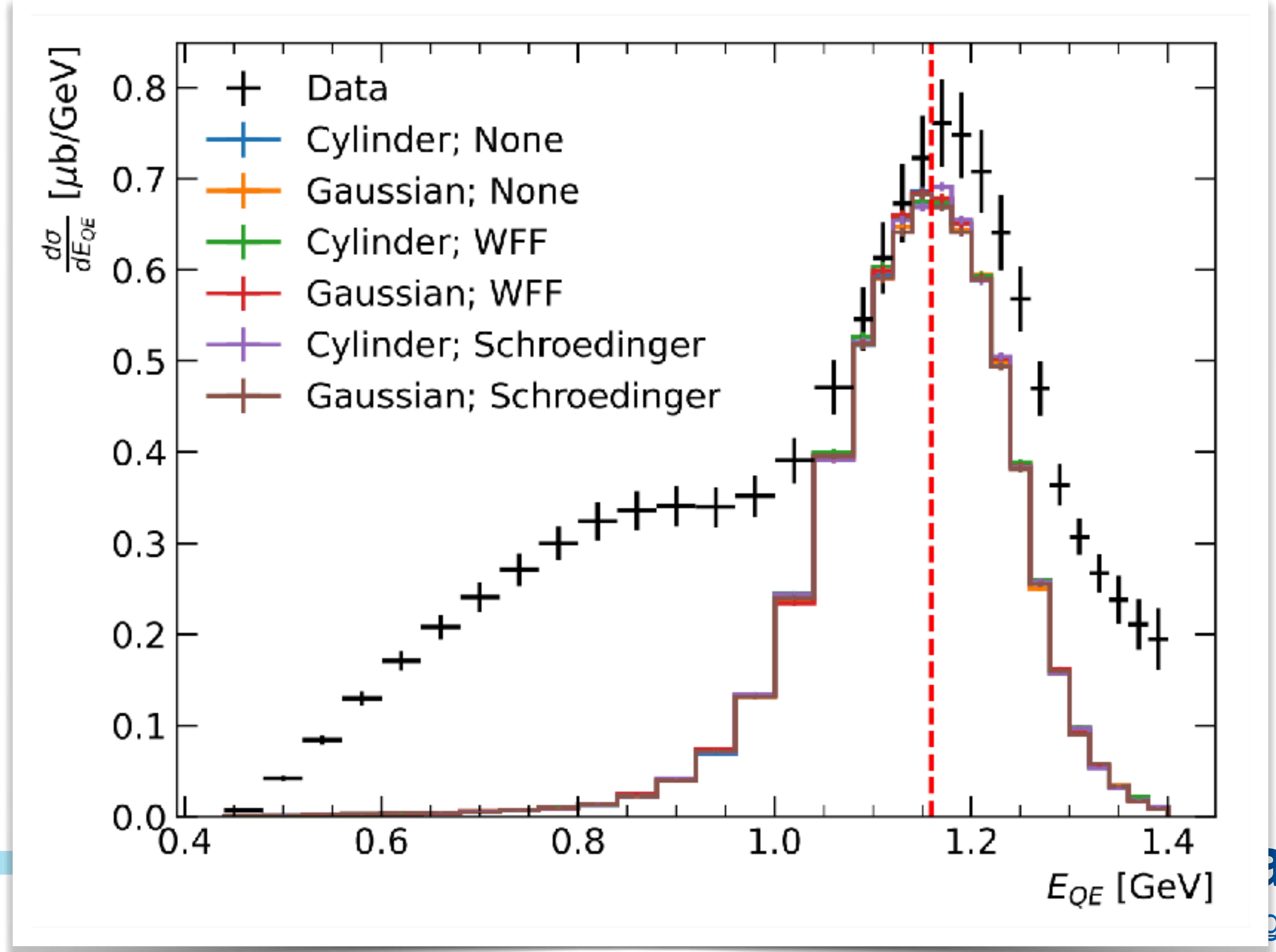
Isaacson **M** et al 2007.15570
Isaacson et al 2110.15319
Isaacson **M** et al 2205.06378
Isaacson et al 2303.08104

Novel event generator, still implementing all interaction modes, etc

FeynRules interface to BSM

Being validated against electron data

Hopefully will be a full-fledged generator by next year!



Conclusions

Neutrino experiments offer unique, nontrivial probes of new physics

New oscillation phenomenology, new neutrino signatures and
new particles produced in the beam can probe the big questions in particle physics:
mechanism of neutrino masses, dark matter, dark sectors, axions, …

There has been a lot of work in the last 5 years in these new directions

There is still a lot to be done!