Some

Theoretical challenges in neutrino physics

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June/2019

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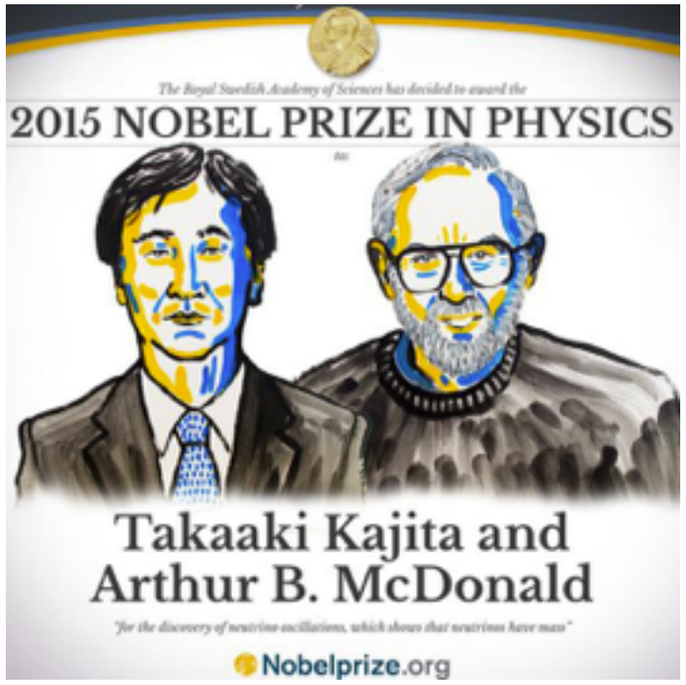
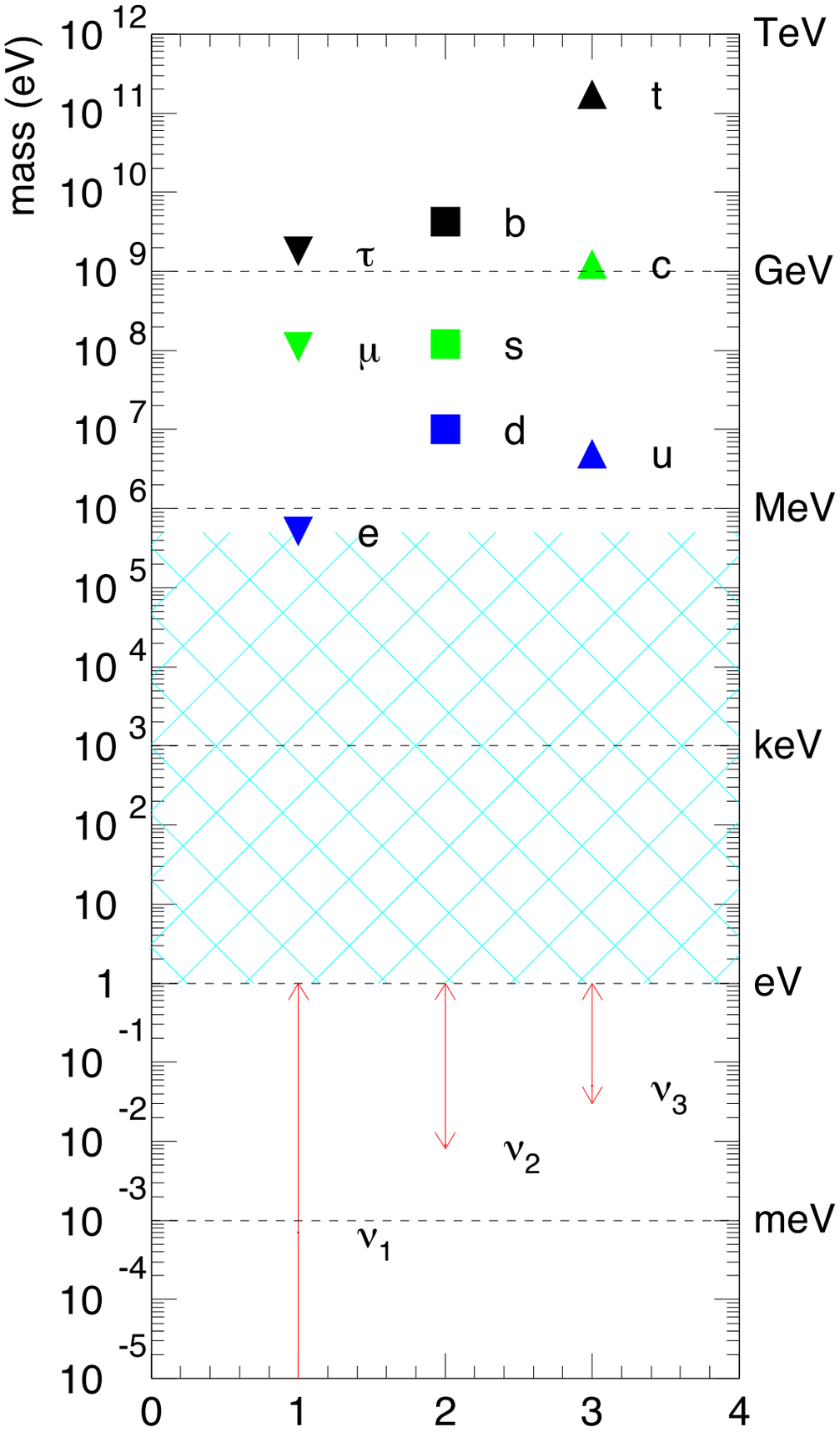


The existence of non-zero neutrino masses,
inferred from neutrino oscillation measurements,
is the only laboratory-based evidence
of physics beyond the standard model

The mass spectrum of the SM (a.k.a. The flavor puzzle)



Neutrinos are at least about 200,000,000,000 times lighter than top quarks!

word

neutrino

top quark

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Neutrino masses

To date, the only observation of non-zero neutrino masses com from oscillation physics

Why are neutrino masses special?

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Are neutrinos Majorana or Dirac fermions?

Except for neutrinos, all fermions of the standard model are electrically charged

Thus, there is a distinction between particle and antiparticle

For neutrinos, this is not obvious - particles could be identical to antiparticles, with only chirality distinguishing them

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$e \neq e^c$

negative charge positive charge

$\nu \neq \nu^c$????

No charge to distinguish them
Are neutrinos Majorana particles?

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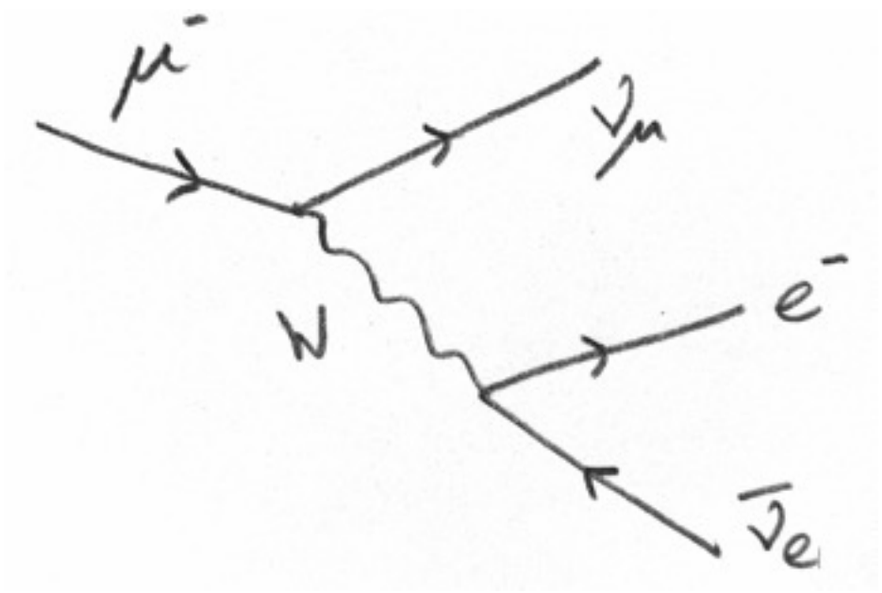
Type-I seesaw

$$\mathcal{L}_\nu = y\bar{L}H\nu_R + M\bar{\nu}_R\nu_R^c$$

$$m_\nu = \frac{y^2v^2}{M}$$

Neutrino oscillations

Neutrinos are only produced by weak interactions



The state produced by
weak interactions
is a quantum superposition of
physical states

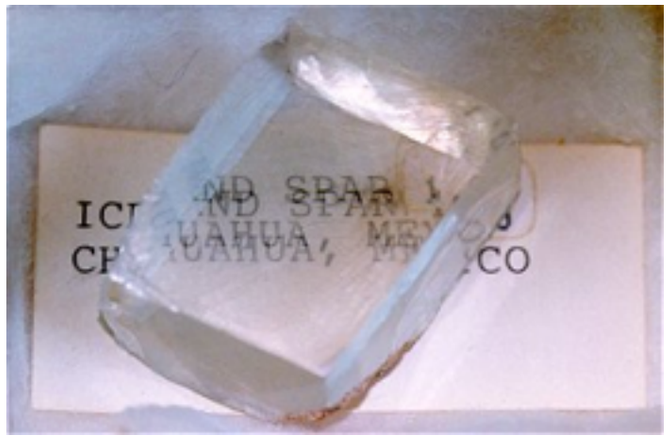
$$|\nu_e\rangle = U^*_{e1}|\nu_1\rangle + U^*_{e2}|\nu_2\rangle + U^*_{e3}|\nu_3\rangle$$
$$\vdots$$

Flavor eigenstates: produced by weak interactions
Mass eigenstates: physical states with well-defined mass

Quantum Mechanics 101
Evolution of flavor state is non-trivial, leading to neutrino oscillations

Neutrino oscillations

Birefringent crystals have different index of refraction for light polarized parallel or perpendicular to its optical axis



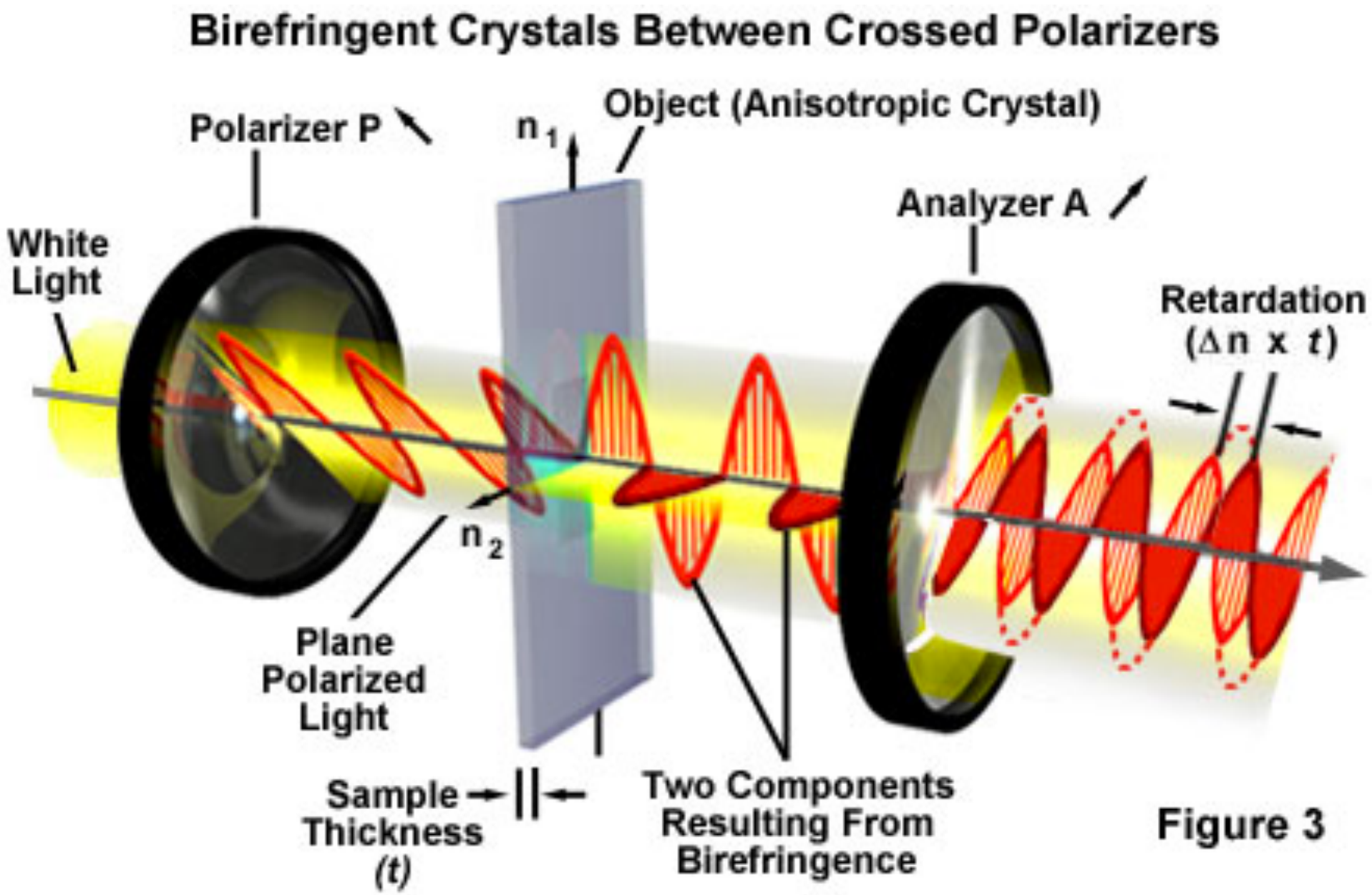


Figure 3

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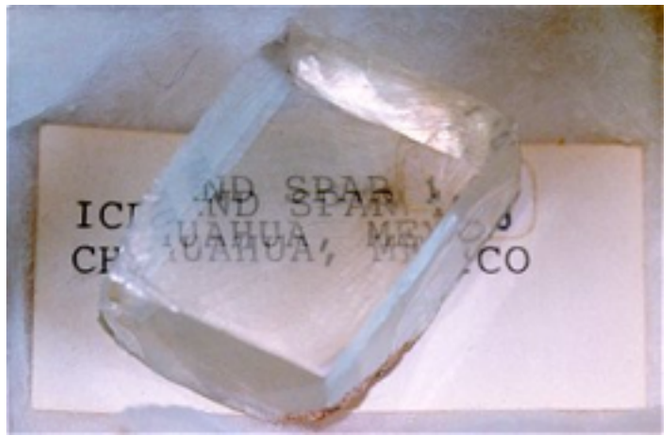
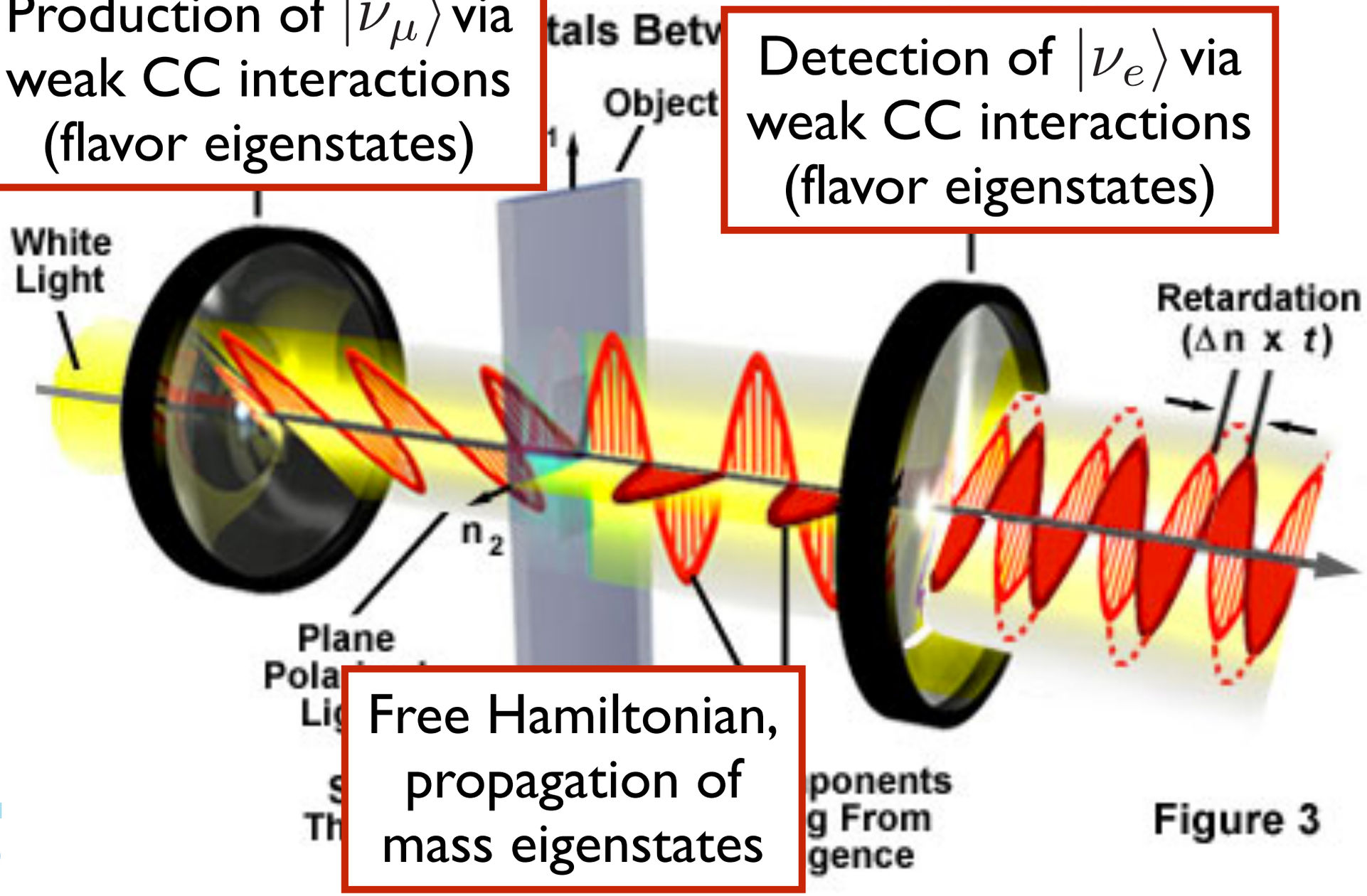
Neutrino oscillations

Birefringent crystals have different index of refraction for light polarized parallel or perpendicular to its optical axis



Production of $|\nu_\mu\rangle$ via weak CC interactions (flavor eigenstates)

Detection of $|\nu_e\rangle$ via weak CC interactions (flavor eigenstates)



Free Hamiltonian, propagation of mass eigenstates

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Neutrino oscillations

A soccer example:

Say I have been ~~oscillating~~ changing teams over the years

2000

2003

2004

2009

Neutrino oscillations

A soccer example:

Say I have been ~~oscillating~~ changing teams over the years

2000

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In reality,

~~teams propagate non-trivially under the free Hamiltonian~~

I don't have a team, I am a fan of Marta!!!

Neutrino oscillations

A soccer example:

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Flavor eigenstates

2000 2003 2004 2009

In reality,

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Mass eigenstate

The neutrino sector

Oscillations parametrized by 2 mass splittings, 3 mixing angles, and 1 phase

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

We have measured all mixings and mass splittings at 4~17% accuracy (3σ)

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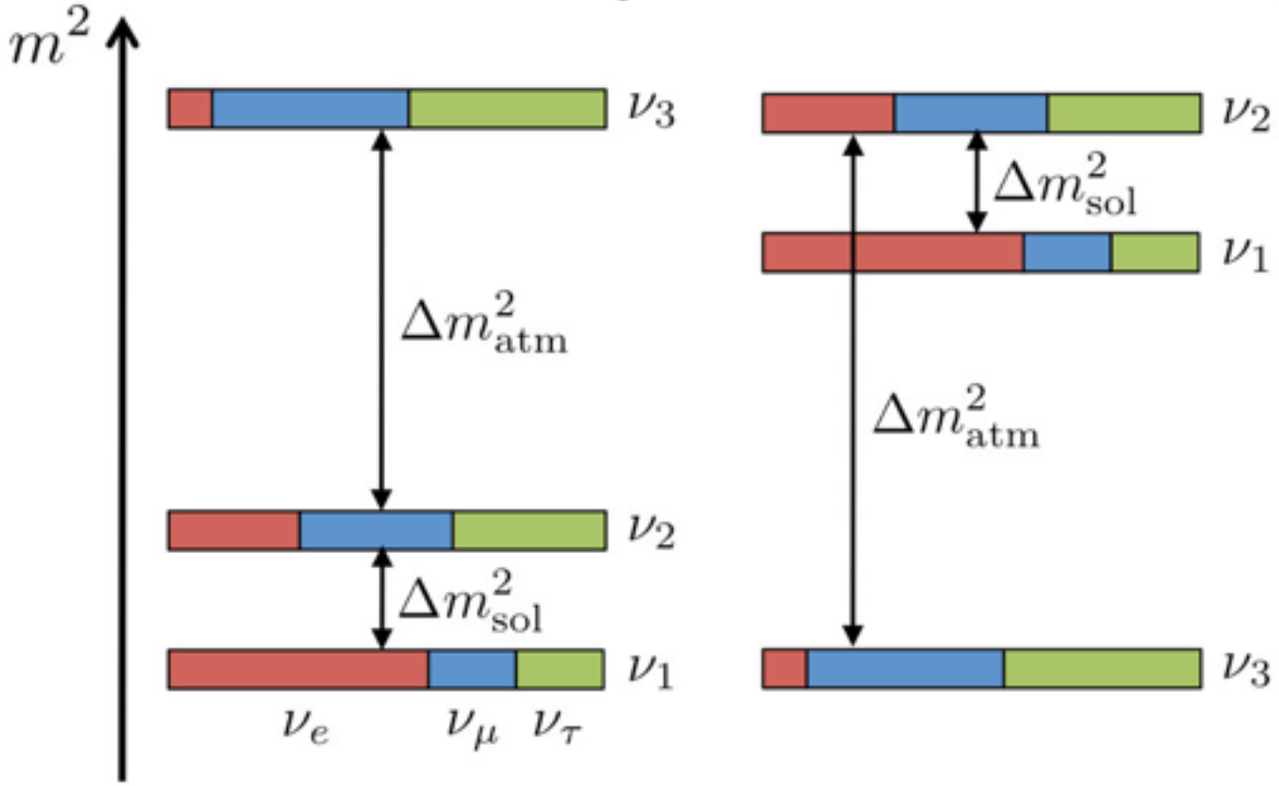
Normal ordering Inverted ordering



Unknowns:

What is the mass ordering?

Does ν_3 have more ν_μ or ν_τ?

What is the CP phase?

What is the absolute mass scale?

Are neutrinos Dirac or Majorana?

What is the mechanism of neutrino masses?

…

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Some theory challenges in neutrino physics

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Some theory challenges in neutrino physics

1. Neutrino interactions
2. Extracting the most out of LArTPCs: standard physics
3. Extracting the most out of LArTPCs: BSM
4. Connecting oscillation physics to other sectors
5. Connecting δ_{cp} to the matter-antimatter asymmetry

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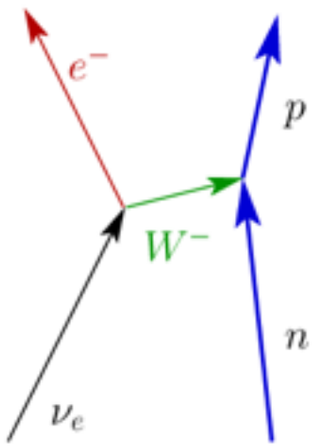
Neutrino interactions

Expectation



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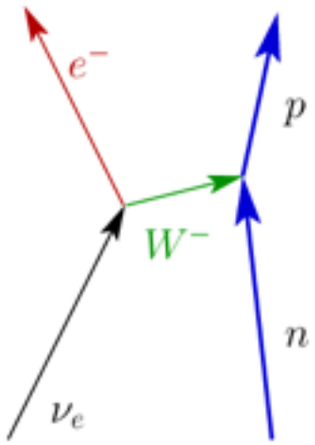
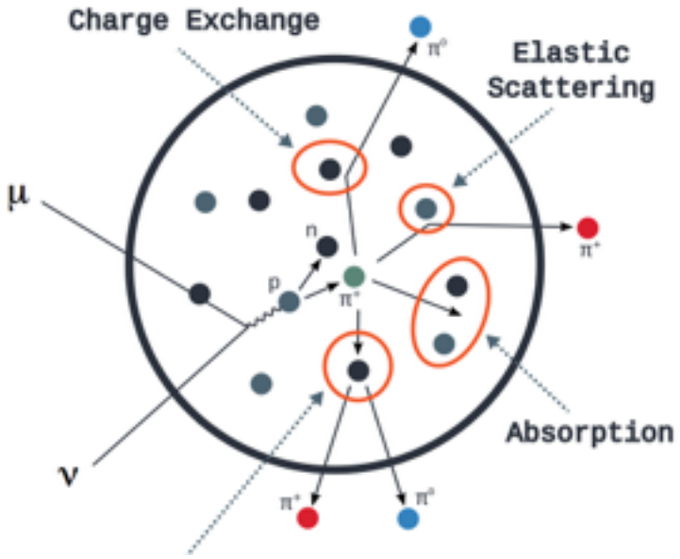


Reality



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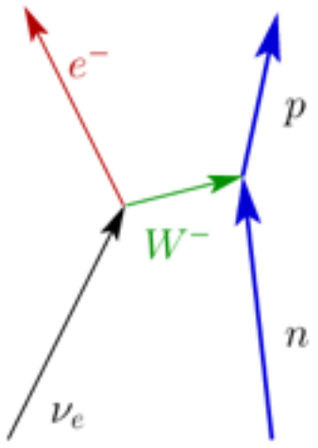
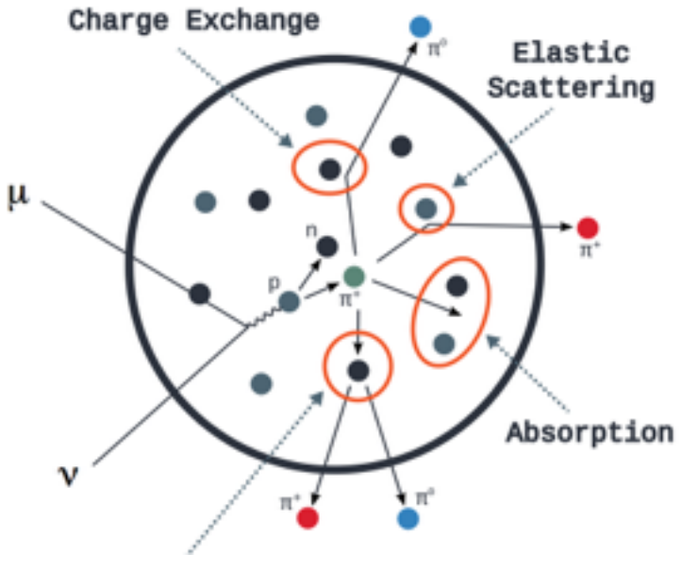
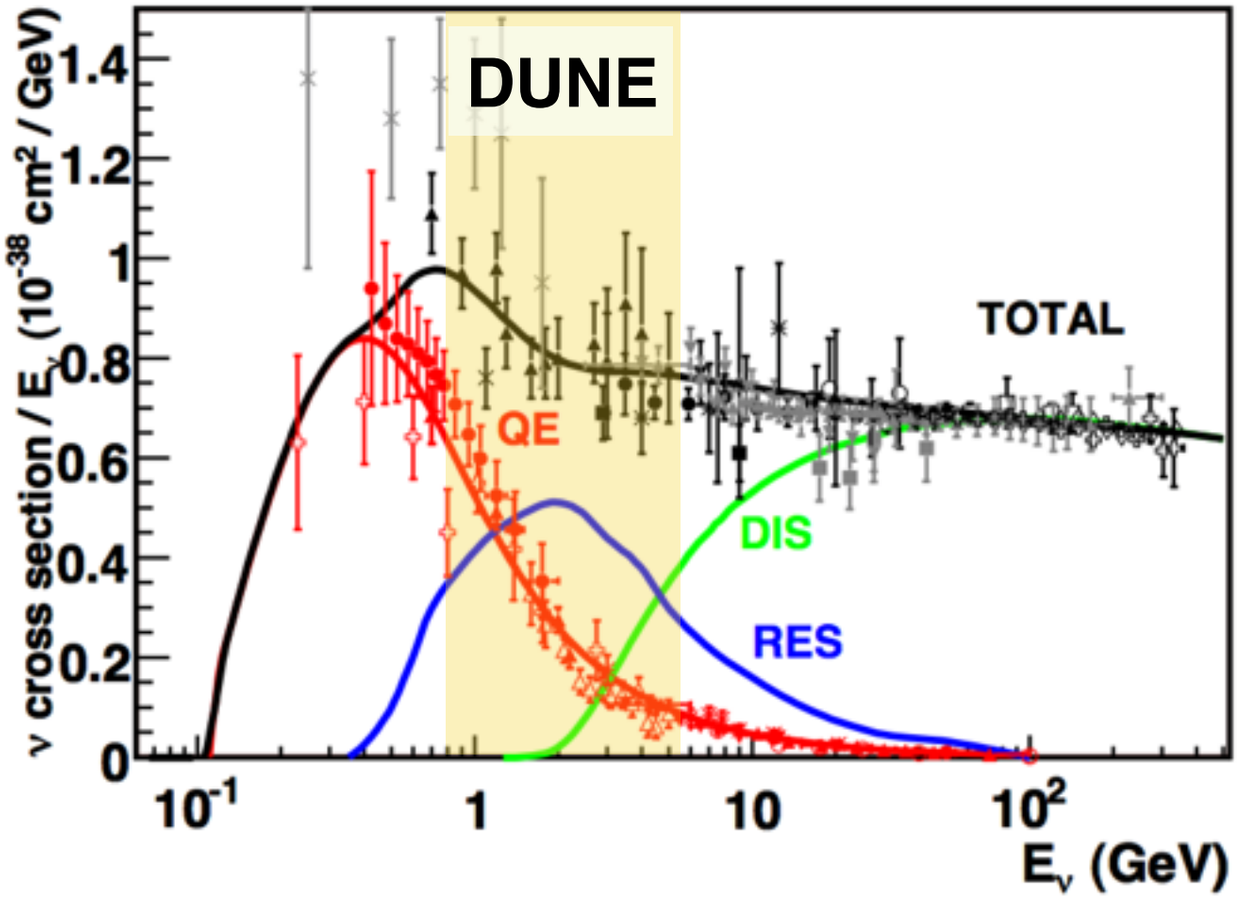


Reality





Neutrino interactions

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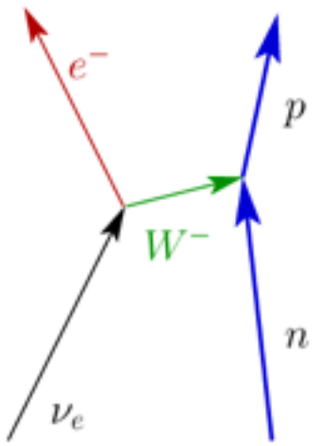

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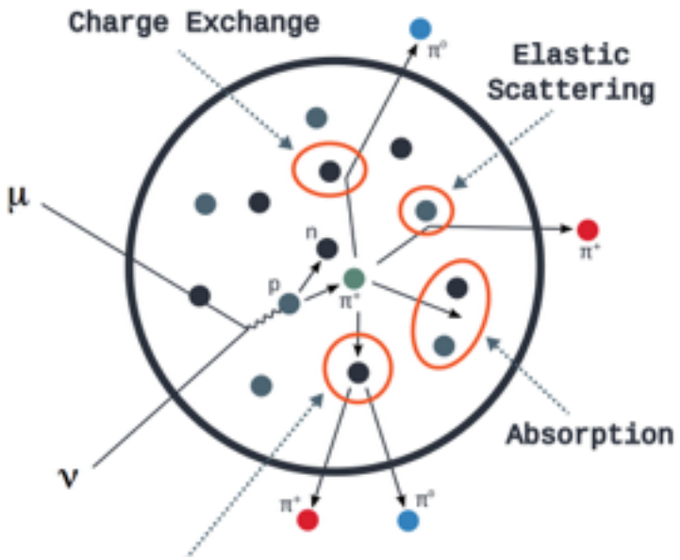
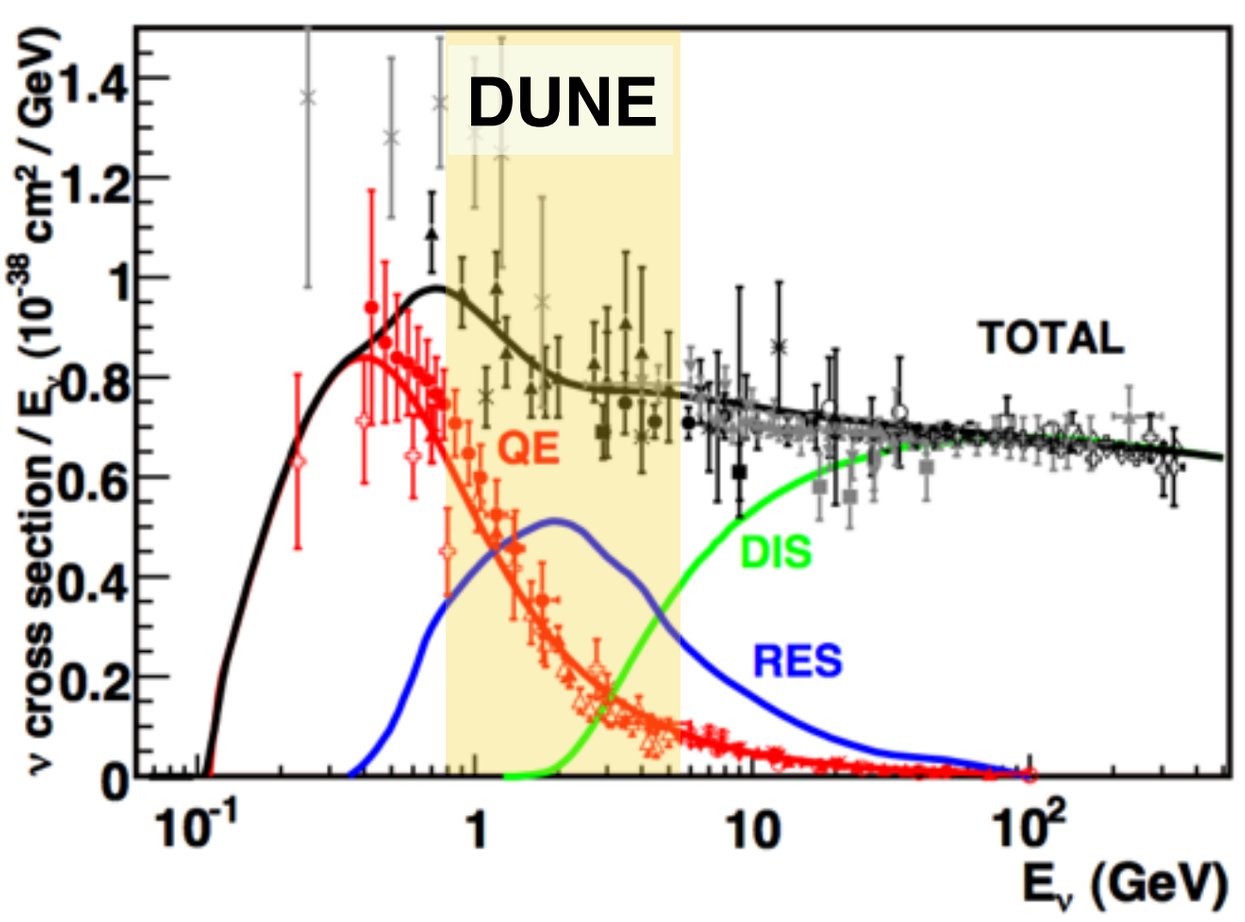
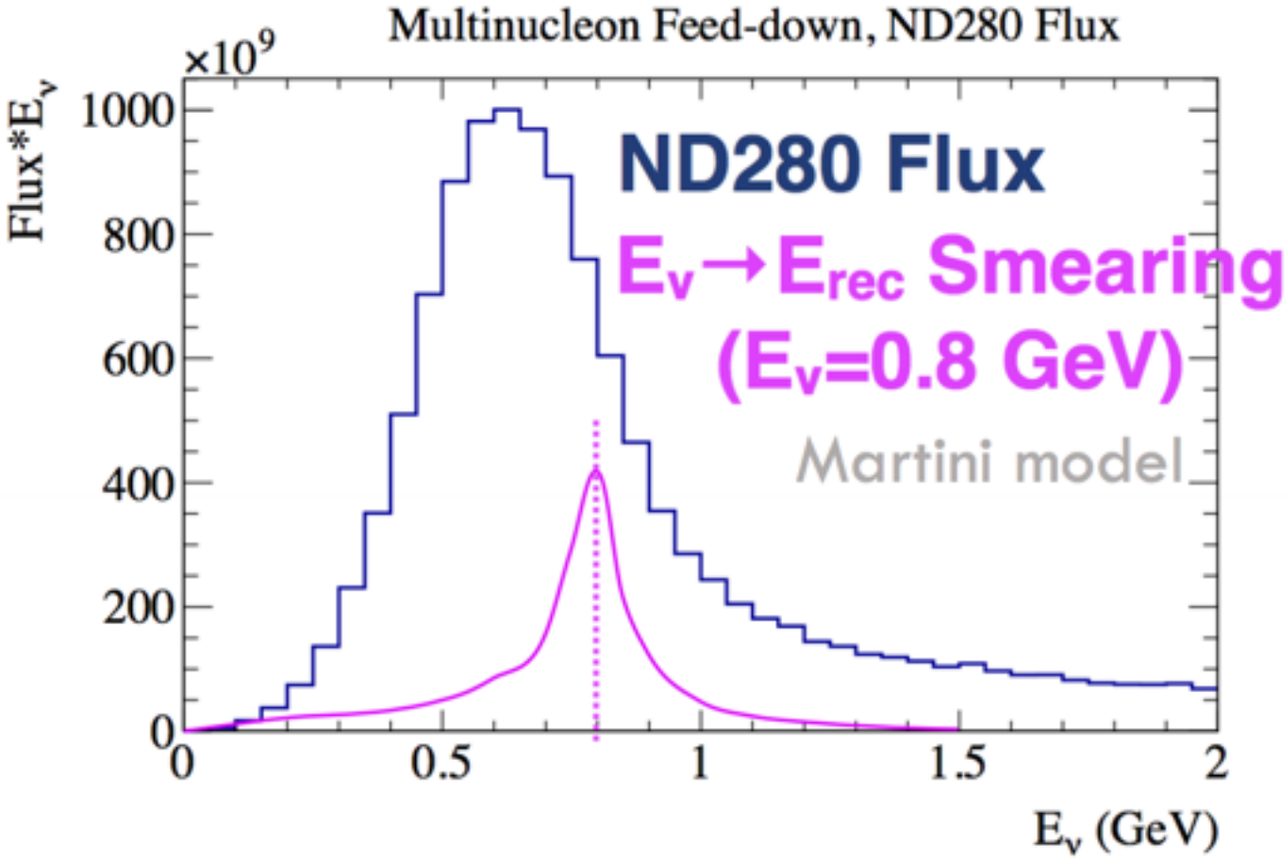
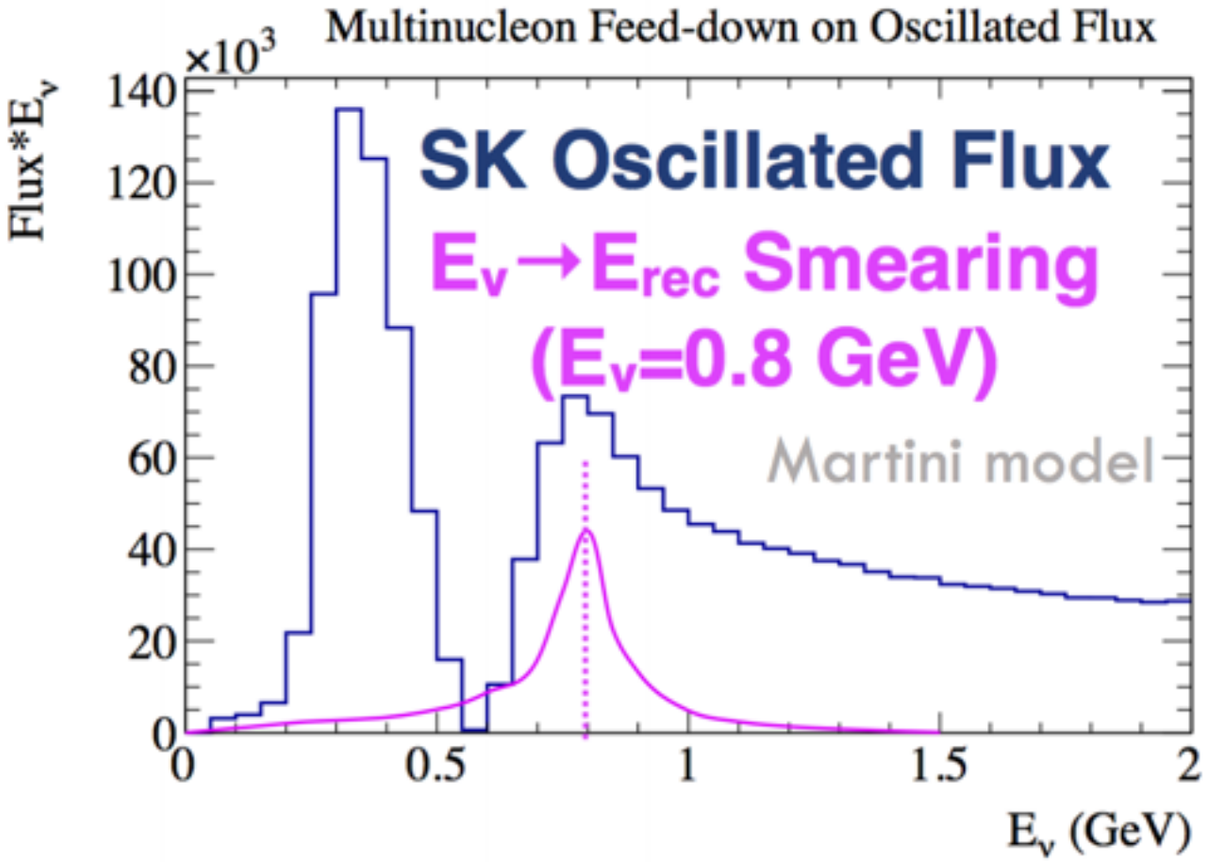




C. Vilela - PONDD





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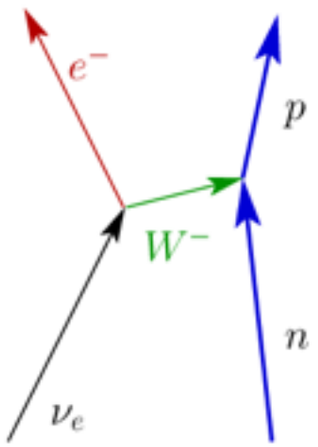

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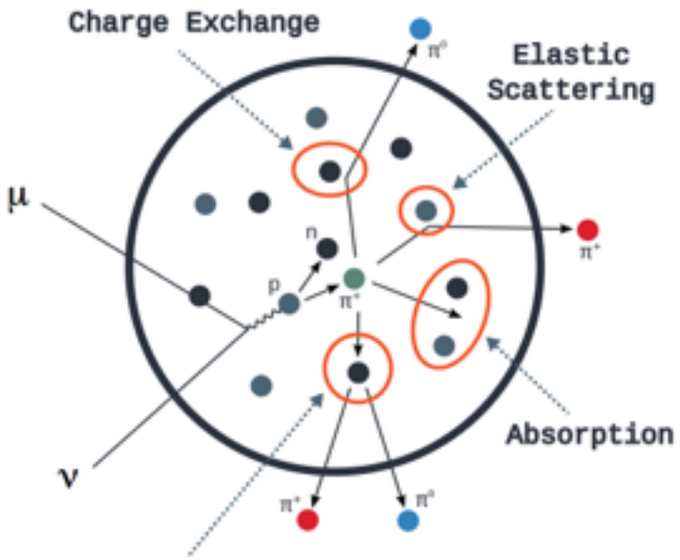

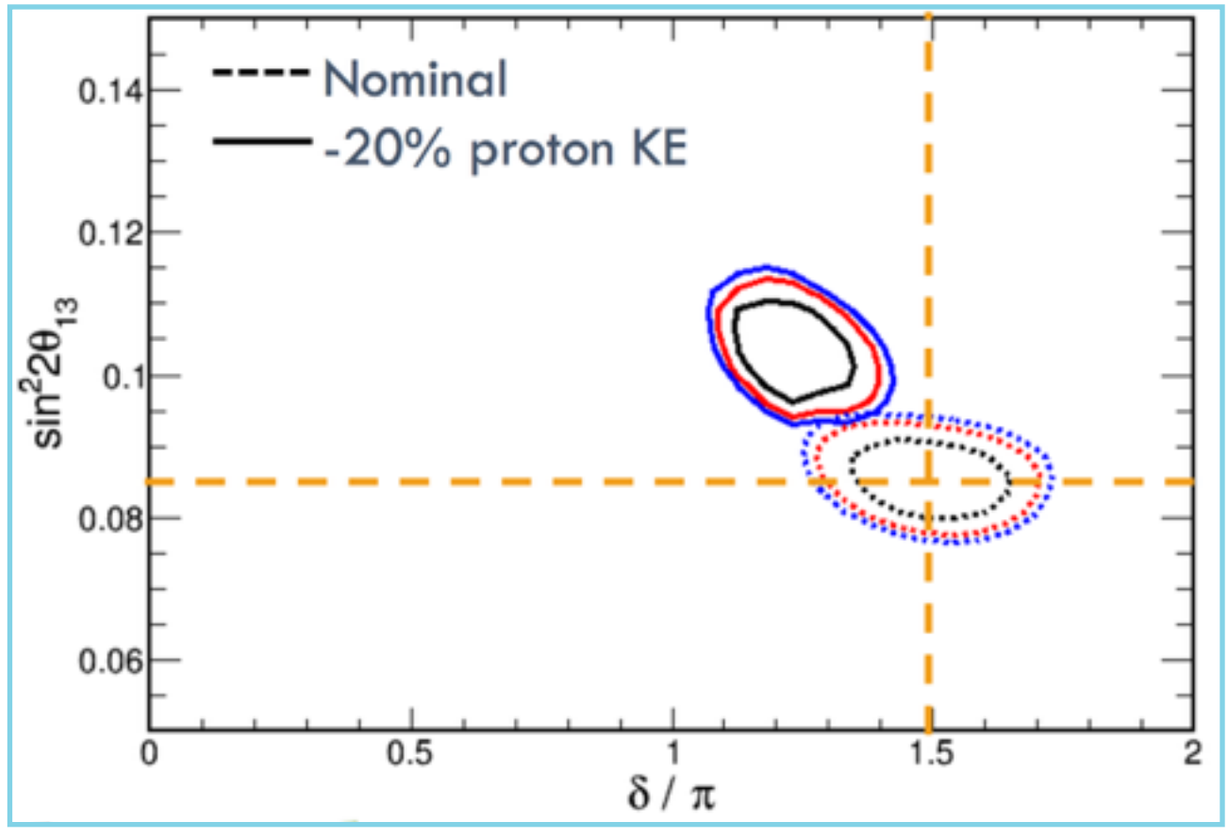

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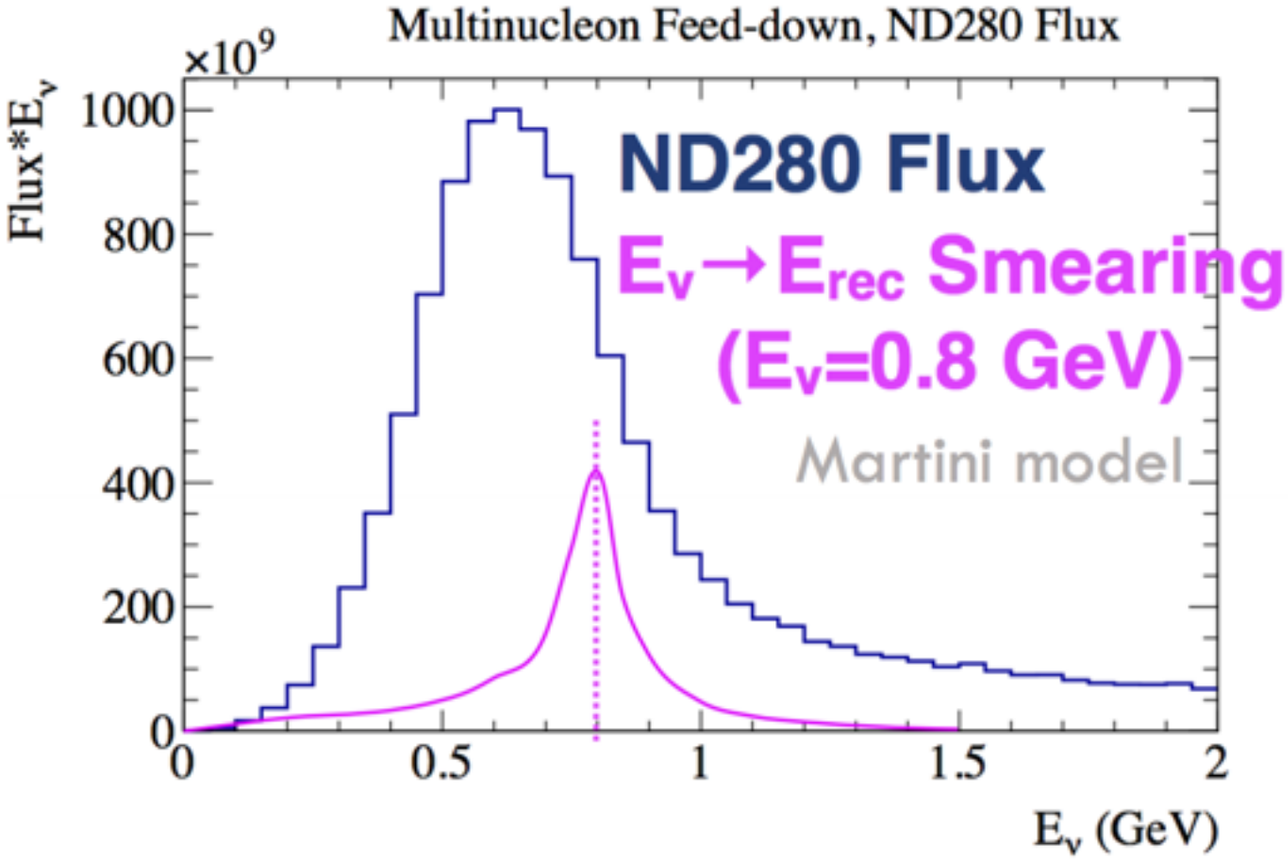
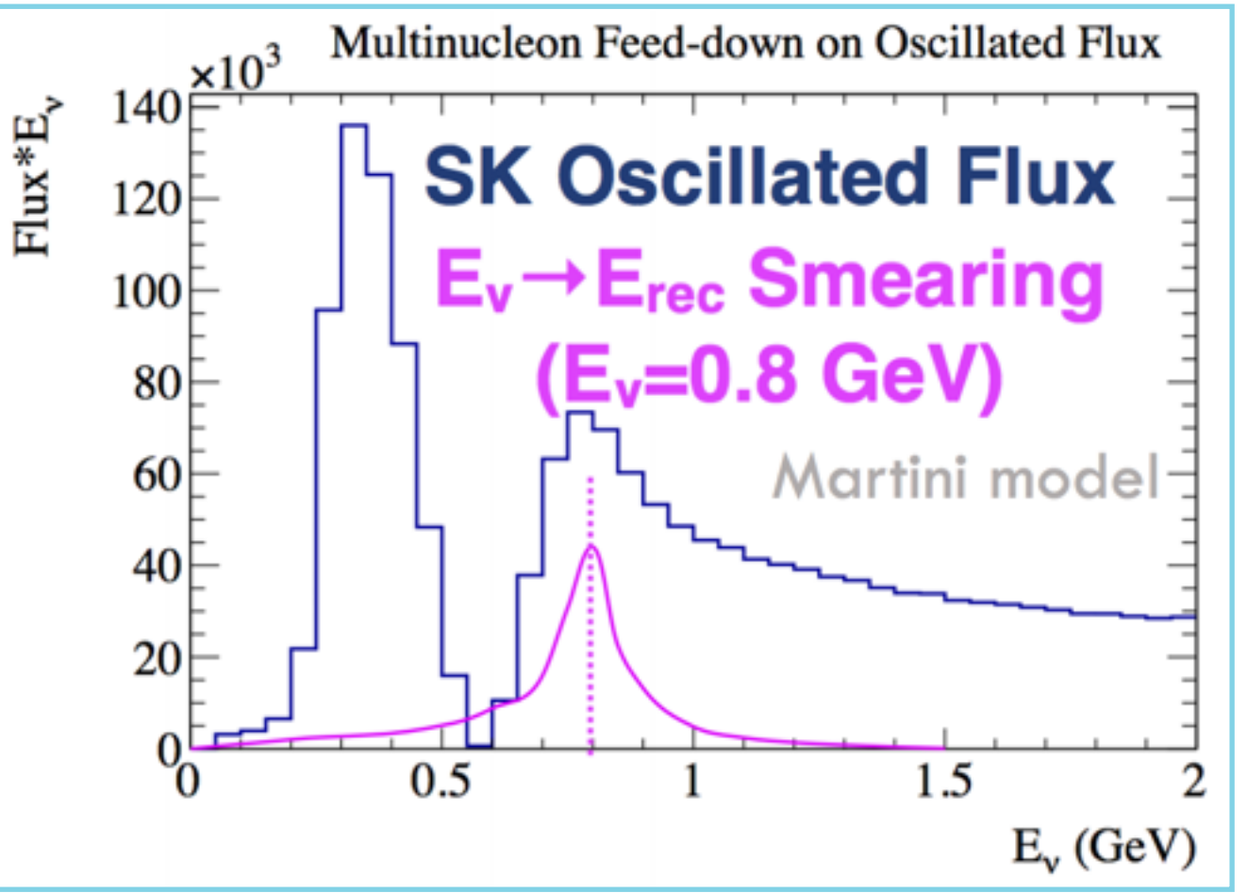
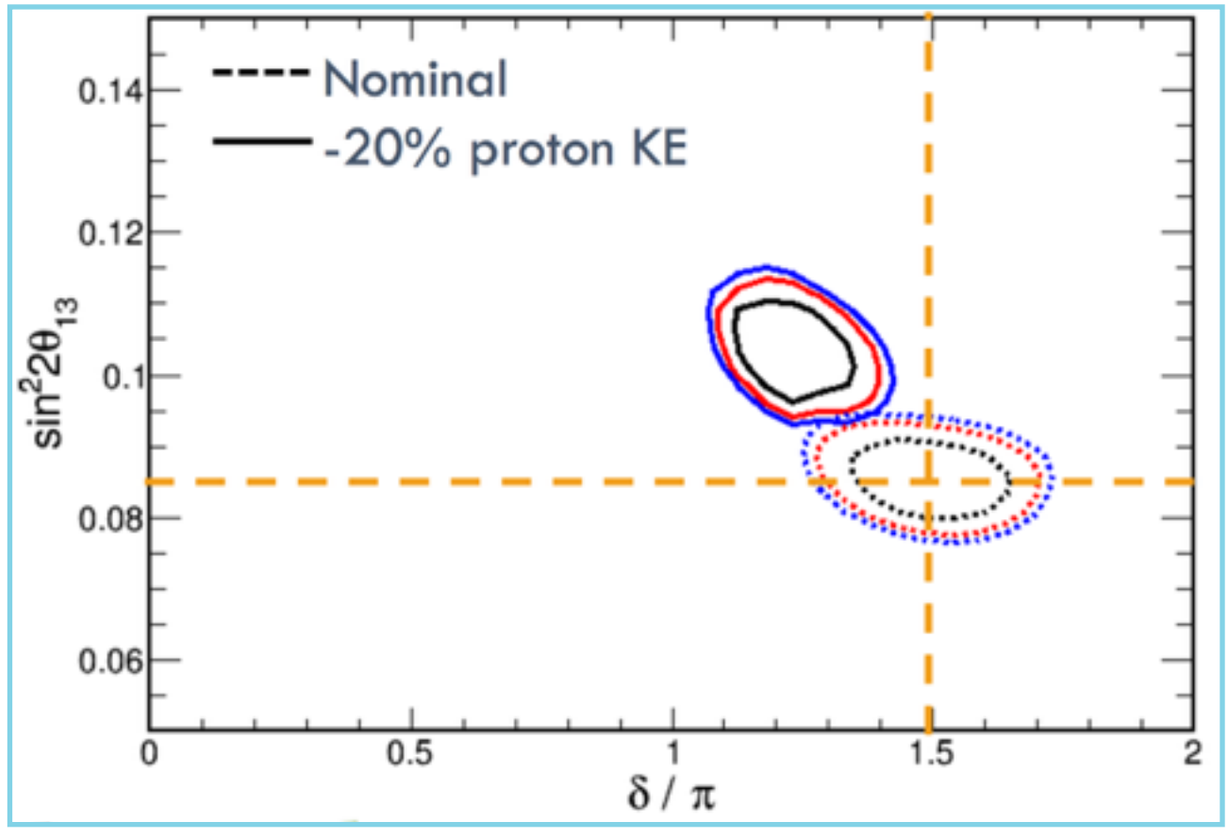




Neutrino interactions

We need better models of neutrino-nucleus interactions!

See Nuclear and Particle Theory for Accelerator and Neutrino Experiments meeting



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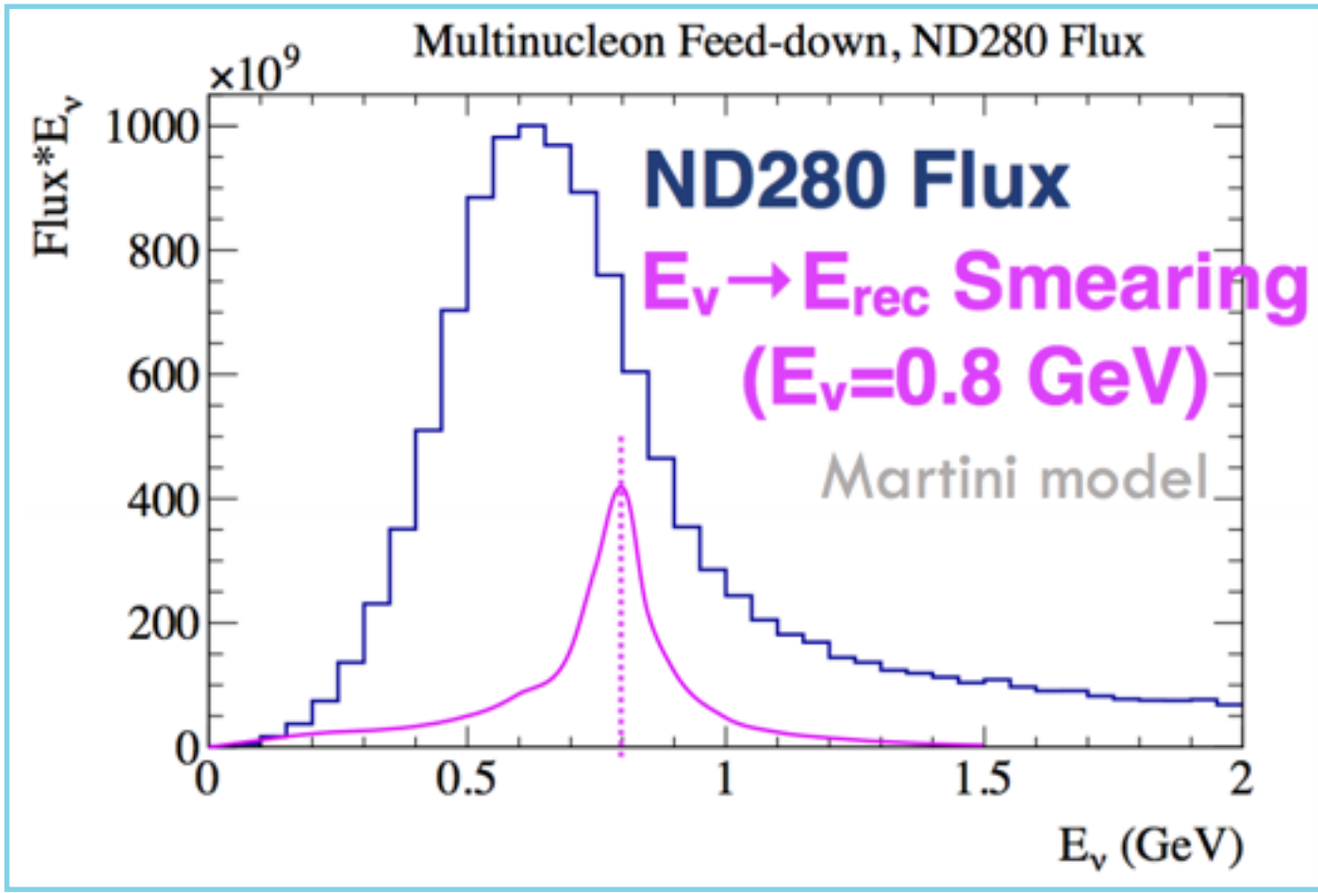
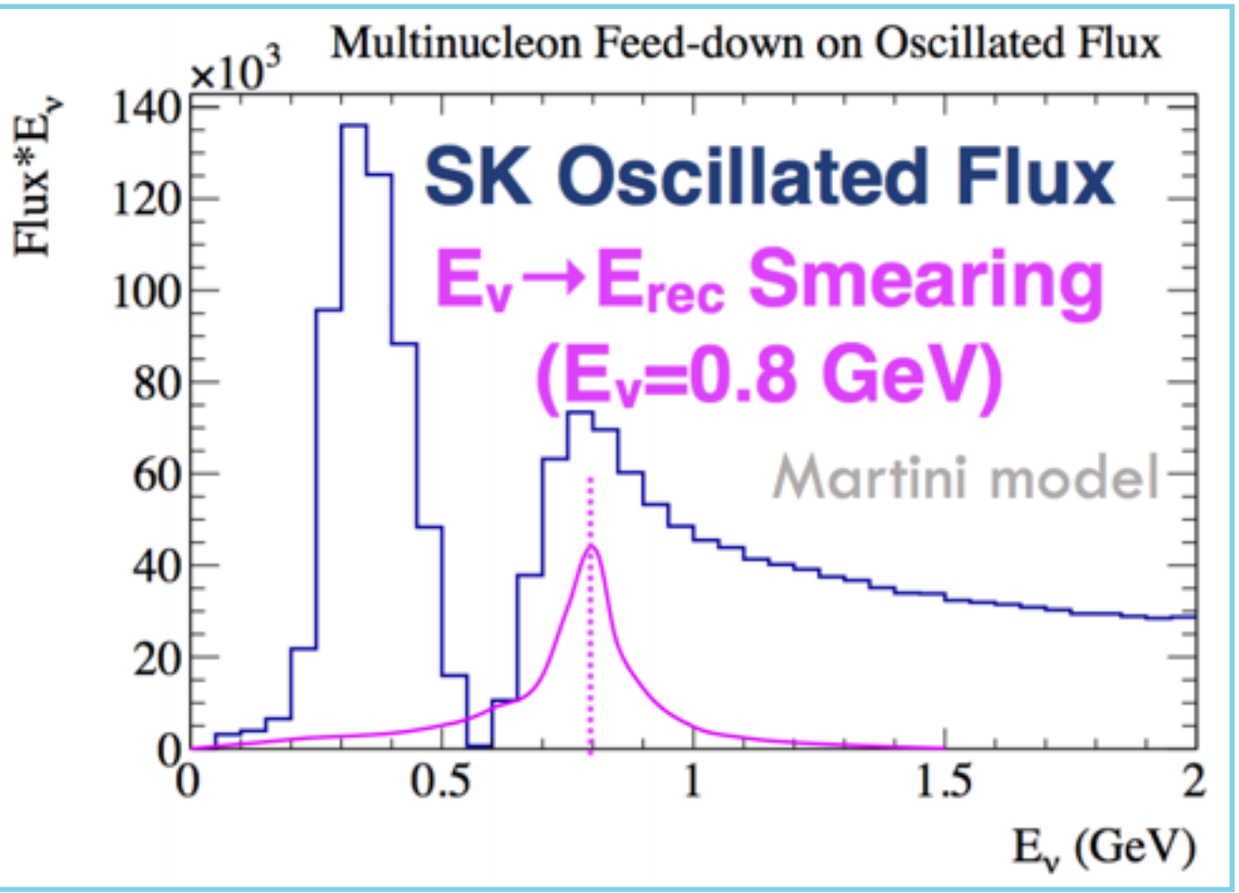
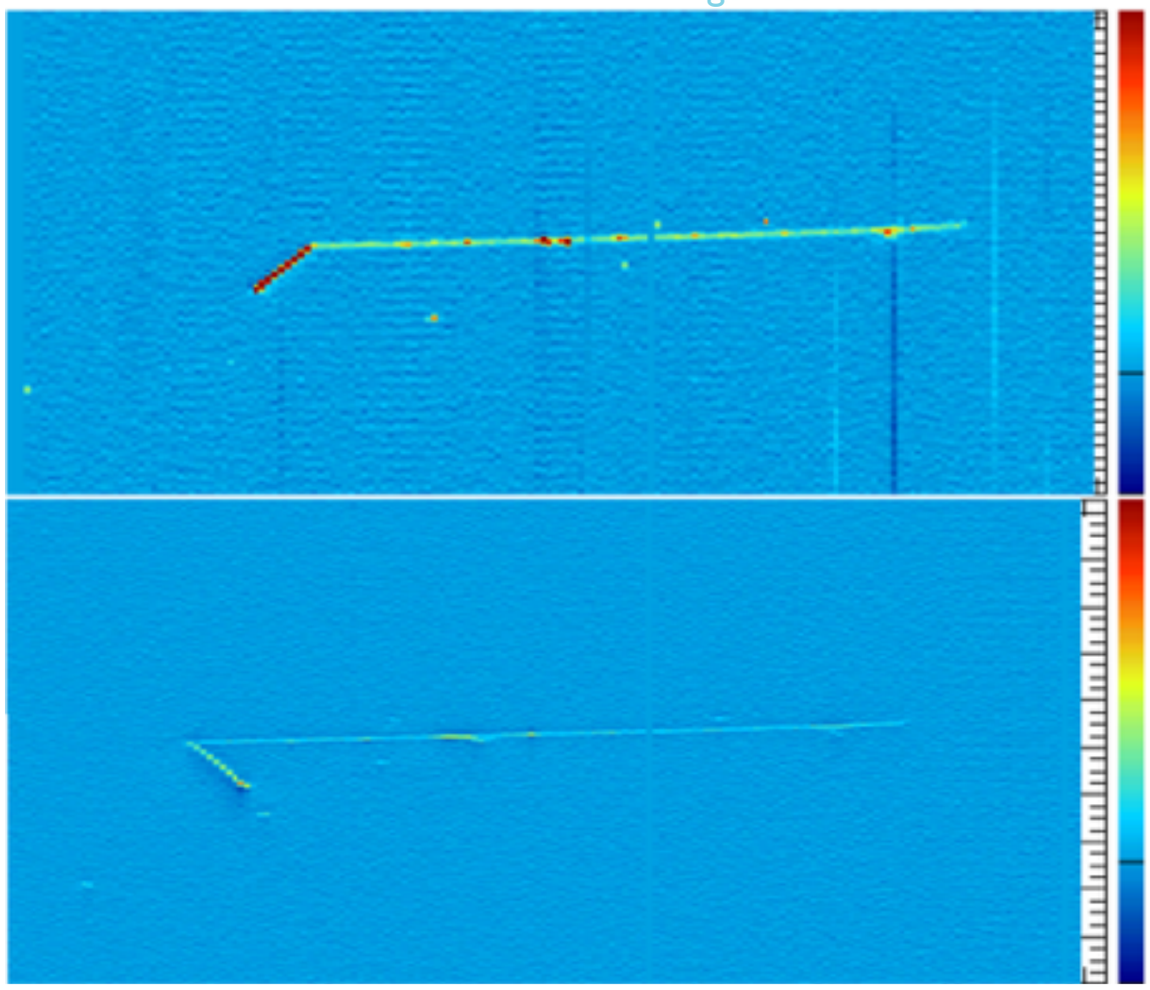




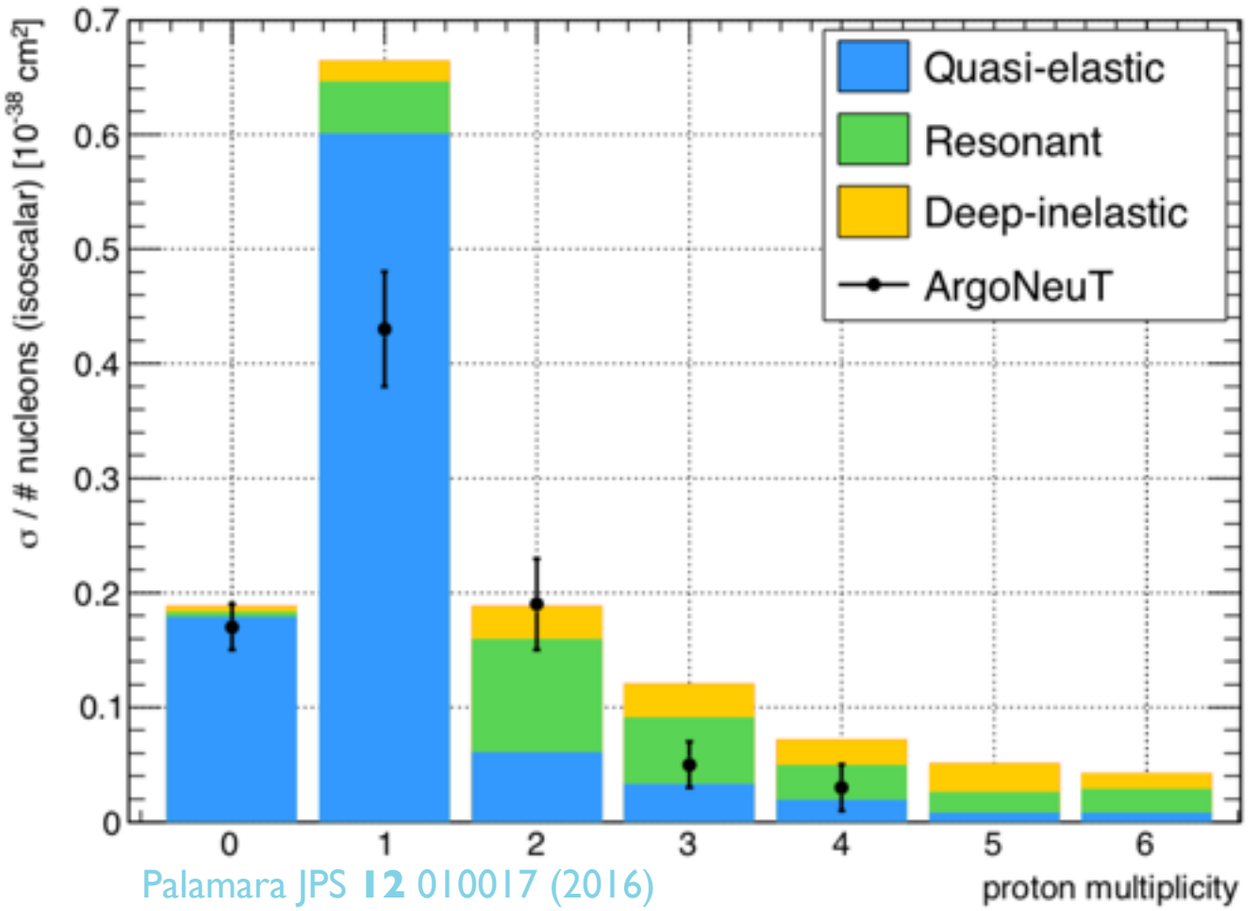
Extracting the most out of LArTPC program

ArgoNeuT 1810.06502



ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons!

And sub-MeV blips!

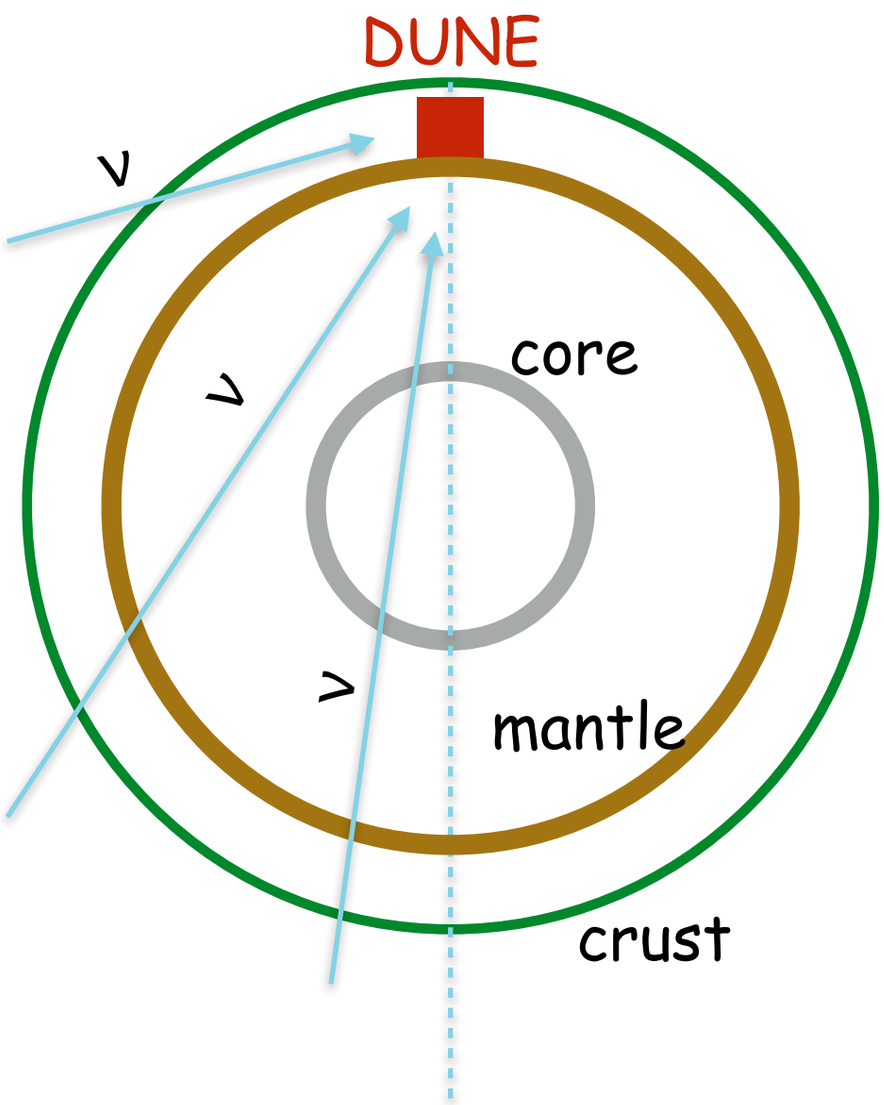


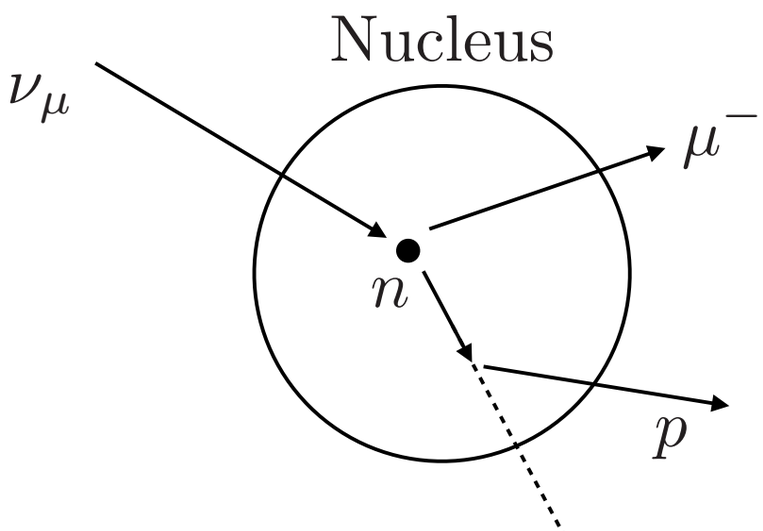
Palamara JPS **12** 010017 (2016)

Event topology carries information

What can we do with that?

Extracting the most out of LArTPC program: Standard





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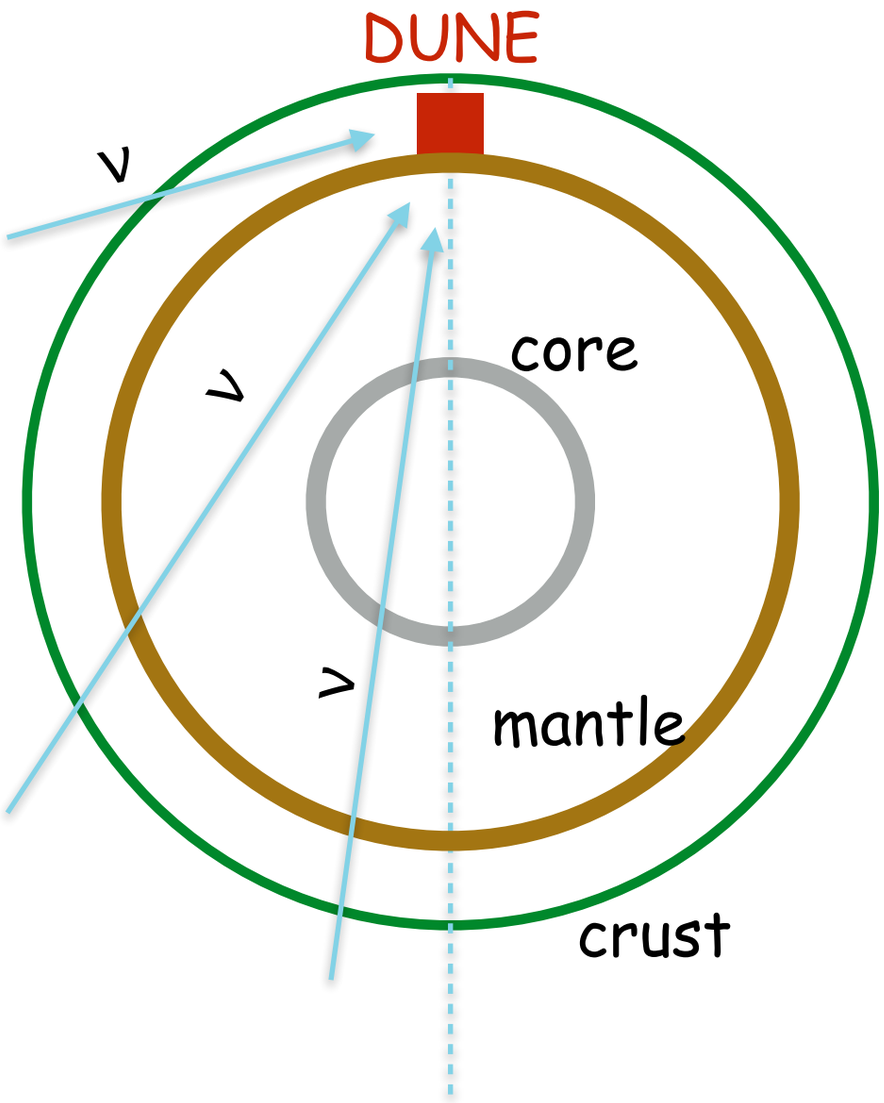

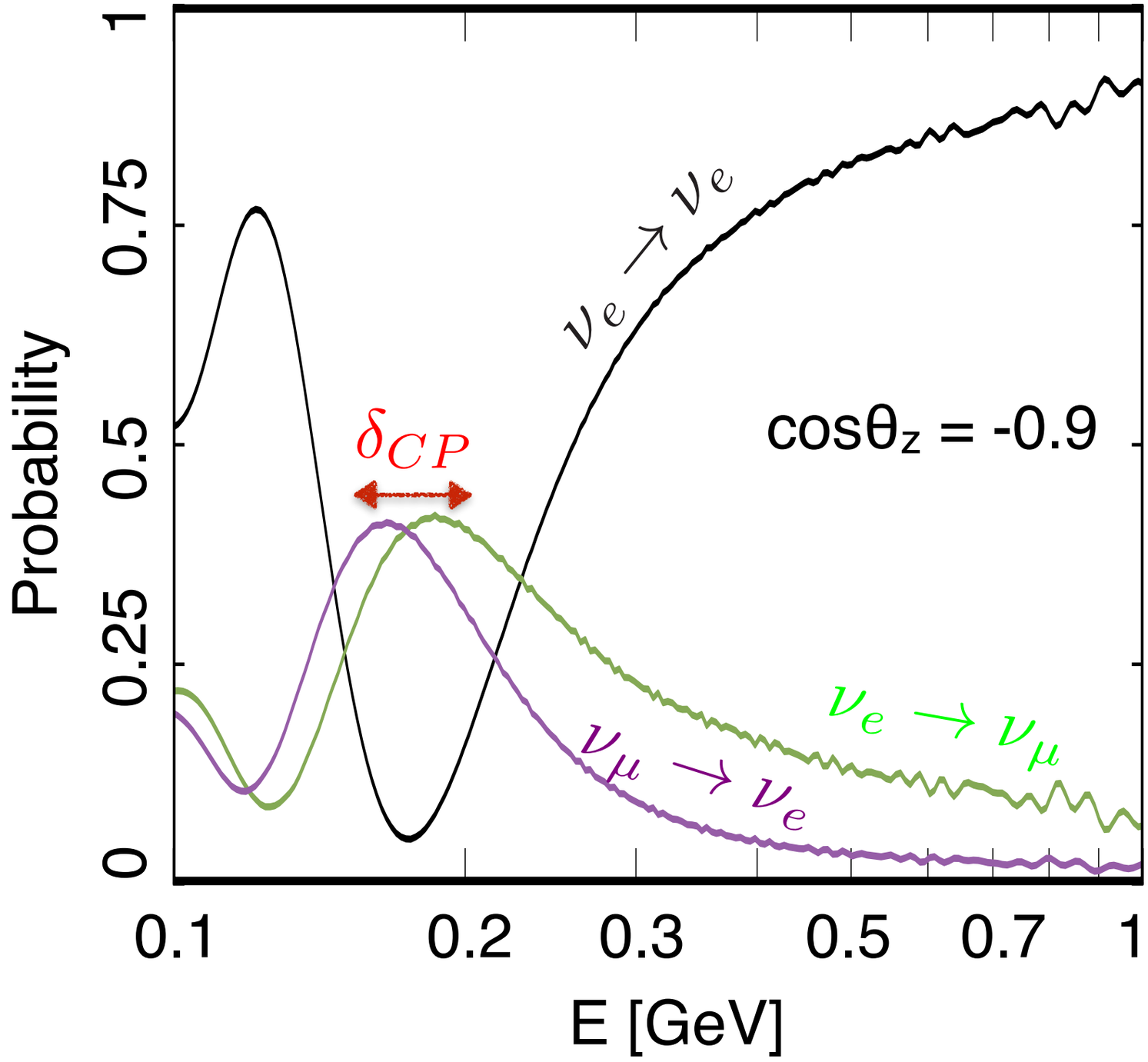

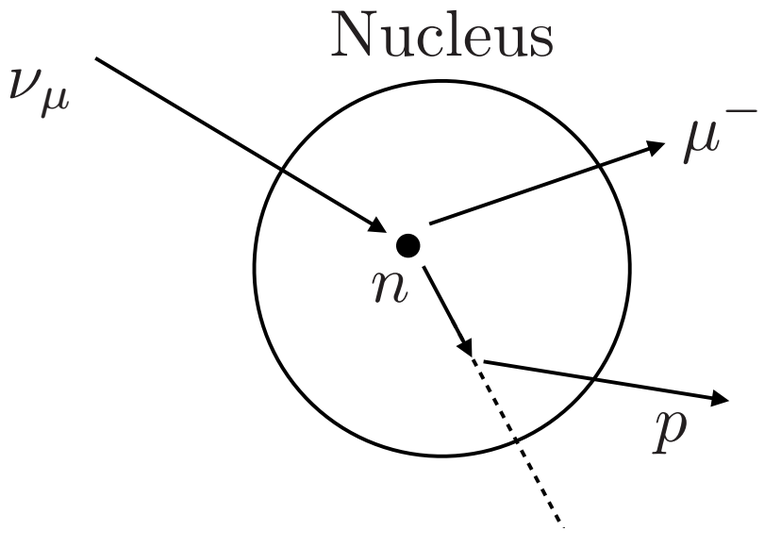

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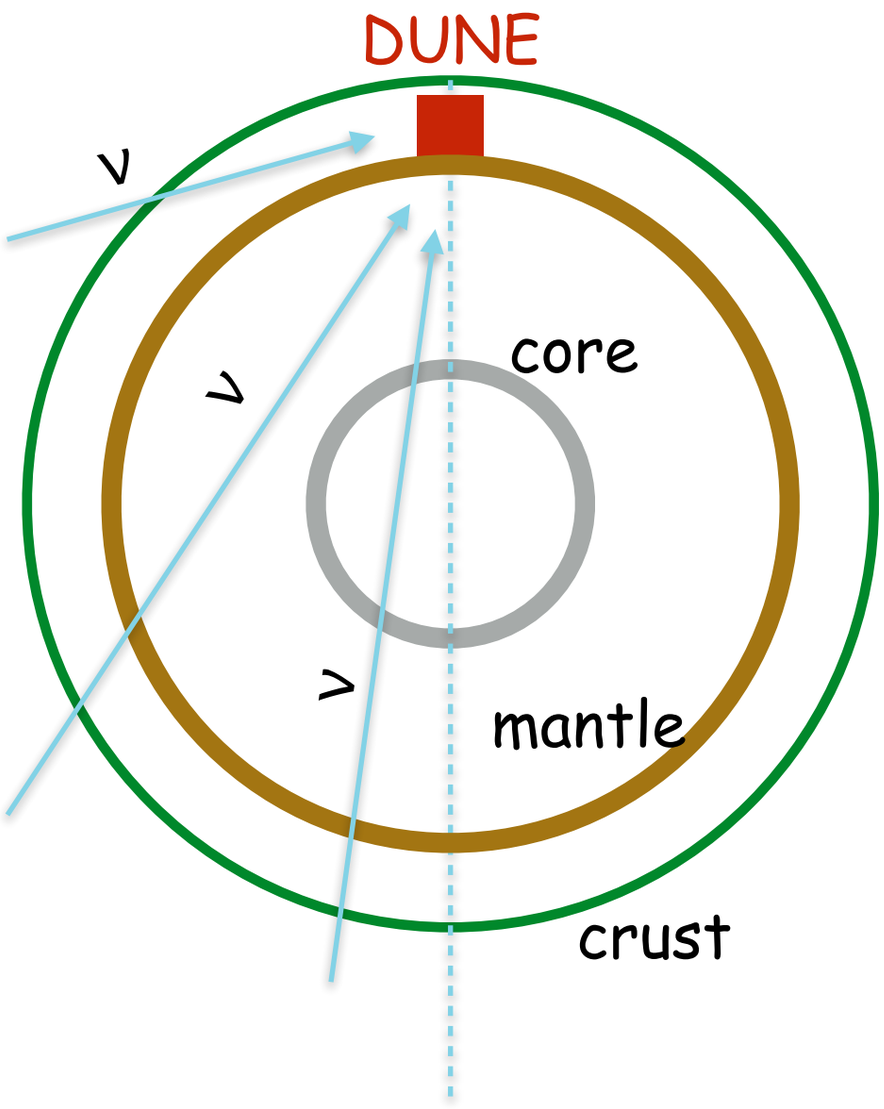

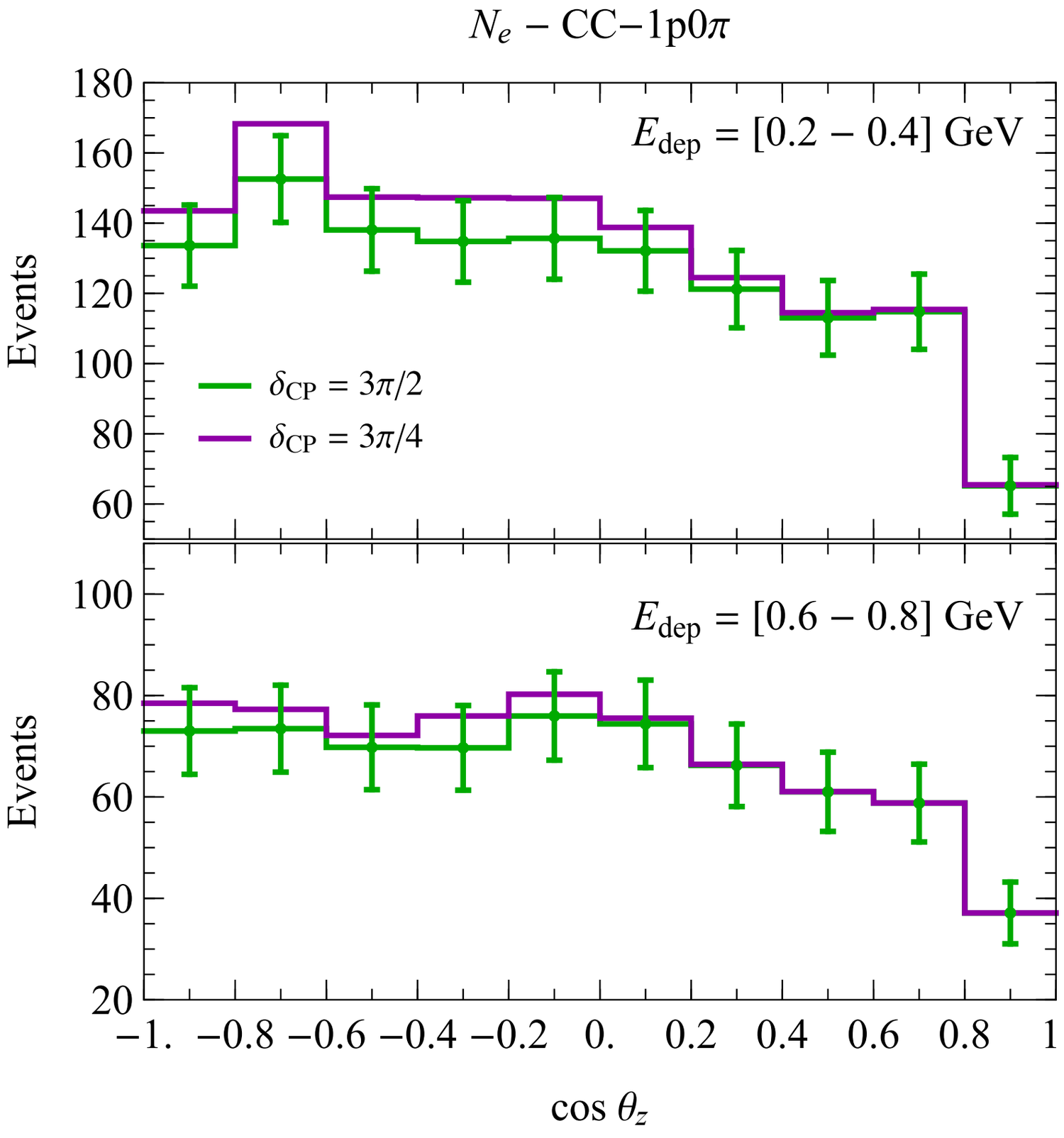

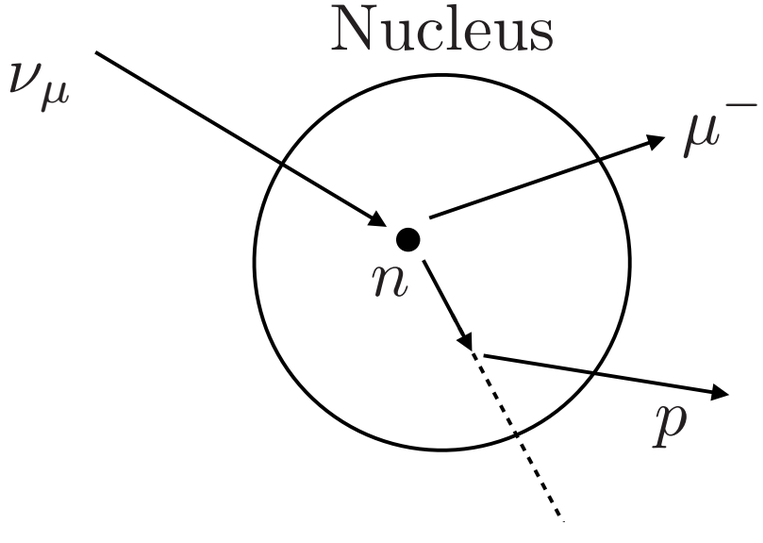

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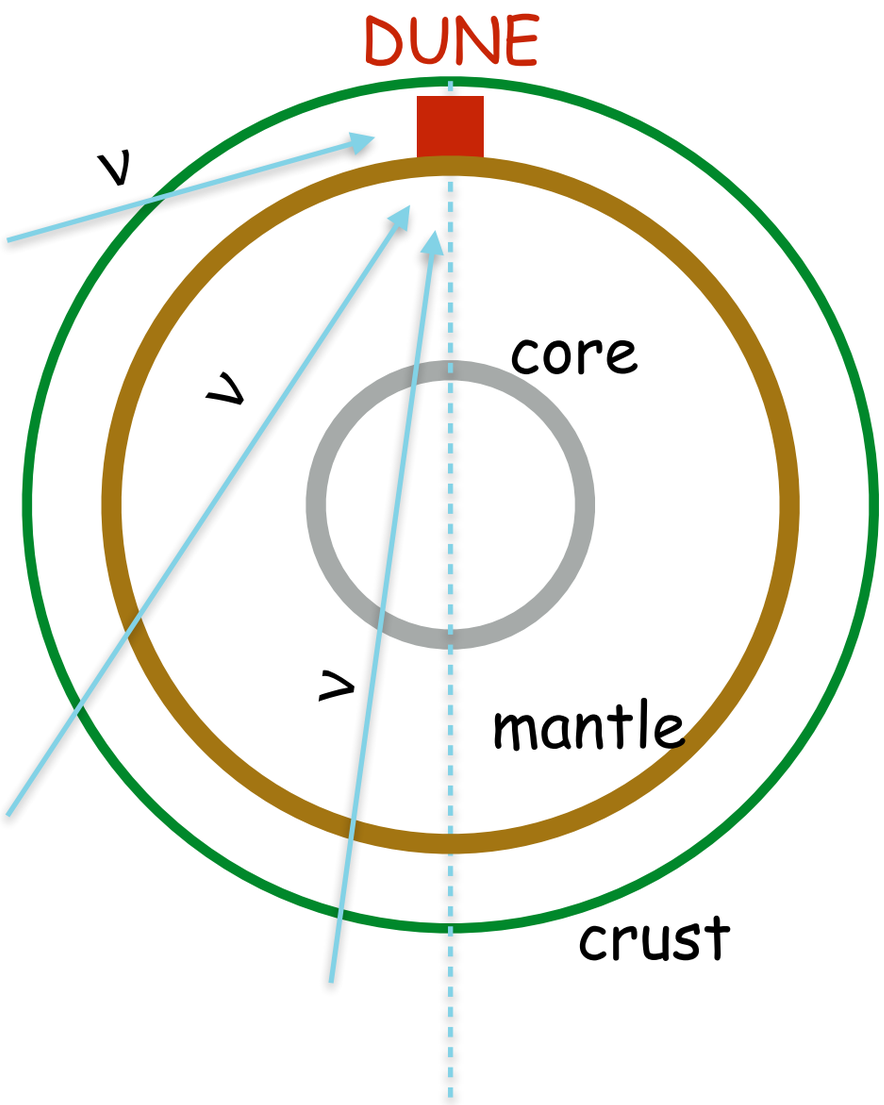
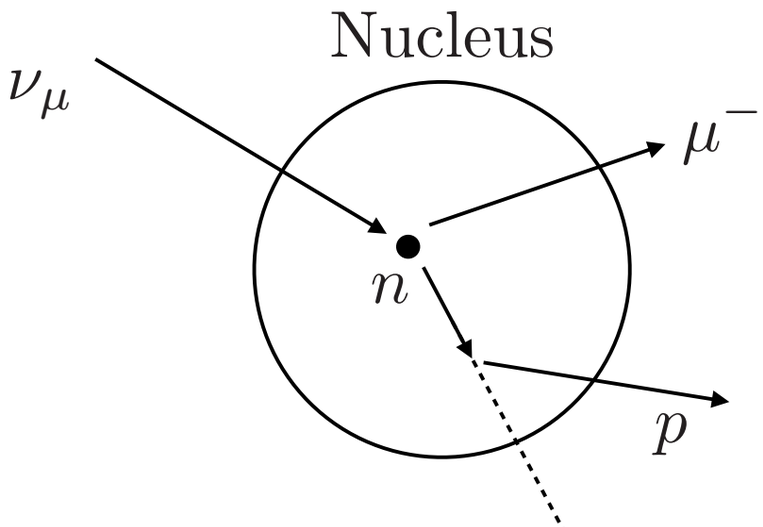
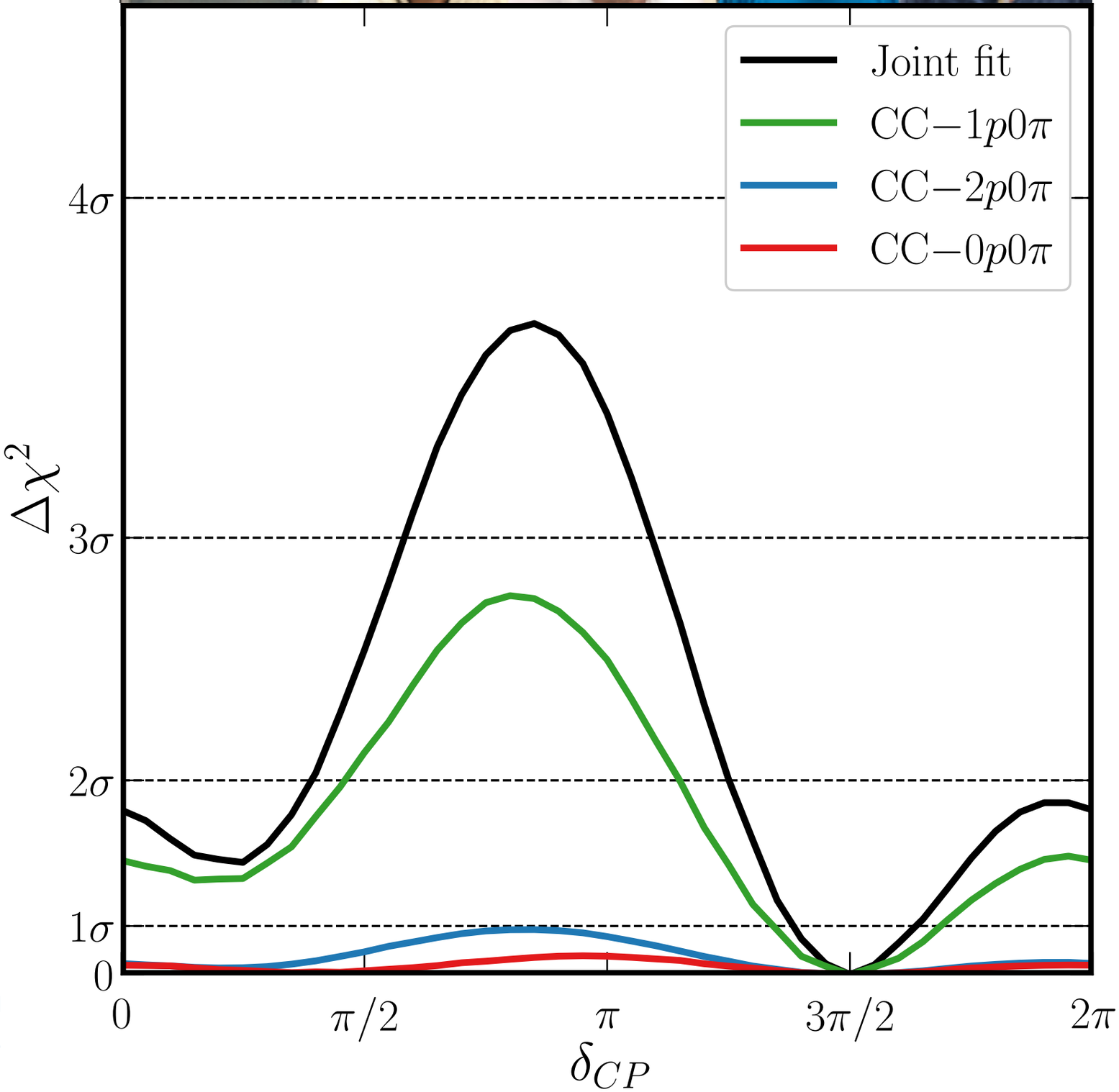


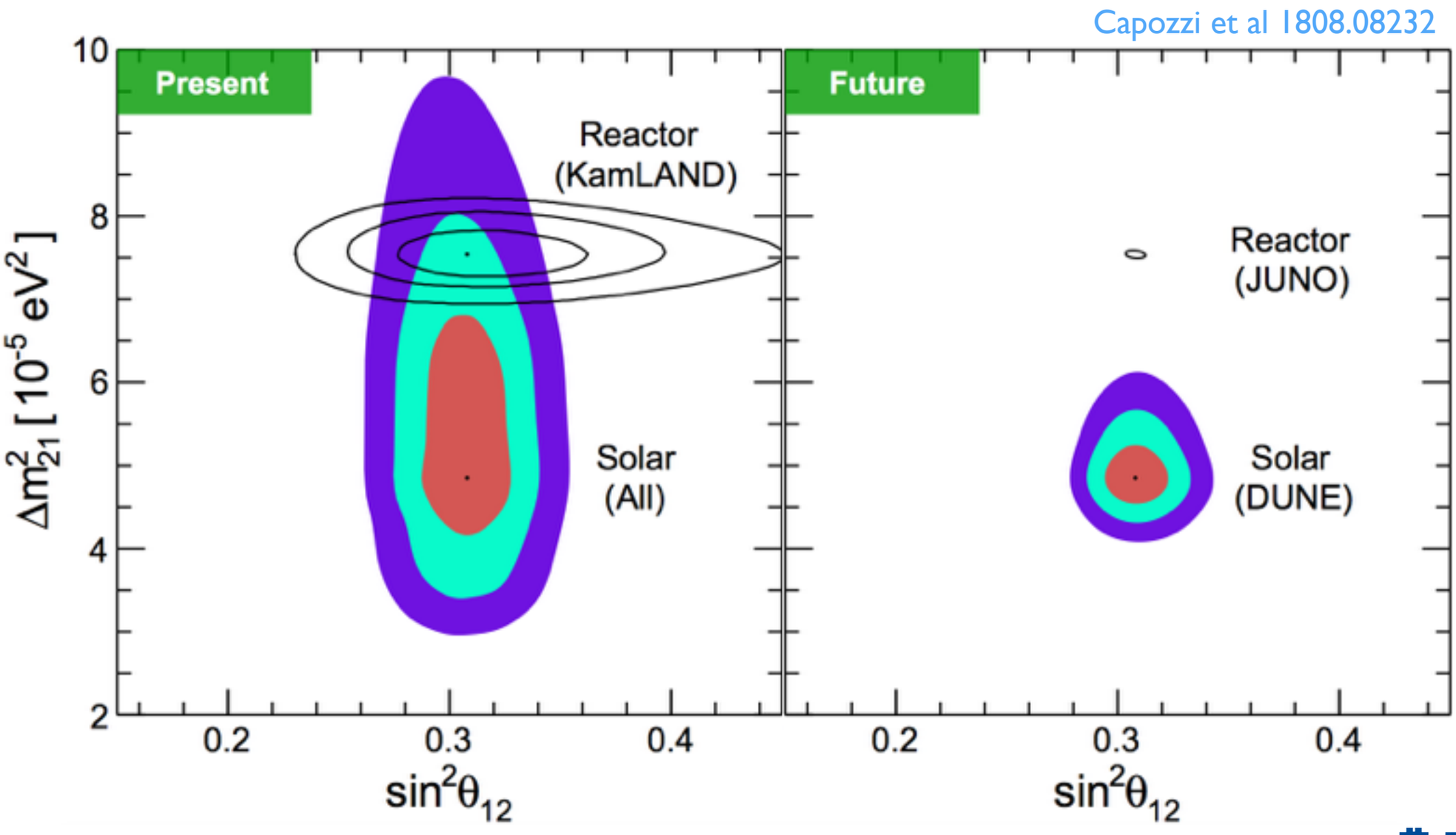




Extracting the most out of LArTPC program: Standard

Use DUNE as a solar neutrino detector

Capozzi et al 1808.08232



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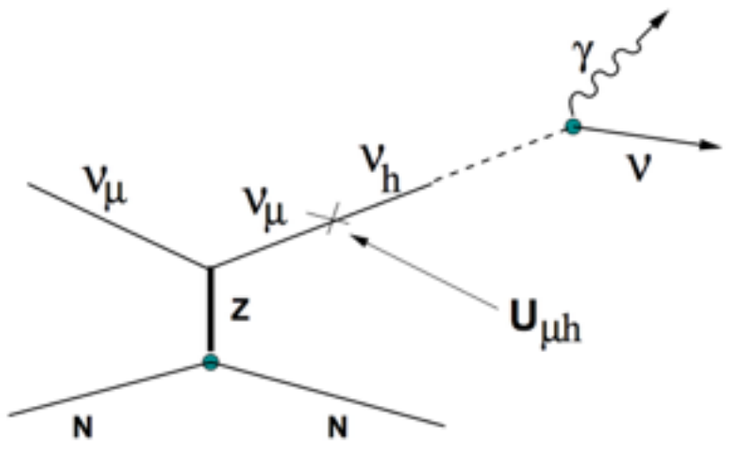
Extracting the most out of LArTPC program: BSM

ν magnetic moment

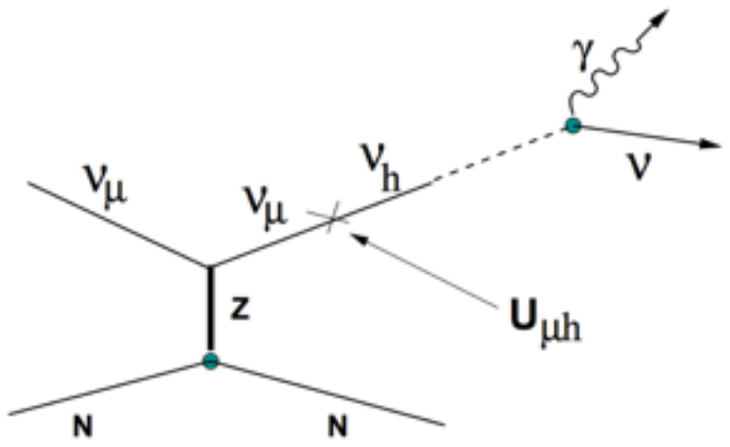


Explains MiniBooNE

Gninenko 0902.3802

Extracting the most out of LArTPC program: BSM

ν magnetic moment



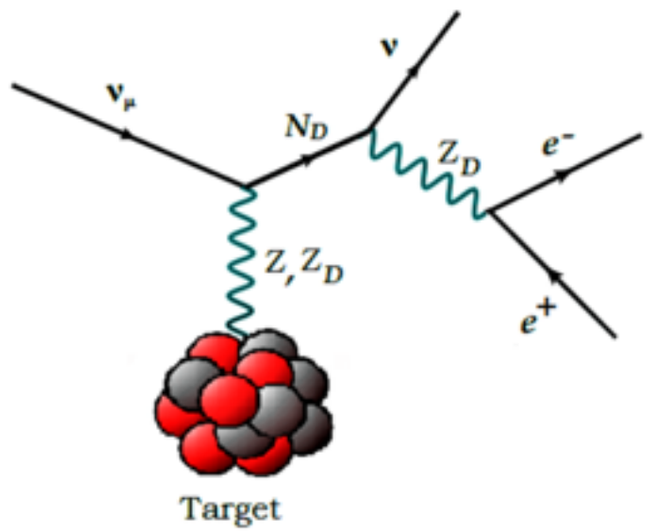
Explains MiniBooNE

Gninenko 0902.3802

Bertuzzo et al 1807.09877, 1807.02500

Ballett et al 1808.02915, Arguelles et al 1812.08768

Dark neutrinos

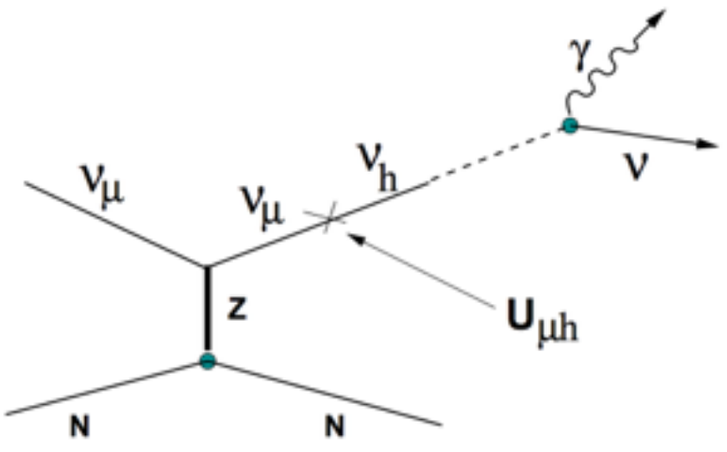


Explains MiniBooNE

Explains m_ν

Extracting the most out of LArTPC program: BSM

ν magnetic moment



Explains MiniBooNE

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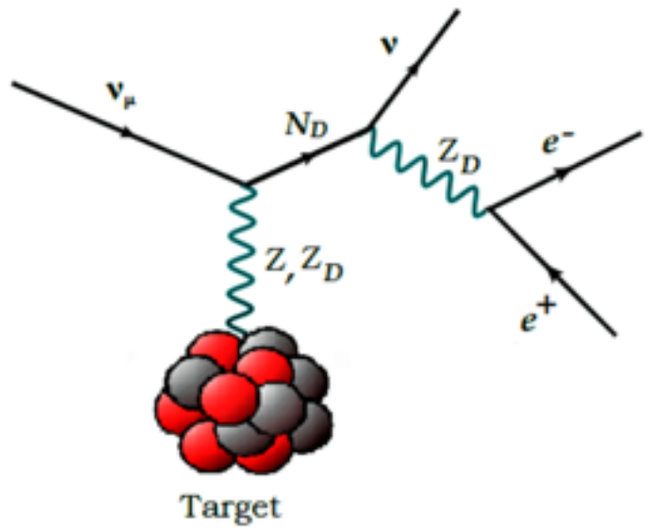
Bertuzzo et al 1807.09877, 1807.02500

Ballett et al 1808.02915, Arguelles et al 1812.08768

Dark neutrinos



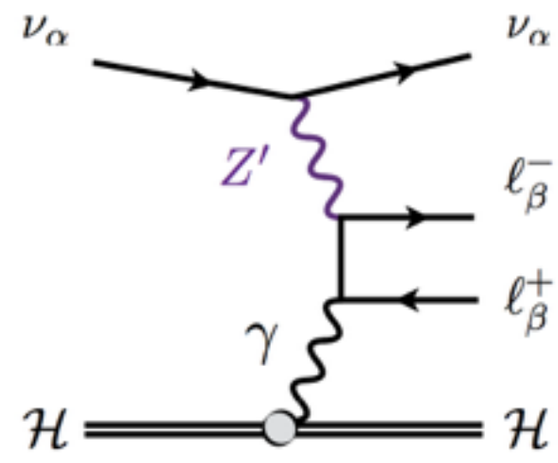
Explains MiniBooNE

Explains m_ν

Altmannshofer et al 1406.2332

Ballet et al 1902.08579

New gauge bosons (e.g. L_μ-L_τ)



Explains $(g-2)_\mu$

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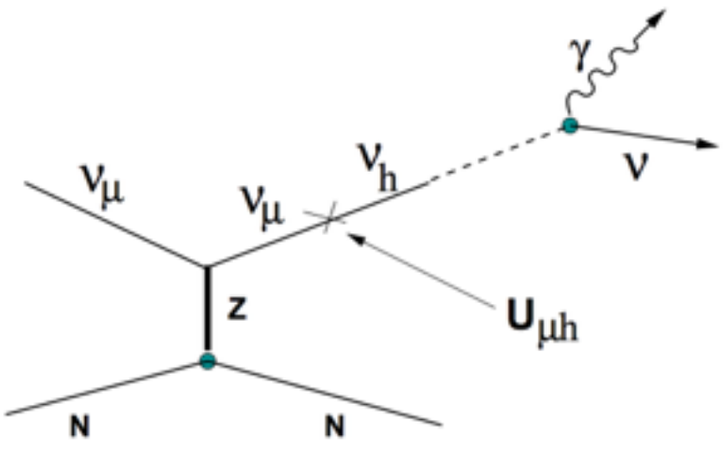
Extracting the most out of LArTPC program: BSM

ν magnetic moment



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Gninenko 0902.3802

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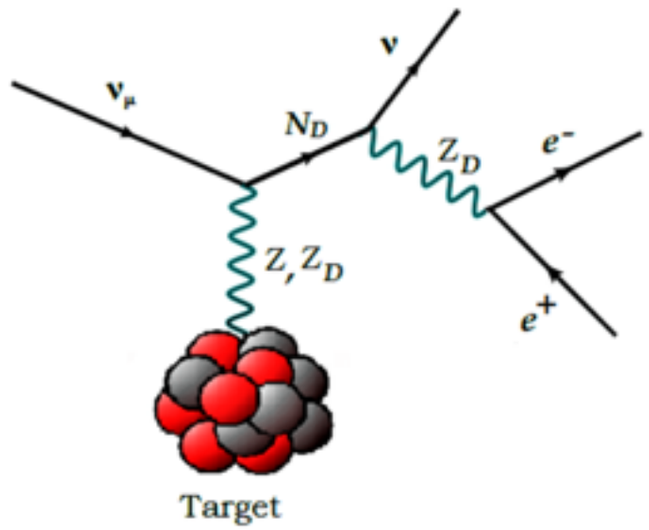
Dark neutrinos



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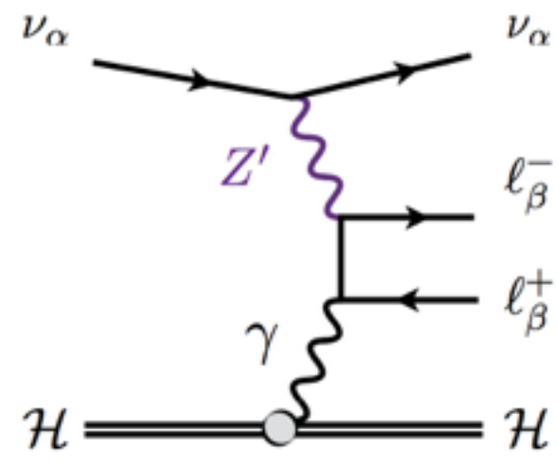

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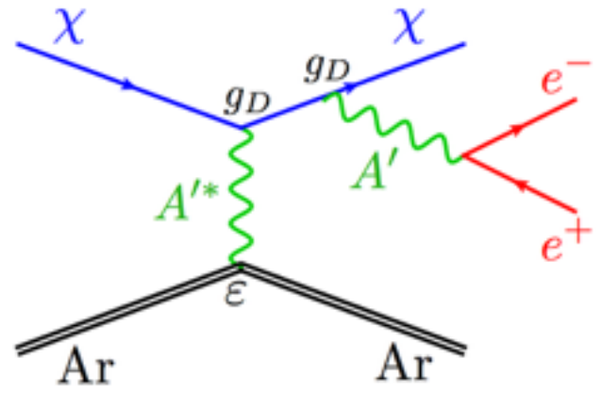
Dark tridents



Explains DM

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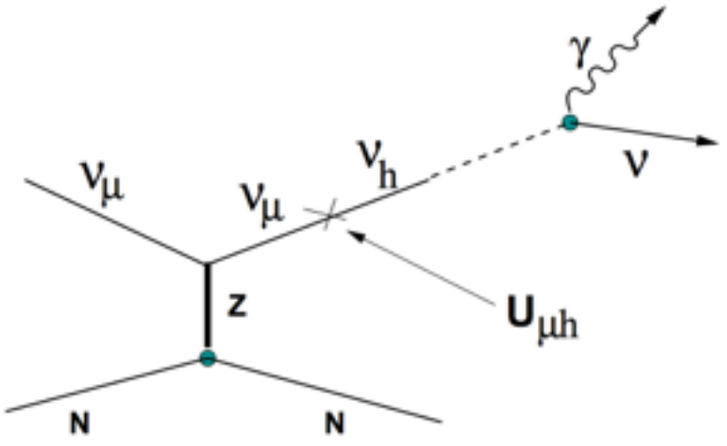

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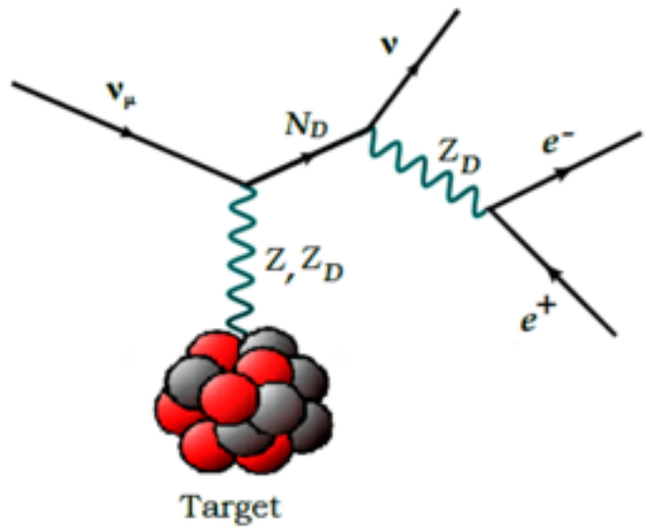

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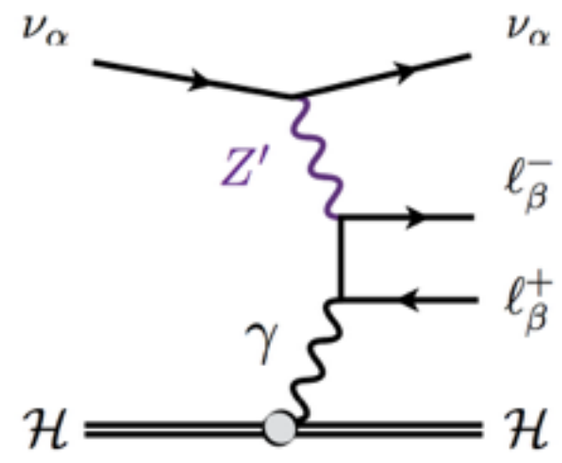

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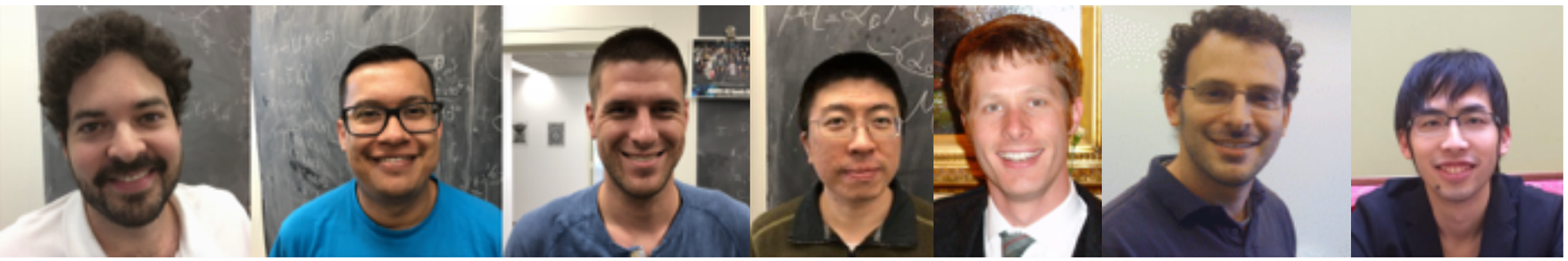

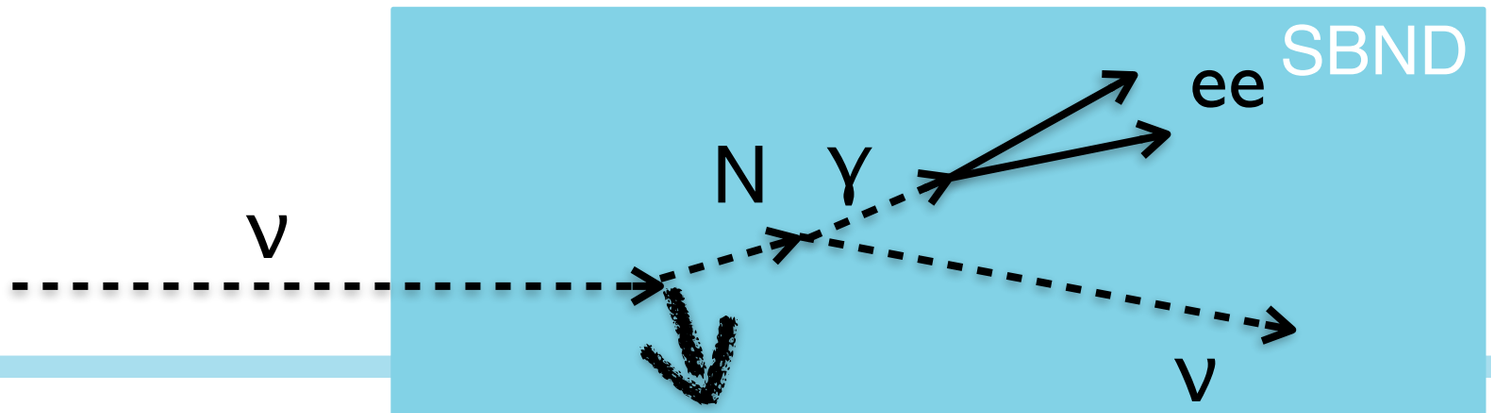

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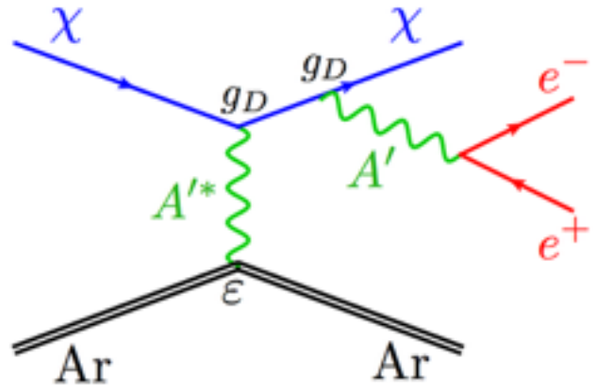

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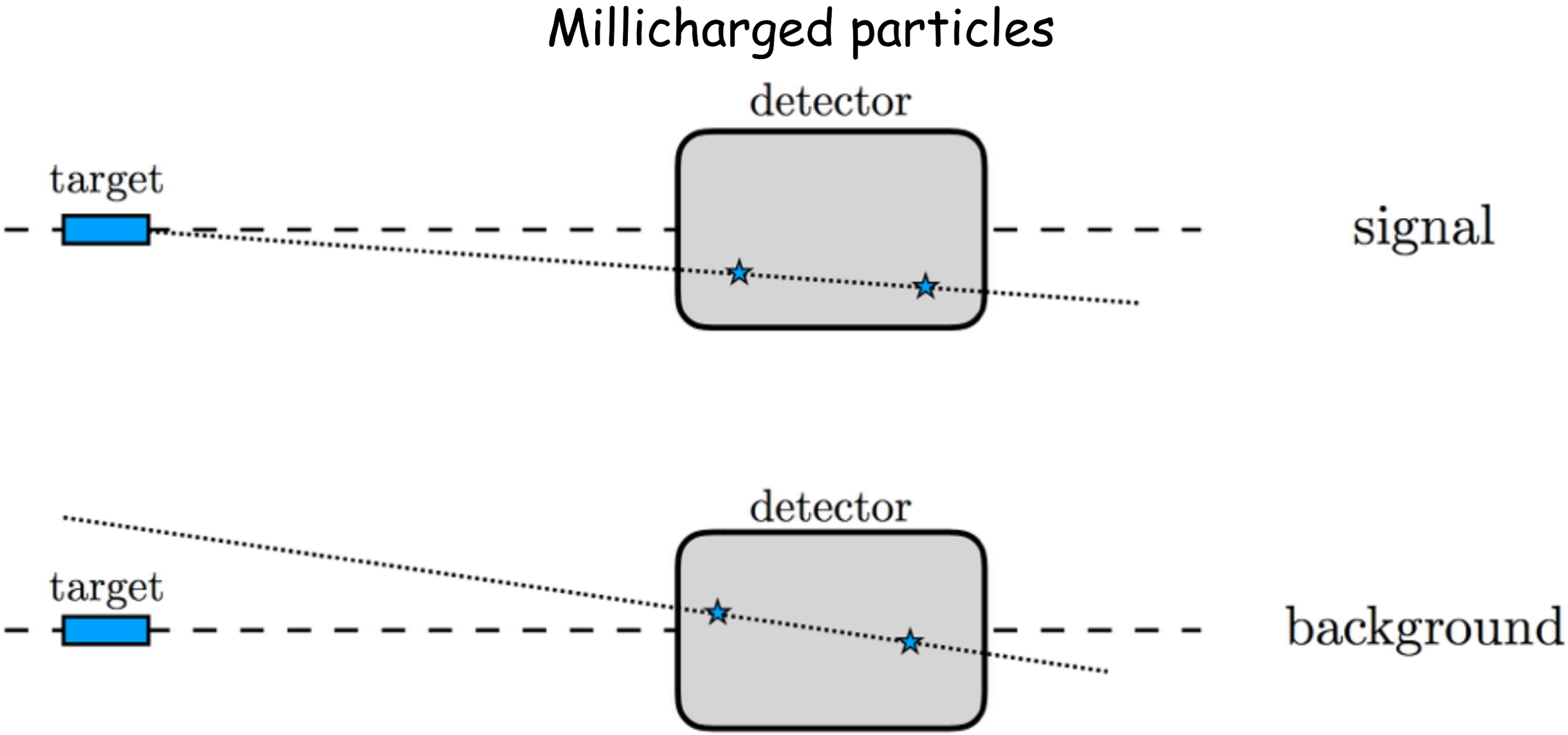
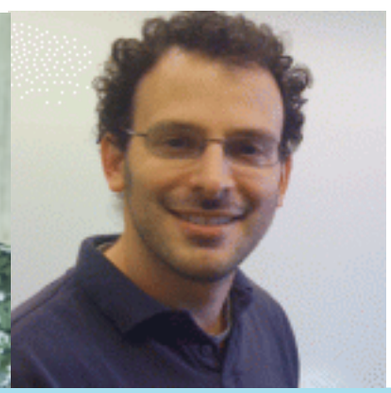
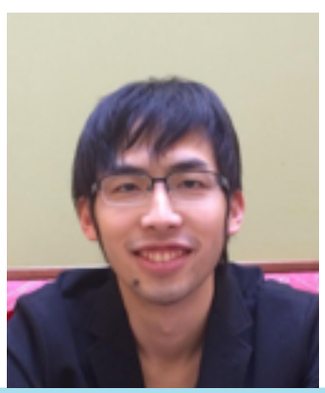


Honorary TH

Magill et al 1806.03310

Harnik et al 1902.03246

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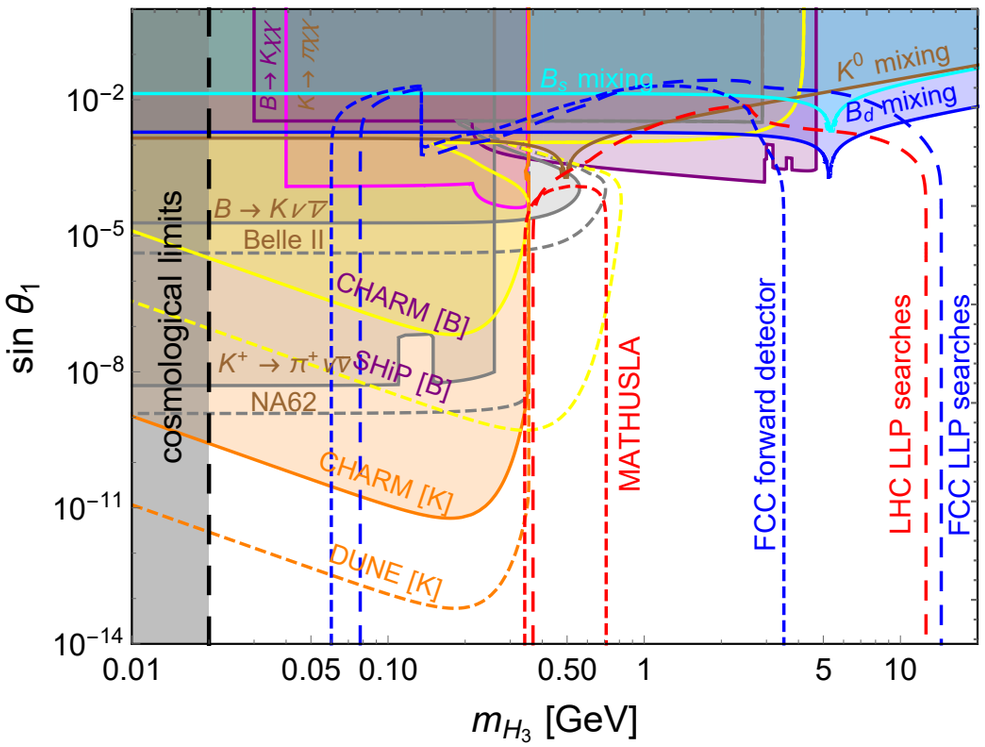
Connections to other sectors

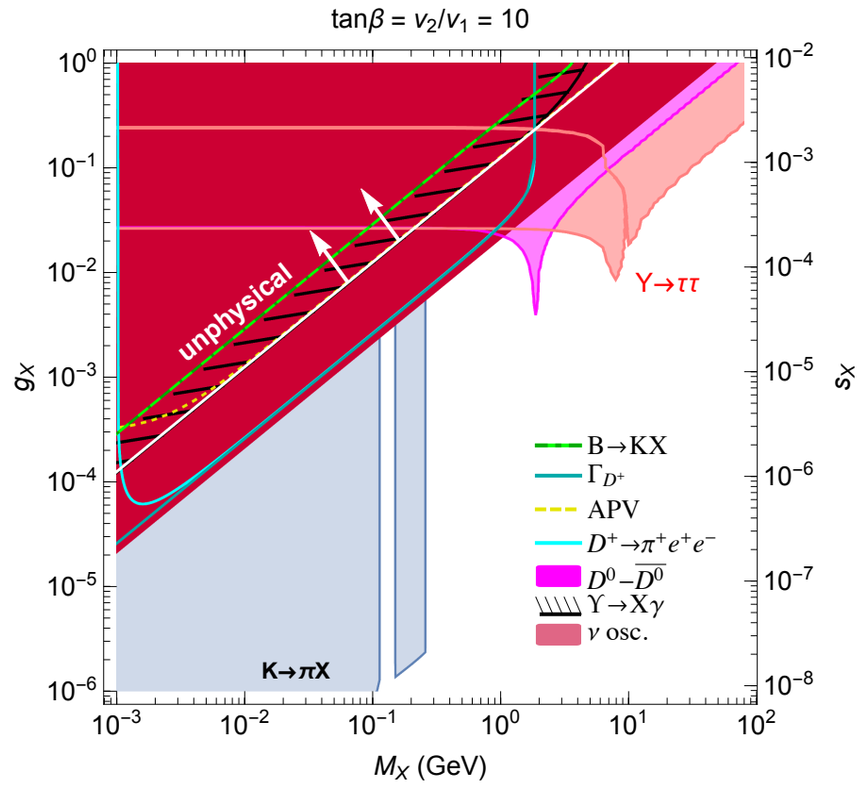
From Tao Han's talk @ NTN Workshop on Neutrino non-Standard Interactions

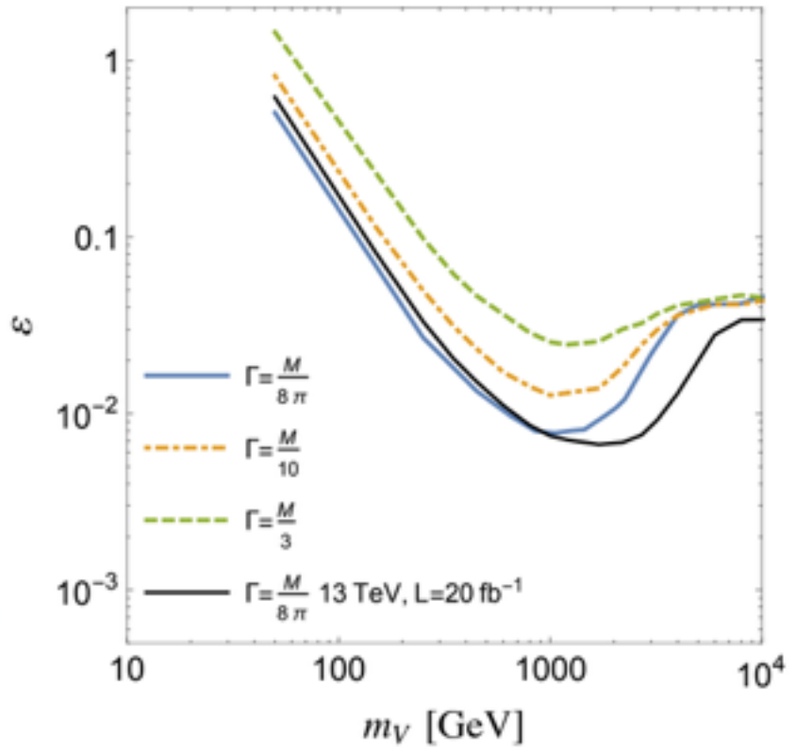
	$0\nu2\beta$	μ-e conversion $\mu \to e\gamma$ etc.	rare decays τ, K, D, B	colliders e^+e^-, pp	features
Type-I	$\surd$	$\surd$	$\surd$	$\surd$	N
Type-II	$\surd$	$\surd$	$\surd$	$\surd$	$H^{\pm\pm}$, $W_R^{\pm}$
Type-III	$\surd$	$\surd$	?	$\surd$	$T^{\pm}$
Zee-Babu	?	$\surd$	?	$\surd$	$k^{\pm\pm}$, $h^{\pm}$
Ma models	?	$\surd$	?	$\surd$	scalars, DM
RPV/leptoquarks	?	$\surd$	$\surd$	$\surd$	ℓ_q
extra-dim	?	?	$\surd$	$\surd$	KK states
Inverse/linear	?	?	$\surd$	$\surd$	
Pseudo Dirac	?	?	$\surd$	$\surd$	
NSI	?	?	?	$\surd$	mediators
... ...					

Connections to other sectors

Efforts on connecting oscillations to collider, flavor, cosmology, … under the context of neutrino mass models and complete frameworks







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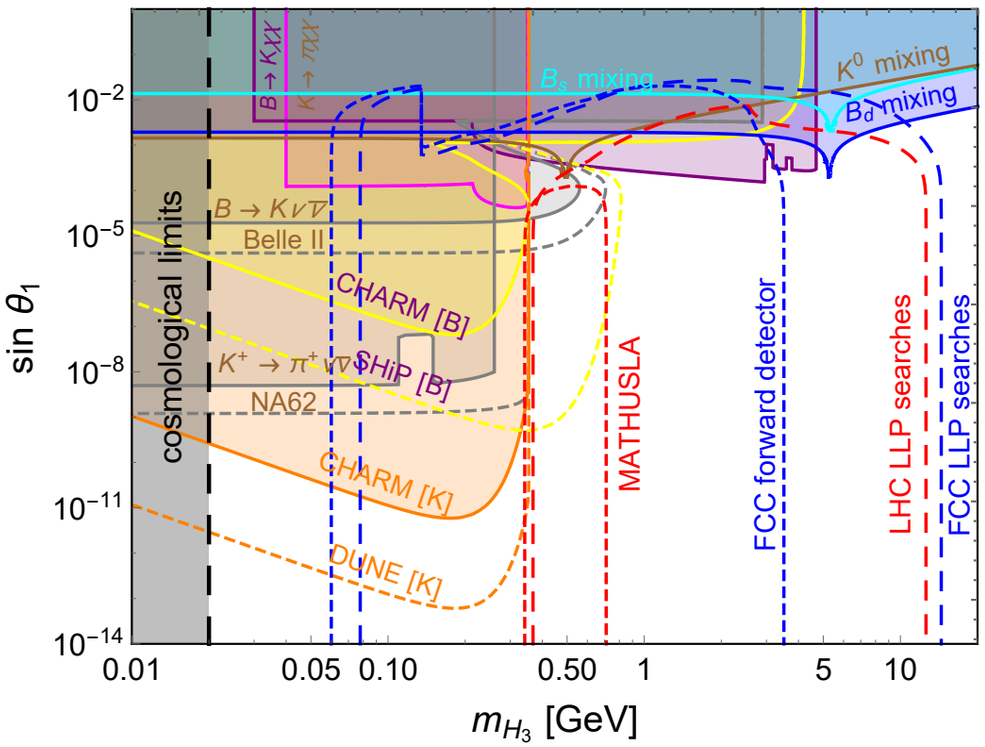

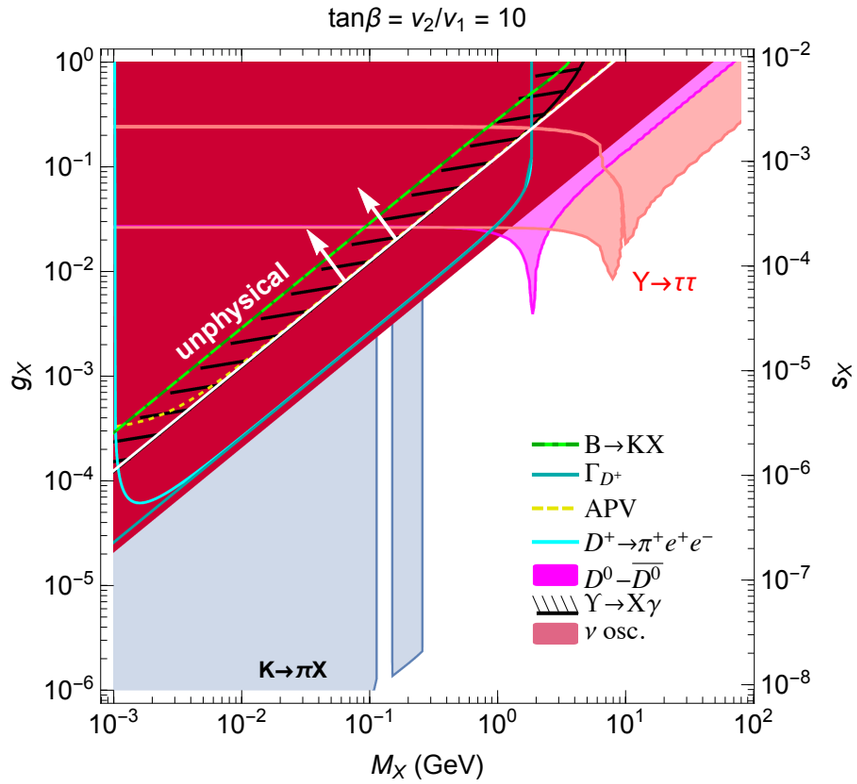

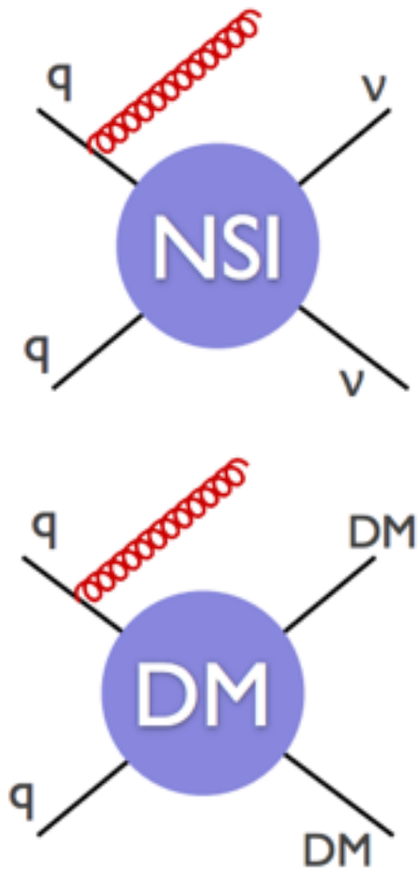

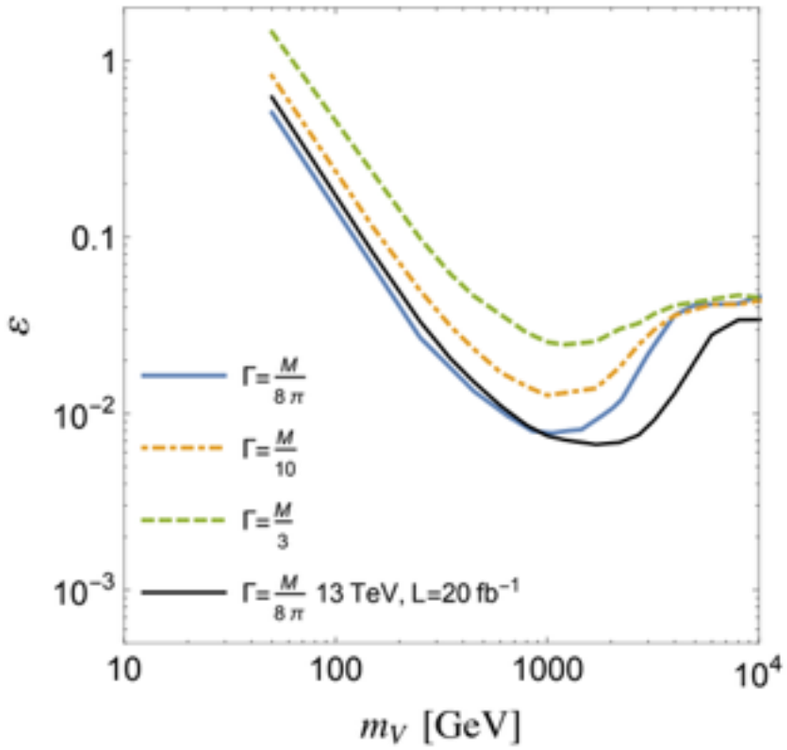

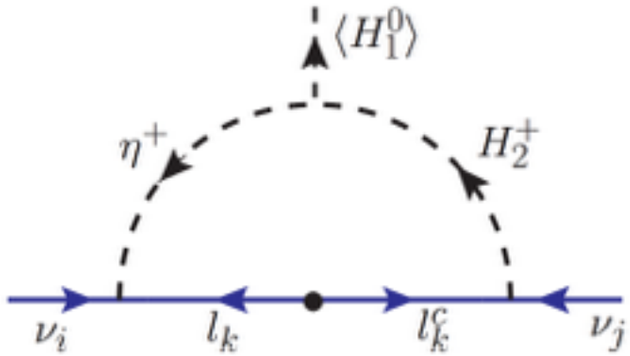

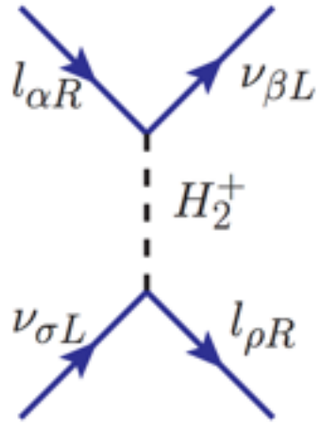

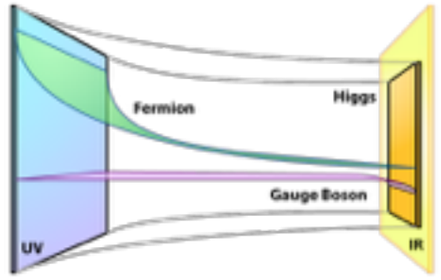

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Connecting δ_{cp} to the matter-antimatter asymmetry

Standard model:

Sakharov's Conditions

☑ Baryon and Lepton Number Violation — Kuzmin, Rubakov and Shaposhnikov

☒ Insufficient CP Violation — Gavela, Hernandez, Orloff, Pene; Huet and Sather

☒ No departure from thermal equilibrium — Kajantie, Laine, Rummukainen, Shaposhnikov

From Jessica's presentation @ NTN NSI workshop

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Leptogenesis could work even if the only CP phases present are the low energy ones

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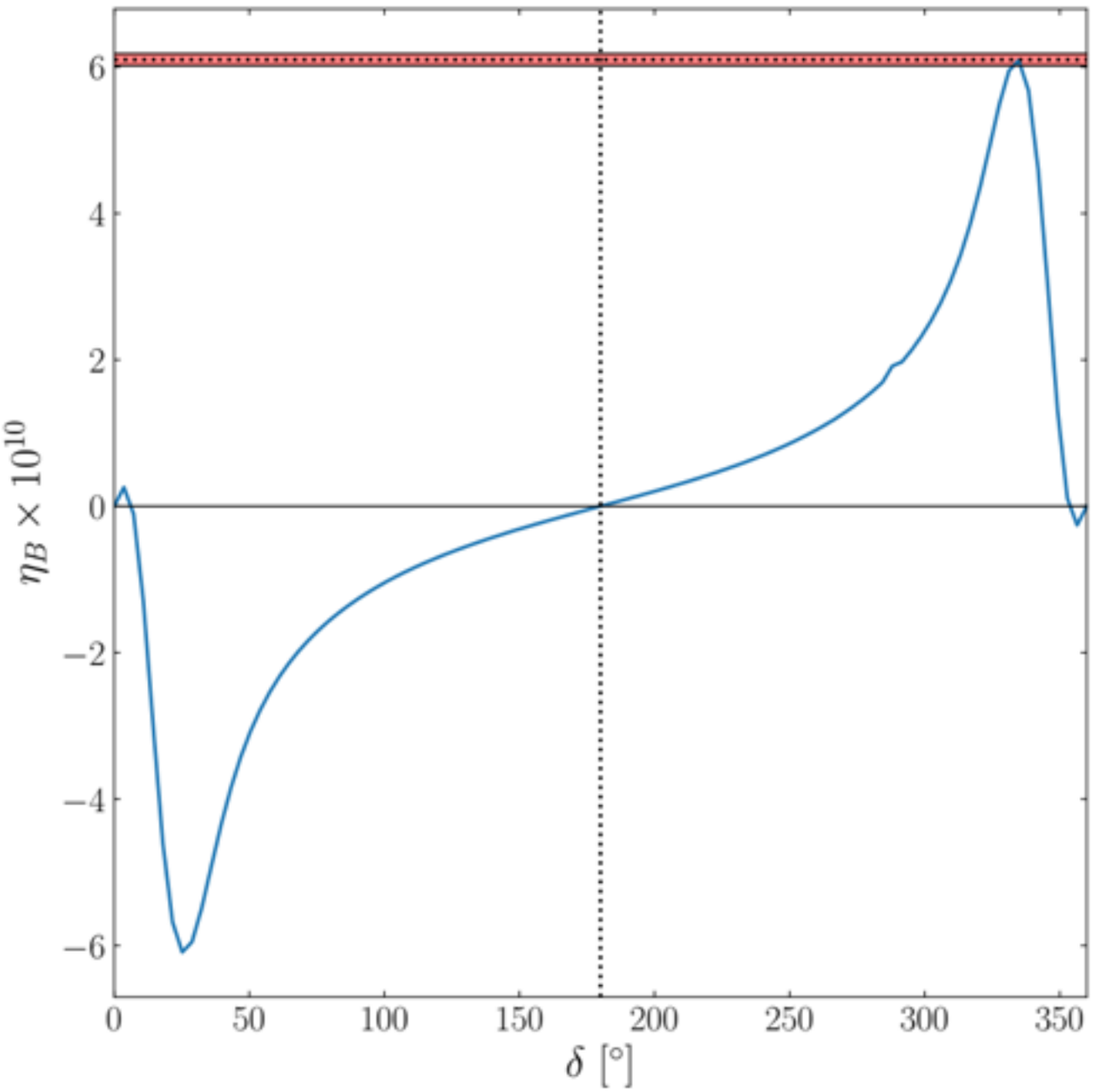

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Conclusions?

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Neutrinos are very much *terra incognita* to be explored

Several challenges for theorists!

(For experimentalists too, don't feel left aside…)

How to model neutrino-nucleus interactions?

How to extract the most from LArTPCS?

What kind of new physics can we look for with LArTPCS?

How to relate oscillations to other observables in complete models or theoretically motivated frameworks?

How to connect δ_{cp} to the matter-antimatter asymmetry?

How to devise tests of the neutrino mass mechanisms?

How to improve knowledge of tau neutrinos?

How to improve tests of unitarity?

What are we missing?

What else may be hiding in the neutrino sector?