URA Early Career Award talk: New horizons in neutrino physics

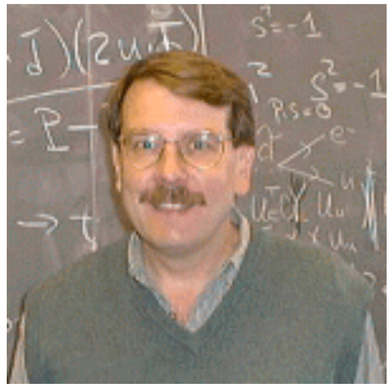
Pedro A. N. Machado

August 4th, 2021

It is a great honor to receive the URA early career prize.

But this is hardly a one-person achievement.

Stephen Parke



Roni Harnik

Noemi Rocco

Ornella Palamara
(honorary theorist!)

Vedran Brdar

Josh Isaacson

Will Jay

Kevin Kelly

Shirley Li

Ivan Martinez-S.

Yuber Perez-G.

Jessica Turner

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But this is hardly a one-person achievement.

Straight to the point: *I would not have gotten the award if I wasn't part of our excellent theory group, working with the* ***best postdocs in the world***.

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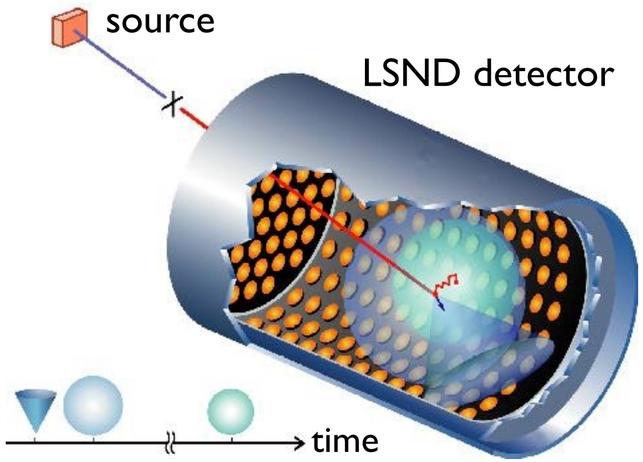
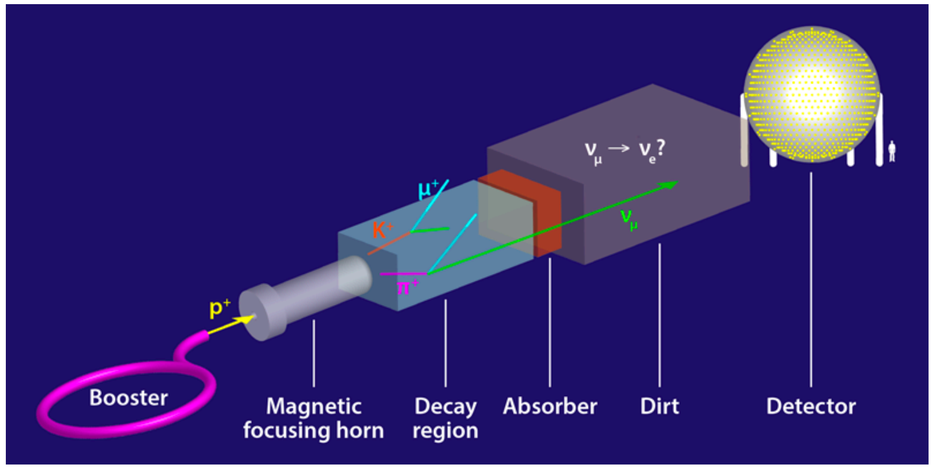
The short baseline neutrino anomalies





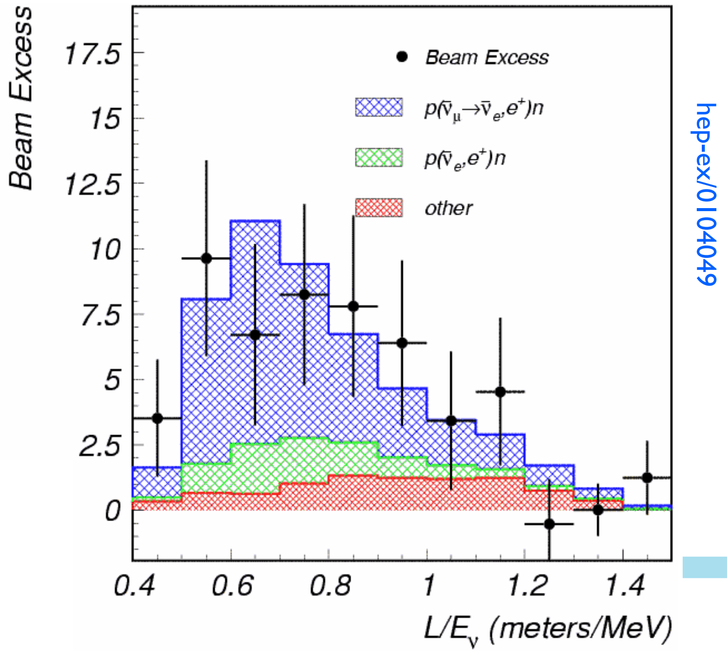
If interpreted as oscillations

$P(\nu_\mu \text{ to } \nu_e) \sim 0.3\%$

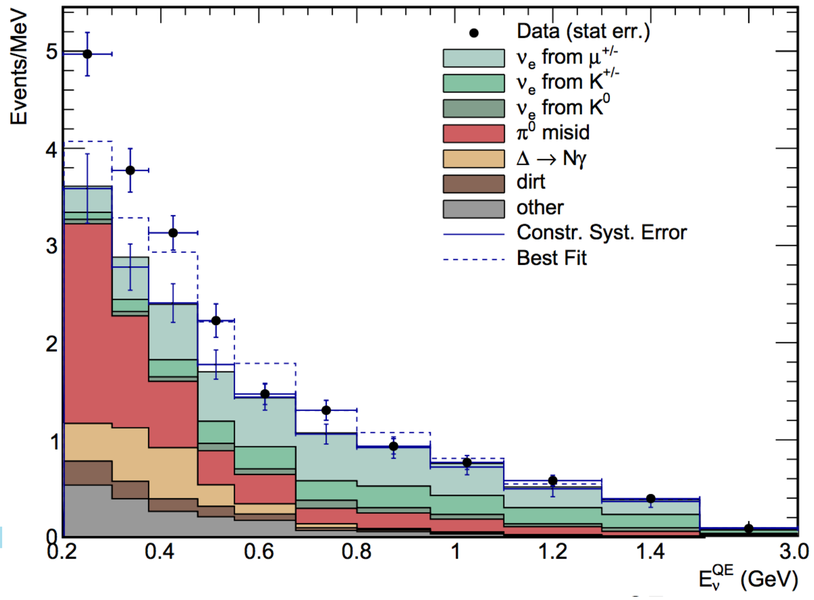
$P(\bar{\nu}_\mu \text{ to } \bar{\nu}_e) \sim 0.3\%$

and

$\Delta m^2 \sim 1\ eV^2$



hep-ex/0104049



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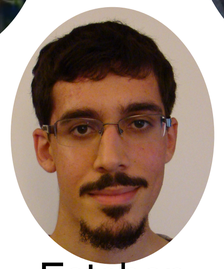
The short baseline neutrino anomalies

Dentler et al 1803.10661, Dentler et al 1911.01427
Bertuzzo et al 1807.09877+1808.02500


Dentler


Hernández


Martínez


Esteban

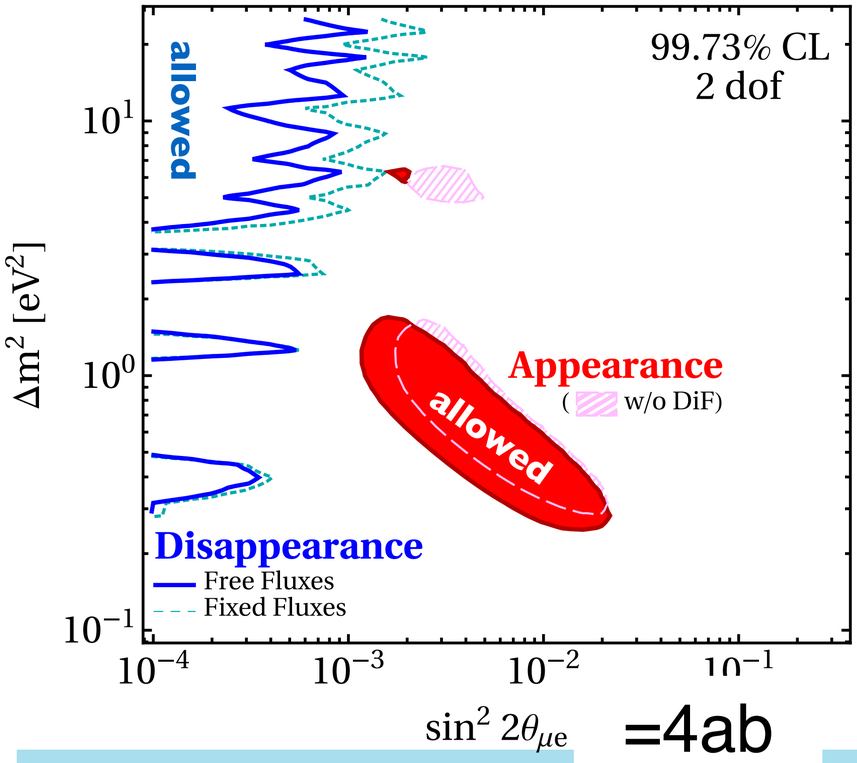

Jana

The issue of sterile neutrinos

$$P(\nu_\mu \to \nu_e) \simeq 4ab \, \sin^2(\text{osc. phase})$$

$$P(\nu_e \to \nu_s) \simeq 4a \, \sin^2(\text{osc. phase})$$

$$P(\nu_\mu \to \nu_s) \simeq 4b \, \sin^2(\text{osc. phase})$$



=4ab

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The short baseline neutrino anomalies

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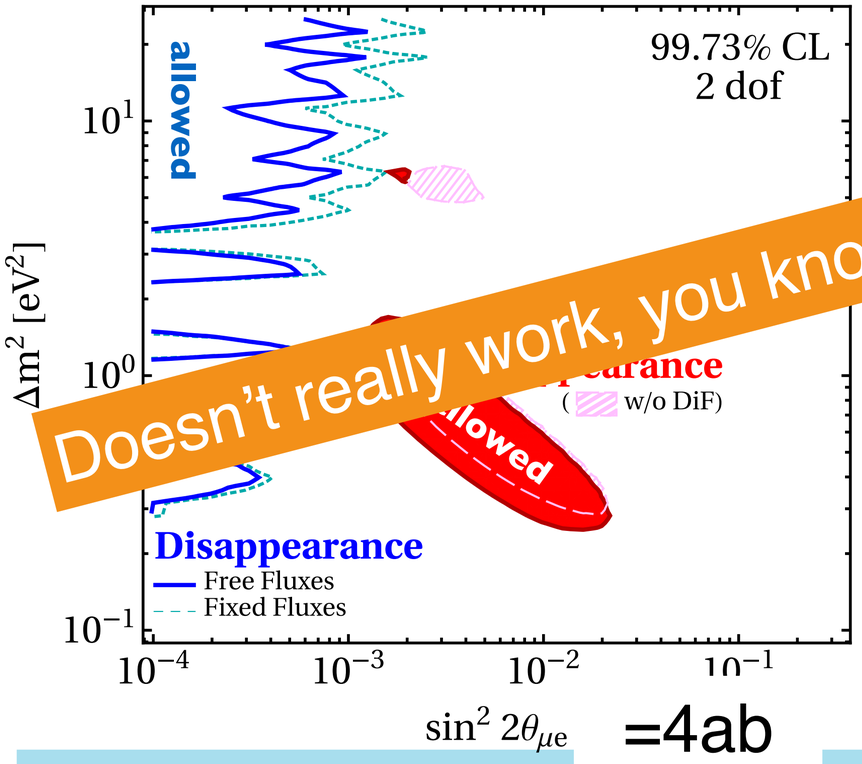

=4ab

Doesn't really work, you know…

Dentler Hernández Martínez





Esteban Jana

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The short baseline neutrino anomalies

Dentler et al 1803.10661, Dentler et al 1911.01427
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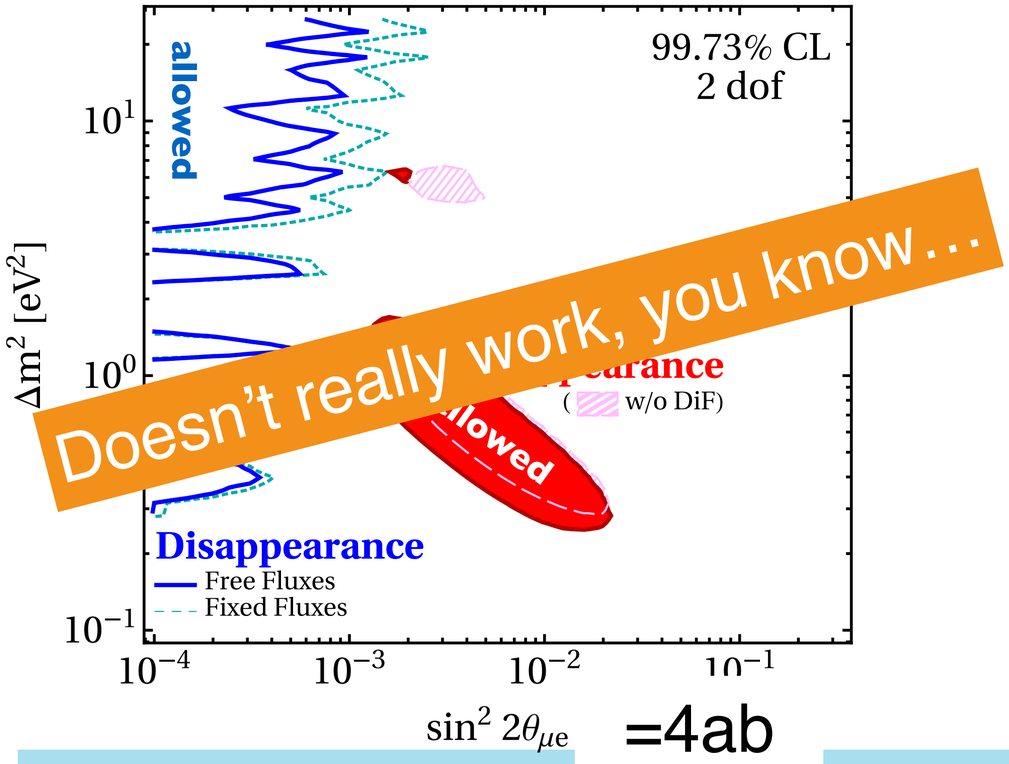
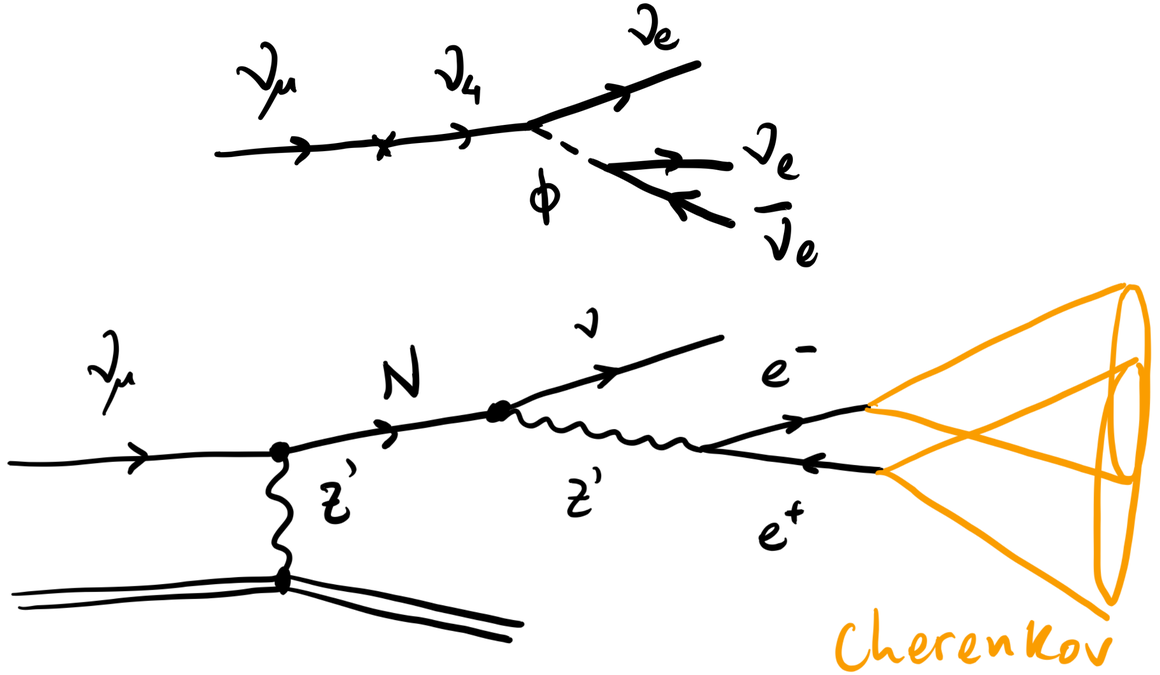


Doesn't really work, you know…

=4ab

There are other possible explanations, each of those presenting distinct signatures.



Distinct signatures = distinct background

==> better description of neutrino-nuclei interactions is needed, see Noemi's talk

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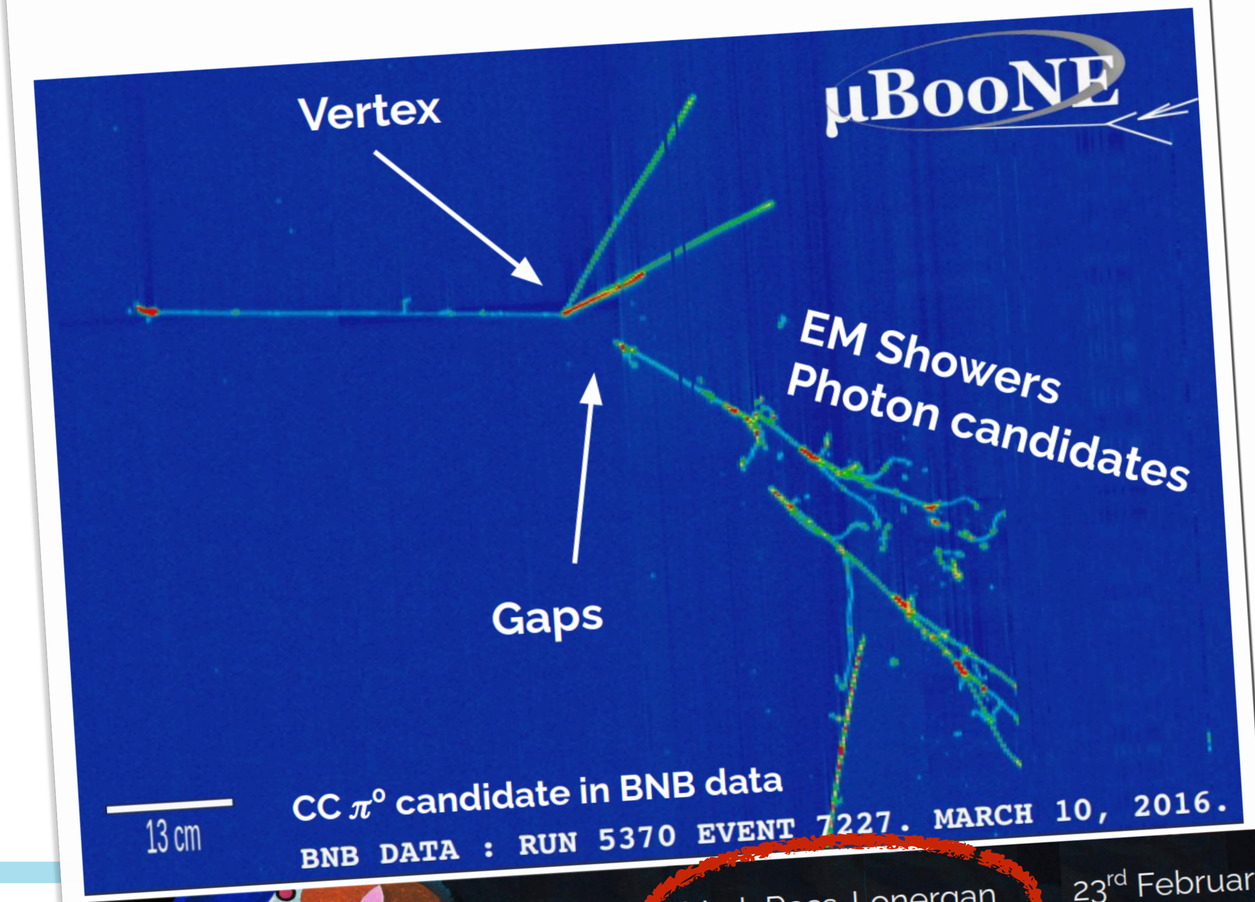
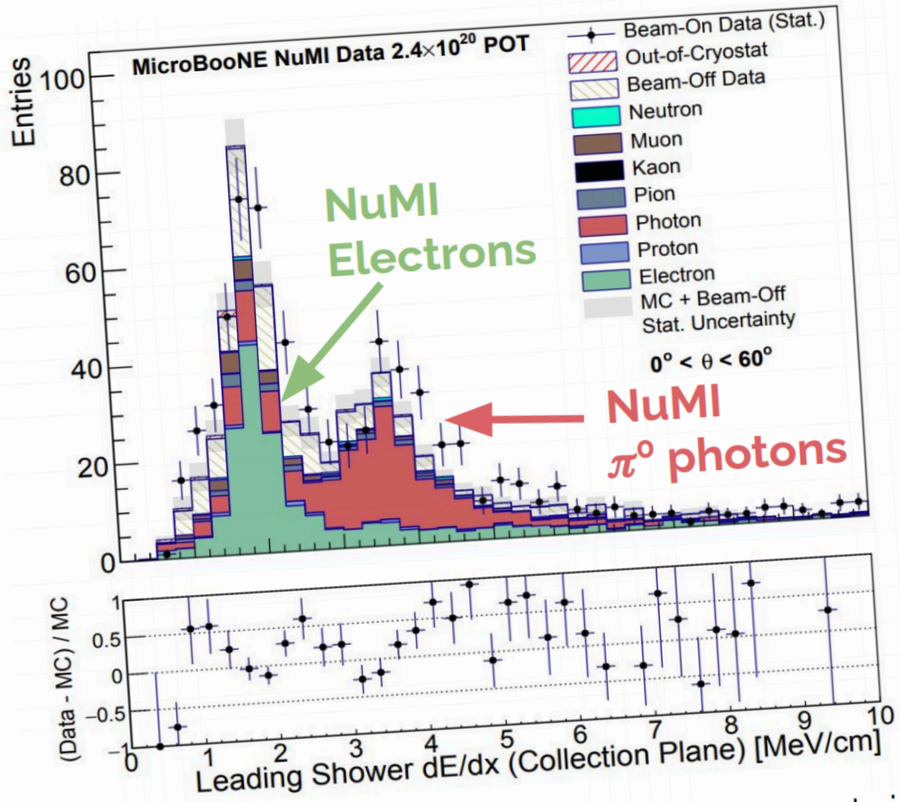
Spatial Resolution: Photon Conversion Distance

LArTPC's are like a **digital bubble chamber.** In argon photons travel with a mean free path of ~15cm before pair converting, and as the photons are neutral this appears as a **distinct gap**.



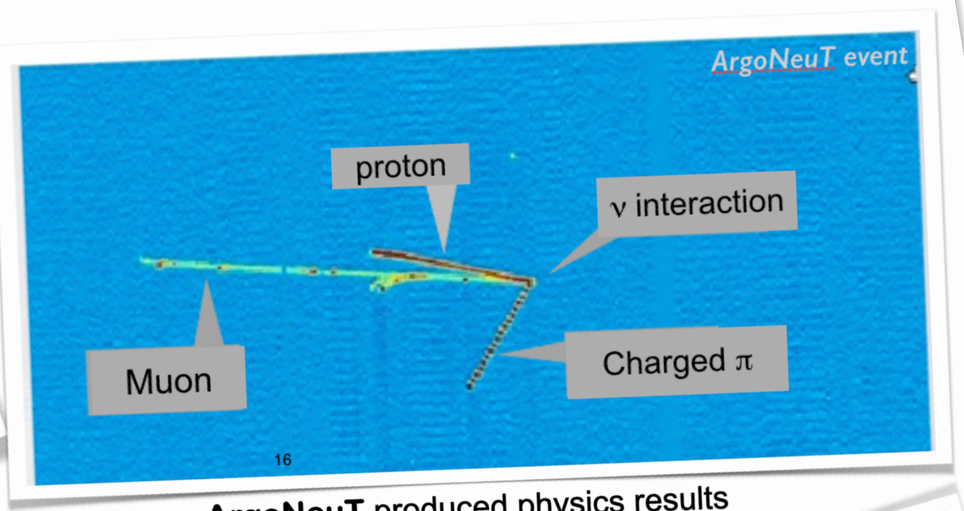
Calorimetry: Shower dE/dx

Photons producing e^+e^- pairs tend to **deposit twice the energy per unit length** as a single electron



Example of shower dE/dx for candidate neutrino events in the NuMI beam at MicroBooNE arXiv:2101.04228

Why Liquid Argon Time Projection Chamber?



ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

slide stolen from O. Palamara

LAr TPC: Bubble chamber quality of data with added calorimetry

...or LArTPC is "a "colored" bubble chamber" (theorist simplified view!)

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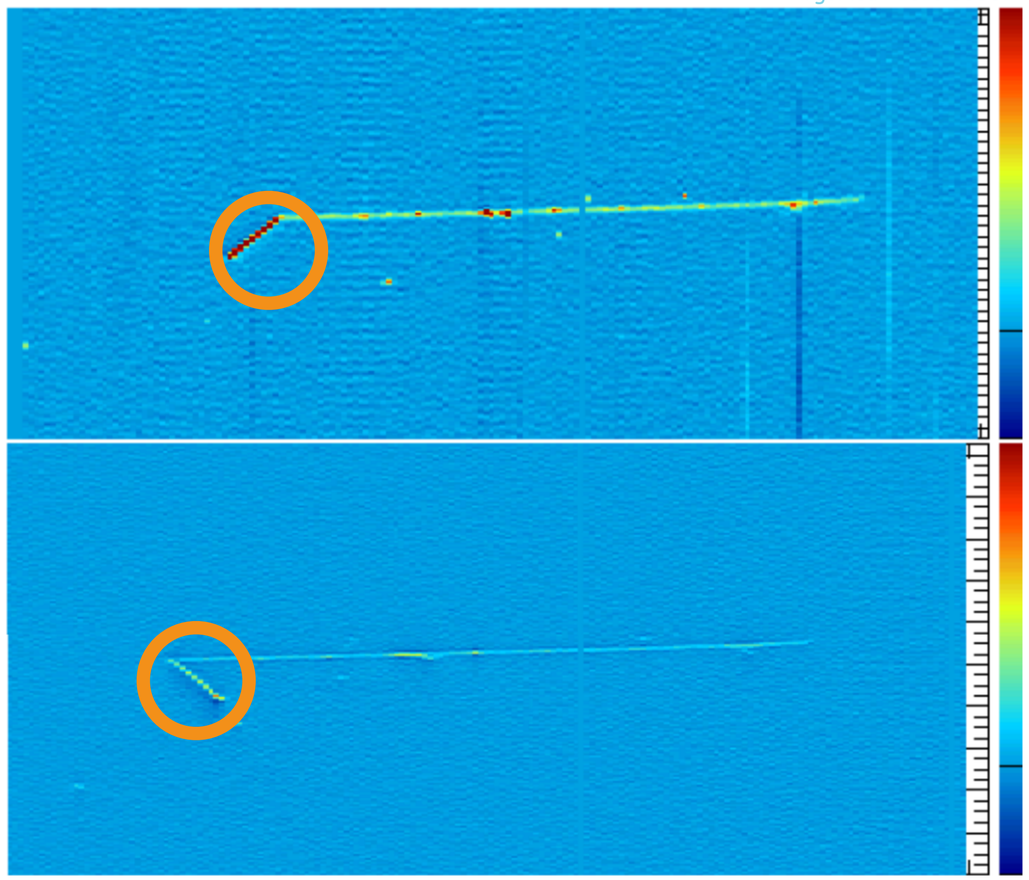
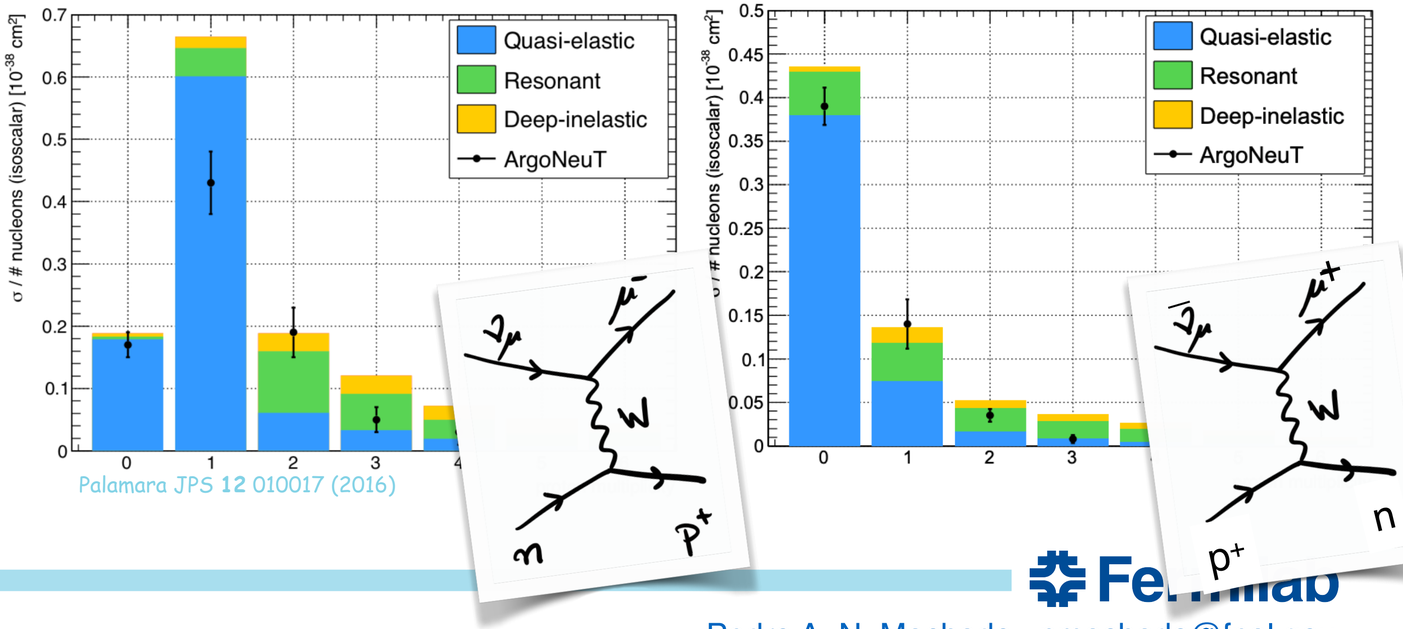
ArgoNeuT demonstrated the LAr capability to detect 21 MeV recoil protons.



Reconstruct, identify and point.

For comparison, SK can only see protons that emit Cherenkov light, that is, protons with kinetic energy above ~ 1.4 GeV

Event topology carries extra information



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What can we learn from LArTPCs?

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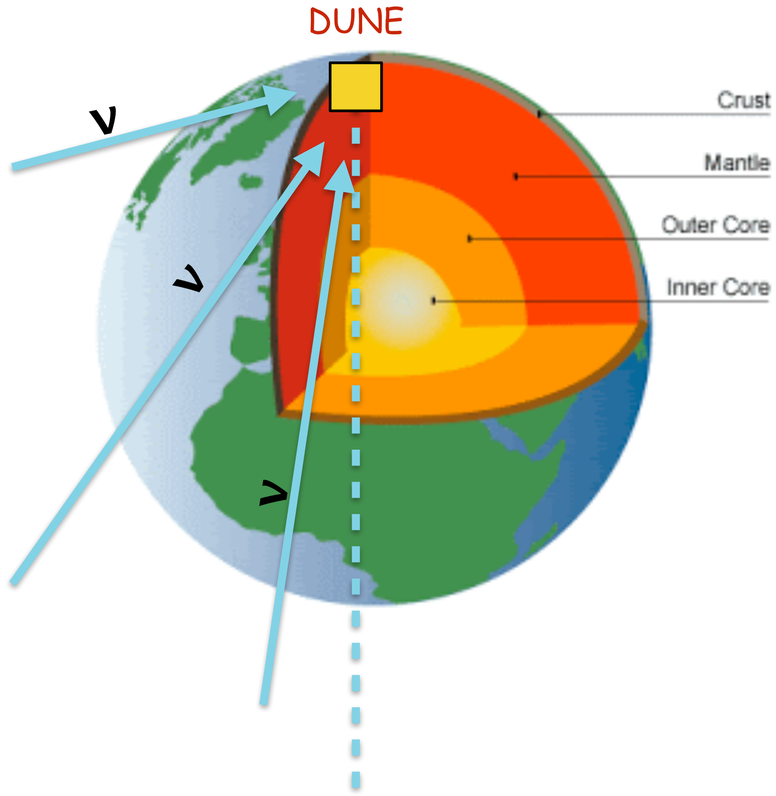
Atmospheric neutrinos below the GeV scale and CP violation

Kelly et al 1904.02751

CP violation effects in sub-GeV atmospheric neutrinos is **10x larger** than in beam neutrinos



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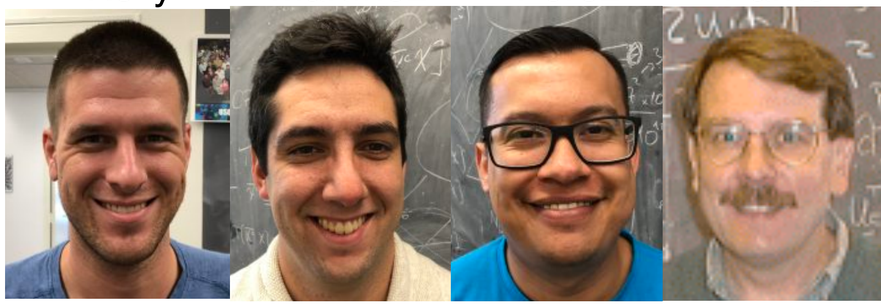
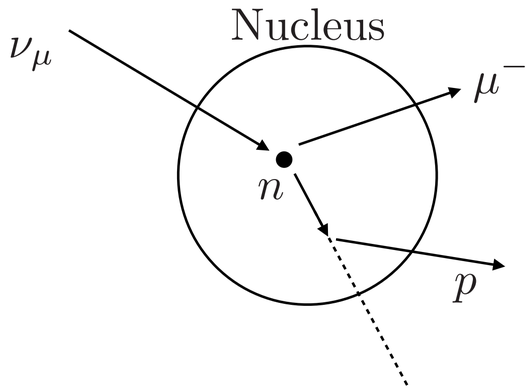
Kelly et al 1904.02751

Kelly Martínez Perez Parke



CP violation effects in sub-GeV atmospheric neutrinos is **10x larger** than in beam neutrinos

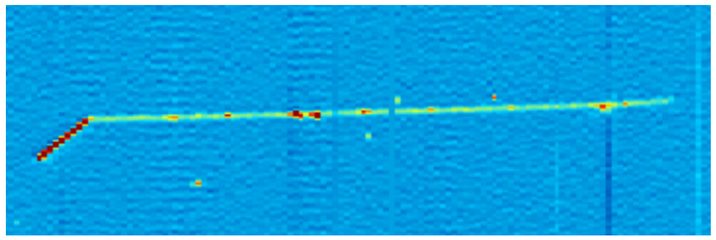
But sub-GeV atmospherics are very difficult...

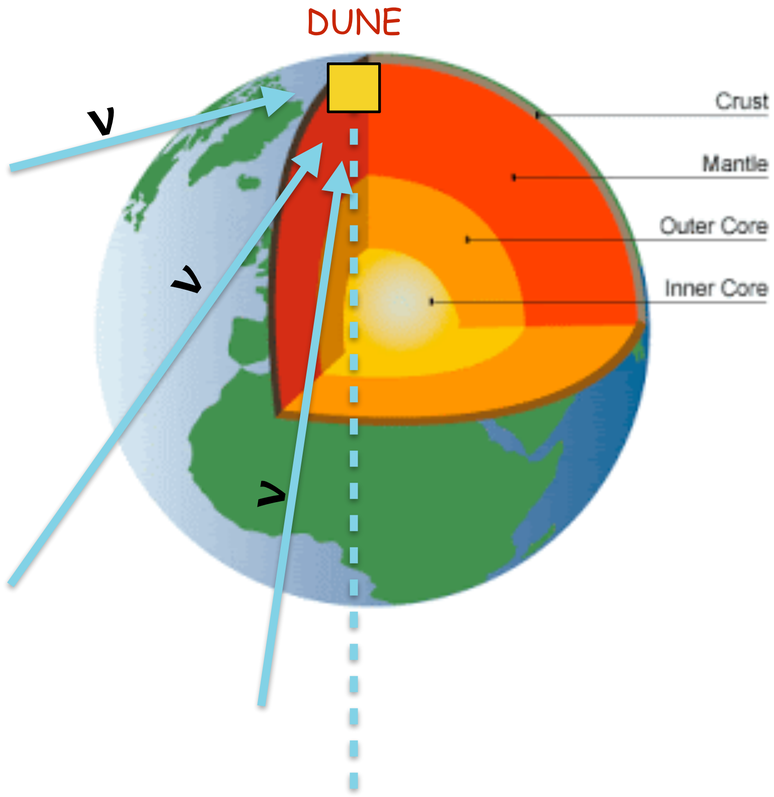


Needs to know neutrino direction

Low E protons are invisible @ Cherenkov detectors

Liquid Argon TPCs can do it!





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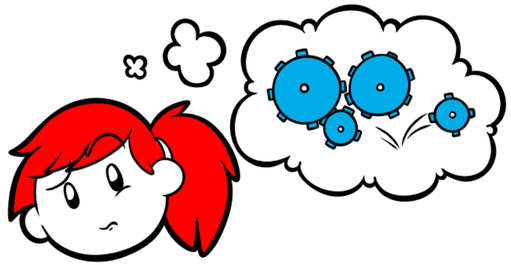
Kelly et al 1904.02751



Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

$$\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$$

Account for uncertainties of atmospheric neutrino fluxes

40% normalization, 5% e/μ ratio, 2% nu/nubar ratio, ± 0.2 spectral distortion coefficient

Realistic LArTPC capabilities

Δp = 5%, 5%, 10%, $\Delta\theta$ = 5º, 5º, 10º, for e, μ, p, K_p = 30 MeV

Classify events by final state topology (number of protons)

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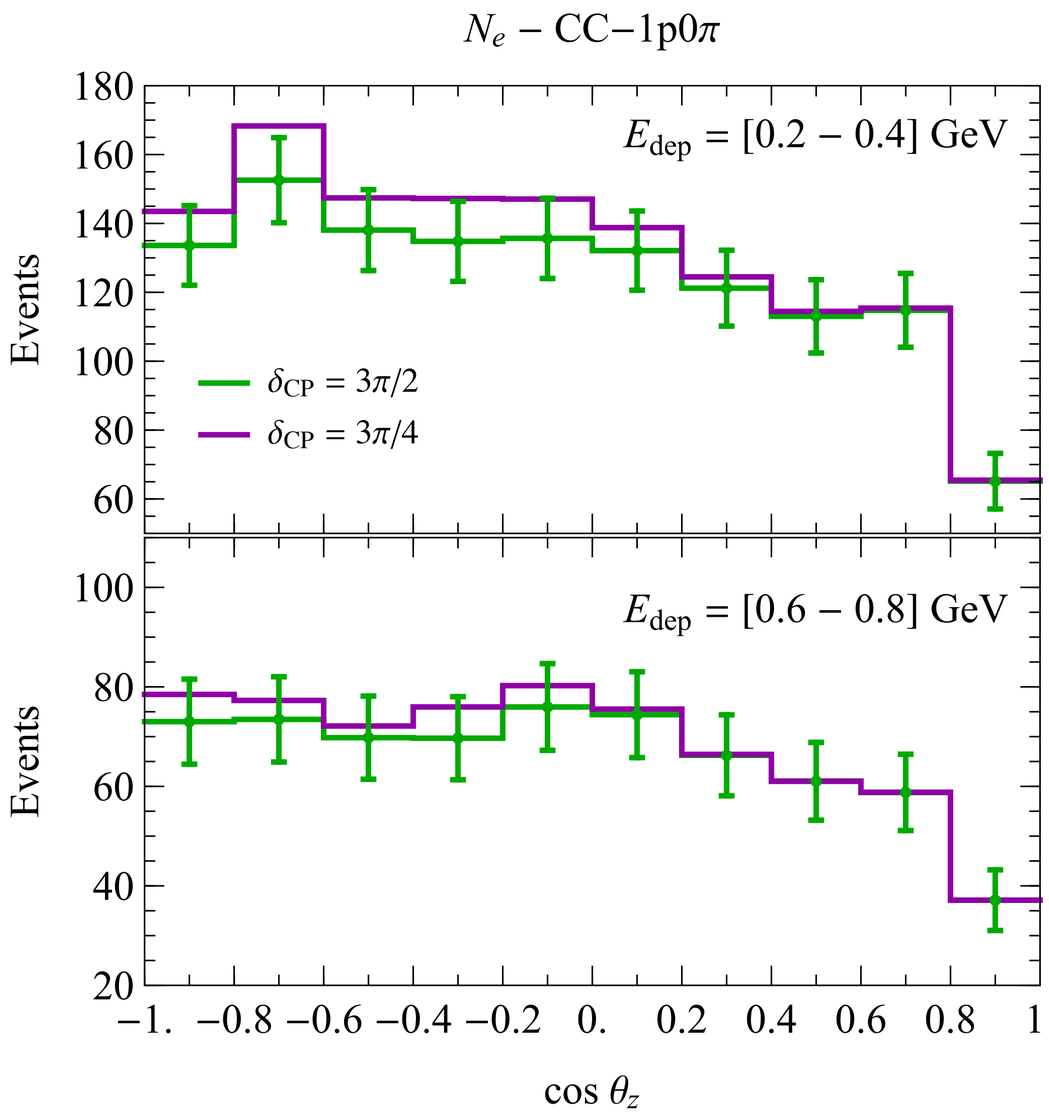

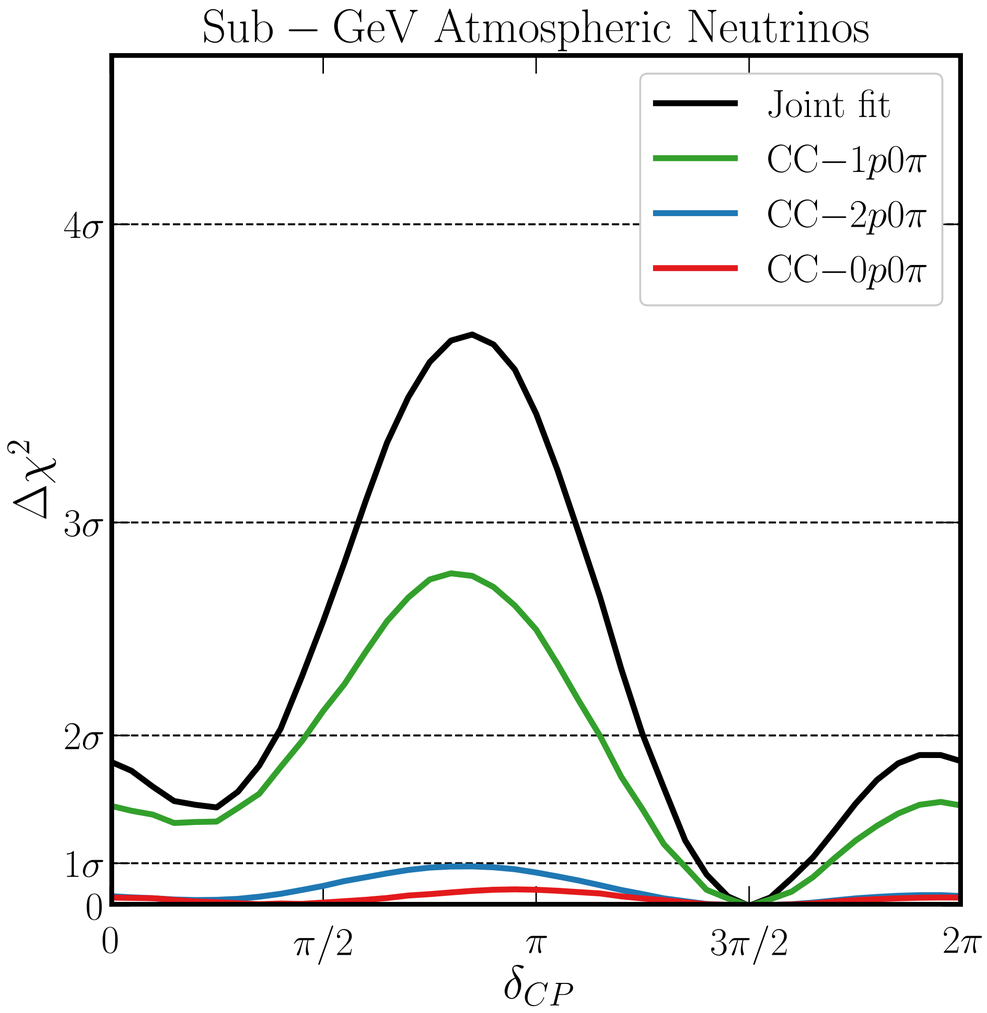

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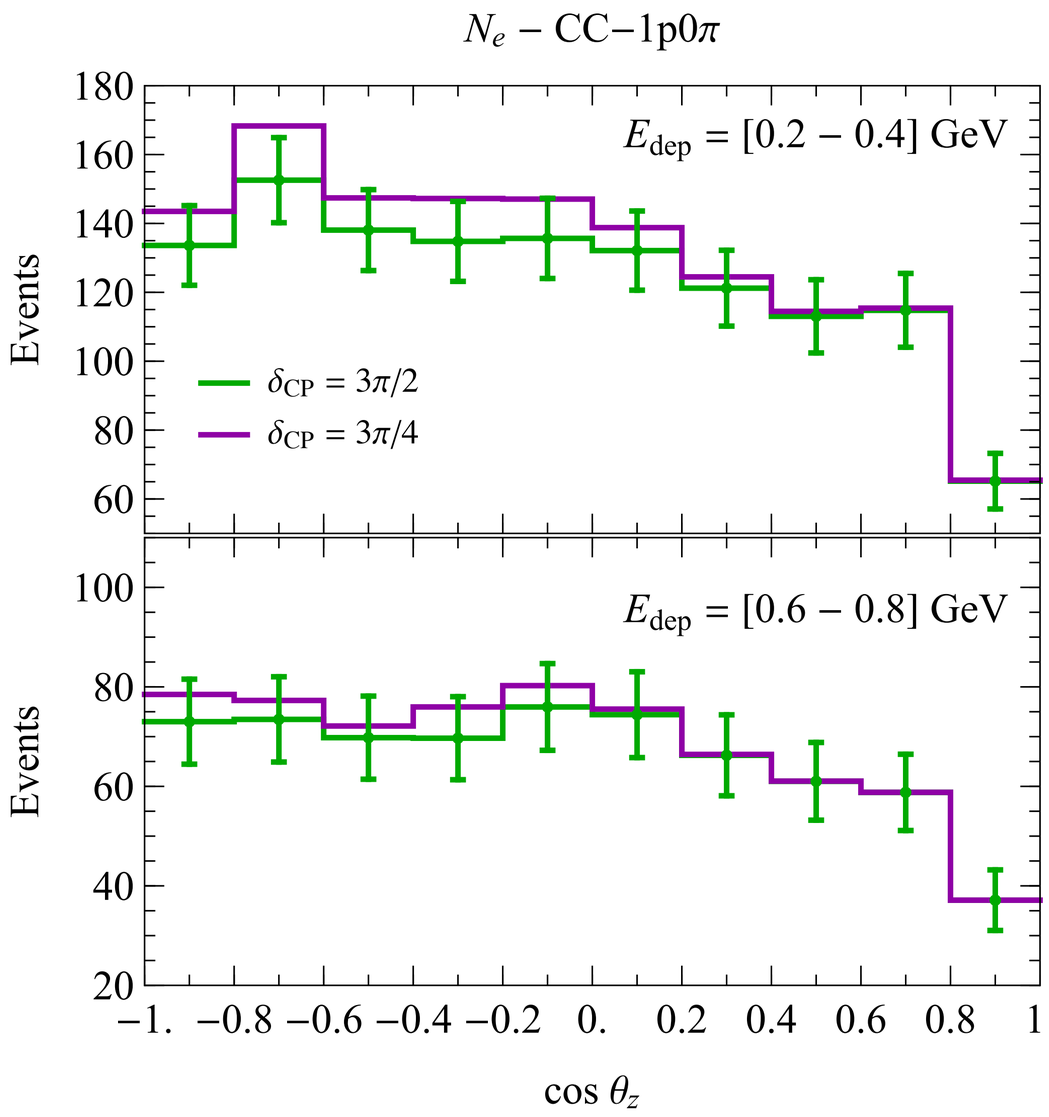

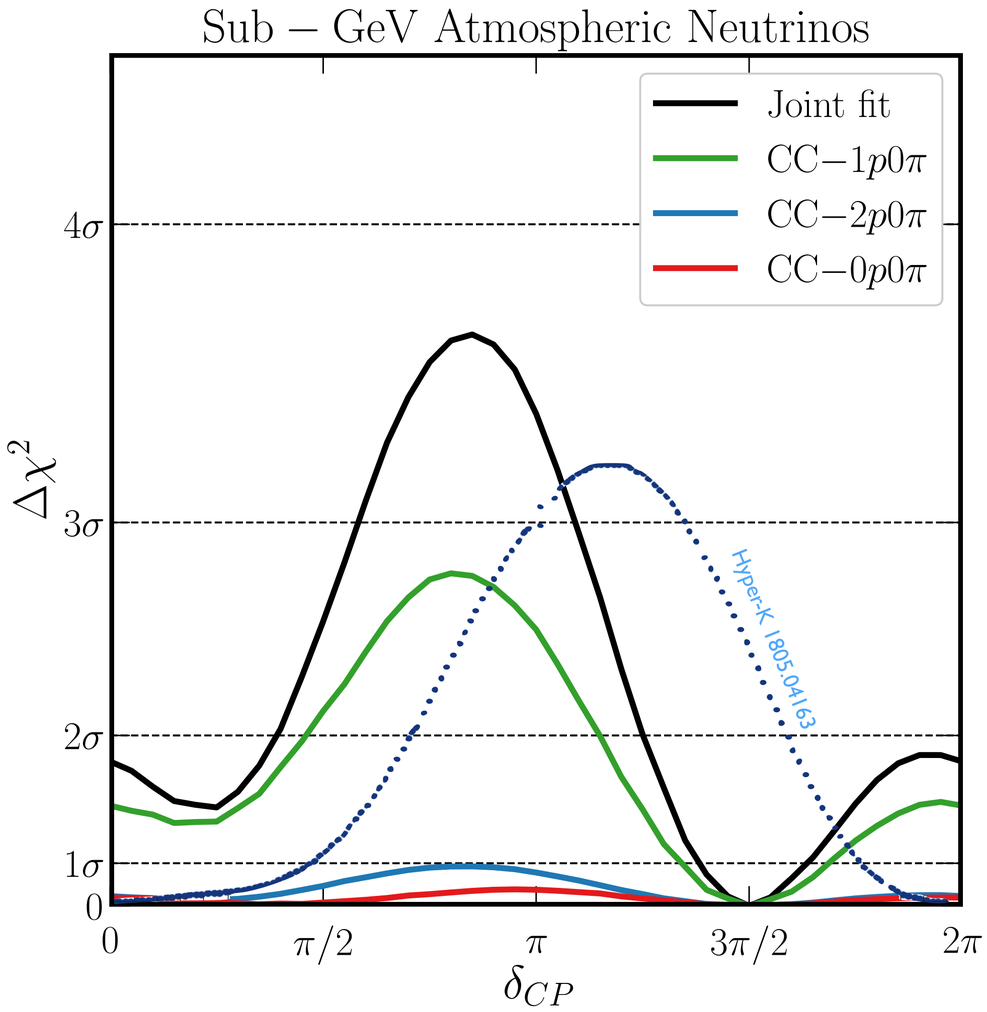

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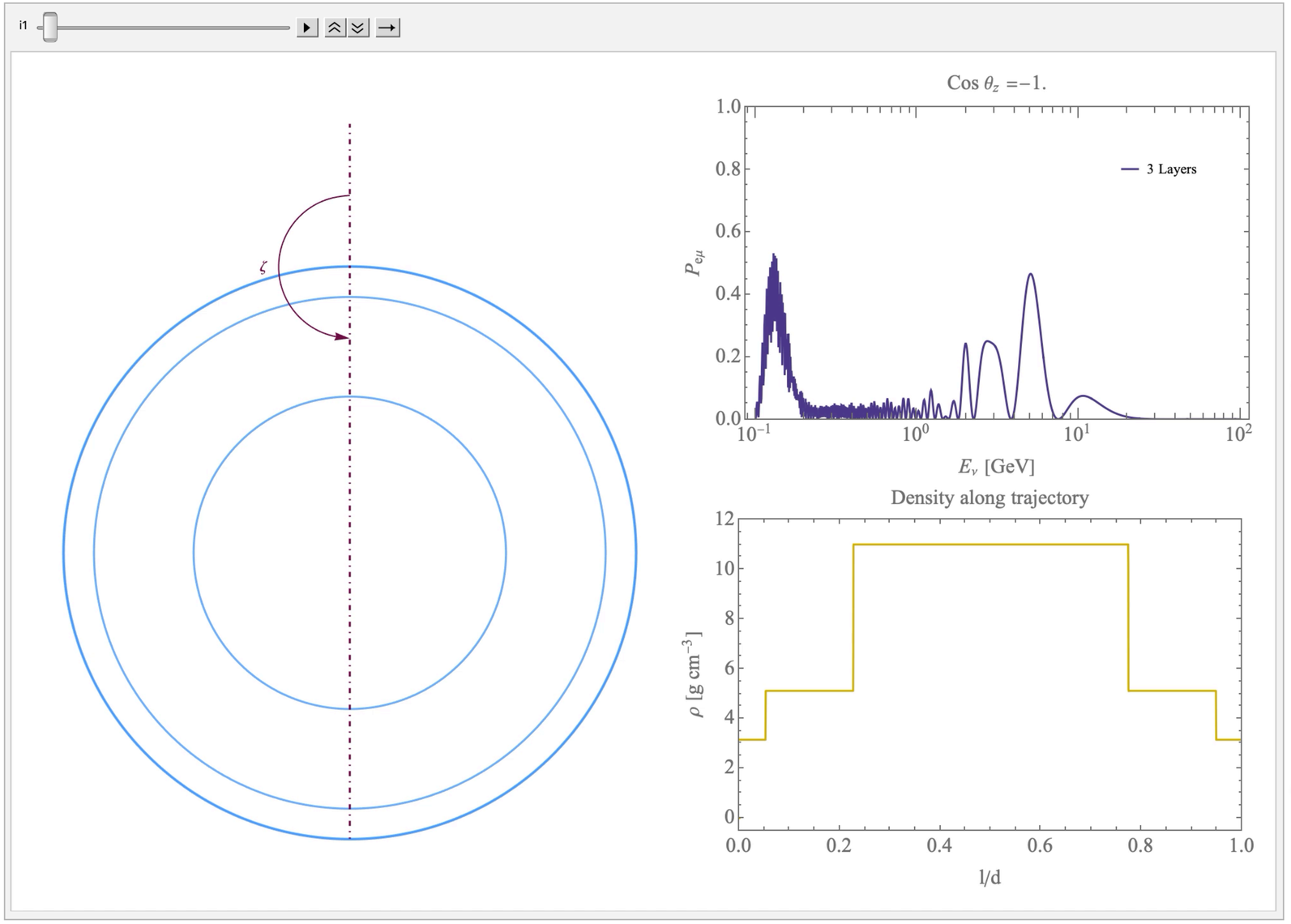
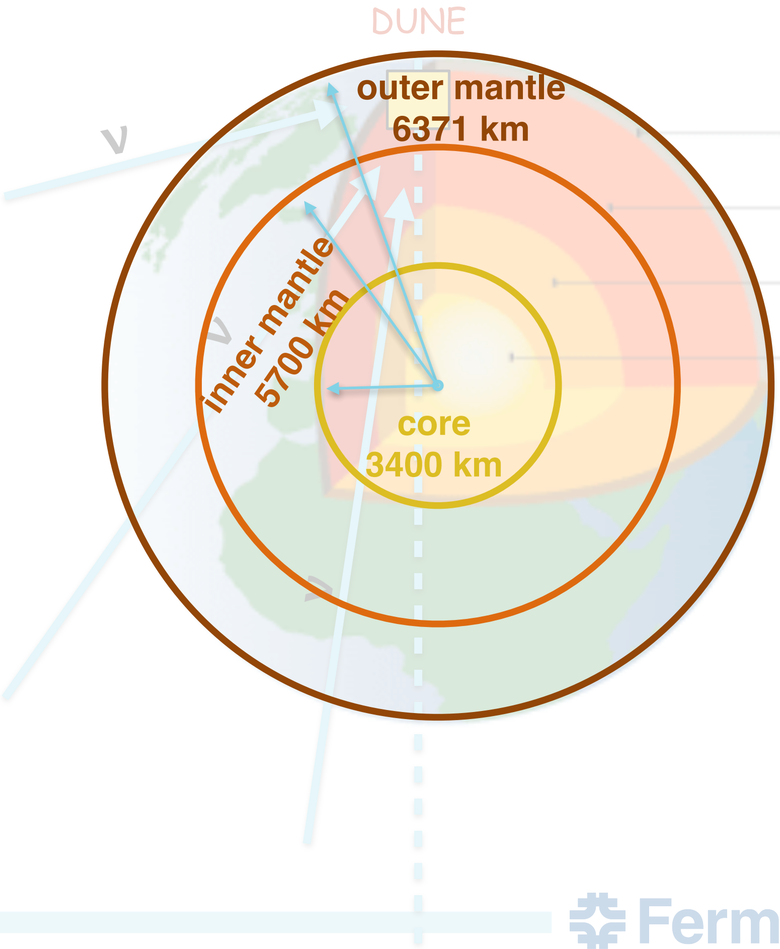
Quantum tomography measurement of Earth's matter profile

in progress...





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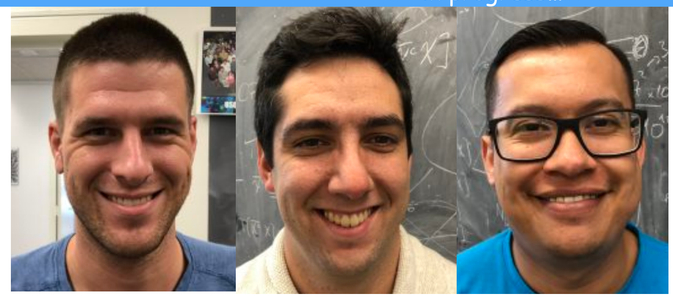


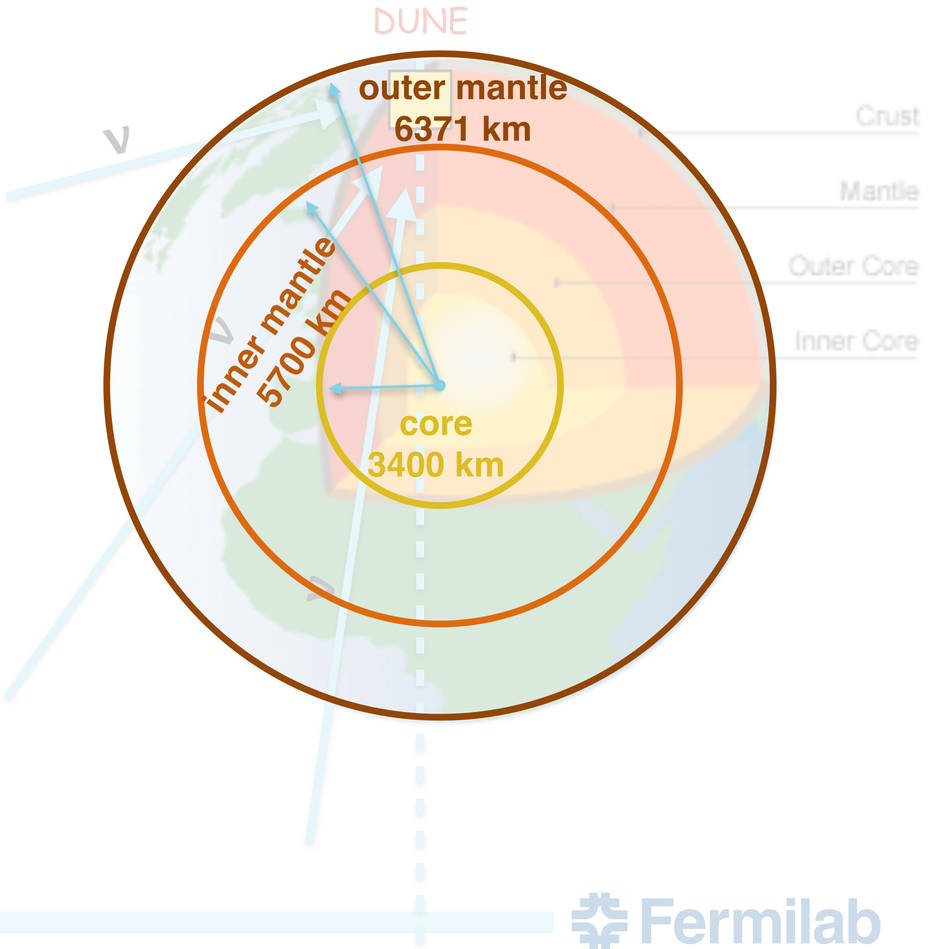
Combine with total mass and moment of inertia measurements

preliminary

Outer mantle: 3.1 ± 0.7 g/cm^3

Inner mantle: 5.1 ± 0.6 g/cm^3

Core: 11 ± 1 g/cm^3



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Take home message

DUNE has a unique opportunity to study sub-GeV neutrinos

This opens up the possibility of

(1) measuring CP violation independently of the beam

(2) doing quantum tomography with neutrinos

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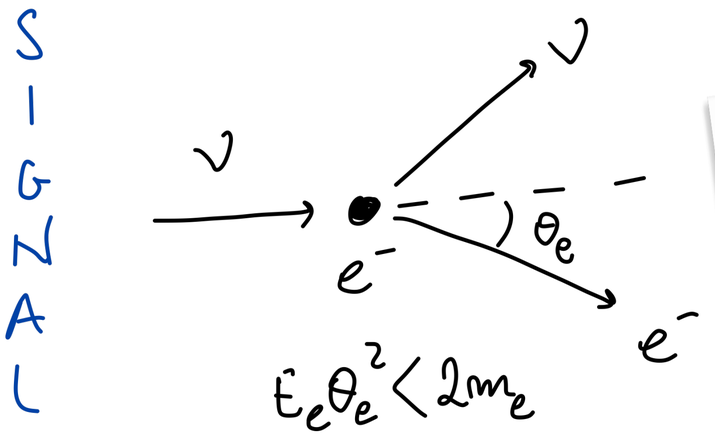
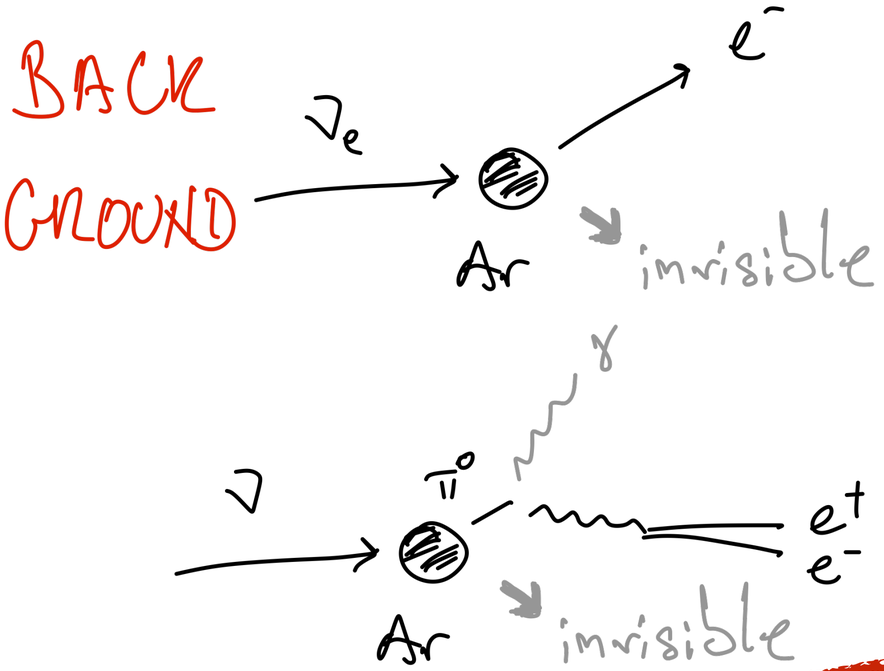
Weak mixing angle measurement

de Gouvea M Perez-Gonzalez Tabrizi 1912.06658



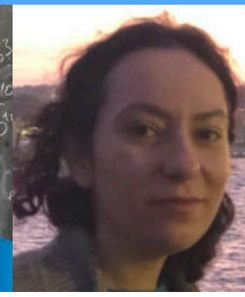
Cross section is flavor dependent, flavor content changes when going off-axis



see Noemi's talk


de Gouvêa


Perez


Tabrizi

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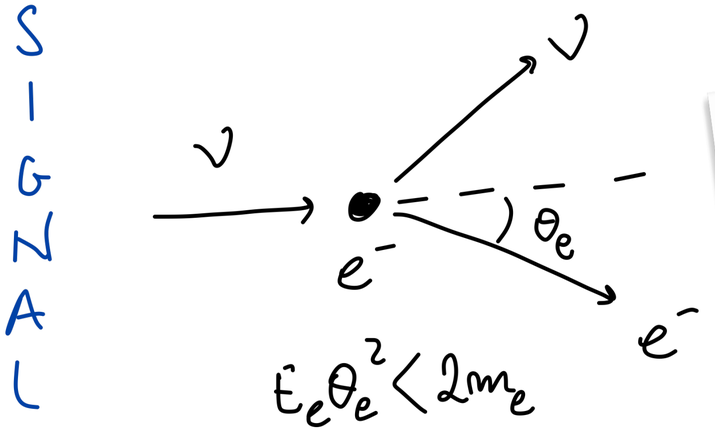

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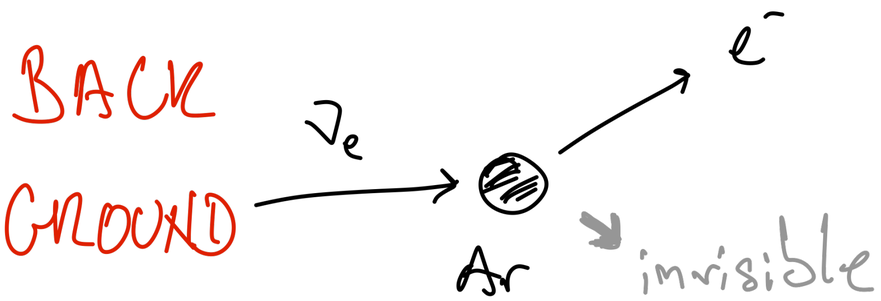

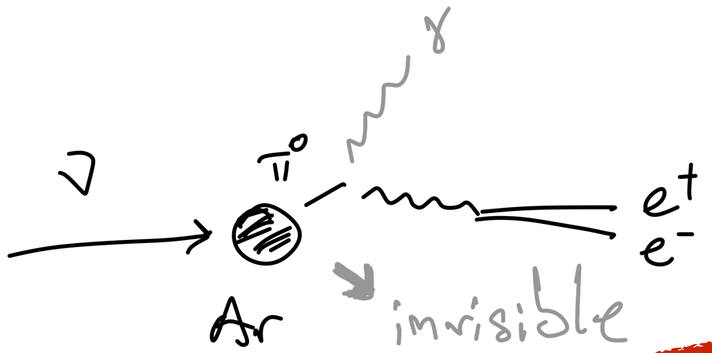

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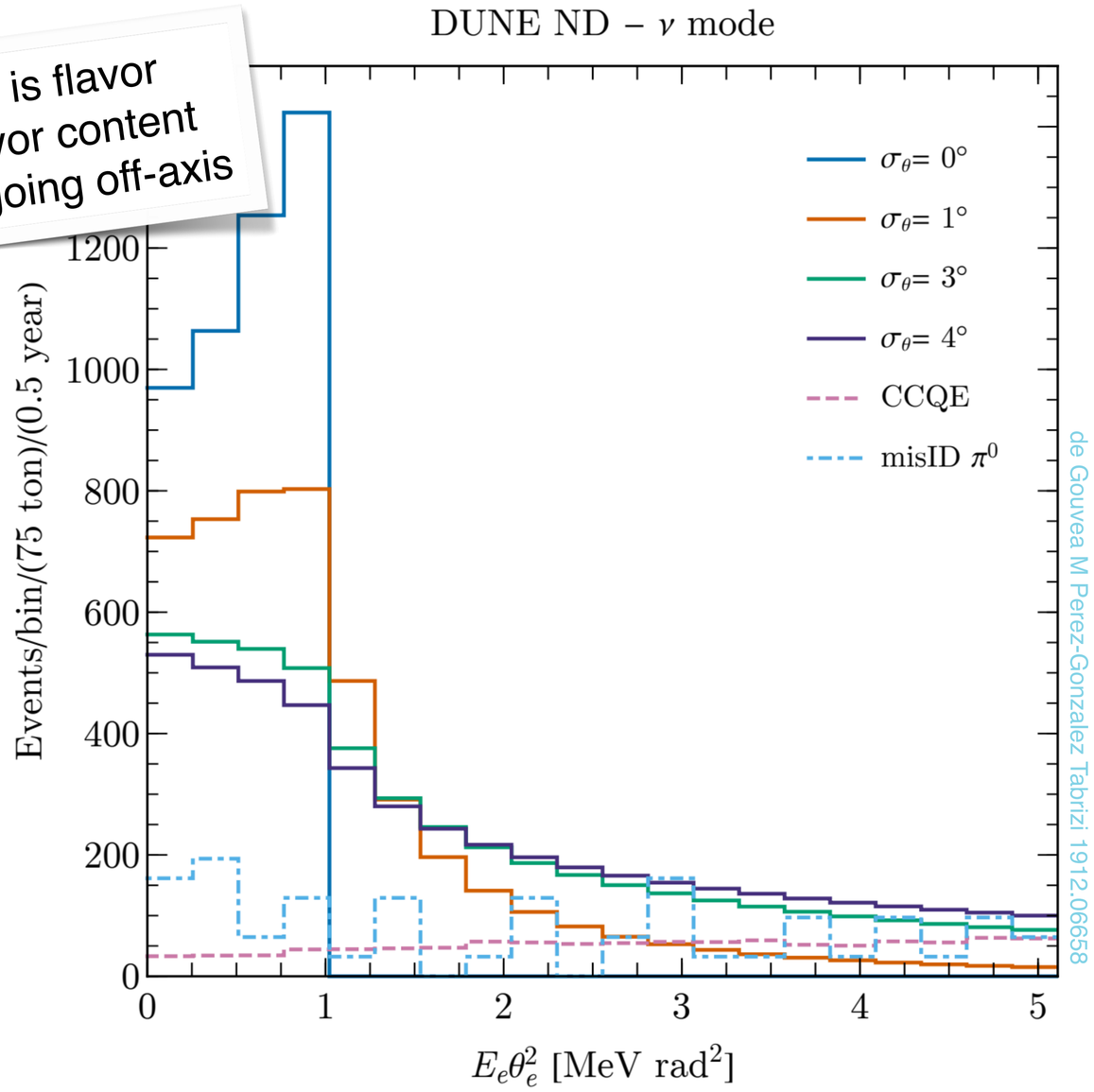

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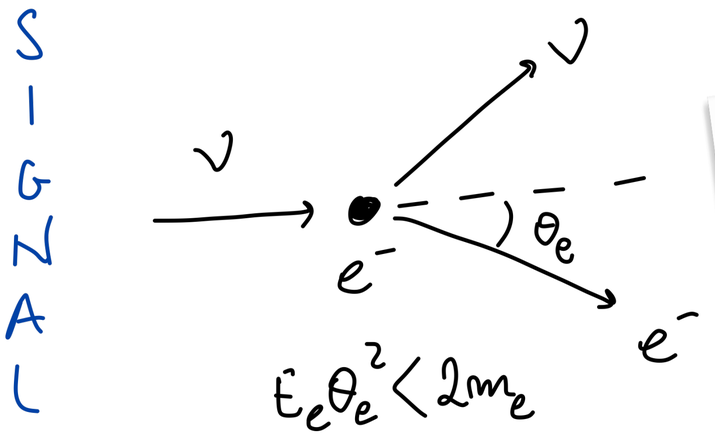

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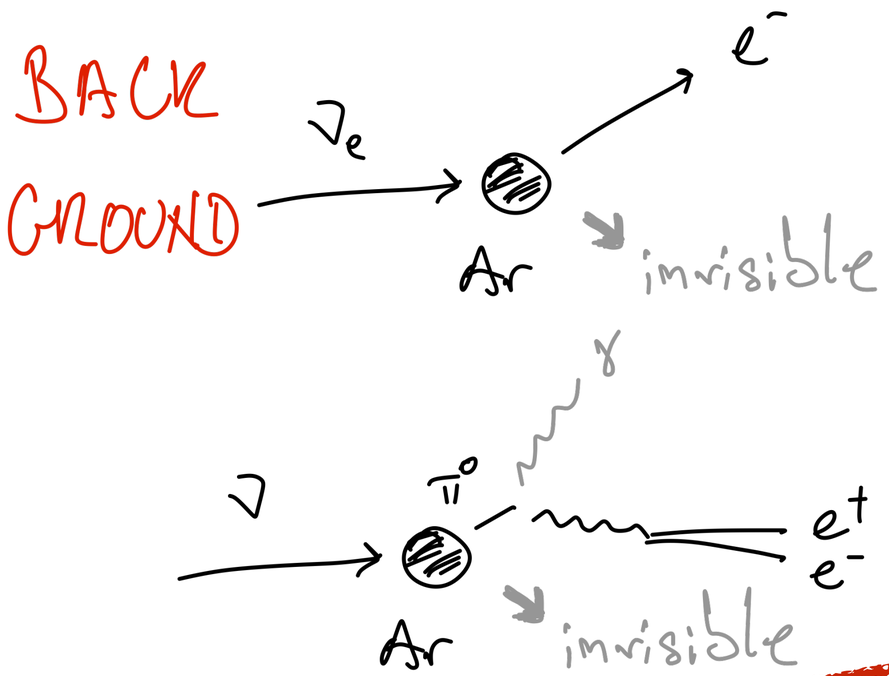

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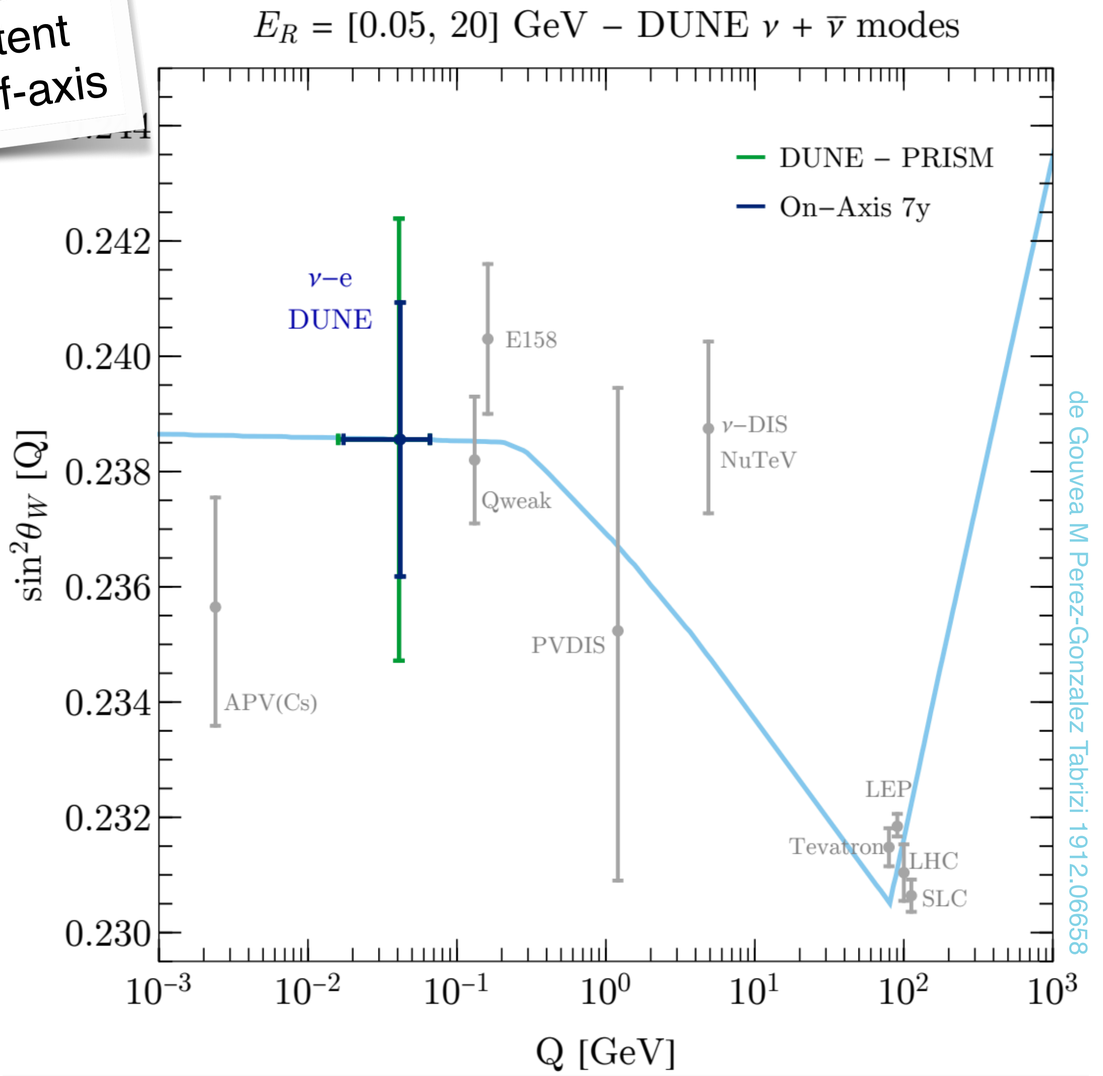

de Gouvea M Perez-Gonzalez Tabrizi 1912.06658

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And much more we have been doing for neutrino theory here at the lab!

Tau neutrino strategies at DUNE inspired in LHC techniques

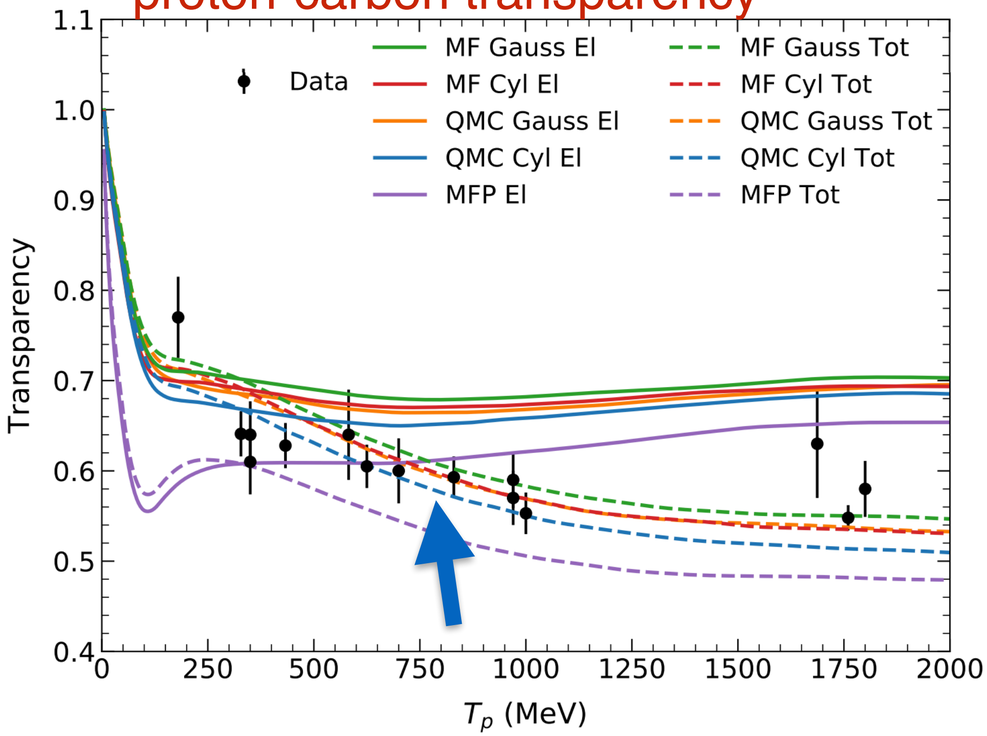
Neutrino-nuclei interaction description

Light (below GeV) and ultralight (below 10^{-12} eV) dark matter in neutrino experiments

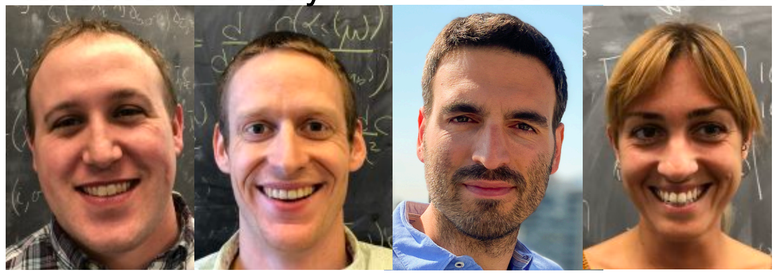
Skipper-CCD physics potential for neutrinos

…

proton-carbon transparency



Isaacson Jay Lovato Rocco



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Conclusions

Full physics potential of LArTPCs is still under exploration:

Exciting times ahead!!!

Very fruitful collaboration between THs and EXPs:

SBN-Theory meetings (with Roni and Ornella)

Diversity, broadly defined, of our theory group is key for innovation

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