New ideas in neutrino physics

Pedro Machado

July 30th, 2023

Users Meeting 2023

Why are we doing this?

Well, I can't answer that on your behalf.
But I am here because I want to break the rules (that is, the standard model).
I will try in as many ways as I can think of.
Why neutrinos?

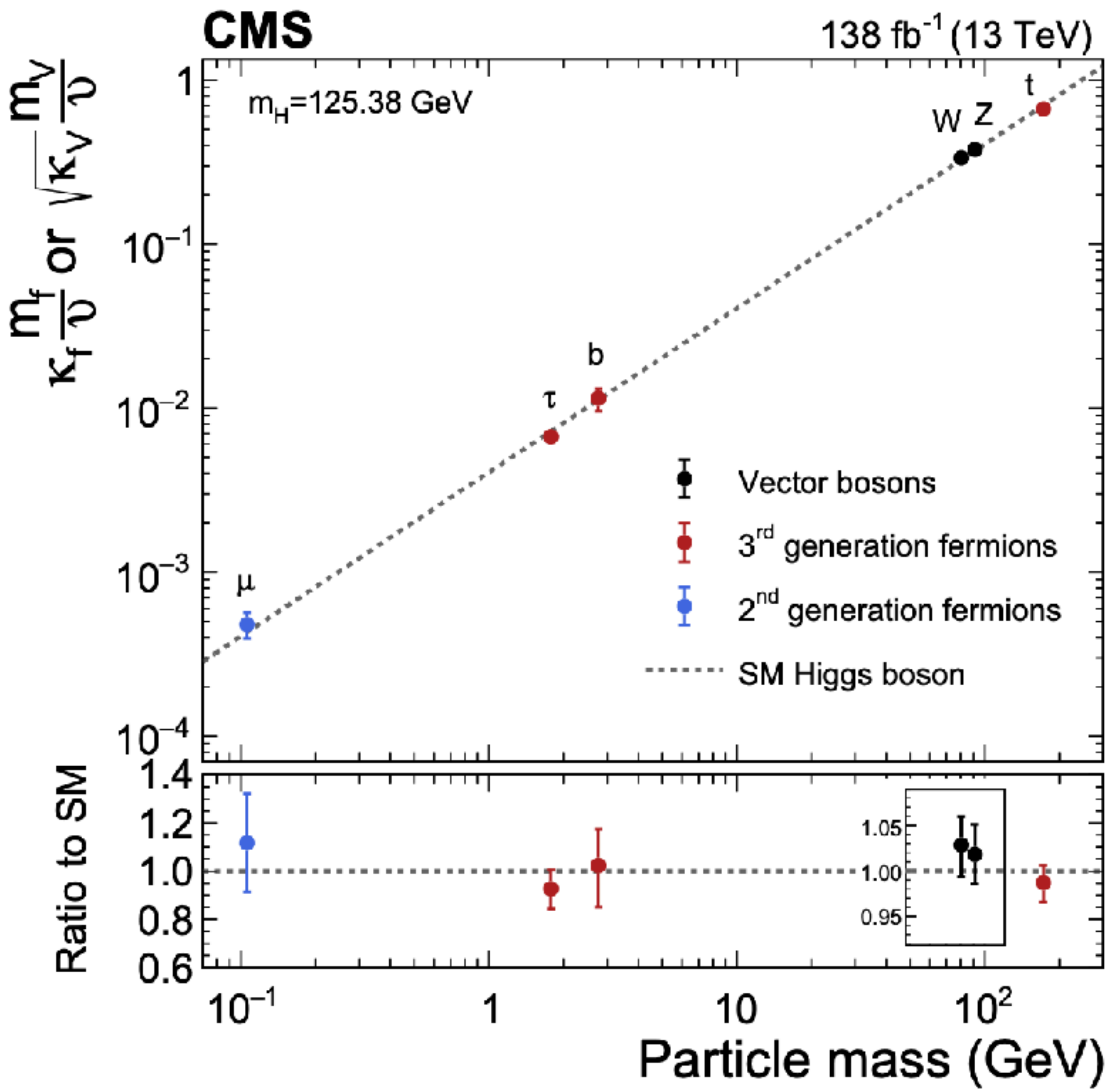
Why neutrinos?

The mechanism of neutrino masses is qualitatively different from charged fermions

All particles within the framework of the standard model, except for neutrinos, get their masses directly and exclusively from the Higgs mechanism

Data points in that direction, at least for charged fermions of the 2nd and 3rd families and gauge bosons

But neutrinos are very different



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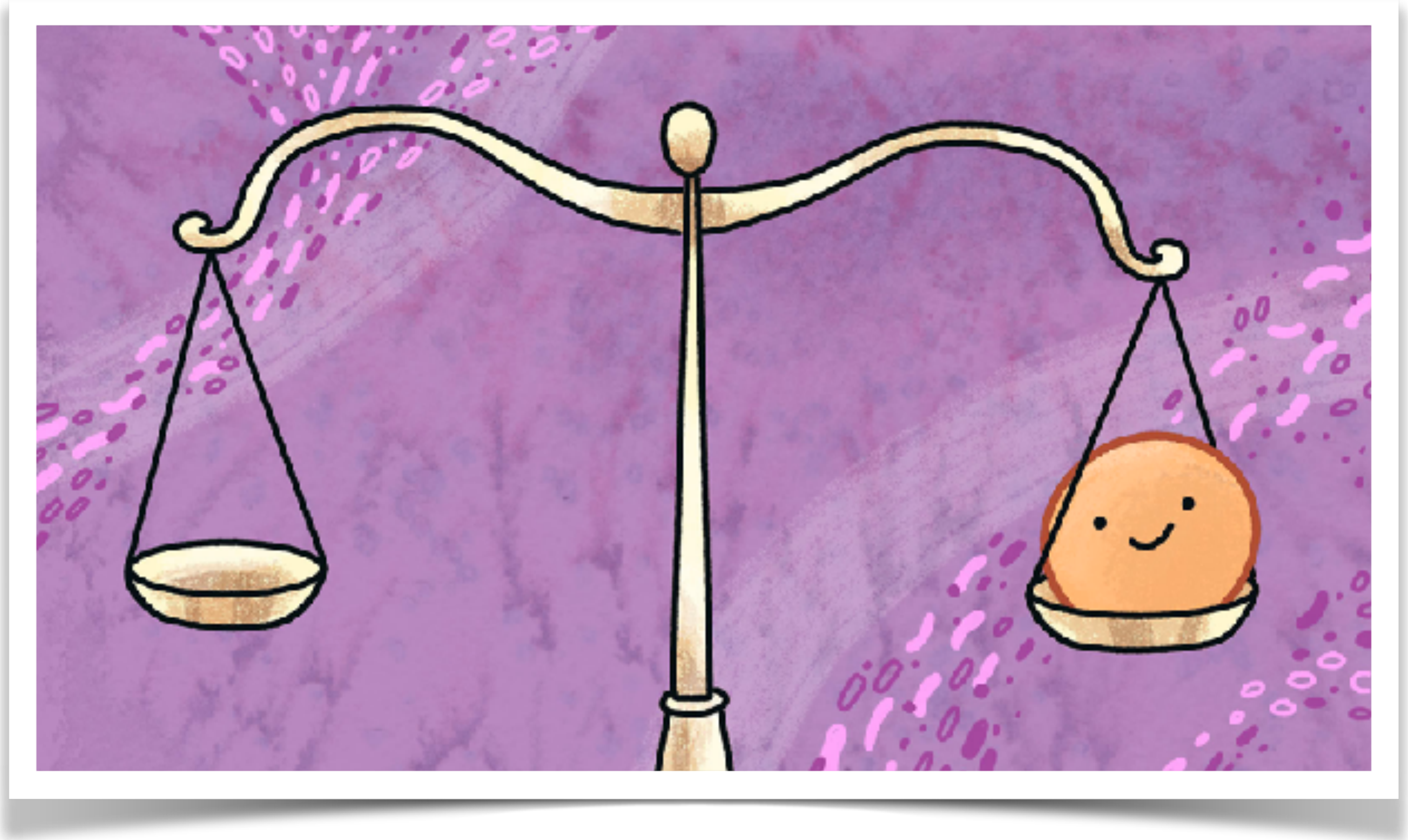
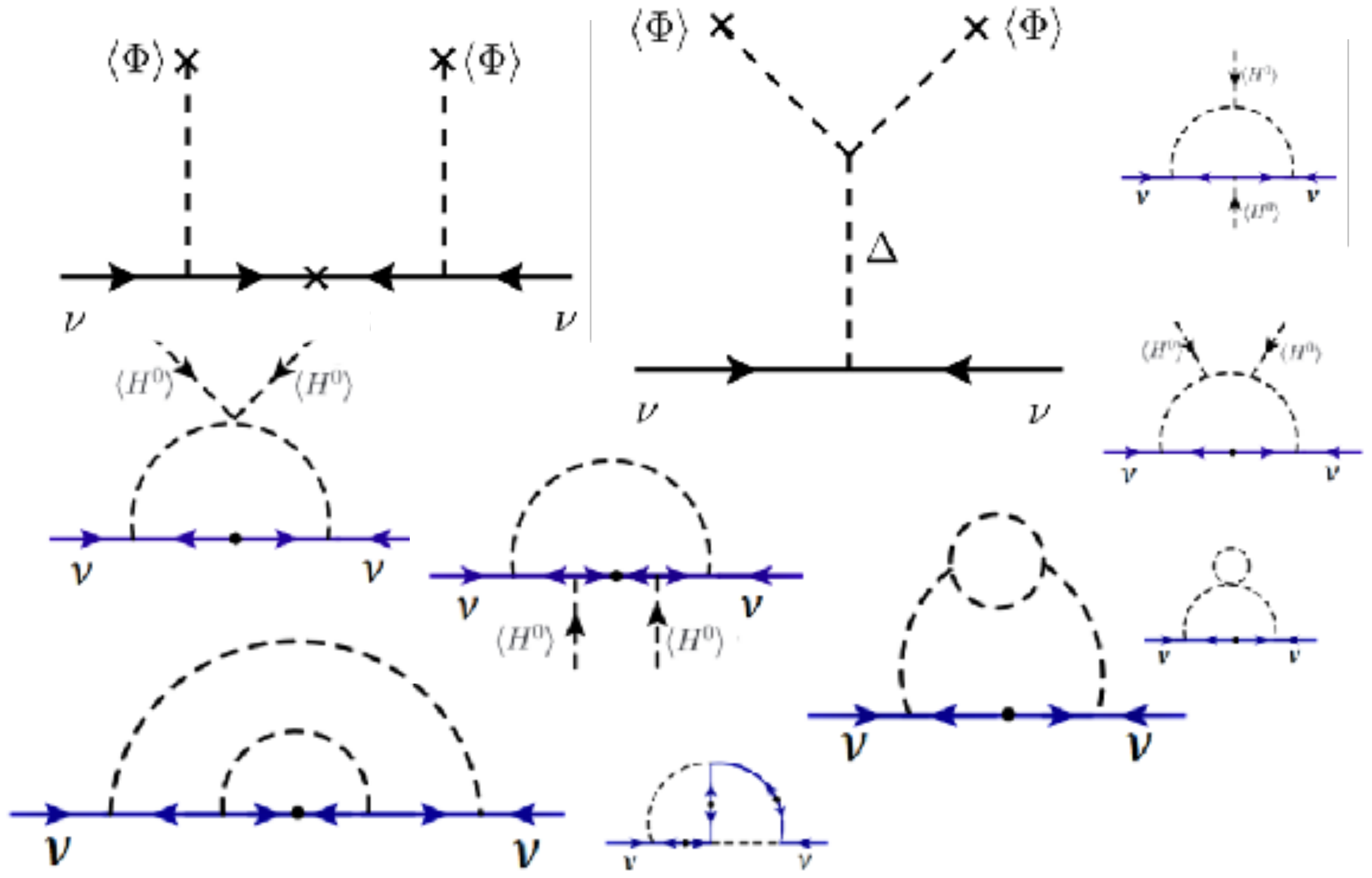
Why neutrinos?



Just repeating the Higgs mechanism for neutrinos (invoking a right-handed neutrino) would **predict a particle that is completely different from all observed particles**: its mass has nothing to do with electroweak symmetry breaking

Possible realizations of the neutrino mass mechanism span at least 20 orders of magnitude in scale, from the sub-eV to grand unification, **and there is little to no experimental guidance on the right energy scale**



Miranda Valle 1602.00864
Babu et al 1907.09498

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Why neutrinos?

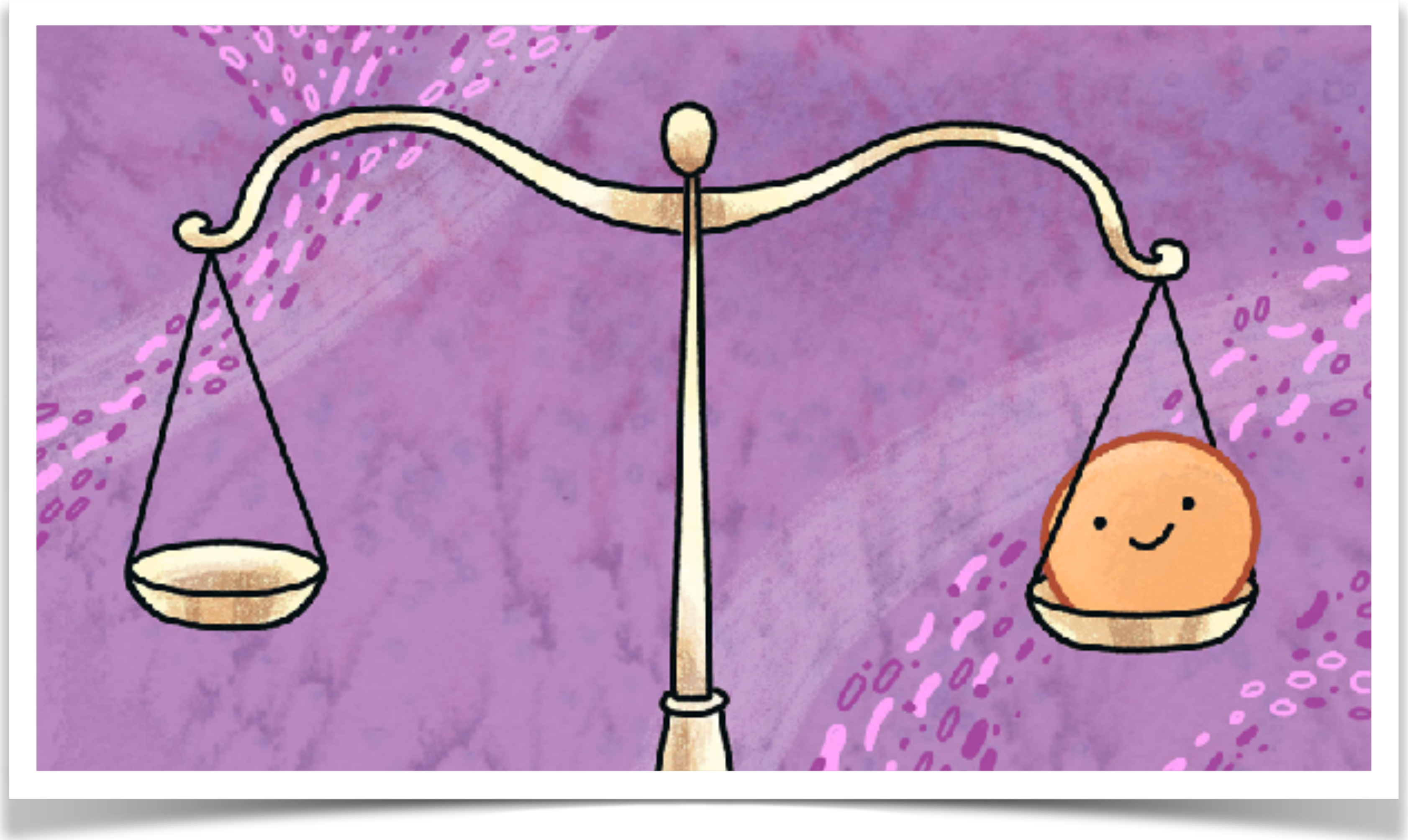
One key point:
The neutrino mass mechanism is much more than neutrino masses, just as electroweak symmetry breaking is much more than the Fermi constant

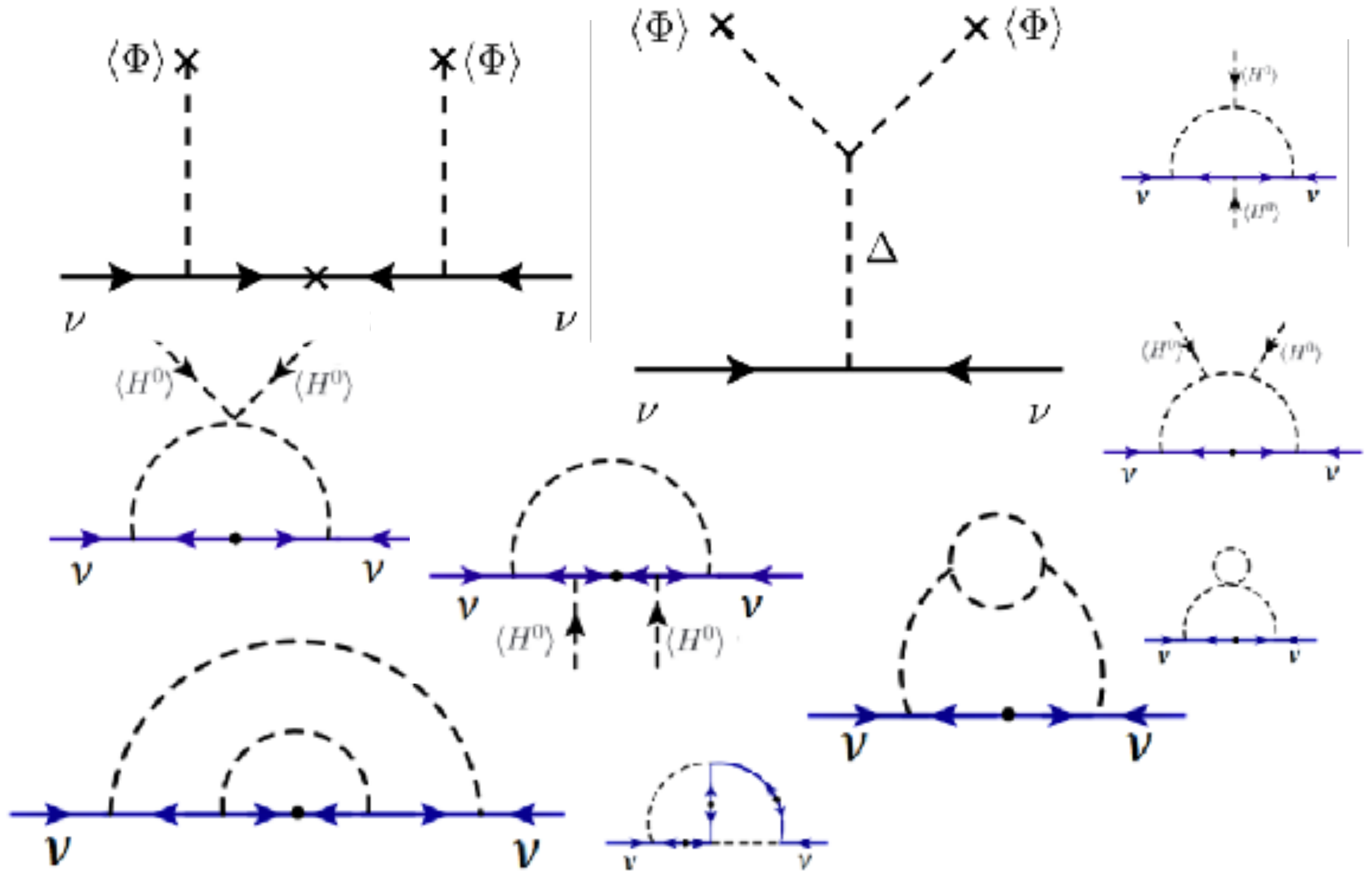
Of course, we need to determine neutrino masses and the nature of neutrinos, but it is crucial that we go beyond these measurements

We need to approach the problem from many sides:

Precision neutrino physics

BSM searches





Miranda Valle 1602.00864
Babu et al 1907.09498

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Precision neutrino physics program

Redundancy, redundancy, redundancy

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What is the deal about precision physics?

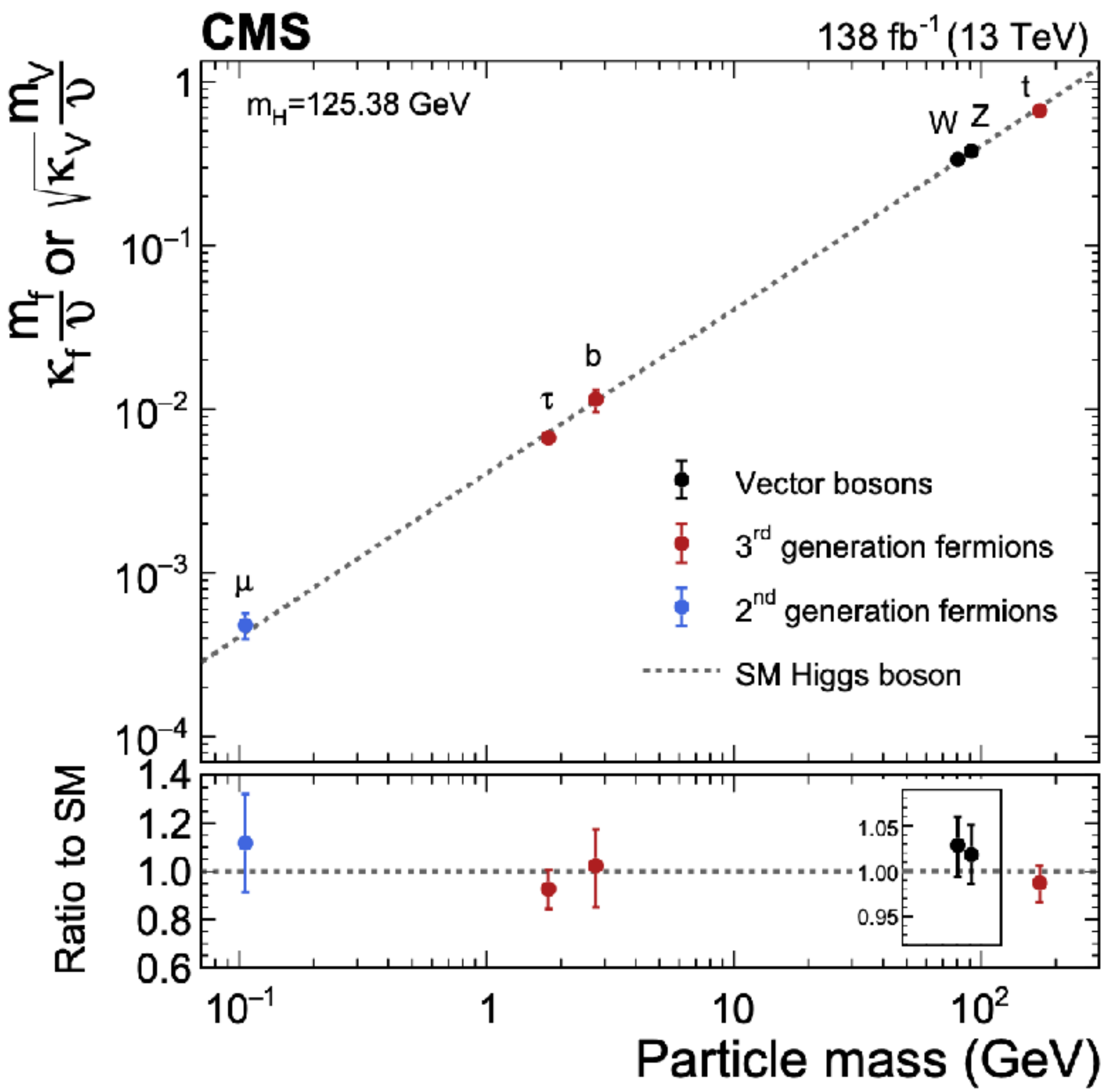
Let's go back to the Higgs example

Within the Higgs mechanism,
the coupling of particles to the Higgs is given by
the mass of the particle divided by the Higgs vev

We measure the mass by looking at, e.g.,
the kinematic threshold in e^+e^- collisions

Now we have a clear prediction for the Higgs coupling

Any deviation is a breaking of the standard model!



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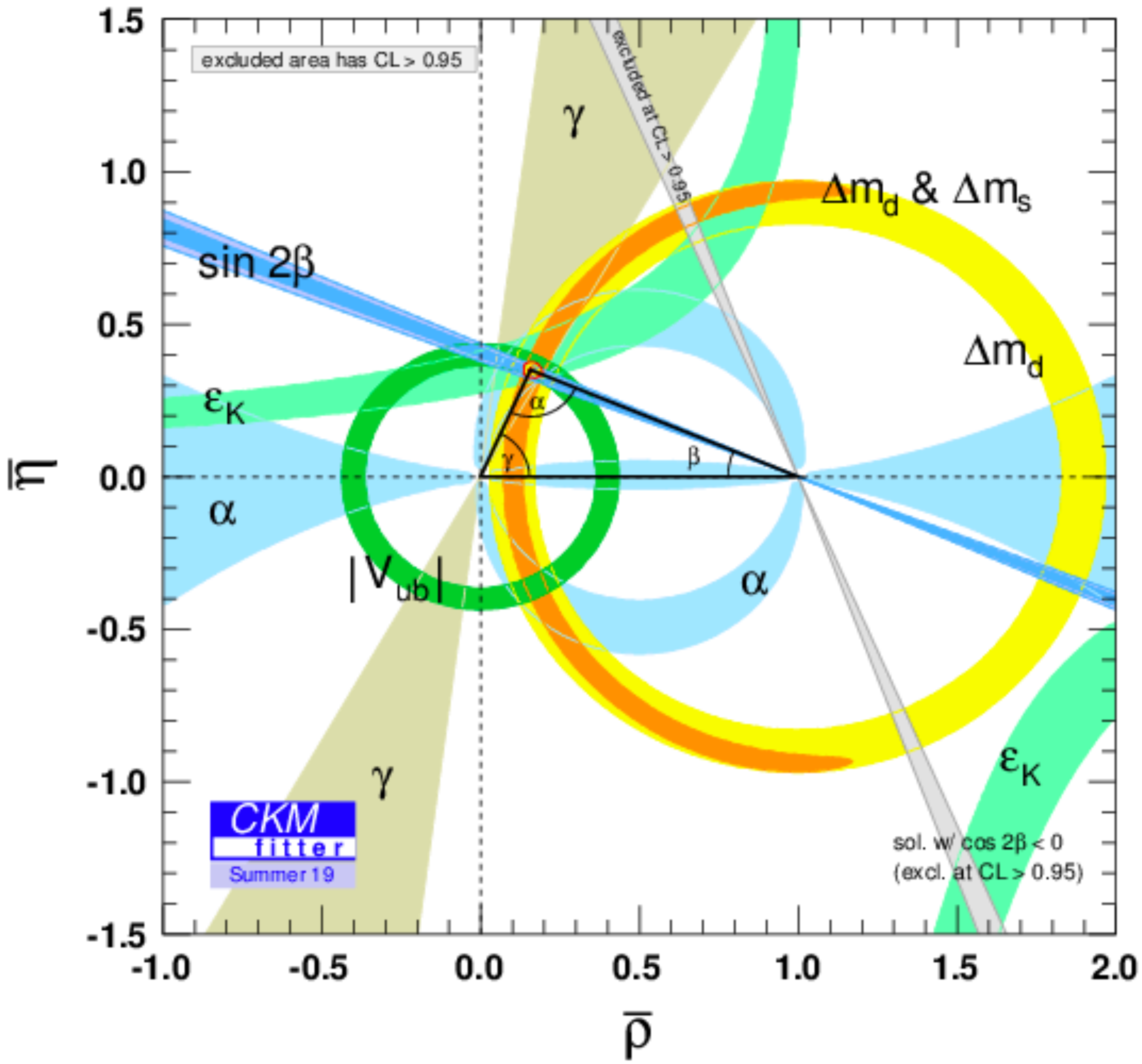
Precision neutrino physics



We have done it for quarks

We got to do it for neutrinos

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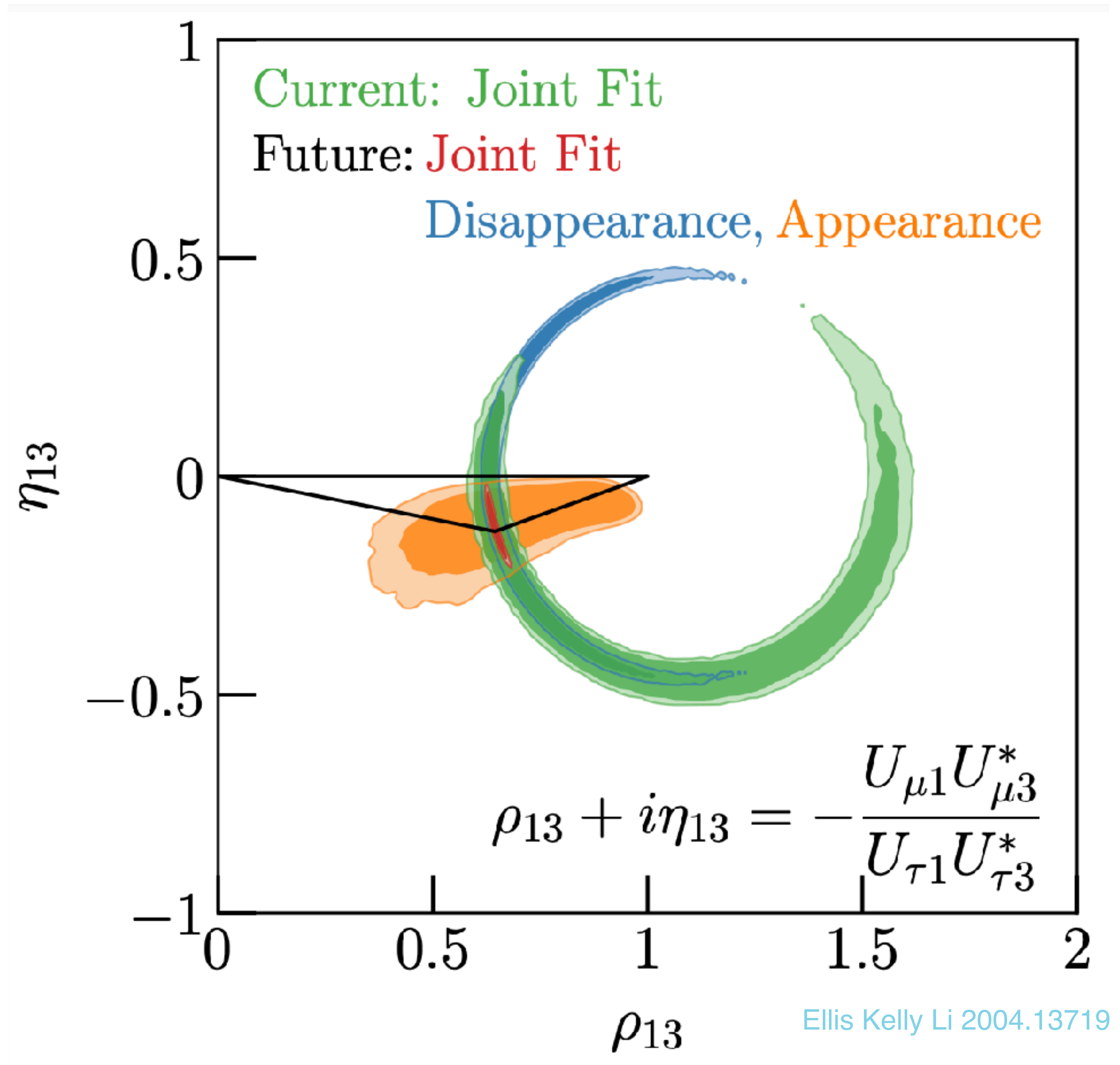
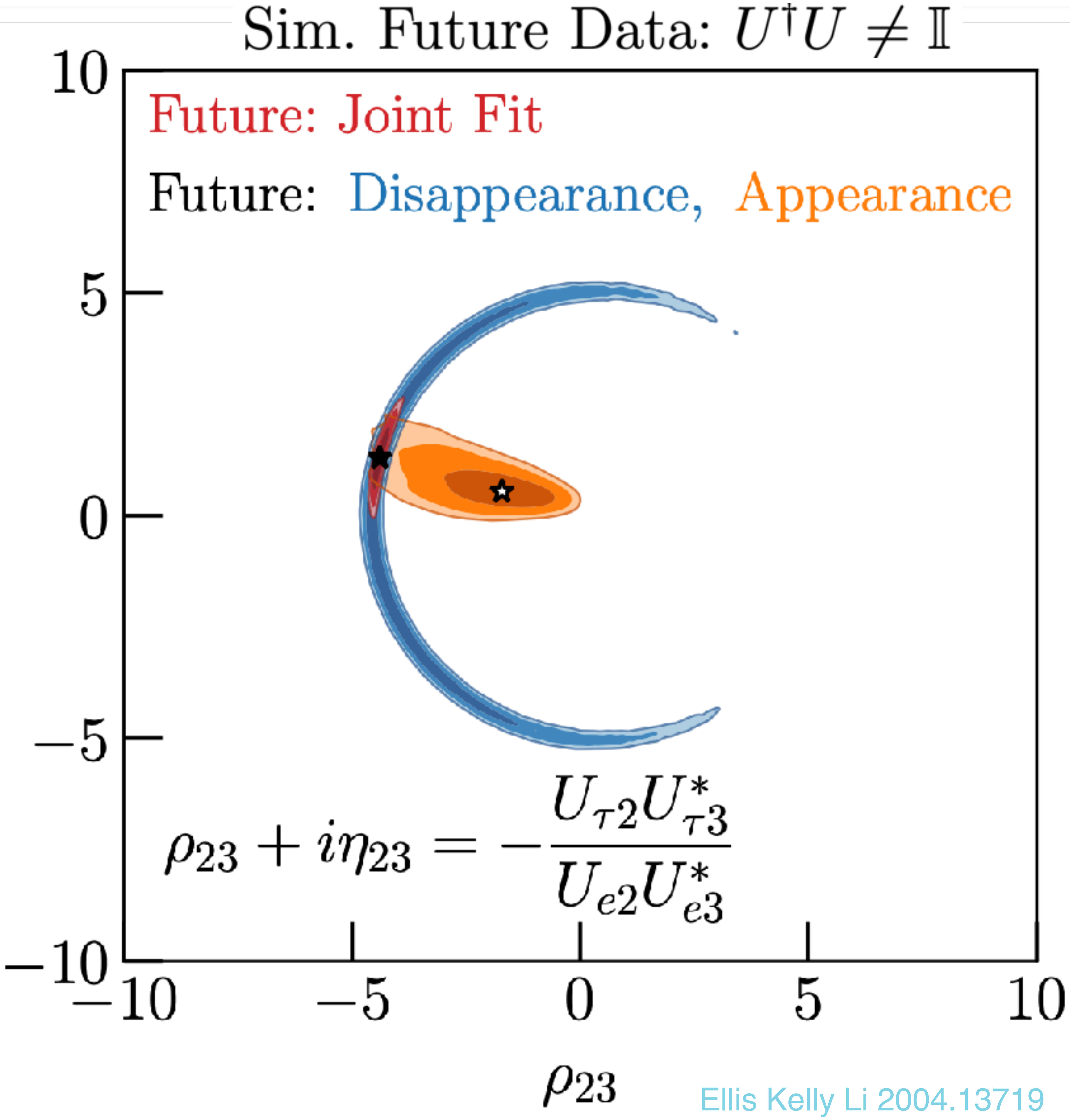
Precision neutrino physics



Ellis Kelly Li 2004.13719

DUNE, HK, JUNO and IceCube will enable a bona fide precision physics program in the neutrino sector

Precision neutrino physics



Ellis Kelly Li 2004.13719

DUNE, HK, JUNO and IceCube will enable a bona fide precision physics program in the neutrino sector

Precision neutrino physics program

New observables = new opportunities

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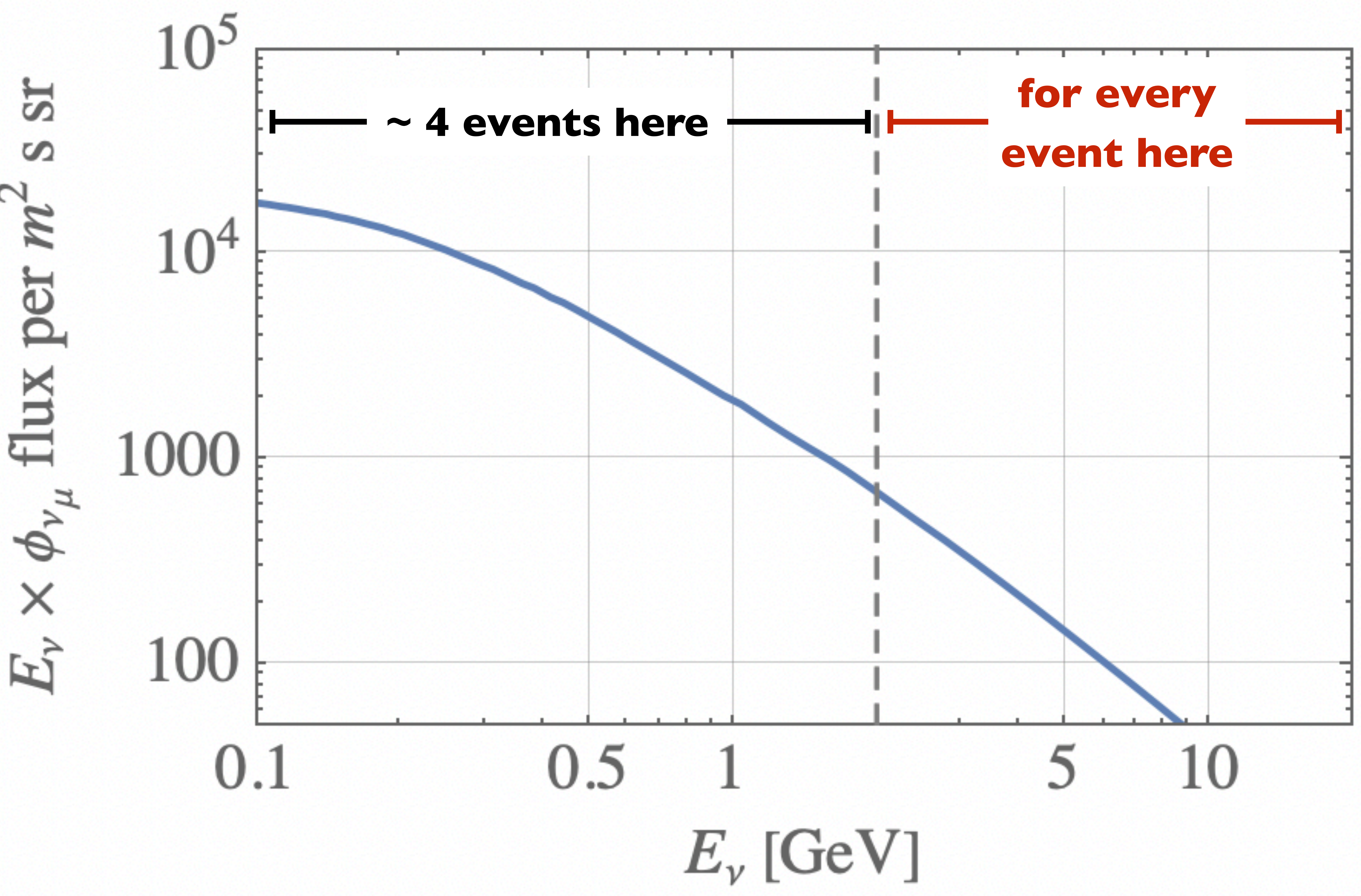
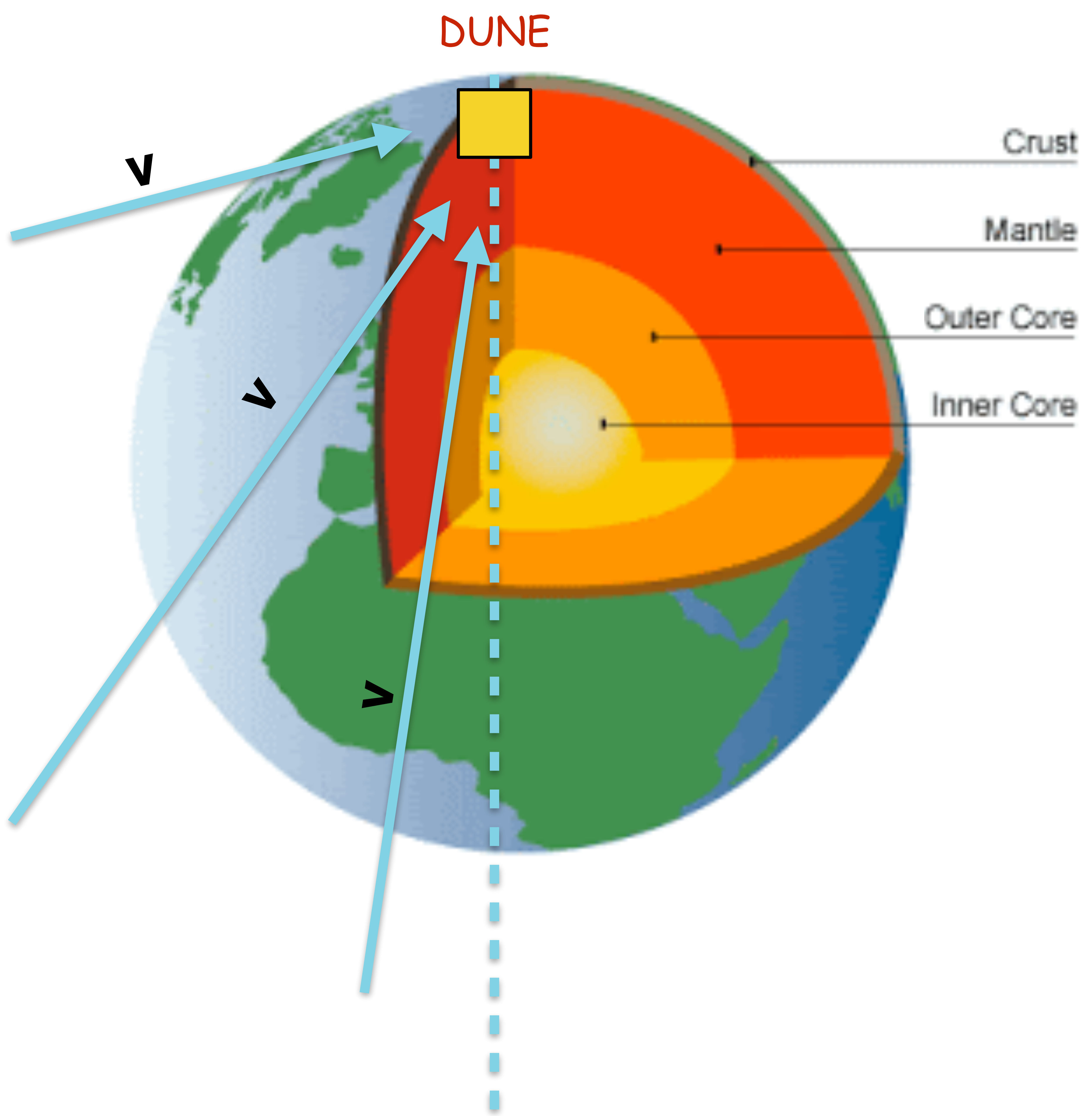
Low energy atmospheric neutrinos

Based on Kelly **PM** et al 1904.02751

Lots of atmospheric neutrinos below the GeV!





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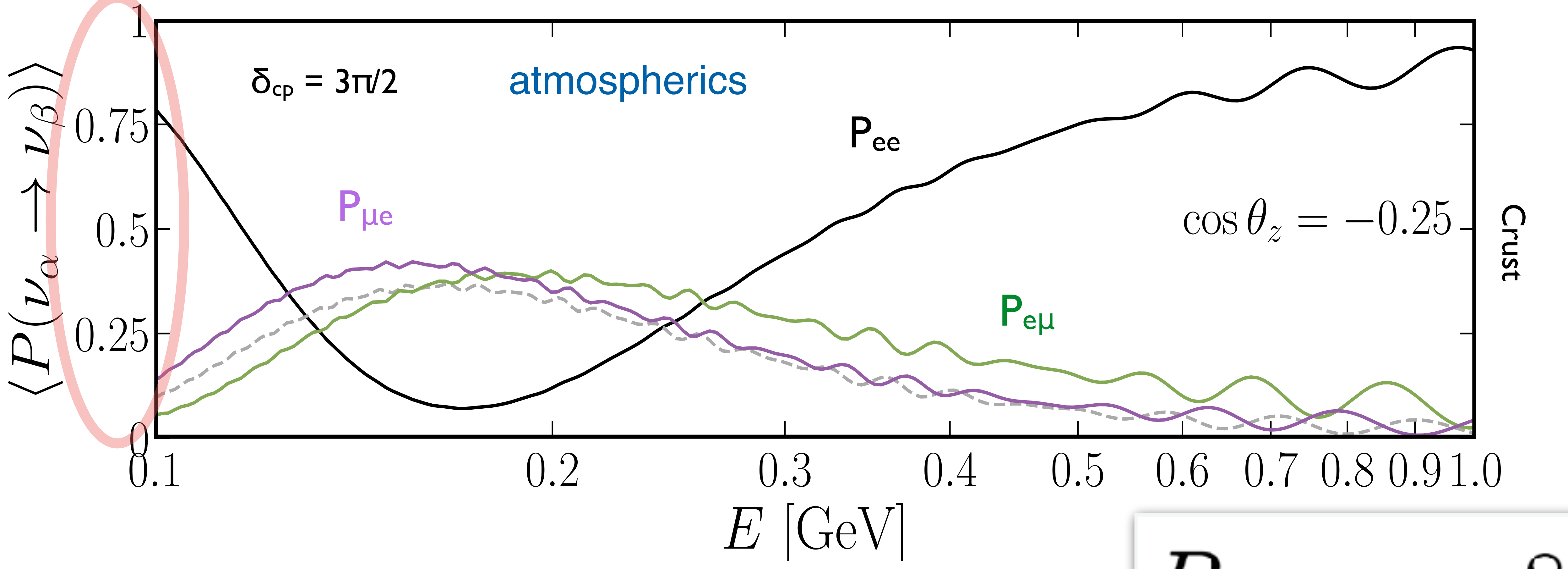
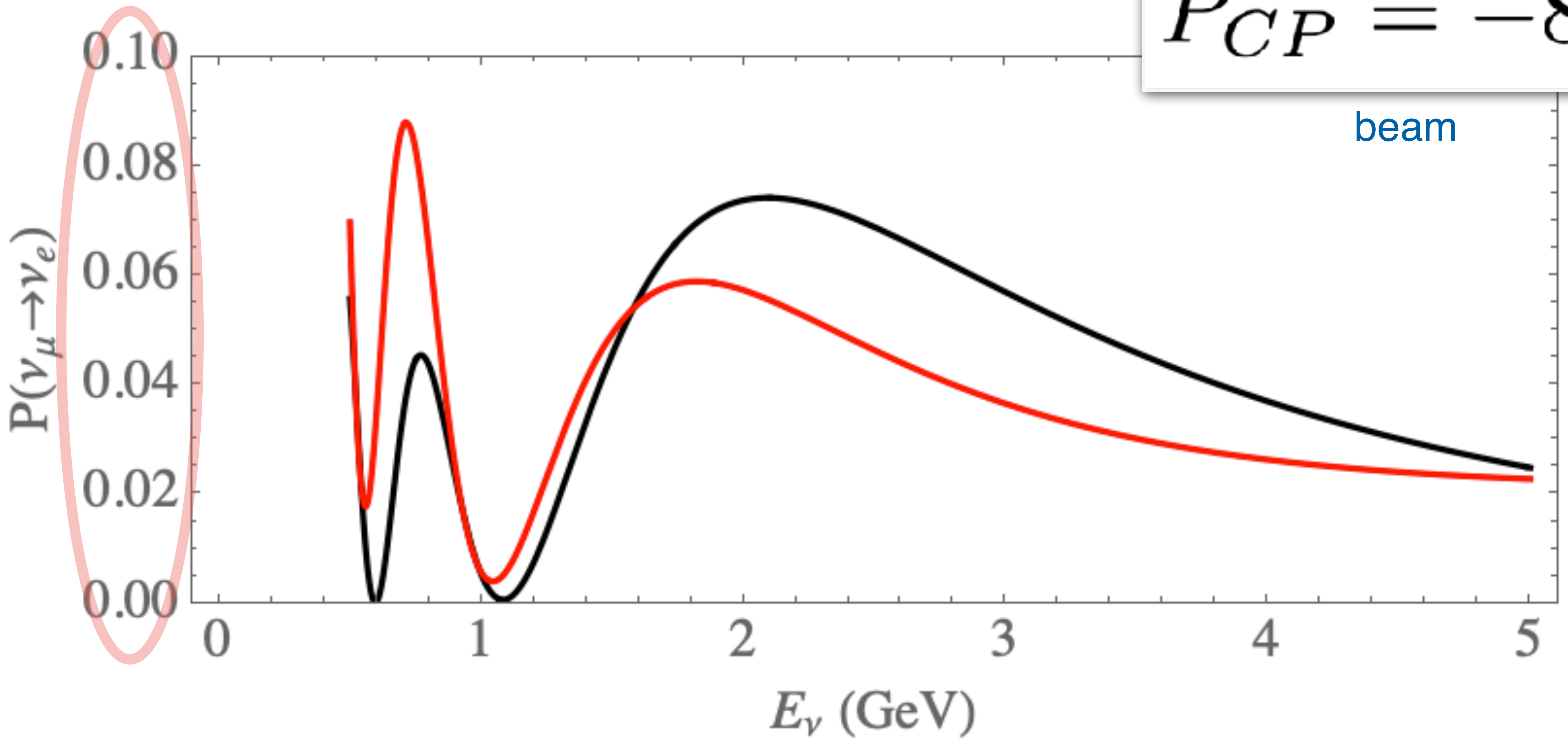
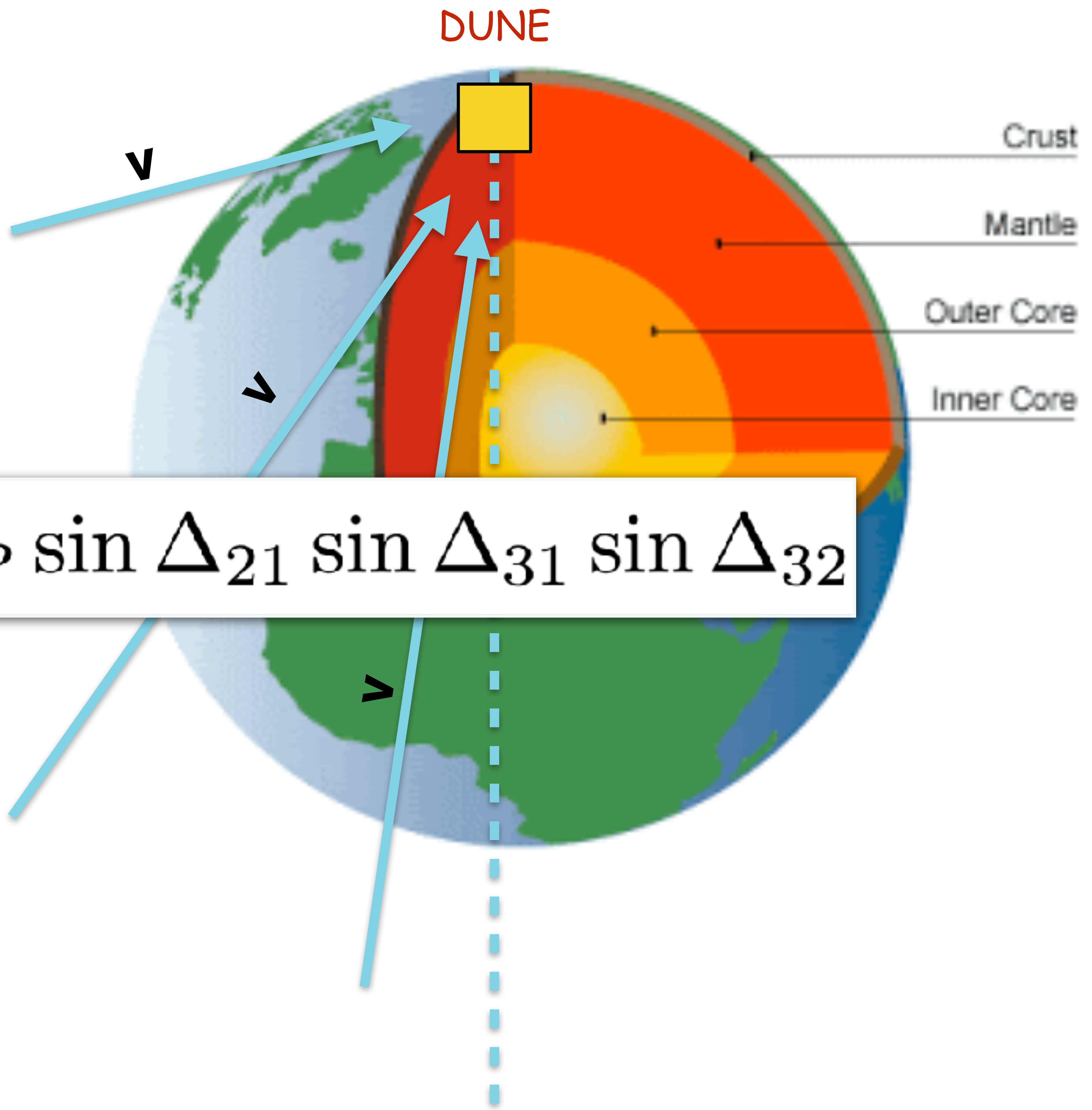
Based on Kelly **PM** et al 1904.02751

CP violation effect for atmospheric neutrinos is 10 times larger compared to beam neutrinos at DUNE!







$$P_{CP} = -8 J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

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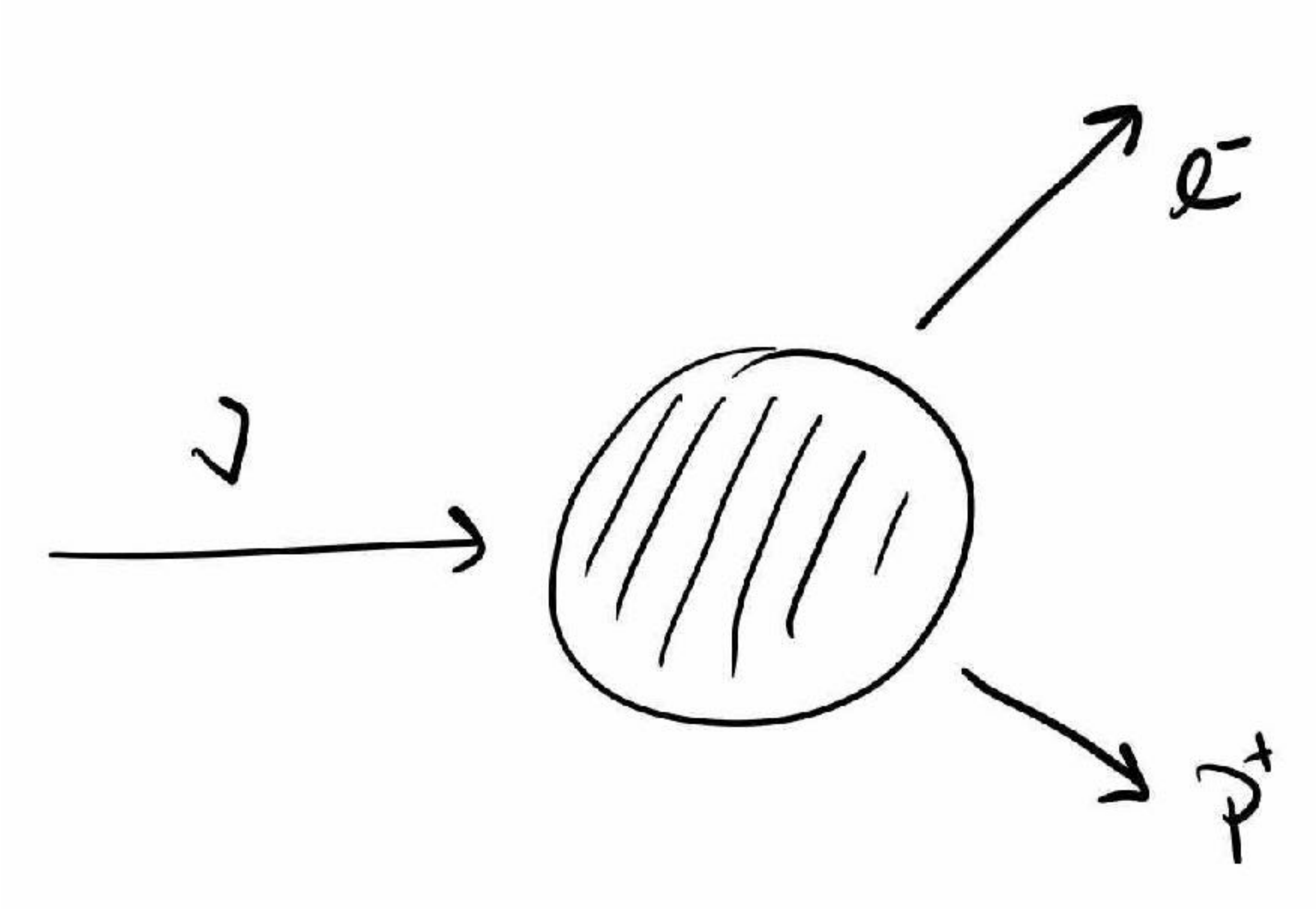
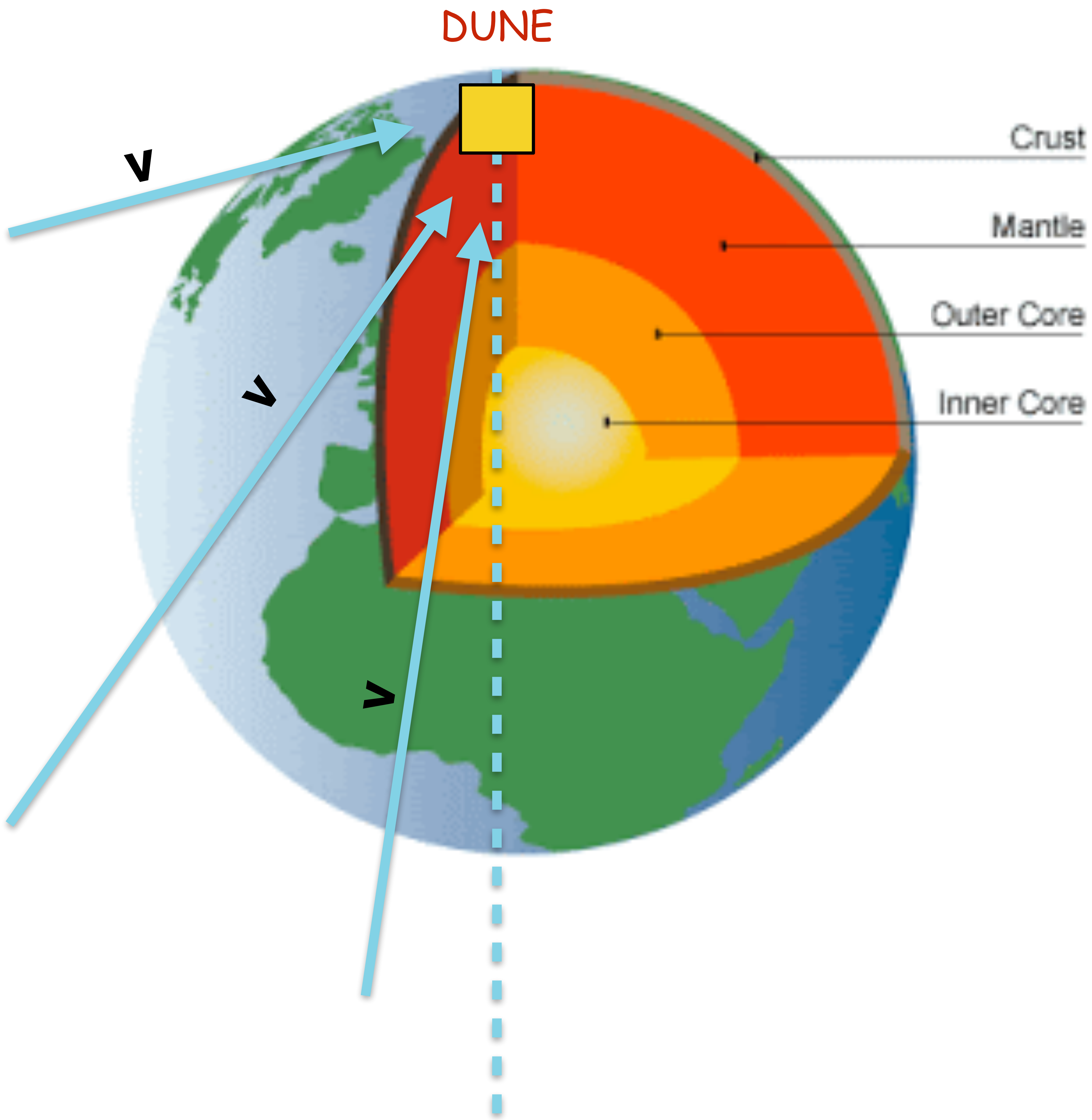
Low energy atmospheric neutrinos

Based on Kelly **PM** et al 1904.02751

Reconstructing neutrino energy and direction for sub-GeV atmospheric neutrinos is also 10x harder…





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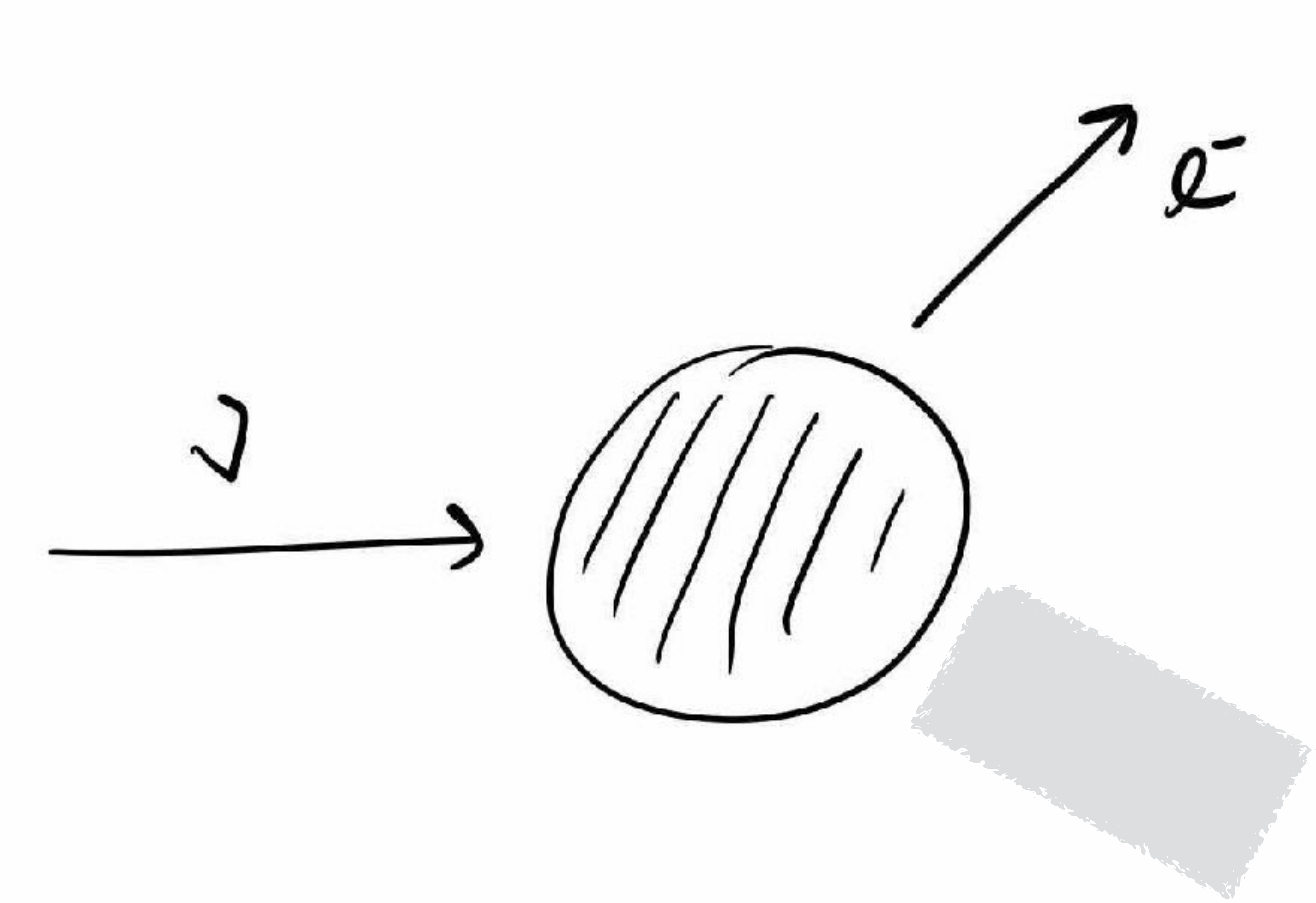

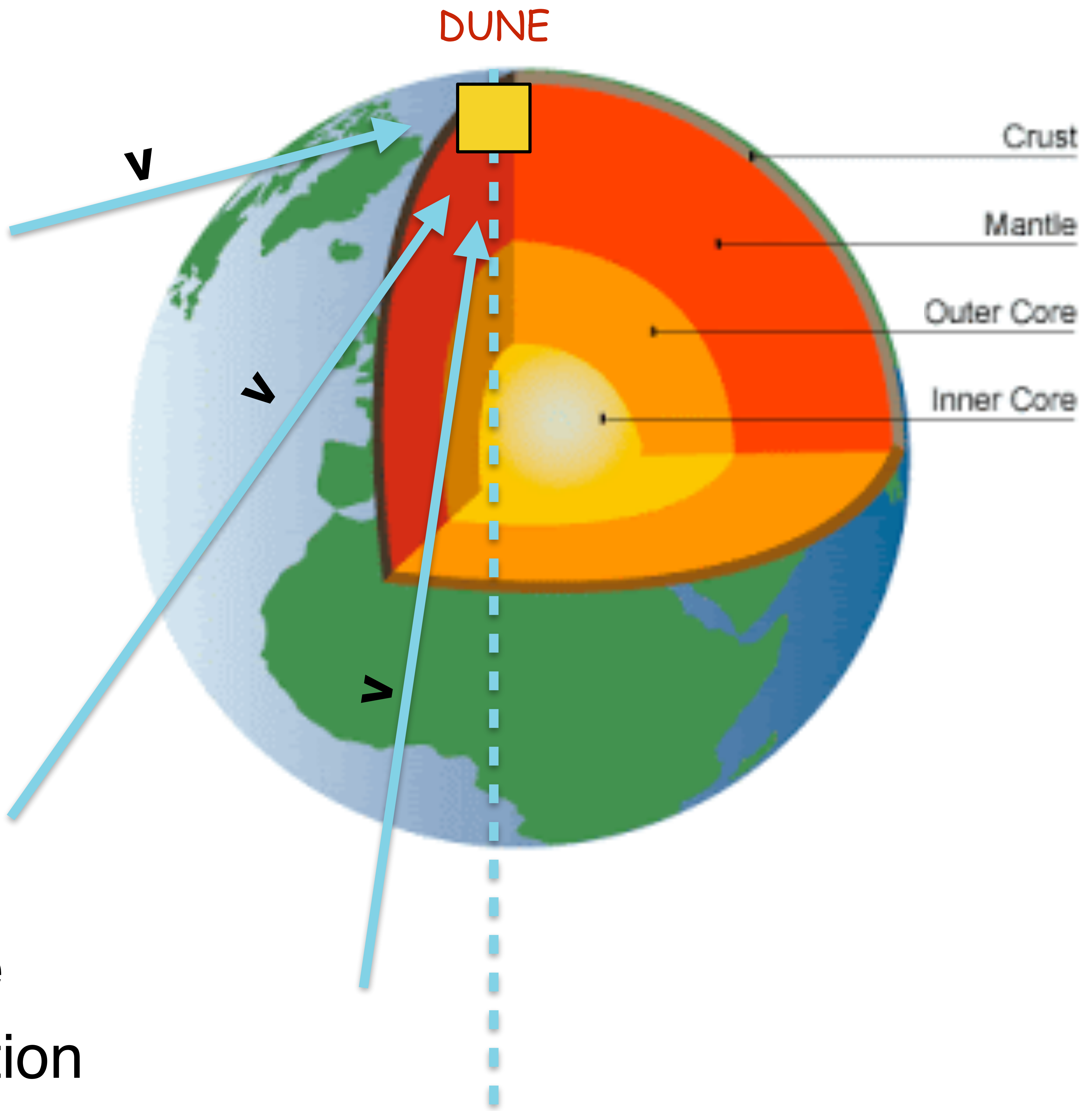

In large Cherenkov detectors, this proton would be invisible, making it very hard to get the neutrino direction

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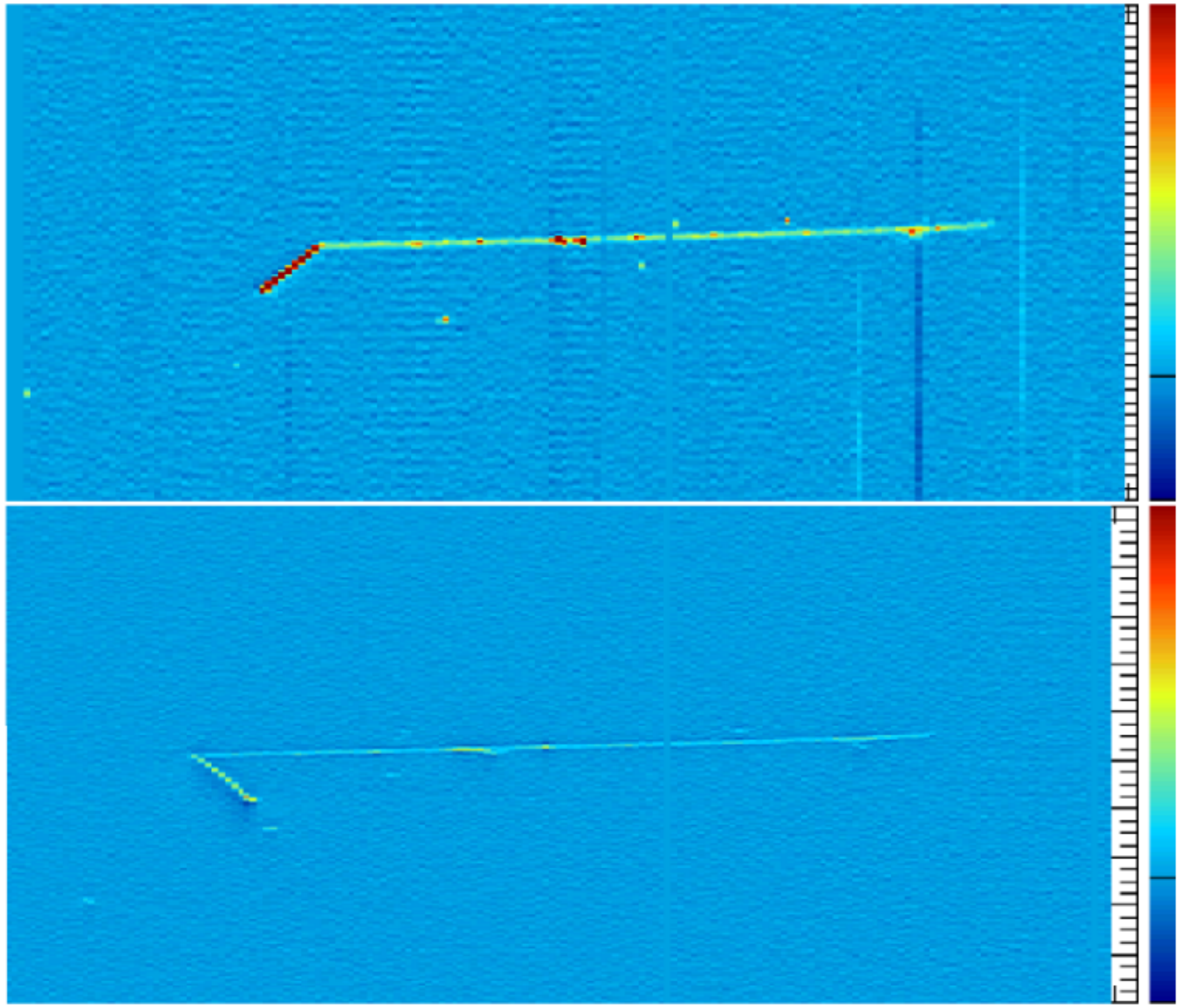
Low energy atmospheric neutrinos

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

ArgoNeuT 1810.06502



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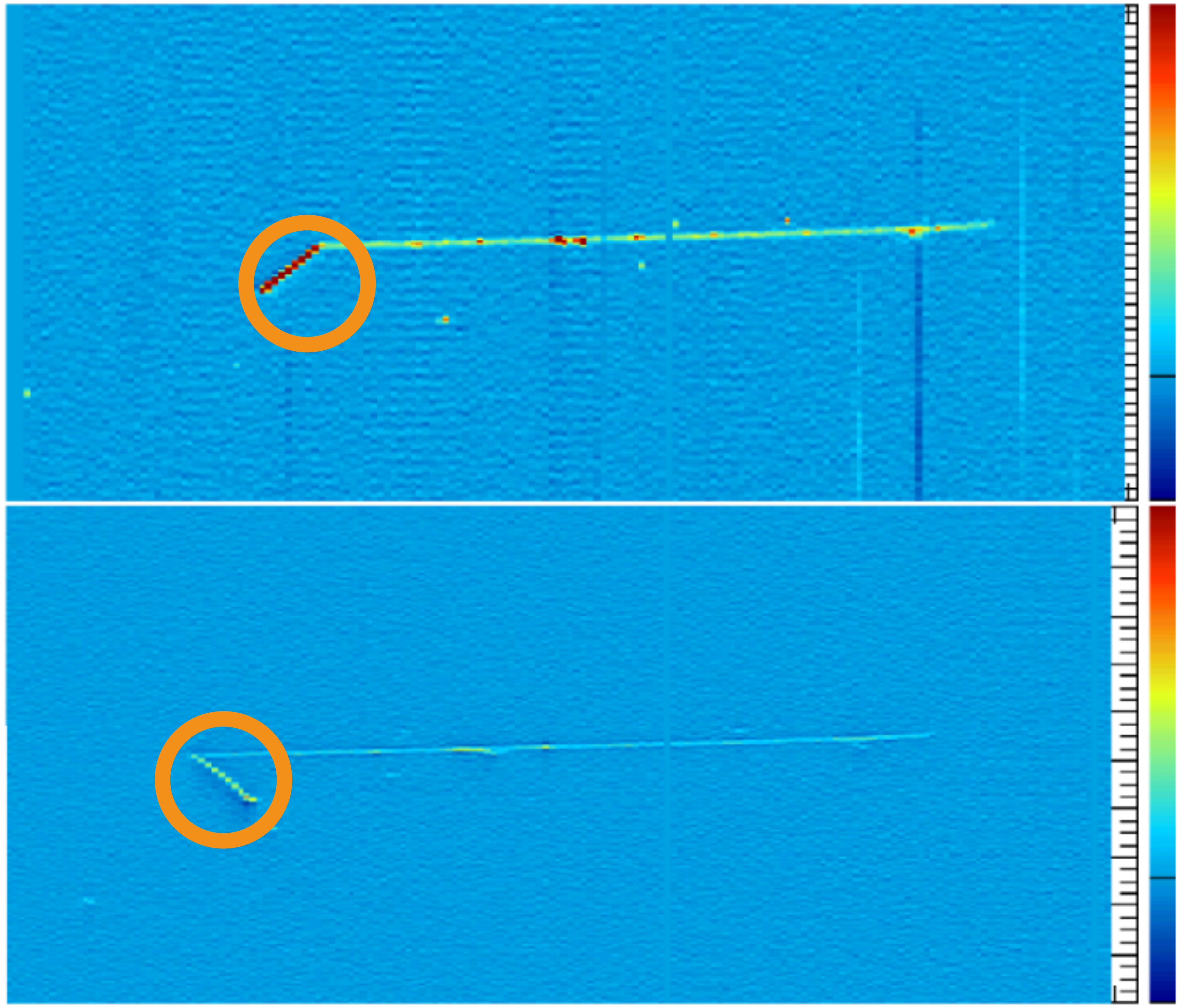

Reconstruct, identify and point.

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

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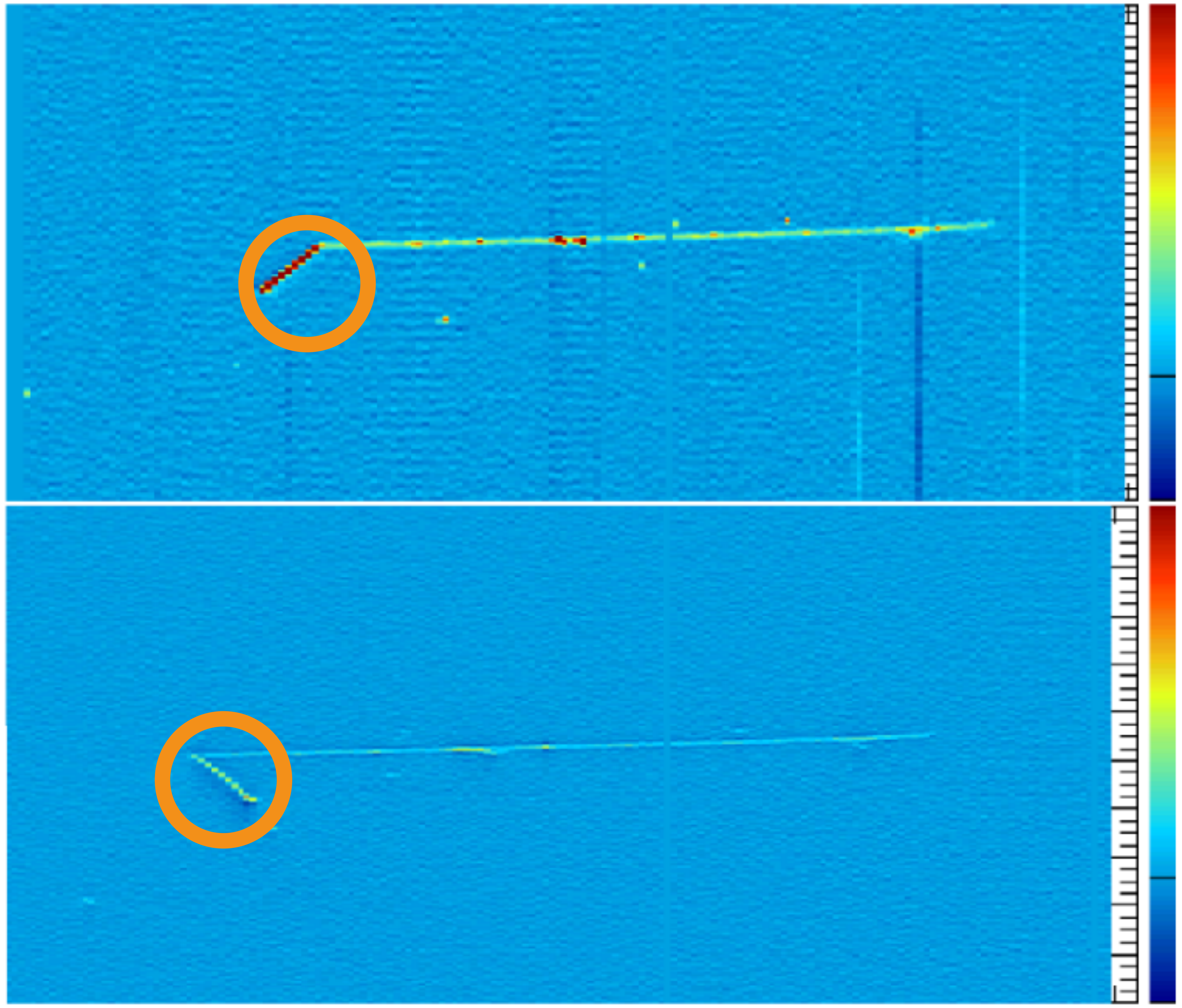

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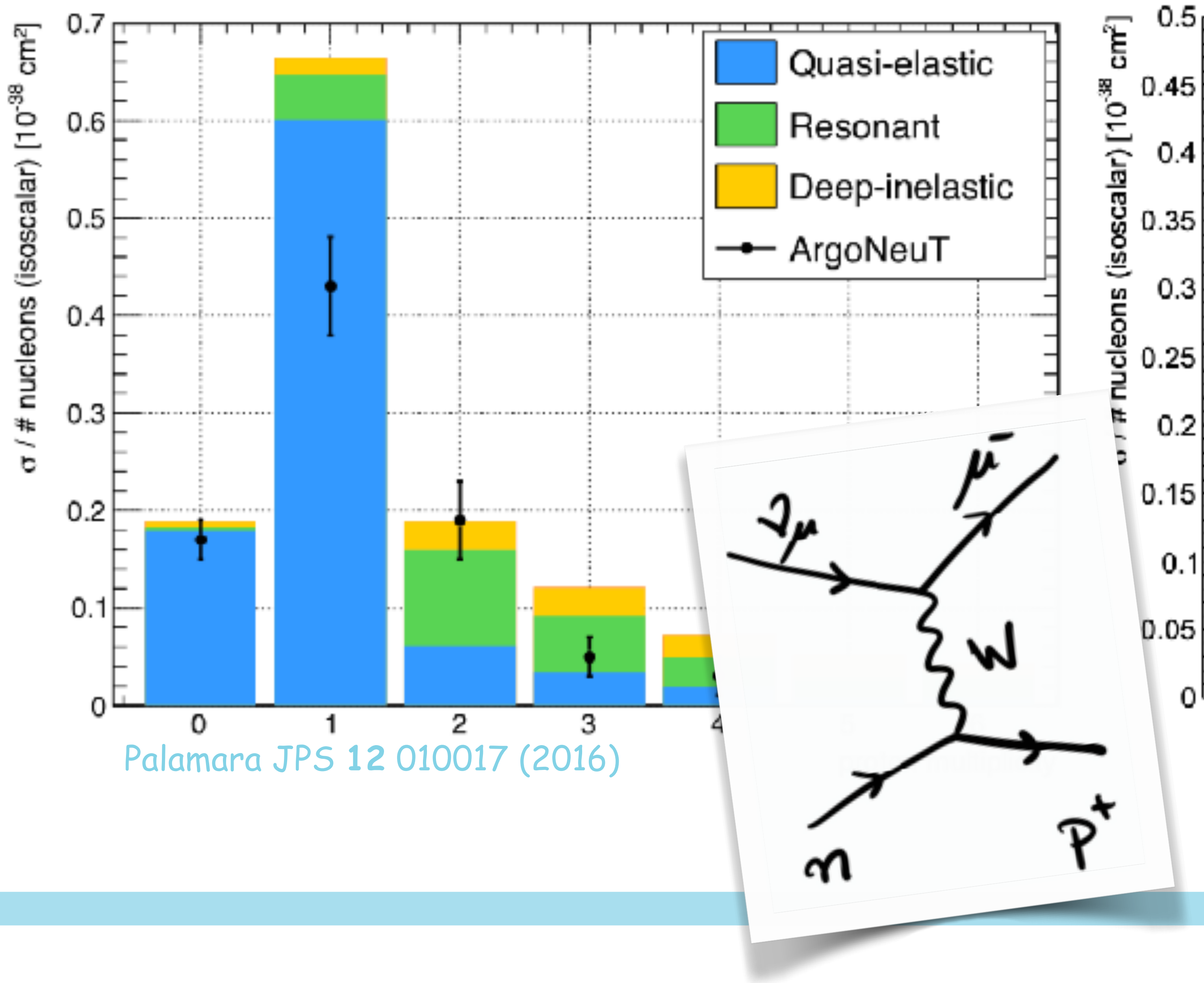
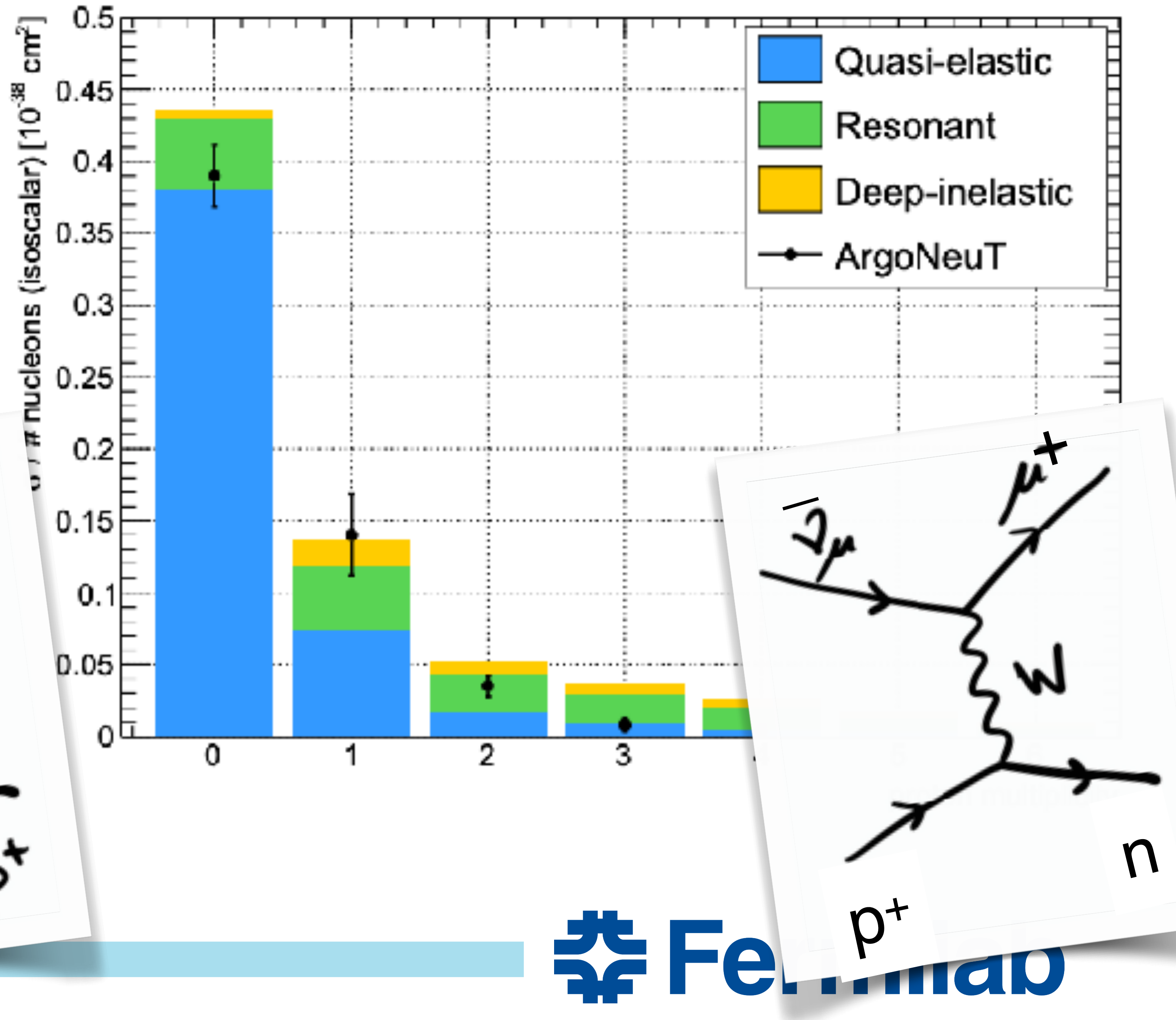
Event topology carries extra information



Palamara JPS 12 010017 (2016)



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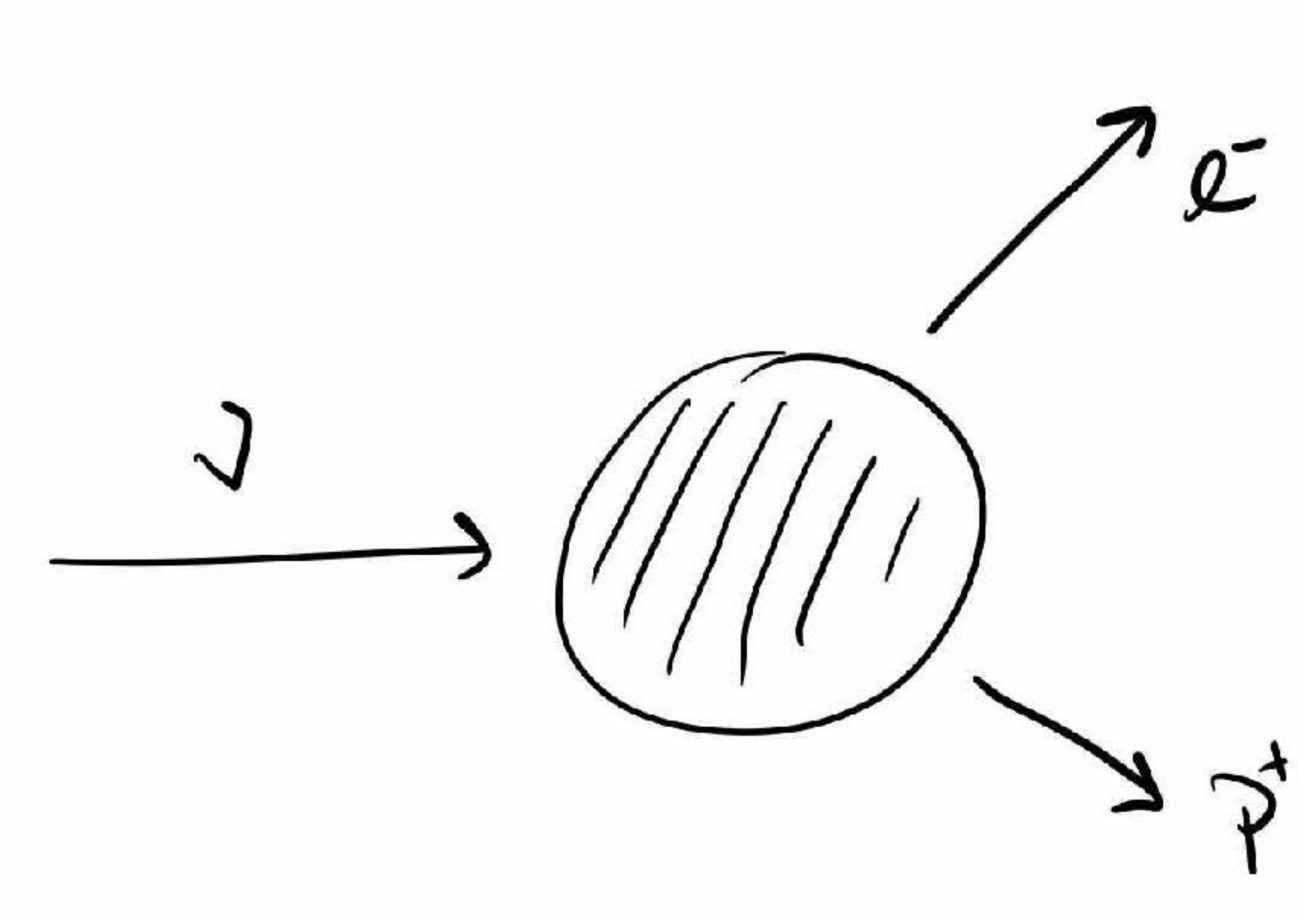

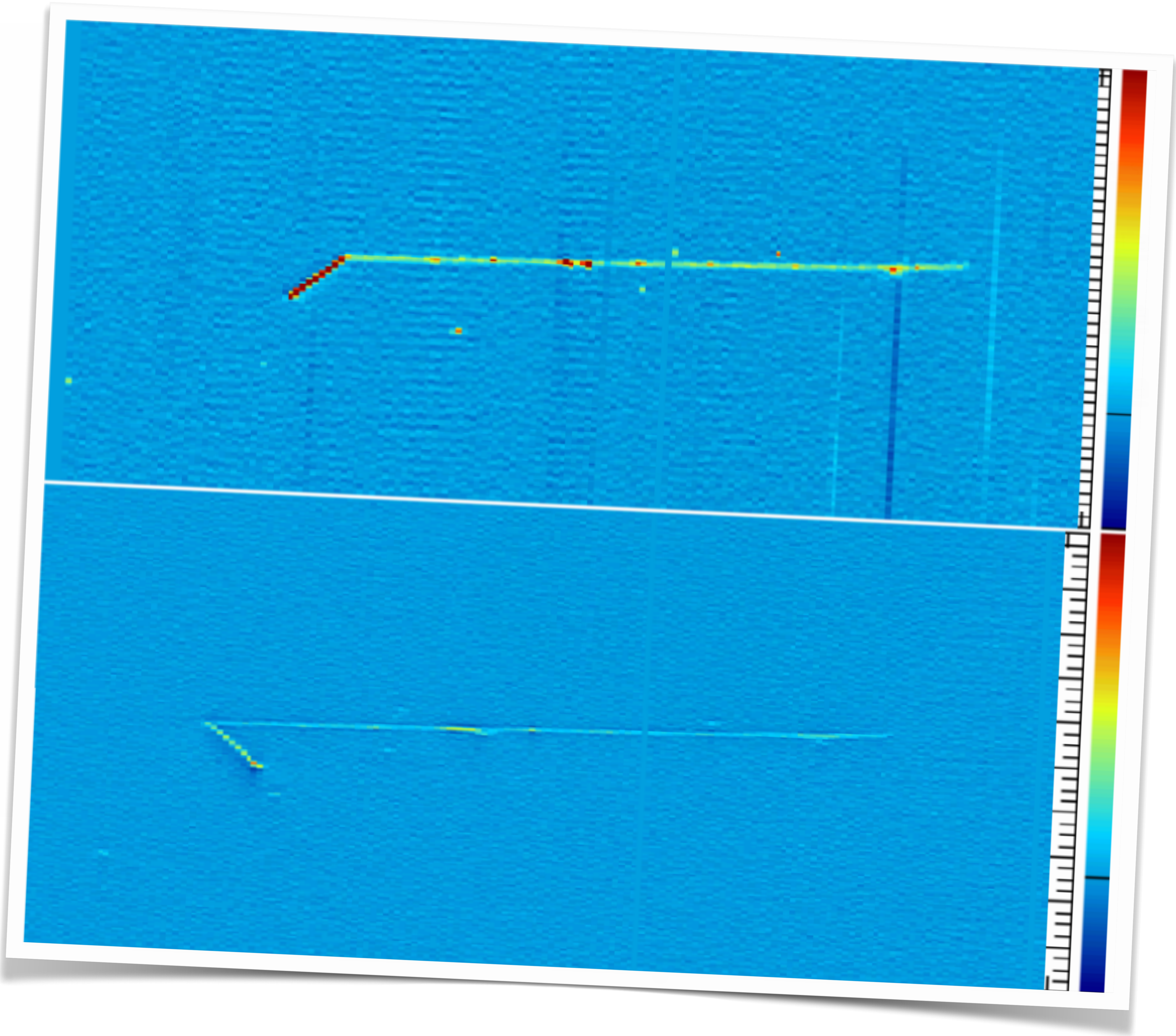

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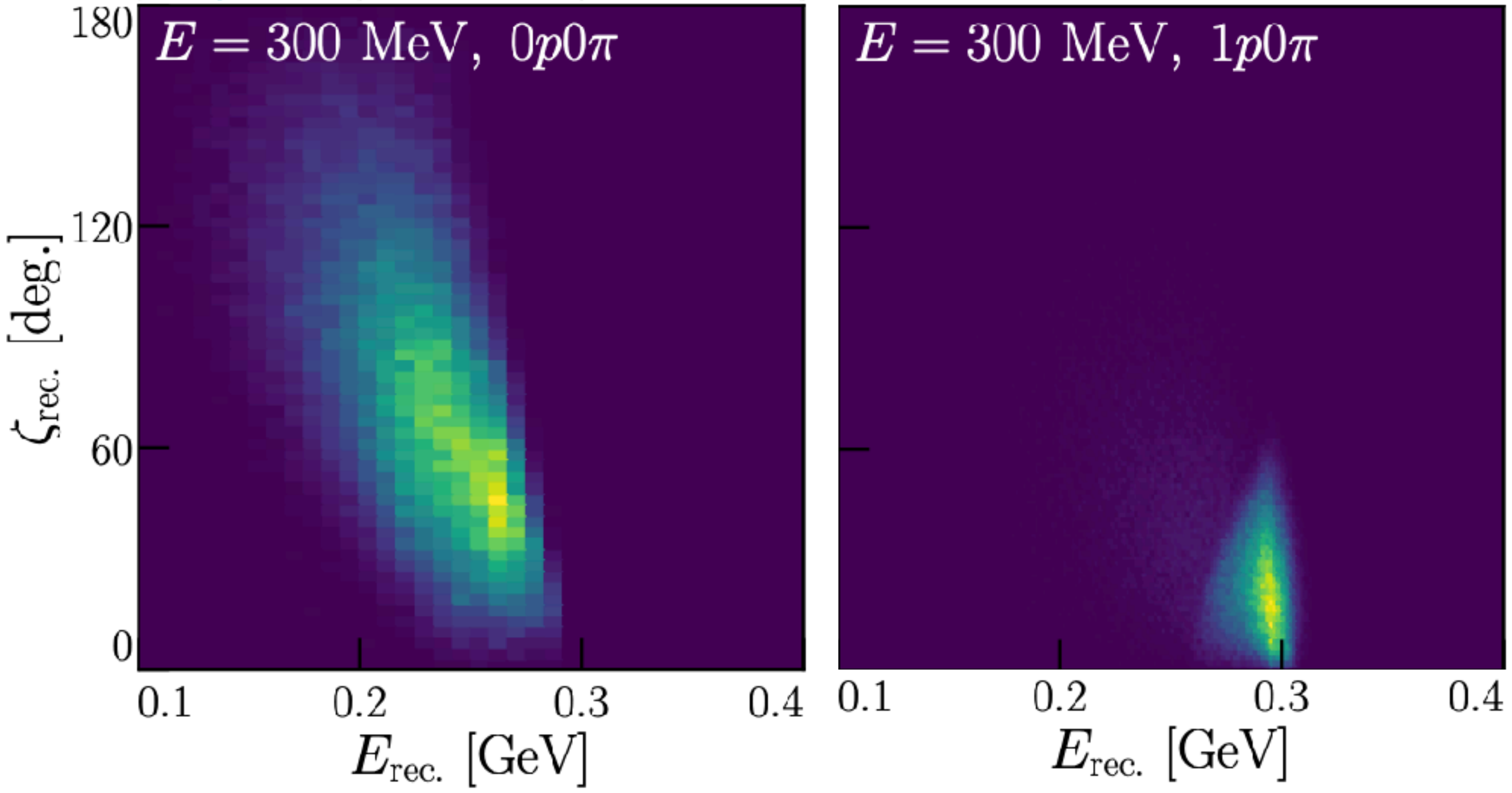
Low energy atmospheric neutrinos

Kelly, PM et al 2110.00003



Details:

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

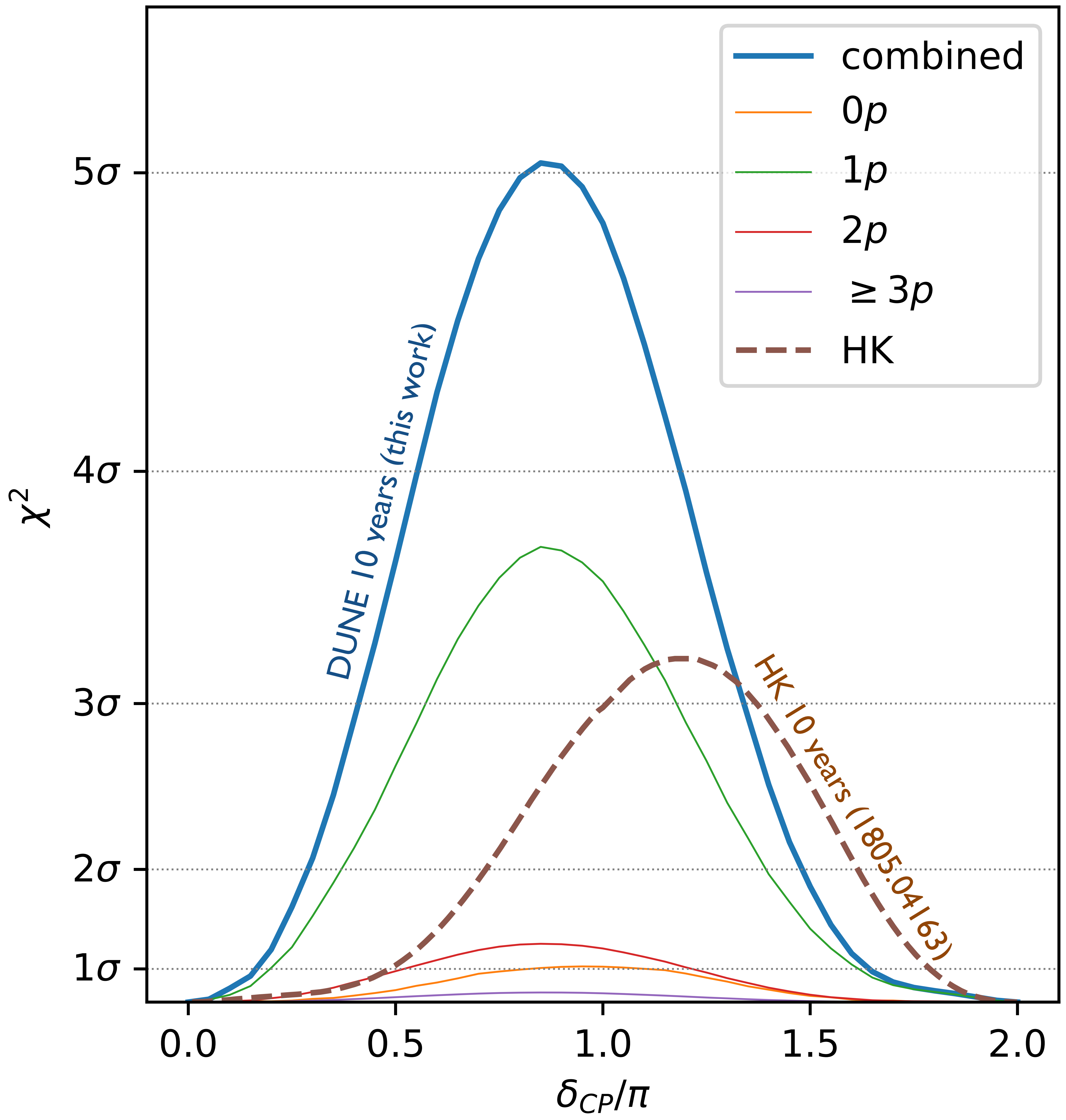
Account for uncertainties of atmospheric neutrino fluxes $\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$

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

Realistic LArTPC capabilities

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

Classify events by final state topology (number of protons)



Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

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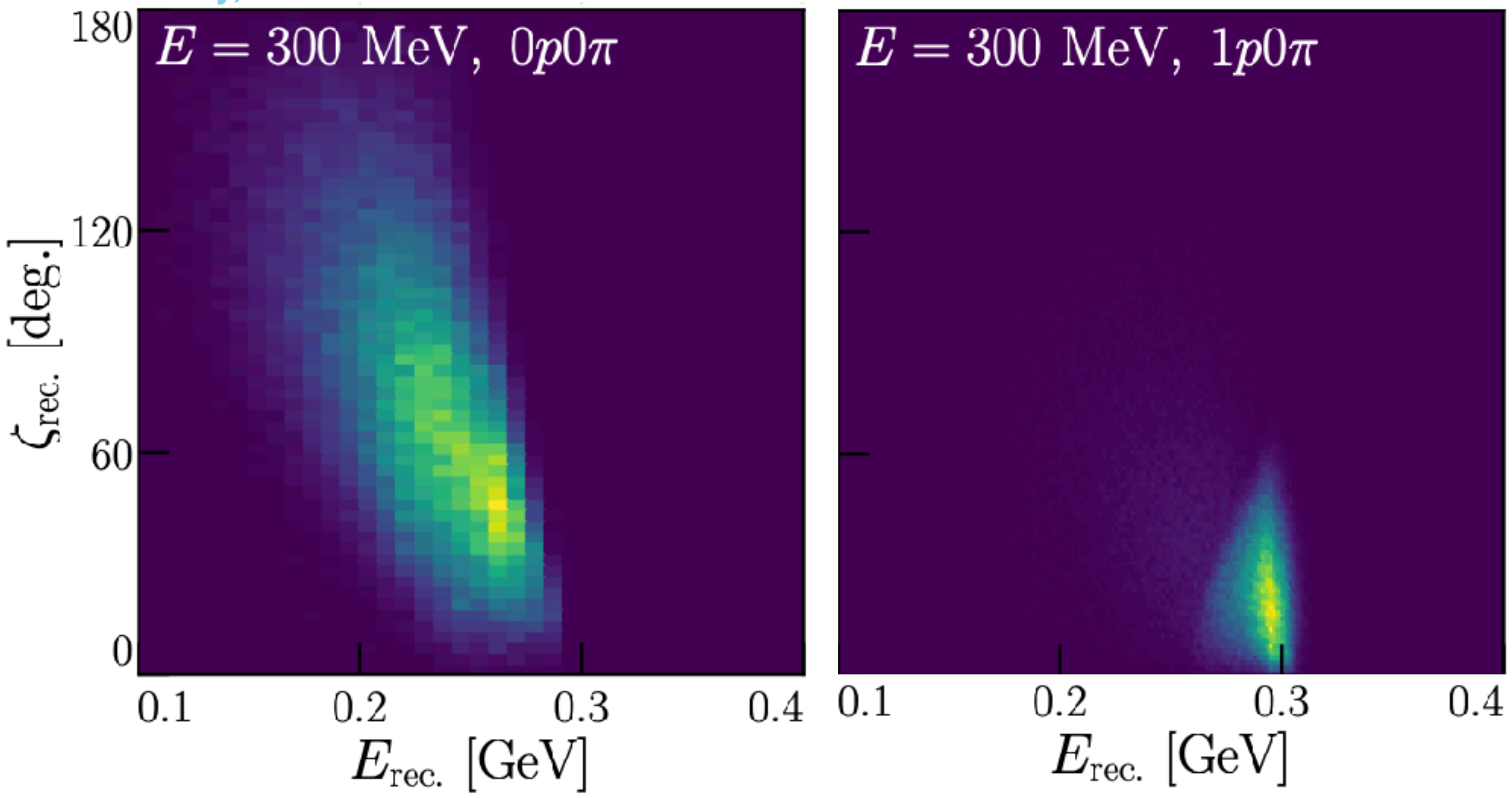
Low energy atmospheric neutrinos

Kelly, PM et al 2110.00003



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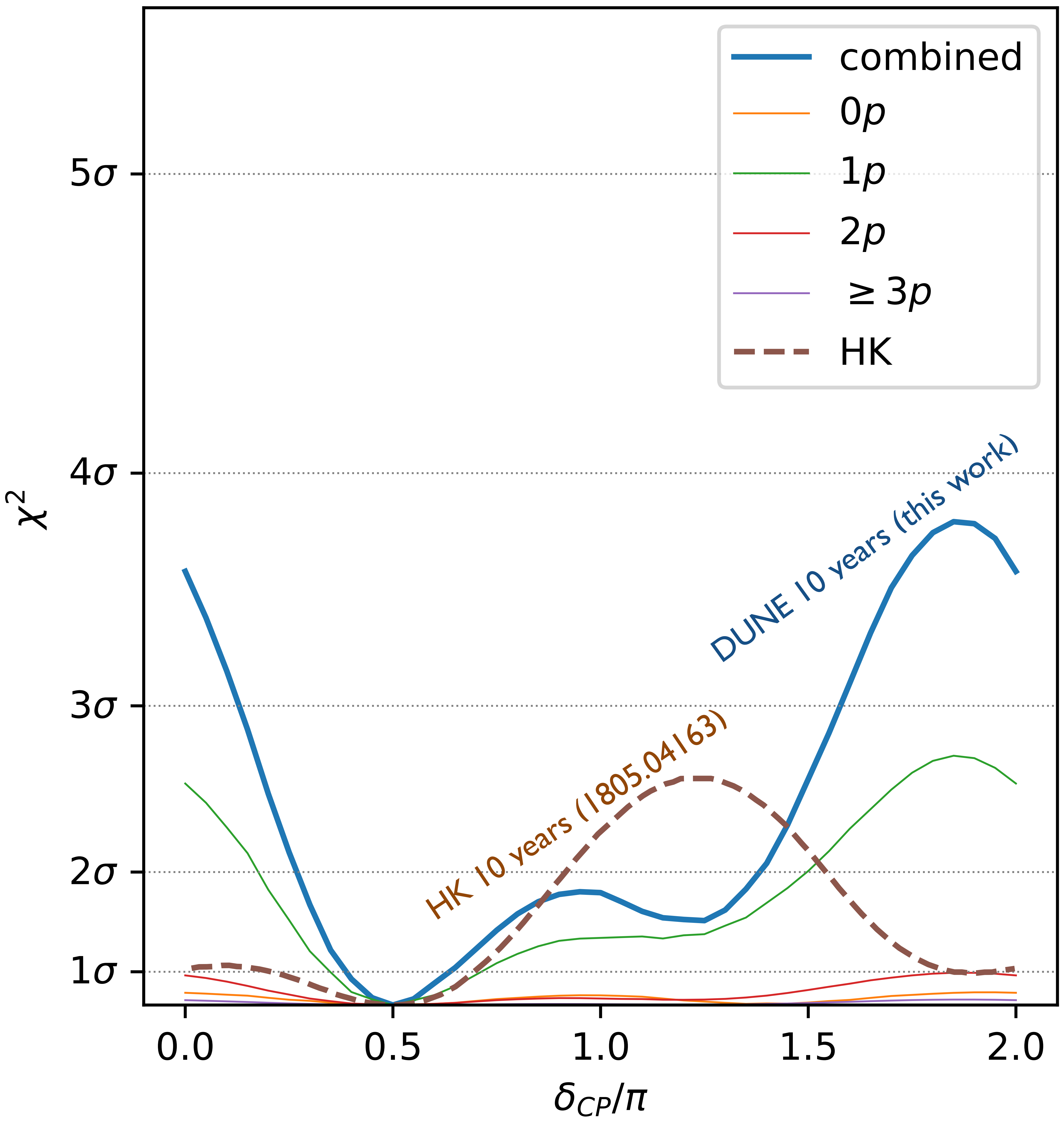

Kelly, PM et al Phys.Rev.Lett. 123 (2019) 8, 081801

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BSM searches in neutrino experiments

What's new? Why now?

BSM in neutrino experiments

LArTPCs are just amazing

How can we leverage that to break the SM?

BSM in neutrino experiments

From a theory perspective, *(LH)* is special: it is a gauge-singlet

Neutrinos are one of the renormalizable portals to new physics

Dark sector

Weak sector ν

The three renormalizable portals to new physics:

Neutrinos (LH)

Higgs $(H^\dagger H)$

Photon $(F_{\mu\nu})$

The overarching physics program should comprehend precise measurements of these three portals

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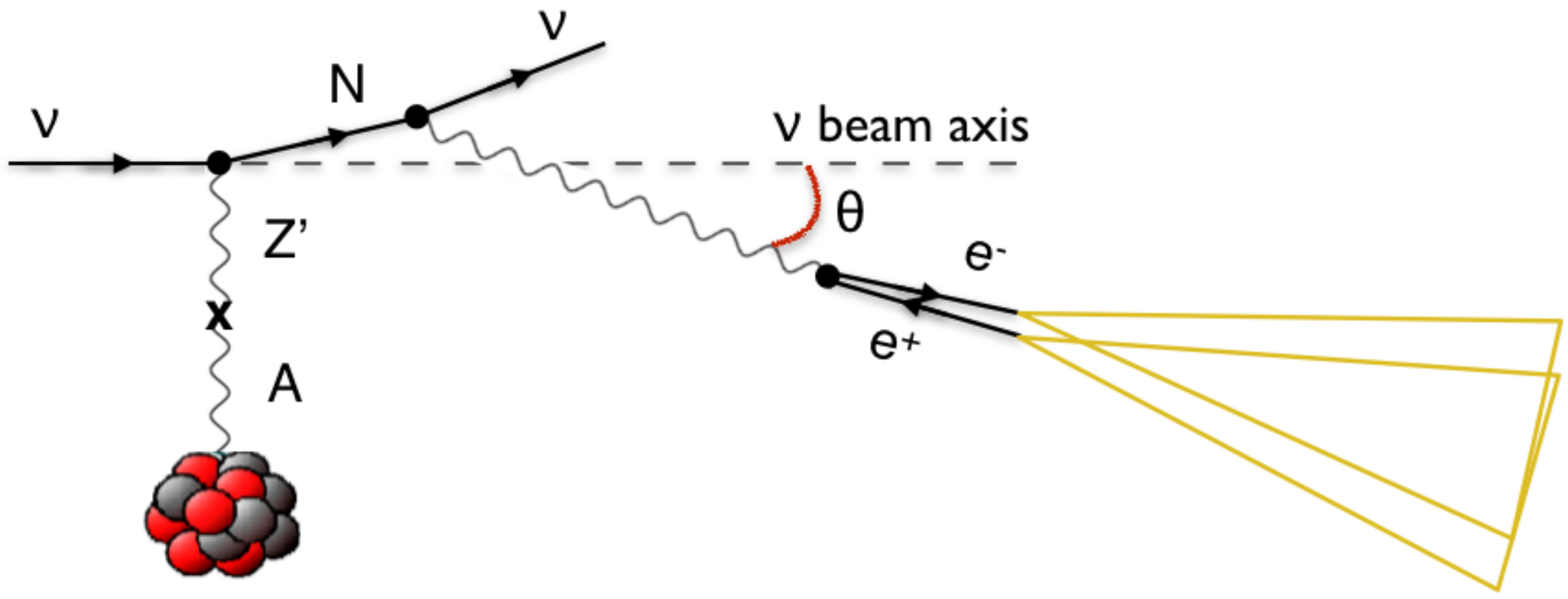
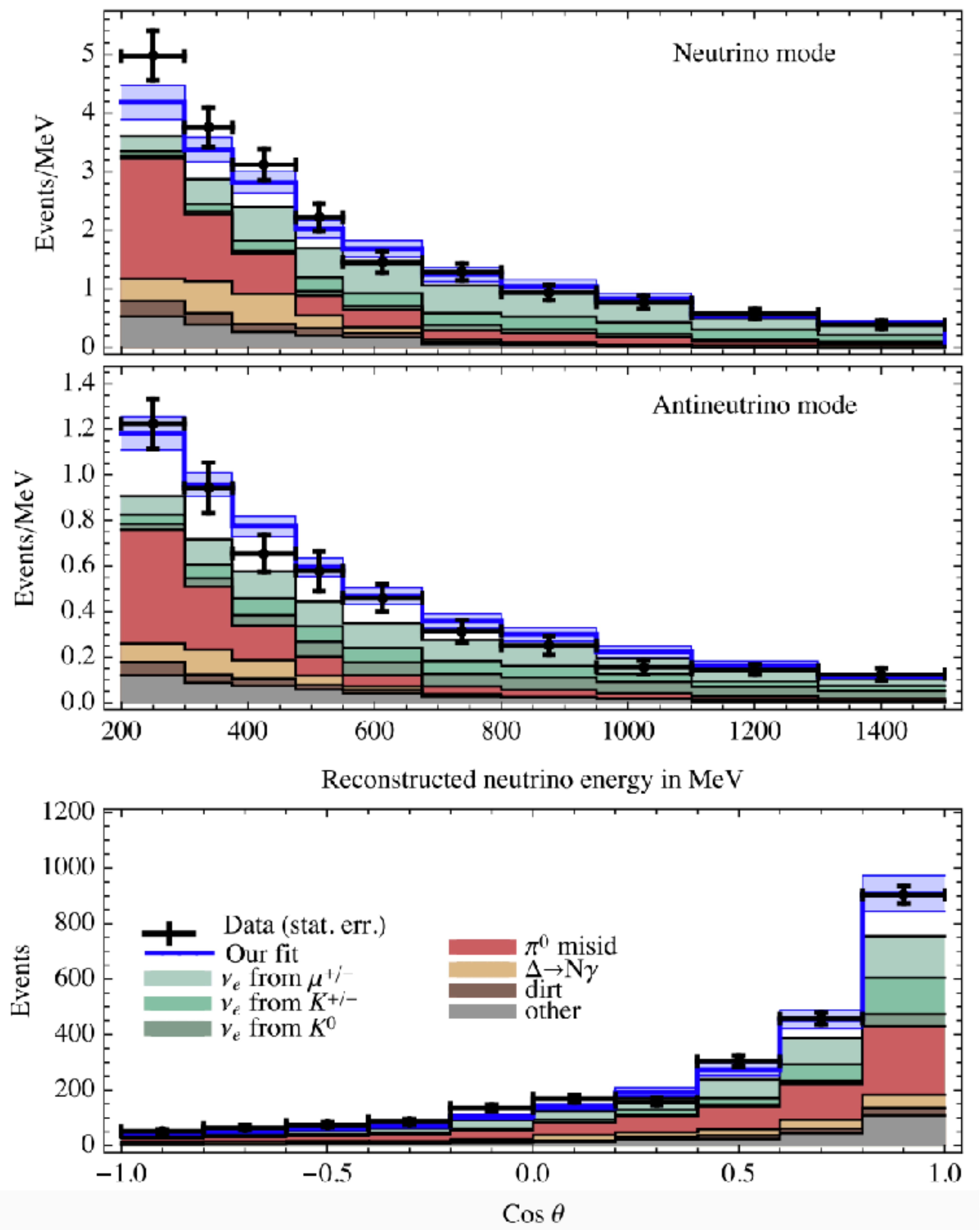
Some novel developments in BSM searches in neutrino experiments

Bertuzzo, **PM** et al Phys.Rev.Lett. 121 (2018) 24, 241801

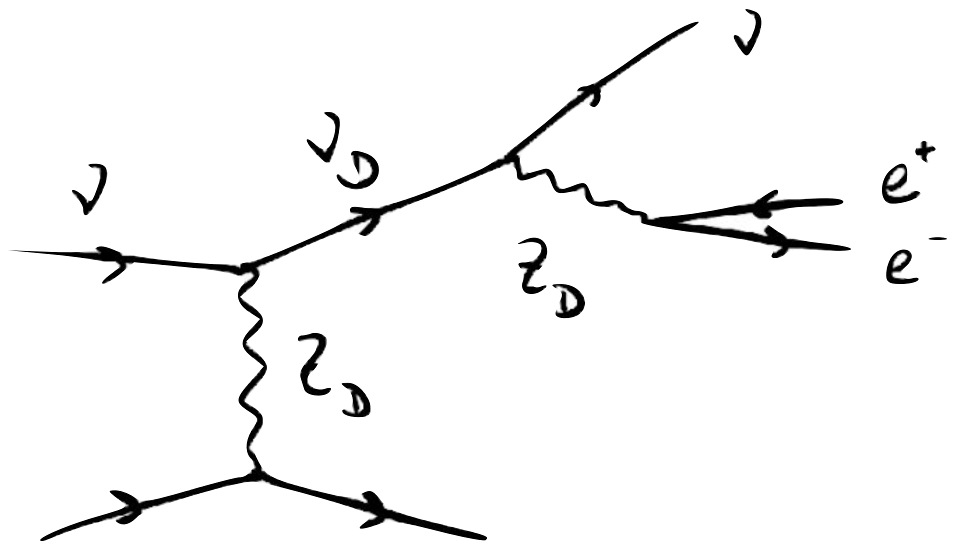




Novel connections between the MiniBooNE anomaly and **the origin of neutrino masses**

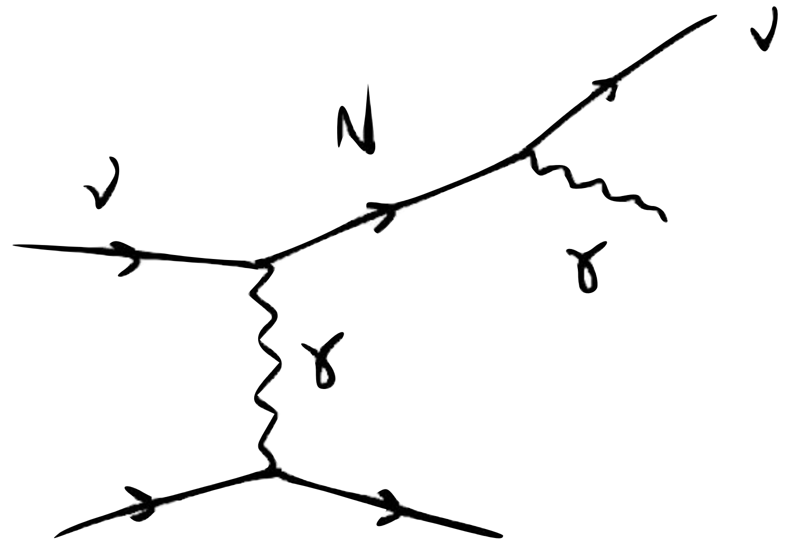
Beyond the Standard Model

Dark Neutrinos



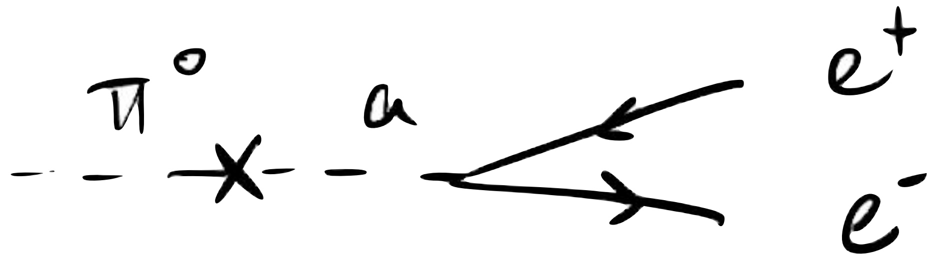
Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment



Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles



Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Alternative explanations to the MiniBooNE excess and other BSM scenarios

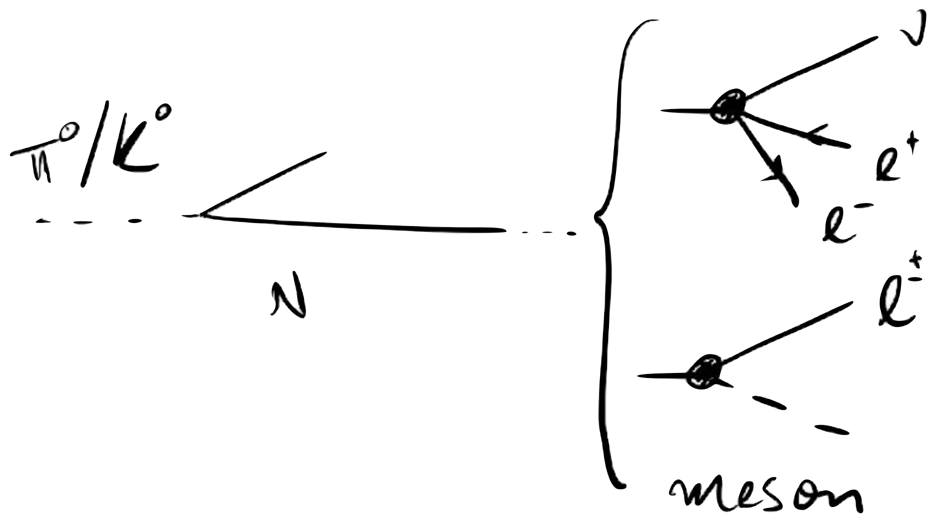
Not an exhaustive list

Some diagram credit: Pedro Machado

Slide credit: Marco Del Tutto

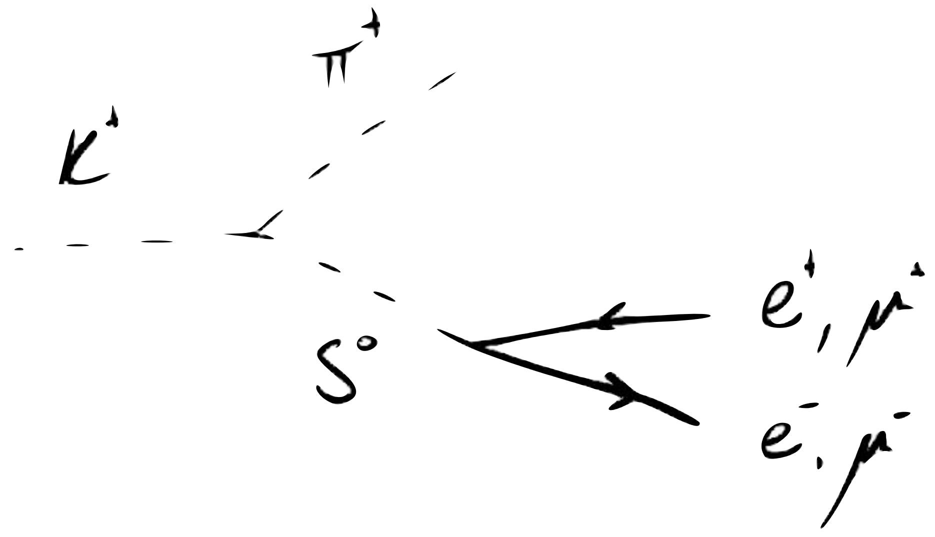
Slide credit 2: Rhiannon Jones

Heavy Neutral Leptons



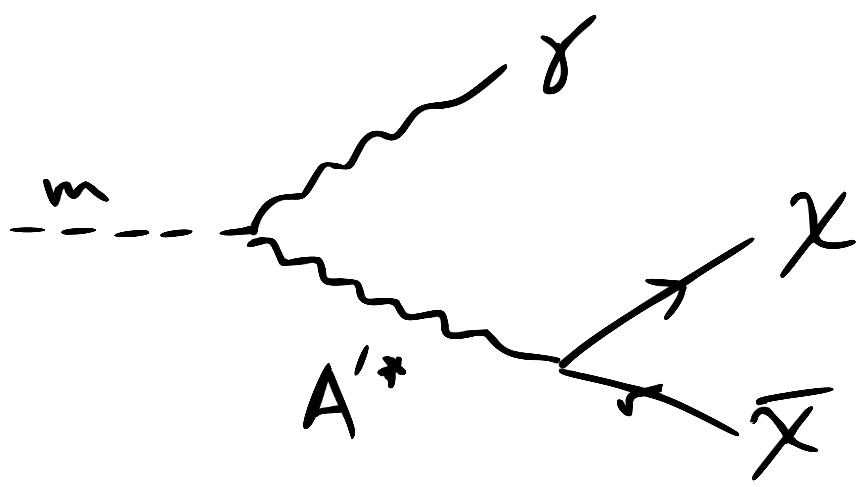
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar



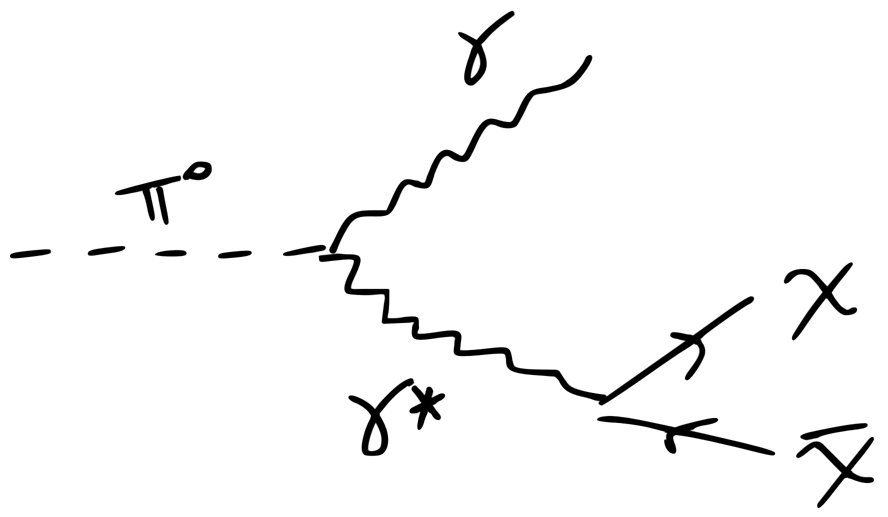
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelley Machado PRD 2019

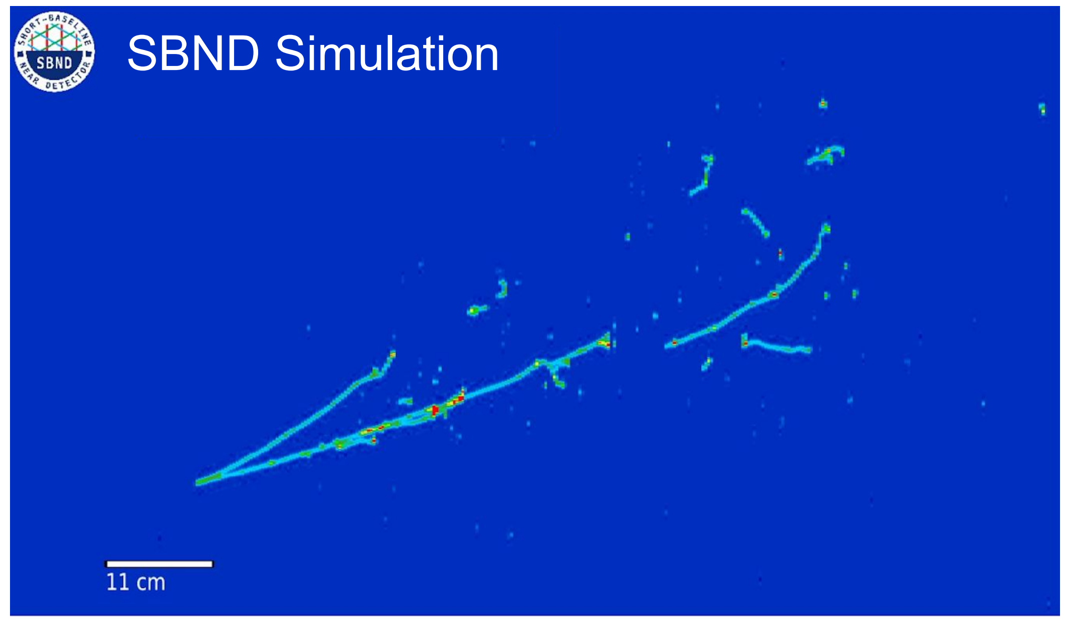
Millicharged Particles



Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

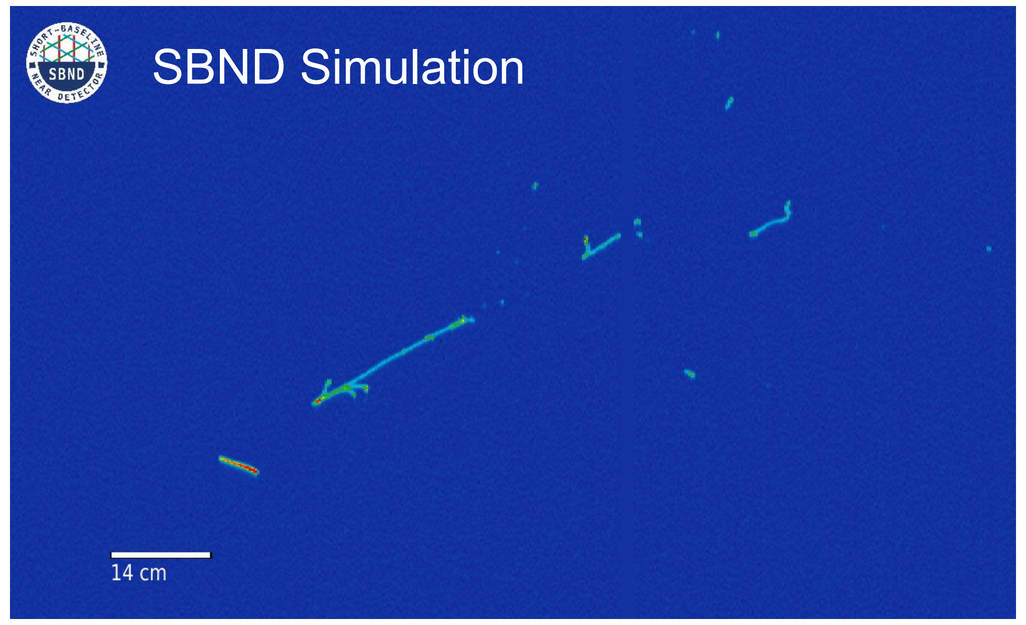
BSM signatures in SBND

Dark Neutrinos



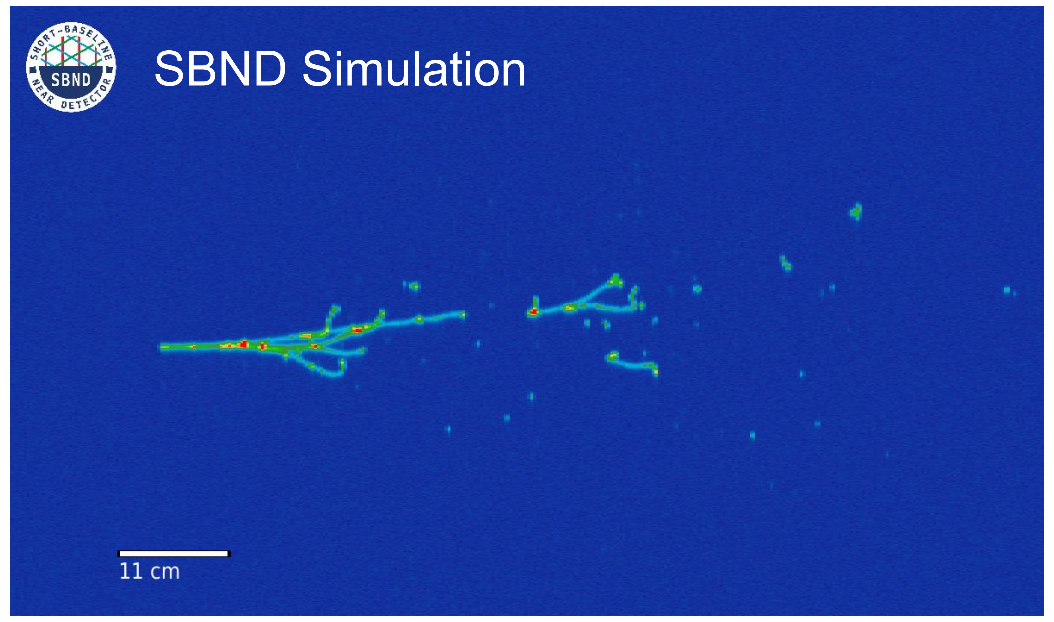
e^+e^- pair with or w/o hadronic activity

Transition Magnetic Moment



Photon shower and hadronic activity

Axion-like Particles



High-energy e^+e^- or $\mu^+\mu^-$

Example signatures and event displays for various BSM scenarios

Not an exhaustive list

Some diagram credit: Pedro Machado

Slide credit: Marco Del Tutto

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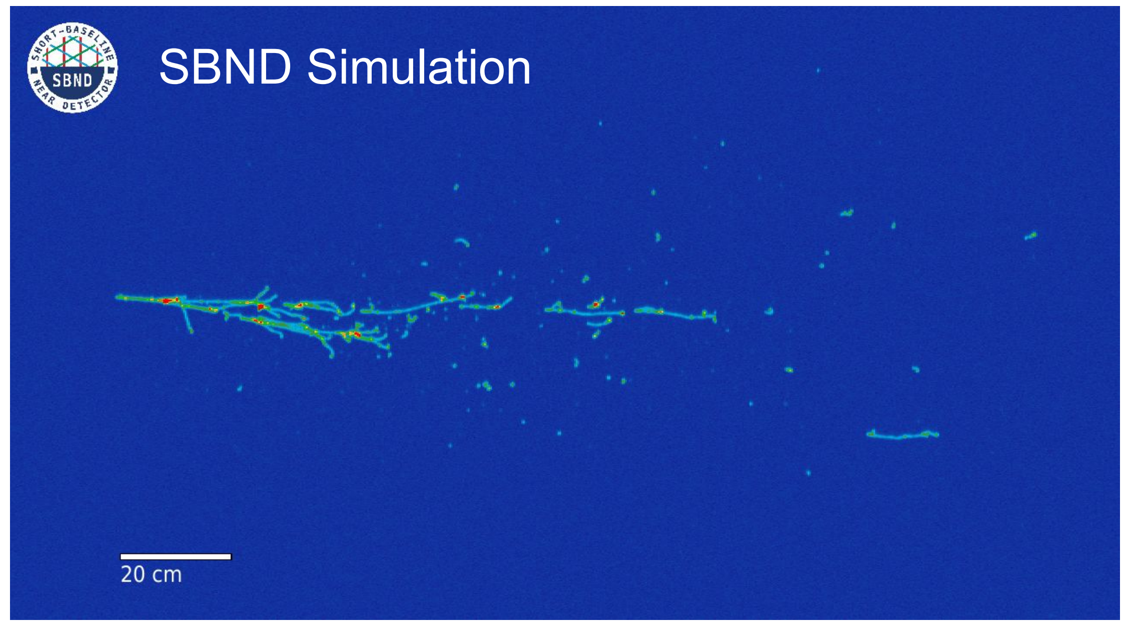
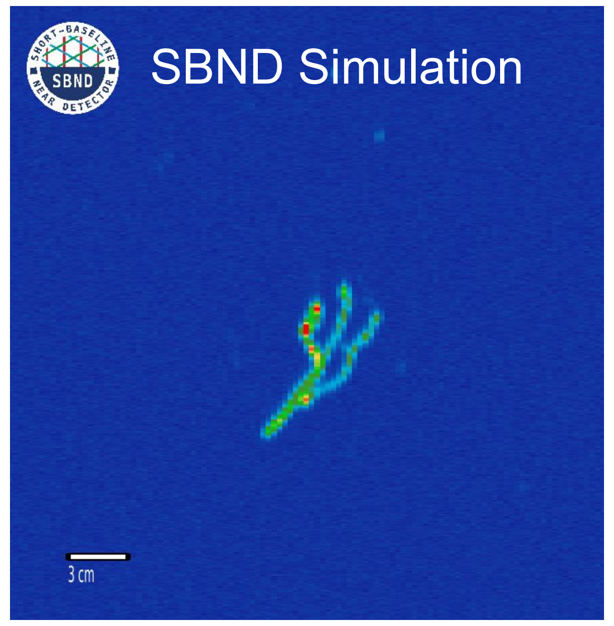
Heavy Neutral Leptons



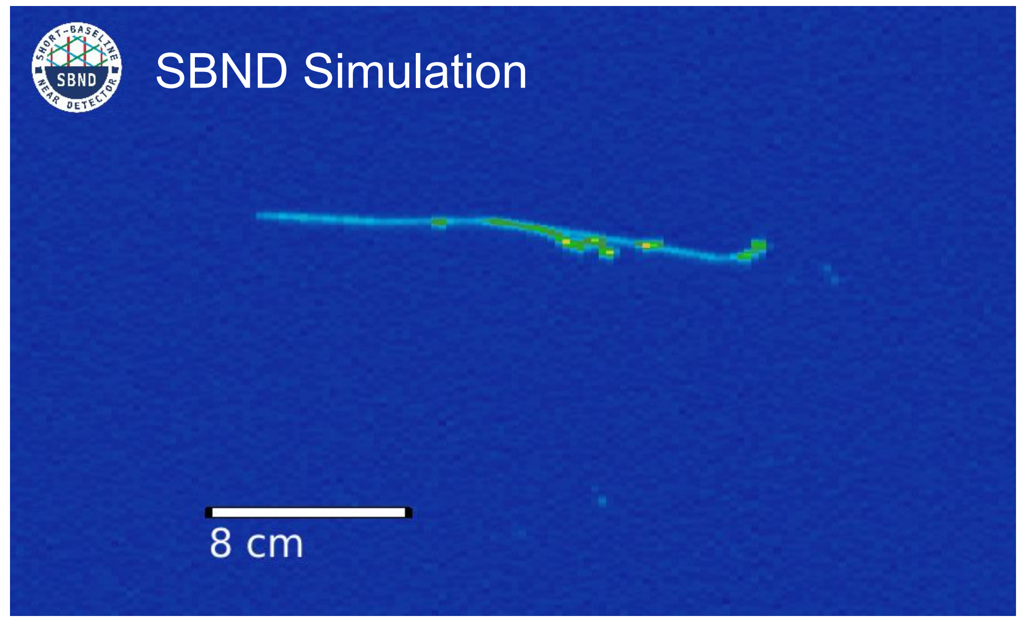
e^+e^-, $\mu^+\mu^-$ or $\mu\pi$

Higgs Portal Scalar



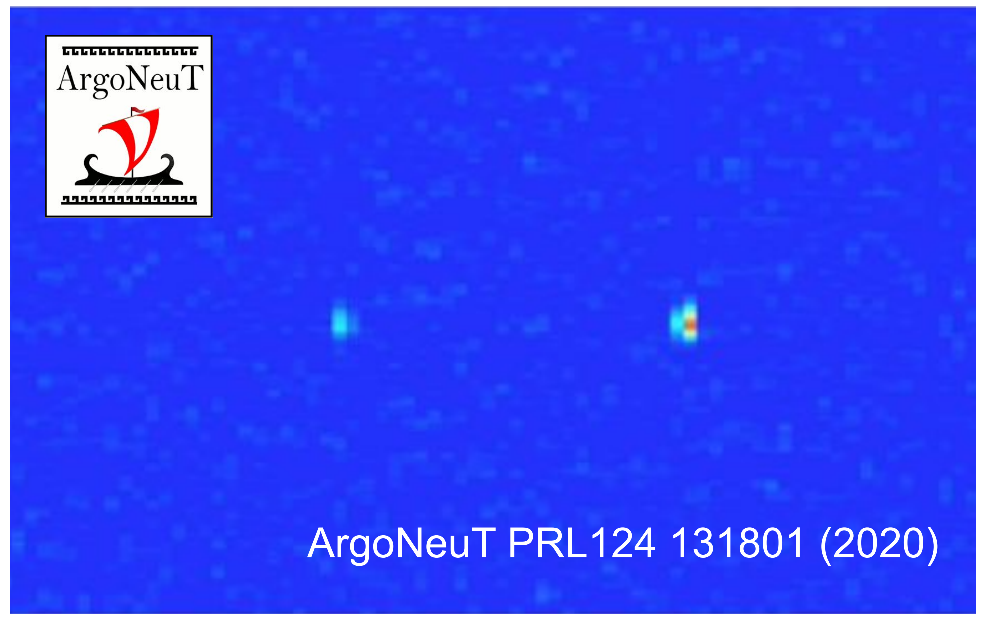
e^+e^- or $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



Electron scattering

Millicharged Particles



Blips/faint tracks

We should not discard the “old” BSM

Take NSI as an example: what does that really mean?

$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F\epsilon(\bar{\nu}_L\gamma_\mu\nu_L)(\bar{f}\gamma^\mu f)$$

A way to answer that is to build up a full model that gives NSI and see what do you learn with it

Be bold:

let’s have new physics that violates flavor

in both quark and lepton sector **at a low scale**

Gauge B – L of the third family only

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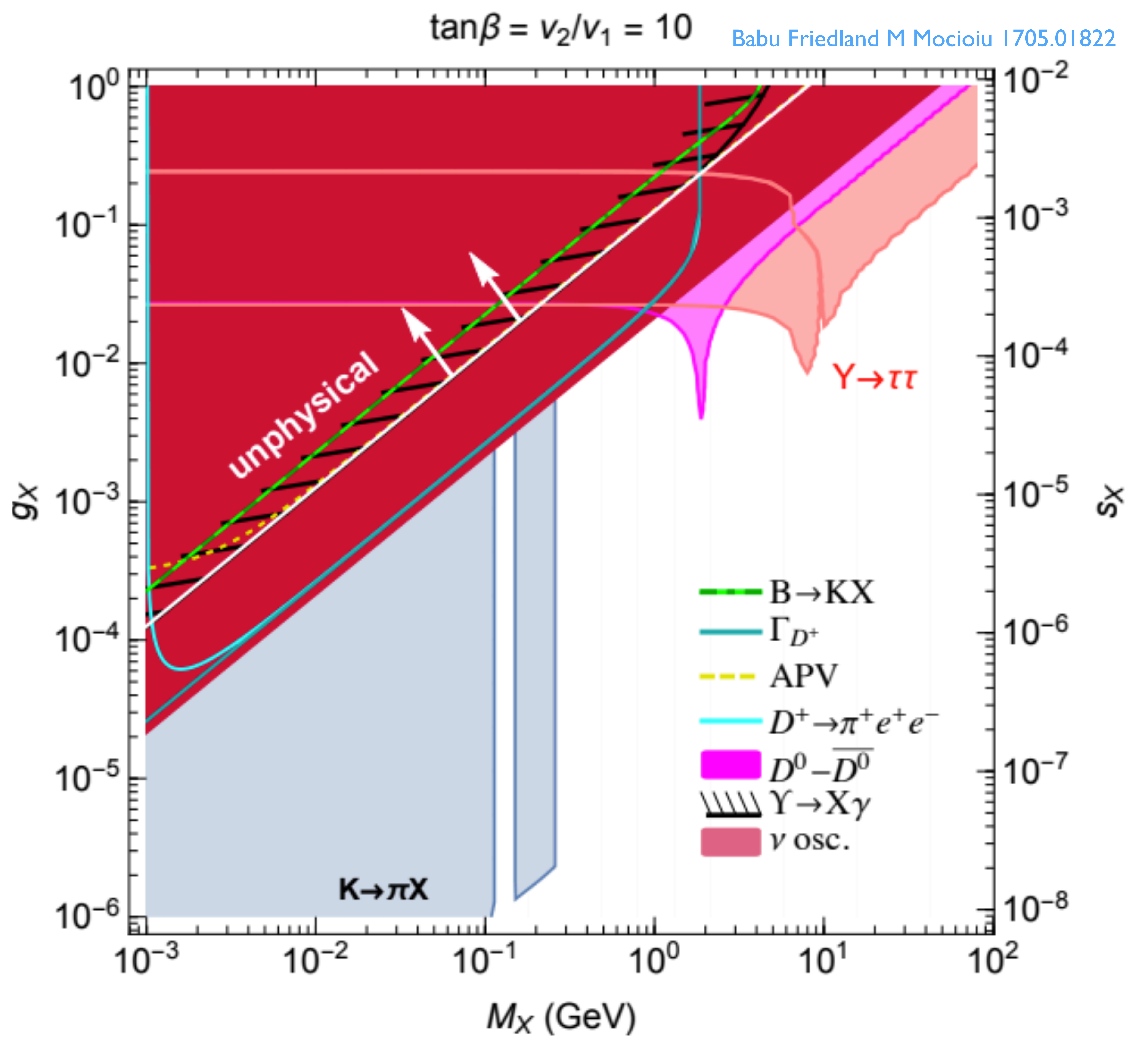
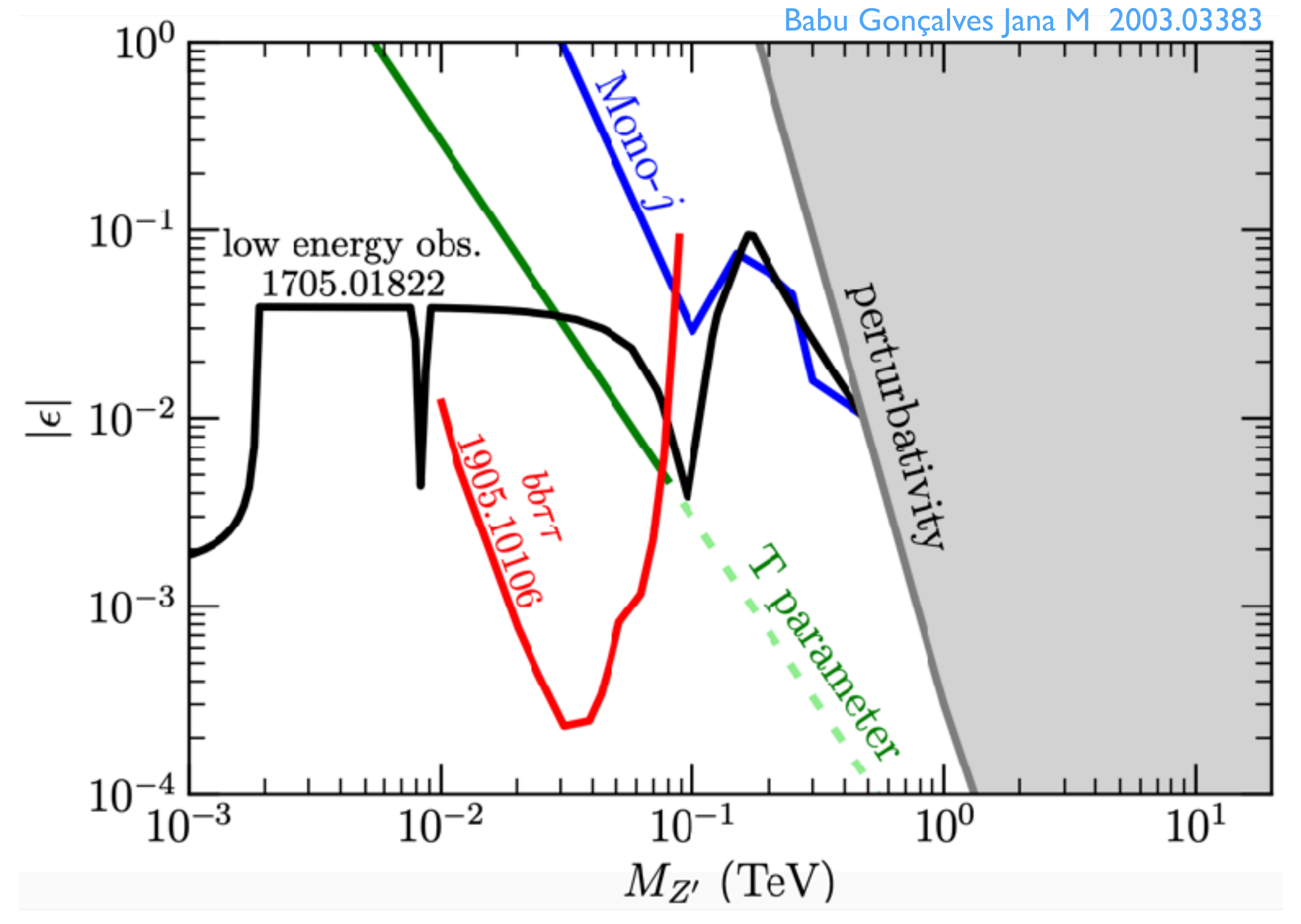
We should not discard the "old" BSM



Complementarity: ν oscillations, meson decay and oscillation, parity violation, kaon physics, LHC, …



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Beyond **DUNE**?

Given the **A**ccelerator **C**omplex **E**volution
and the large community interest in hosting a Muon Collider in the US in the future,
it seems timely to re-address the physics case of a neutrino factory.
(neutrino factory = a neutrino experiment in which the flux comes from muon decay)
Or a muon storage ring to measure neutrino-nucleus interactions.

What can we learn with it?
How much precision neutrino physics can we extract out of that?
Which BSM searches could shine in a neutrino factory setup?
What are the complementarity to other experiments?
What is the physics case beyond neutrinos?

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Conclusions

We do not know where new physics is

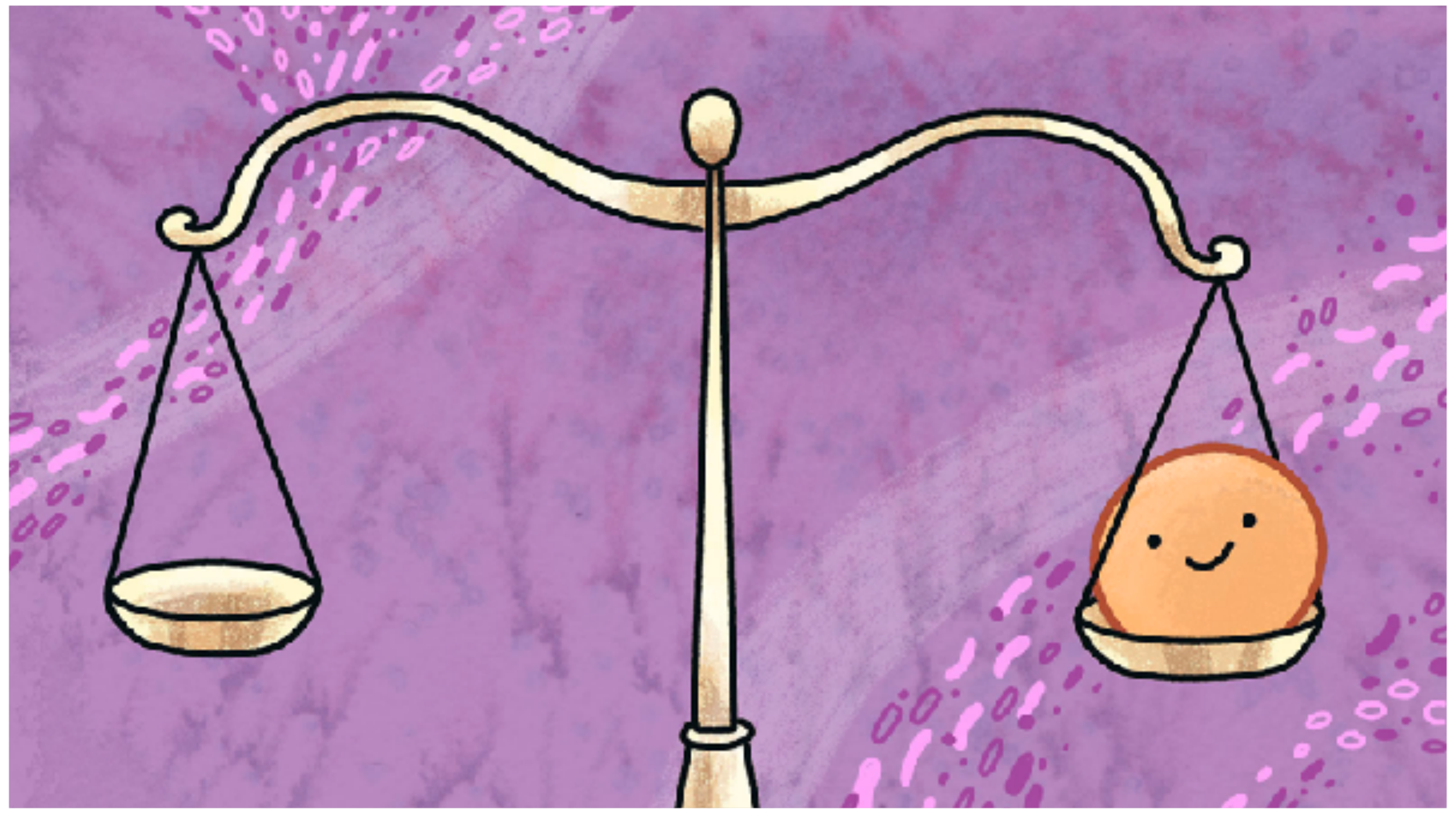
But we know that there needs to be new physics that address the outstanding questions of the standard model, in particular the mechanism of neutrino mass generation

LArTPCs offer novel opportunities

Improving neutrino-nucleus interaction modeling will further enable this program

Neutrino experiments are multipurpose experiments
neutrino experiments >> neutrinos

A precision neutrino physics program can stress-test the least known sector of the standard model



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Backup

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Dark matter at DUNE

Based on de Romeri Kelly **PM** 1903.10505

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Dark matter at DUNE

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Dark matter at DUNE

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Dark matter at DUNE

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Maybe dark matter is been produced in neutrino beams as of right now

To search for it, we need very detailed detectors to disentangle the DM signal from the neutrino scattering background

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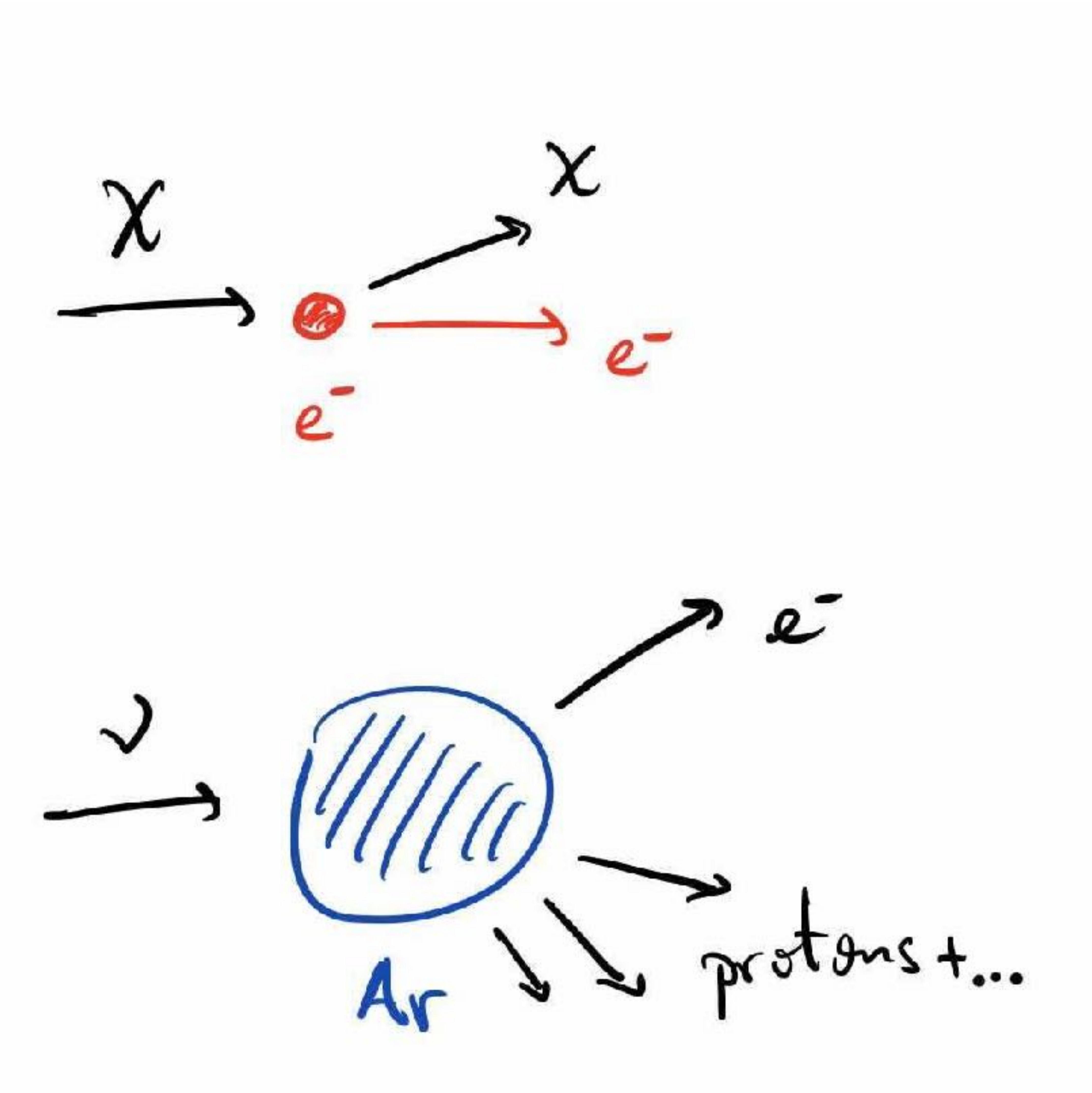
Dark matter at DUNE

Based on de Romeri Kelly **PM** 1903.10505



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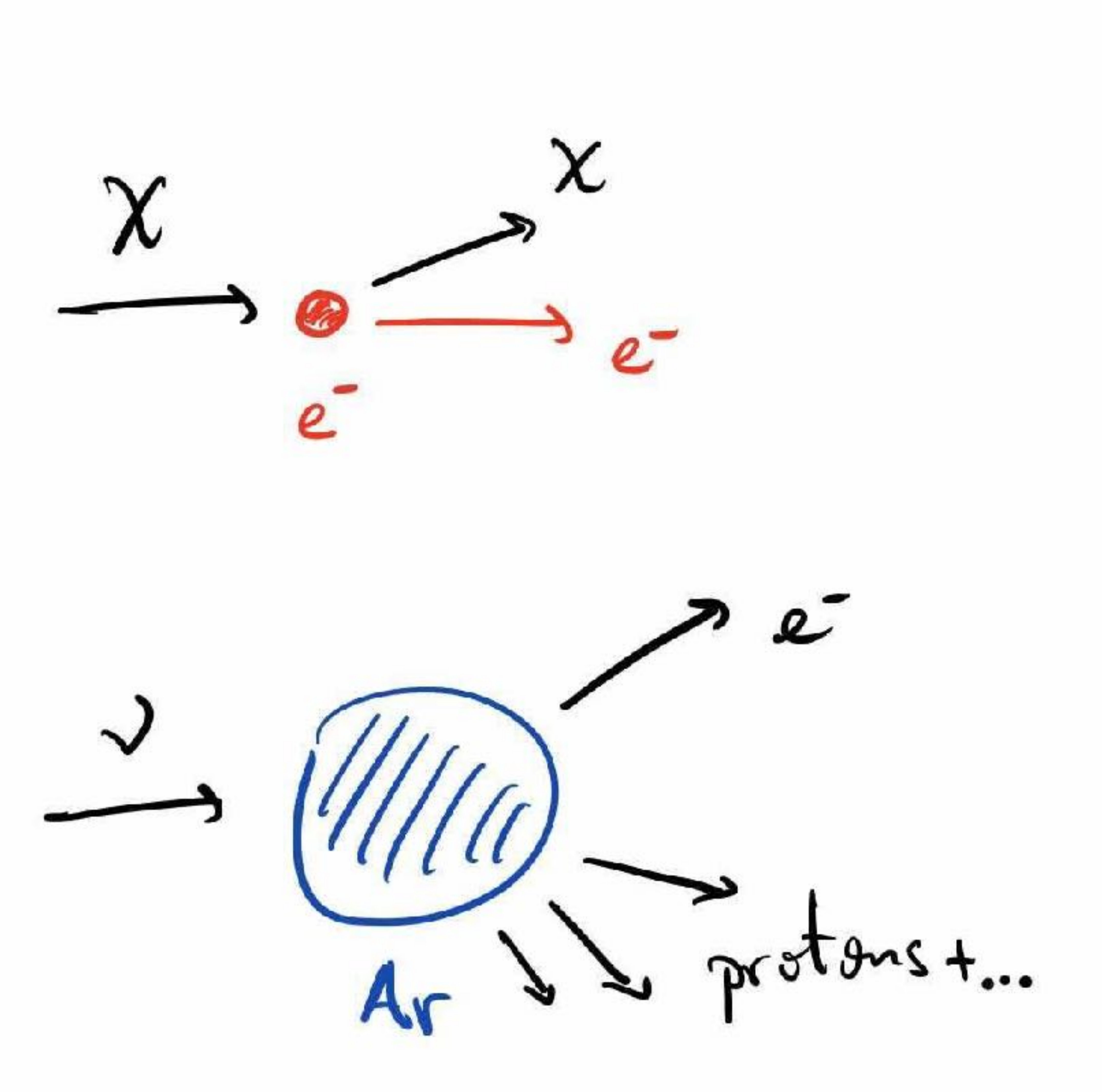

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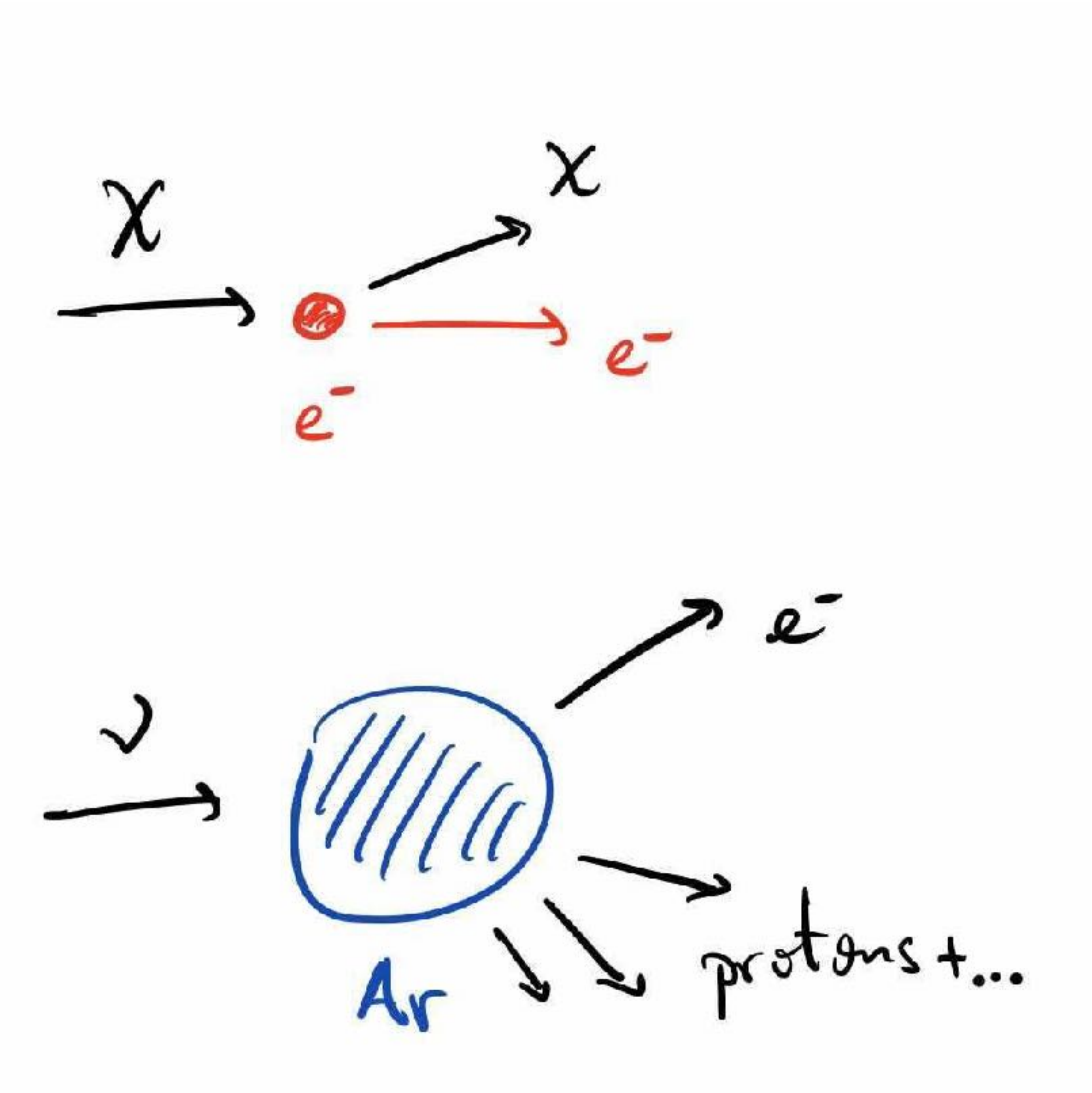
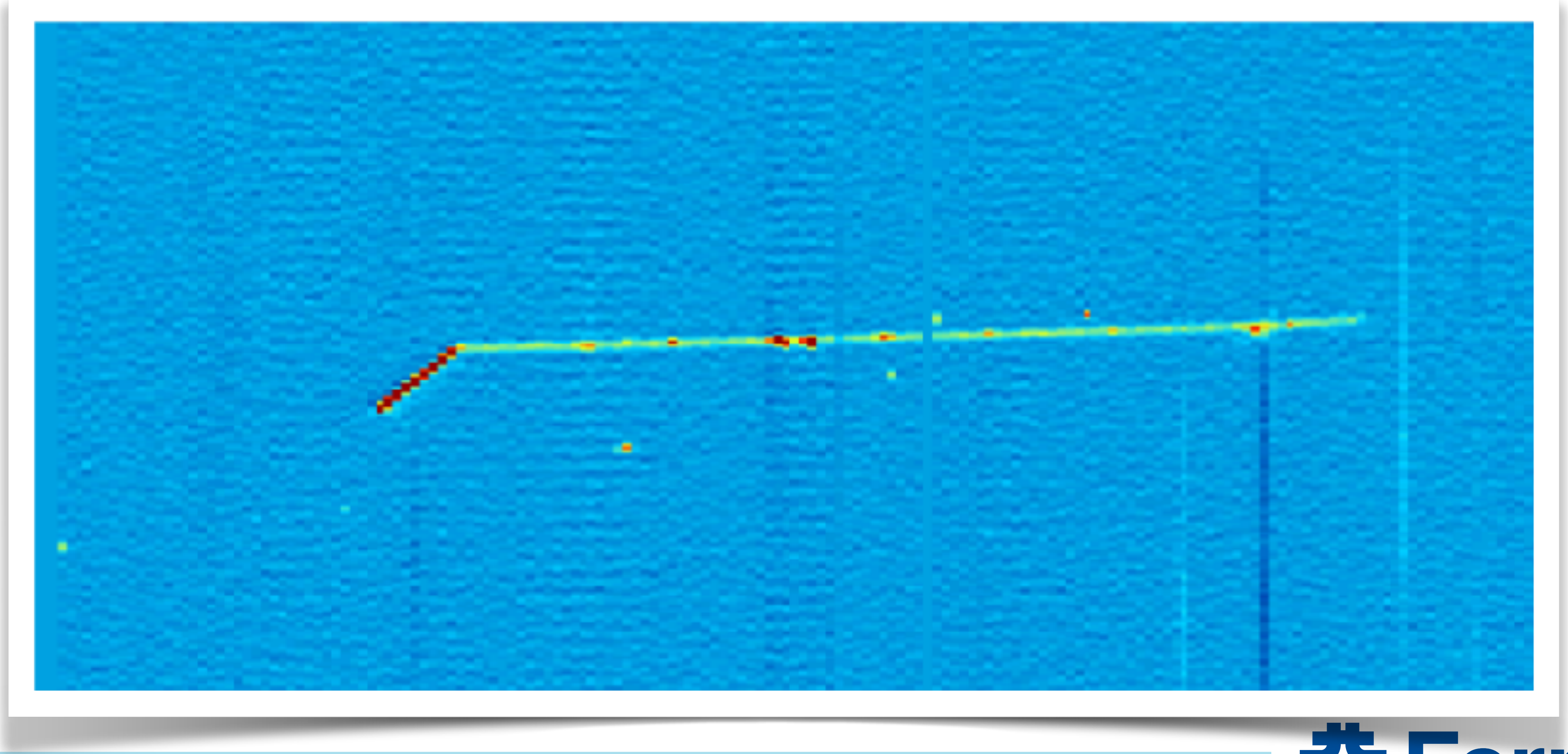


When DM scatters off electrons, the outgoing electrons are very forward

This is different from when neutrinos scatter off nuclei

LArTPC topological capabilities can play a crucial role in rejecting backgrounds



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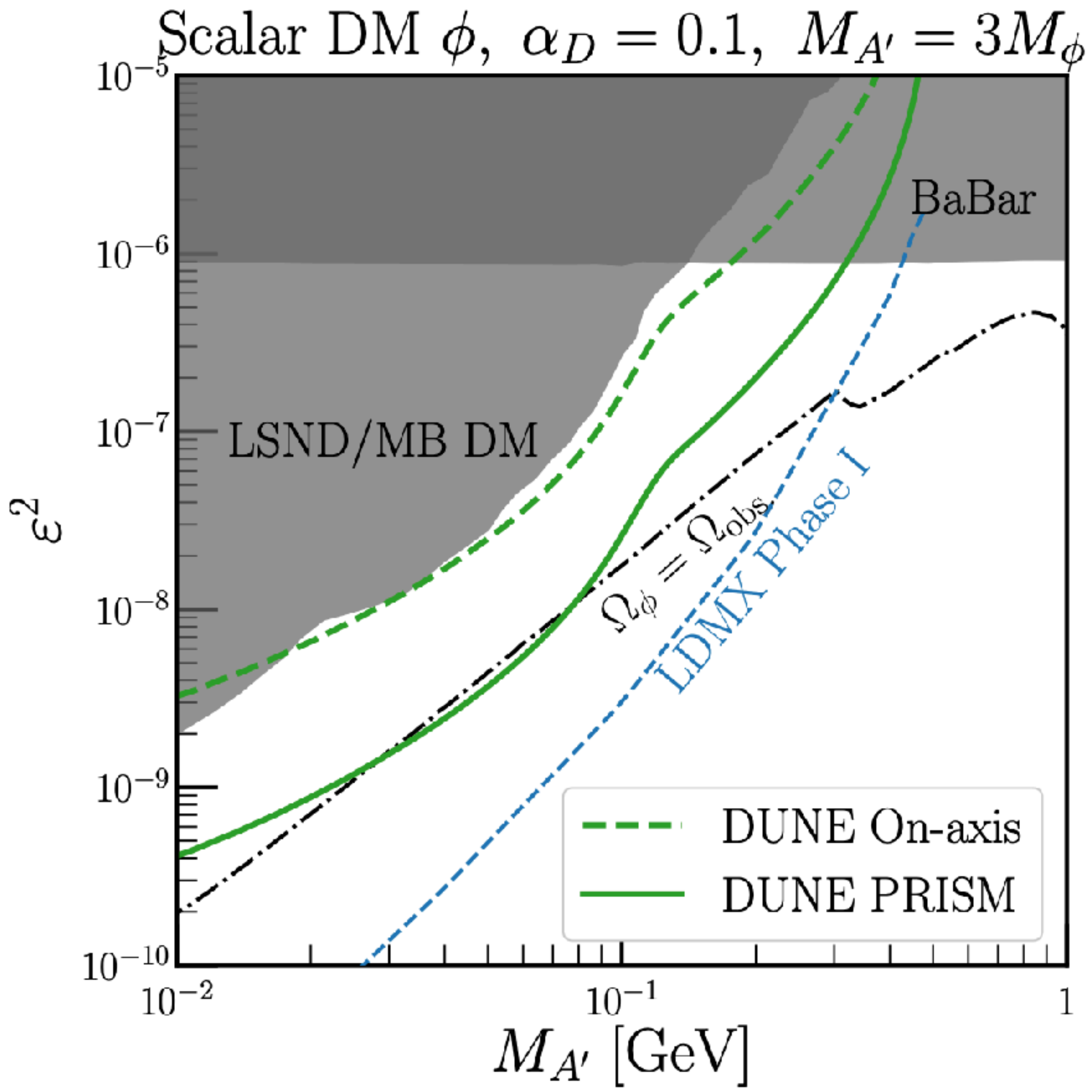

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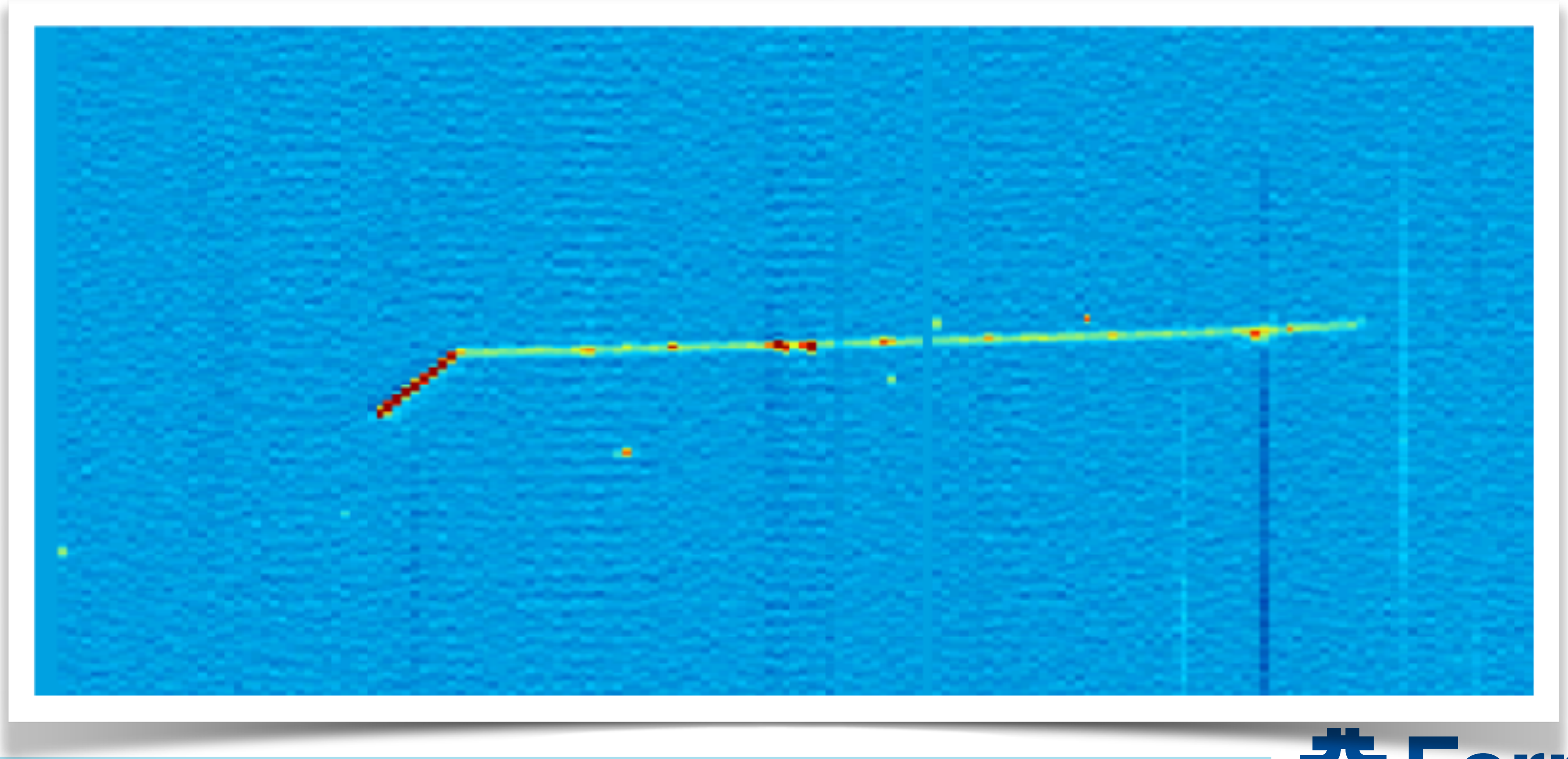

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