The Large Neutrino Collider

or "Physics opportunities with future liquid argon time project projection chambers"

Pedro Machado

CERN Theory Colloquium

November 16th, 2020

What is the goal of the LHC?

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What is the goal of the LHC?

Discover the Higgs?

Understand EWSB?

Measure Higgs couplings?

Discover SUSY (or your preferred BSM model)?

Probe unexplored energy scales?

…?

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What is the goal of the LHC?

Discover the Higgs?

Understand

In this colloquium I will advocate that the future liquid argon neutrino detectors (e.g. DUNE) will also be multi-purpose, going much beyond CP violation, mixing angles, proton decay, etc.

preferred BSM model)?

Probe unexplored energy scales?

…?

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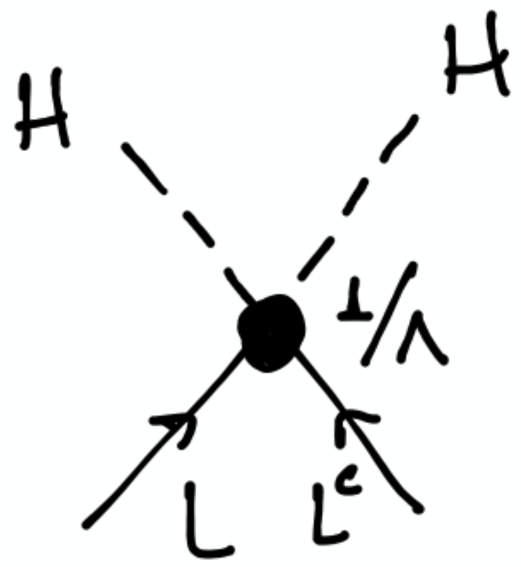
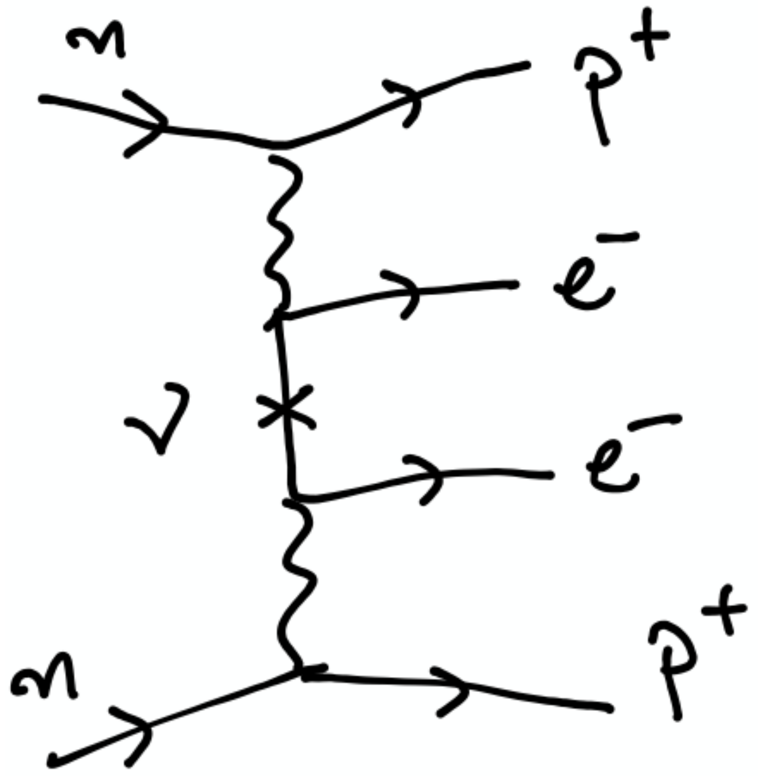
Why neutrinos?

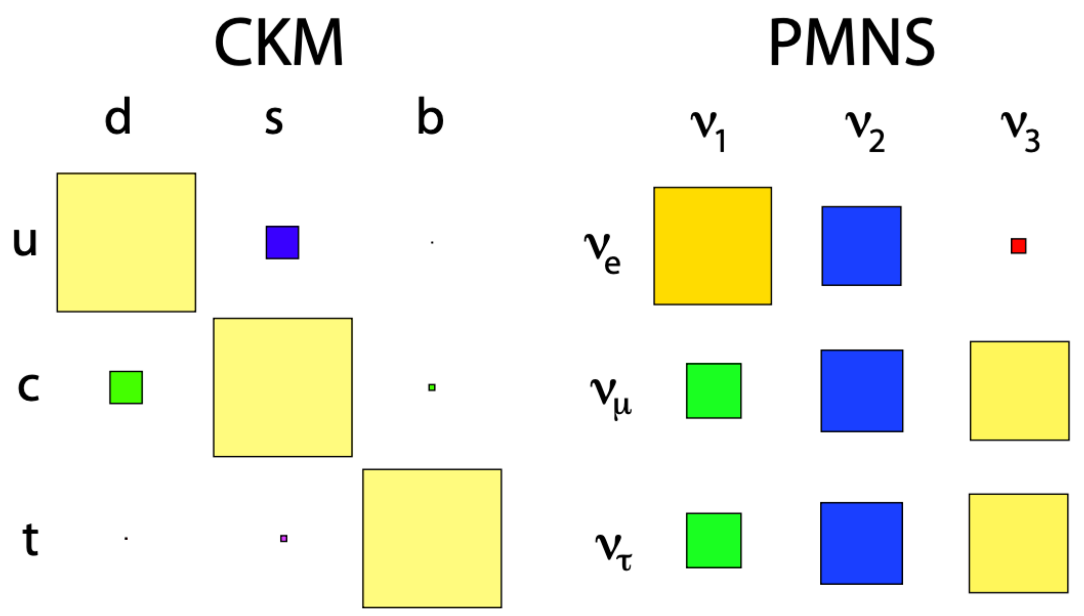
Neutrino masses



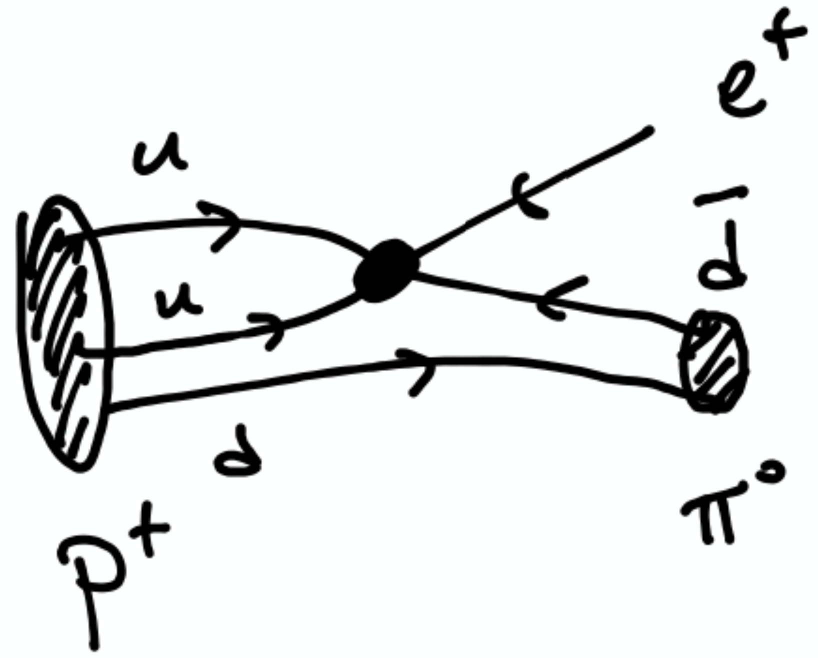
The nature of neutrinos



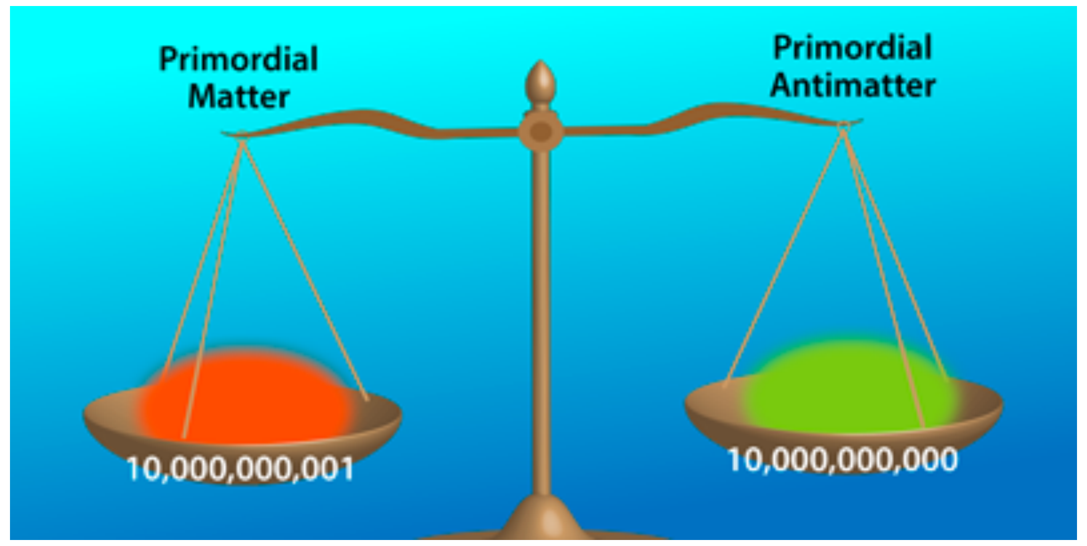
Flavor Puzzle



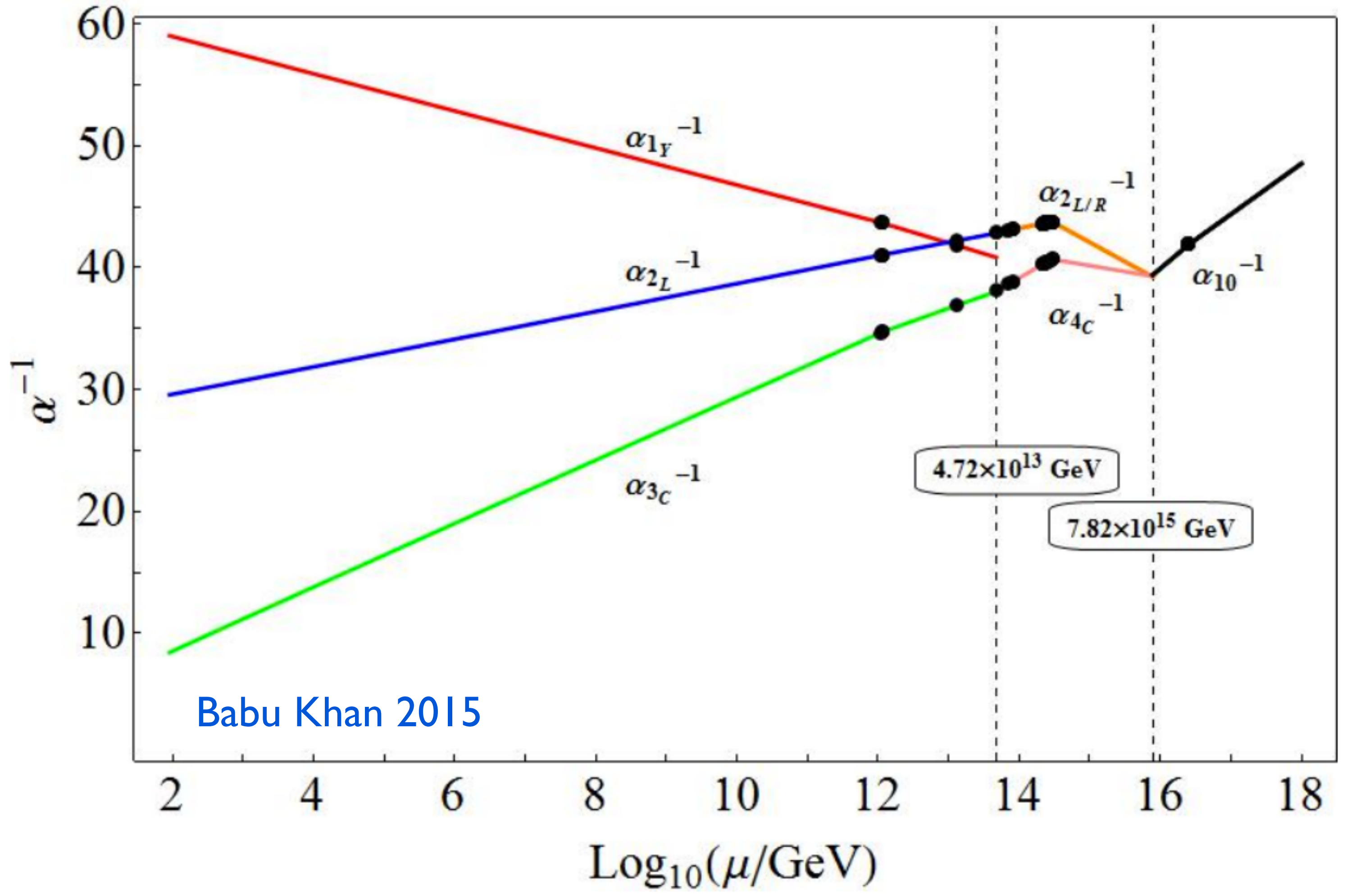
Proton decay



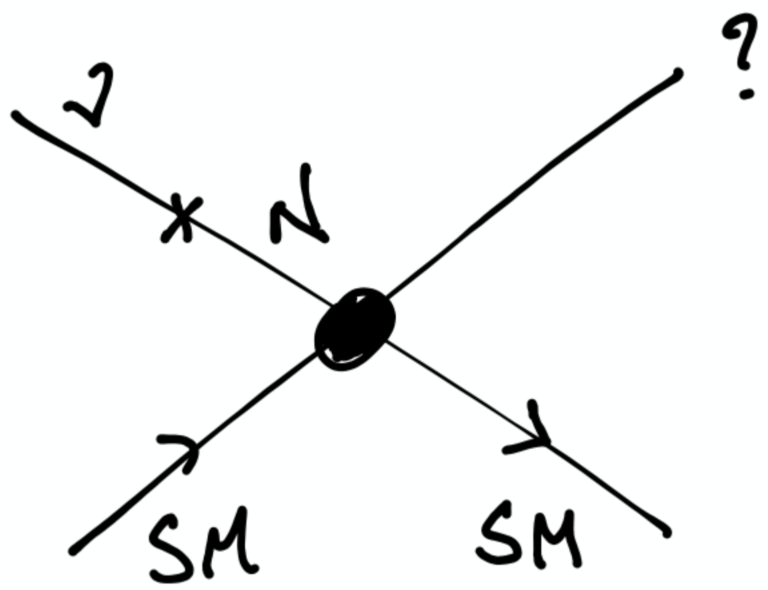
Matter-antimatter asymmetry



Unification



Portal to new physics?



Disclaimer

**I am part of the DUNE collaboration,
but I am *not* speaking on behalf of DUNE.
Views here are my own.
Mistakes too.**

Also, I will not touch DUNE's main goals: measuring CP violation with beam neutrinos, detecting supernova, measuring proton decay, …

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Some key aspects of LArTPCs

and the opportunities they provide

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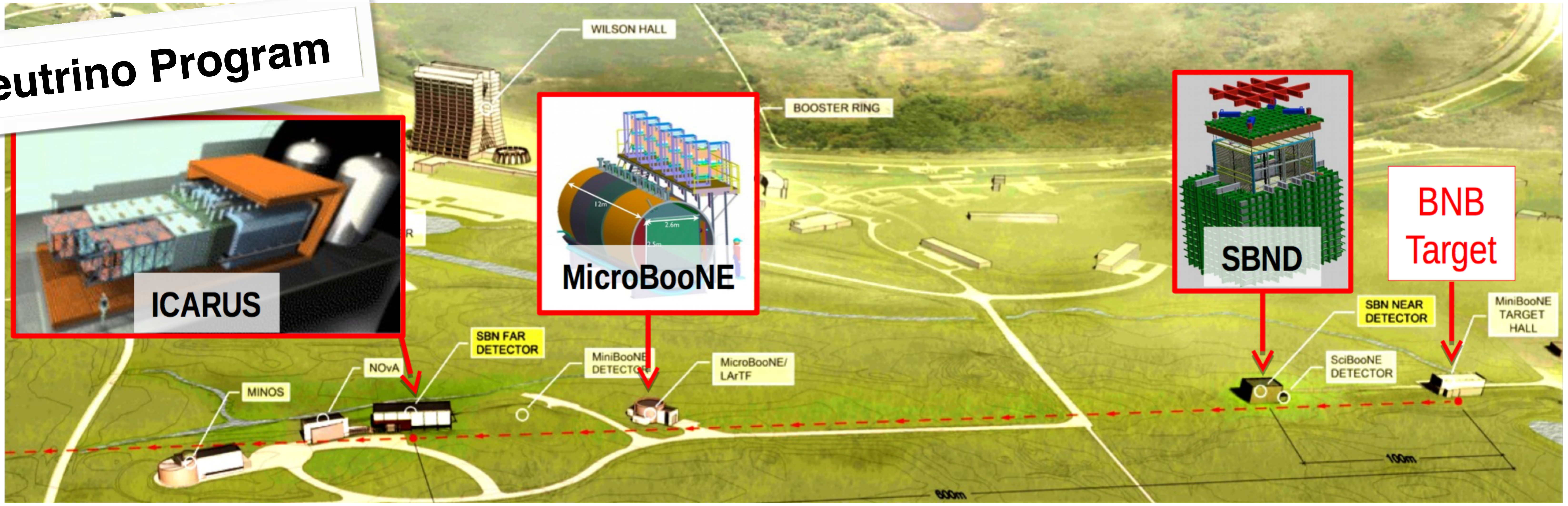
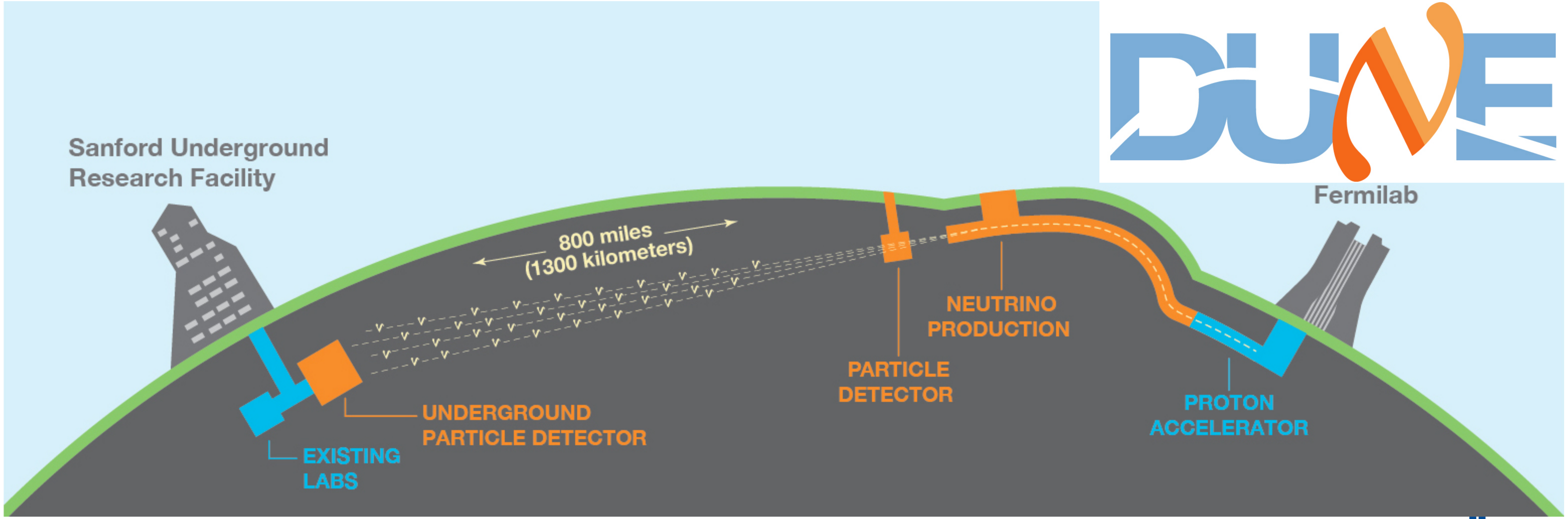
Liquid argon time projection chambers

Short Baseline Neutrino Program





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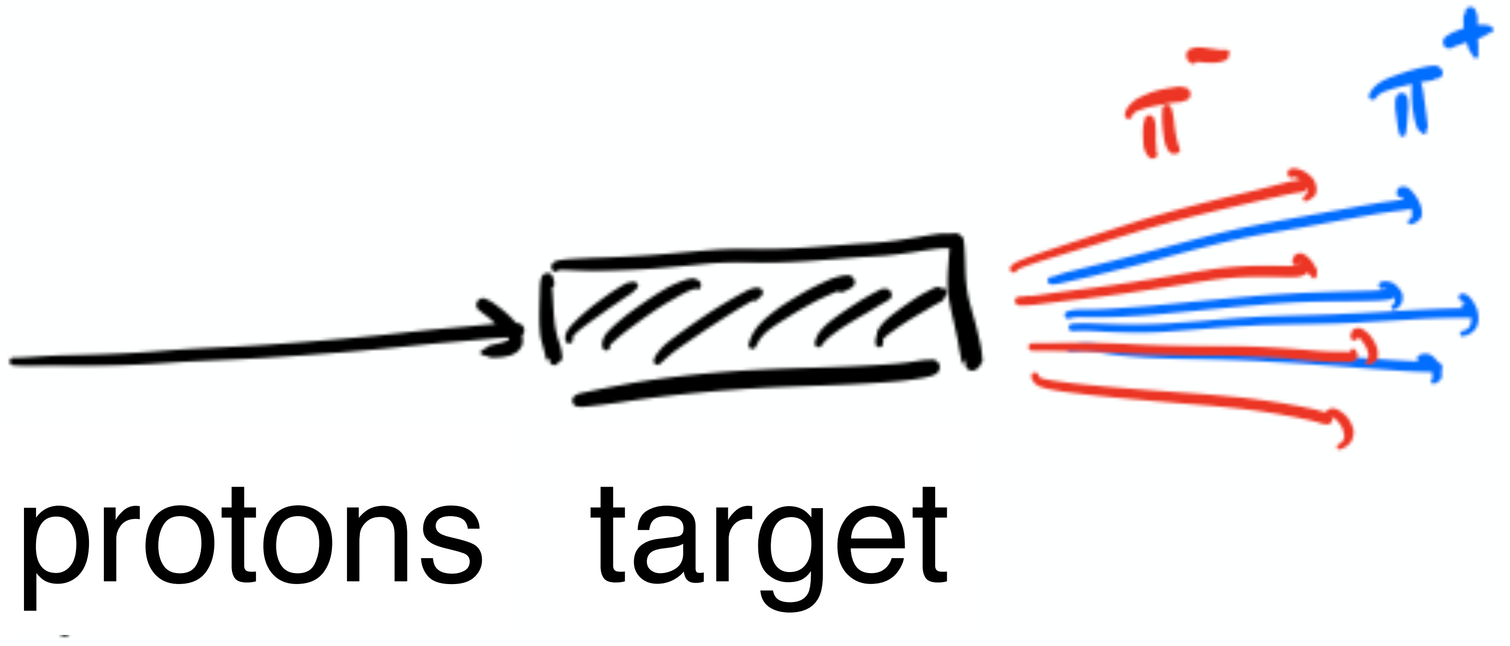
(1) Huge flux and massive detectors



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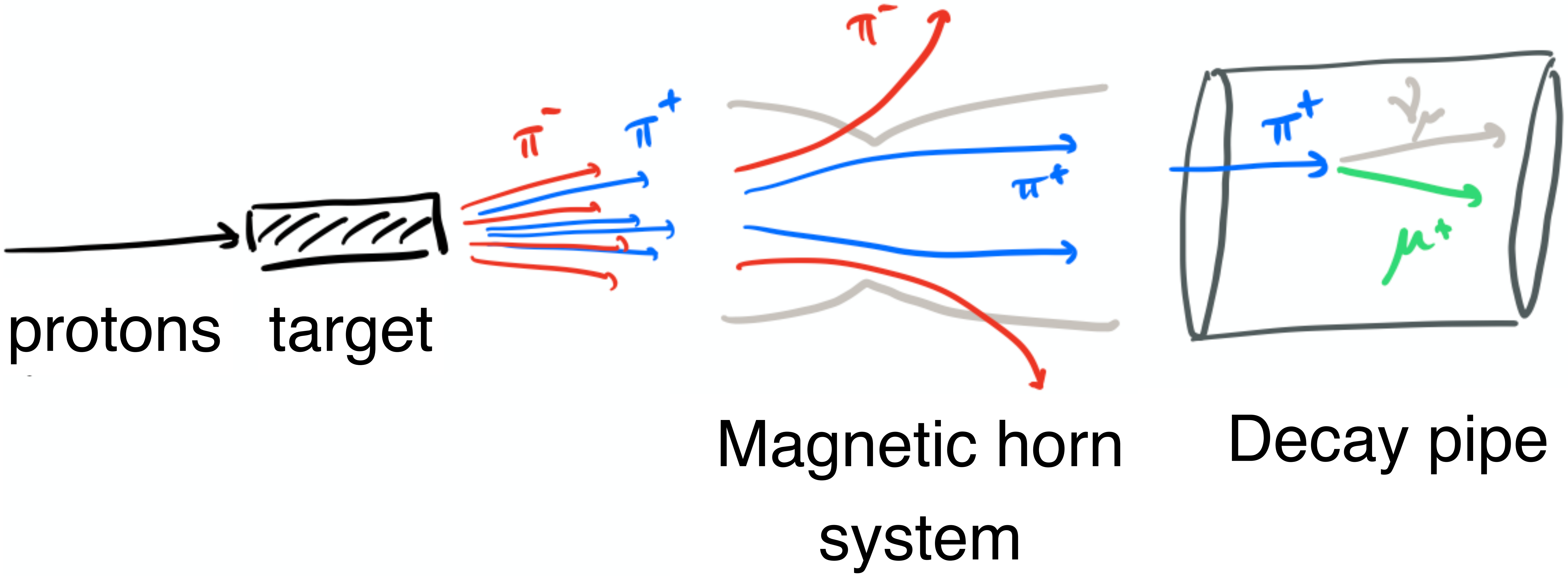

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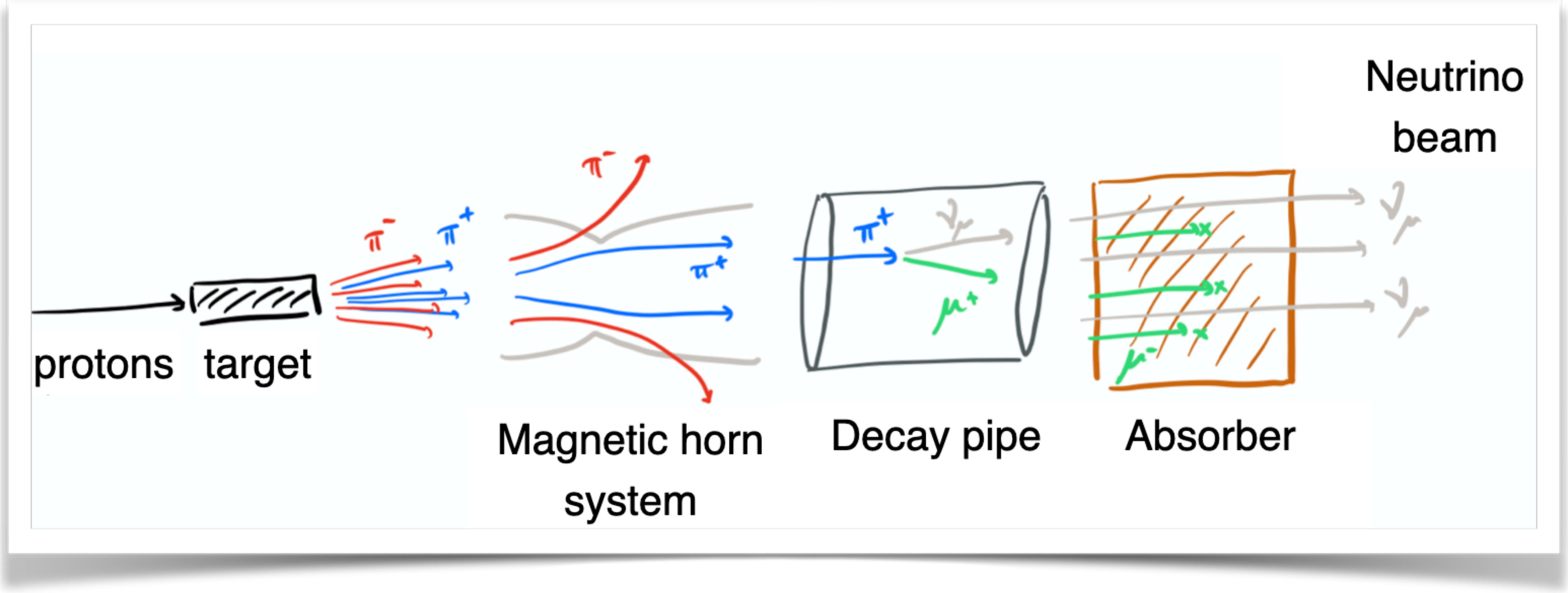

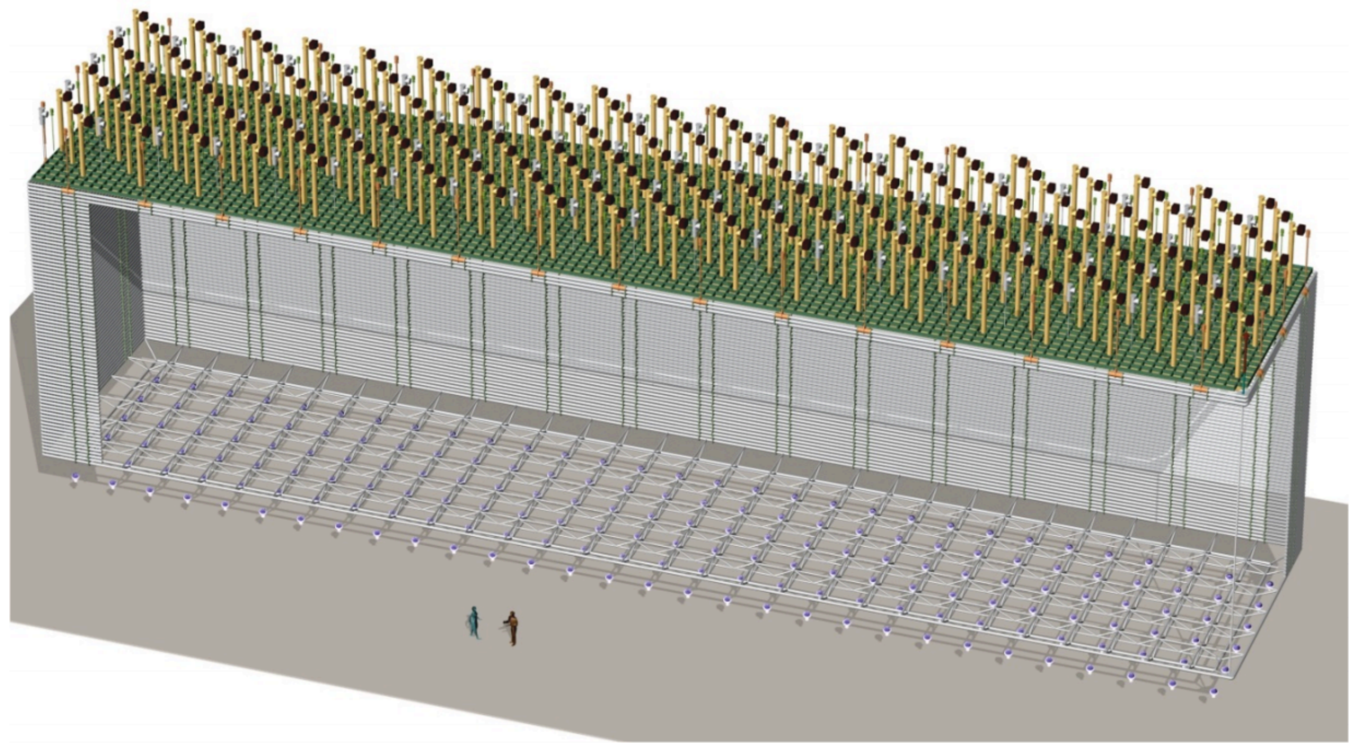

Beam: ~ 10^{21} protons on target per year (120 GeV, 1.2 MW)

Near detector: 67 ton (though this can change), 574 m from target, multi-purpose (more on this later)

Far detector: 40 kton fiducial mass, 1300 km from target

DUNE is a massive, nonstandard beam dump experiment

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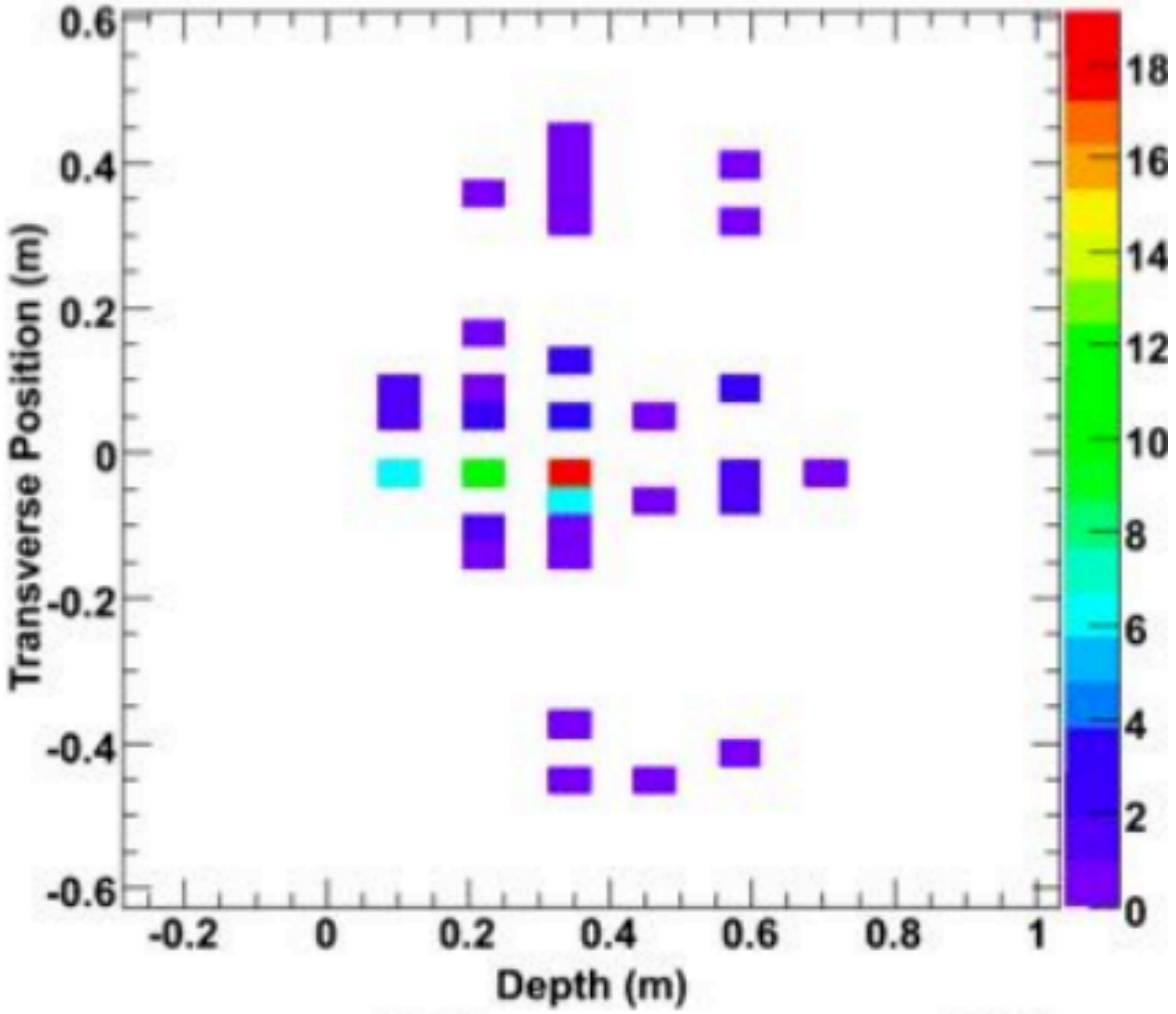
MINOS event

ν_e CC

1511.06178



$$\nu_e + N \to e^- + X$$

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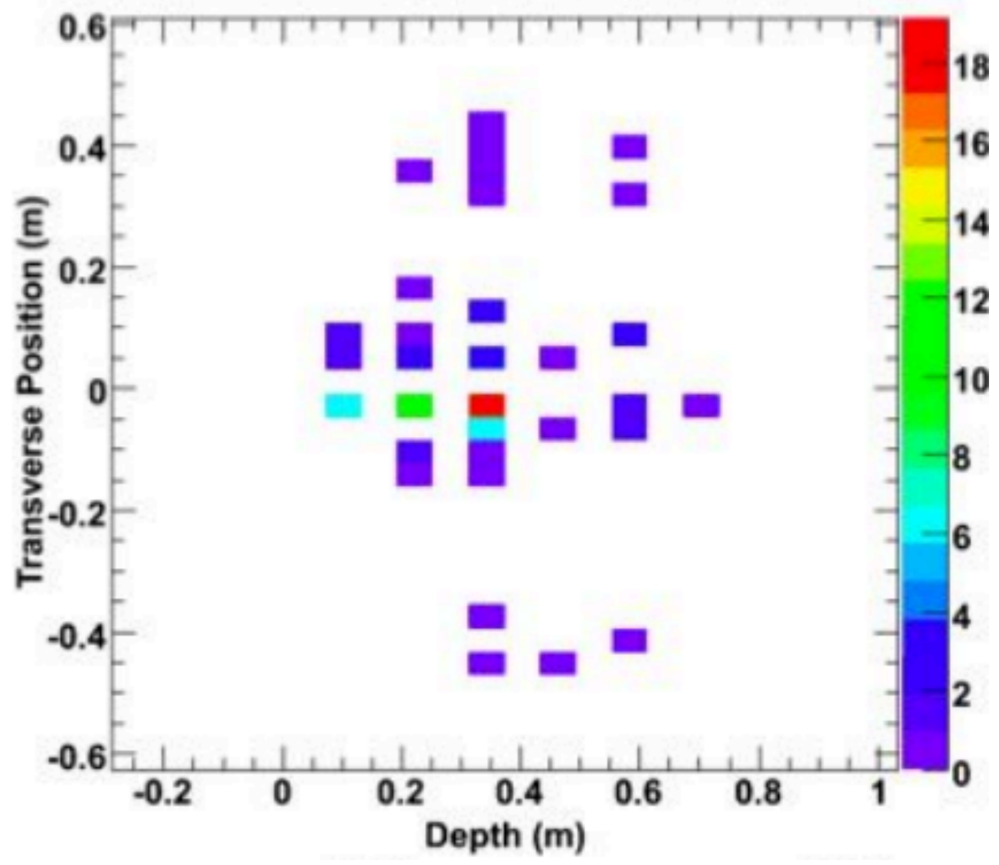
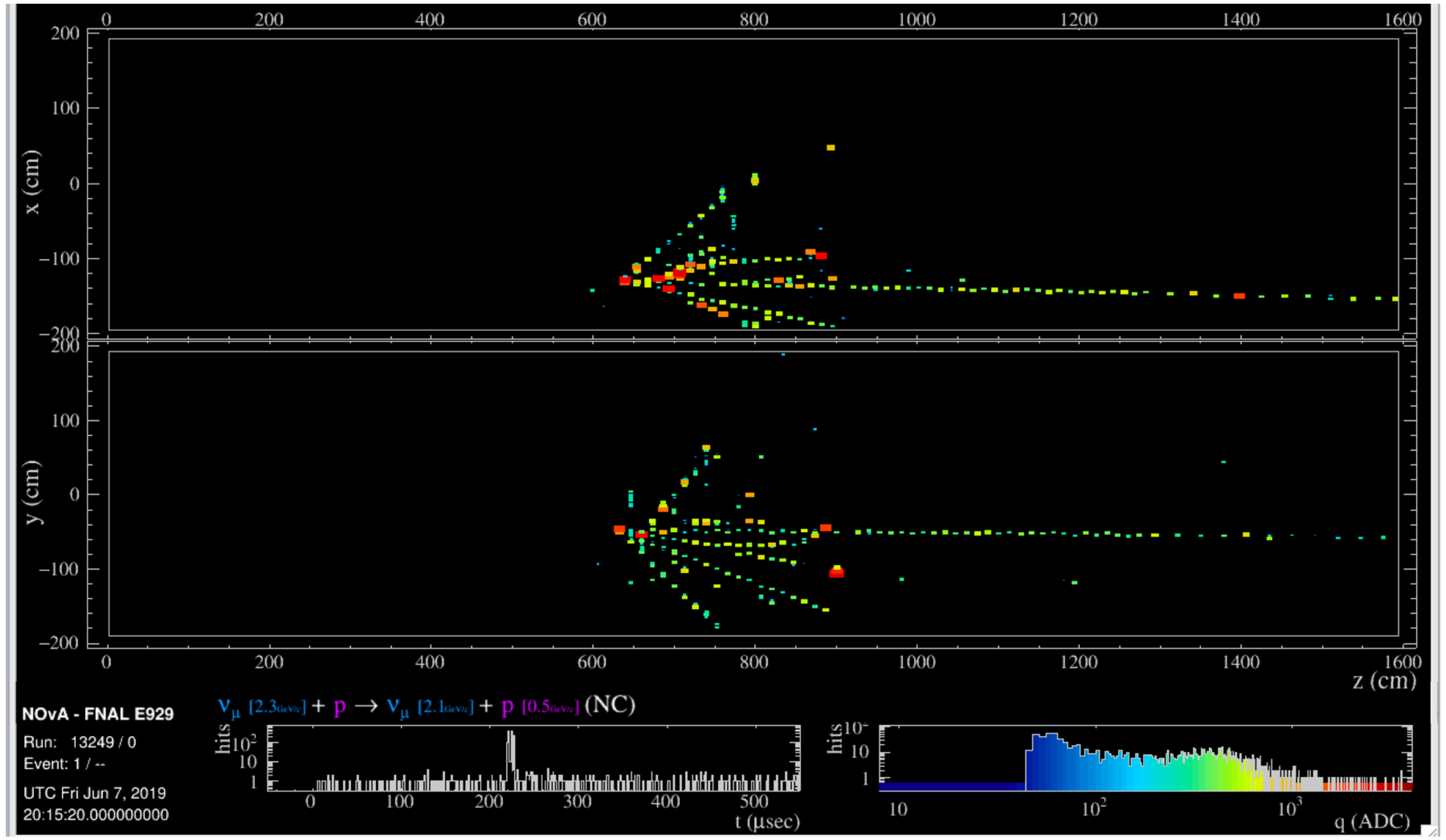
(2) Topological capabilities: 3D tracking and calorimetry

MINOS event



NOvA event



https://cdcvs.fnal.gov/redmine/projects/novaart/wiki/Running_the_EventDisplay

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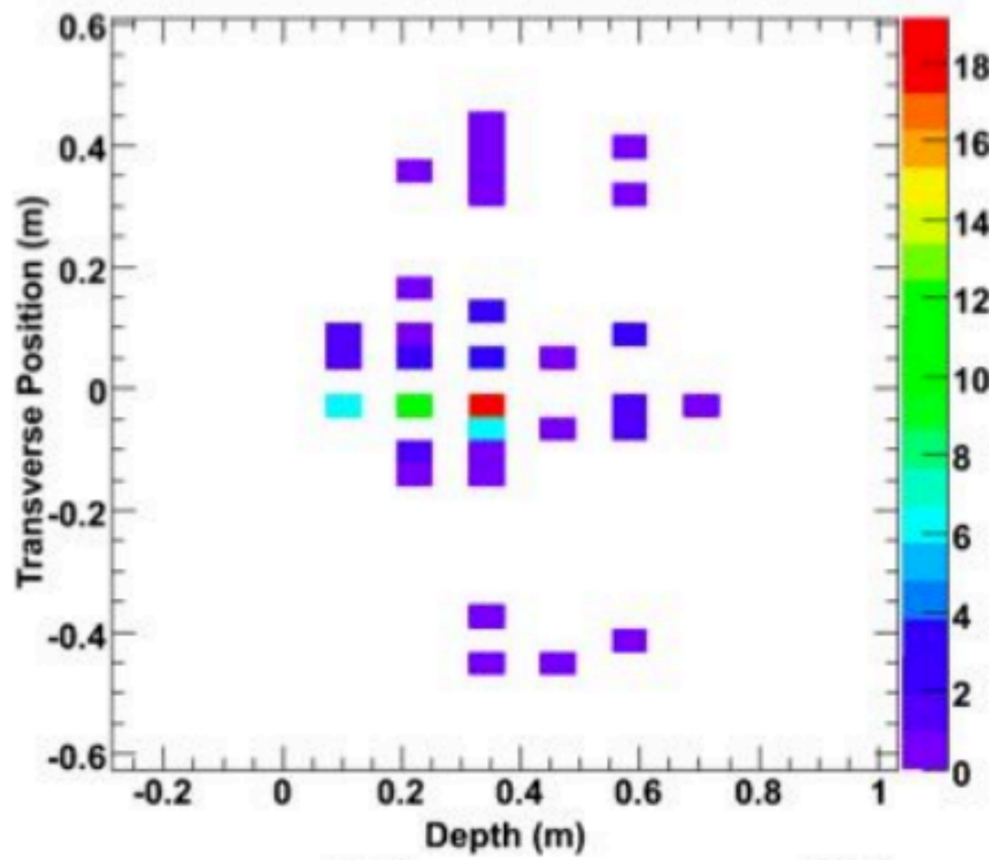
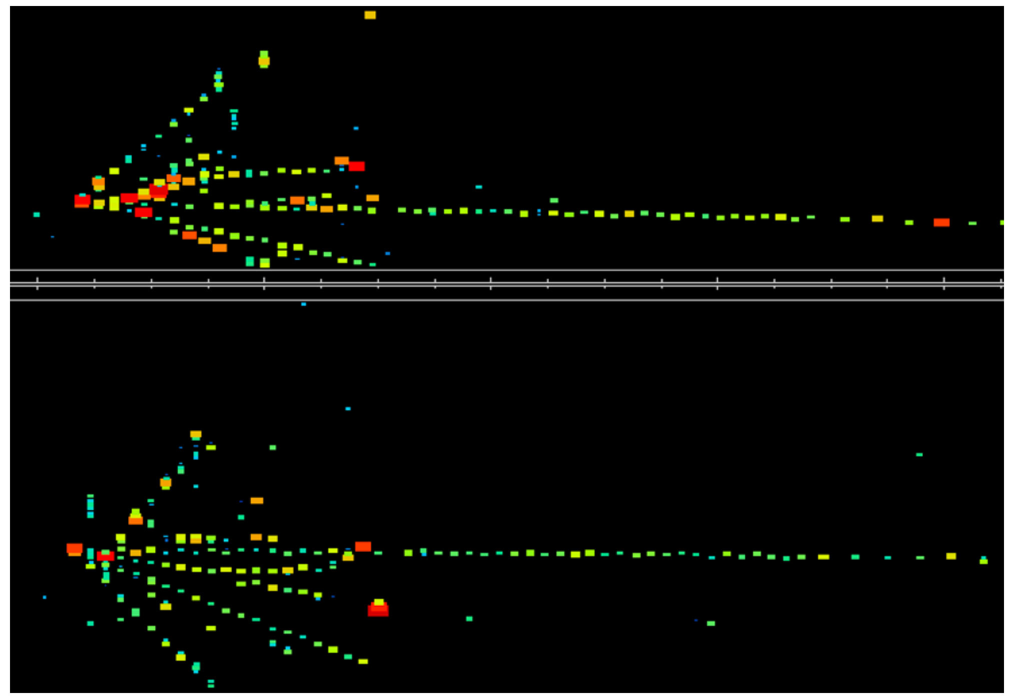
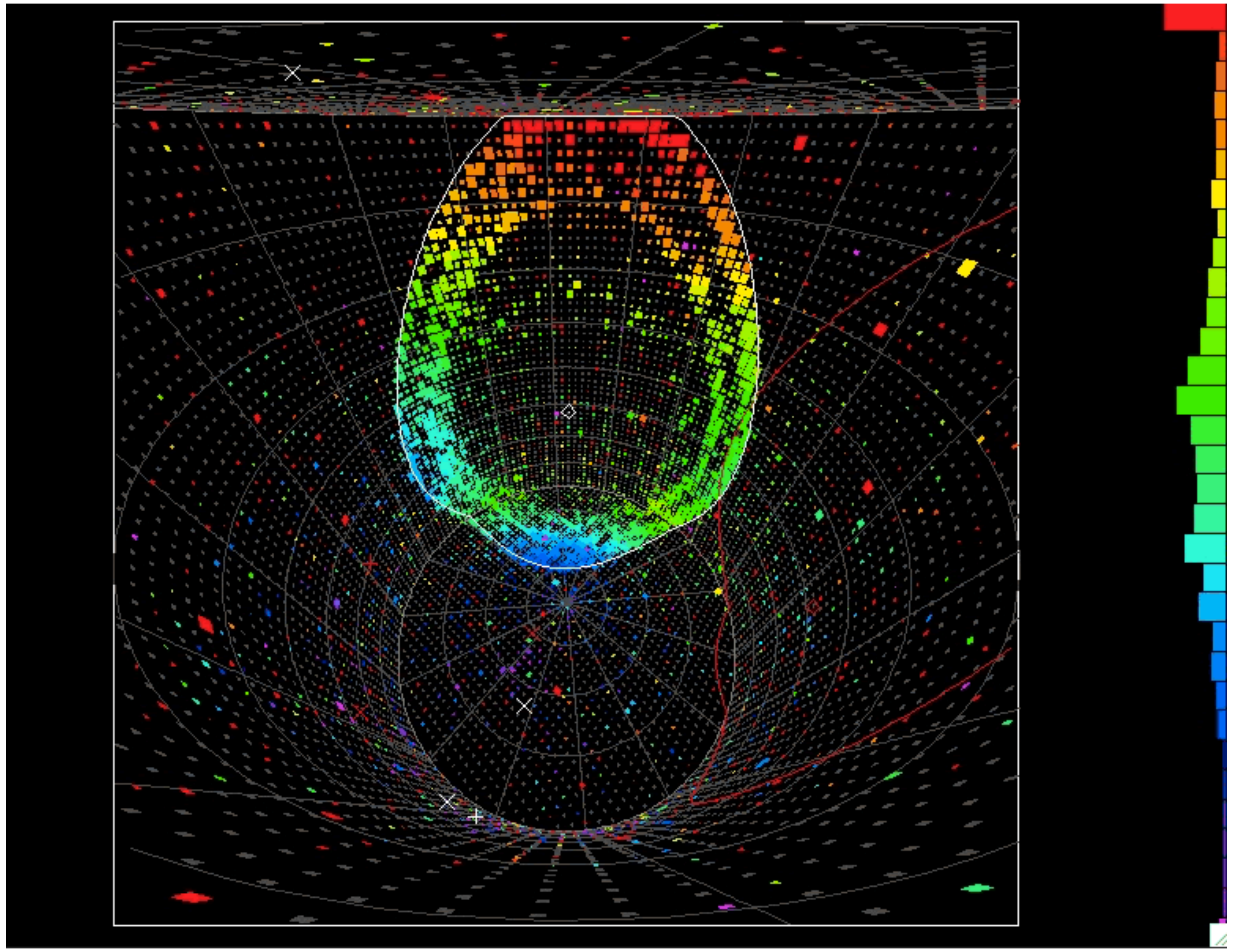


NOvA event



SK/T2K event



http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/t2k-e.html

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(2) Topological capabilities: 3D tracking and calorimetry

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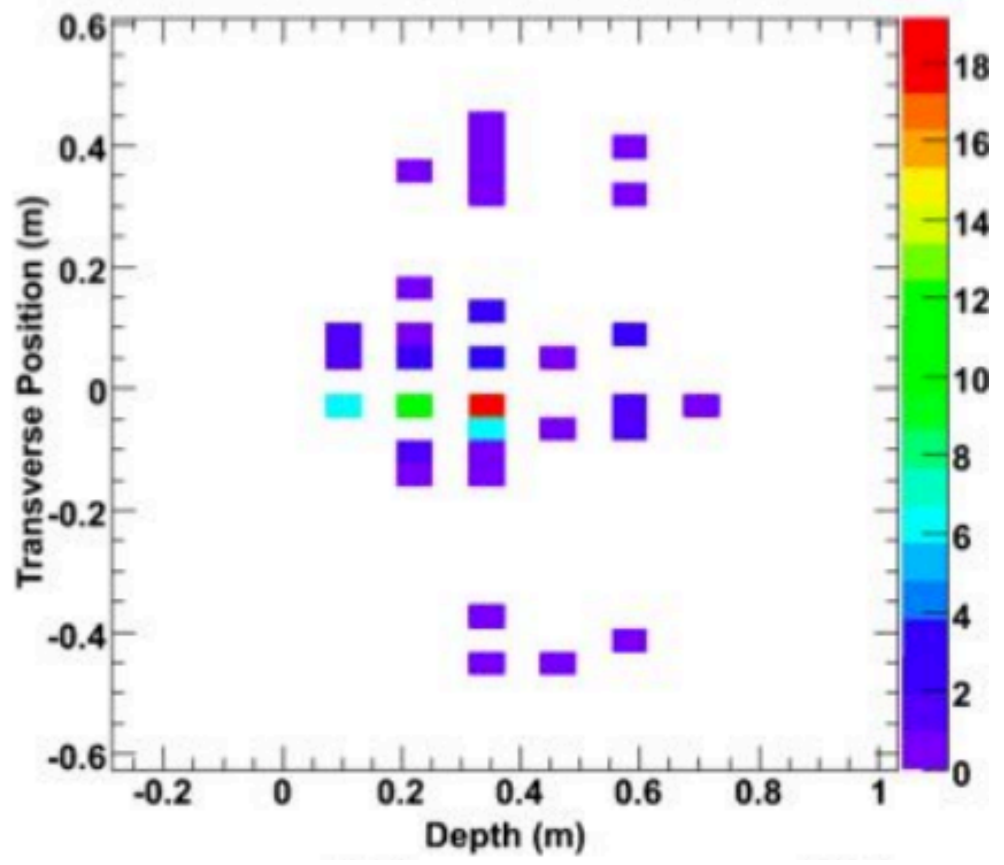

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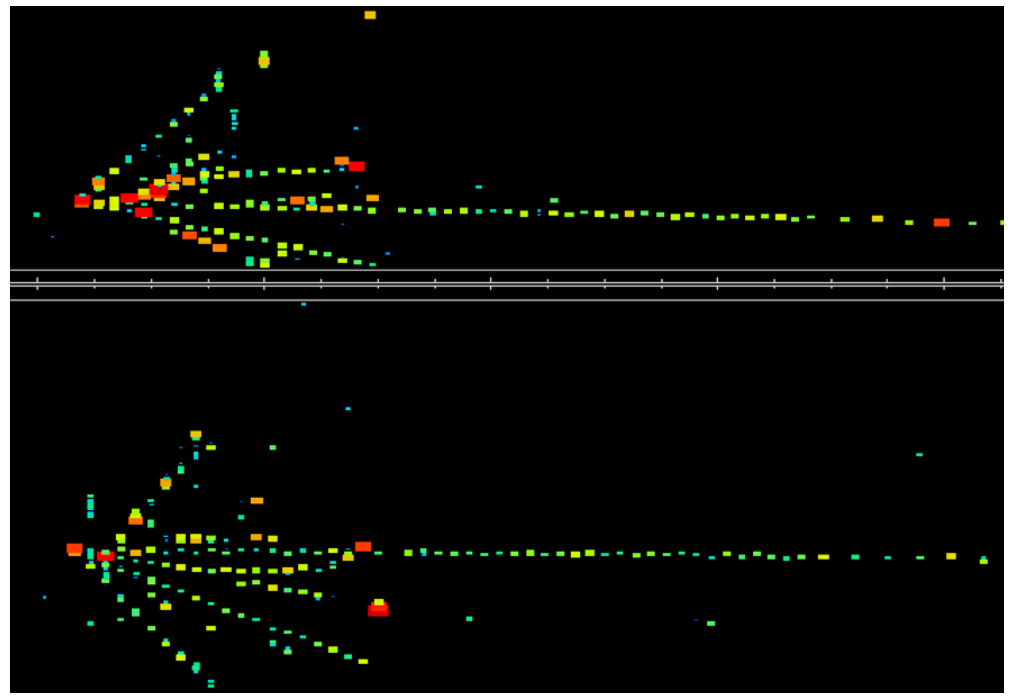

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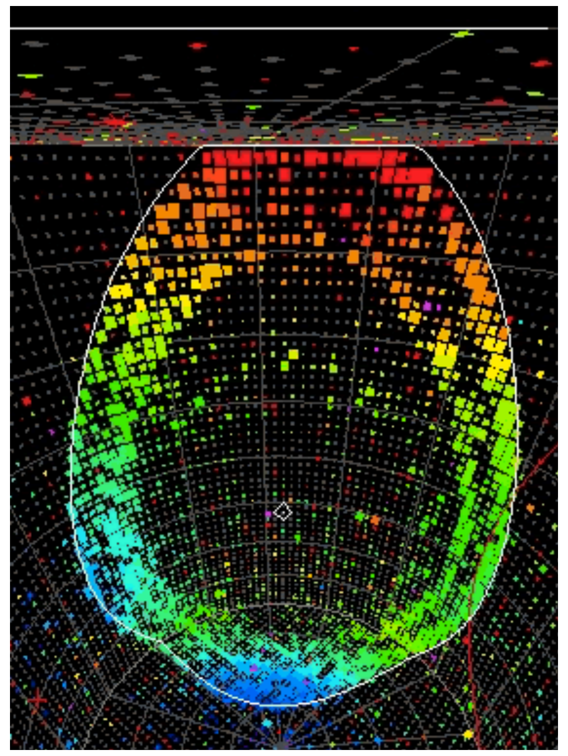
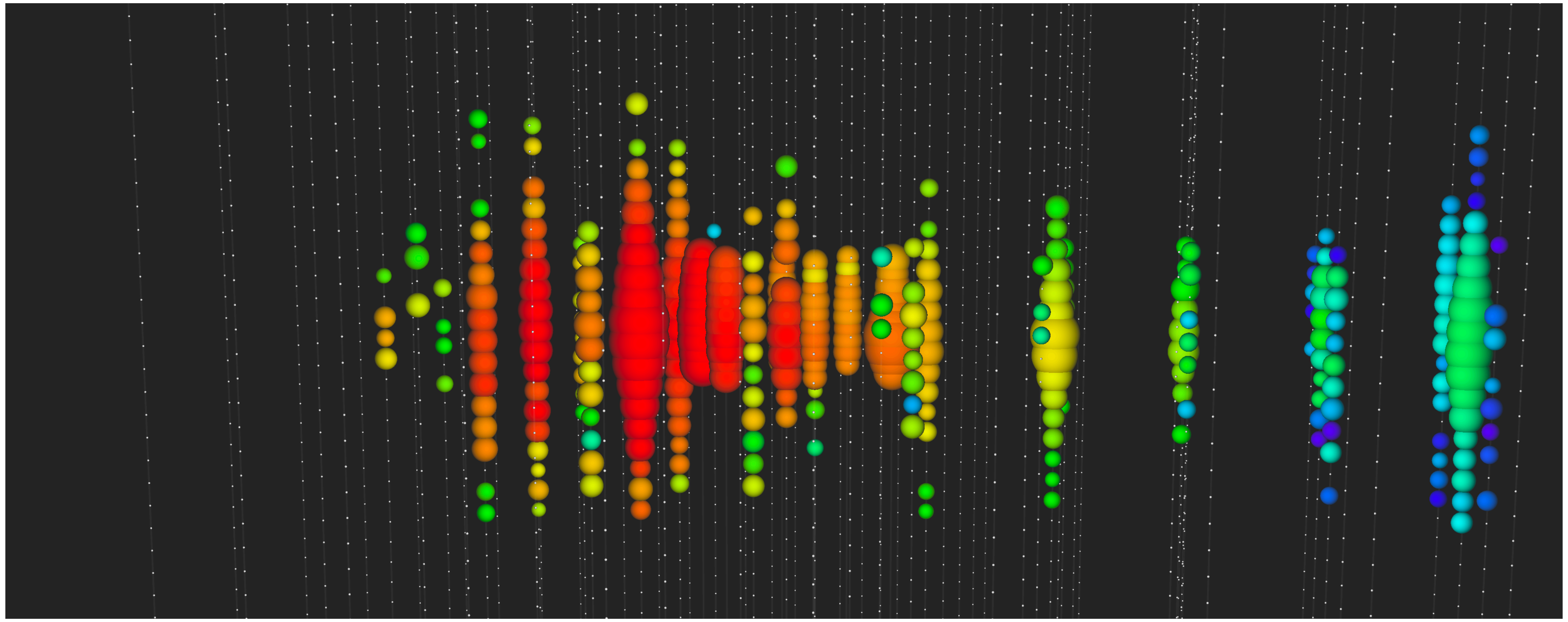


IceCube event



https://icecube.wisc.edu/science

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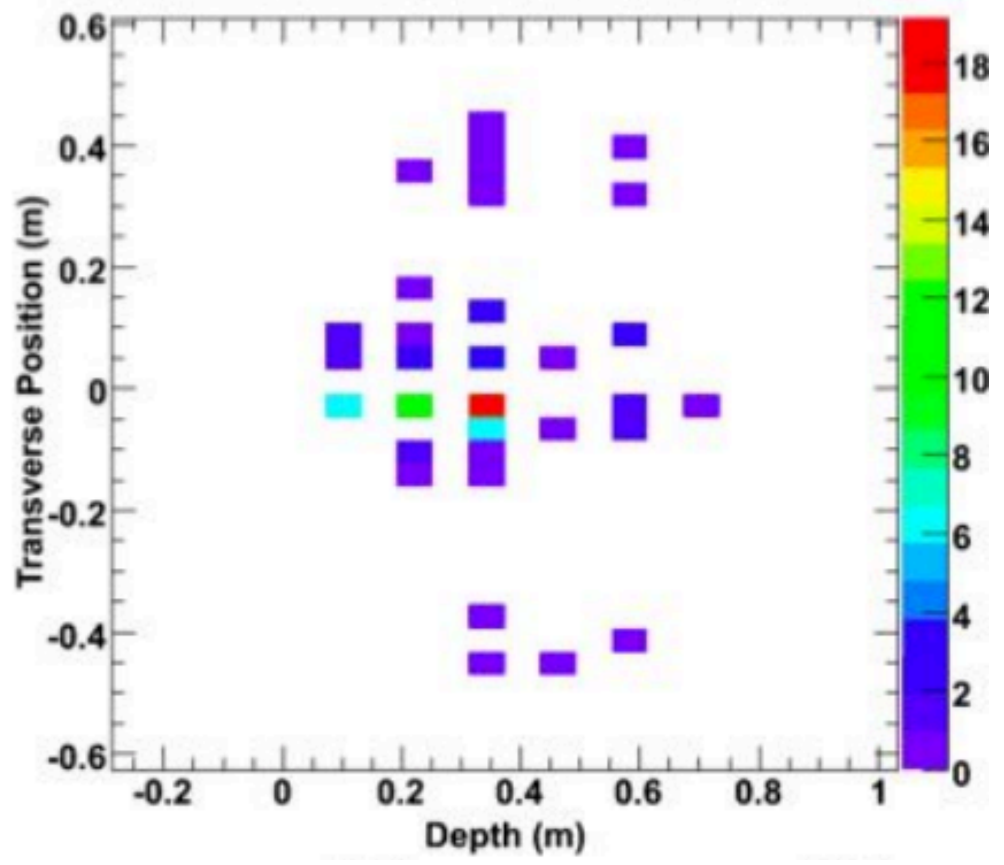
MINOS event



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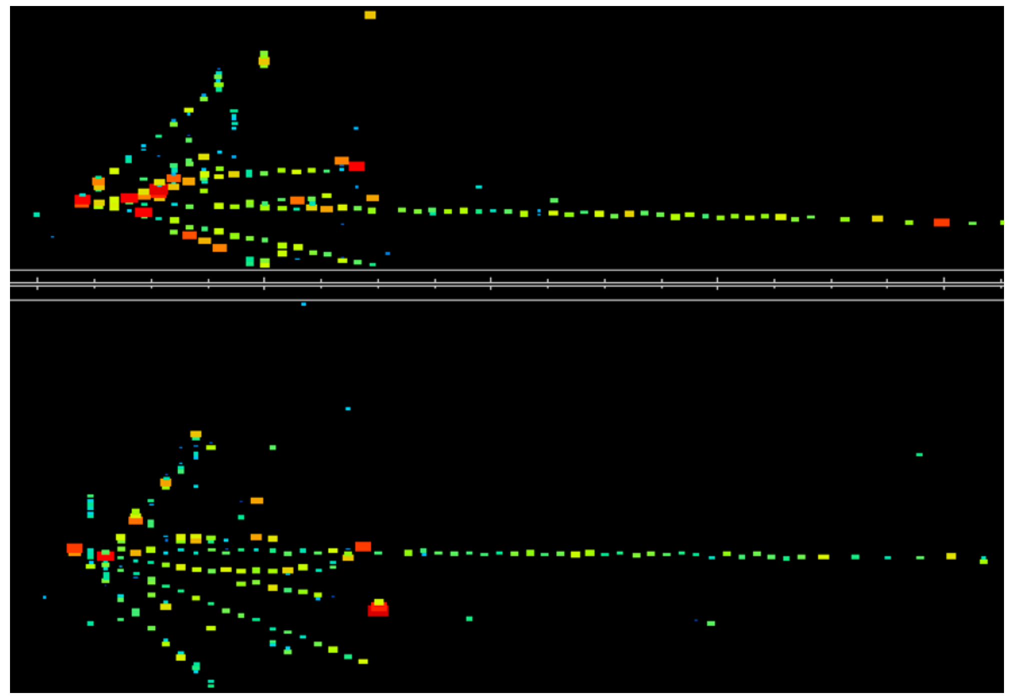

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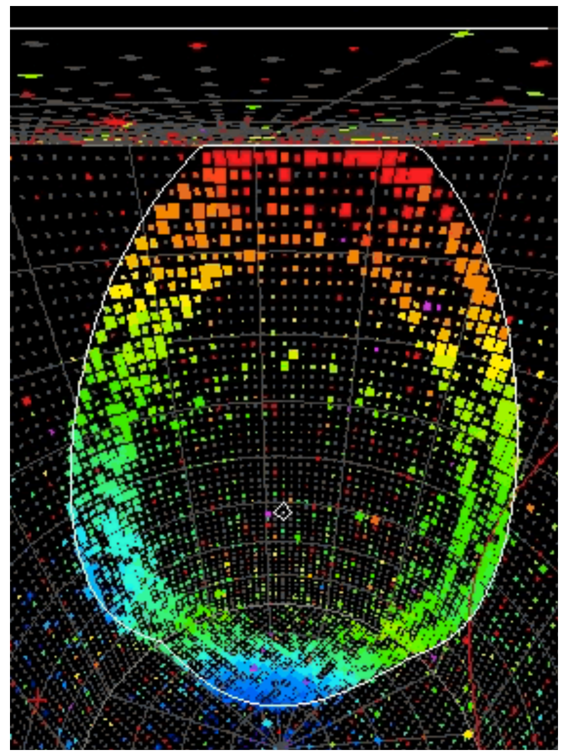

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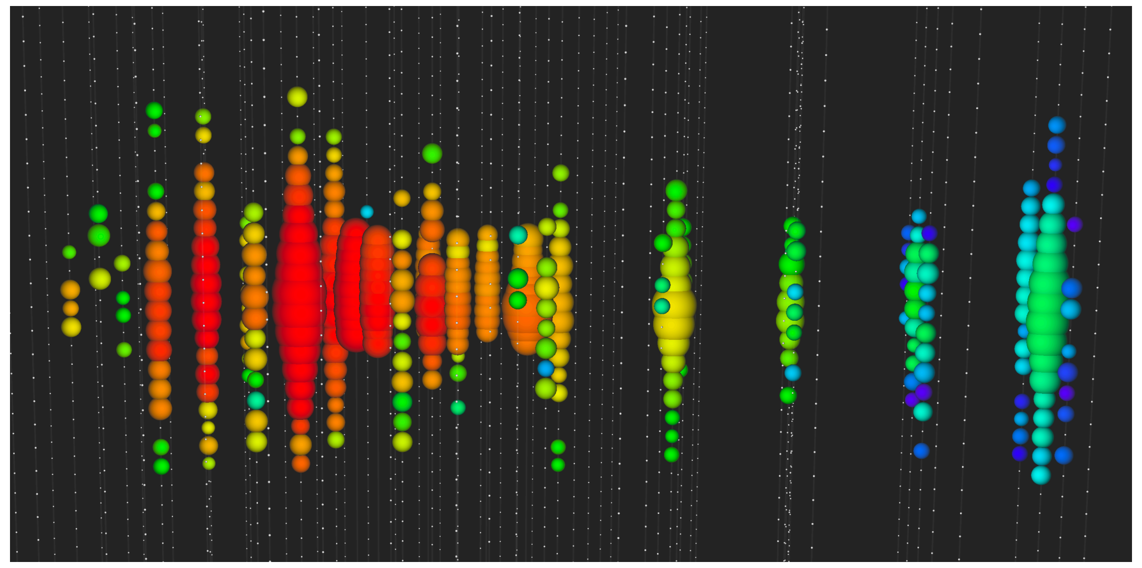
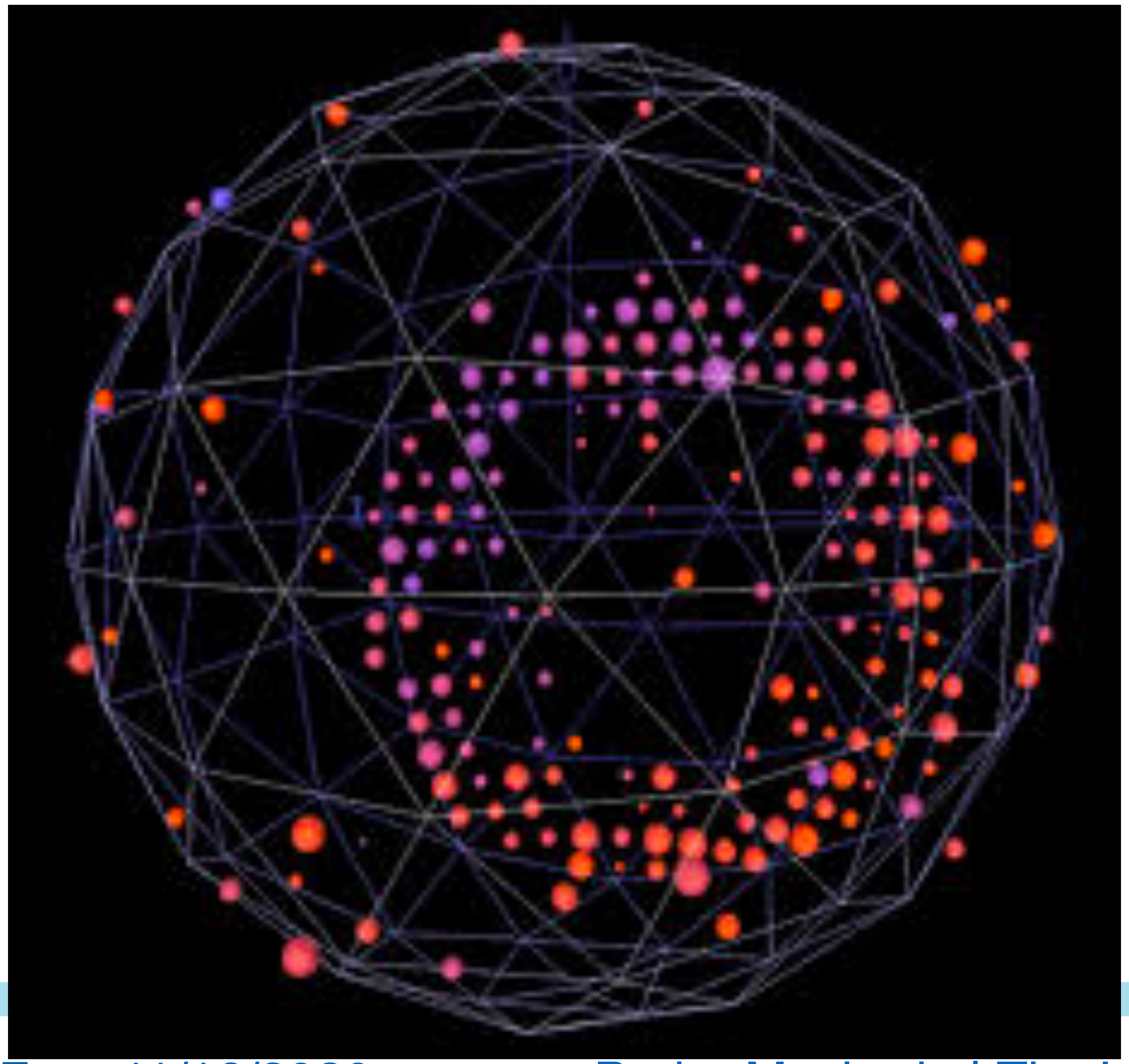


MiniBooNE event



http://www2.lns.mit.edu/~conrad/miniboone.html

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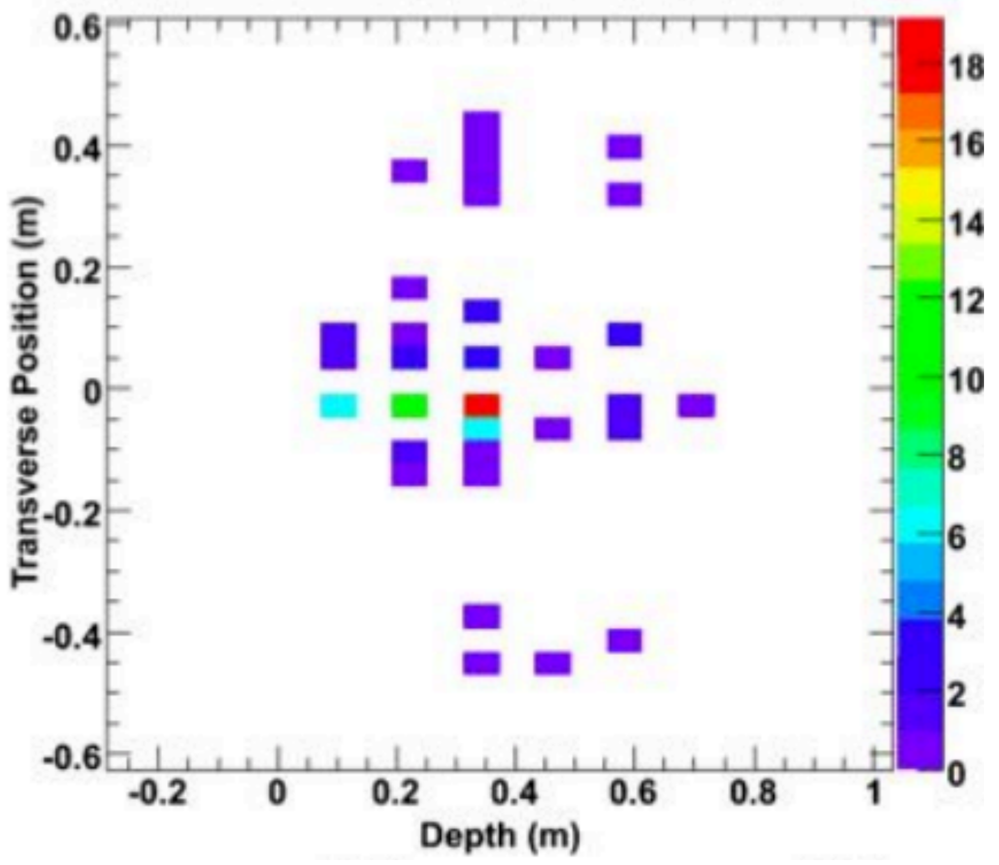
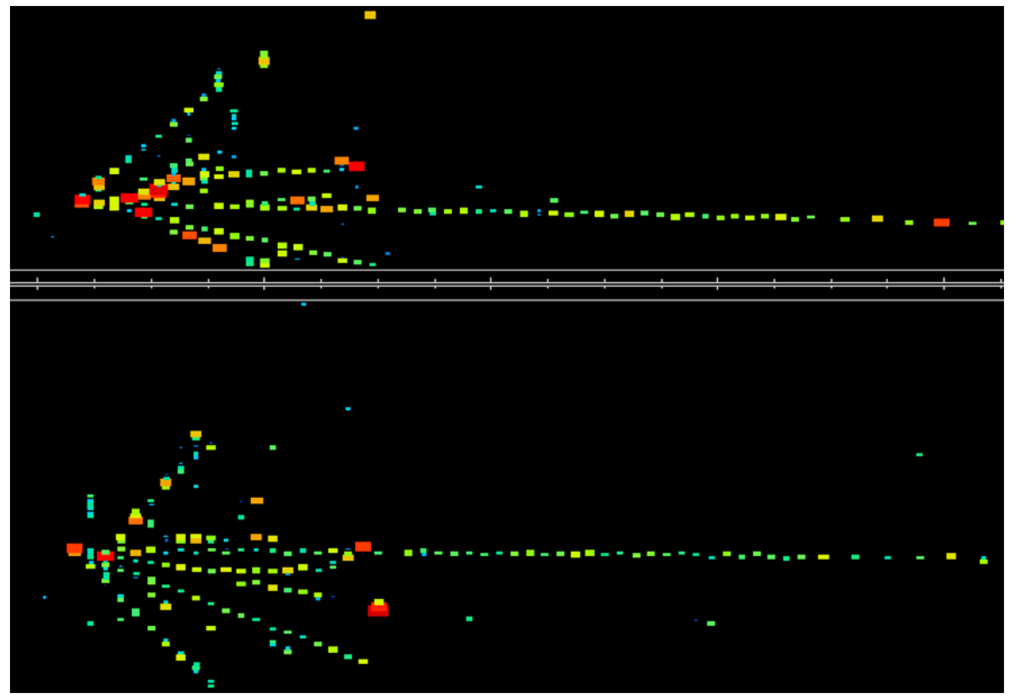
(2) Topological capabilities: 3D tracking and calorimetry

MINOS event



NOvA event



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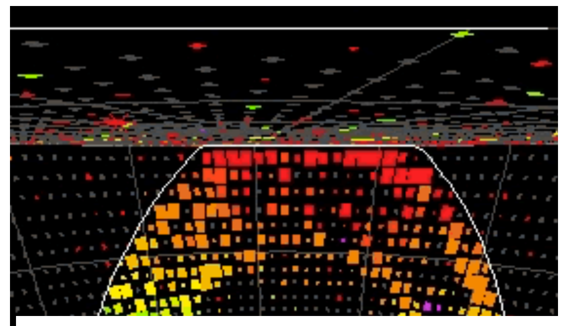

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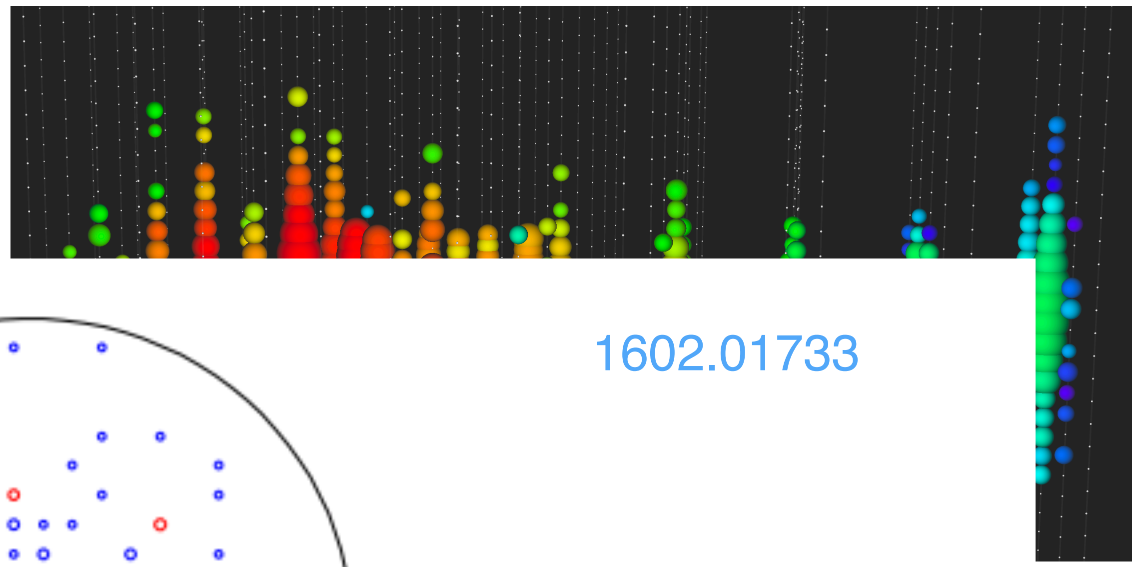

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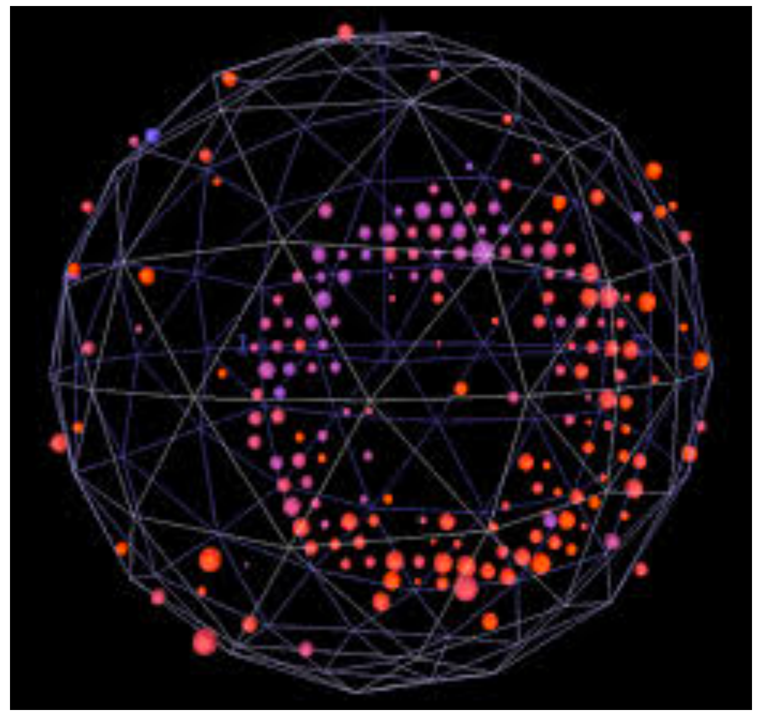
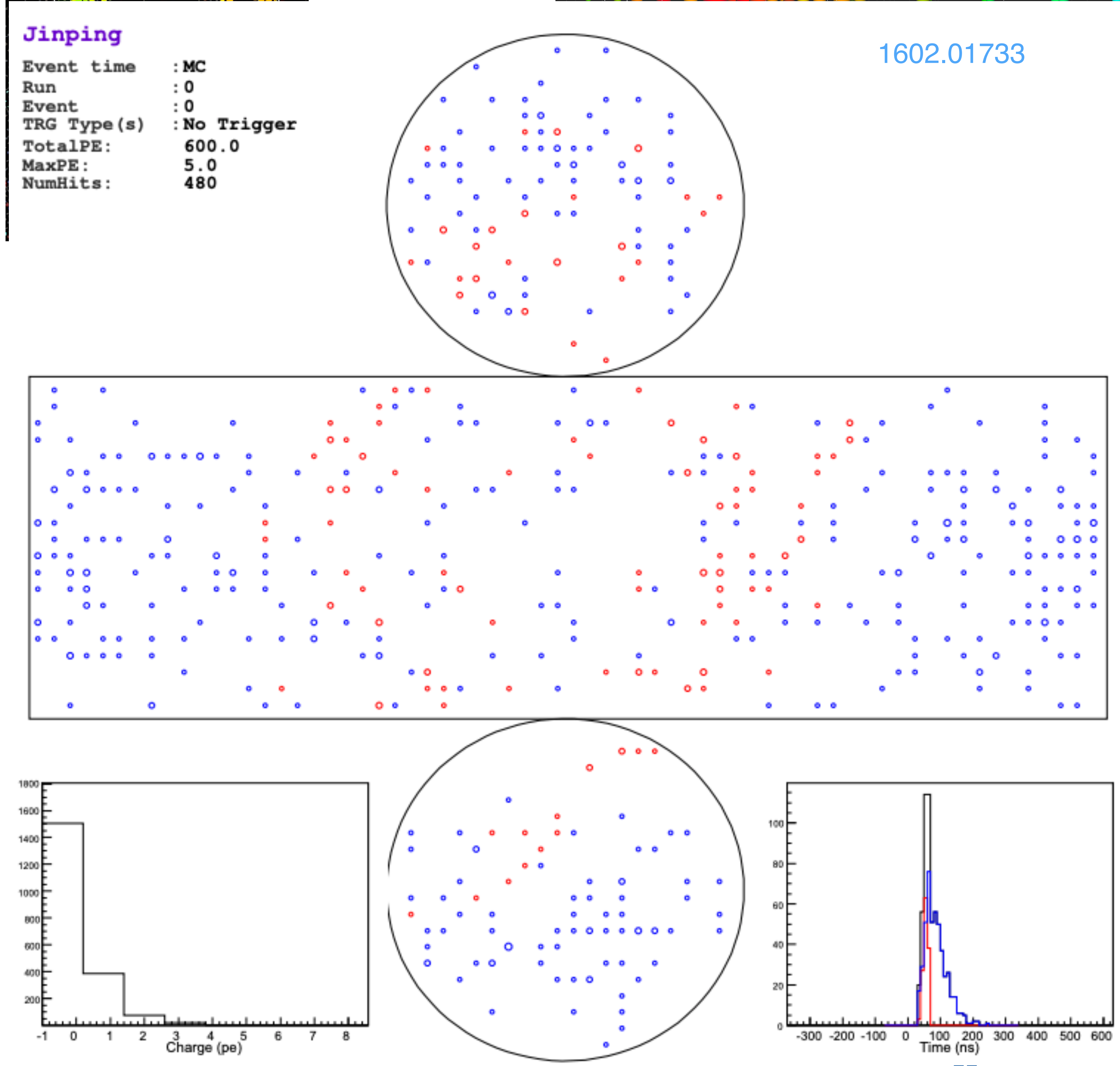


Liquid scintillator event
(e.g. Daya Bay, JUNO, RENO, …)



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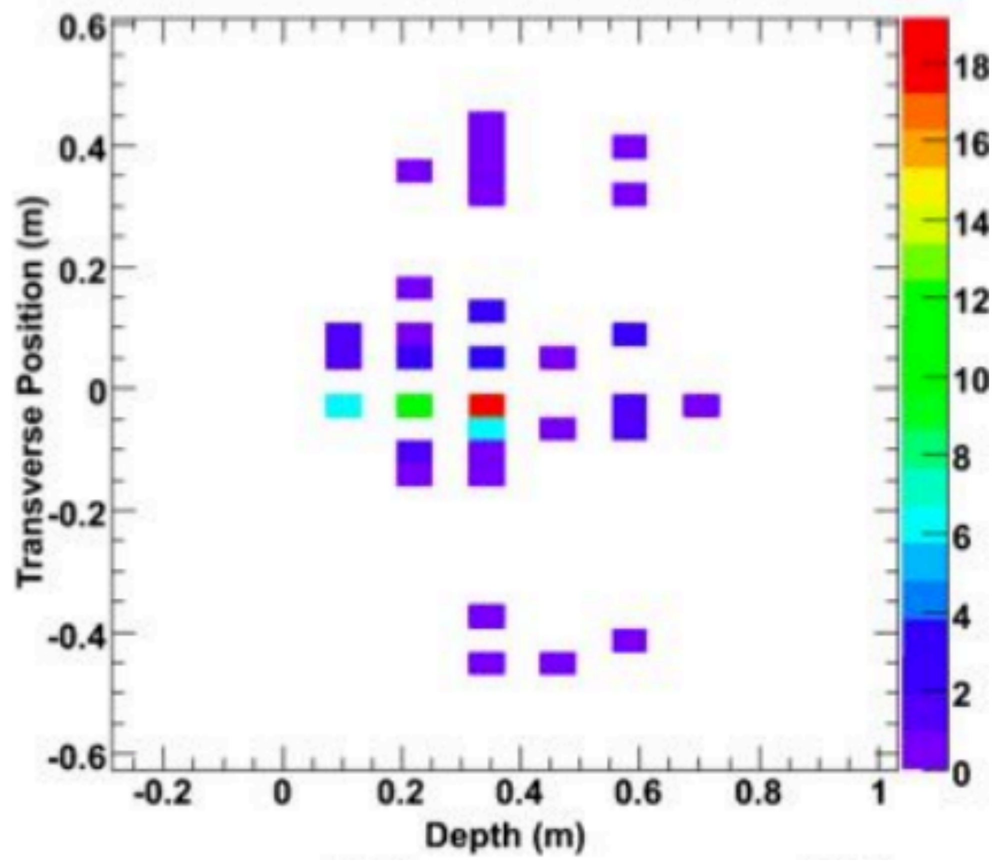
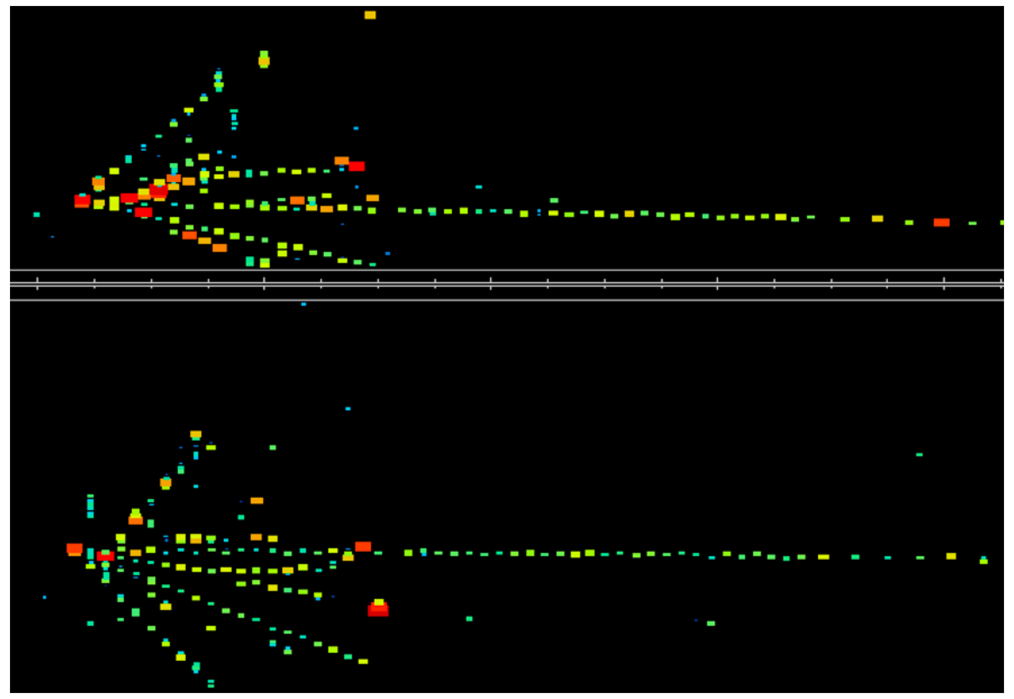
(2) Topological capabilities: 3D tracking and calorimetry

MINOS event



NOvA event



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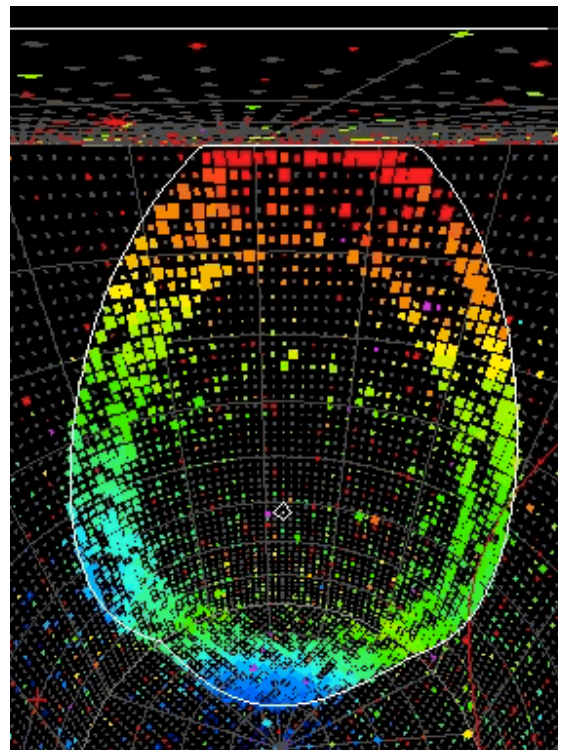
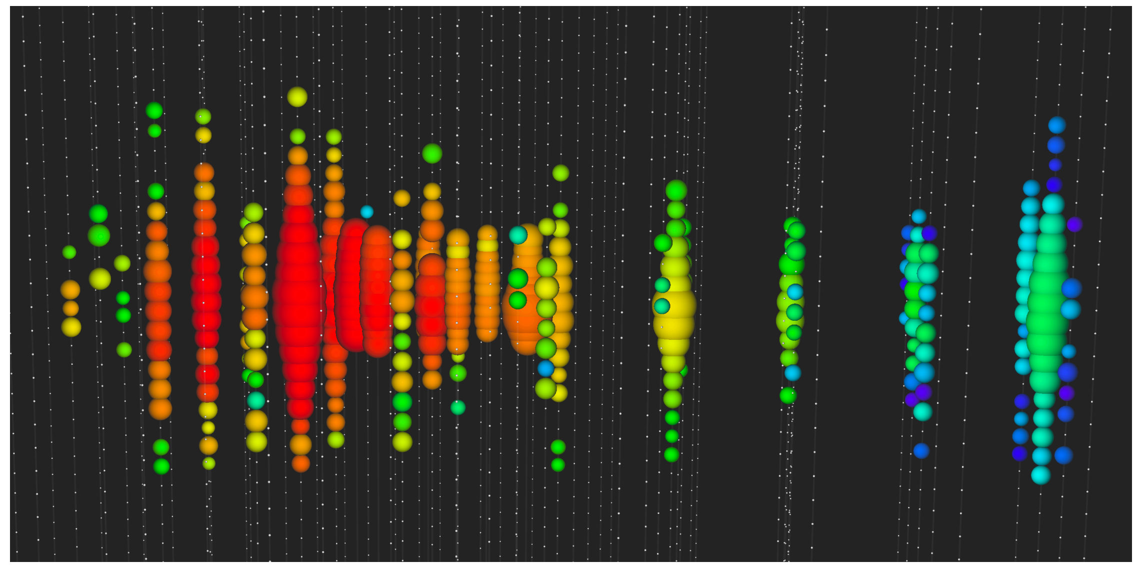
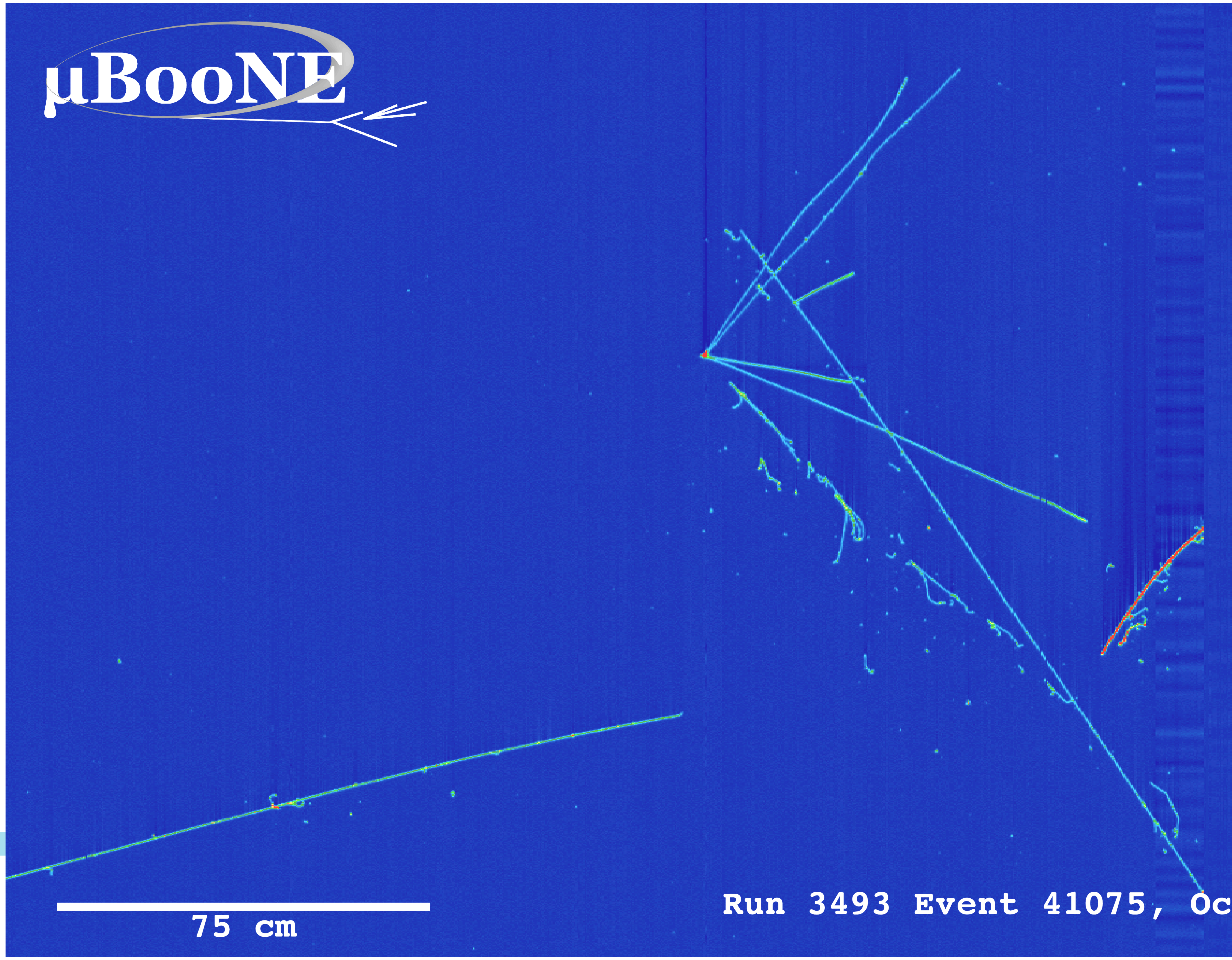


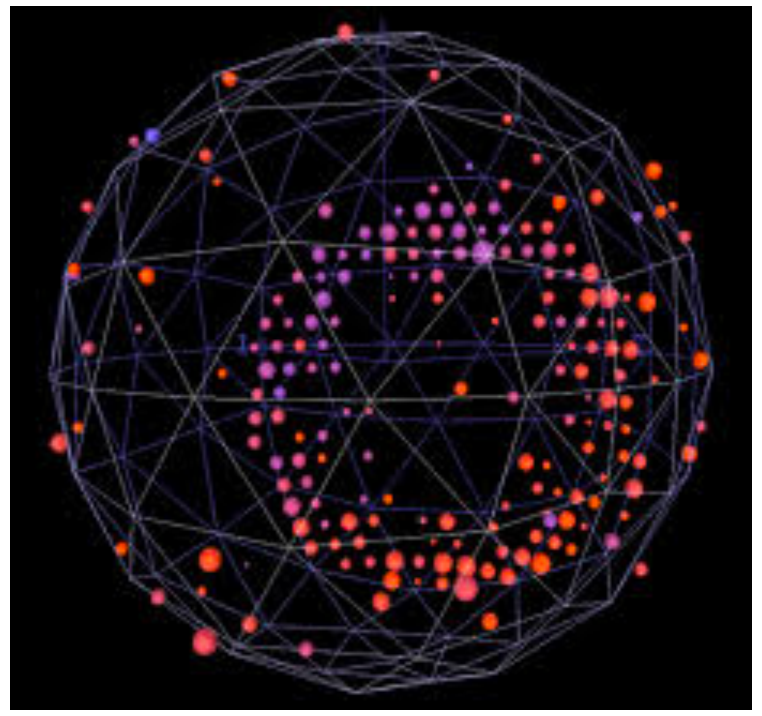
IceCube event



LArTPCs



MiniBooNE event



Liquid scintillator event

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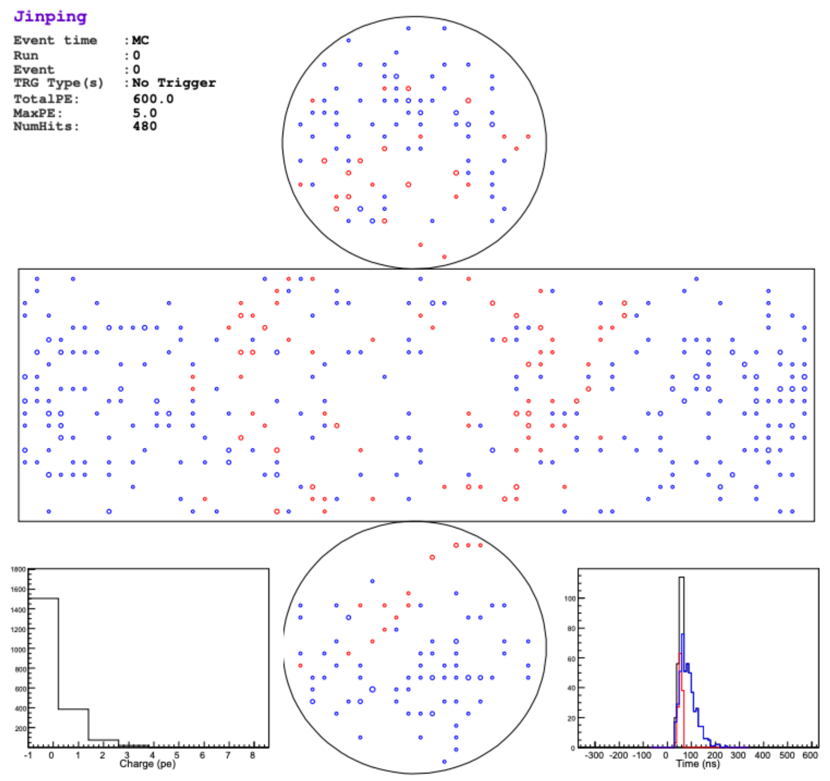

(2) Topological capabilities: 3D tracking and calorimetry

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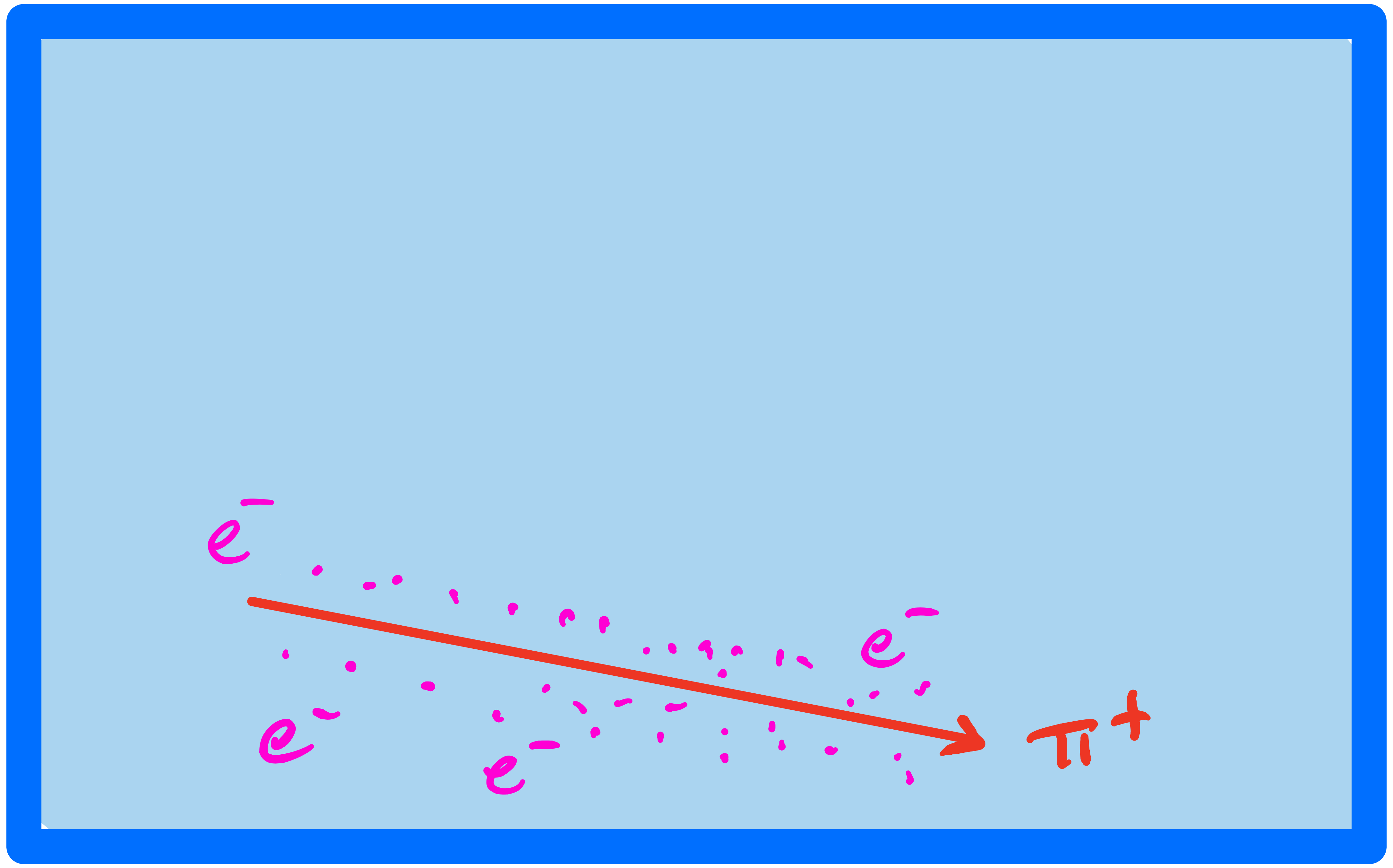

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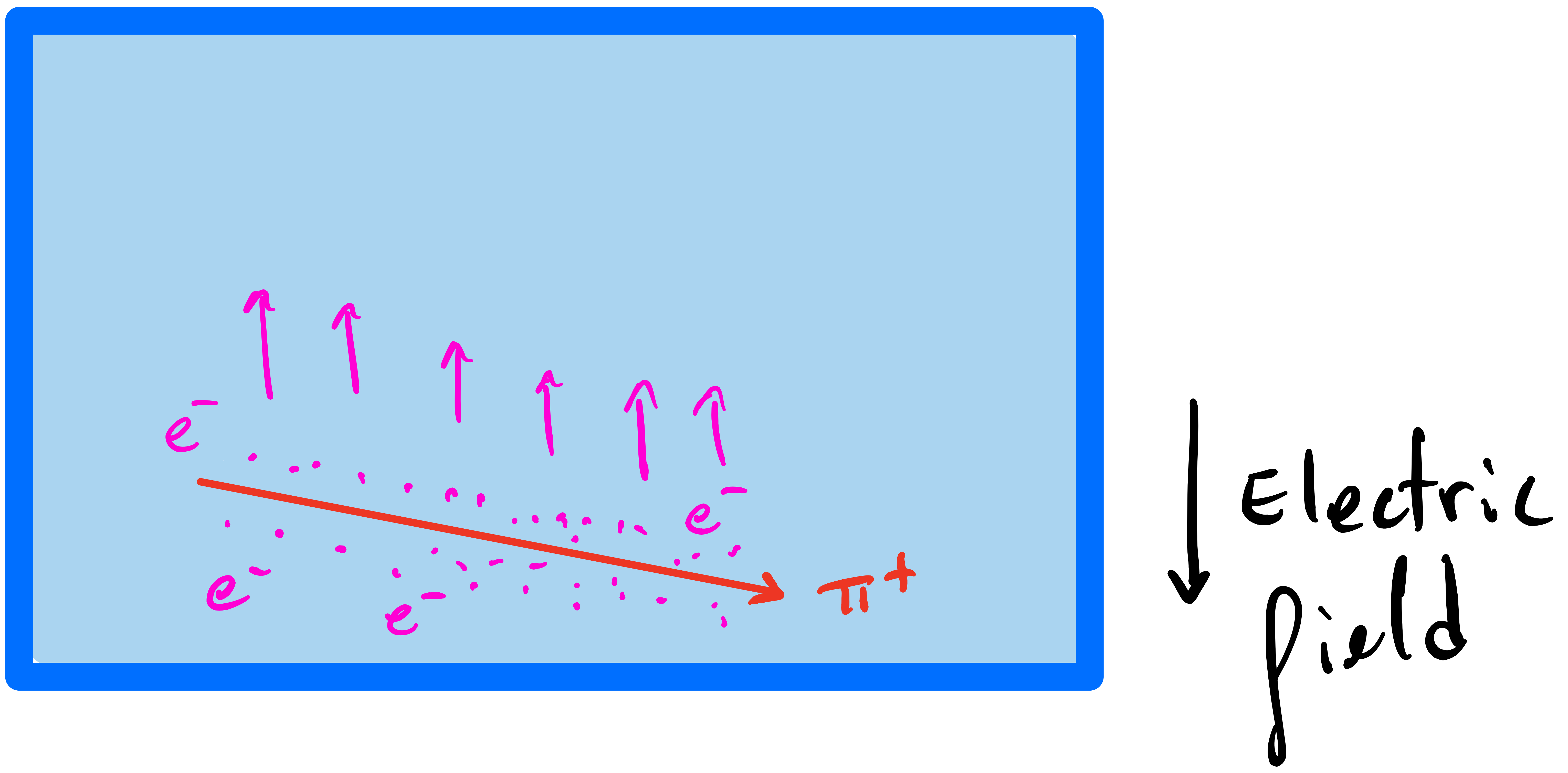

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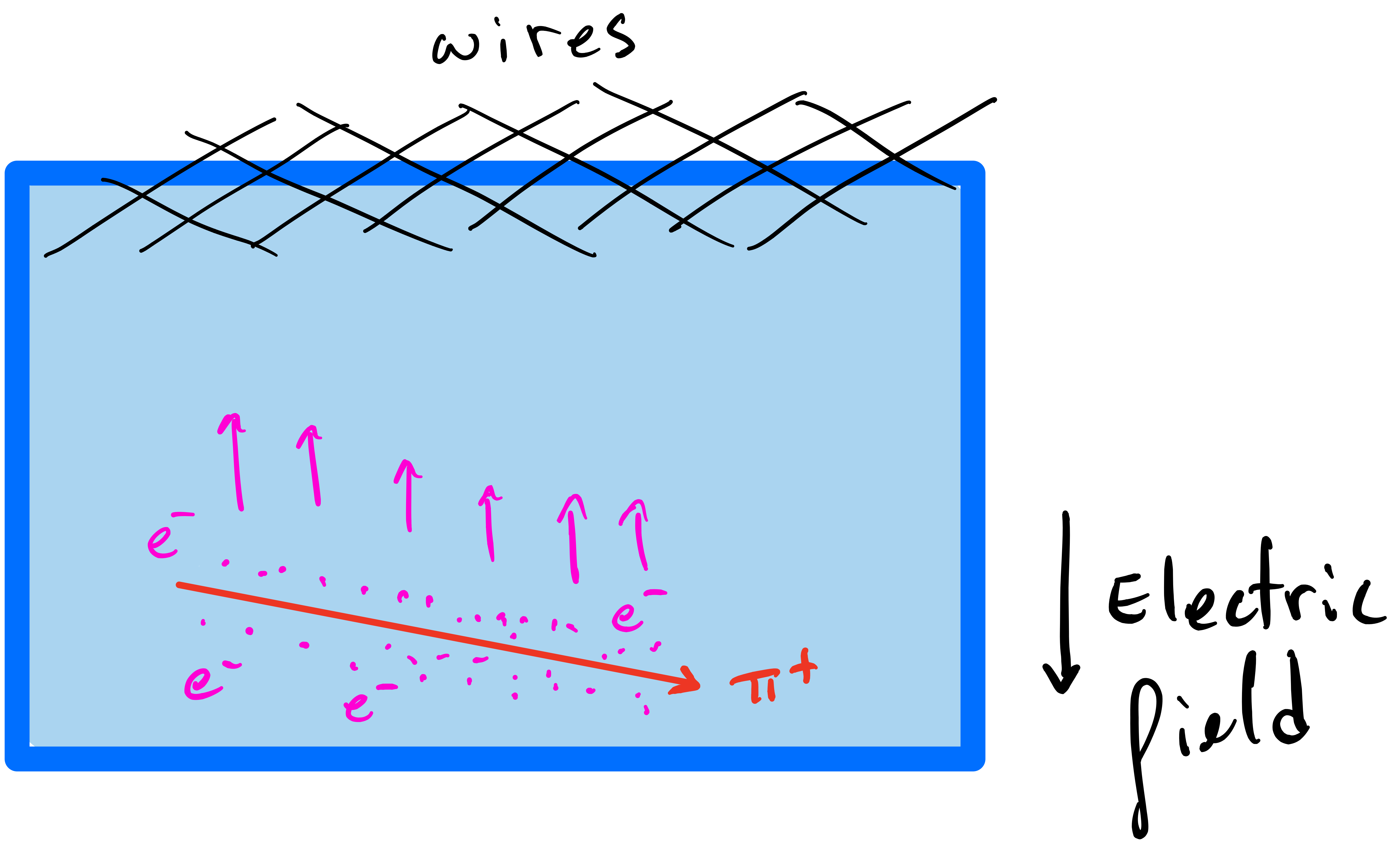

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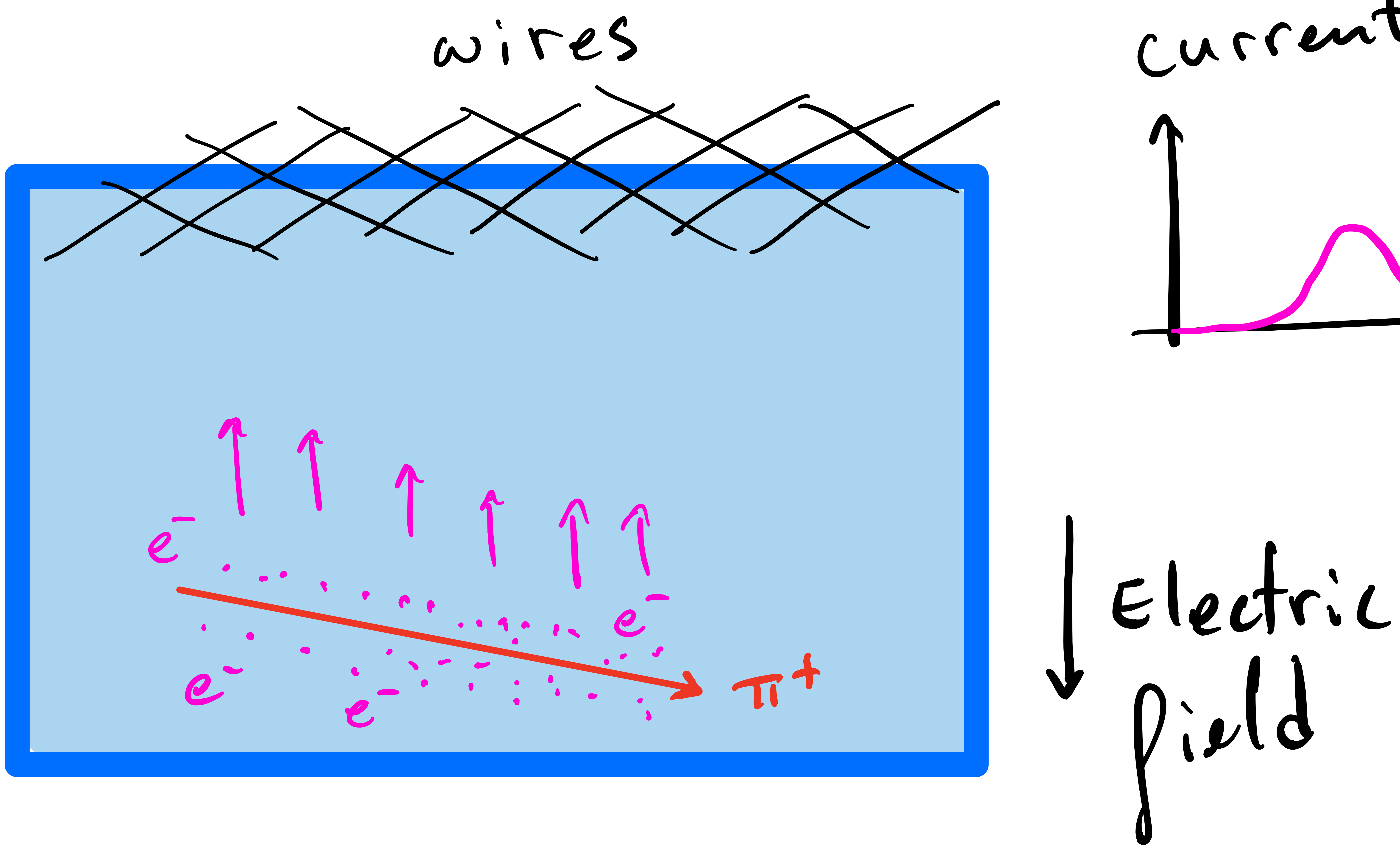

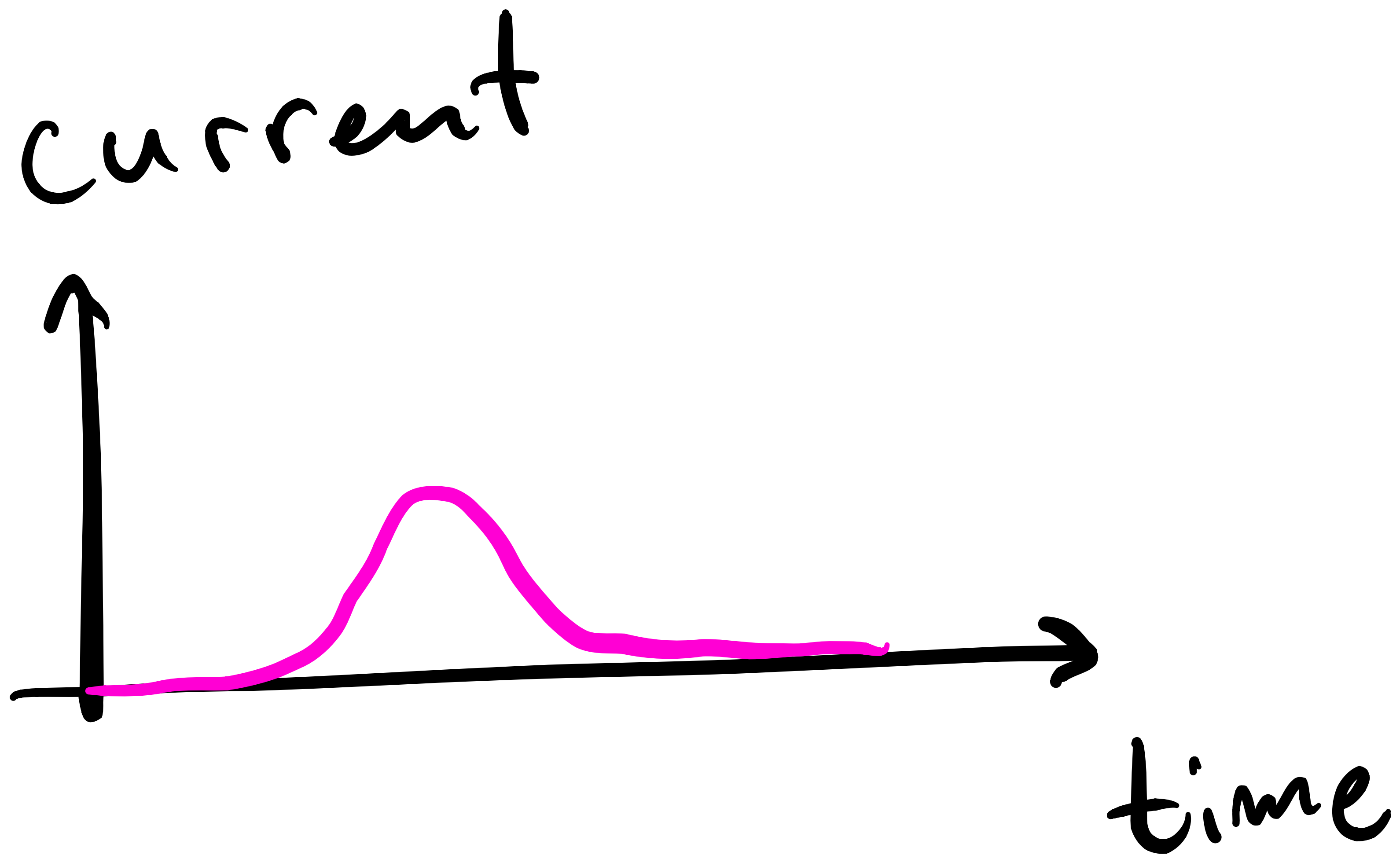

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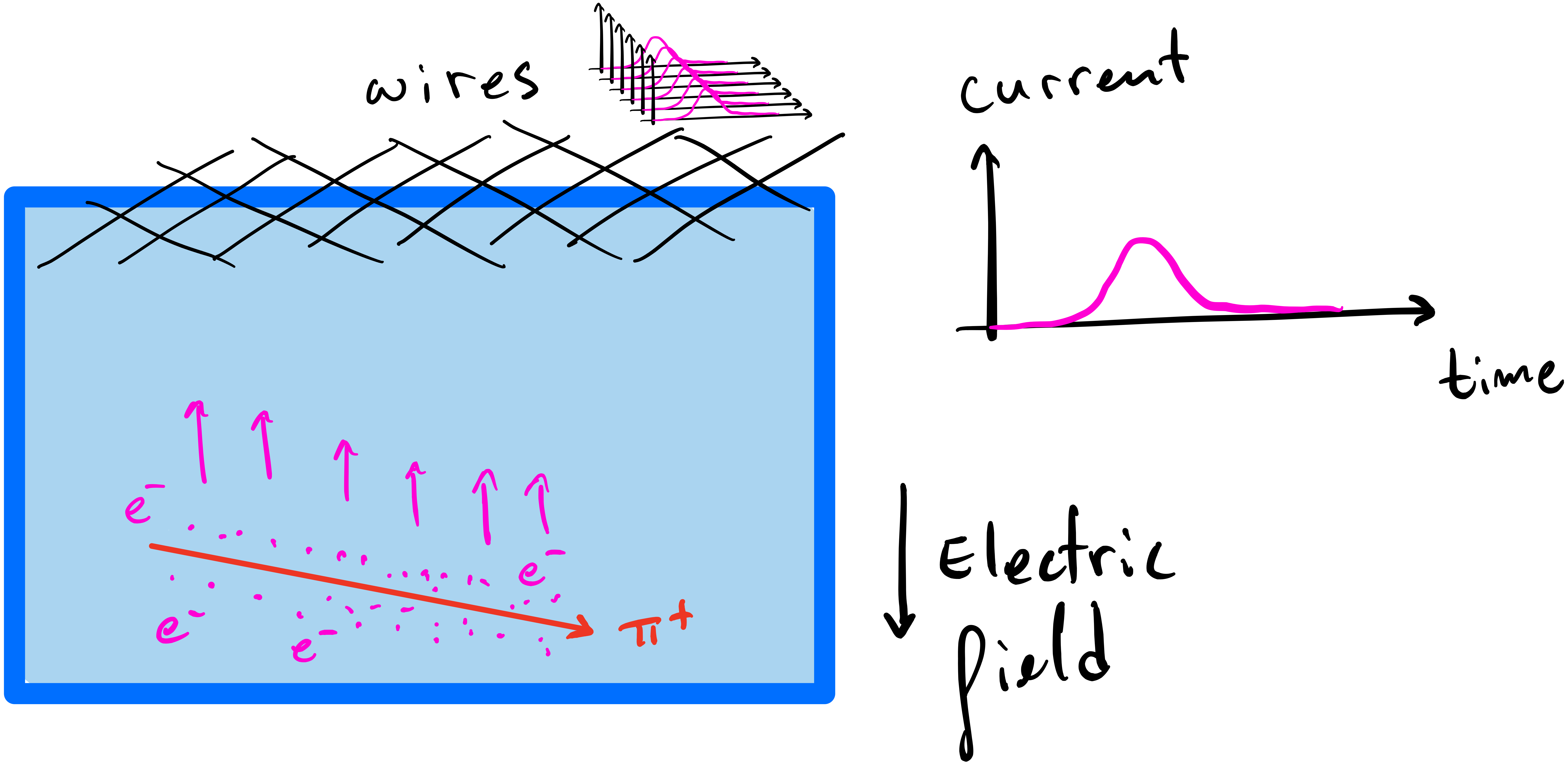

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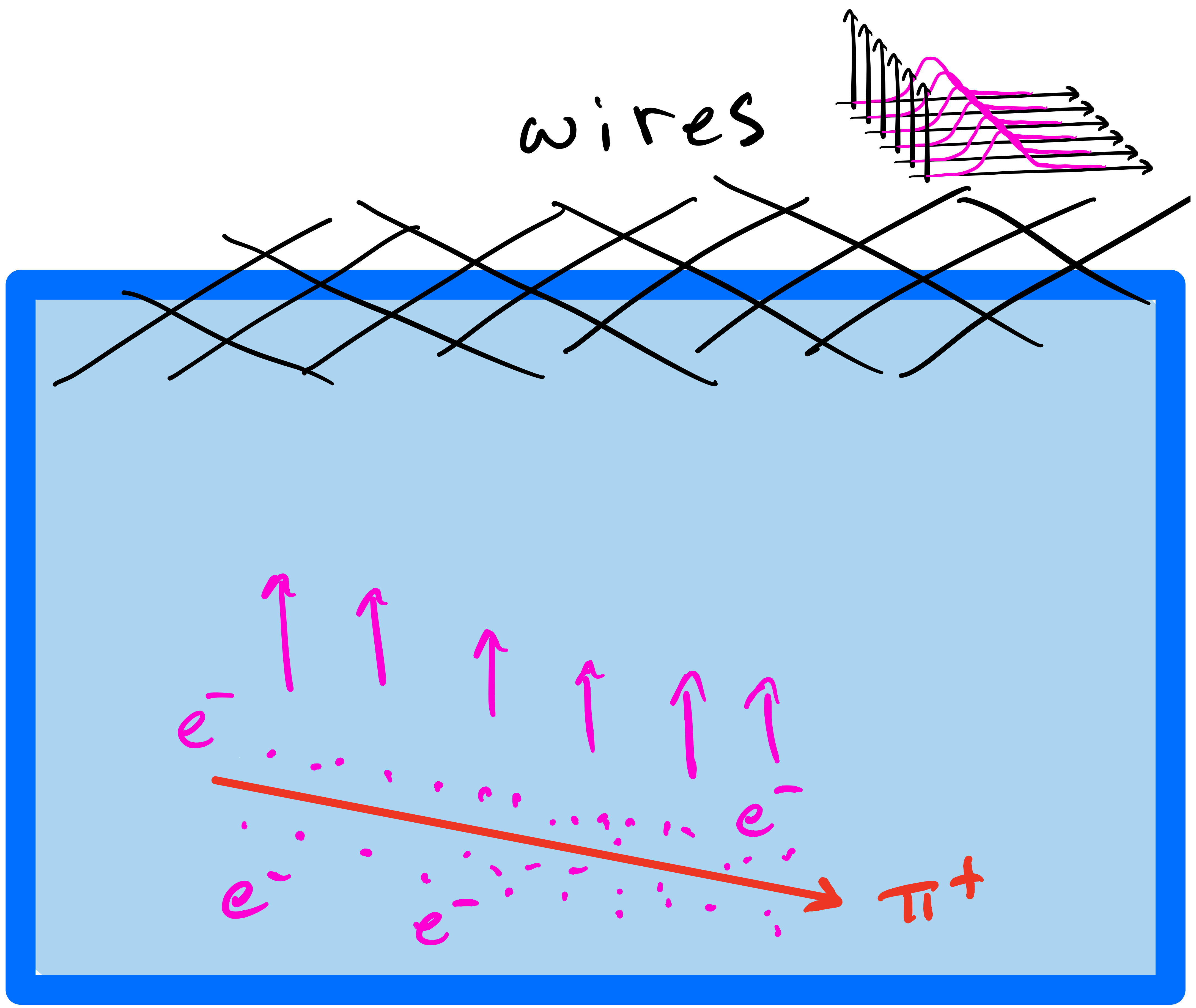

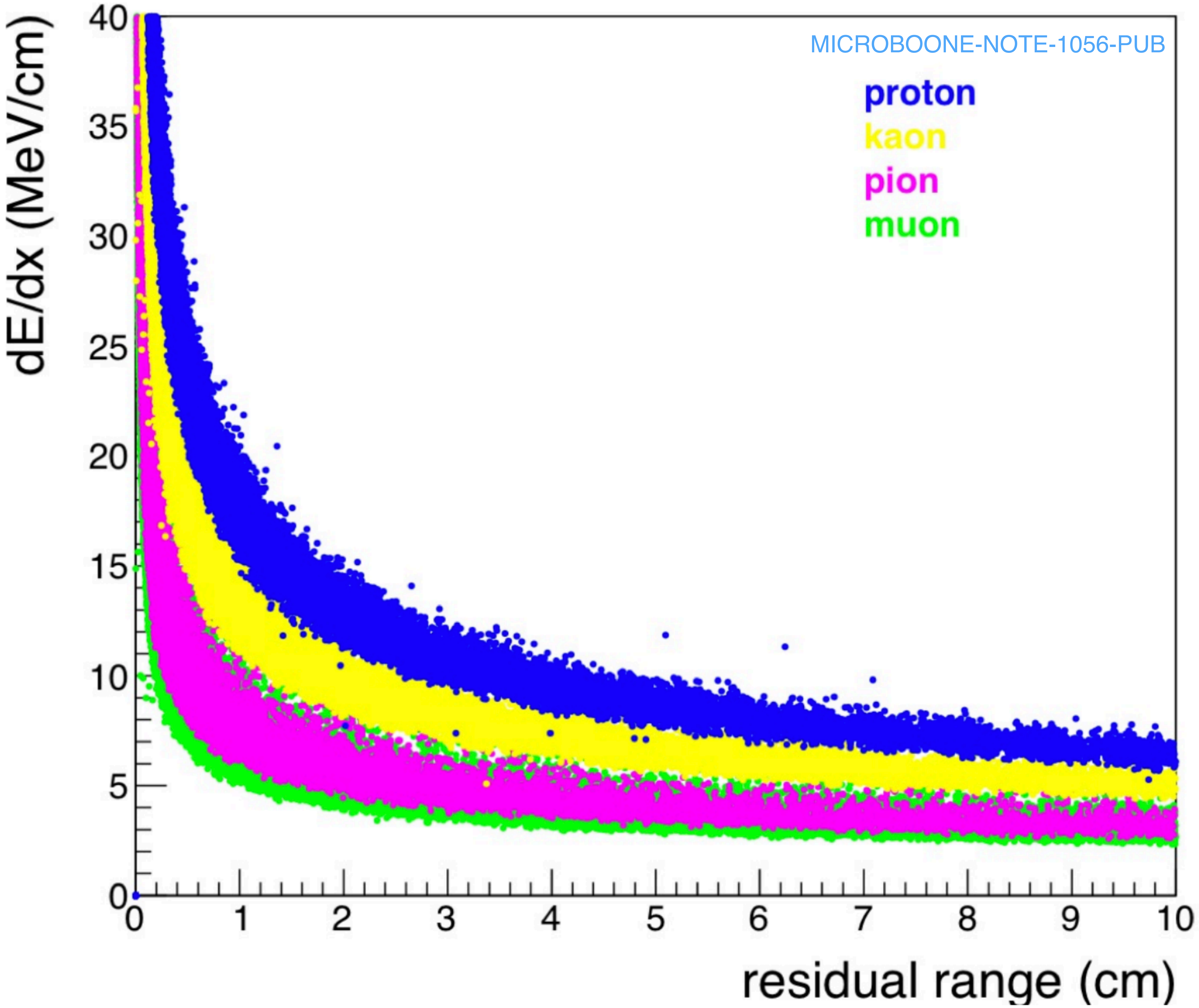

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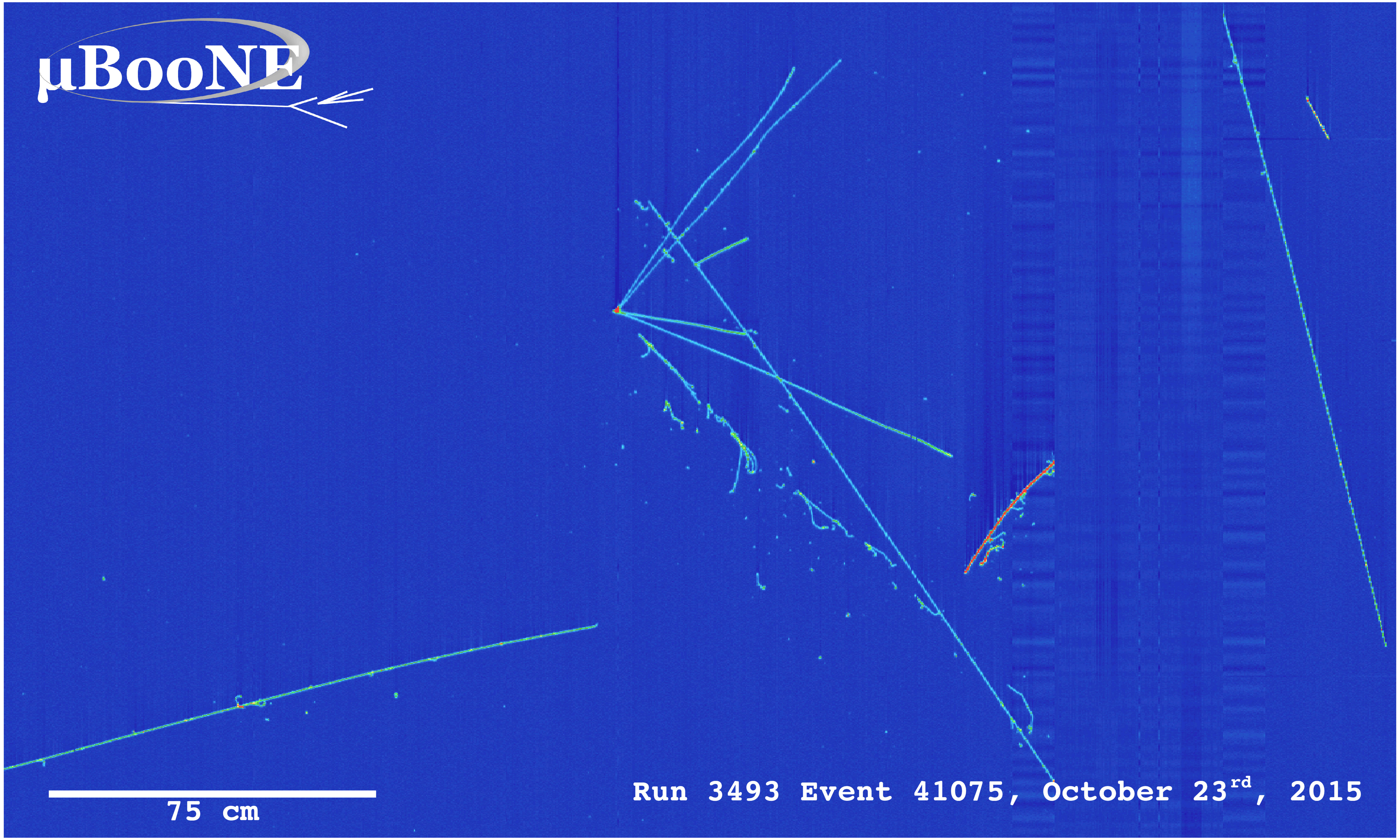

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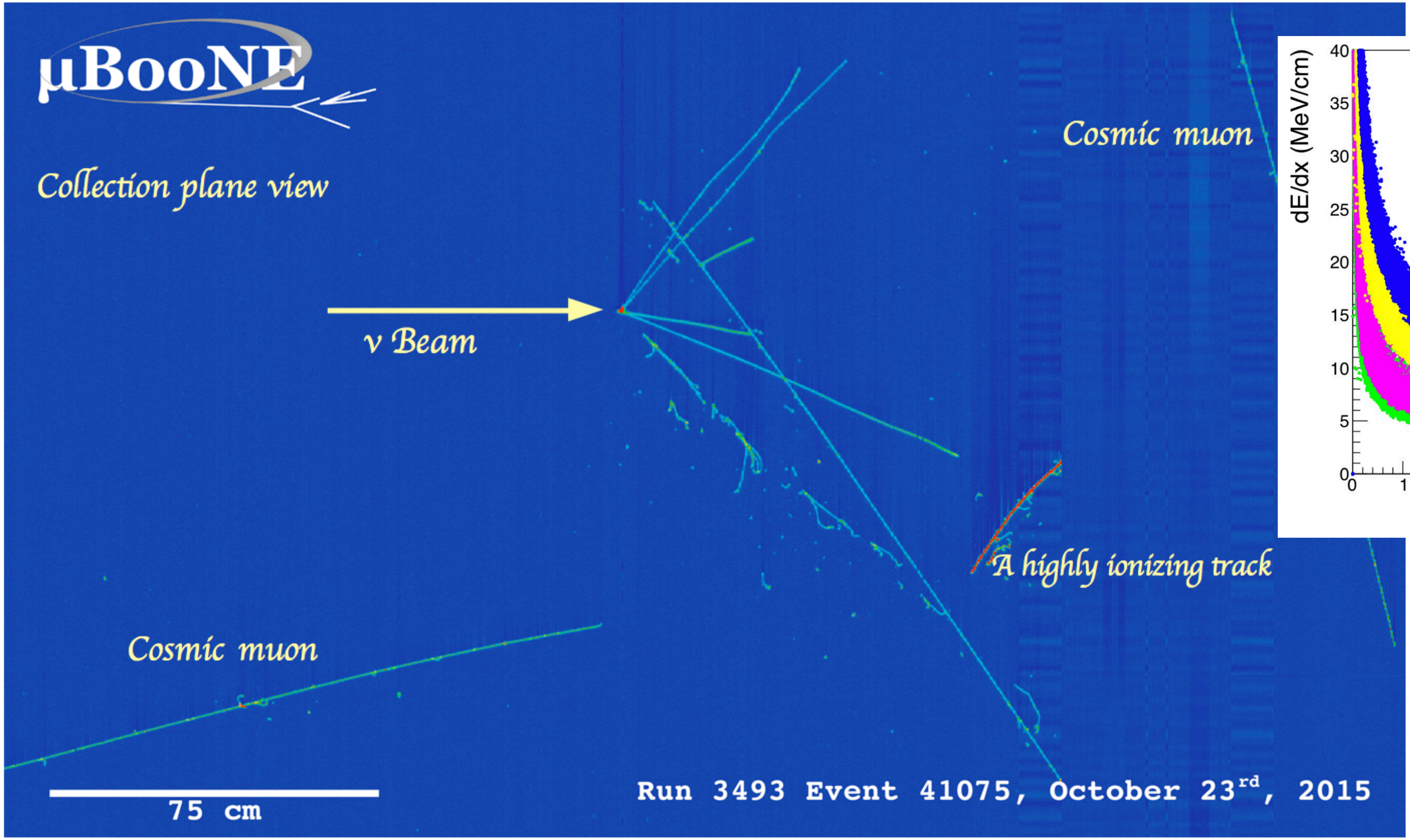

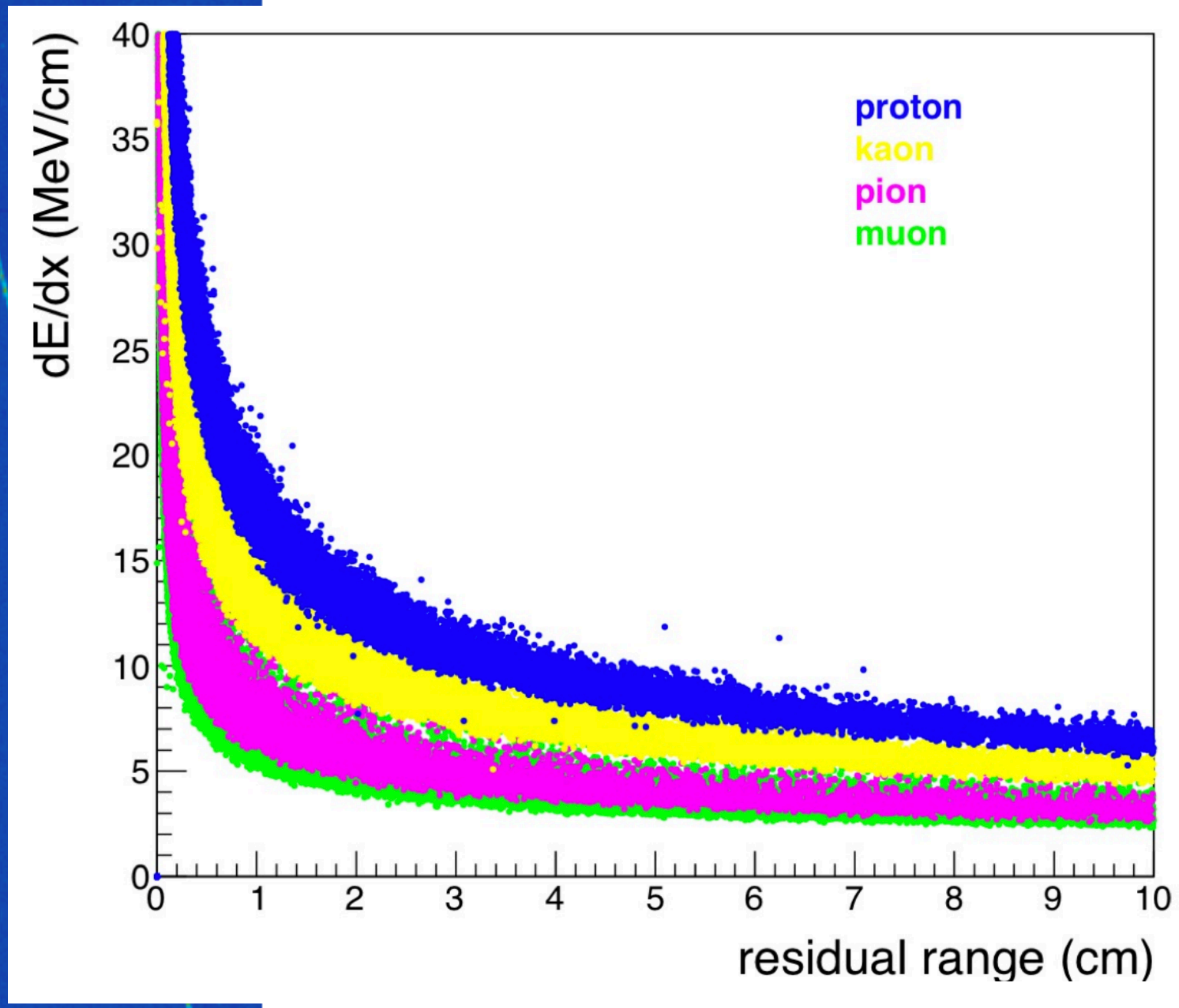

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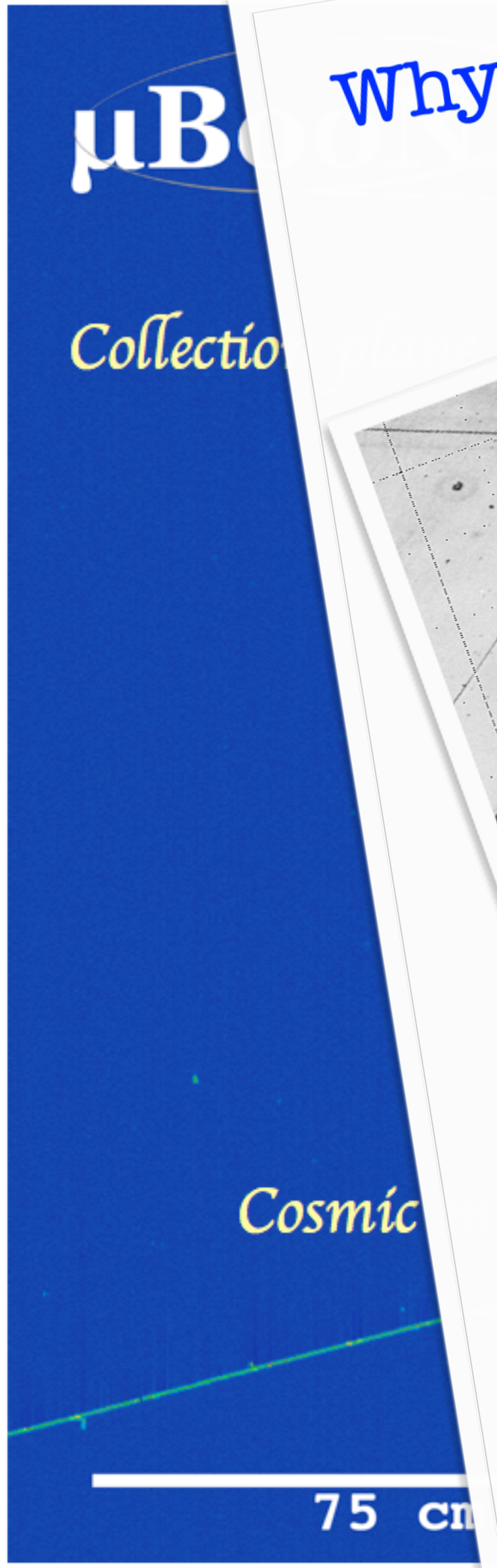
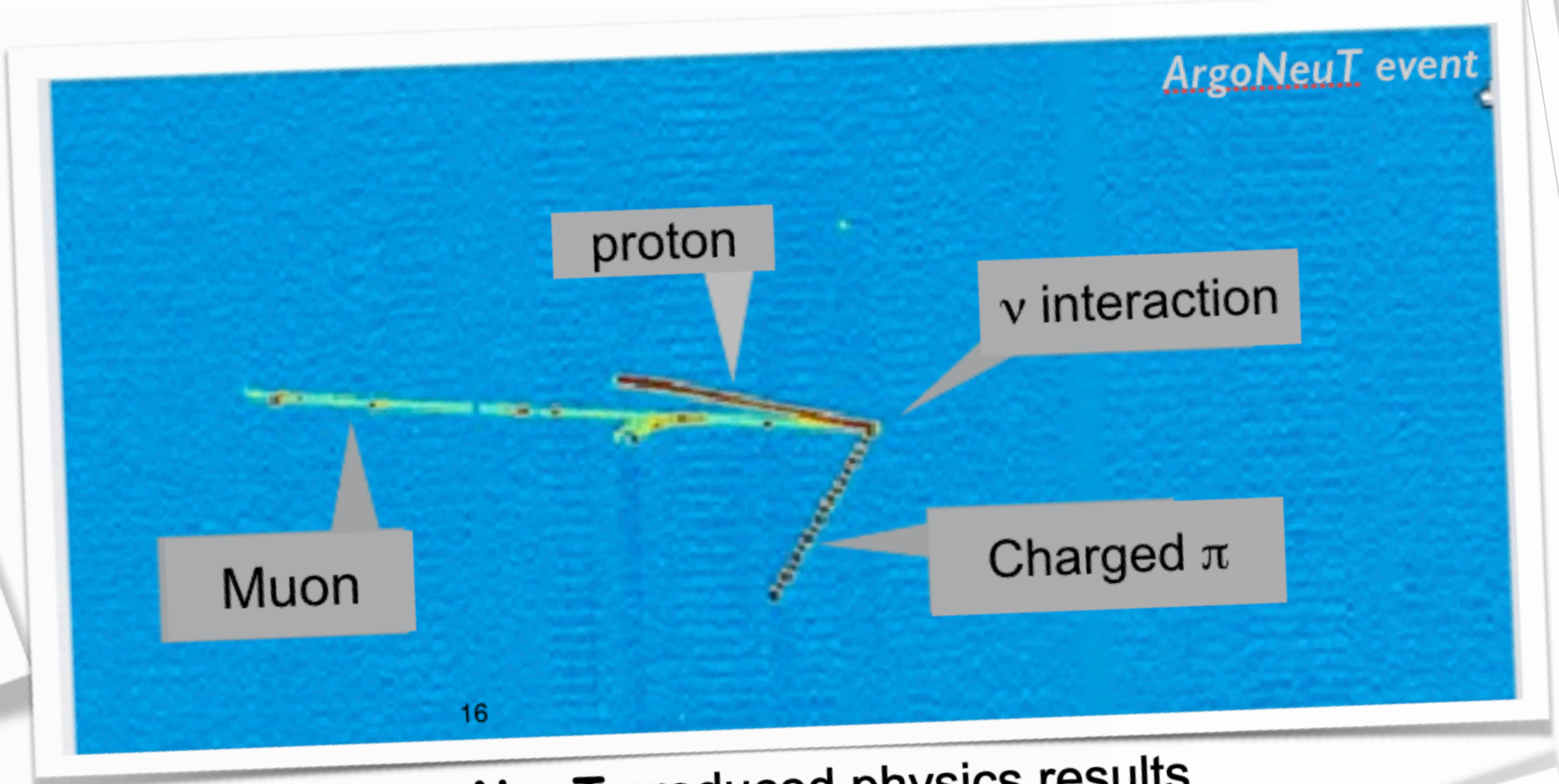
(2) Topological capabili… ry



Why Liquid Argon Time Projection Chamber?



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

LAr TPC: Bubble chamber quality of data with added calorimetry

…or LArTPC is “a “colored” bubble chamber” (theorist simplified view!)

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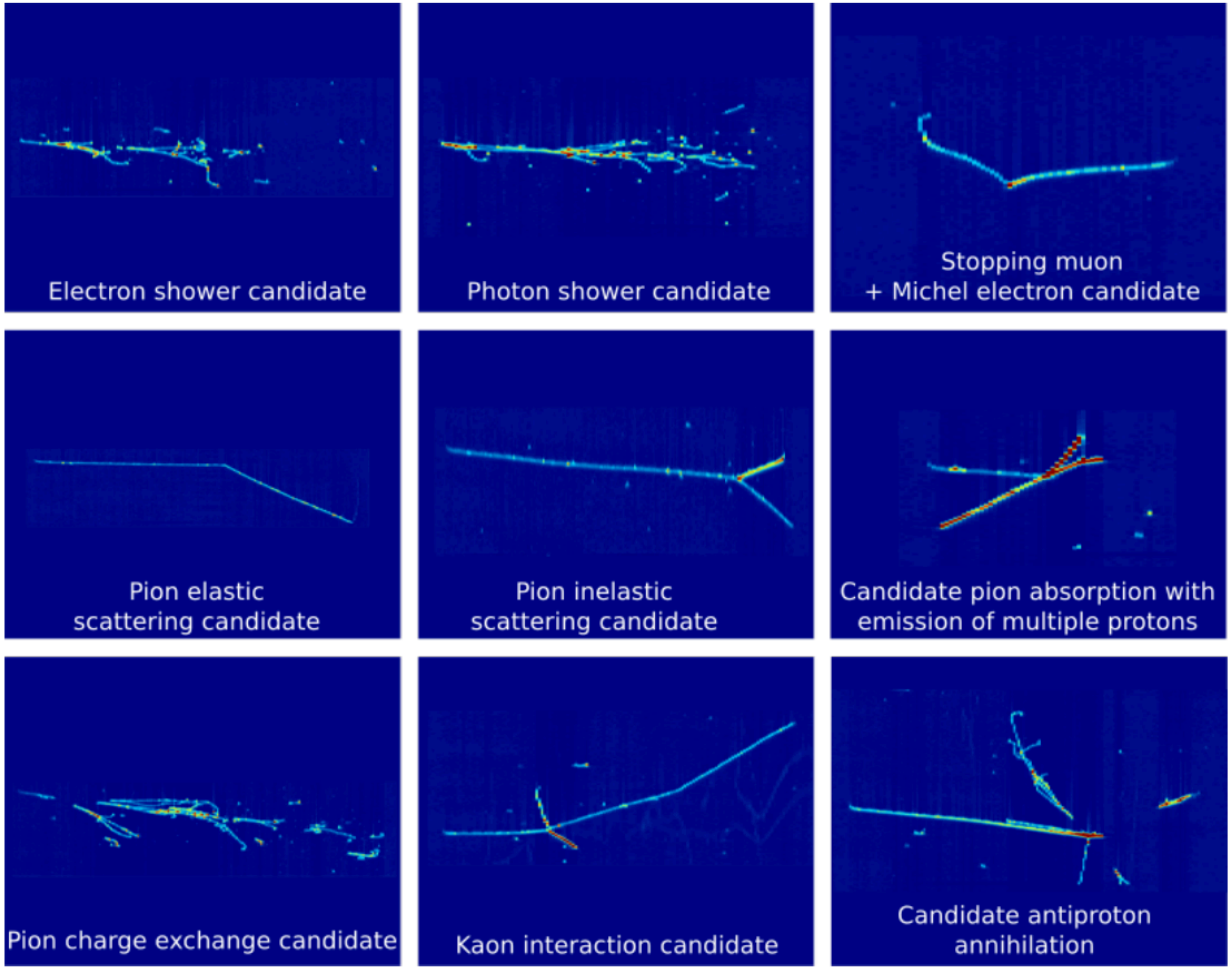
slide stolen from O. Palamara

(2) Topological capabilities: 3D tracking and calorimetry



LArIAT 1911.10379

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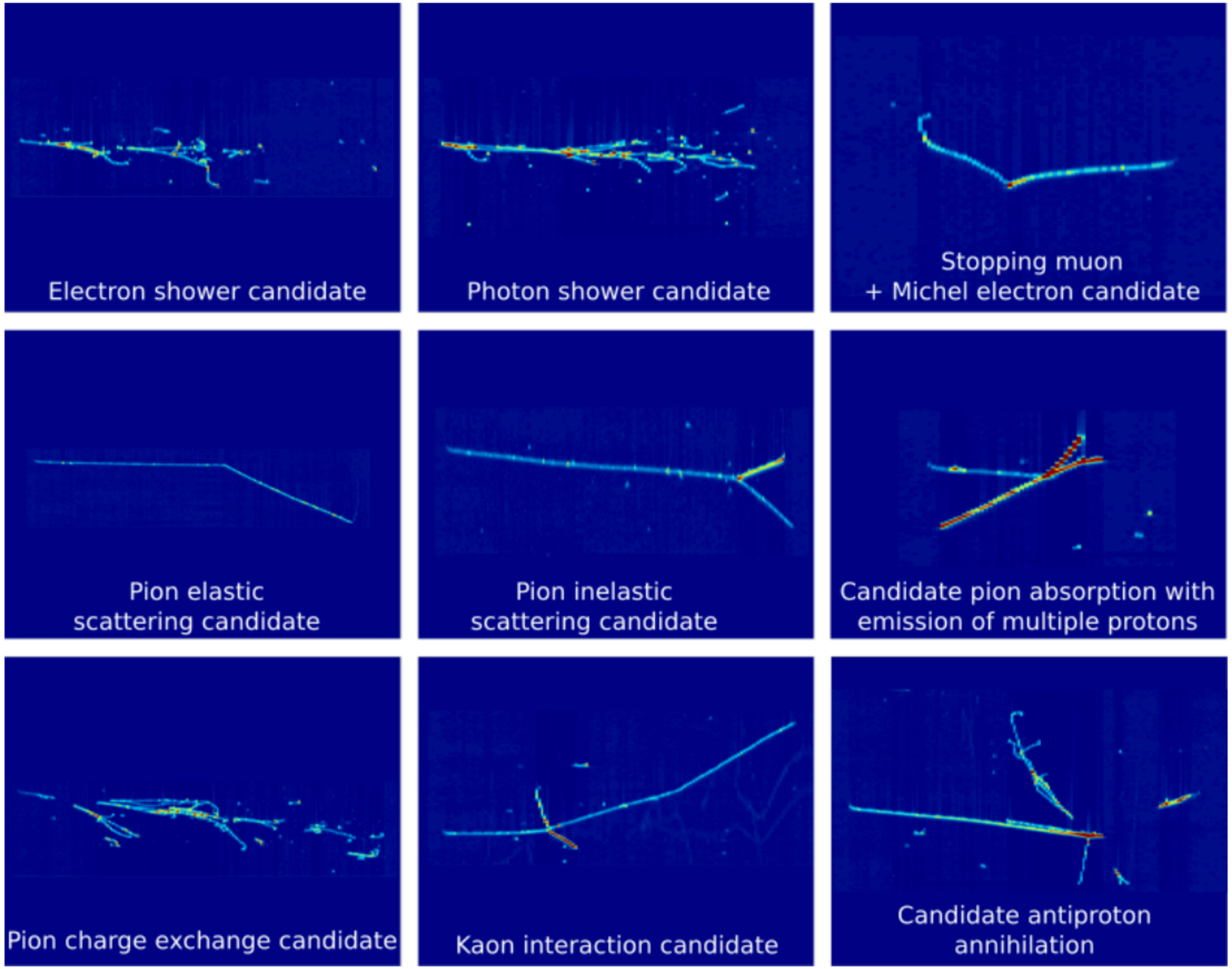

LArIAT 1911.10379

Muons:

$\mu^+ \to e^+ \nu_\mu$
$\mu^- p^+ \to \bar{\nu}_\mu + n$

Pions:

$\pi^+ n \to \pi^0 p^+$
$\pi^- p^+ \to \pi^0 n$

Topology depends on particle and its charge

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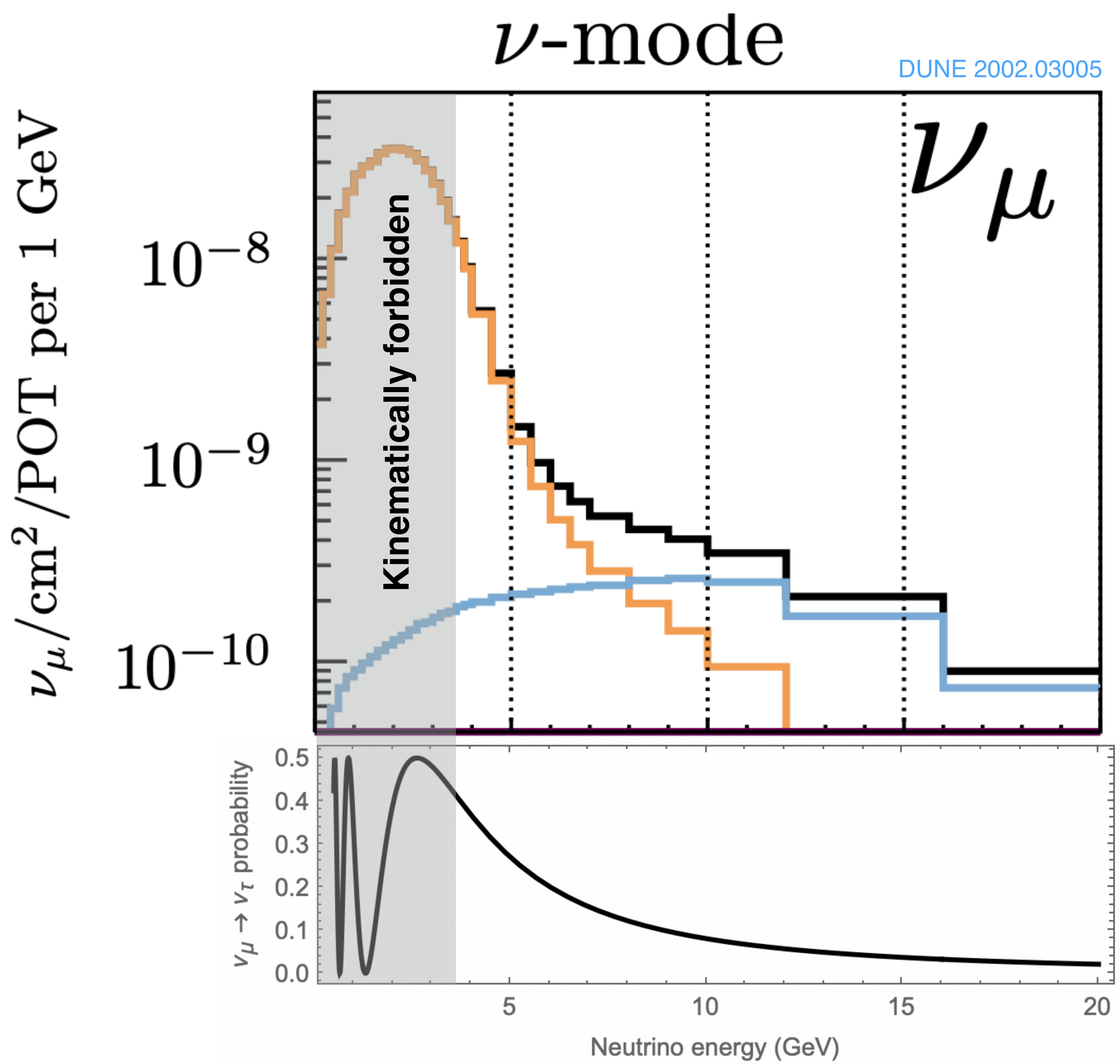
Based on M Schulz Turner 2007.00015
see also
Albright Shrock 1979
NOMAD hep-ex/0106102
Hagiwara et al hep-ph/0408212
Aoki et al hep-ph/0503050
Conrad et al 1008.2984
...

τ lifetime of is too short for DUNE (cτ = 87μm versus mm wire distance)



Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

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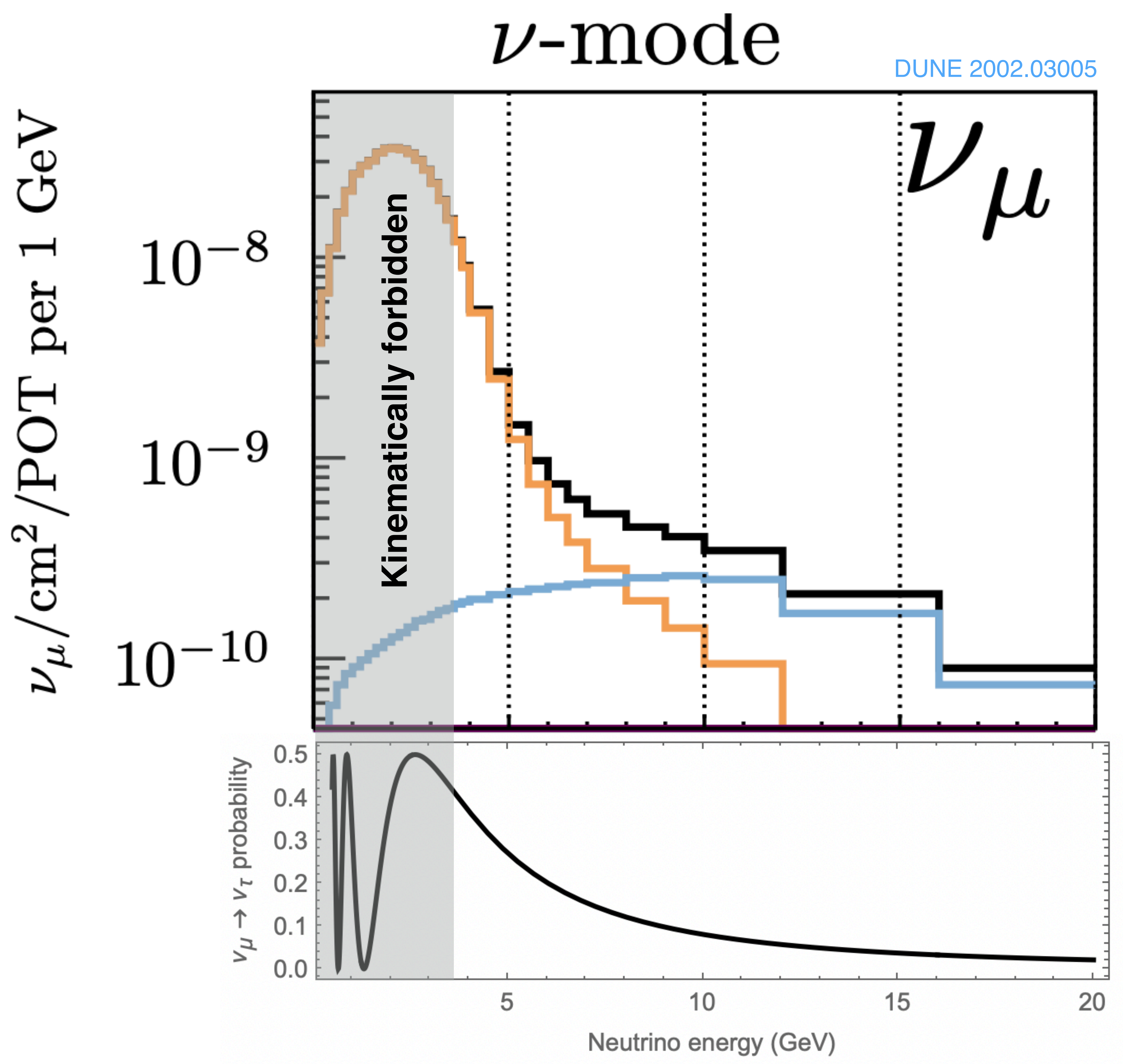
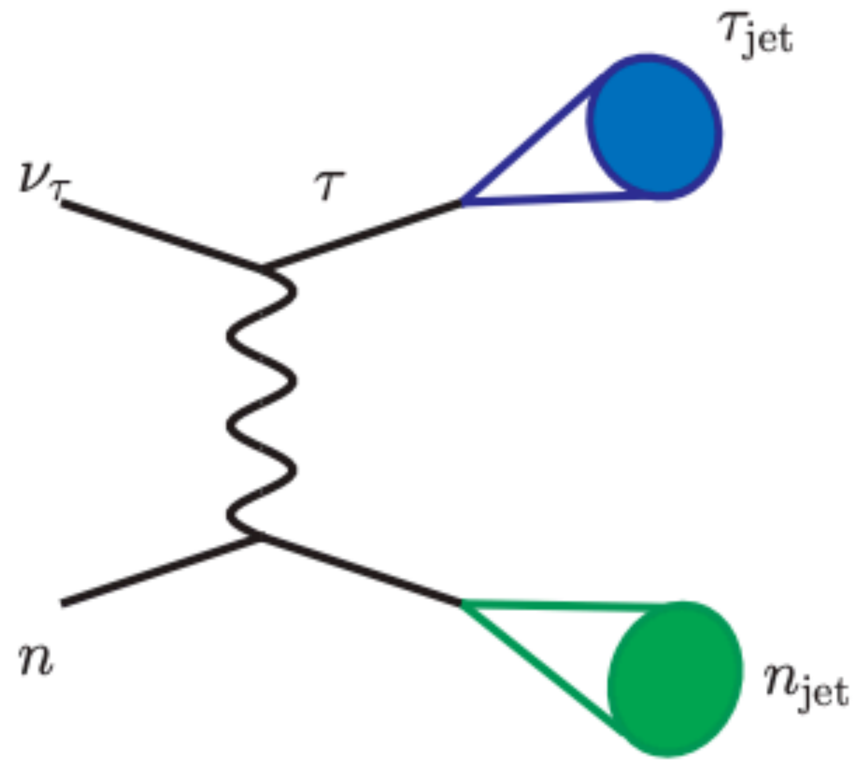
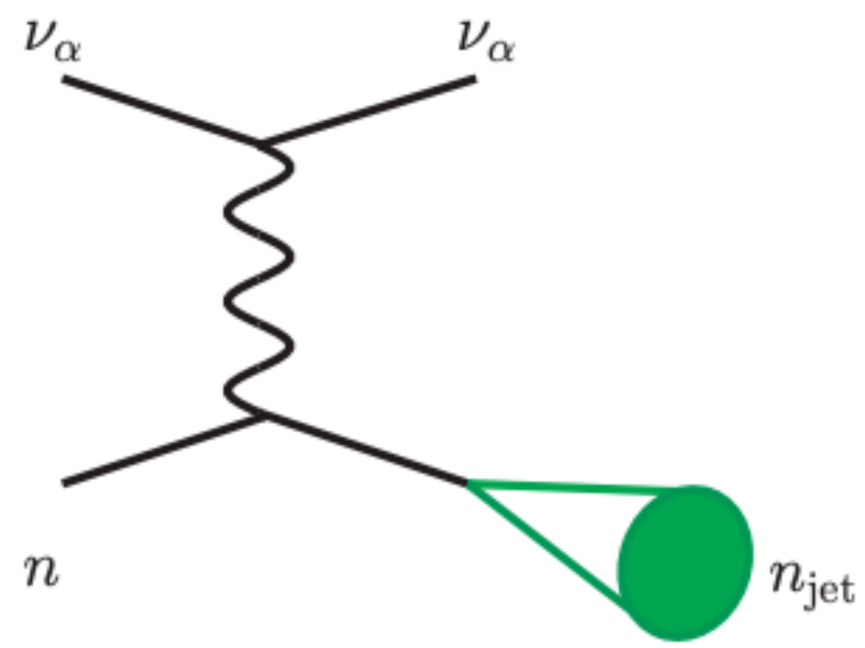


Hadronic tau signal



Hadronic tau background
(all neutrinos contribute!)



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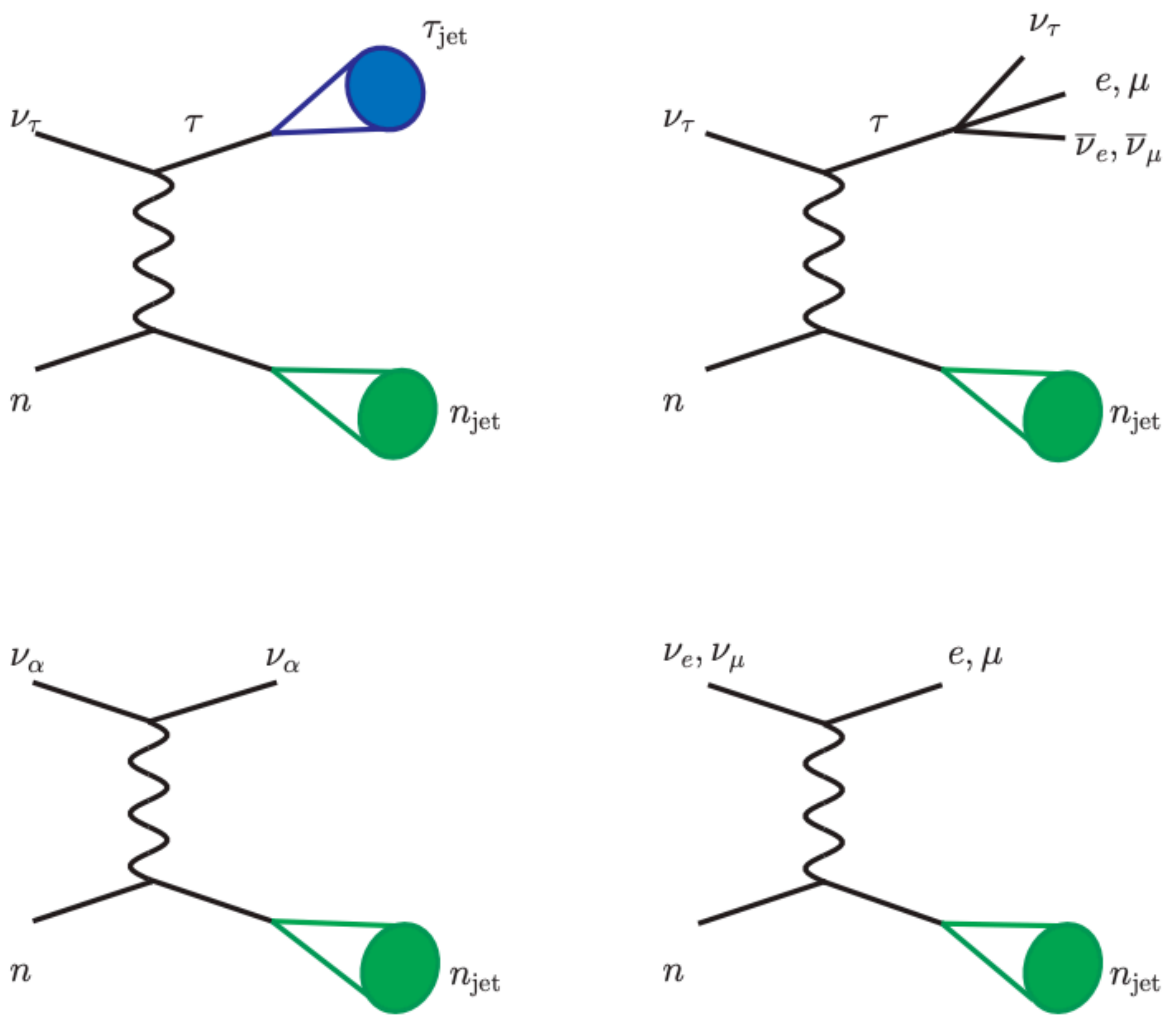
(a) Tau reconstruction in LArTPCs

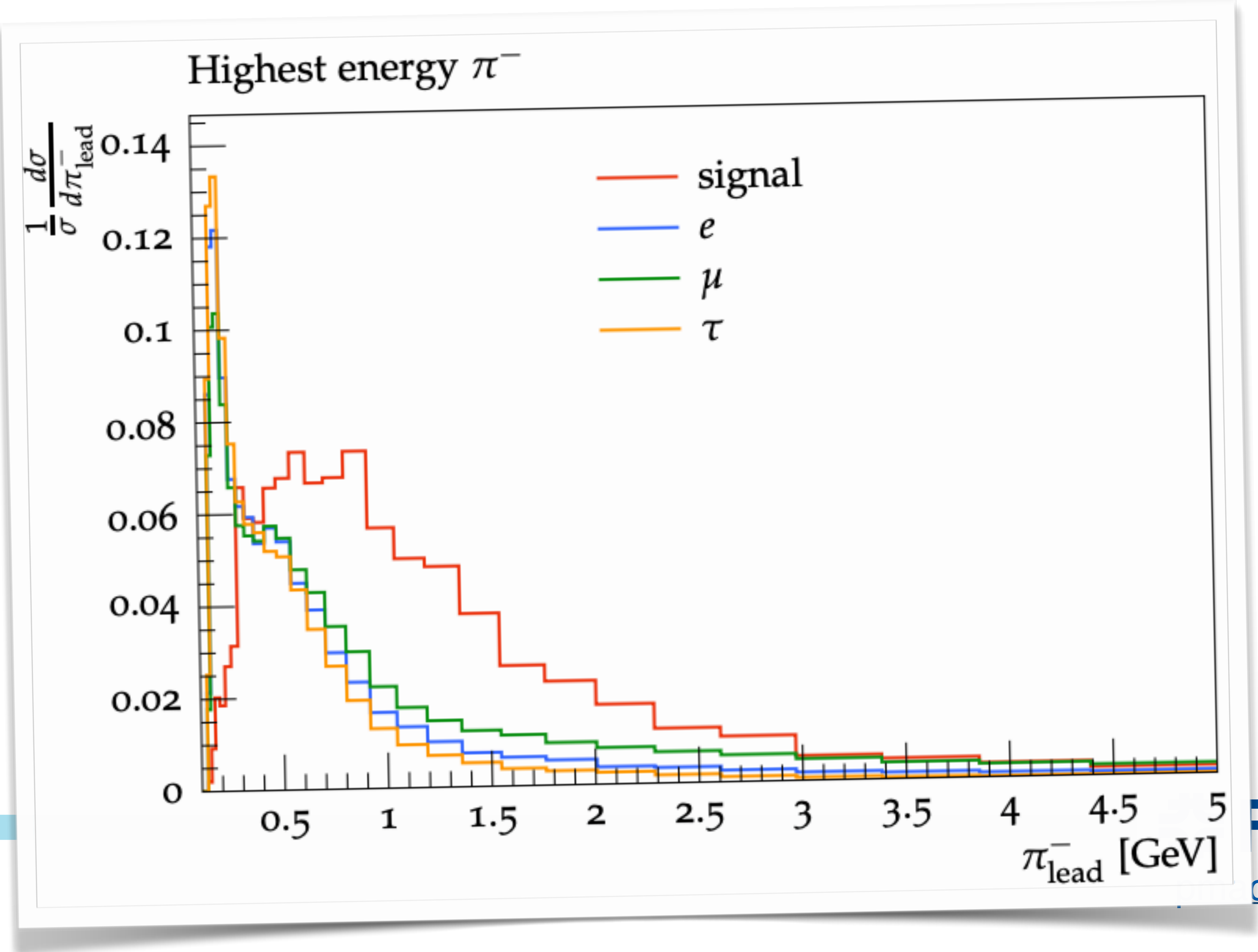
Based on M Schulz Turner 2007.00015
see also
Albright Shrock 1979
NOMAD hep-ex/0106102
Hagiwara et al hep-ph/0408212
Aoki et al hep-ph/0503050
Conrad et al 1008.2984
…

τ lifetime of is too short for DUNE (cτ = 87μm versus mm wire distance)



Perform a cut and count analysis taking into account

1. Number of leptons
2. Number of pions
3. Energy of leading pion
4. Total visible energy
5. Missing p_T
6. Number of jets



chado@fnal.gov

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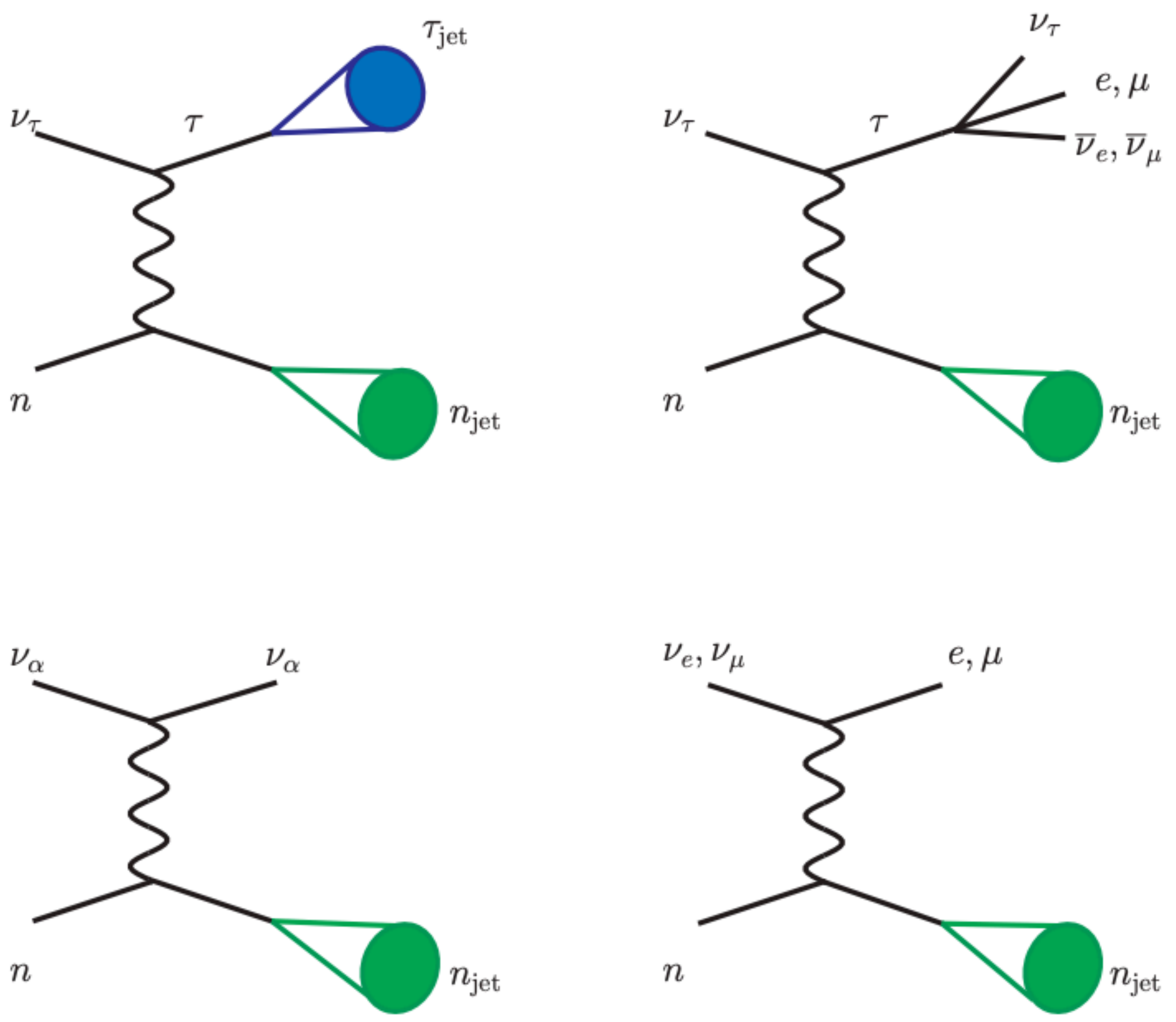

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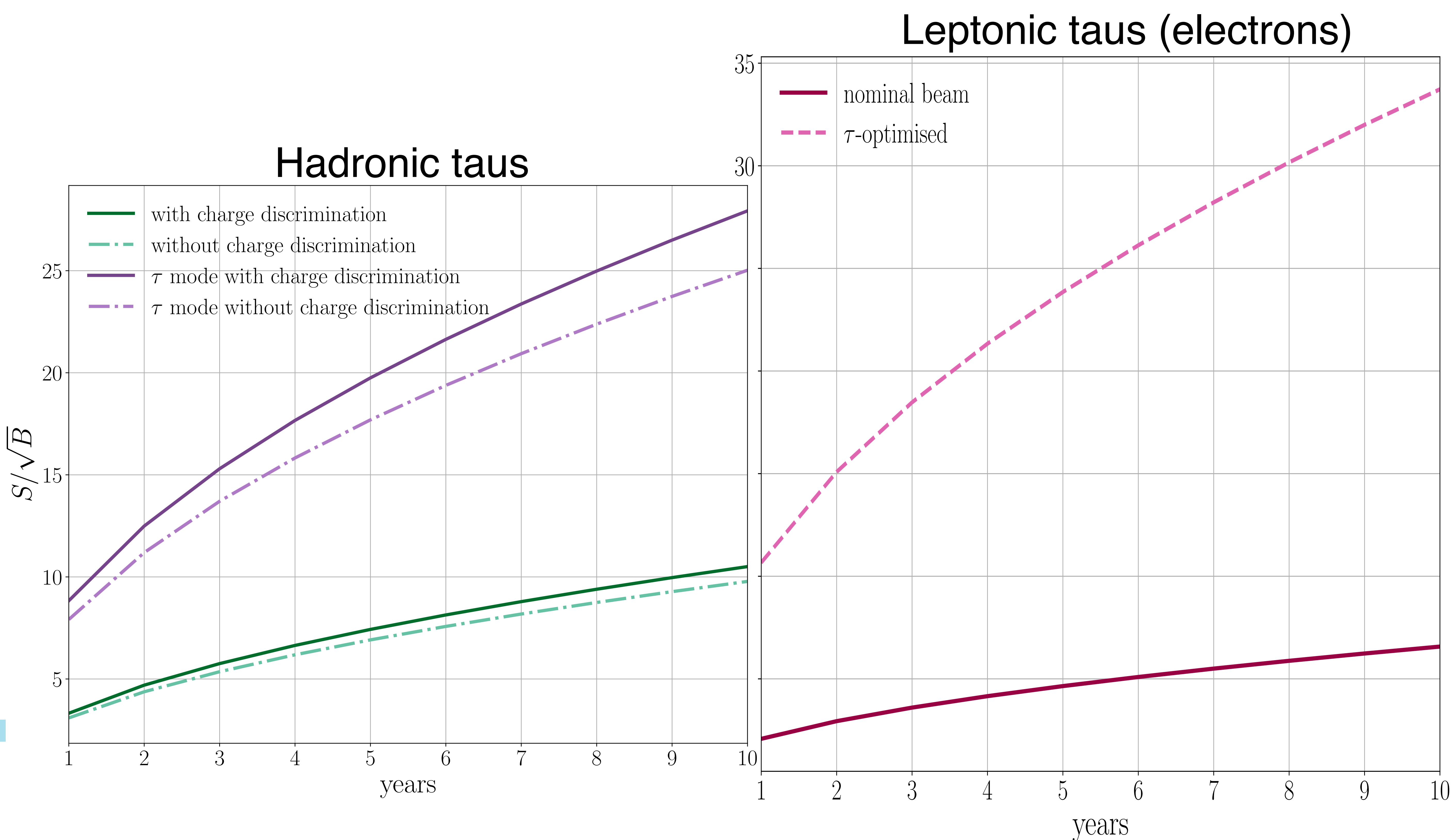
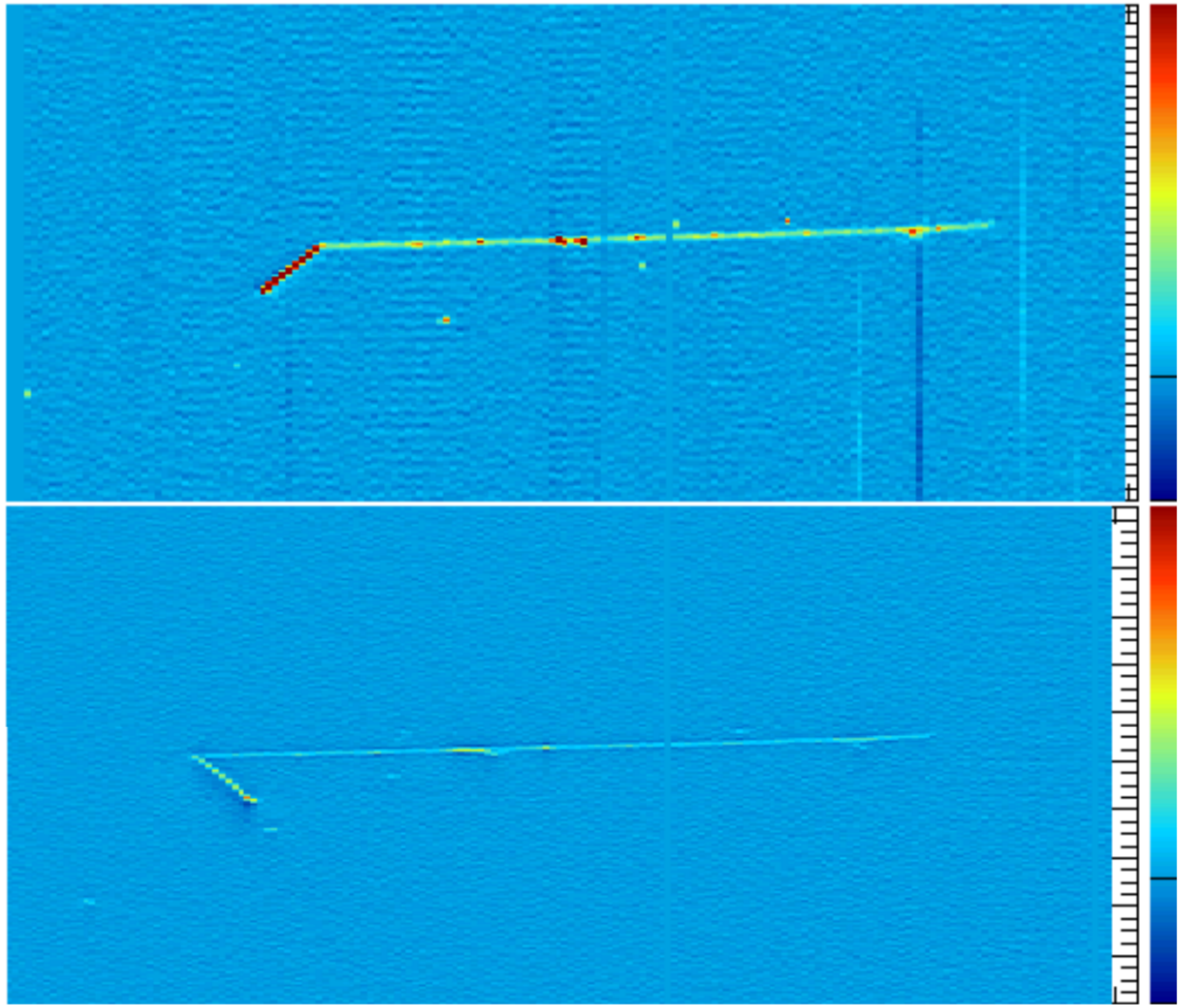


(3) Very low energy threshold

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

ArgoNeuT 1810.06502



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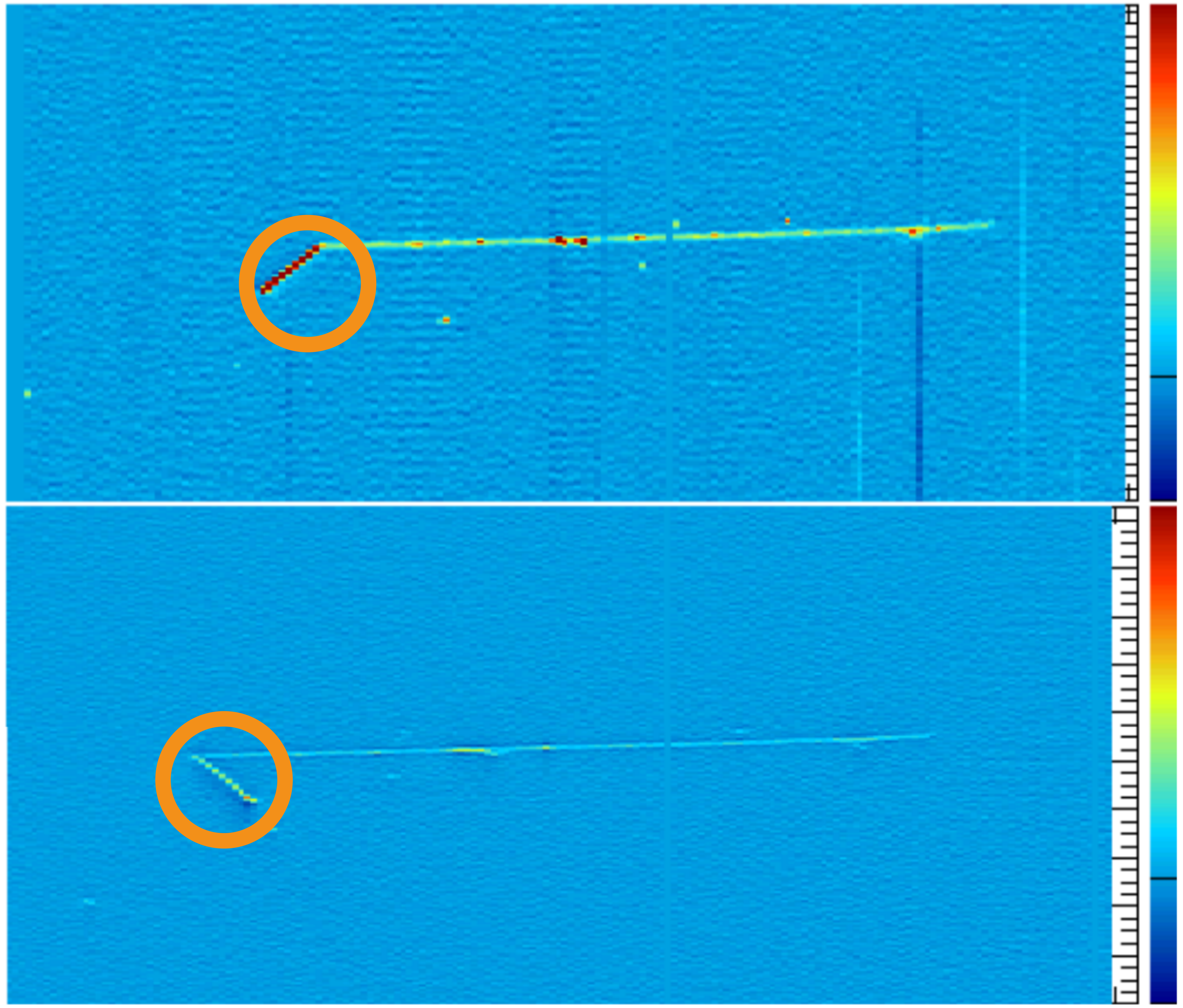

Reconstruct, identify and point.

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

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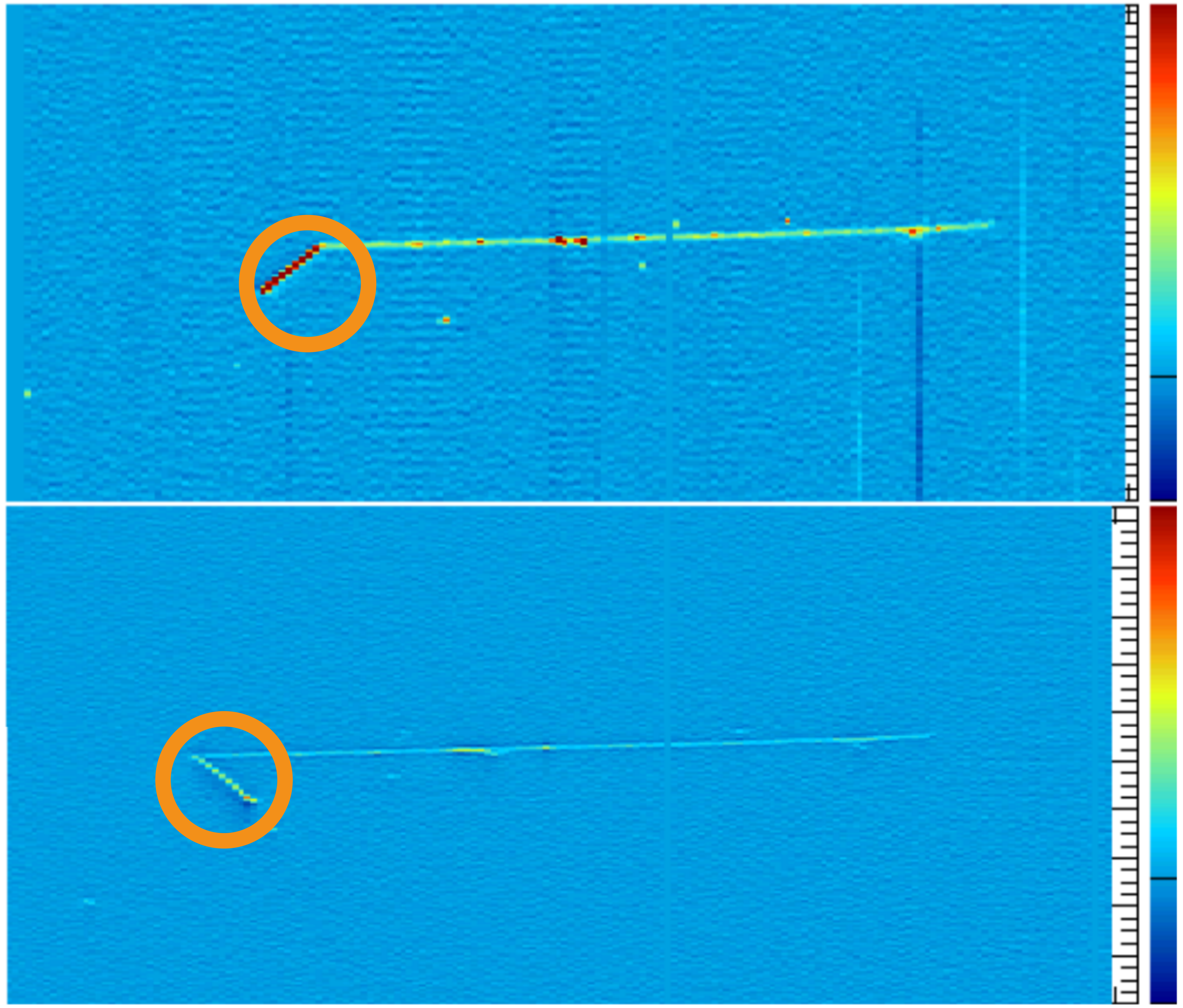

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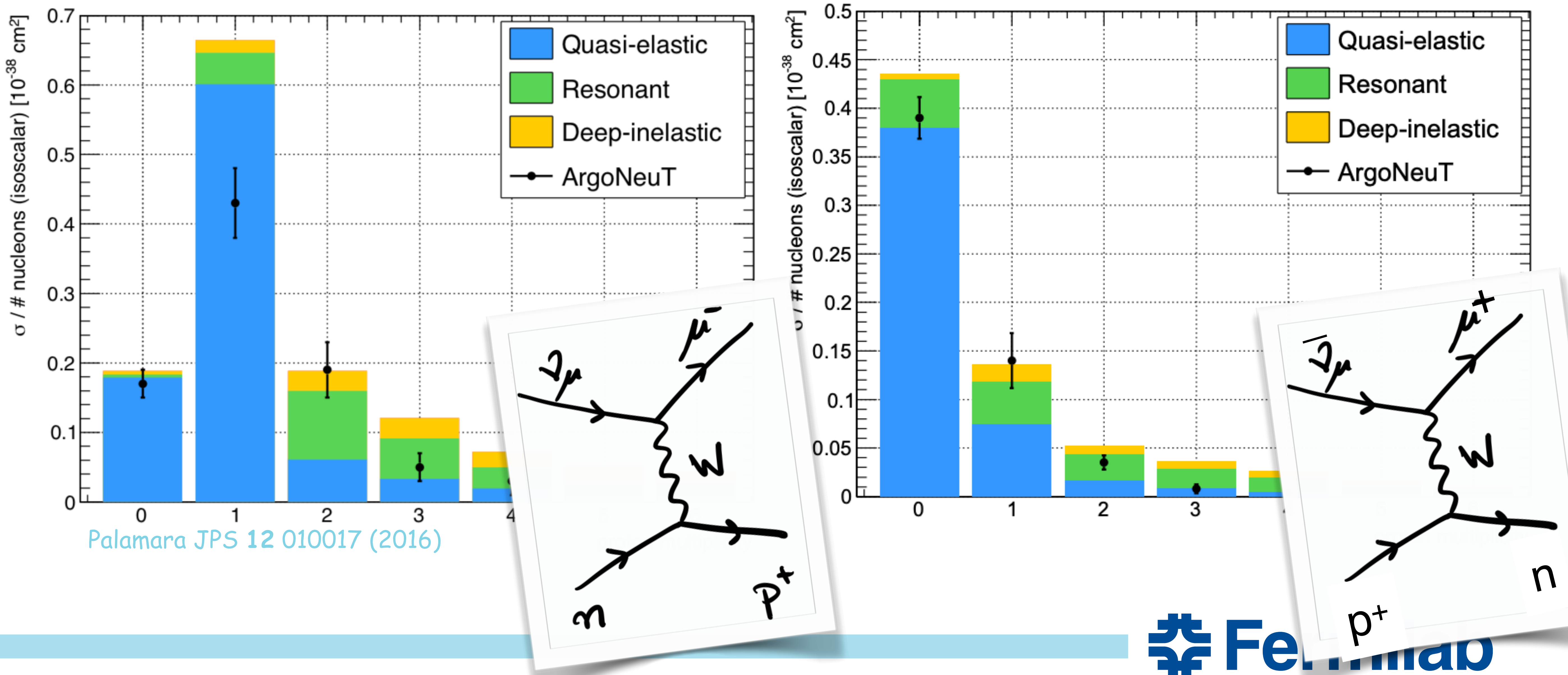
Event topology carries extra information



Palamara JPS 12 010017 (2016)

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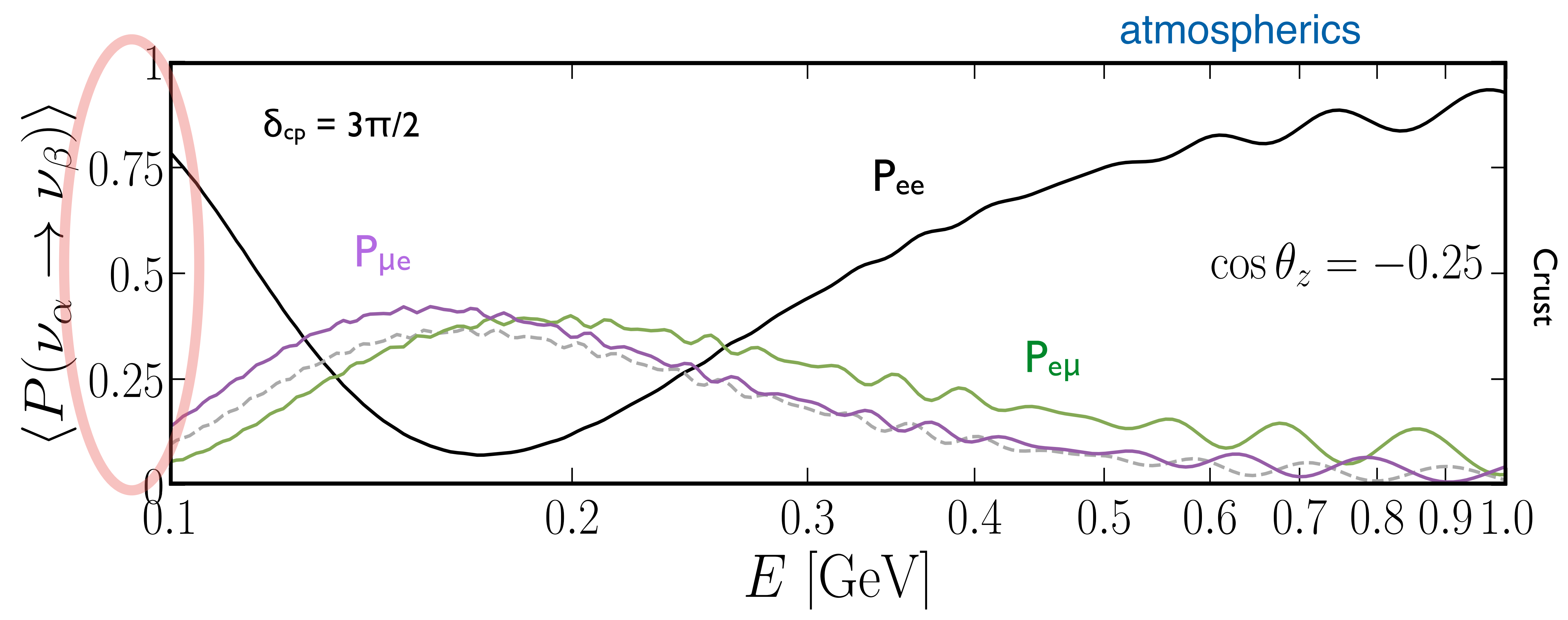
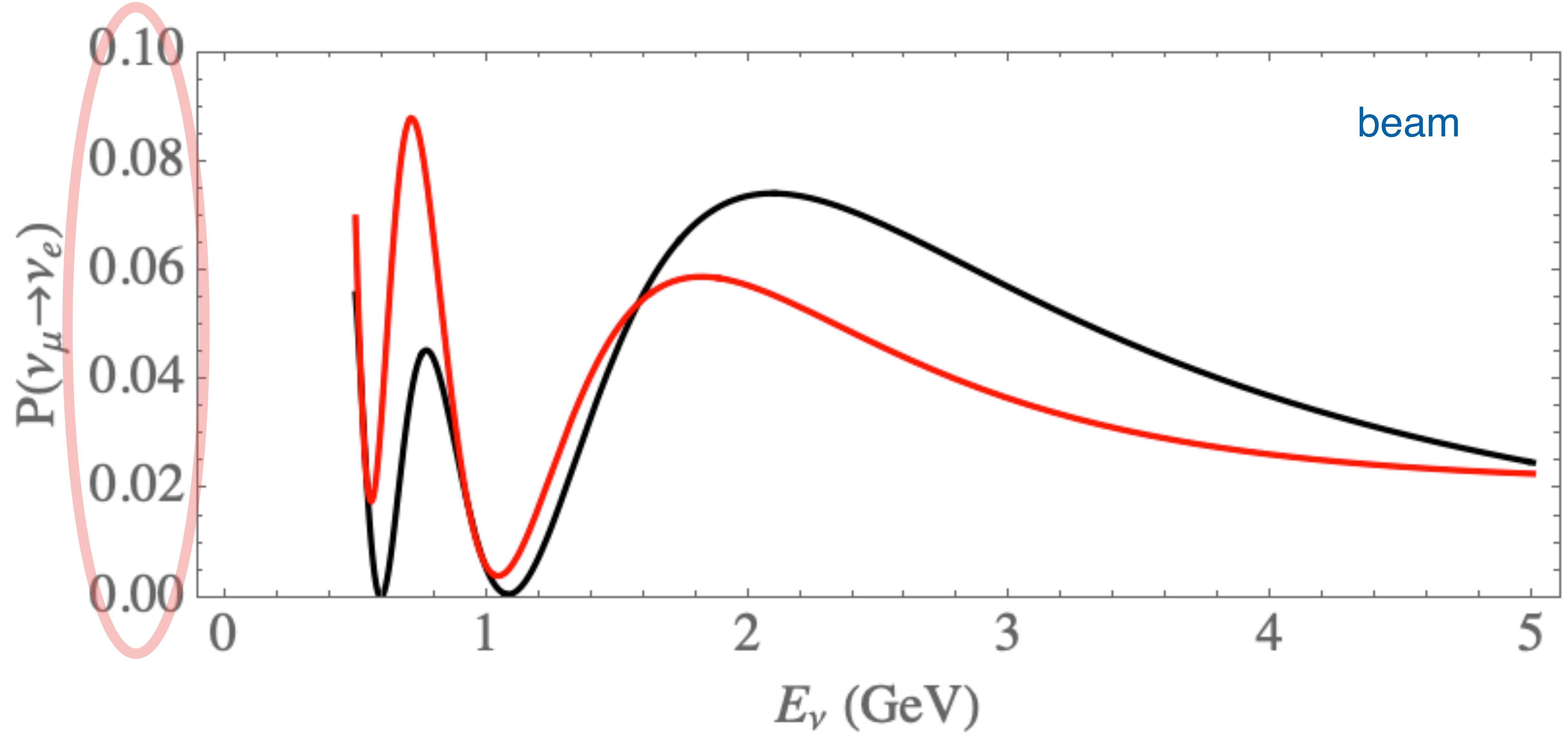
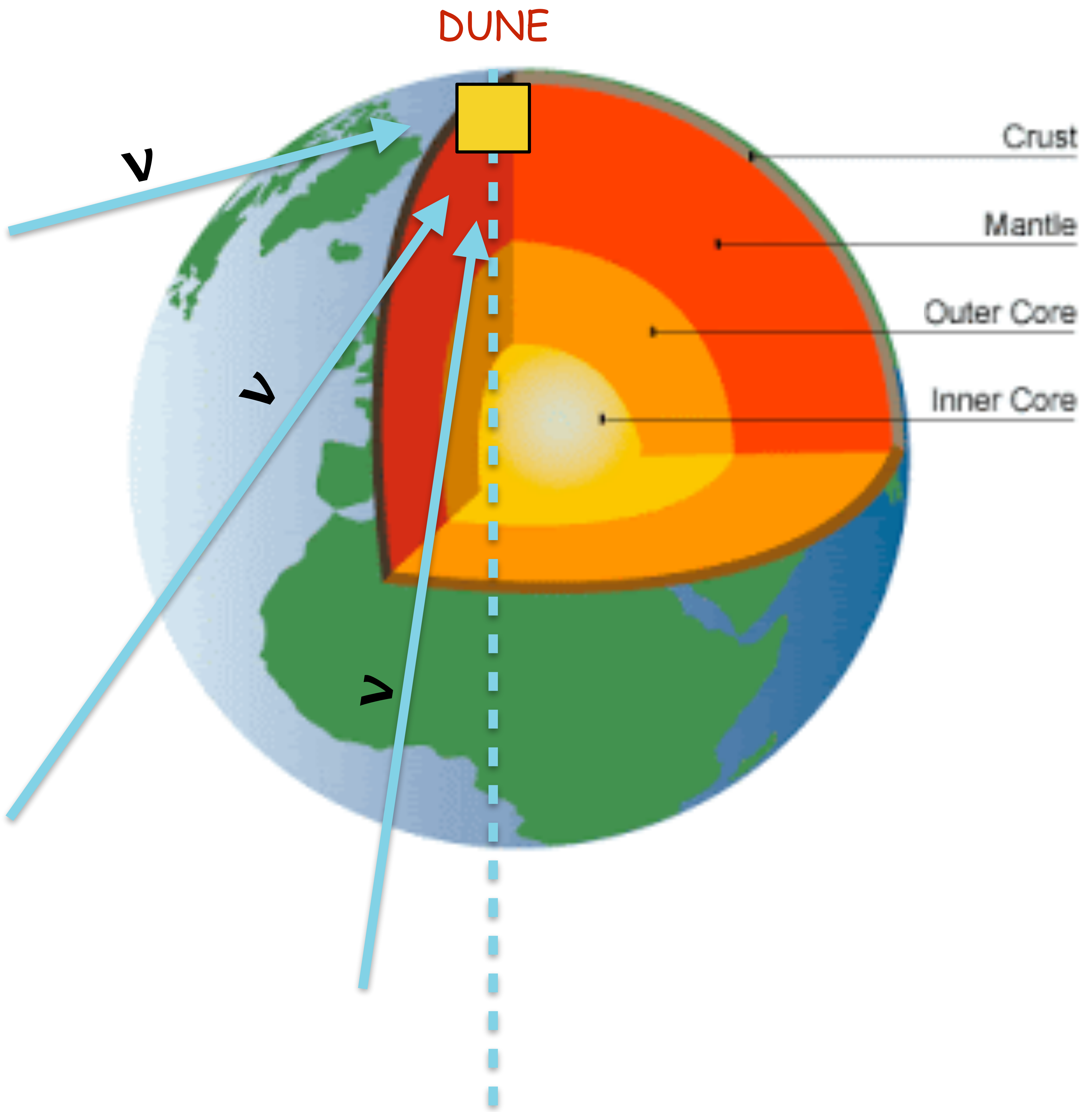
(b) Sub-GeV atmospheric neutrinos

Based on Kelly et al 1904.02751

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



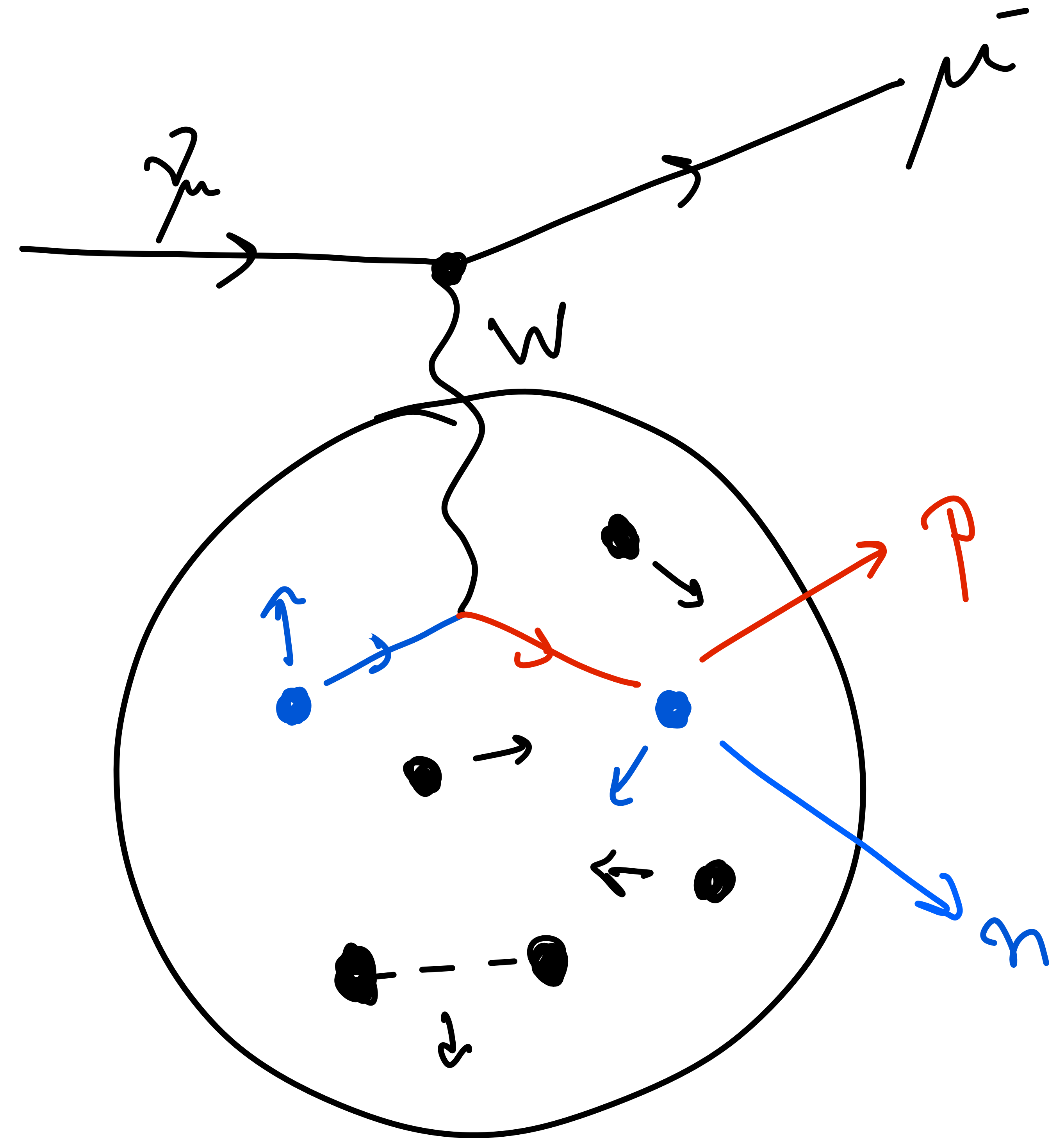


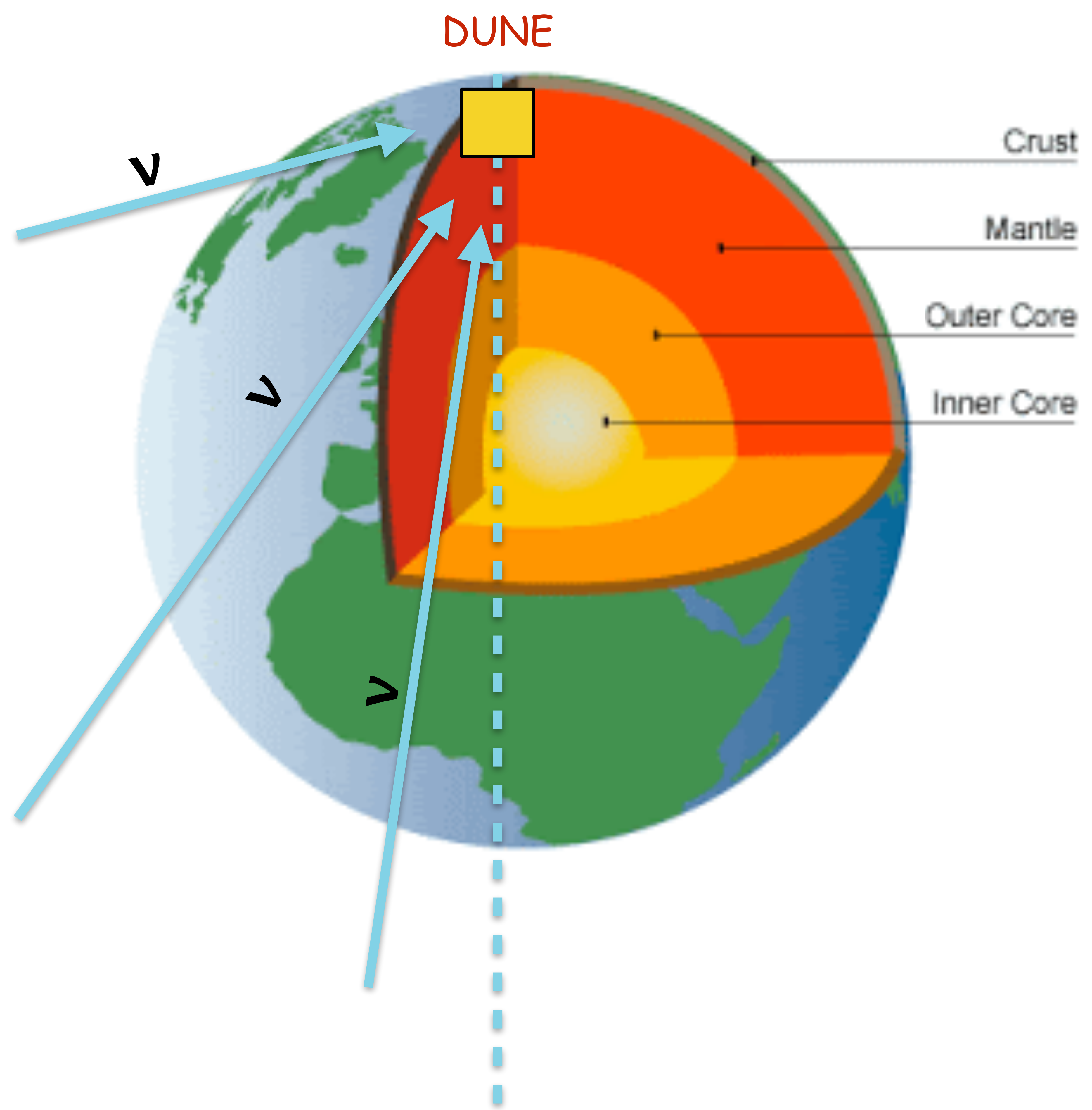


(b) Sub-GeV atmospheric neutrinos

Based on Kelly et al 1904.02751

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





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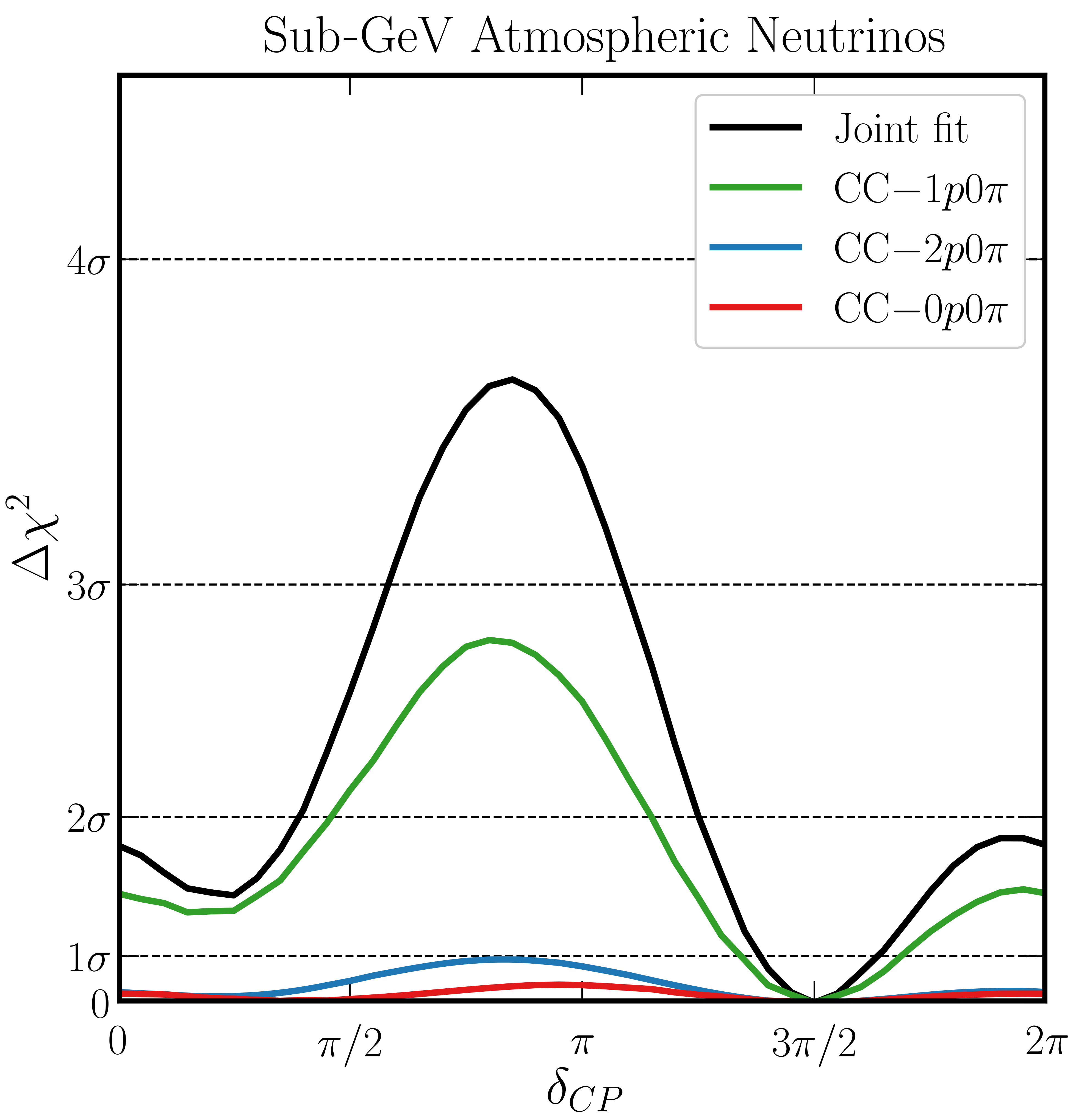
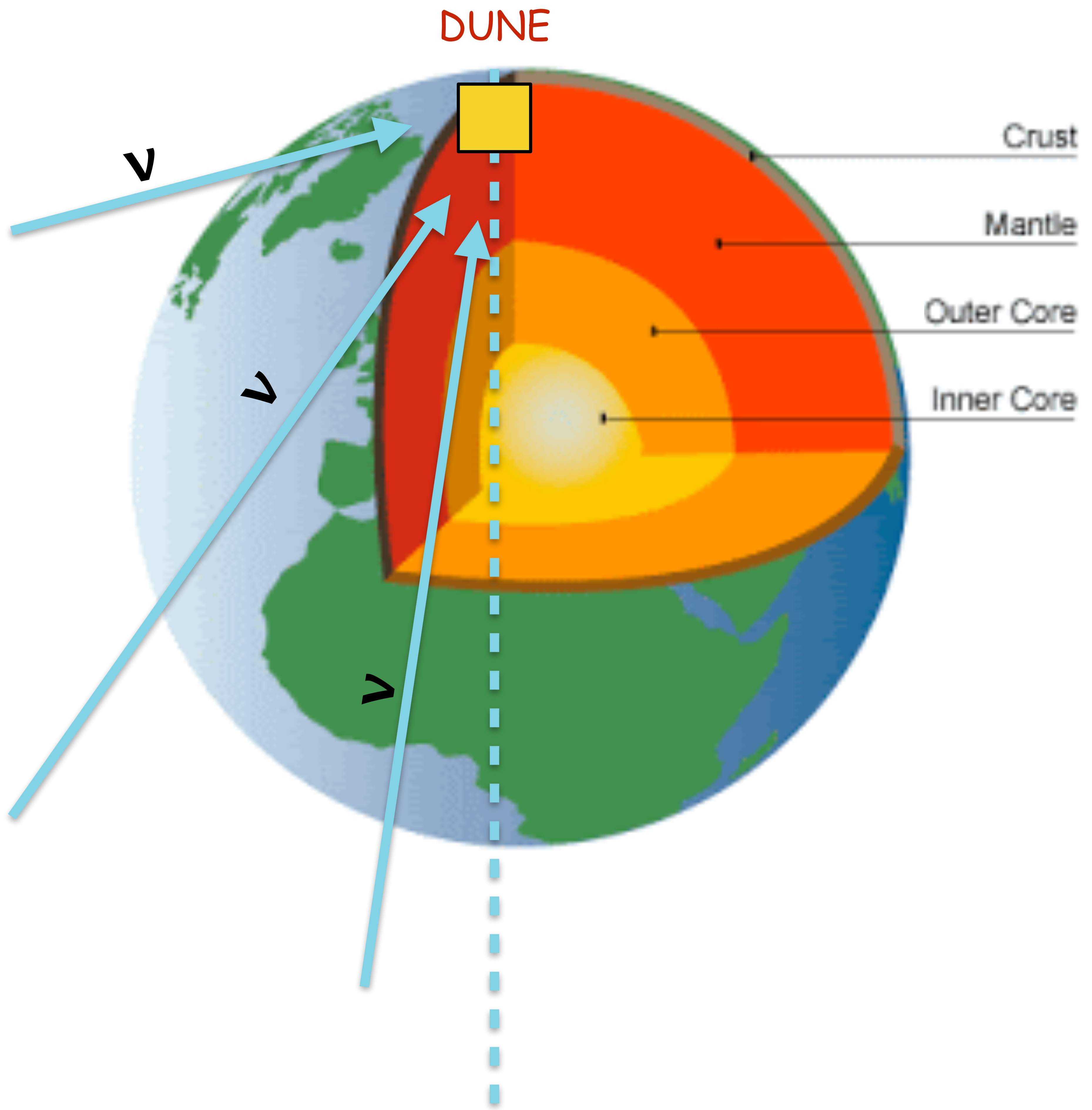
(b) Sub-GeV atmospheric neutrinos

Based on Kelly et al 1904.02751

Sub-GeV atmospheric neutrinos could provide the only measurement of CP violation which is independent of beam neutrino uncertainties and driven by the solar mass splitting.





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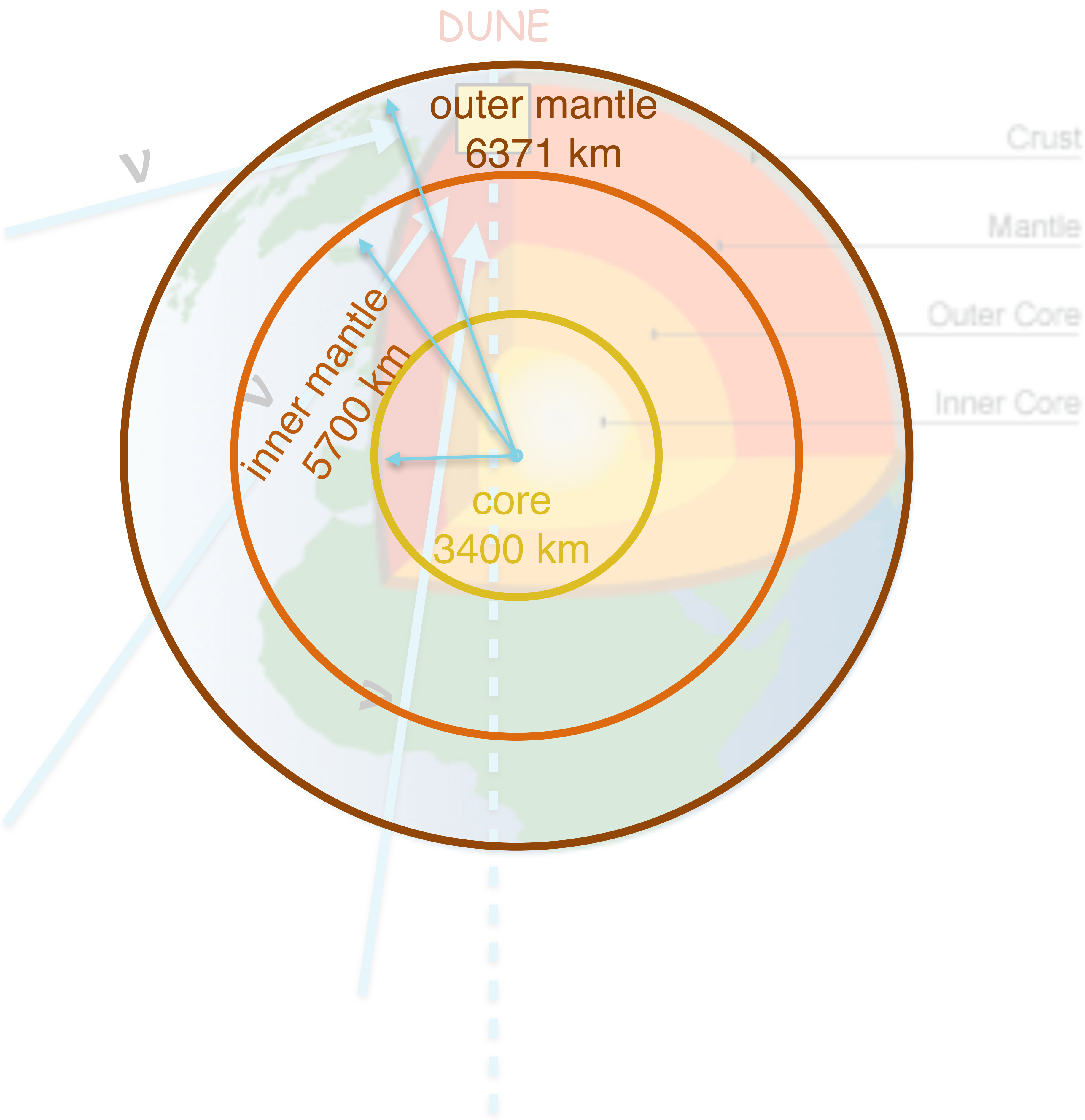
(b) Sub-GeV atmospheric neutrinos

Based on Kelly et al 1904.02751

Sub-GeV atmospheric neutrinos could also provide quantum tomography measurement of Earth's core



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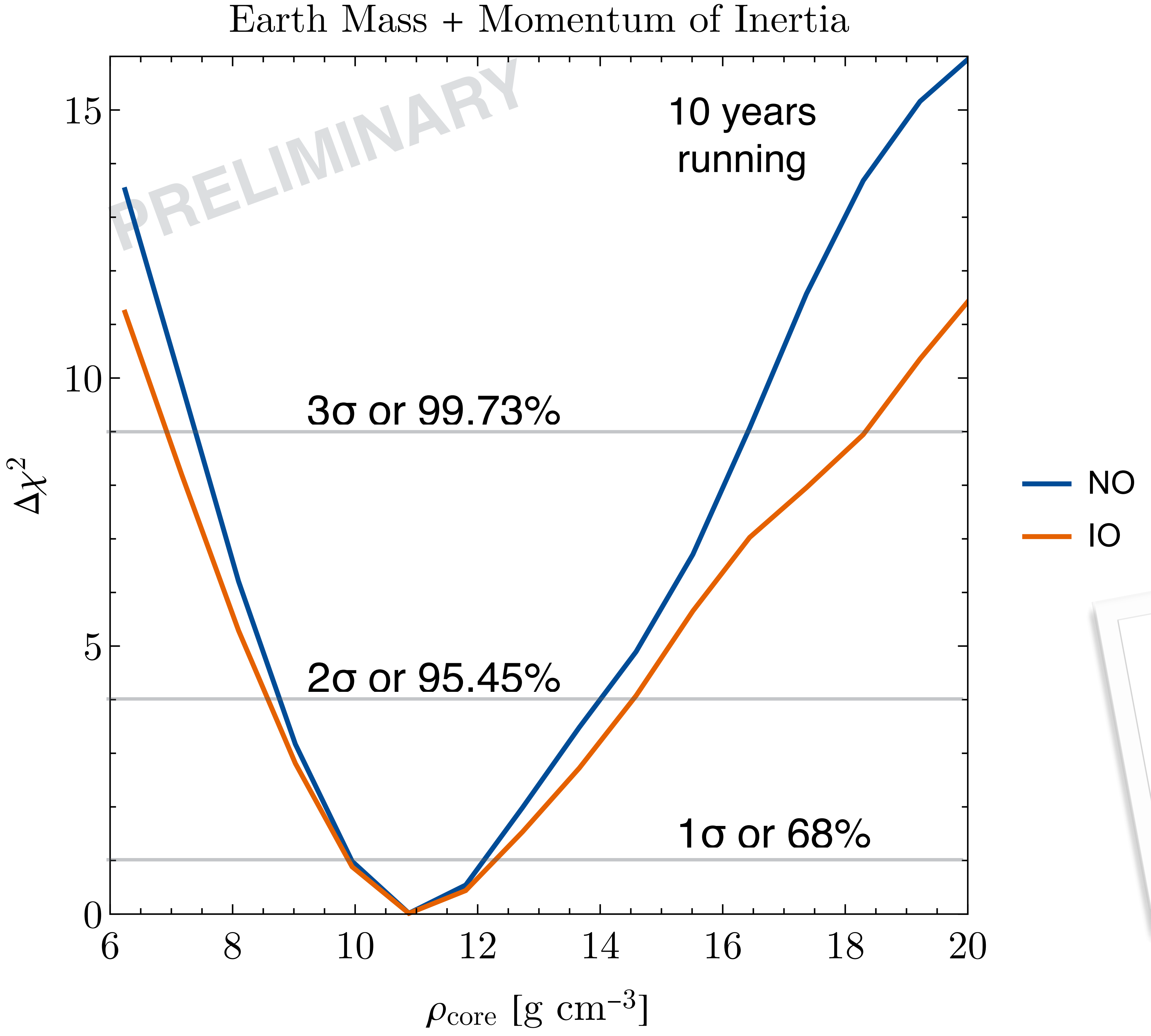
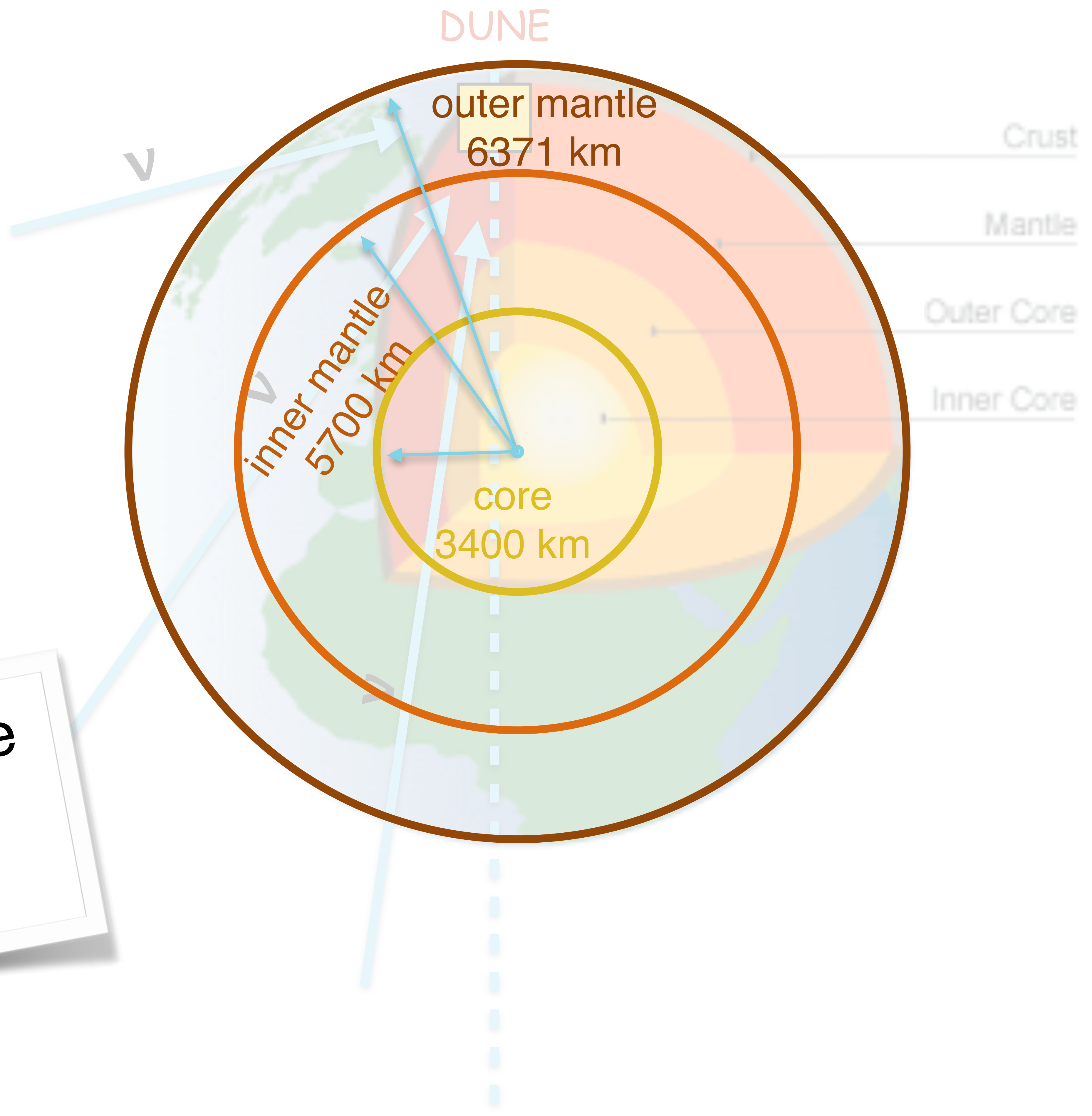
Based on Kelly et al 1904.02751

Sub-GeV atmospheric neutrinos could also provide quantum tomography measurement of Earth's core

Radii from earthquakes + total mass measurements
+ moment of inertia measurements + neutrino oscillations =

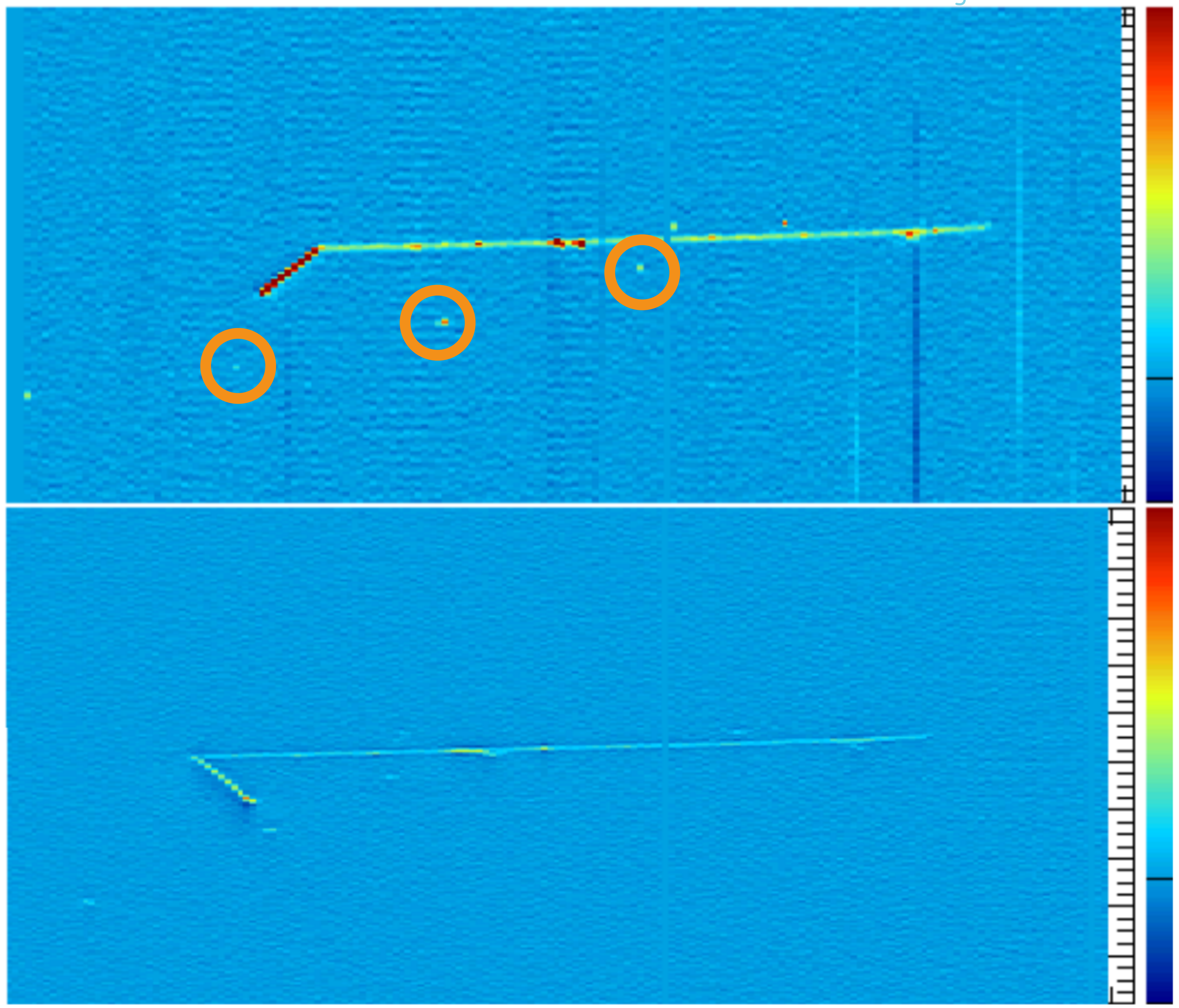


Quantum tomography of the Earth with neutrinos:
$\rho_{core} = 11 \pm 1$ g/cm^3



(3) Very low energy threshold

ArgoNeuT also demonstrated the LAr capability to detect sub-MeV depositions (blips)



No particle identification, no track, just a blip

What can be done with it?

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(c) Millicharged particles

All electric charges, in the SM, are multiples of the down quark charge

Q(down quarks) = -1/3 Q(up quarks) = +2/3 Q(e,μ,τ) = -1

Are there particles with tiny charges?

“Dark electromagnetism” typically leads to millicharged particles

$$\mathcal{L}_{mix} = \frac{\epsilon}{4} B_{\mu\nu} F'^{\mu\nu}$$

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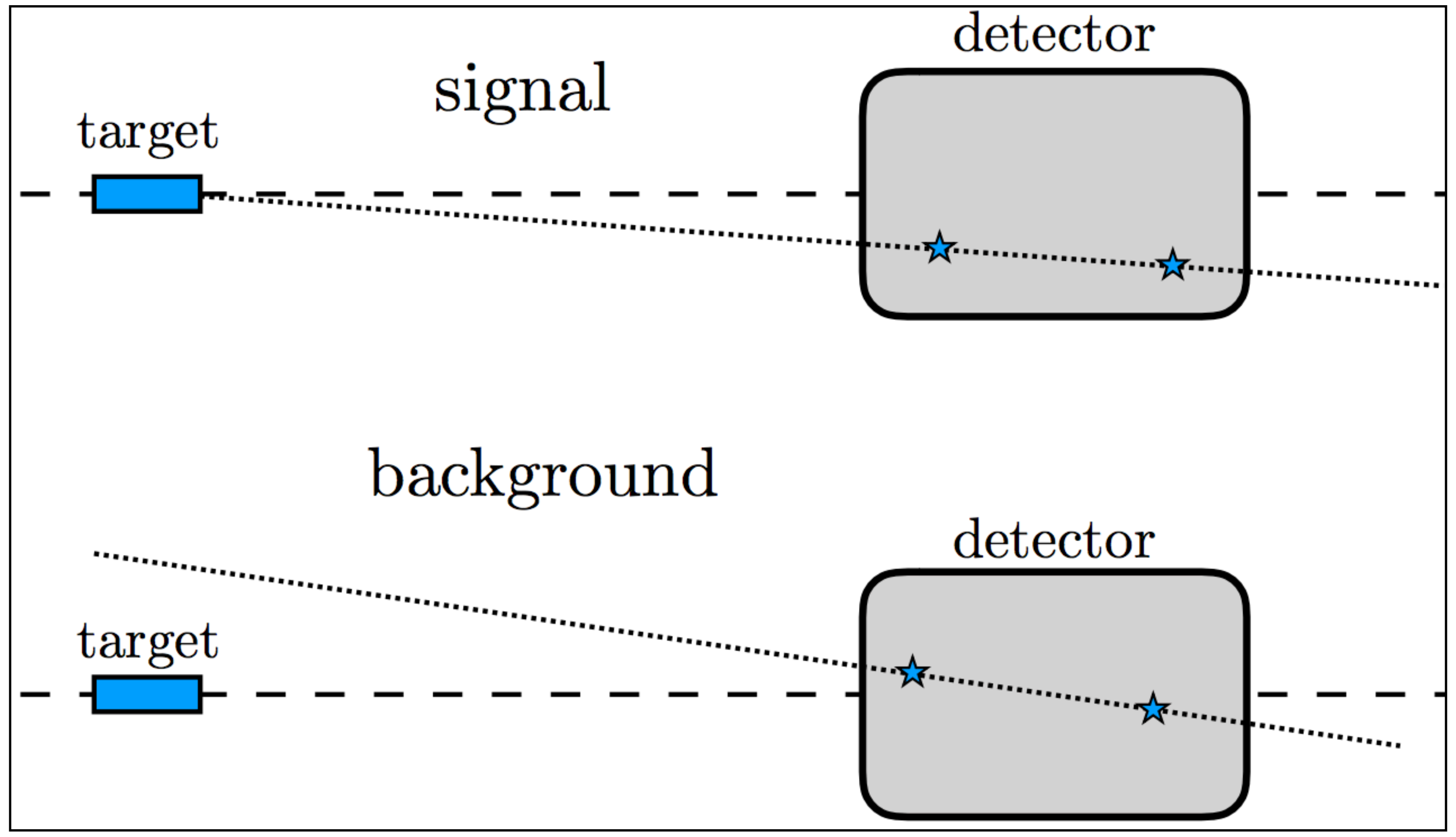
(c) Millicharged particles

R. Harnik, Zhen Liu, and O. Palamara, arXiv:1902.03246



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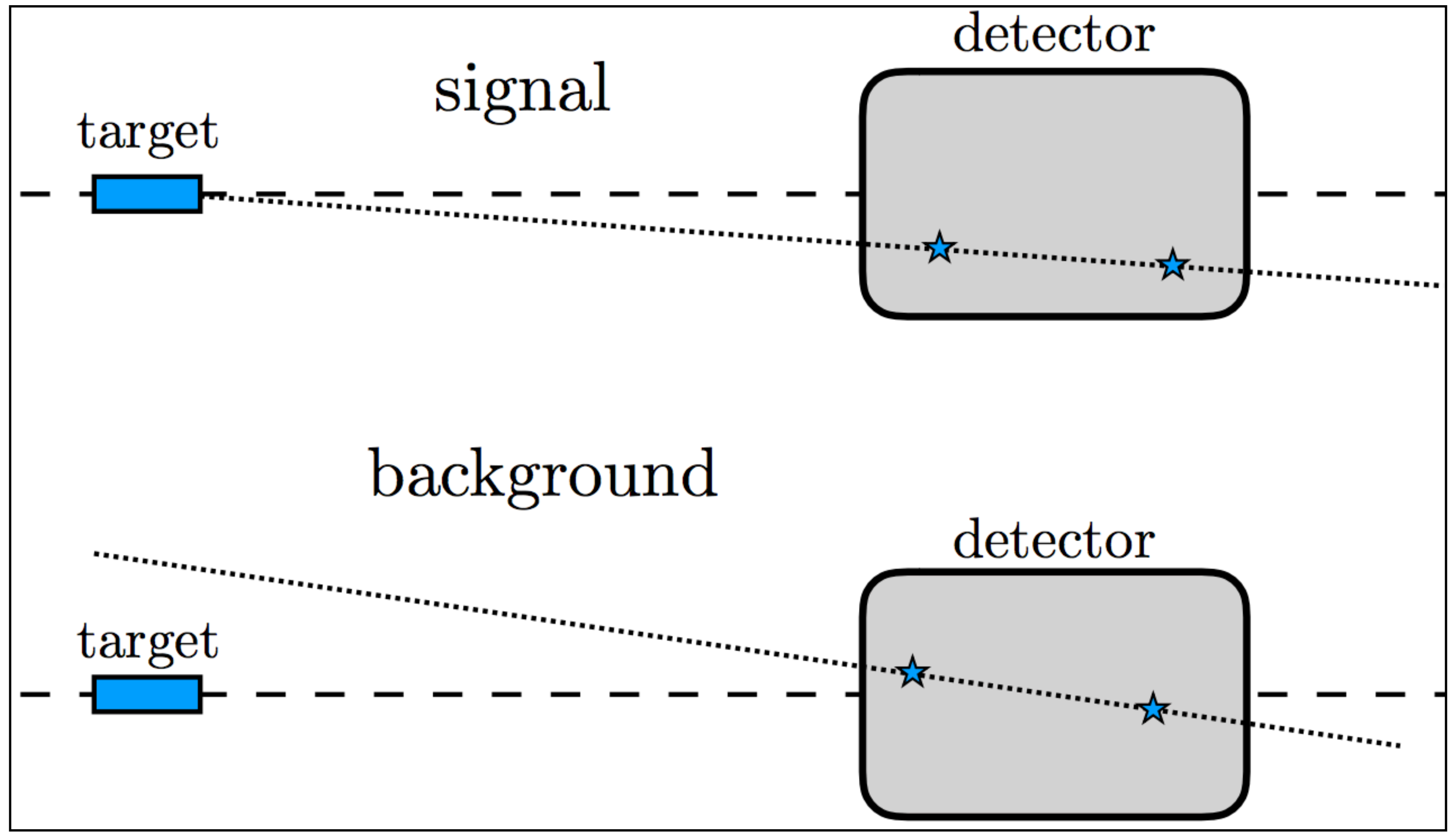

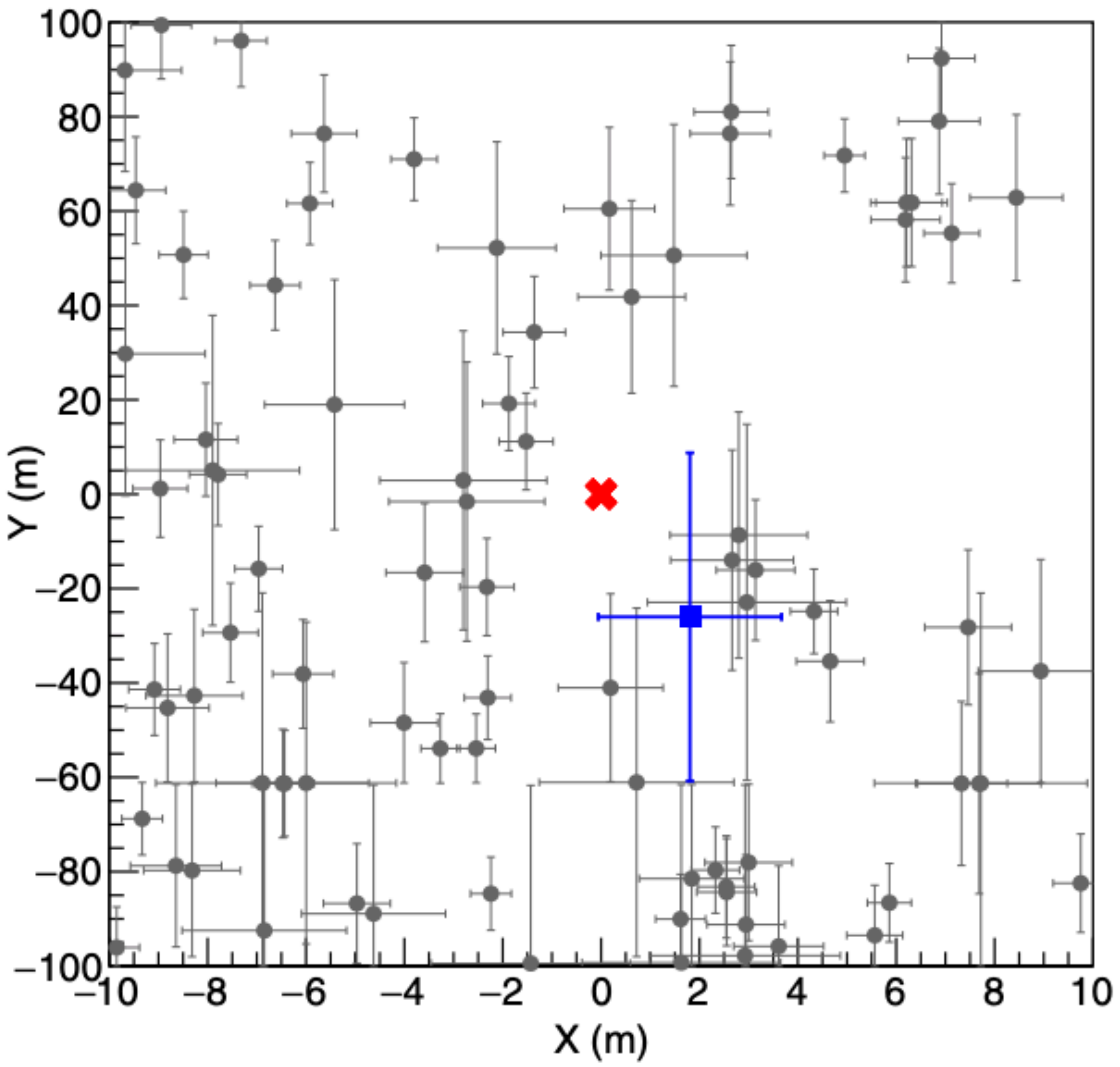

PHYSICAL REVIEW LETTERS **124,** 131801 (2020)

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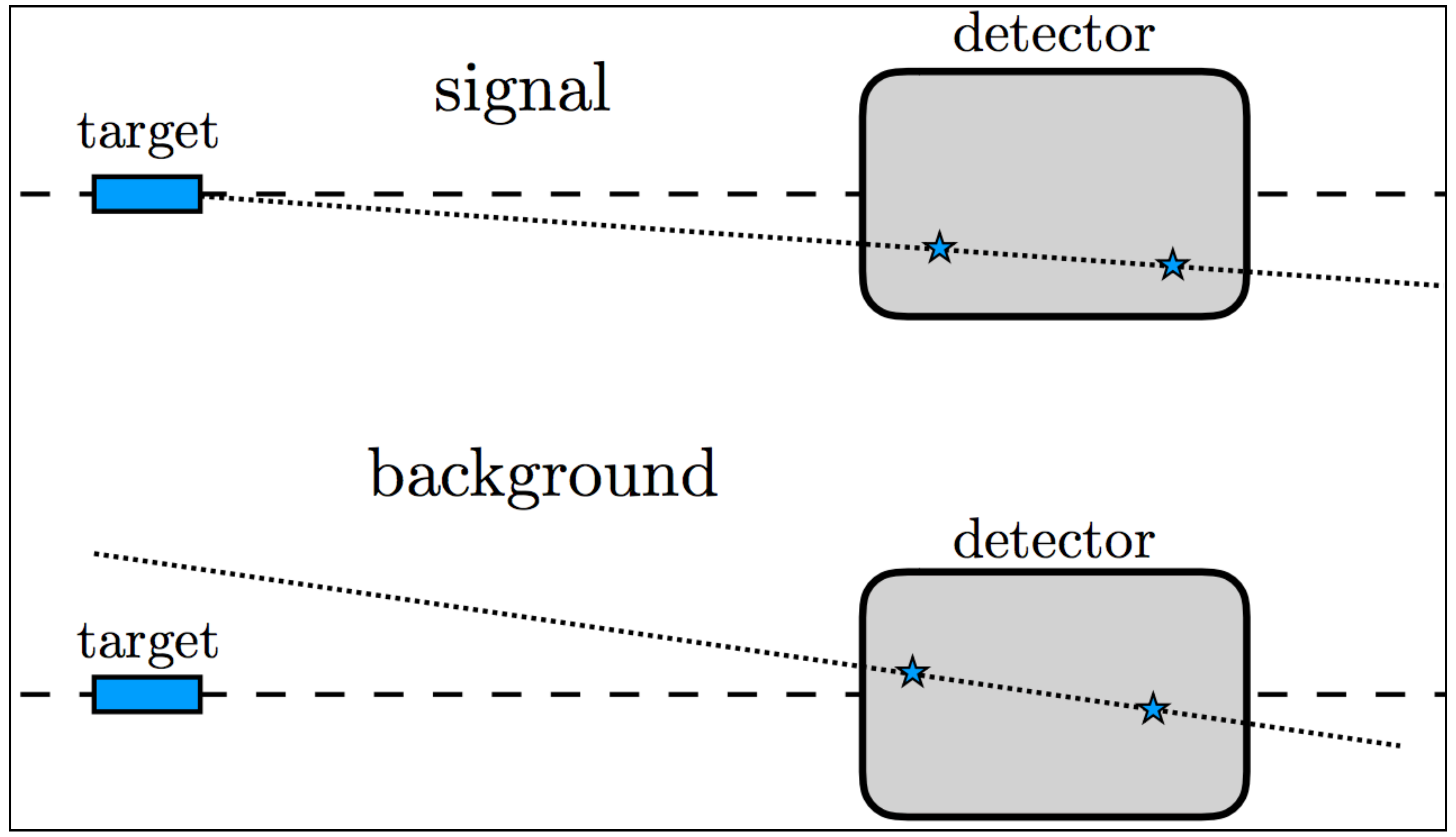

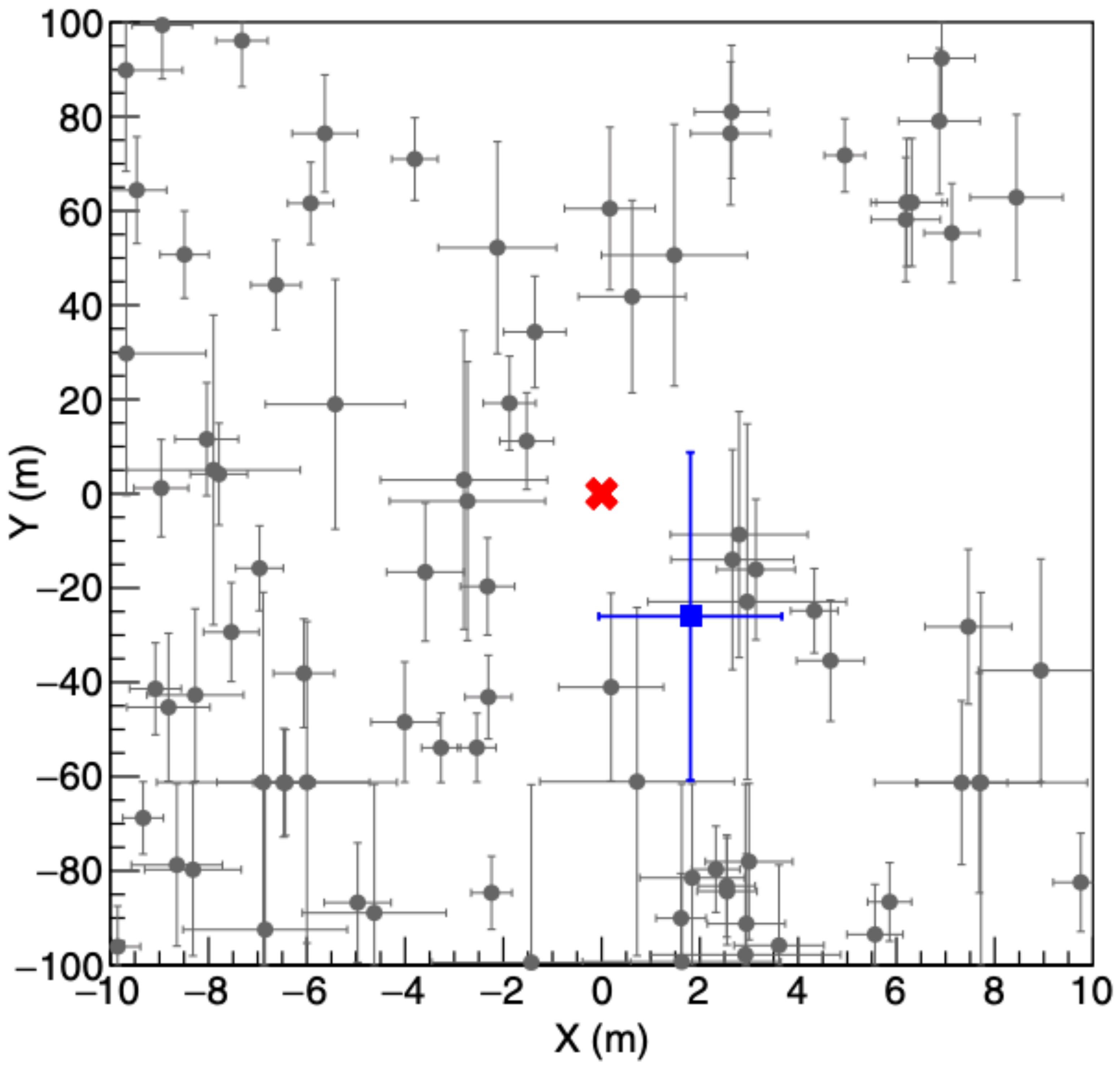

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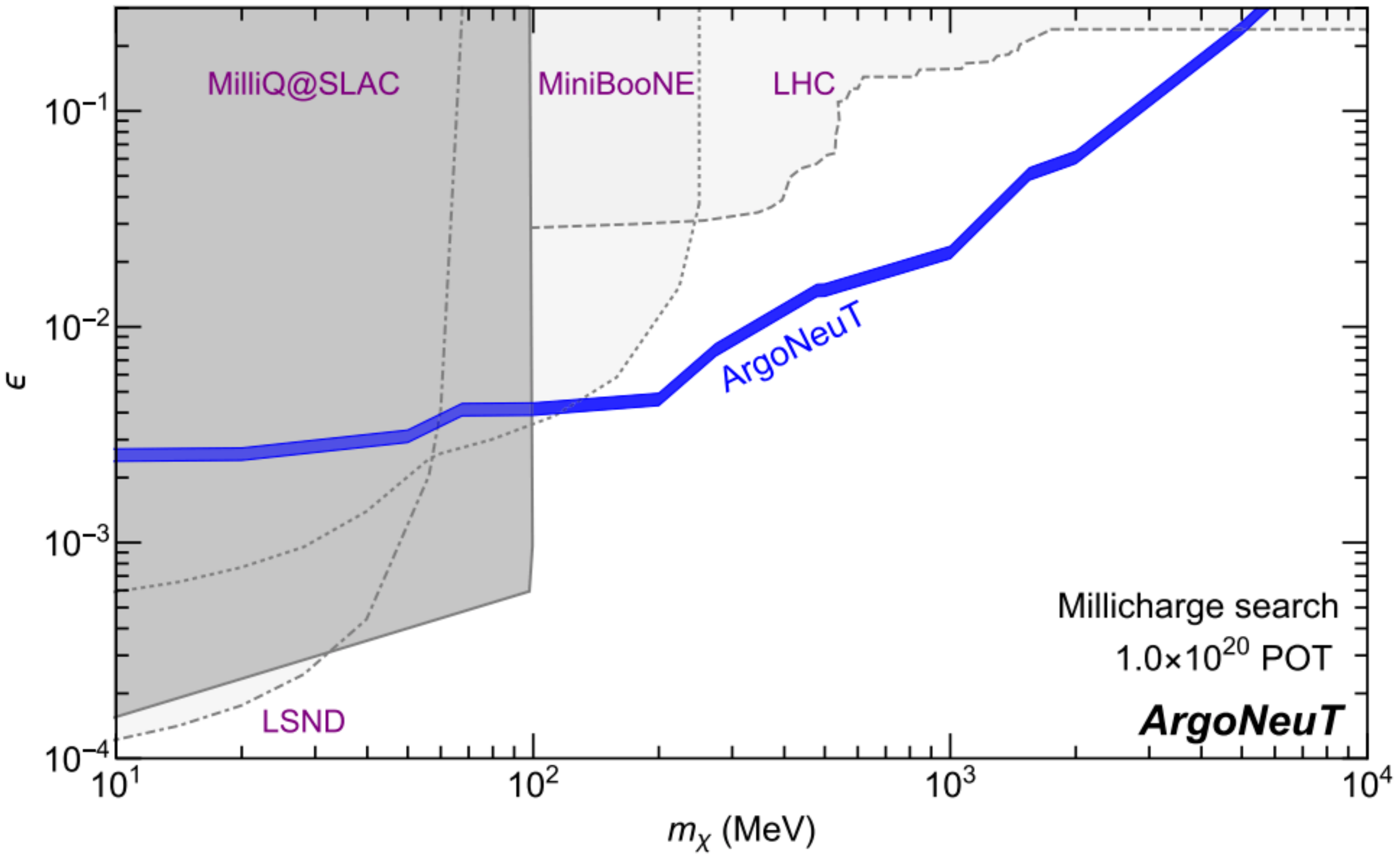
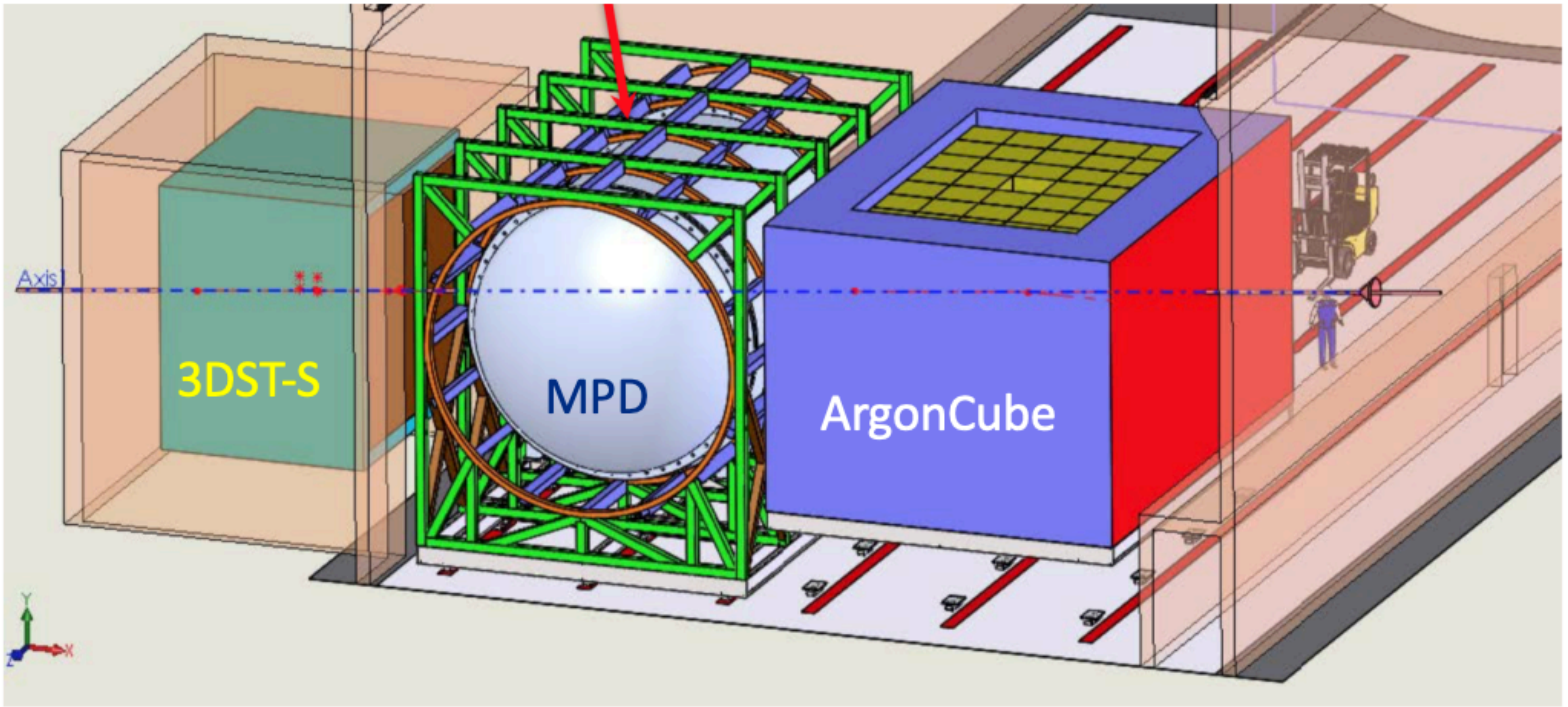


(4) Multi-purpose near detector complex

The DUNE Near Detector Complex



ArgonCube: Pixel-based LArTPC, unmagnetized (150 Tons)

MPD: "Multi-Purpose Detector": High-Pressure Gas TPC, solenoid, ECAL, muon stack

3DST-S Plastic scintillator, gas TPC, magnet, and ECAL

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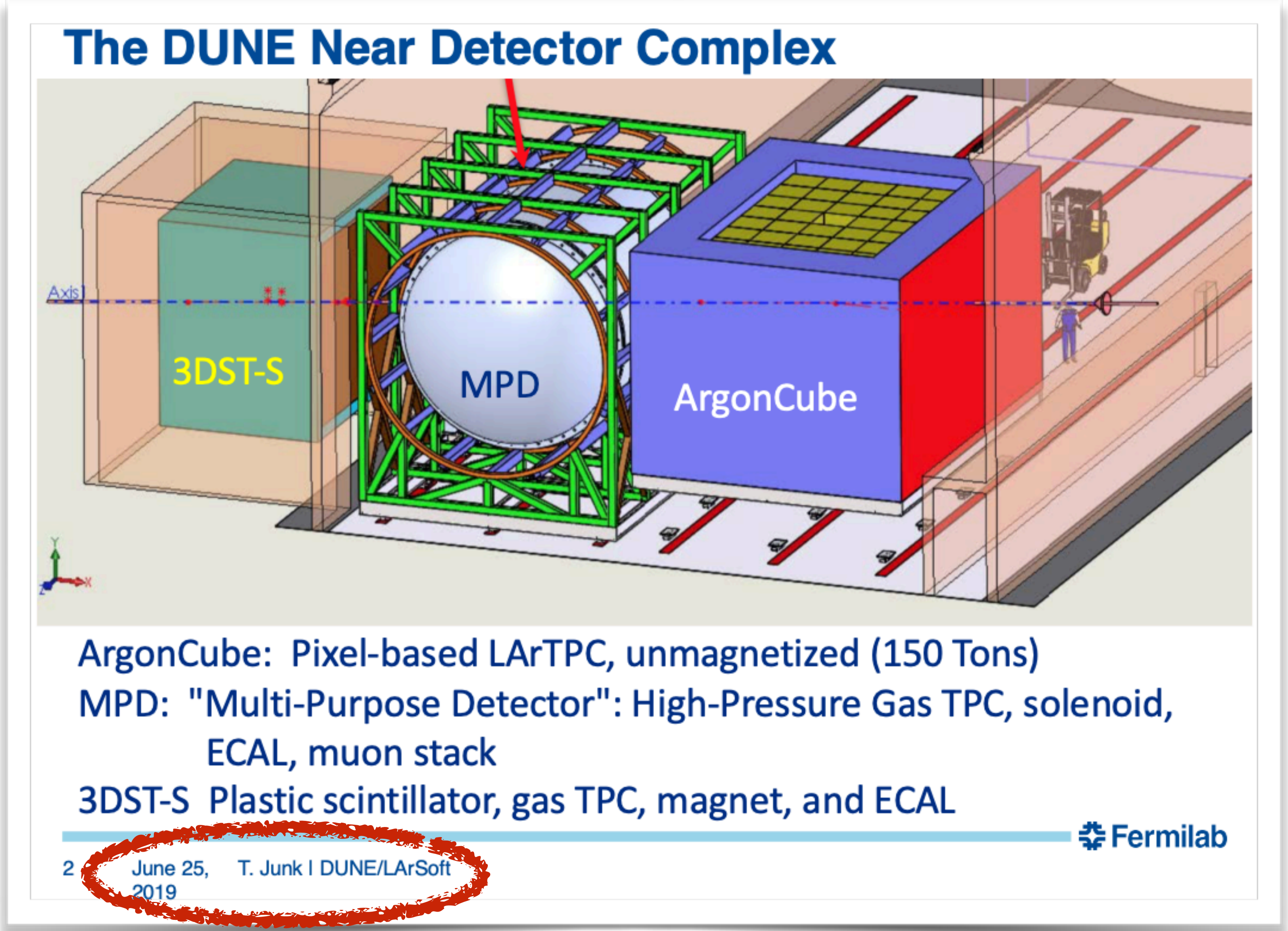
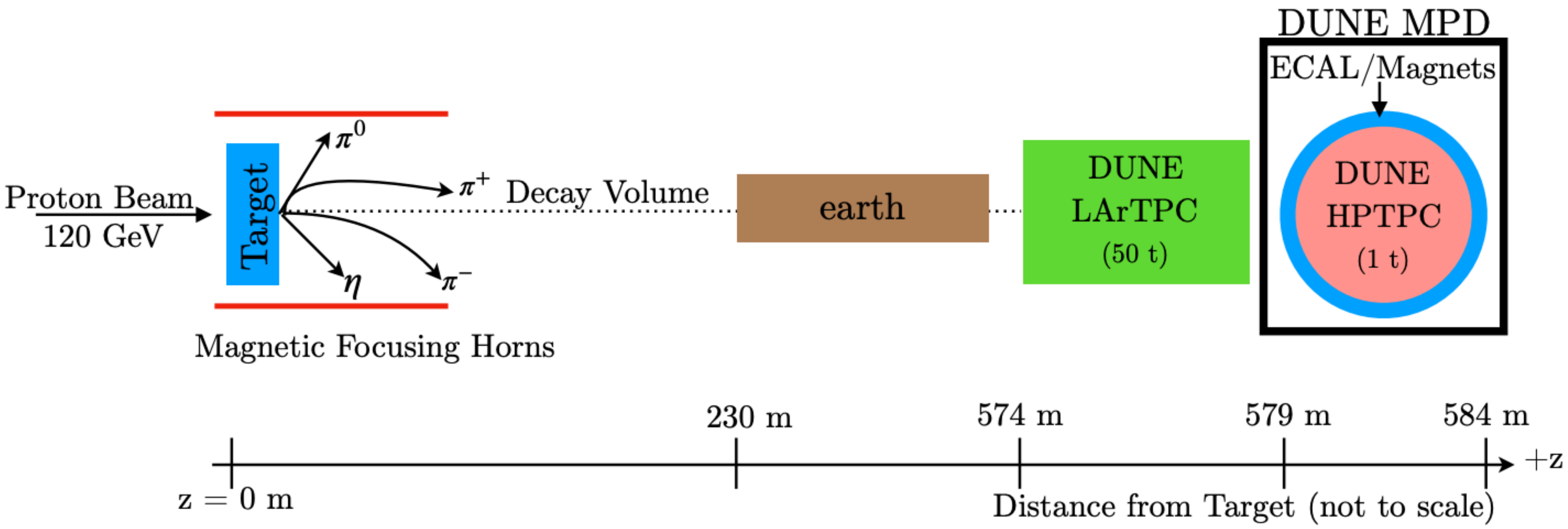
2 June 25, 2019 T. Junk I DUNE/LArSoft

(4) Multi-purpose near detector complex



Berryman et al 1912.07622



DUNE 2002.03005

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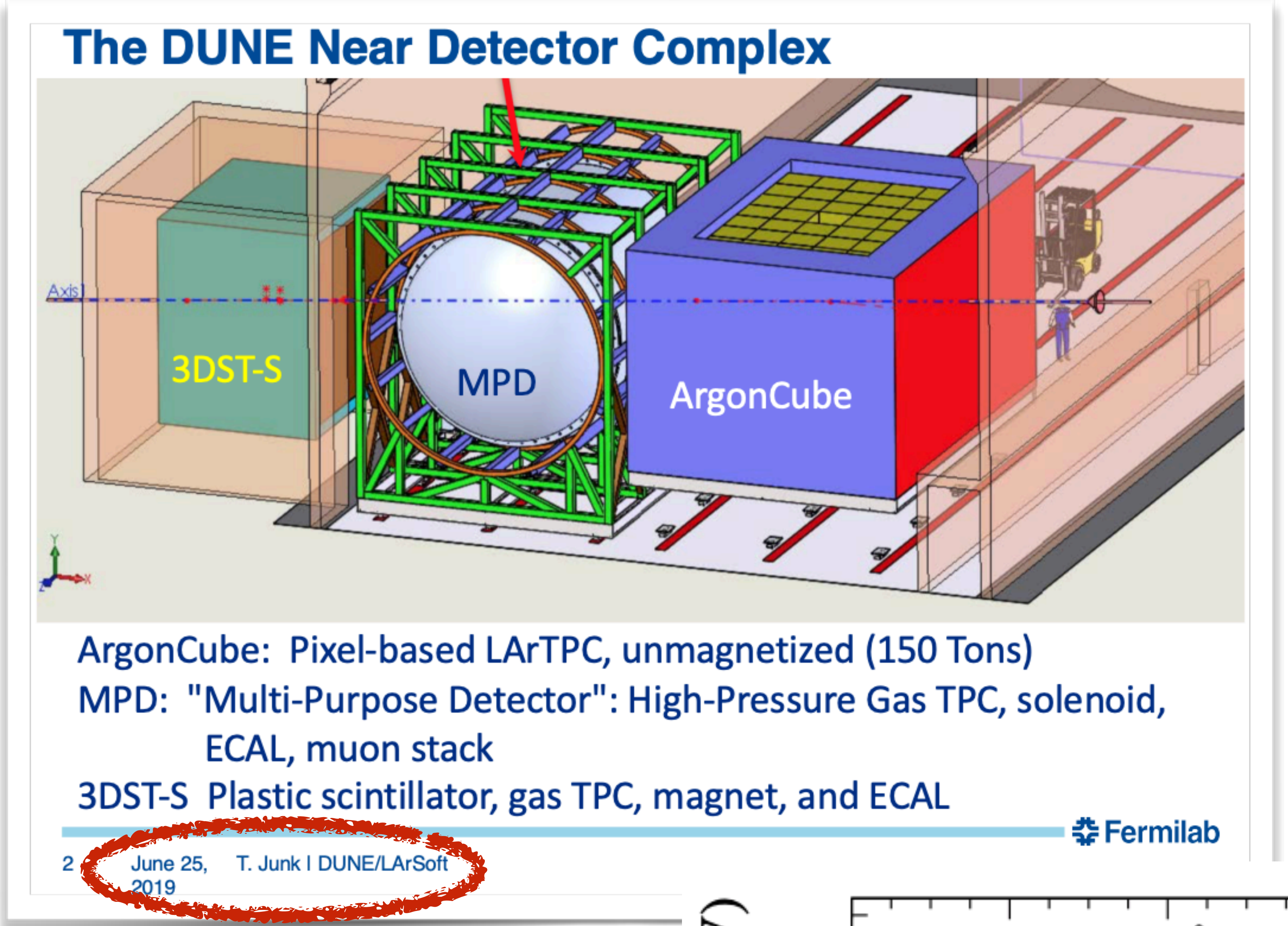

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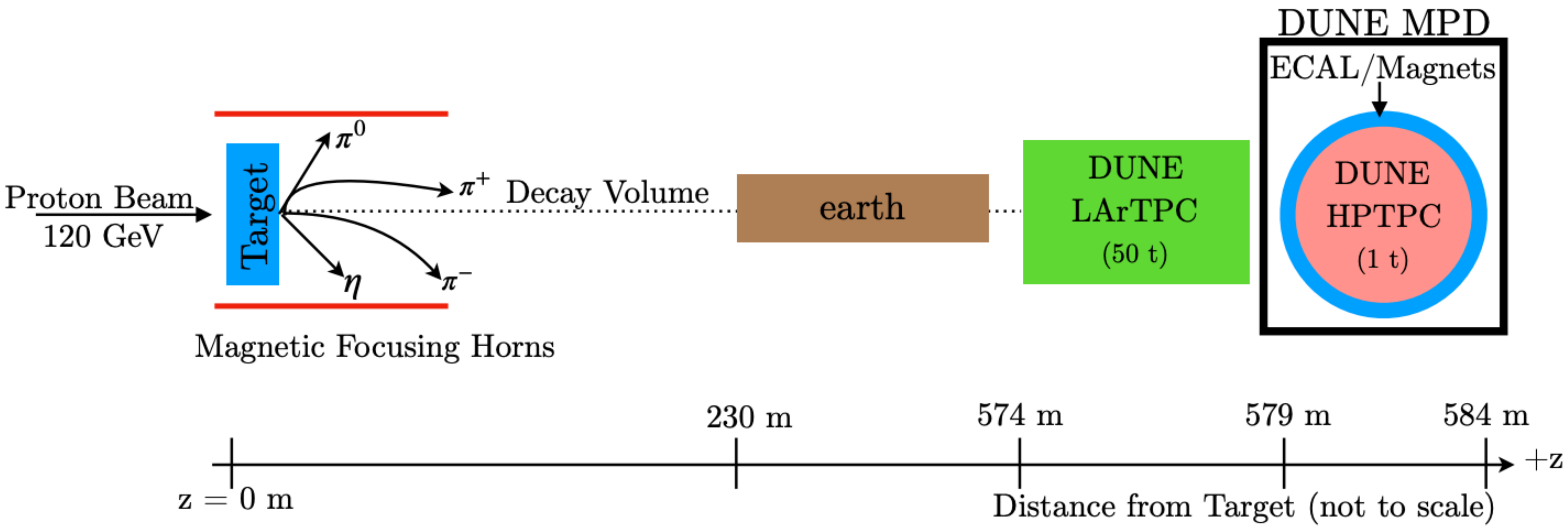

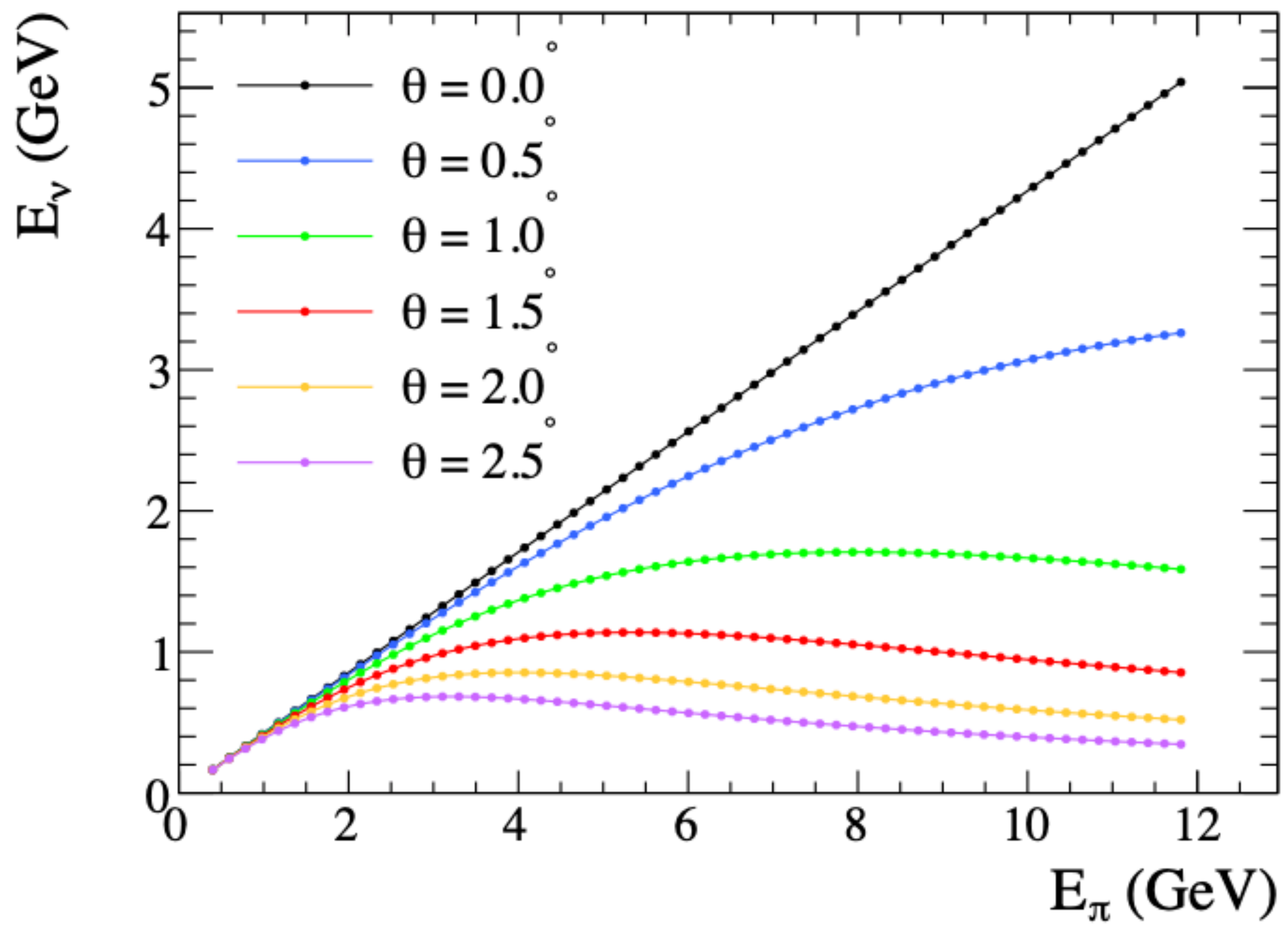

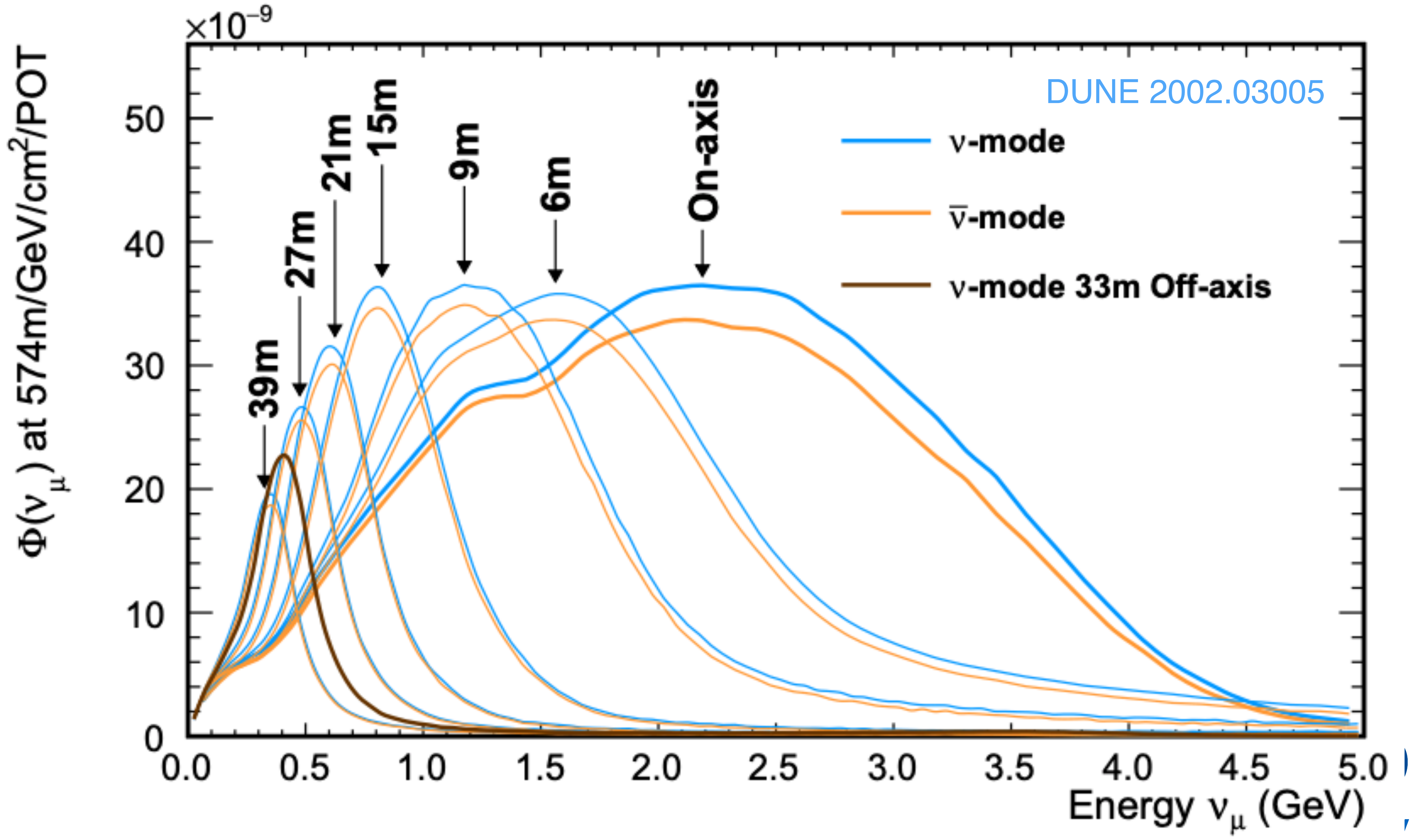

(d) Weak mixing angle measurements

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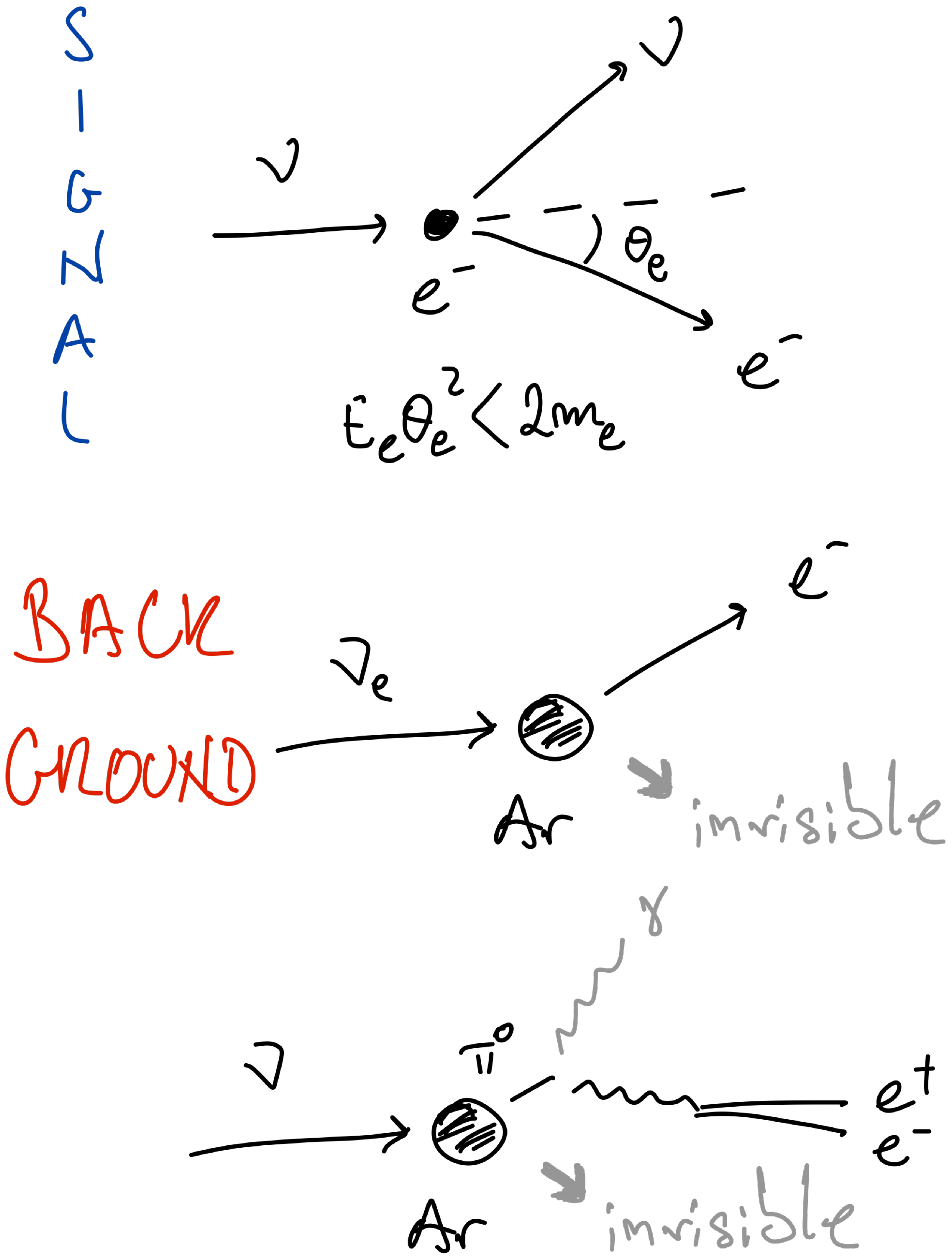

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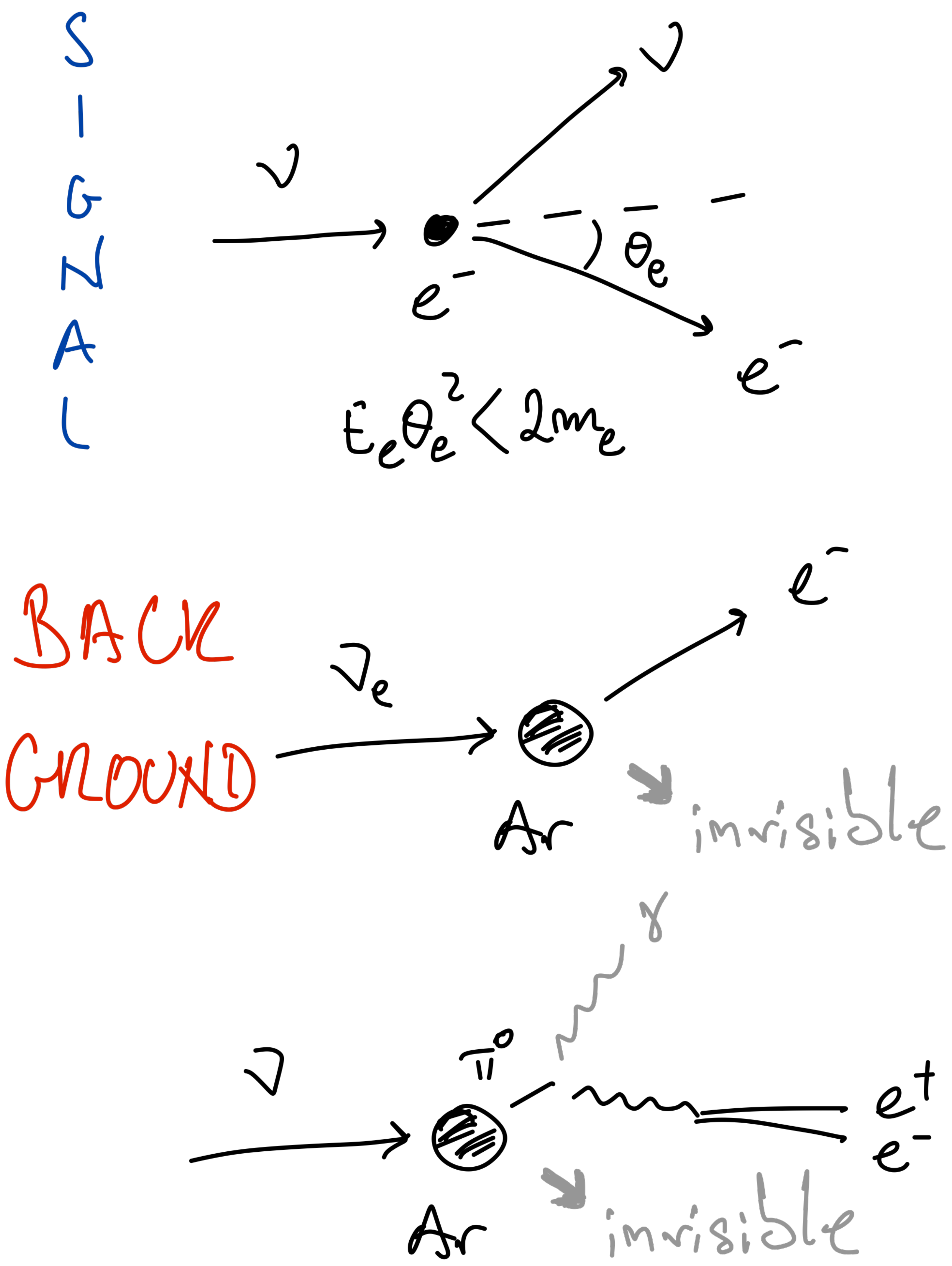

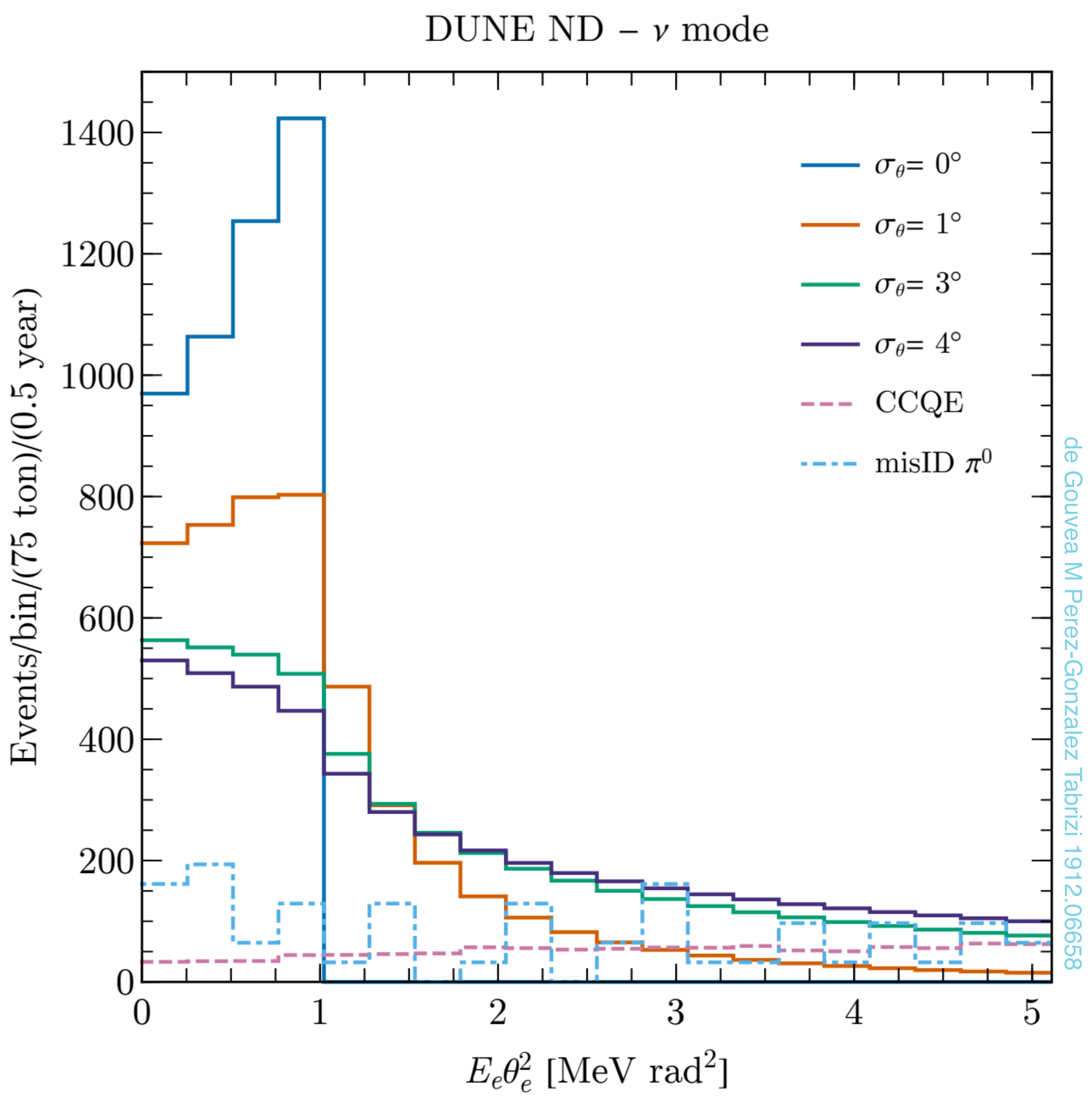

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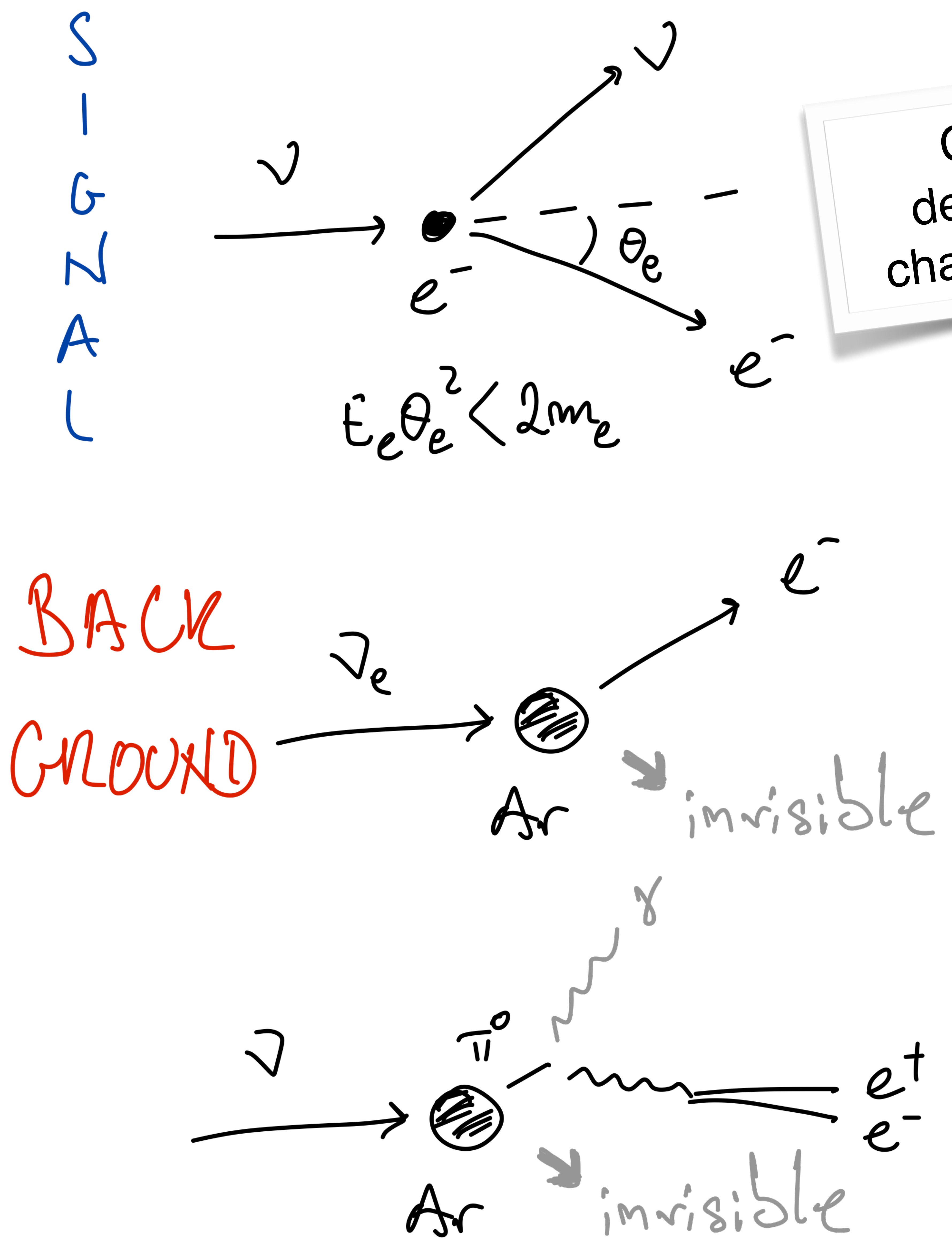
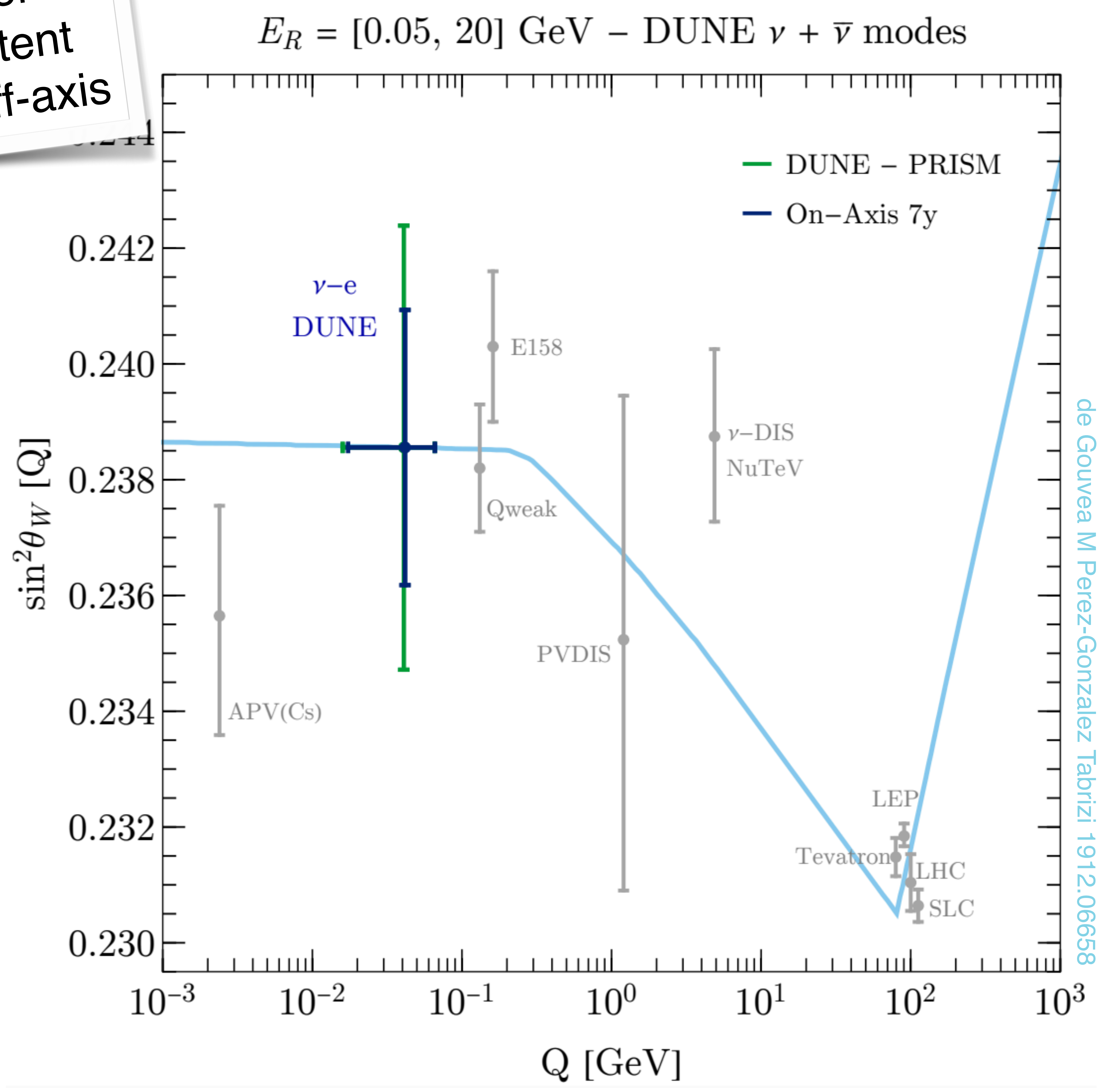


Cross section is flavor dependent, flavor content changes when going off-axis



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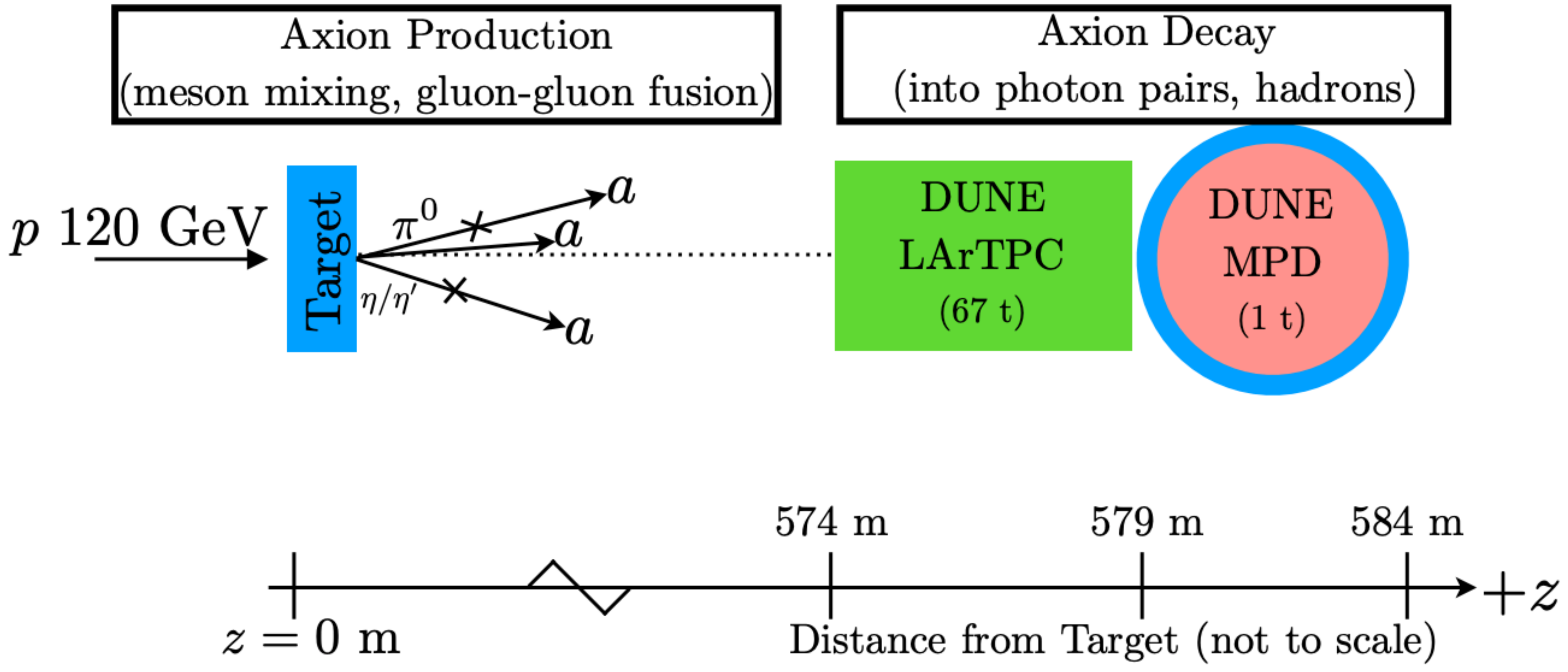
(e) Axion searches at the DUNE near detector complex

Based on Kelly Kumar Liu 2011.05995
see also Brdar et al 2011.07054



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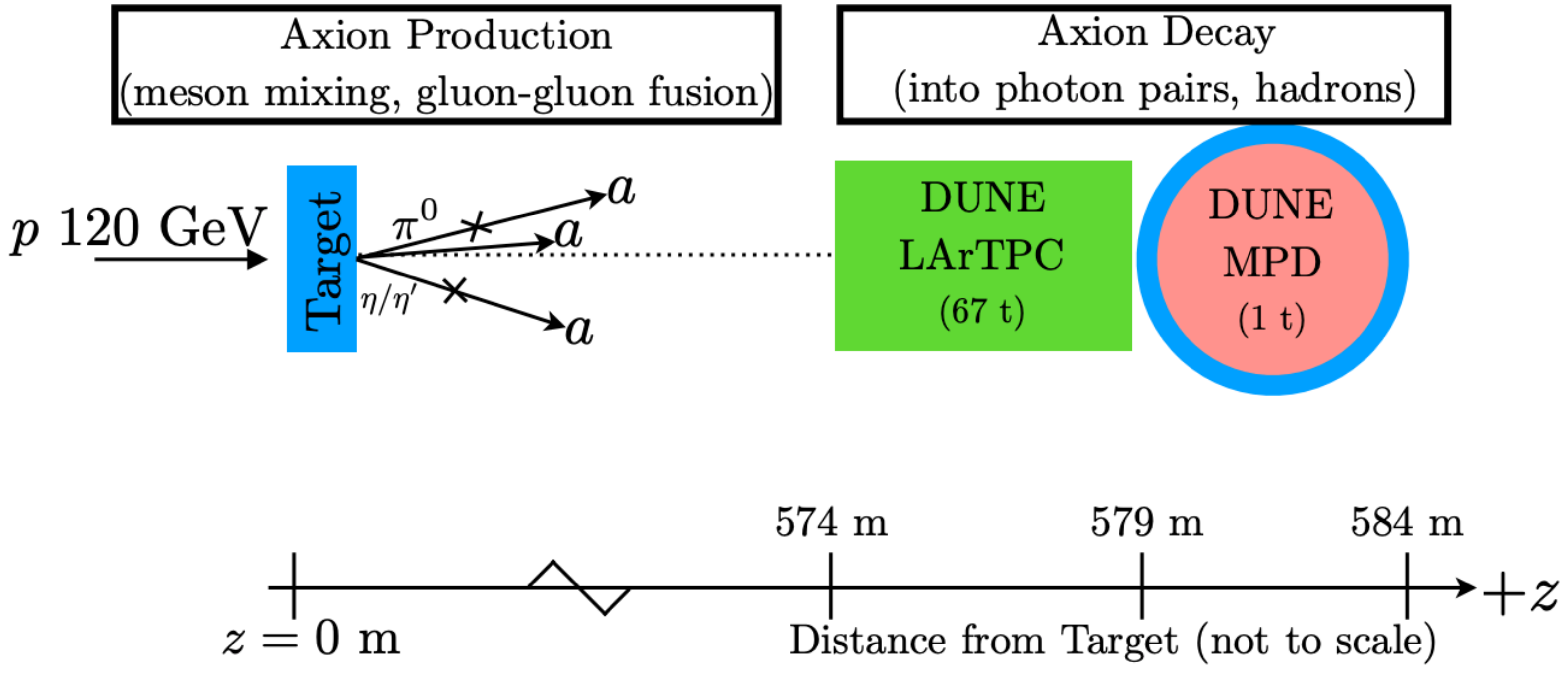
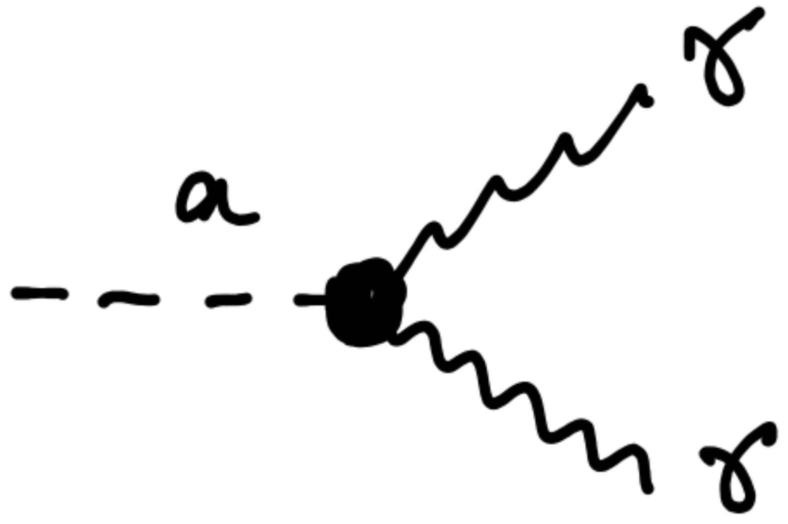


$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right) \rightarrow \frac{a}{8\pi f_a} c_\gamma \alpha_{\rm EM} F\tilde{F}$$



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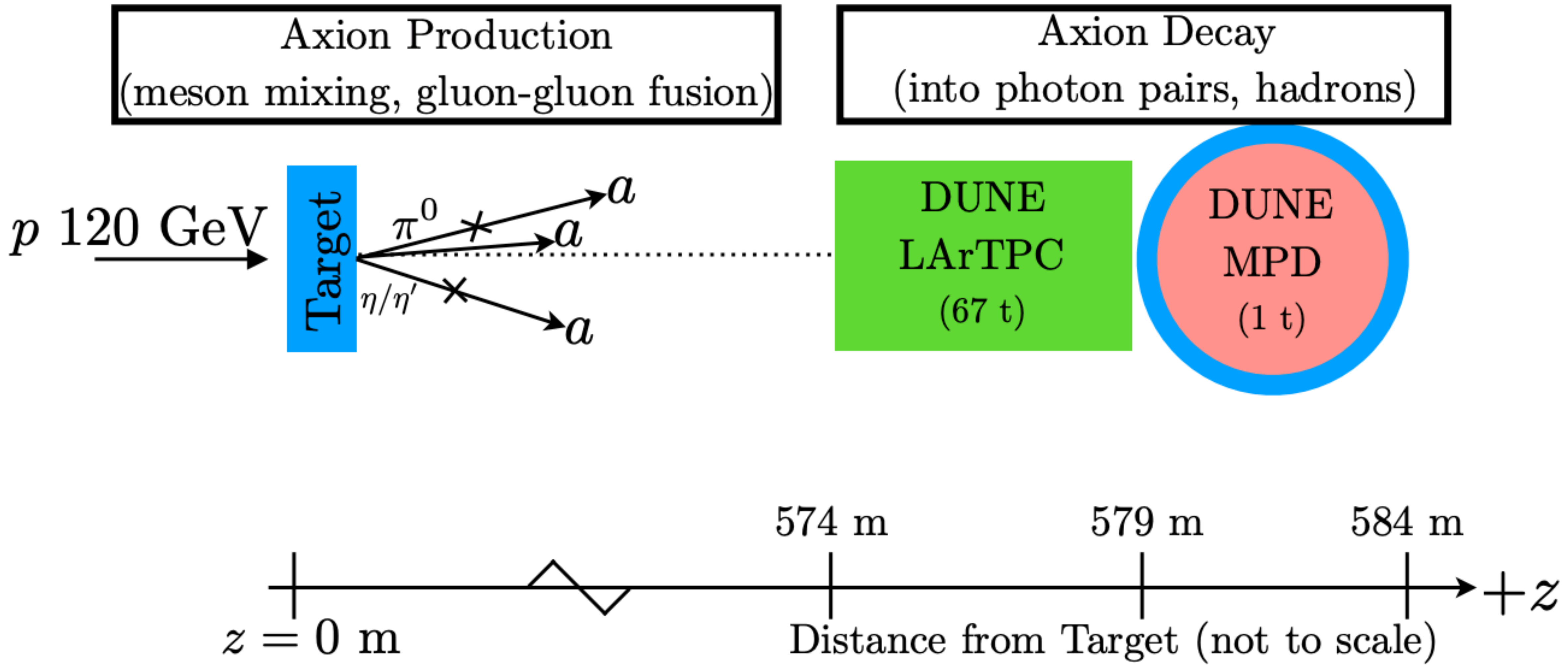
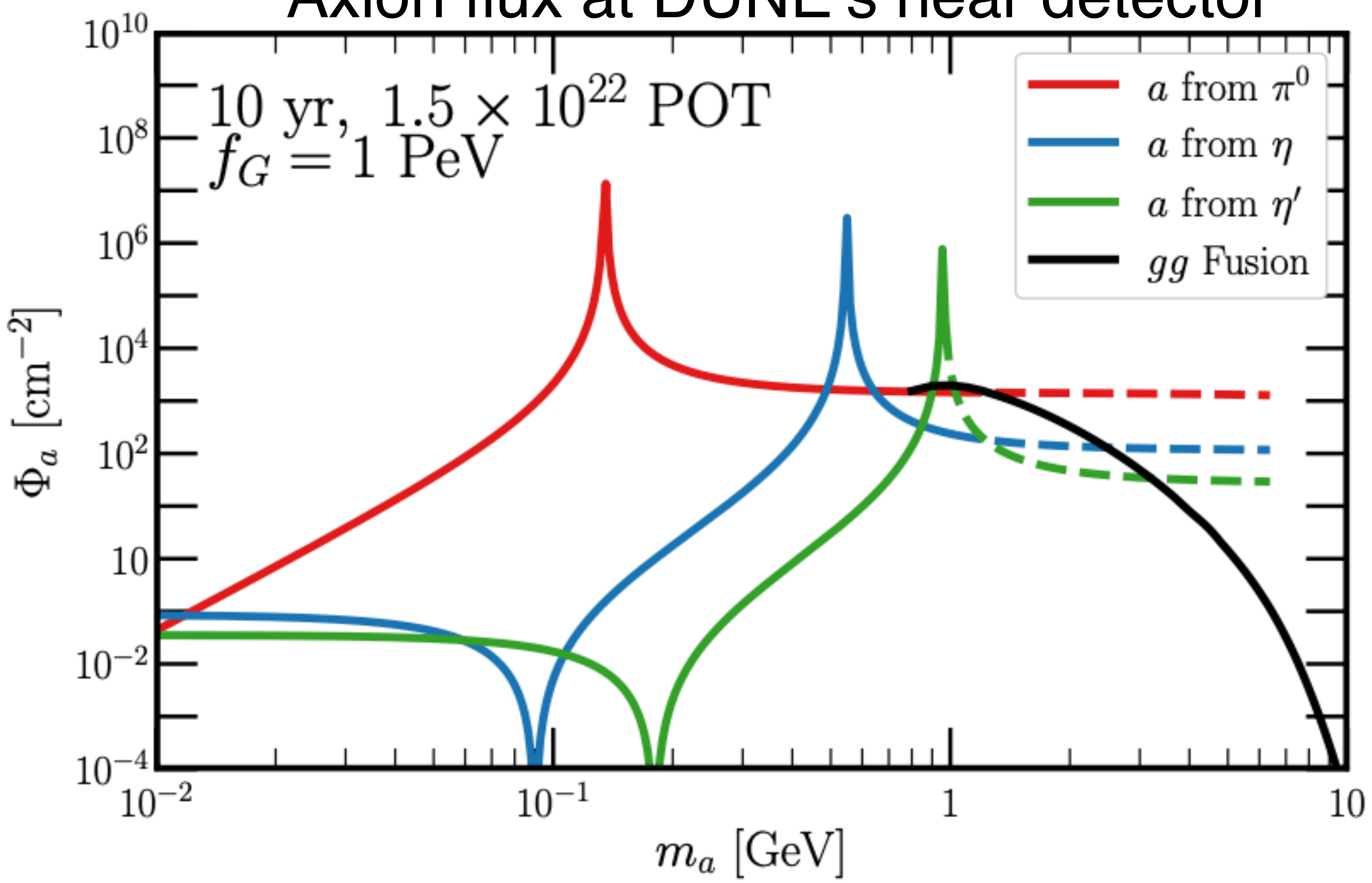


Axion flux at DUNE's near detector



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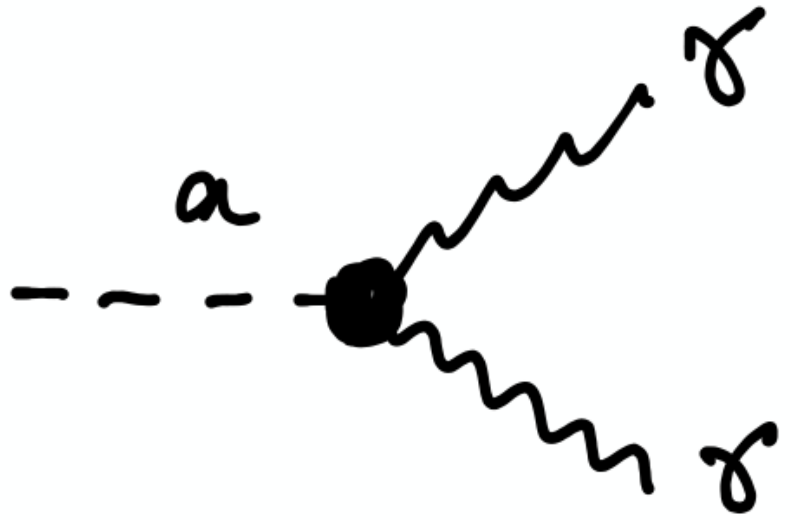
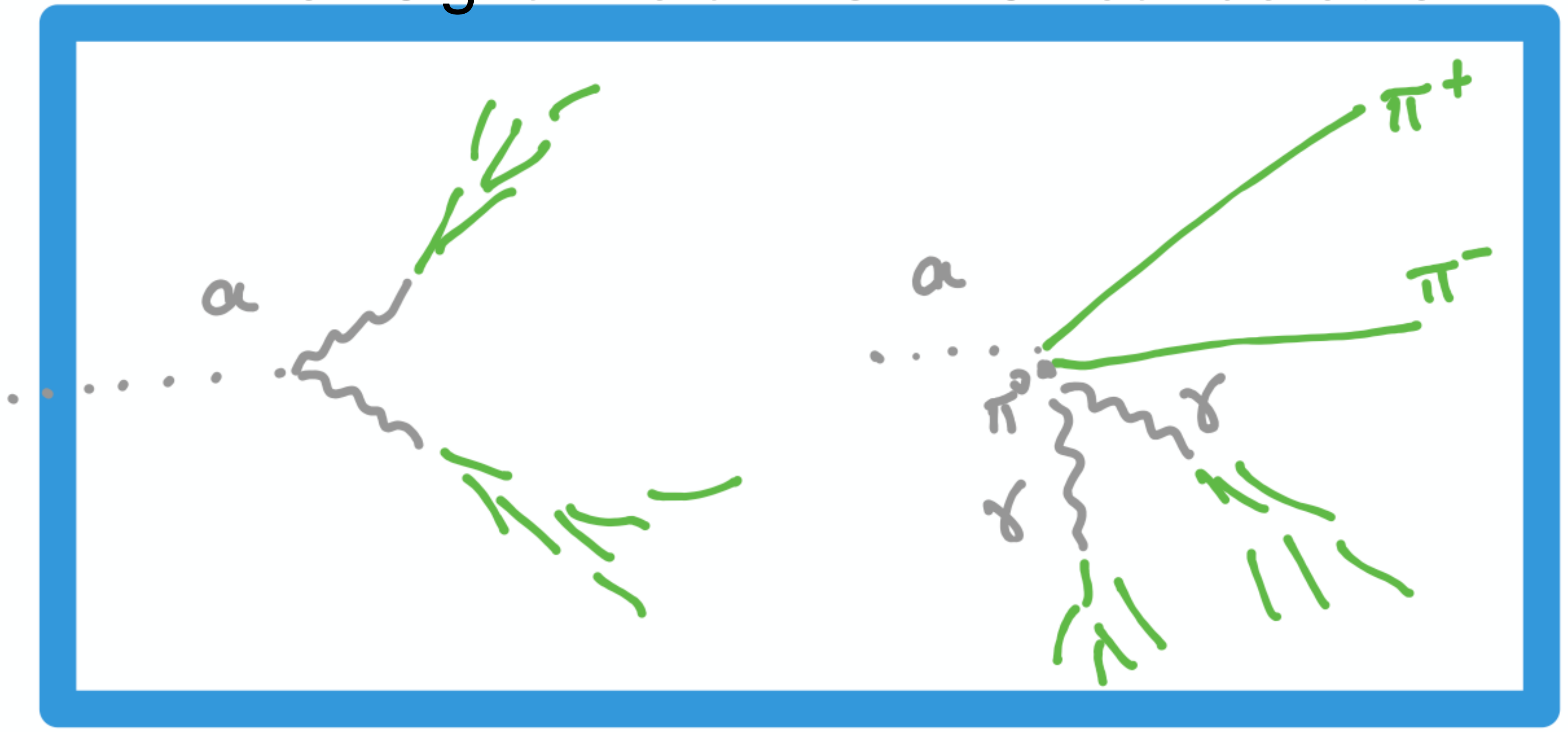


Axion signature at DUNE's near detector



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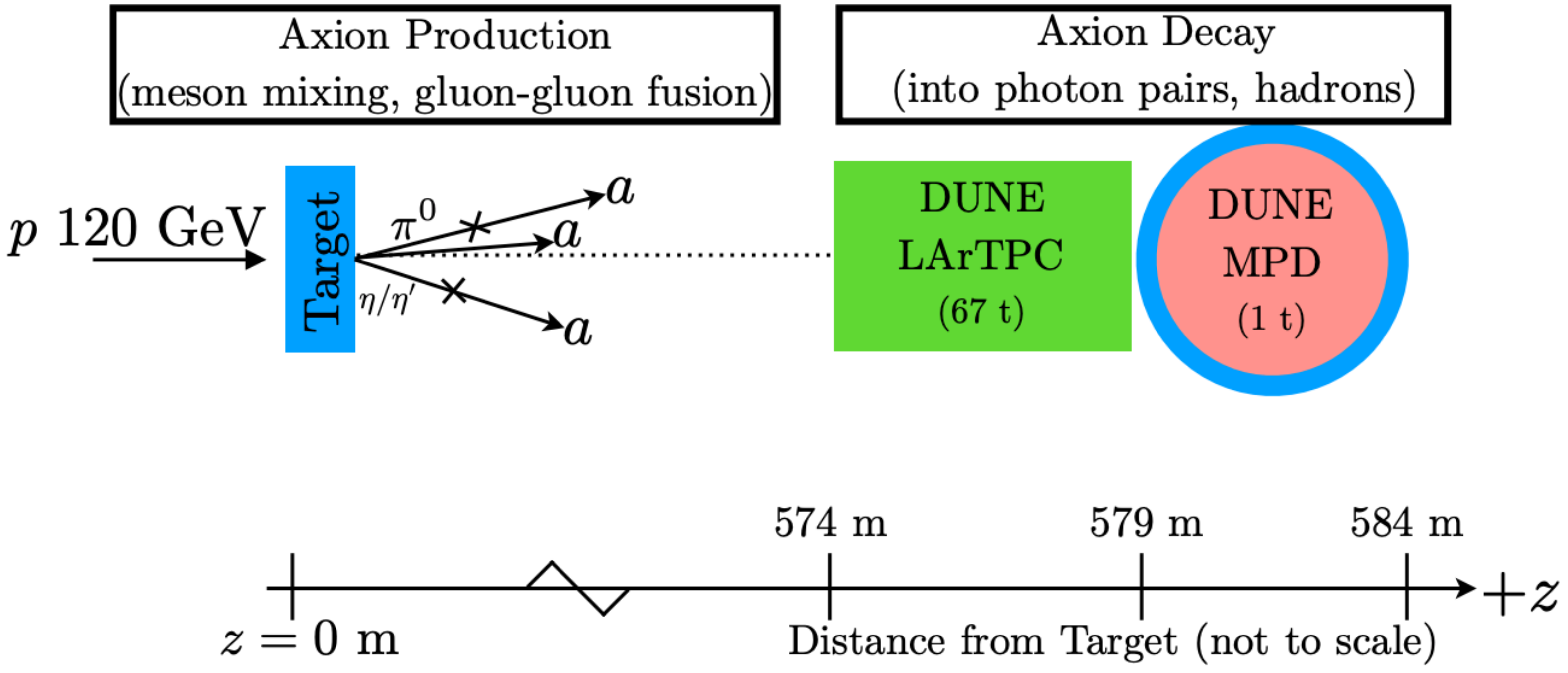

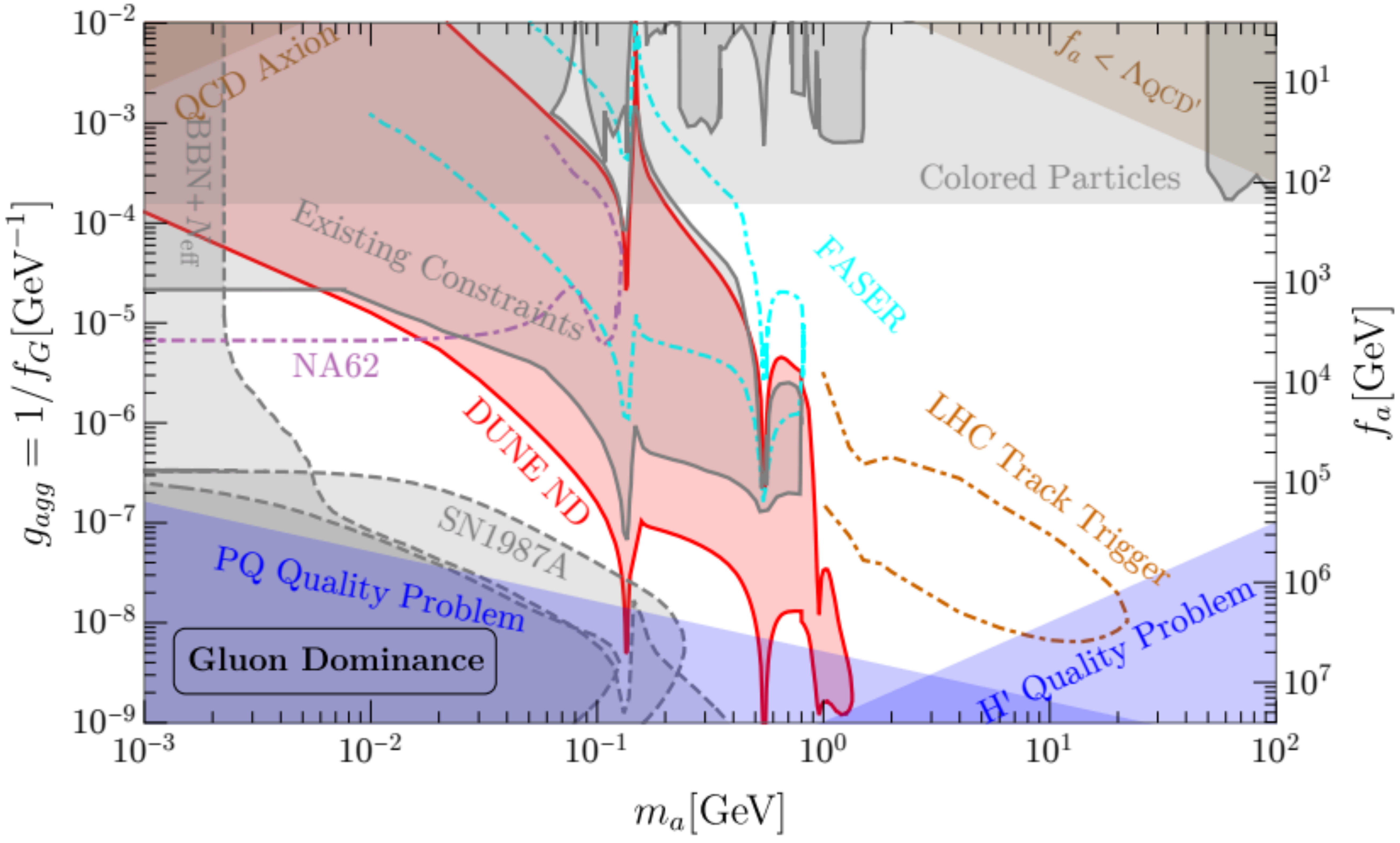

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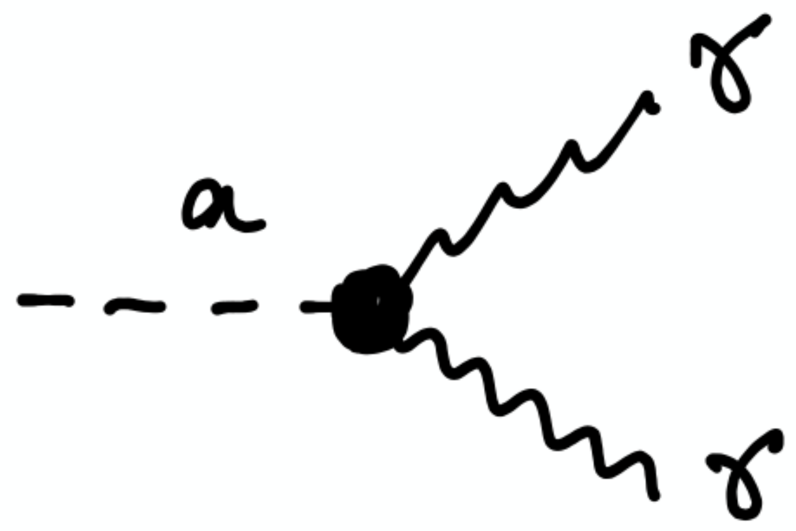

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New capabilities lead to novel opportunities

New capabilities will make SBN and DUNE multi-purpose physics programs, but will also require several areas of expertise: neutrino physics, nuclear physics, lattice, QCD, BSM, DM, …

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New capabilities lead to novel opportunities

Large flux, large detectors

3D reconstruction and calorimetry

Low energy thresholds

Multi-purpose near detector complex

→

Tau neutrino reconstruction

Sub-GeV atm neutrinos: CPV/tomography

Millicharged particles

Weak mixing angle

Axion searches

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New capabilities lead to novel opportunities

Large flux, large detectors

3D reconstruction and calorimetry

Low energy thresholds

Multi-purpose near detector complex

Electron-photon separation

Angular resolution

Light collection system

…

Tau neutrino reconstruction

Sub-GeV atm neutrinos: CPV/tomography

Millicharged particles

Weak mixing angle

Axion searches

Neutrino tridents

Mass hierarchy from atm neutrinos

Solar neutrinos

Supernova neutrinos

Neutron-antineutron oscillations

Heavy neutral leptons

Neutrino Portal

+ all standard BSM + …

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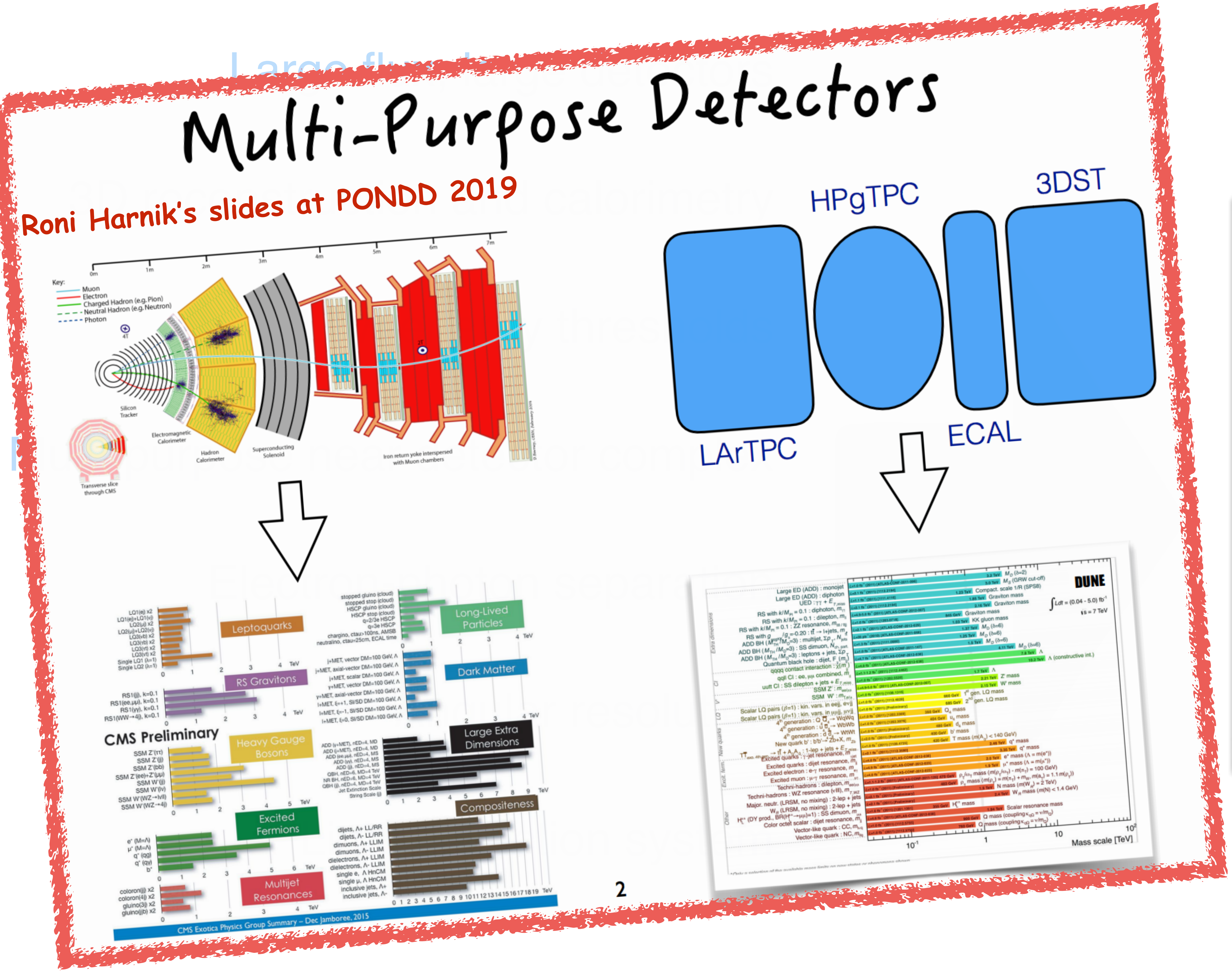
New capabilities lead to novel opportunities



Tau neutrino reconstruction

Sub-GeV atm neutrinos: CPV/tomography

Millicharged particles

Multi-purpose program needs

- **Broad TH coverage**
- **TH and EXP developments**
- **TH+EXP collaboration**

Exciting times ahead!!!

Neutron-antineutron oscillations

Heavy neutral leptons

Neutrino Portal

+ all standard BSM + ...

...

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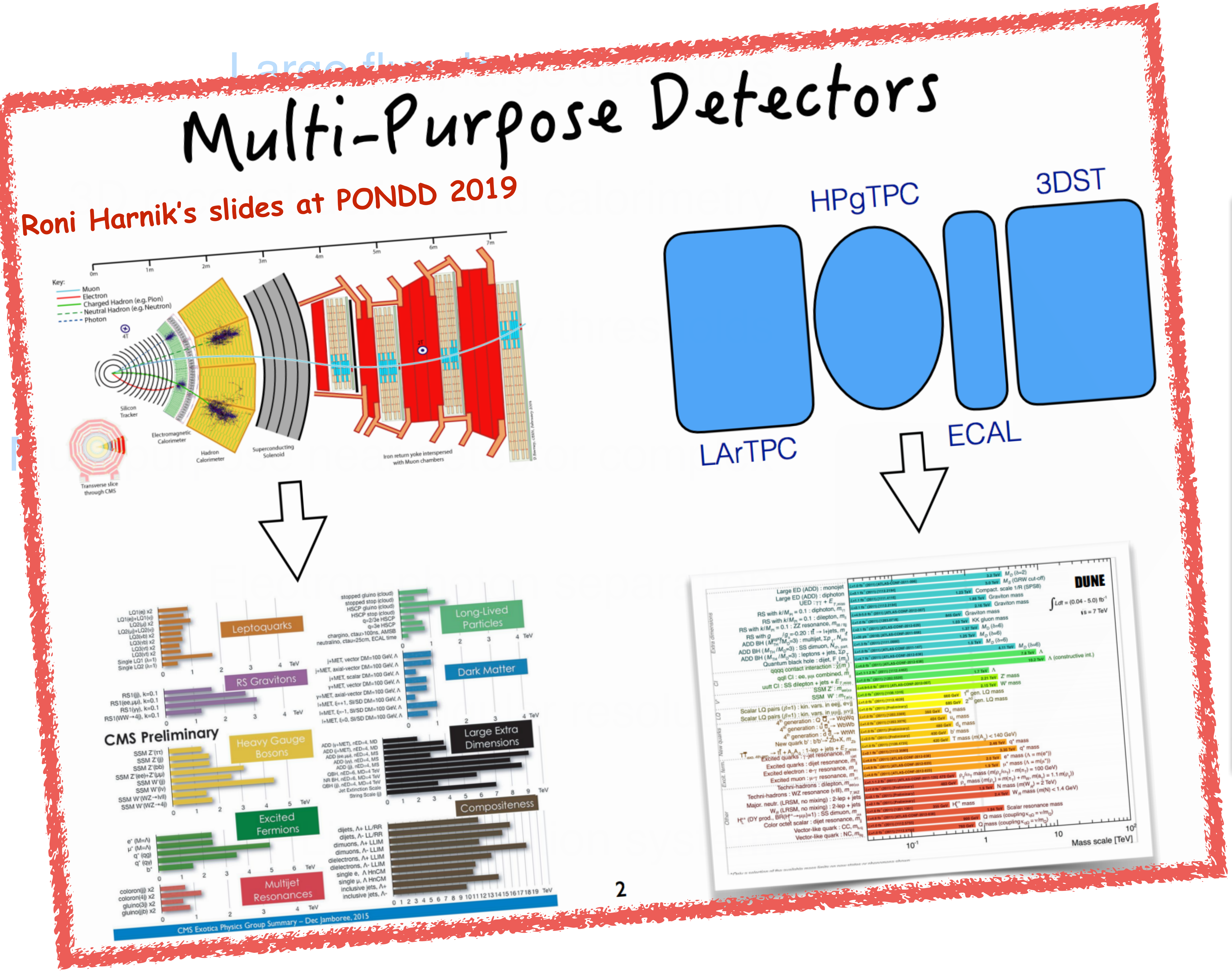
New capabilities lead to novel opportunities



Tau neutrino reconstruction

Sub-GeV atm neutrinos: CPV/tomography

Millicharged particles

Multi-purpose program needs

- **Broad TH coverage**
- **TH and EXP developments**
- **TH+EXP collaboration**

Exciting times ahead!!! *Thank you*

Neutron-antineutron oscillations

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