Models of Particle Signatures in KM3NeT ORCA

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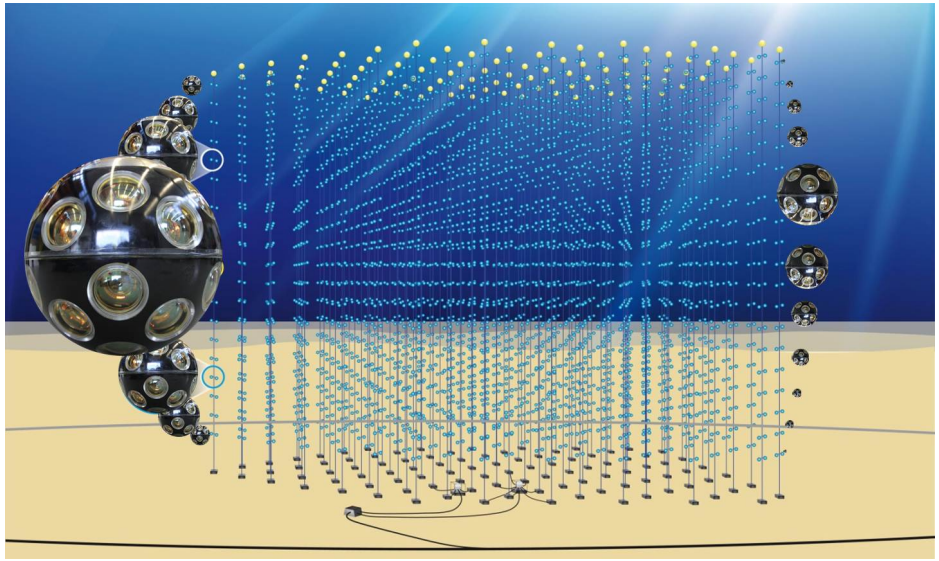
November 2, 2018

Photo by Blaque X from Pexels

- Introduction
- Procedure
- Models
- Reconstructions
- Conclusion

Introduction



$\mathcal{O}$(GeV) detector, KM3Net **ORCA**

Dense compared to ARCA

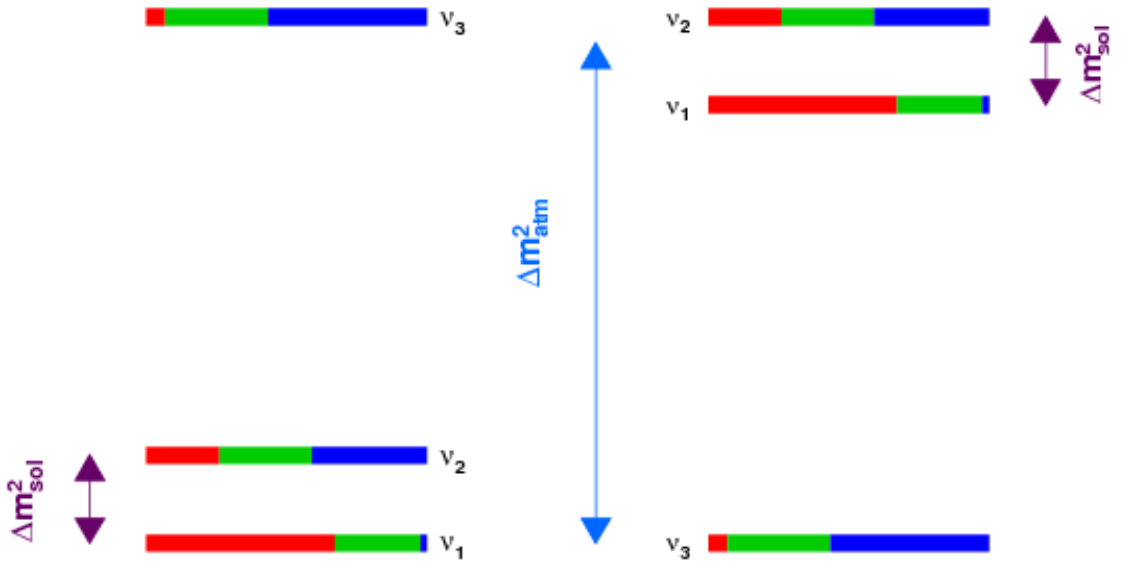
68 000 PMTs.

$0.004\ \mathrm{km}^3 = 4$ MegaTonnes $= 80\times$Super-Kamiokande.

very cool multi-directional detection modules.

Introduction

KM3NeT ORCA's goal: **What is the *Neutrino Mass Ordering* (NMO)?**



[1]

Normal Ordering (NO) Inverted Ordering (IO)

[1] [Gomez-Cadenas et al., 2012]

Introduction

Here are the parameters necessary to predict the oscillation probability of a neutrino through matter:

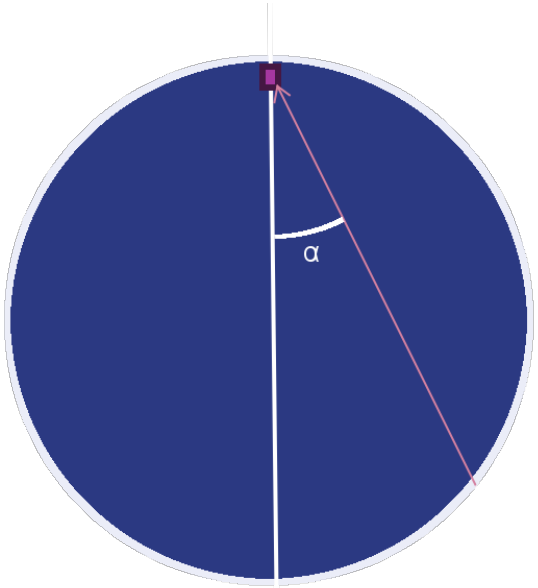
- **Oscillation parameters**
- **The number of electrons in the neutrino's path**
- **Energy of the neutrino**
- **Flavor of the neutrino**
- **Neutrino Mass Ordering (NMO)**

$$P_{3\nu}m(\nu_\mu \to \nu_\mu) \simeq 1 - sin^2 2\theta_{23} cos^2\theta_{13}^m sin^2\left(\frac{AL}{4} + \frac{\Delta m_{31}^2 + \Delta^m m^2)L}{8E_\nu}\right)$$

$*$

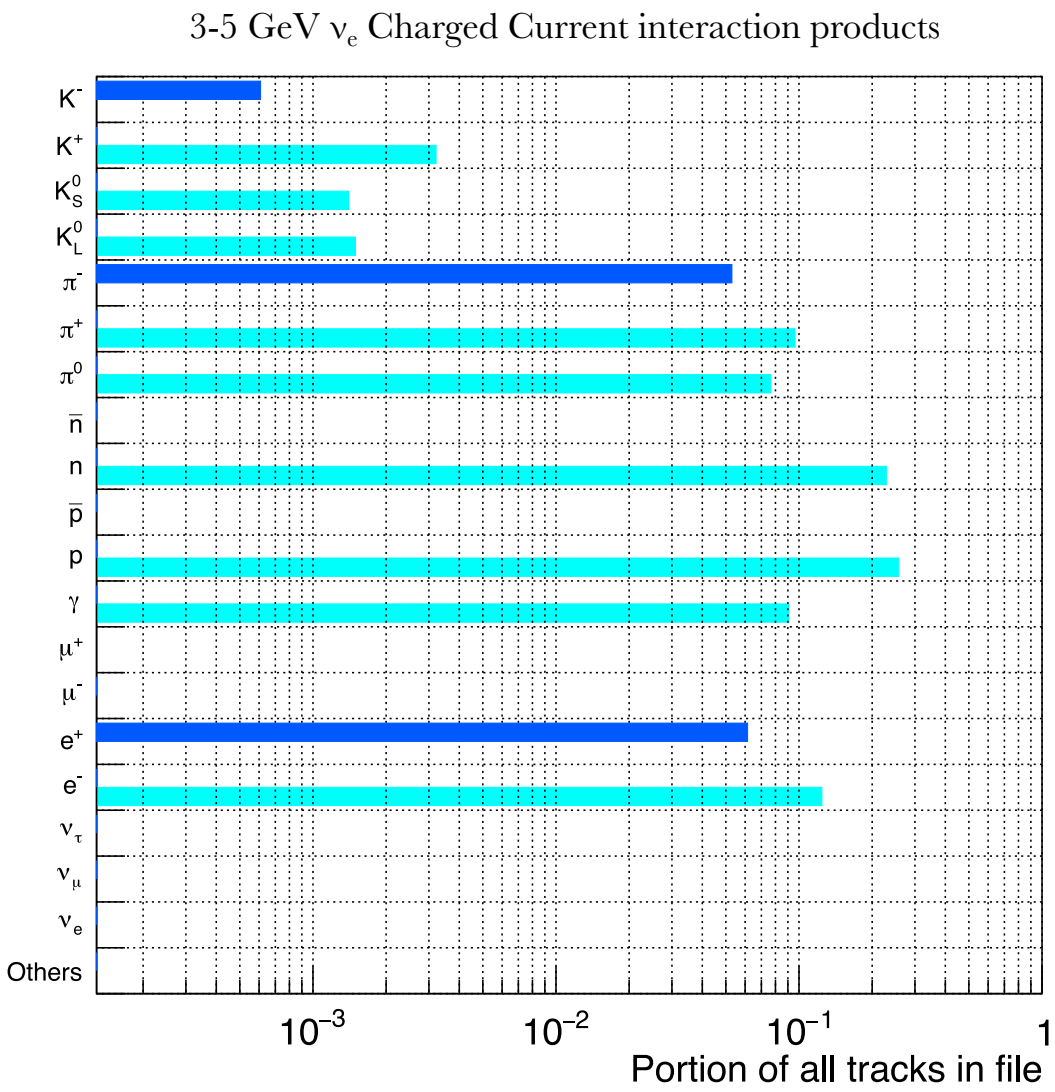
+some other terms

(1)



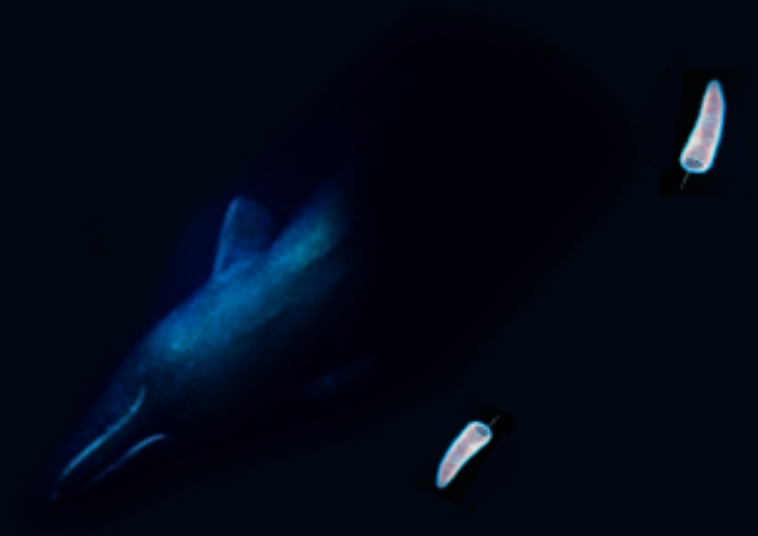
Introduction

Atmospheric neutrinos can interact in water and create *product particles*.

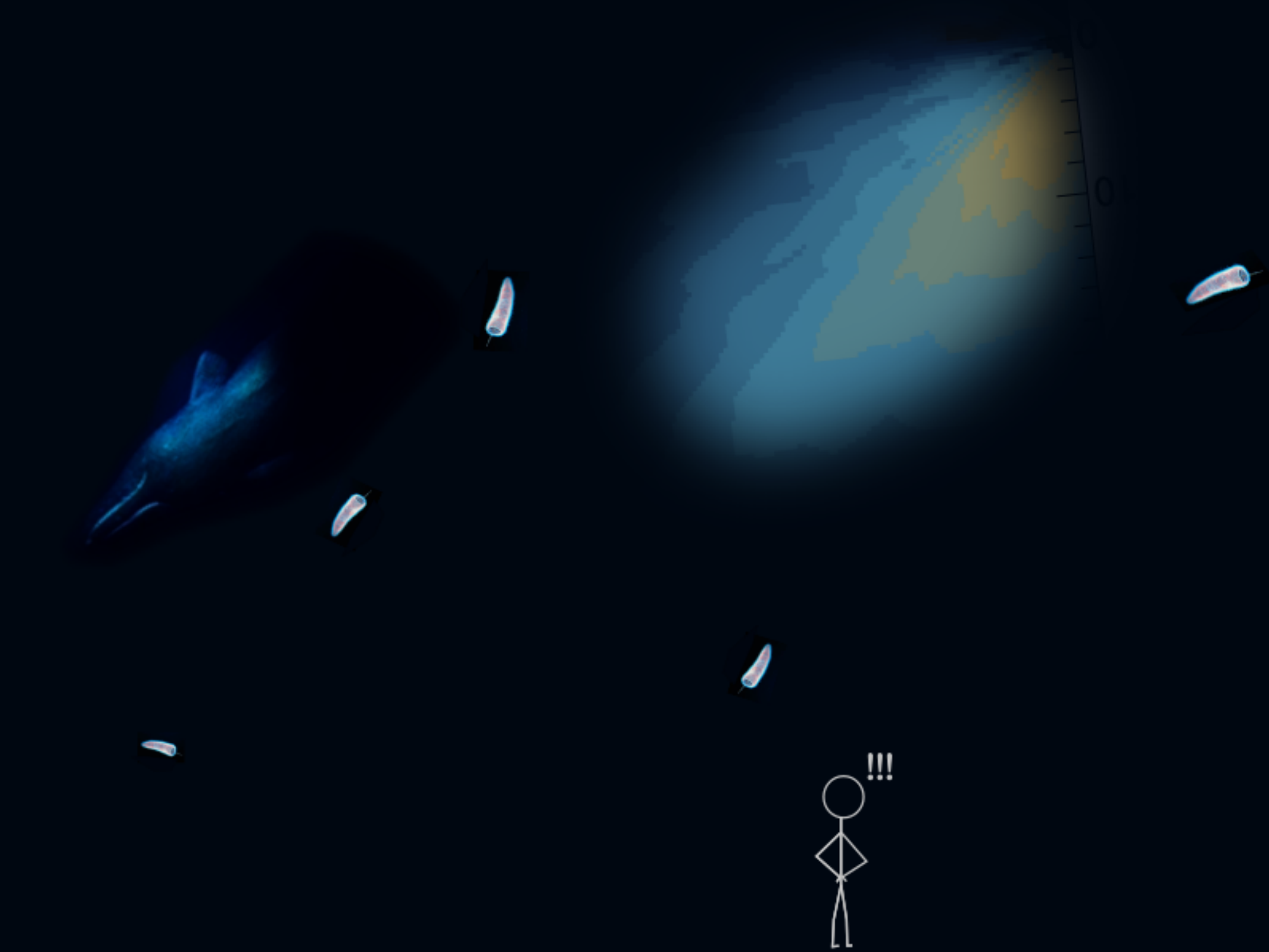


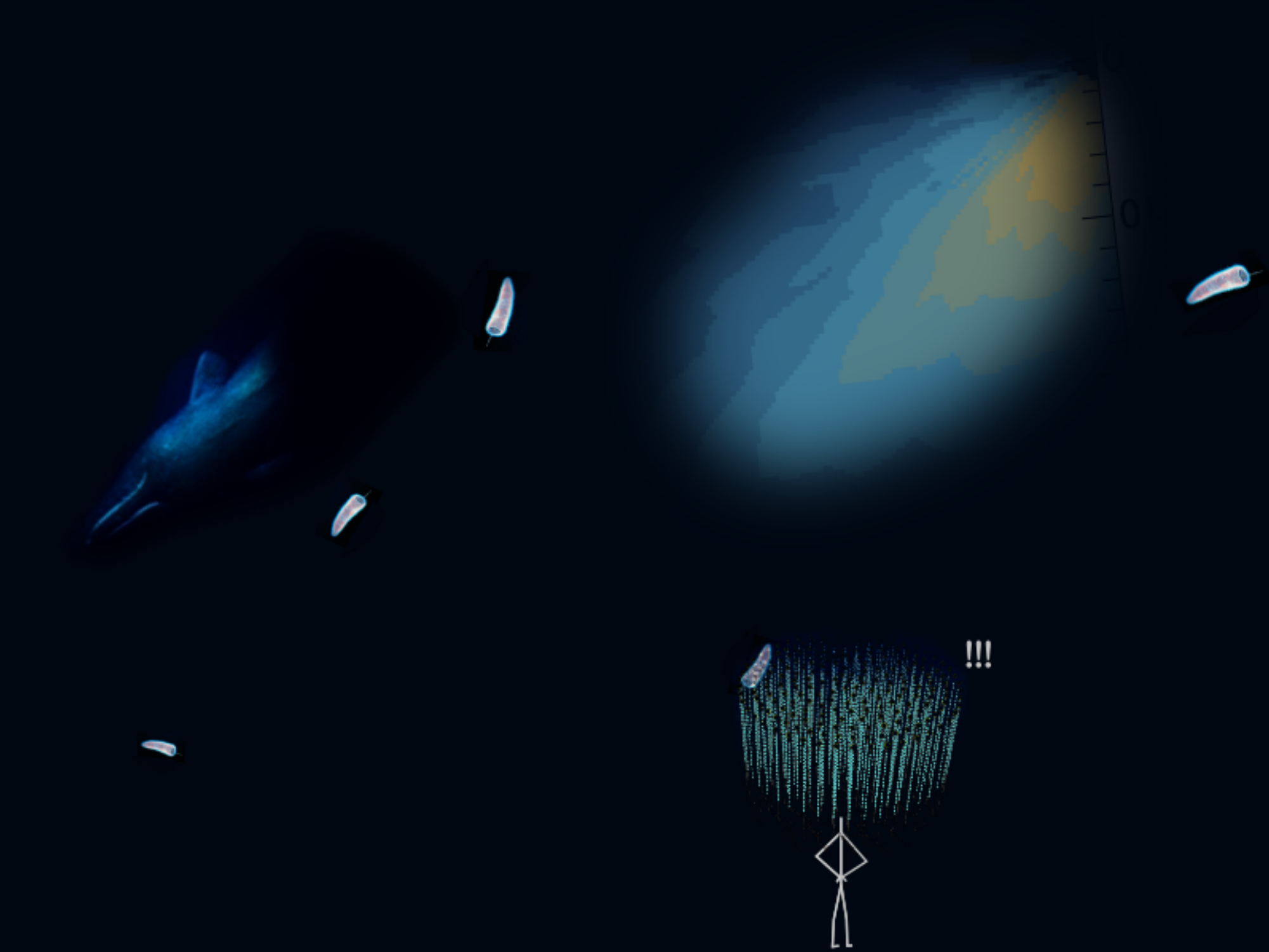
Neutral current $\rightarrow$ **hadronic particles.**

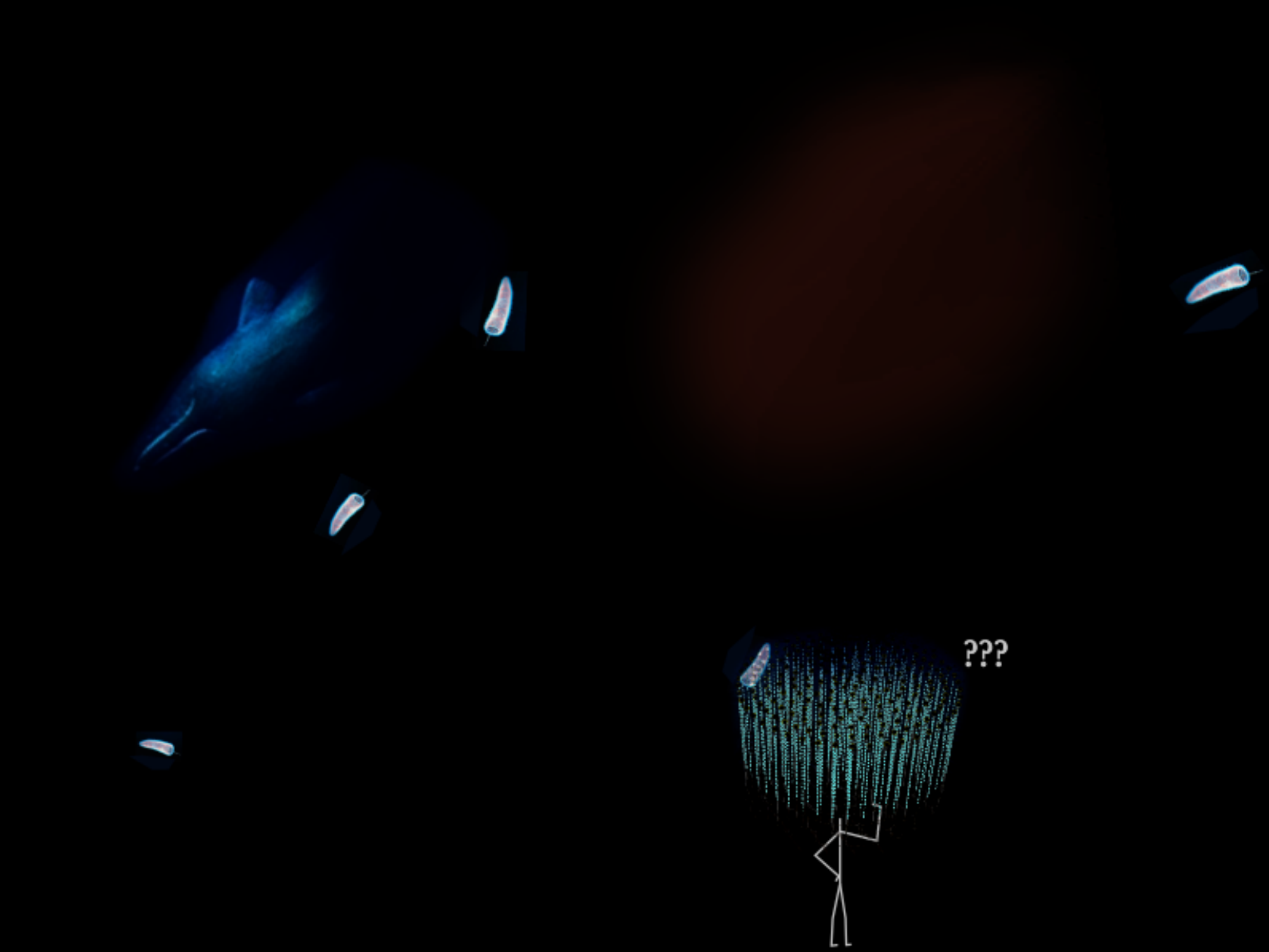
Charged current $\rightarrow$ **lepton + hadronic particles**

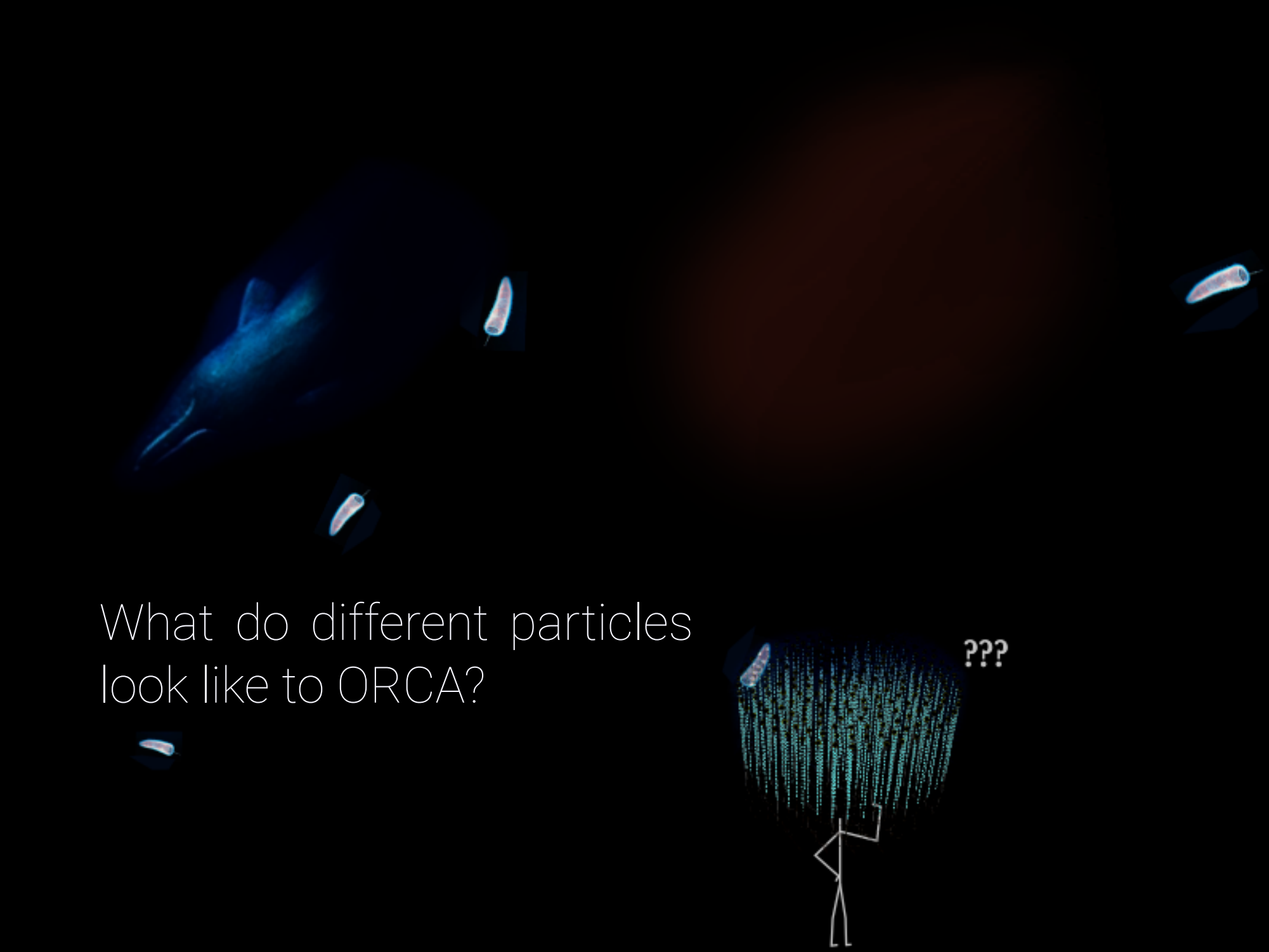


2 Image of Pyrosome courtesy of Jeff Milisen








What do different particles look like to ORCA?
???

The plan

1. Create models of **light signatures** in ORCA from ν interaction **product particles**.

2. Use models for reconstruction of particle showers and ν events.

Procedure

Monte Carlo sample of signal from energetic particles in ORCA.

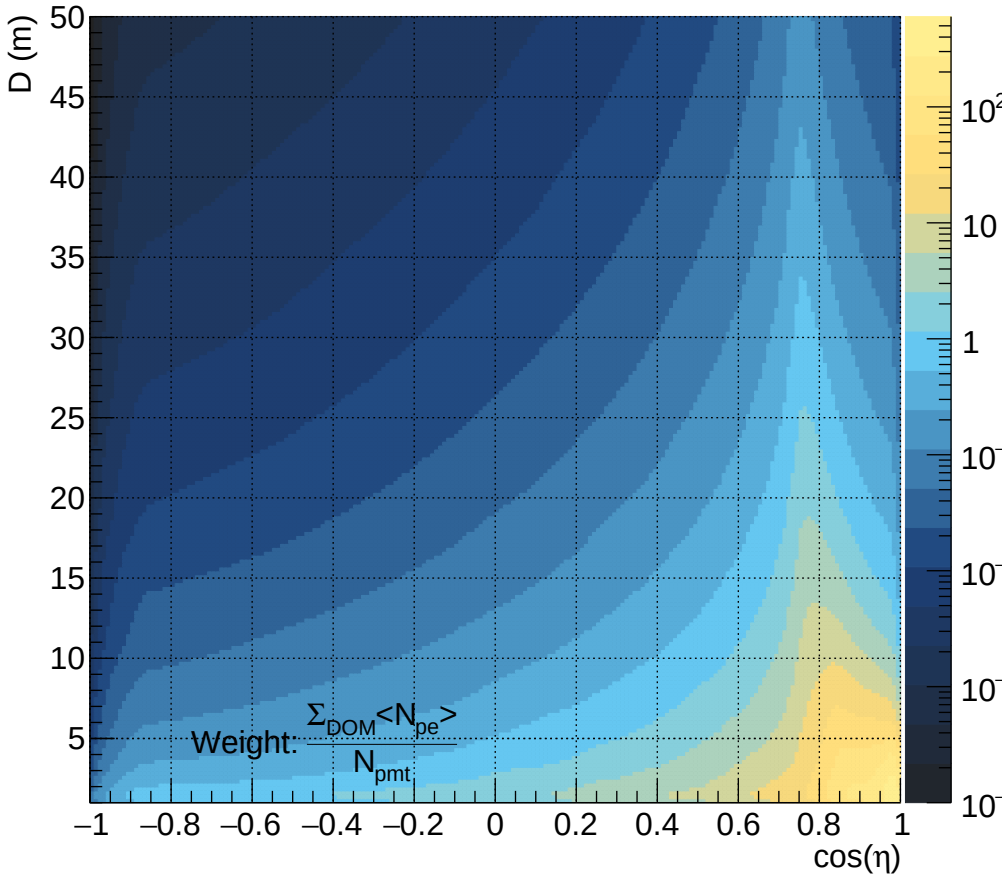
↓

Create **photo-electron Pattern PDFs (PEPPs)** from sample for each particle type.

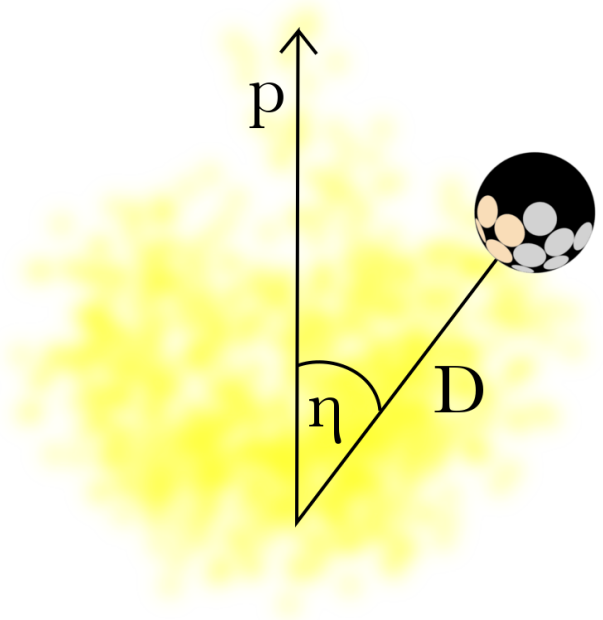
The PEPP tells you **the probability of obtaining a p.e.** given **particle type** and **position in phase space**

"It's basically an interpolation of our particle interaction modelling in water." – me

PEPPs Geometry



30GeV Electron PEPP

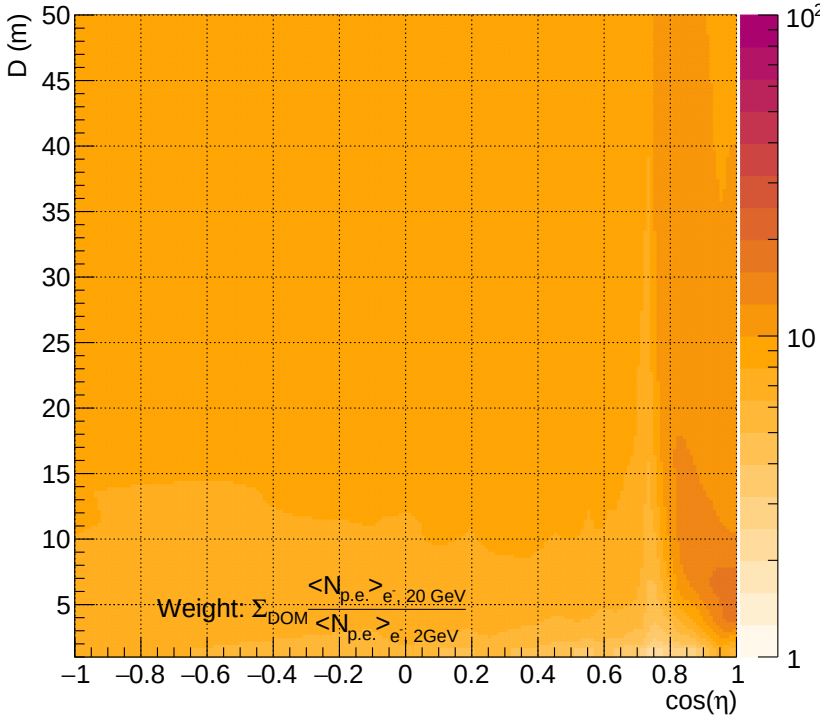


- In water, $\cos\theta_{\text{Cher.}} \simeq 0.75$ for $\beta \simeq 1$, explaining the peak.
- For 30 GeV electron, expect an EM shower of ~ 6 m.

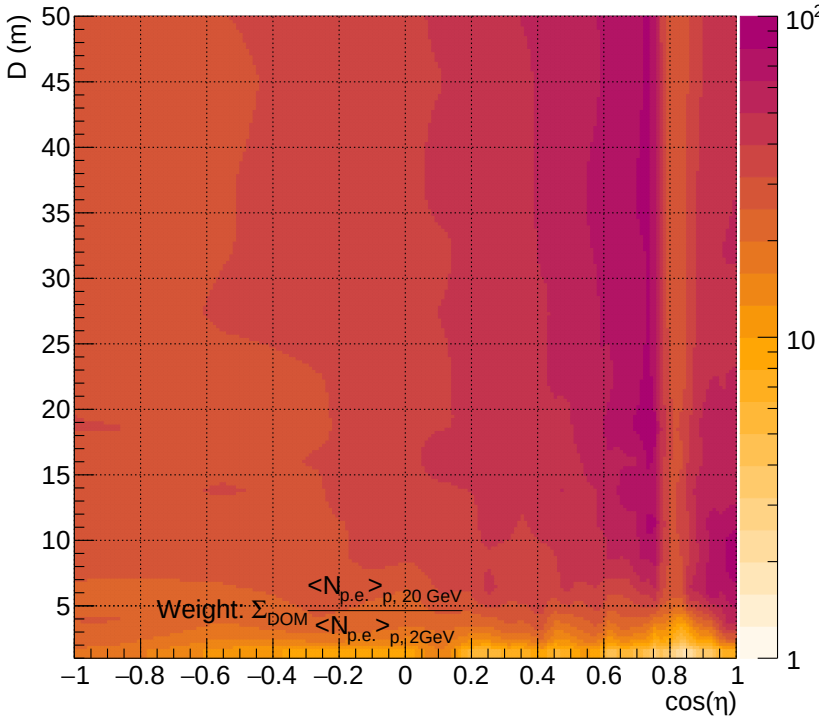
PEPPs agree with theoretical expectations

PEPPs Energy Dependence

Left (right): $\frac{20\ \text{GeV}}{2\ \text{GeV}}$ electron (proton)



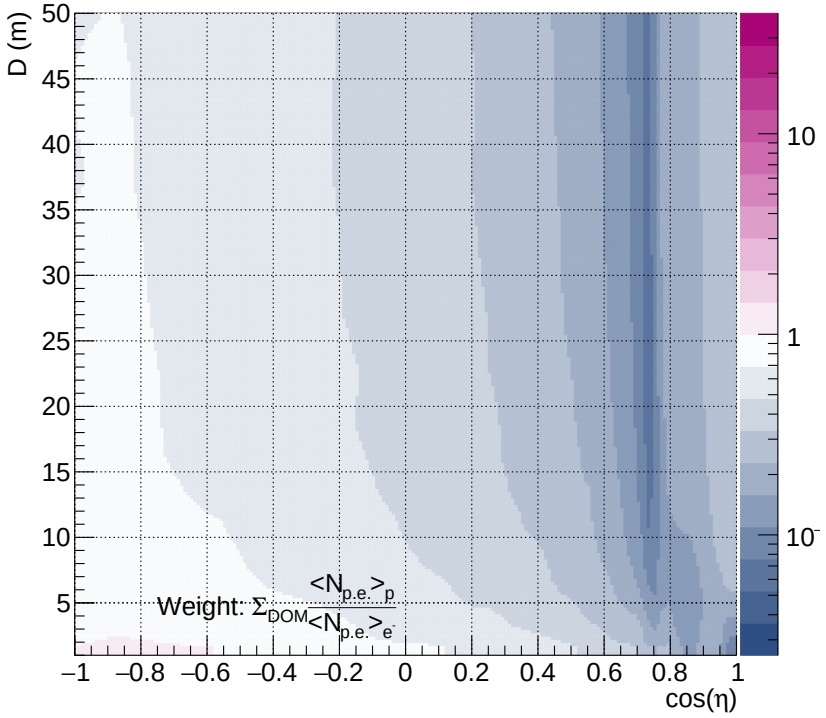
Uniform increase of $10 \times N_{\text{particles}}$

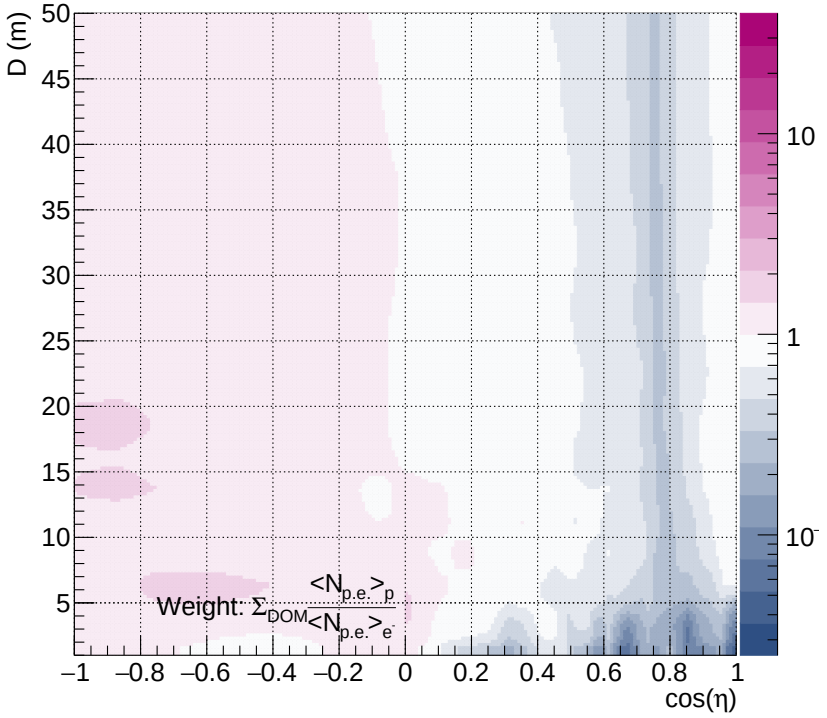


Features near Cherenkov angle (note: log scale)

PEPPs EM/Hadronic Comparison

$$\frac{\text{protonPEPP}}{\text{electronPEPP}}$$



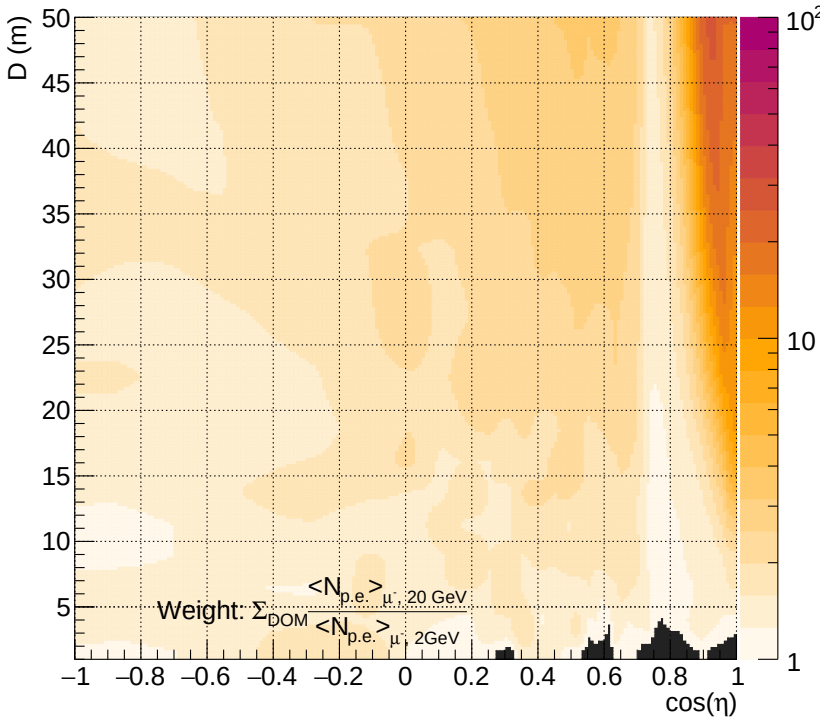


3 GeV: very different

30 GeV: similar → larger portion of EM particles in hadronic shower.

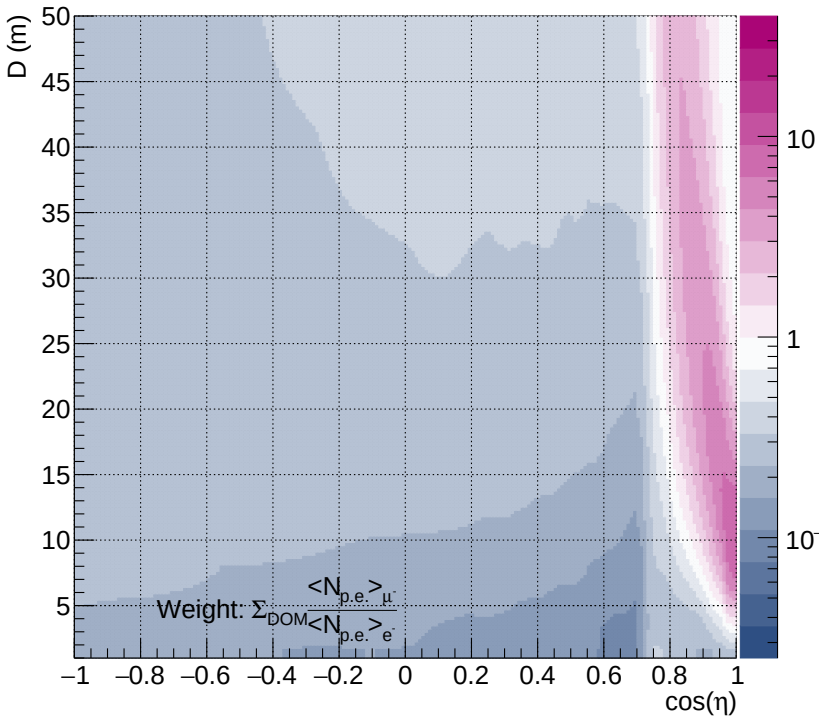
PEPPs Geometry

$\frac{20\ \text{GeV}}{2\ \text{GeV}}$ muon



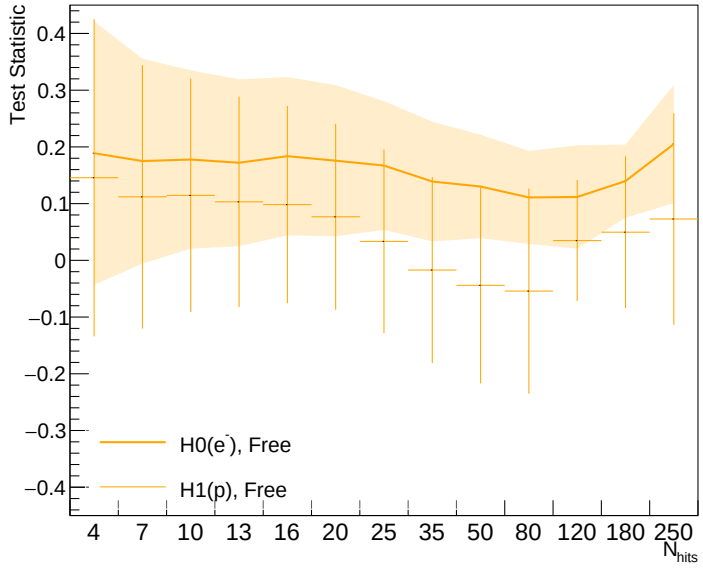
Bulk of increase in very forward direction.

$3\text{GeV}\,\frac{\text{muonPEPP}}{\text{electronPEPP}}$



Strictly brighter than electron in front of Cherenkov angle.

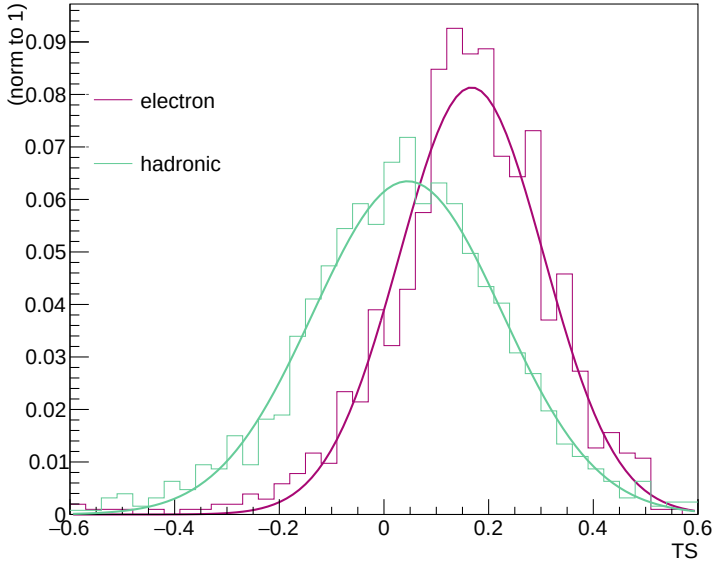
Preliminary Reconstruction of EM and Hadronic Showers



Test statistic for **single electron (EM shower)** and **hadronic shower**.

Top: 25 - 80 hit region shows promise for 1σ separation.

Bottom: Projection along X for 25 - 35 hits.

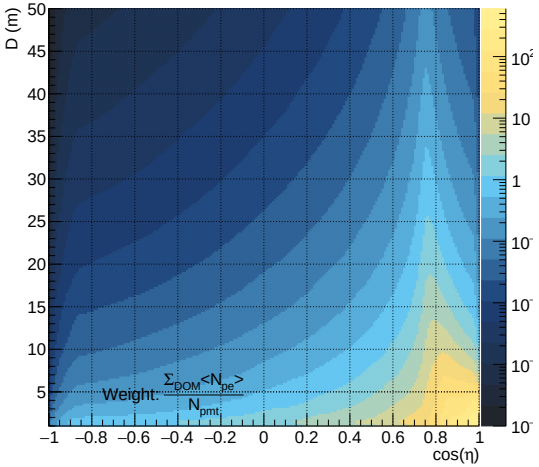


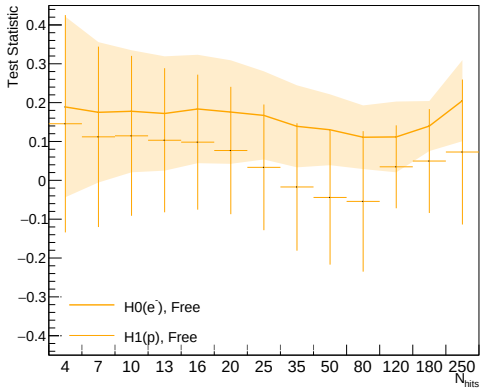
Distinguish hadronic shower from electron shower possible?

At higher energies,
EM shower $\simeq$ hadronic shower
$\rightarrow$ loss of distinguishing power.

Conclusion

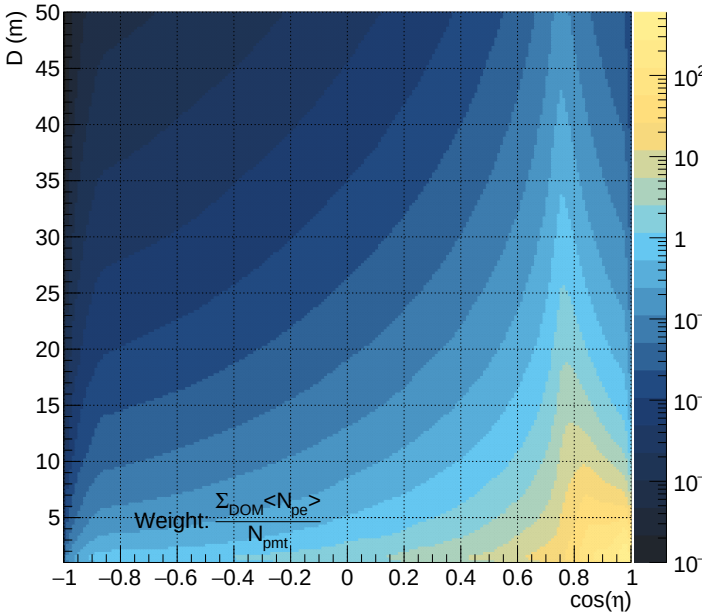
- KM3NeT **ORCA** aims at measuring the *Neutrino Mass Ordering*.
- Identifying the *type* of neutrinos and secondary particles assists this goal.
- Produced models of various particles which show their expected signals.
- The models can be put to use for reconstruction of events in the detector, including particle type.

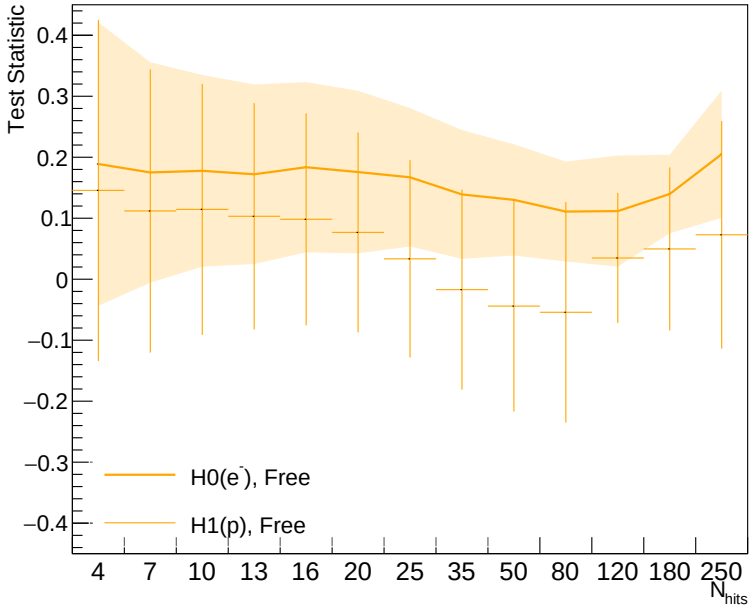




Thank you for your attention!

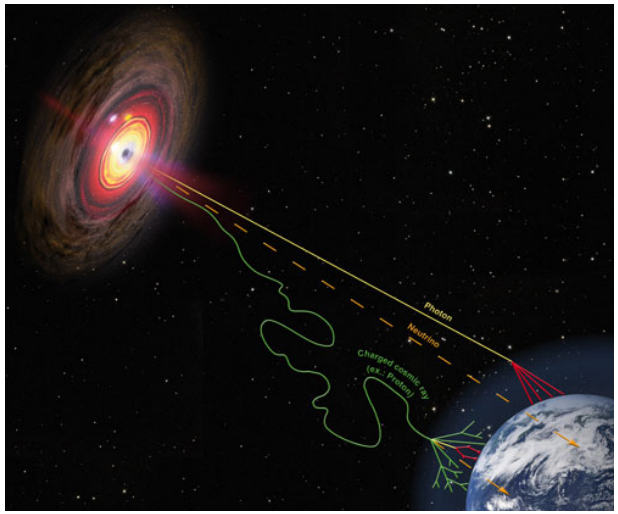
Questions please.



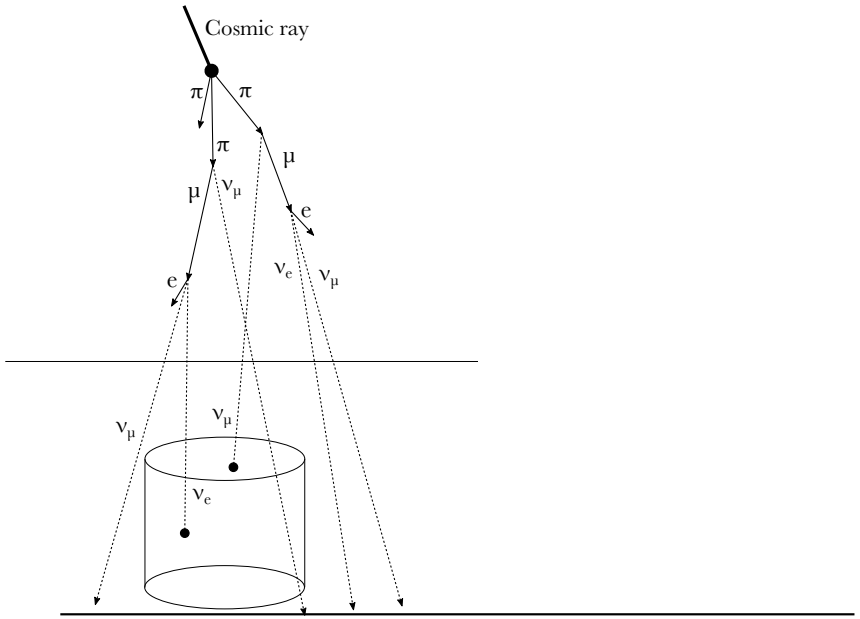


Leftover slides

Introduction



[3]



Certain extrasolar objects accelerate particles to high energies, which are called *cosmic rays*.

Cosmic rays collide with the Earth's atmosphere and produce neutrinos.[4]

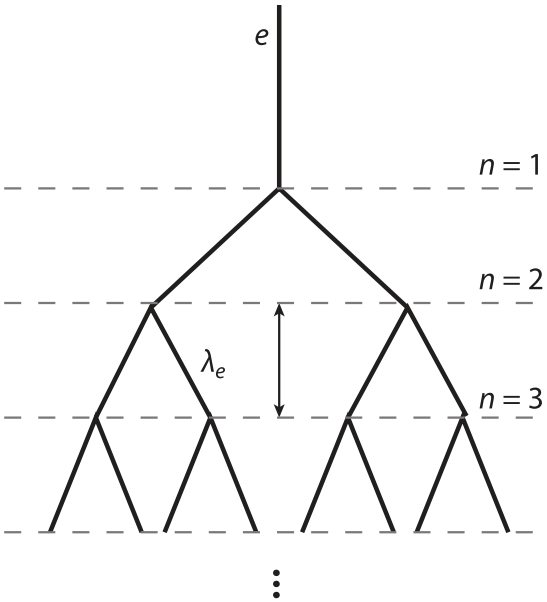
Atmospheric neutrinos can travel through the entire Earth virtually unaffected, causing a ubiquitous flux.

[3] Artist's impression by HAP / A. Chantelauze

[4] [Molerach and Roulet, 2018][Honda et al., 1995]

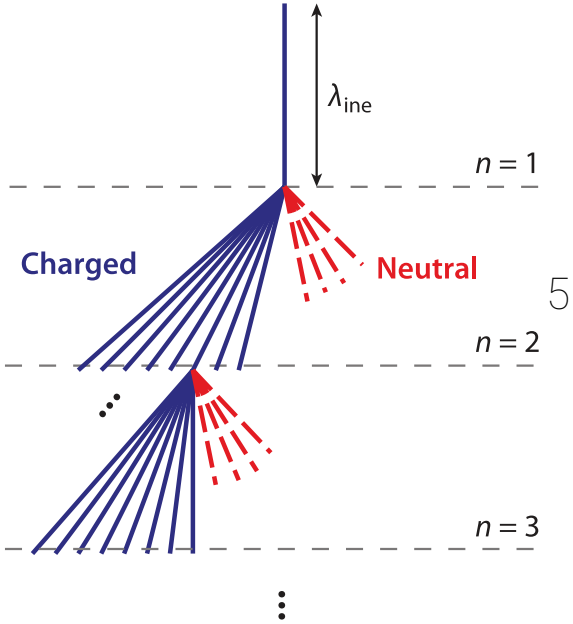
Introduction

Product particles from neutrino interactions produce more particles in *showers*



EM shower

$$N_{\text{particles}} \propto E$$
$$X \propto \log E$$



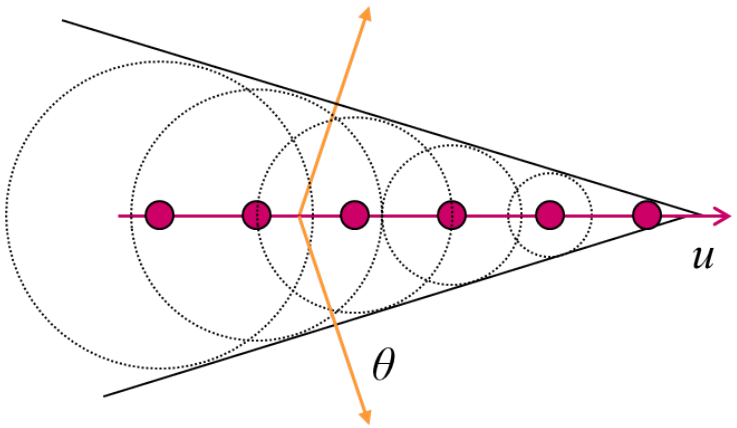
[5]

Hadronic shower

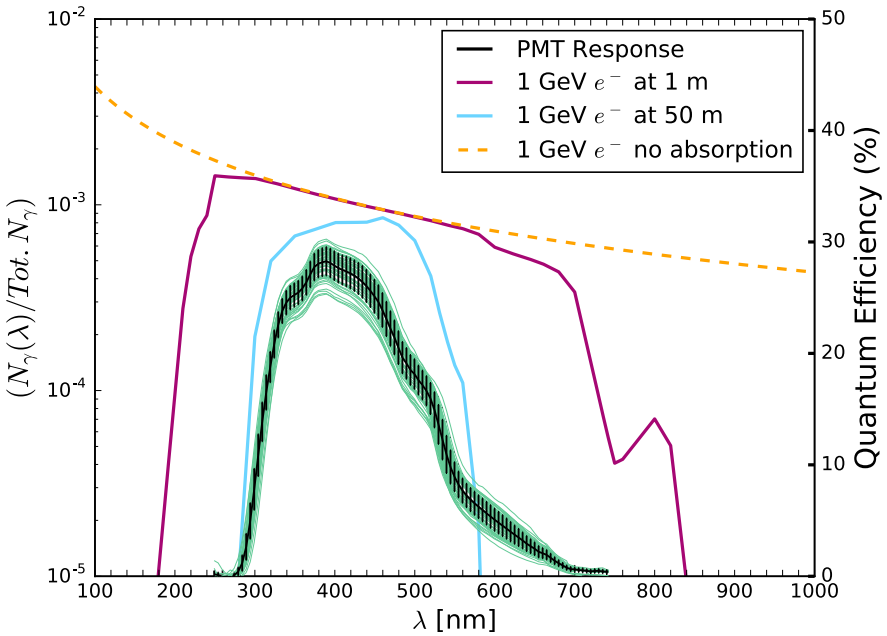
Complicated!

[5] Diagram from [Engel, 2011]

Introduction



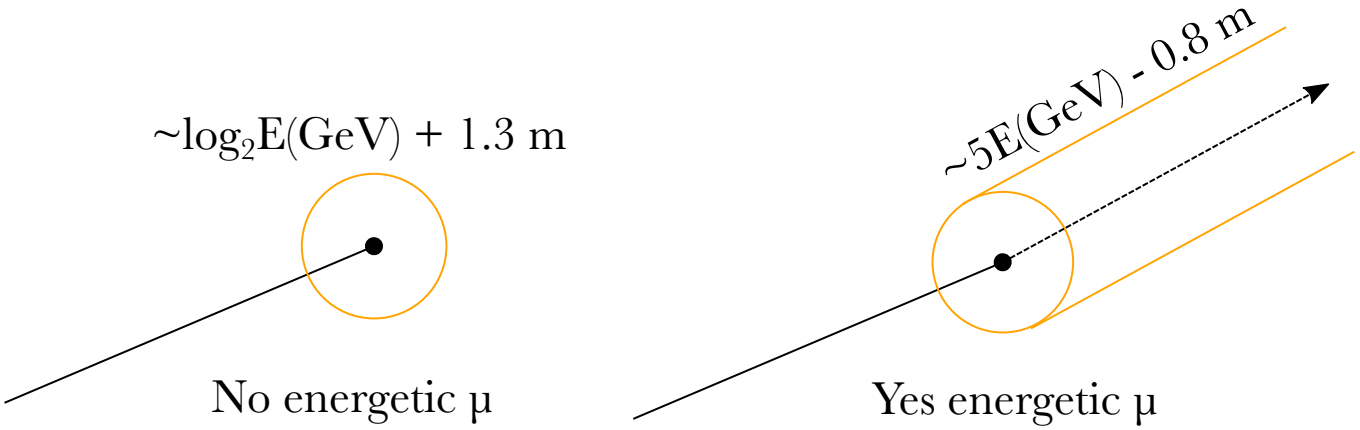
Charged particles emit *Cherenkov light* in water.



This light is emitted at an angle θ, and can be seen by *Photomultiplier tubes* (PMT)[6]

[6] Diagram from [Alaeian, 2014]

Motivation

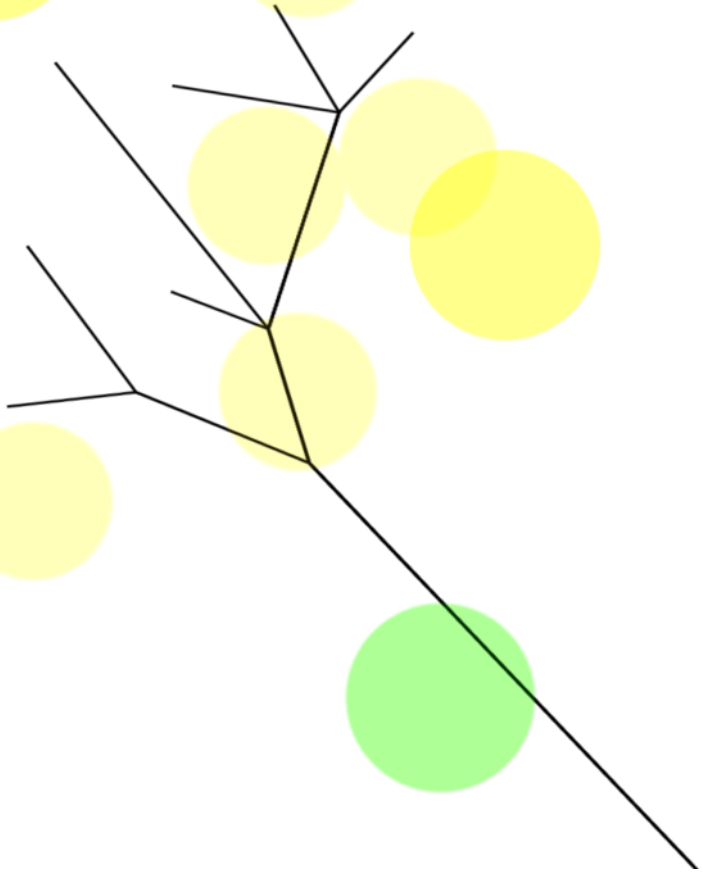


Current models lump all events into showers or tracks.

- Only large scale differences used
- Simplified energy scaling

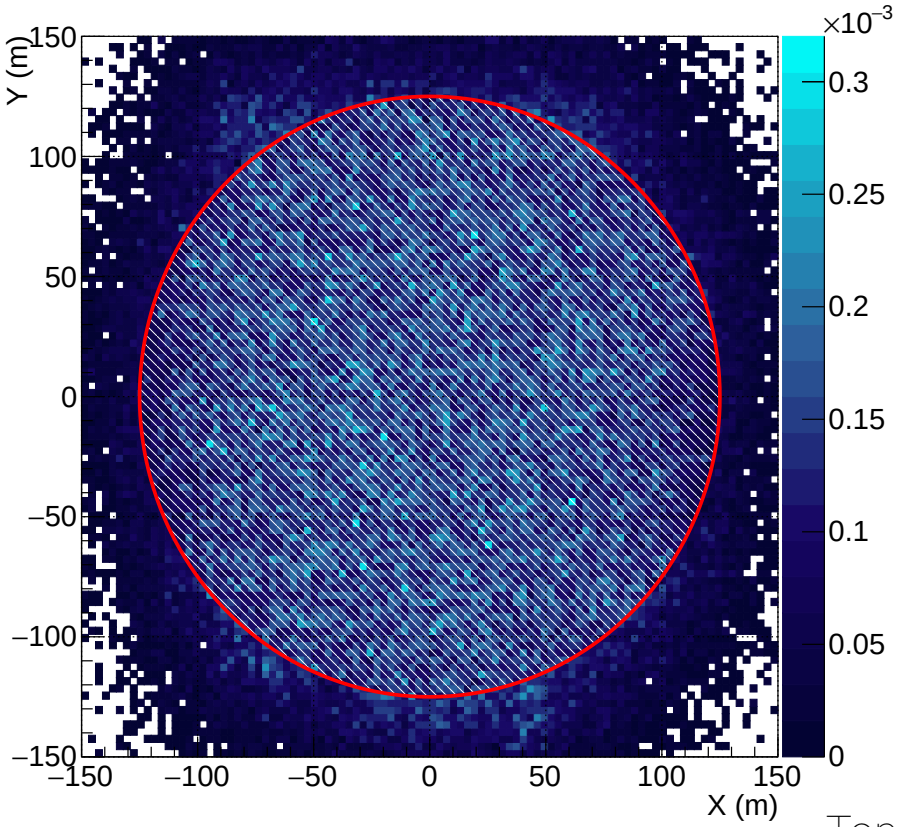
There is more stuff going on inside!

Can we exploit *details*?



→ Create models of different **product particles**.

Procedure



Top view of simulated interaction vertices and ORCA outline.

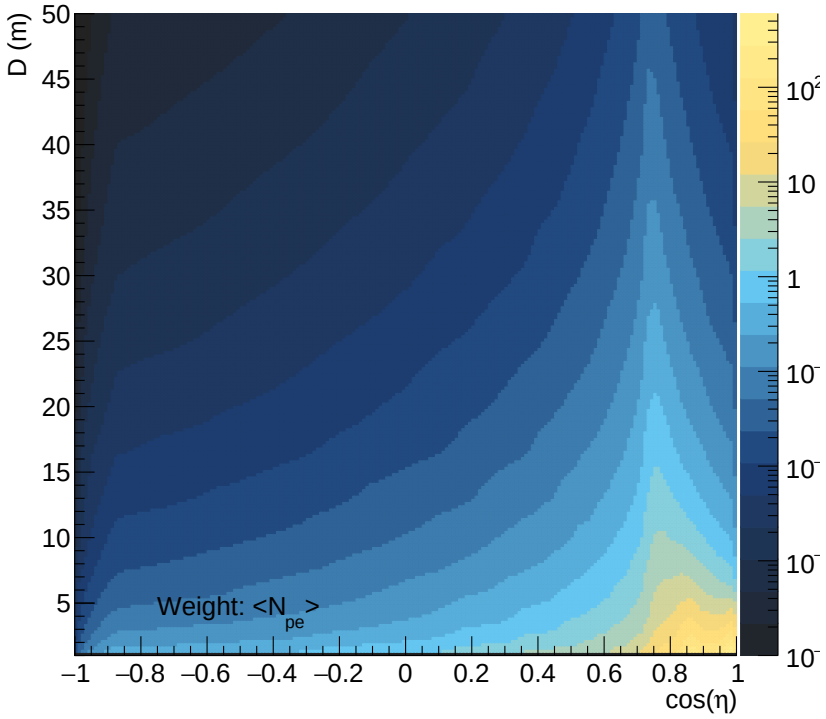
Start off with simulated sample of ν-events in ORCA

Propagator and hit simulator is GEANT4 based **KM3Sim**

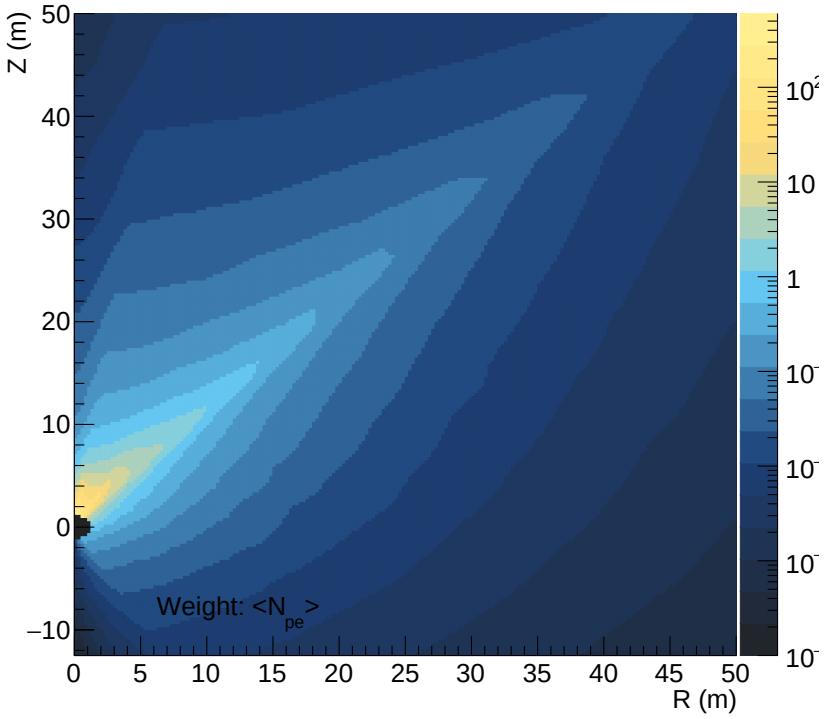
~ 250 M events

PEPPs Geometry

3 GeV electrons



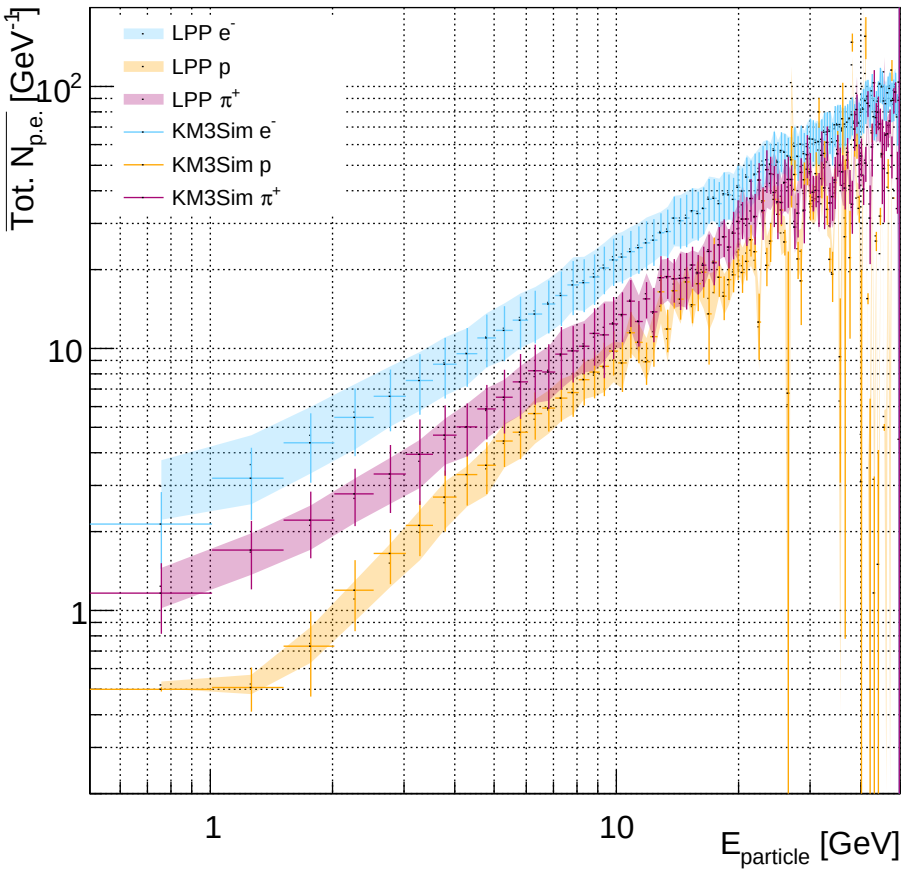
Native coordinates



Cartesian transformation

Remember this because only native coordinates will be shown from now on.

PEPP Monte Carlo Simulations

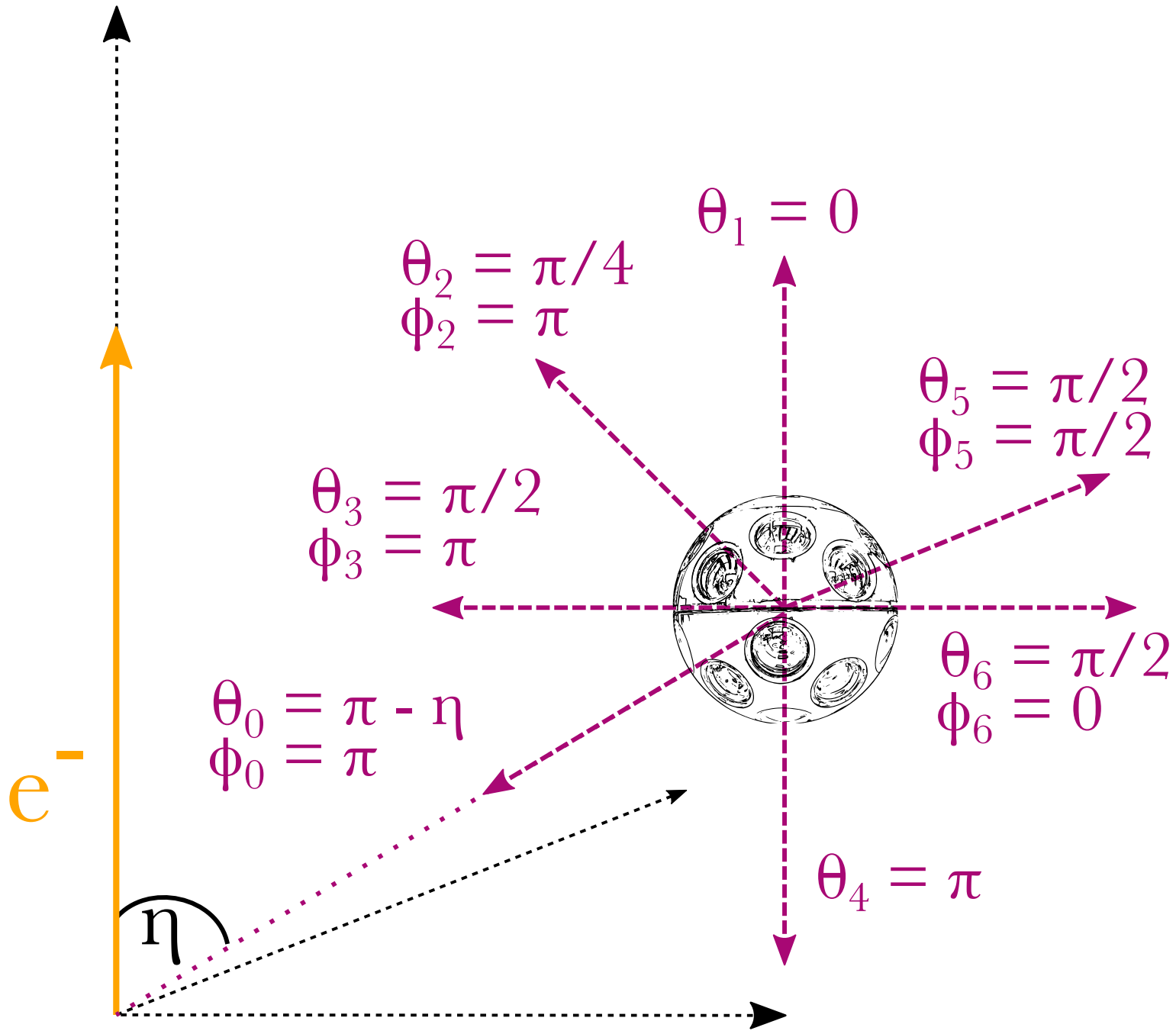


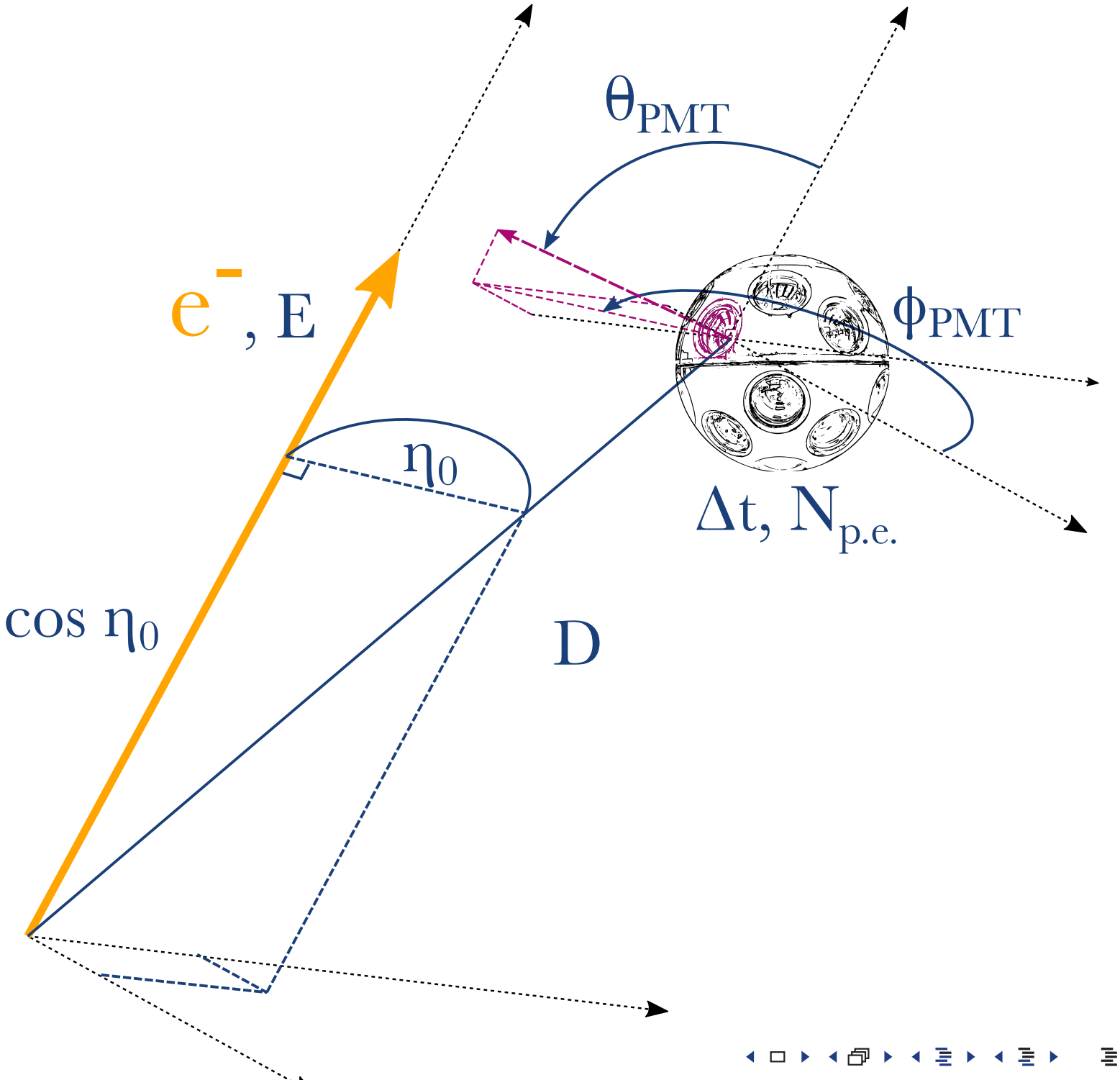
Comparison of KM3Sim and PEPP MC, error bars and bands are for $\frac{1}{10}\sigma$.

Excellent match for

$$\overline{TotN_{\text{p.e.}}} \equiv \sum^{N_{\text{events}}} N_{\text{p.e.}}.$$

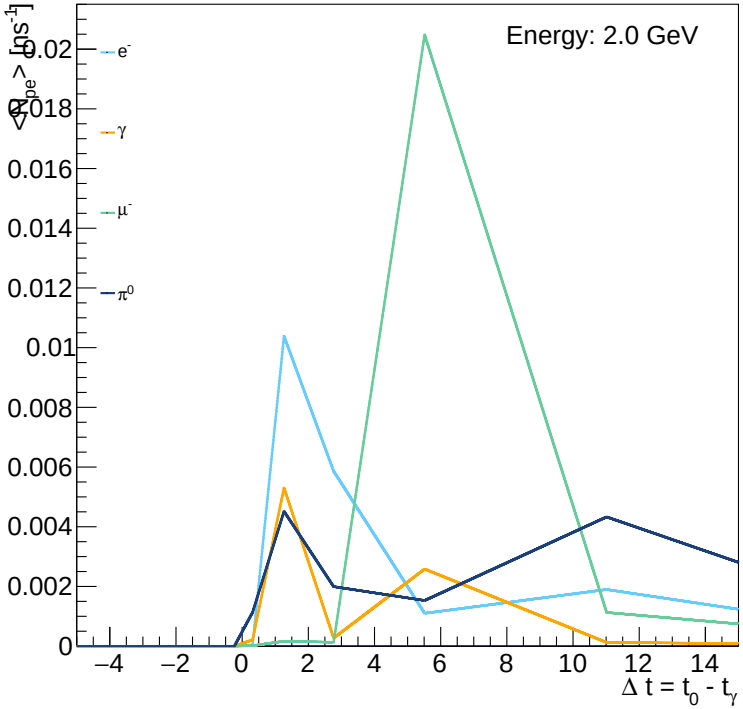
PEPPs agree with original Monte Carlo simulation

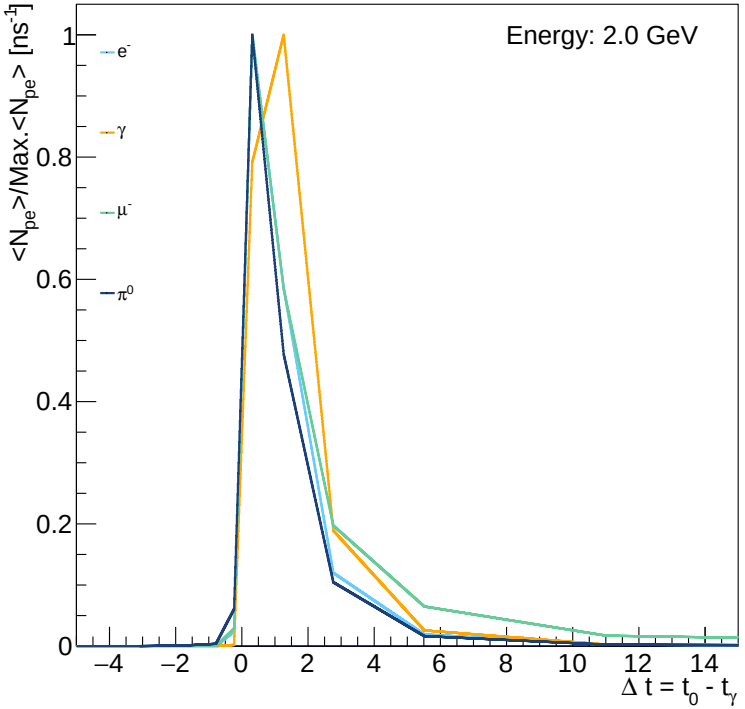

$\theta_1 = 0$
$\theta_2 = \pi/4$
$\phi_2 = \pi$
$\theta_5 = \pi/2$
$\phi_5 = \pi/2$
$\theta_3 = \pi/2$
$\phi_3 = \pi$
$\theta_6 = \pi/2$
$\phi_6 = 0$
$\theta_0 = \pi - \eta$
$\phi_0 = \pi$
e^-
η
$\theta_4 = \pi$


θPMT
e⁻, E
ϕPMT
η0
Δt, Np.e.
cos η0
D

PEPPs Time Arrival

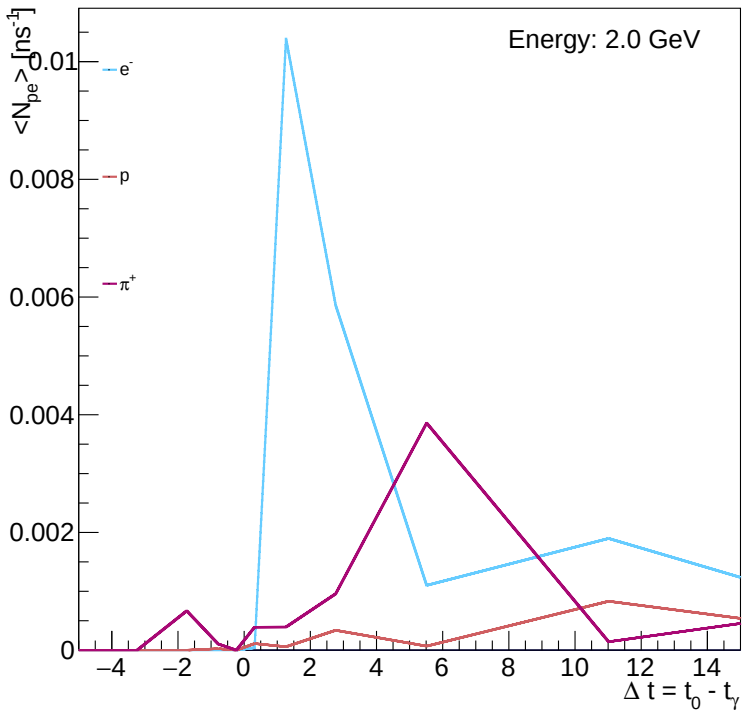
Discerning power in time dependence

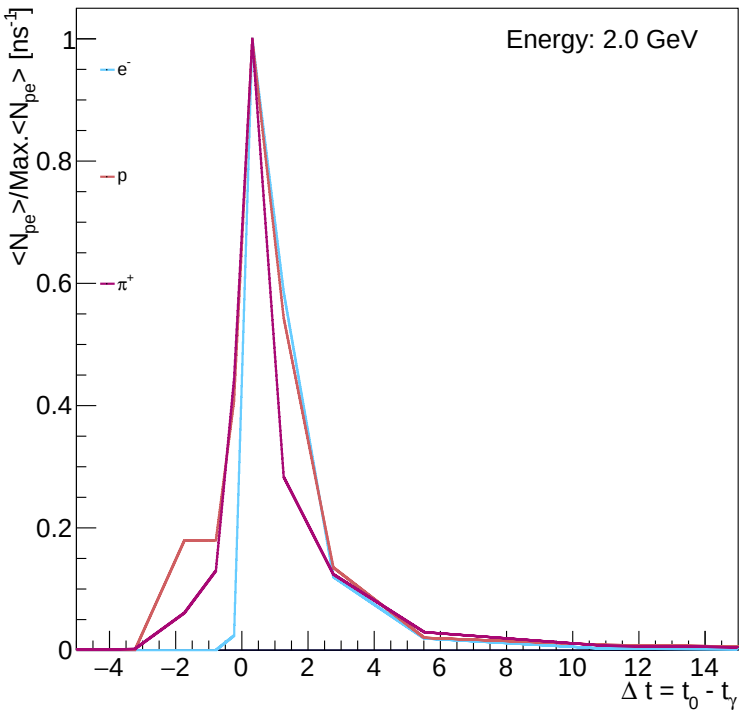




PEPPs Time Arrival

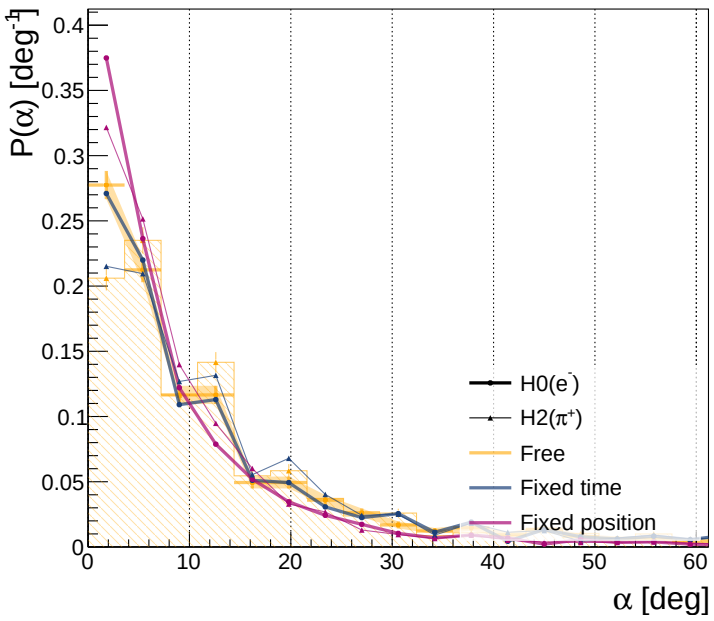
Discerning power in time dependence

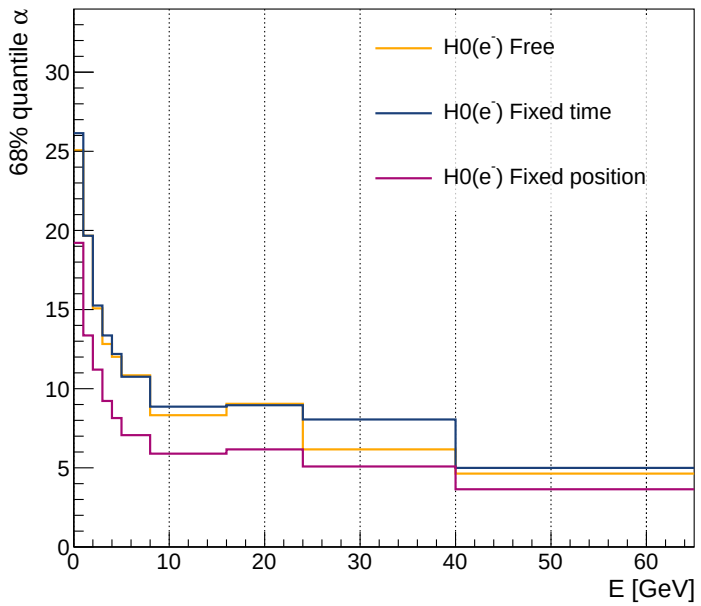




Reconstruction Single Shower

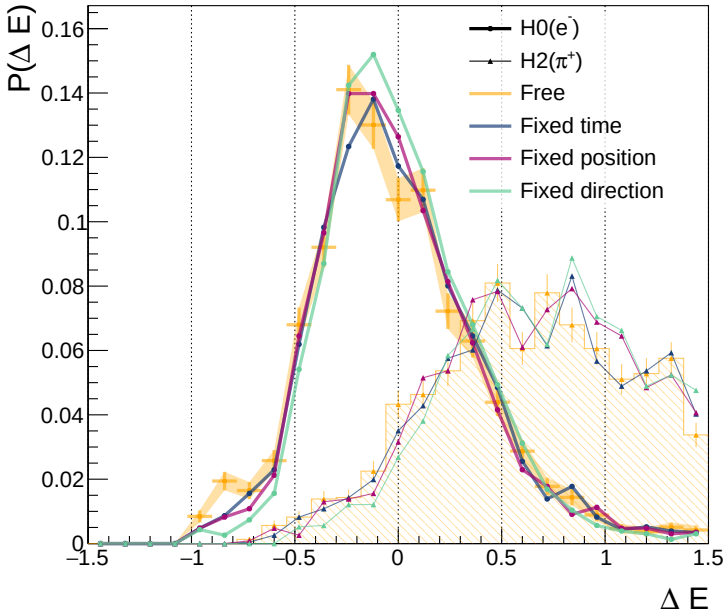
Direction electron

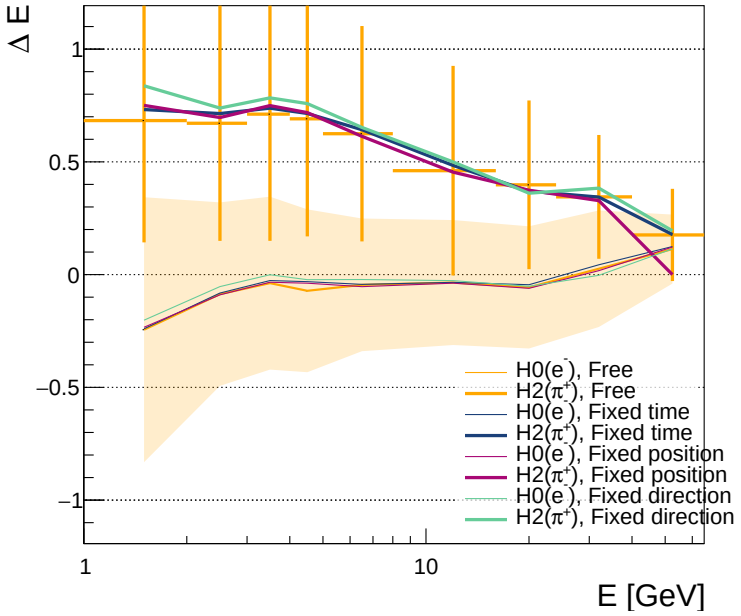




Reconstruction Single Shower

Energy electron

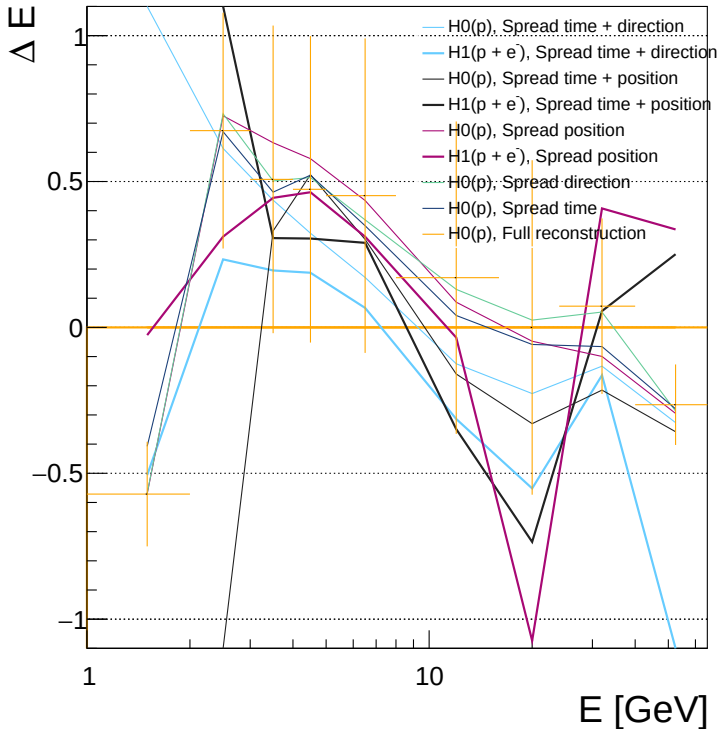


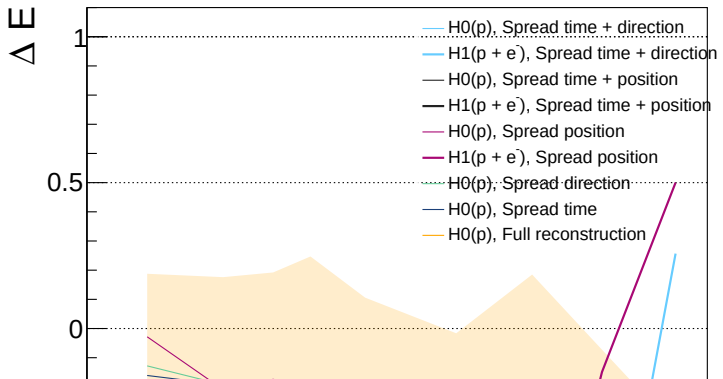


Reconstruction Neutrino Event

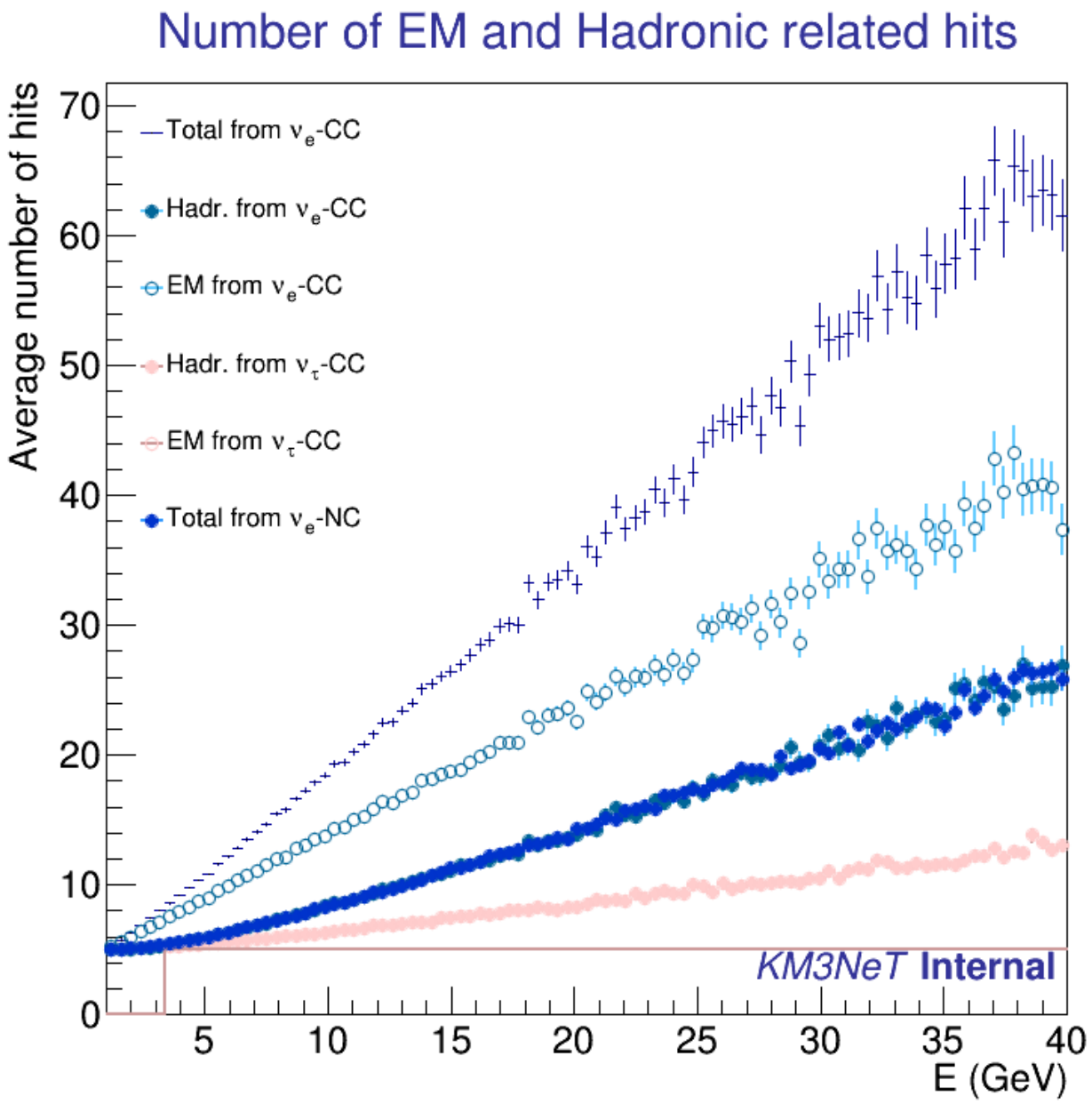
Reconstruction Neutrino Event

ΔE for ν_e-CC (ν_e-NC) above (below)

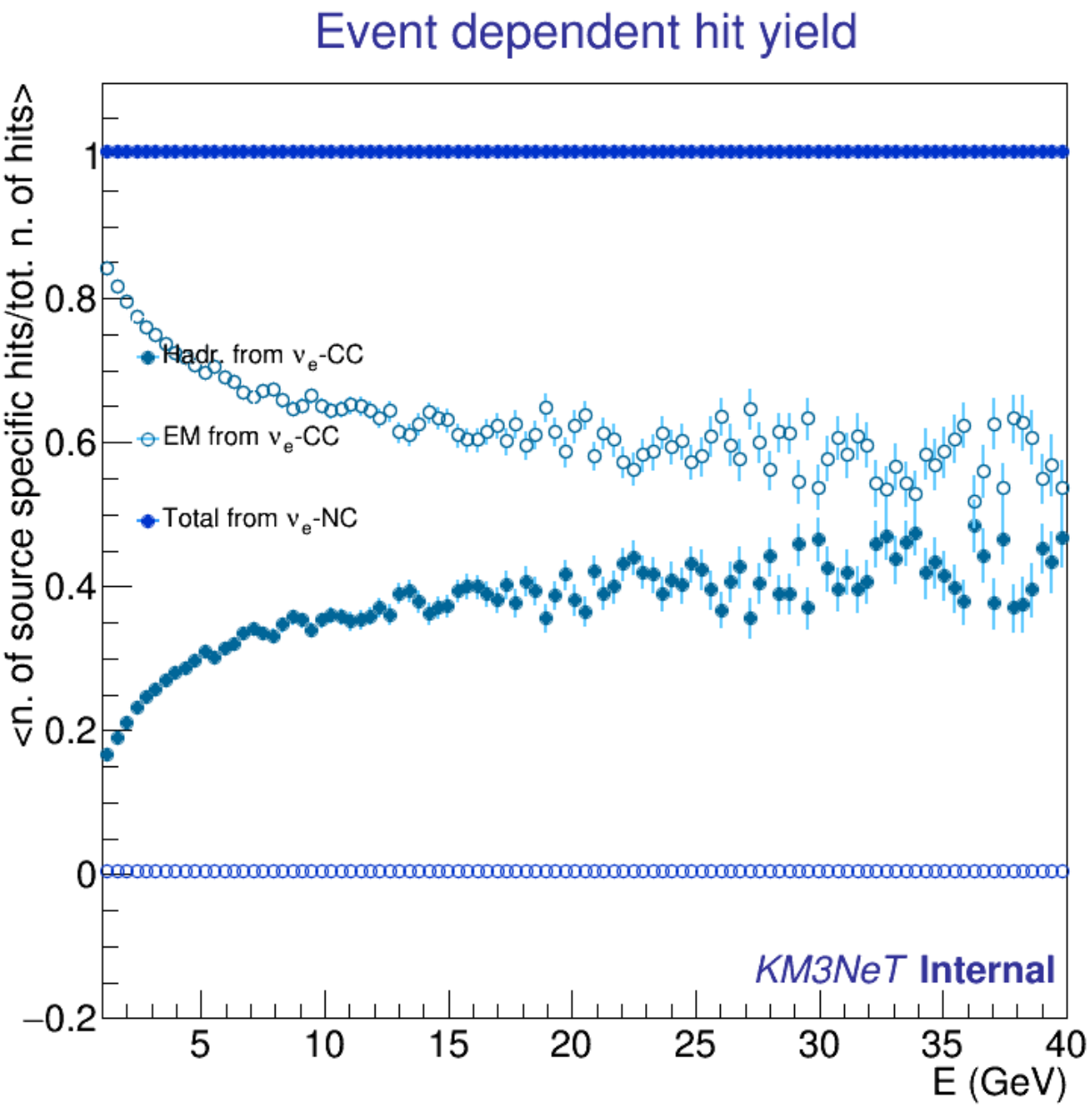




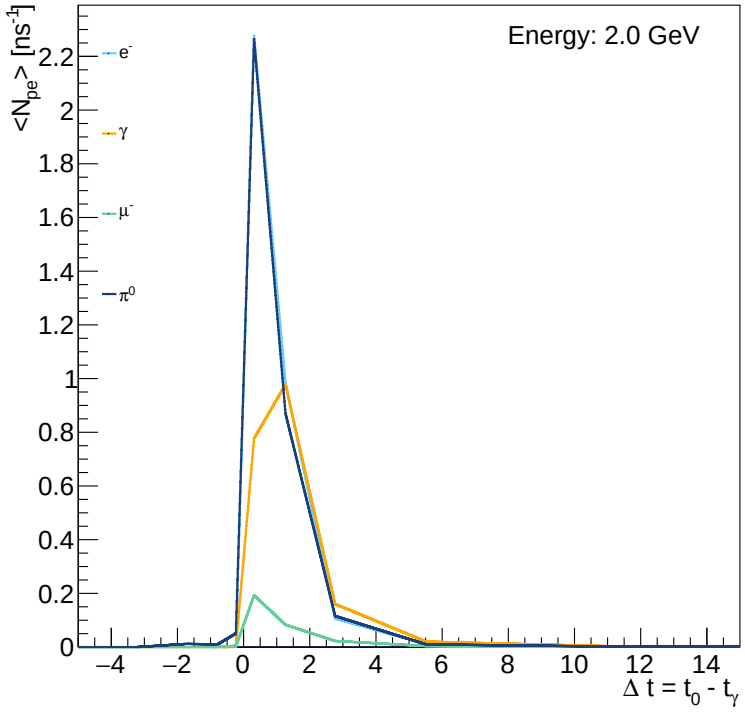
Secondaries



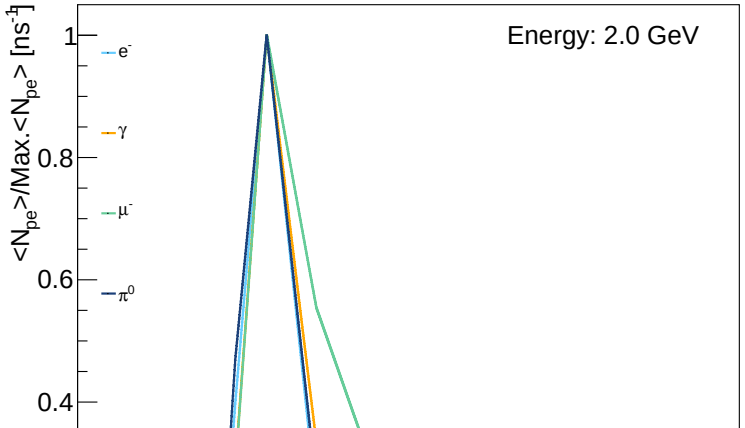
Secondaries



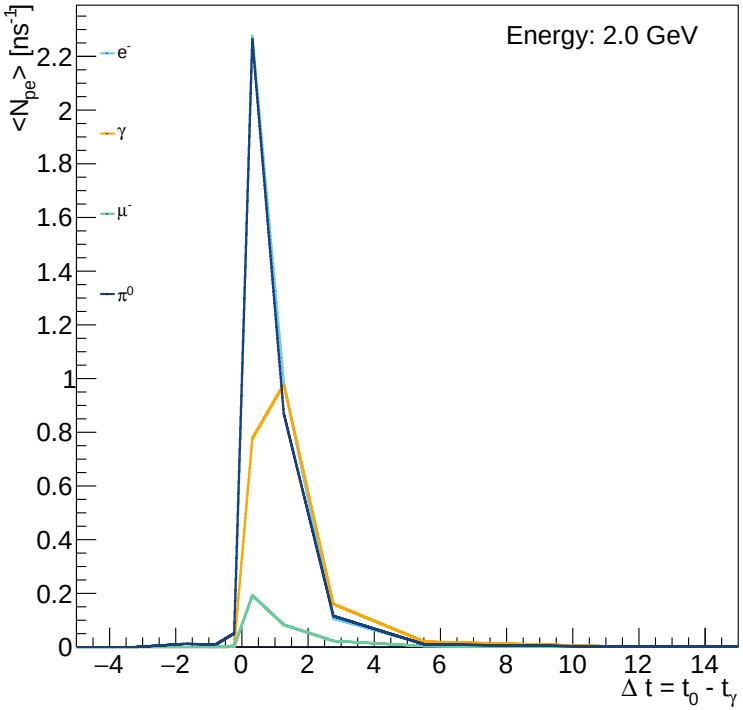
PDFs Time Arrival



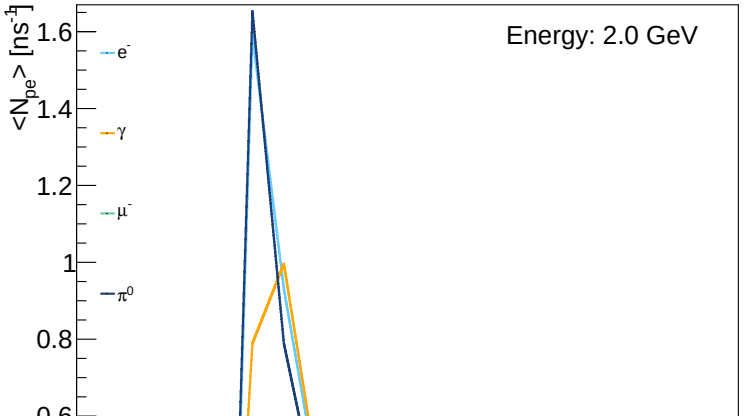
Normalised view



PDFs Time Arrival

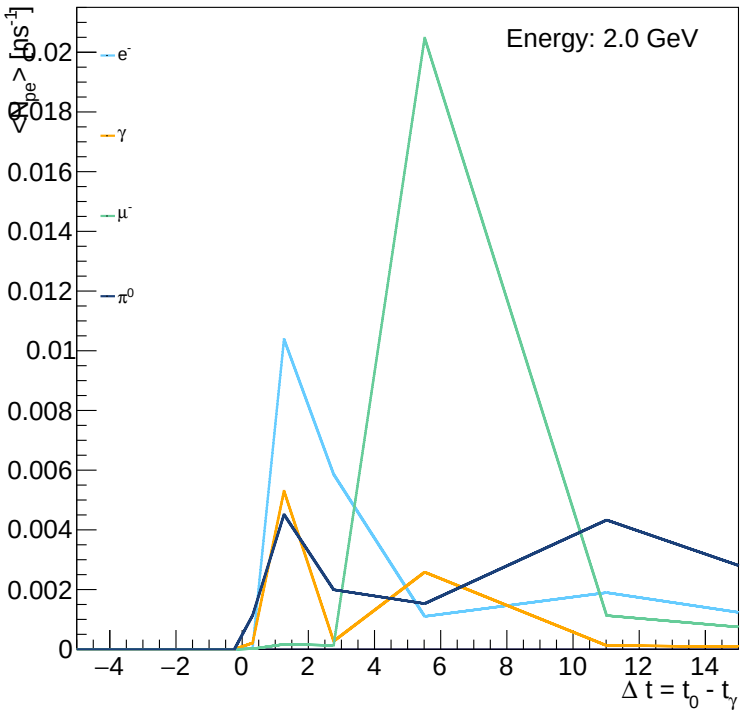


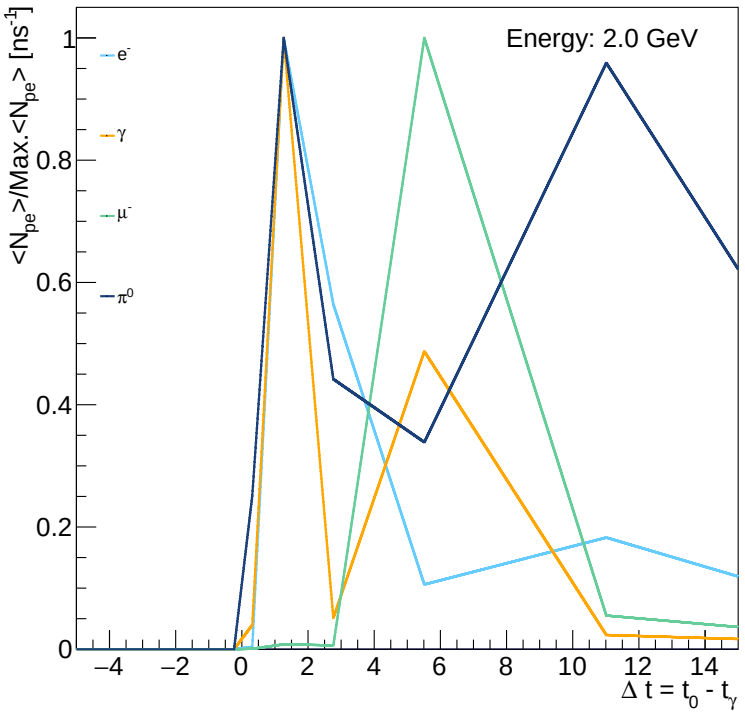
Angle dependence

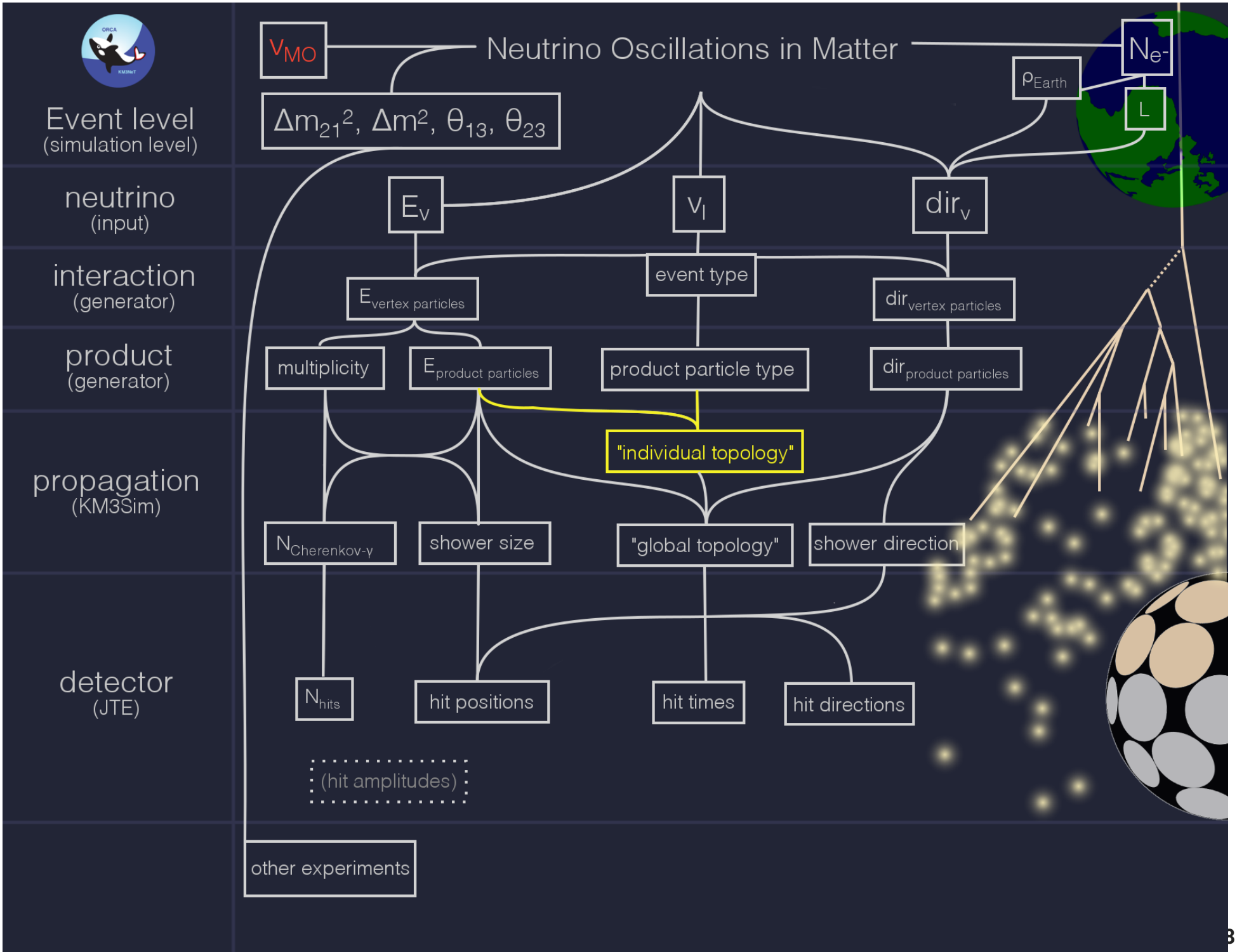


PDFs Time Arrival

Discerning power in time dependence

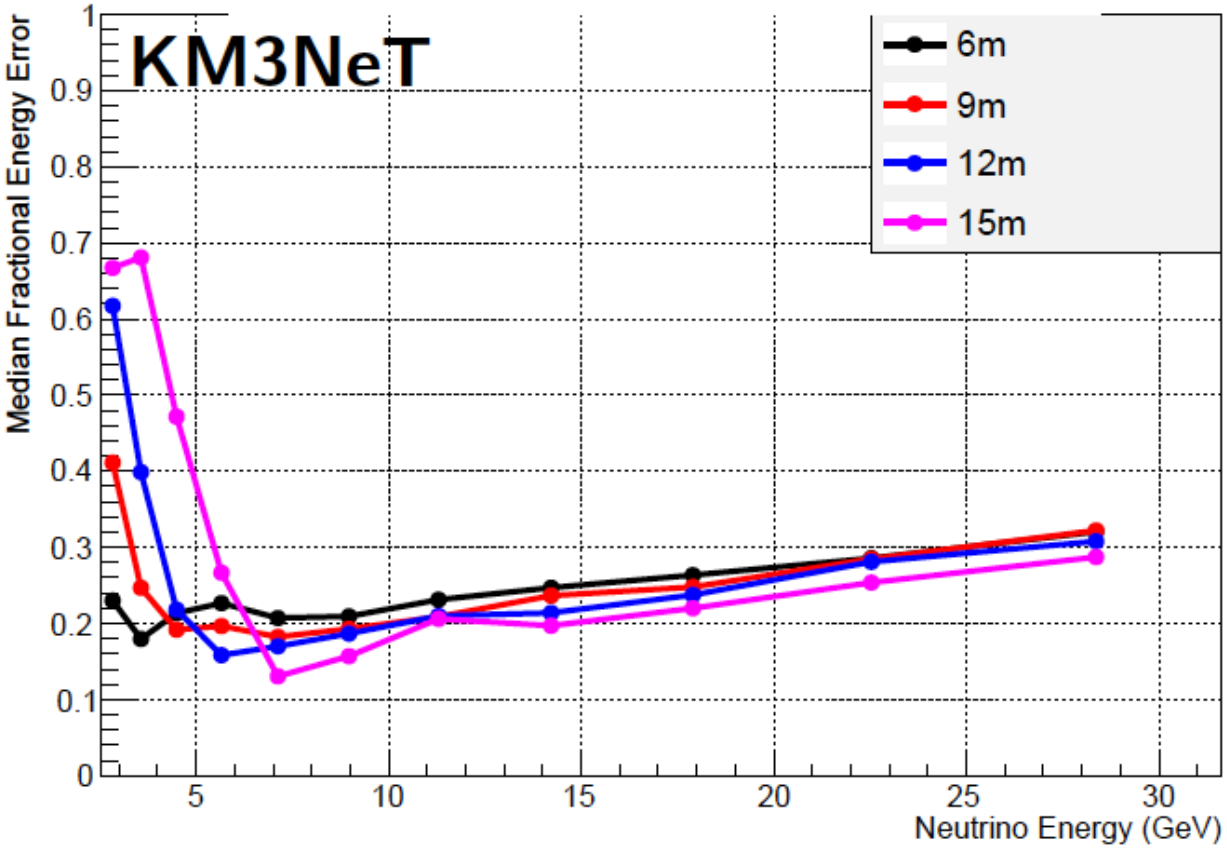





Neutrino Oscillations in Matter
Event level
(simulation level)
neutrino
(input)
interaction
(generator)
product
(generator)
propagation
(KM3Sim)
detector
(JTE)
ν_{MO}
Δm_{21}^2, Δm^2, θ_{13}, θ_{23}
N_{e^-}
ρ_{Earth}
L
E_ν
ν_l
dir_ν
event type
$E_{vertex\ particles}$
$dir_{vertex\ particles}$
multiplicity
$E_{product\ particles}$
product particle type
$dir_{product\ particles}$
"individual topology"
$N_{Cherenkov\text{-}\gamma}$
shower size
"global topology"
shower direction
N_{hits}
hit positions
hit times
hit directions
(hit amplitudes)
other experiments

Motivation

Orca Energy resolution



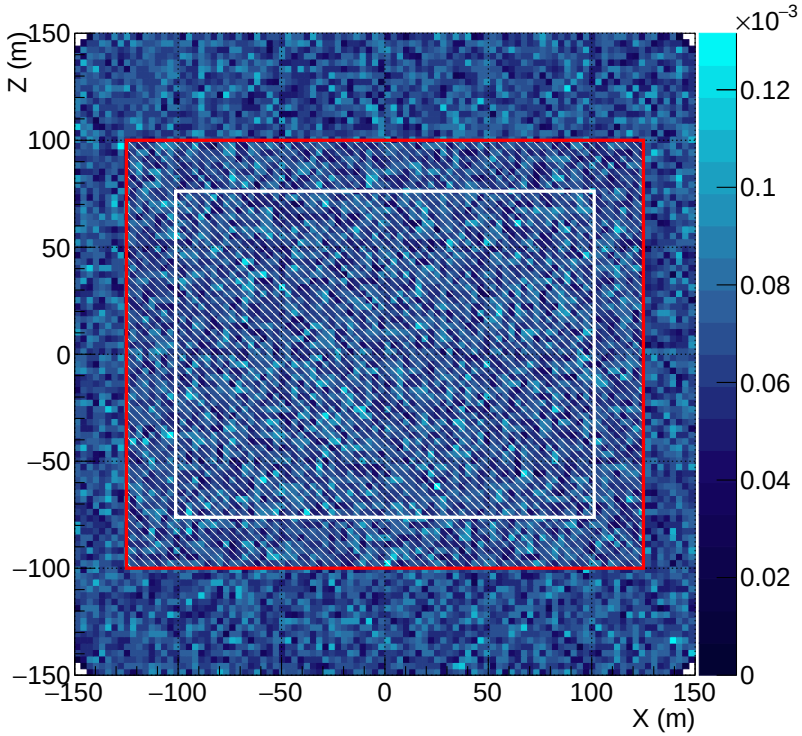
[7]

[7] KM3NeT Phase II LOI

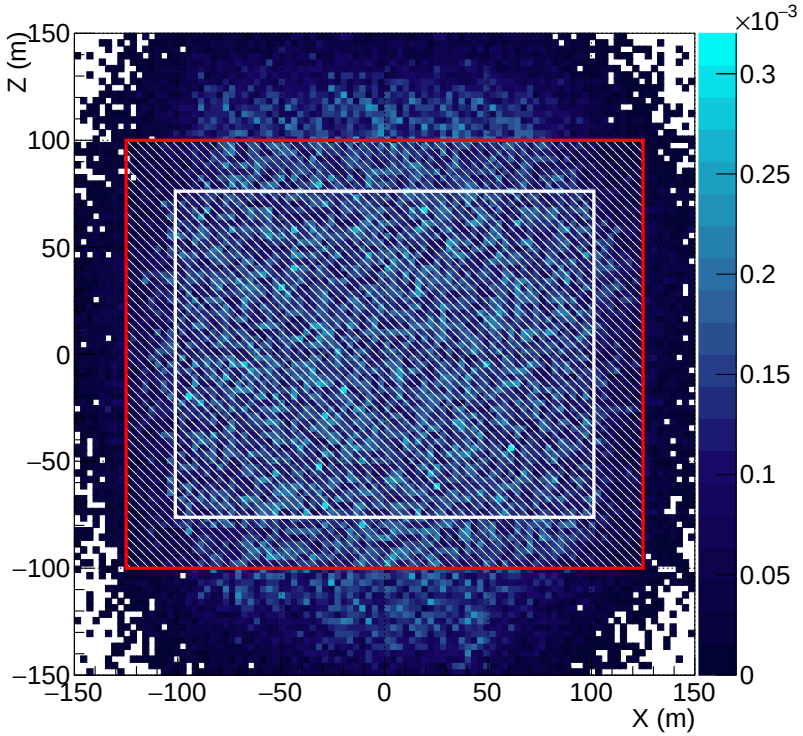
Reconstructions

Data cuts

1. > 4 hits
2. Within inner half volume of ORCA

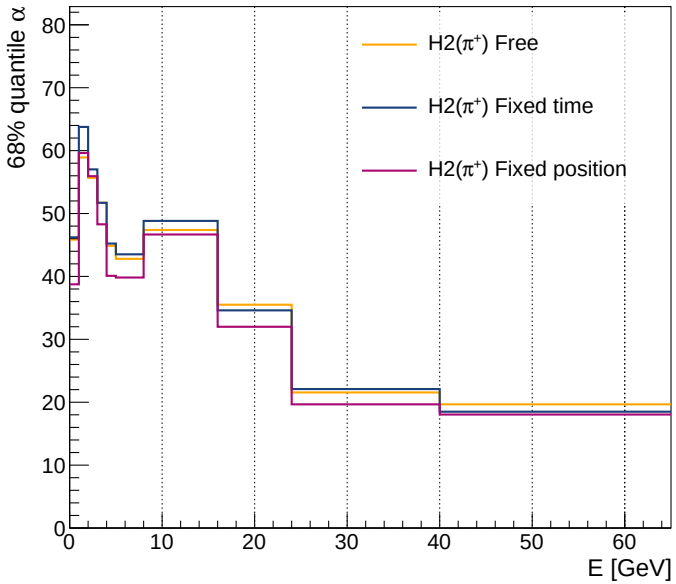


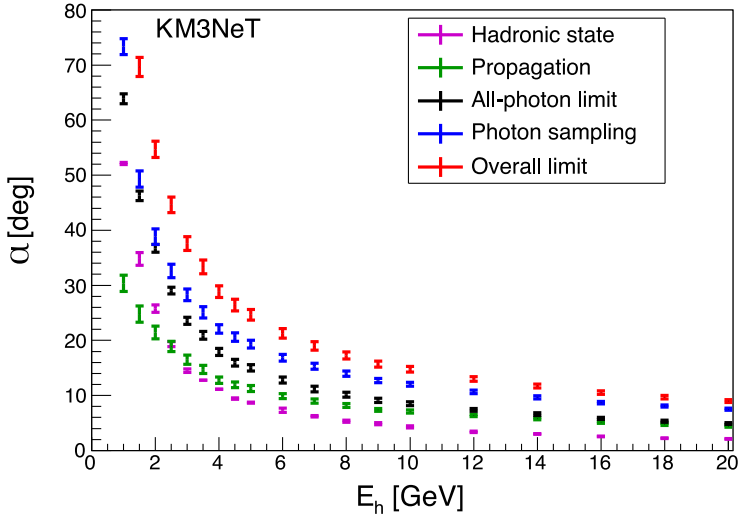
Before hit number cut



After hit number cut

Reconstruction Single Shower





Single hadronic shower ≡all ν-interaction secondaries minus leading lepton.

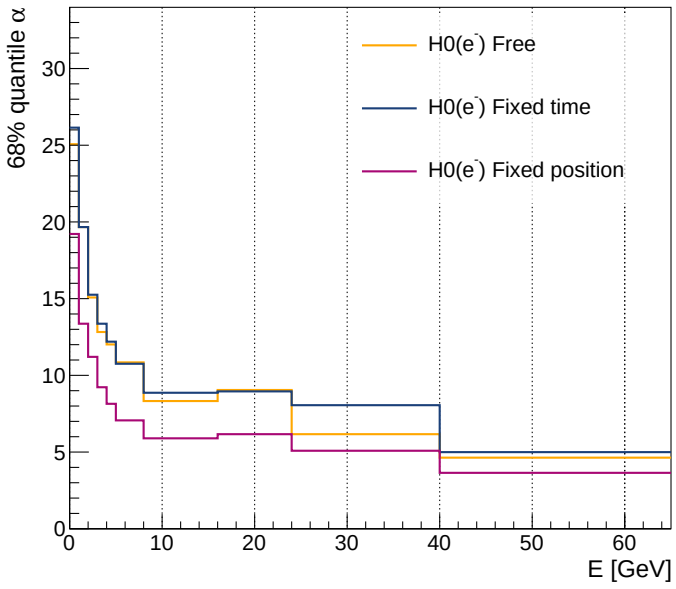
Angle difference
$\alpha \equiv \cos^{-1} \hat{p}_{\text{true}} \cdot \hat{p}_{\text{reco.}}$, where
$\hat{p} \equiv \frac{1}{E_{\text{tot.}}} \sum_i^N \hat{p}_i E_i$.

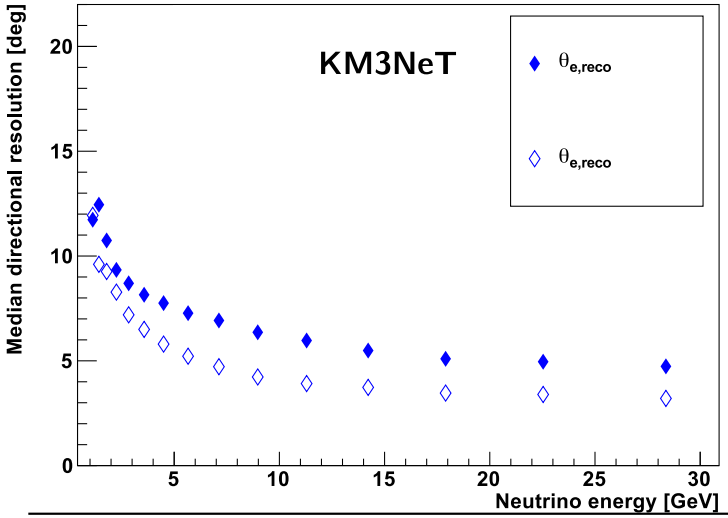
Intrinsic limit paper[8] shows **best possible resolution** of ORCA.

Not directly comparable due to hit cut, but gives an idea.

[8] [Adrian-Martinez et al., 2017]

Reconstruction Single Shower





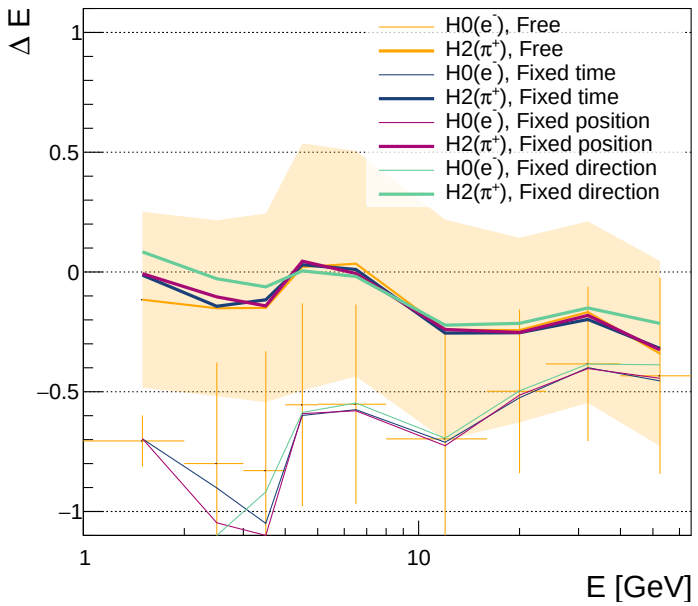
Single electron.

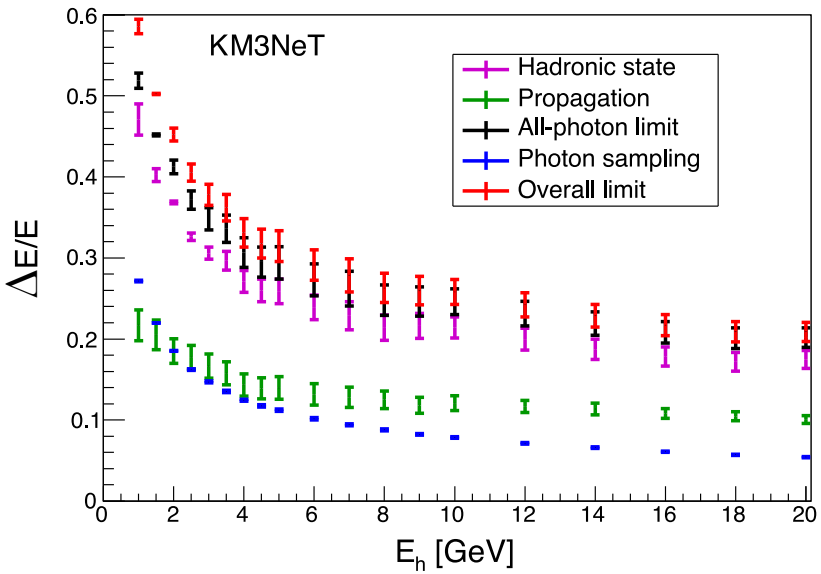
Angle difference
$\alpha \equiv \cos^{-1} \hat{p}_{\text{true}} \cdot \hat{p}_{\text{reco.}}$, where
$\hat{p} \equiv \frac{1}{E_{\text{tot.}}} \sum_i^N \hat{p}_i E_i$.

Resolution reproduces that of LOI

[8] [Adrian-Martinez et al., 2017]

Reconstruction Single Shower



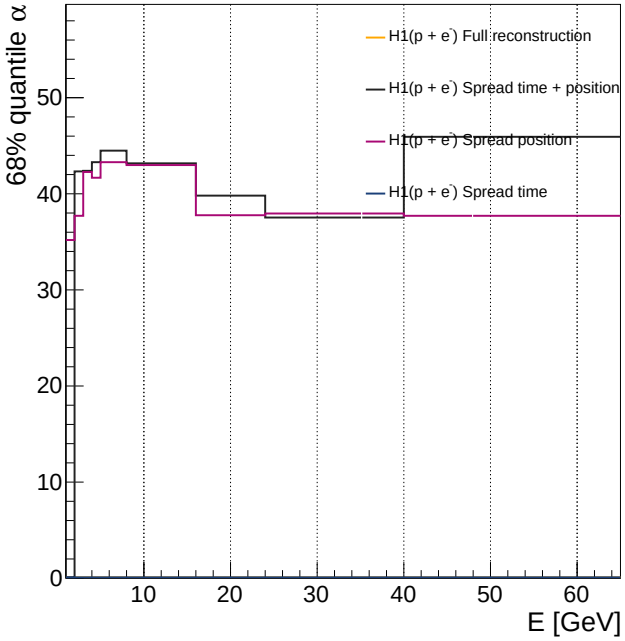


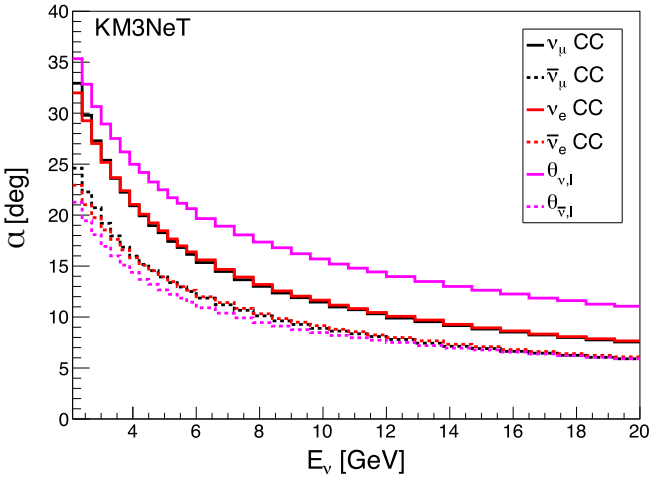
Single hadronic shower energy difference $\Delta E \equiv \frac{E_{h,\text{true}} - E_{h,\text{reco.}}}{E_{h,\text{true}}}$, where $E_h \equiv E_\nu - E_{\text{lep.}}$.

Energy difference resolution for low energies, close to intrinsic resolution for >4 hits.

π_+ best at reconstructing hadronic showers, supposedly due to high presence of $\pi_{+/-}$ in hadronic showers.

Reconstruction Neutrino Event



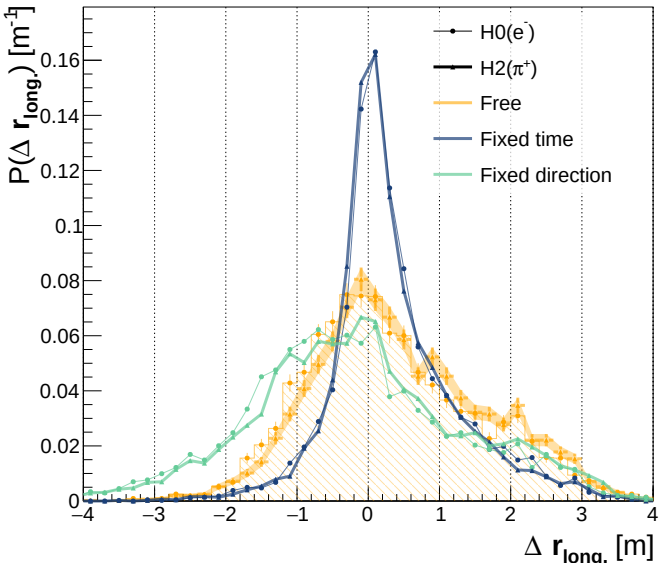


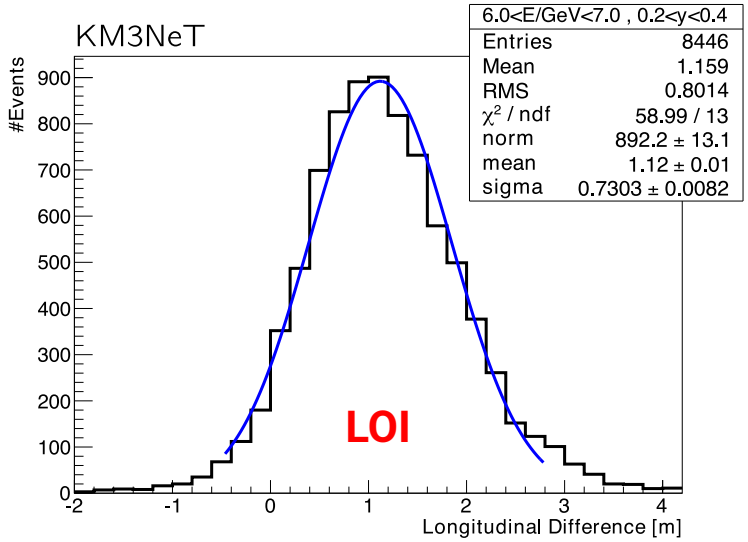
ν_e-charged current angle difference.

Assuming 3 m position resolution and 5 ns timing resolution

Close to intrinsic limits at low energies.

Reconstruction Neutrino Event



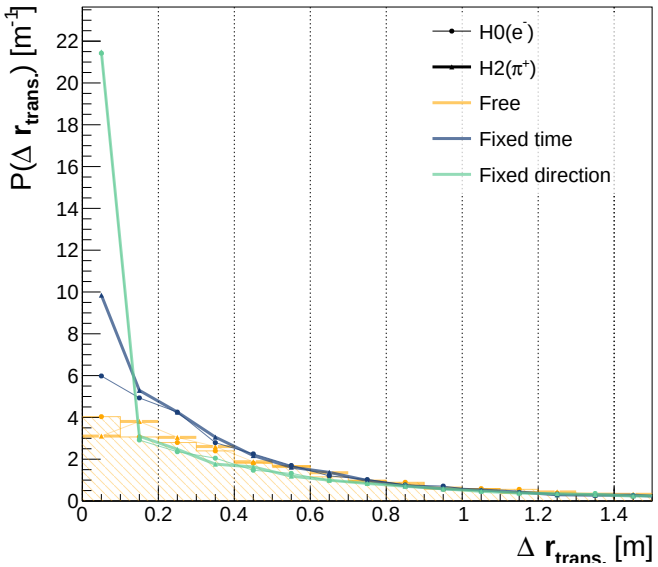


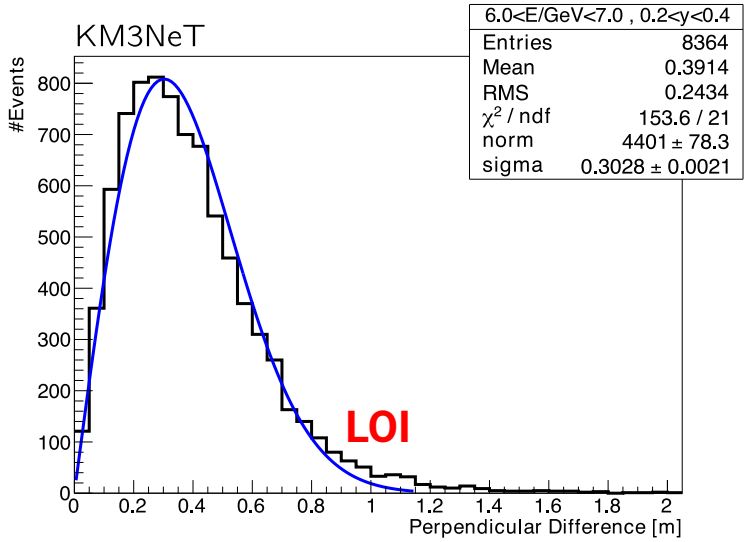
Position of single hadronic shower, identical to ν-NC.

Reproduces resolutions for ν-CC as reported in LOI, but better resolution in other parameters accentuates this resolution!

Distance between shower maximum and vertex folded into model
$\rightarrow$ naturally centres at zero.

Reconstruction Neutrino Event





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- Motivation
- Procedure
- **Models**
- Reconstructions
- Conclusion