University of Amsterdam
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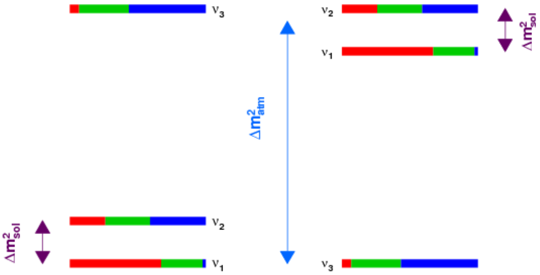
Nikhef
KM3NeT

Models of Particle Signatures in KM3NeT ORCA

Jordan Seneca
November 1, 2018

Introduction

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

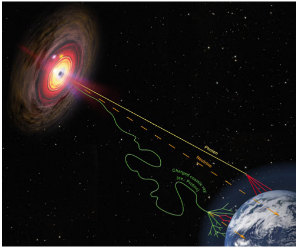


[1]

Normal Ordering (NO) Inverted Ordering (IO)

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

Introduction



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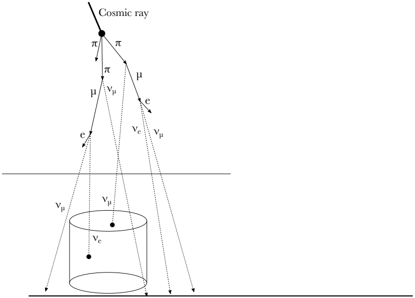


Certain extrasolar objects accelerate particles to high energies, which are called *cosmic rays*.

Cosmic rays collide with the Earth's atmosphere and produce neutrinos.[3]

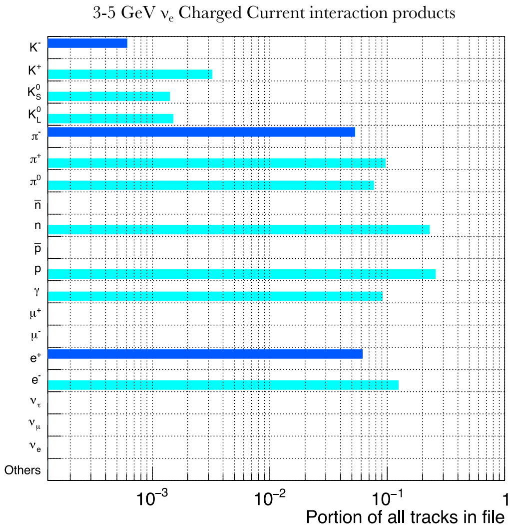
Atmospheric neutrinos can travel through the entire Earth virtually unaffected, causing a ubiquitous flux.

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

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

Introduction

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

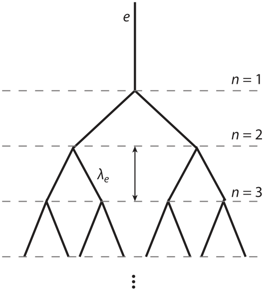


Neutral current $\rightarrow$ hadronic particles.

Charged current $\rightarrow$ lepton + hadronic particles

Introduction

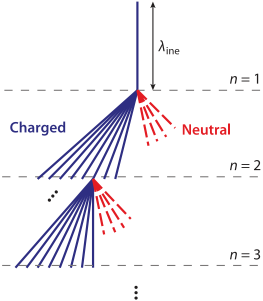
Product particles from neutrino interactions produce more particles in *showers*



EM shower

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

$X \propto \log E$



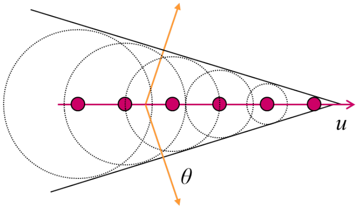
[4]

Hadronic shower

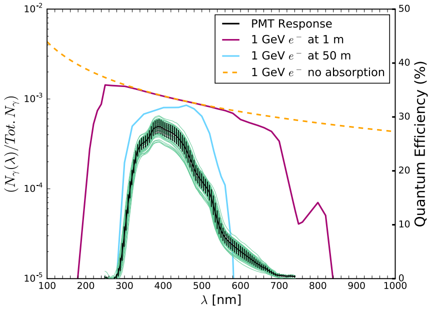
Complicated!

[4] Diagram from [Engel, 2011]

Introduction



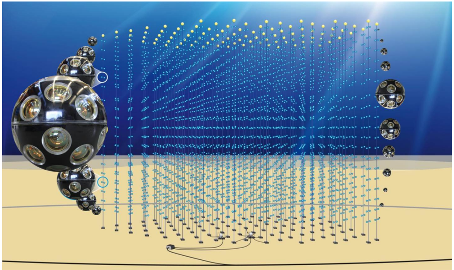
Charged particles emit *Cherenkov light* in water.

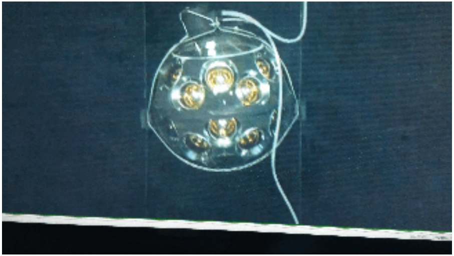


This light is emitted at an angle θ, and can be seen by *Photomultiplier tubes* (PMT)[5]

[5] Diagram from [Alaeian, 2014]

Introduction





KM3Net ORCA

[6] 68 000 PMTs.

$0.004\ \mathrm{km}^3$

[6] [KM3NeT, 2015]

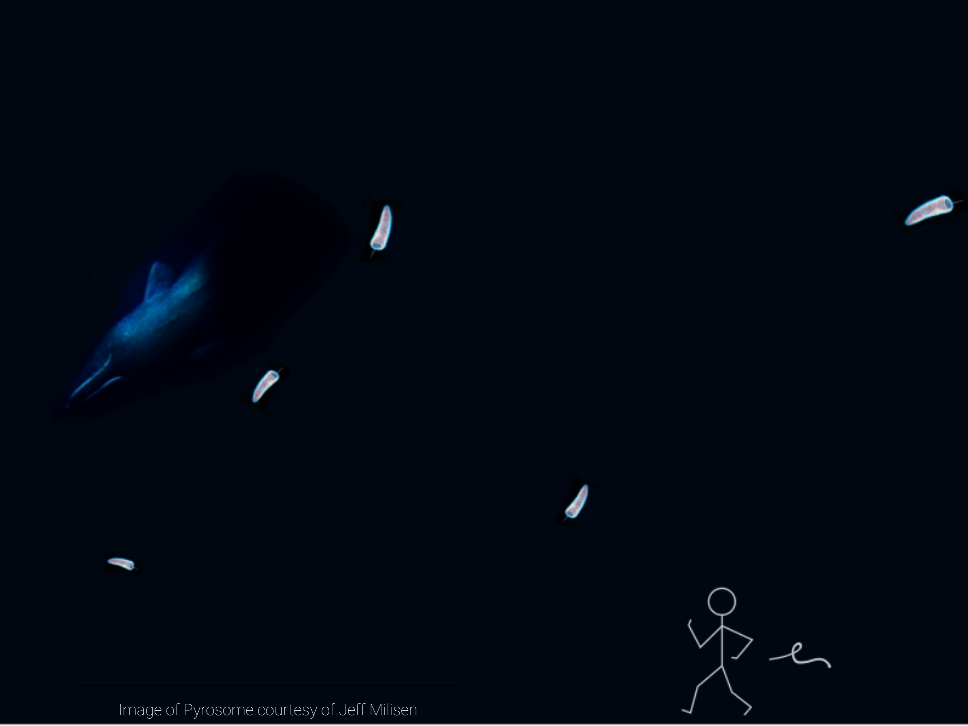
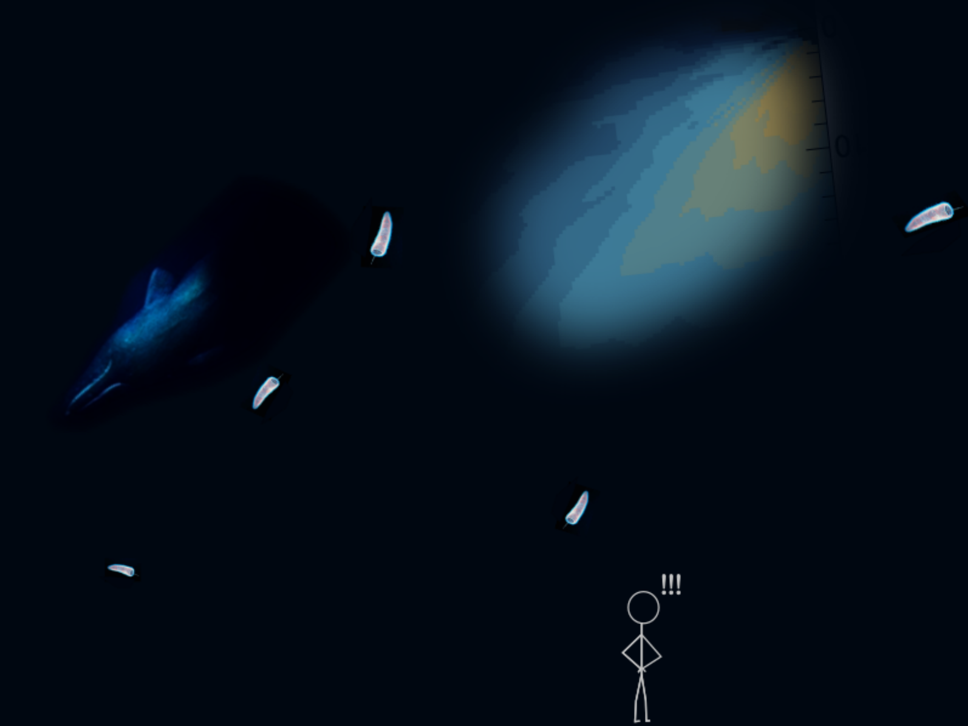
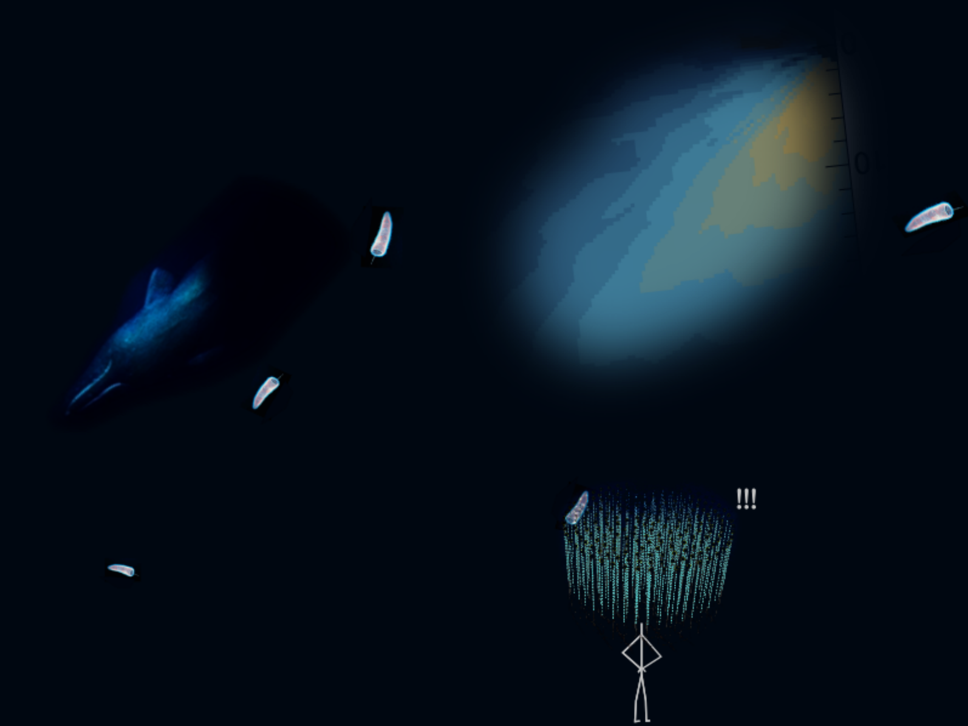
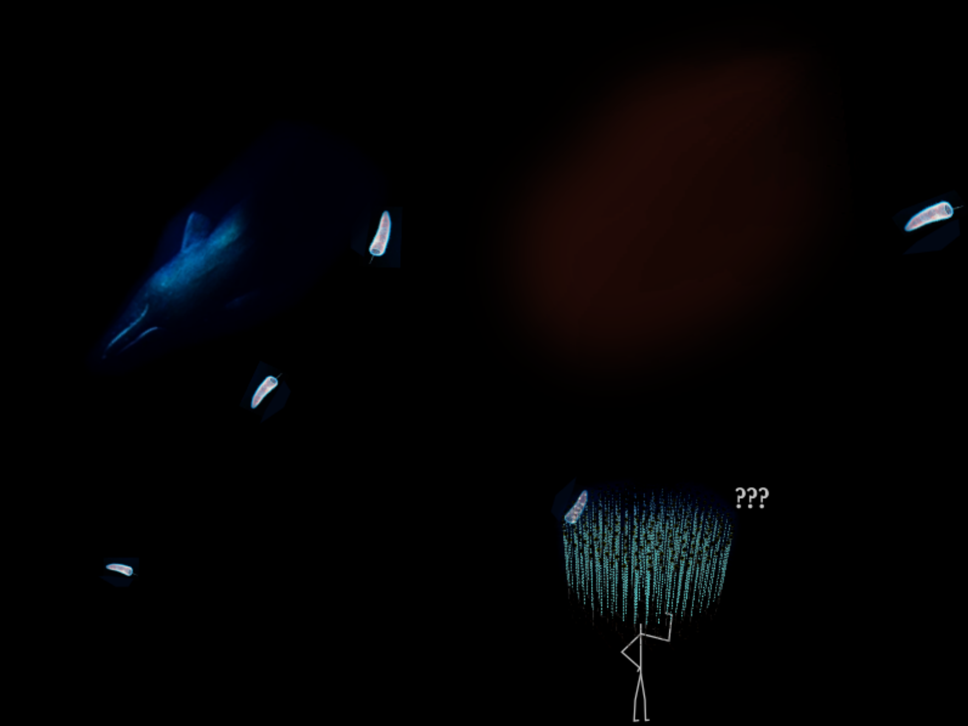


Image of Pyrosome courtesy of Jeff Milisen





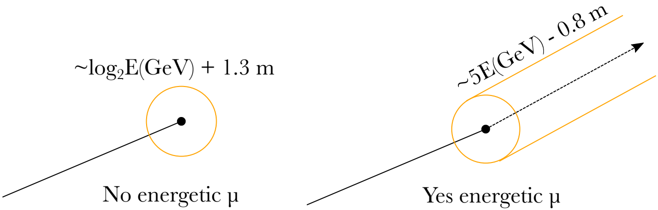


What do different particles look like to ORCA?

Aims of this work

- Create model of light signatures in ORCA from ν interaction products.
- Use models for Monte Carlo simulation shortcut.
- Use models for reconstruction of particle showers and ν events.

Motivation

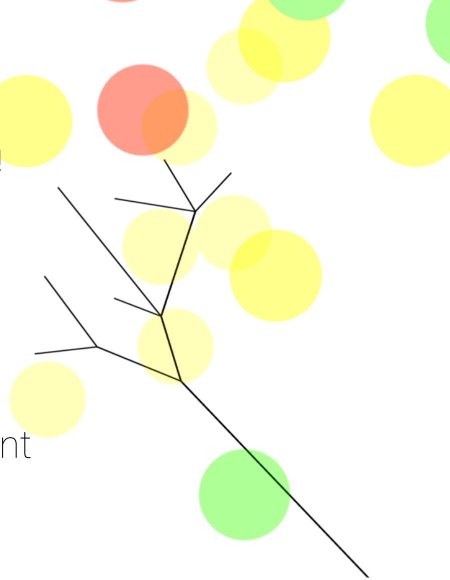


Current models lump all events into showers or tracks.

- 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**.

Motivation

Advantages of KM3NeT ORCA:

1. **ORCA is dense.**
   (Detect small events and finer features)

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   (Straighter light path than in ice)

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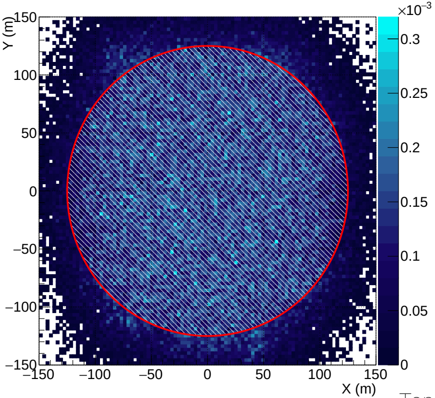
   (Additional dimensions in phase space and larger sensitive area)
3. **Events propagate in water.**
   (Straighter light path than in ice)
4. **(Our detection modules look super cool.)**

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

Procedure



Top view of simulated interaction vertices and ORCA outline.

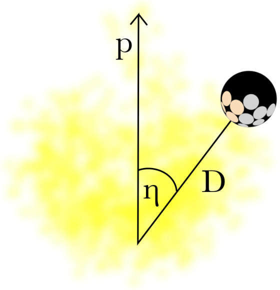
Start off with simulated sample of ν-events in ORCA

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

$\sim 250\ \mathrm{M}$ events

Procedure

1. Pick product particle form sample
2. $N_{\text{p.e.}}$ of every particle hit gets filled in the $(E_{\text{particle}}, D, \eta, \theta_{\text{PMT}}, \phi_{\text{PMT}}, \Delta t_{\text{arrival}})$ bin of 6d histogram.
3. Interpolate histogram and expand $\langle N_{\text{p.e.}} \rangle$ into Poisson distribution to obtain the ***p.e. Pattern PDF*** (PEPP).
4. Repeat process for each particle to obtain each particle PEPP.



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 state of the art particle interaction modelling in water." – me

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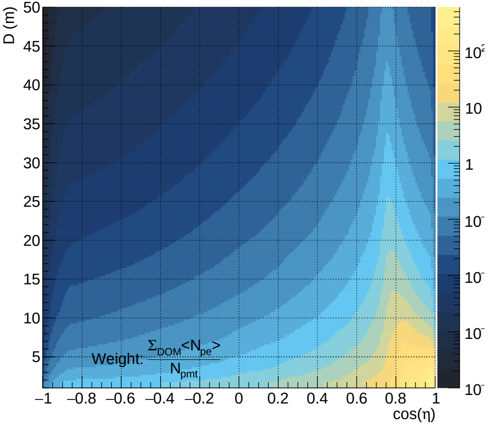
PEPPs Geometry

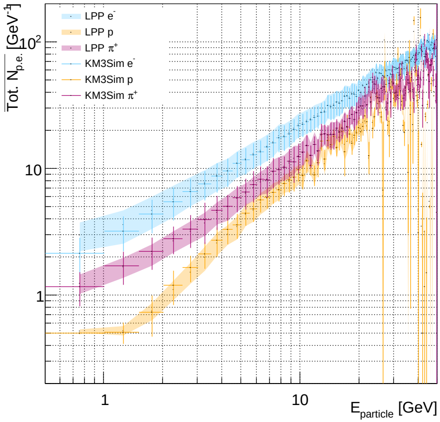


30GeV Electron PEPP

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

PEPPs agree with theoretical expectations

PEPP Monte Carlo Simulations



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

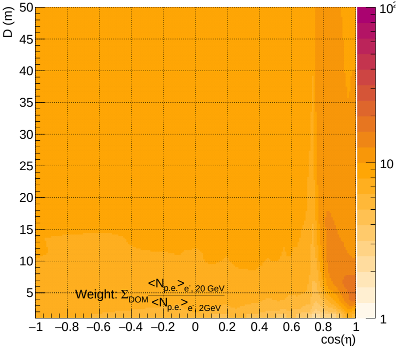
Excellent match for

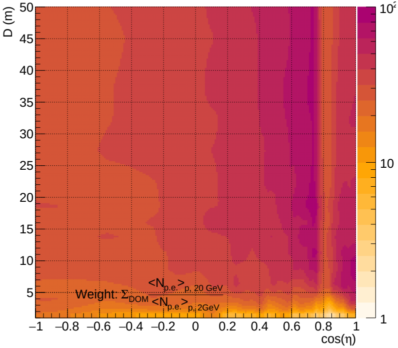
$$\overline{TotN_{\text{p.e.}}} \equiv \sum^{N_{\text{events}}} N_{\text{p.e.}}.$$

PEPPs agree with original Monte Carlo simulation

PEPPs Energy Dependence

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



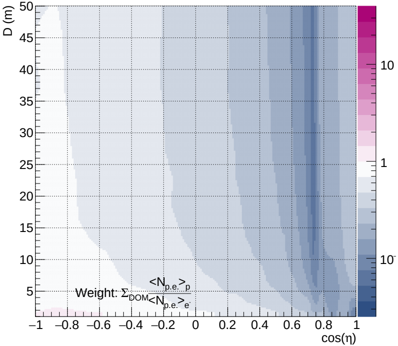


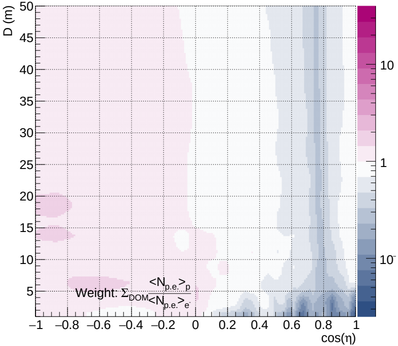
Expected flat $10 \times N_{\text{particles}}$
Good agreement!

Features near Cherenkov angle
(note: log scale)

PEPPs EM/Hadronic Comparison

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





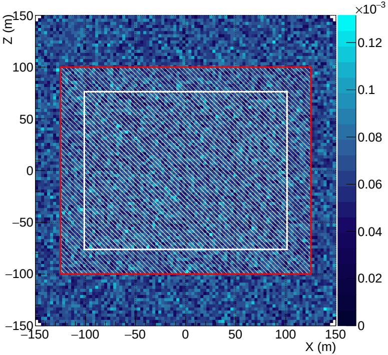
3 GeV: very different

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

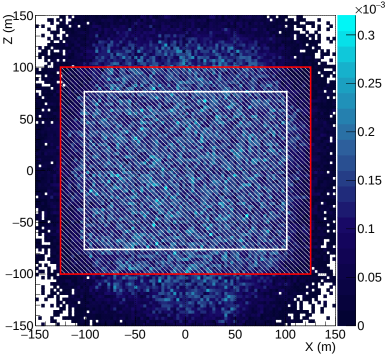
Reconstructions

Data cuts

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

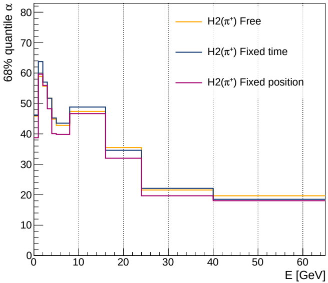


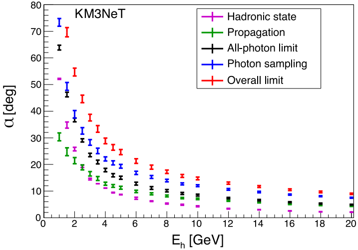
Before hit number cut



After hit number cut

Reconstruction Single Shower





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

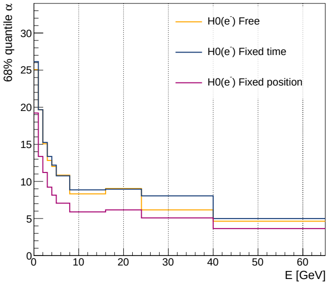
Angle difference $\alpha \equiv \cos^{-1} \hat{p}_{\text{true}} \cdot \hat{p}_{\text{reco.}}$, where $\hat{p} \equiv \frac{1}{E_{\text{tot.}}} \sum_i^N \hat{p}_i E_i$.

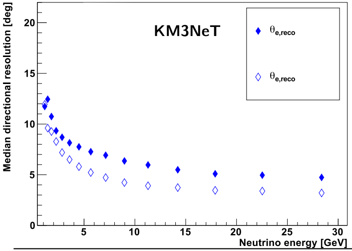
Intrinsic limit paper[8] shows **best possible resolution** of ORCA.

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

8 [Adrian-Martinez et al., 2017]

Reconstruction Single Shower





Single electron.

Angle difference

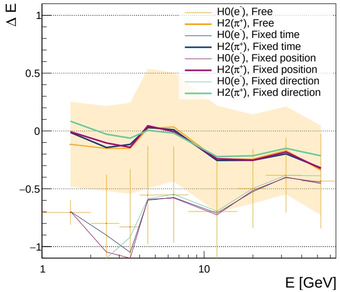
$\alpha \equiv \cos^{-1} \hat{p}_{\text{true}} \cdot \hat{p}_{\text{reco.}}$, where

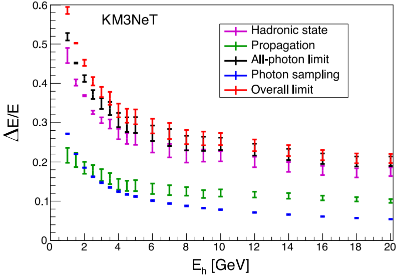
$\hat{p} \equiv \frac{1}{E_{\text{tot.}}} \sum_i^N \hat{p}_i E_i$.

Resolution reproduces that of LOI[8]

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

Reconstruction Single Shower



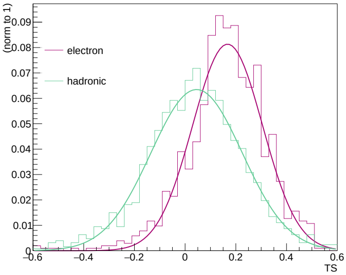


Single hadronic shower energy difference $\Delta E \equiv \frac{E_{h,\text{true}} - E_{h,\text{reco.}}}{E_{h,\text{true}}}$, where $E_h \equiv E_\nu - E_{\text{lep.}}$.

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.

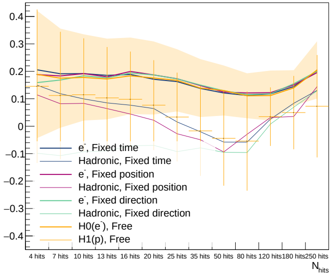
Reconstruction Single Shower



Identifying hadronic shower possible?

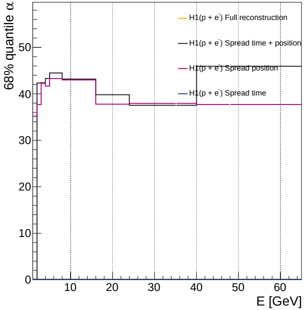
Top: 25 - 35 hits.

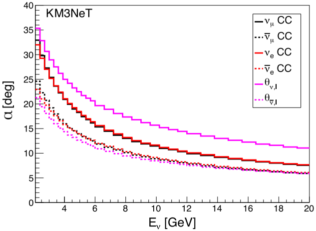
25 - 80 hit region shows promise for 1σ separation.



At higher energies,
EM shower $\simeq$ hadronic shower
$\rightarrow$ no distinguishing power.

Reconstruction Neutrino Event



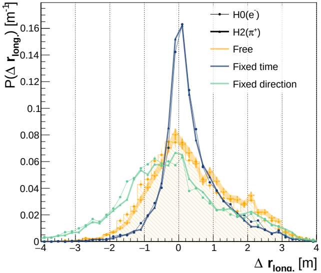


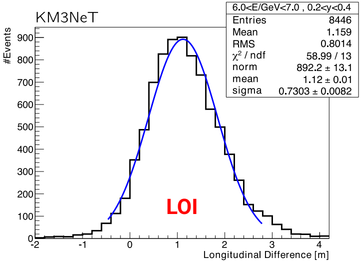
ν_e-charged current angle difference.

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.

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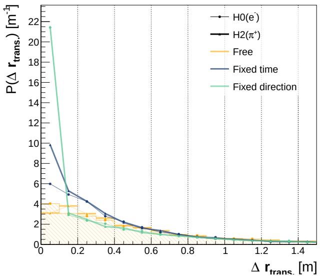

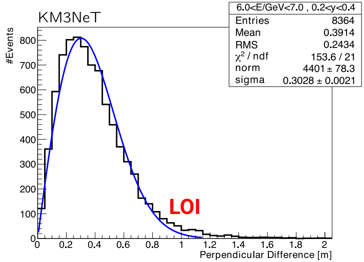

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Conclusion

- Produced models of the signal of various particles in ORCA, PEPPs.
- PEPPs reproduce KM3Sim results with some deviations in timing.
- Reconstructions with PEPPs is possible, and competitive at best.

Next steps

- Investigate time arrival deviations from KM3Sim.
- Optimise PEPP reconstruction for full neutrino events.
- Reconstruct Bjorken-Y, improve sensitivity of ORCA to NMO.
- Include K-40 background + PMT response, next stage of tests for reconstruction.

Thank you for your attention!

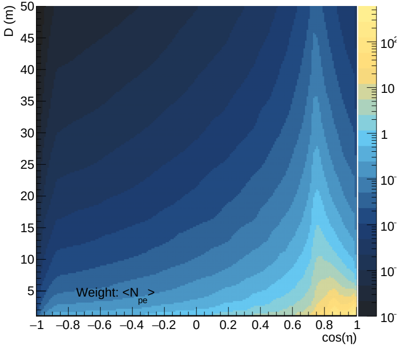
Questions please.

Bibliography

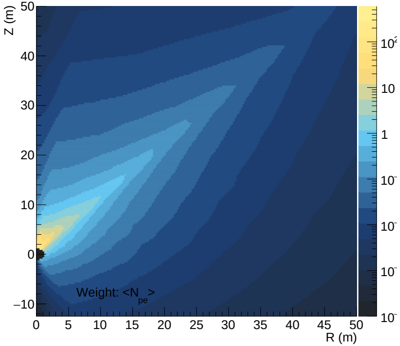
Leftover slides

PEPPs Geometry

3 GeV electrons

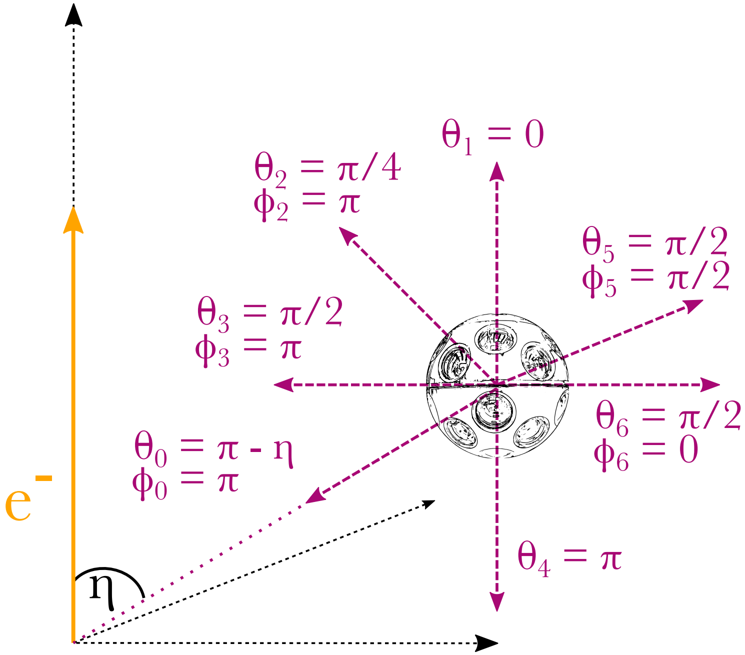


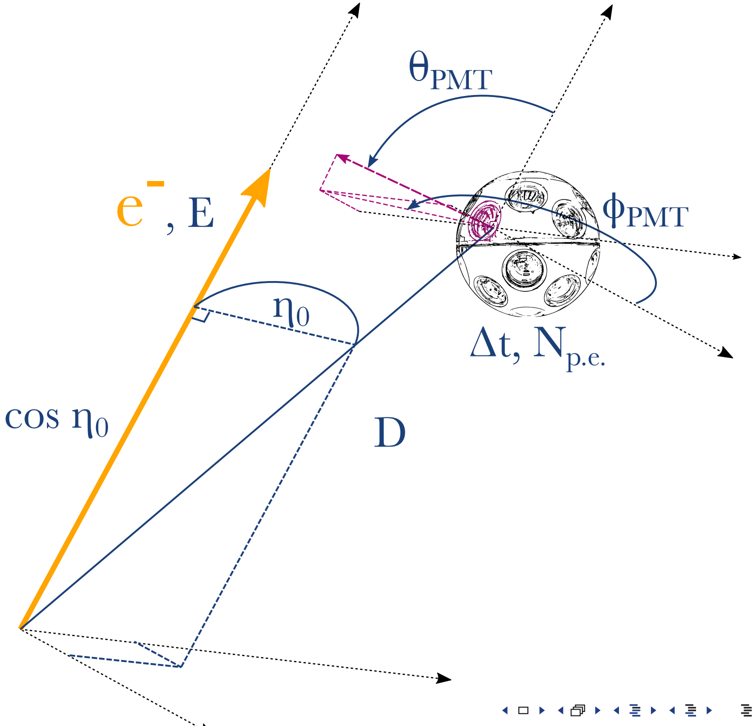
Native coordinates



Cartesian transformation

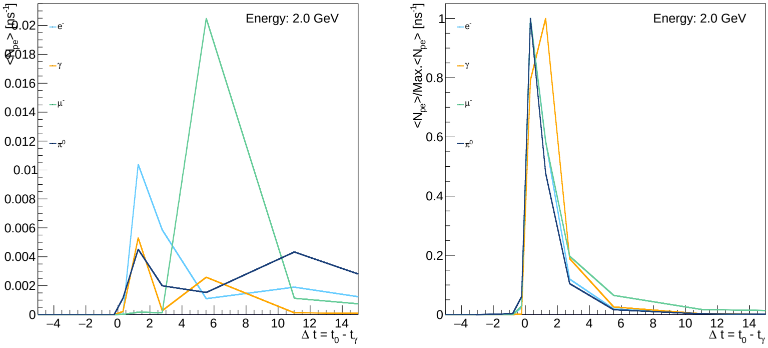
Remember this because only native coordinates will be shown from now on.


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


θPMT
φPMT
e-, E
η0
Δt, Np.e.
cos η0
D

PEPPs Time Arrival

Discerning power in time dependence



PEPPs Time Arrival

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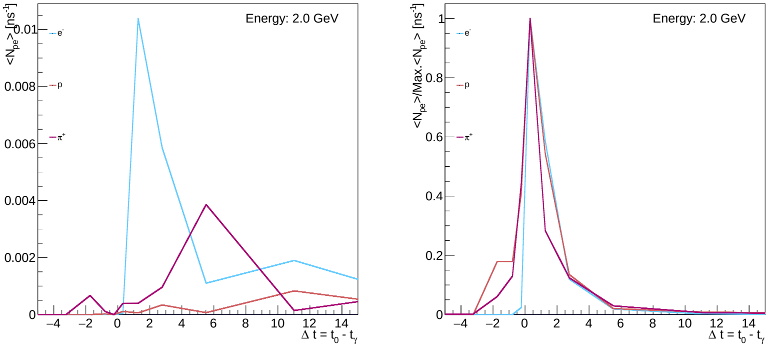
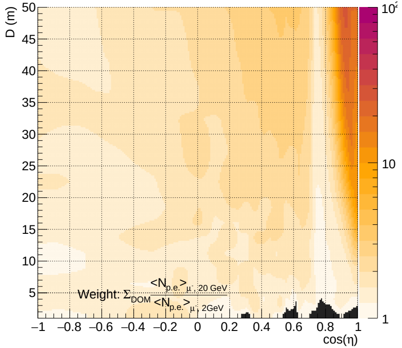
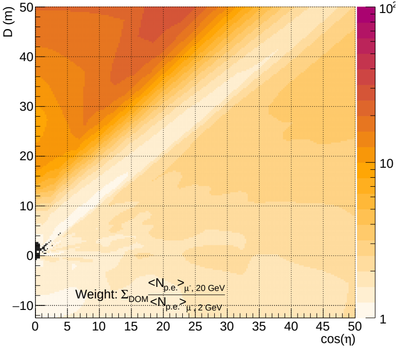


PEPPs Geometry

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





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Features near Cherenkov angle
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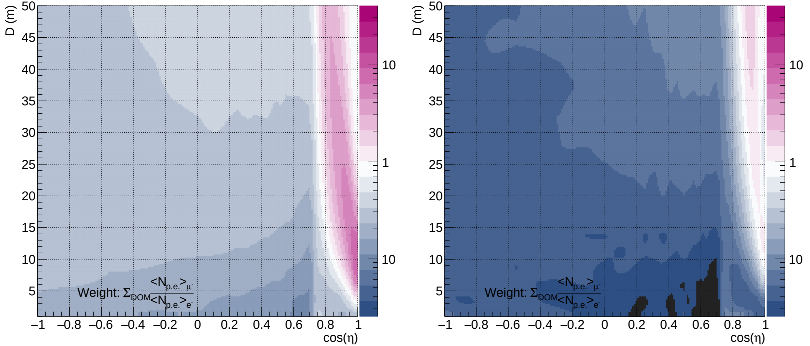
PEPPs Geometry

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



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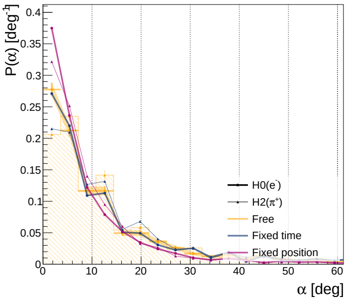
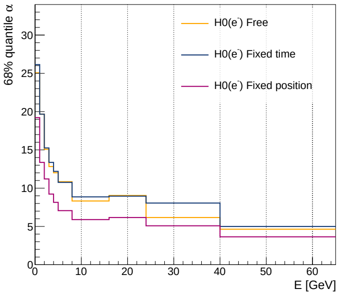
Reconstruction Single Shower

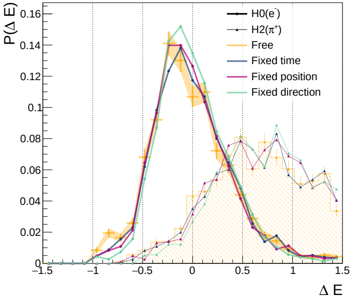
Direction electron

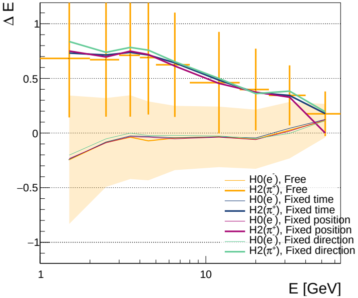




Reconstruction Single Shower

Energy electron

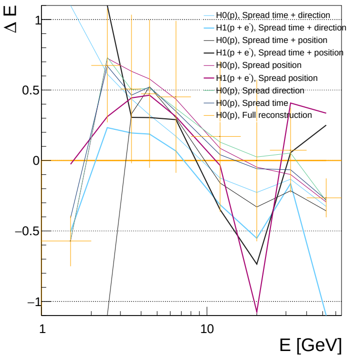


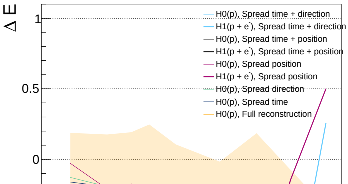


Reconstruction Neutrino Event

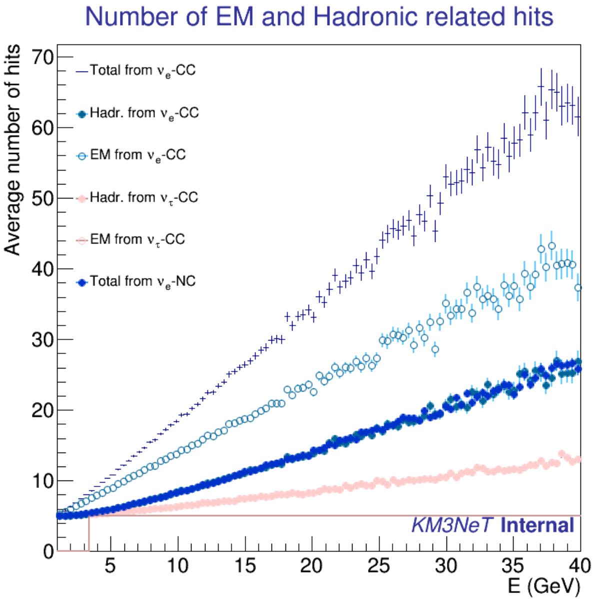
Reconstruction Neutrino Event

ΔE for ν_e-CC (ν_e-NC) above (below)

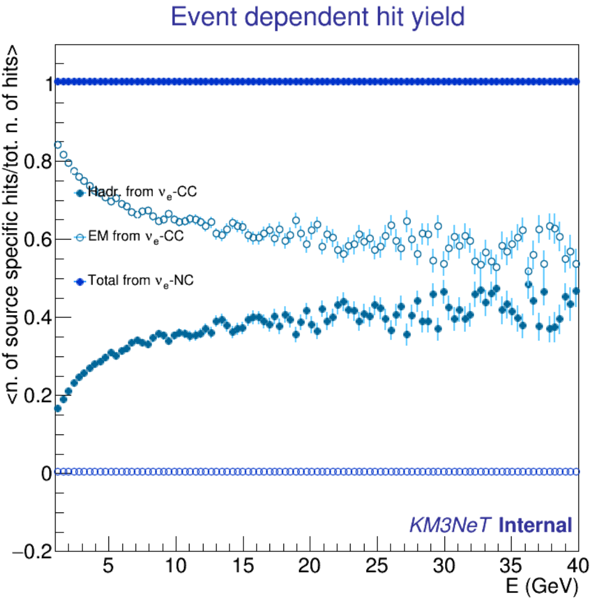




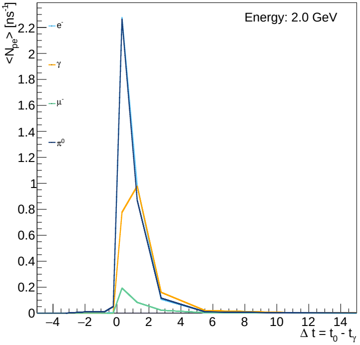
Secondaries



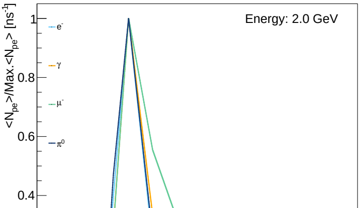
Secondaries



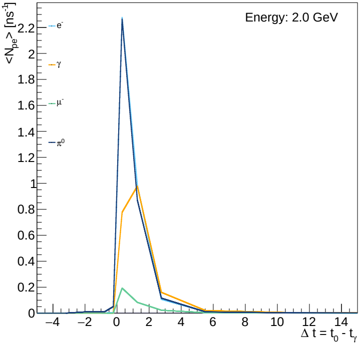
PDFs Time Arrival



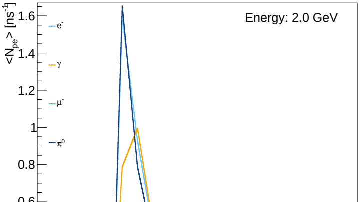
Normalised view



PDFs Time Arrival

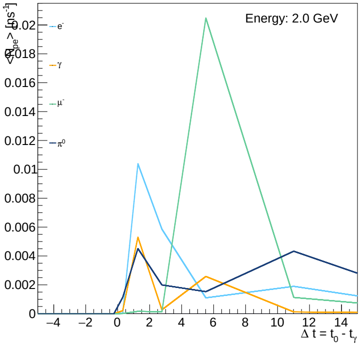


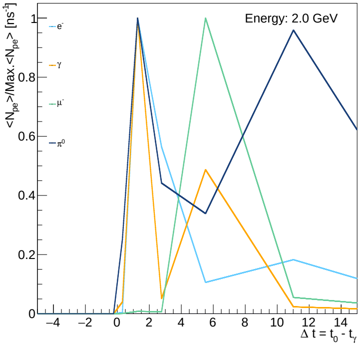
Angle dependence



PDFs Time Arrival

Discerning power in time dependence



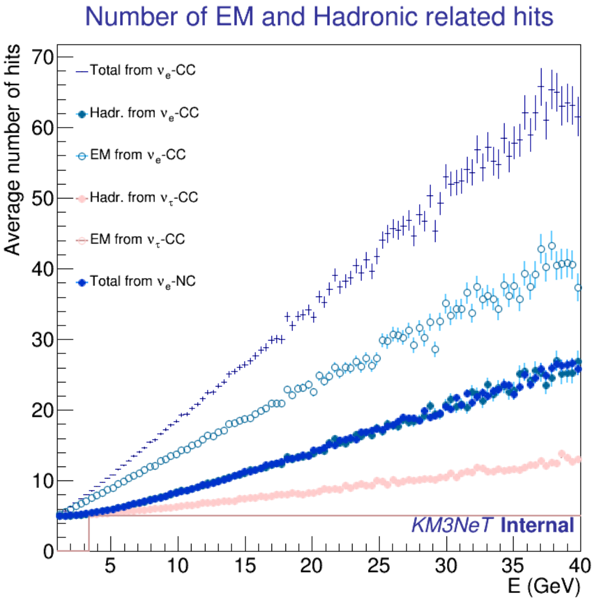


Procedure

Chain of simulation:

↓ - Input ν
↓ GENIE - - - - - - - - - - - - Interaction
↓ Km3Sim - - - Propagation + Re-interactions
JTE - - - - - - - - - - -PMT response + Trigger

Secondaries



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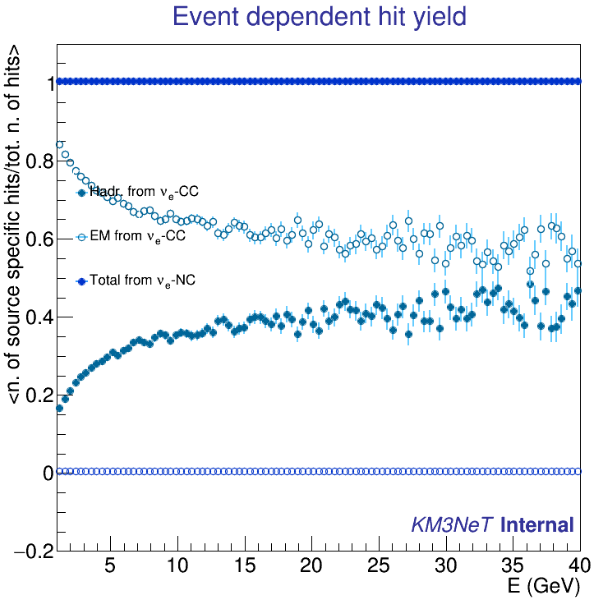
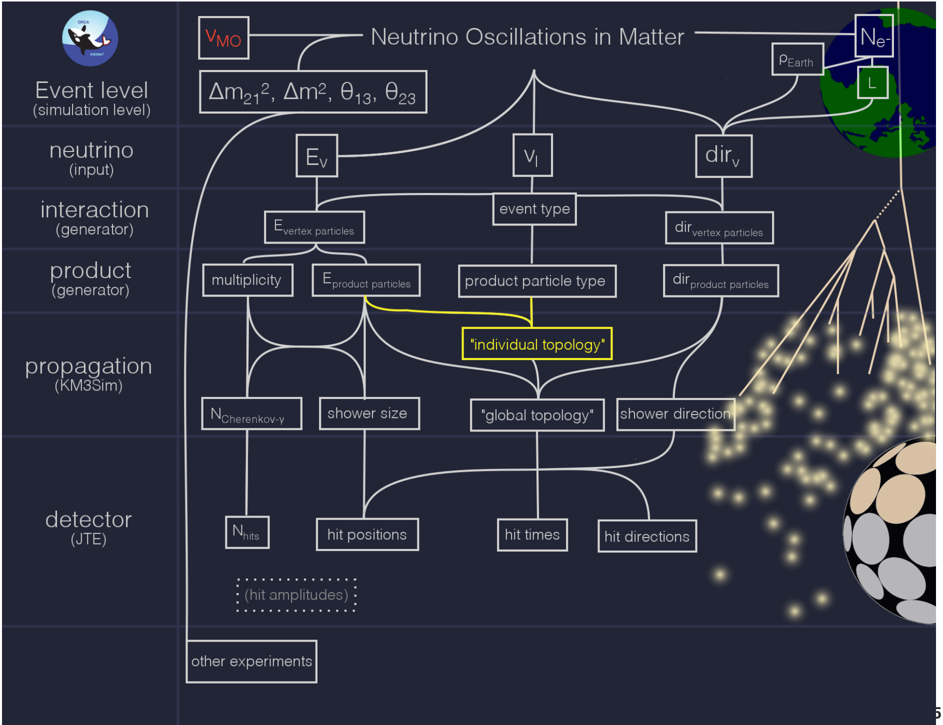


Procedure

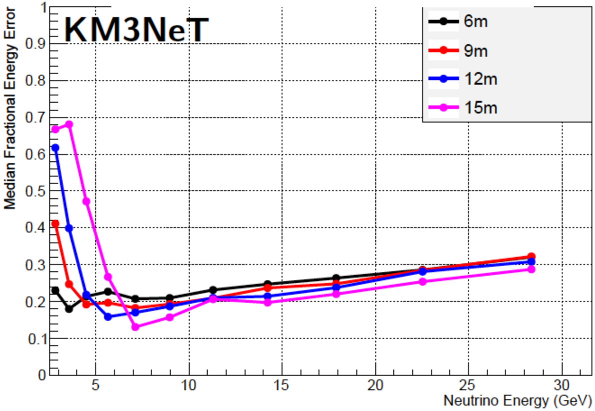
Used ORCA 1-100GeV all flavours ν-interaction samples



Event level
(simulation level)
neutrino
(input)
interaction
(generator)
product
(generator)
propagation
(KM3Sim)
detector
(JTE)
ν_MO
Neutrino Oscillations in Matter
Δm21², Δm², θ13, θ23
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-γ
shower size
"global topology"
shower direction
N_hits
hit positions
hit times
hit directions
(hit amplitudes)
other experiments

Motivation

Orca Energy resolution



9

[9] KM3NeT Phase II LOI

Motivation

Here are the parameters necessary to accurately 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)

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

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Motivation: number of electrons in path

Requires knowledge of the following:

- The matter density of the Earth
- The distance travelled through the Earth

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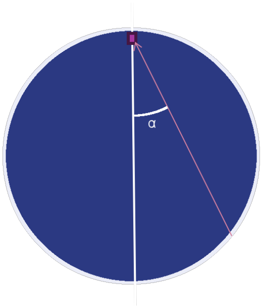
Motivation: number of electrons in path

Requires knowledge of the following:

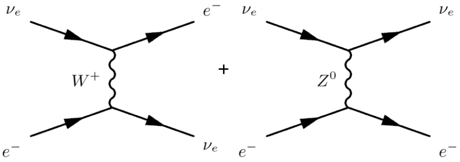
- The matter density of the Earth
- The distance travelled through the Earth
  - → known by neutrino direction

Figure: Parametrization of electrons in path using the Earth



Motivation: neutrino flavor

The flavor of a neutrino is defined by the interaction it induces.



- Type of product particles
- Energies and directions of product particles

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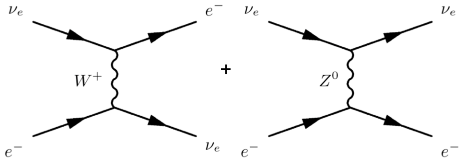

- Type of product particles
- Energies and directions of product particles

Motivation: neutrino energy

The neutrino energy affects the following outcomes:

- The size of the event in the detector (PMT positions)
- The number of $\gamma_{cherenkov}$

Procedure

Signatures are visible in the detector *hit pattern*.

What affects the hit pattern?

Procedure

Global topology, size, brightness, and direction *directly* couple to hit pattern.

Procedure

Global topology, size, brightness, and direction *directly* couple to hit pattern.

"Global Topology": The shape of an entire event

vs.

"Individual topology": The shape of a single particle

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"Global Topology": The shape of an entire event

vs.

"Individual topology": The shape of a single particle

Disclaimer: not *really* individual since particle themselves decay/re-interact into other particles.

What affects global topology?

Product particle types

Product particle energies

Product particle directions