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Studies of intrinsic resolution to low energy electron and muon neutrino events with neutrino telescopes

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on behalf of the **KM3NeT Collaboration**

KM3NeT

1. Motivation

Two megaton-scale water/ice Cherenkov detectors have been proposed to precisely measure the energy and arrival direction of GeV-scale atmospheric neutrinos in order to determine the neutrino mass hierarchy:

- ORCA, as part of KM3NeT in the Mediterranean Sea
- PINGU, as an infill to the IceCube detector at the South Pole

In relevant energy regime of 1-20GeV intrinsic fluctuations of particle behaviour become important**:**

➔ **What is the best possible reconstruction accuracy of these detectors?** Assuming an ideal use of the information carried by each detected photon.

➔ **What could be achievable with denser detectors?** How do intrinsic fluctuations limit the reconstruction accuracy if every single photon is detected?

We have derived intrinsic limits on the energy and direction reconstruction accuracy of muon tracks, and electromagnetic and hadronic cascades for an ORCA-like detector by means of analysing the output of simulations. Combining these results give the limitations for ν_e and ν_μ charged current events.

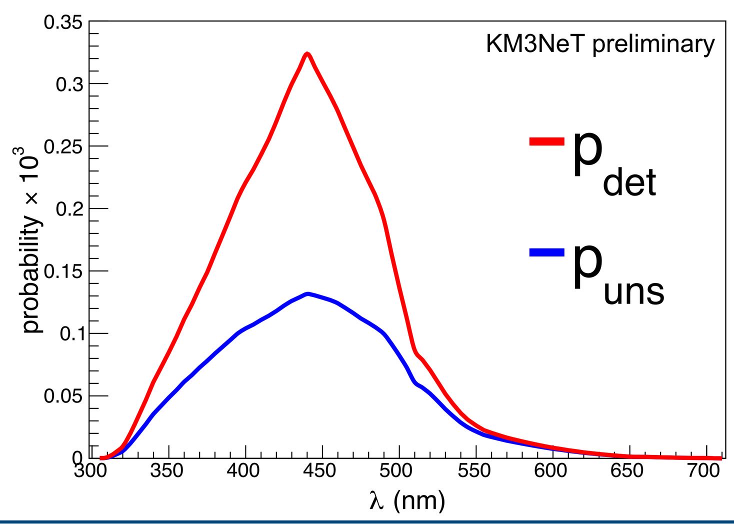
2. Methodology

- Always optimistic assumptions, so that a 'real detector' will always be worse
- Applying generic energy and direction reconstruction methods
- Always 'forward' problem, i.e. fluctuations in observables energy resolution: RMS; direction resolution: 68% quantile
- Considering neutrino event components in isolation: muon tracks, electromagnetic and hadronic cascades
- (un)scattered photons identified perfectly
- Two idealised detectors: 'perfect' and 'finite'

'perfect' detector:
- events fully contained
- every emitted photon is detected
- perfect timing & position calibration
- no background

'finite' detector:
- only small fraction of photons detected
- ORCA benchmark detector characteristics (detector density, water properties)
  → average detection probability for unscattered and all photons

Simulations:
- neutrino interaction: GENIE
  Andreopoulos et al. Nucl. Instrum. Meth. A614 (2010), 87-104
- particle propagation: GEANT 3.21 (GEISHA)
  CERN program library, http://cernlib.web.cern.ch



3. Cascades

- Electron → electromagnetic cascade
- Hadrons → hadroinc cascade, defined via 4-momentum conservation:

$$(E_h, \vec{p}_h) = (E_\nu, \vec{p}_\nu) - (E_\ell, \vec{p}_\ell)$$

- Different sources of fluctuations:
  - had. cascades consist of different sets of initial particles produced at the **vertex**
  - random particle **propagation** for same initial particles
  - Poissonian photon **detection**

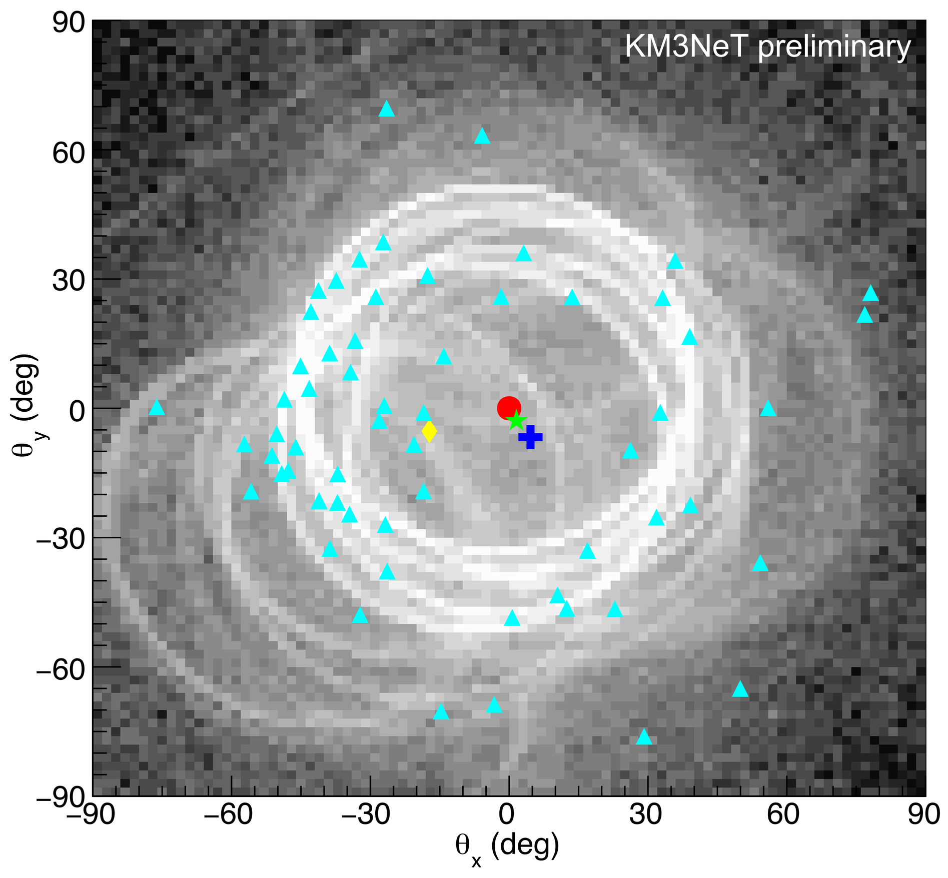
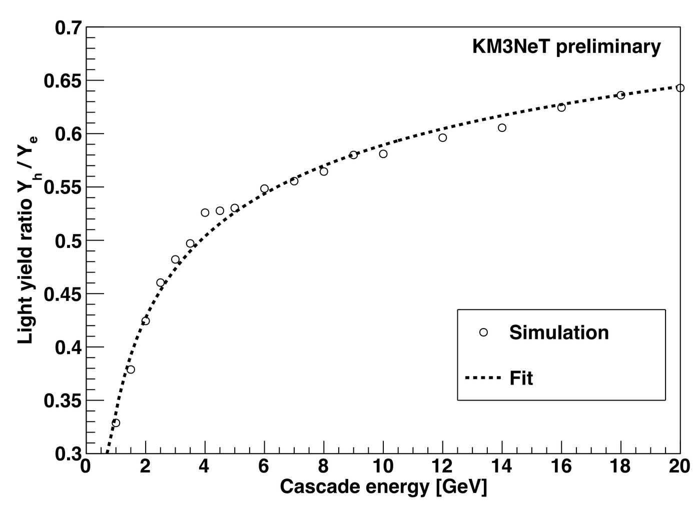


Figure: Example emitted photon distribution for E_h=10GeV.
★ cascade direction (θ_x,θ_y) = (0,0).
● mean direction of all photon averaged over many simulations.
✚ mean direction of all photon for this particular simulation.
◆ mean direction for given sample of detected photons ▲.

Energy reconstruction

- number N of detected photons
  - for electrons: $E_e \propto N$
  - for had. cascade: see plot below
  - error estimates:

  perfect: $\Delta E / E = \sigma_N / N$
  finite: ⊕ Poissonian detection



Direction reconstruction

- mean direction of unscattered photon

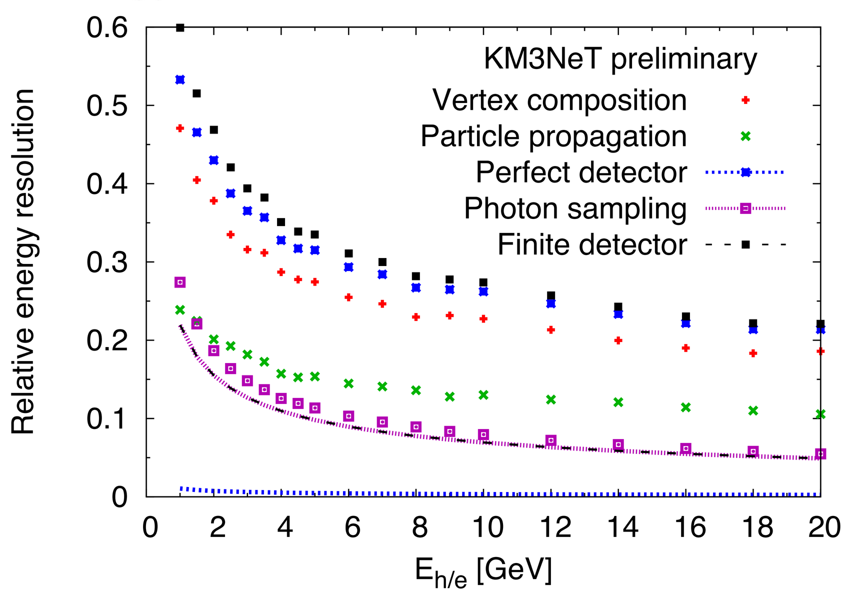
error estimates:

$$\Delta\theta = \cos^{-1}(\vec{\gamma}, \vec{c})$$

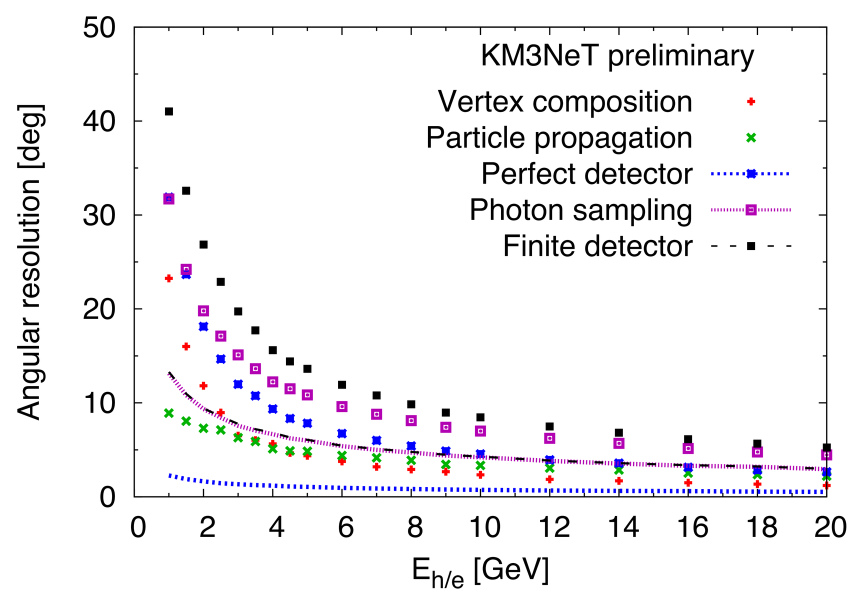
$\vec{\gamma}$ mean photon direction
$\vec{c}$ cascade direction

perfect: using all photons
finite: using small sample of detected photons

Energy resolution



Direction resolution



4. Muons

Energy reconstruction

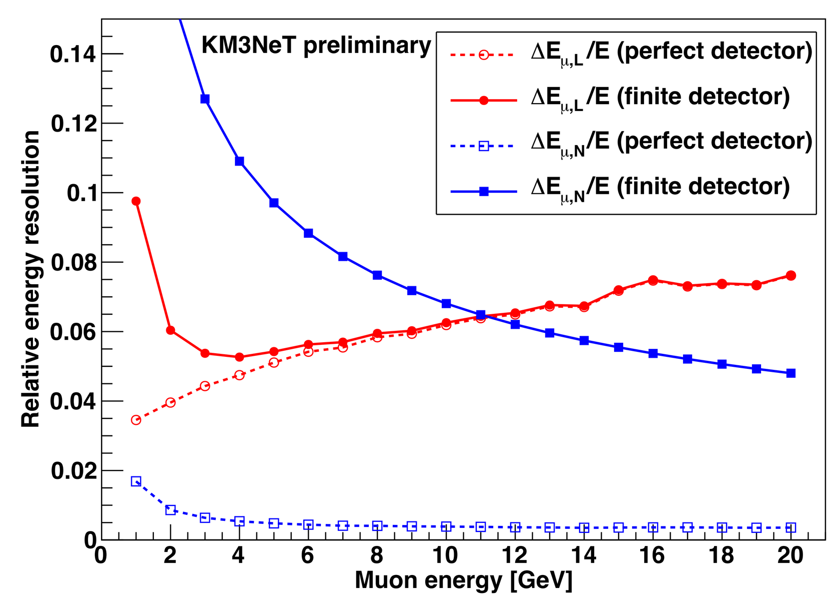
- number N of detected photons, $E_\mu \propto N$,

  error estimates: → same as cascades

- length L of muon track, $E_\mu \propto L$,

  error estimates:
  perfect: $\Delta E / E = \sigma_L / L$
  finite: ⊕ const. $\Delta L^d \approx 0.1$GeV from detecting endpoint

Energy resolution



Direction reconstruction

- Straight line fit to muon track
  error estimates: straightness of track → negligible (0.7°-2°)

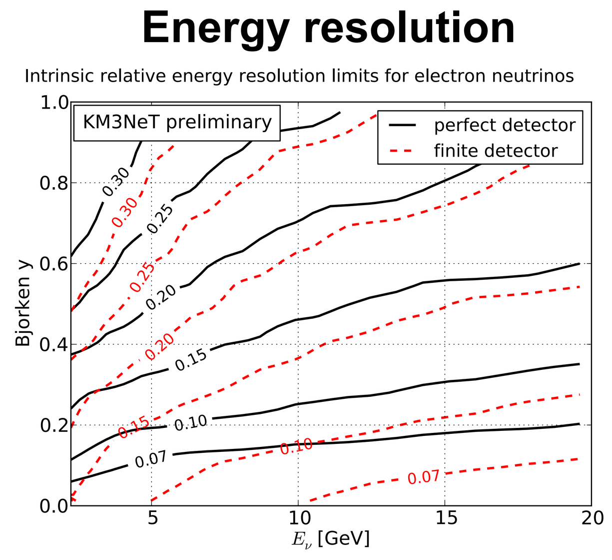
5. ν_e and ν_μ Charged Current Events

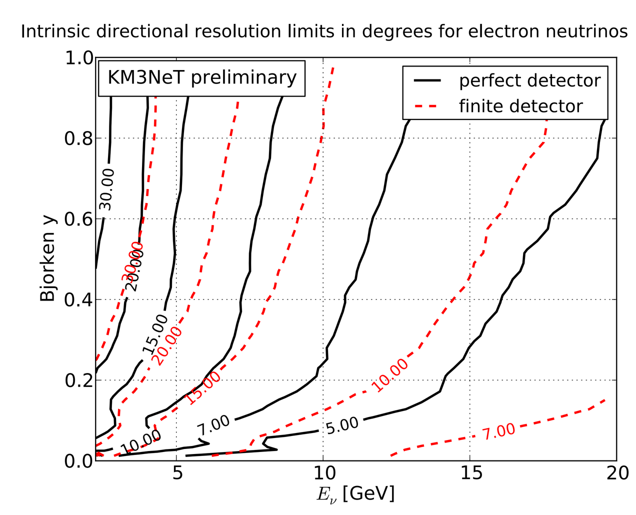
- Combining results to reconstructed neutrino properties

$$E_\nu = E_{e/\mu} + E_h \qquad \hat{p}_\nu = \frac{E_{e/\mu}}{E_{e/\mu}+E_h}\hat{p}_{e/\mu} + \frac{E_h}{E_{e/\mu}+E_h}\hat{p}_h$$

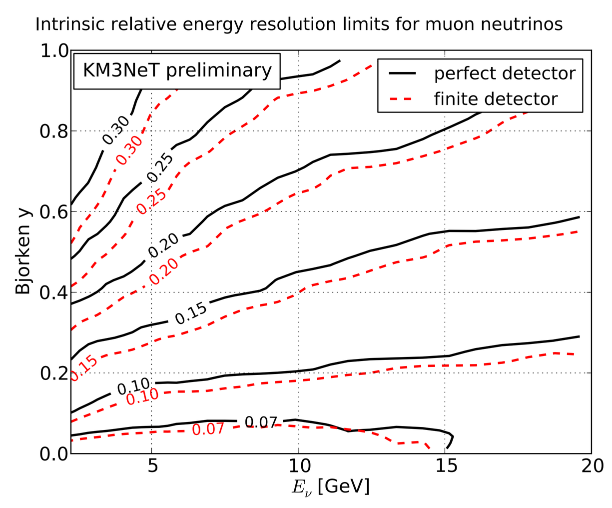
Energy resolution | **Direction resolution**

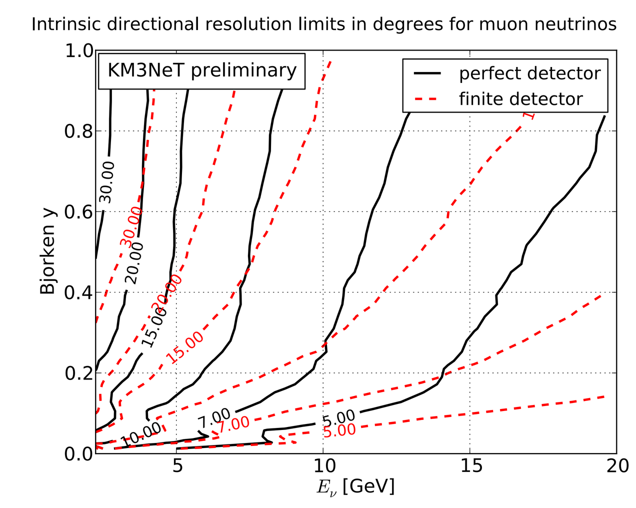
ν_eCC





ν_μCC





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