The km3 monte carlo package: description and performance

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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MANTS, Garching, Oct 2013

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ANTARES

KM3NeT

ORCA KM3NeT

Principles

Km3: photon propagation and PMT hits

- Some particles (fast or unstable) come near the detector – what do you see?
- Method 1: Full MC (HOURS, CLSIM, AASIM)
  - Simulate particles and light production
  - Track photons directly to detector to get hits
  - Time per event: $N_{photons}$ (+ small 'detector structure' term)
- Method 2: Histogramming (km3, photonics)
  - Simulate particles & light [many times; once]
  - Histogram output [imperfect process]
  - Sample over N dimensions to get hits
  - Time per event: $N_{pieces} \times N_{pmts}$
- Histogramming saves time at the cost of histogram inaccuracy.

Histogramming in km3 (and water)

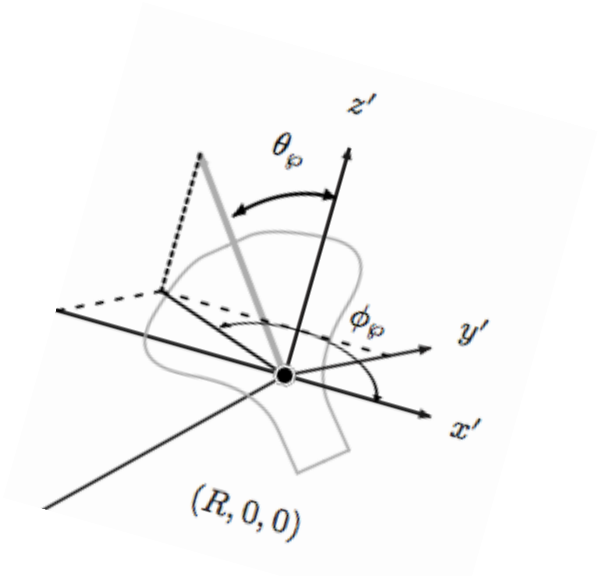
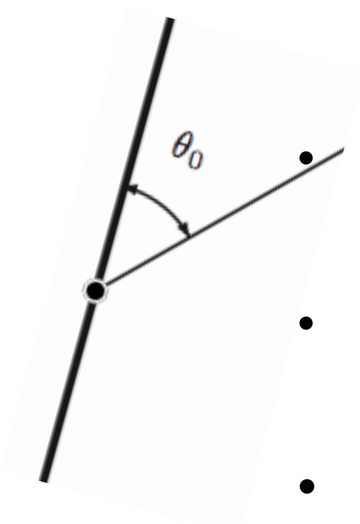
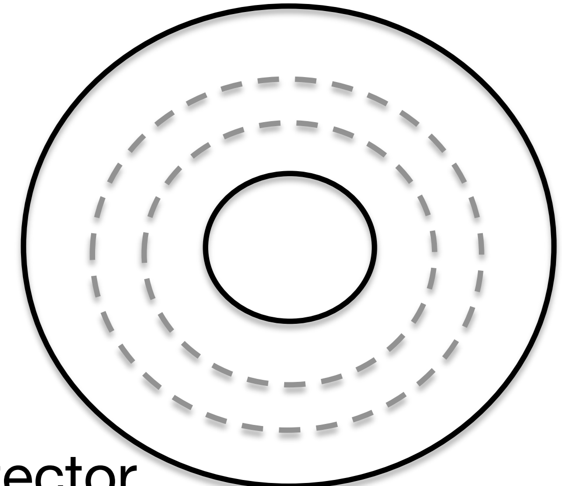


Fig. stolen from C. Kopper from when he was one of us

- Emitting particle type/energy
  - 4 electron energies (10^2, 10^3, 10^4, 10^5 MeV)
  - 1 muon energy (10^5 MeV)
- Distance from track segment
  - 18 log-spaced bins in r for all photons
- Angle from track segment
  - 1 bin for direct photons from muons
  - 20 bins for all other cases
- OM orientation (in angles θ,ϕ)
  - Direct: 40, Scattered: 240
- Hit times (t)
  - 100 bins in time
- Water isotropic: applies to entire detector





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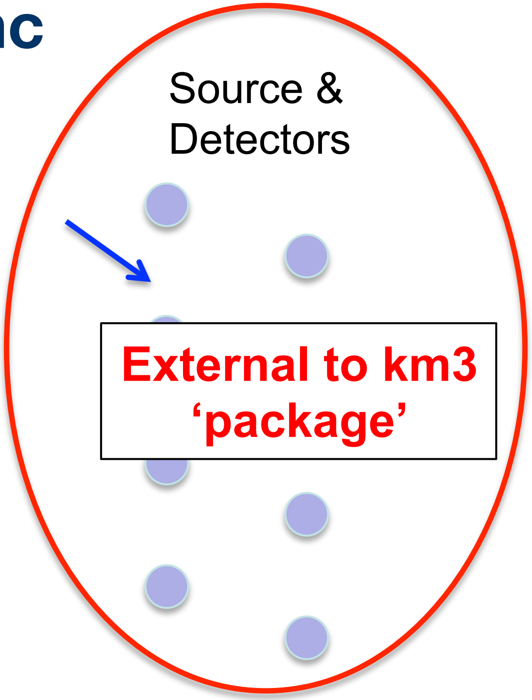
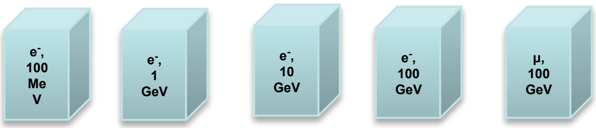
The km3 package: gen, hit, and km3mc



- Gen:
  - generate photons from (GEANT 3.21-simulated) short particle track segments
  - write photons to disk



- Hit:
  - read gen photons
  - create probability tables
- Km3mc
  - Step 1: generate muon & secondary tracks (use MUSIC)

km3mc

Physics packages called by km3

  - Step 2: : interpolate between, and sample from, tables to get photons from tracks → Detector hits
- Coded in fortran 77 ☹
- Now version 5.0: previous 4.5, 4.4 …

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Gen (physics lives here)

- Source simulation: GEANT 3.21
  - 1m minimum-ionising muon tracks
  - Single energetic electrons

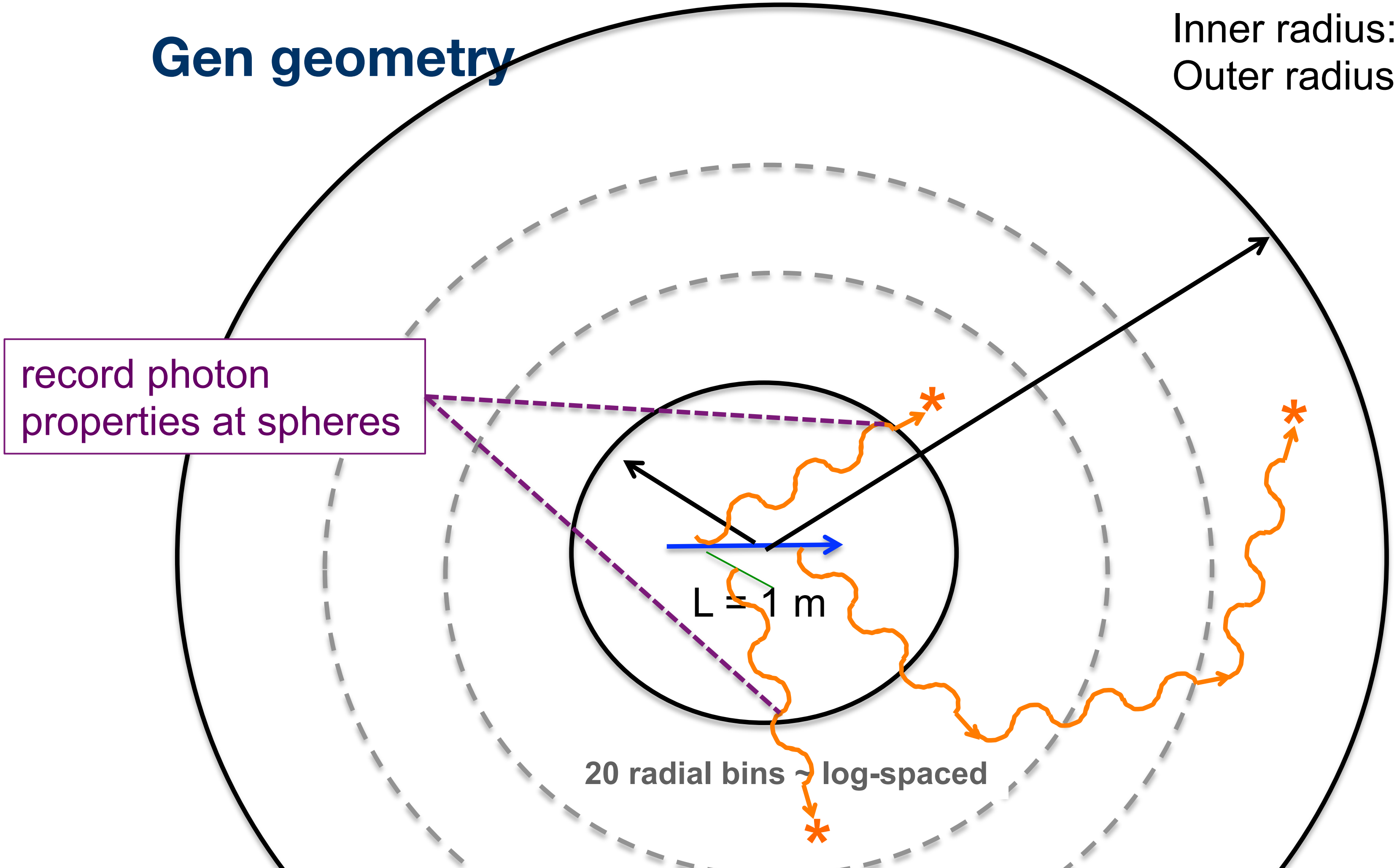
- Generate Cherenkov photons from GEANT sub-tracks.

- Propagates photons using (wavelength-dependent) scattering and absorption.

- Records photon properties to disk at each of several spheres.

Gen geometry

Inner radius: 2m
Outer radius: 194m



- **Problem:** Few photons make it to the outer shells: generate many photons
- Excess of photons on inner shells
- **Solution:** never absorb photons – weight by $\exp(-d/L_{abs})$

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Gen output:

- Writes photon information at each shell:

$$N_{\text{shell}},\ N_{\text{scat}},\ \vec{x},\ \vec{k},\ t$$

  - Writes only a fraction of the photons generated.
  - Fraction increases with distance
  - (less photons make it to outer shells)
- Repeat for:
  - 1 muon track energy (100 GeV)
  - 4 electron energies (0.1,1,10,100 GeV)
- Major disk-space requirement!
  - Total output size: ~90 GB
  - Run-time: <1 day. Do this once.

N_{shell}	current shell number
N_{scat}	number of scattering interactions
$\vec{x}$	position on shell
$\vec{k}$	direction vector & wavelength
t	time at shell

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Hit (the boring program)

- Photon list -> summary histograms
  - Reads photon data from Gen.
  - Fold in optical module response.
  - Make hit probability and hit time histograms

$$N_{\text{shell}},\ N_{\text{scat}},\ \vec{x},\ \vec{k},\ t$$
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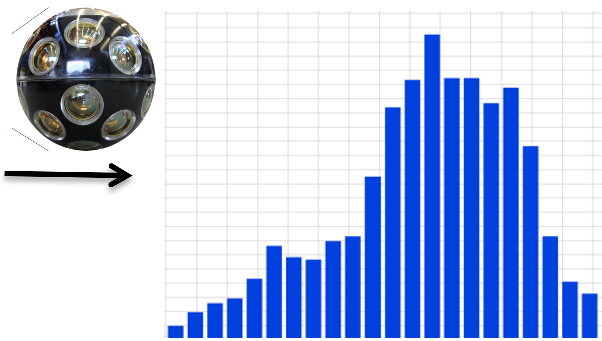

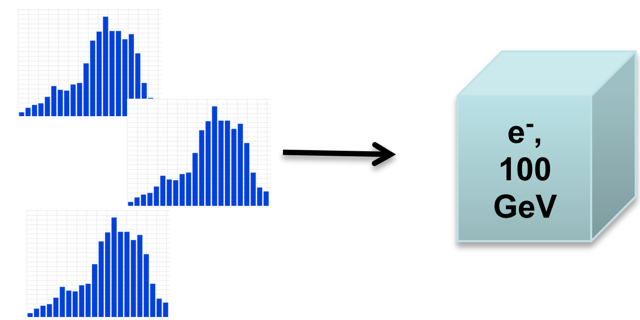

- Summary tables -> file.
  - Inverse cumulative time distributions & hit probabilities.
  - All tables for given [gen] particle type/energy
- *Completely deterministic*

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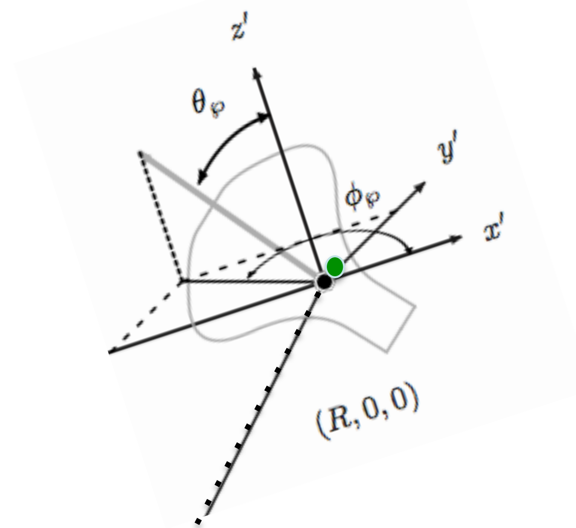
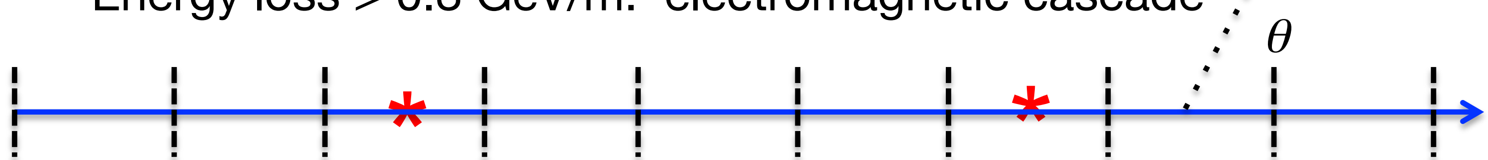
Km3mc: the program that gives you photons



- Inputs:
  - Detector geometry
  - Initial particles (muons + others)
  - Hit histograms
  - MUSIC muon propagator
- What it does
  - MUSIC propagates muon (2m track segments)
  - Energy loss > 0.3 GeV/m: 'electromagnetic cascade'



  - Interpolate geometry, get number and time of hits

Muon tracks: direct and scattered photons separate

Electron showers: direct added to scattered distribution

No hadronic cascades!

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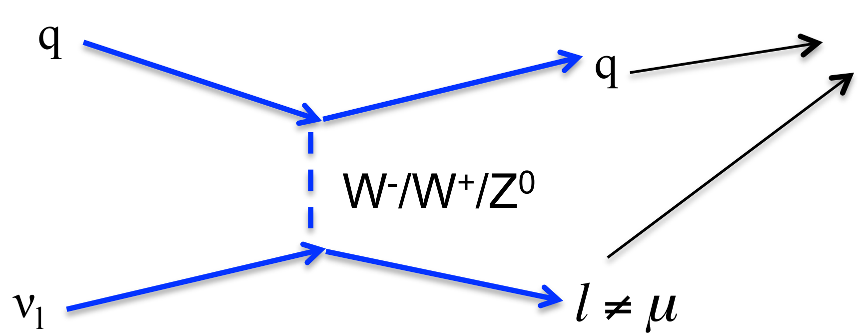
One Particle Approximation (OPA) Principles

- Two steps
  - #1: weight each particle with a 'Cherenkov light production efficiency weighting' w_i relative to an electron
  - #2: combine all weights from a cascade into one particle (e^-)



$$E_{e^-} = \sum E_i w_i(E_i)$$

$$\hat{v}_{e^-} = \frac{\sum \hat{v}_i E_i w_i(E_i)}{\sum E_i w_i(E_i)}$$

- OPA implemented in km3 v4r5
  - Weights functions of energy
  - Weights for miscellaneous particles (e.g. κ^+, p, n) currently calculated as per pions

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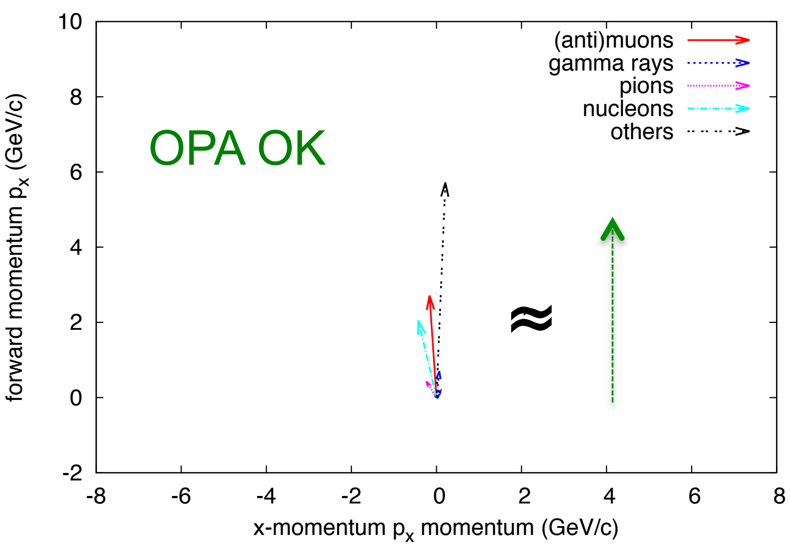
Problems with OPA at ORCA energies

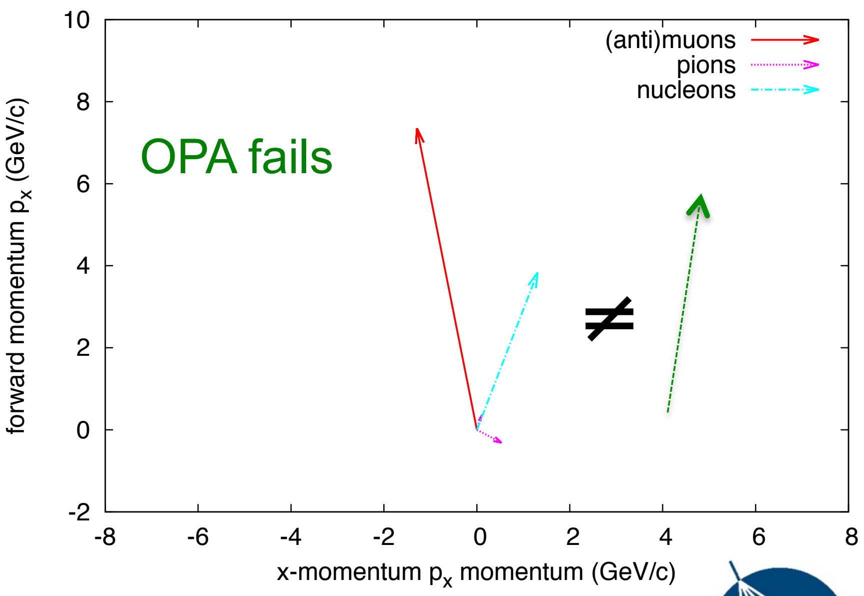
- Low-energy regime:
  - Rest-mass significant
  - Current OPA: crude adjustment for rest mass
  - Hadrons behave differently

$$w_p\left(E_p\right) = w_\pi\left(E'_p\right)$$

$$E'_p = E_p - \left(M_p - M_\pi\right)$$

- Significant angles:





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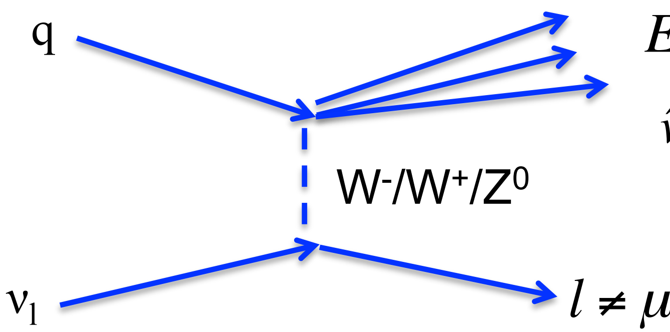
Multi-Particle Approximation (MPA) Principles

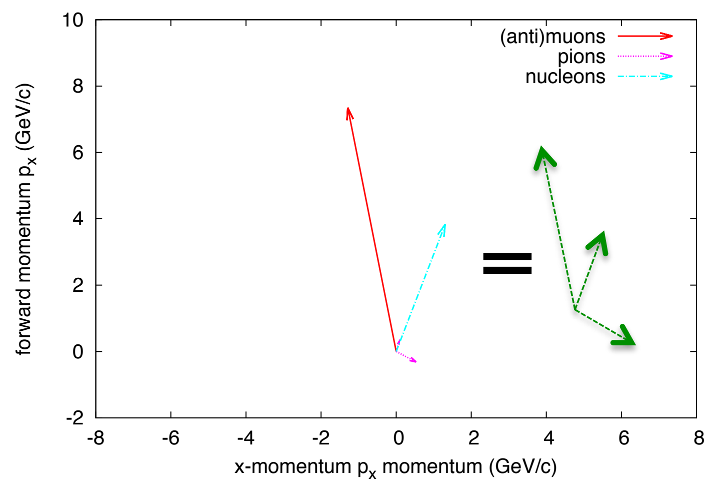
- ~~Two~~ One step~~s~~
  - #1: weight each particle with a ‘Cherenkov light production efficiency weighting’ w_i relative to an electron
  - ~~#2: combine all weights from a cascade into one particle (e^-)~~

    treat each particle as an electron with its original direction



$$E_i^{'} = E_i w_i \left(E_i, \mathrm{id}_i \right)$$

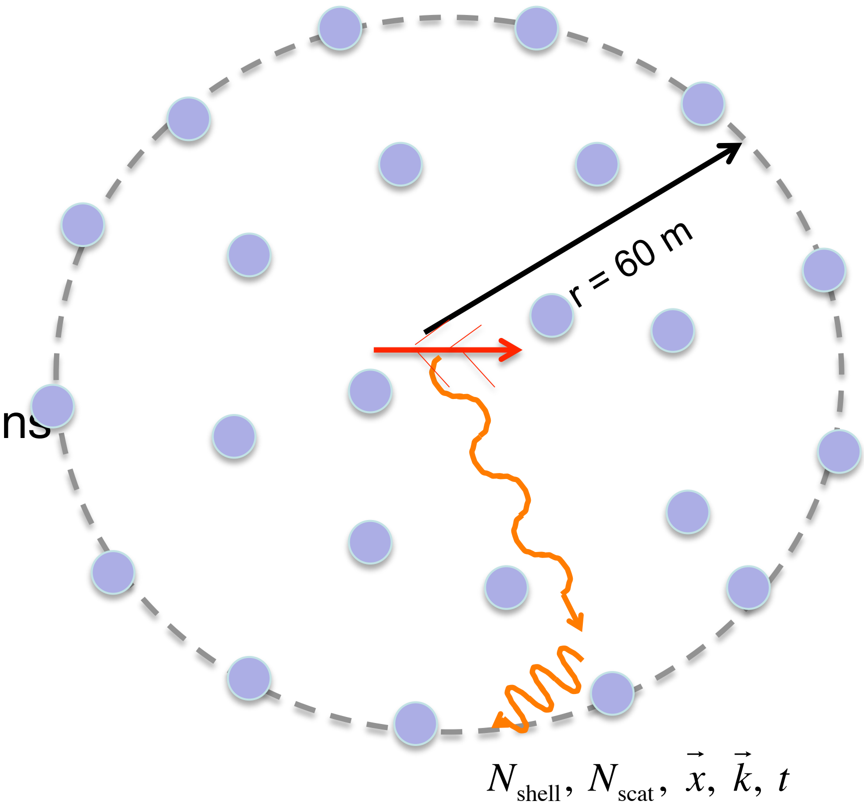
$$\hat{v}_i^{'} = \hat{v}_i$$



KM3: Performance

Histogramming tests – 'spheres'

- How to test km3 histogramming?
- Compare it to actual gen output!
- Gen:
  - Place EM cascade at origin
  - o/p: photon times on spheres
- Km3:
  - Sphere of 1000 OMs
  - 1000 EM showers w random orientations
  - x10 artificial photons for better stats
- Histogramming:
  - Averages over all angles
  - Single radial and energy interpolation
- *Total normalisation will be arbitrary*



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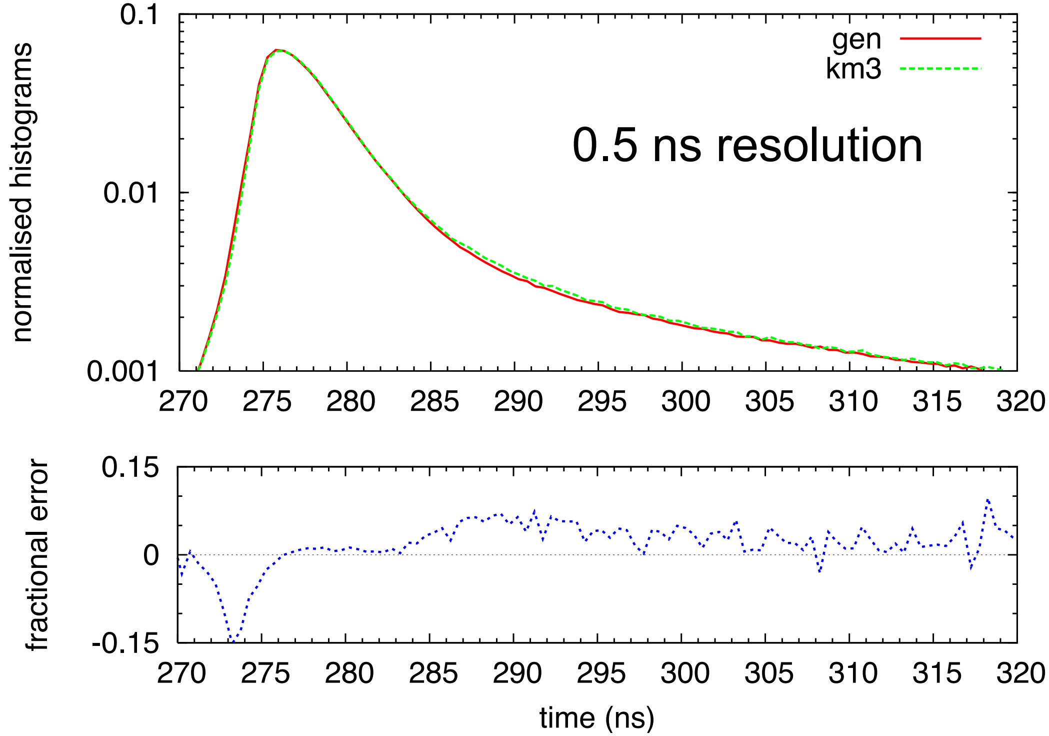
Results – worst case

- Gen 33 GeV electrons (bins at 10-100 GeV)
- 60m radius (bins at 55 and 67 m)



- 5ns resolution: 5% maximum error in very fine time detail (expect 3% from random PMT orientations)

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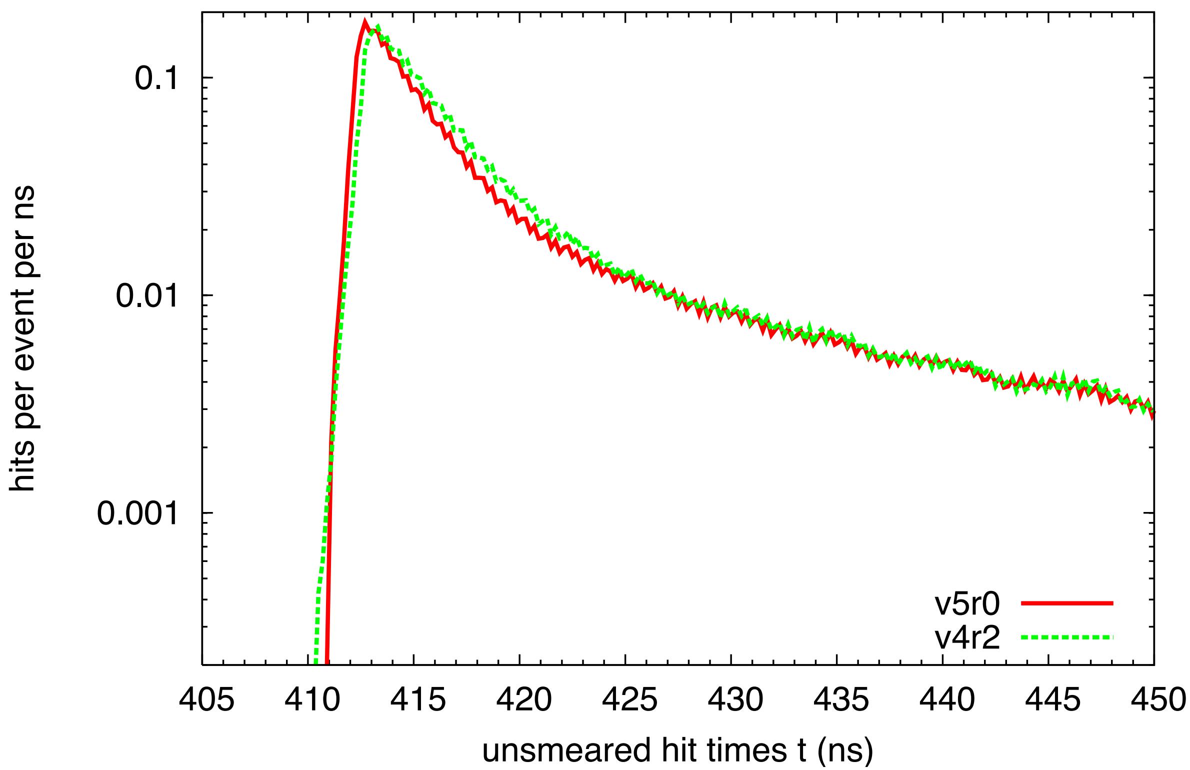
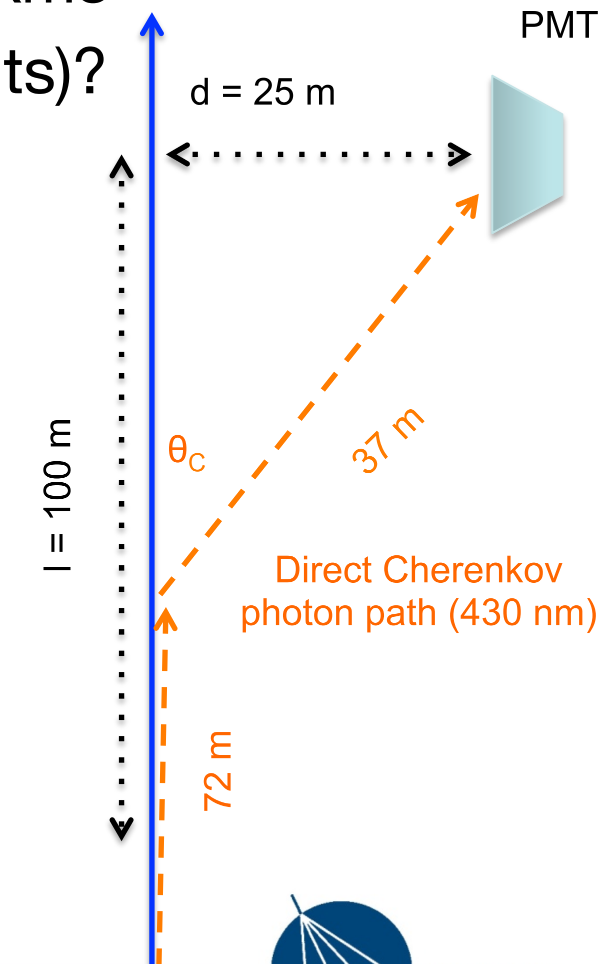
Performance: muons

- Compare new and old versions of km3
- How stable is it (inc. changing inputs)?





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Performance: OPA

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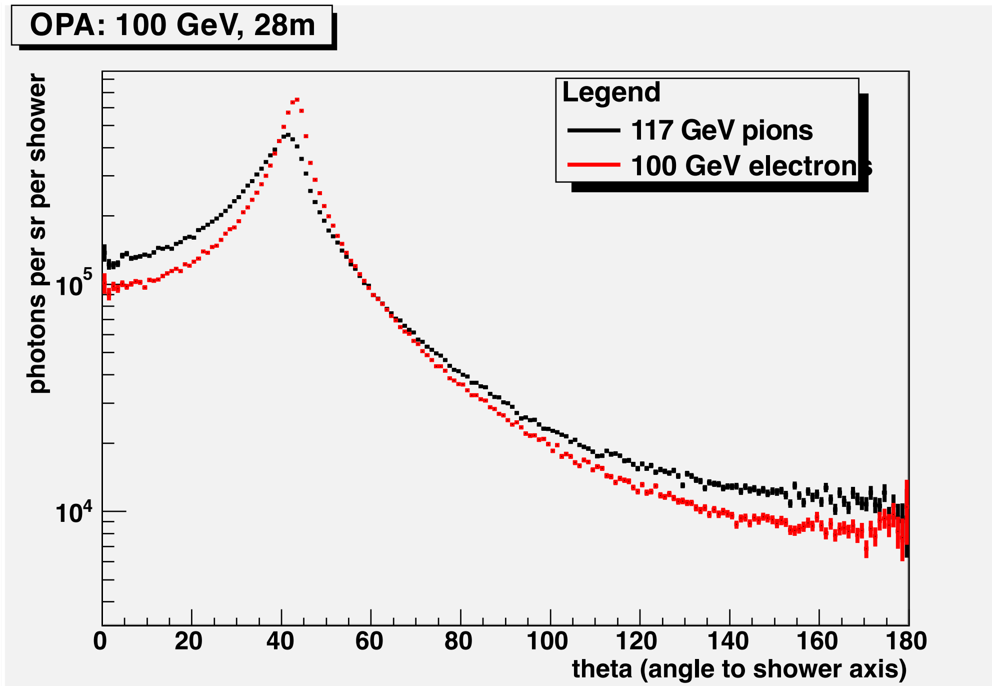
OPA performance: ANTARES

Characteristic distance: 28m

$$w_{\pi}(117 \text{ GeV}) = \frac{100}{117}$$

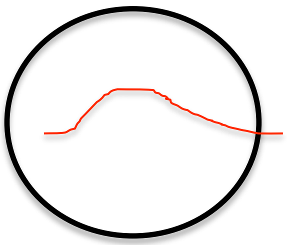
Run 100 GeV e⁻ and 117 GeV π through gen and compare!

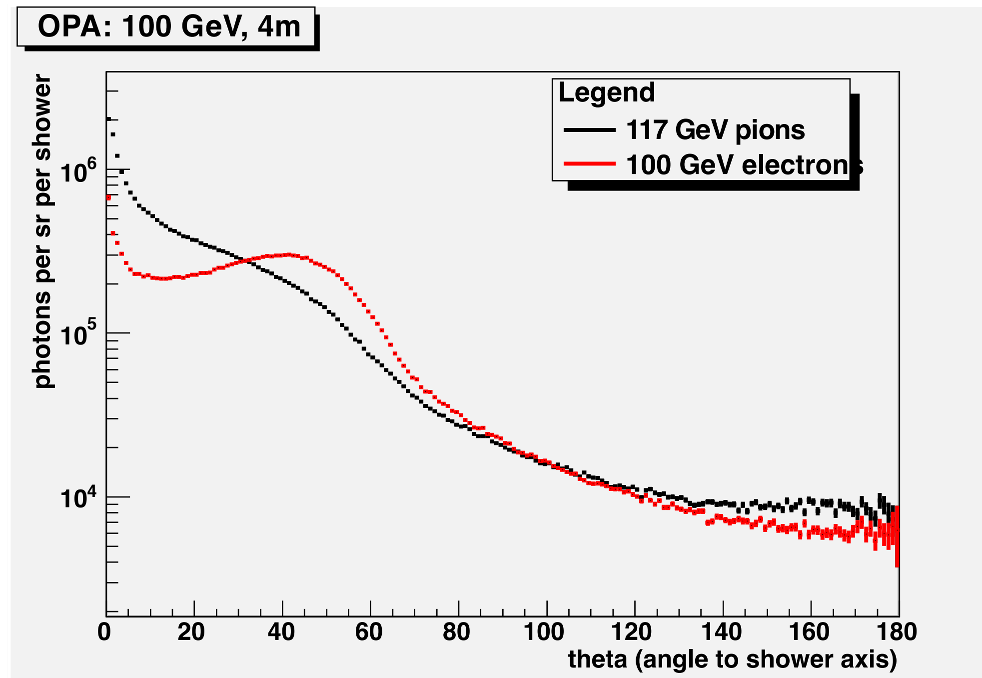


- 28m: small changes in distribution evident
- Very large speed-up: this is important!
- Will be better for KM3NeT

OPA performance: ORCA (smaller distances)

Photon distributions at 4m





- Small distances – cascade structure becomes visible
- Might be important for ORCA

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Summary

- Km3: current simulation package to model ANTARES detector response
  - Incomming muons -> muon tracks and EM sub-showers
  - Sources -> photon hits
  - Accuracy limited by knowledge of e.g. scattering, absorption
  - Used also (but not solely) for KM3NeT and ORCA
- Handles hadronic cascades via one-particle approximation
  - KM3NeT/ANTARES: ‘pretty good’
  - ORCA: some open questions
- Constantly updated – current version v5r0