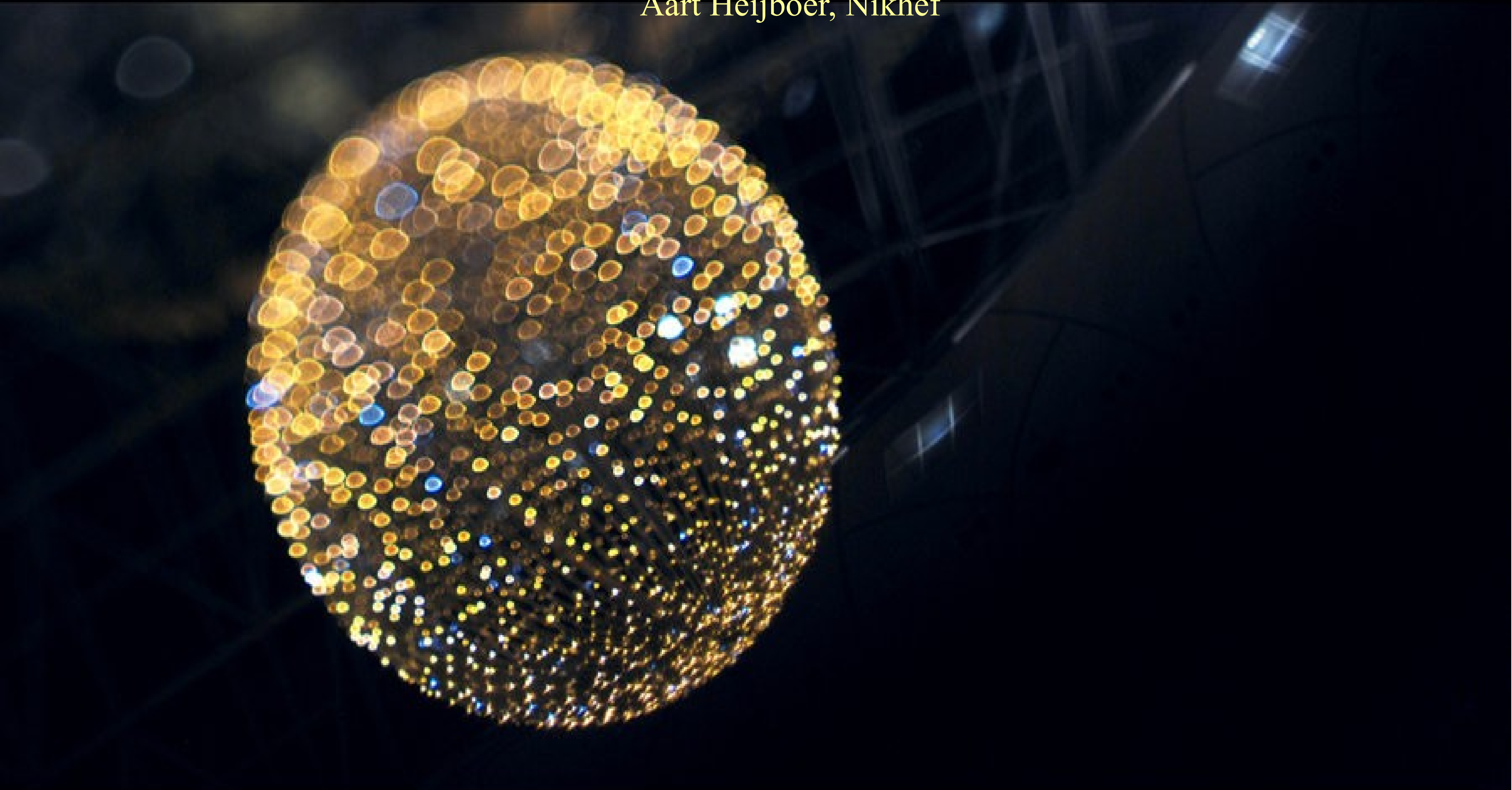
Cascade reconstruction in KM3NeT (& Antares)

Aart Heijboer, Nikhef



all plots are MC-only
and “preliminary”

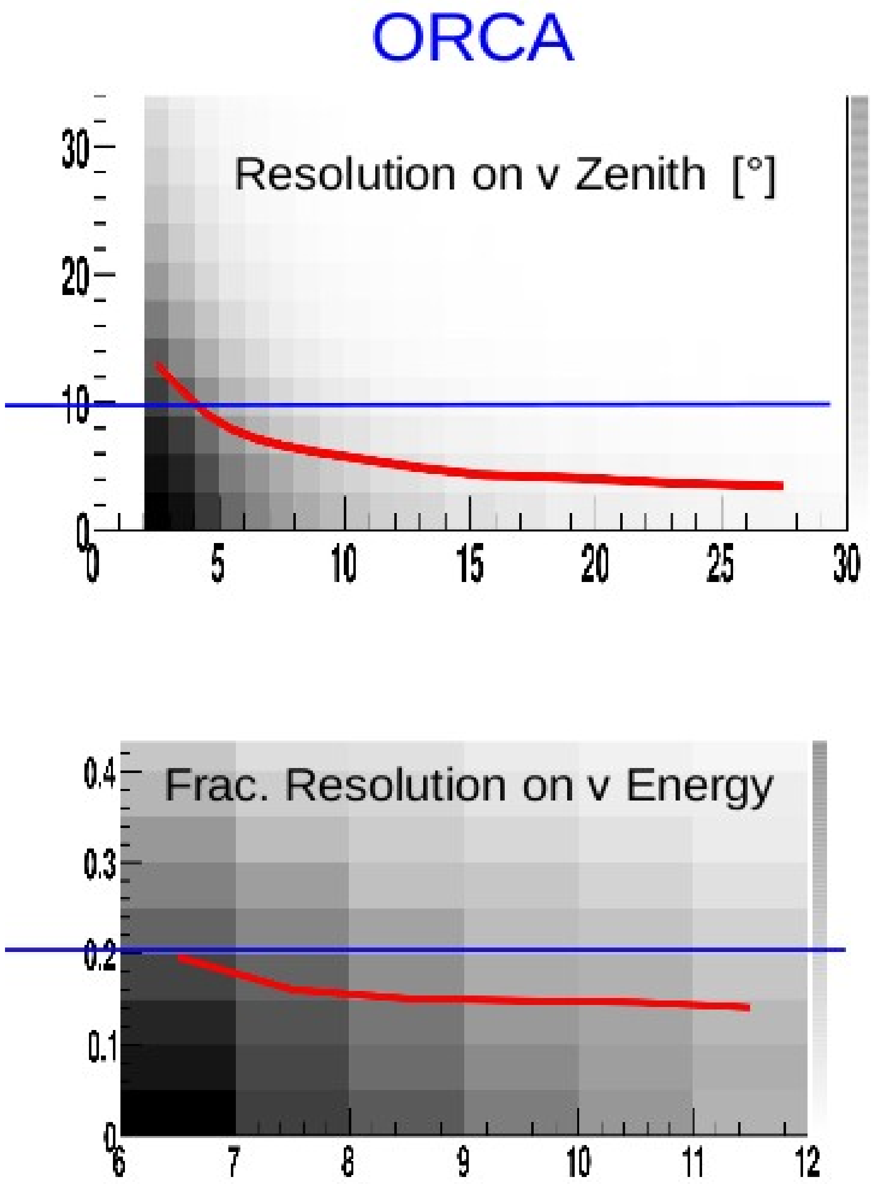
Motivation

- As detectors become larger →cascade/track ratio grows
- All cascades look the same (contrary to muons)
 → potential to have very clean signal and 100% efficiency.
- Potential for *very* good energy resolution → line searches
- Physics backgrounds (atm. nu) are low → can use in point source searches despite worse angular resolution.
- Step-up to nu-tau detection
- When we have a source, lot's of physics is the flavour ratios

Disclamer

This talk is about method high energy cascades that are currently used in KM3NeT.

Will not talk about:
– Very promising results for ORCA (J Hofestaedt talk this morning)
– Other algotihms that are under development in ANTARES.



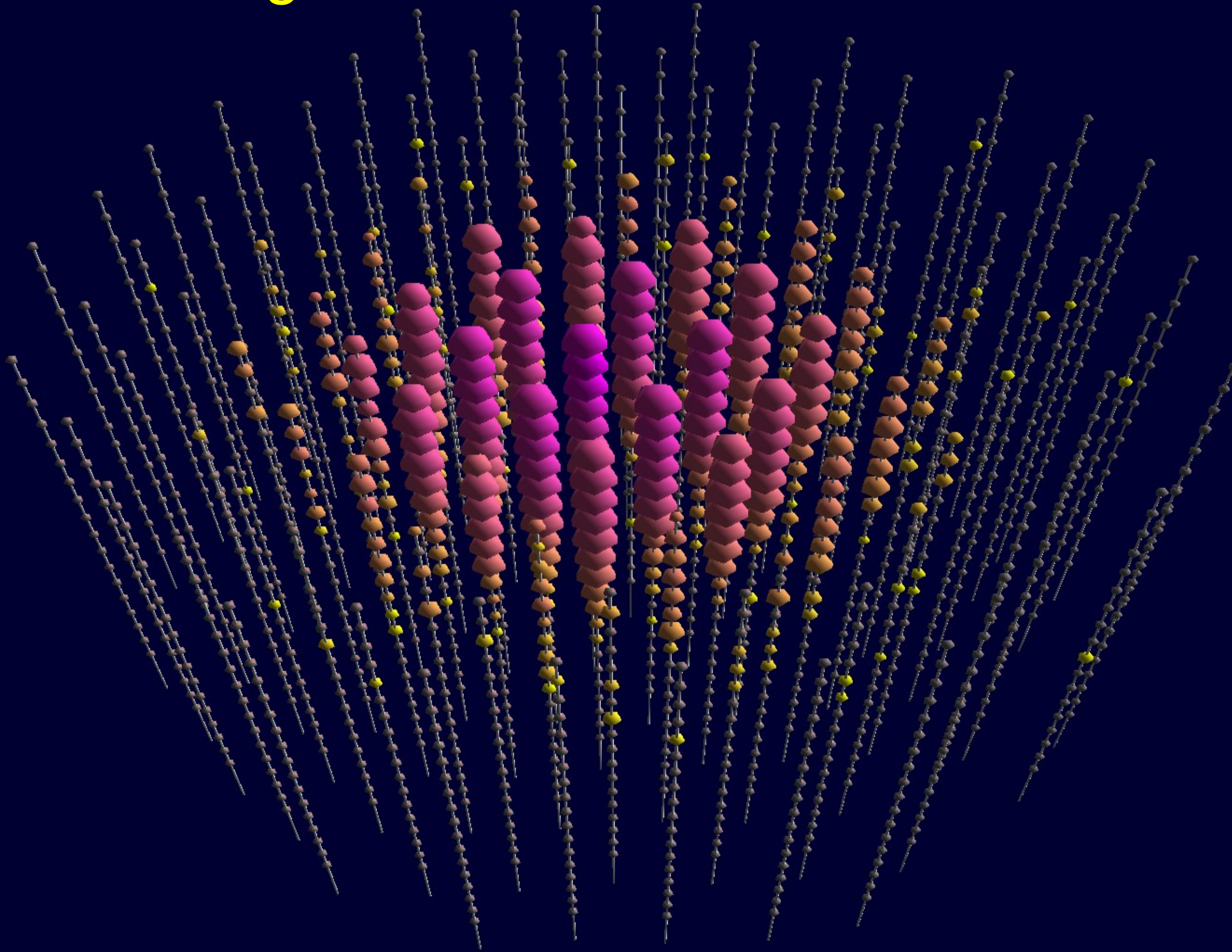
In KM3NeT

three algorithms:

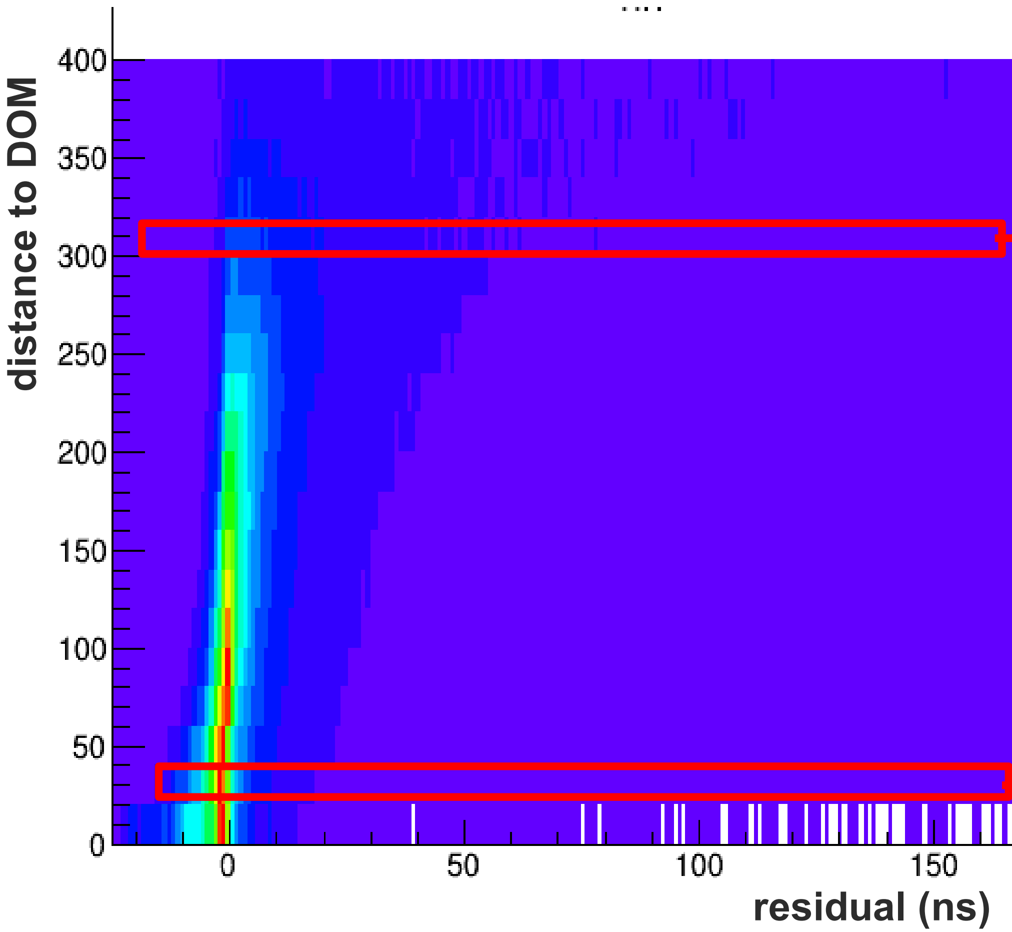
name	trajectory	vertex fit	direction fit
Algorithm 1 (Q-strat):	Antares → KM3NeT	x	
Algorithm 2 (Dusj) :	Antares → KM3NeT	x	x
Algorithm 3 (aashowerfit):	KM3NeT → Antares	x	x

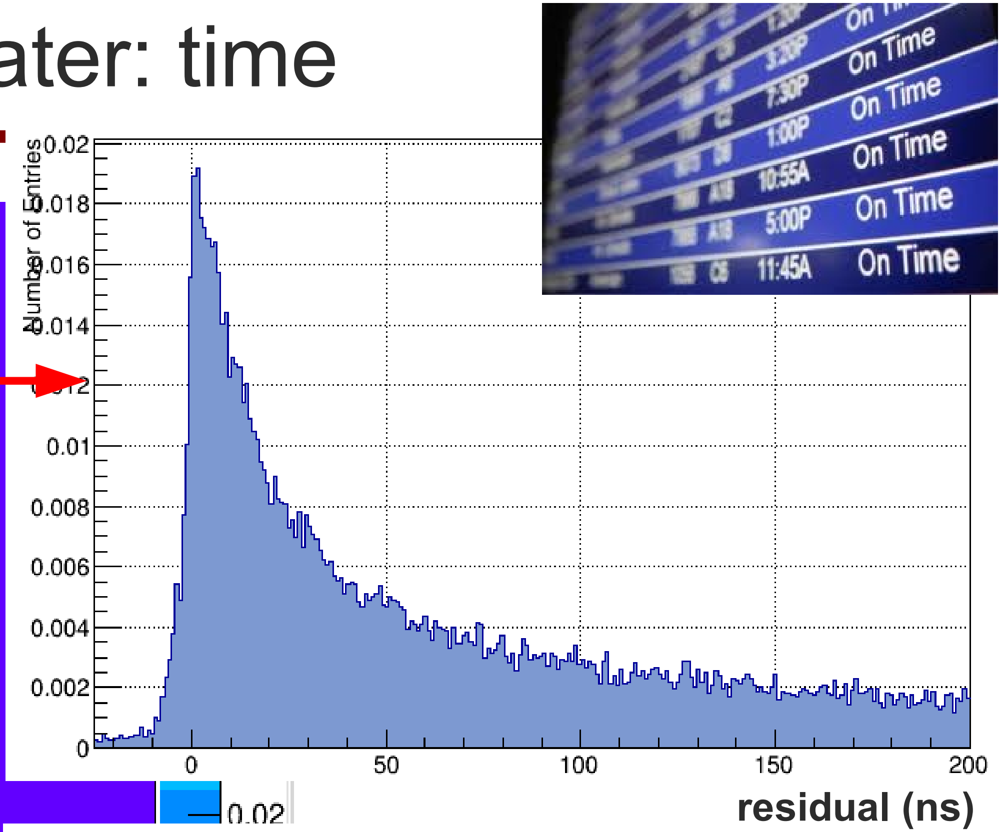
1 & 2 have been used for phase 1.5 sensitivity studies
2 has been used in antares for latest diffuse flux search (previous talk)
3 is recent development with good prospects

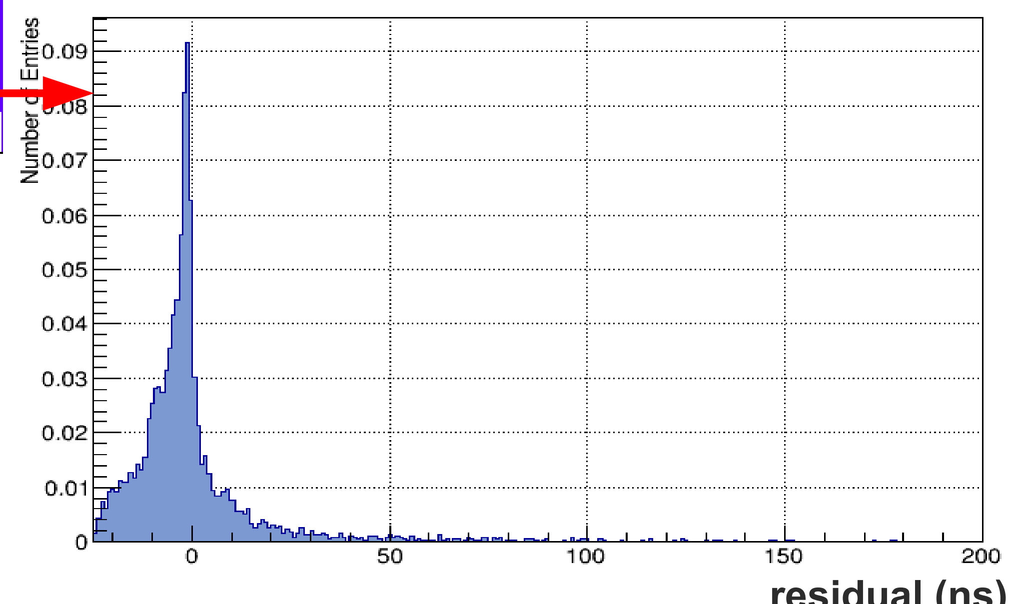
Cascade signature in water



Cascade signature in water: time

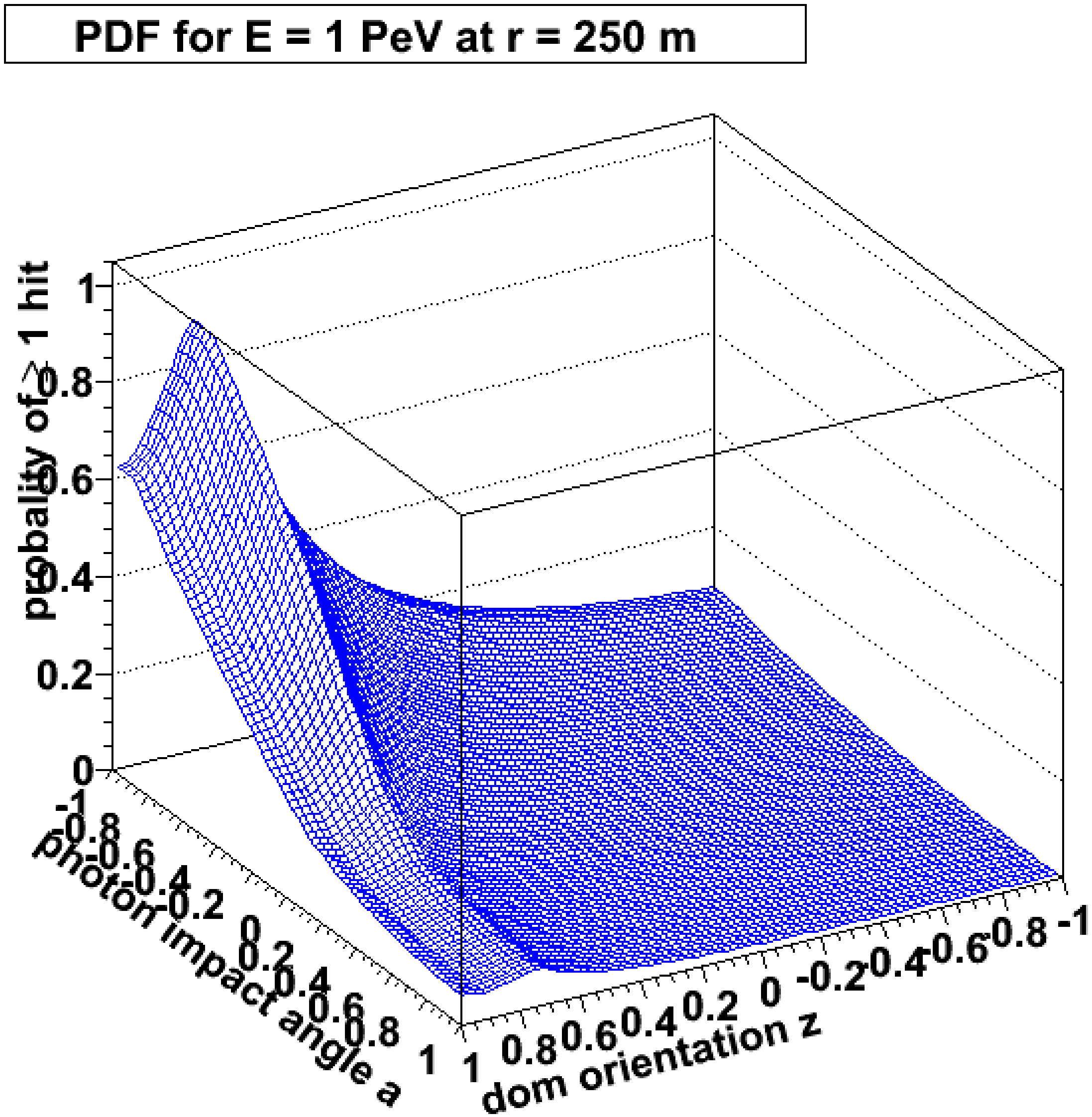






- spherically expanding shell of light
- allows accurate vertex resolution

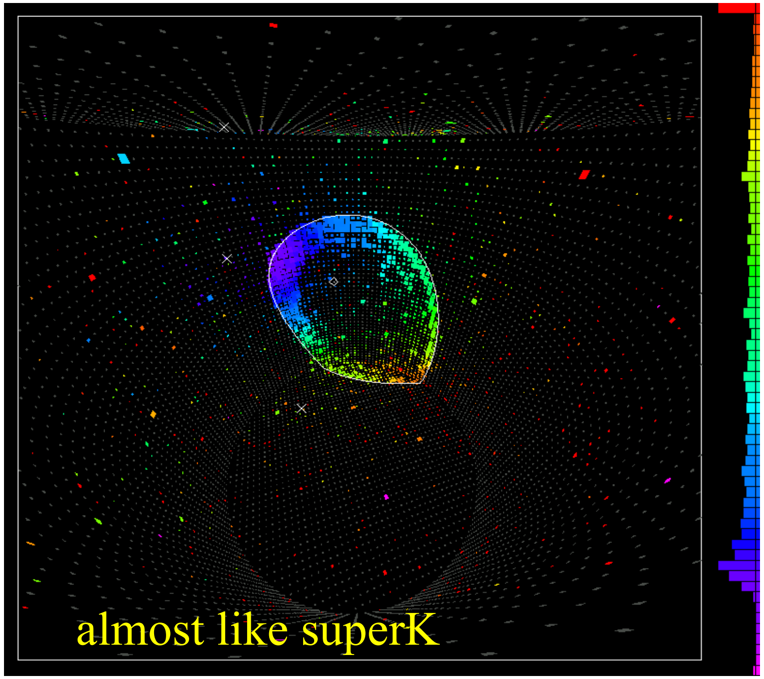
Cascade signature in water: intenstity



– Light is beamed in the Cherenkov direction.

– Pattern remains at large distances from the shower.

-- energy independent!



need to measure the light amplitude (ToT)

Algorithm 1

1. Pre-hit selection
   - Minimal hit selection (triggered hits)
2. Vertex reconstruction – prefit; mean light direction
   - Vertex prefit → mean-space-time of hits
   - LightDirection → average of the versor from the first hit to the following
3. Post-hit selection:
   - Coincident hits on DOMs && Largest hit among the coincidences && causal connection + residuals window wrt the prefitted vertex
4. Vertex reconstruction – final fit:
   - M estimator with selected hits, using the prefit as starting point for minimization
5. Shower light direction; energy estimation:
   - ShowerLightDirection → as LightDirection but wrt the fitted shower with sel. hits
   - Energy estimation → Total ToT of sel. hits rescaled to the distance from the fitted vertex

Algorithm 1

1. Pre-hit selection
   - Minimal hit selection (triggered hits)
2. Verte

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3. Post-

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4. Verte

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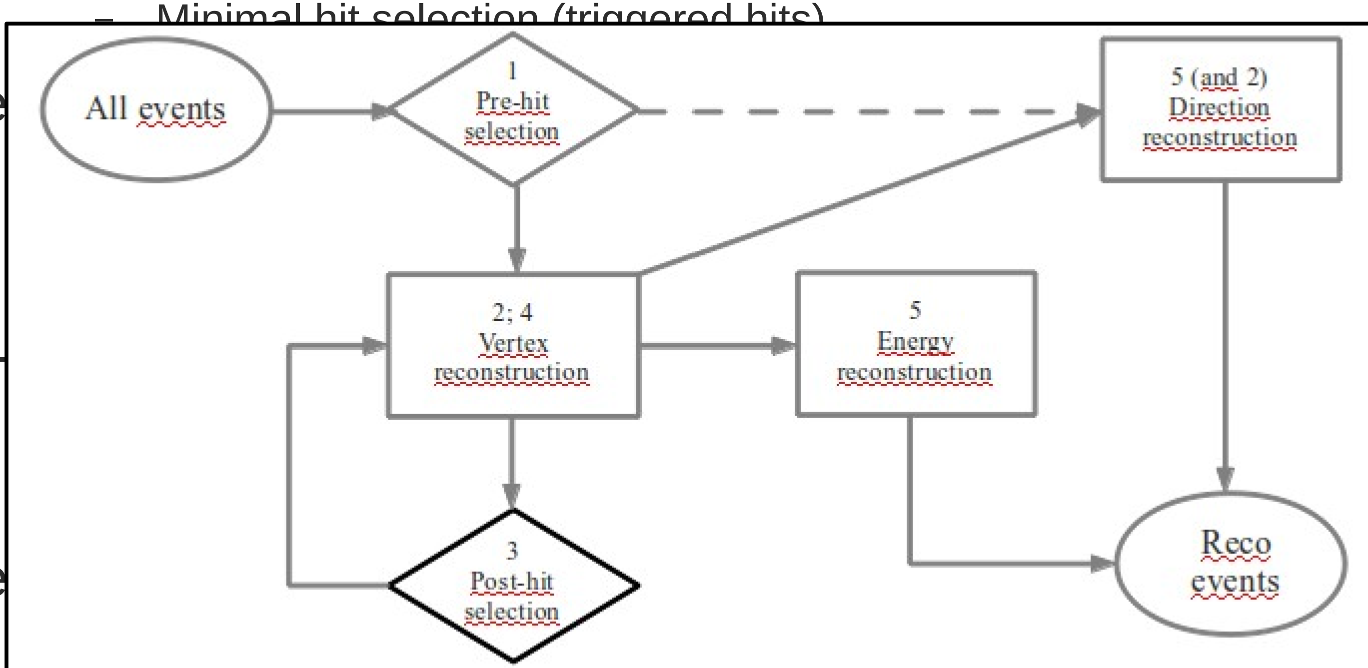
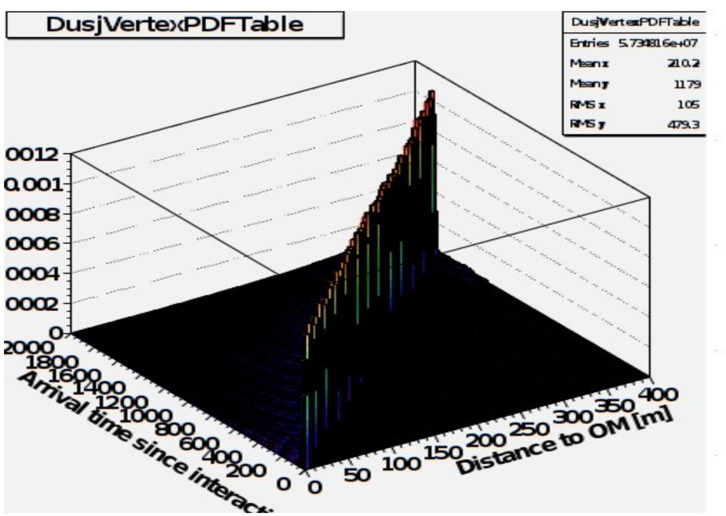
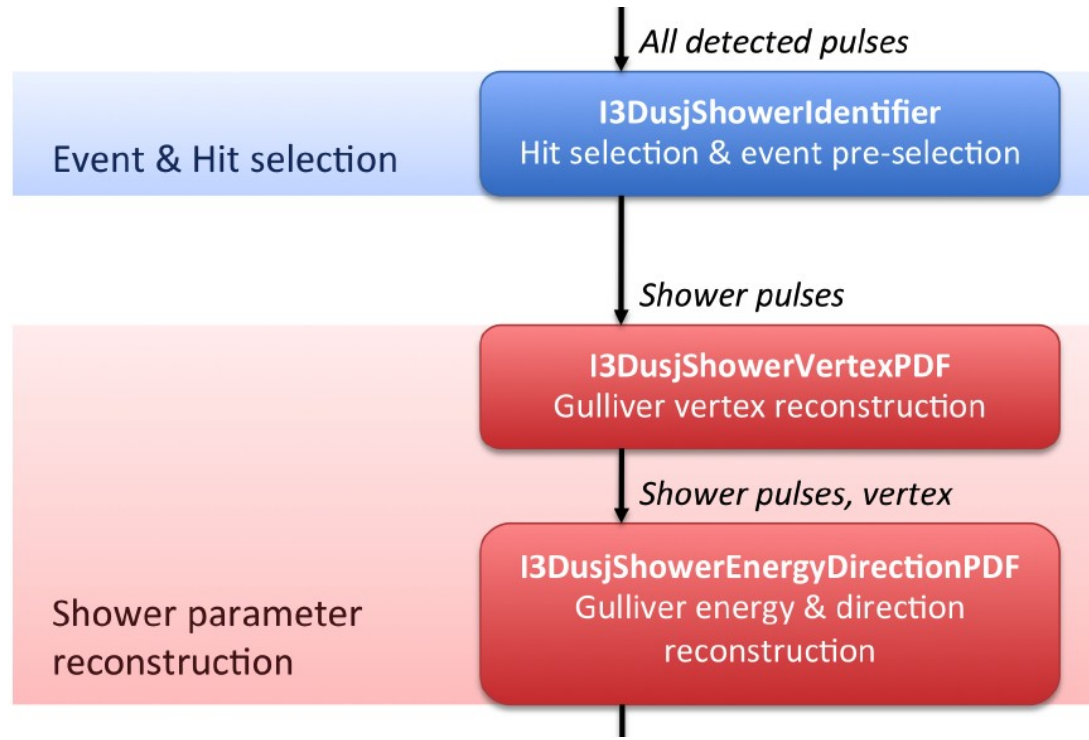


5. Shower light direction; energy estimation:
   - ShowerLightDirection → as LightDirection but wrt the fitted shower with sel. hits
   - Energy estimation → Total ToT of sel. hits rescaled to the distance from the fitted vertex

Algorithm 2 overview

- Used for mature Antares analysis
- Adapted to KM3NeT
- Likelihood Method
  - PDF from monte carlo
- Independent reco for
  - Vertex
  - Energy/Reconstruction



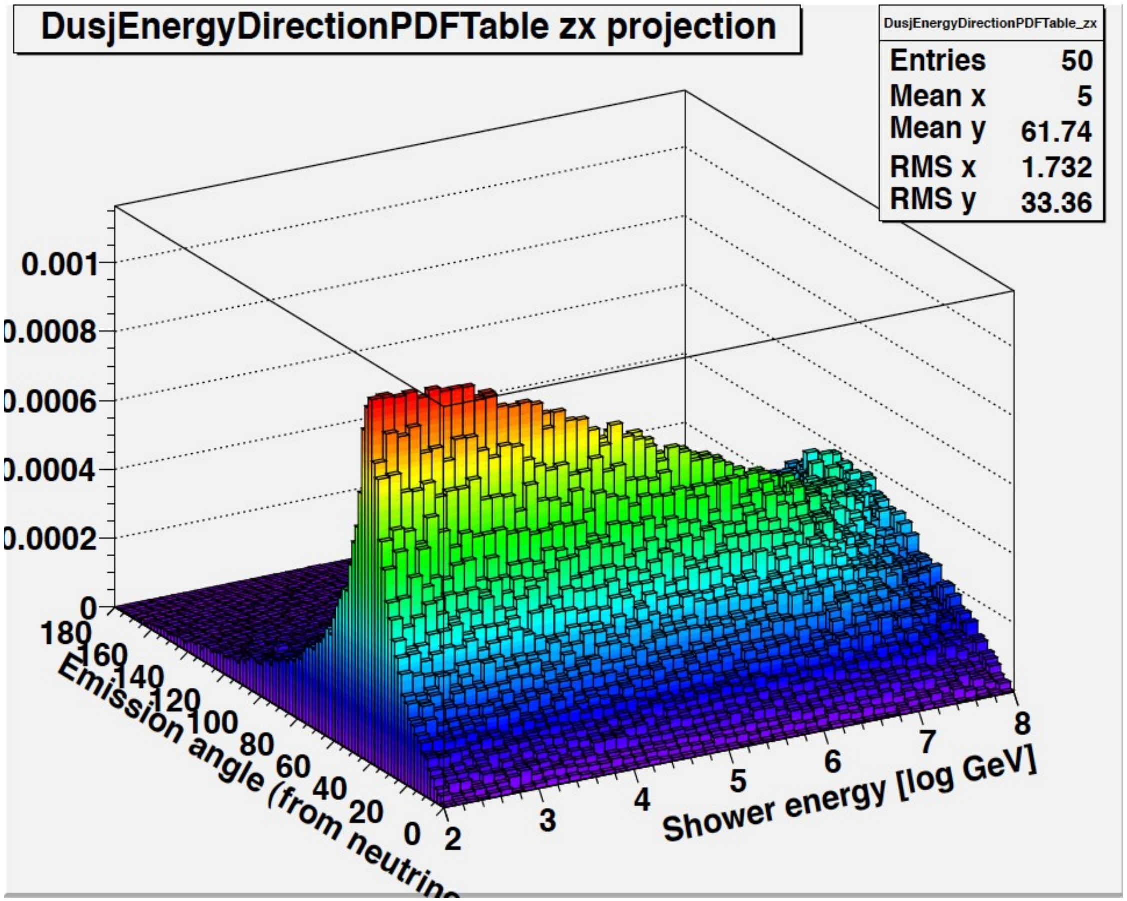


Algorithm 2: Direction and energy reconstruction

- PDF with 3 variables
  - shower energy
  - emission angle
  - 'vertex charge'

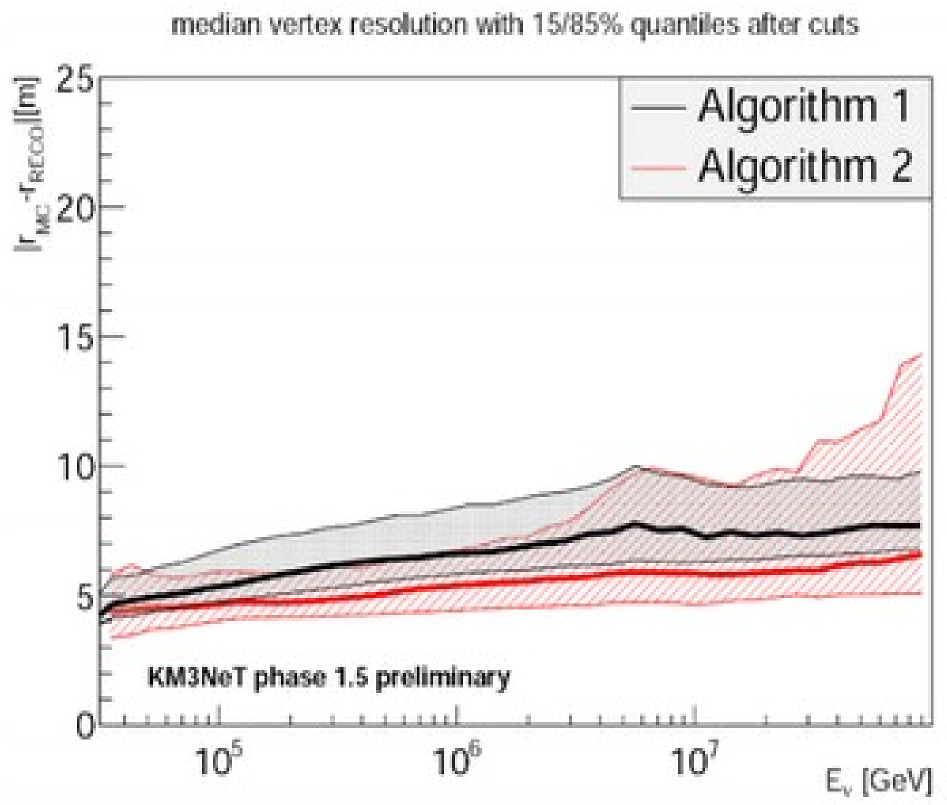
vertex charge: number of photons that should have been emitted from shower to produce observed ToT.

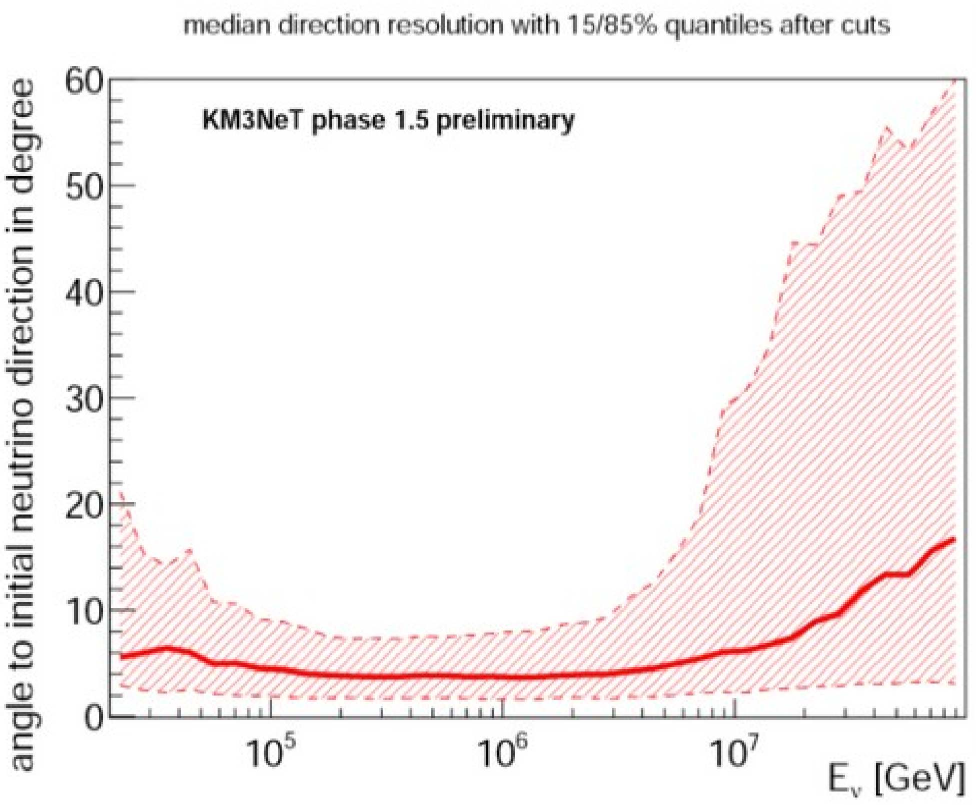
- cherenkov angle visible in PDF slice.
- saturation at high energies



Algorithms 1 & 2: position and direction reconstruction

after analysis cuts (BDT, energy) – see Luigi's talk

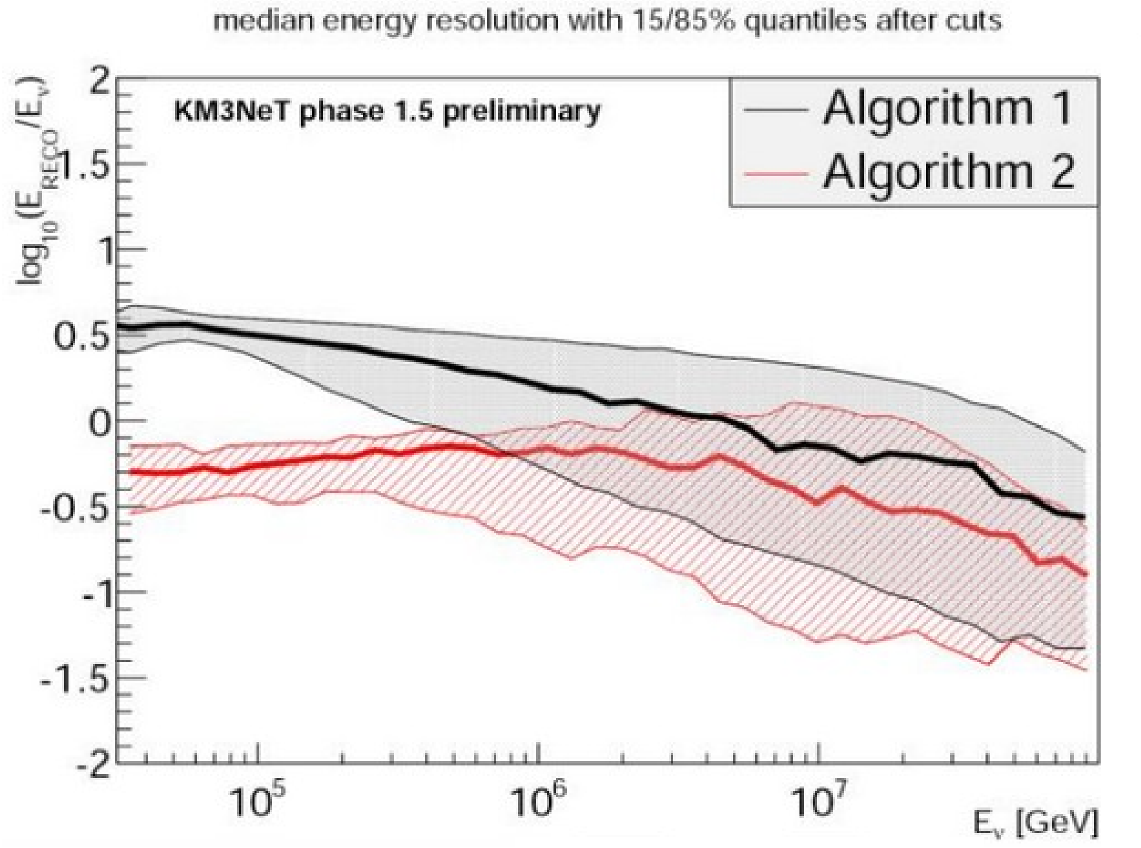




- distance to neutrino vertex (not the full story – see later)
- comparible resolutions for both

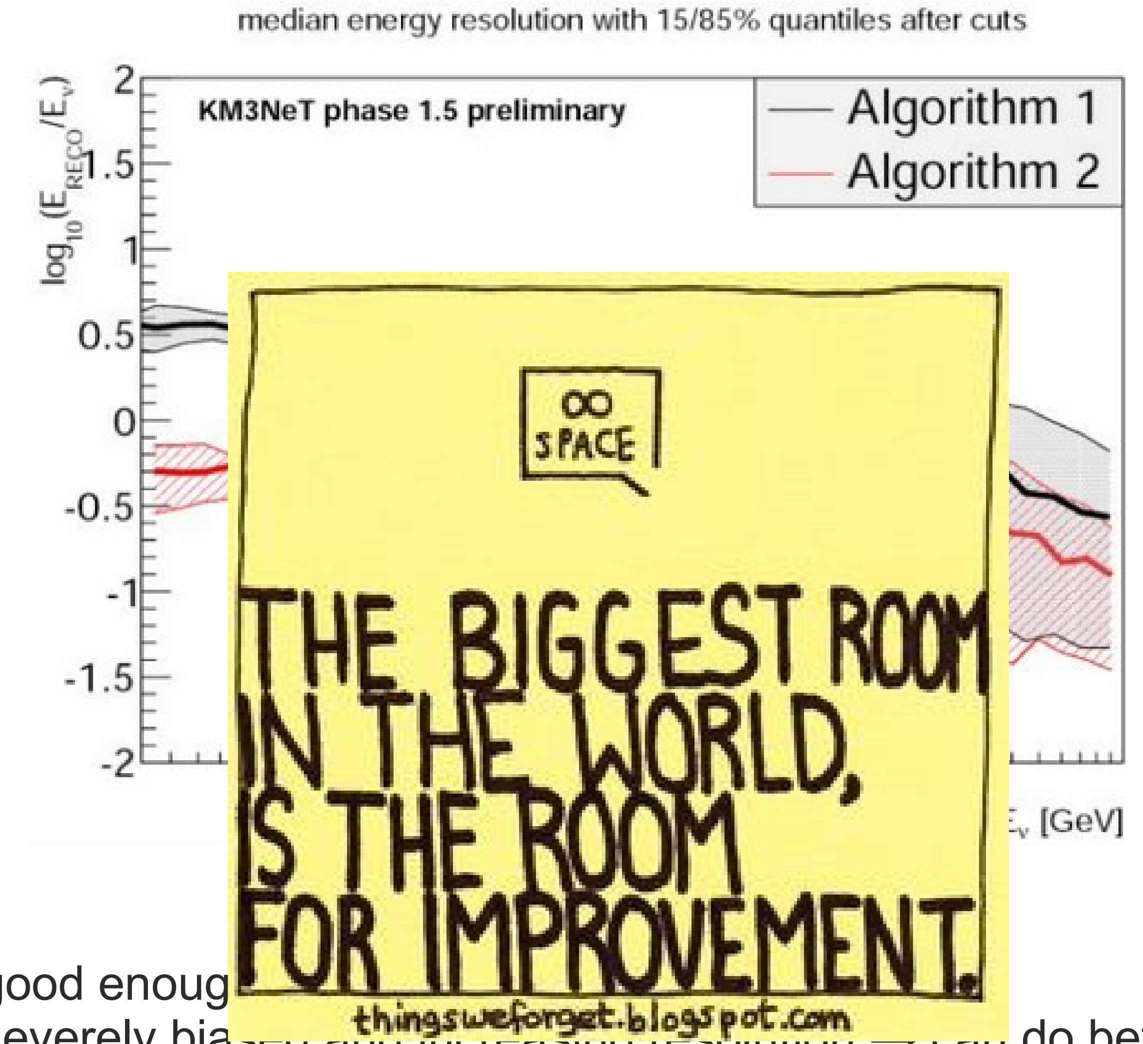
- Algorithm 2: around 4 degree resolution

Algorithms 1 & 2: energy reconstruction



-- good enough for cutting on, but
-- severely biased and increasing resolution → can do better

Algorithms 1 & 2: energy reconstruction



-- good enoug

-- severely biased and increasing resolution → can do better

14

algorithm 3

same idea again:

-- hit selection (resembles "bb-fit")

– vertex fit (m-estimator) using hit times

– direction reconstruction with likelihood for light intensity.
  – start at 12 different directions to increase chance to find global minimum

we are reinventing the wheel (and learning in the process).

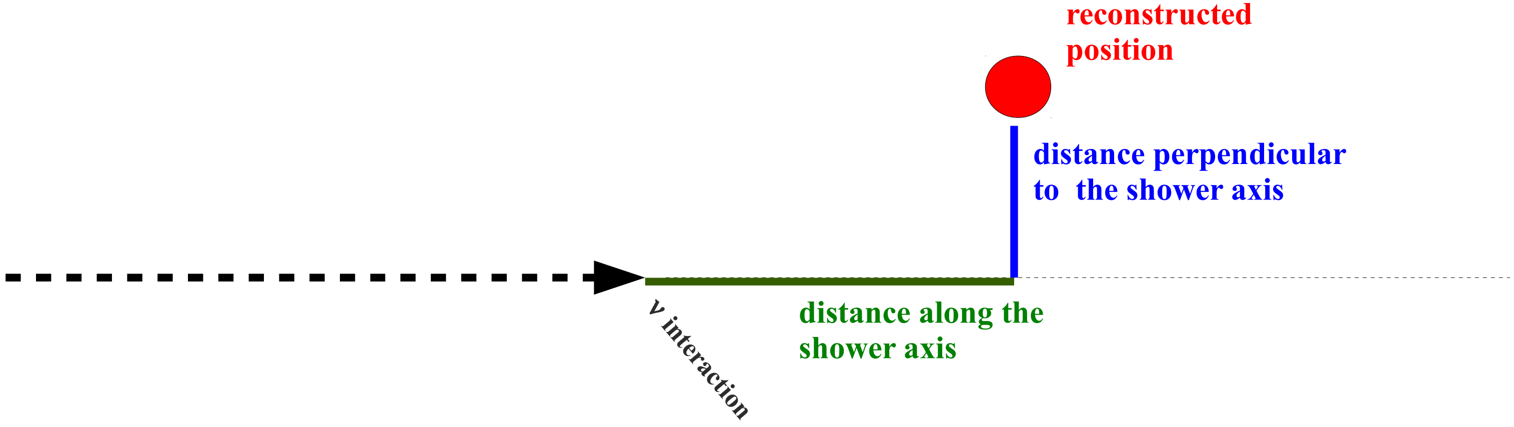
position fit

– shower is extended (several m), but photons look very much like they are emitted from a single point at the same time.

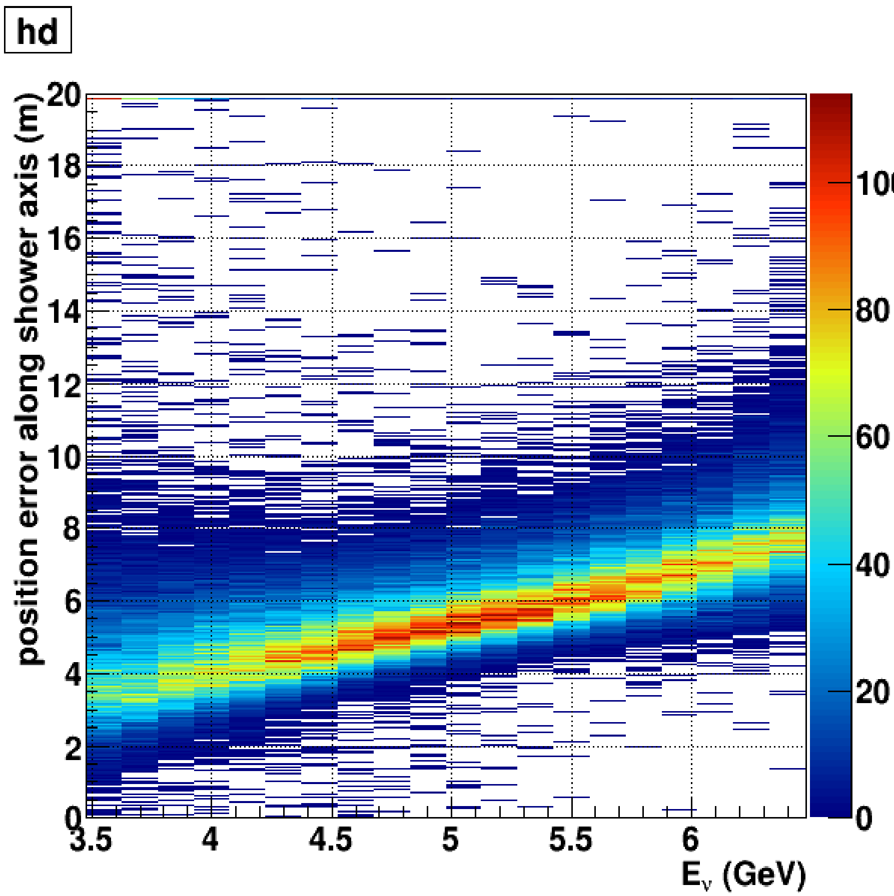
– shower position and time fitted by M-estimate of the hit residuals

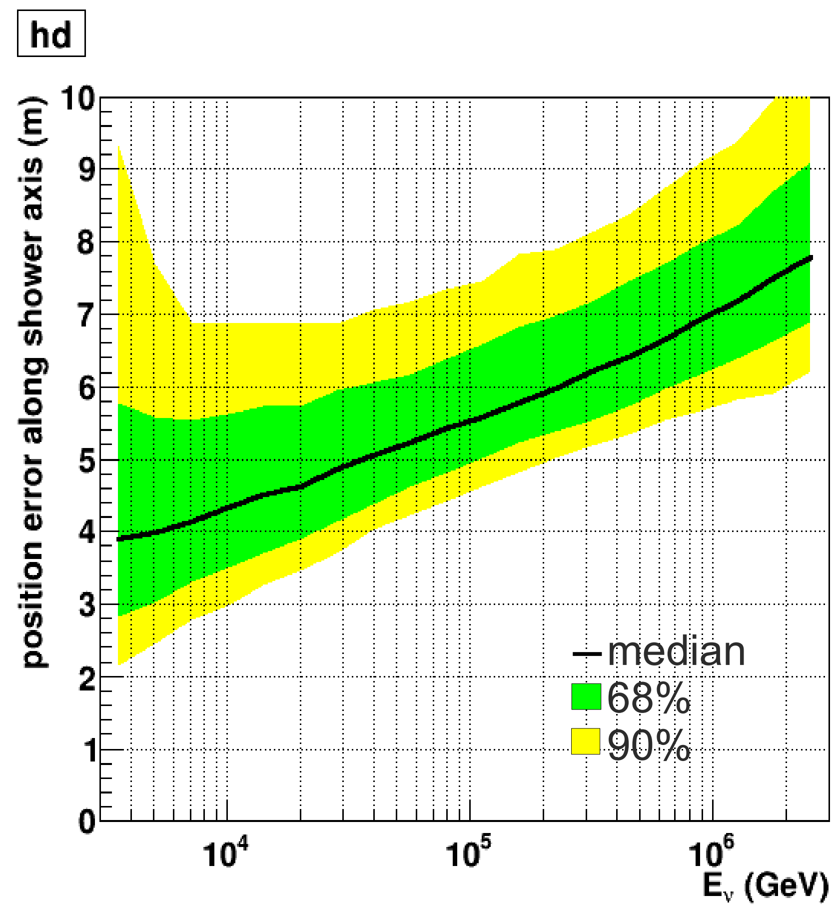
residual r = hit.t – | hit.pos – **shower.pos** | / v + shower.t

$$M = \sum_{\text{hits}} \sqrt{1 + r_i^2}.$$



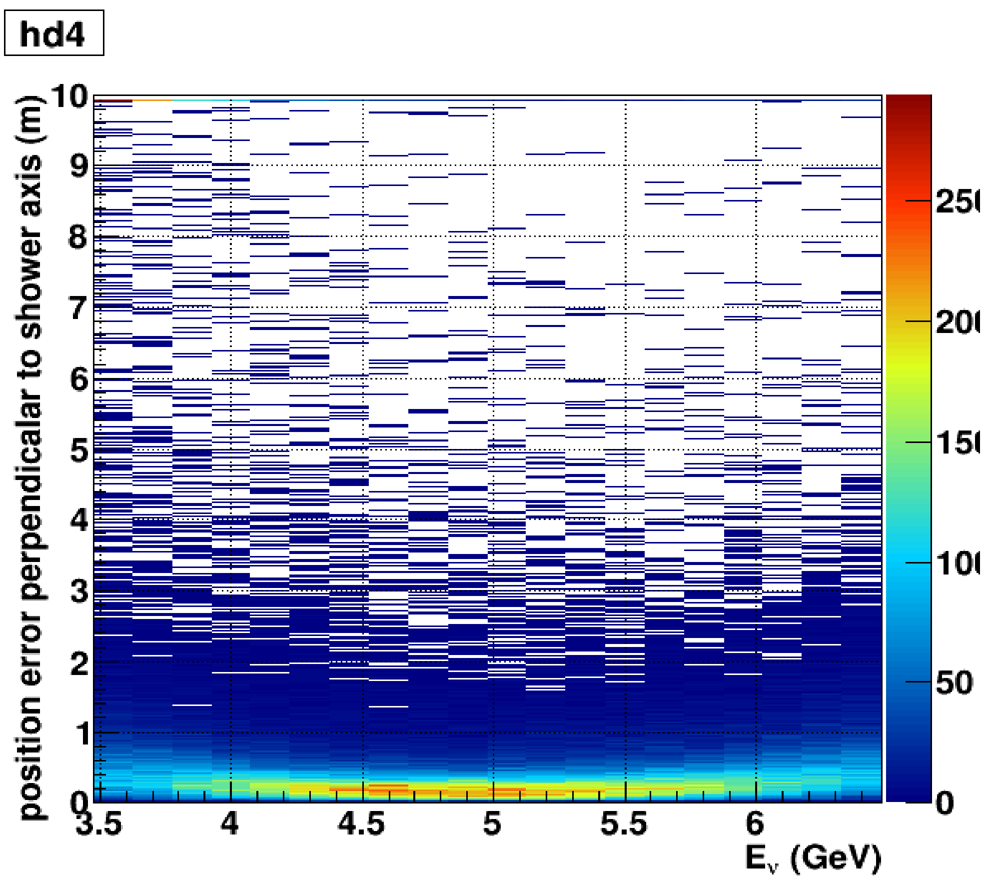
position fit: along the shower axis

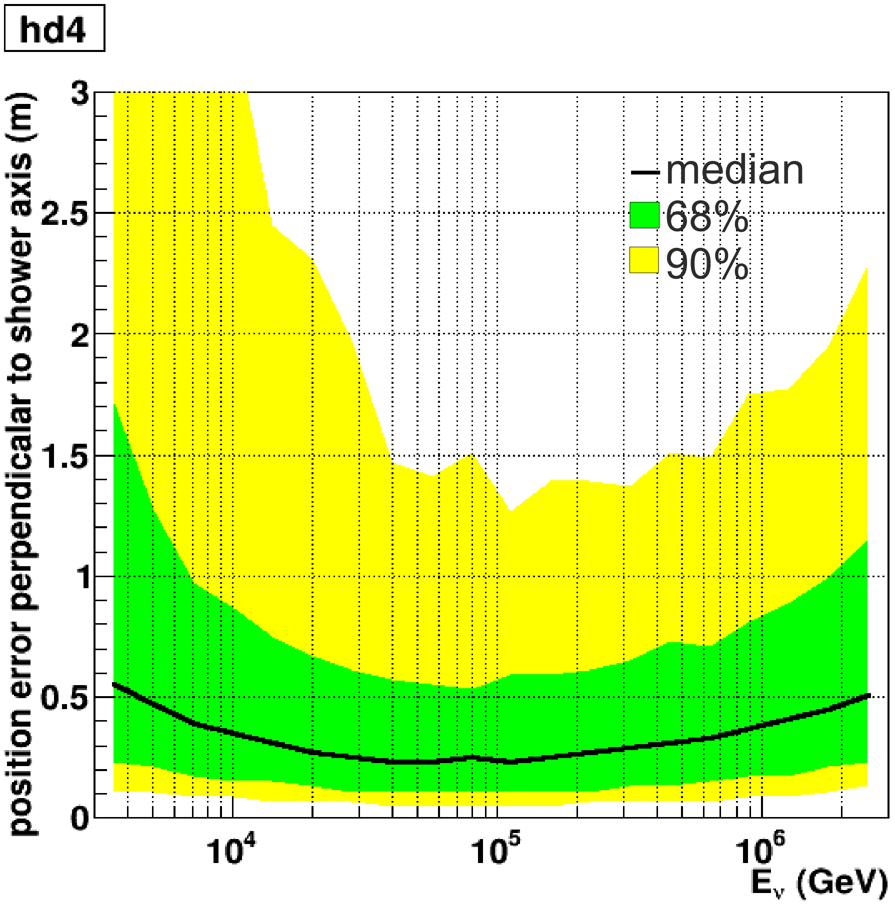




– see increase of shower size with energy
– resolution ~1 m

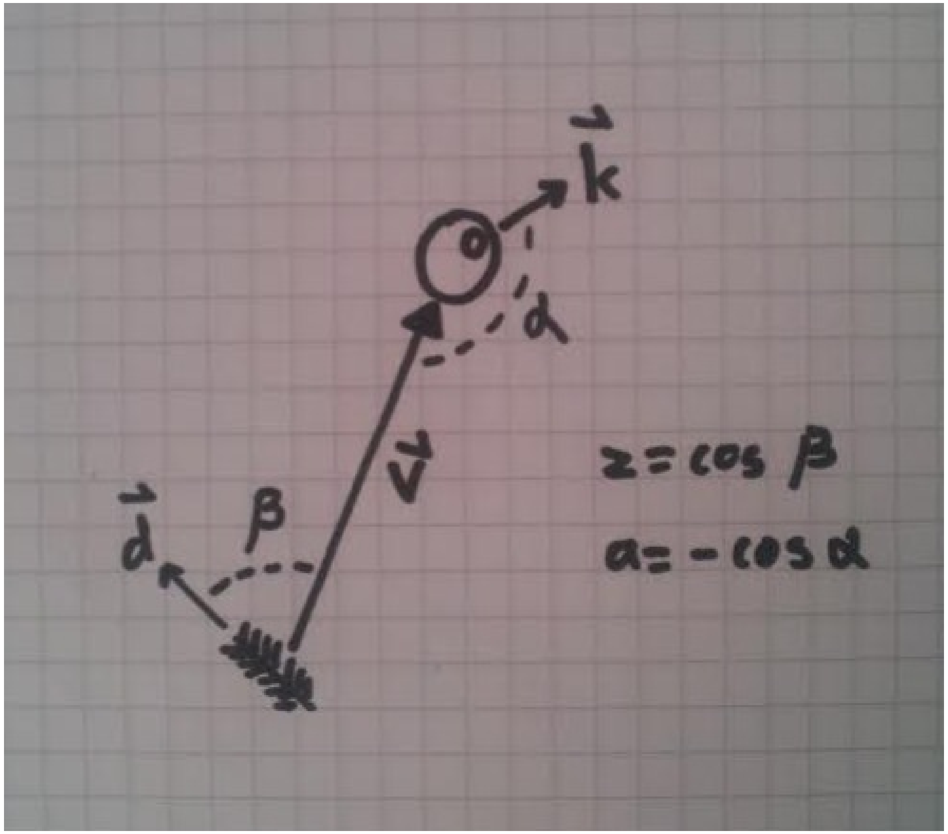
position fit: distance to the shower axis





– much better than 1 m

direction fit



3D function (histogram) describing

μ^{sig} = number of detected photons
from a PeV shower as function of

– r = |v| : distance shower to DOM
– a : cos angle of impact with PMT axis
– z : angle of DOM with shower axis

note: z depends on shower direction

note: μ^{sig} can be scaled easily to
correspond to other shower energies

– in KM3NeT: number of photons (μ^{sig}) not measured directly on a ***PMT***
– we have ToT, but it needs thought/work/calibration

– but we do not even need it!

measuring the light intensity

With a single DOM, we can just count the photons

- at low intensity, $N_{hit} \sim N_{\gamma}$
- at high intensity, start to see light on oblique PMTs
- at very high intenstity, will start to see light at the back (via scattering)

→ **effectively have very large dynamic range.**

measuring the light intensity

With a single DOM, we can
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→ effect
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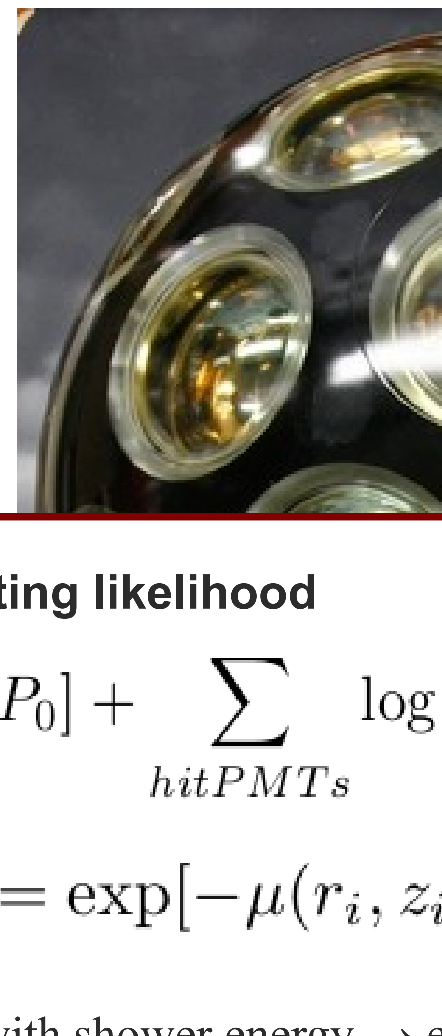
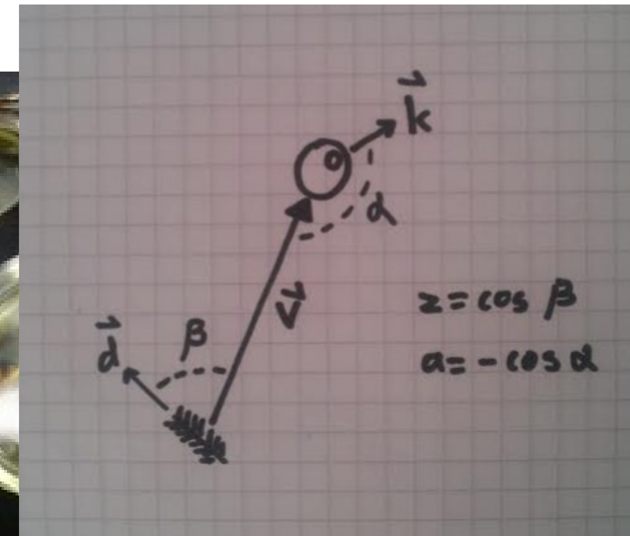




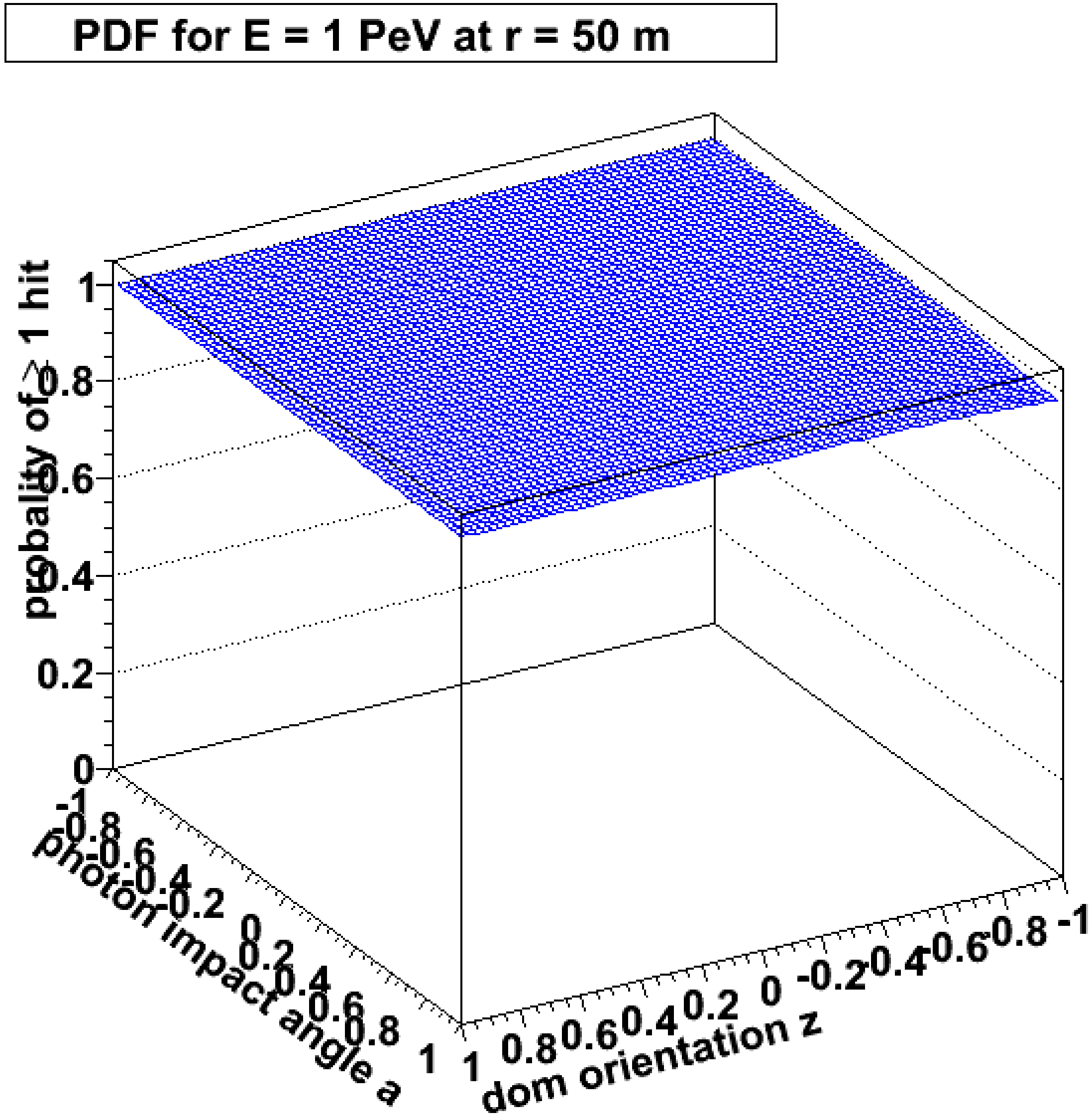
counting likelihood

$$\log \mathcal{L} = \sum_{empties} \log[P_0] + \sum_{hitPMTs} \log[1 - P_0],$$

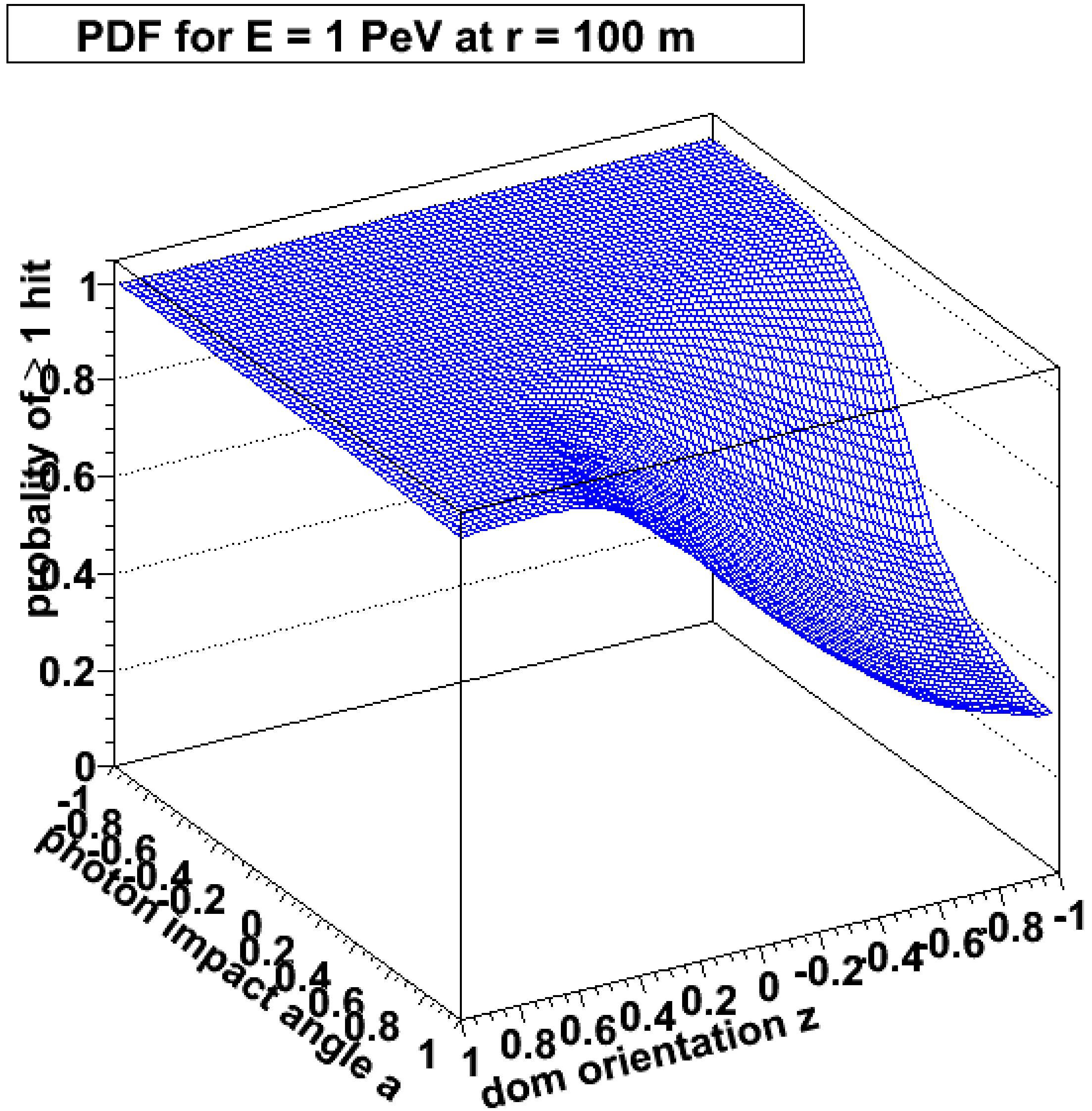
$$P_0(r_i, z_i, a_i, E) = \exp[-\mu(r_i, z_i, a_i, E)]$$

- note μ scales linearly with shower energy → easy to fit for E
- P_0 can be very robustly calculated (in contrast to ToT)

direction fit



direction fit



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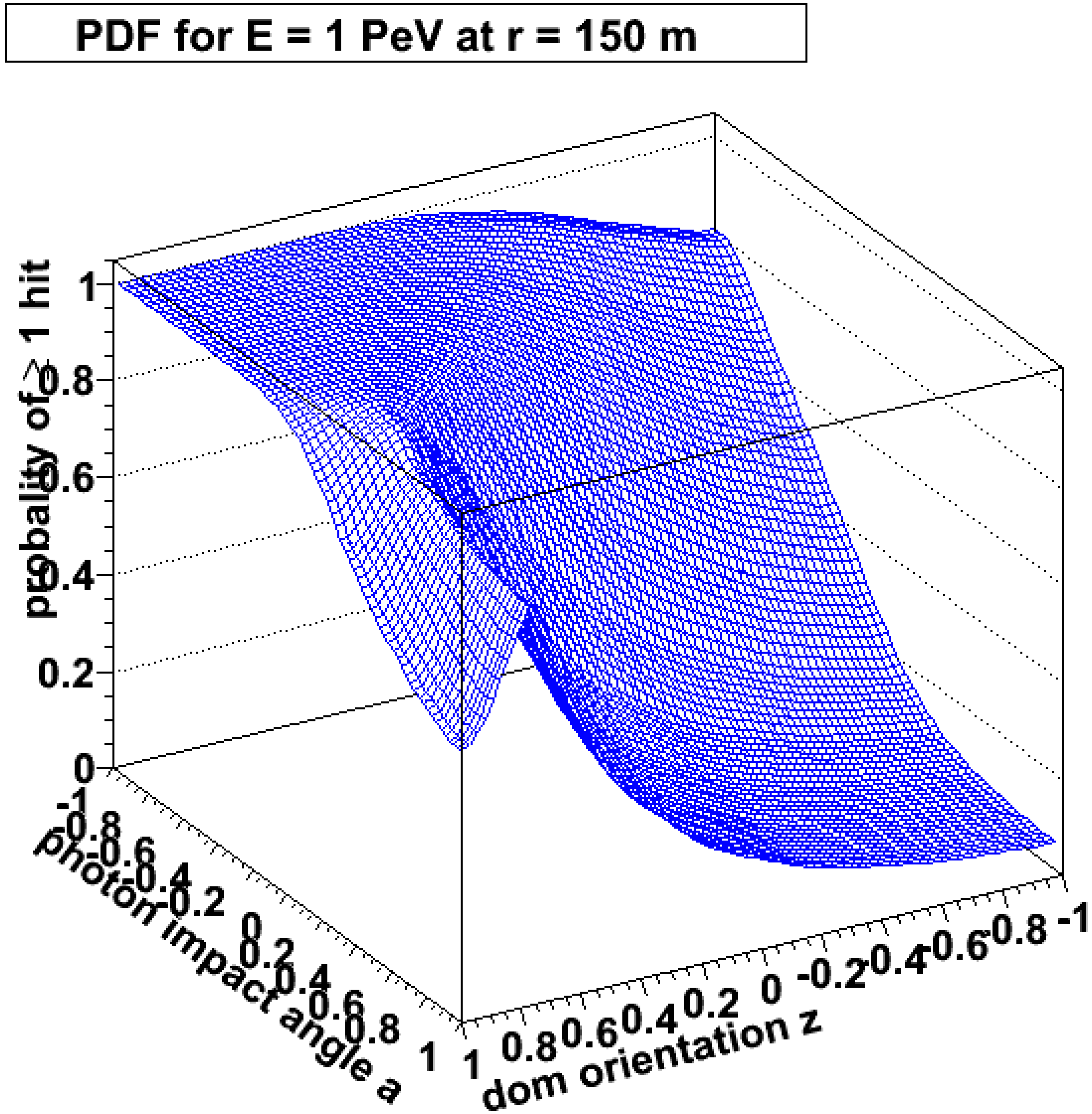
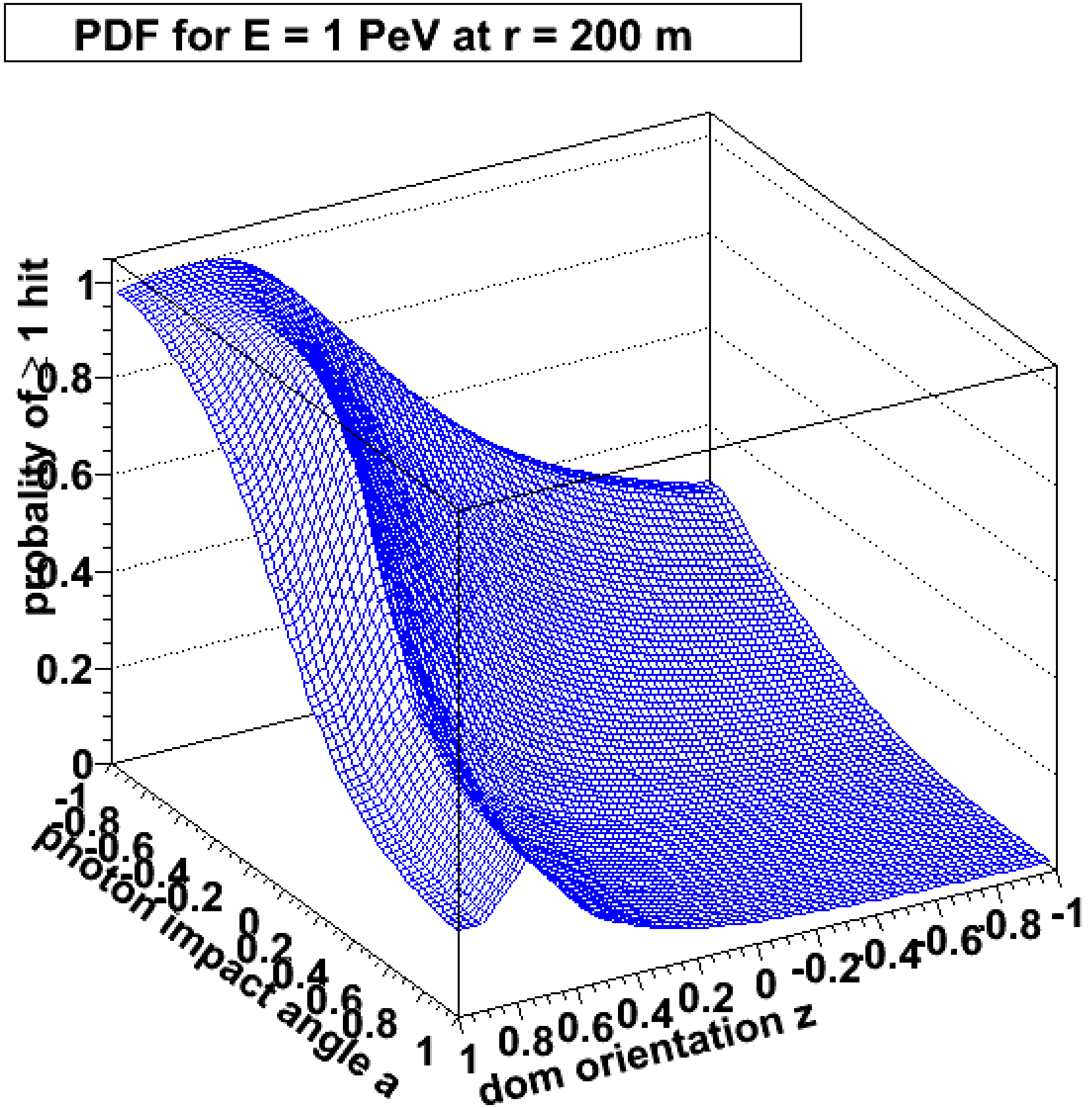
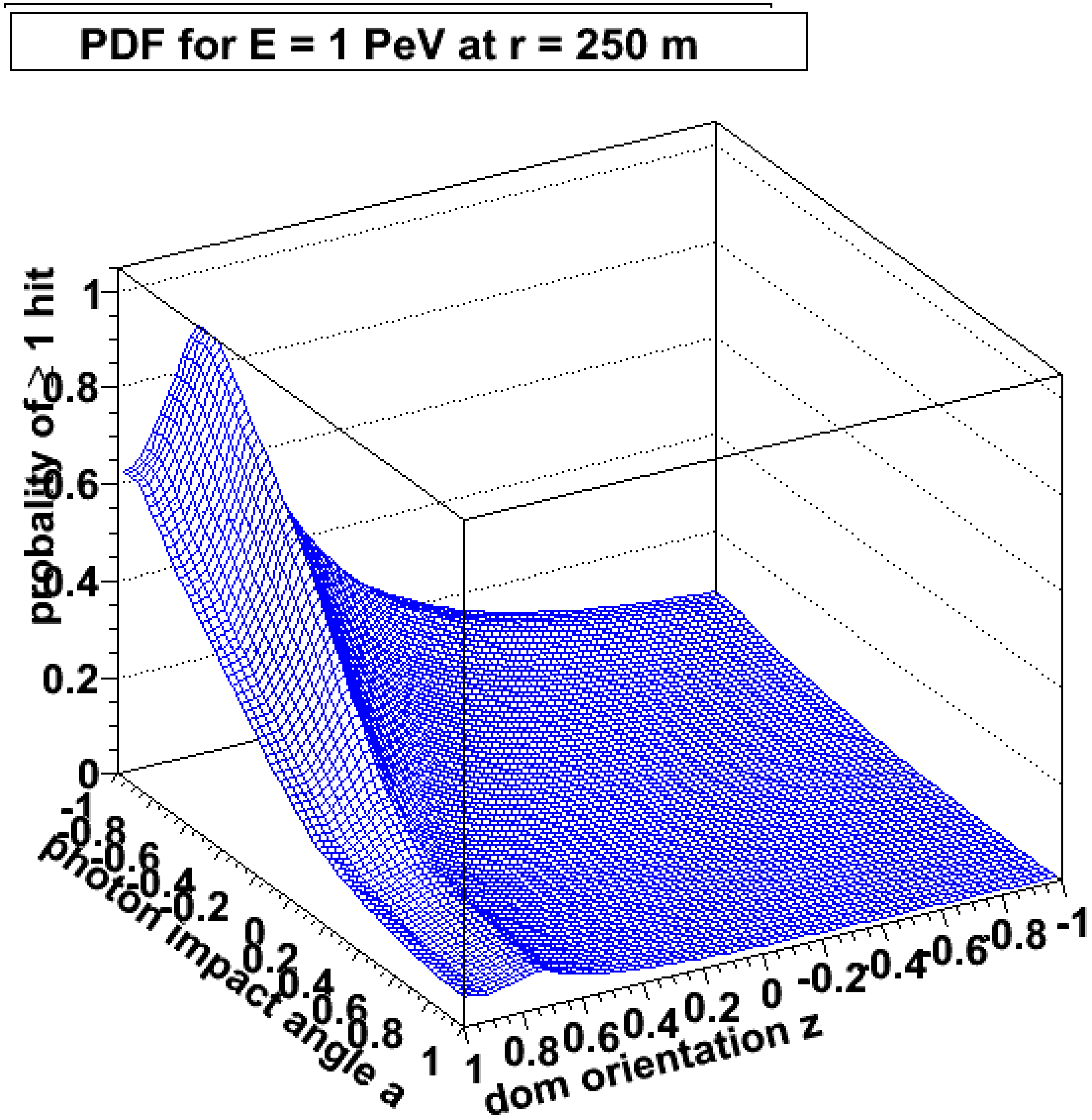


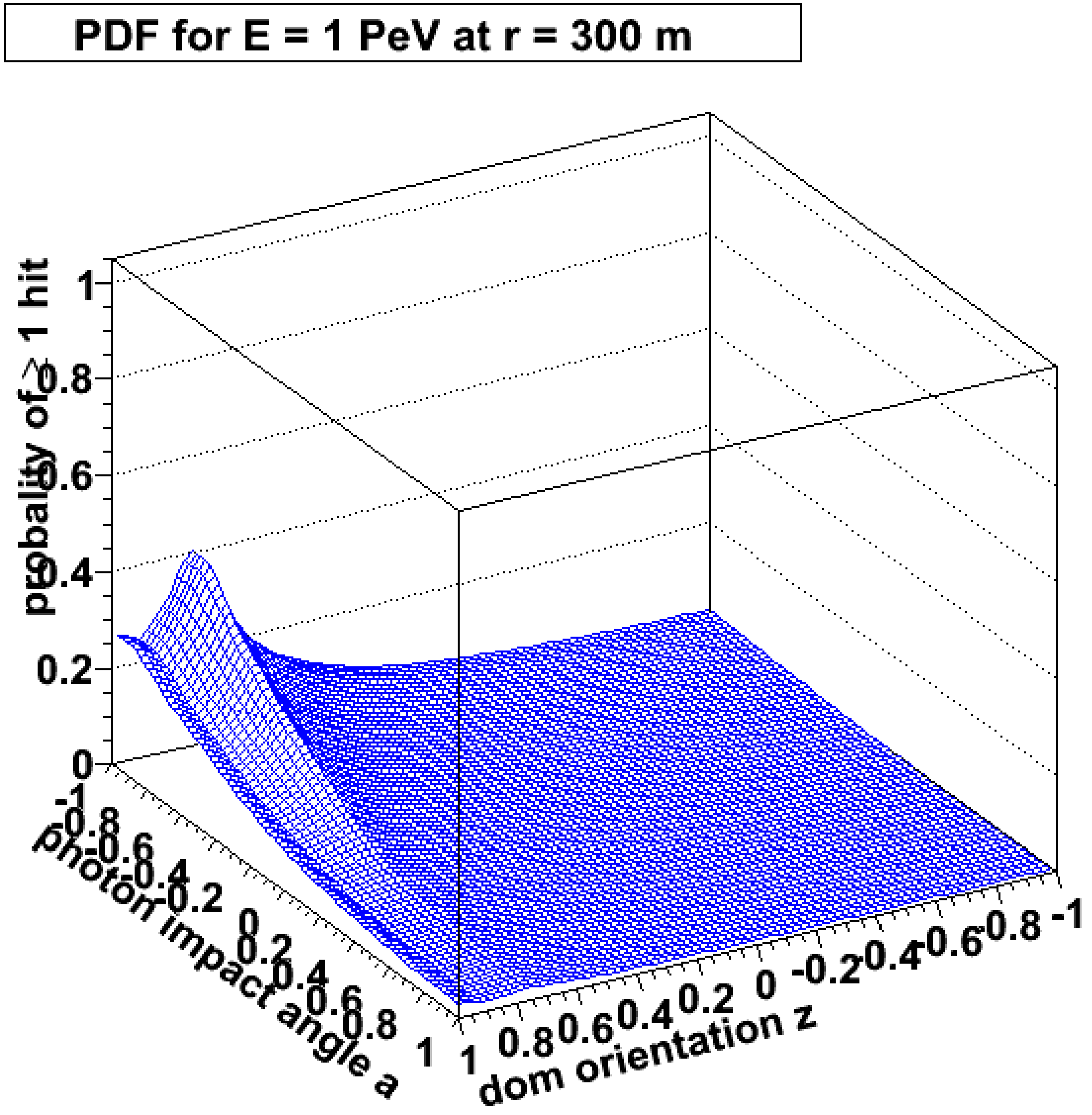
direction fit



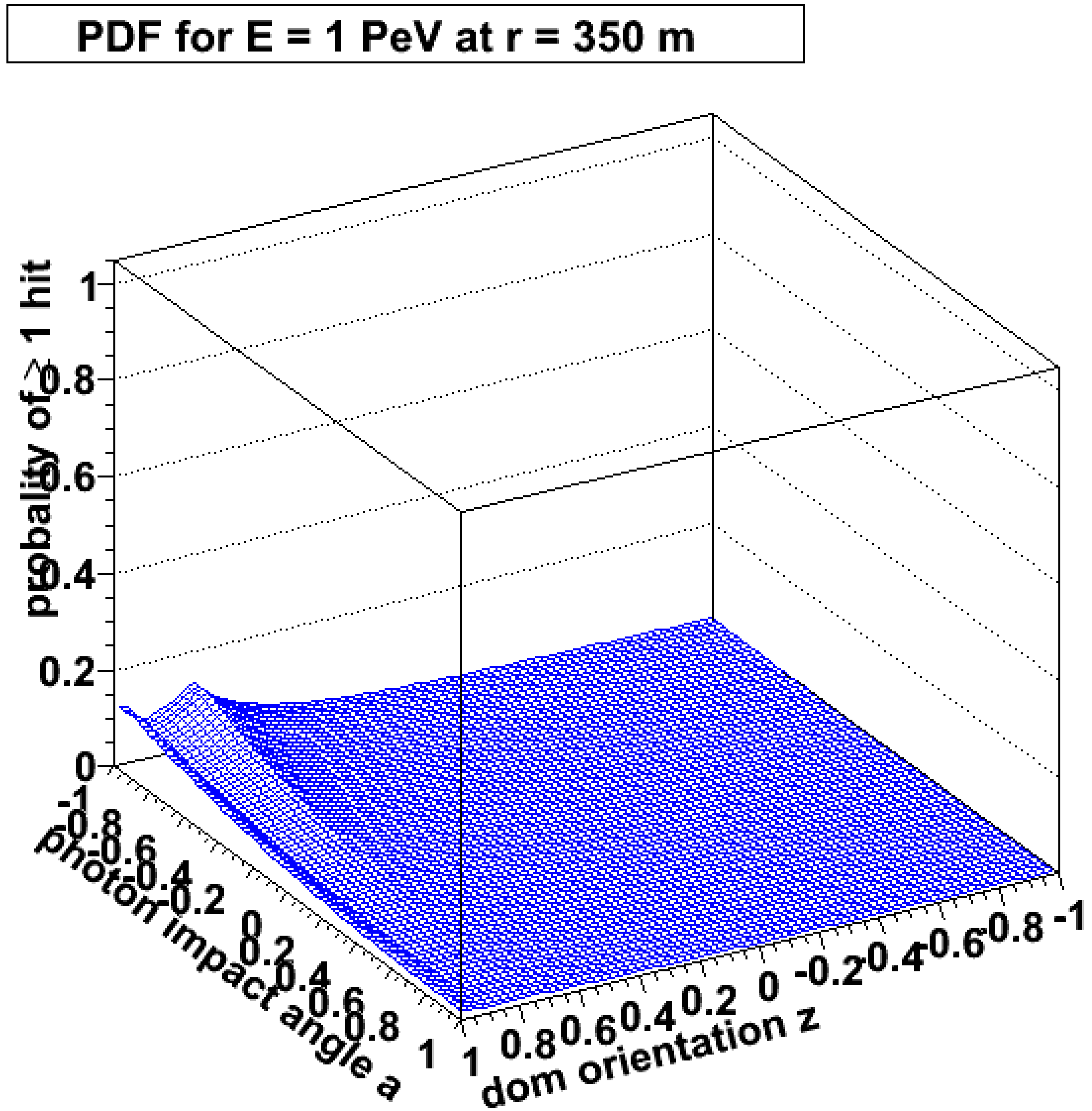
direction fit



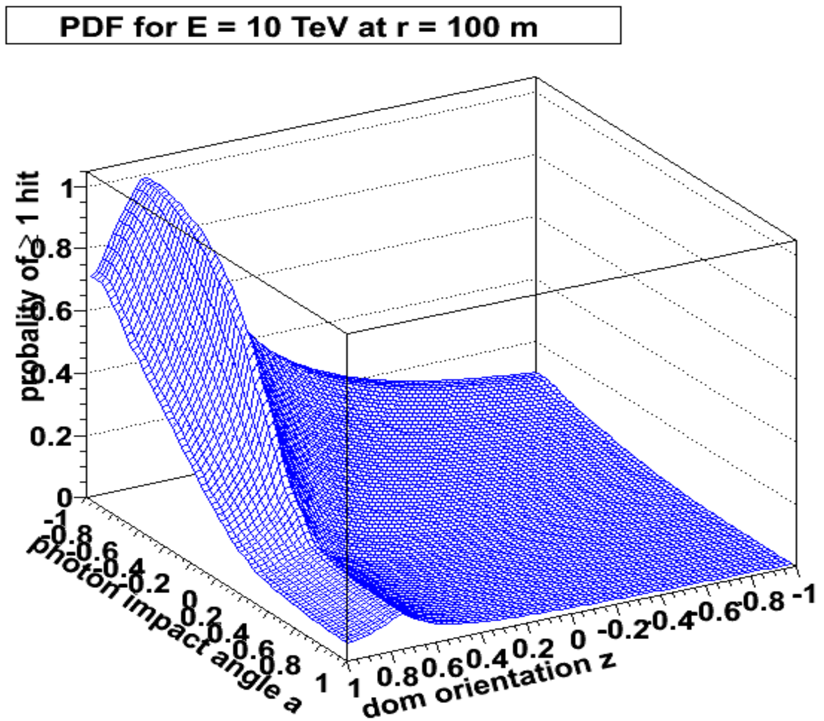
direction fit

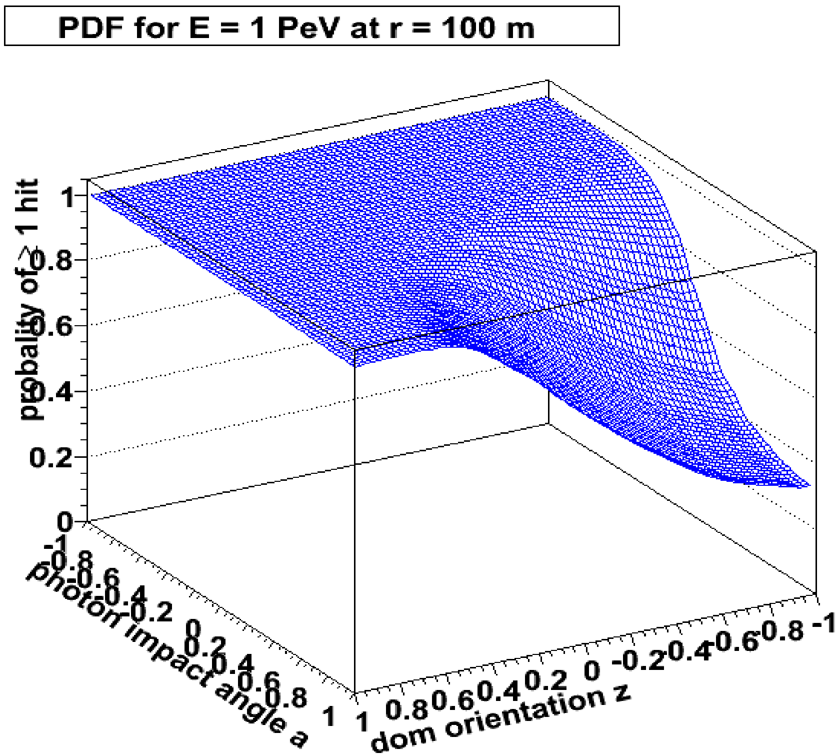


direction fit



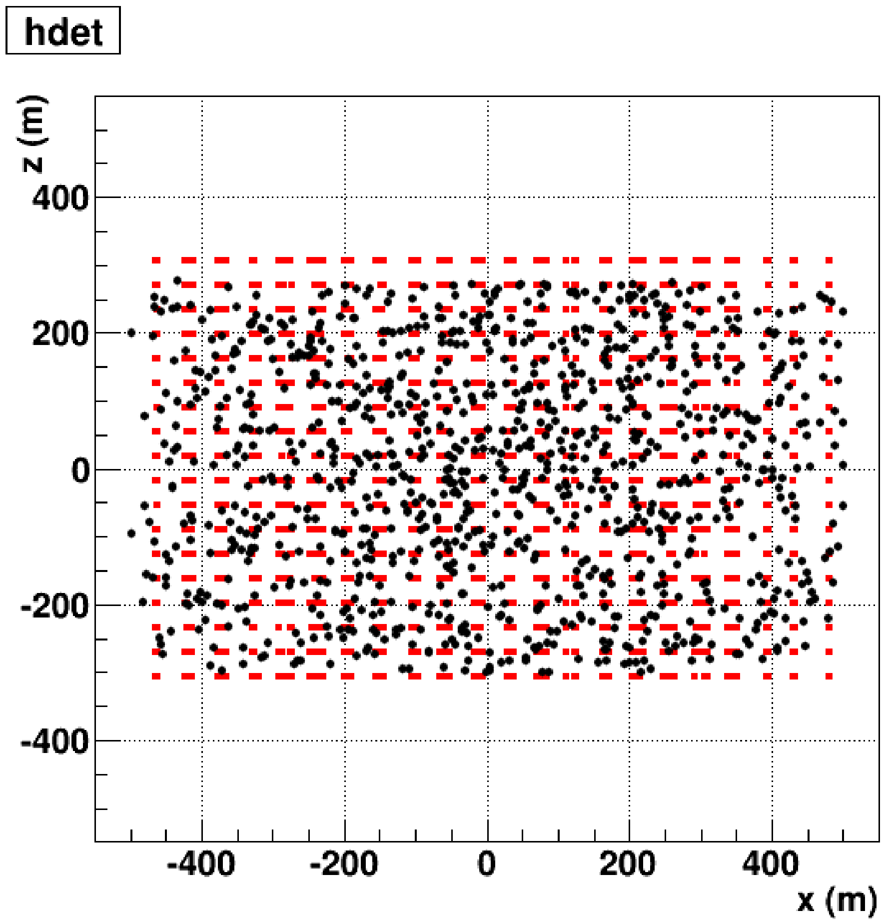
direction fit

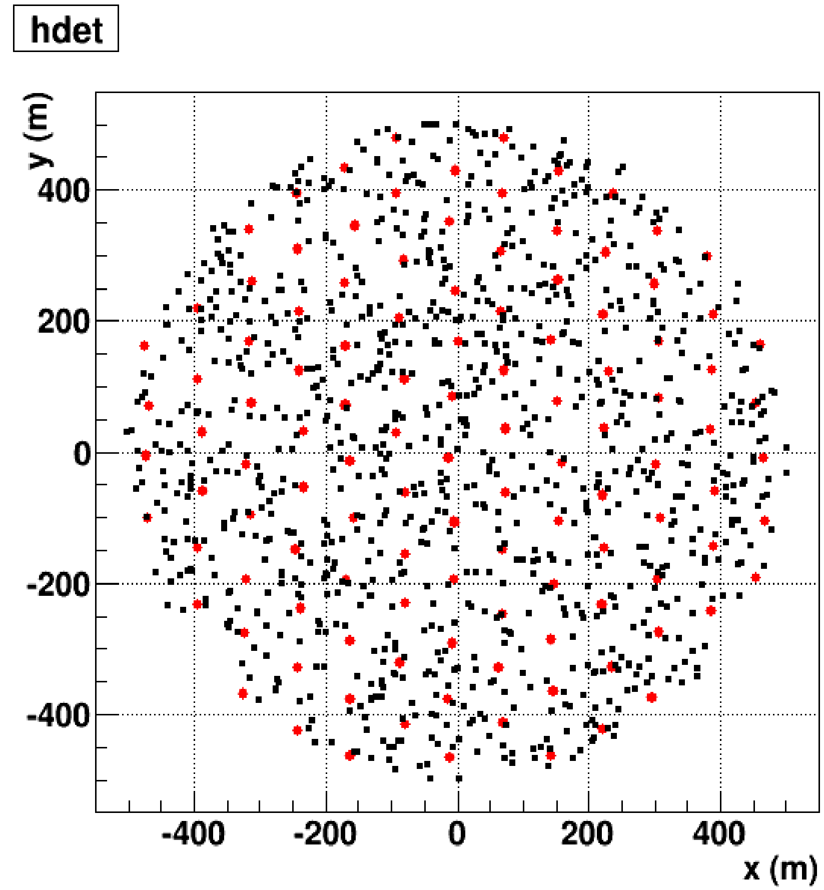




At high energies, all PMTs have a hit for r < 50 m.
But there is *always* a region of r, a where there
is a significant z-dependence
→ direction sensitivity.

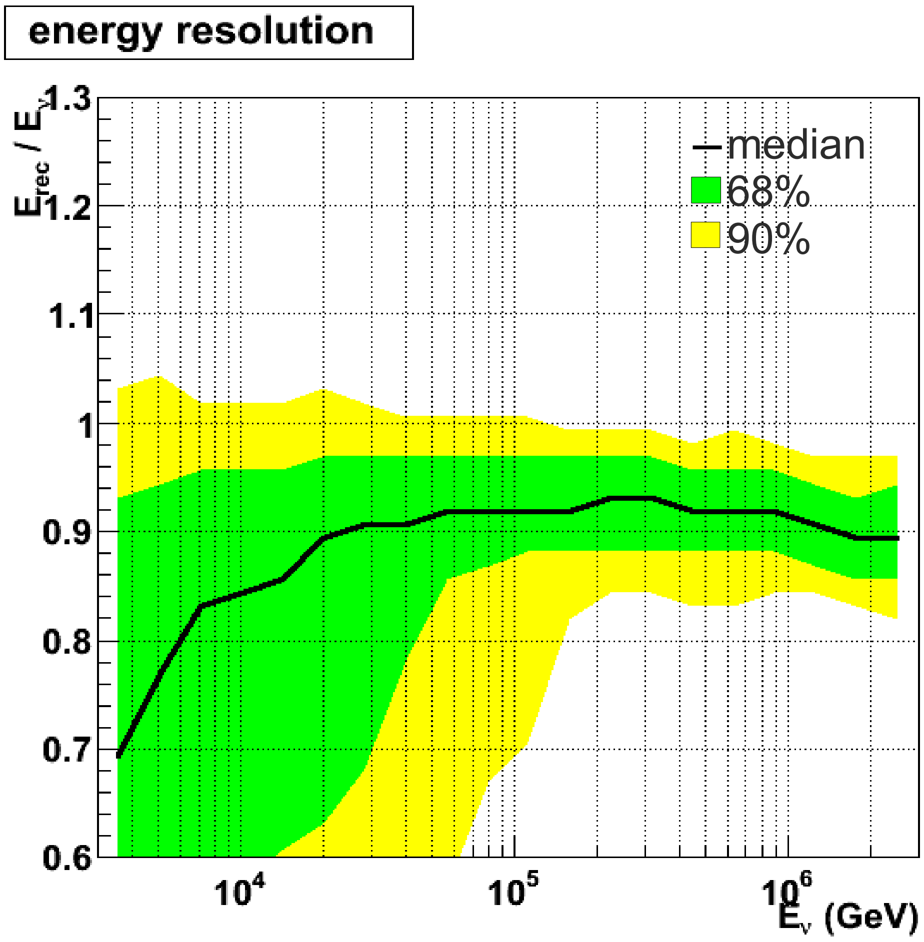
Containment cut applied for following results



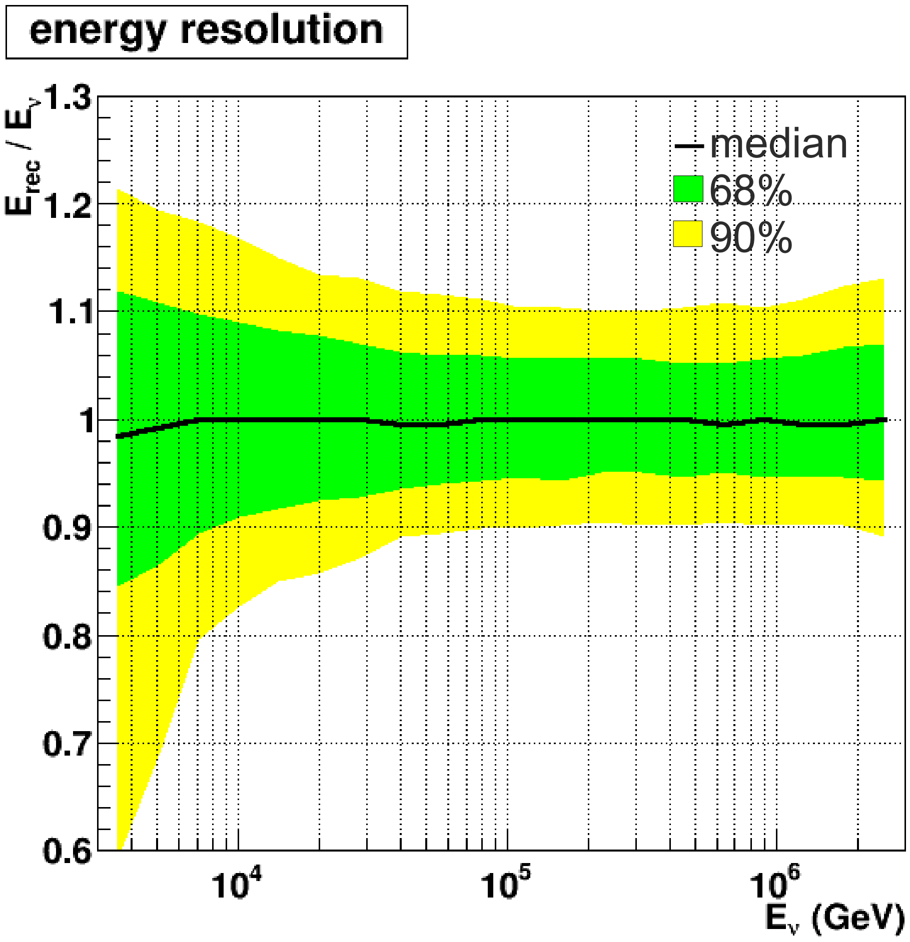


detector = 115 string phase 1.5 building block (90 m string spacing)

Energy resolution

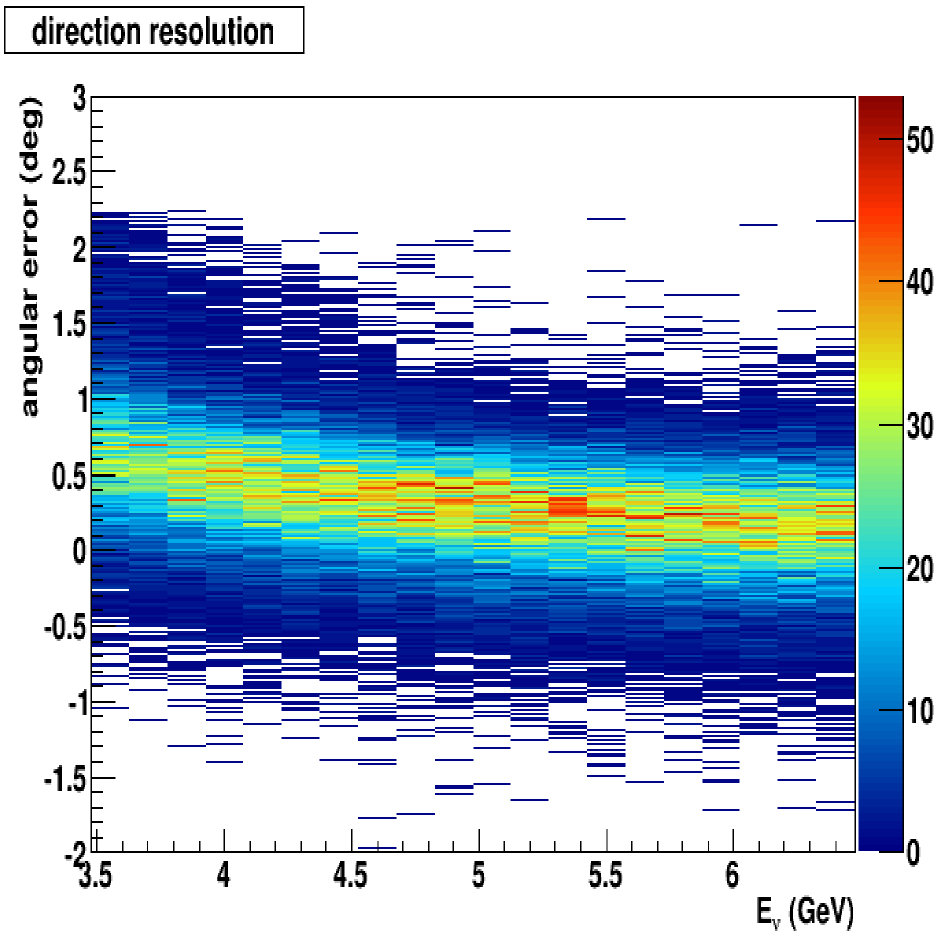


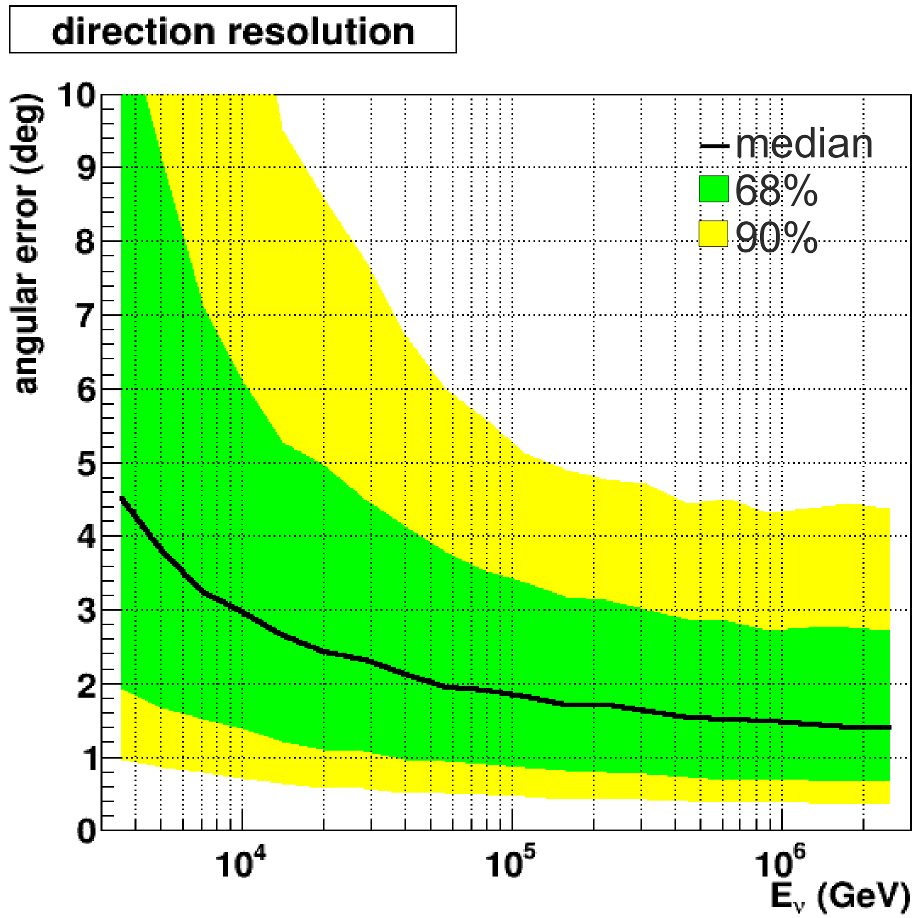
out of the box: O(10%) bias



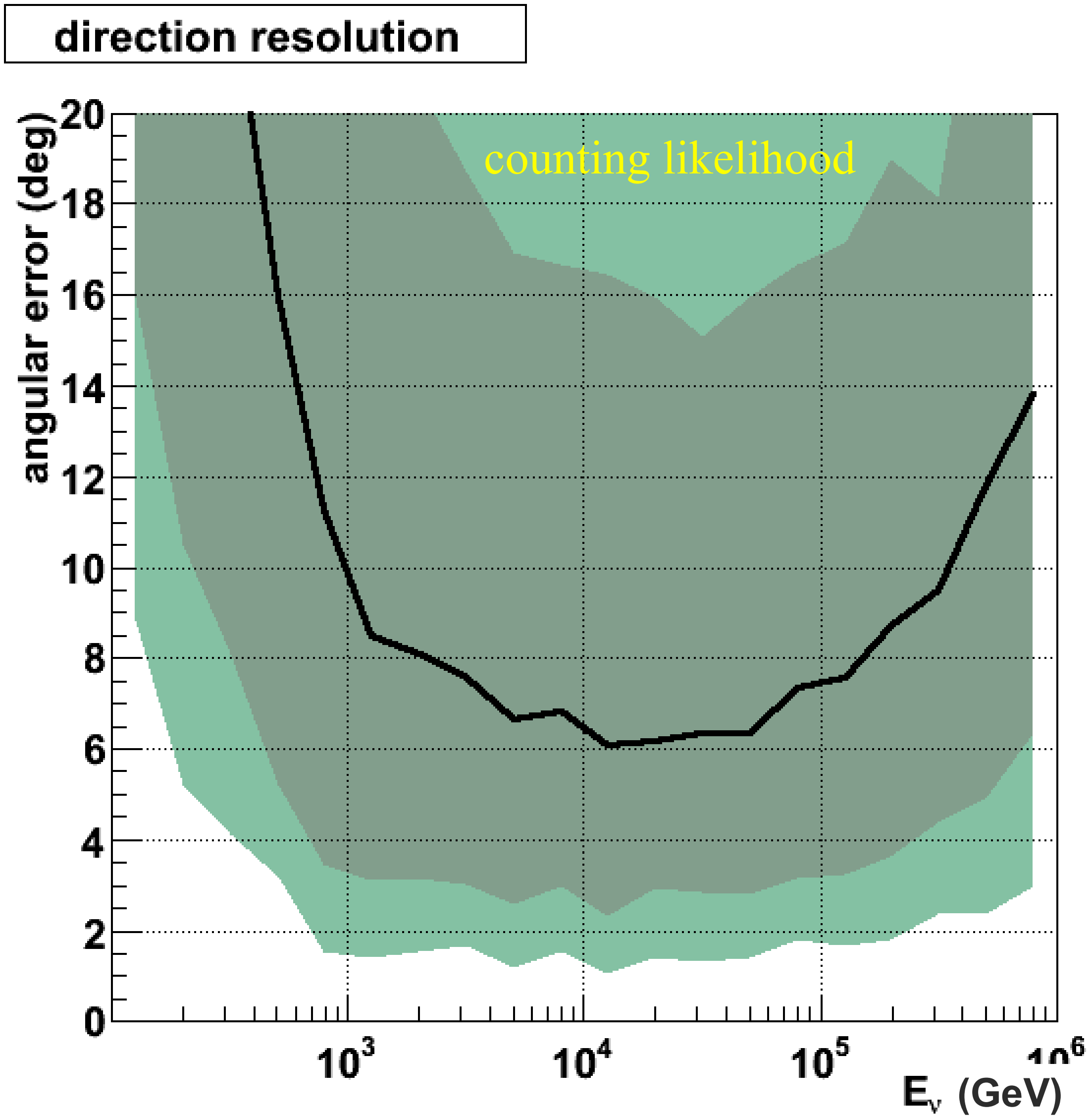
bias easily corrected
<10% resolution

Direction resolution





Does it work in Antares?



Counting PDFs using only hit/nohit information

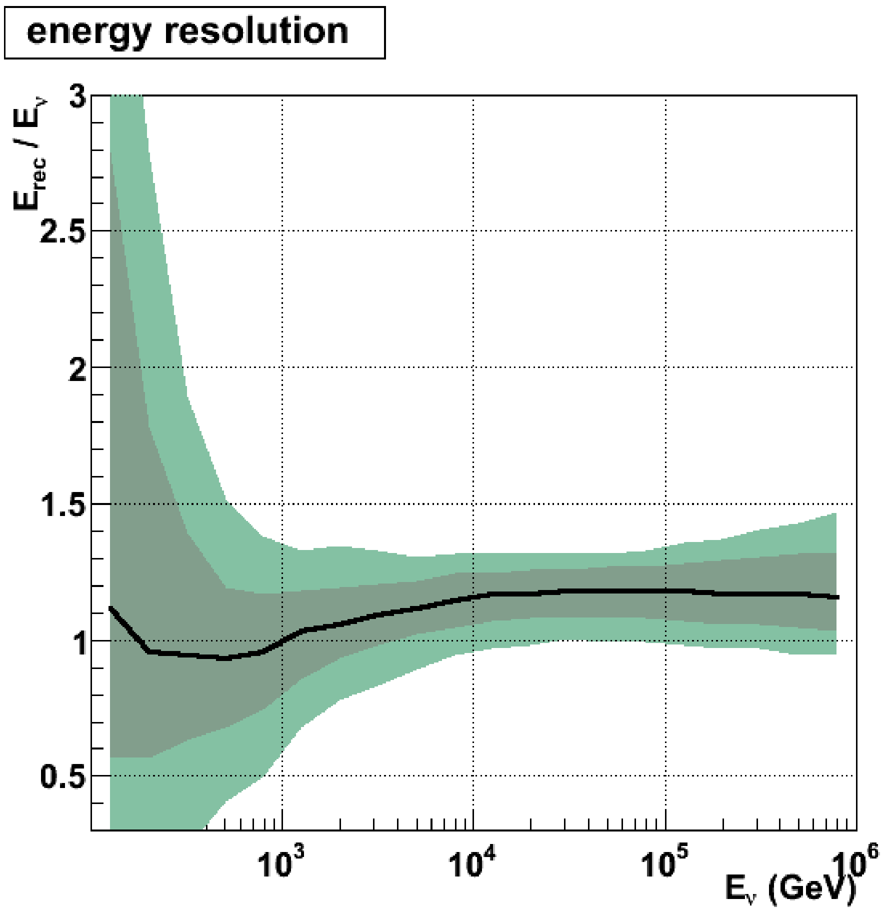
-- does ***not*** work very well in Antares
(not enough granularity)
-- need to rely on per PMT charge measurment
-- which we have!

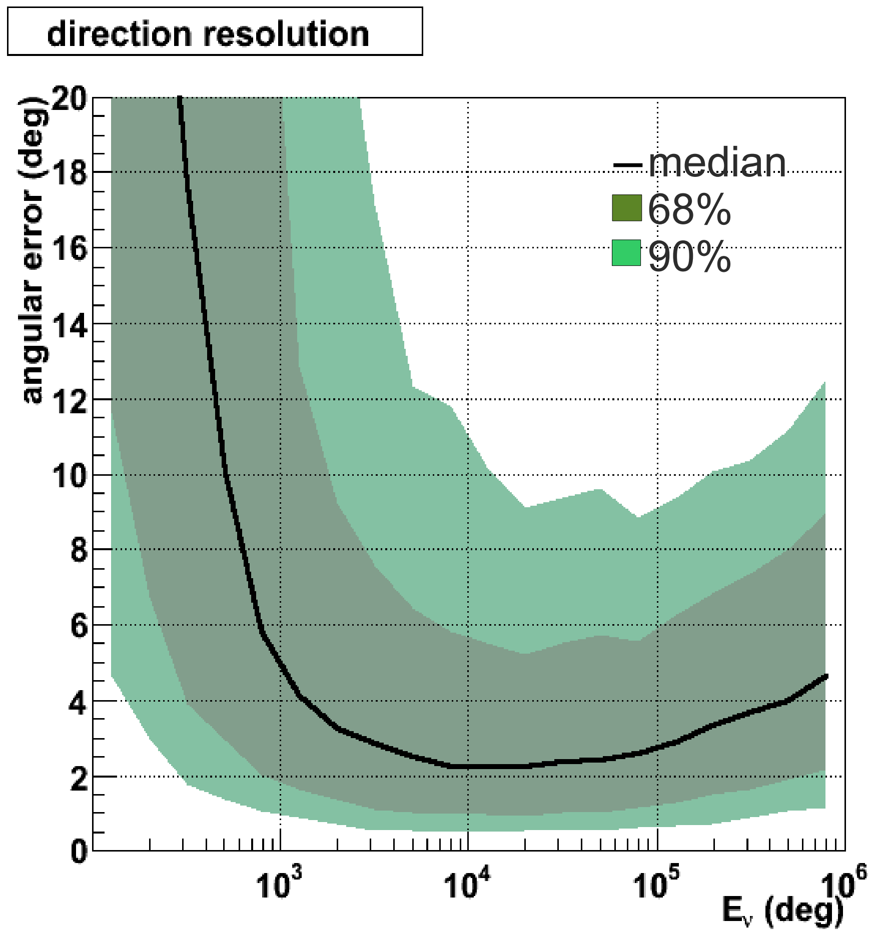
In Antares: decent charge measurement between 1 and ~20 p.e.

→ instead use 'normal' Poisson likelihood

$$\log \mathcal{L} = \sum_i \log \mathcal{P}(a_i | \mu_i)$$

ANTARES, Poisson likelihood





– Full detector (no dead OMs), contant 60 kHz background
– fresh results
– systematics & background rejection to be studied
– lot's of room for imrovement still

conlusions

– in water, shower reconstruction very naturally factorizes:
  – position + time of the shower ← hit times
    ns accuracy even at large distances

  – direction and energy of the shower ← light intensity
    cherenkov 'beaming' observed up to large distances

– Vertex fits all work well (M-estimators are good enough)
  – shower max reconstructed within 1 m

– Direction + energy fit needs likelihoods..
  and results depend on best likelihood formulation and accurate implementation.

– multi-PMT design allows photon counting
  → simple reconstruction by just using information on hit/empty PMTs.

– resolutions reached (contained events)
  direction: 4 – 1.5 degrees for 3 TeV – PeV
  energy : <10 % for E > 3 TeV [beter for more central events]

– Opens up exciting possibility to use showers even in
  point source searches. (will try it out in Antares)