Signal classification and event reconstruction for acoustic neutrino detection in sea water

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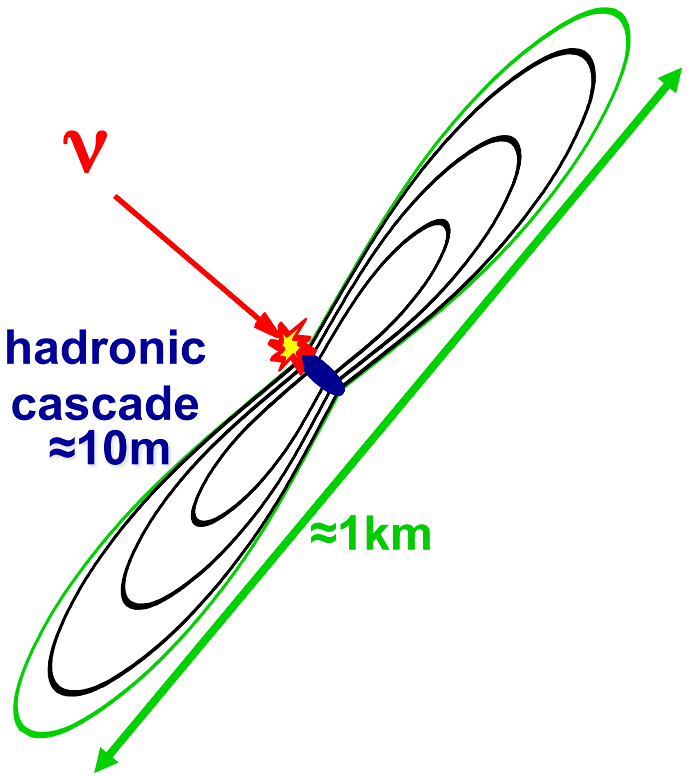
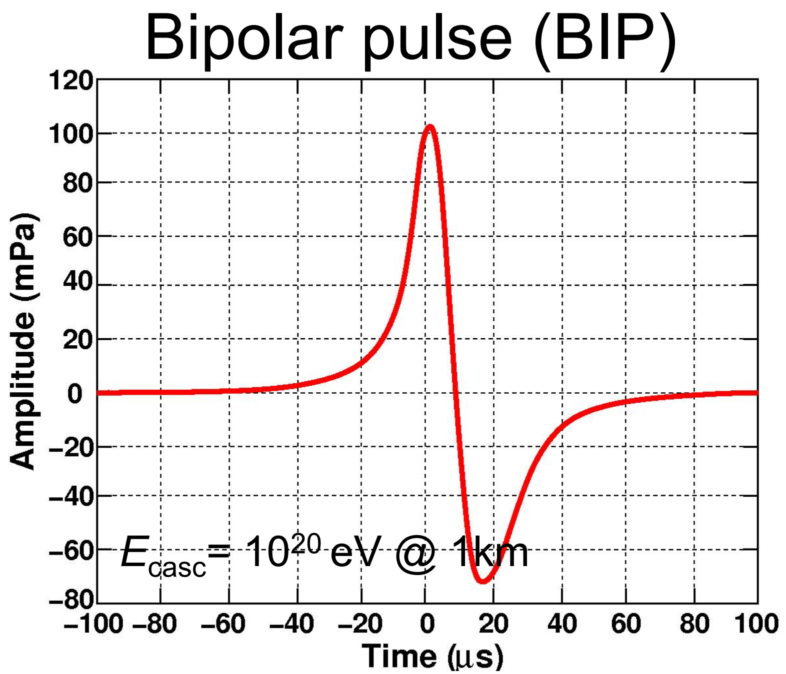
Acoustic signals from Neutrinos

Thermo-acoustic effect: (Askariyan 1979)

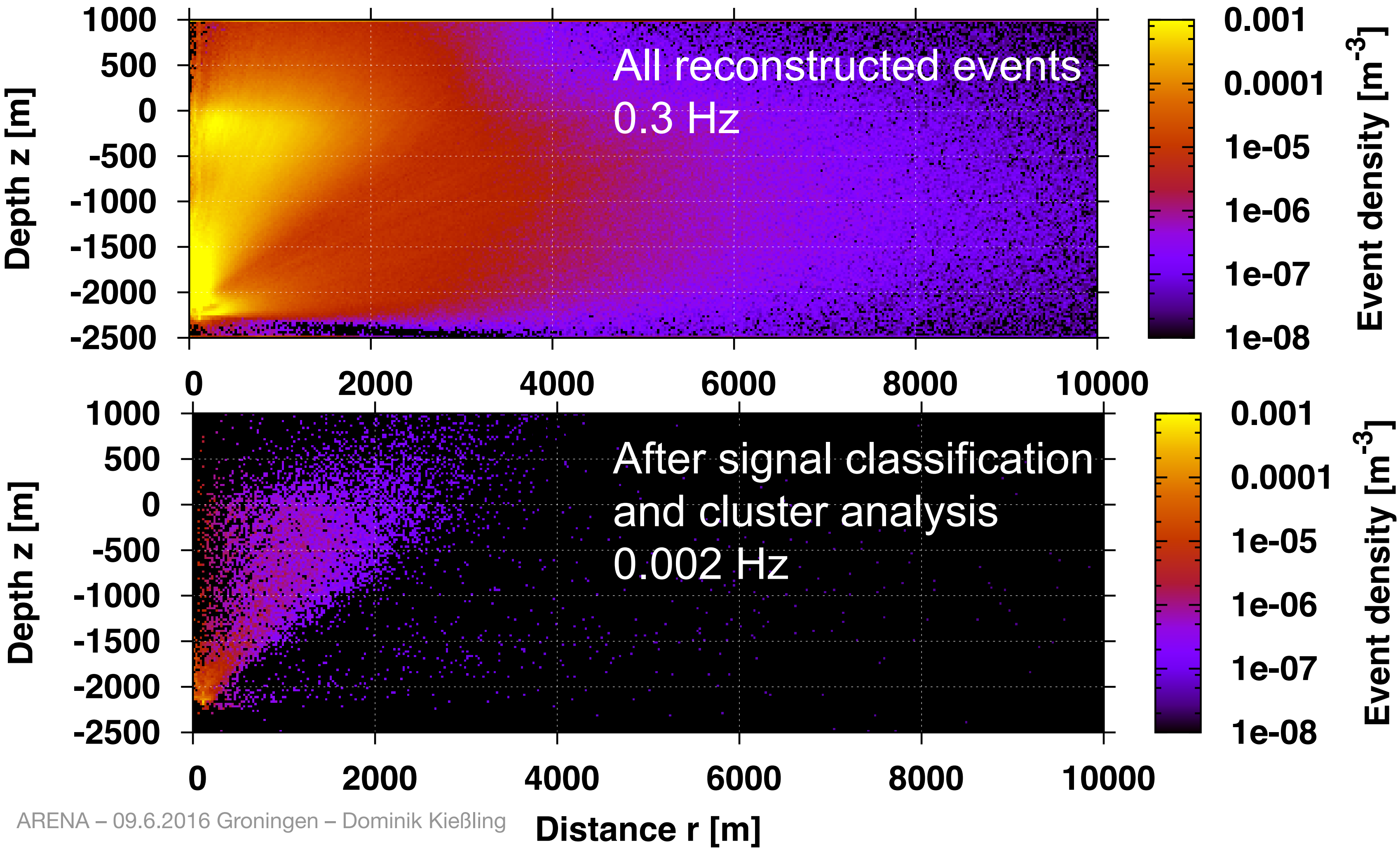
Energy deposition ➔local heating(~µK) ➔ expansion ➔ pressure signal





Adapted from arxiv/0704.1025v1 (Acorne Coll.)

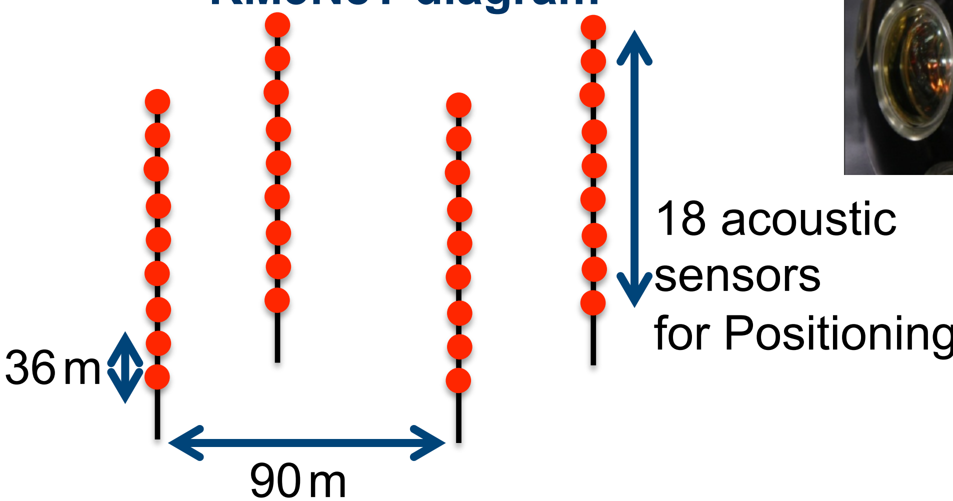
Spatial distribution of transient background

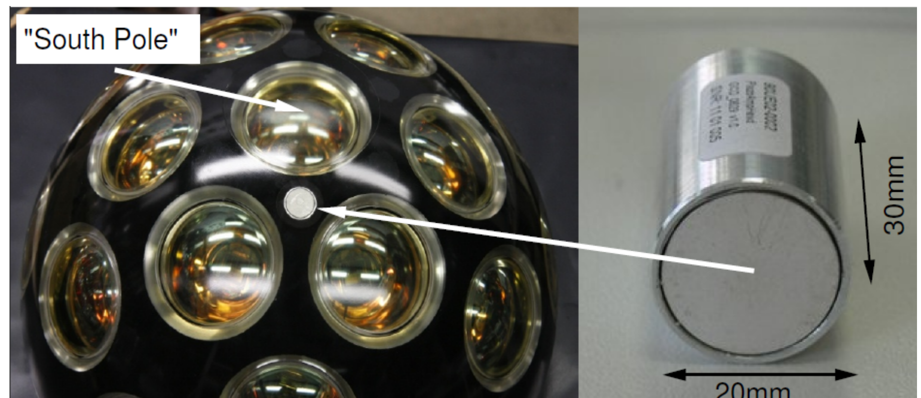


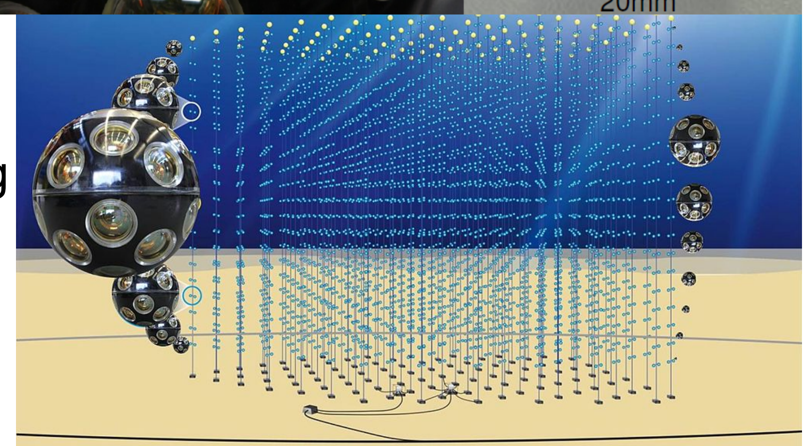
Simulation studies

- 24 Lines ~ KM3NeT-Phase 1 Italian site
- 100 Lines ~ KM3NeT Building Block

KM3NeT diagram

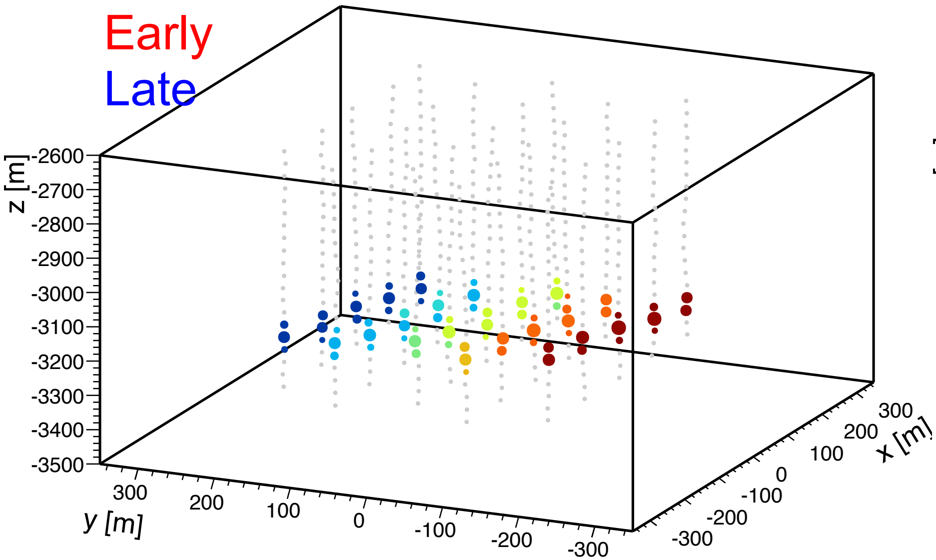




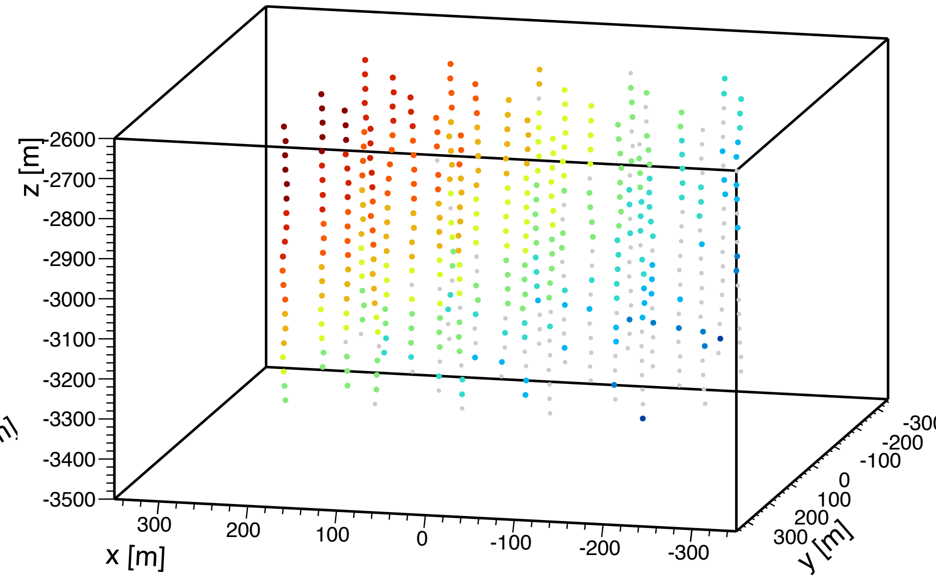


Simulated Events

Neutrino @ 1.8 km, E=10^{21}eV, Θ=16°



Spherical background (e.g. ship)

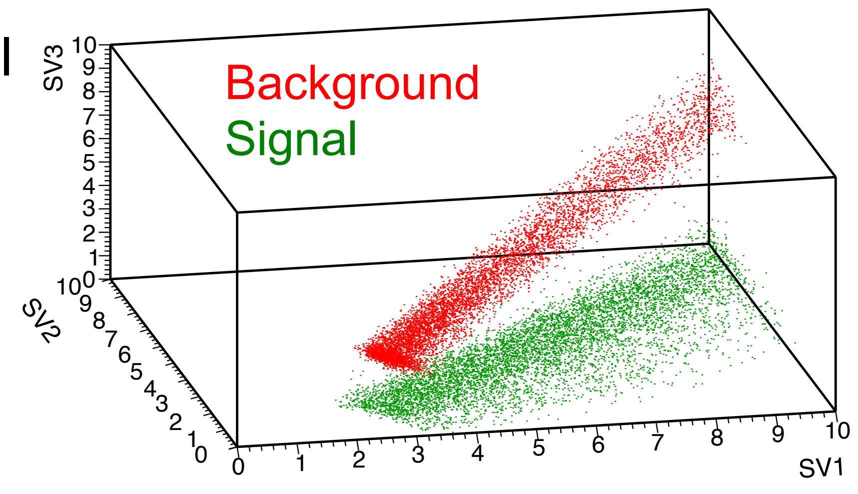


- Neutrinos (Energy 10^{18} – 10^{21} eV)
- Signals of the positioning system
- Spherically emitting sound sources
- Random coincidences

Characteristic traits of neutrino signatures

- Good candidates for machine learning features are (in total 16):
  - Singular values from distribution of hits in detector (Pancake reconstruction as by-product)
  - Correlation coefficient of the amplitude and the distance to the pancake
  - “likelihood” of the event
  - Distance of the sensors from plane
- “Boosted Decision Trees” (bdt) well suited from OpenCV*
  - Recognition rates ~99%

Distribution of the singular values



*http://opencv.org

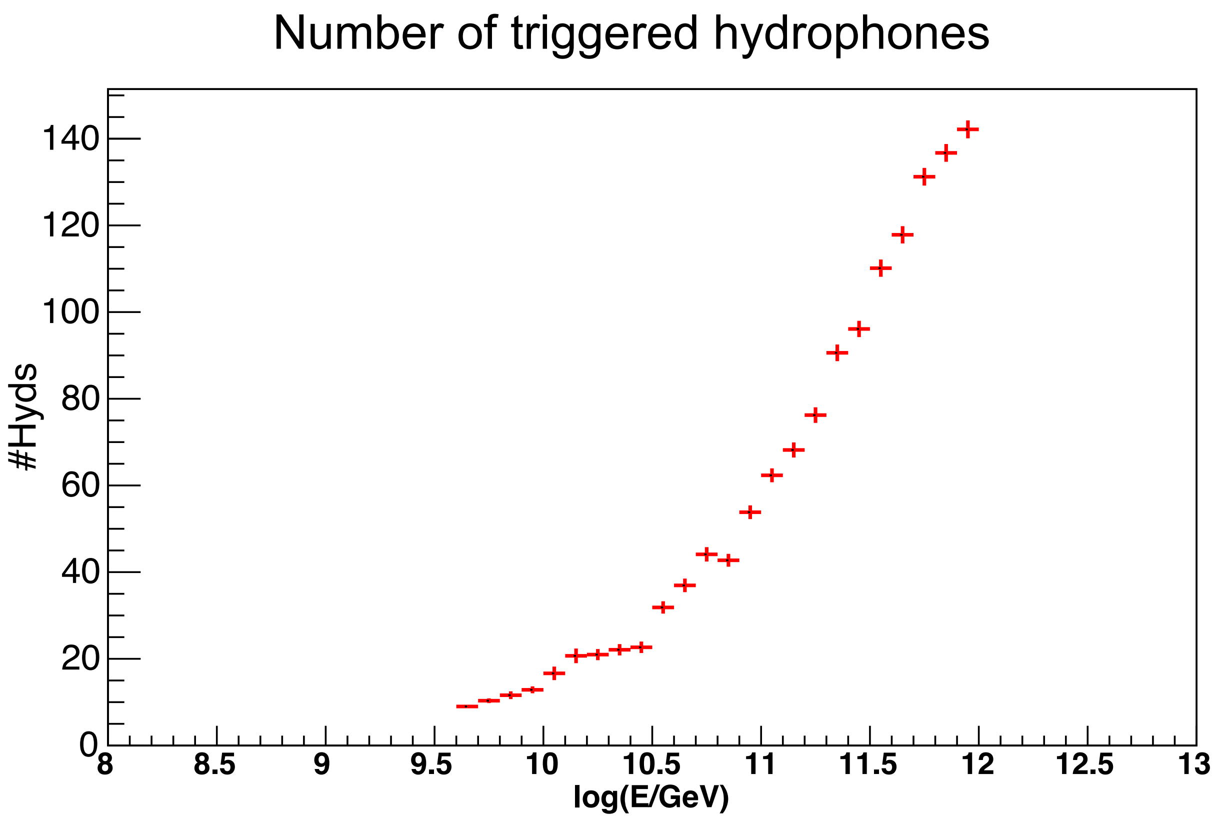
Events rates and cascading classifiers

- Rates derived from AMADEUS data
- Reduction to less than 1 event/yr neccessary

Stage	Events/year
Sources with pos. reco	10 000 000
BIP-Classification	315 000
Clustering	63 000
Pancake-bdt	12.6
Pancake-cascade	7

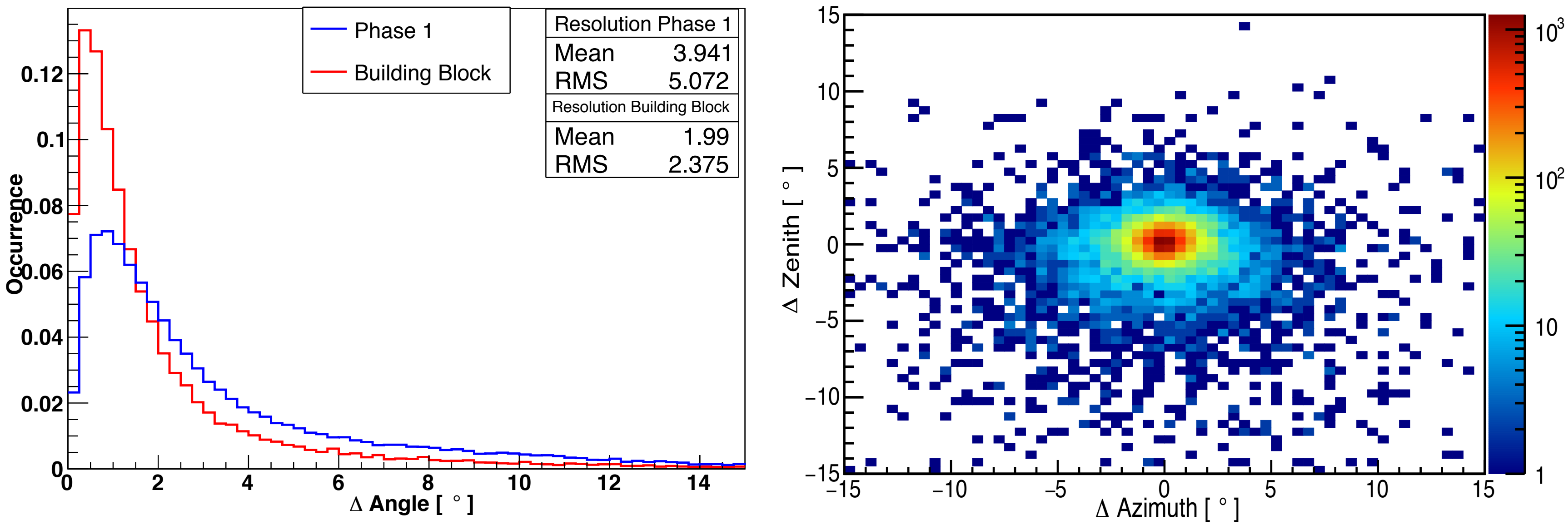
- Cascading classifiers improves background suppresion (here bdt, decision tree and random forest)
- 98% of triggered neutrinos pass whole chain

Energy threshold



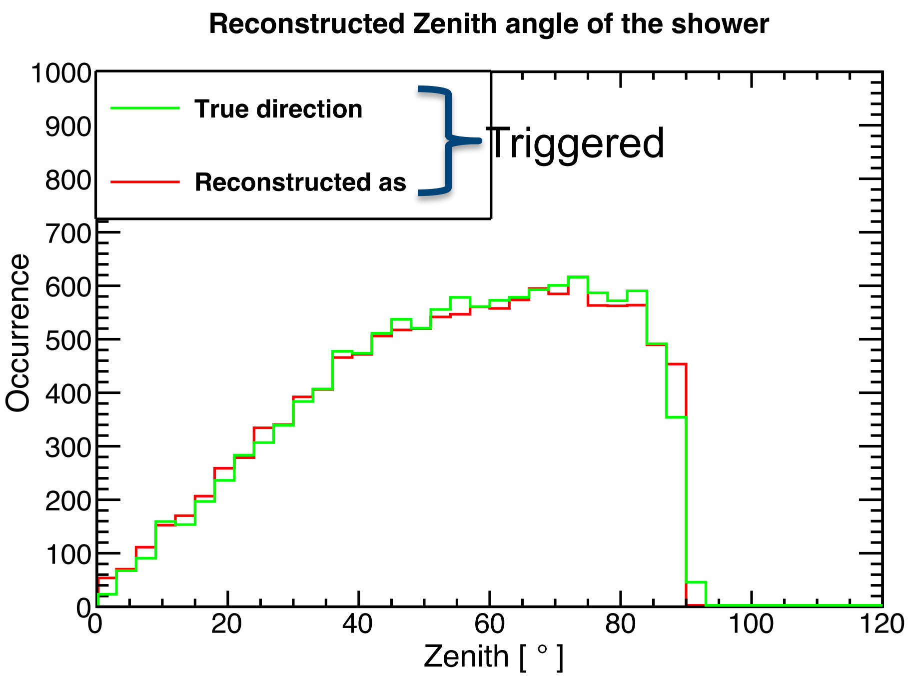
- Energy threshold ≈$5 \cdot 10^{18}$ eV

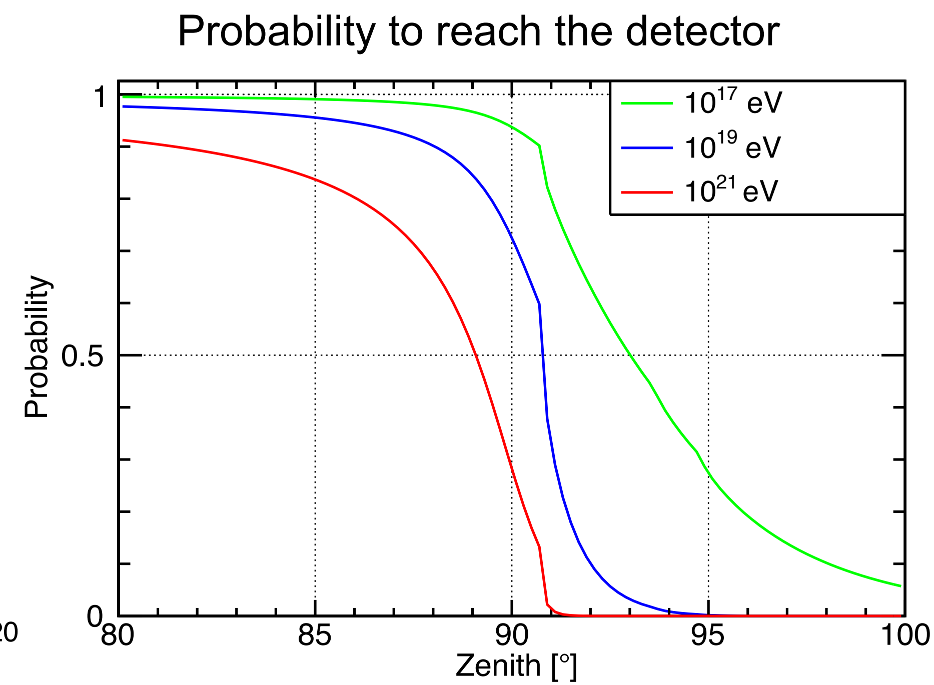
Angular resolution of the direction from the SVD



- Discriminating between up- and down-going events not possible
- Assumption: all neutrinos are downgoing
- Error region around the horizon [+5°,-5°] (depending on energy)

Probability for a neutrino to reach 1500m depth in water



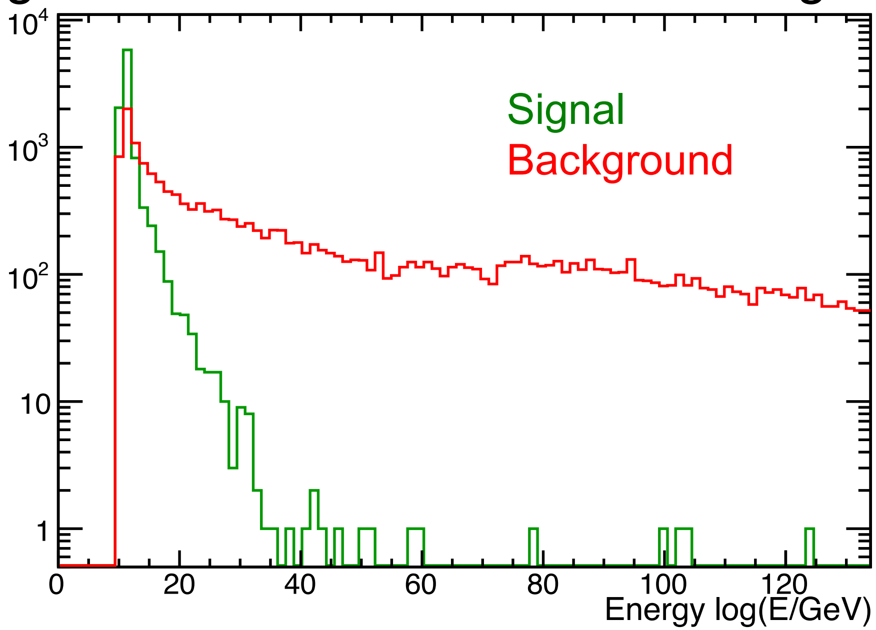


- Earth is opaque for ultra high energy neutrino

  ➡ Ambiguity only causes minimal problems

Energy estimate as feature for the classification

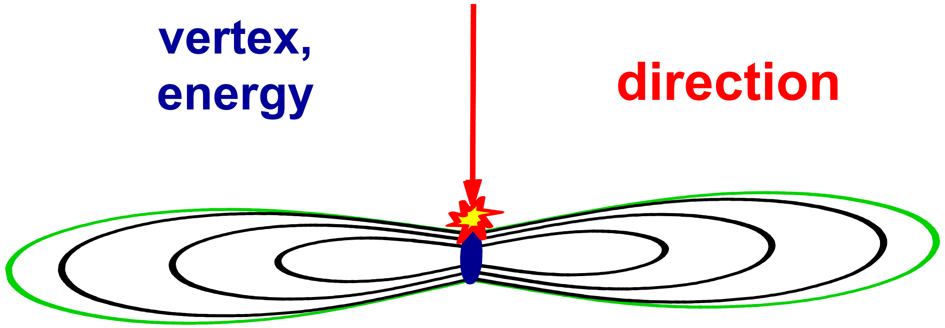
- Vertex and direction of the neutrino used as input
- Average amplitude at vertex used in linear regression
- Error can become very large, overestimating the energy several oders of magnitude if the direction is a few degrees off



- Requires a combined fit for vertex, direction and energy!

Toy Monte Carlo for the fit

- Generating events has to be fast
- Create event using position, direction and shower energy
- Peak to peak amplitude from simple linear function
- Arrival time and amplitude at the hydrophones from position and direction



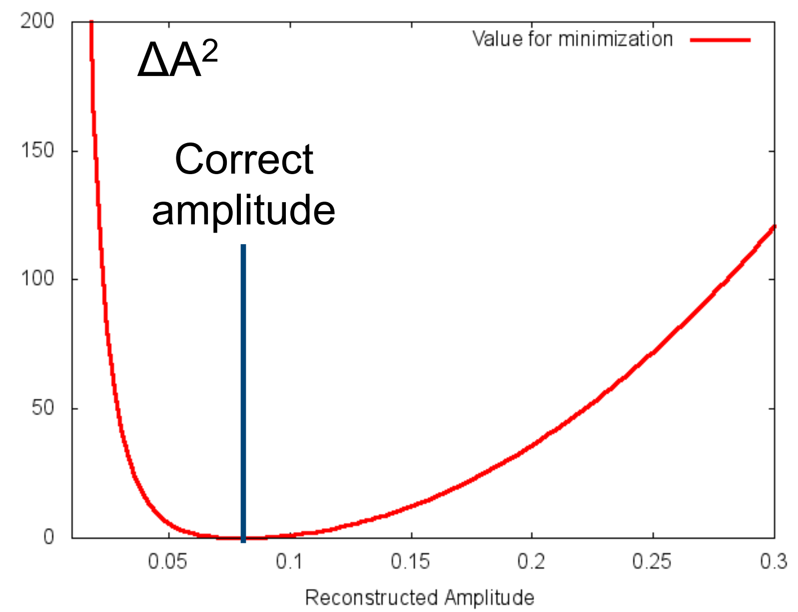
Combined fit

- Generate an event from the toy MC
- Define a function to minimize:

$$f = \sum_i \left(\frac{(t_i - t_i^{rec})^2}{\sigma_t^2} + \Delta A_i^2 \right)$$

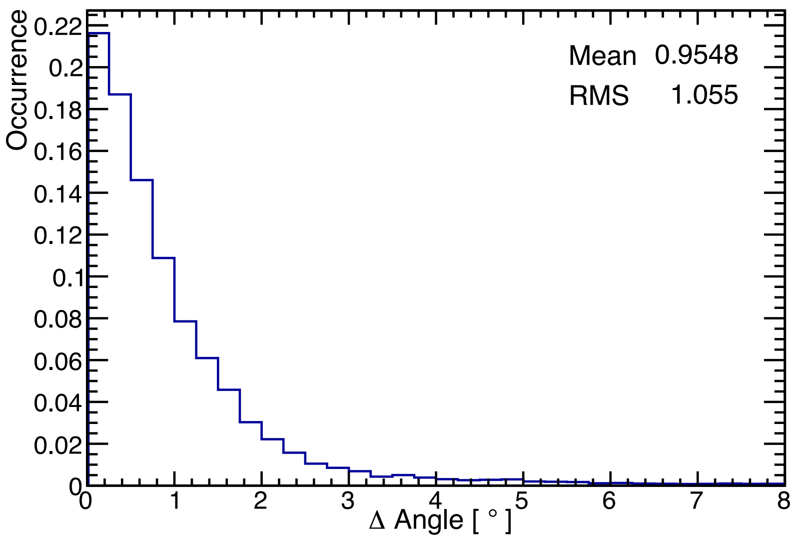
  - t_i : arrival time at hydrophone i
  - a_i : peak to peak amplitude at hydrophone i
  - *σ : weights of the values*
- Amplitude depends on all values, time only on vertex position
- Use Minuit to find vertex, shower direction and shower energy

$$\Delta A_i = \begin{cases} \dfrac{a_i - a_i^{rec}}{\sigma_a} & for\ a_i \leq a_i^{rec} \\ \dfrac{a_i(a_i - a_i^{rec})}{\sigma_a \cdot a_i^{rec}} & else \end{cases}$$

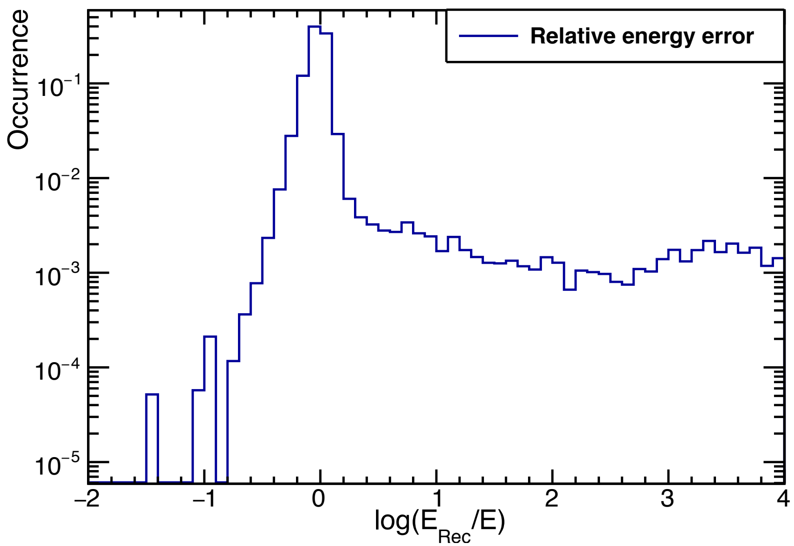


Results of the combined fit

Angular resolution

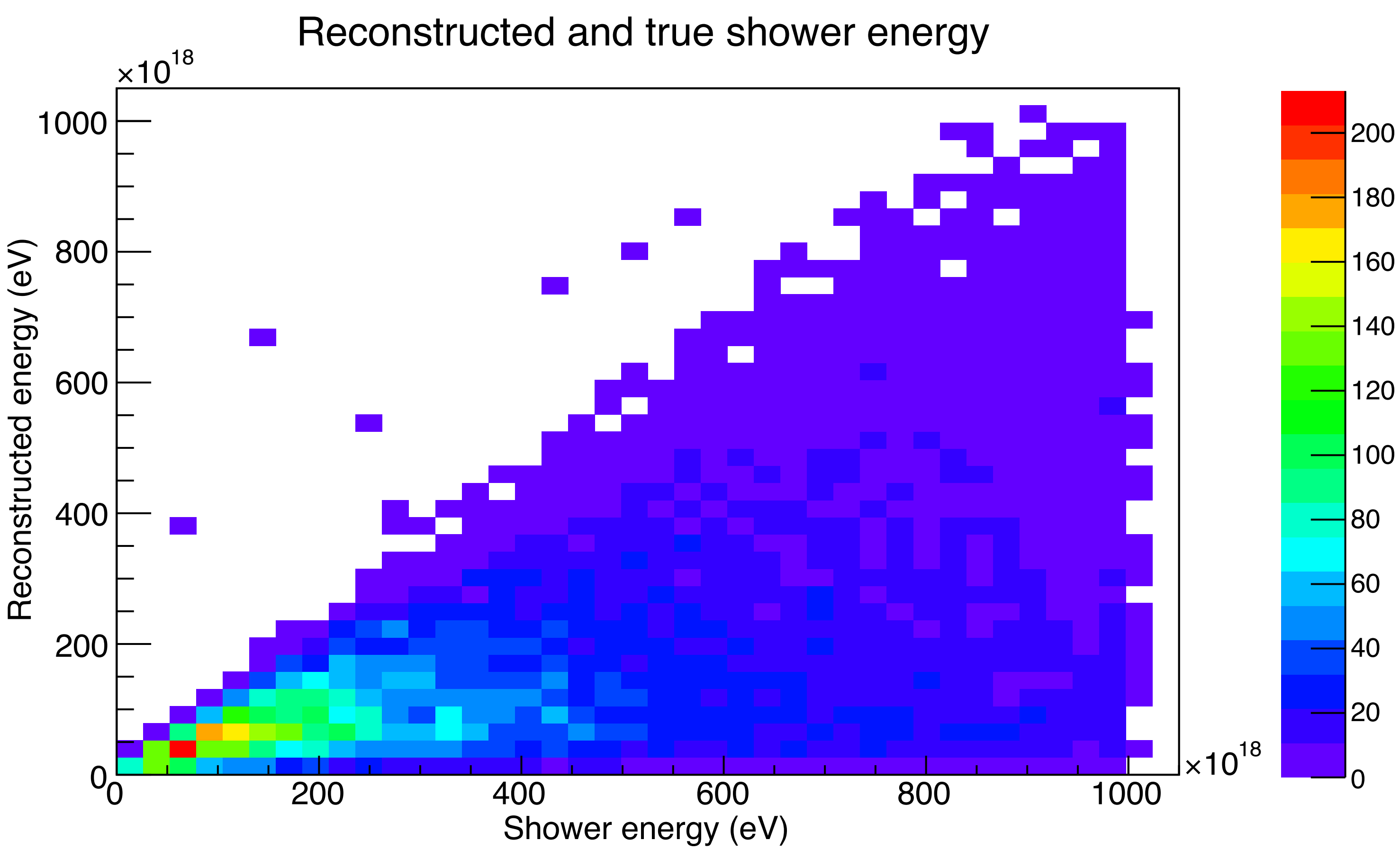


Relative energy error



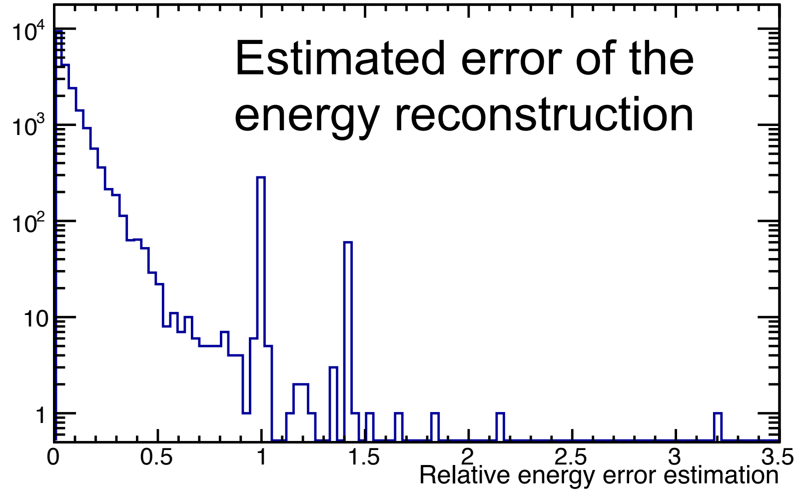
- Average direction error 1.0° (90% Quantile: 2.3°)
- Average vertex error 250m (90% Quantile: 620m)
- Average energy error 30% (90% Quantile: 75%)

Energy reconstruction



Cuts on the quality parameters of the fit to improve background suppression

- Minuit gives error estimates for all fitted parameters
- Define cuts for these parameters to remove badly reconstructed events



- E.g. estimated error of the energy: $\Delta E \leq 0.5\ E$
- Removes a lot of falsely classified neutrinos
  - In a test run with 2 neutrinos and 120k background events, 1 neutrino and 1 falsely classified background event was found

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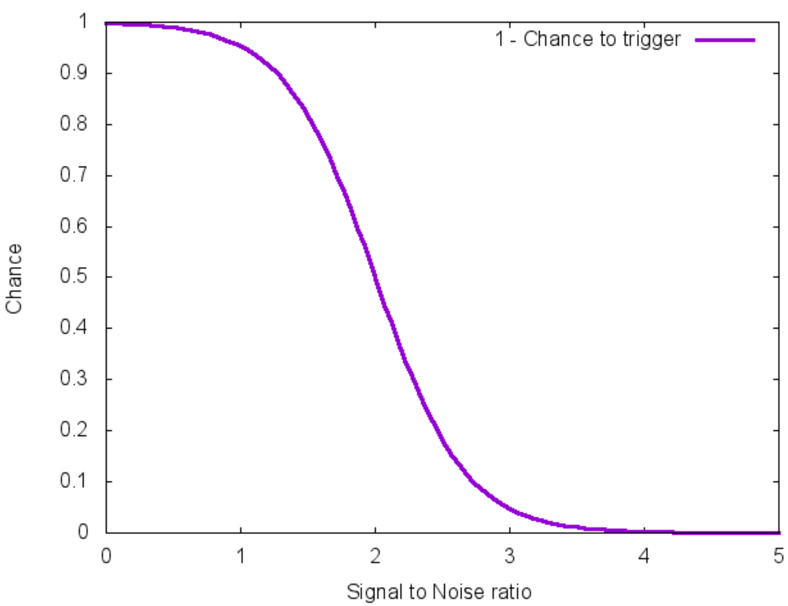
Combined fit with the information of hydrophones NOT in the event

- If a sensor does not detect an event, then the amplitude was too small there
- This provides additional information for the fit

$$g = \sum_i \ln\left(0.5 - 0.5 \cdot \tanh\left(\frac{3 \cdot a_i^{rec}}{2 \cdot Noise} - 3\right)\right)$$

Logarithm of chance not to trigger (approximation)



- Use a linear combination of f and g for the minimization
- Improves reconstruction for some events
- Investigation ongoing whether this is a better reconstruction method

Summary

- Signal classification for KM3NeT using the pancake is under investigation. Improvements by cascading machine learning algorithmns. Background rates reduced by 4 orders of magnitude
- Energy reconstruction requires combined fit of vertex, direction and energy. Achieves accuracy of 30% for the shower energy
- Cutting on the quality parameters of the combined fit improves background suppression by a factor of $\gtrsim$15

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Thank you for your attention!

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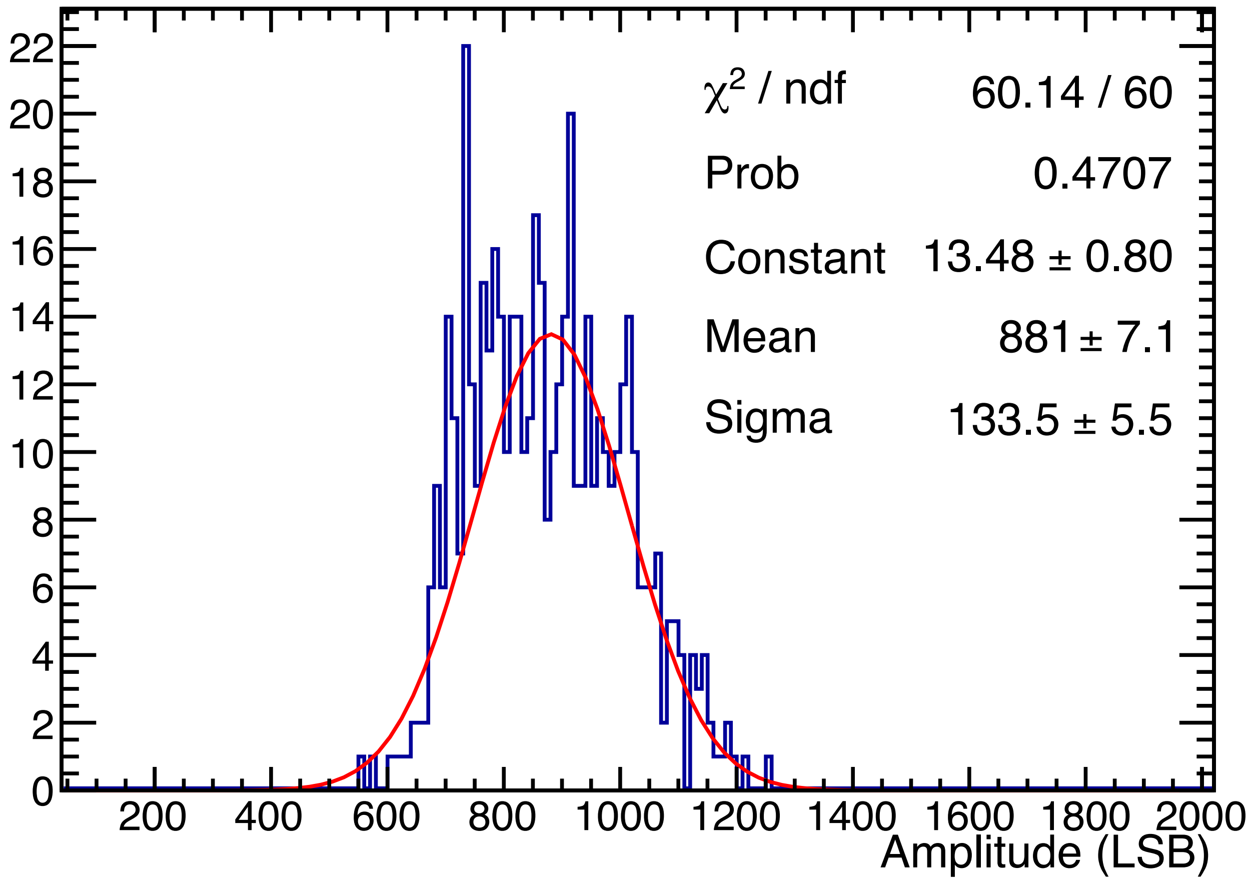
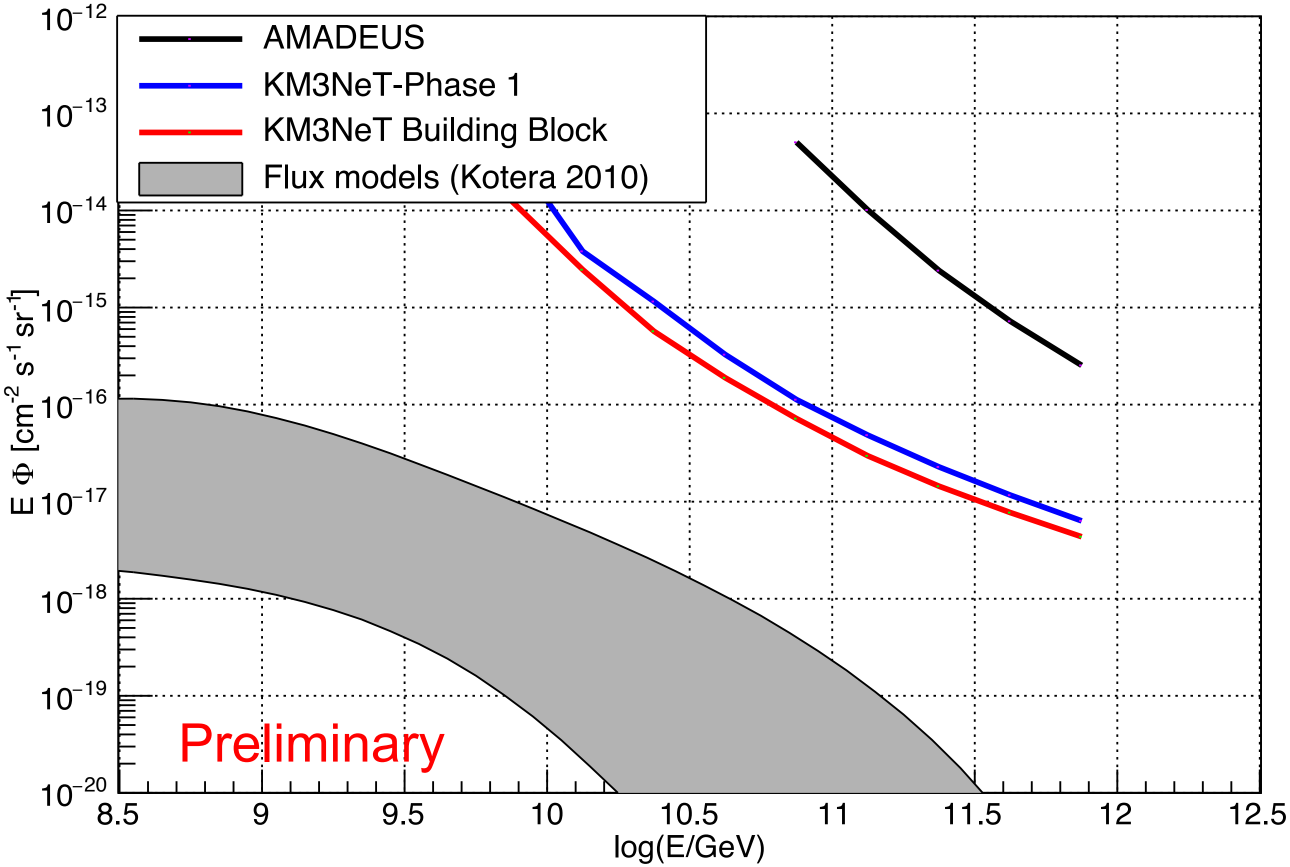
Intrinsic variance

- Shower with 5e19 eV 200m from the sensor



Sensitivity of the Detectors (transient free limit)



$$\Phi_L = \frac{N_{CL} \cdot \lambda}{\Omega \cdot T \cdot V_{eff} \cdot E}$$

with:

N_{CL} = 2.44

T : life time (1 year)

λ : mean free path

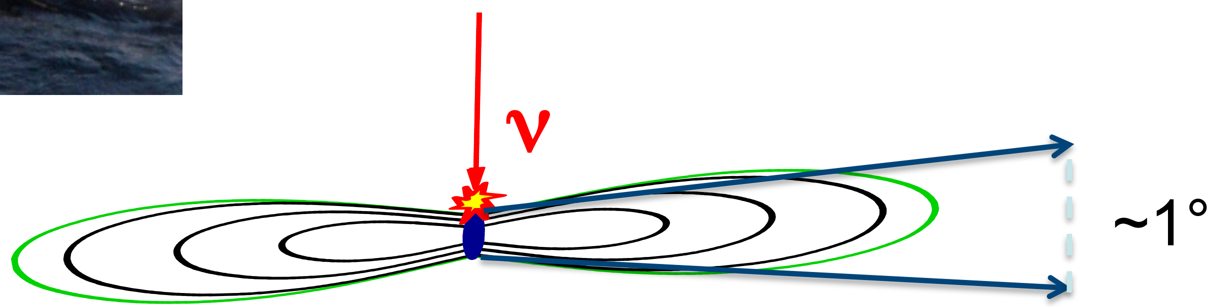
Ω : solid angle

E : energy

V_{eff} : eff. volume

Signal classification needed

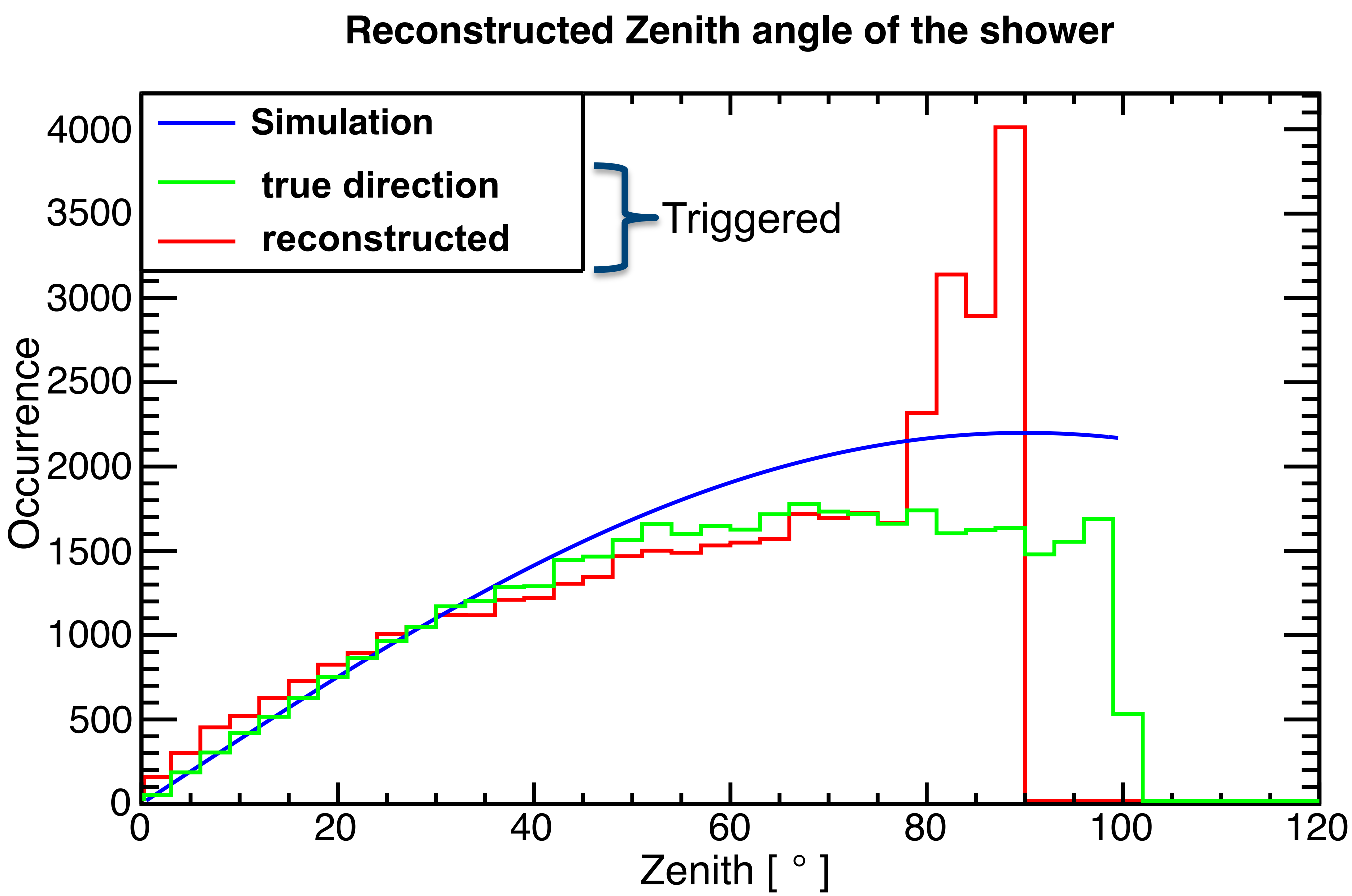
- High rate of transient background with bipolar pulses, from e.g. whales and dolphins
- Additional background suppression is necessary



- Acoustic signal from neutrinos is emitted in a *O*(20 m) thick plane
- Most background is emitted as spherical waves

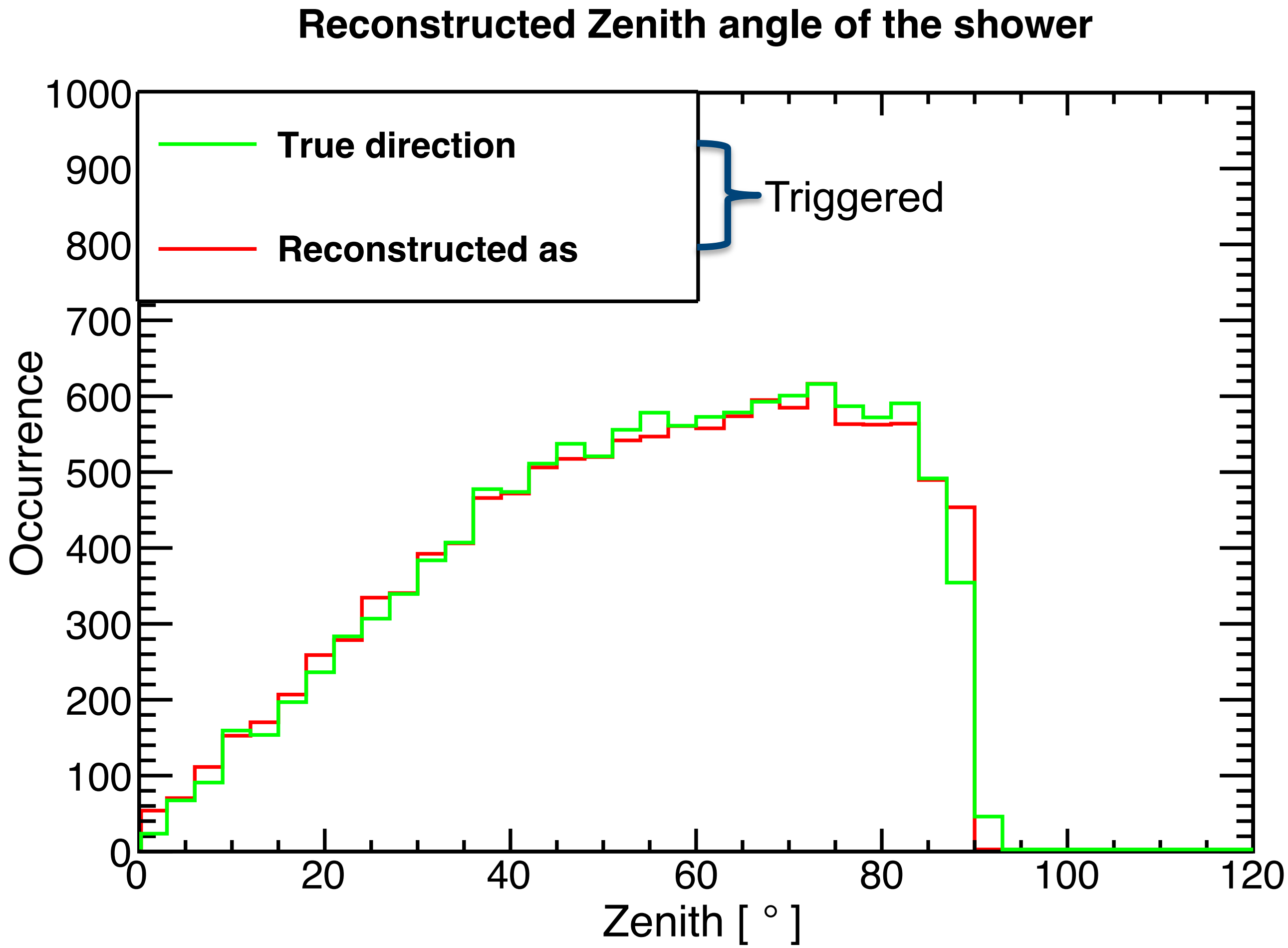
➡ Use the sound propagation geometry as classification for the signals in a large volume acoustic detector

Error of the zenith angle reconstruction for a building block (no earth model)



Earth model is not included to emphasize the effect!

Error of the zenith angle reconstruction for a building block (WITH earth model)



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