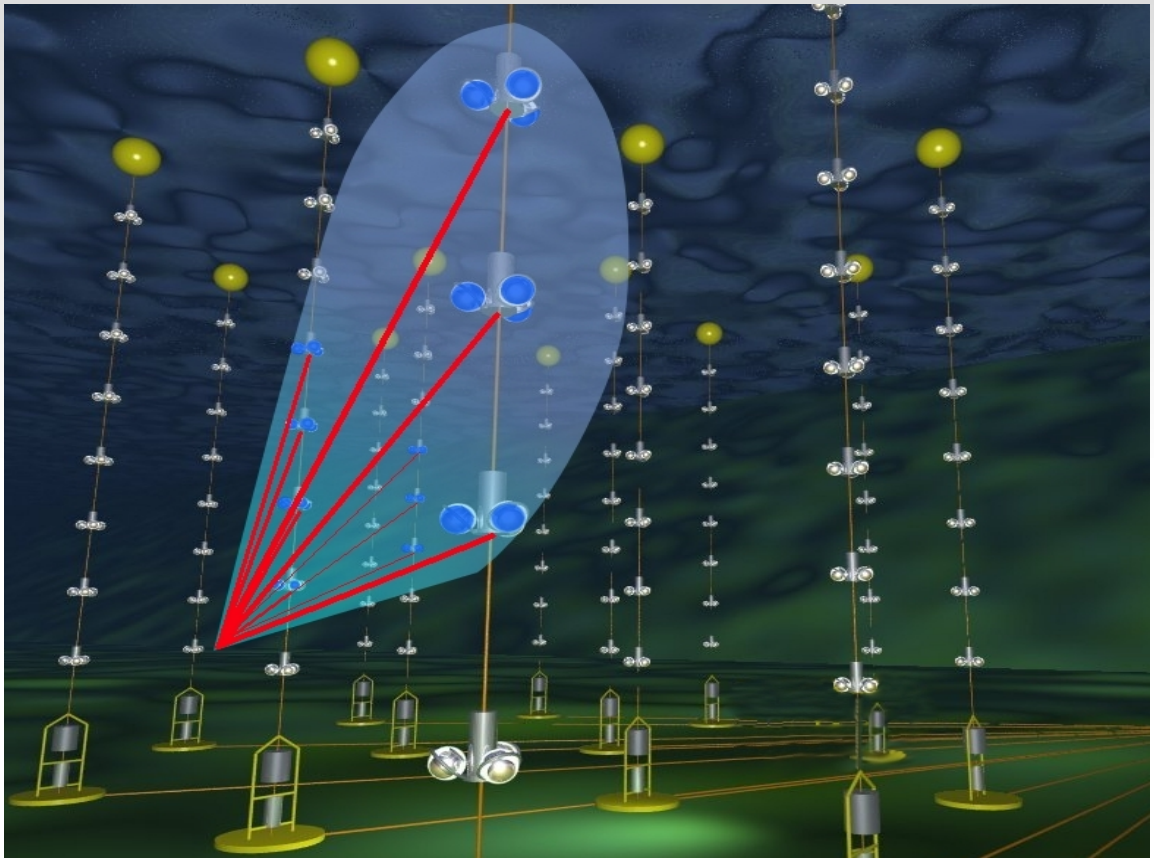
Neutrino-induced showers in the ANTARES deep-sea telescope

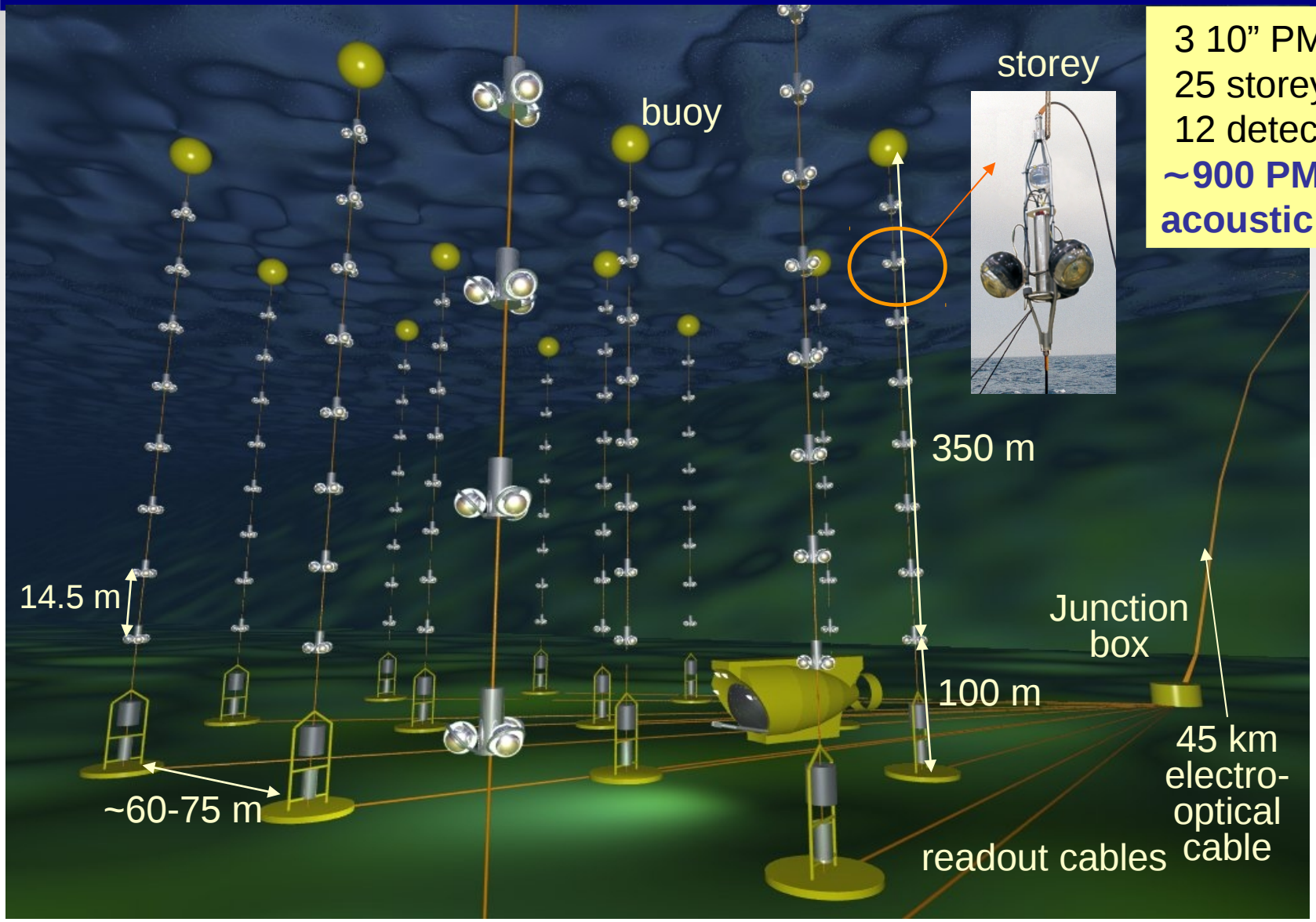


Outline:

- **ANTARES Telescope**
- **Shower signatures**
- **Shower reconstruction**
- **Shower selection strategy**
- **Performance Data vs. MC**
- **Conclusion & outlook**

Qader Dorosti, Herbert Löhner
KVI Groningen, Netherlands
on behalf of the ANTARES Collaboration

ANTARES layout



3 10” PMT/storey
25 storeys/line
12 detection lines:
~900 PMT +
acoustic detection

Why showers?

ANTARES event classes:

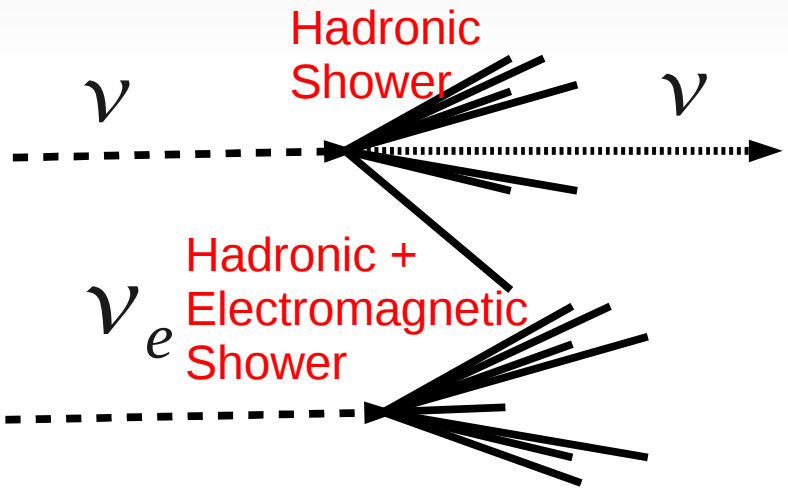
Event Classes **with a Track**

$\nu_\mu, \bar{\nu}_\mu$ *Charged Current*

Event Classes **without a Track**

$\nu_l, \bar{\nu}_l$ *Neutral Current*

$\nu_e, \bar{\nu}_e$ *Charged Current*



Extend the sensitivity of the detector to all neutrino flavors
→ provide constraints on astrophysical models

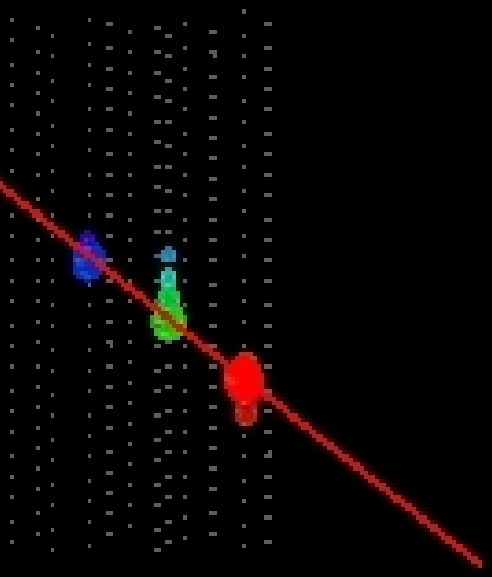
T. Kashti, E. Waxman, Phys. Rev. Lett. 95 (2005) 181101

Signatures of showers

Features of Antares simulated events

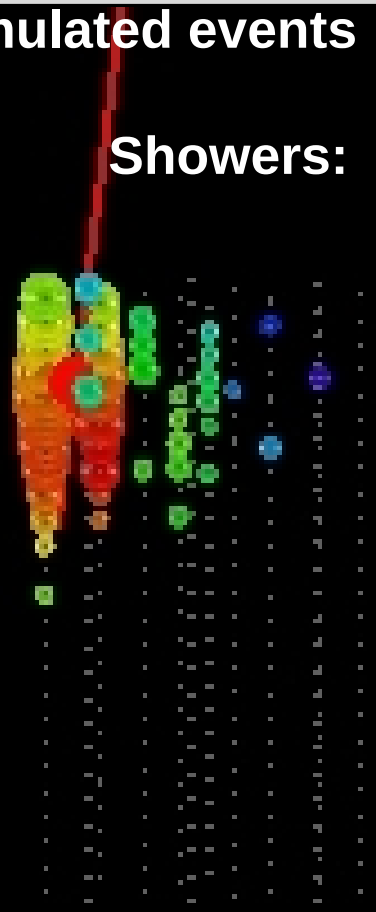
Muon tracks

- Deposit only part of their energy inside the detector
- All light produced along the muon track



Showers:

- Deposit their energy in a small volume
- All light produced in narrow region (presently assumed point-like)



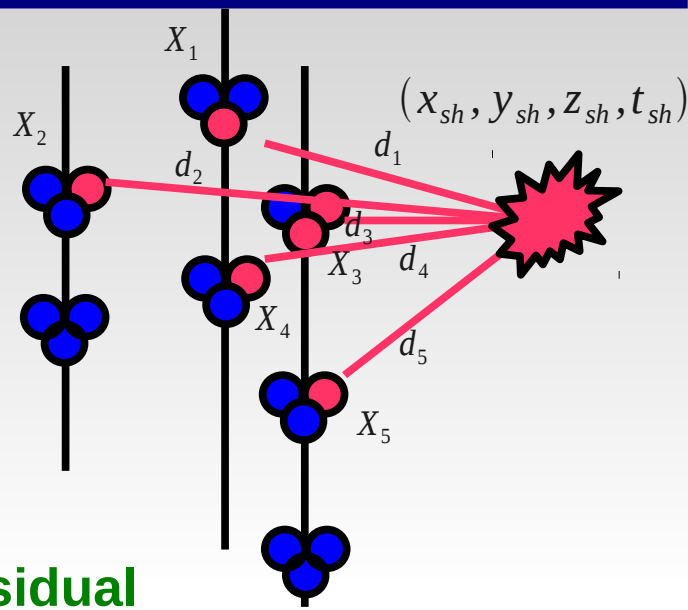
How can we efficiently identify the point-like objects?

Interaction vertex reconstruction

Causality relation for Cherenkov light emitted from shower particles

$$t_i - (t_{sh} + n/c\, d_i) = 0 \qquad i = 1,2,3,\ldots,N$$

hit time – expected time of hit



Step I:

mean space-time position

→ starting points for M-estimator

→ **Residual**

Step II:

space-time position

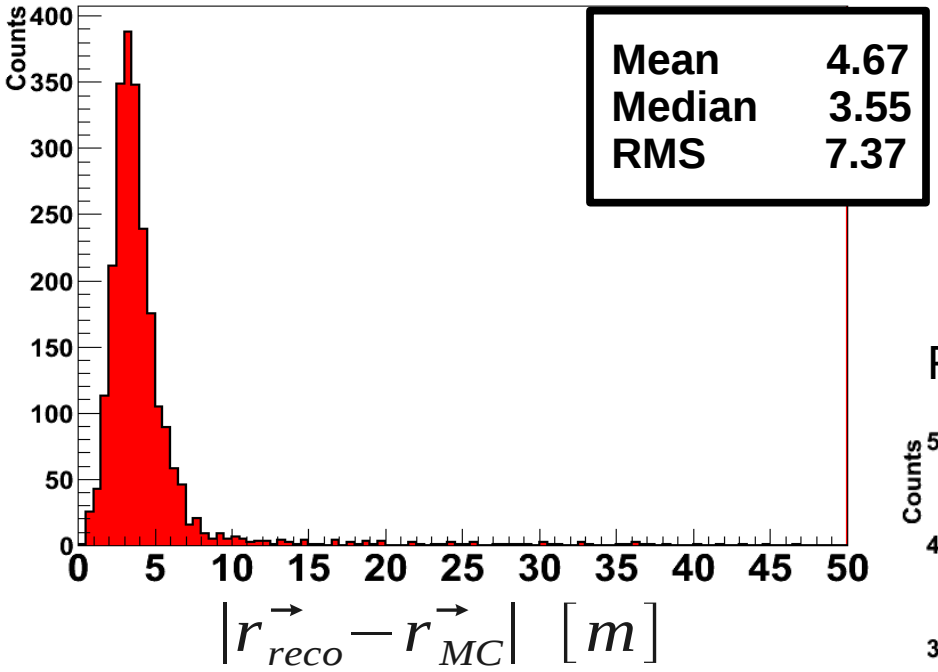
$$M = \sum_{i=1}^{N} \left(2\sqrt{\left(1 + \frac{(t_i - (t_{sh} + n/c\, d_i))^2}{2\sigma_t^2} \right)} + 2 \right)$$

→ **M**

→ **shower selection**

Performance of vertex reconstruction

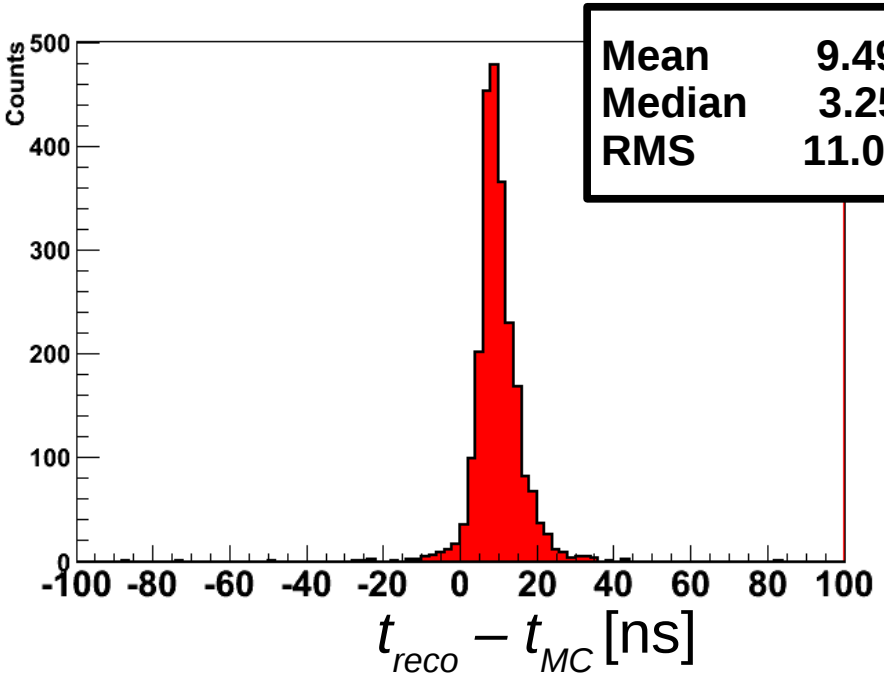
Reconstruction error of **vertex position**



Mean	**4.67**
Median	**3.55**
RMS	**7.37**

type	Energy range	Interaction
Atmospheric	10^2 - 10^7 GeV	ν_μ NC

Reconstruction error of **interaction time**



Mean	**9.49**
Median	**3.25**
RMS	**11.00**

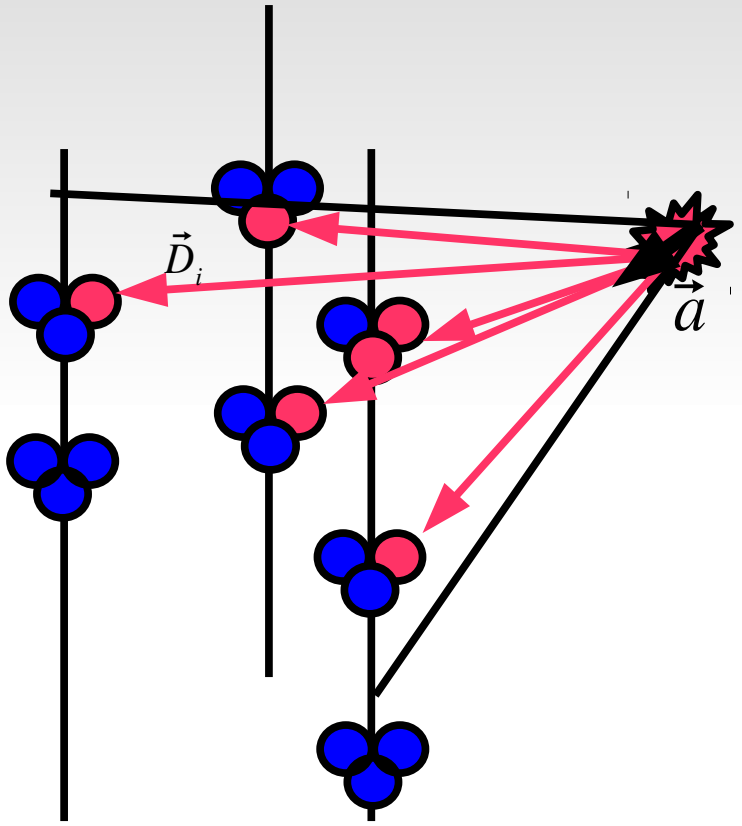
Light direction

Hypothesis:

- Shower has a preferred direction
- Photons are produced
  on a Cherenkov cone
- Mean light direction
  → Preferred shower direction

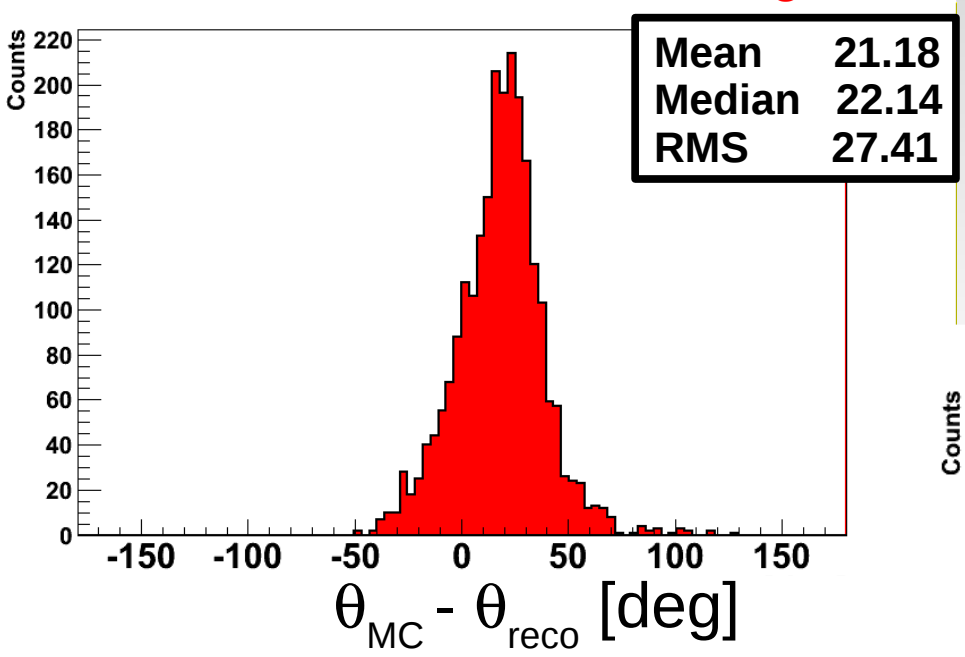
$$\vec{D}_{tot} = \frac{1}{(N\ hits)} \sum_{i=1}^{N} \vec{D}_i \ \| \vec{a}$$

Propagation of light from shower axis

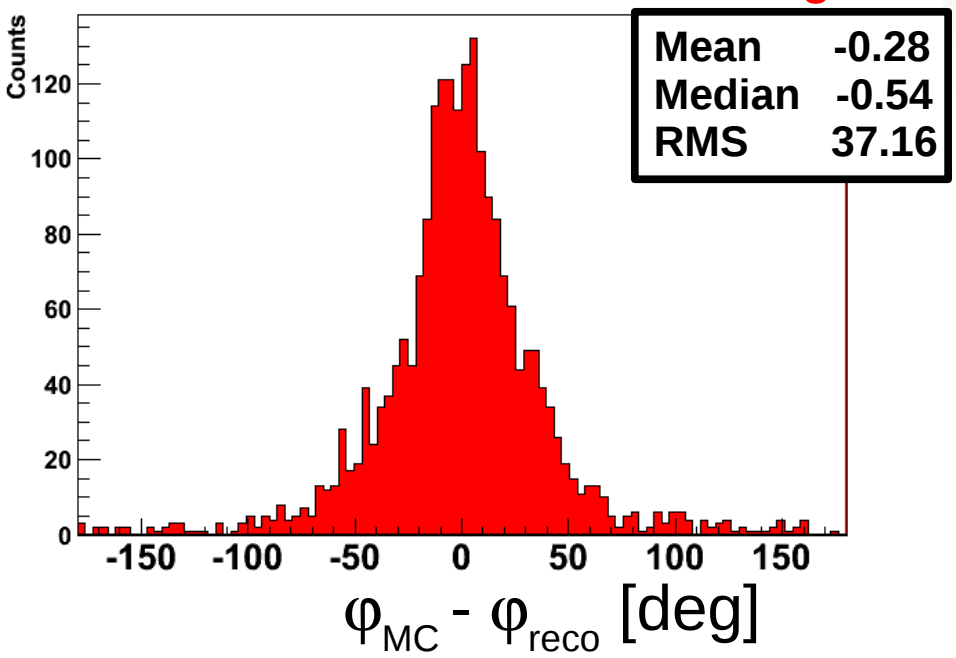


Performance of direction reconstruction

Reconstruction error of **zenith angle**



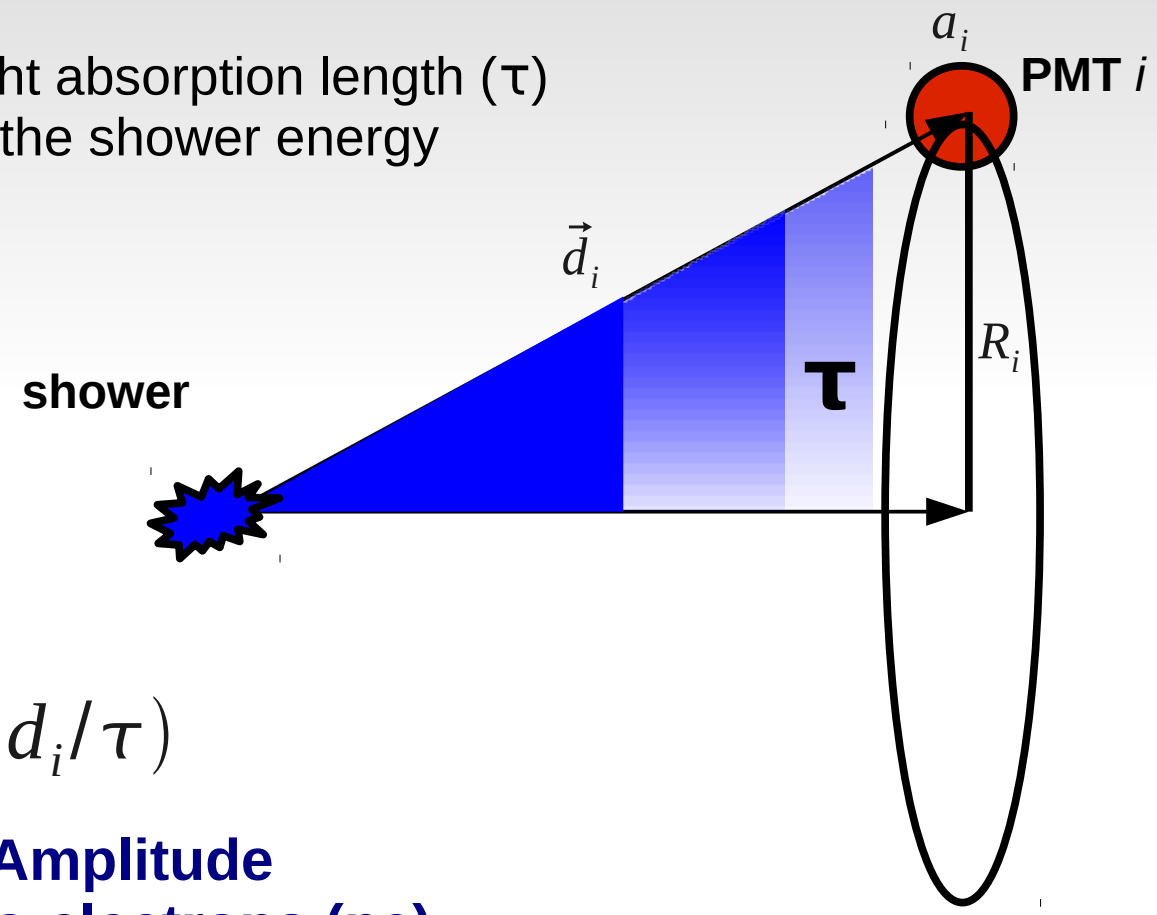
Reconstruction error of **azimuth angle**



Reconstruction of energy for selected shower events

Hypothesis

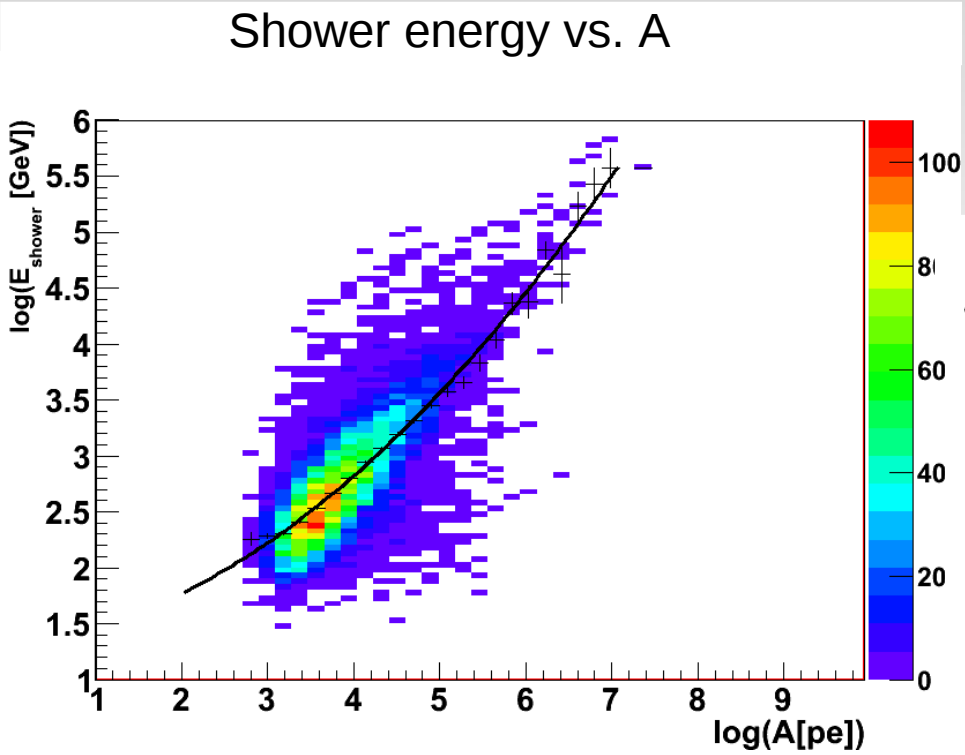
- Sum of all hit amplitudes,
  corrected according to light absorption length (τ)
  → correlated to the shower energy

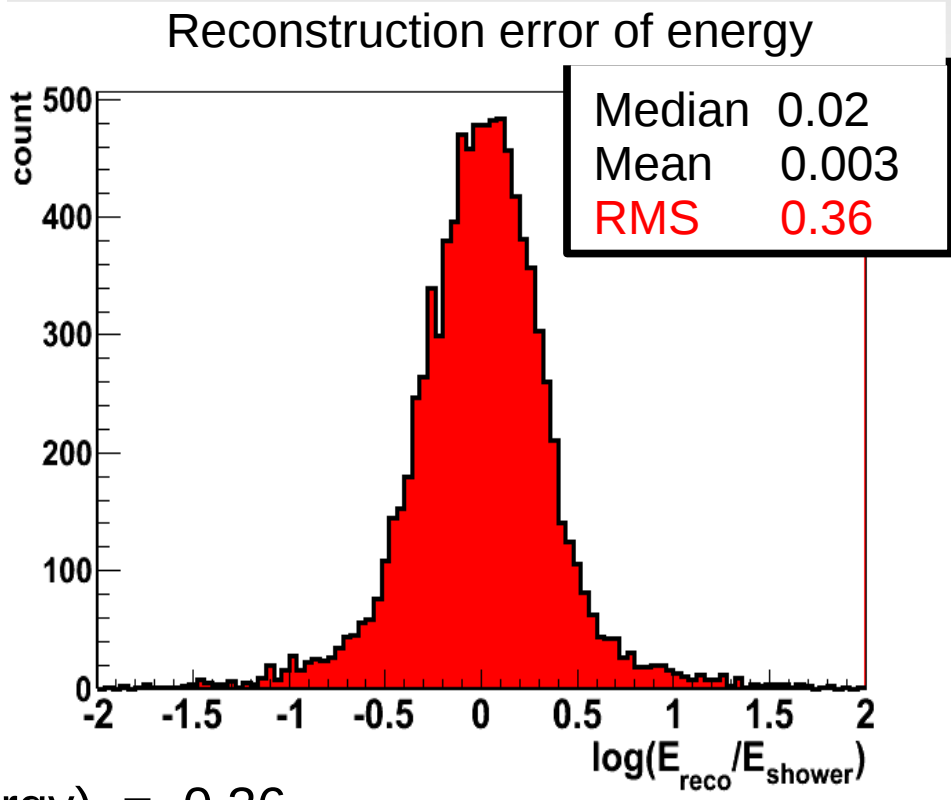


$$A[pe] = \sum_{i=1}^{N} a_i R_i \exp(d_i/\tau)$$

A [pe] = Reconstructed Amplitude in units of photo-electrons (pe)

Performance of the energy reconstruction





RMS of log (reconstructed shower energy) = 0.36

(≅ factor 2.2 on shower energy)

Reconstruction quality

Reconstruction error @ 10 TeV neutrino energy	RMS / Median
Vertex position	4.5 m / 3.5 m
Interaction time	11 ns / 9.5 ns
Direction	36 deg. / 30 deg.
Log (shower energy)	0.36 / 0.02

Shower selection strategy

Suppress atmospheric muons:

→ direction reconstruction: $\theta < 90^{o}$
(Light Direction & BBFit)

→ total charge / event: >100 pe

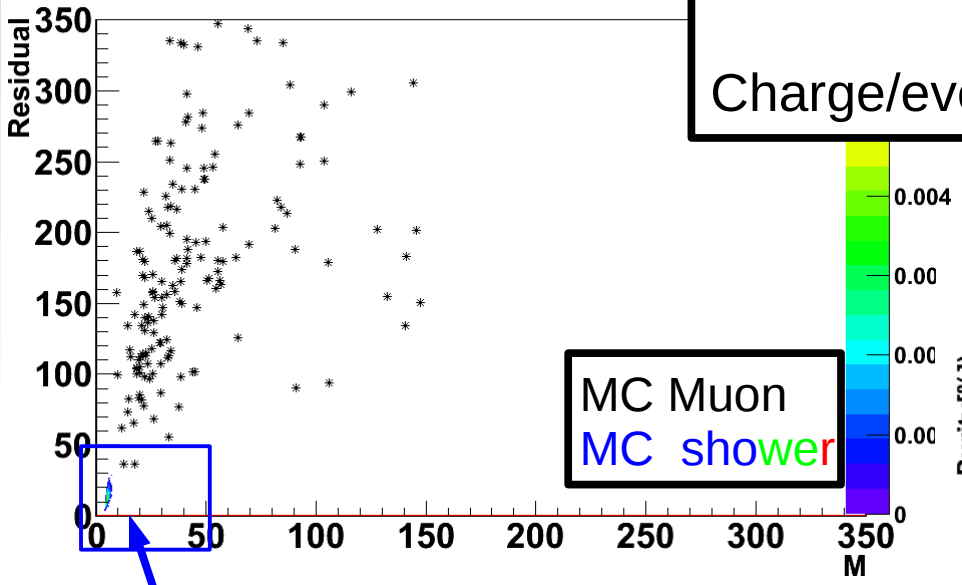
Select showers:

→ shower vertex reconstruction

→ cuts on shower observables: **Residual**
M - estimator

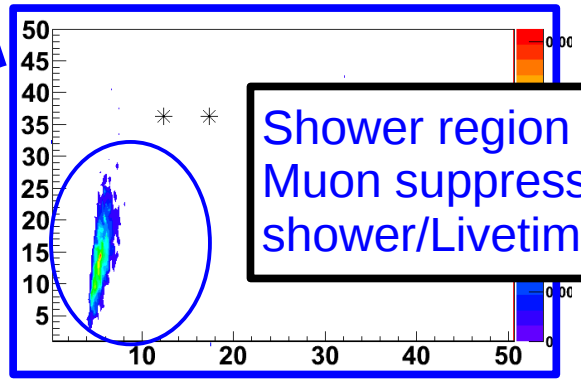
Shower selection

Residual vs M



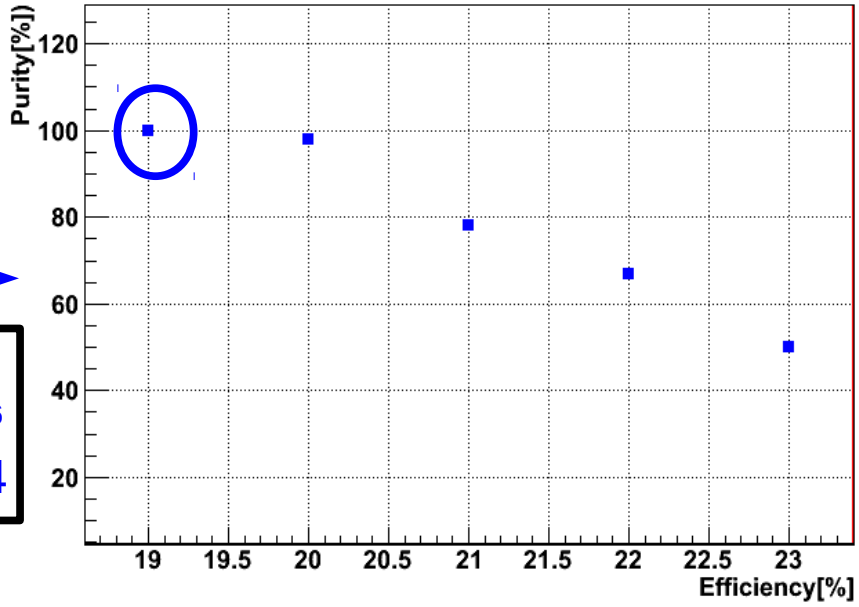
MC
Livetime: 2.3 days
θ: < 90 ^{o}
Charge/event: > 100 pe

MC Muon
MC shower



Shower region
Muon suppression: 10^{6}
shower/Livetime: 0.34

purity vs. efficiency

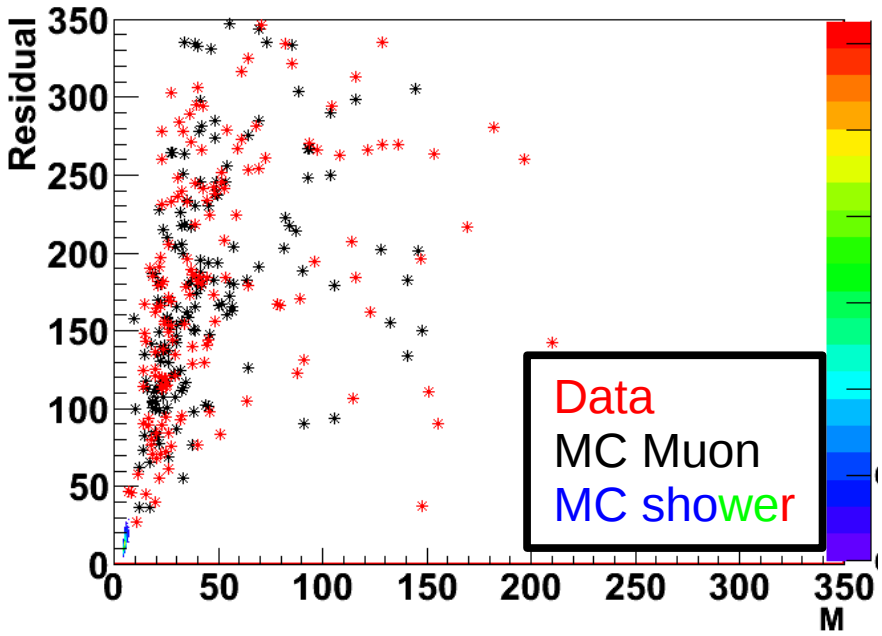


Shower selection with high purity

Data-MC comparison

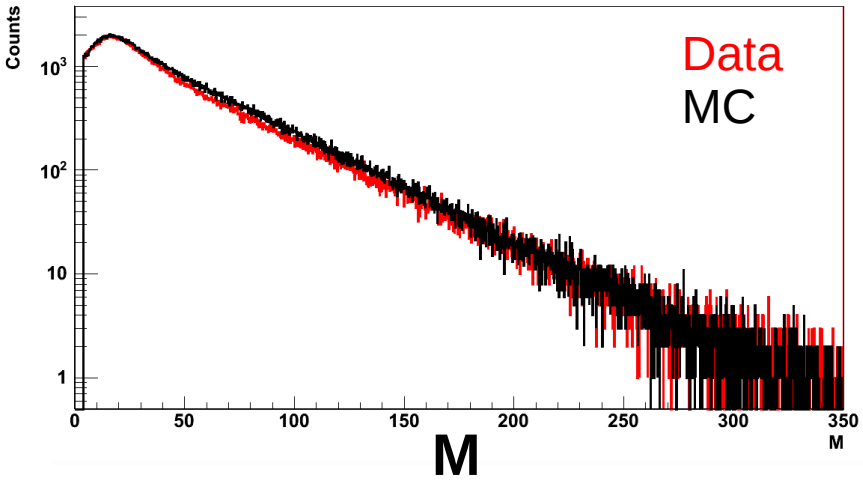
Preliminary

Residual vs M

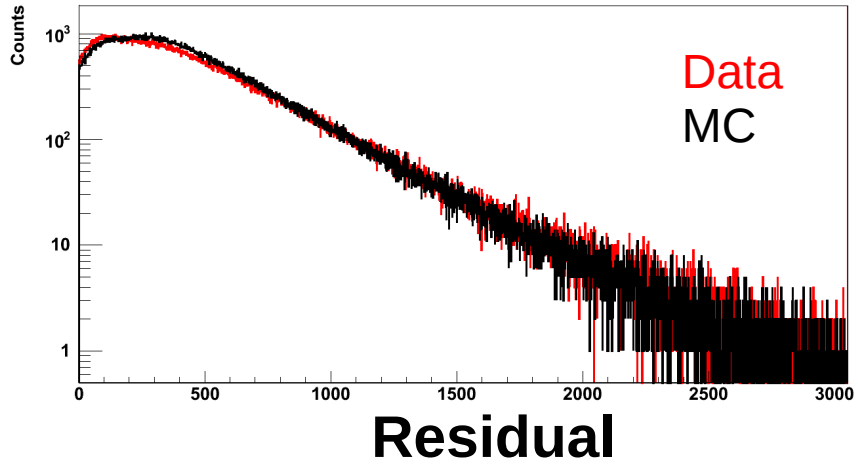


Livetime:	2.3 days
Data / MC:	1.01
Expected shower:	0.34
Found shower:	0

M-estimator distribution



Residual distribution

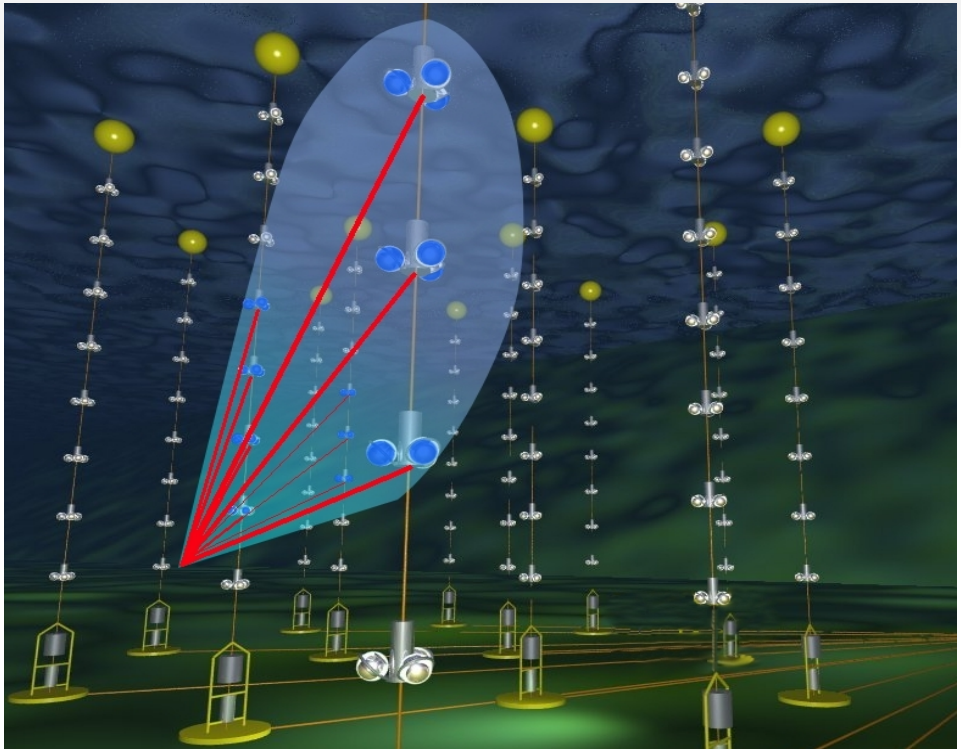


Conclusions

Shower selection strategy:

Vertex reconstruction:	< 5 m
Interaction time:	< 12 ns
Direction:	< 36 deg.
Log (shower energy)	< 0.36

Very good agreement
in background observables
between Data & MC



Outlook:

Selection strategy
ready to use
for physics analysis

$$\text{Efficiency} = \frac{\#\text{ of good events}}{\text{total }\#\text{ of good events}}$$

$$\text{Purity} = \frac{\#\text{ of good events}}{\#\text{ of good events} + \#\text{ of bad events}}$$

Causality relation for Cherenkov light emitted from shower particles

$$d_i = \sqrt{(x_{sh}-x_i)^2+(y_{sh}-y_i)^2+(z_{sh}-z_i)^2} = c/n.(t_{sh}-t_i) \qquad i=1,2,3,\ldots,N$$

Pairwise subtraction of the above equations:

$$x_{i+1}^2 - x_i^2 + y_{i+1}^2 - y_i^2 + z_{i+1}^2 - z_i^2 - (c/n)^2(t_{i+1}^2 - t_i^2) =$$

$$2(x_{i+1}-x_i)x_{sh} + 2(y_{i+1}-y_i)y_{sh} + 2(z_{i+1}-z_i)z_{sh} - 2(c/n)^2(t_{i+1}-t_i)t_{sh}$$

$$\vec{b} = A \cdot \vec{\xi}_{sh} \qquad N > 4$$

In practice small residual *r* is expected

$$\vec{r} = A \cdot \vec{\xi}_{sh} - \vec{b} \xrightarrow{\text{Minimization}} \frac{d}{d\xi_{sh}} |\vec{r}| = 0$$

$$\vec{\xi}_{sh} = (A^T A)^{-1} A^T \vec{b}$$

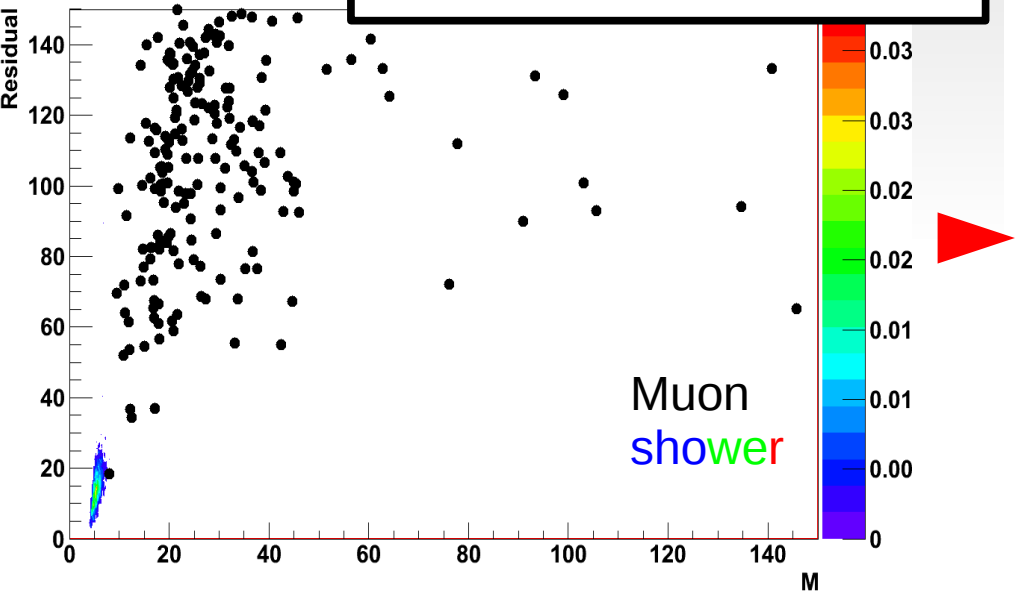
Achieved shower energy resolution compared to muon tracks

Muon energy resolution	Shower energy resolution
A factor of 3 on the energy (RMS log of 0.51)	A factor of 2 on the energy (RMS log of 0.31)

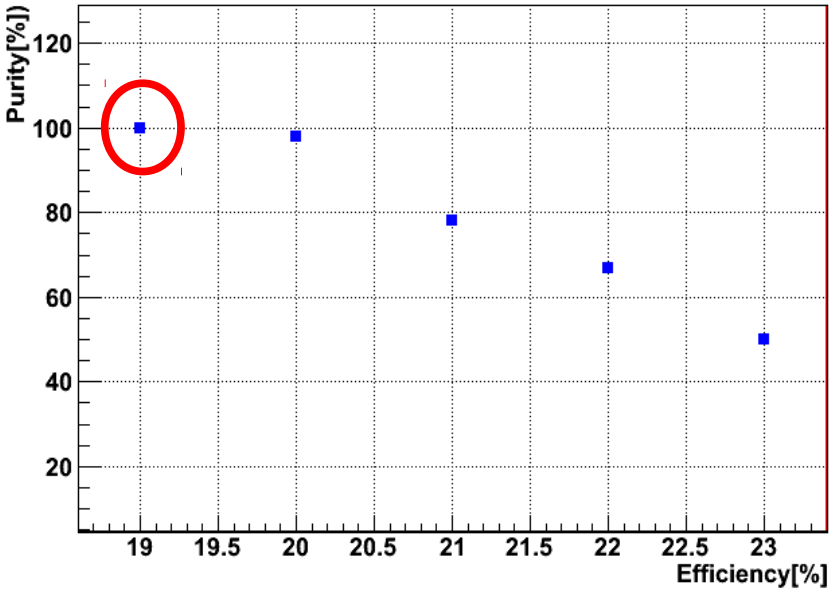
Shower selection

Lifetime	7.4 days
Up-going	
Charge/event	>100 pe

Muon background:
→ official TE muon production 2009



Residual vs M for MC showers and muons



Efficiency vs shower energy

Shower selection with high purity