Shower reconstruction and analysis with ANTARES & KM3NeT

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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Outline

- Showers in ANTARES
  - Simulation
  - Reconstruction tools
  - Ongoing analyses
- Showers in KM3NeT

Shower simulation in ANTARES

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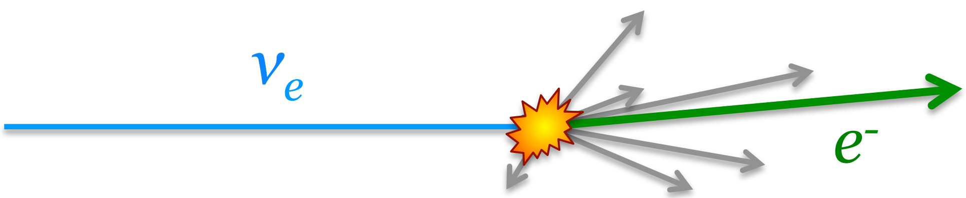
Status quo in shower simulation

Run-by-run based shower simulation of ν_μ and ν_e CC and NC interactions taking into account currently valid

- calibration for optical modules
- optical background
- detector status (line configuration, dead channels etc…)
- Note: no photon scattering included for showers

4 GeV – 100 TeV	50 TeV – 100 PeV
Geant-based shower shower particle simulation	Geant-based shower shower particle simulation only to a certain level of secondary particles
Cerenkov light from each individual shower particle, em-shower from parameterized tables	Cerenkov light from **One-Particle-Approximation**

One-Particle-Approximation



Idea:
Replace all shower particles by one equivalent electron transferring

- 100% of the energy from π^o, γ, e^+, e^-
- 20% of the energy from π^+, π^-

<u>Possible improvements for future simulations:</u>

- **energy-dependent particle weights** *(Bachelor thesis of M. Dentler)*
- replace each single particle by an equivalent energy without merging them (**Multi-Particle-Approximation**) *(C. James)*

Tau neutrino interactions

Currently not simulated, but estimated from electron neutrino

NC: *Identical cross-sections for all three flavours* → $n_{\nu_\tau \mathrm{NC}} = \frac{n_{\nu_\mu \nu_e \mathrm{NC}}}{2}$

CC: $n_{\nu_\tau \mathrm{CC}} = n_{\nu_e \mathrm{CC}} \cdot (1 - \eta_{\mathrm{Glashow}}) \cdot \eta_{\tau-\mathrm{shower}}$

fraction of electron neutrinos that interact in Glashow resonance (η_{Glashow})

fraction of tauon decays that produce showers ($\eta_{\tau-\mathrm{shower}}$)

Studies on tau neutrino simulation are ongoing. *(S. Schulte)*

Shower reconstruction in ANTARES

Shower reconstruction tools

Q-Strategy *(Q. Dorosti Hasankiadeh)*

- Vertex and shower axis reconstruction from geometrical calculations
- Neutrino energy from Monte-Carlo based parameterization

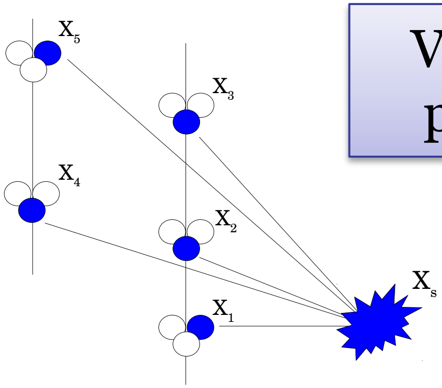
Dusj-Reco *(F. Folger)*

- Full shower reconstruction using Maximum-Likelihood fits
- PDF tables based on Monte-Carlo NC+CC shower simulations

T-Strategy *(T. Michael)*

- Currently in development
- Intended for point source analyses, focused on angular resolution

Q-Strategy – Hit selection & vertex reconstruction



Vertex prefit

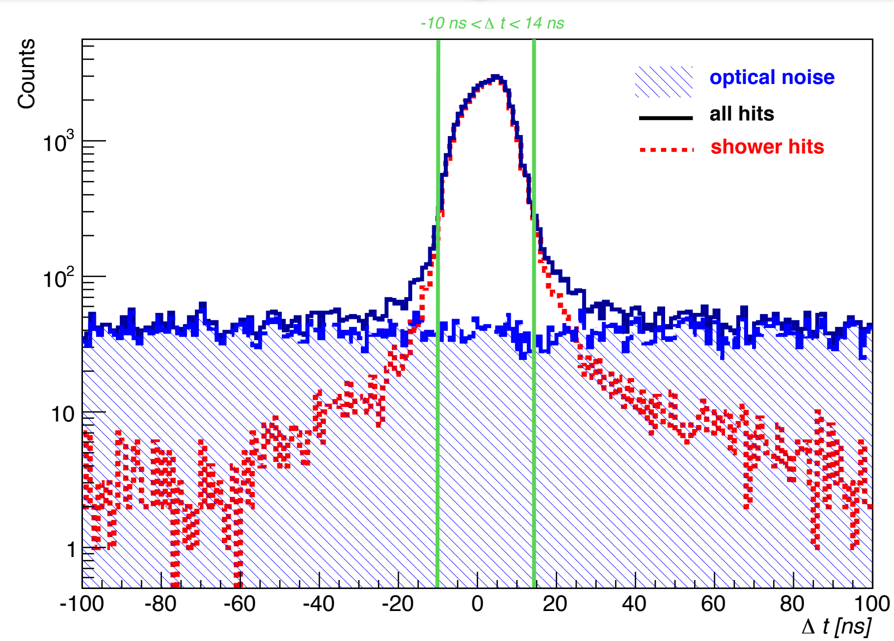
$$\Delta T = \frac{n}{c}\left|\vec{r}_s - \vec{r}_i\right| + (t_s - t_i) = 0,$$

time residual equation
for each pulse i

➡ *system of equations for r_s and t_s*

Hit selection

cut on time residual window



Vertex fit

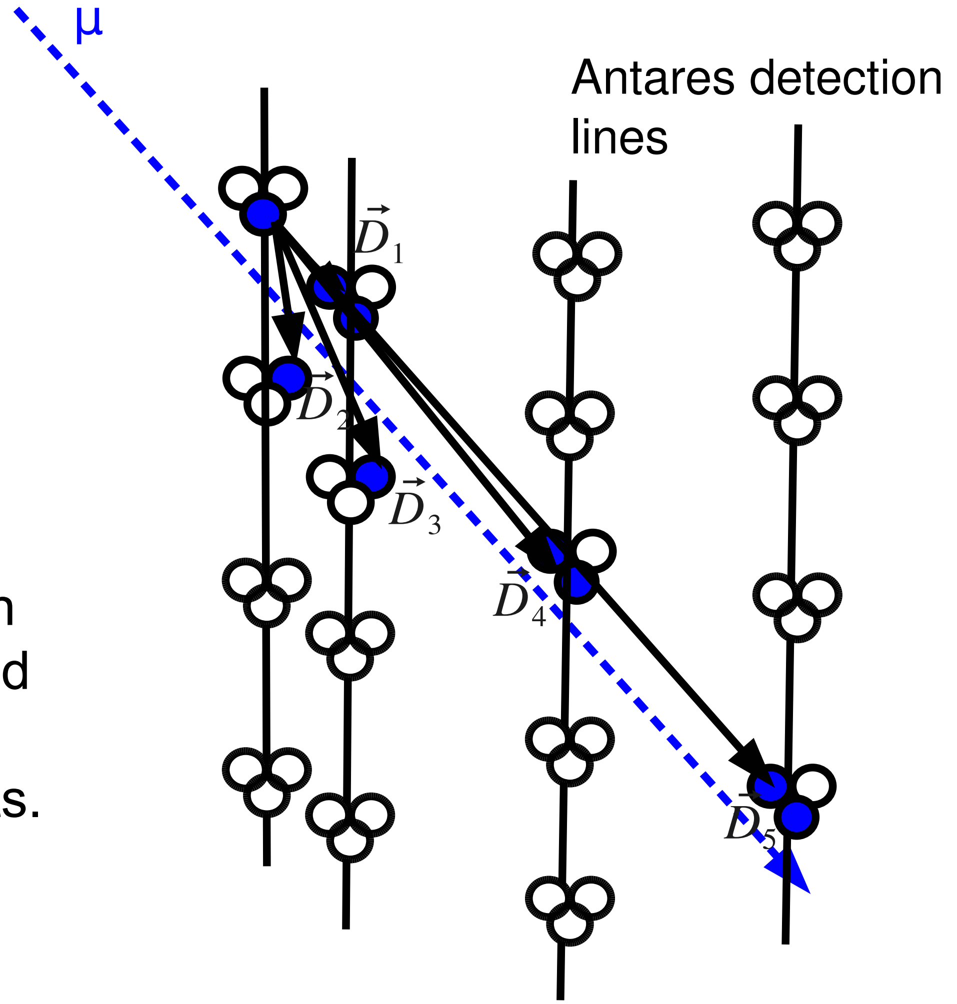
repeat fit routine using selected pulses only

Q-Strategy – shower axis reconstruction

Evaluate the mean of the light vectors from the earliest hit pointing to the other hits

$$\vec{D} = \frac{1}{N-1} \sum_{i=1}^{N-1} \vec{D}_i.$$

The method provides a rough estimation of the direction and can be used to suppress downgoing muon track events.



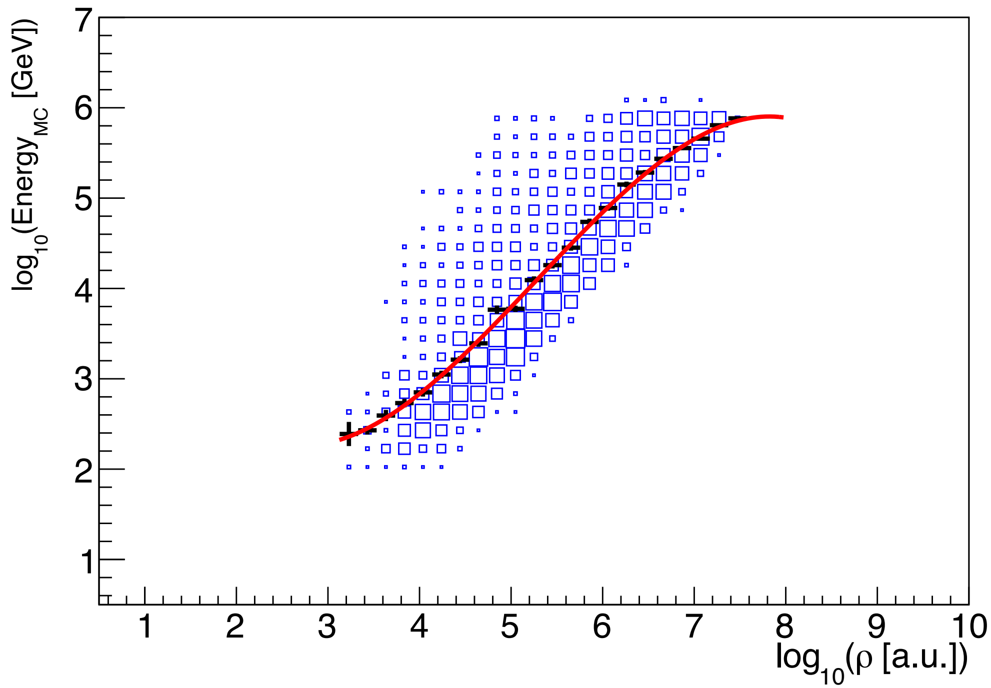
Q-Strategy – neutrino energy reconstruction

Evaluate an energy estimator ρ that is the total detected charge, corrected by

- *light attenuation in water*
- *PMT angular acceptance*

$$\rho[a.u.] = \frac{A^{tot}}{\frac{1}{N}\sum_{i=1}^{N}\frac{\alpha_i}{|\vec{r}_i - \vec{r}_s|}e^{-|\vec{r}_i - \vec{r}_s|/\tau}}$$

The relation between ρ and the neutrino energy has been parameterized from a fit on Monte-Carlo simulations.



Dusj-Reco scheme

Hit selection

- *Evaluate a rough vertex estimation from the distribution of coincident and big hits*
- *Apply a cut on the time residual respective this vertex*

Shower reconstruction

- *2-step Gulliver maximum-likelihood fit where the likelihood is calculated from Monte-Carlo based pdf values (idea firstly introduced by R. Auer)*

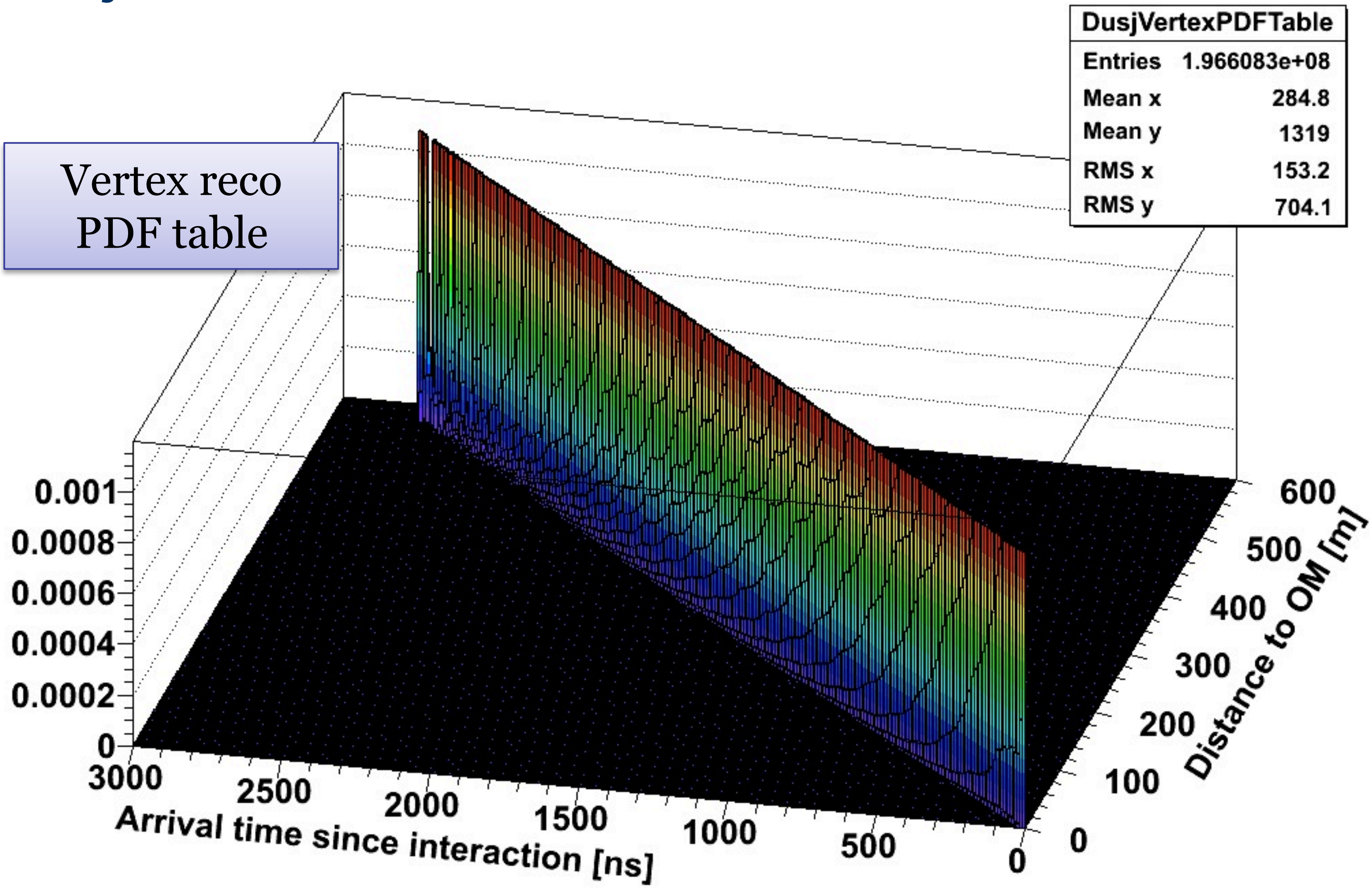
$$-\log LLH = \sum_{i=1}^{N_{\text{pulses}}} -\log pdf_i$$

probability that the whole event has been caused by a certain shower assumption

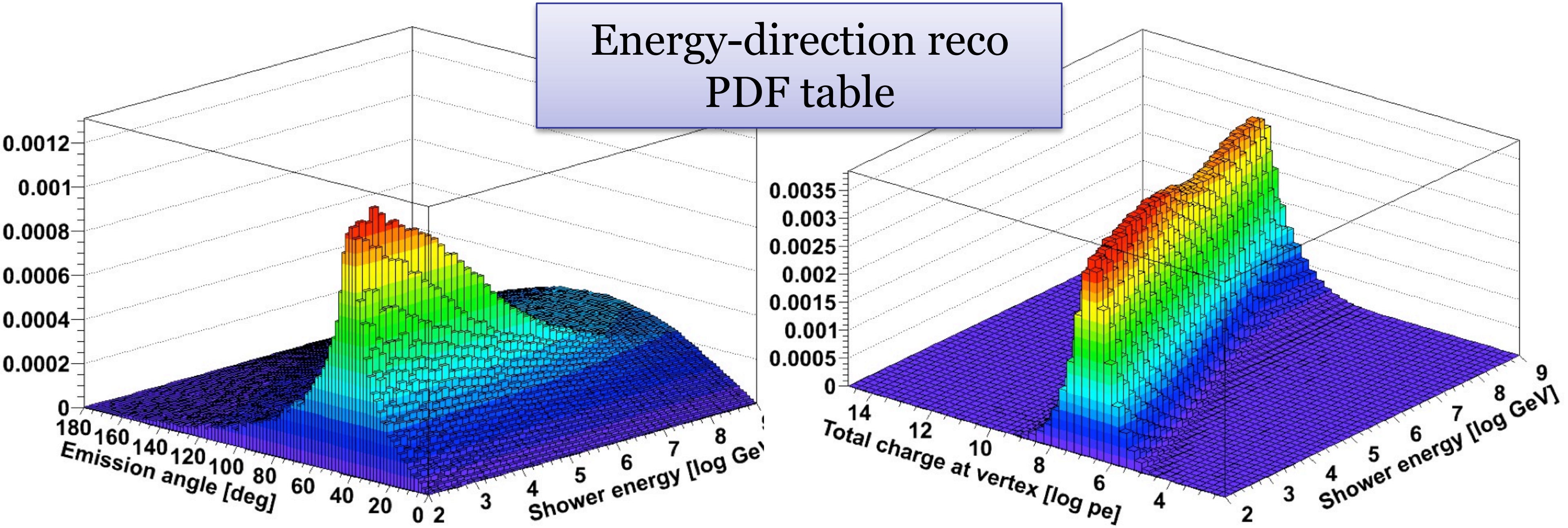
probability that one single hit has been caused by a certain shower assumption (stored in tables that were filled from Monte-Carlo simulations)

Dusj-Reco – Vertex reconstruction

Vertex reco PDF table



Dusj-Reco – Shower energy and neutrino direction reconstruction



3-dimensional table relating for each hit:

- *Energy of the shower*
- *Photon emission angle with respect to neutrino track*
- *Total expected charge at the vertex*

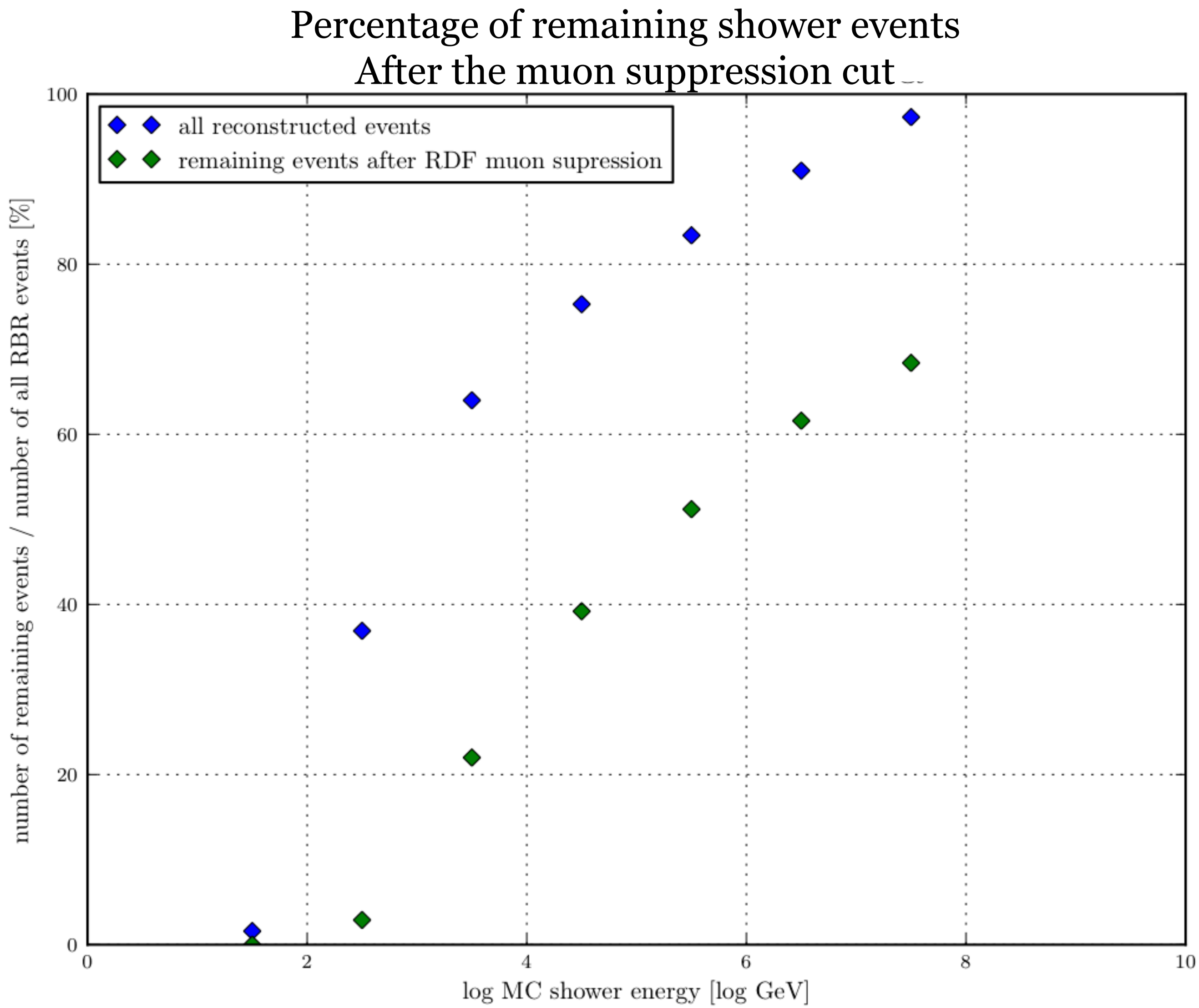
$$c_{\mathrm{vertex}} = c_{\mathrm{pulse}} \cdot e^{\frac{d}{\lambda_w}} \cdot \frac{1}{\alpha} \cdot \frac{4\pi d^2}{A_{\mathrm{OM}}^2}$$

Dusj-Reco – Muon suppression

Muon track events are suppressed with a random decision forest trained with quality parameters

- *Final likelihood values*
- *Time residual chi square*

Yields a suppression of atmospheric muons by 5-6 orders of magnitude



Dusj-Reco - Performance

Shower energy	@ 1 TeV	@ 100 TeV	@ 10 PeV
Vertex median error *	3.5 m	5.2 m	8.4 m
Interaction time median error	4 ns	7 ns	25 ns
Neutrino direction median error **	8.4 deg	5.2 deg	37.3 deg
Shower energy reconstruction offset	-0.3 orders of mag	-0.2 orders of mag	-0.5 orders of mag
Shower energy RMS error	0.2 orders of mag	0.4 orders of mag	0.6 orders of mag

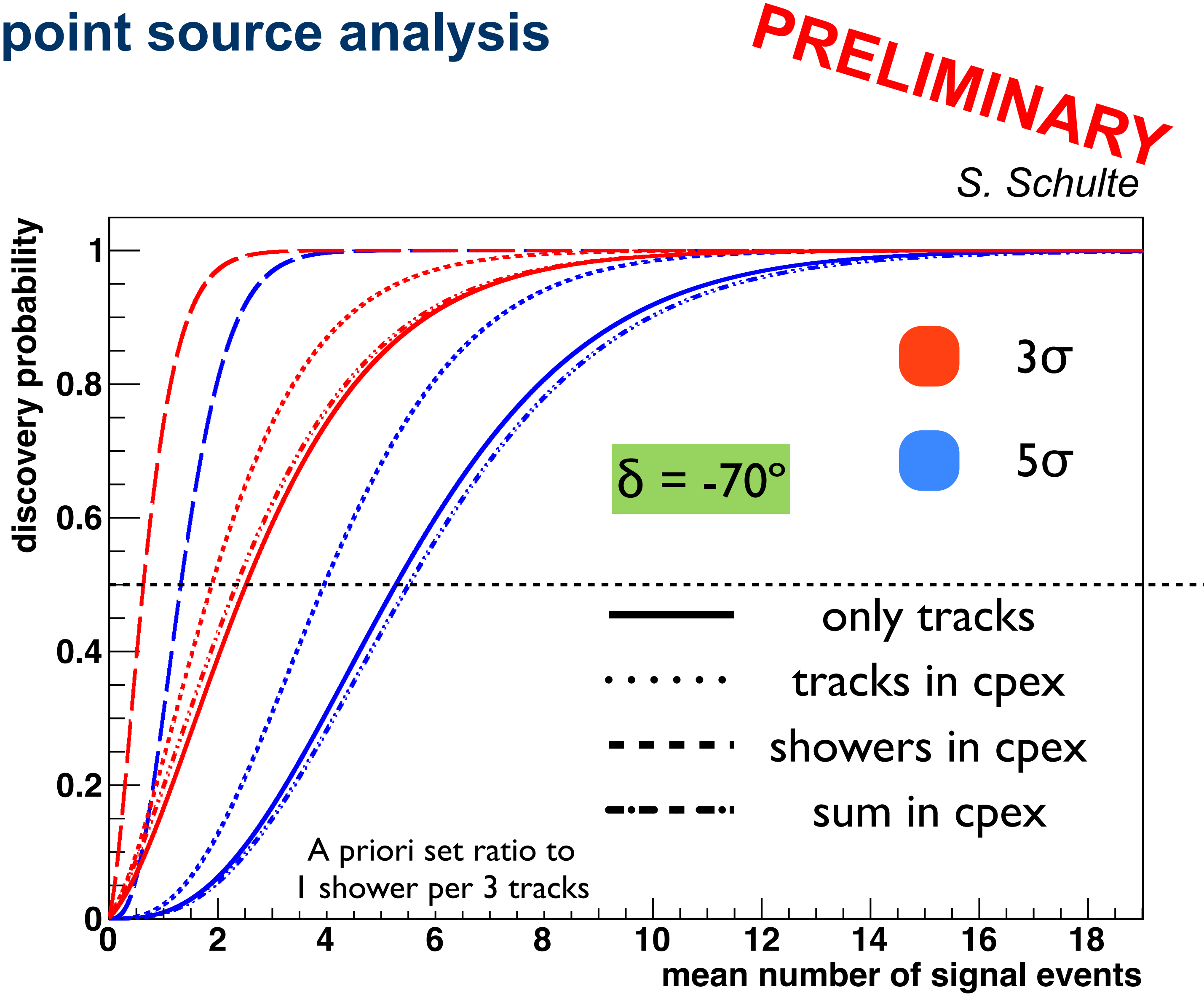
* Q-Strategy yields slightly better results.
** T-Strategy is in development to provide a better angular resolution, but has not reached this aim so far.

Shower analyses in ANTARES

Showers in point source analysis

Feasibility study to include point source sensitivity by including shower events

➡ *Already one shower event can help making a 5σ discovery*



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Recent diffuse flux analyses

showers (shaded) | tracks (grey)

PRELIMINARY

Data/Reco	Lifetime [days]	Channels	Sensitivity per flavour [E² * GeV/s*sr*cm²]	Upper limit per flavour [E² * GeV/s*sr*cm²]	
2008-2010 Q-Strategy	656	$\nu_\mu \nu_e \nu_\tau$ ★ showers	$8.4 * 10^{-8}$ ★★	-	Q. Dorosti PhD thesis
2009-2010 Q-Strategy	1000 (scaled)	$\nu_\mu \nu_e \nu_\tau$ ★ showers	$8.3 * 10^{-8}$ ★★	-	L. Ambrogi Master thesis
2007-2011 Aafit	885	ν_μ tracks	$4.7 * 10^{-8}$	$4.8 * 10^{-8}$	S. Biagi finished
2007-2011 Aafit/ANN	1179	ν_μ tracks	$4.2 * 10^{-8}$	$7.0 * 10^{-8}$	J. Schnabel finished
2008-2011 Aafit/Bbfit	933	ν_μ tracks	$3.6 * 10^{-8}$	-	L. Core ongoing
2007-2012 Dusj-Reco	1326	$\nu_\mu \nu_e \nu_\tau$ ★ showers	$1.6 * 10^{-8}$ ★★	-	F. Folger ongoing

★ Tau neutrino contribution was estimated

★★ Current shower Monte-Carlo is without photon scattering

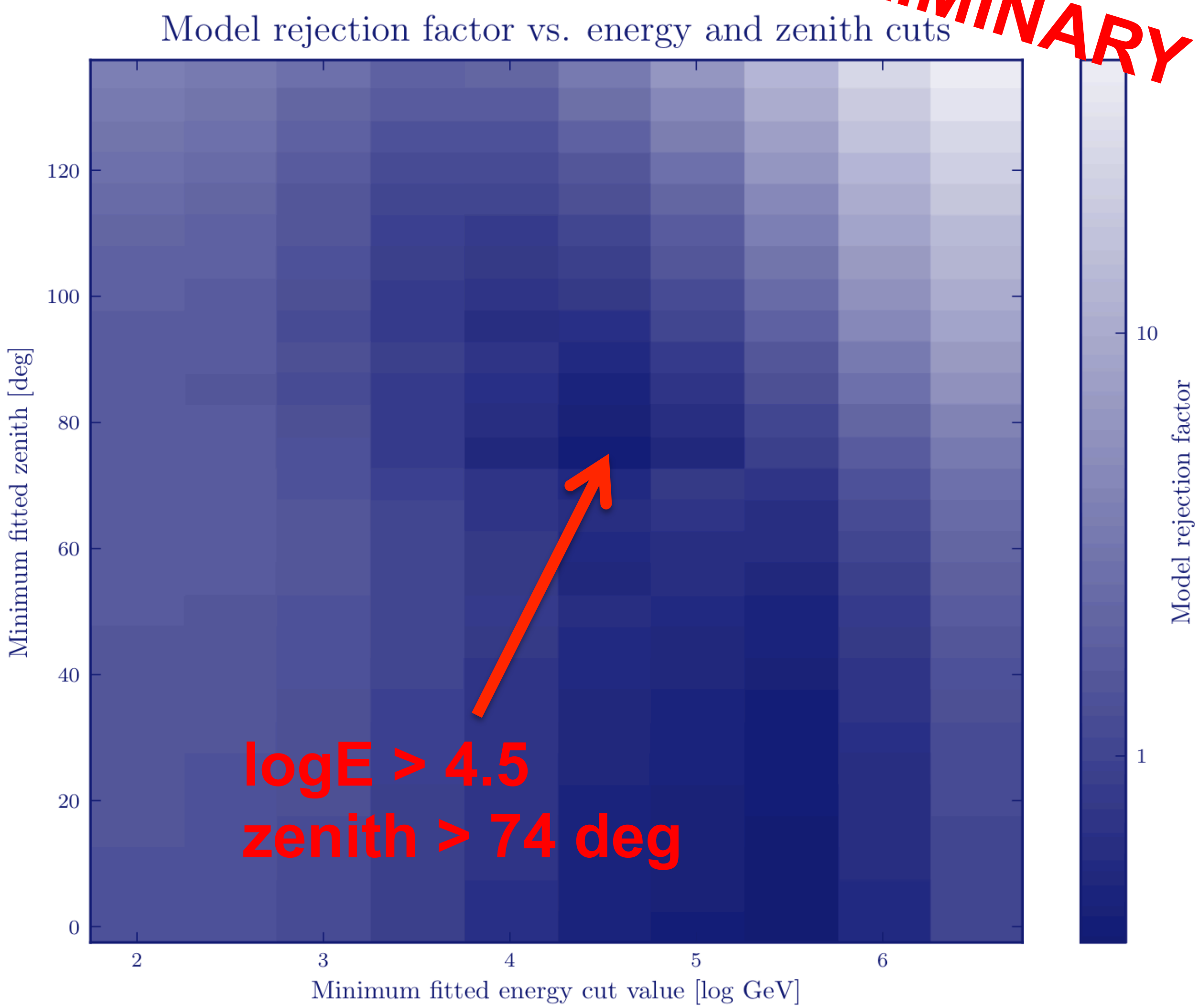
2007-2012 shower analysis - sensitivity

PRELIMINARY

Model rejection factor is minimized as function of a 2-dimensional lower cut on

- *fitted shower energy*
- *fitted neutrino zenith*

from events that have been reconstructed and selected by the Dusj reconstruction.



2007-2012 shower analysis - sensitivity

PRELIMINARY

EVENT NUMBERS AFTER MRF MINIMIZING CUTS	Cosmic flux ($4.5 * 10^{-8} E^{-2}$ per flavour)	Conventional atmospheric flux (Bartol)	Prompt atmospheric flux (Enberg)
Muon neutrino CC tracks	**0.53**	**0.42**	**0.03**
Muon neutrino NC showers	**0.65**	**0.21**	**0.12**
Electron neutrino CC showers	**6.38**	**0.10**	**1.70**
Electron neutrino NC showers	**0.65**	**0.01**	**0.20**
Tau neutrino CC showers *	**3.75**	**0**	**0.06**
Tau neutrino NC showers *	**0.65**	**0**	**0.01**
TOTAL	**12.61**	**0.74**	**2.12**

** estimated from electron neutrino*

Sensitivity per neutrino flavour:

$$E^2 \cdot \Phi_{90\,\%,\nu_\mu\nu_e\nu_\tau} = 1.6^{+0.5}_{-0.2} \cdot 10^{-8}\,\mathrm{GeV/cm^2 \cdot sr \cdot s}$$

Further development

Recent updates to the shower Monte-Carlo software, that are mainly:

- The inclusion of photon scattering
- More accurate event weighting in the One-Particle-Approximation

First checks with the new MC on the diffuse flux analysis give indications that the presented sensitivities might change to higher values.

But, further more detailed systematic studies are necessary and currently ongoing.

Showers in KM3NeT

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Pseudo experiment for high energy showers

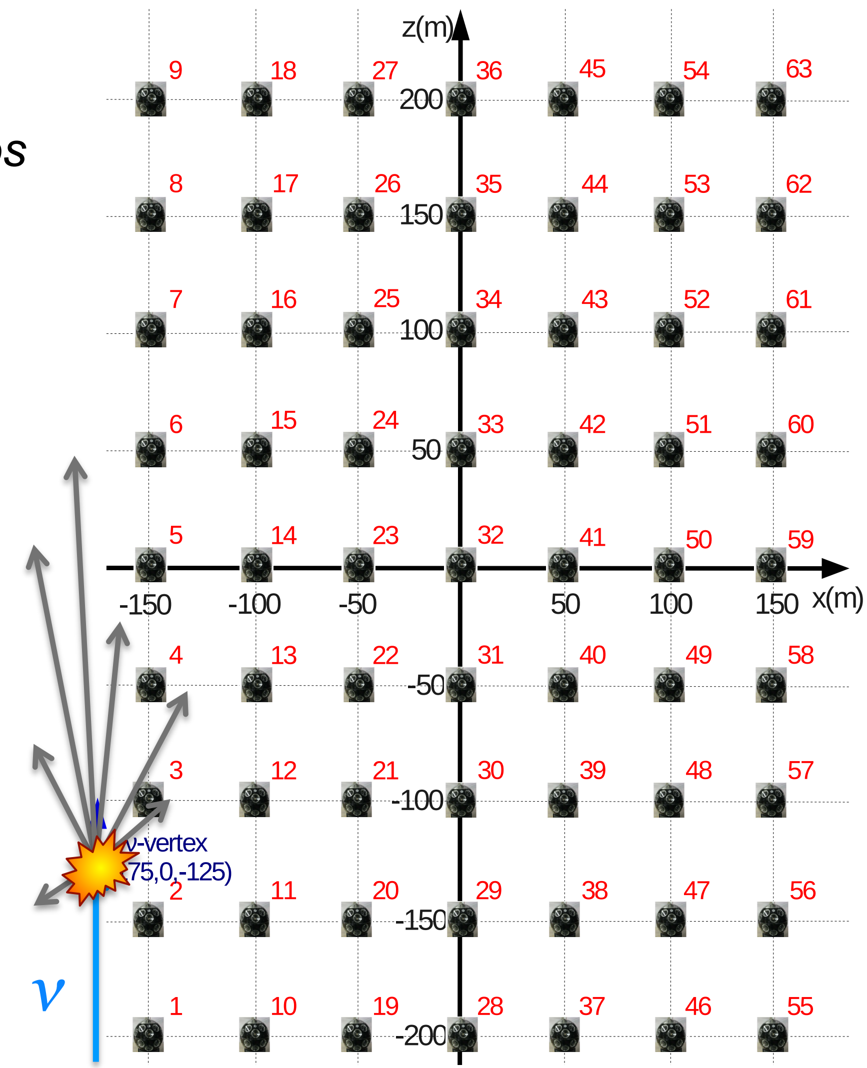
A. Tsirigotis

First look into PeV NC and CC interaction of electron and tau neutrinos simulated with ***PYTHIA***

Simulation setup contains

- *63 fixed DOMs arranged in xz plane*
- *fixed neutrino direction in positive direction*
- *fixed neutrino energy of 1 or 10 PeV*
- *forced interaction vertex at (-175, 0, 125)*

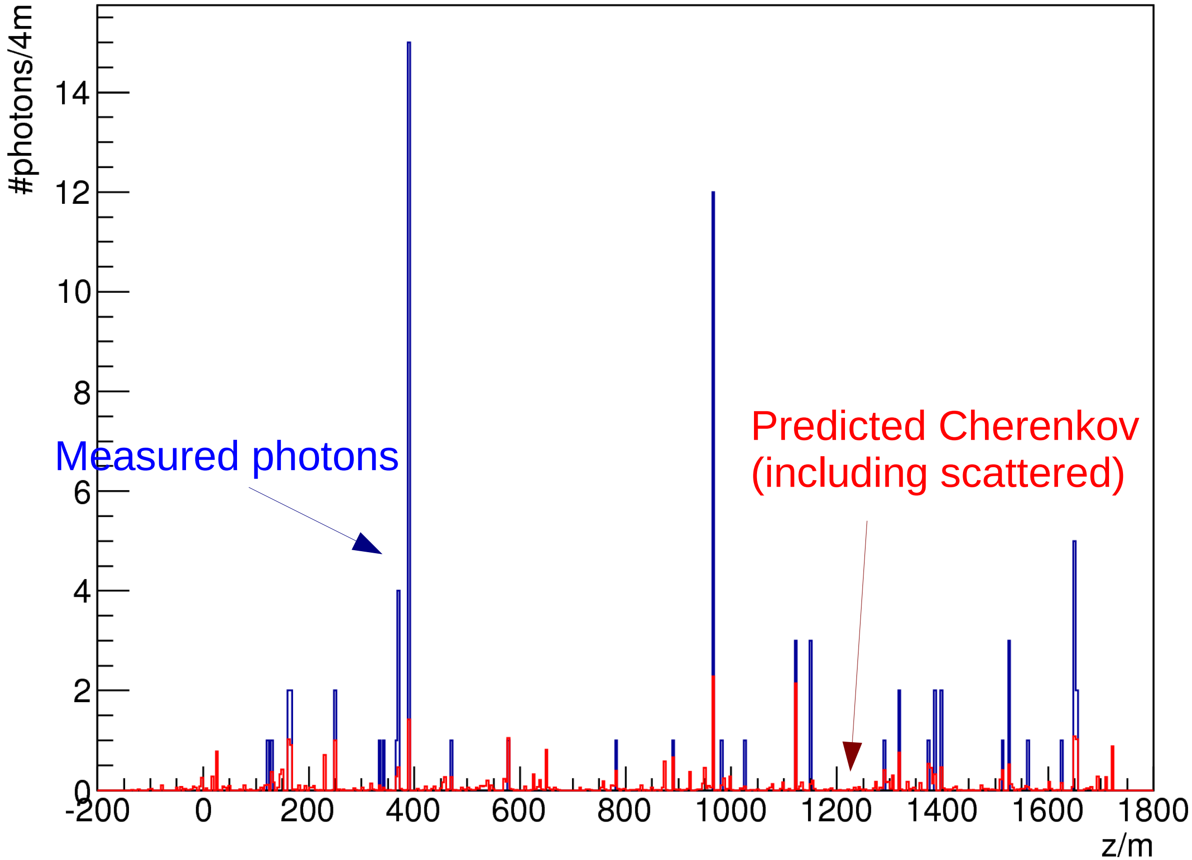
Work is in progress.



EM-Showers along muon tracks

Method to reconstruct the position and energy of em-showers along a muon track via the ***energy loss profile***

R. Bruijn



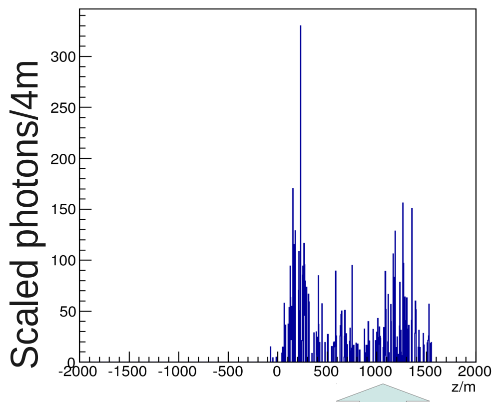
1. Reconstruct muon track
2. Project detected photons back on muon trajectory assuming pure Cerenkov emission
3. Evaluate **excess in measured photons** above the predicted Cerenkov photons (including detector geometry)

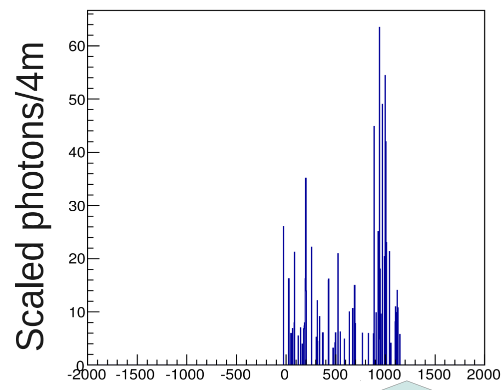
EM-Showers along muon tracks

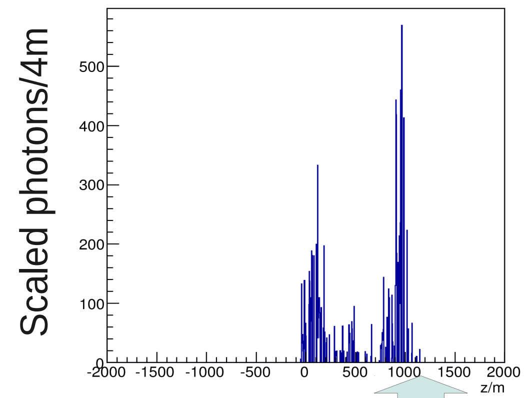
R. Bruijn

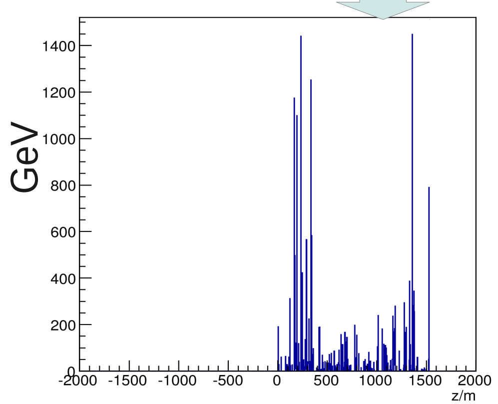
Event 1 | Event 2 | Event 3

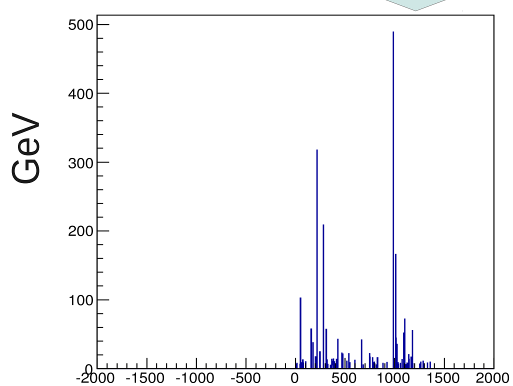
'Reconstructed' Energy loss profiles

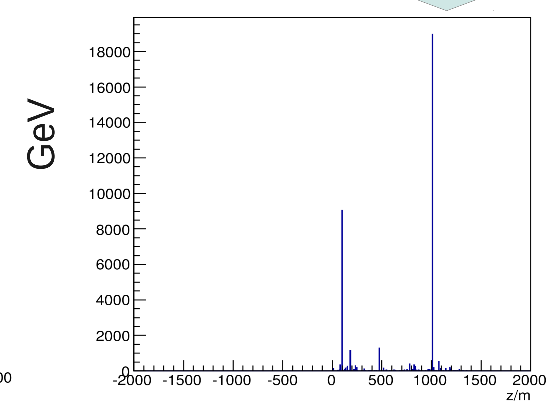






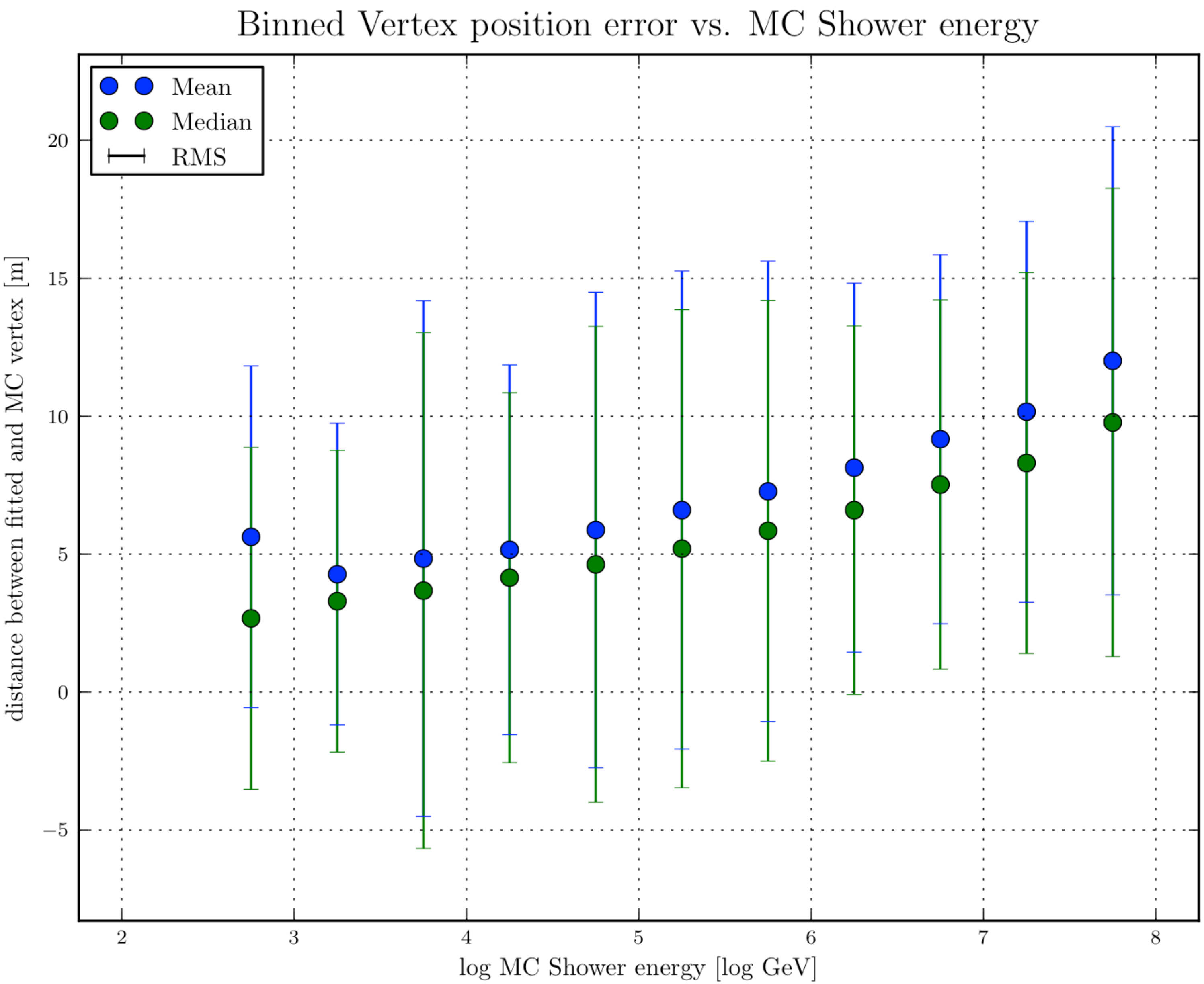




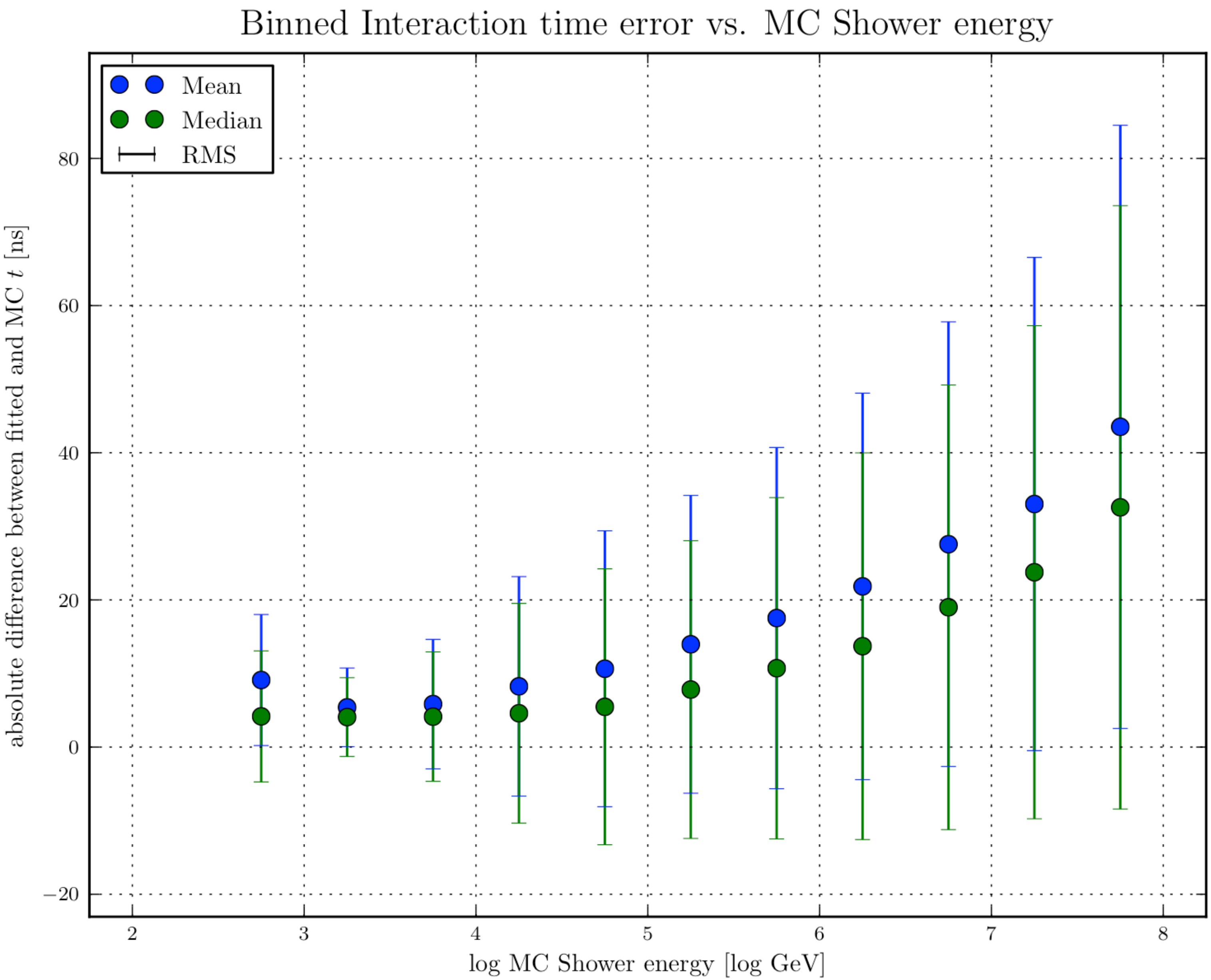


Energy loss from Monte Carlo (showers with energy > 5GeV)

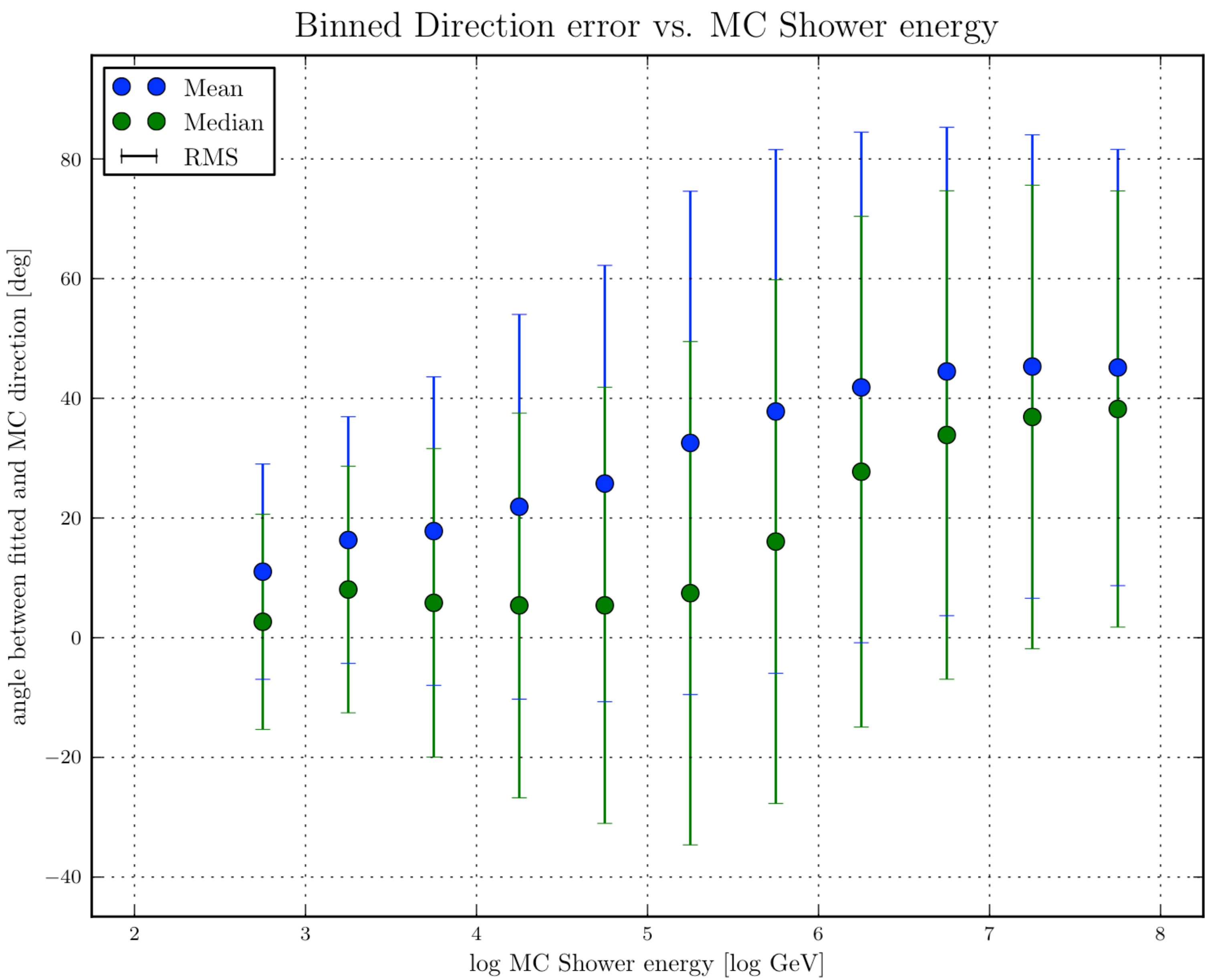
Backup slides

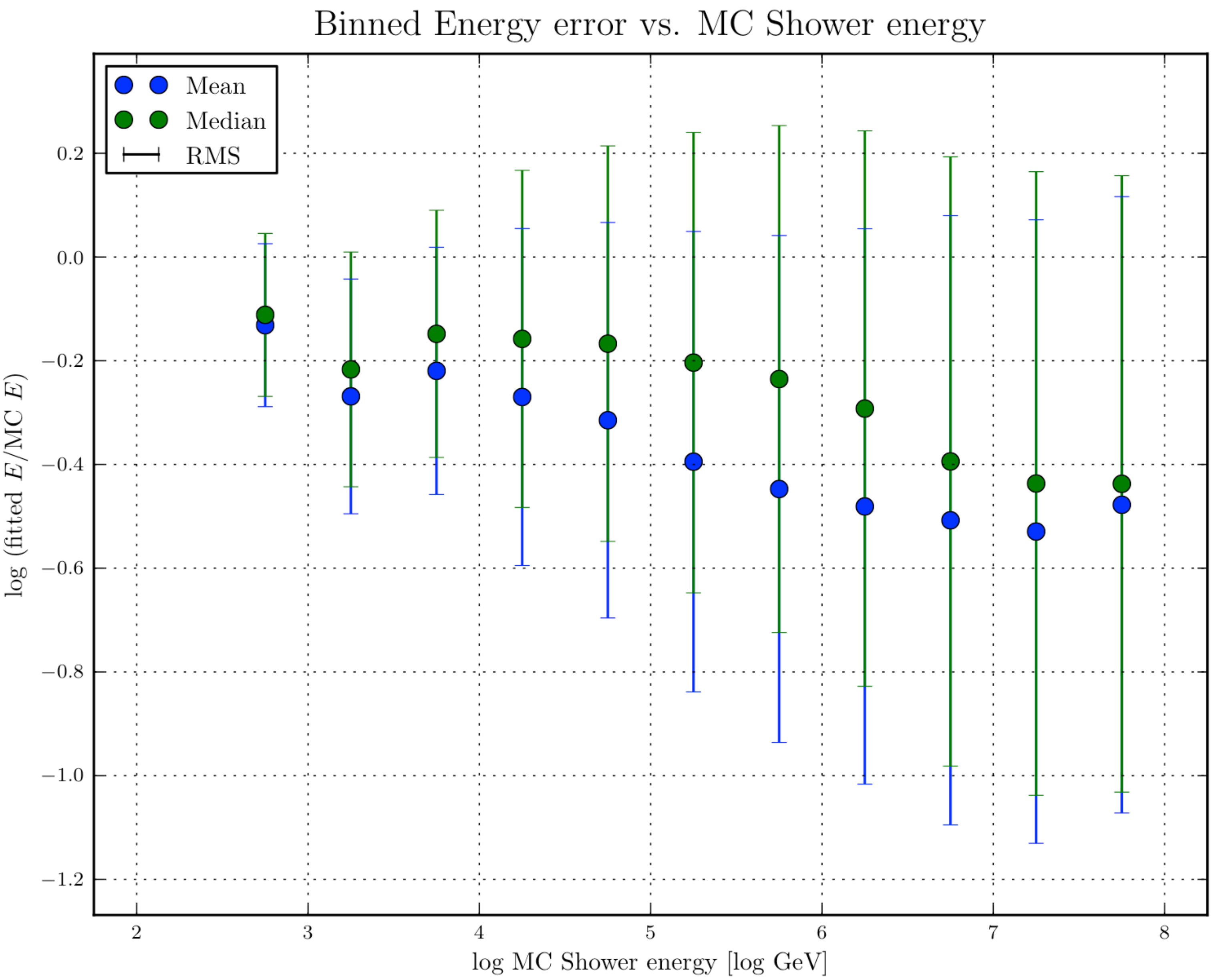


Binned Vertex position error vs. MC Shower energy
Mean
Median
RMS
distance between fitted and MC vertex [m]
log MC Shower energy [log GeV]
20
15
10
5
0
−5
2
3
4
5
6
7
8



Binned Interaction time error vs. MC Shower energy
Mean
Median
RMS
absolute difference between fitted and MC t [ns]
log MC Shower energy [log GeV]
80
60
40
20
0
−20
2
3
4
5
6
7
8


Binned Direction error vs. MC Shower energy
Mean
Median
RMS
angle between fitted and MC direction [deg]
log MC Shower energy [log GeV]
80
60
40
20
0
−20
−40
2
3
4
5
6
7
8



Binned Energy error vs. MC Shower energy
Mean
Median
RMS
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
log (fitted E/MC E)
2
3
4
5
6
7
8
log MC Shower energy [log GeV]

Suppression of atmospheric muons – Selection of cut parameters

Selected 5 from 24 possible Dusj cut parameters to be used as features in a random decision forest classification:

- *Reduced final likelihood value of the vertex fit*
- *Reduced final likelihood value of the energy-direction fit*
- *Time residual chi square with respect to prefit vertex*
- *Time residual chi square with respect to final vertex*
- *Quadrupole moment of selected shower pulses*

Selection criteria on parameters:

- Good agreement between Data and MC
- Separating values for muon and shower events

Supression of atmospheric muons – Training of a random decision forest

Used 25% of the burn sample for the training of the RDF with

- 2 classes (muon, shower)
- 100 random trees per RDF
- 3 RDFs (for Line5, Line10 & Line12 periods)

Class 0
Muon

Class 1
Shower

Example tree: