Measuring the Muon Content of Air Showers with IceTop

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Hans Dembinski

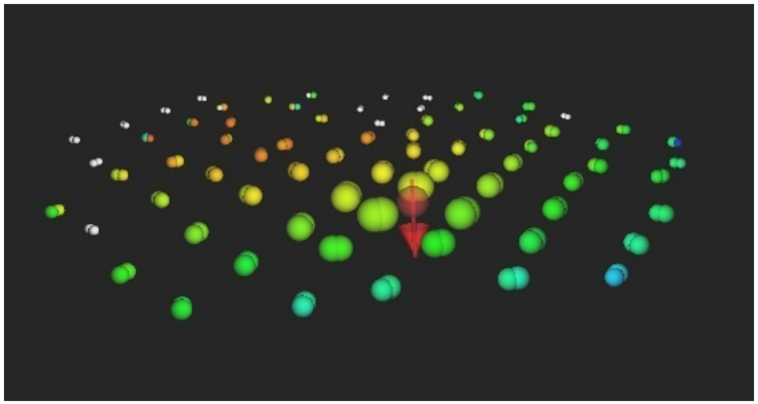
IceCube

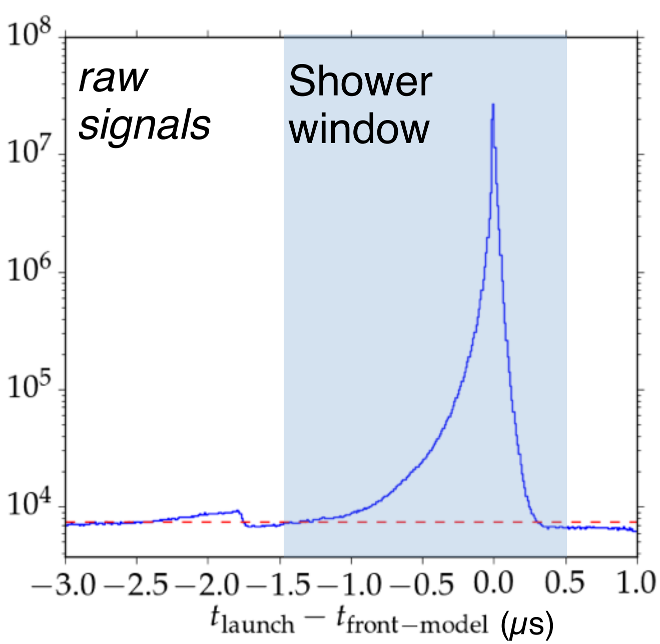
- IceTop detects the **low energy** muons far away from the shower axis
  (E > 200 MeV, r > 300 m).
  expected to correlate with primary mass.
  expected to scale as a power of the primary energy.

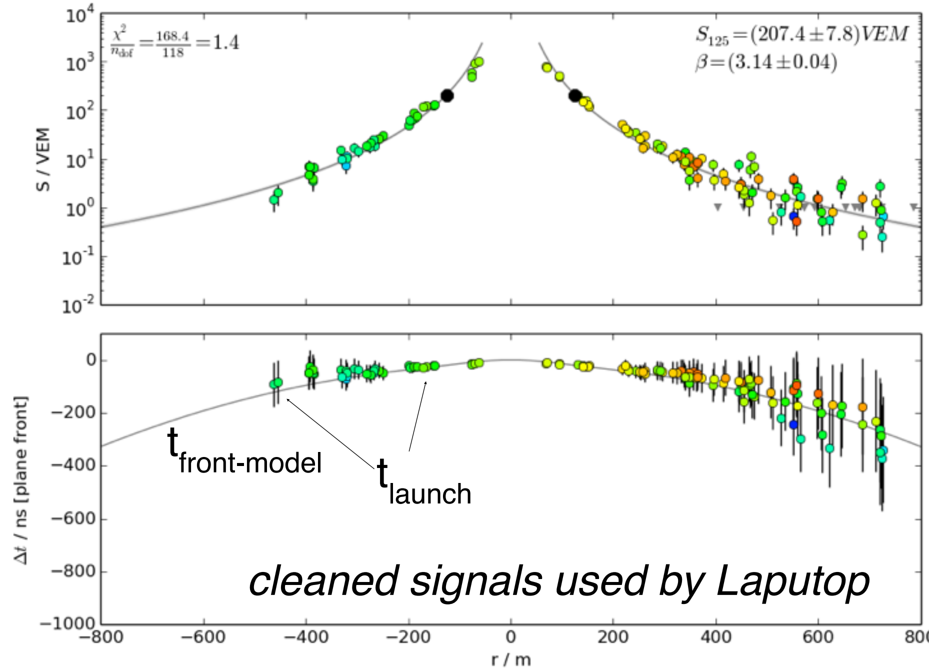
- We will look at:
  - how one can estimate the muon lateral distribution function using IceTop,
  - the energy dependence of the muon density at a fixed reference radius for near-vertical events.

- Analysis being independently validated
  (with some improvements)

Launch Selection







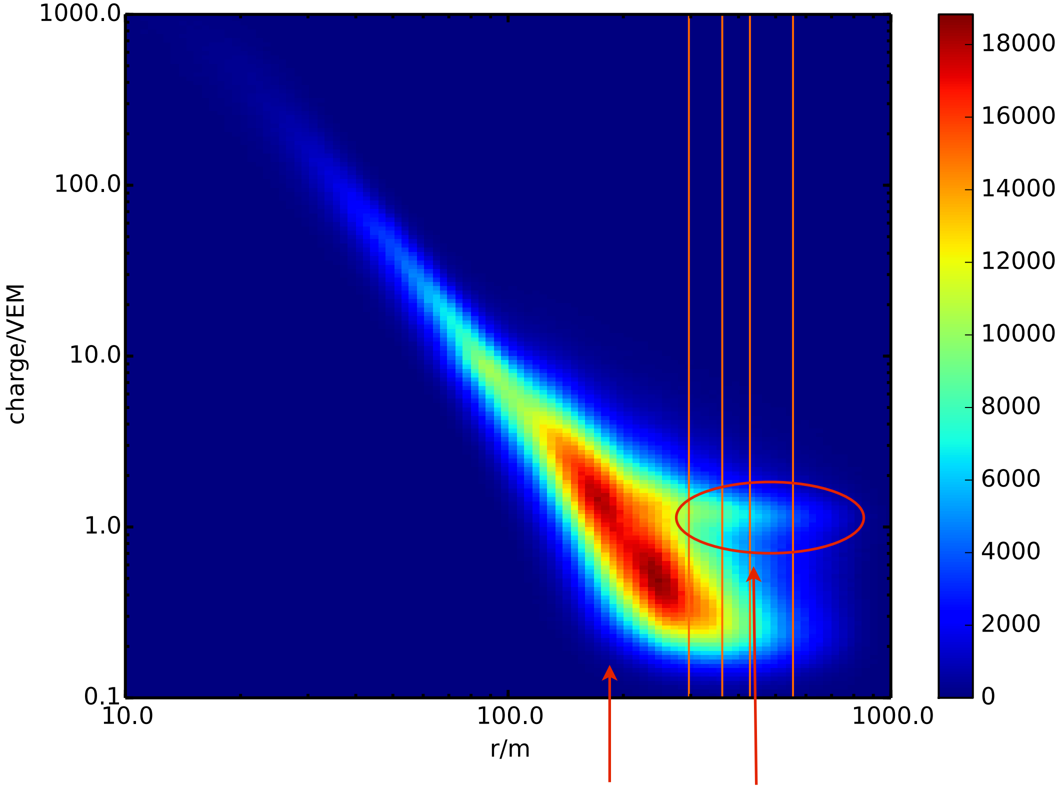
Shower window also catches
uncorrelated background signals

$$N = N_{Shower} + N_B$$

N … number of tanks with signals

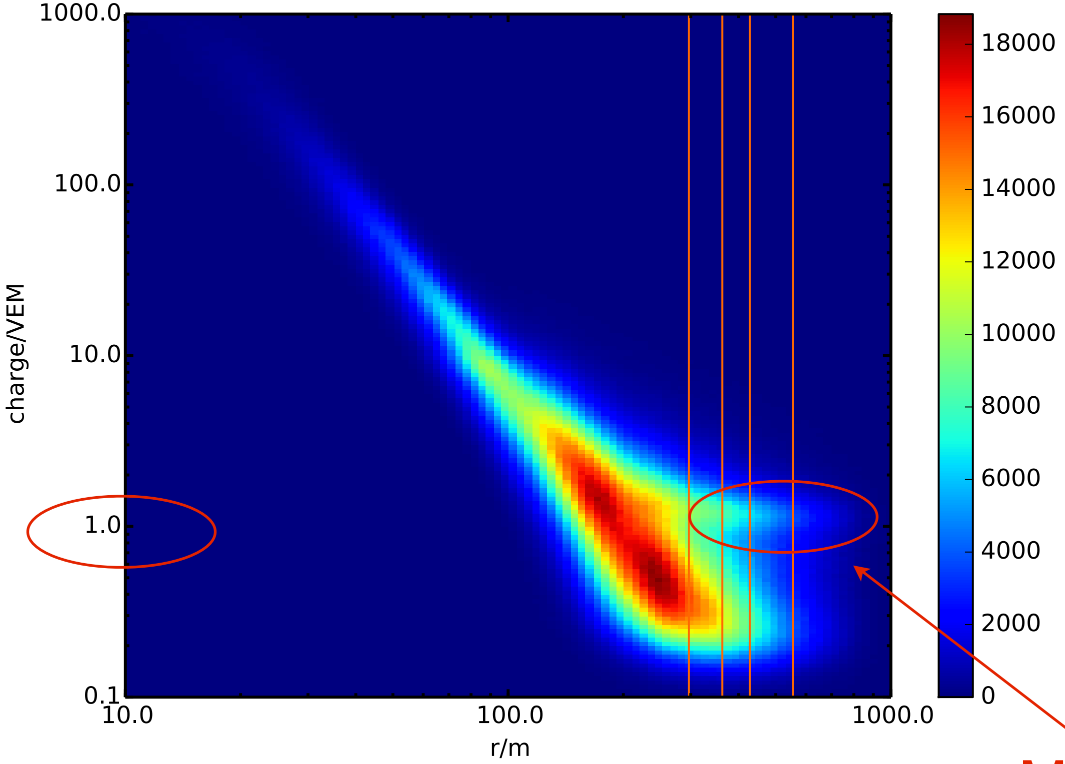
Charge-Distance to Axis Distribution

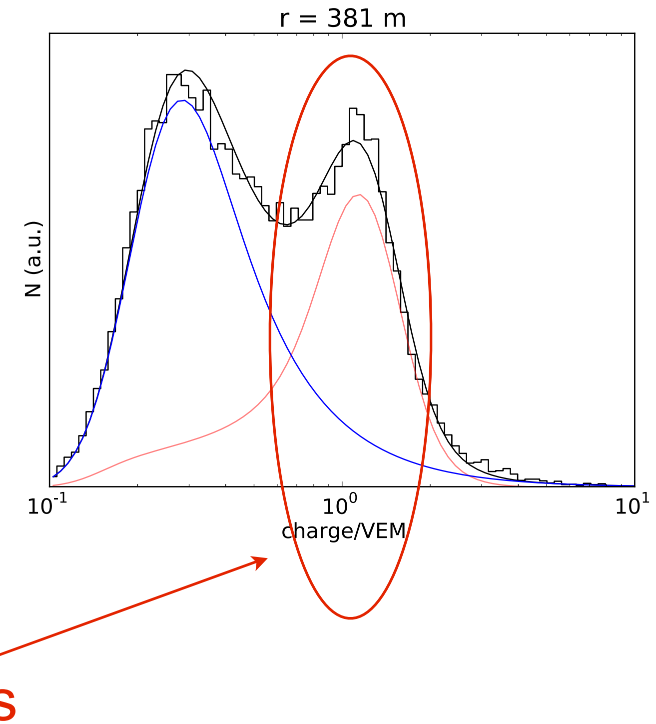
(all tanks)



- Three years data (IC79, IC86.2011, IC86.2012)
- Tank selection according to agreement with angular reconstruction.
  Time residual less than 1000 ns
- Selected events with 5 stations or more (16 tanks or more)
- Good runs, contained,
  max. signal, IceTop filters.
- **my own attenuation**
- 18 zenith bins from 0 to 70 degrees. roughly equally spaced in $\sin(\text{zenith})^2$
- 23 energy-bins from 1 to 200 PeV,
- 100 log(r) bins from 10 to 1000 m.
- Example of lateral charge histogram:
  - 4.49 PeV < E < 5.66 PeV
  - 29.9 < zenith < 33.45 degrees

Charge-Distance to Axis Distribution





$28^{\circ} < \theta < 32^{\circ}$ 10 PeV < E < 12.6 PeV

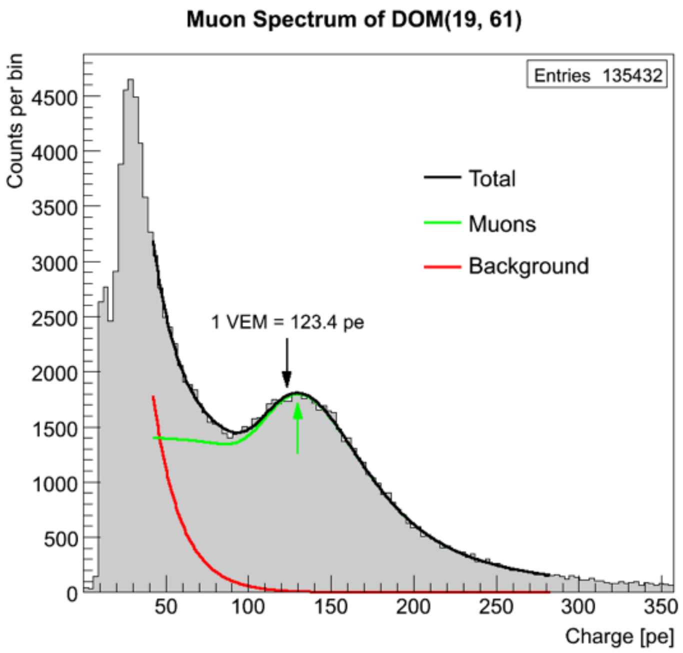
Counting muons in air showers

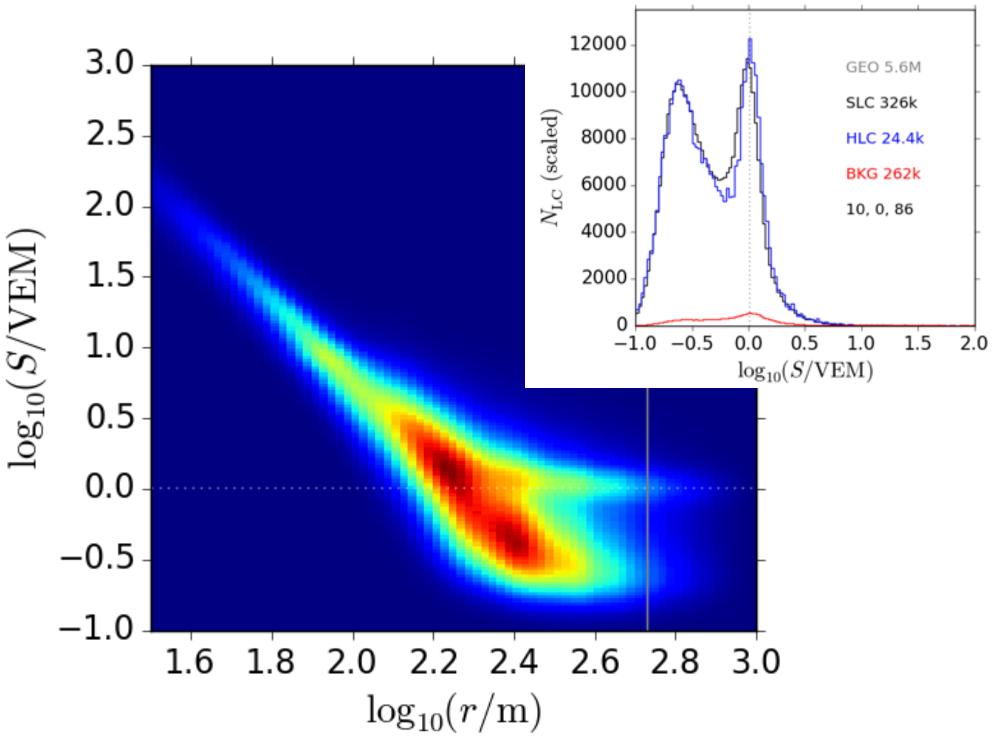
VEM calibration

- Min-bias data
- Muon peak over smooth em background
- Use **mode** to calibrate **VEM** unit

Our approach

- Small signals in air showers
- Muon peak over smooth em background
- Use **integral** to get **average local muon density**

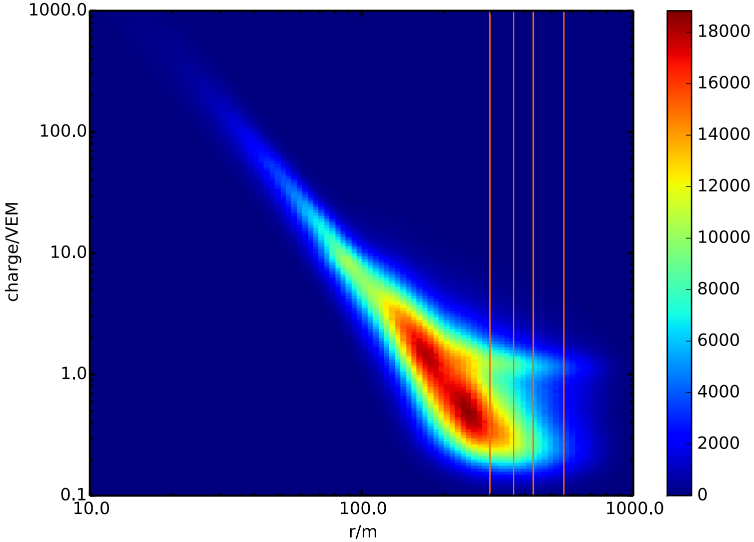


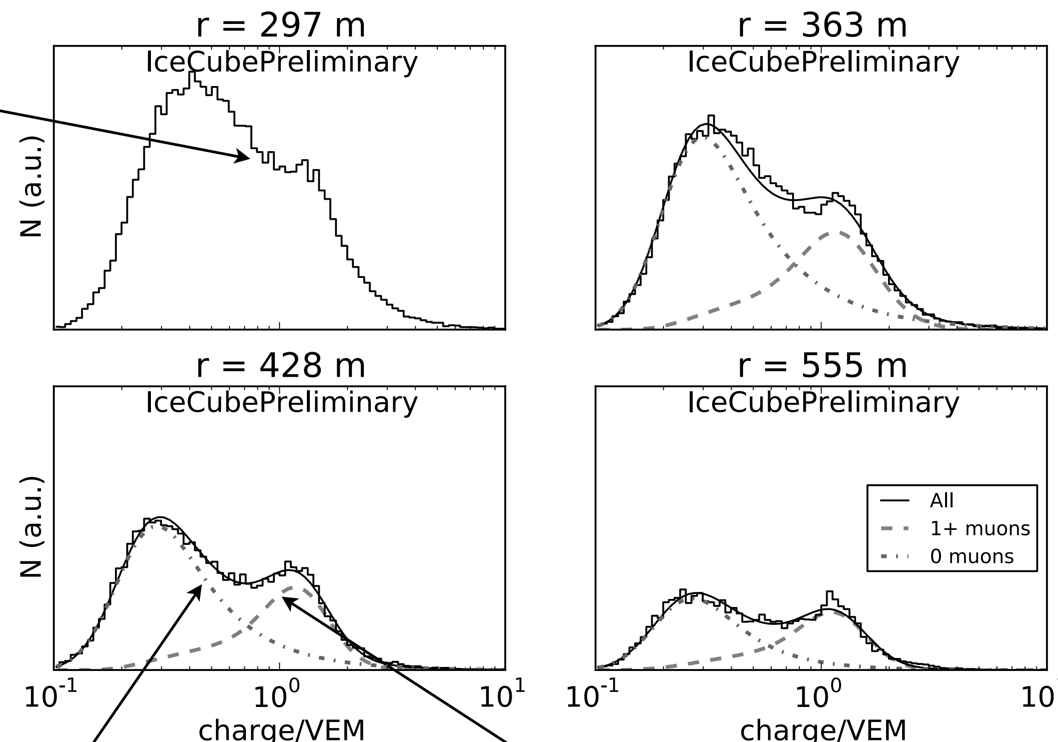


We analyze **radial slices of showers** and obtain a **muon density** for each

Charge Distributions at Different Radii

Muon peak
not clearly seen





Signal distribution for tanks detecting no muon (Tail of the EM distribution)

Signal distribution for tanks detecting at least one muon

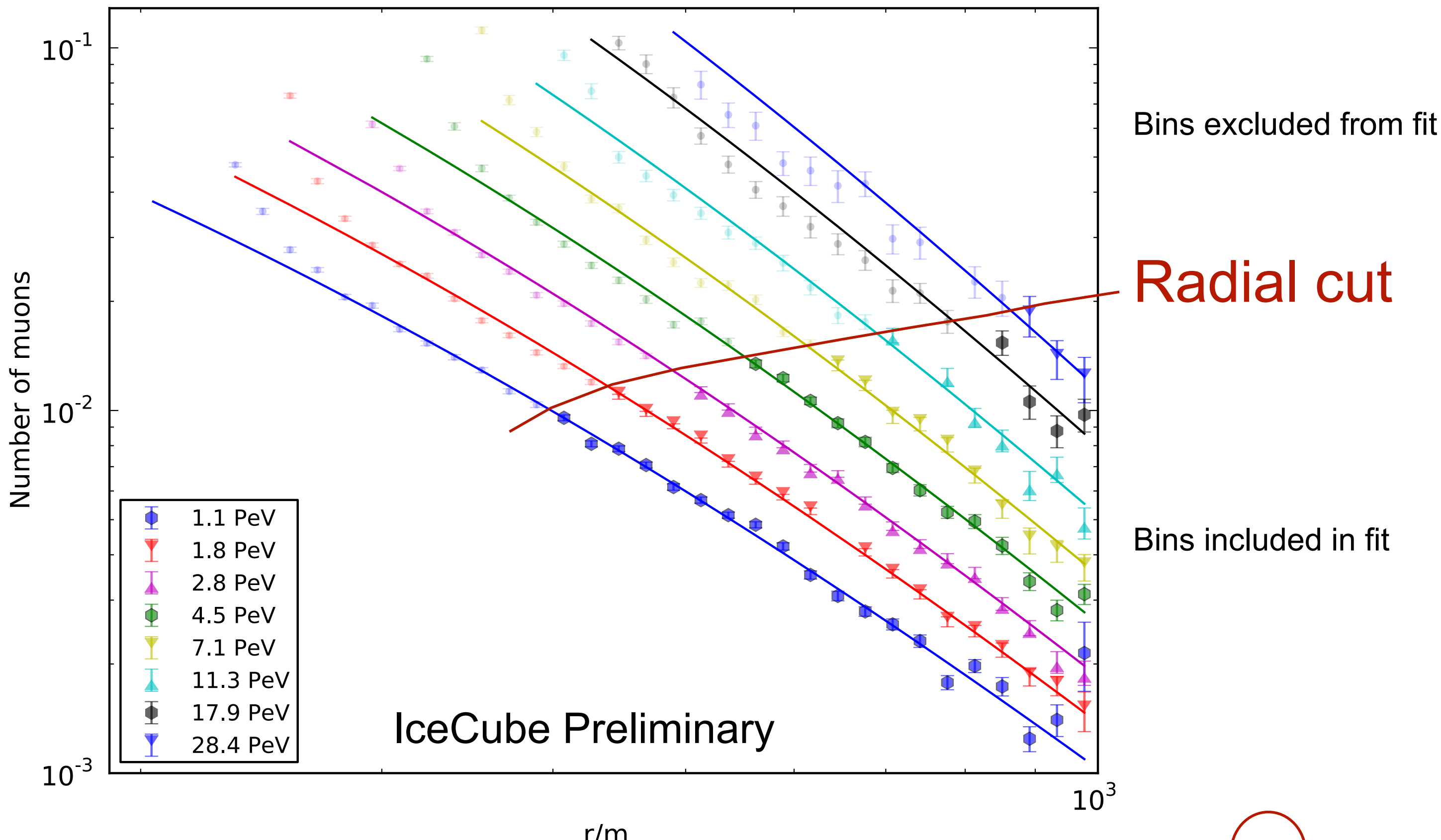
$$p_{\mu\, hit} = \frac{N_{\mu \geq 1}}{N_{tanks}}$$
$$= 1 - e^{-\langle N_\mu \rangle}$$

The muon response is widened and shifted to account for the EM component

A radial cut is required to decrease contribution from EM LDF

Muon LDFs at 0 degrees

(HLC and SLC)

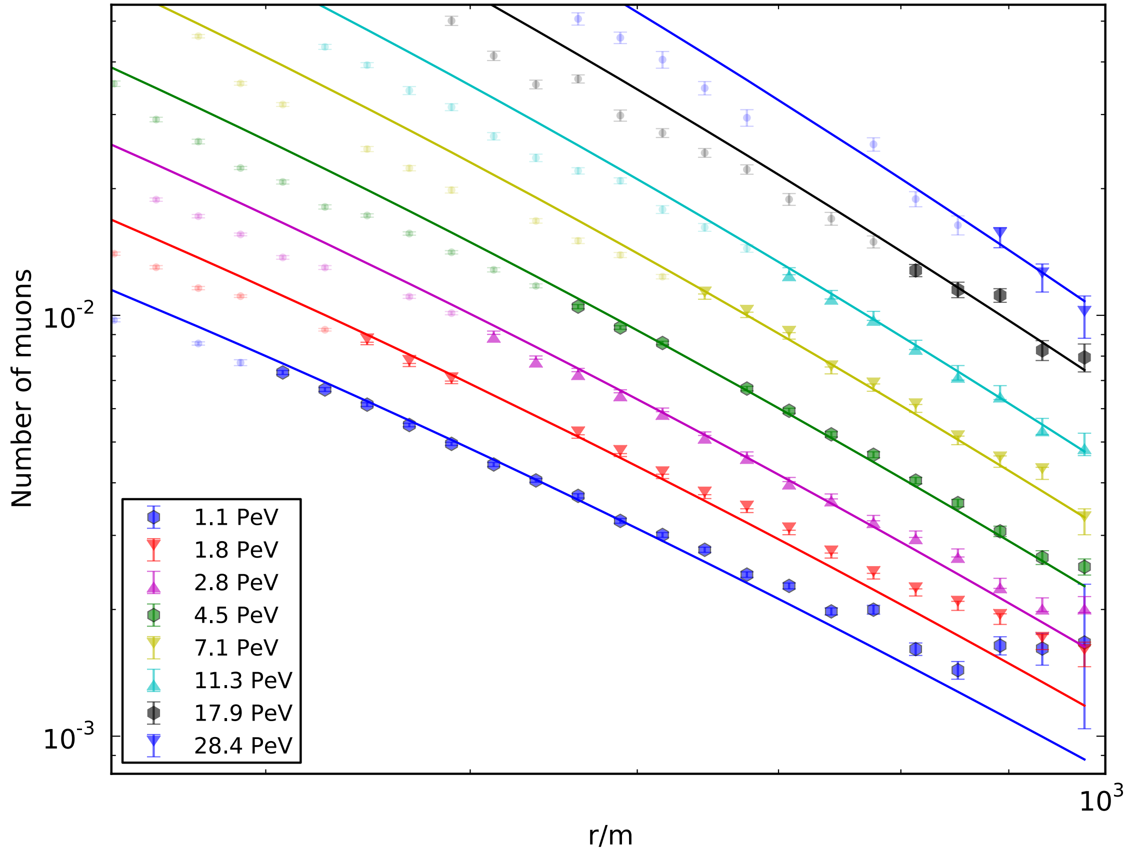


Two free parameters

$$N_\mu(r) = N_{r_0} r^{-0.75} \left(\frac{320\,\mathrm{m} + r}{320\,\mathrm{m} + r_0} \right)^{-\gamma}$$

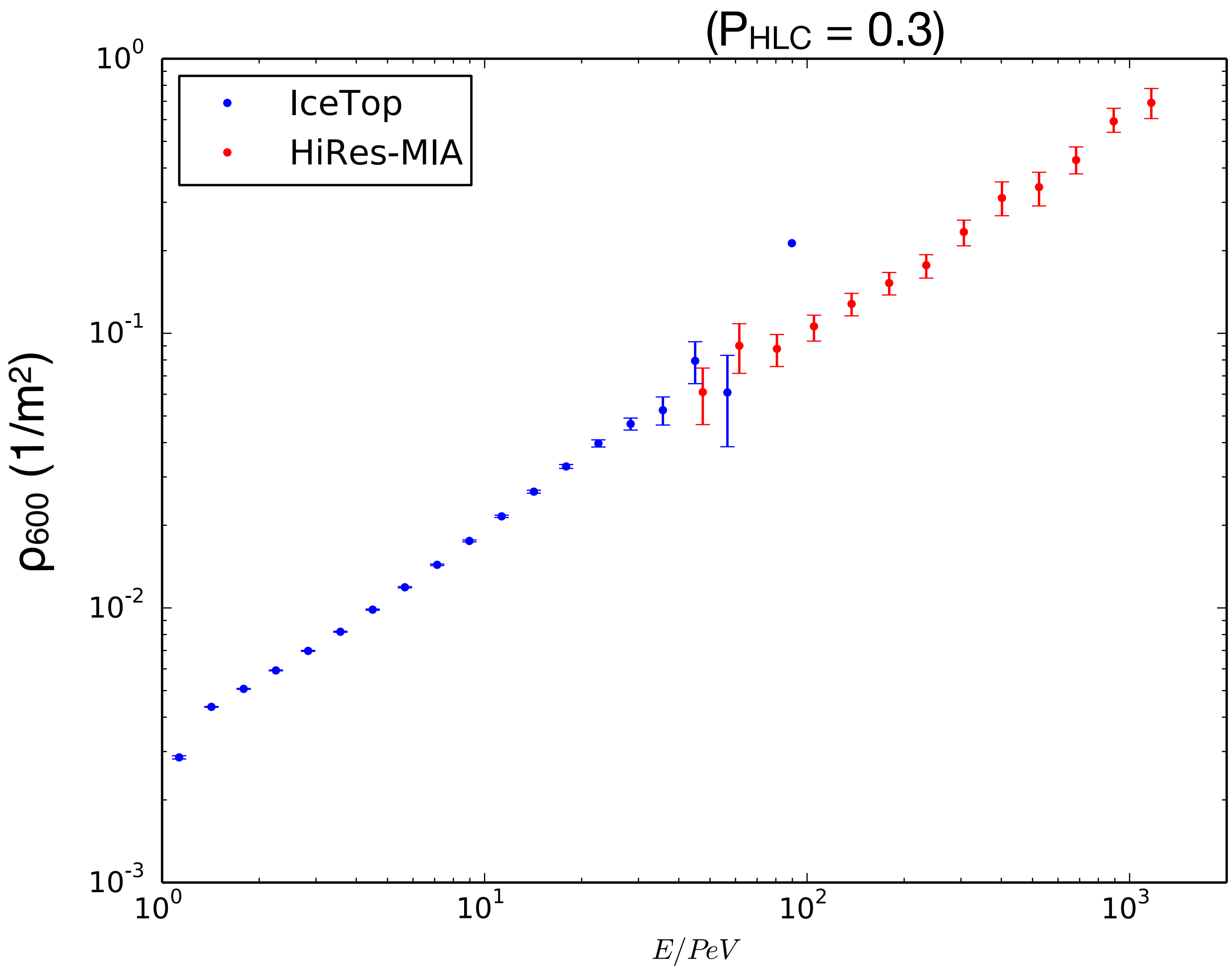
(two params fixed to values in K. Greisen, Annu. Rev. Nucl. Sci. 1960)

Muon LDFs at 30 degrees



$$N_\mu(r) = N_{r_0}\, r^{-0.75} \left(\frac{320\,\mathrm{m} + r}{320\,\mathrm{m} + r_0} \right)^{-\gamma}$$

Comparison to HiRes-MIA



$$\rho_\mu = \frac{N_\mu}{A_{top}\cos\theta + A_{side}\sin\theta}$$

N_{600} scales geometrically as expected

p_μ ~ 0.83 as in Akeno

M Nagano et al

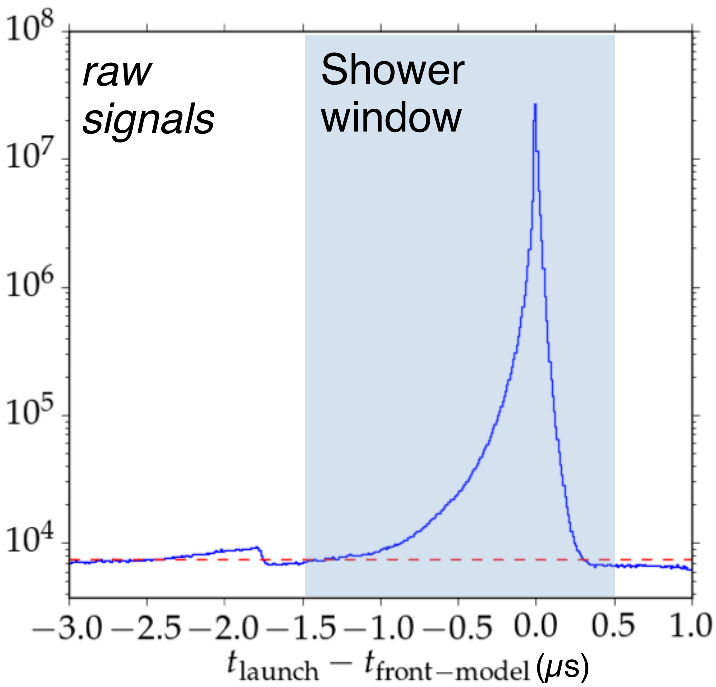
J. Phys. G: Nucl. Phys. 10 1295, 1984

CAVEATS:

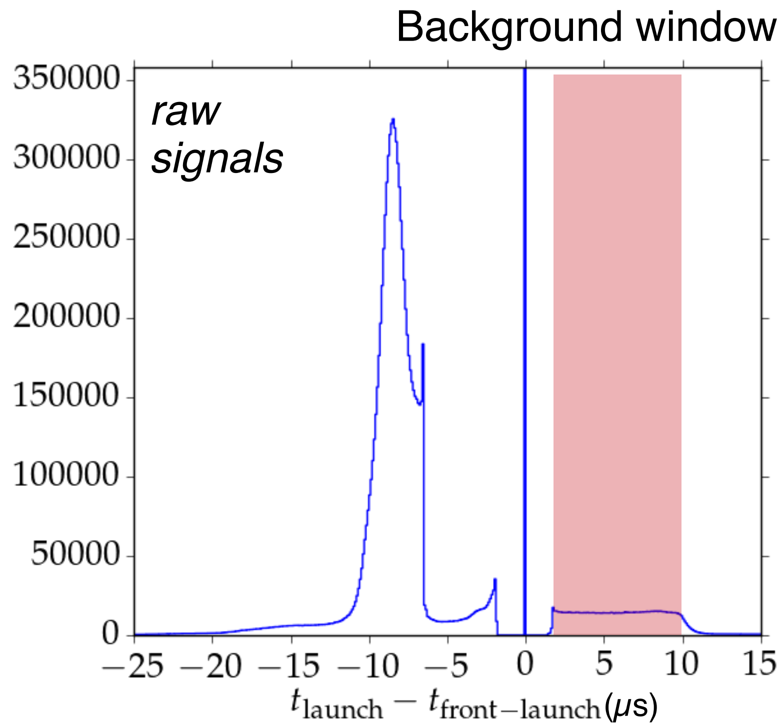
MIA and IceTop are at different depths (860 g/cm2 and 680 g/cm2 respectively)

Depth correction is not done. Such a correction would lower the IceTop value by ~20-30%

Background selection



A) Select launch in shower window

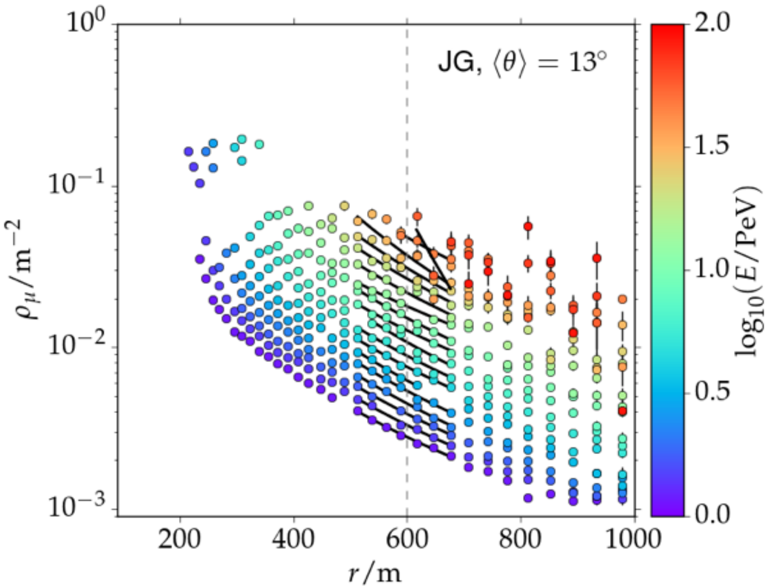


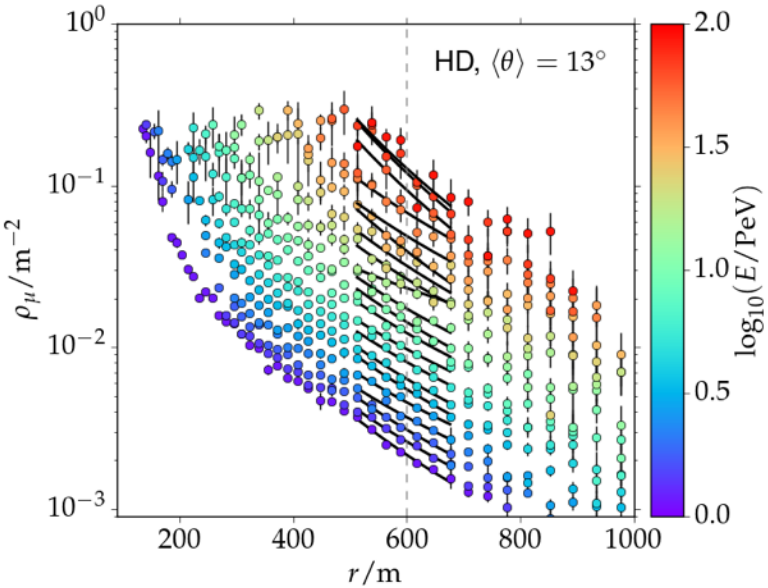
B) Select launch in background window [2, 10] μs **before** shower launch

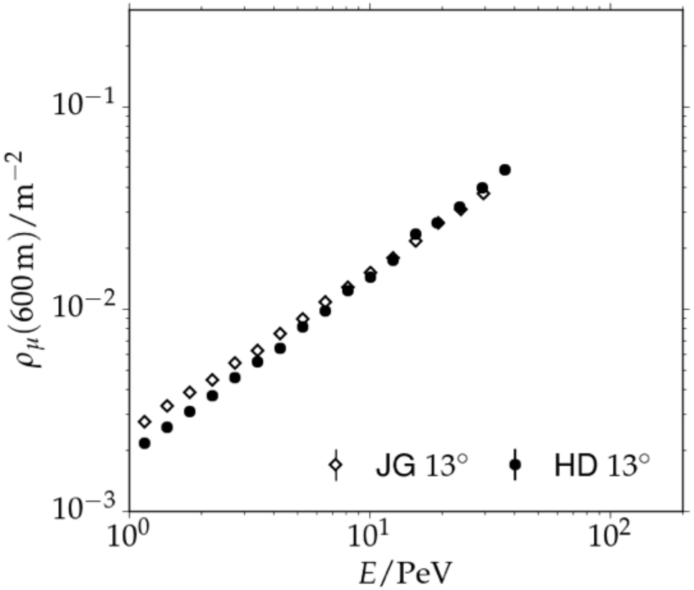
- Time window [2, 10] μs before shower launch holds perfect background
- Background estimate is extracted **in situ** from the normal data stream

Measured background rate per tank ~ 1466 Hz

Independent Validation



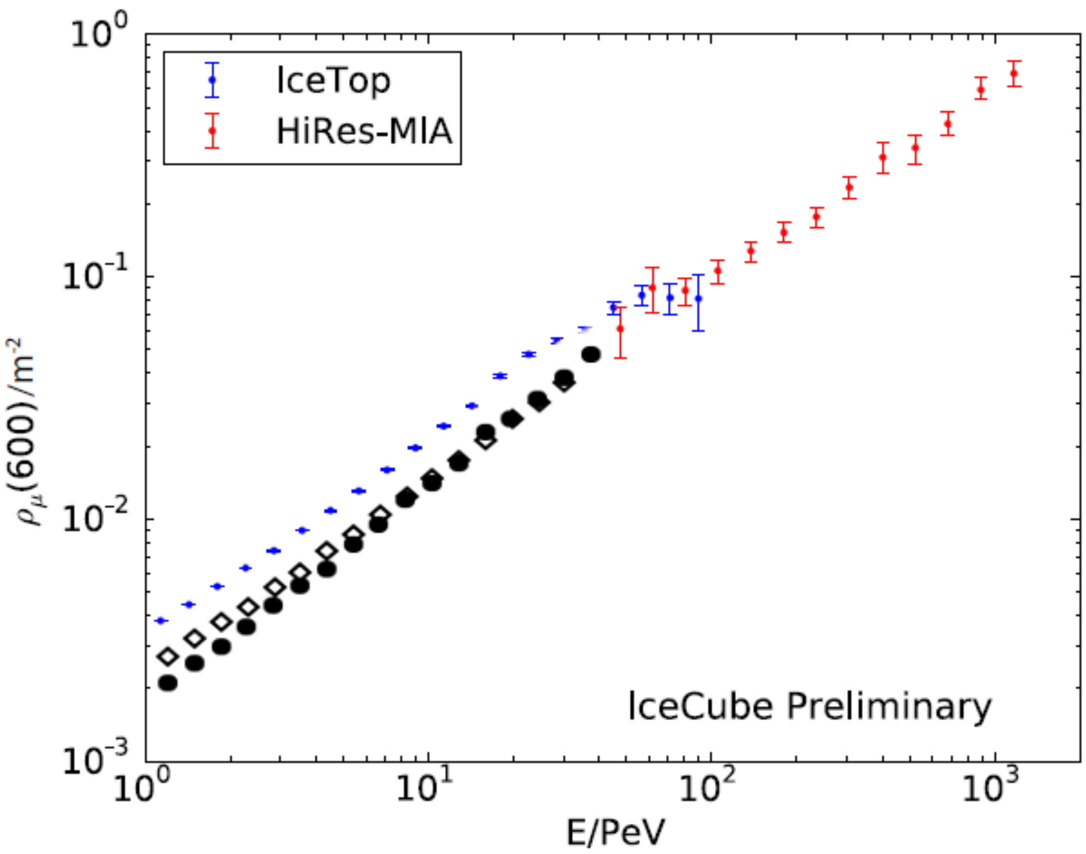




Analyses agree!

Expected deviation at 1 … 10 PeV due to subtracted **background** (new feature)

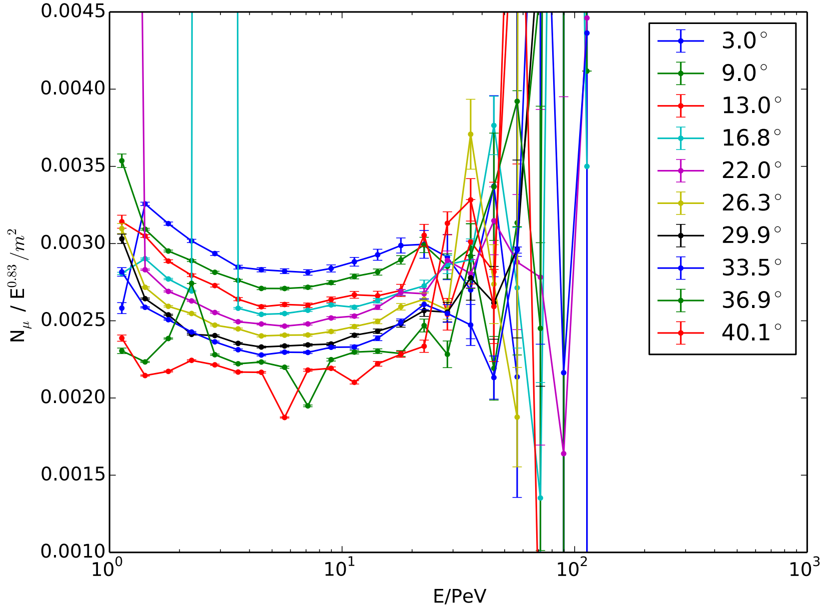
Independent Validation

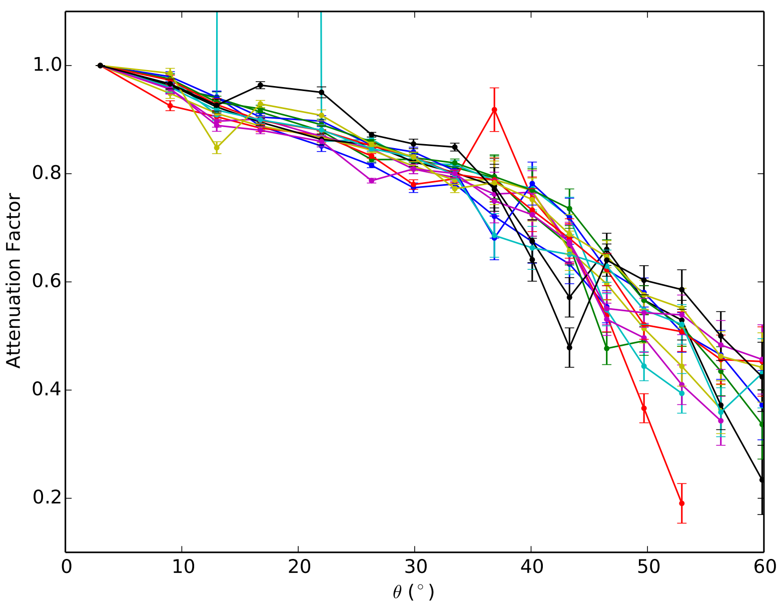


- Calculation error discovered in preliminary analysis
- **New $\rho_\mu(600)$ lower by factor ~1.7**

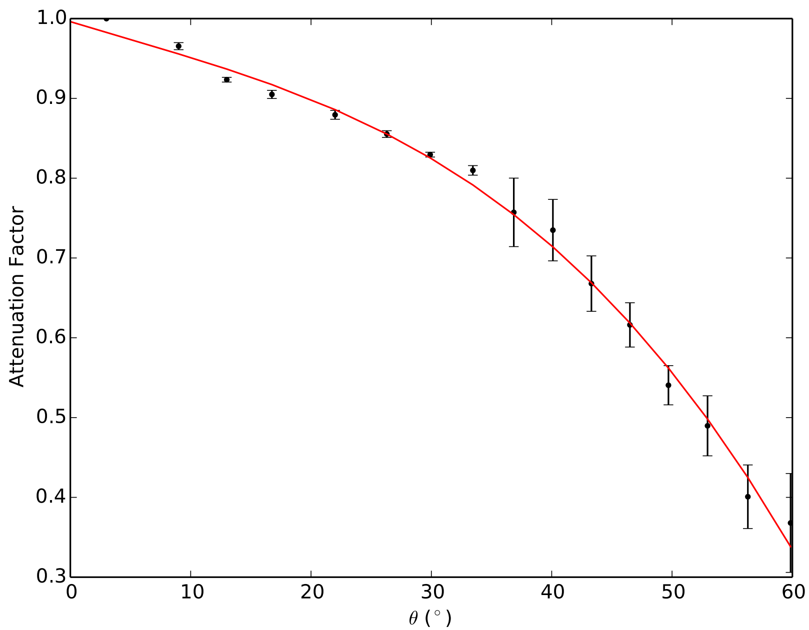
Zenith Angle Comparison

pHLC = 0.3

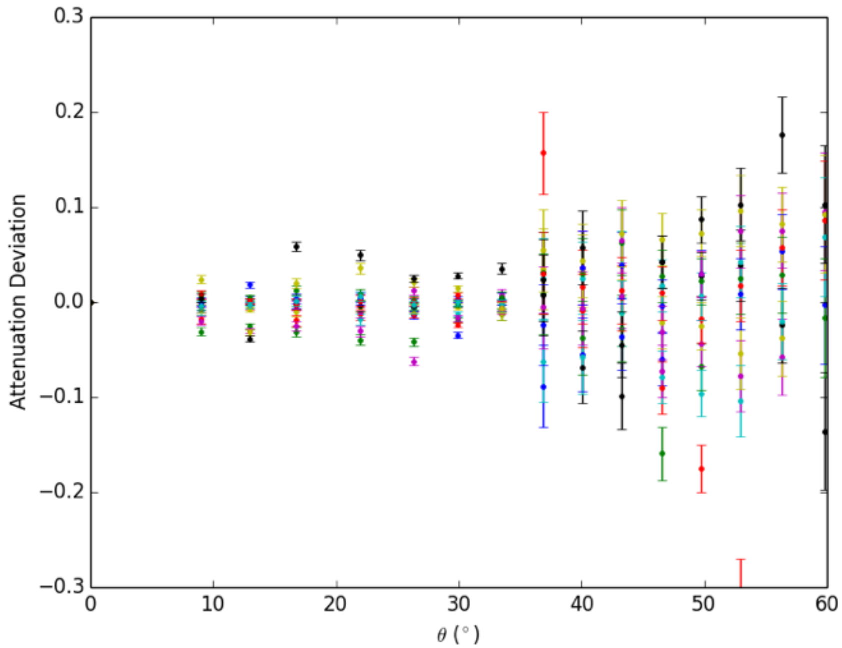




$N_{\mu\,600}$ Attenuation…

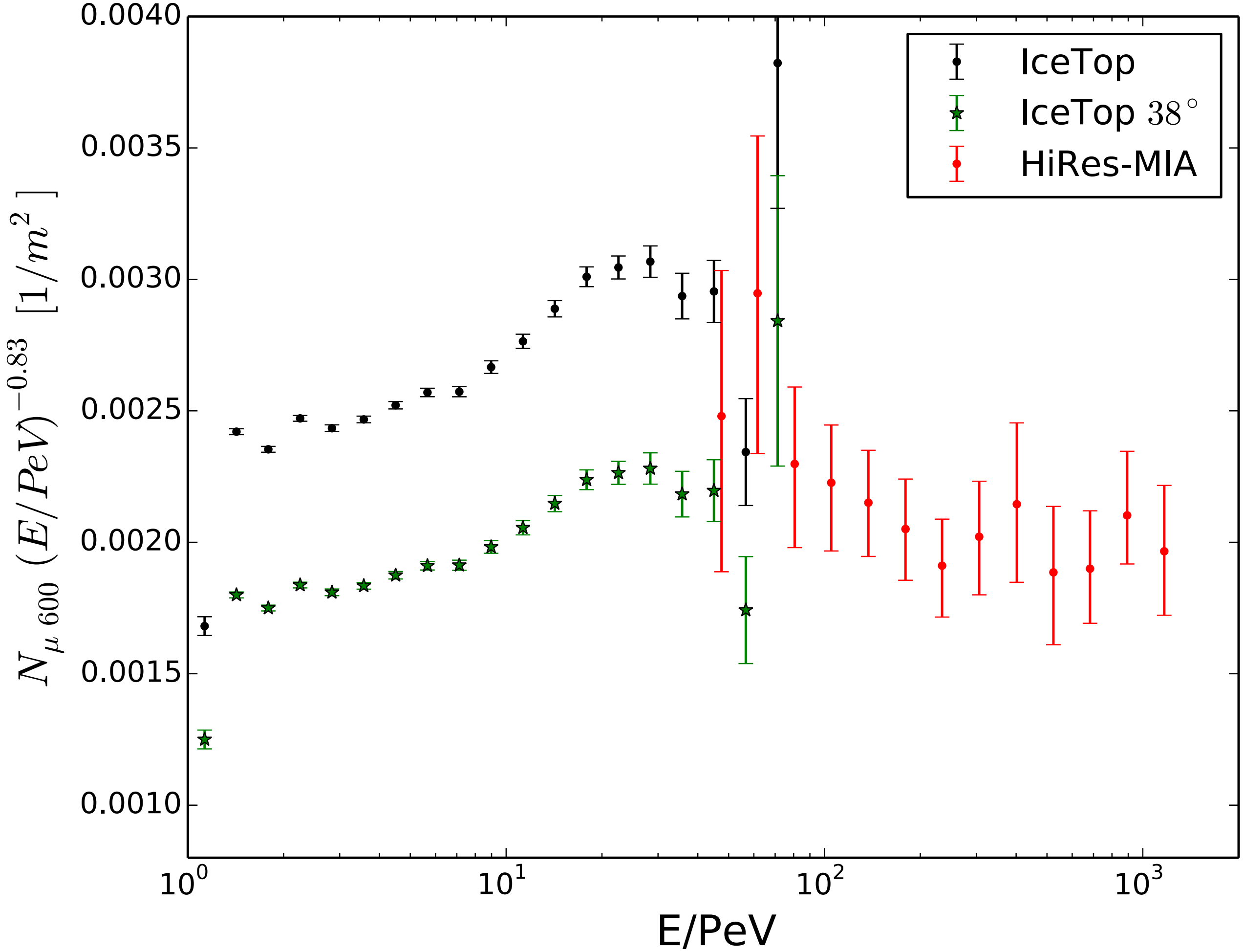


differences



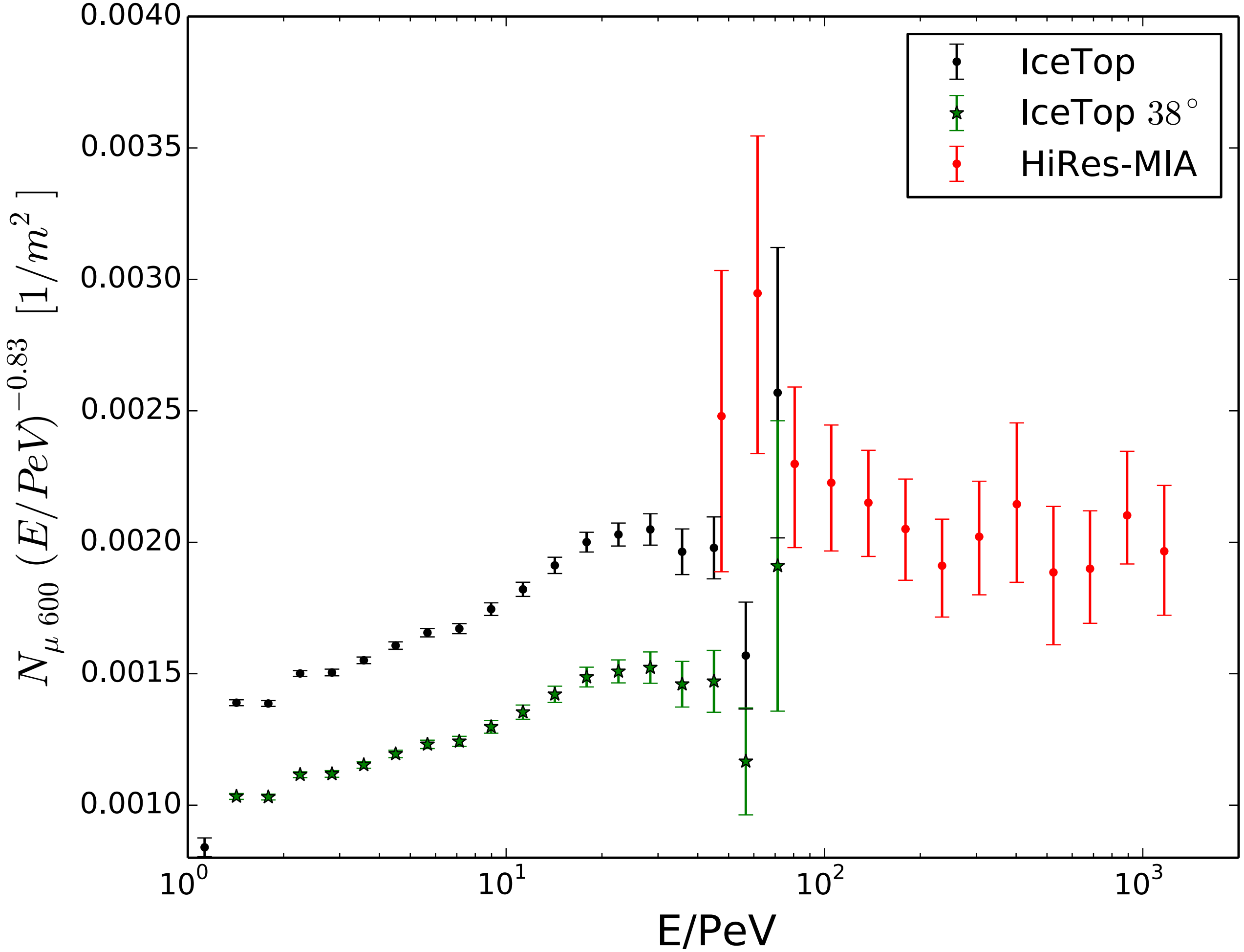
All within 10% (below 30 PeV)

N_μ (Over-)Corrected to 38 deg.



MIA depth ~ 860 g/cm^2
IceTop depth ~ 680 g/cm^2

N_μ (Over-)Corrected to 38 deg.



MIA depth ~ 860 g/cm^2
IceTop depth ~ 680 g/cm^2

Conclusions

- With IceTop we can measure the average number of muons at large distances from the shower axis. Specifically 600 m.
- IceTop's N_{600} displays remarkable agreement with HiRes-MIA at 50 PeV, even though we expect systematic corrections that could change this.
- Preliminary $\rho_{\mu}(600)$ validated (lowered by ~1.-1.7)
- Improvements:
  - Parametric signal model
  - Uncorrelated background properly treated
  - Started looking into the early/late part of the shower.

Random slides

Effect from Random Coincidences

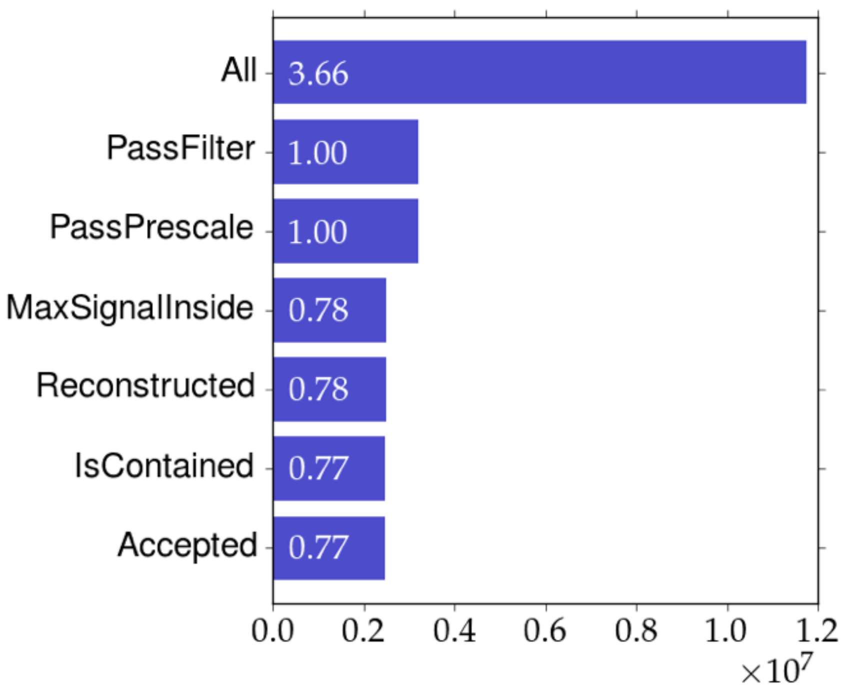
(order of magnitude)

- Low energy showers produce signals in the tanks that can fall in the 1 microsecond window just by chance.
- Let's say the background rate is 1 KHz.
- The probability p_b that there is at least one signal in the time window is
  $1 - e^{-0.001}$
- Let's say there are N tanks in a given (E, θ, r) bin.
  The expected number of tanks with background signal is given by a binomial:
  $N_b = N p_b^n (1 - p_b)^{(N-n)}$
  and the mean is what you expect:
  $$\langle N_b \rangle = N p_b = N(1 - e^{-0.001}) \sim 0.001N$$
- We can then correct the equation we used for the number of muons:
  $$p_{\mu\, hit} = \frac{N_{\mu \geq 1}}{N_{tanks}} - 10^{-3} = 1 - e^{-\langle N_\mu \rangle}$$

Event selection

- Selection may **not** bias mass composition
- Don't need to define exposure for our selection
  - We are not computing muon flux, but average muon density per shower

- **Exploration data set**: IC-86 level 3 data (prepared by JG), June 2011
  - About 2 million accepted events



Cuts from IC-73 spectrum paper

- FilterMask: **IceTopSMT8_11**
  - filterPassed: **true**
  - prescalePassed: **true**
- IceTopMaxSignalInEdge: **false**
- Laputop reconstruction **ok**
- Containment (IC-73 paper): **true**
- S125 > **0.1 VEM** and zenith < **60°** (later: events are binned in S125)

Going beyond simulations

(Hans Dembinski)

- Need plausible variations of our μ-signal model to estimate **systematics**
- **Parametric model** based on theory allows us to see which variations are **plausible**

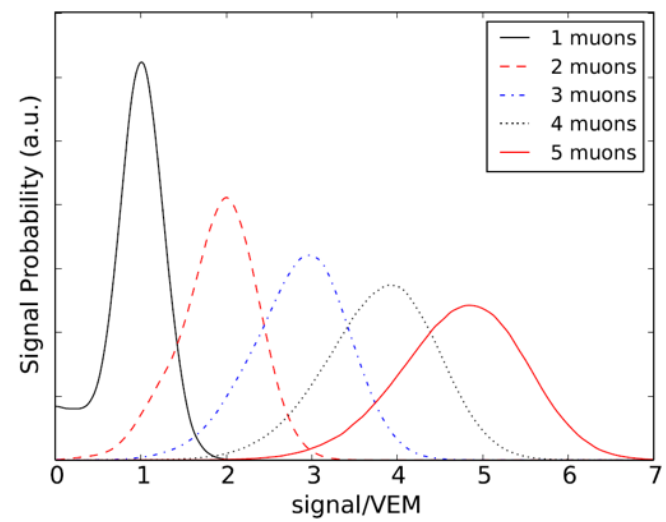
$$f(S) = \int \mathrm{d}l K(S;l)g(l)$$

Signal distribution to **one** muon

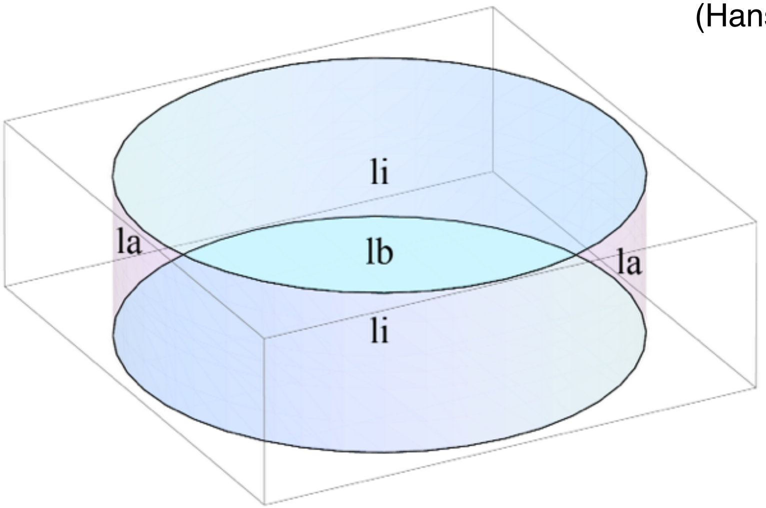
Response kernel (ExGaussian tuned to G4TankResponse)

Statistical track length distribution for through-going muons **(pure geometry)**

Response to ***k*** muons is ***k***-fold **auto-convolution** of single muon response **(JG)**



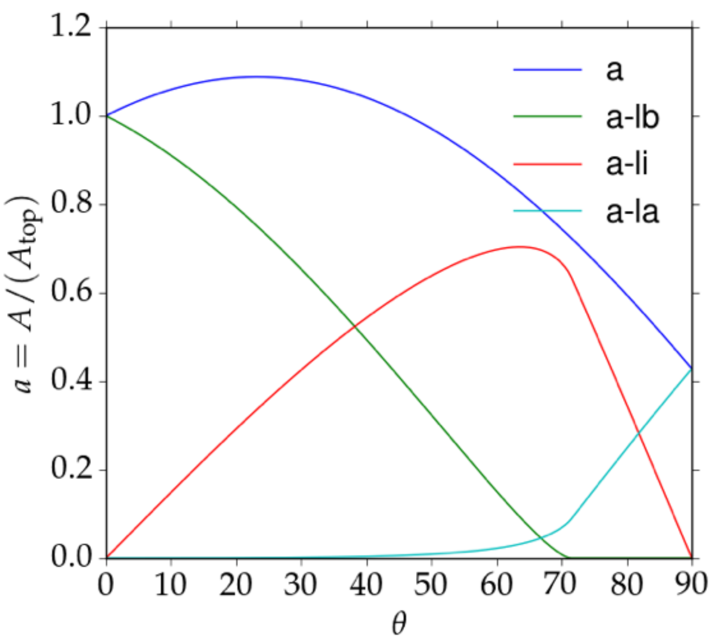
Track length distribution

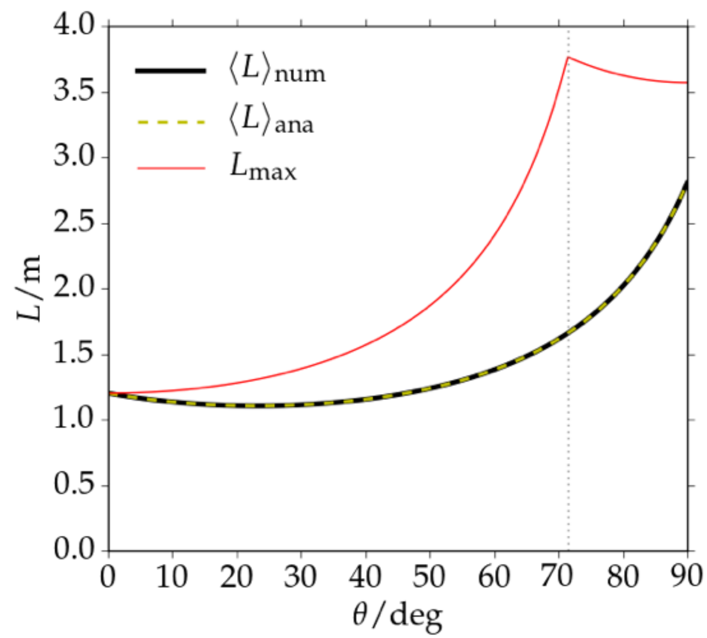


(Hans Dembinski)

http://arxiv.org/abs/1502.03347
Balazs Kegl, Darko Veberic

Analytical solution to statistical track length distribution of uniform hits on a cylinder





op, M

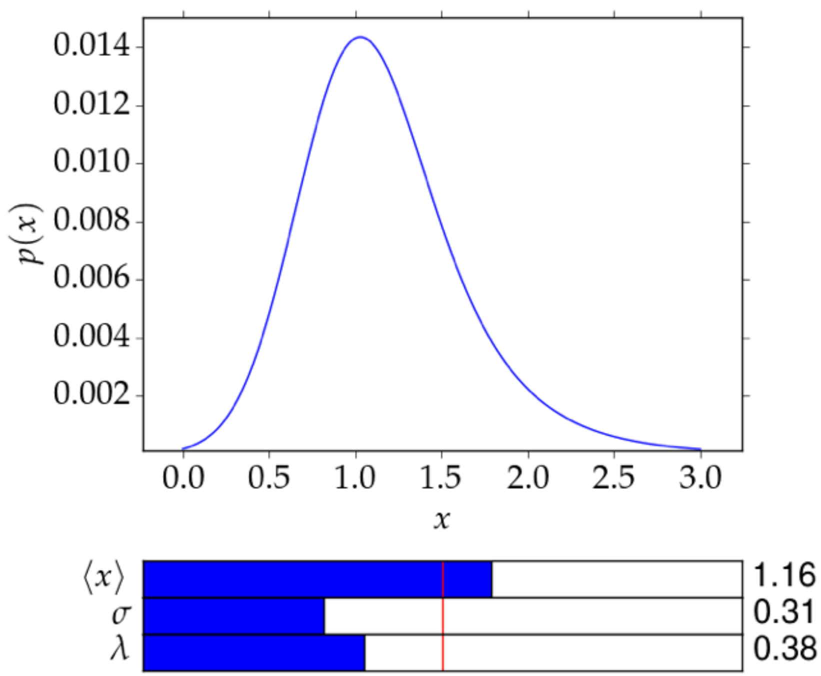
Response kernel

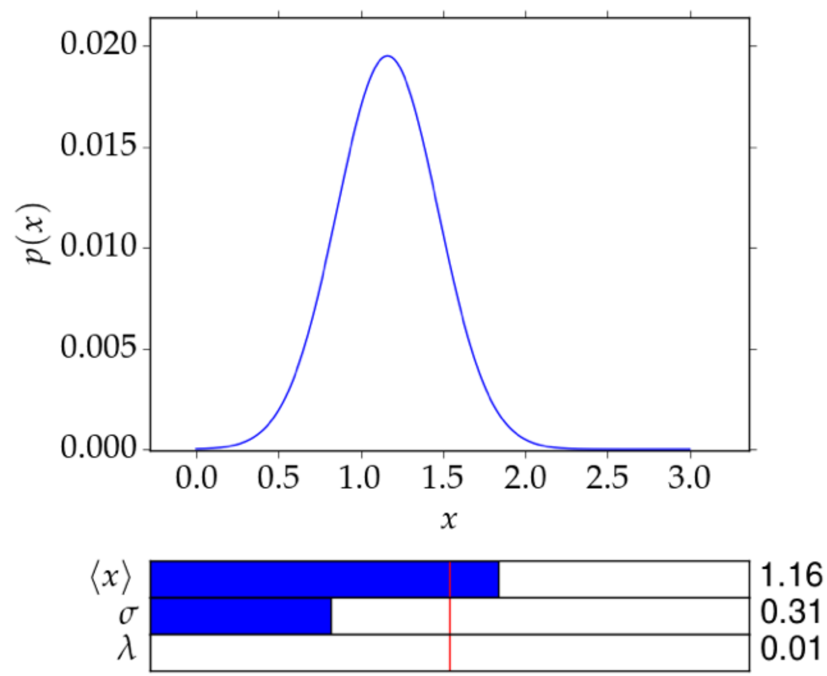
(Hans Dembinski)

ExGaussian http://en.wikipedia.org/wiki/Exponentially_modified_Gaussian_distribution

Analytical convolution of normal distribution and exponential distribution

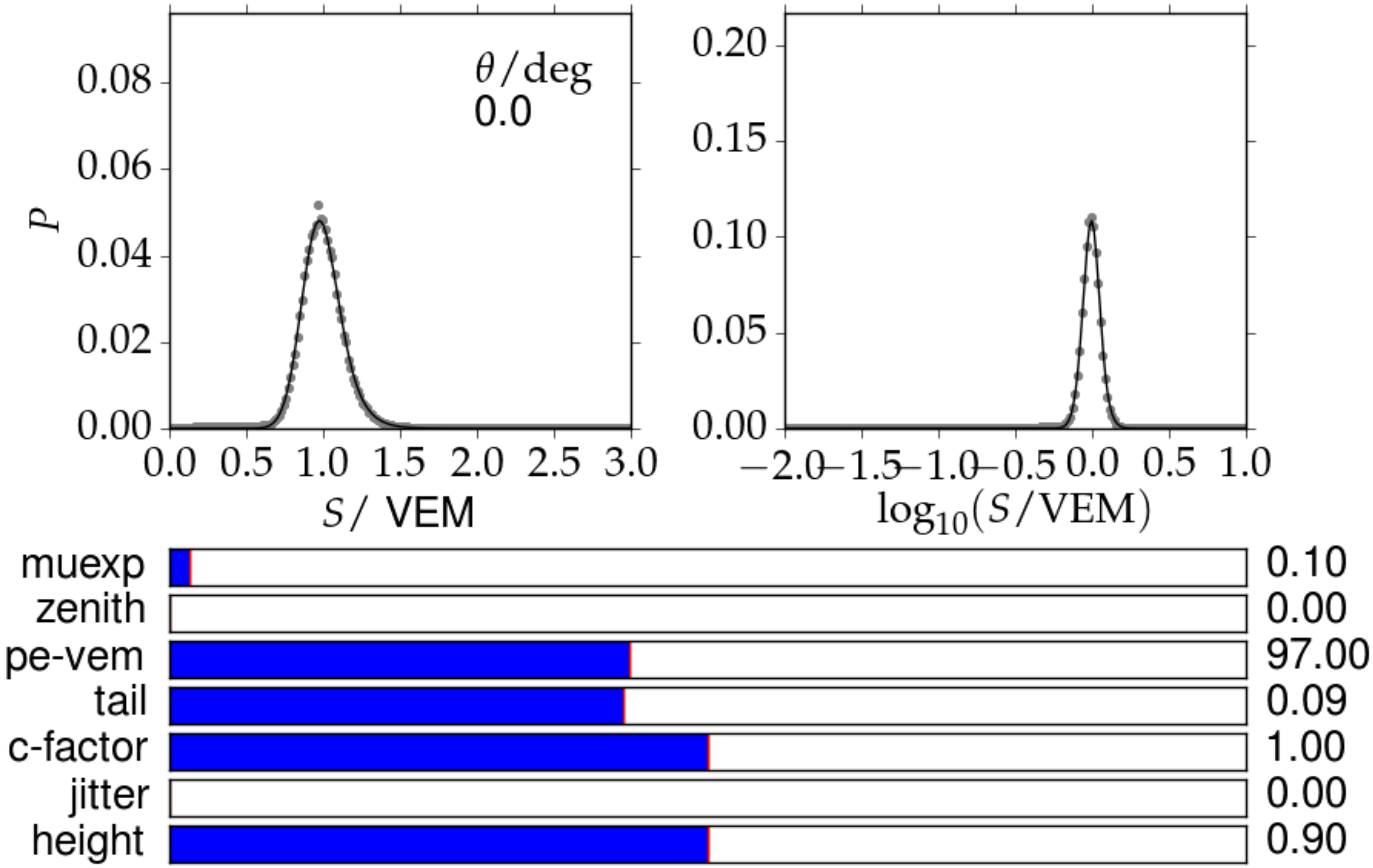
$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$





μ-model reproduces

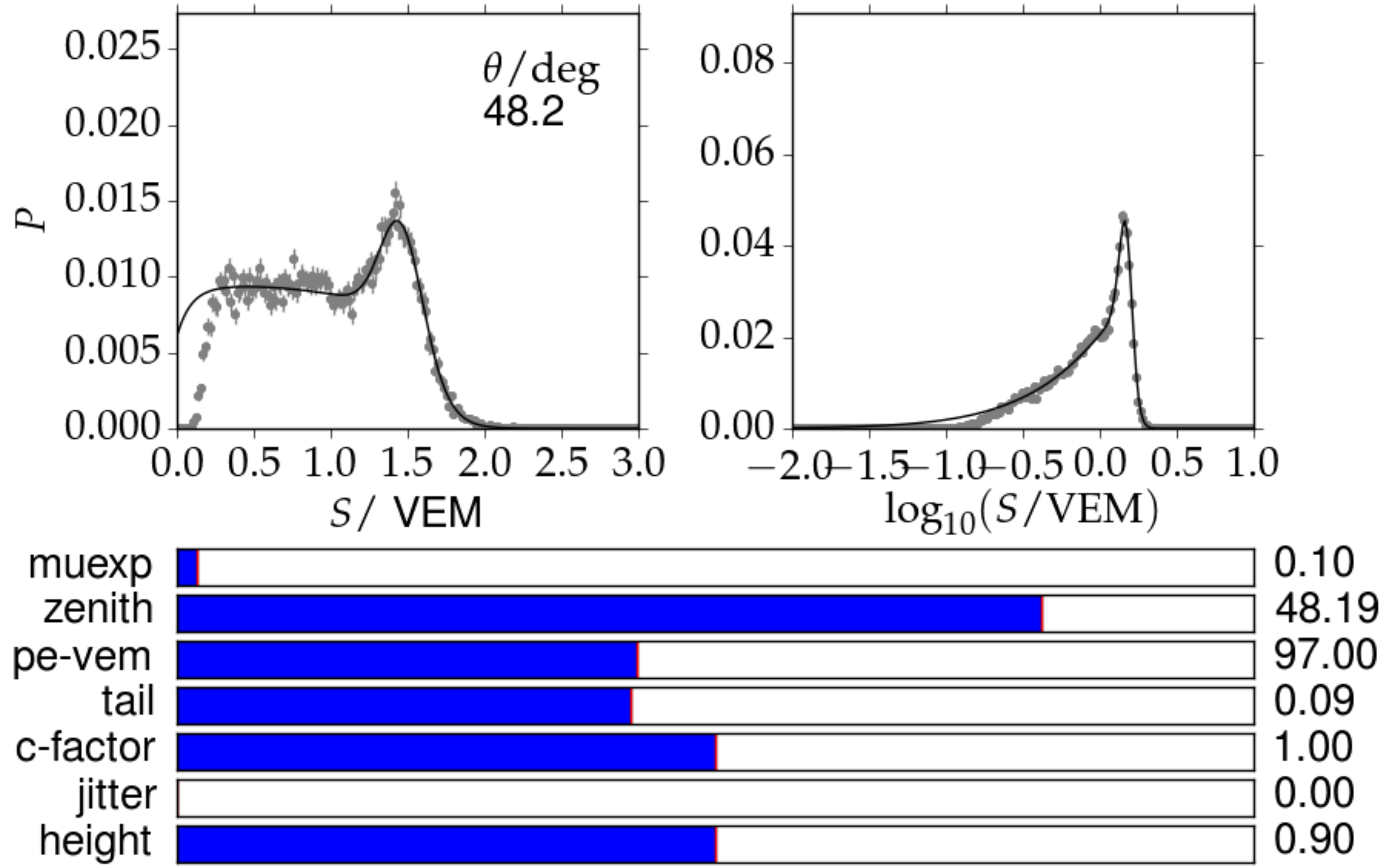
(Hans Dembinski)



Data points: G4TankResponse

μ-model reproduces

(Hans Dembinski)

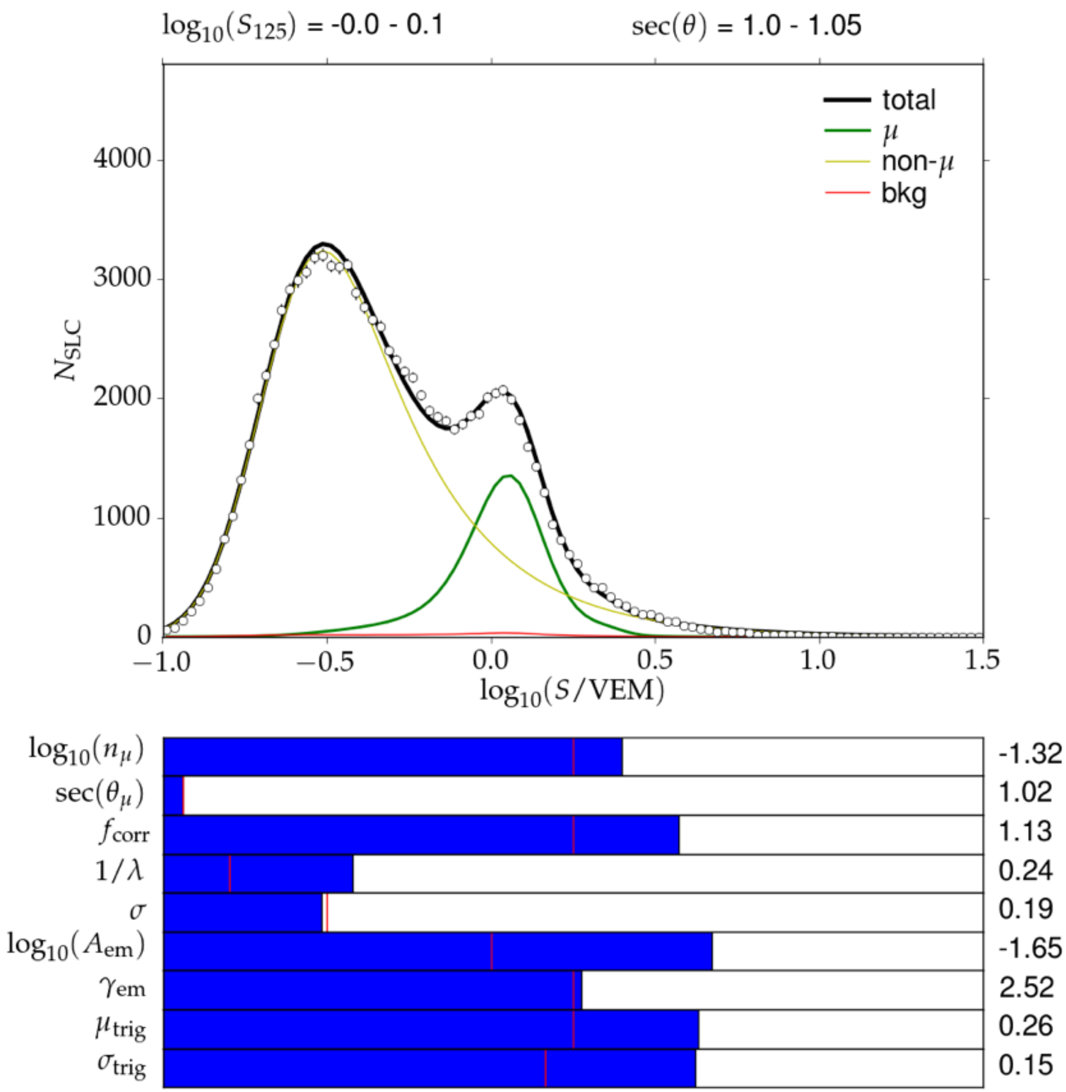


Data points: G4TankResponse

Fits of charge

Full model regards em signals and trigger

$$\bar{N} = P_{\mathrm{trig}}(\bar{N}_\mu + \bar{N}_{\mathrm{em}}) + \bar{N}_B$$ **(JG)**



Components

μ … parametric model (following slides)

em … power law (empirical)

$$\bar{N}_{\mathrm{em}} = A_{\mathrm{em}} S^{\gamma_{\mathrm{em}}}$$

trigger … normal cdf in $\log_{10}(S)$ (empirical)

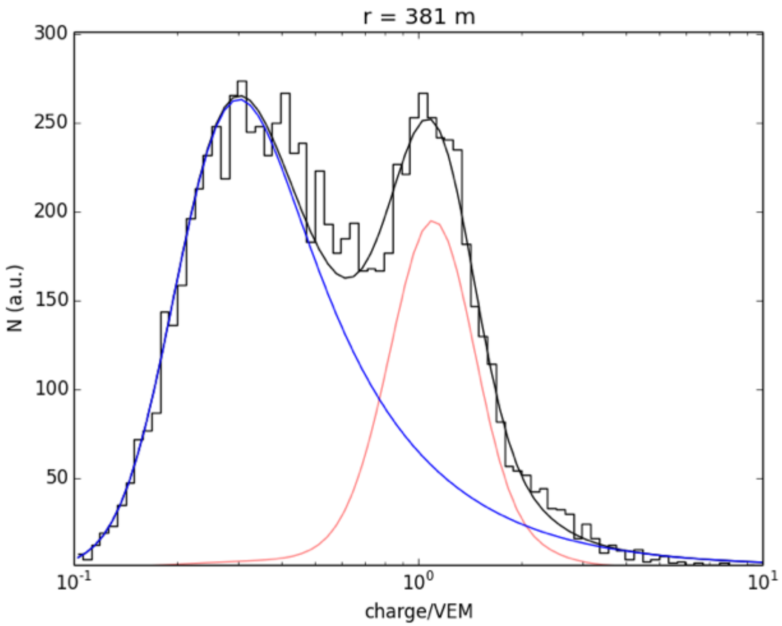
Full model has 9 parameters, we fit 8 bin-by-bin

"Punch-through"

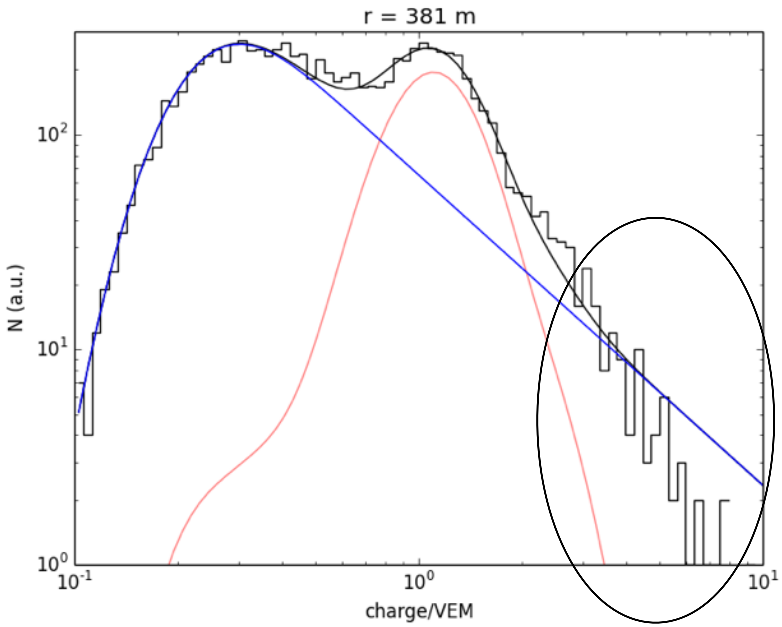
Some people ask me about "punch-through"…
as if I was measuring muons by shielding against the EM component.

Punch-through does not apply in this case, but anyway…

my usual plot:



in log scale:



In the experiment they have in their mind….
these would "punch through" some shielding above the detector and pass as muons.

That is not the case here

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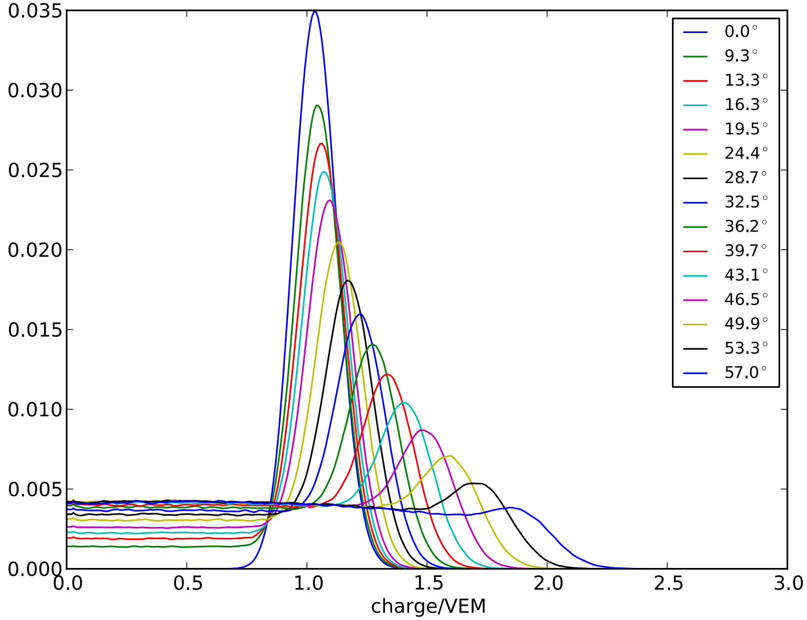
Detector Response to Muons

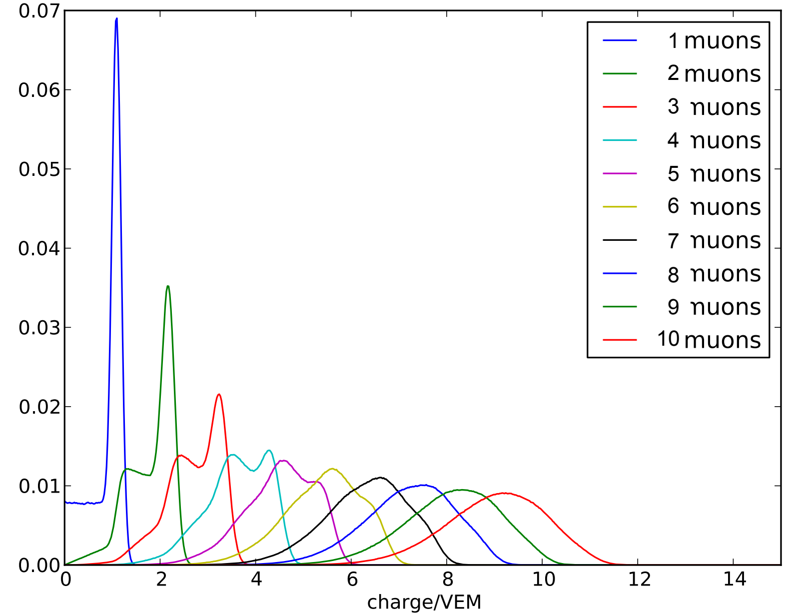
given a zenith angle and expected number of muons

Single muons, various angles



Response to single muons obtained from Geant4 simulations of IceTop detectors

Few muons, fixed angle (~10º)



The response to n muons is the n-th order autoconvolution of the single-muon response

$$p(q|N_\mu,\theta) = \sum_n \frac{p^n e^{-\langle N_\mu \rangle}}{n!} p(q|n,\theta)$$

Expected number of muons

response to a number of muons

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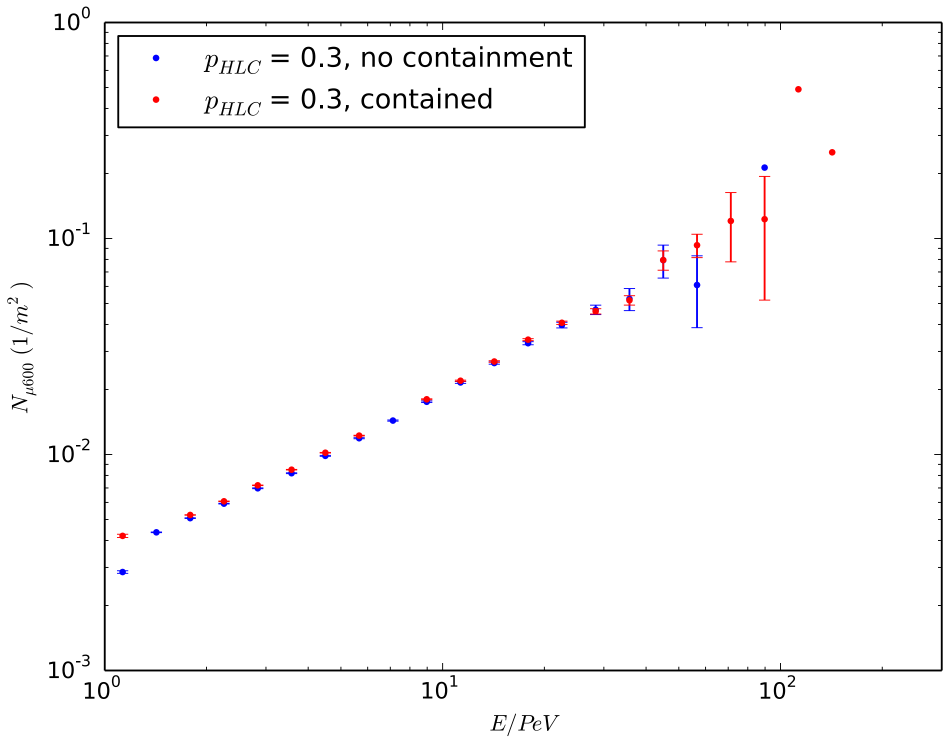
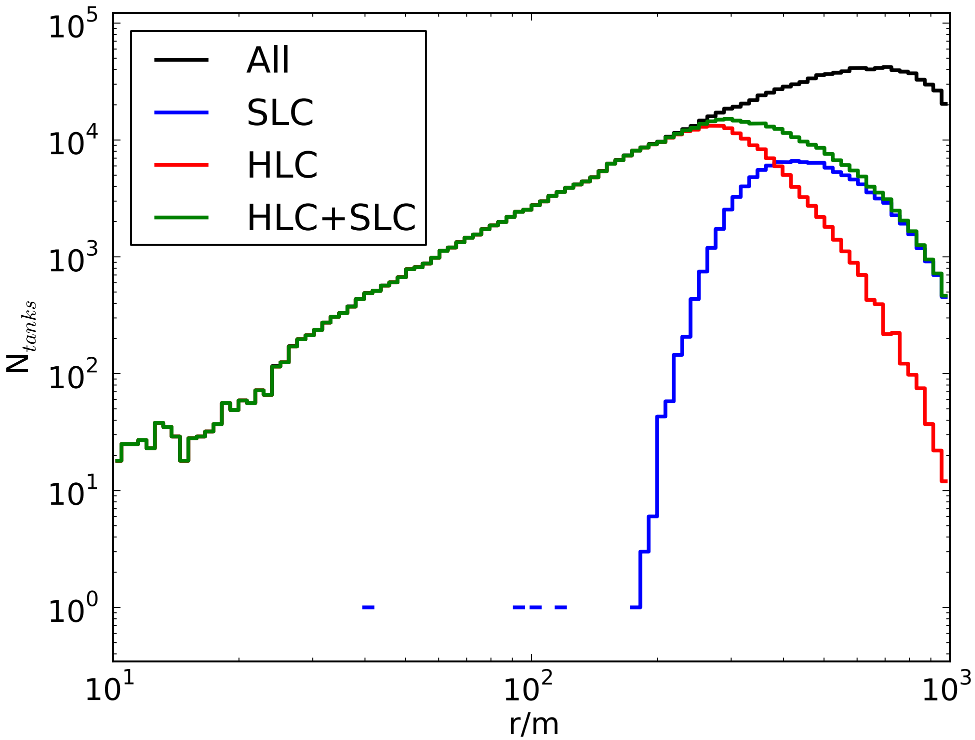
Effect of Containment Cut



- Three years data (IC79, IC86.2011, IC86.2012)
- Snow:
  - Banff tables
  - lambda: (2.1, 2.2, 2.3)
- Attenuation ‘corrected’
- Energy conversion at 34 deg.
- Included standard cuts:
  - good runs
  - filter checks
  - maximum signal checks
  - containment
- Containment cuts have an effect at the highest energies

Tank Distribution Relative to Shower Axis

($\theta < 6^\circ$, E~10 PeV)

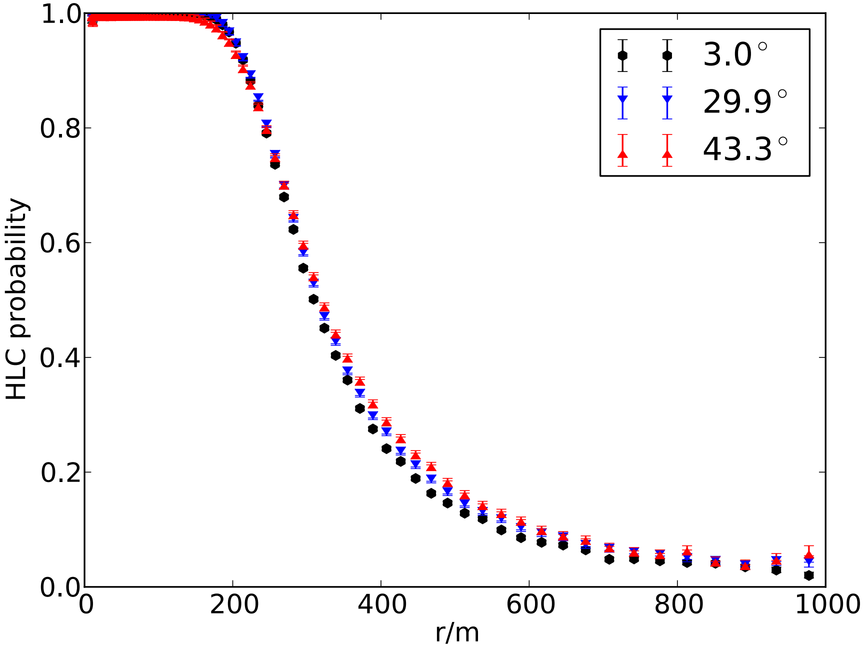


HLC: Tanks with signal whose partner within a station also has a signal
SLC: Tanks with signal whose partner within a station does not have a signal

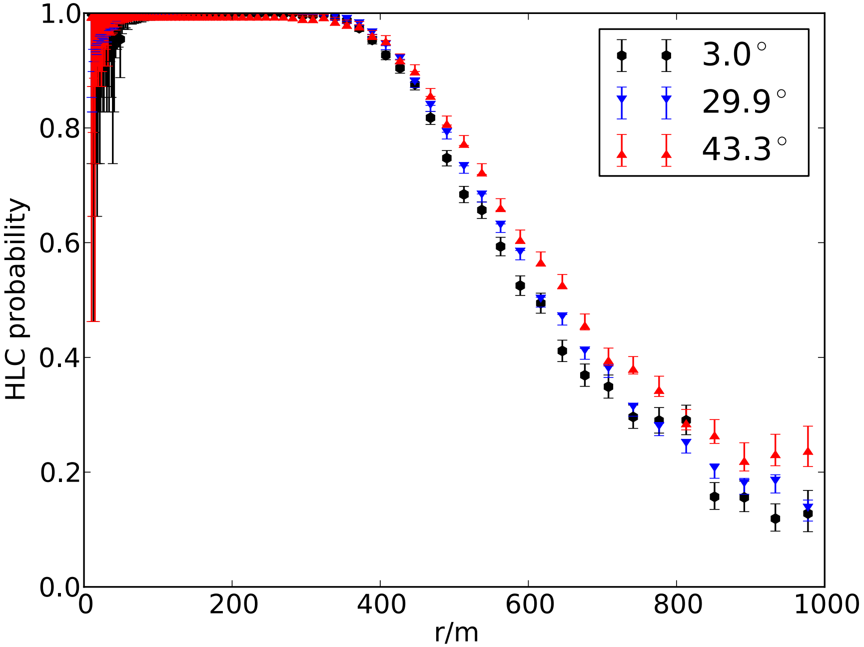
Note that SLC tanks are relatively few and far from the shower axis.
Energy and direction reconstruction does not use SLC tanks at this time.

Defining a Radial Cut

5.7 VEM



71 VEM

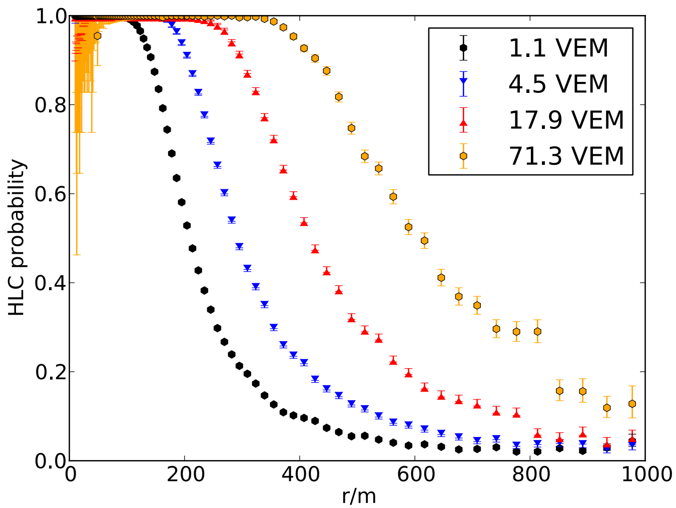


p_{HLC}: The probability that the partner of a given tank with signal also has a signal.

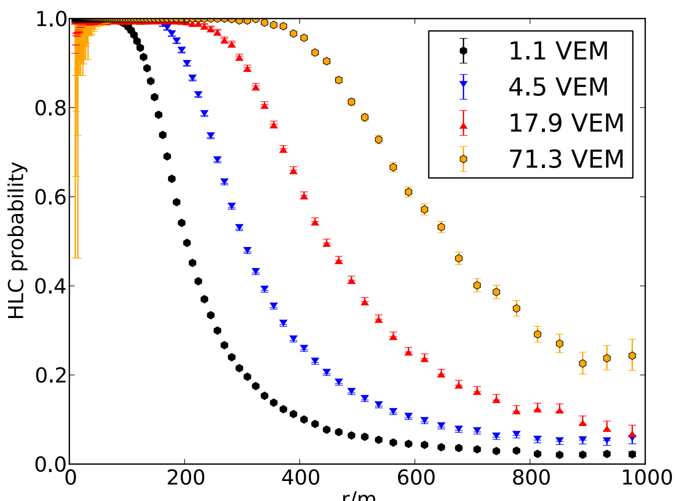
It can be determined from data (from slide 4) and does not to depend strongly on zenith angle, only on s_{125}.

Lateral HLC Probability

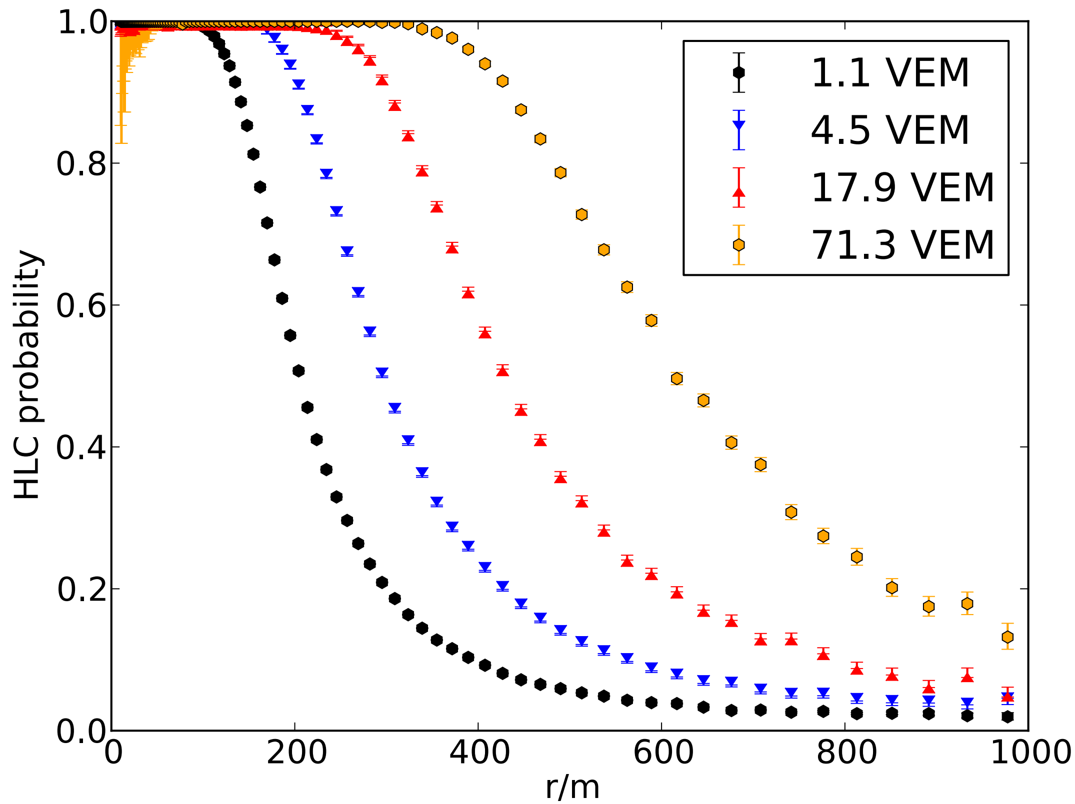
3 deg



43 deg

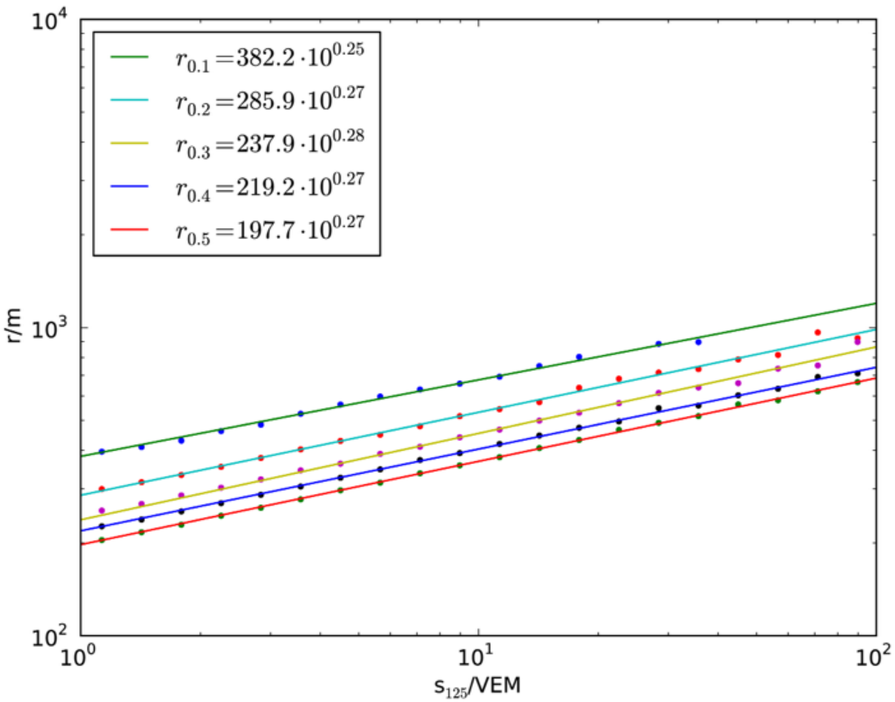


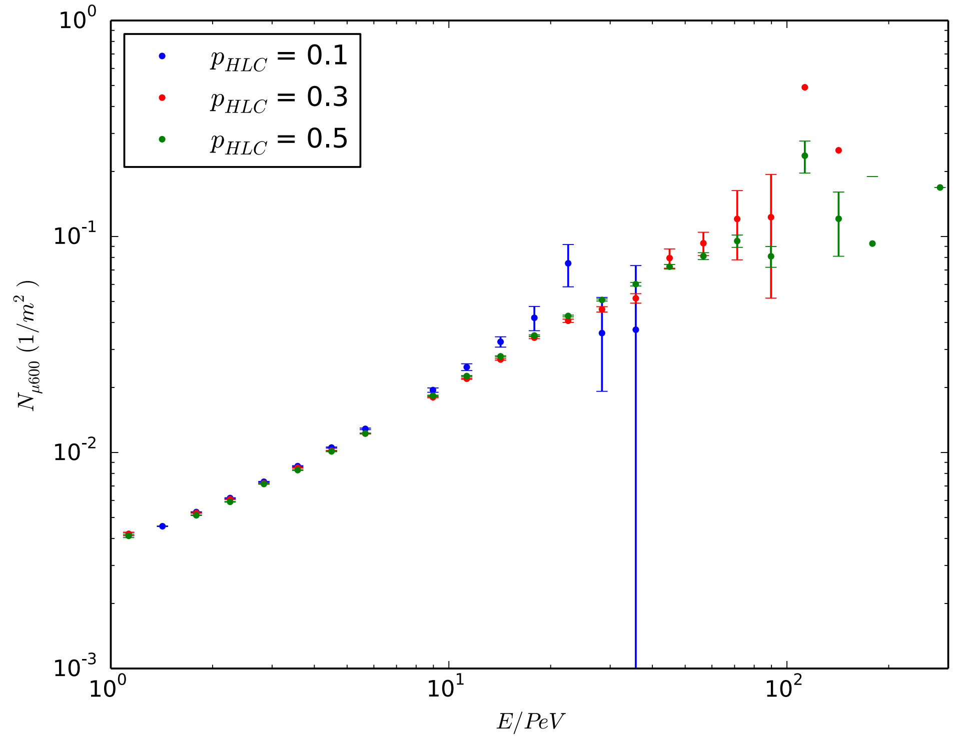
30 deg



The radial cut is such that $p_{HLC} < 0.1$ at 30 degrees.

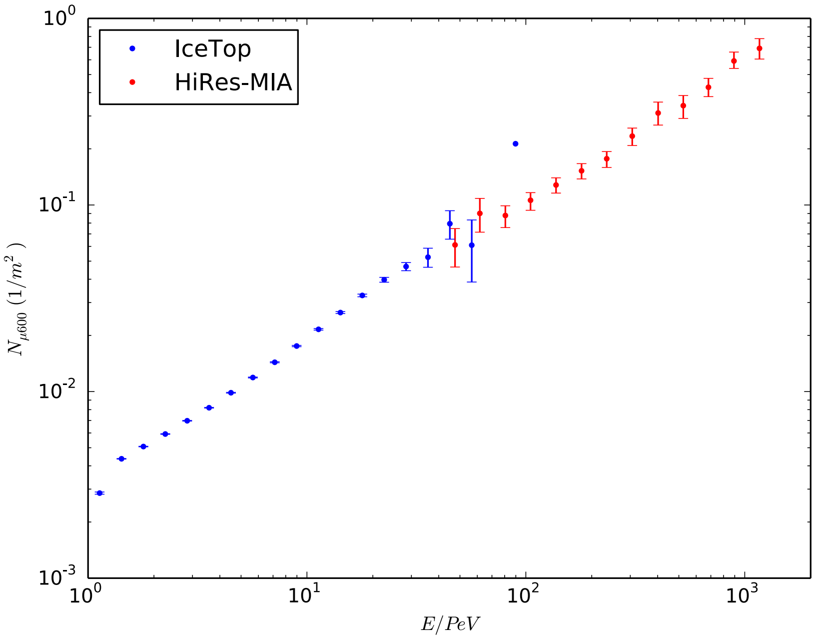
Effect of RadialCut



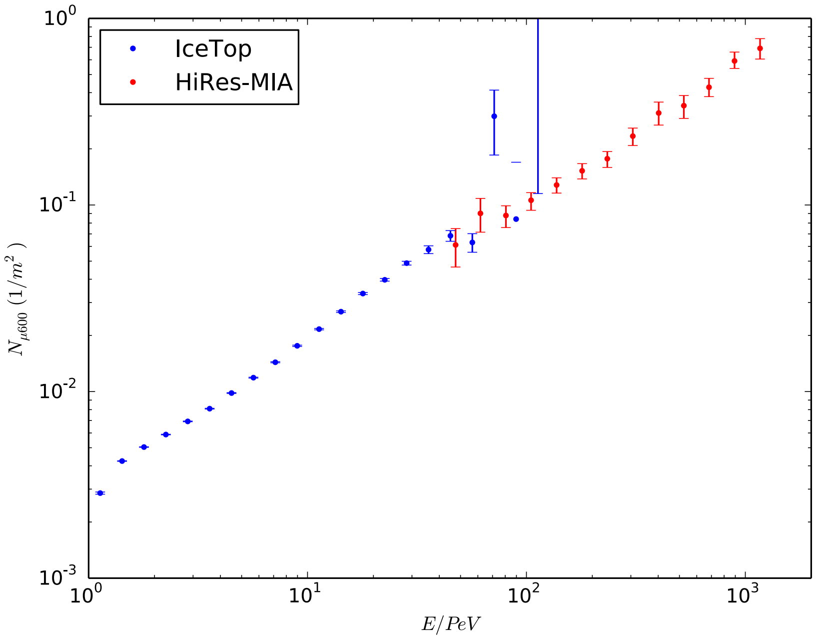


P_{HLC} also affects the maximum attainable energy.

Comparison to HiRes-MIA



$P_{HLC} = 0.3$



$P_{HLC} = 0.4$

Outline of analysis

- Data selection
  - Select events with good reconstruction
  - Select launches compatible with shower front (HLC, SLC)
  - Select uncorrelated launches (to subtract)
- Histogram generation
- Fit histograms

} Background

  - **Parametric** μ-signal model