Reconstruction in DeepCore and PINGU

PENNSTATE

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Avviso!

- The results shown in this presentation are preliminary
  - Contents under pressure
  - Listeners assume all liability for damages, incidental or otherwise
  - This material may be hazardous to your health or scientific reputation
  - I was never here. You do not know me.
  - The Secretary will disavow all knowledge of this talk
  - The first rule of Fight Club is that you don’t talk about Fight Club
  - Burn before reading
  - These slides will self-destruct in 5 seconds

The Problem (as I see it)

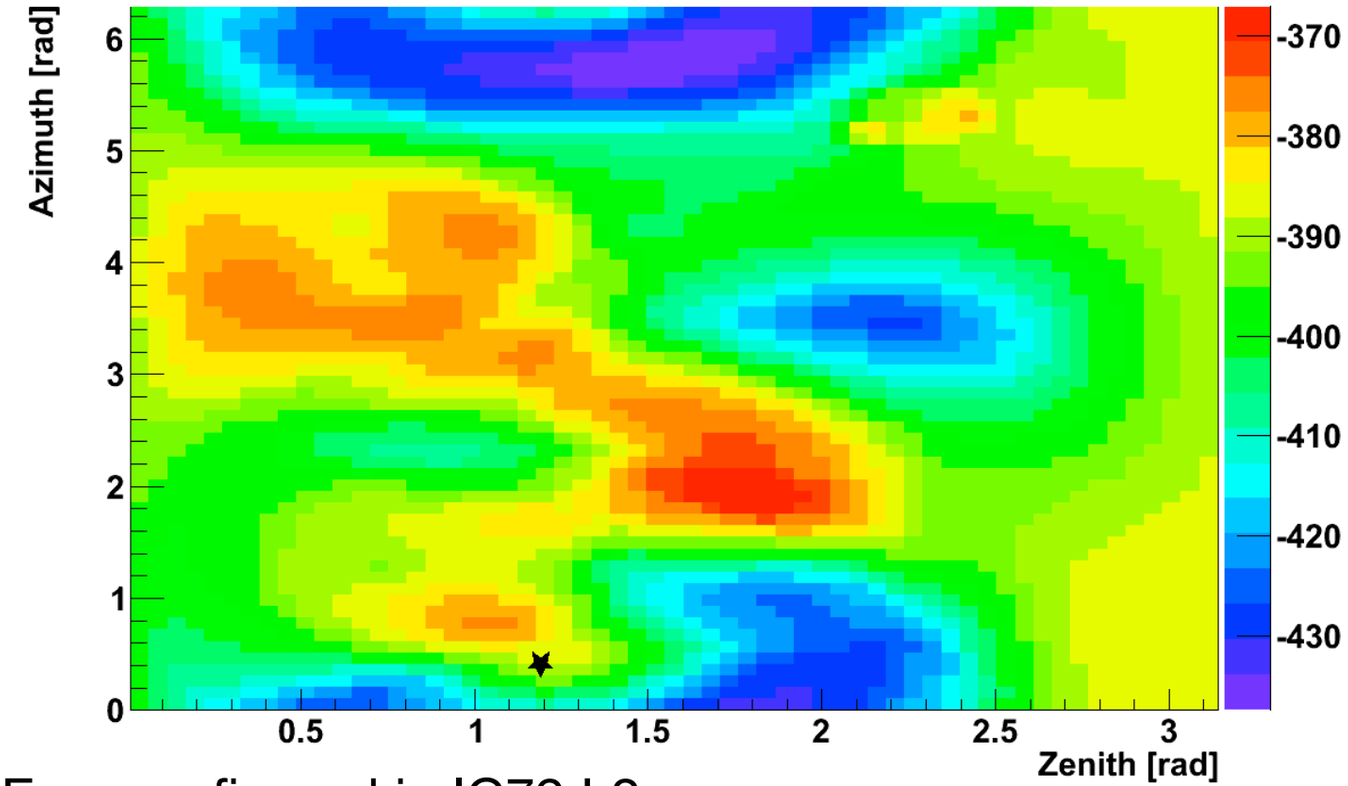
- Our traditional techniques were developed originally for small detectors and high energies
- They assume infinite tracks, starting outside the detector and passing completely through
  - Five parameters: x, y, t, θ, ϕ
  - No attempt to discriminate particle type – at best, compare separate likelihoods
  - Assume minimum ionizing, and measure energy separately ex post facto
  - Rely on high photon statistics to counteract any problems with description of photon transport
  - Use only first arriving photon (basically, enforce causality), and ignore dogs that don't bark
- For (most of) these physics topics, we need to do better
  - Eight parameters (or 10?): x, y, z, t, $\theta_{(\mu)}$, $\phi_{(\mu)}$, Ec, L_μ, (θ_c, ϕ_c)?
  - Accurate track vs. no-track discrimination very important
  - Can we play statistical games to separate ν from $\bar{\nu}$, ν_τ from ν_e, and/or NC from ν_e?

The Story So Far

- In IceCube, we have suffered from unrecognized numerical problems in our photon transport models for many years
  - Affected both reconstruction and simulation
  - Separate from uncertainties in optical properties of ice
- Fixing the obvious problems in our reconstruction algorithms did not yield expected improvements (often made things worse)
  - Likelihood space fundamentally inaccurate – better minimizers gave worse results, more correct descriptions gave worse results, etc.
  - Kudos in particular to Jakob v. Santen, Marek Kowalski, and Nathan Whitehorn for figuring out what was wrong

A Tale of ~~Two~~ Three Likelihoods

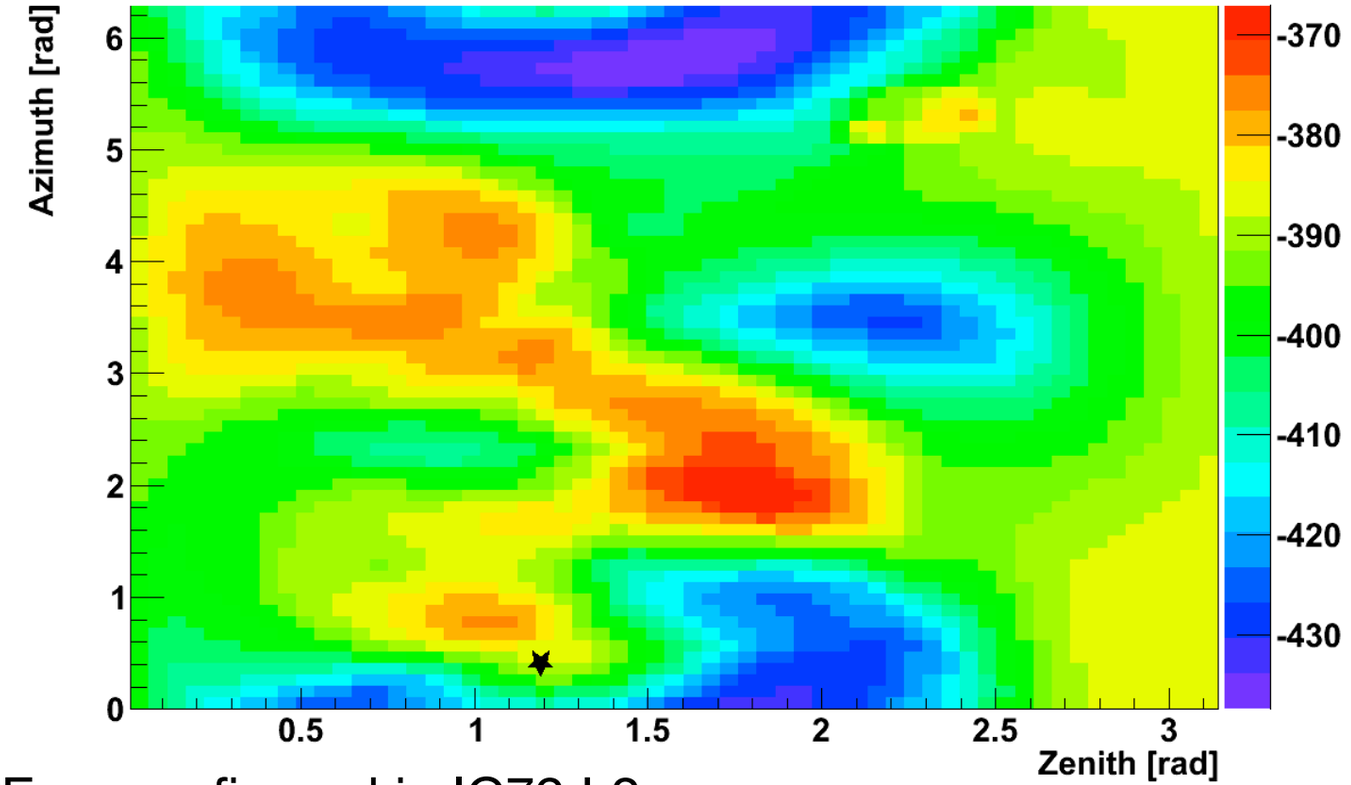
SPE/Pandel



SPE as configured in IC79 L2

A Tale of ~~Two~~ Three Likelihoods

SPE/Pandel



SPE as configured in IC79 L2

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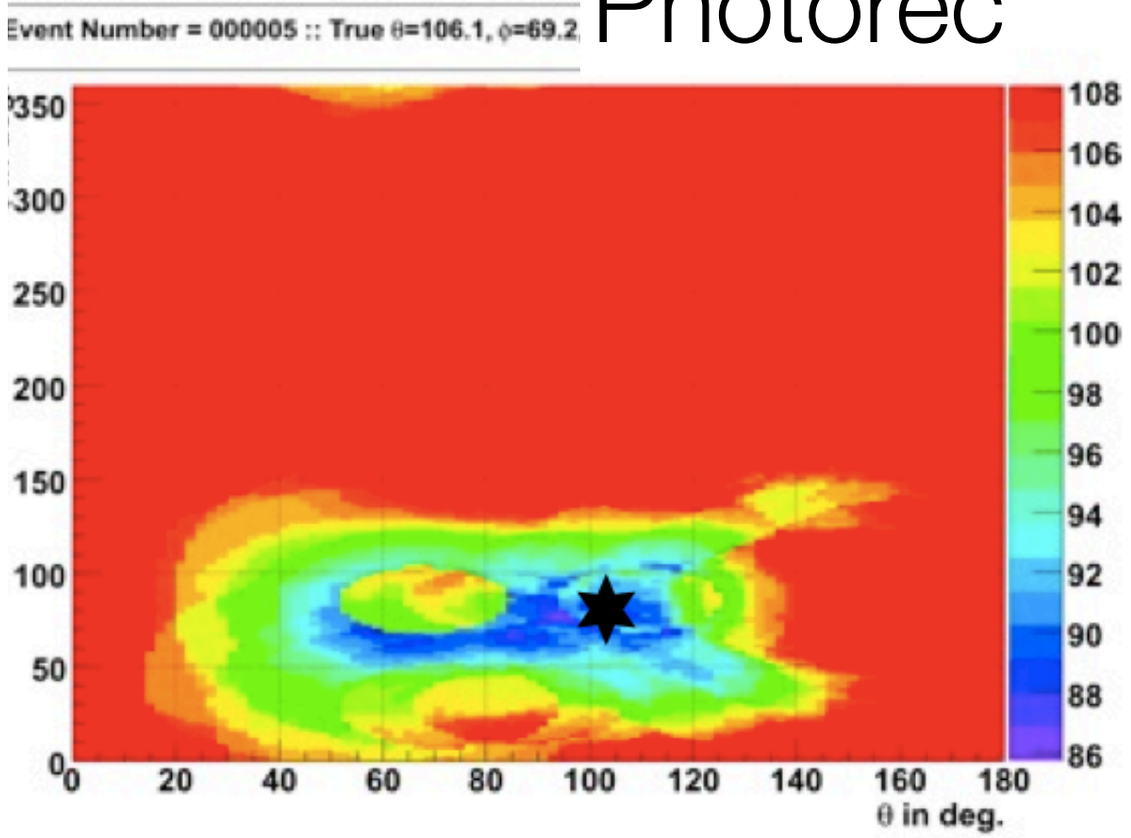
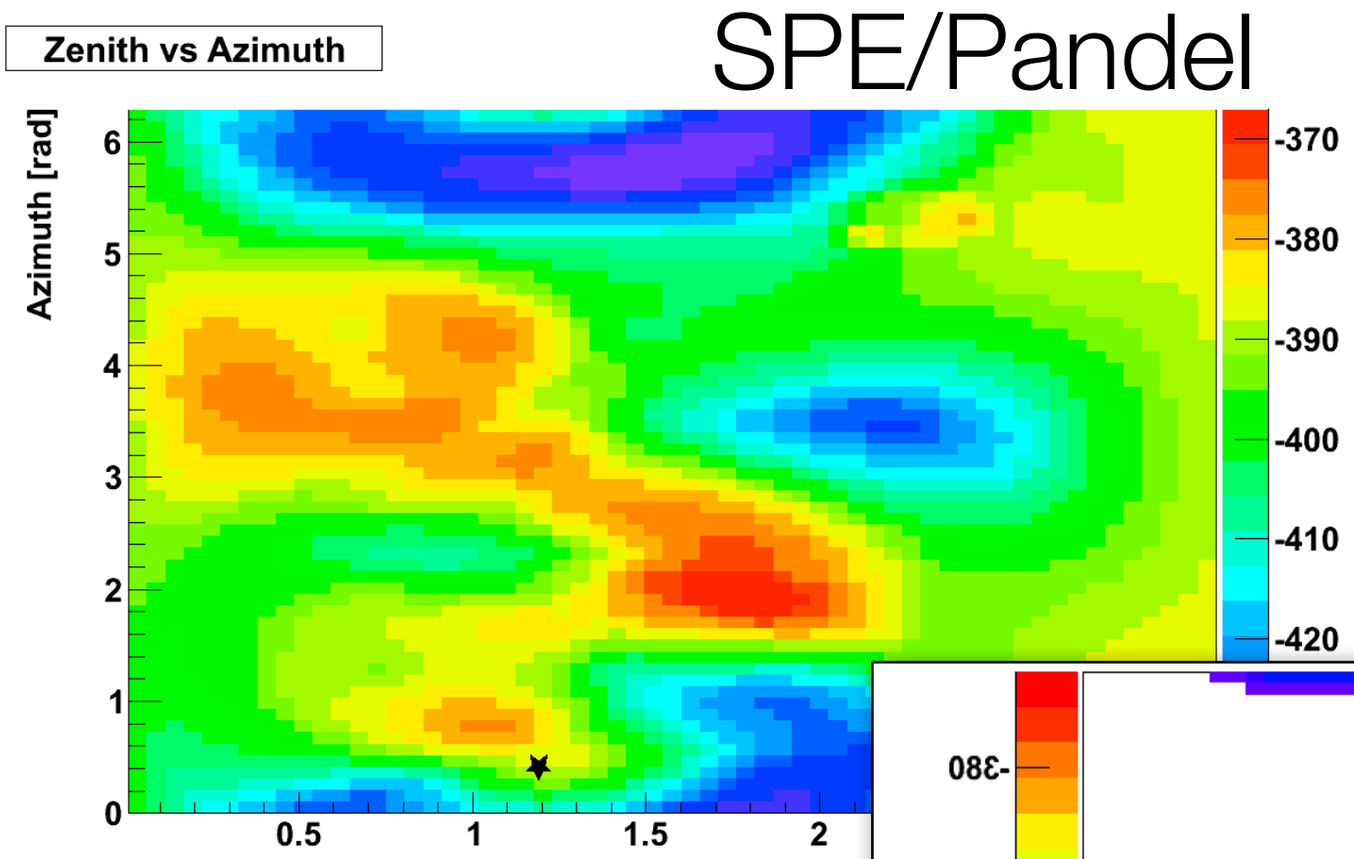


From Chang Hyon's Uppsala talk

Binning artifacts, and older likelihoo

A Tale of ~~Two~~ Three Likelihoods

SPE/Pandel



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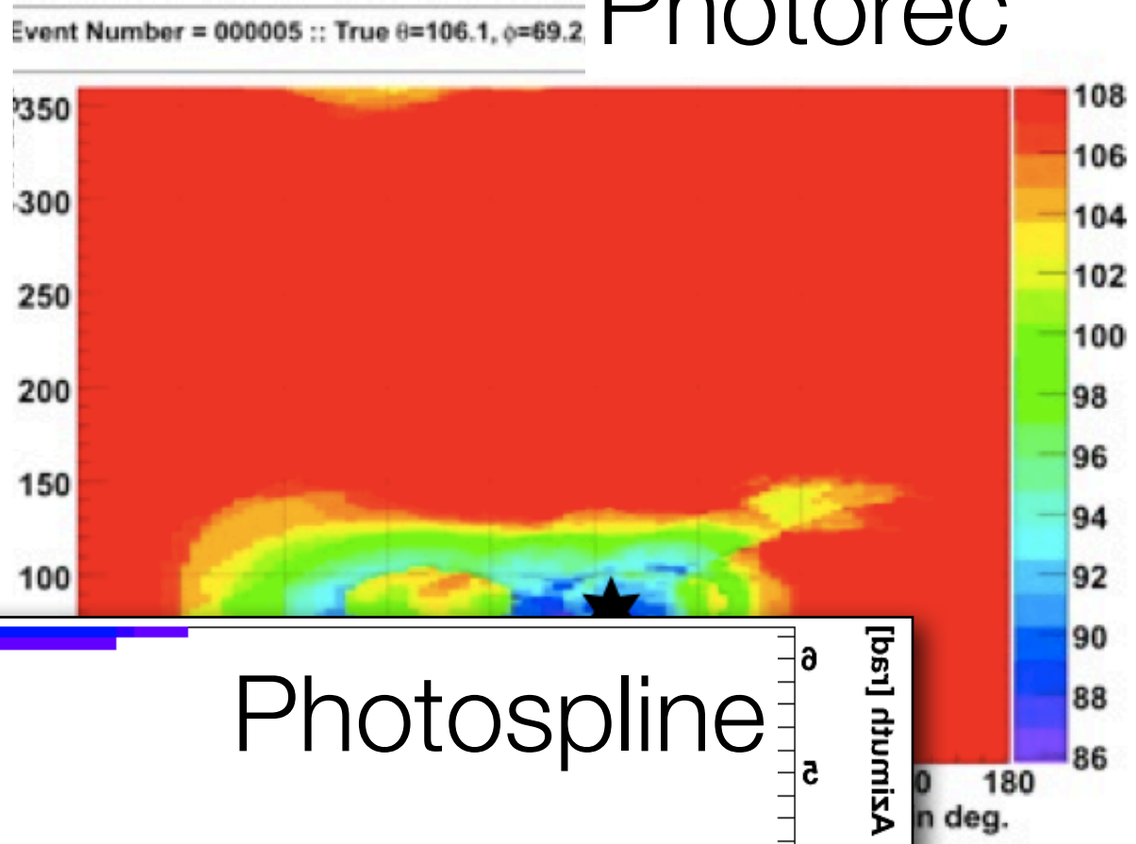
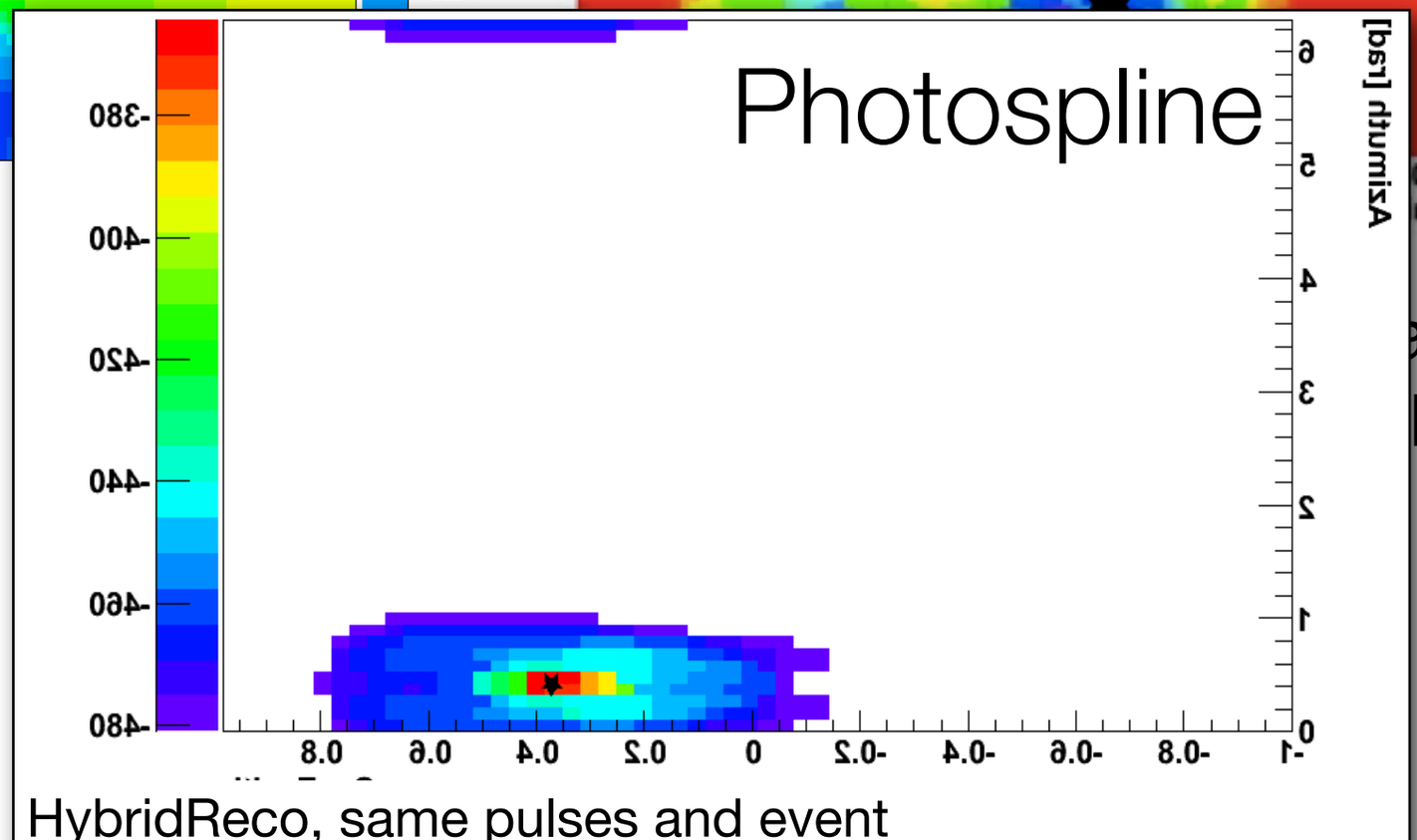


la talk
kelihoo

Photospline



HybridReco, same pulses and event

Where We Stand

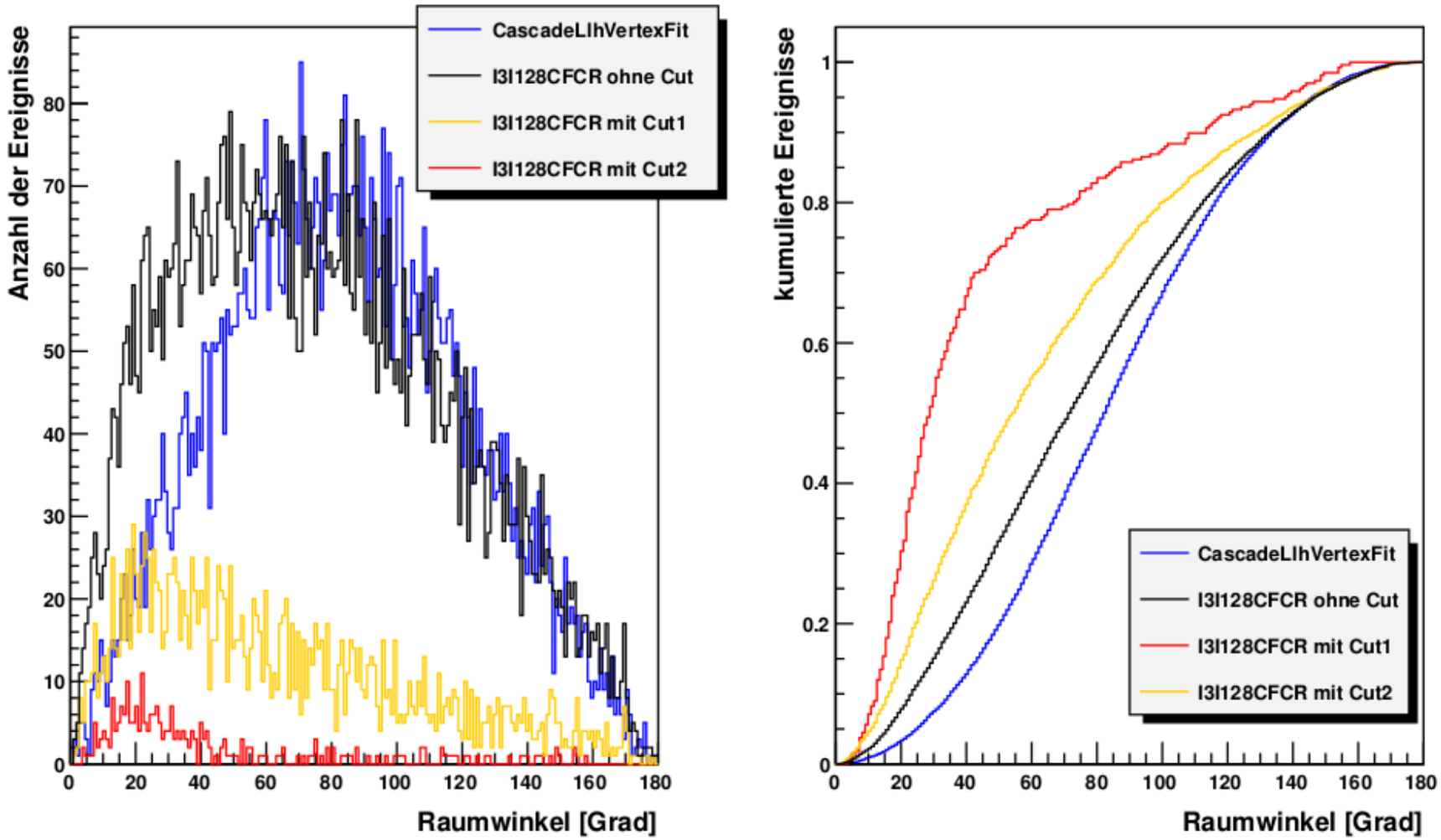
- We have (mostly) fixed those issues in the last year
  - In the process of implementing all the ideas we had over the last decade…
- Key new techniques are GPU-enabled direct photon transport simulations, and a smooth, non-parametric spline-based descriptor of photon transport for reconstructions
- The next few slides were smuggled out of Aachen and show the current state of the art with (mostly) fully-implemented production reconstructions
  - Numerical issues solved in cascade reconstructions
  - Track reconstructions allowing non-infinite tracks, but either based on direct photorec tables (with artifacts)…
  - …or with splined photon description but numerical approximations for high light levels (e.g. Gaussian amplitude distribution)

Directional Reconstruction (Cascades)

- Decent angular resolution possible with Credo and enough CPU cycles

Klaus Wiebe, Alexandra Schulte

- Median space angular res. around 25° for reasonable NCh and NStr
  - Around 50° for NCh > 8
- Good enough for interesting physics



Remarks: Cut1 is nstr>1 and nch>8, Cut2 is nstr>4 and nch>21, switch red and yellow in legend of right plot
x axis: angular resolution, y axis: abundance (left), cumulative events (right)

Courtesy of Alexandra Schulte (Bachelor Thesis, 2012)

Energy Reconstruction (Cascades)

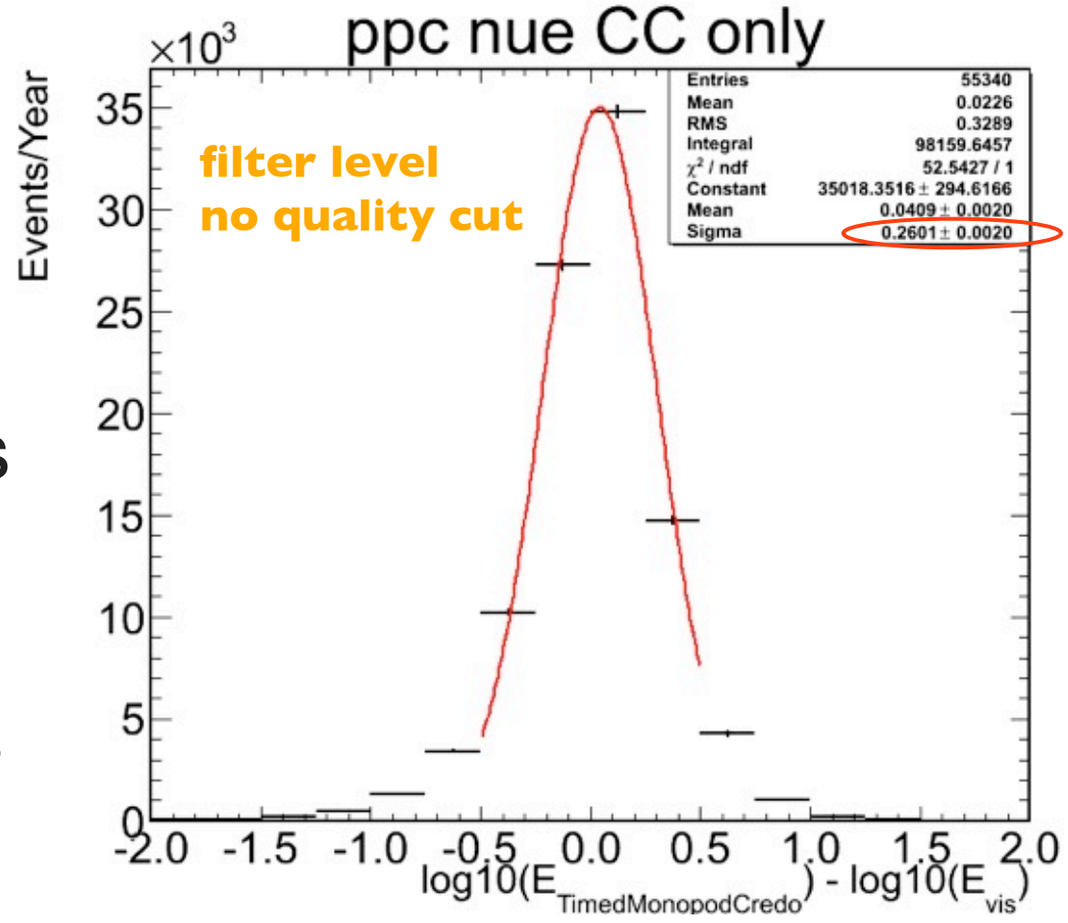
- With appropriate seeds, energy resolution comparable to that at higher energies

- Some oddities seen in DOM responses, improvements still possible?

Donglian Xu

Current low-en cascade reco. status: Monopod seeded with Credo

MC: GENIE PPC 1200



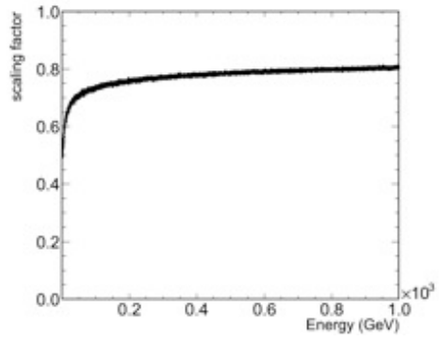
Resolution: ~0.26

E_{vis} :

- CC events:
Vertex.energy* f_{had} + Particle.energy
- NC events:
Vertex.energy* f_{had}

$$f_{had} = 1 - (E/E_0)^{-m} * (1 - f_0)$$
$$E_0 = 0.399, m = 0.130, f_0 = 0.467$$

Ref: Marek Kowalski's PhD dissertation

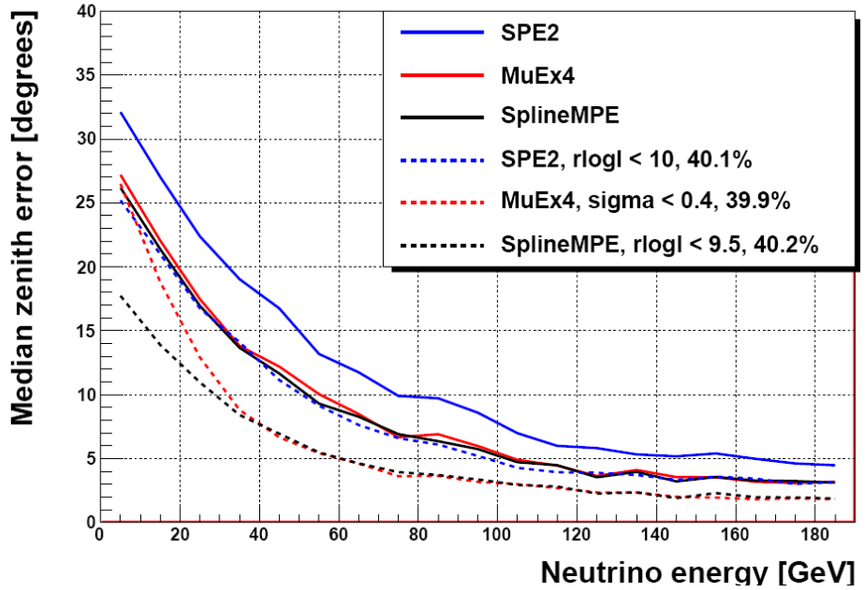


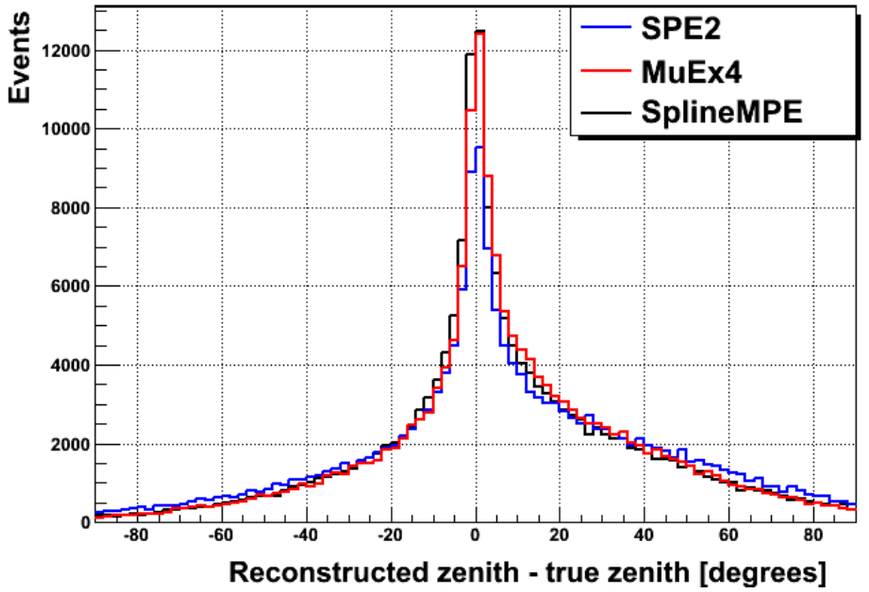
Directional Reconstruction (Muons)

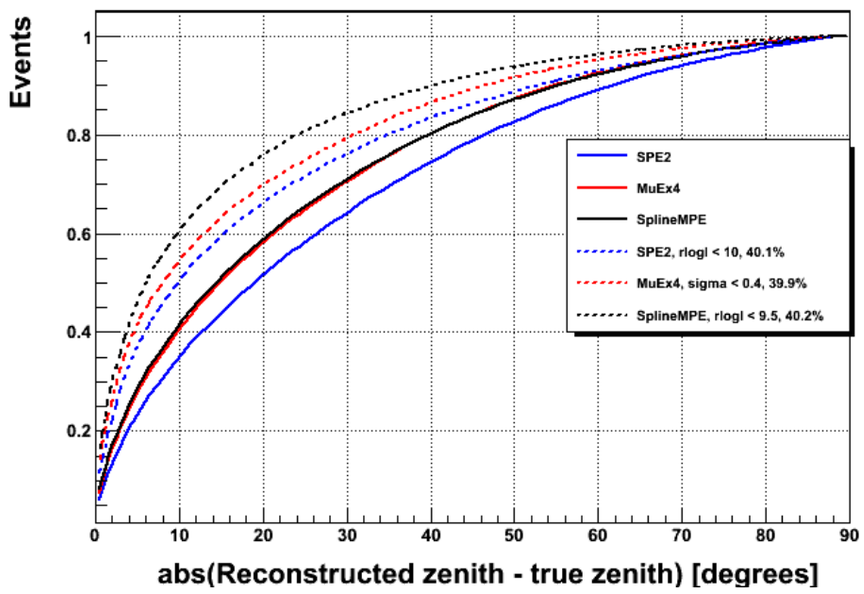
- Advanced fits with some quality cuts now achieve decent ang. resolution at oscillation E's
  - 12º-15º in zenith at 25 GeV
- Signal loss around 50%, but we are not statistically limited

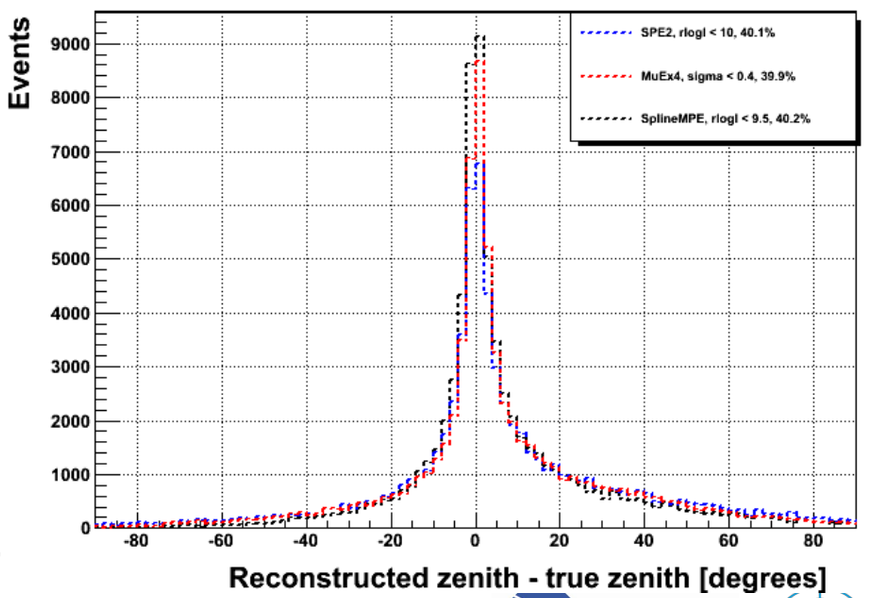
Results for only zenith

Meike de With





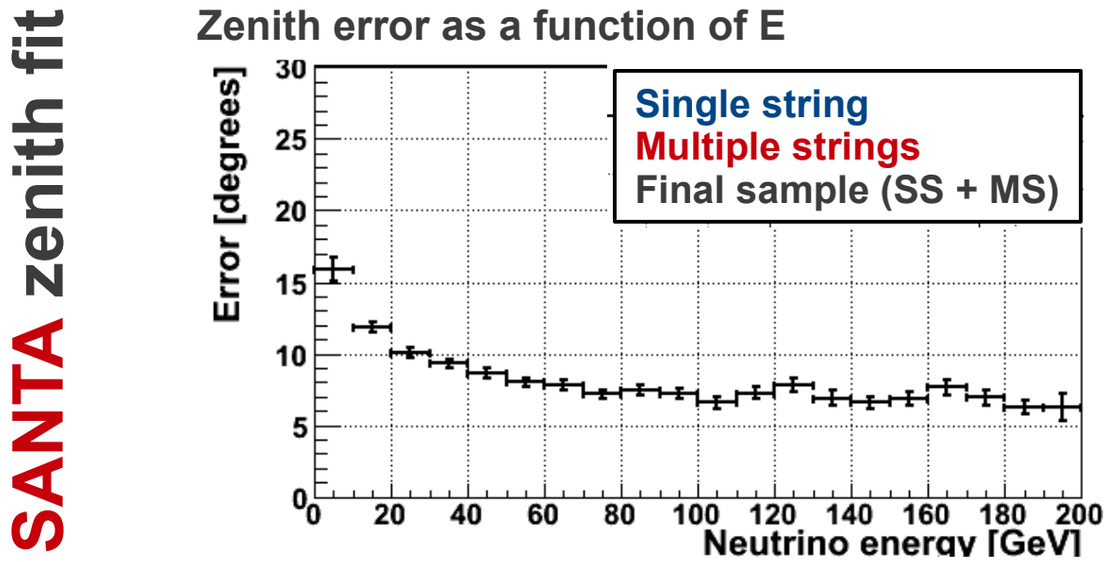




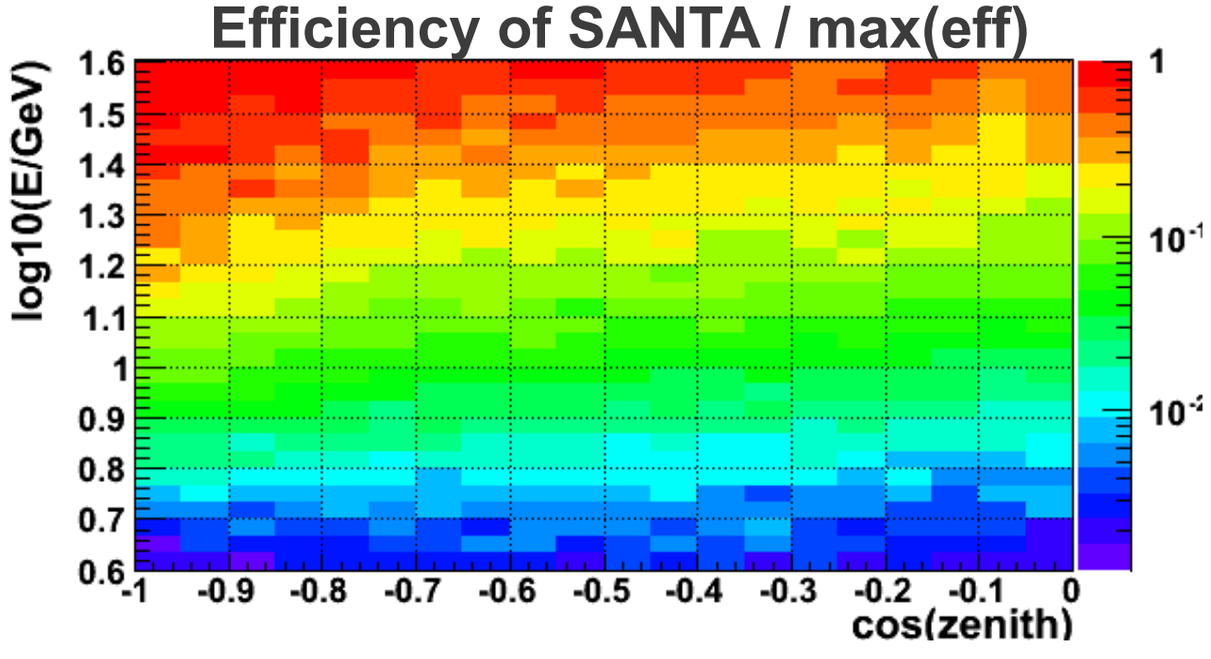
Directional Reconstruction (Muons)

Juan Pablo Yañez, Jürgen Brunner

- An alternative approach to fitting, focusing on zenith directly
  - Avoids direct dependence on ice modeling, but at the cost of lower efficiency



- Maintains resolution better than 10º down to 20 GeV *neutrino* energy, for the selected events



Track Length Reconstruction

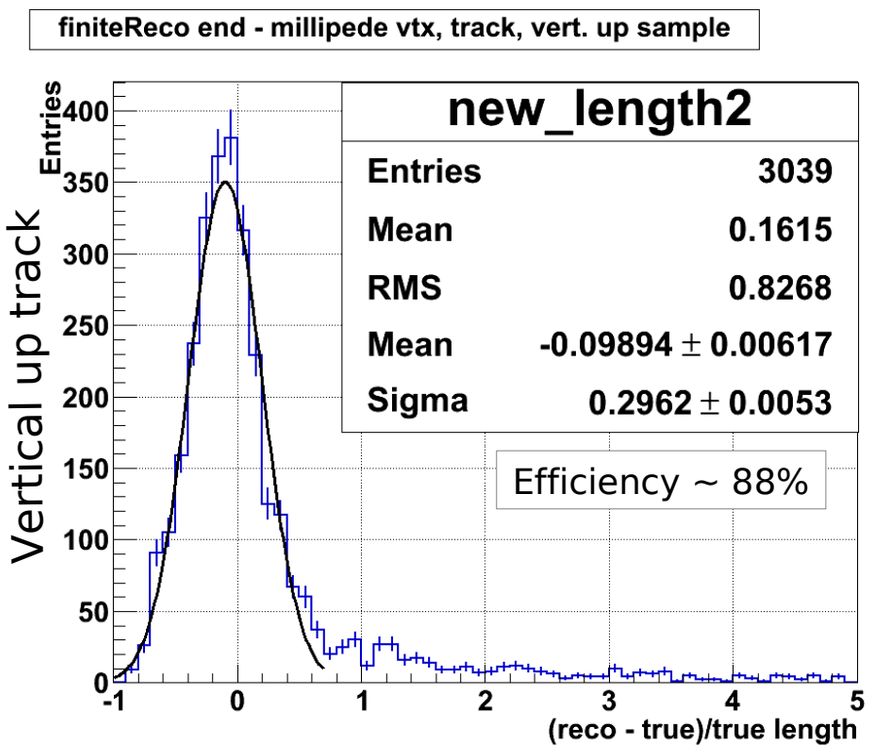
Andrii Terliuk

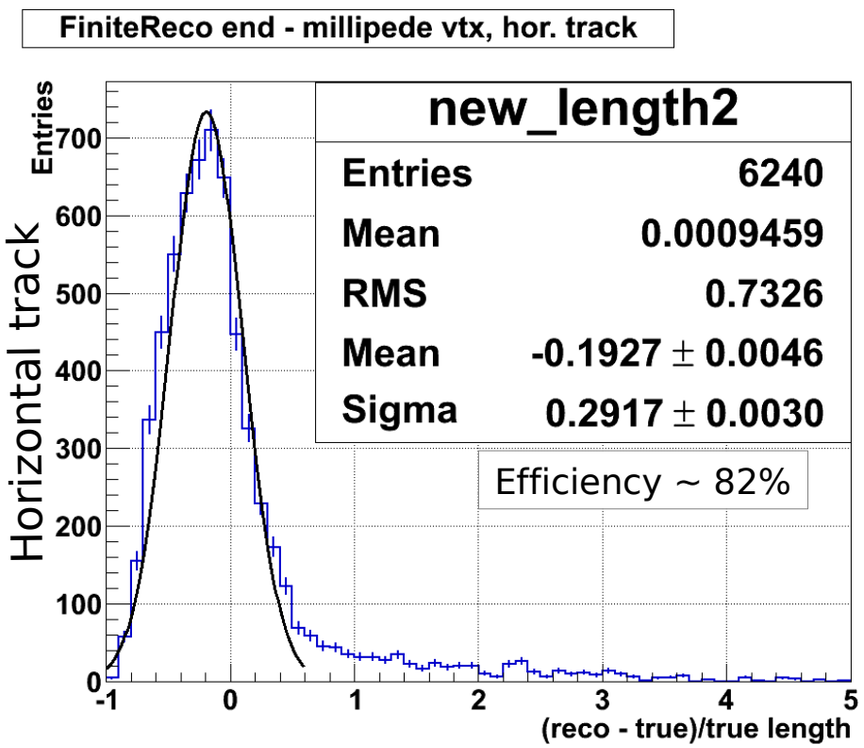
- Reconstructed neutrino energy depends largely on track length (min. ionizing tracks)
  - With correct trajectory, can achieve decent length reco. (~30% if vertex cascade small)
    - Better for vertical events, worse for larger cascades

Millipede/finiteReco combination

- Better end point estimation of finiteReco
- Better vertex reconstruction by millipede

} Length = finiteReco end – millipede vtx.





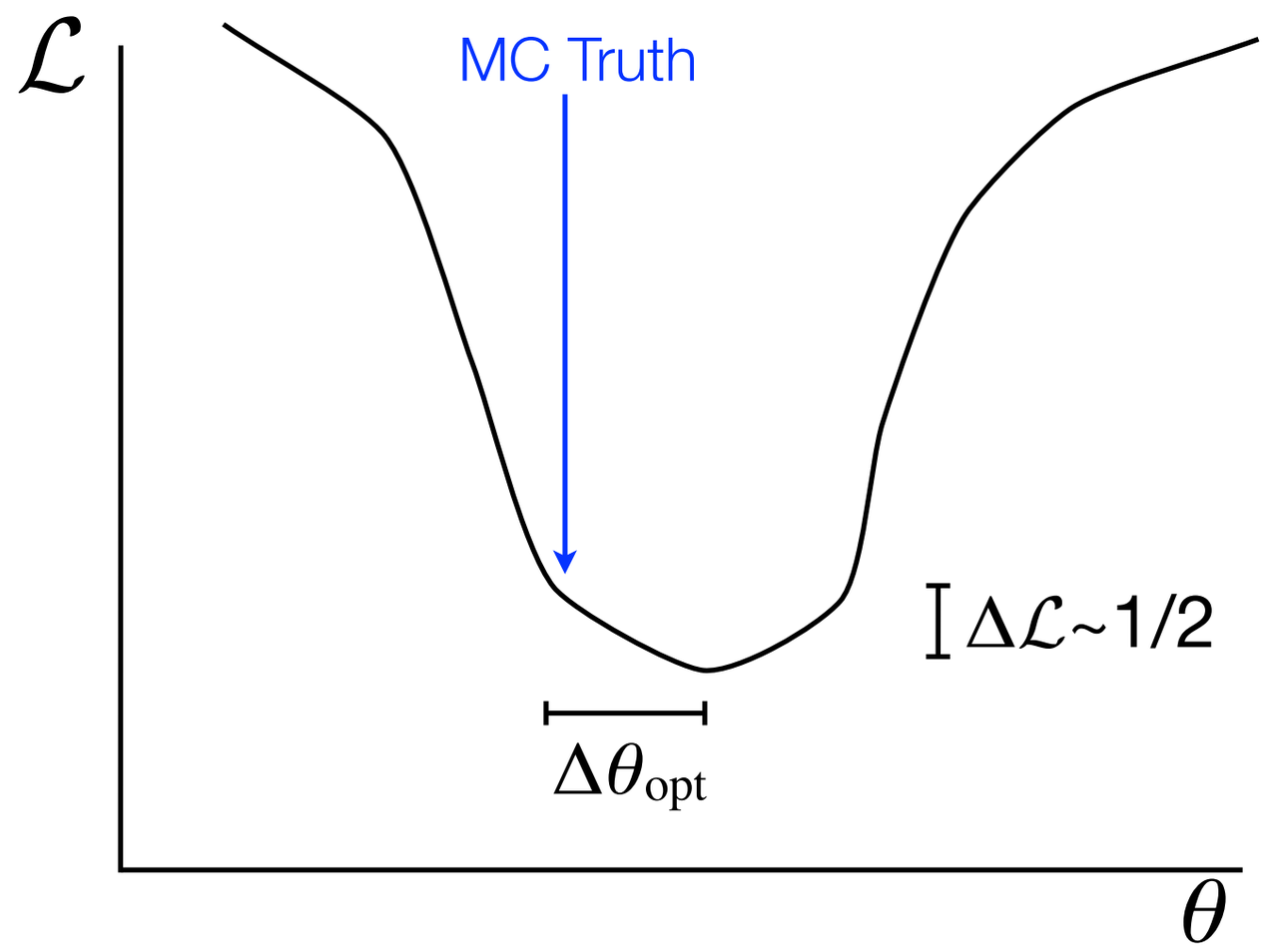
Better performance with better tails, but lower efficiency of the method.

Hybrid Reco

- At Penn State, we've been working on a full likelihood description of events, with the following assumptions:
  - One event in the detector at a time
  - Cascade vertex aligned with muon track, if one exists
  - Muons are minimum-ionizing, no stochastics
  - (Assume no physics hits expected more than 300 m from light sources, only noise)
  - Poisson likelihood based on spline-fitted light tables for muon track segments and cascades, full waveform information used, all DOMs included
  - Based on several years of work by Pat Toale, Sven Lafèbre, Chang Hyon Ha, Mike Prikockis, and most recently Matt Dunkman and Ryan Eagan

First Step: Validate Likelihood

- MC truth will not, in general, have the best likelihood
  - With a perfect likelihood description, the true values will be distributed with characteristic spread of 1σ around the extremum of the likelihood space
  - The corresponding errors in the parameters of interest represents the (optimal) resolution of the detector



- This presumes that the optimum associated with the MC truth is the global optimum
  - In the past, this has not been true
  - Manual scans of slices of likelihood space *suggest* this is now the case (for at least 90% of events), but it remains to be proven definitively

Intrinsic Resolutions

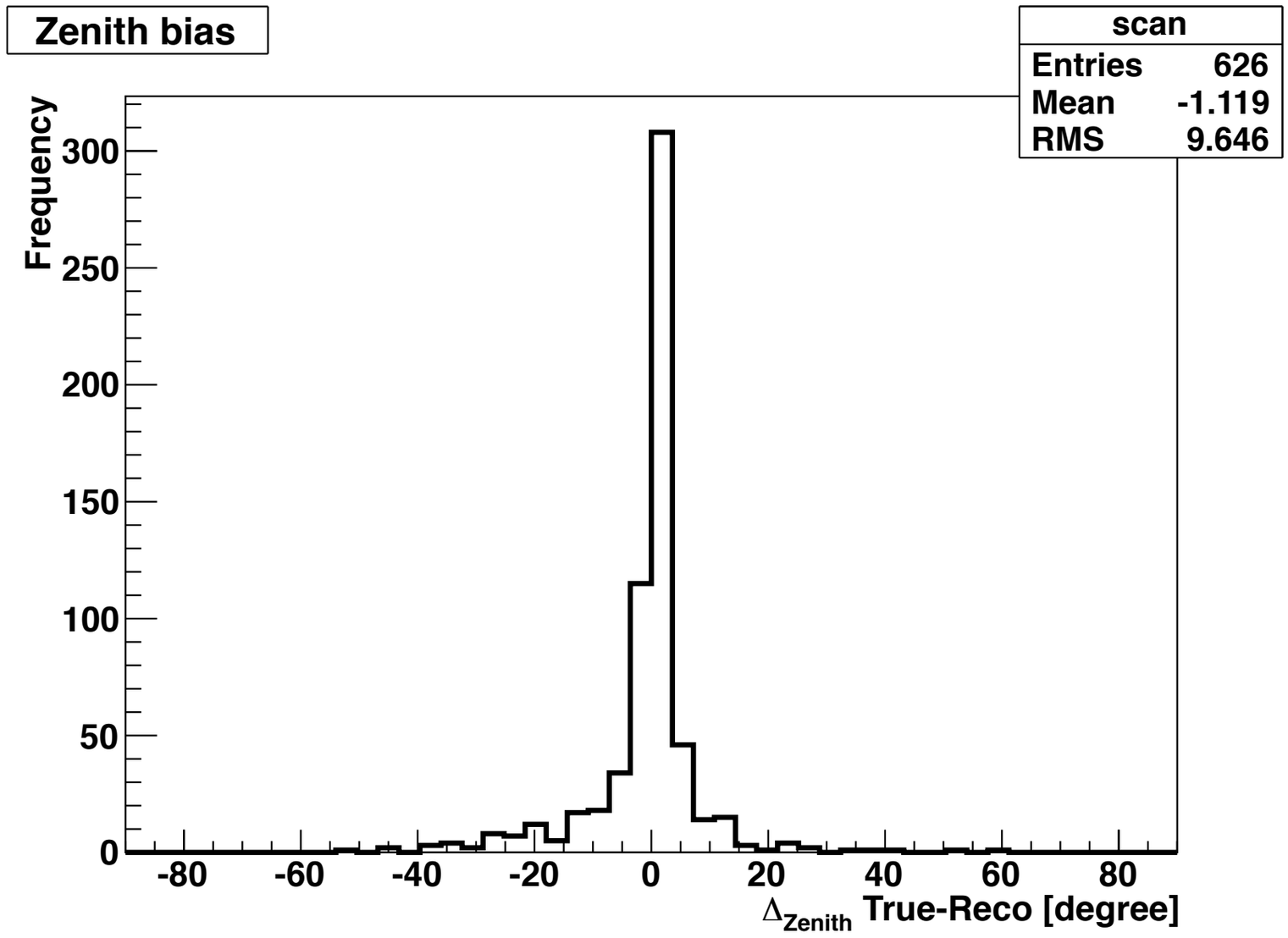
- In the following plots, we attempt to measure the intrinsic resolution (error between truth and likelihood optimum nearest the true values)
  - We run the full 8-parameter reconstruction, using the MC truth as the seed value
  - Not a perfect measure – minimizer can get stuck or not find the likelihood optimum, and conversely the optimum may not be global
- Nonetheless, this is a meaningful measure of detector performance
  - A detector incapable of measuring parameters would have a shallow likelihood space, and the 1σ range would be wide
  - We have verified that the minimizer is exploring the local space (50-100 steps)
  - If optima are global, sufficient application of computing power will allow us to approach arbitrarily close to the optimal resolution – a matter of event selection

Event Sample

- Charged current muon neutrino events, 10 GeV < E_ν < 100 GeV
  - Hadronic cascade at interaction vertex included, but using generic nugen simulation, not full GEANT
- Neutrino interaction vertex within DeepCore
  - Radial distance less than 150 m of DeepCore central string (a bit larger than the detector radius)
  - Vertical position -200 m < z < -400 m (DeepCore DOMs range from -150 m to -500 m)
- More than 8 hits remaining after standard hit cleaning
- Recently squished a bug and reimplemented for speed, low statistics available at present

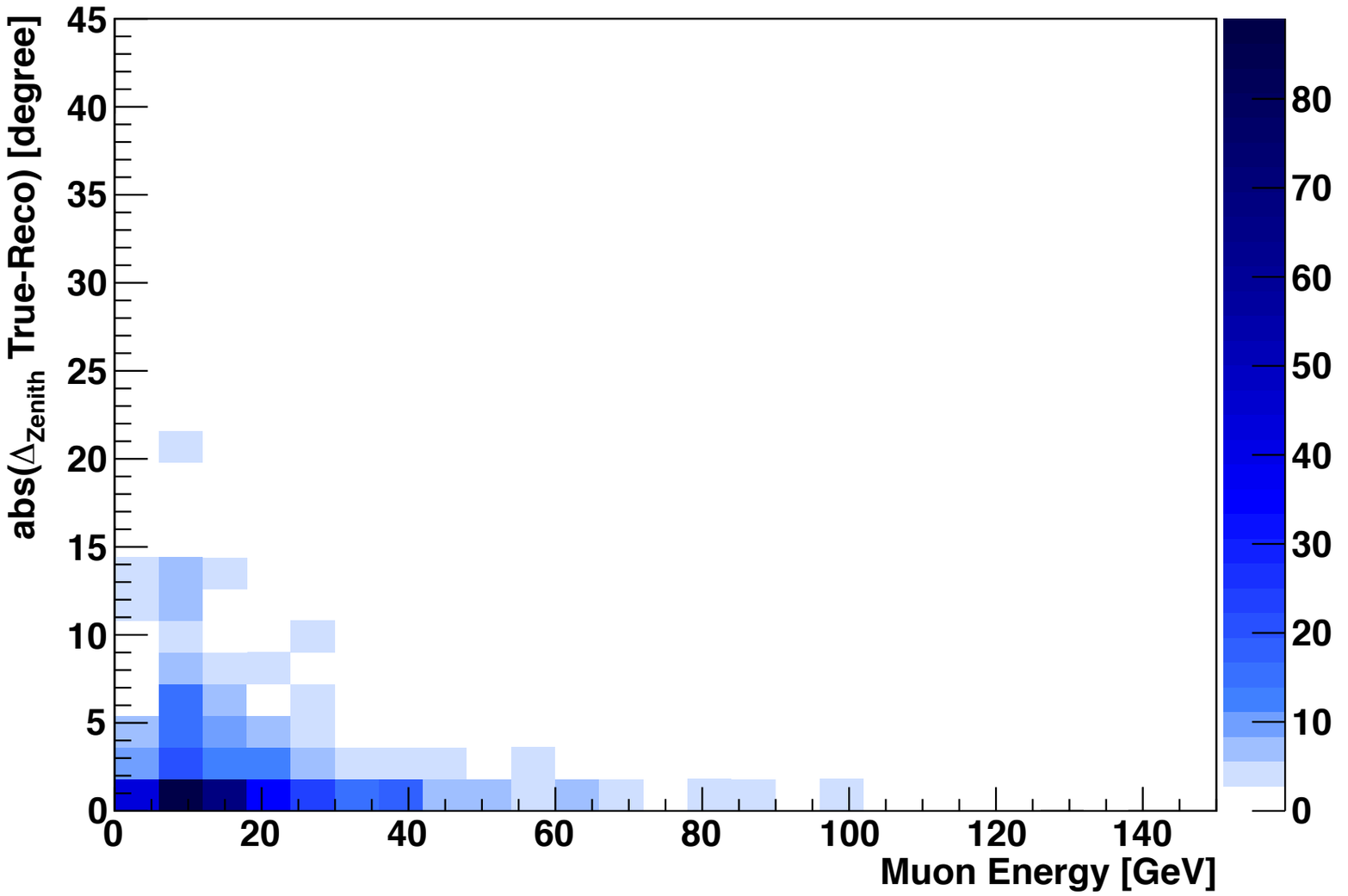
Zenith Angle Resolution

- Zenith angle is the relevant one for oscillation studies
  - Comparing to true muon direction, not the neutrino (kinematics significant at these energies)
  - Nearly unbiased, RMS resolution < 10°
  - Azimuthal resolution worse, due to asymmetric spacing (72 m between strings, 7 m between DOMs)



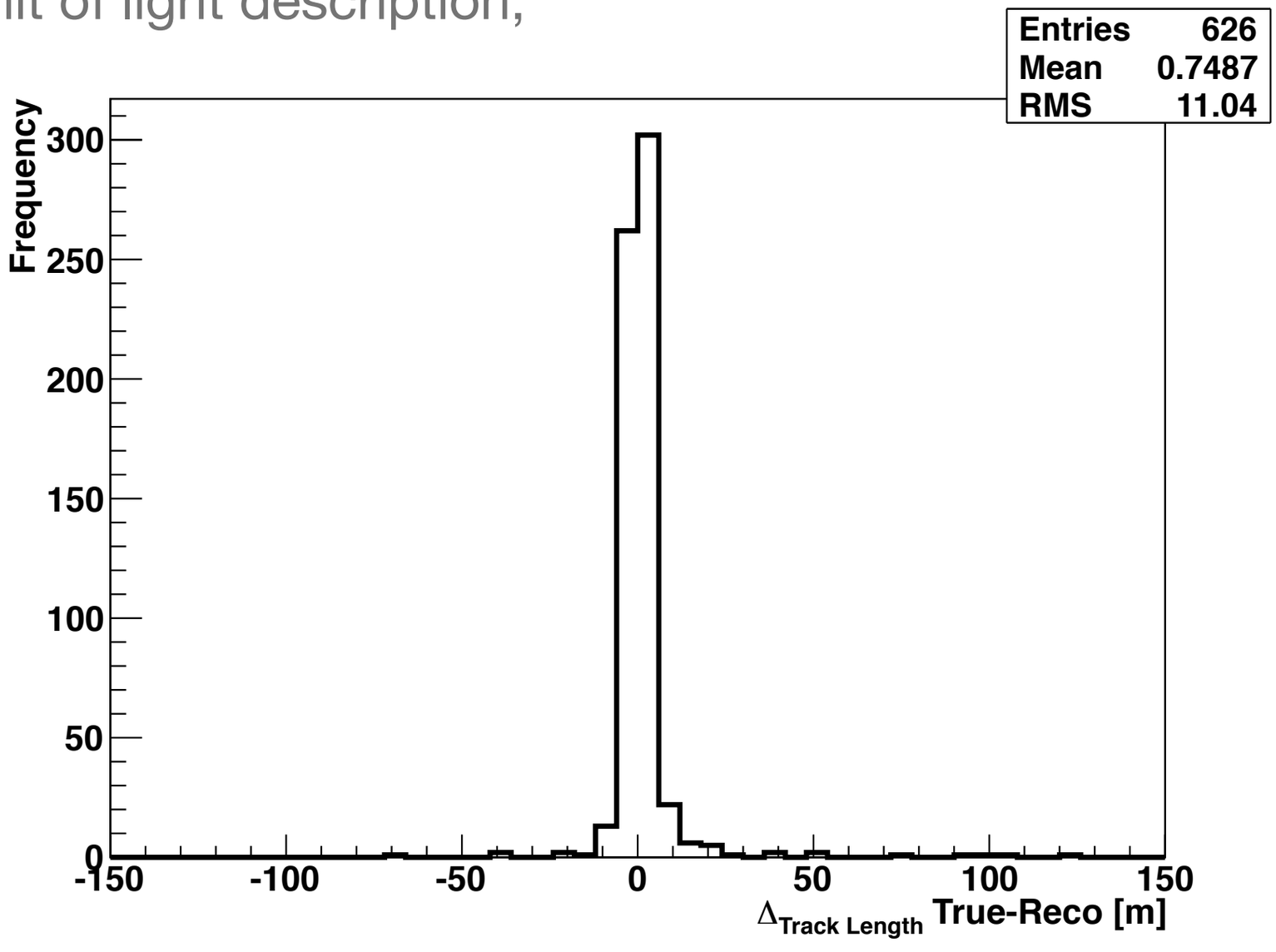
Energy Dependence

- In pre-bugfix version, median zenith resolution around 10º at lowest muon energy (1-10 GeV), down to <5º at 25 GeV
  - Neutrino energies a factor of 2 higher, on average (but with large spread)
  - Need more statistics to confirm with current version, but resolution looks good
  - Angular errors will likely be dominated by kinematics of neutrino interaction



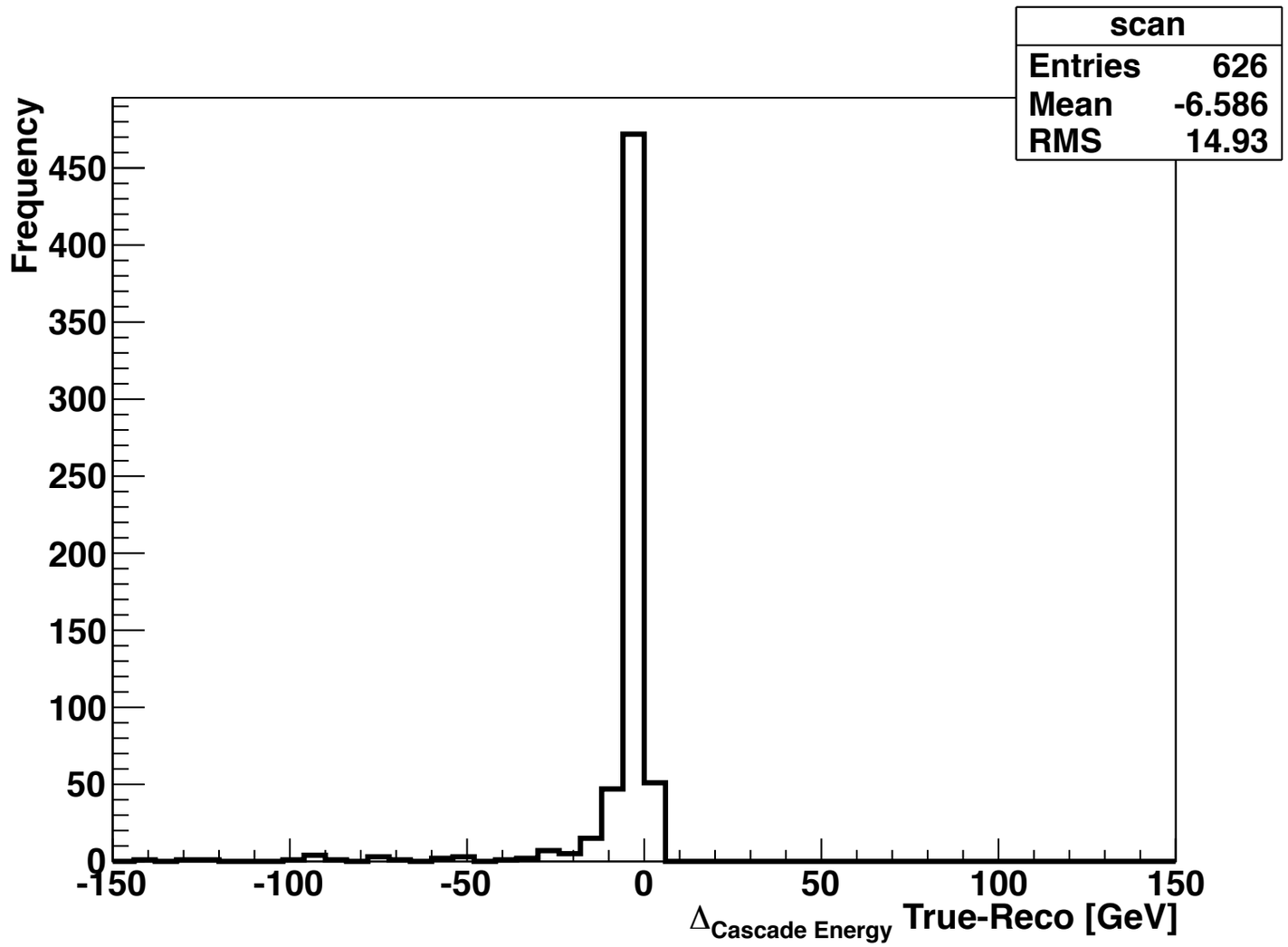
Track Length Resolution

- Unbiased, RMS resolution 11 m (equivalent to ~2.3 GeV)
  - Note: track segment granularity is 15 m!
  - Hitting numerical limit of light description, work to produce continuously-variable tables in progress



Cascade Energy Resolution

- A tail to overestimated energy, RMS resolution 15 GeV
  - Relation to event parameters (position, Björken-y, etc.) unknown at present
  - Apparently the dominant component of the energy resolution
  - Can we improve resolution, or select events with better reconstructions?

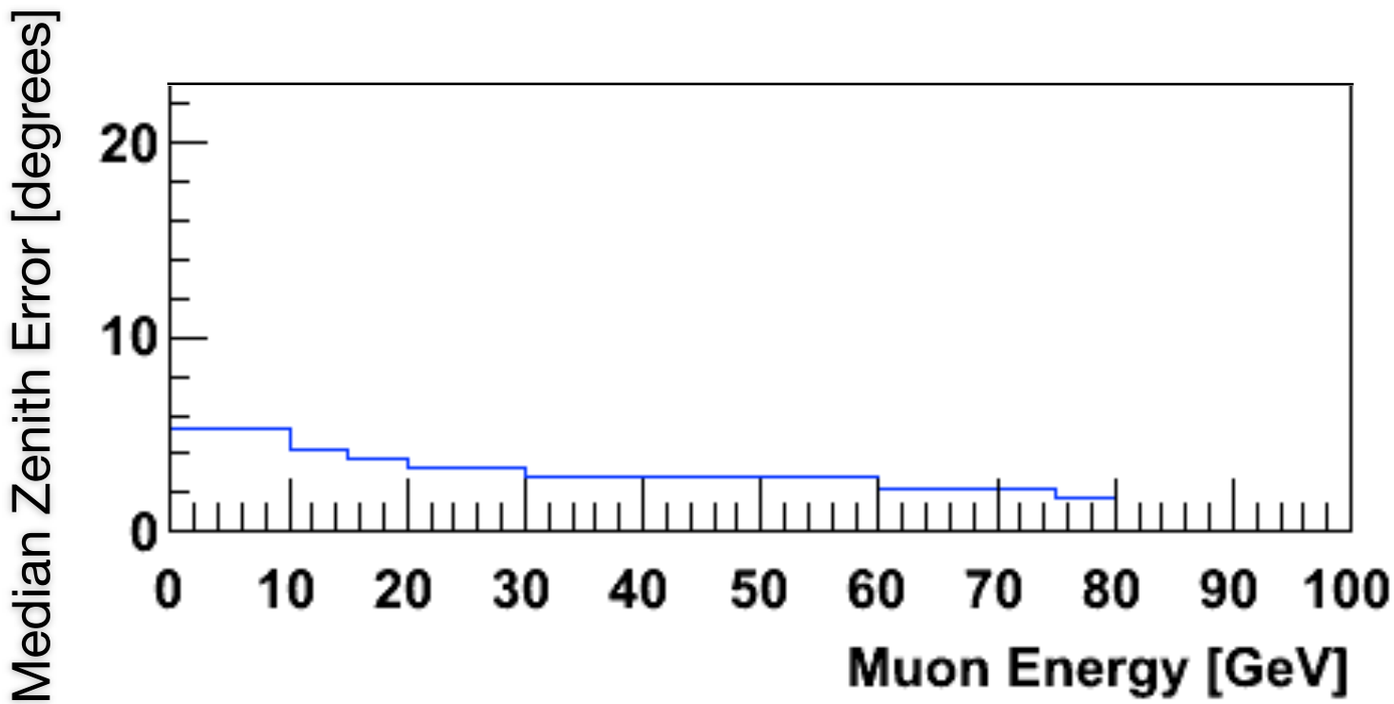


PINGU Reconstruction Studies

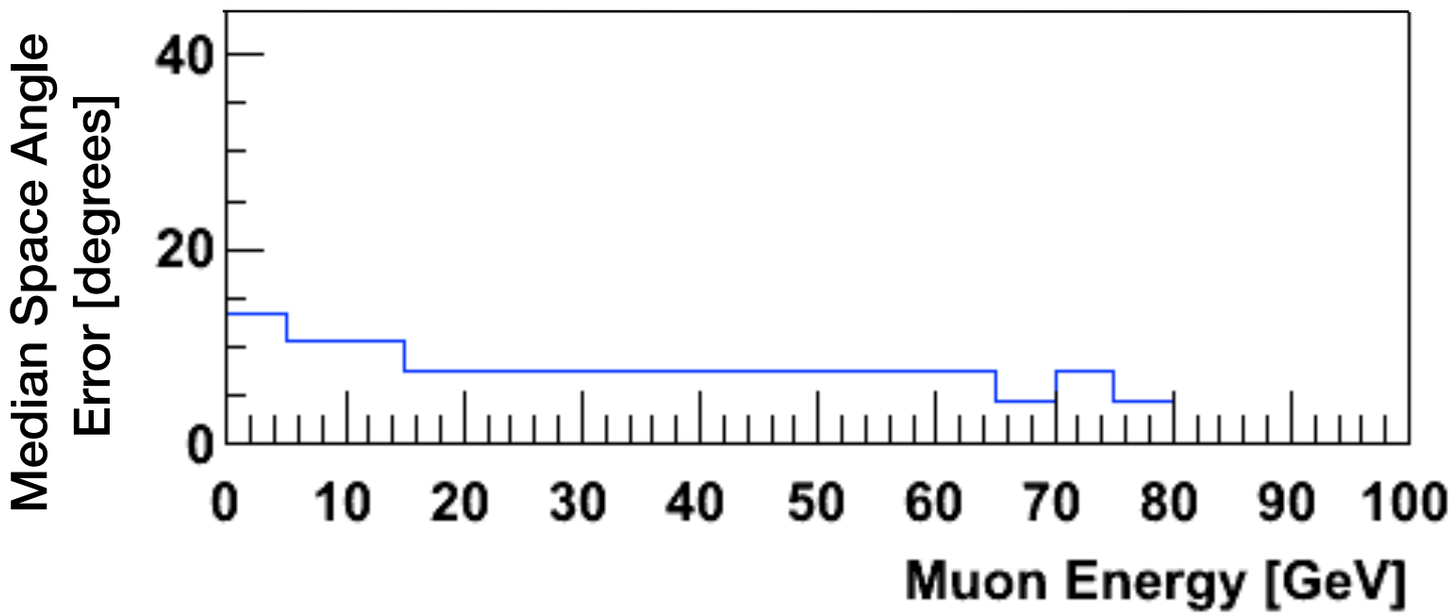
- Uses one candidate geometry, of several under discussion
  - 20 strings of 60 DOMs
  - 26 m inter-string spacing, 5 m DOM spacing
  - Full GENIE simulation, including hadronic vertex alignment and GEANT tracking of all charged particles
- Again, a study of intrinsic resolution theoretically possible
  - Assumes selection of events interacting within the volume
  - No data processing pipeline, just examination of the precision of the likelihood minimum around the MC truth
  - No estimate of efficiencies associated with background rejection
- So: preliminary!

PINGU Reconstruction Studies

- Errors relative to true muon direction, not neutrino direction



- Track length resolution similar to DeepCore
  - Limited by current tables, not detector



Outlook

- Full likelihood reconstruction looks promising
  - Intrinsic resolution is very good, and we *think* the global optima are in the right place
  - Current version running quickly (~1 second per event in DeepCore, 5-10 in PINGU)
  - Somewhat longer processing times expected with real seeds, and of course much longer if intensive scans of the likelihood space are required – but this would be an annoyance, not a fundamental problem
- Need to establish complete analysis pipeline
  - Optimization is difficult – likelihood falls away very quickly in all parameters, so accurate seeds for all parameters are needed
  - May require new minimizers or other tricks
  - Event selection efficiencies are still unknown (in DeepCore: 10-20%)