Muon Calibration for GCT

- Full Reconstruction: Rates and muon efficiency
- Degradation study

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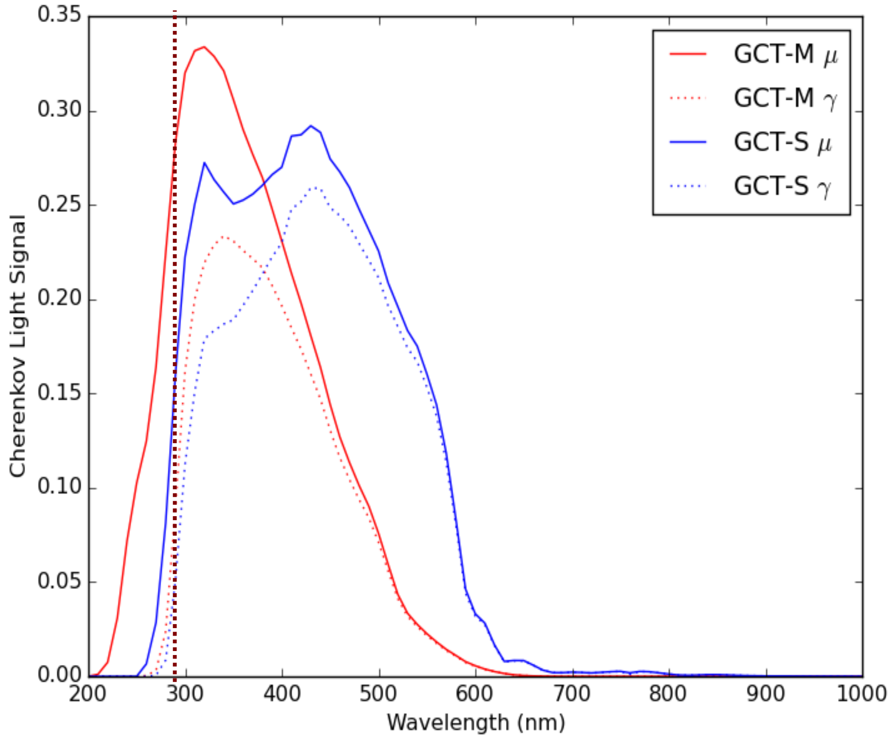
on behalf of Thomas Armstrong

Full Reconstruction - Overview

- Aim:
  Obtain Efficiency from modeling muon ring
  Obtain Expected Detection Rate
- Using Corsika, sim_telarray, read_hess and custom analysis code
- Configurations
  - GCTM: GCT using a camera with MaPMs
  - GCTS: GCT using a camera with SiPMs
  - Both available with most recent corsika_simtel package

Optical Efficiency

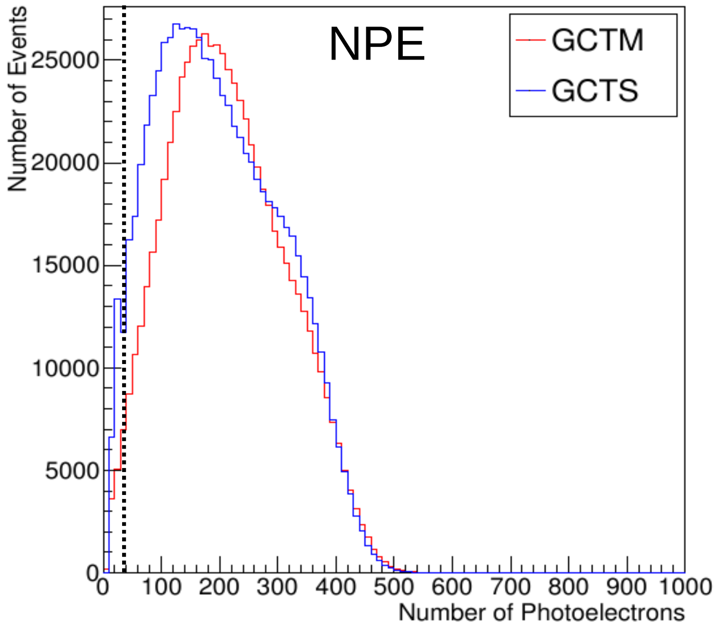


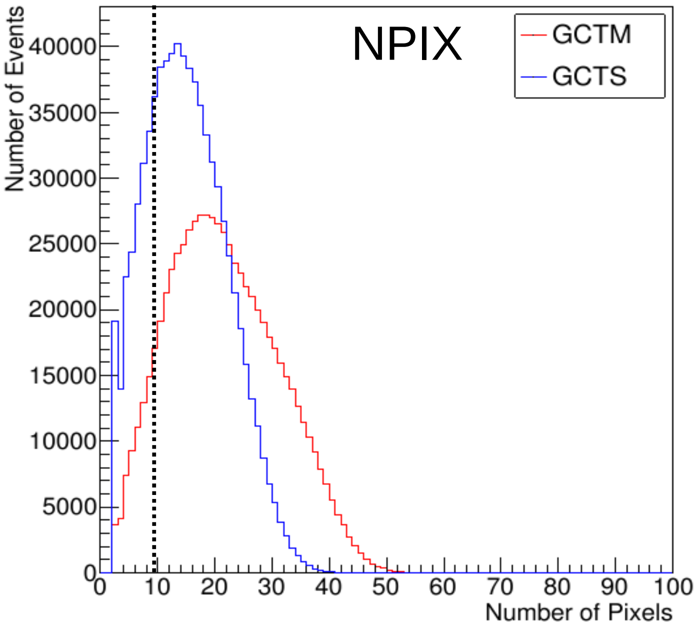
- Current configuration for GCTM fails requirement **B-xST-1500**
- Contribution bellow 290 nm equates to 14.66% (Needs to be bellow 5%)
- Possible to use non UV enhanced coating for MaPM
  - Need to redo analysis using new PDE
- GCTS: 2.72%, meets requirement

Simulated Data

- Simulated Site: Paranal
- Particle: μ^-
- Number of events: 1e6
- View cone: 0 – 4.7^o
- Maximum impact radius: 4.4 m
- Energy Range: 10 – 1e3 GeV
- Energy Spectrum: -2

Initial Cuts





- Use different tail cuts for each configuration
  - GCTM: 3,6
  - GCTS: 4,8
- Minimum number of p.e. In image: 40 p.e.
- Minimum number of pixels in image: 10

- **All preliminary and require further investigation**

Taubin Fit

- Using Taubin fit algorithm (same as ASTRI)
- Minimising function:

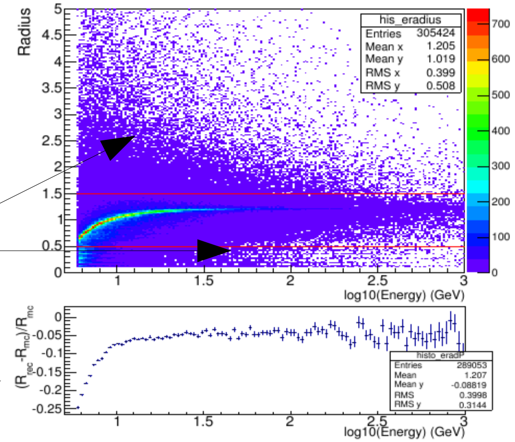
$$\mathcal{F}_T = \frac{\sum_i^n [(x_i - a)^2 + (y_i - b)^2 - R^2]^2}{4n^{-1} \sum_i^n [(x_i - a)^2 + (y_i - b)^2]}$$

- Obtains a best fit of a ring to image pixels, returning ring radius, ring centre and F_T
- Appears to be robust. Currently implemented in read_hess.

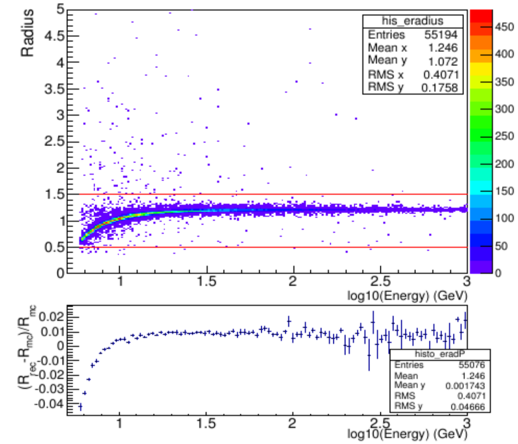
Post fit cuts

- Reconstructed Ring Radius
  - $0.5 < R < 1.5$
  - Not such a large effect as poorly reconstructed events are rejected by other cuts (p.e. and npix)
  - Resolution reasonably stable

No cuts

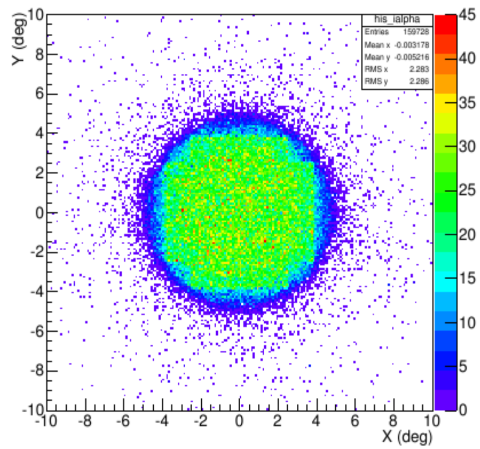


With cuts

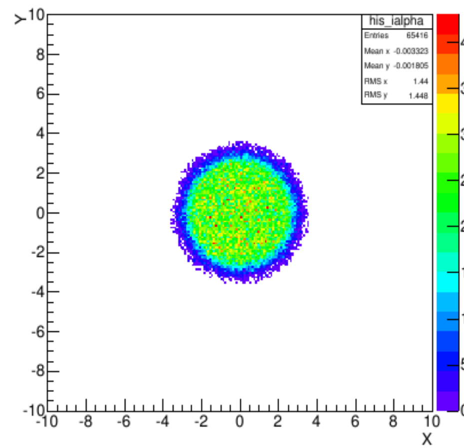


- Edge Cut
  - Removes events within 0.3° from camera edge: $(x^2+y^2)^{1/2} + R < R_{cam} - 0.3^o$
  - Removes large fraction of events
- Images are for GCTM

No Edge Cut

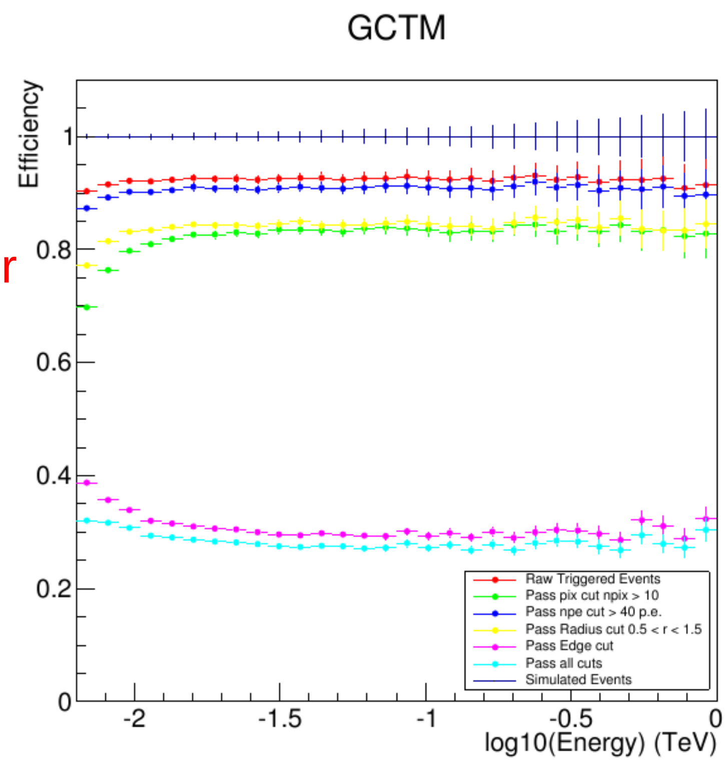


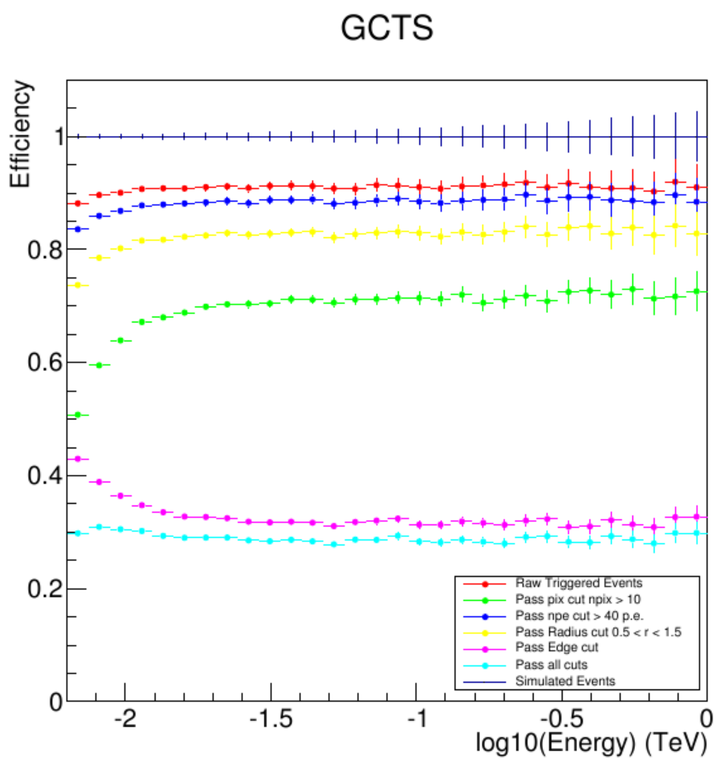
Edge Cut



Selection Efficiency

Raw Trigger
NPIX cut
NPE cut
Radius cut
Edge Cut
All Cuts

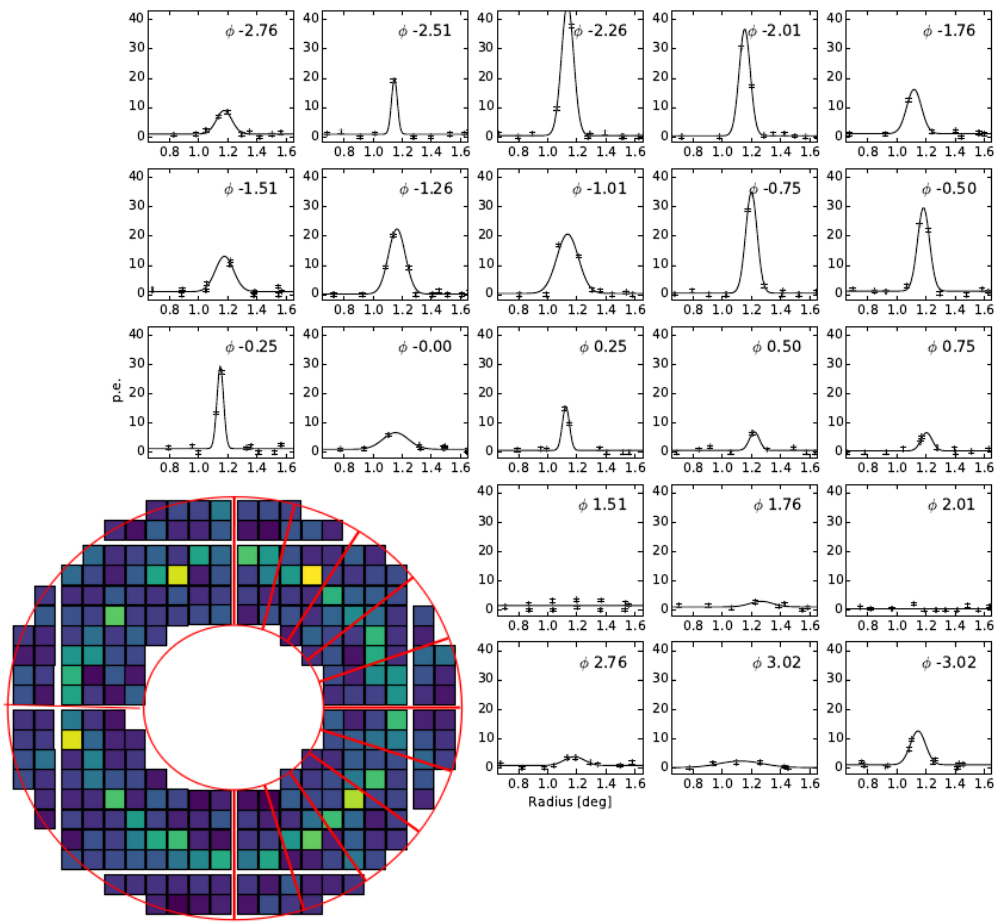




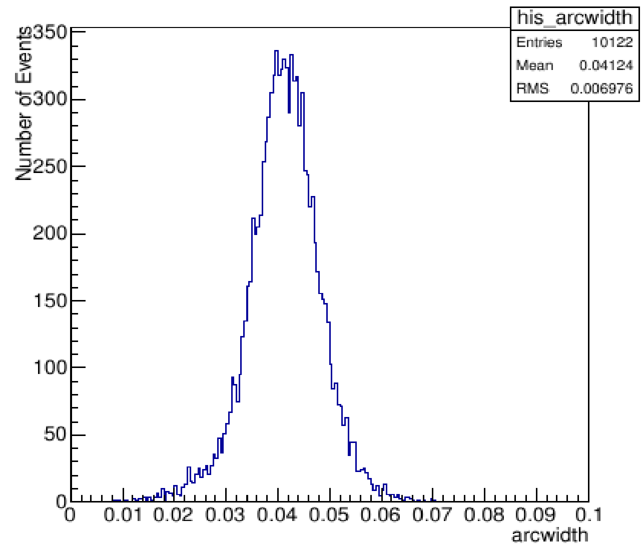
- **Only events landing within primary**
- Edge cut removes largest fraction events
- While cut on number of pixels effects GCTS more, both configurations end up with similar **total efficiency ~30%**

Arc Width and PSF

Binning of pixels along ring

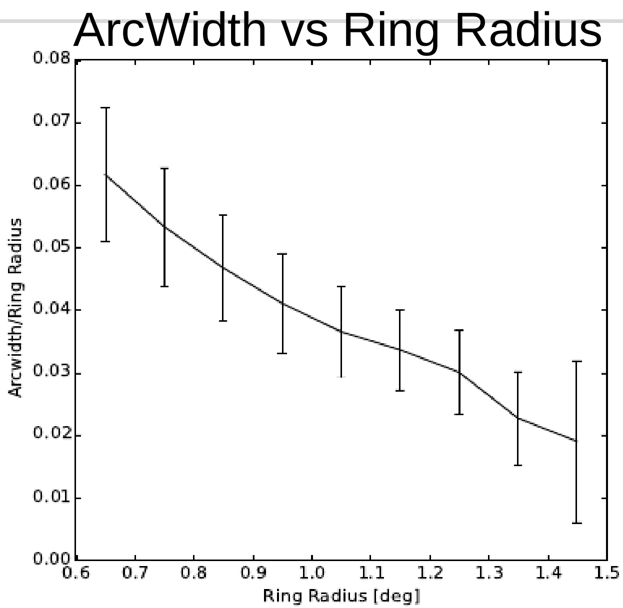


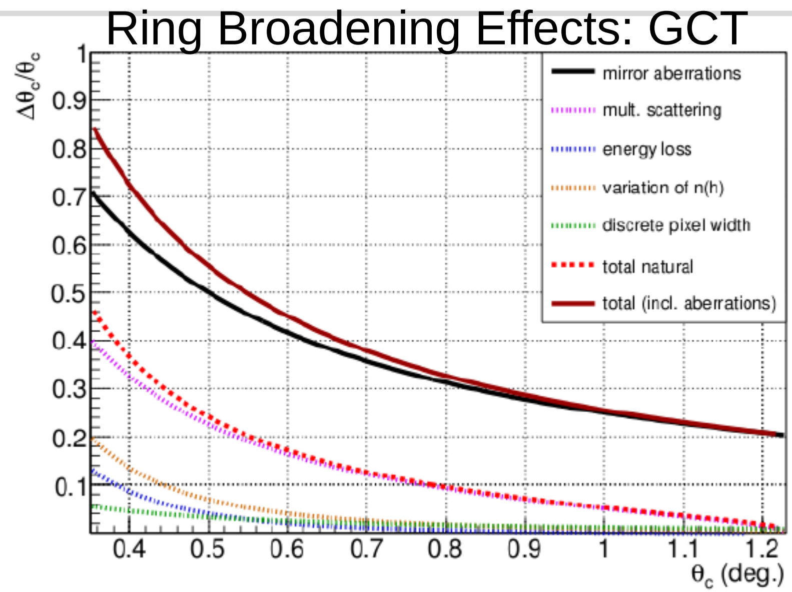
Distribution of ArcWidth



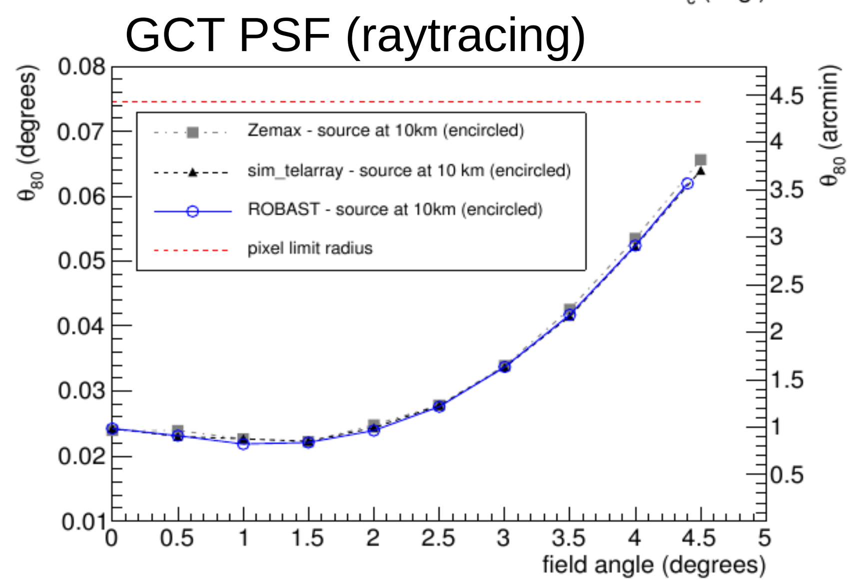
- All pixels within +/- 0.26^{o} of ring are taken
- Binned according to ring radius
  - Nbins=25 x (R_{reco}/1.2)
- Apply Gaussian fit radially to each bin to obtain σ = ArcWidth

Arc Width and PSF





- Considered ArcWidth as function of ring radius
- For larger rings, mirror aberrations becomes main factor => better representation of PSF
- At larger radii, ArcWidth comparable for on axis PSF determined from ray tracing



Impact Distance and Efficiency

Impact distance and efficiency are obtained from fitting the following function
To the modulation of light along the muon ring:

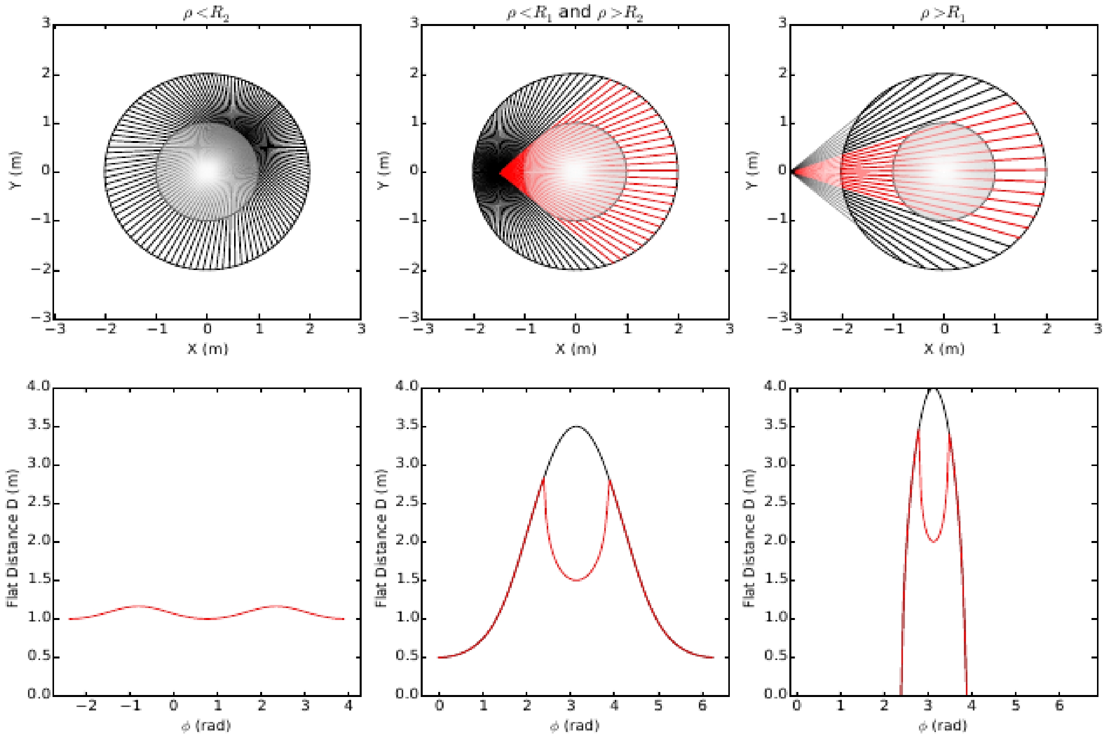
$$\frac{dN_{obs}}{d\phi}(\rho, \phi_o) = \frac{\alpha}{2} \cdot \frac{\omega}{\theta_c} \cdot sin(2\theta_c) \cdot \boxed{D(\rho, \phi - \phi_o)} \cdot I \cdot T \cdot \epsilon_\mu$$

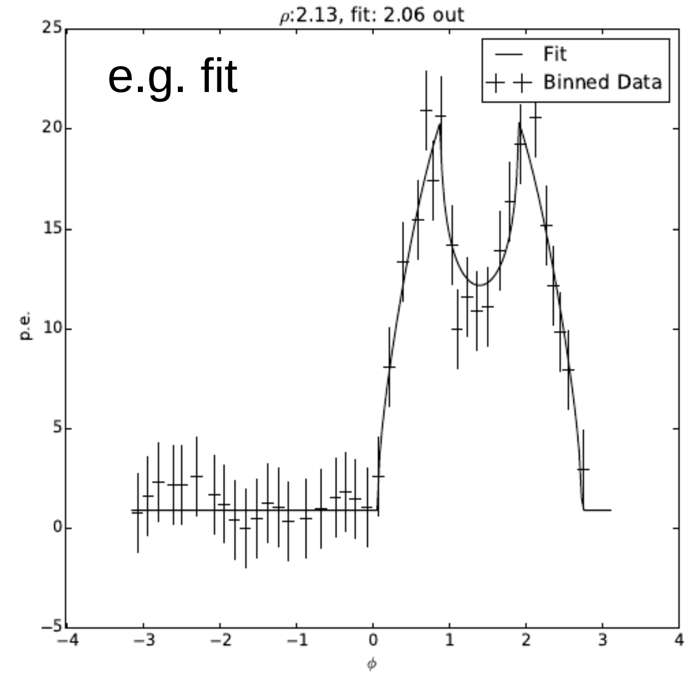
- Represents the radial path length across the mirror from which the muon light is focused
- For 2 mirror system, need to account for secondary. Defining: C=D-D'

Where C is now a complicated case function...

$$C = \begin{cases} R[\sqrt{1-(\rho/R)^2 sin^2(\phi)} + (\rho/R)cos(\phi)] - R'[\sqrt{1-(\rho/R')^2 sin^2(\phi)} + (\rho/R')cos(\phi)] & \text{for: } \rho < R' \text{ and } d > R' \text{ and } d < R \\ R[\sqrt{1-(\rho/R)^2 sin^2(\phi)} + (\rho/R)cos(\phi)] & \text{for: } R' < \rho < R \text{ and } d > R' \\ R[\sqrt{1-(\rho/R)^2 sin^2(\phi)} + (\rho/R)cos(\phi)] - 2R'\sqrt{1-(\rho/R')^2 sin^2(\phi)} & \text{for: } R' < \rho < R \text{ and } d \leq R' \\ 2R\sqrt{1-(\rho/R)^2 sin^2(\phi)} & \text{for: } \rho > R \text{ and } d > R' \text{ and } d < R \\ 2R\sqrt{1-(\rho/R)^2 sin^2(\phi)} - 2R'\sqrt{1-(\rho/R')^2 sin^2(\phi)} & \text{for: } \rho > R \text{ and } d \leq R' \\ 0 & \text{for: } \rho > R \text{ and } d > R \end{cases}$$

Impact Distance and Efficiency





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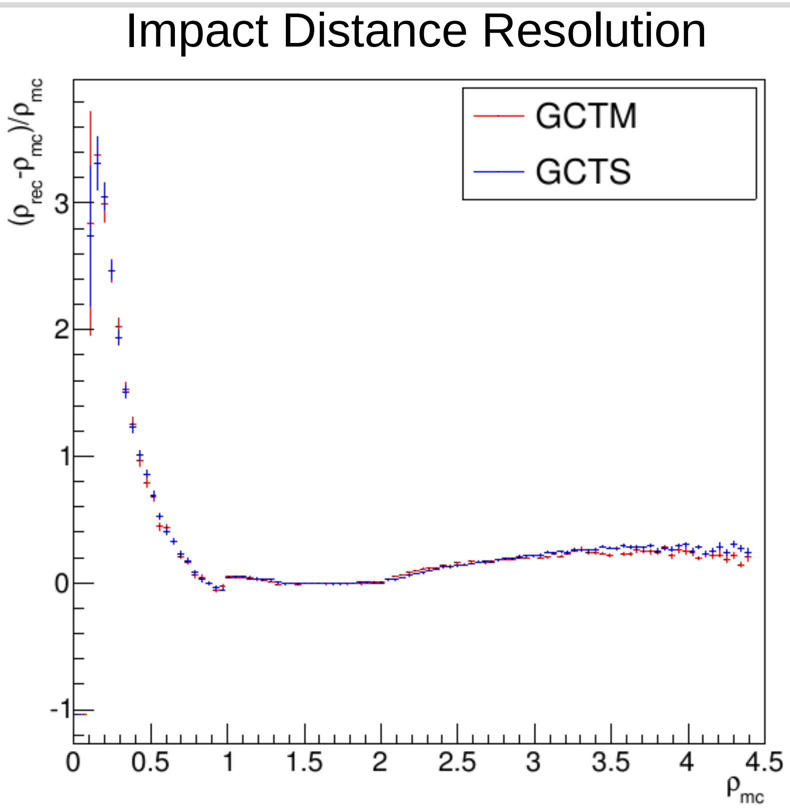
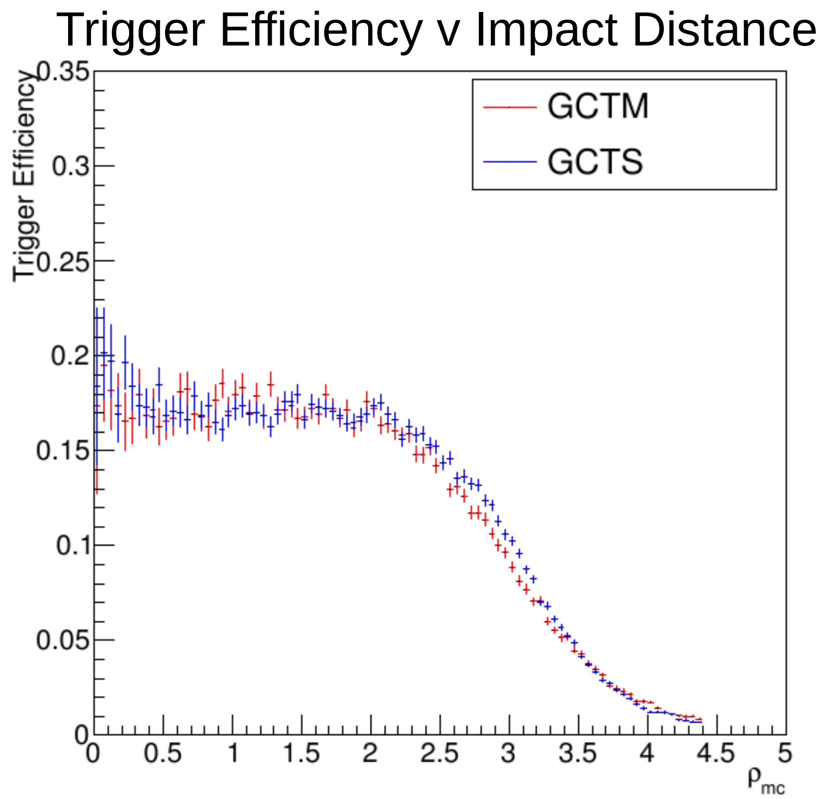
\end{cases}
$$

Impact Distance Resolution





Impact Distance Resolution

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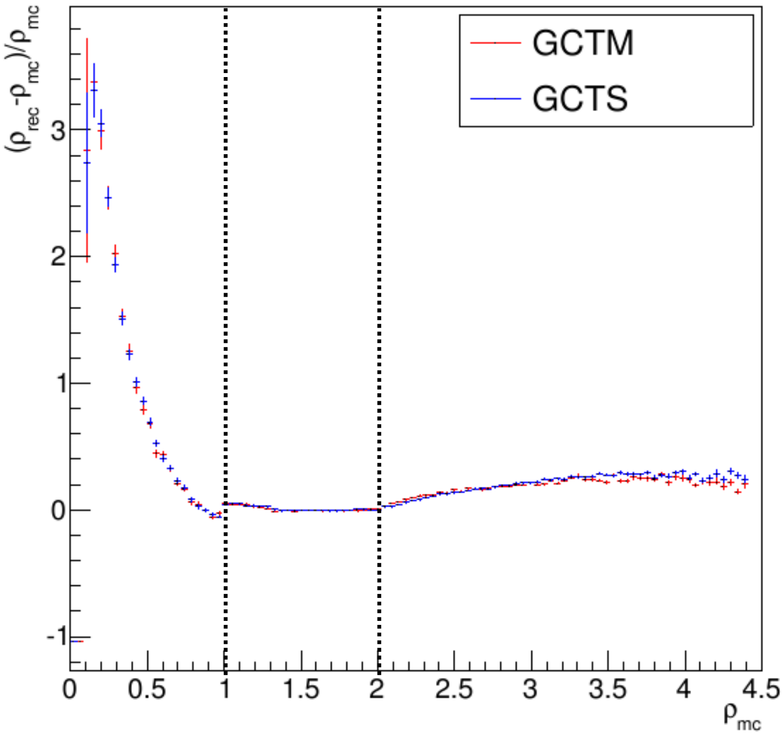
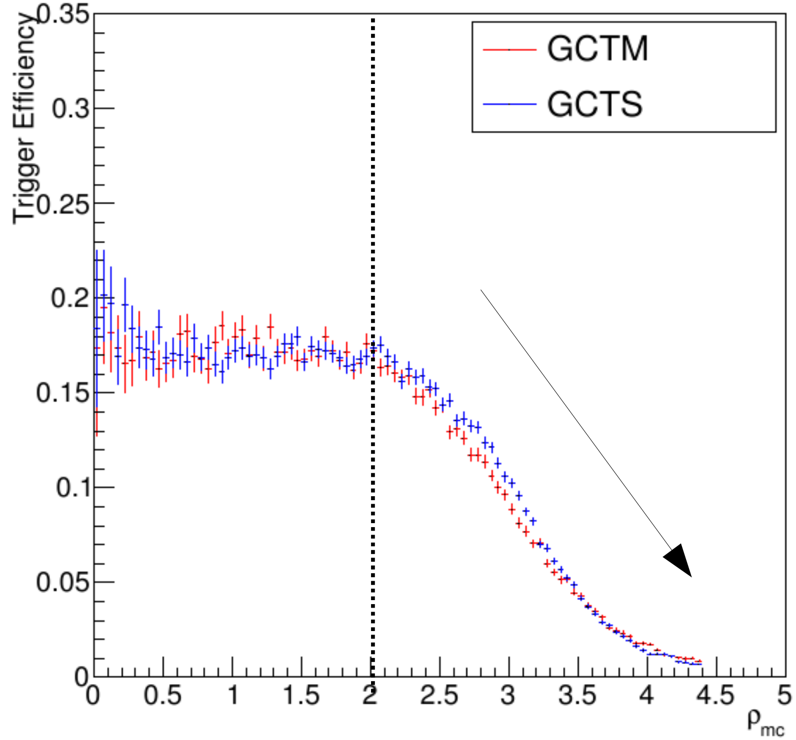
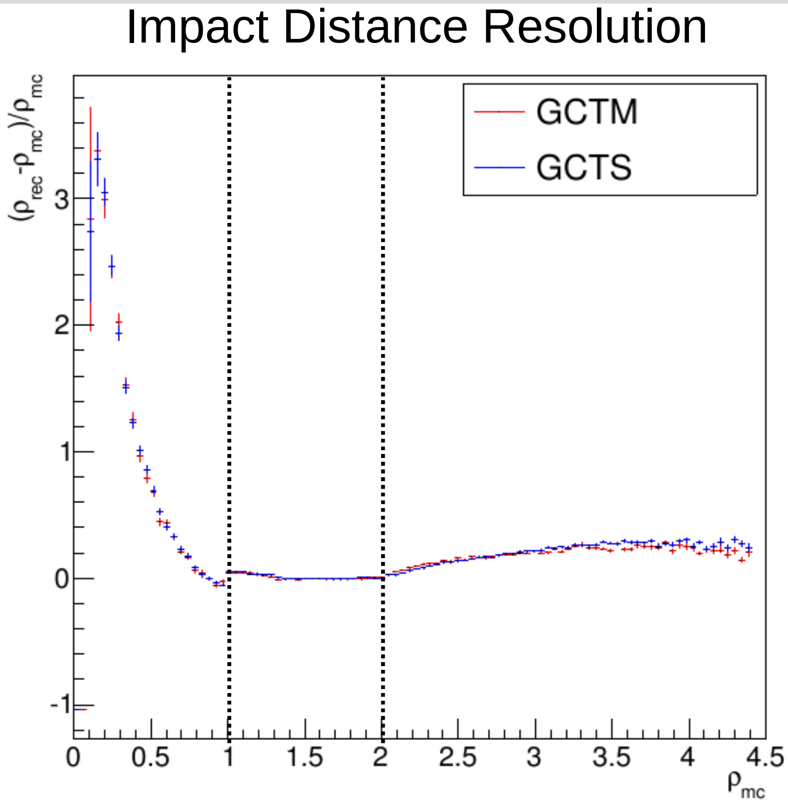


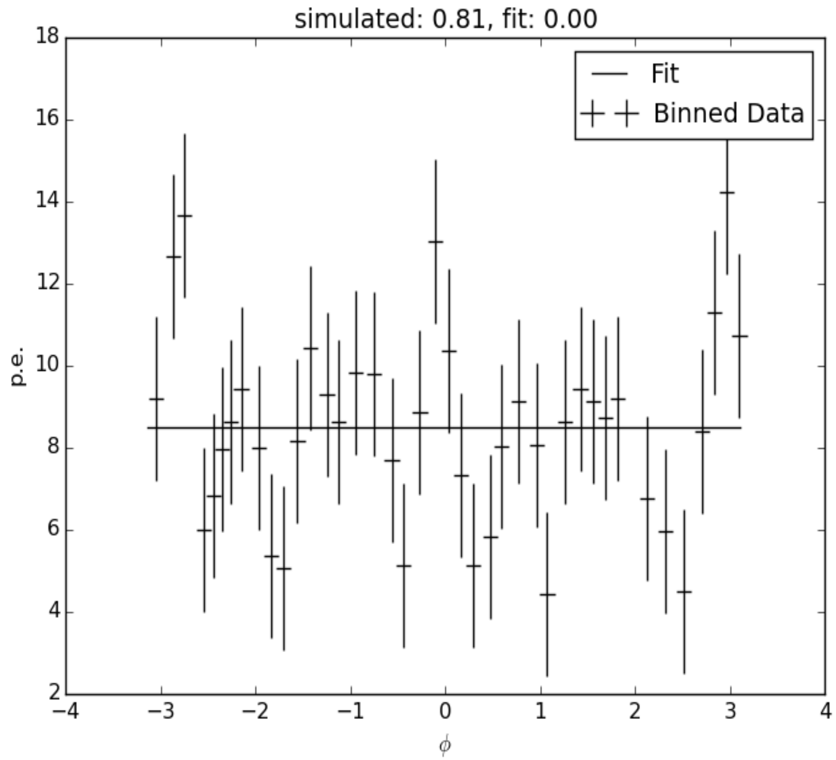
Trigger Efficiency v Impact Distance



- Difficulty fitting rings that fall within the radius of secondary
  - May have a hard time getting around this, secondary does block a lot of light....
- Expected drop in trigger efficiency beyond the radius of the primary
  - **Apply cut to remove events landing outside of the primary mirror.**

Impact Distance Resolution





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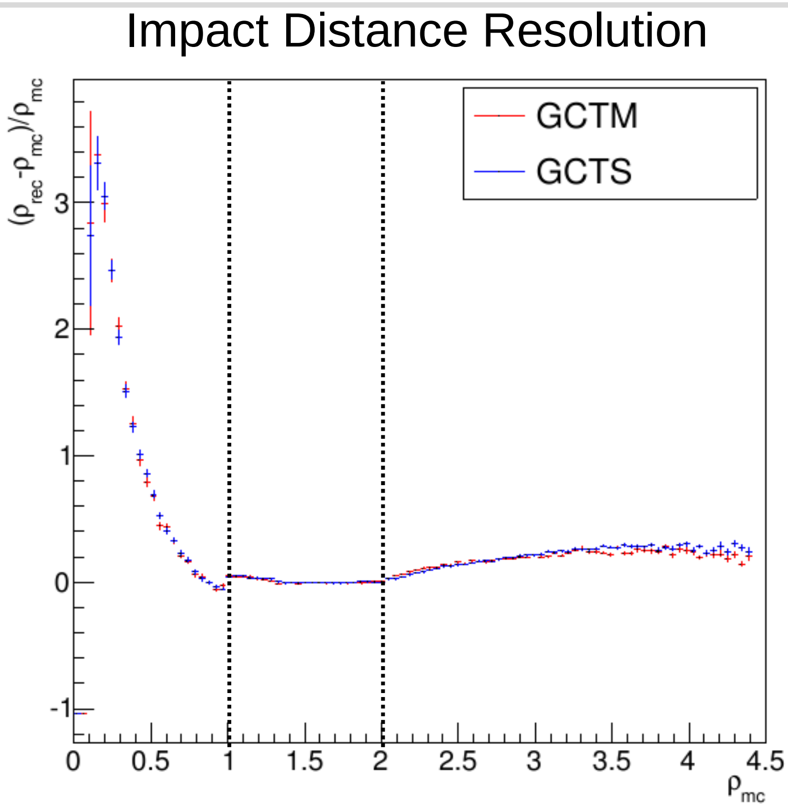

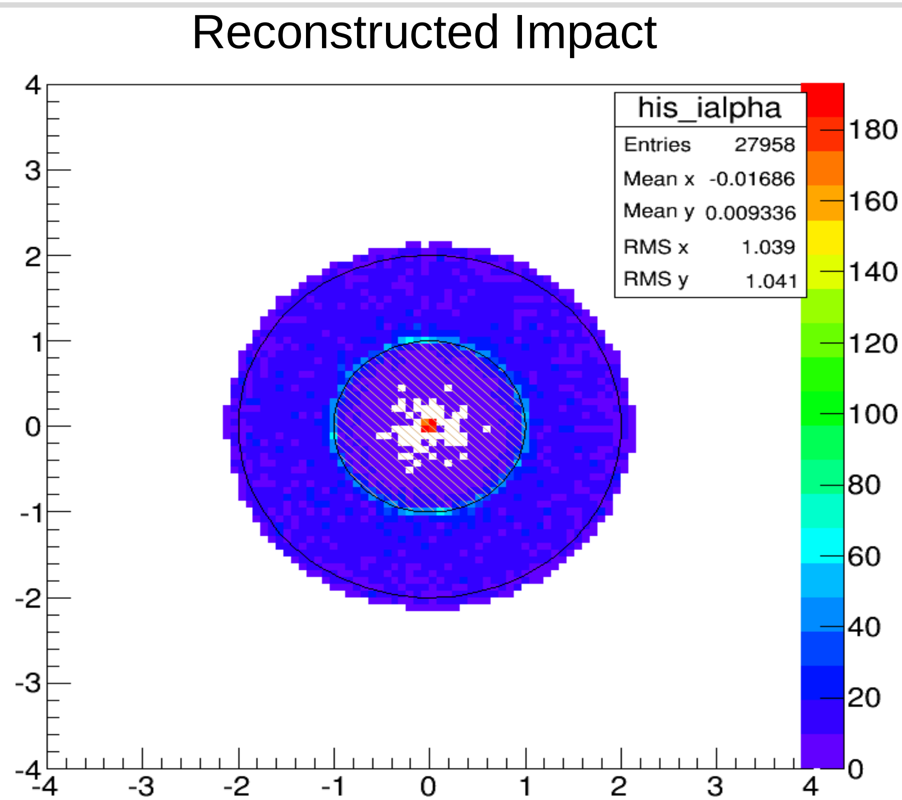

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Muon Efficiency

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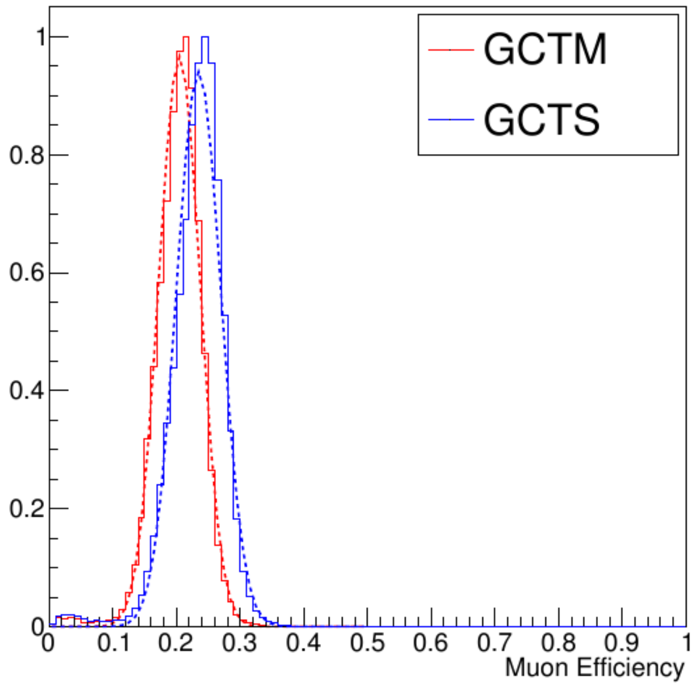
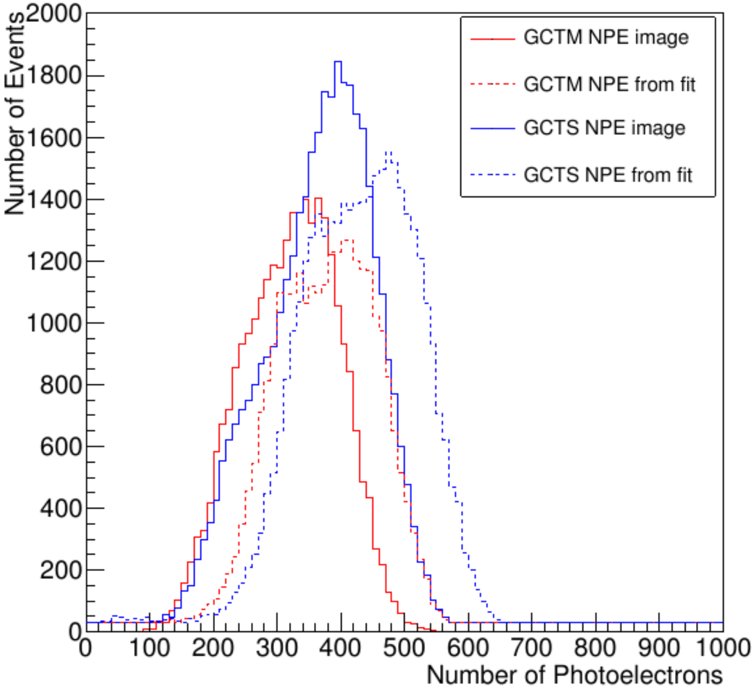
Muon Efficiency



GCTM: ε_{reco} = (20.5±3.25)%

GCTS: ε_{reco} = (23.5±3.50)%

Image size, observed v reconstructed



Fit currently overestimates the image size

Bias in Efficiency

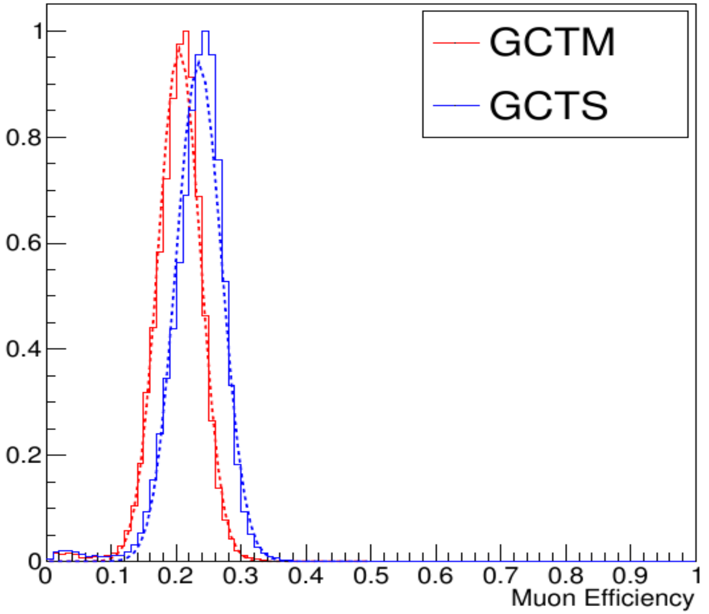
Compare reconstructed efficiency to “theoretical” derived from optical efficiency (from configuration parameters)

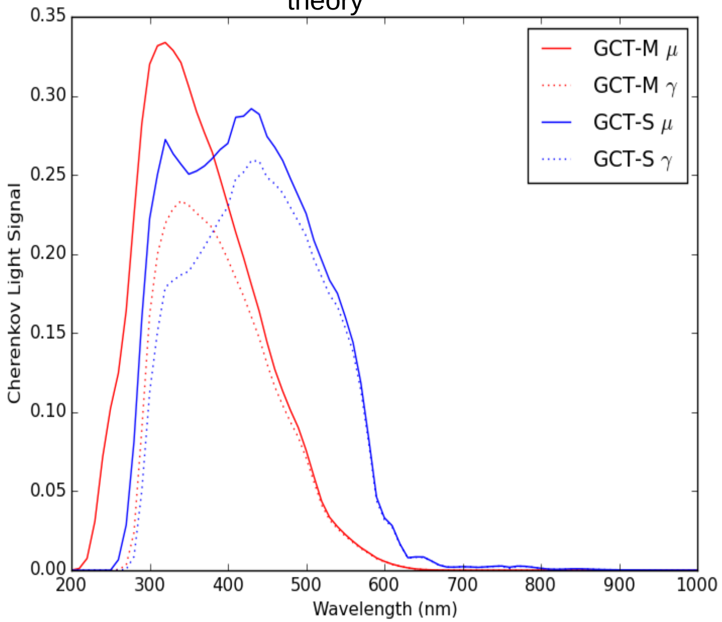
GCTM: ε_{reco} = (20.5±3.25)%

GCTS: ε_{reco} = (23.5±3.50)%

GCTM: ε_{theory} = 17.68%

GCTS: ε_{theory} = 25.06%





Therefore there is currently a bias introduced in the analysis (or inherent to the design)

Expected Rate

Using muon spectrum defined in muon document, calculated the expected rate of “good” muons (i.e. Passing all cuts)

Max simulated impact dist

Muon Selection efficiency

$$ER_{good} = \int_0^{\inf} F(E,h) \cdot R^2_{\text{imp}} \cdot \pi \cdot 2\pi \cdot (1 - \cos(\theta_{\text{max}})) \cdot \eta(E) dE$$

Muon flux

Size of simulated viewcone

Applying this to results obtained so far, the expected rate for both GCTM and GCTS equates to: **~0.42 Hz**

Need ~400 events to obtain an RMS error of less than 20% on ε.
Time for observations => ~16 min

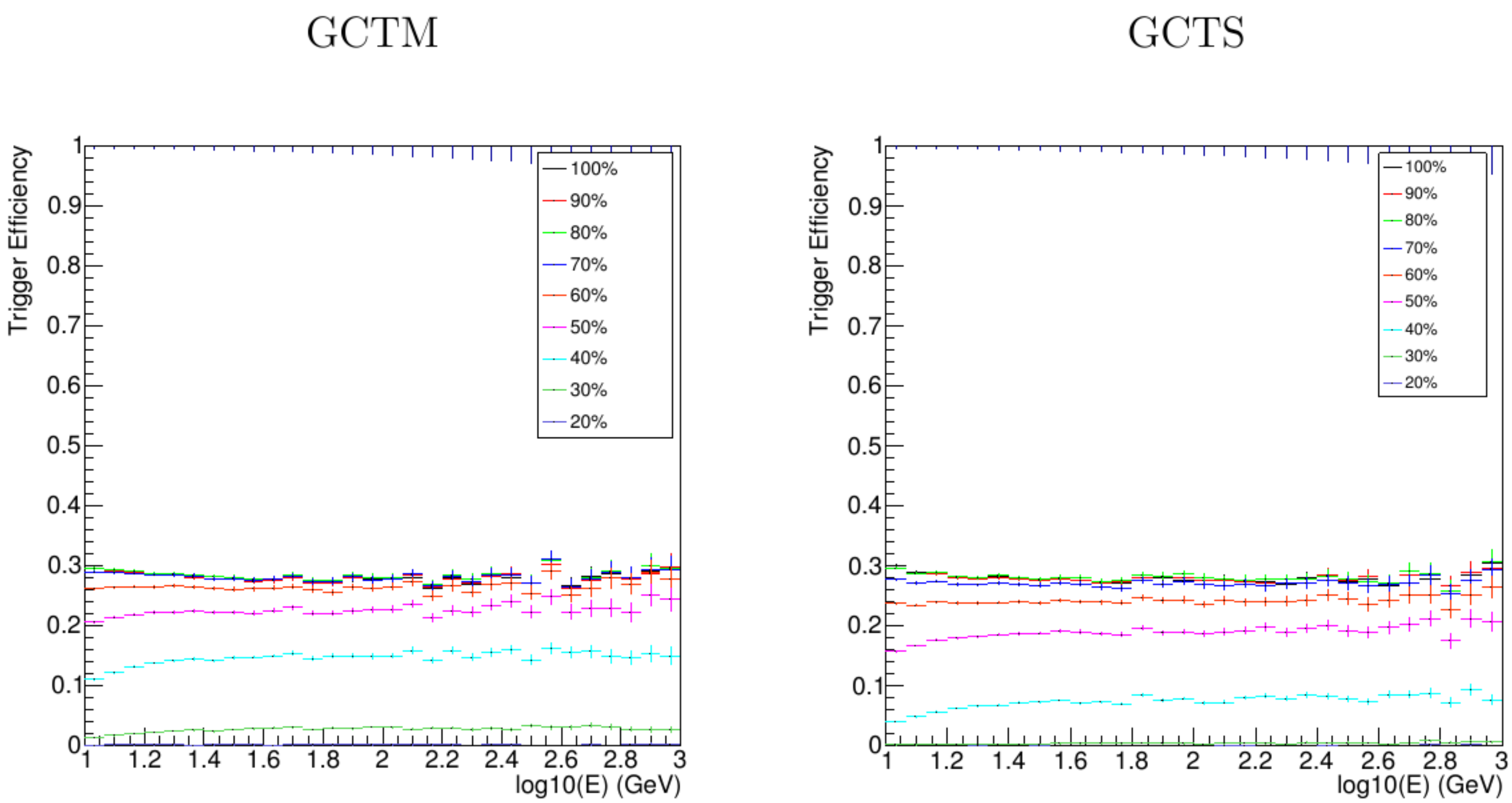
System Degradation

Simulated Data

• Simulated Site:	Paranal
• Particle:	μ^-
• Number of events:	1e6
• View cone:	0 – 4.7^o
• **Maximum impact radius:**	**2.0 m (within primary)**
• Energy Range:	10 – 1e3 GeV
• Energy Spectrum:	-2
• Optical Efficiency	20-100%

Assume efficient rejection of events landing outside of primary mirror

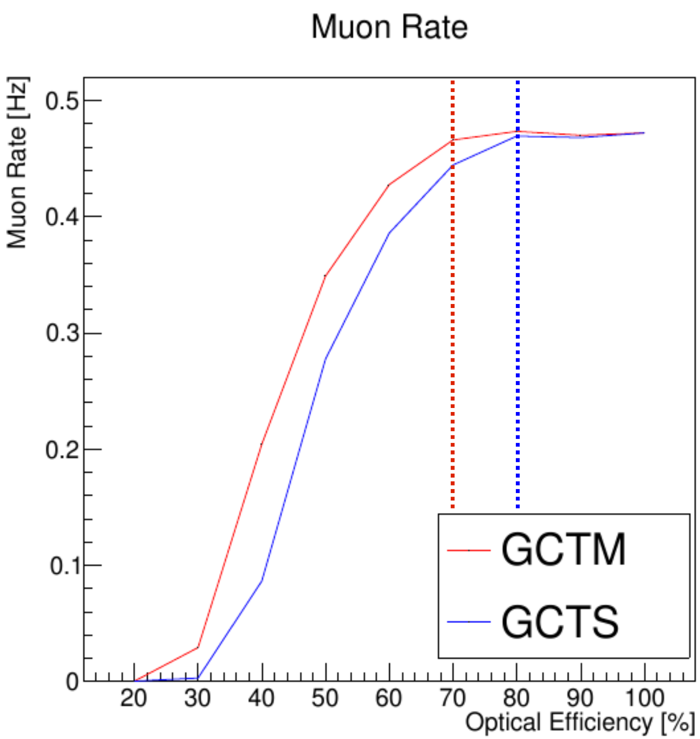
Selection Efficiency

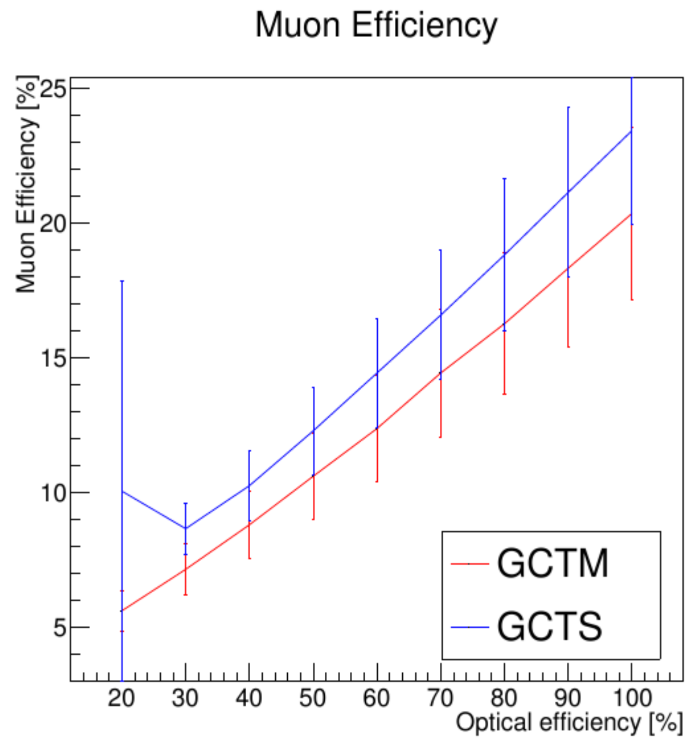


Using same method as previously stated: total selection efficiency passing all cuts for optical efficiency of 100,90,80,70,60,50,40,30,20%

Relatively stable

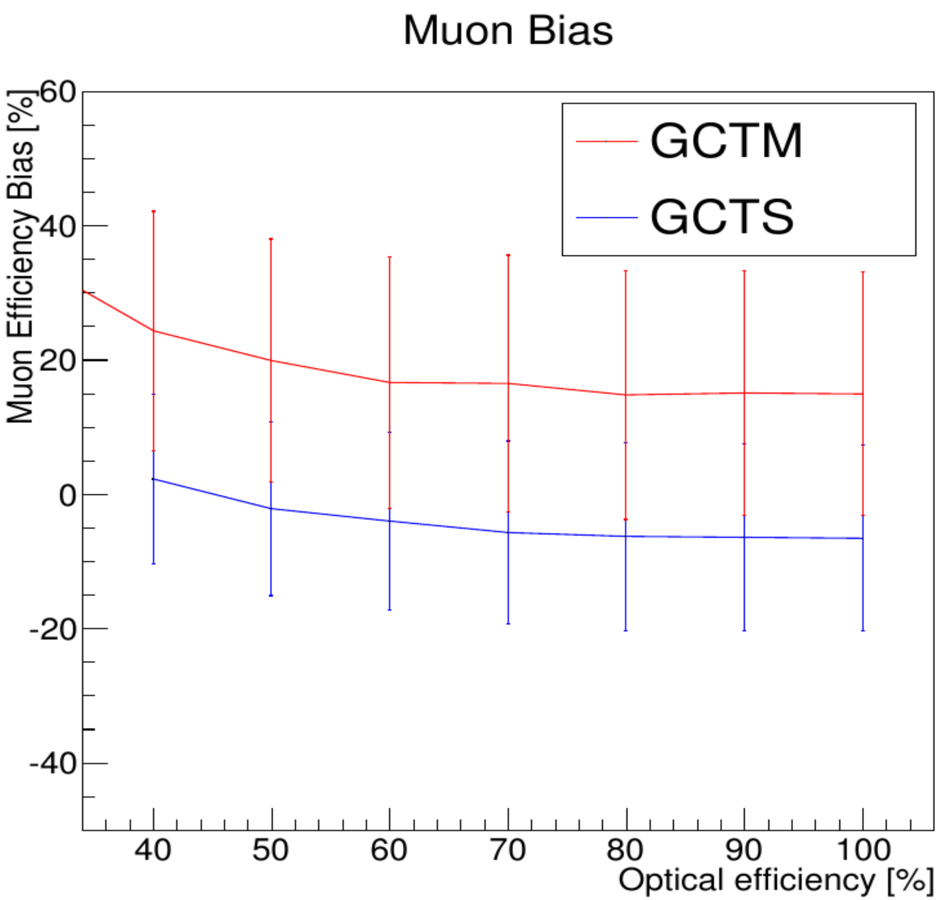
System Degradation





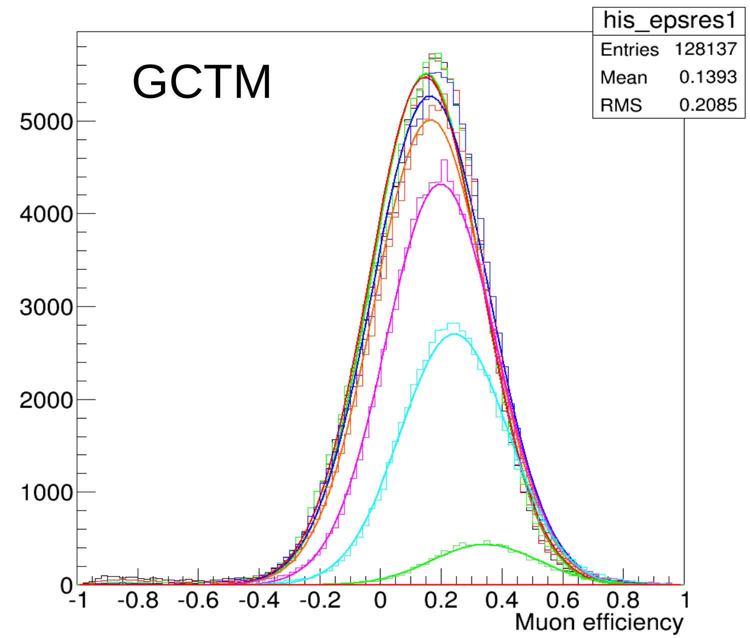
- Muon rate stays stable down to 80% optical efficiency for GCTS and 70% for GCTM
- Needs improving:
  - GCTS theoretical efficiency 25.06%.
  - Minimum required efficiency: 15% (A-PERF-2020)
  - Therefore GCTS needs to be stable down to ~60%
- Reconstructed efficiency look linear...

Efficiency Bias



Evolution of muon efficiency bias with degraded optical efficiency

Need to understand what level is unacceptable...



Conclusion and Future Work

- Simulated GCTM and GCTS
- Apart from tail cuts, all other cuts are the same. These need optimising for each configuration separately.
- Initial results show that detection rate of “good muons” if of the order 0.4Hz requiring 16 minutes of observations to obtain an acceptable data set.
- Events Falling within secondary poorly reconstructed
- Efficiency was reconstructed, appears to be a bias which is larger for GCTM
- Performance of muon calibration with increasing optical degradation is adequate for GCTM but the process will need optimising for GCTS
- Performance of GCTM will drop without use of UV enhanced MaPM coating
- Need to investigate muon trigger