Photon Transport Simulations (and some measurements)

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Fermilab

Big Picture:
Provide optical modeling for MINERvA and TASD

a) Study photon propagation times
b) Fast parametric response modeling

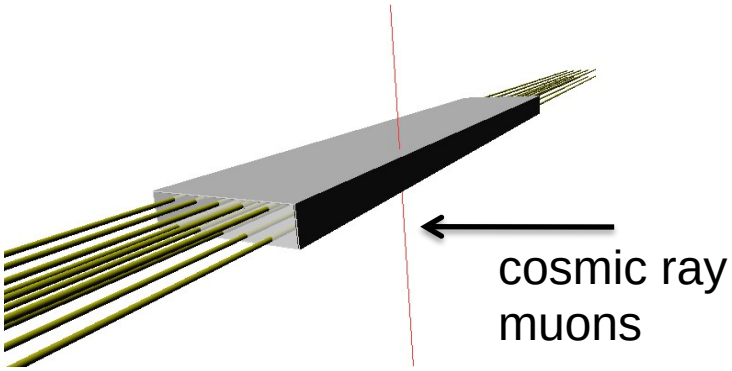
Outline:

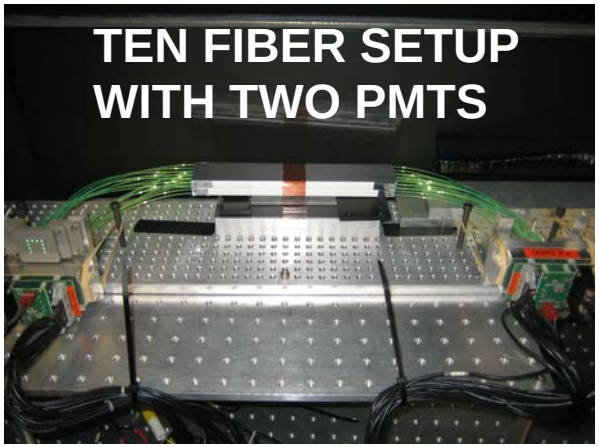
a) Past simulation experience
b) WLS Fiber measurements at UT Austin
c) NOvA prototype cell measurements
d) NOvA prototype cell simulations

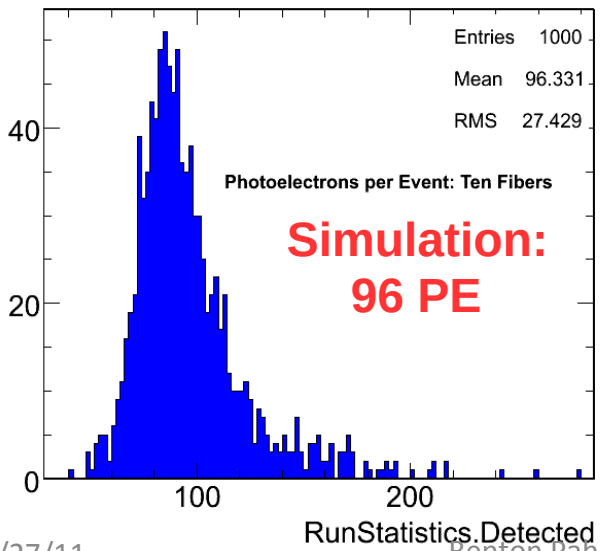
Initial Validation
Modified MINOS Strips

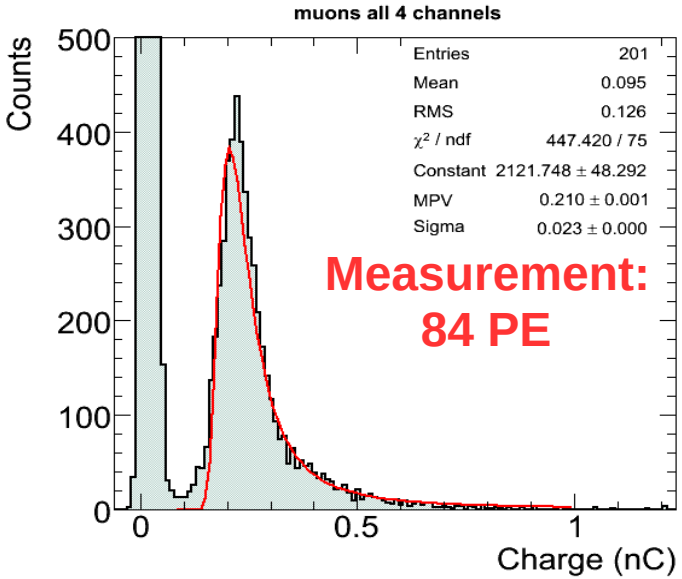
Studies with modified MINOS strips showed good agreement

TEN FIBER SIMULATION





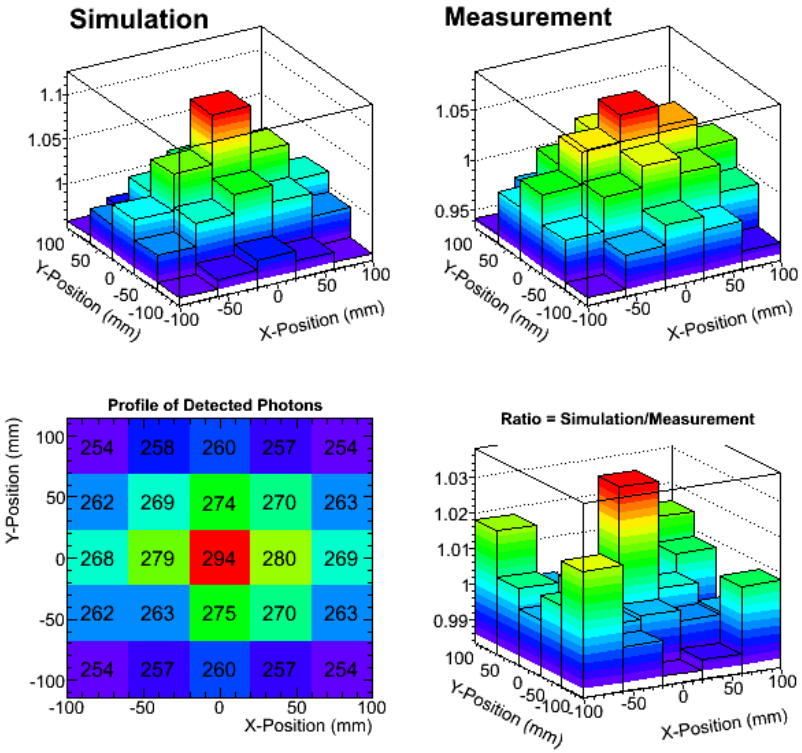




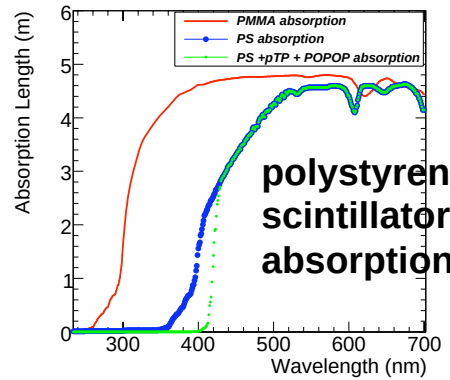
NEMO-3 Optical Simulations

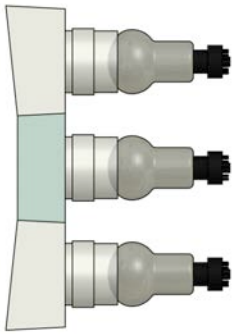
Simulations of large NEMO-3 scintillators agree with measurements

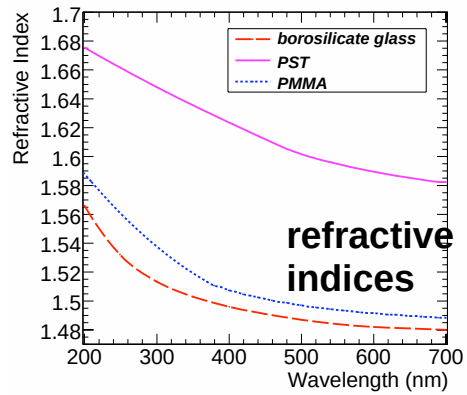
1 MeV electrons on the block face

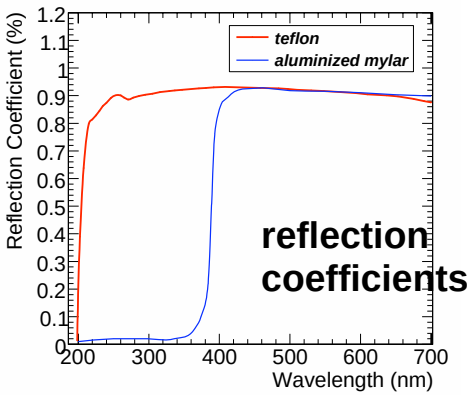


Comparison of measurement and simulation for a NEMO-3 external wall block.





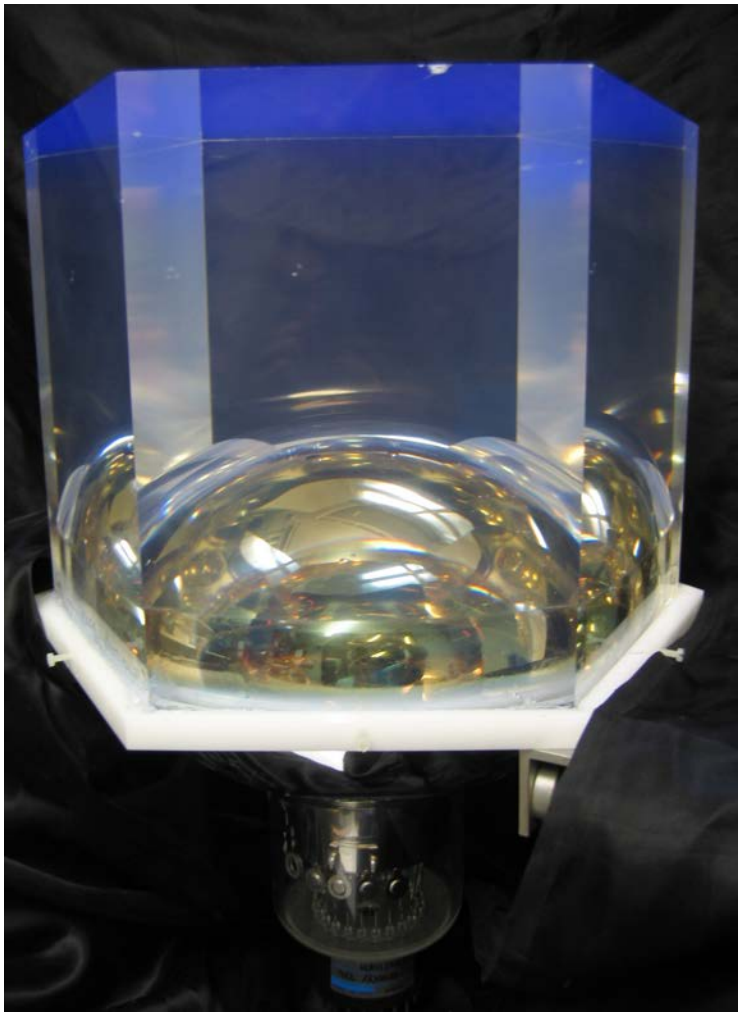




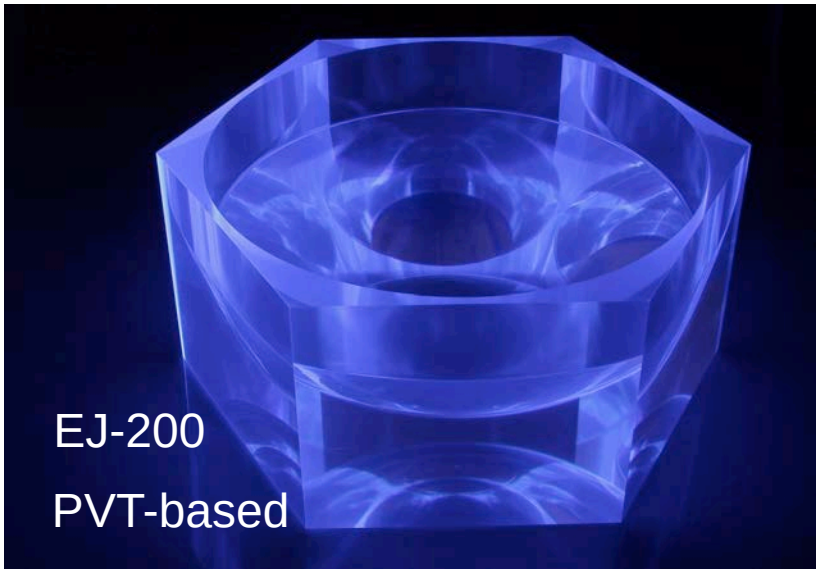
(Published in NIM, Nov. 2010)

Results: 14.4% FWHM @ 1 MeV simulation
13.8% FWHM @ 1 MeV measurement

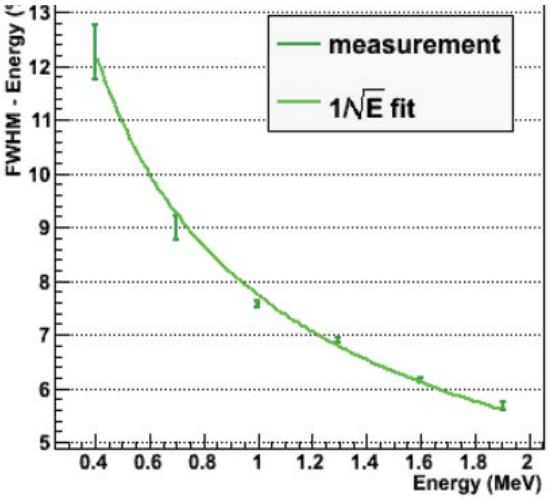
SuperNEMO Calorimeter Blocks



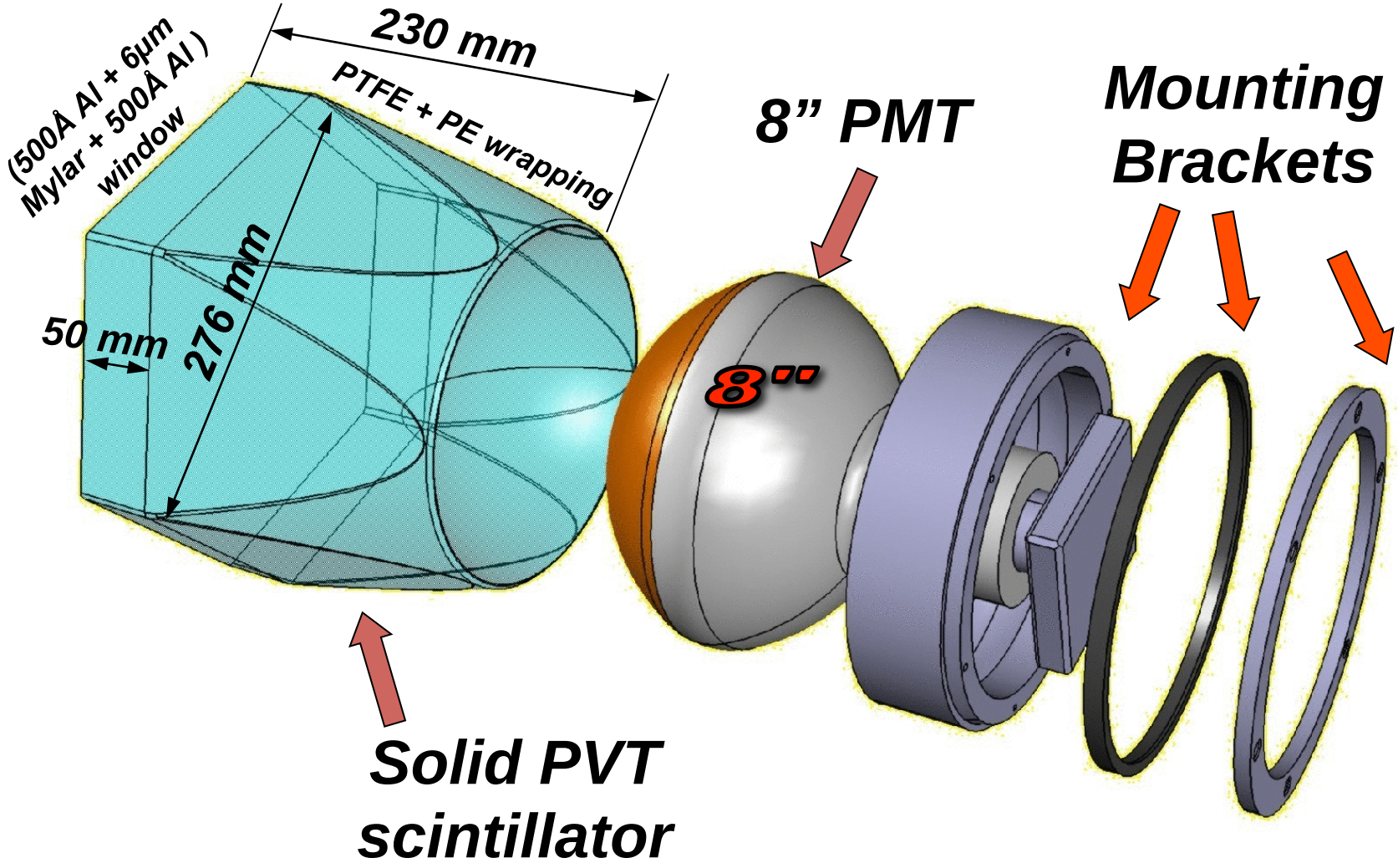
8" Hamamatsu R5912-MOD Super-Bialkali PMT with 276 mm diameter block



ΔE/E ~ 7.2% (FWHM) at 1 MeV (corrected)

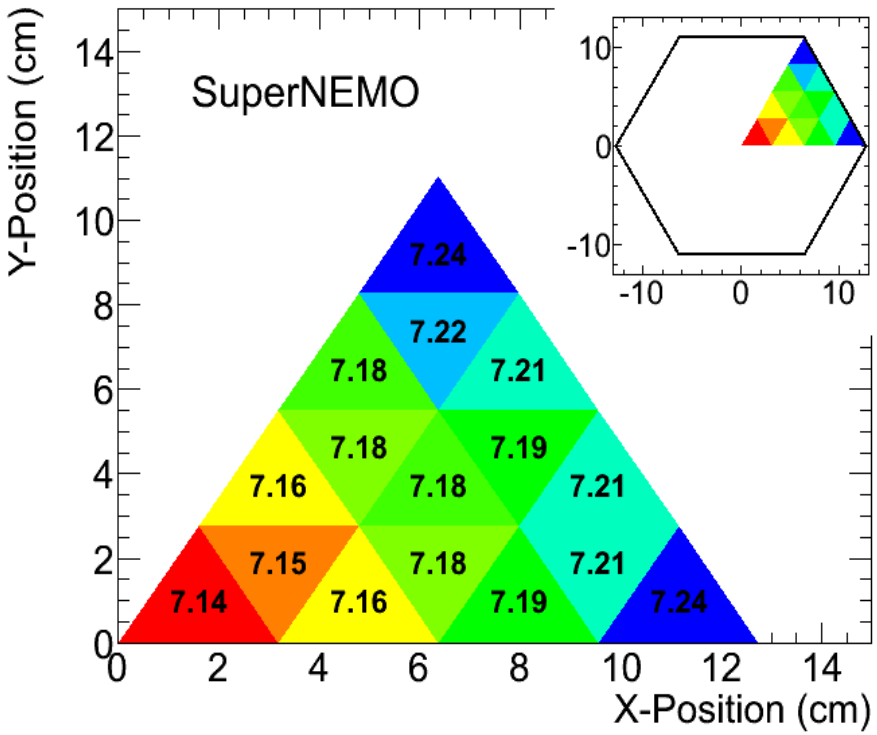


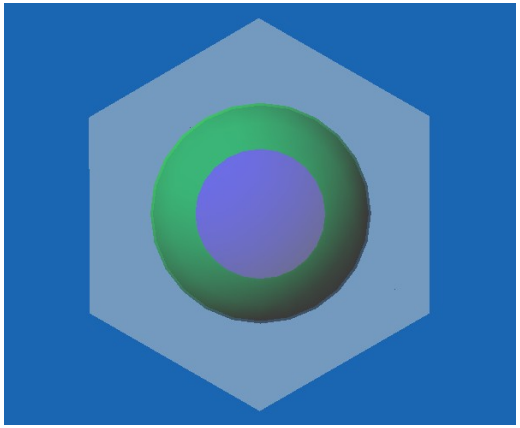
A SuperNEMO Module

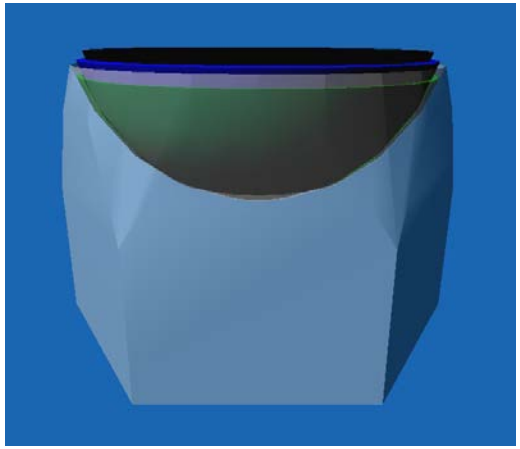


SuperNEMO Block Simulations

Simulations of large hexagonal scintillators agree with measurements





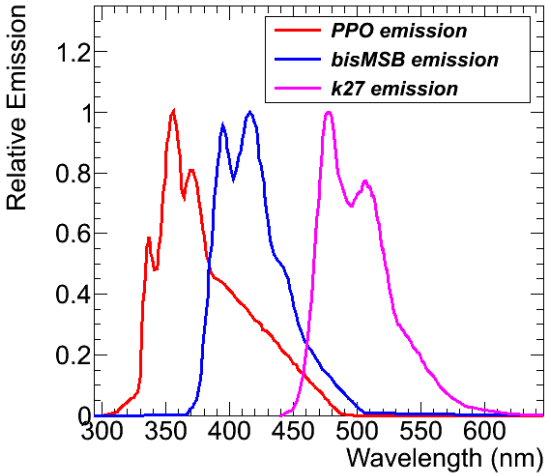


Simulations of a large hexagonal prototype block coupled to an 8” PMT to be used for SuperNEMO. Measurements of 7.5 ± 0.5% FWHM @ 1 MeV have recently been obtained.

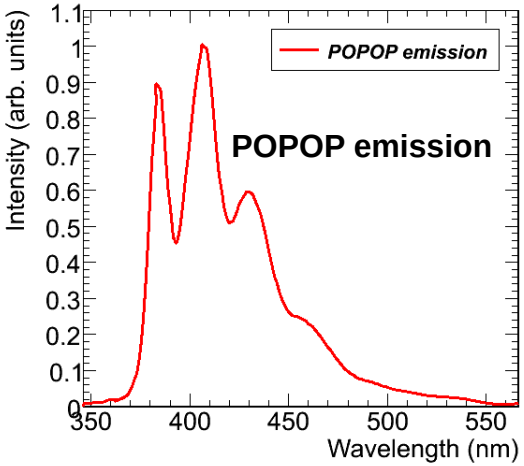
Optical Photon Model Ingredients

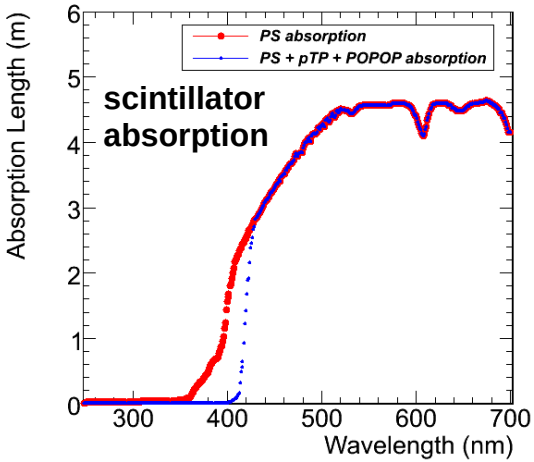
- Emission and absorption spectra
  - base scintillator
  - primary and secondary fluors
  - Stokes shifting and fluorescent quantum yield
- Spectral reflectivity of all relevant materials
- Spectral indices of refraction
- Spectral QE of photodetector

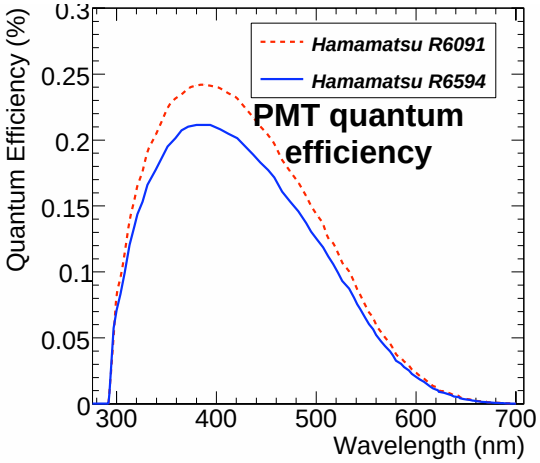
GEANT4 + ROOT framework



Example input data for optical simulations:

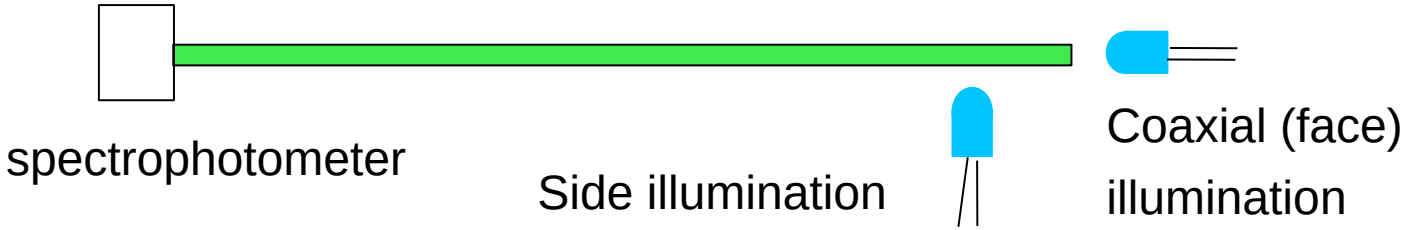






LED Measurements

We illuminated several 200 ppm Kuraray fibers on the side and face



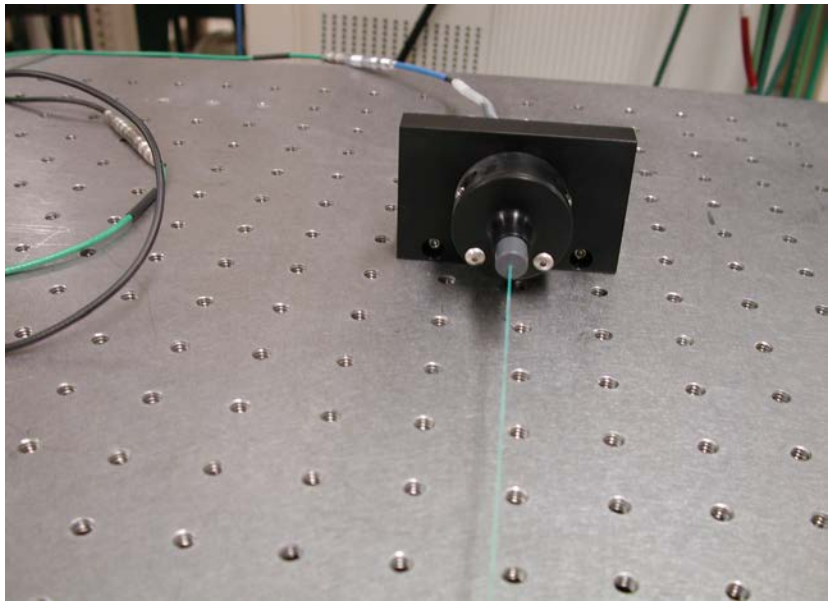


Photo of face illumination jig to align LED and fiber.

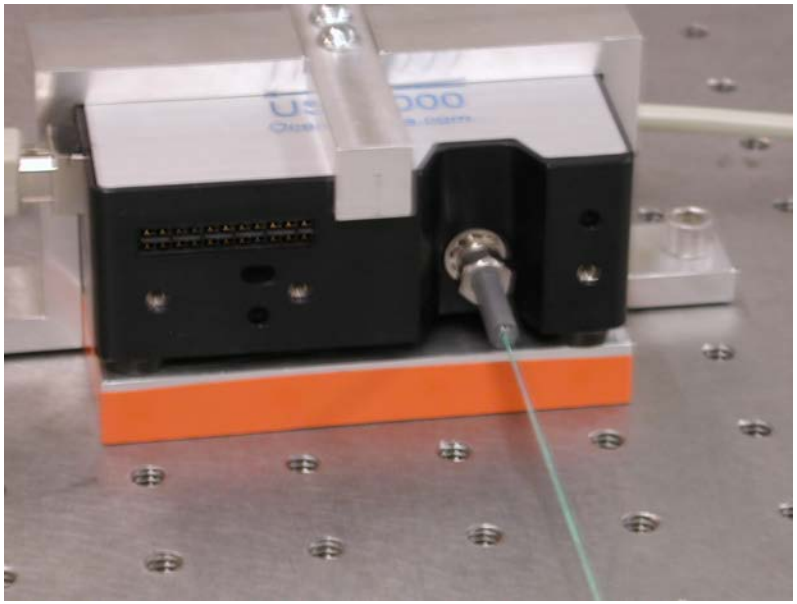
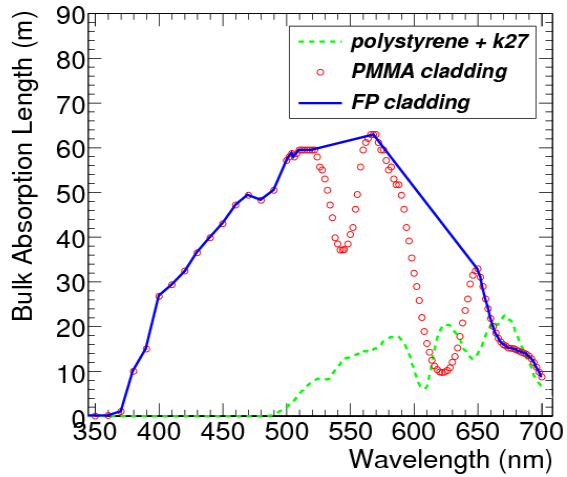
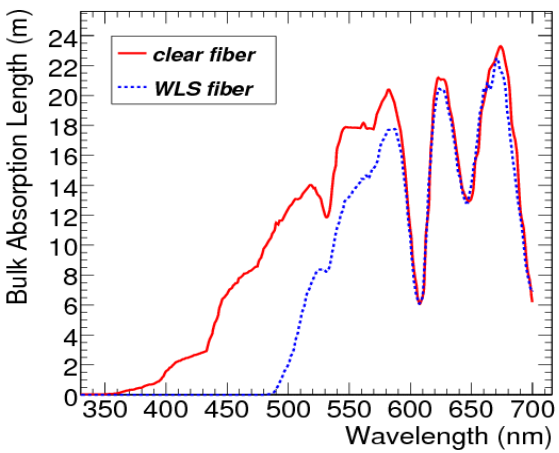


Photo of fiber coupling to an Ocean Optics 2000 spectrophotometer.

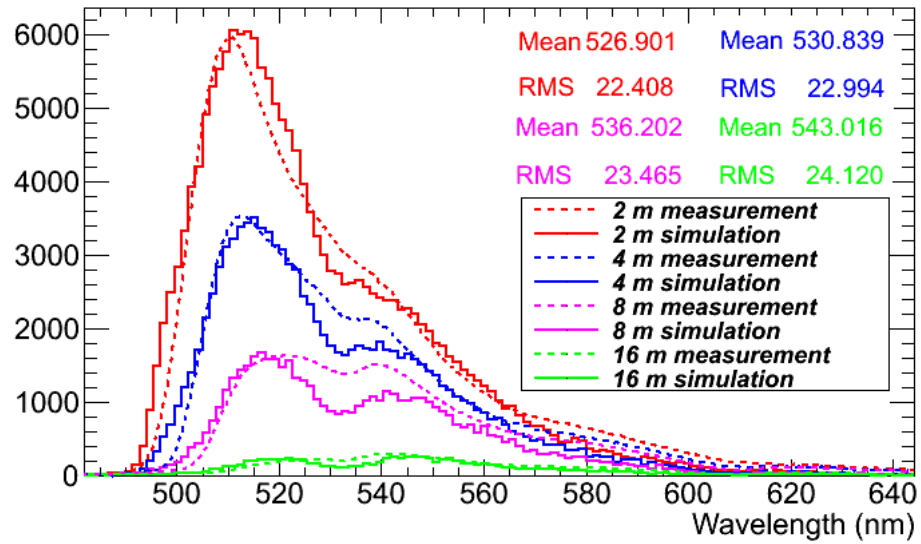
Fiber Simulations

Compare fiber simulations to fiber measurements





Comparison of measurements at UT of 430 nm face illumination with simulations

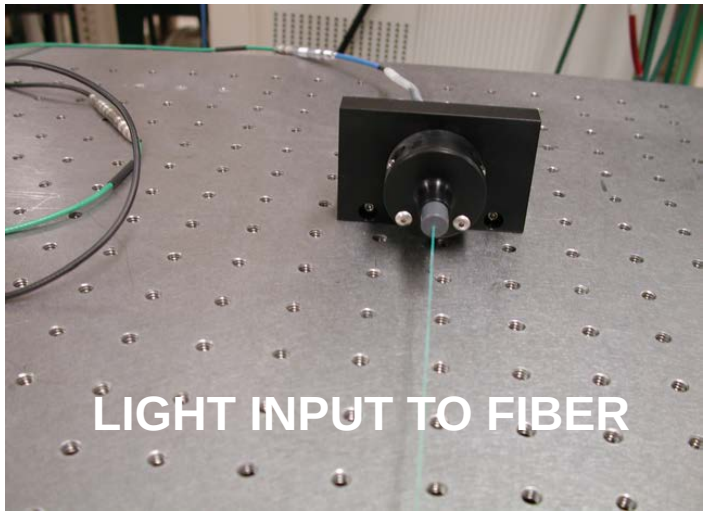


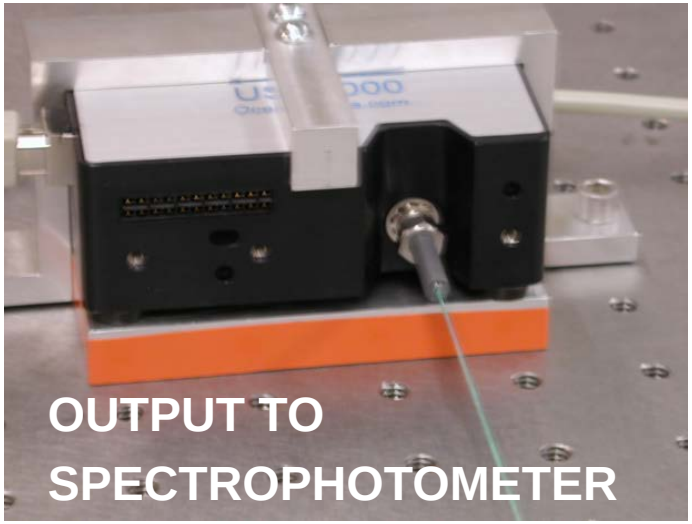
- Y11 and clear fiber data from Kuraray*
- Absorption in WLS is for 200 ppm
- Account for k27 wavelength shifting
- Account for dual cladding interaction
- Face and side simulations yield same results

*polystyrene + k27 and clear Ref. Kuraray
PMMA Ref. A. Weinert, Plastic Optical Fibers, 1998

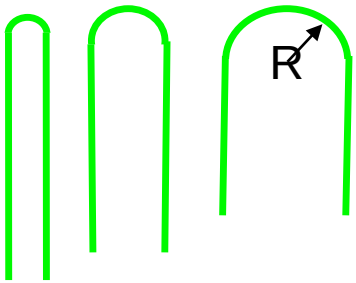
Effect of Fiber Bending

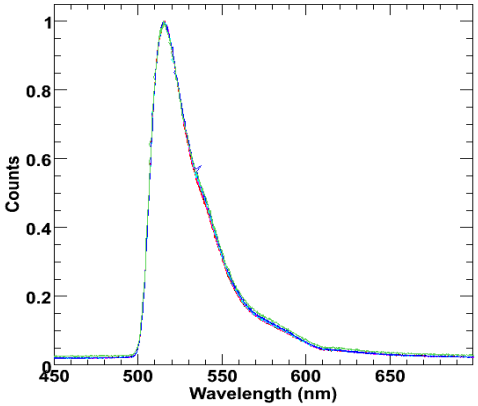
- **2.0 m 0.7 mm diameter** Kuraray Y-11 WLS **(200 ppm)** coupled to 400 nm LED
- Measurements taken at bending radius of 13.5 cm to 1.5 cm in 2 cm increments

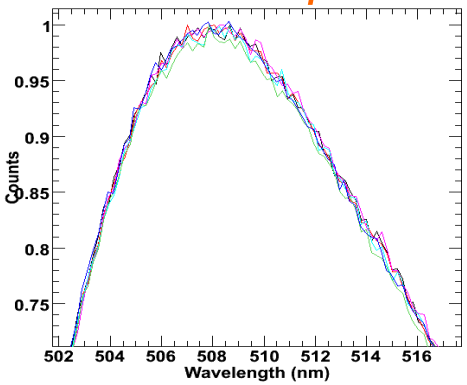




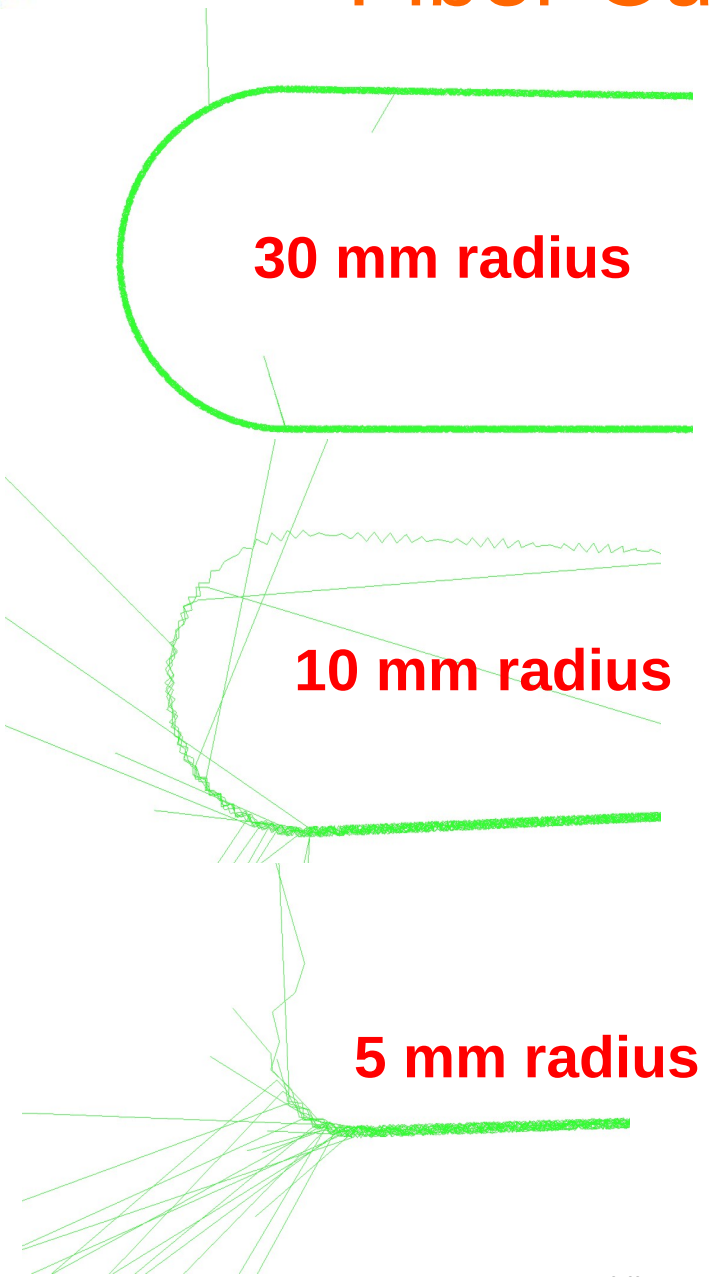
Measurement Results: No light loss at all up to 1.5 cm

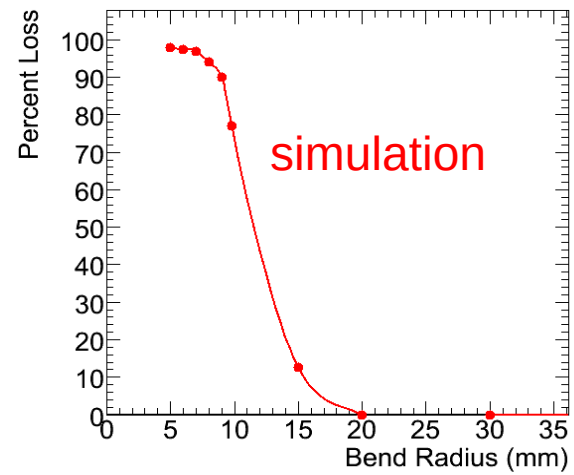


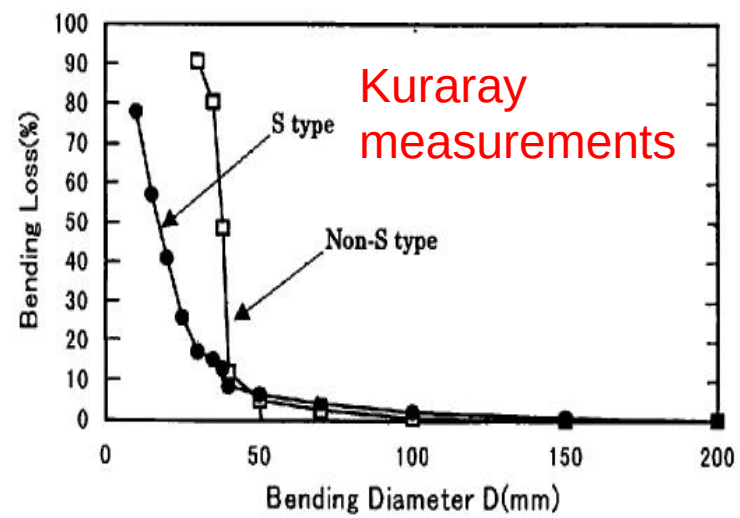




Fiber Curvature Studies



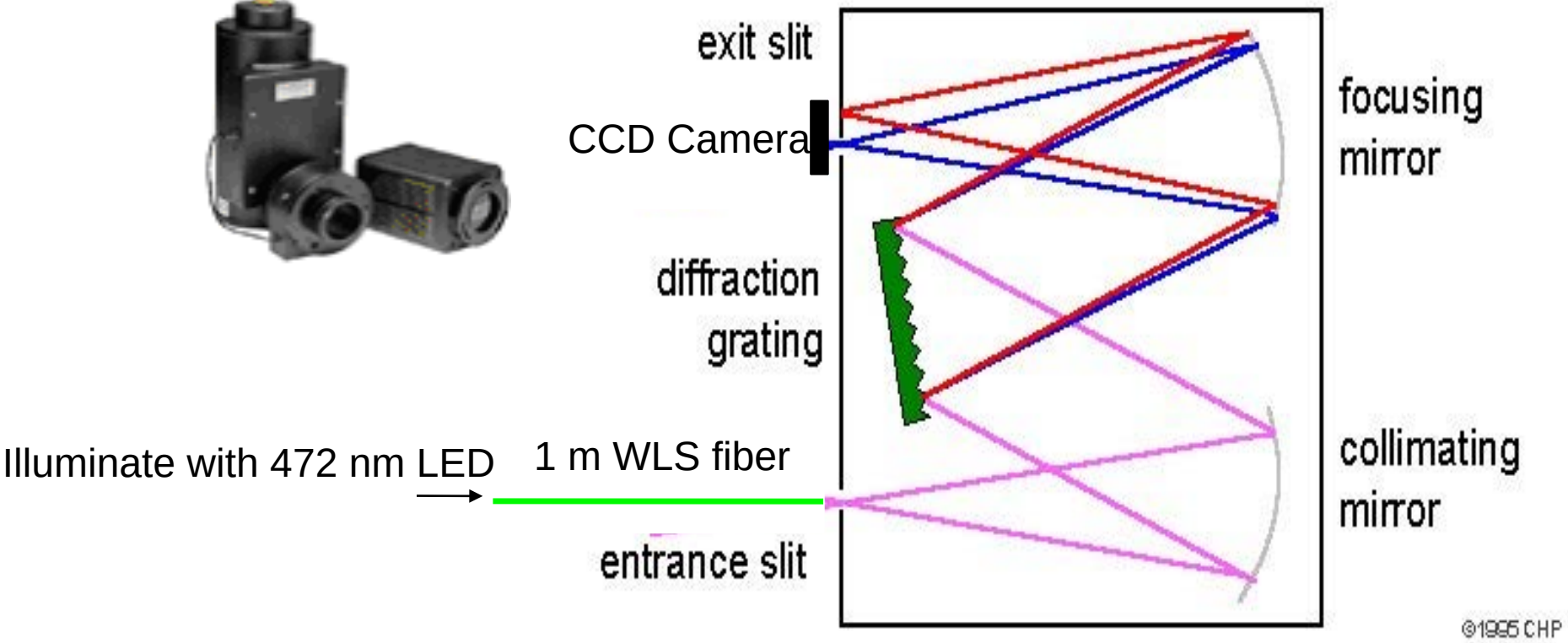




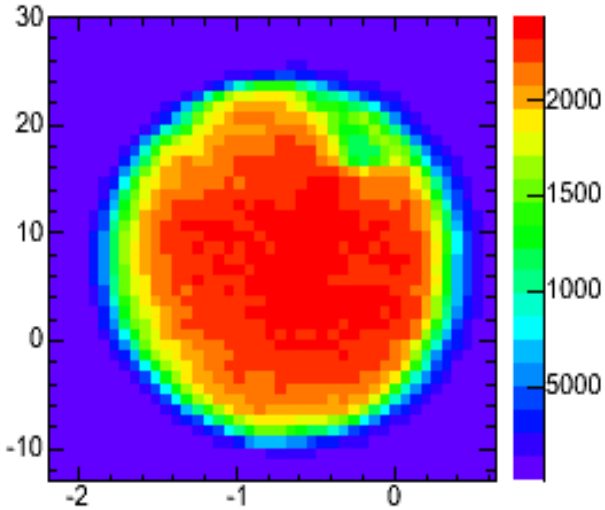
Comparison of simulations and Kuraray measurements for the bending radius.

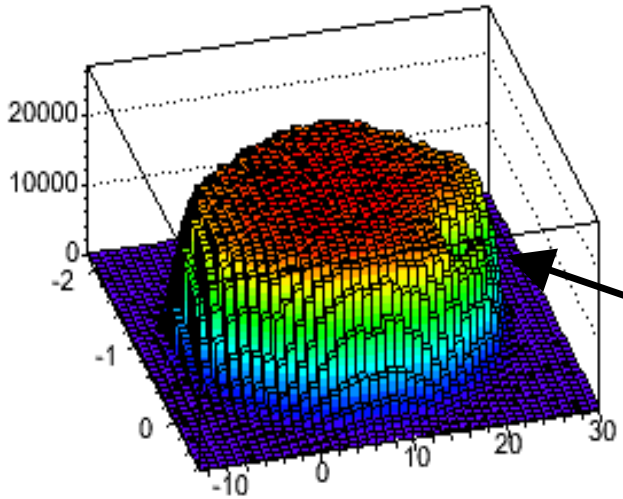
Fiber Imaging

- Princeton Instruments SPEC-10 CCD (liquid nitrogen cooled)
- 1340 X 1340 pixels
- Coupled to spectrometer, illuminate fiber with 472 nm LED
- Observe light output profile and/or wavelength



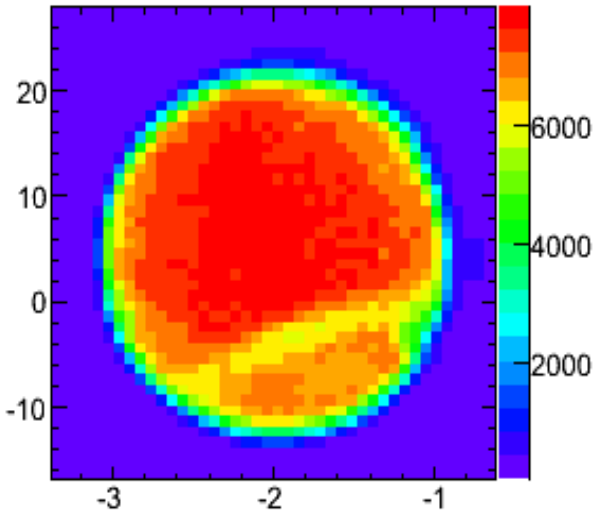
0.7 mm Diameter Fiber

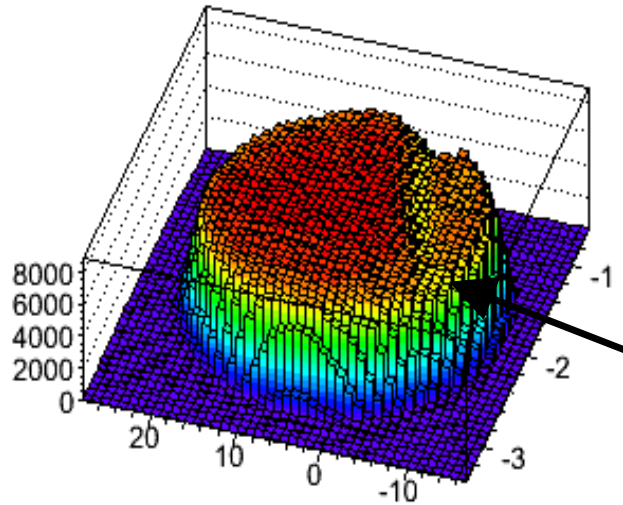




- 1 m fiber
- Polished by hand

CHIP IN CLADDING

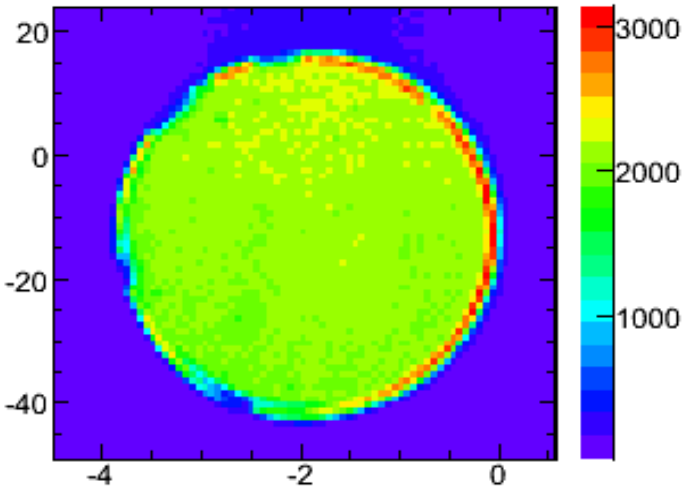


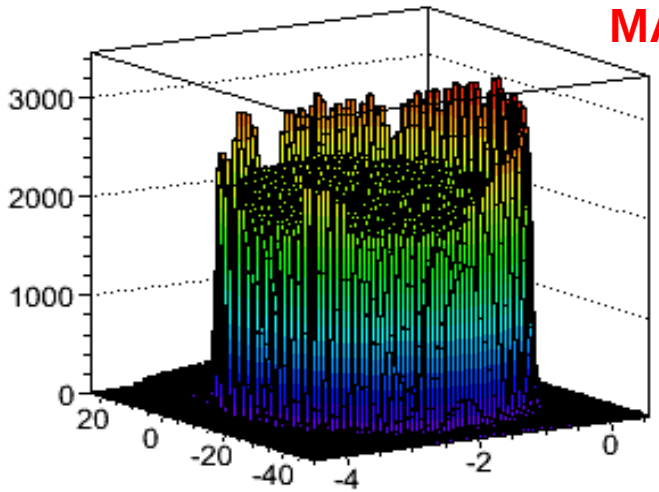


- 32 m fiber
- Polished by hand

SCRATCH ON FACE

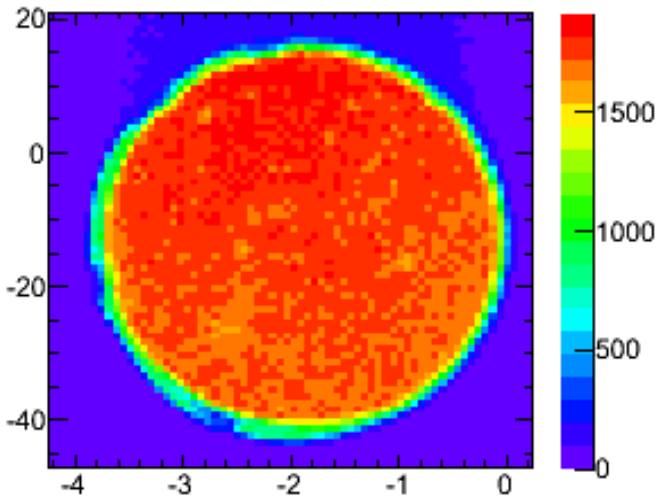
1.2 mm Diameter Fiber

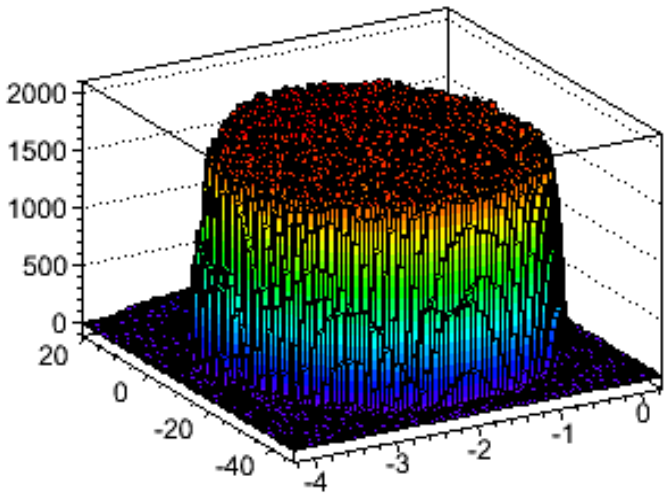




MACHINE POLISHED

Ring on right edge due to small amount of ambient light

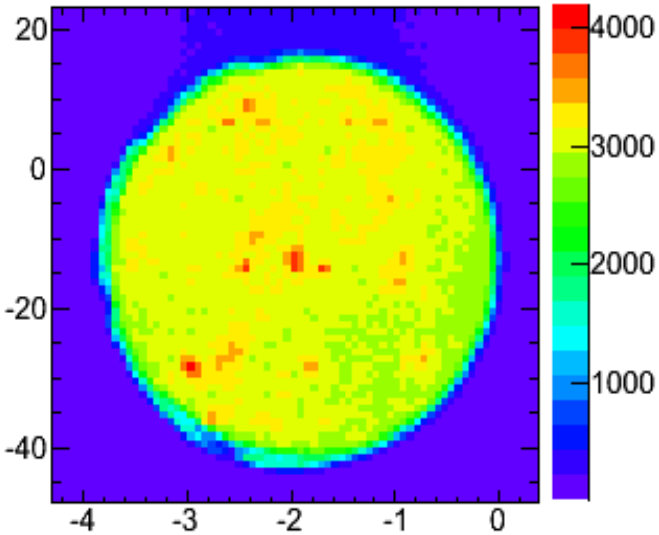


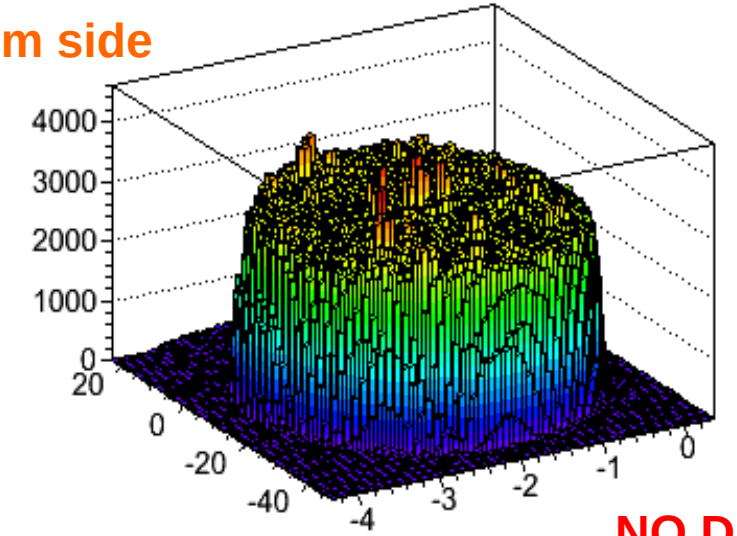


After removal of ambient light

Side vs. Face Illumination

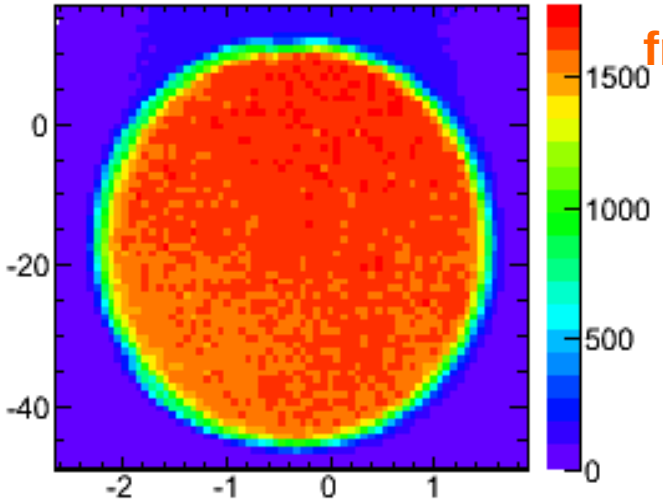
Illuminated from side

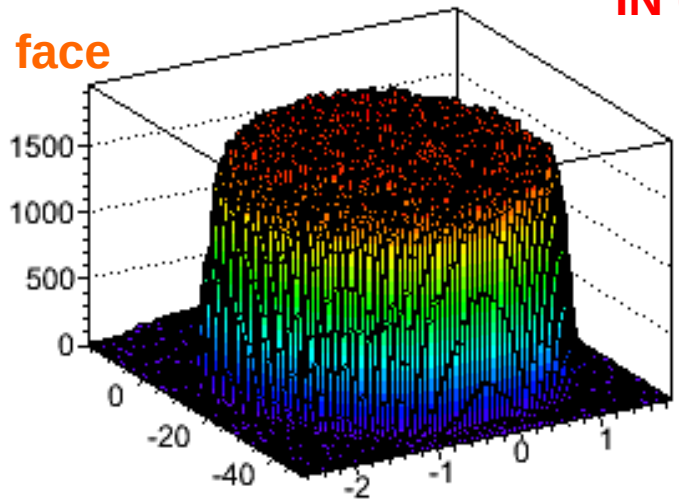




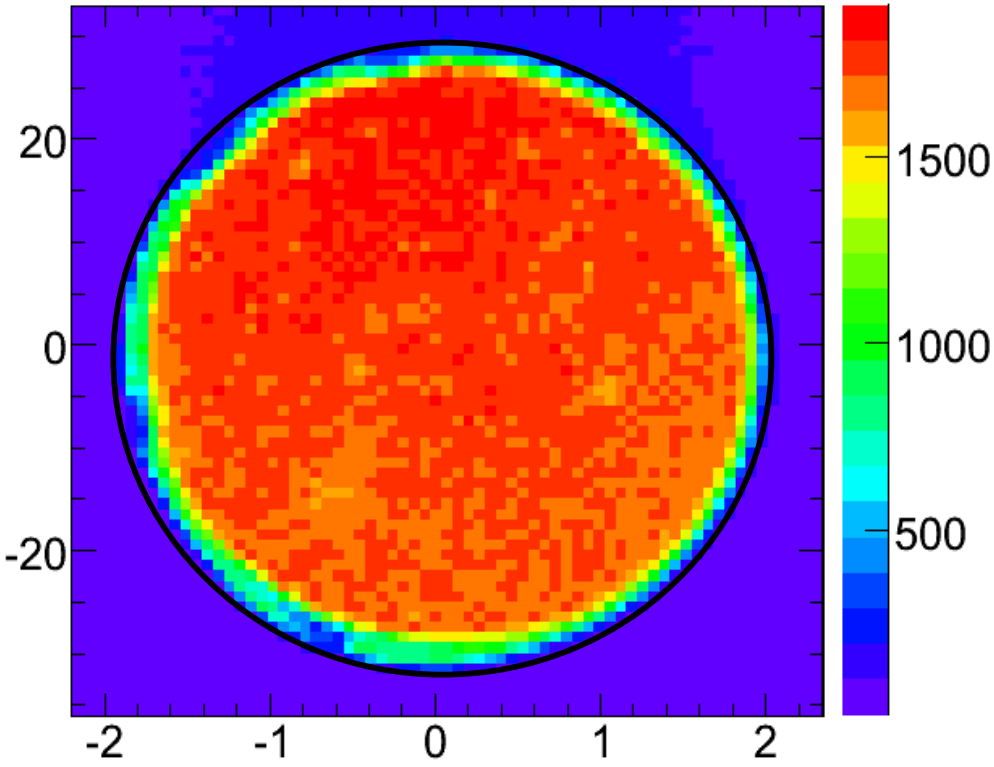
NO DIFFERENCE IN UNIFORMITY!

Illuminated from face





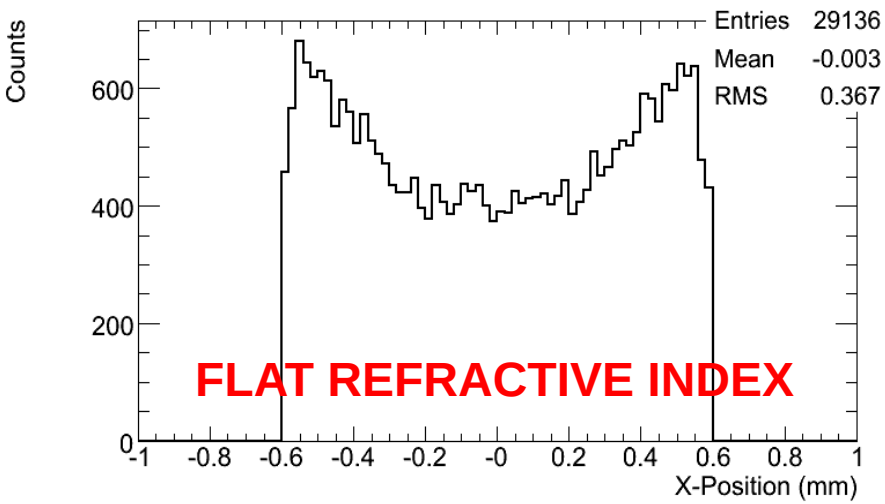
Light Output Profile: 1.2 mm Fiber

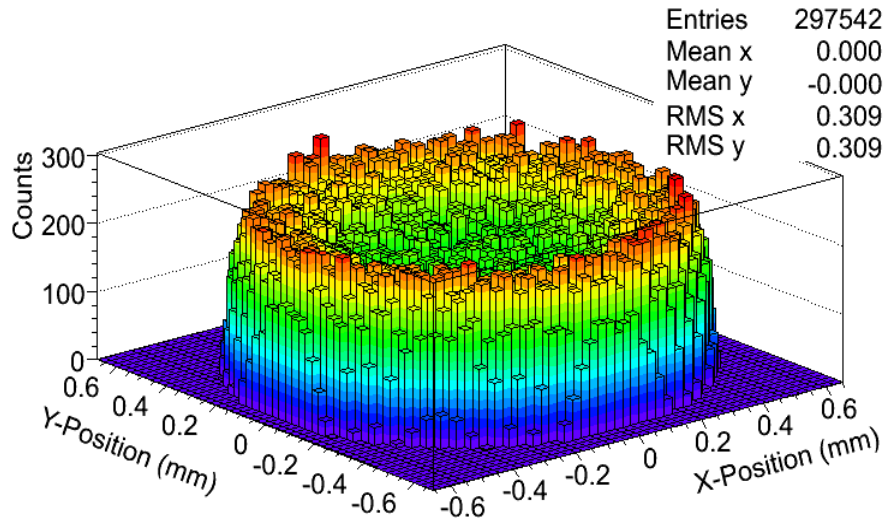


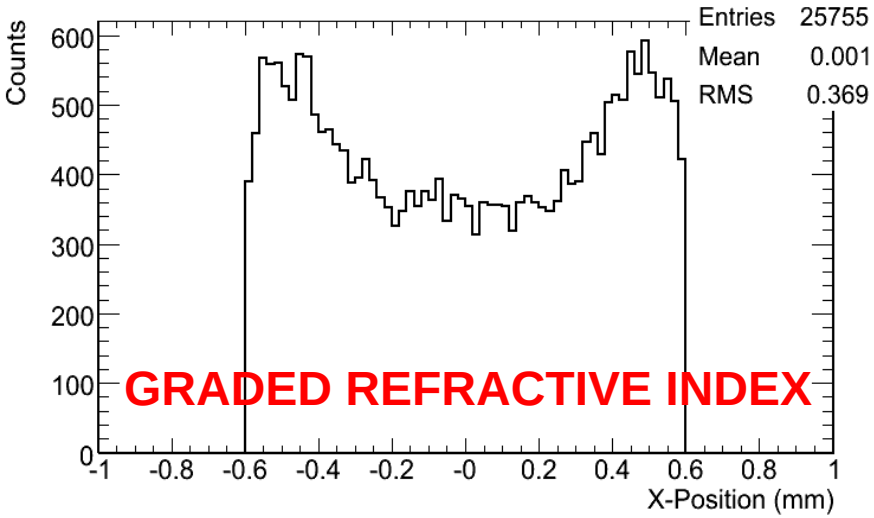
- 20 microns/pixel
- 60 pixels across
- black ring is exactly 1.2 mm

Graded vs. Flat Refractive Index

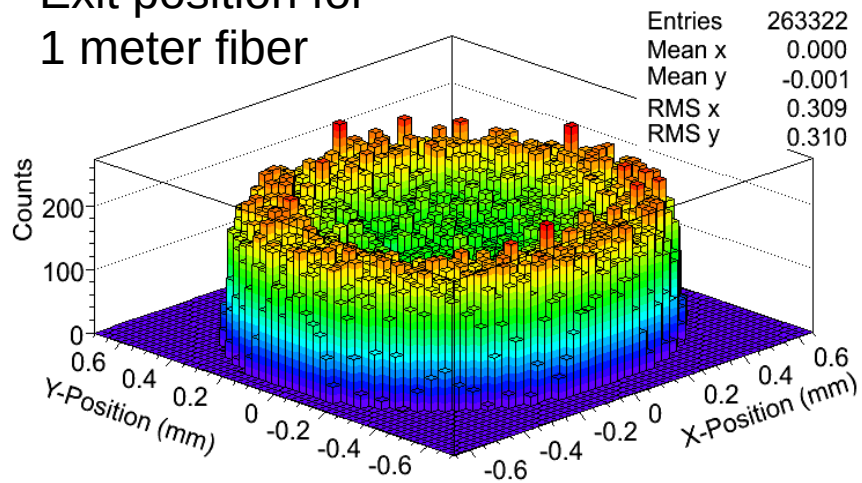
- Flat Refractive Index: 1.59 core, 1.49/1.42 for claddings
- Graded Refractive Index: 1.59 to 1.50 core, 1.49/1.42 for claddings





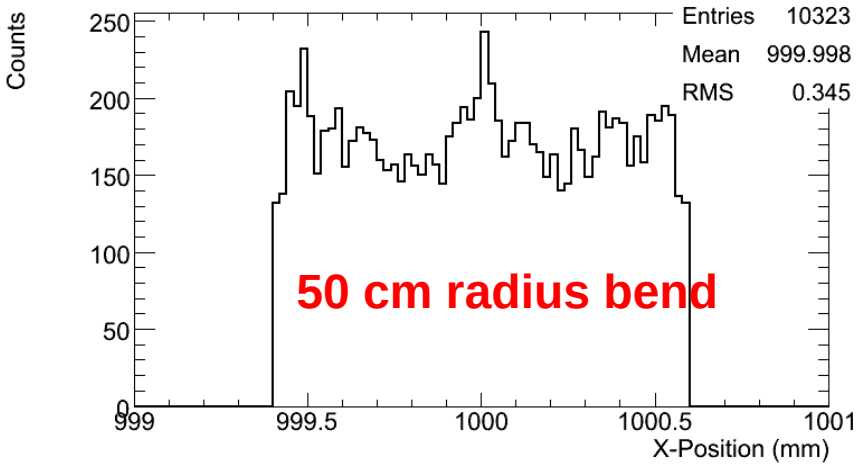


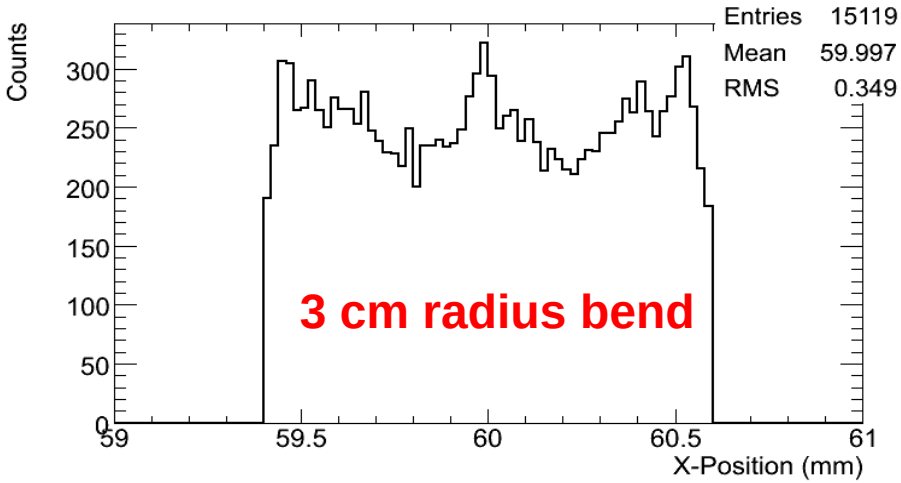
Exit position for
1 meter fiber

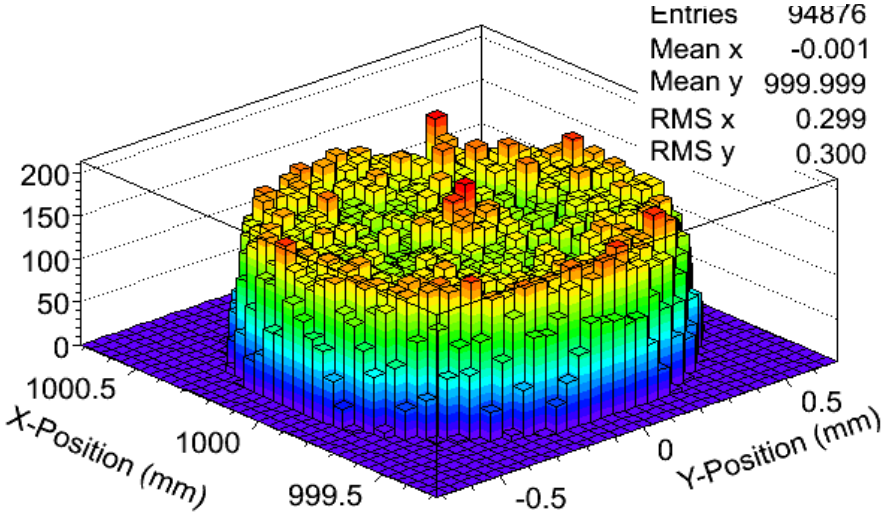


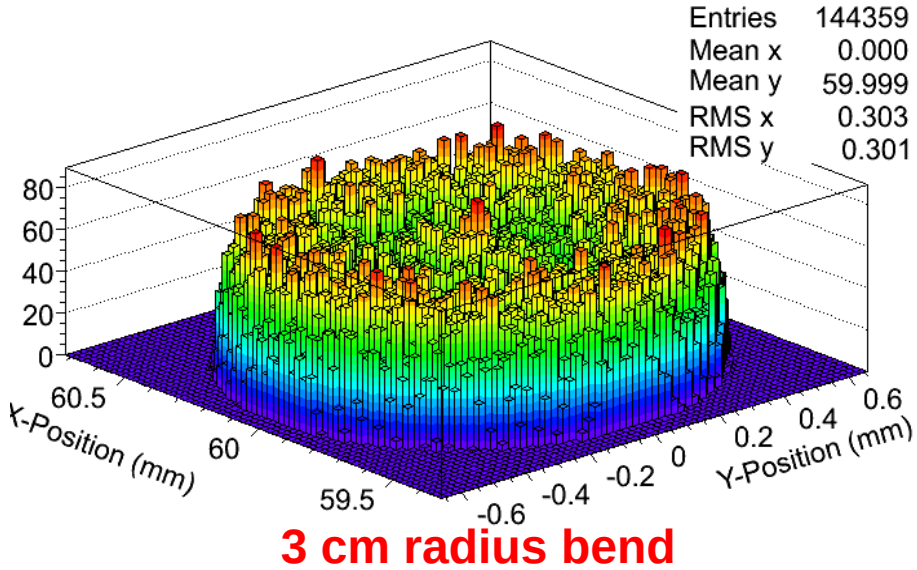
Exit Position for Bent Fiber

- Results are for 50 cm and 3 cm radius bends.
- Light input is a pencil beam centered on the side of the fiber.





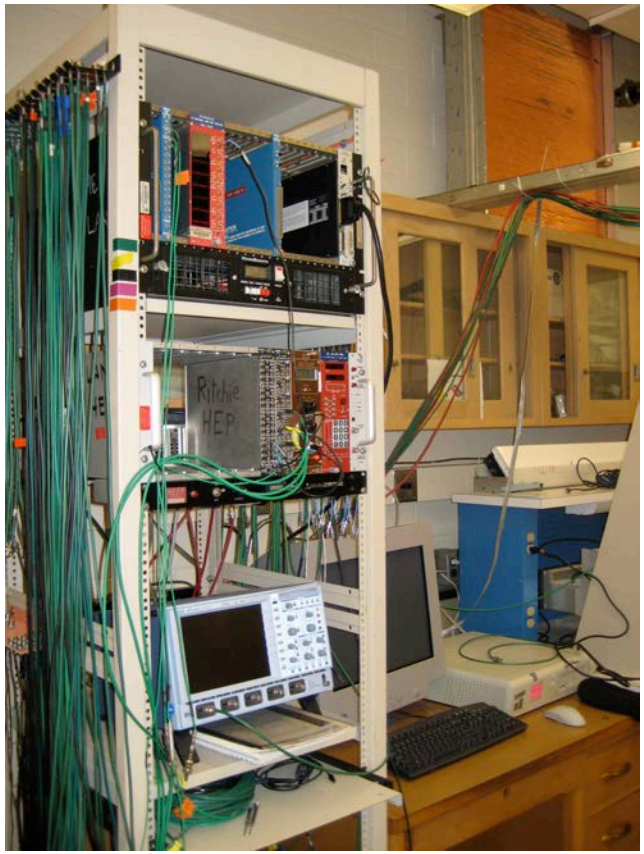


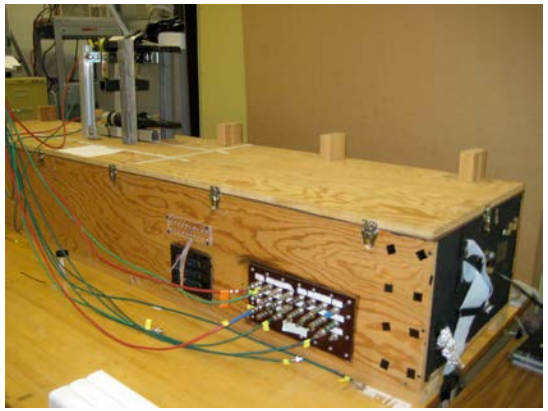


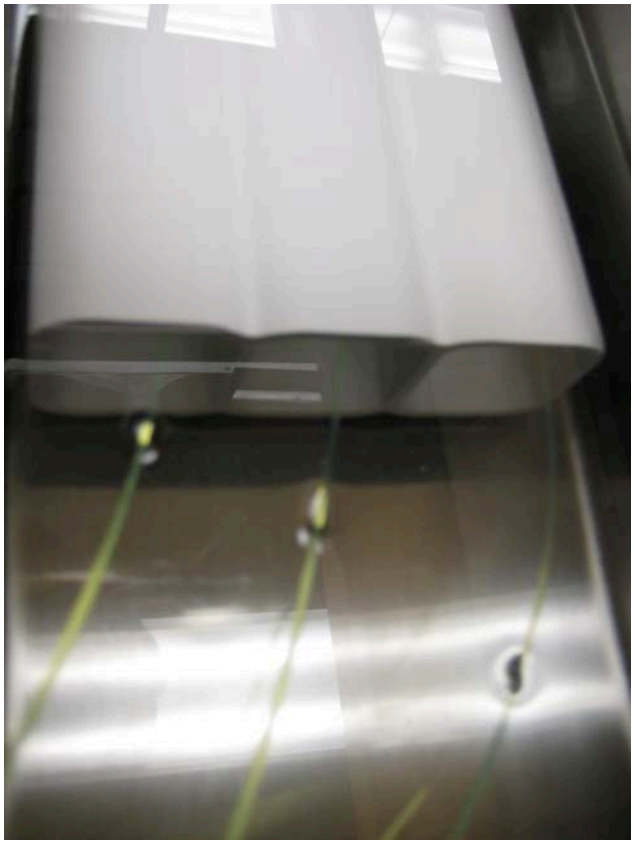
NOvA cell simulation validation

Prototype Cell at UT Austin

Tested the simulation model using a small version of a NOvA cell.



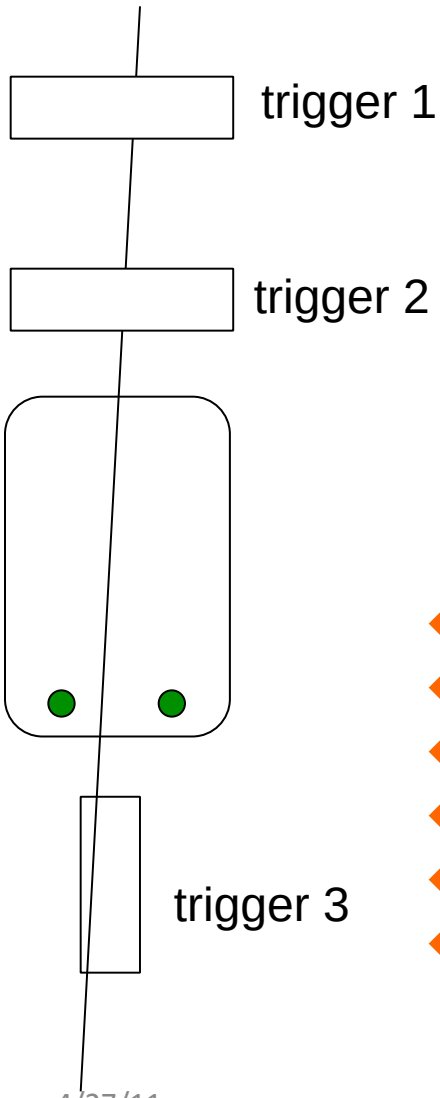


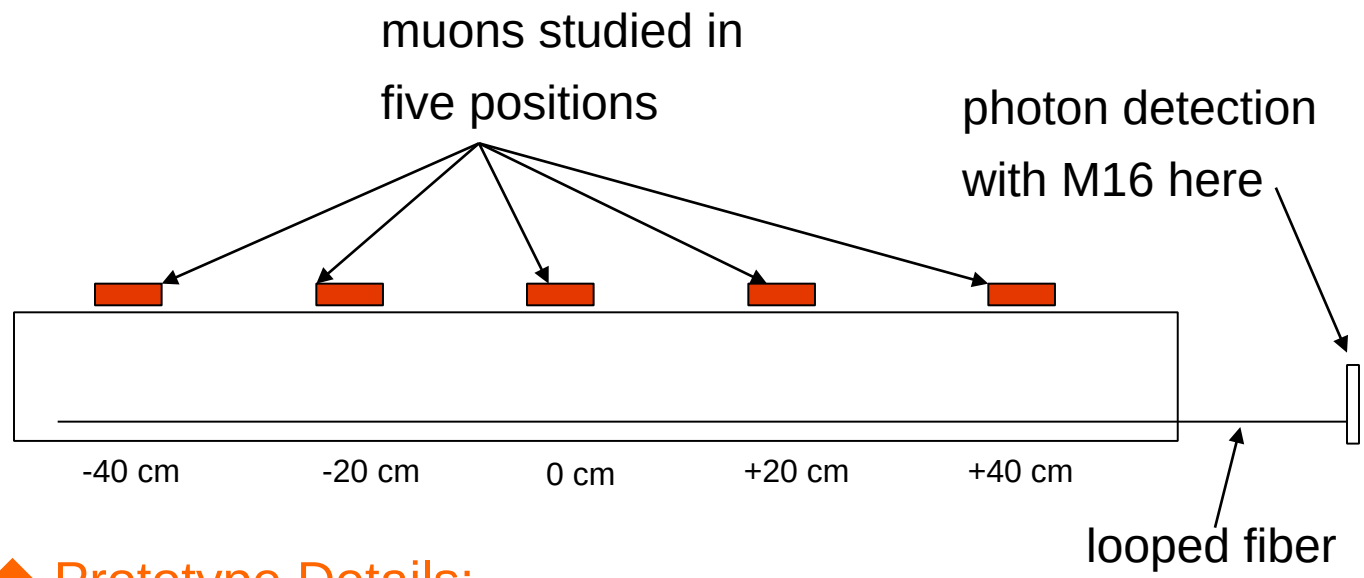


Data acquisition:
Jorway 73A crate controller – LeCroy ADC – Philips discriminator/coincidence

Prototype Cell Setup

A simple setup with triple coincidence using scintillator paddles



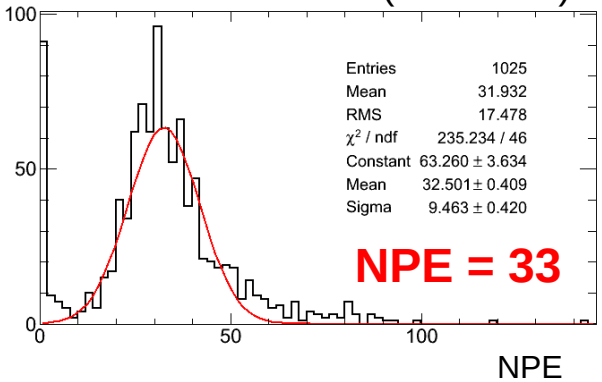


- Prototype Details:
- NOvA 27A PVC extrusion – length = 1.2 m
- NOvA liquid scintillator (2007)
- 200 ppm 0.7 mm diameter looped fiber to M16 PMT
- M16 readout at two opposite pixel corners
- Positions are center, ± 20 cm and ± 40 cm off center

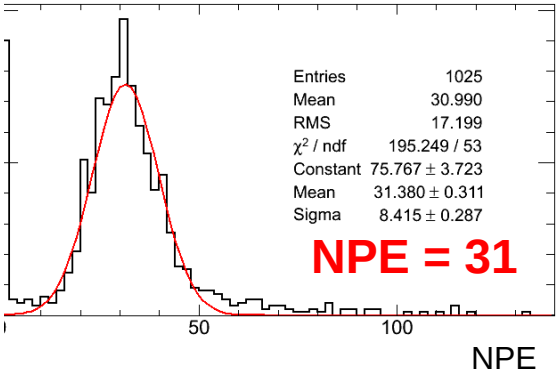
Prototype Measurements

Results for three positions and a comparison with simulations

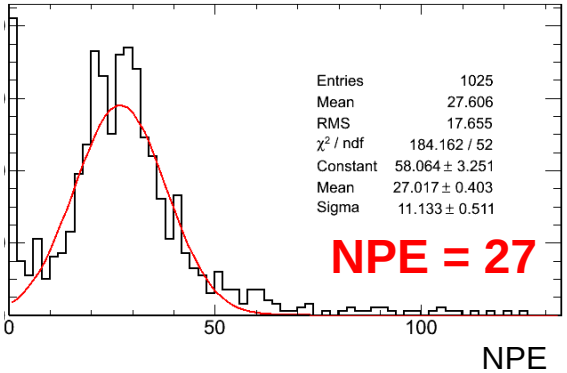
+20 cm from center (near PMT)

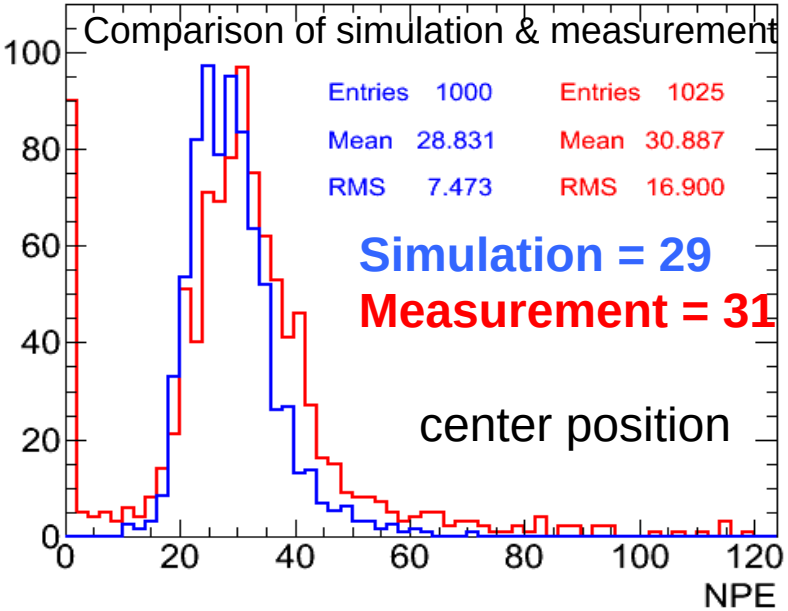


center position



-20 cm from center (far from PMT)



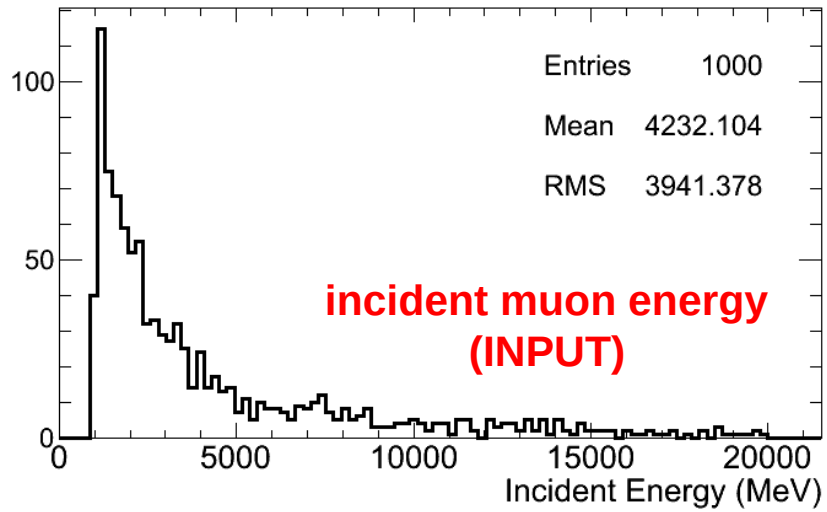


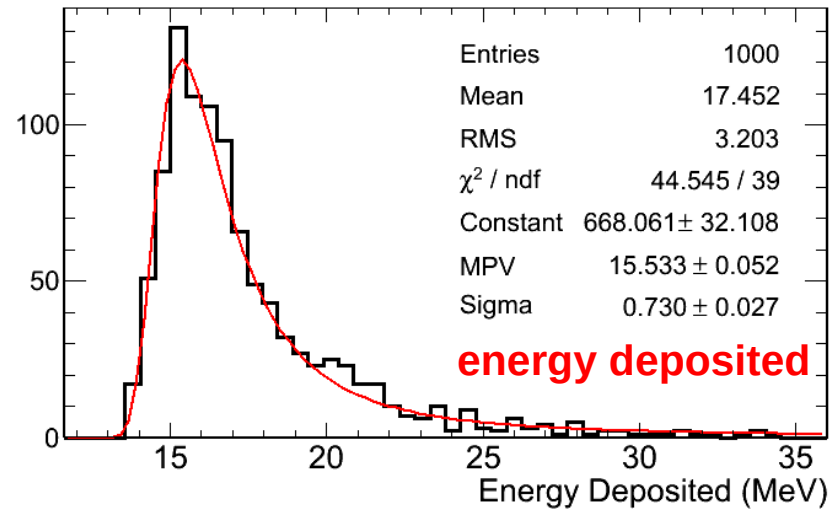
Details:

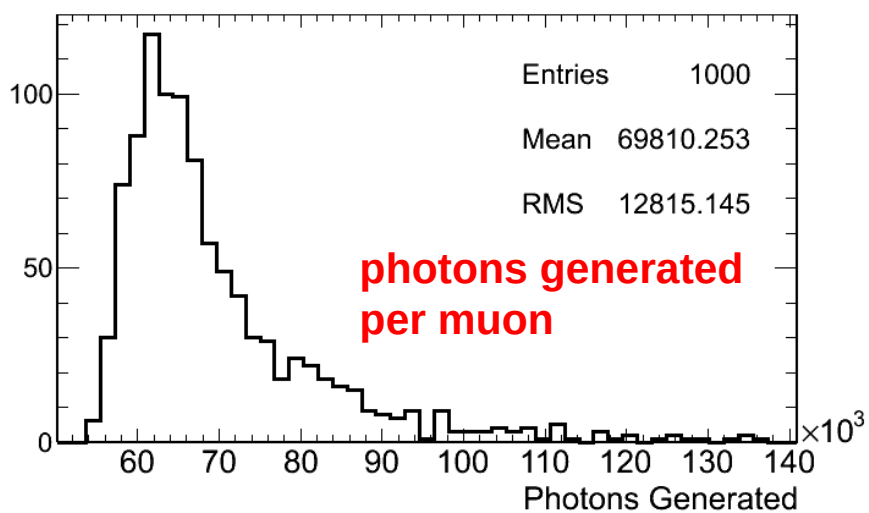
- 1000 muons at each location
- NPE calculated from ADC mean and SPE
- Simulation normalized to measurement peak

Simulation Results

Overall results for energy deposition and photon production





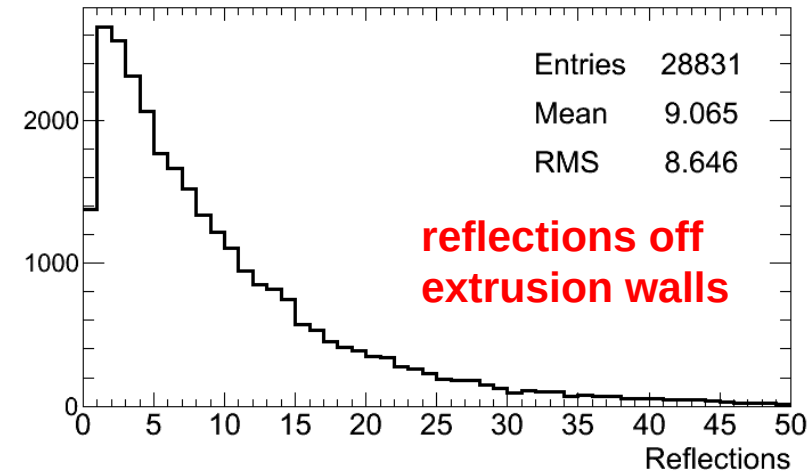


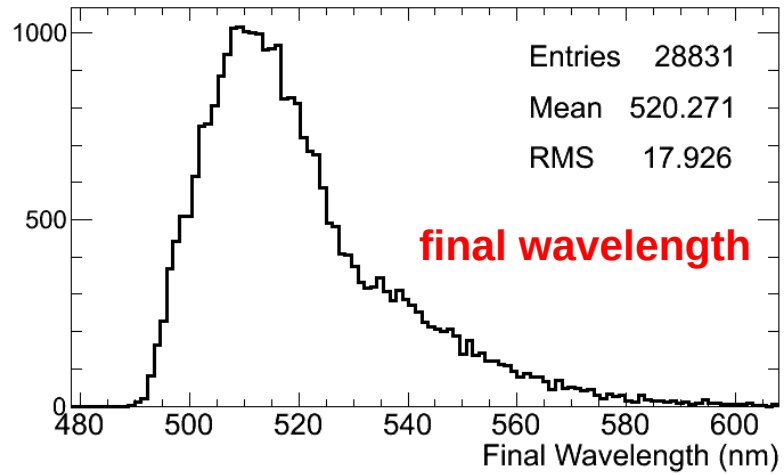
Details:

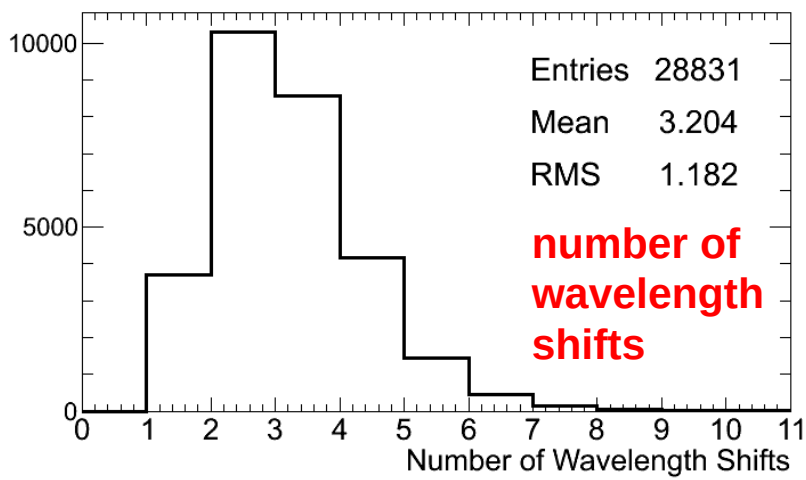
- using vertical cosmic muon spectrum
- 1000 muons generated in center
- ~ 5 minutes per muon = 40 hours
- ~ **70,000** photons generated per muon

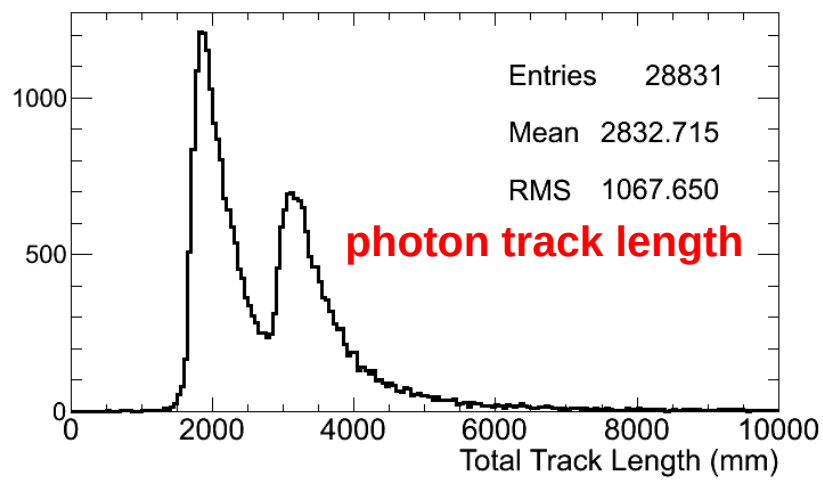
Simulation Results

Distributions of photoelectrons collected at the PMT (center point)



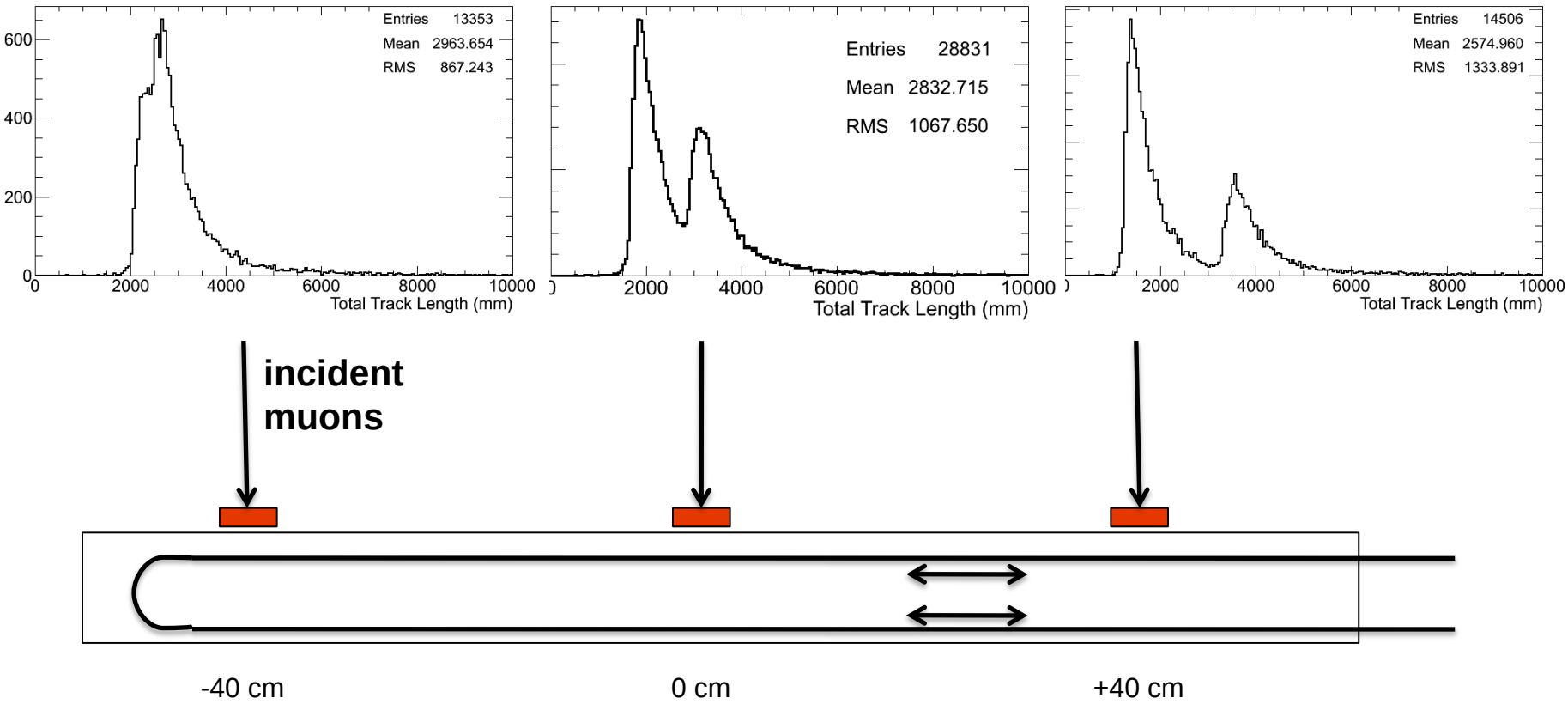






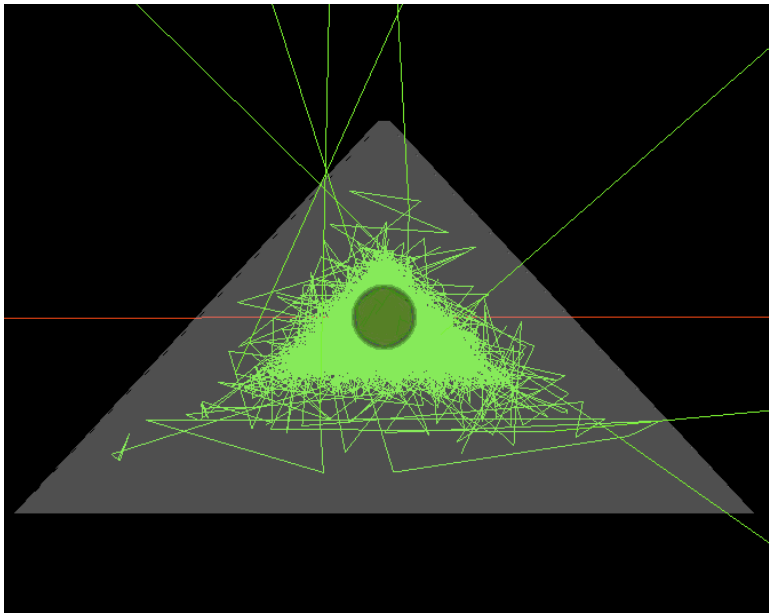
Simulation Results

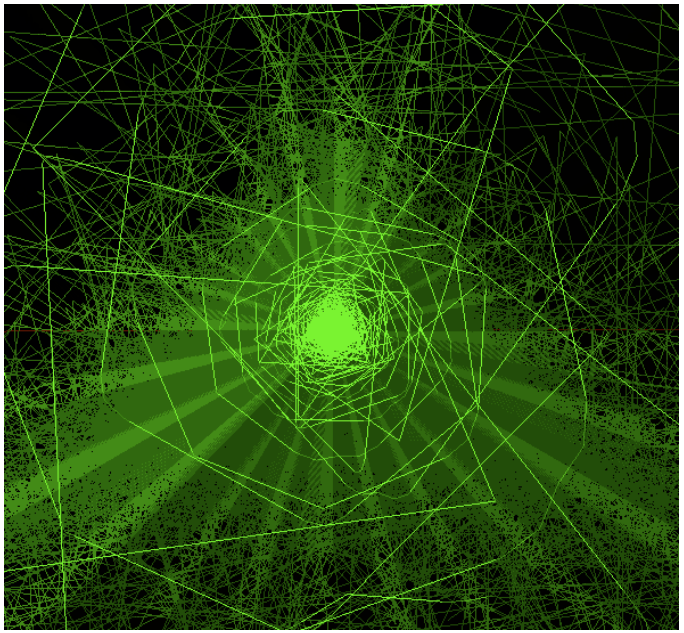
Comparison of track lengths for three positions

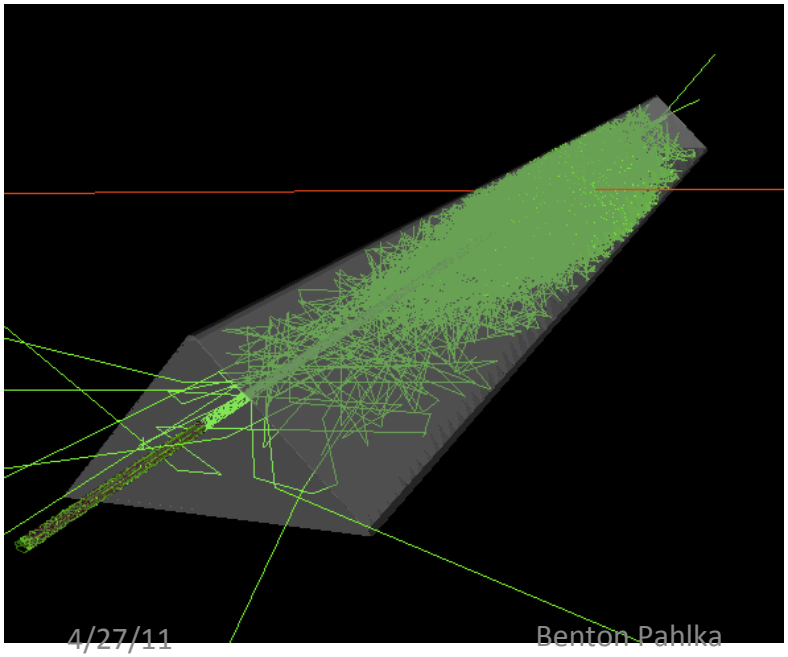


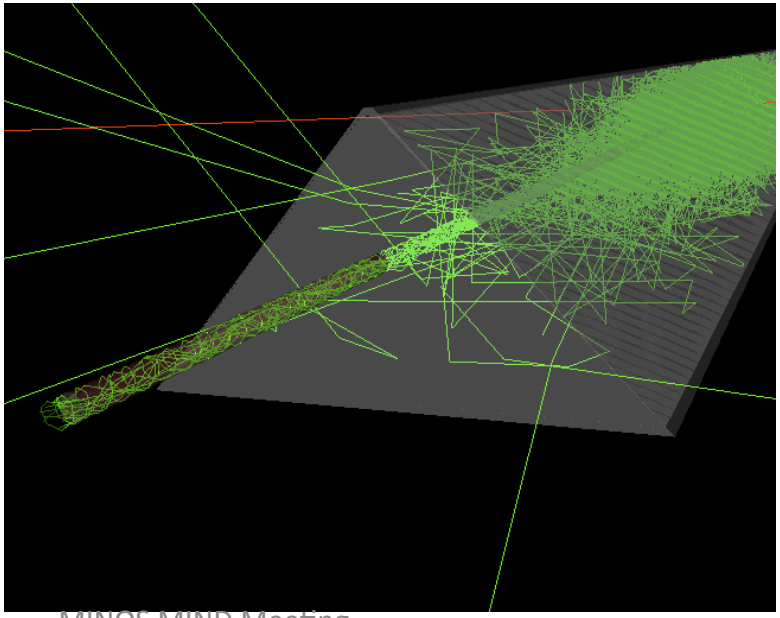
Demonstrates propagation in curved fiber

Preliminary MINERvA Setup









Single Strip MC Comparison

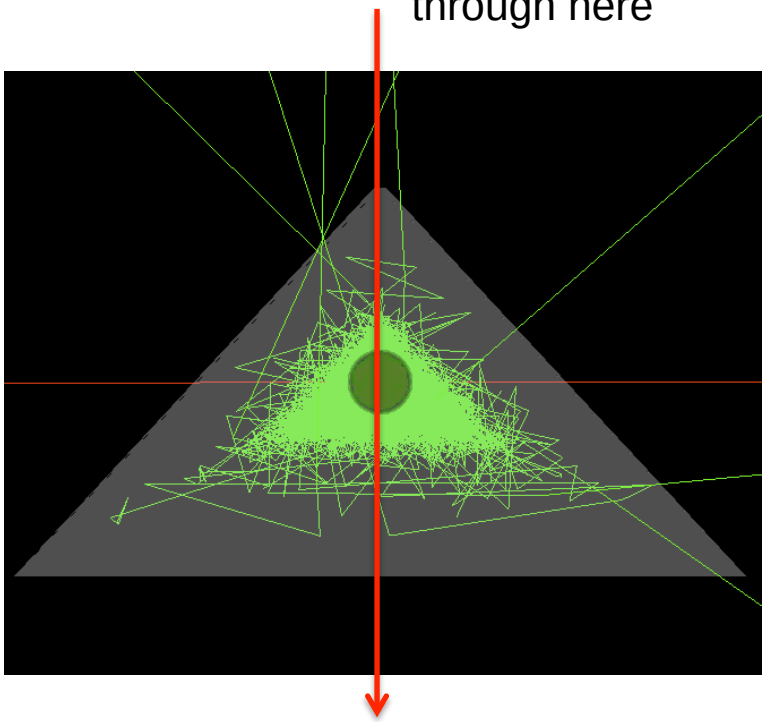
Compare energy deposition profiles (neglect photon generation)

This analysis:

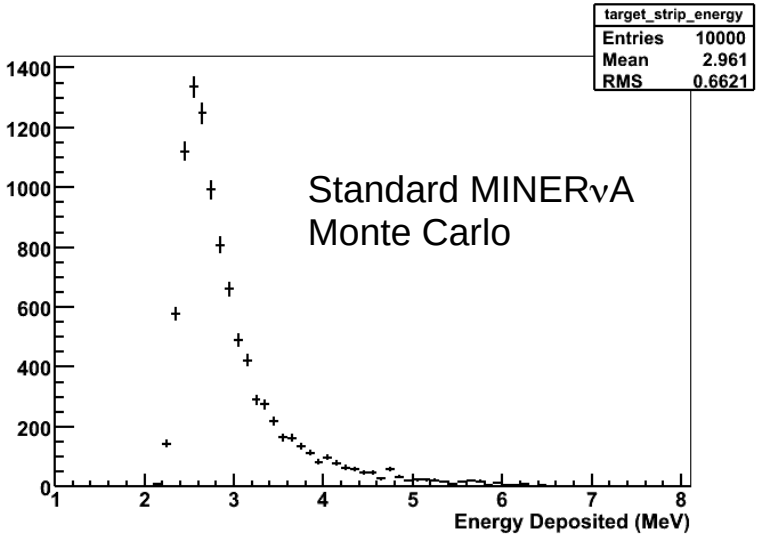
- 10000 muons at 1 GeV
- muons generated at center of strip
- pencil beam at largest scint thickness
- Birk's constant = 0.133 mm/MeV

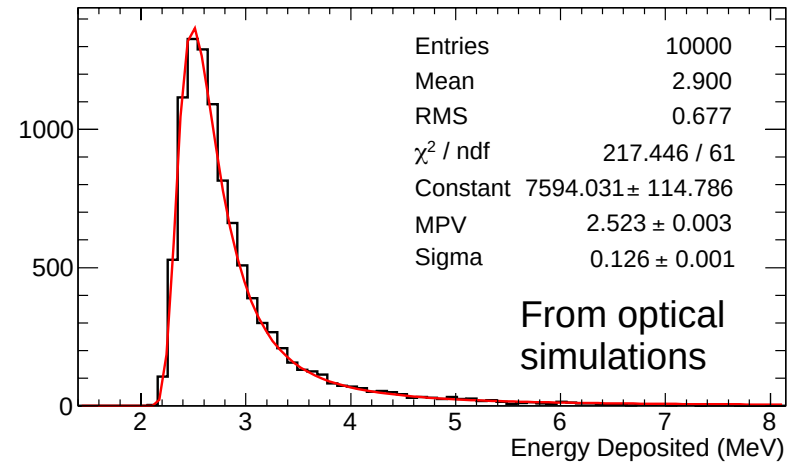
From our detector geometry description:

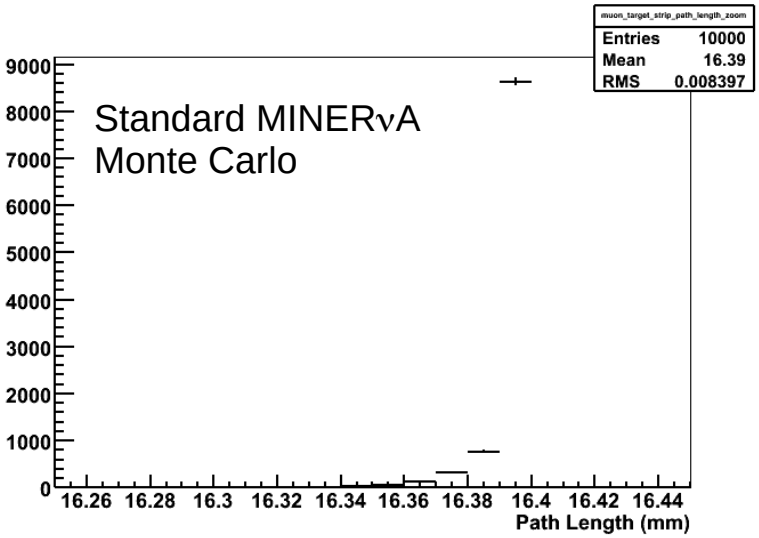
- extrusion thickness is 1.7 cm
- TiO_2 coating thickness is 0.0607 cm
- difference gives a thickness of 1.6393 cm for the active scintillator

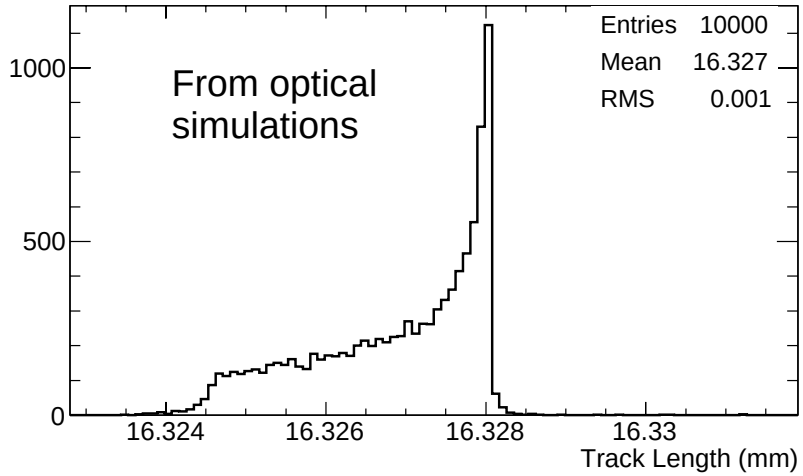


Results of MC Comparison









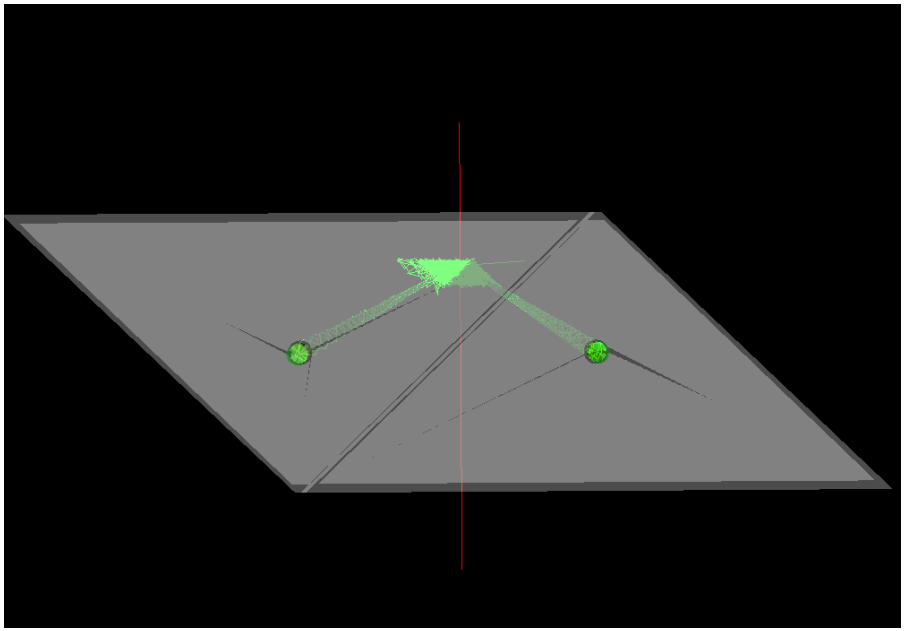
Good agreement between two sets of simulations

Two Strip Configuration

Direct comparison of data to optical simulations

Extrusion details:

- Avg. scintillator strip length = 2.33 m
- Only extrusions with:
  - WLS baggie length = 0.775 m
  - Clear fiber length = 1.067 m
- Simulation input details seen previously



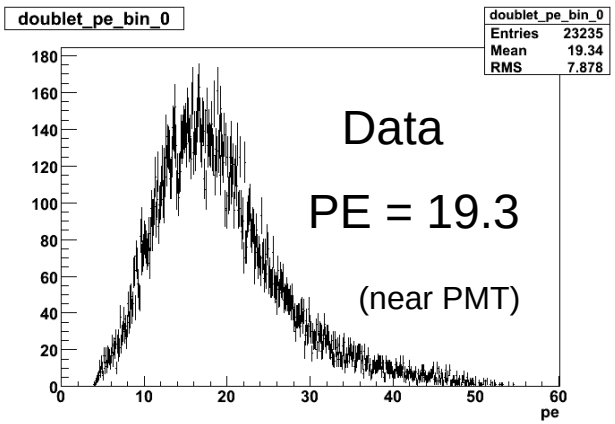
Details of rock muon data:

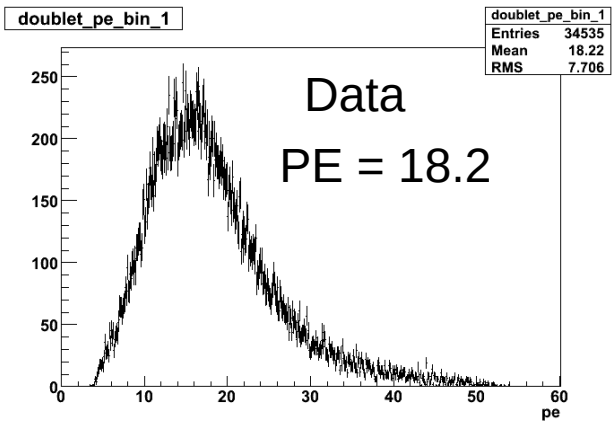
- 6 equal length positions along strip
- Require two strips to be hit
- Randomly distributed over width
- No more than 10 degrees off axis
- bin “0” closest to PMT; bin “5” furthest

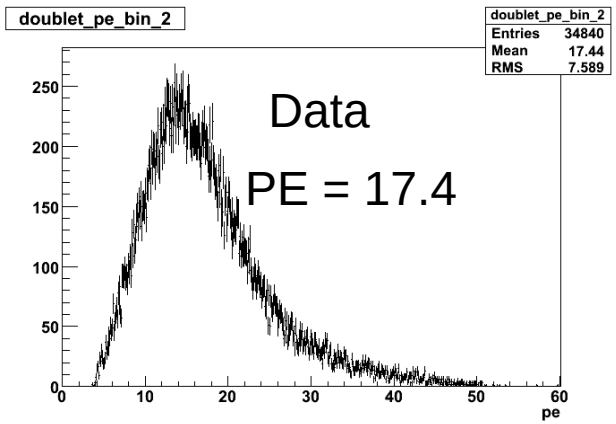
Details of optical simulations:

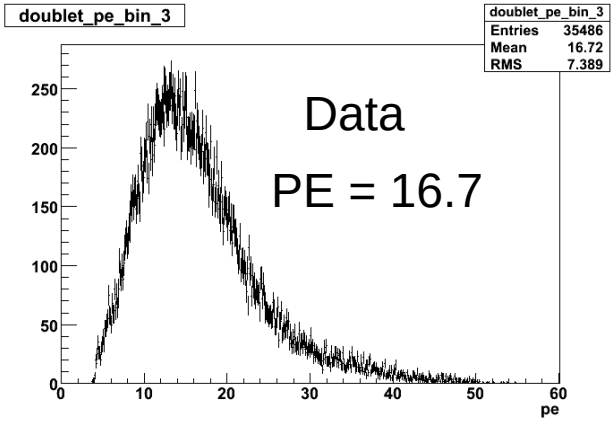
- 6 positions along strip (fixed points)
- Require two strips to be hit
- Randomly distributed over width
- No angular distribution

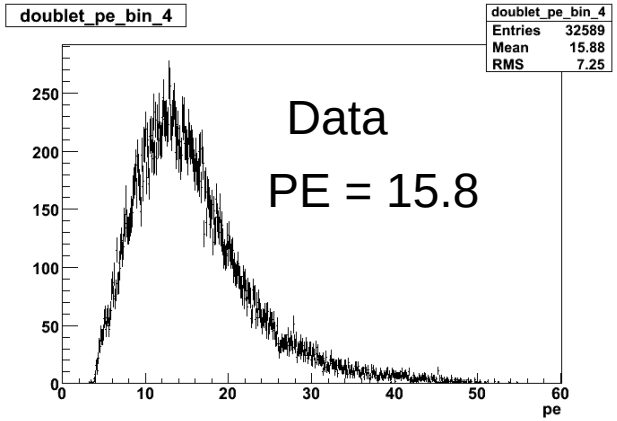
Results from Data

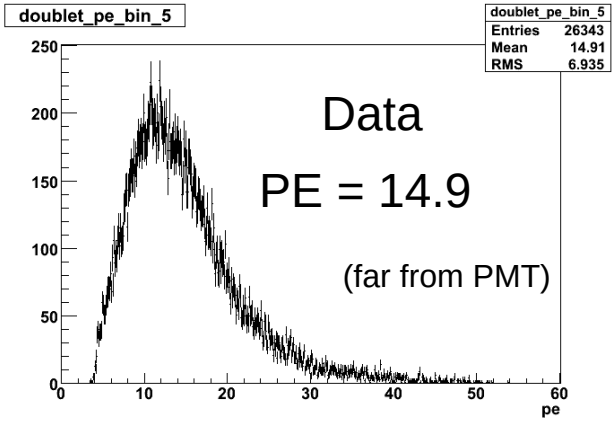




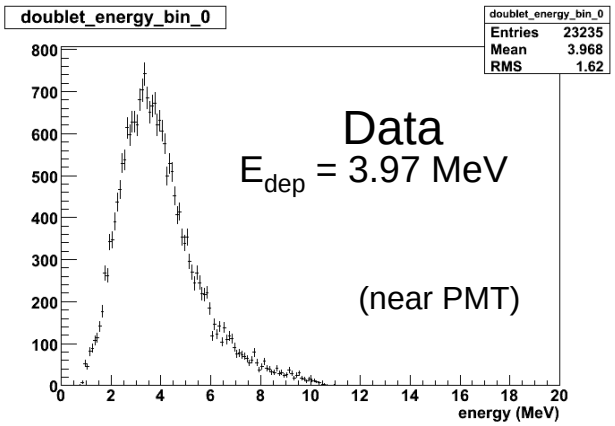


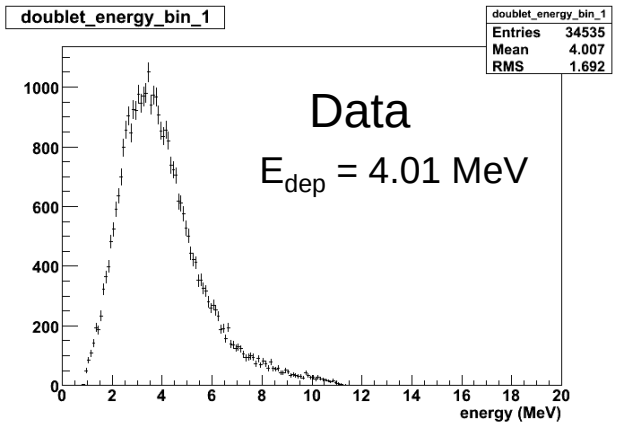


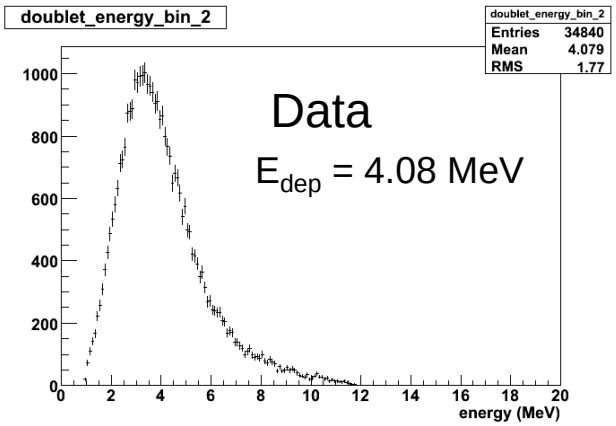


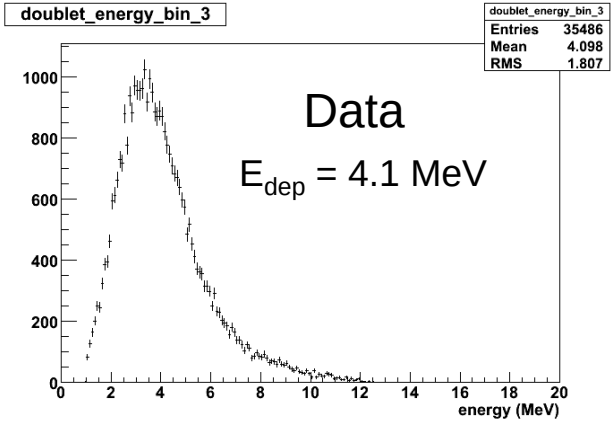


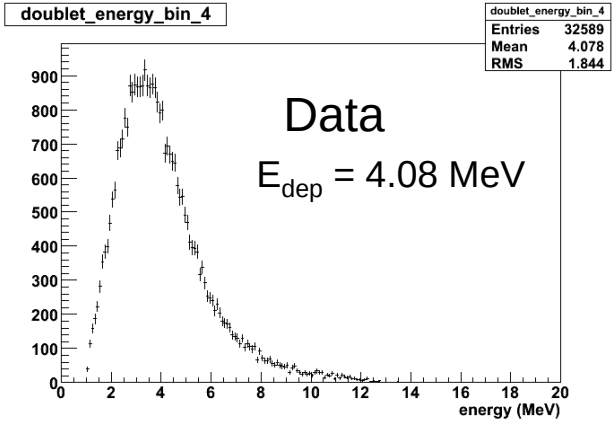
Results from Data

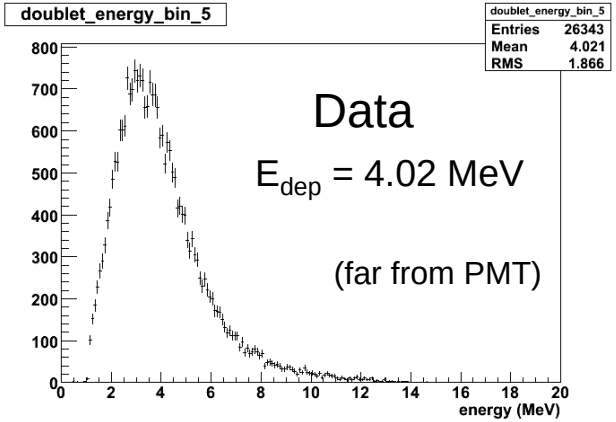








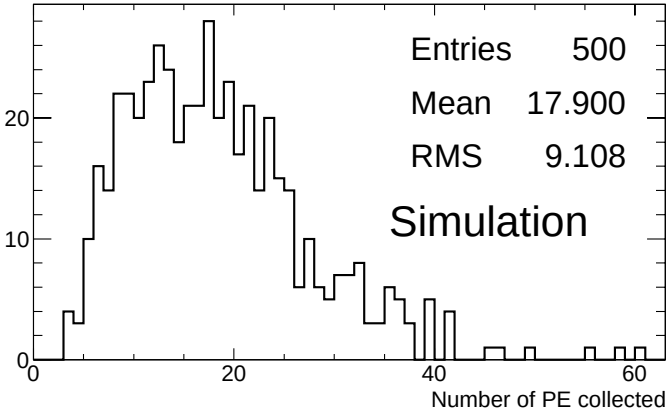


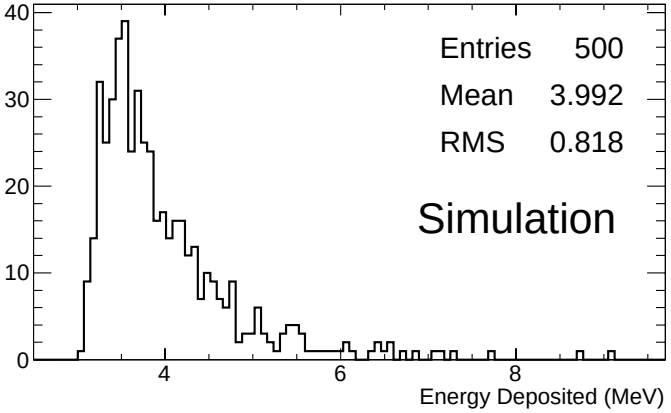


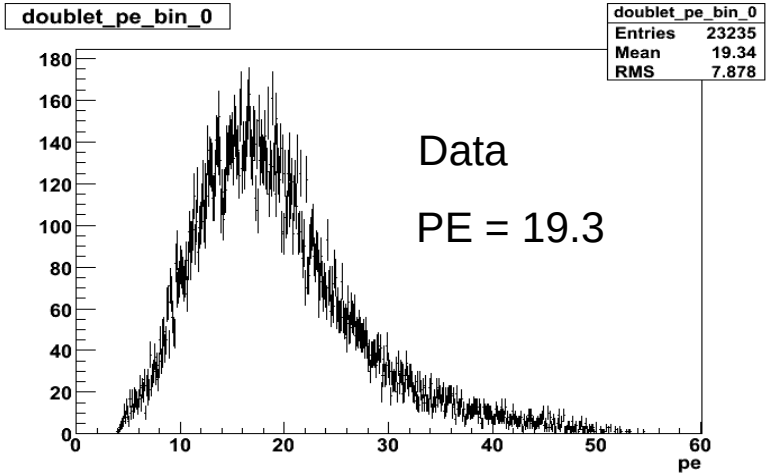
Energy deposition is back-corrected from PE count and attenuation

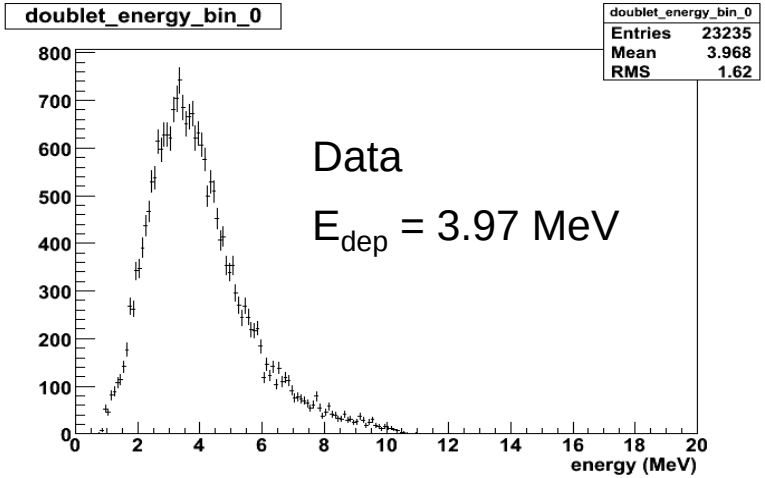
Results from Optical Simulation

Results for the bin nearest the PMT







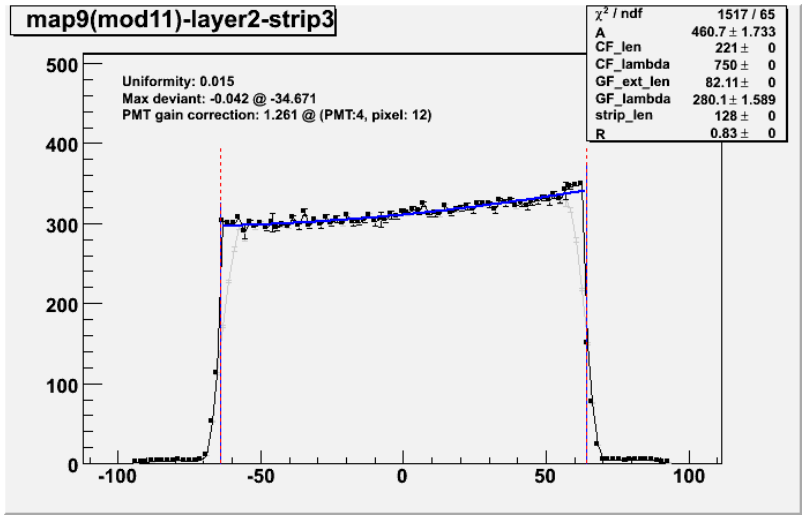


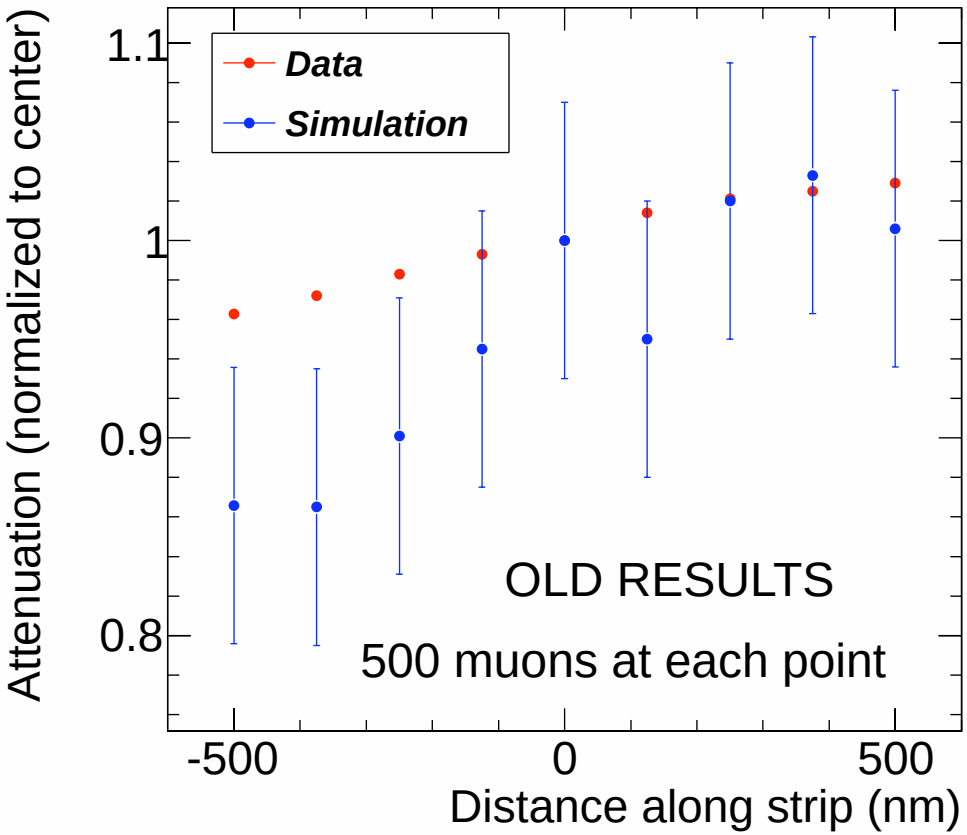
…more results very soon

Preliminary MINERvA Setup

Return to the 1.25 m extrusion: Add more statistics

- Normalize data spectrum to center
- Normalize simulation to center
- Errors are statistical for sim

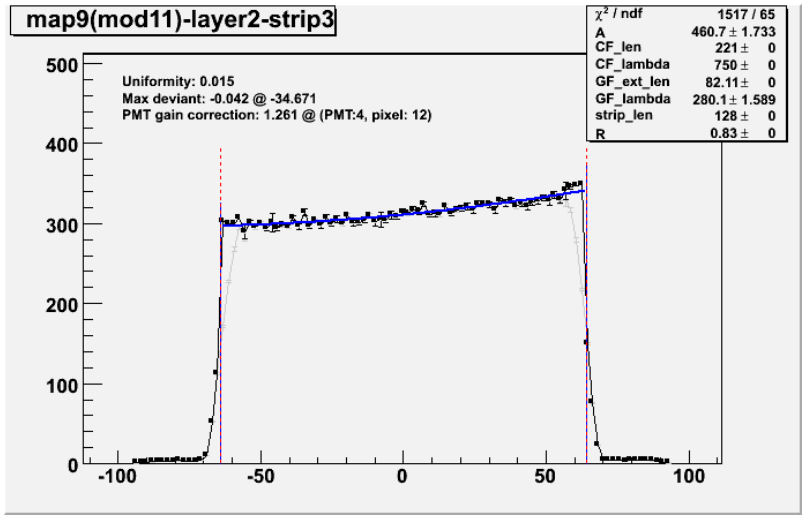


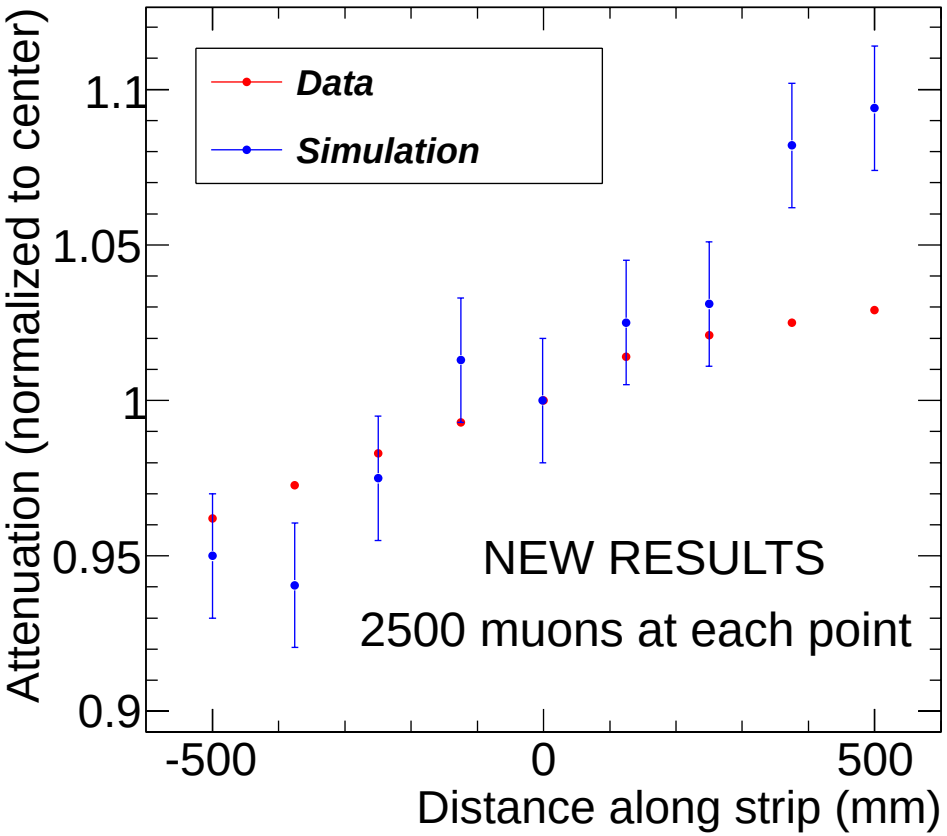


Clearly need more statistics. Normalization to center may skew this plot.
Data was scanned "crudely" with a plot digitizer. Room for improvement!

Preliminary MINERvA Setup

- Normalize data spectrum to center
- Normalize simulation to center
- Errors are statistical for sim





Clearly STILL need more statistics. Room for improvement?

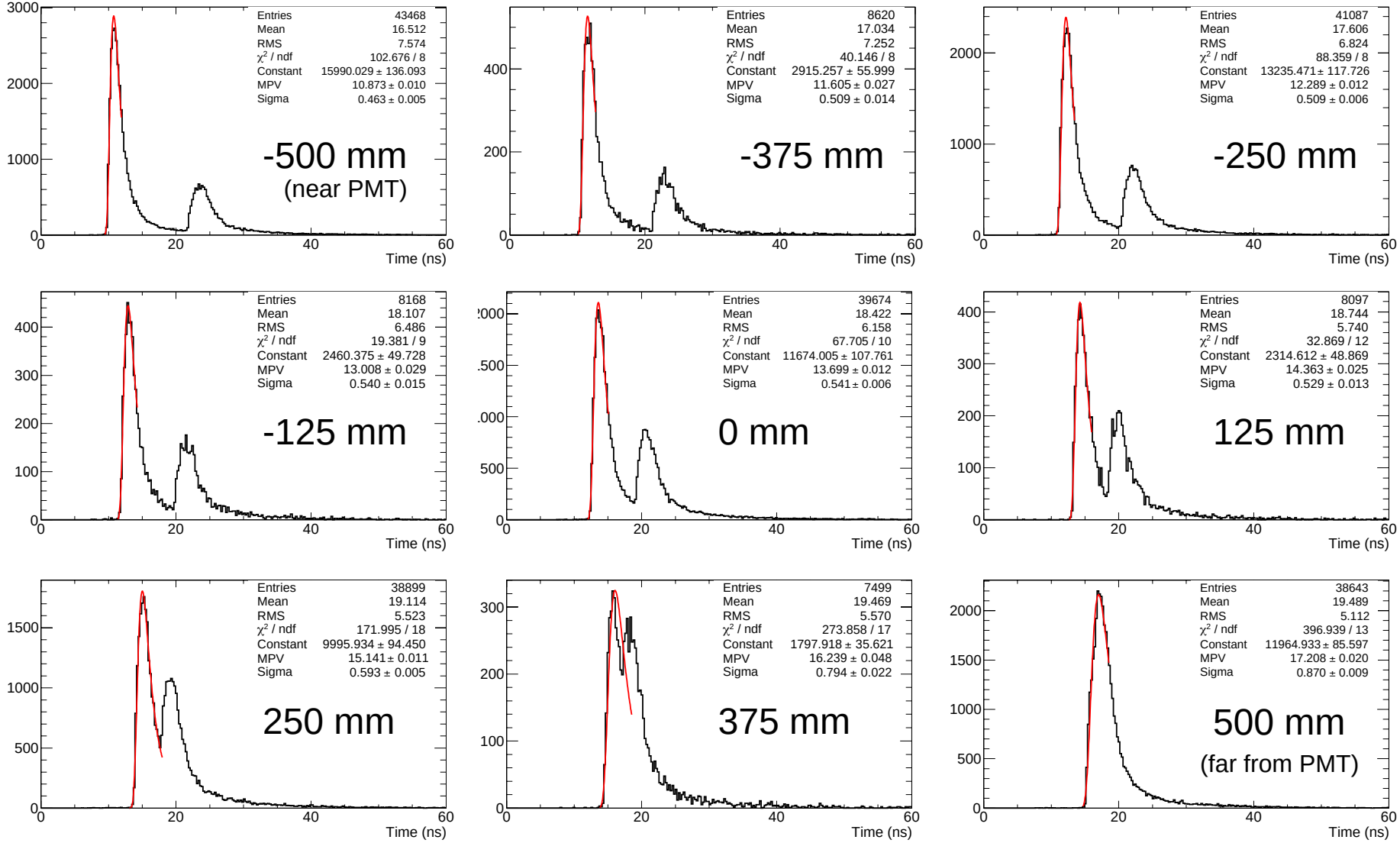
Timing Simulations

Analysis details:

- For a 1.25 meter extrusion with:
  - WLS baggie length = 0.775 m
  - Clear fiber length = 1.067 m
- Create distributions of arrival time for several positions
- Fit first peak to Landau distribution (arbitrary)

Timing Simulations

Results for the 1.25 m extrusion, 0.7 m WLS baggie, 1.1 m clear fiber



Timing Simulations

- Simulations can report a mean, sigma, MPV, and first photon arrival
- Which is relevant?
- Can include one of these as a parametrization very easily
- Do we want to include the distribution in the parametrization?

Parametrization Thoughts

Response is (could be) a function of:

- Energy deposited
- Position in “x” (width)
- Position in “z” (distance from PMT)
- Strip length L

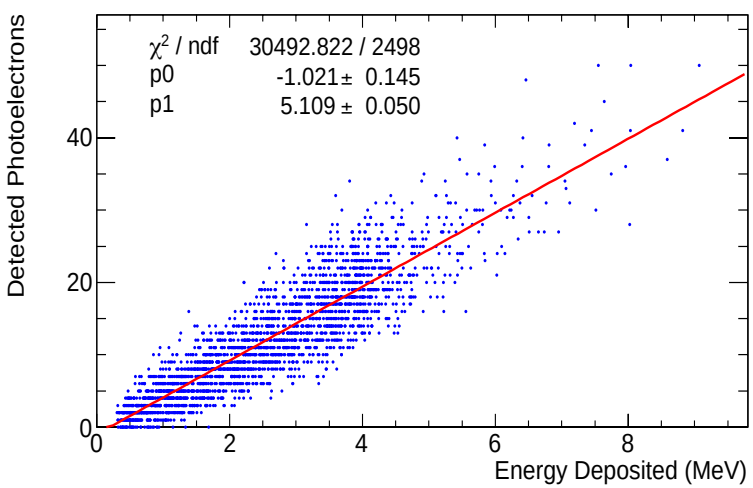
$$R = R(E_{dep}, x, z, L)$$

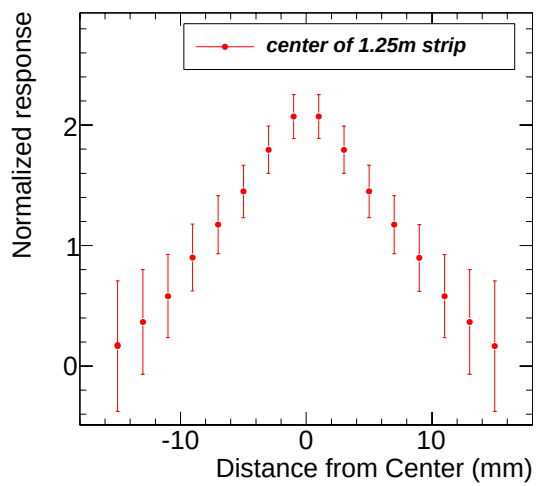
$$R = R(E_{dep}) \times R(x) \times R(z)$$

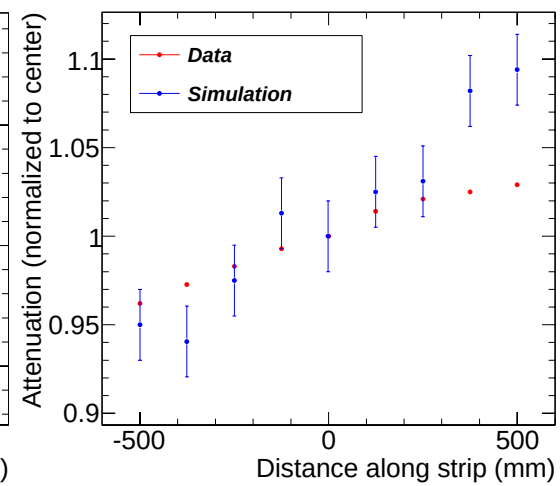
where

$$R(E_{dep}) = aE_{dep} + b$$

for each strip…
then interpolate between strips







Summary

- Single strip energy deposition show good agreement at baseline level
- Two strip data/MC comparison shows good agreement at end points
- Attenuation curve for 1.25 m extrusion better but still lacking stats
- Considered full timing response for the 1.25 meter extrusion
- Considered a possible parametrization

Future Plans

- Study timing characteristics for extrusions of different lengths
- Consider response for different path lengths
- Consider parametrization of the response
- MUST speed this up! One billion photons already run…need 10x

Summary

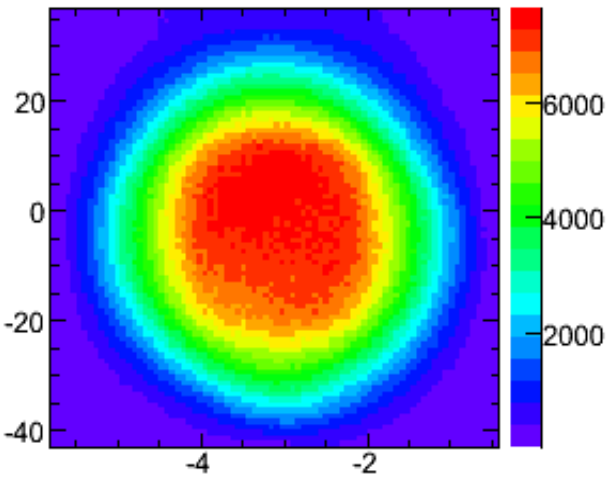
- A comprehensive optical photon model has been developed
- NEMO-3/SuperNEMO simulations agree with measurement
- WLS fiber simulations better understood
- NOvA prototype cell simulations agree with measurement
- Started preliminary work on MINERvA extrusions

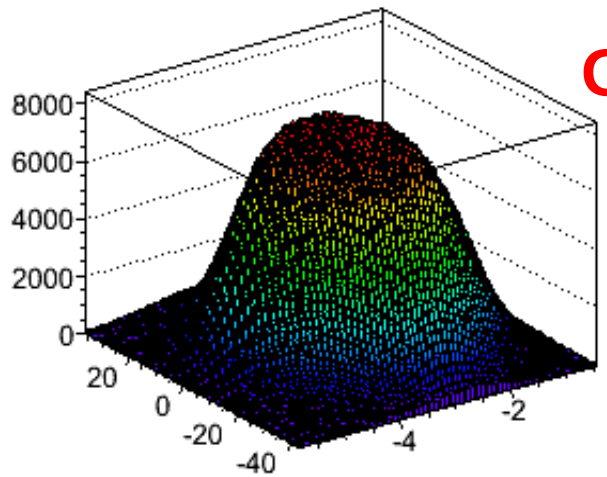
Current Plans

- Complete the detailed model of the MINERvA extrusion
- Study timing characteristics for extrusions of different lengths
- Consider a possible parametrization of the response

Backup Slides

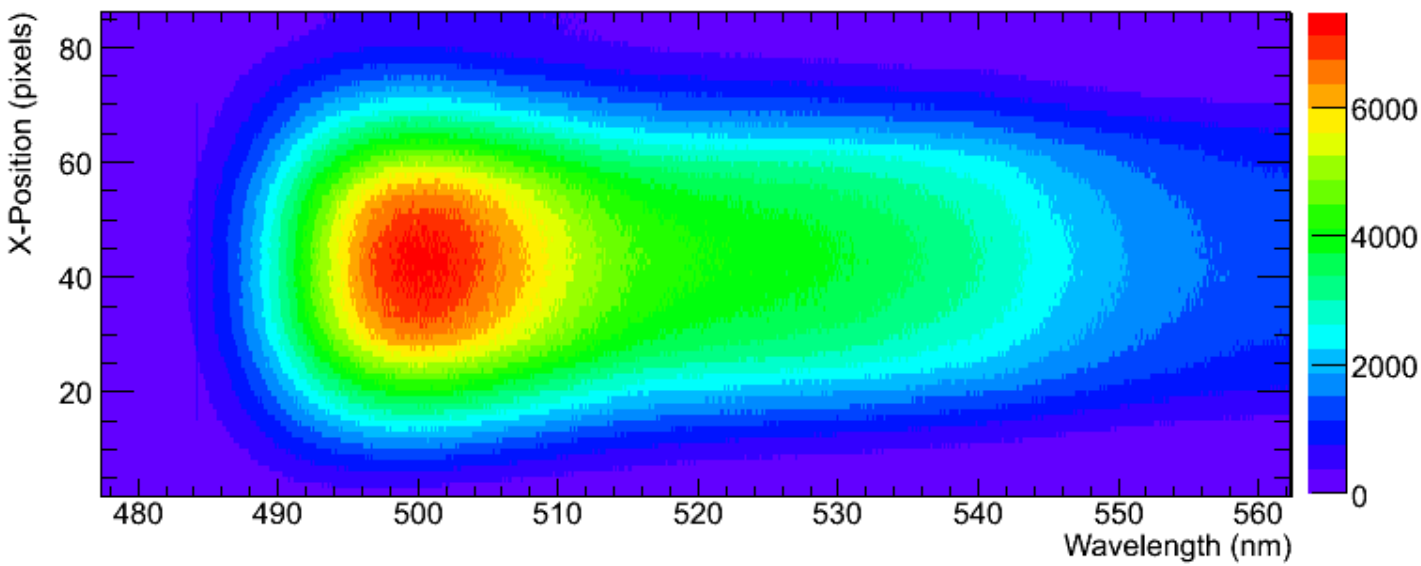
First Try: 1.2 mm Fiber



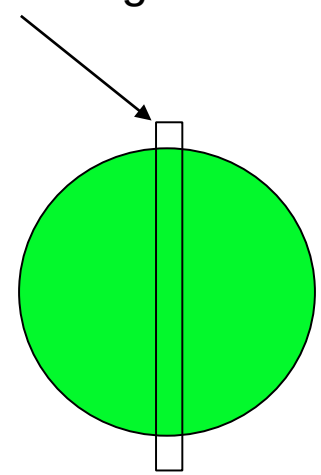


OUT OF FOCUS!

arbitrary units (pixel position)

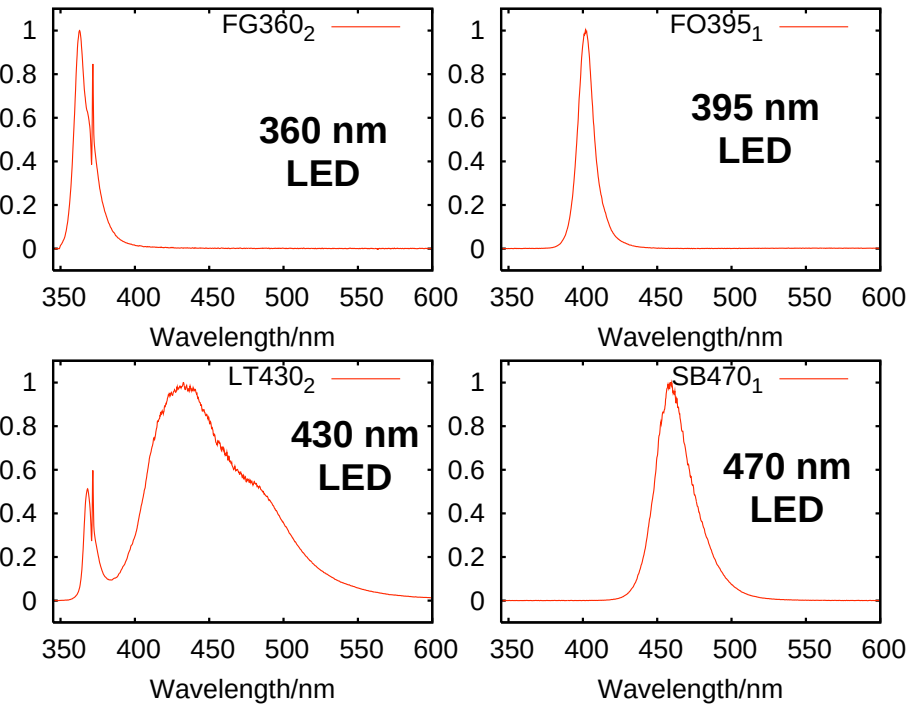


Narrow exit slit for center position vs. wavelength

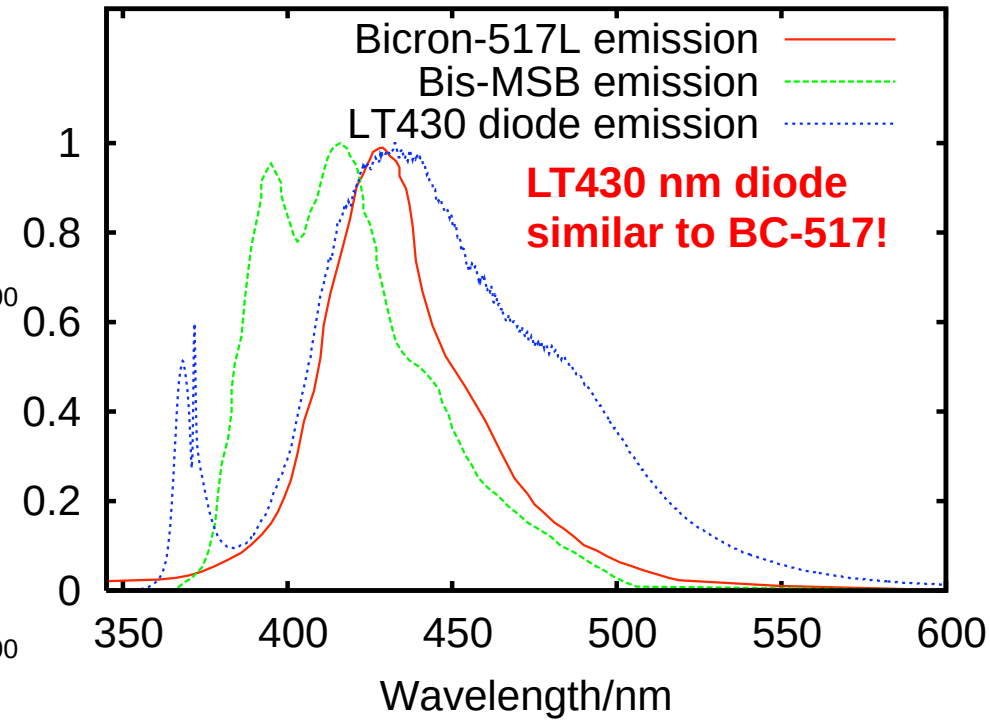


Long-distance light transport LED Measurements

Use LEDs to study fiber attenuation…and test the simulation



Spectra of select LEDs used to illuminate fibers.

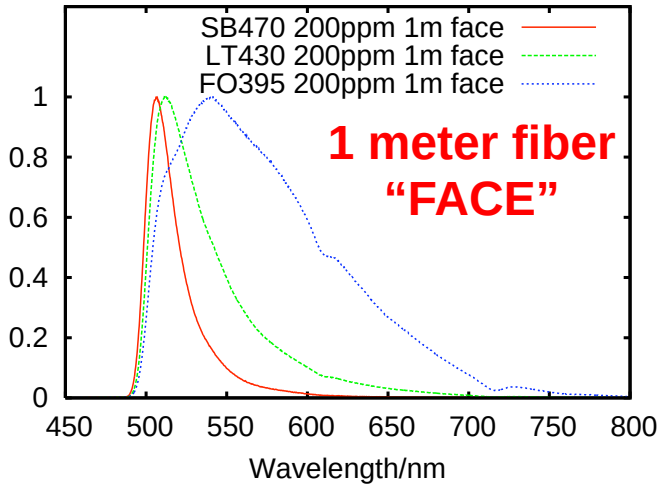


Comparison of LT430 diode with 517L scintillator and bis-MSB fluor.

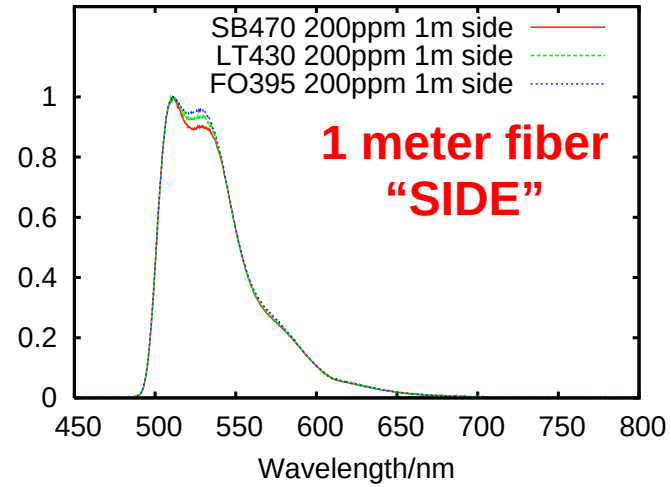
Measurements by Gabriel Elpers

Fiber Measurements (1)

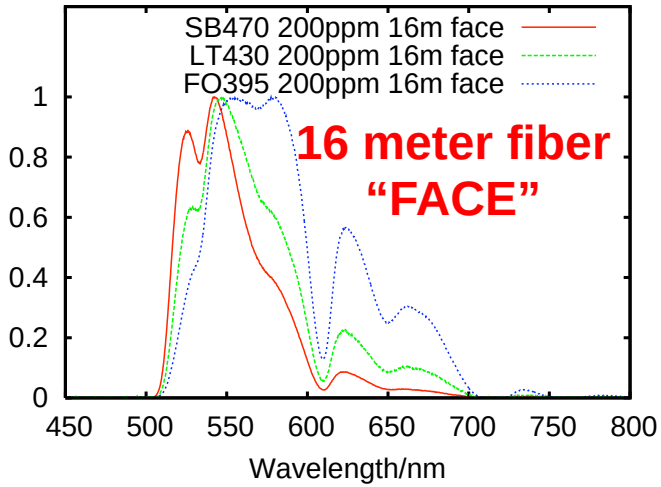
Illumination on the face shows large difference in spectra



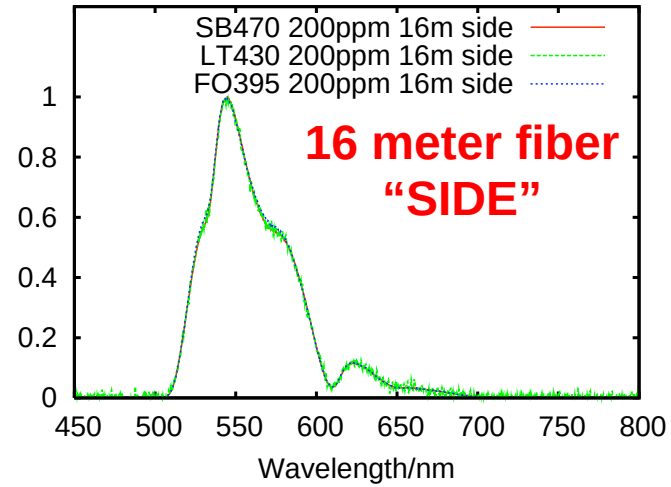
1 meter "face" illumination with three LEDs



1 meter "side" illumination with three LEDs



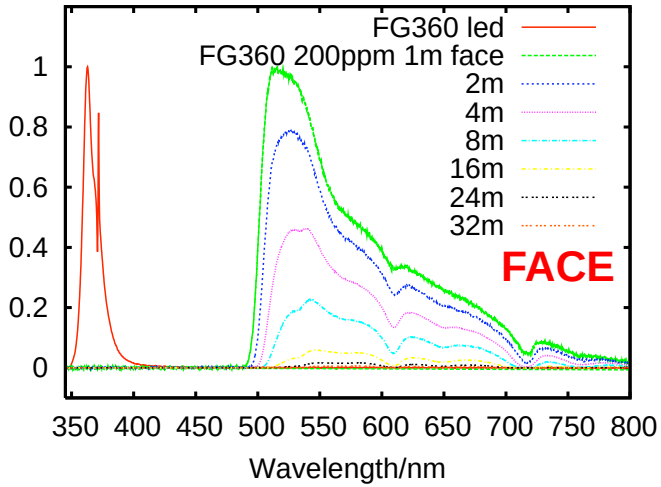
16 meter "face" illumination with three LEDs

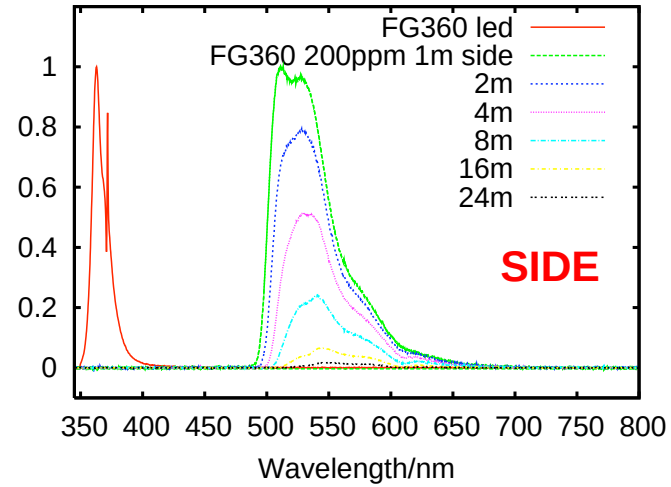


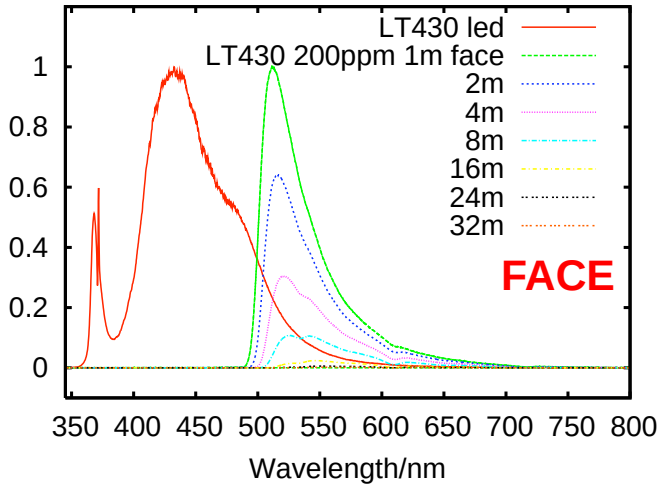
16 meter "side" illumination with three LEDs

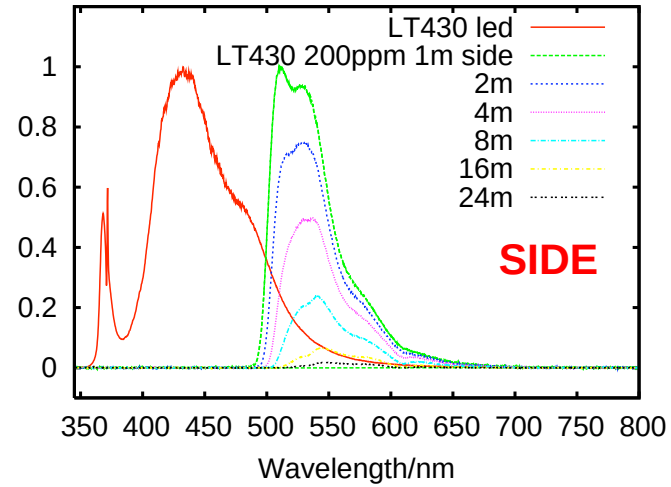
Fiber Measurements (2)

Results for two full sets of measurements for two LEDs



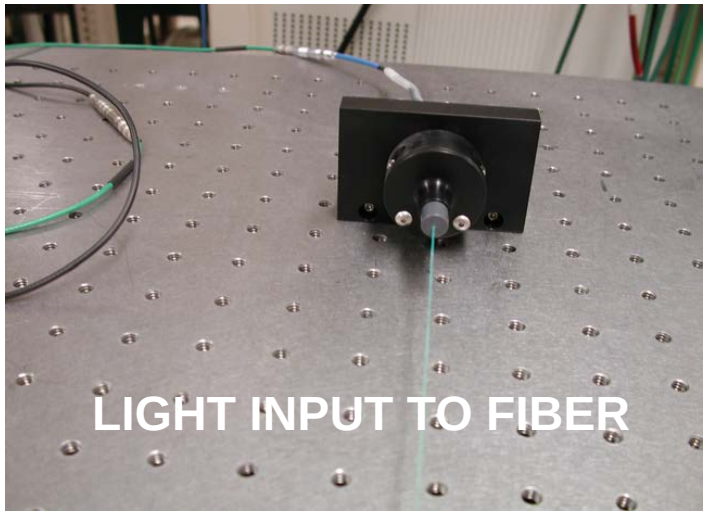


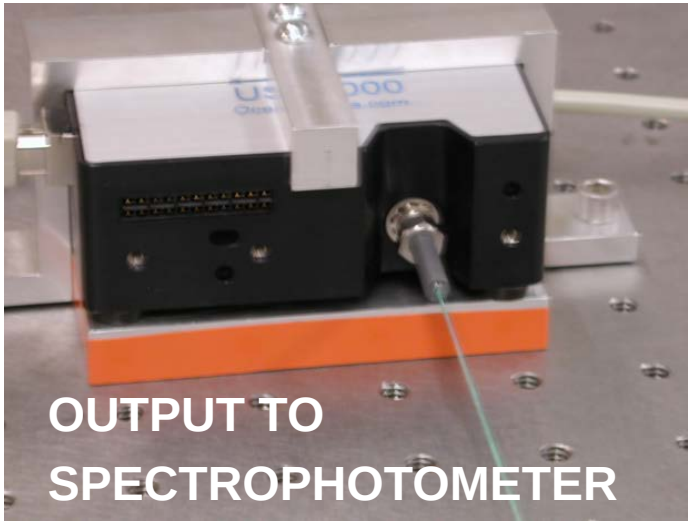


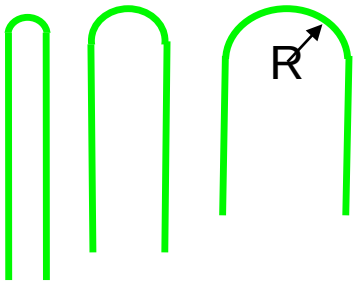


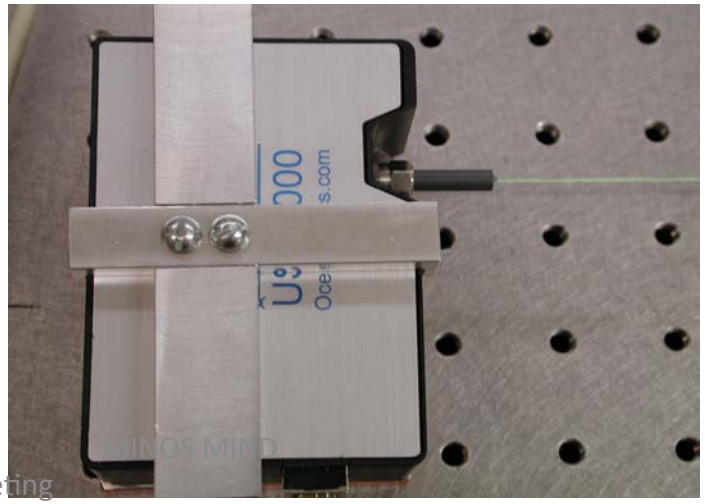
Effect of Fiber Bending

- **2.0 m 0.7 mm diameter** Kuraray Y-11 WLS **(200 ppm)** coupled to 400 nm LED
- Measurements taken at bending radius of 13.5 cm to 1.5 cm in 2 cm increments

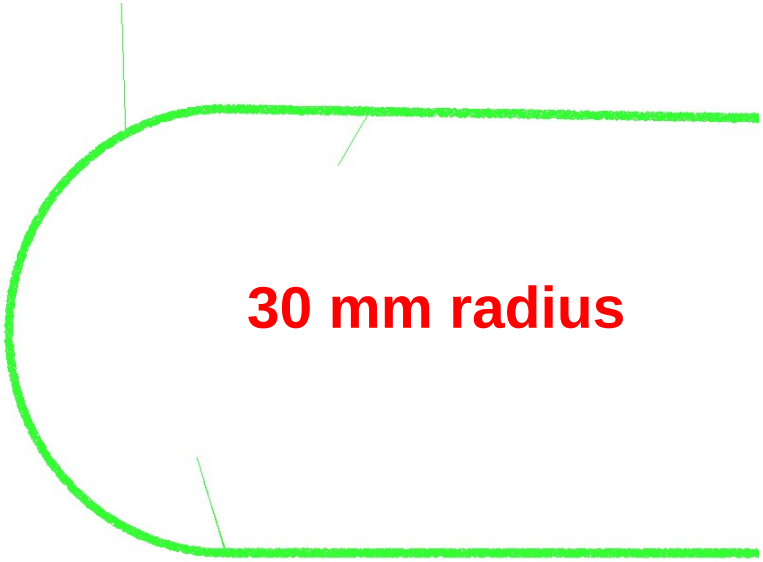


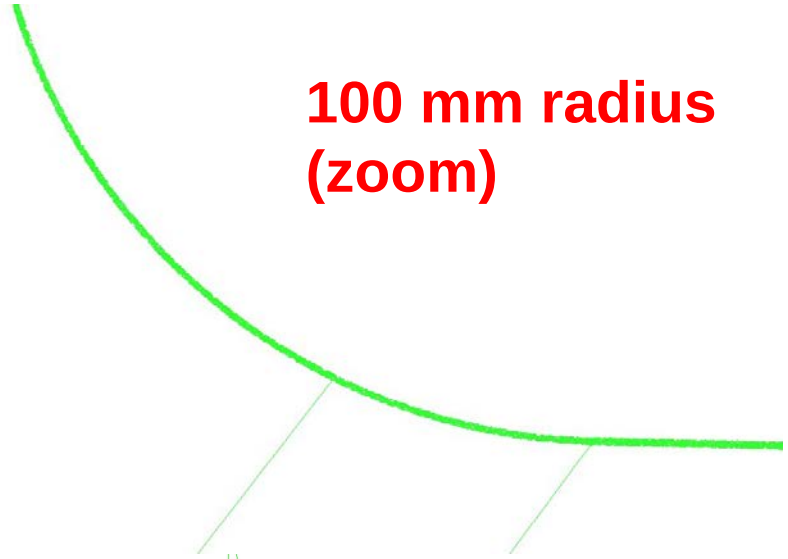


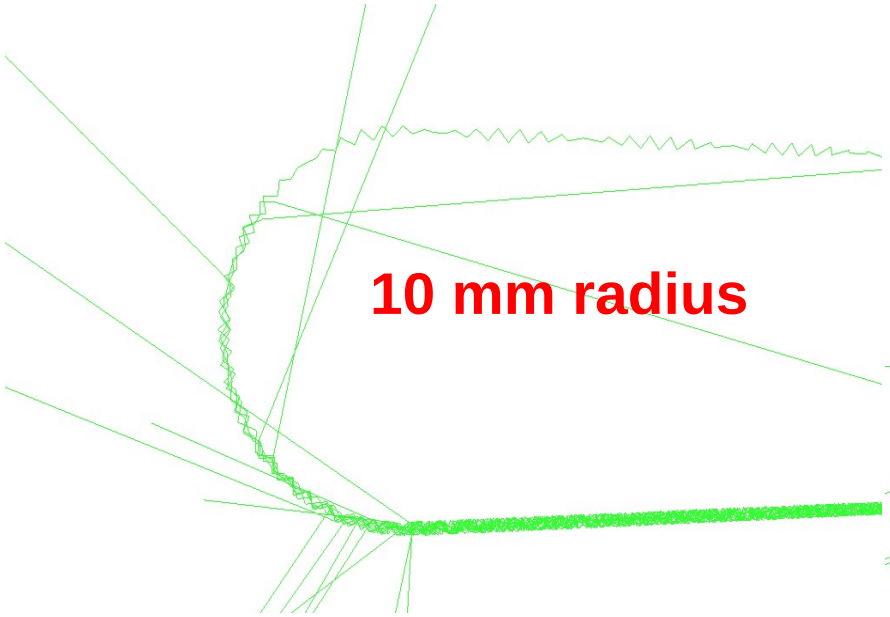


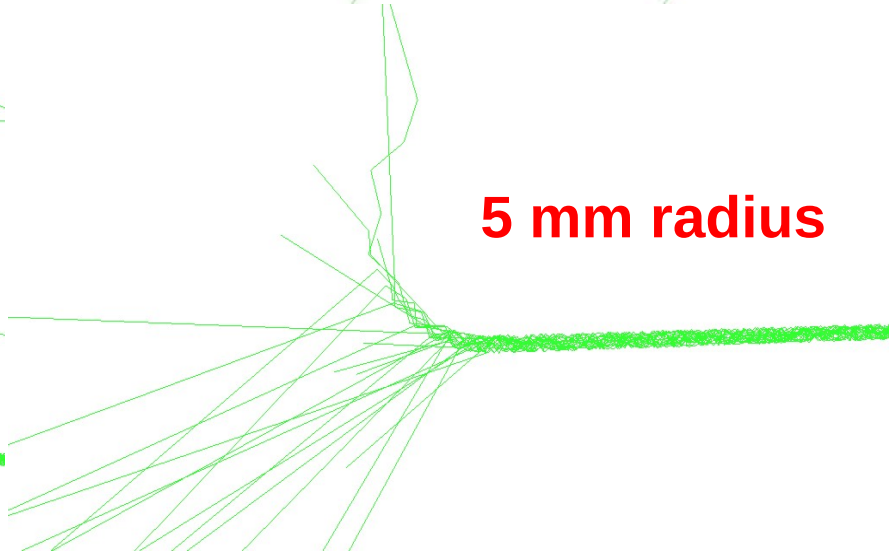


Bending Radius Studies: Images



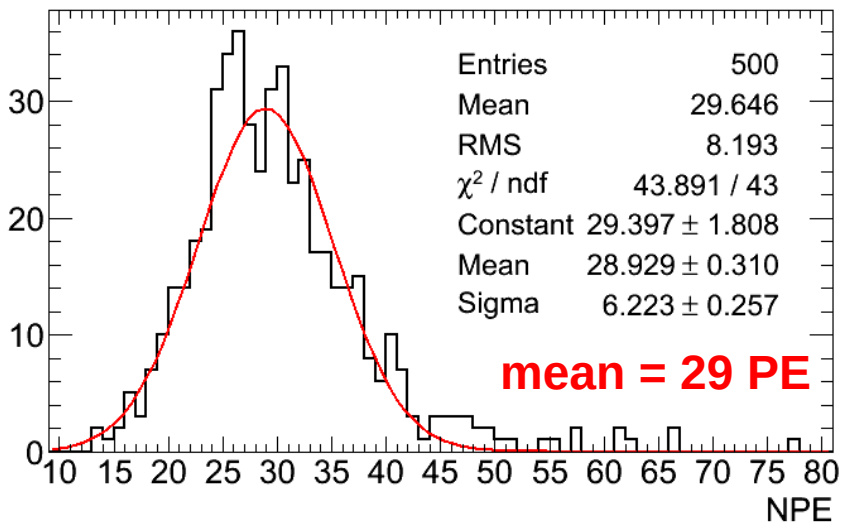






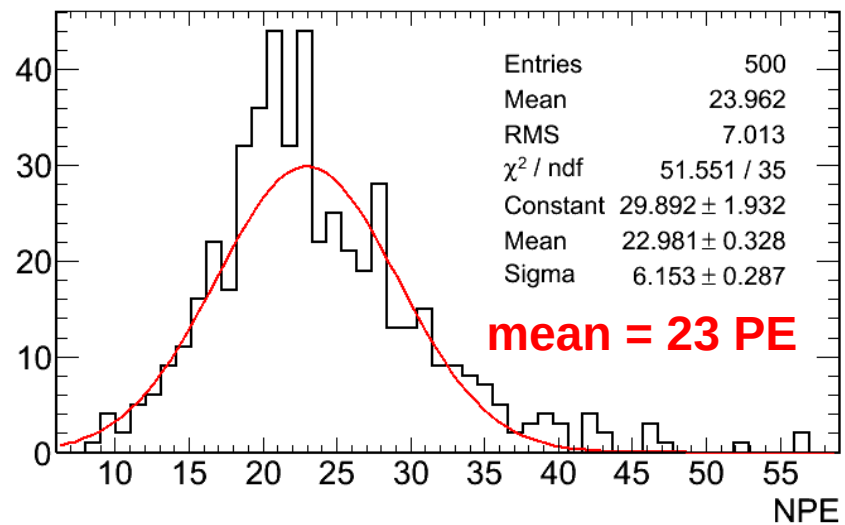
Simulation Results

Simulations show a large difference between anatase and rutile!



Photons detected using anatase

(anatase reflectivity Ref. NOvA TDR)



Photons detected using rutile

(rutile reflectivity Ref. Ana Pla-Dalmau, 2008)

NOvA Cell Simulations

MODEL:

- All materials modeled with wavelength dependence
- Uses PPO and bisMSB as fluors
- WLS for ALL fluors (PPO -> bisMSB-> k27)
- Scintillator absorption length from TDR in 400-460 nm
- Light yield = 4,000 photons/MeV (~28% anthracene)
- Accounts for all fluorescent quantum yields
- Fluorescent quantum yields are: PPO/bisMSB = 93% k27 = 70%