



Photon Transport Simulations (and some measurements)

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Fermilab

Big Picture:

Provide optical modeling for extrusion-based scintillator bars

- a) Geometry, fiber and wrapping optimization
- b) Fast parametric response modeling

Outline:

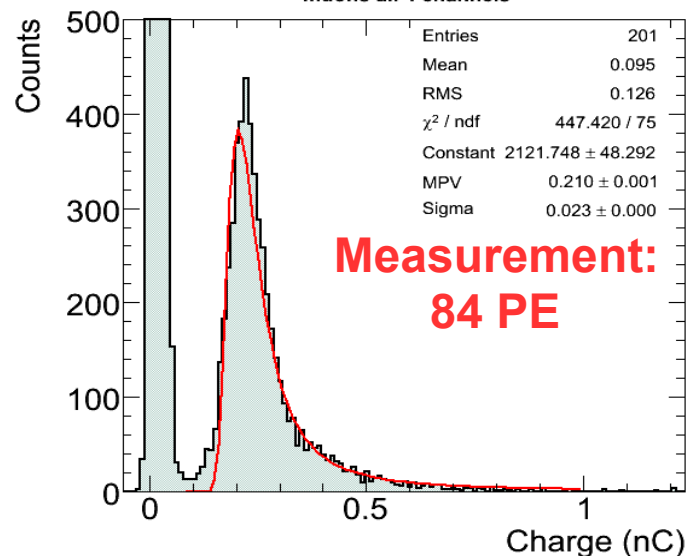
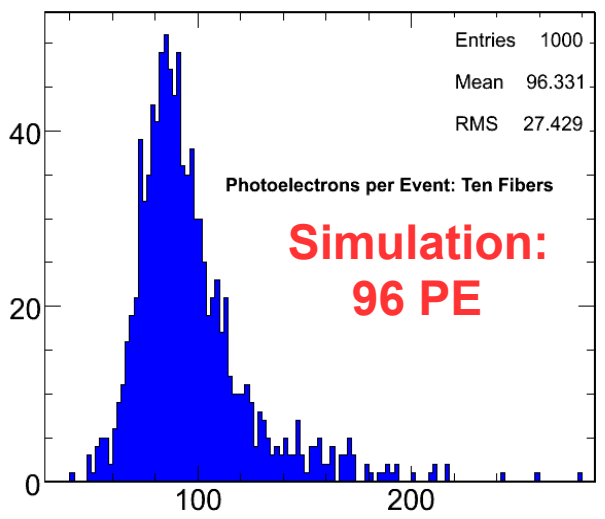
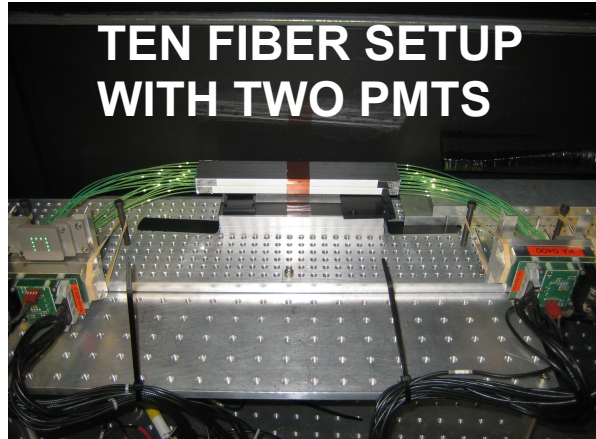
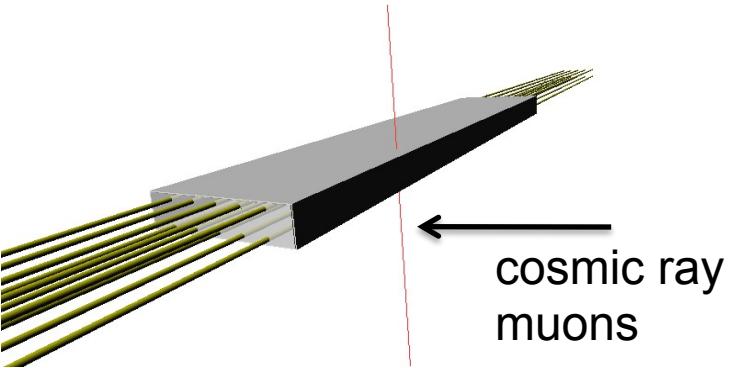
- a) Past simulation experience
- b) WLS Fiber measurements at UT Austin
- c) NOvA prototype cell simulations/measurements
- d) MINERvA simulations/measurements
- e) Other select studies



Initial Validation Modified MINOS Strips

Studies with modified MINOS strips showed good agreement

TEN FIBER SIMULATION





NEMO-3 Optical Simulations

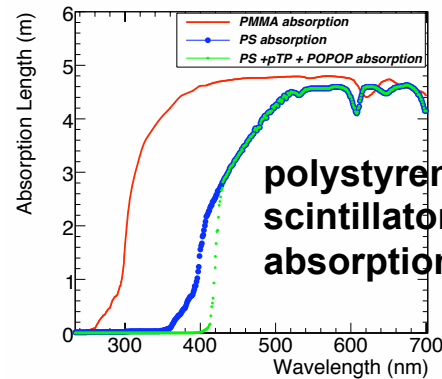
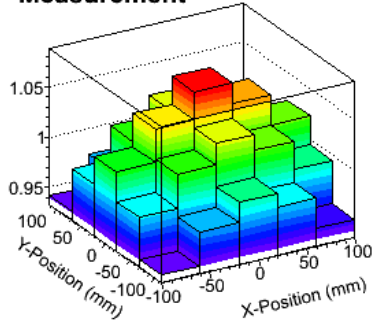
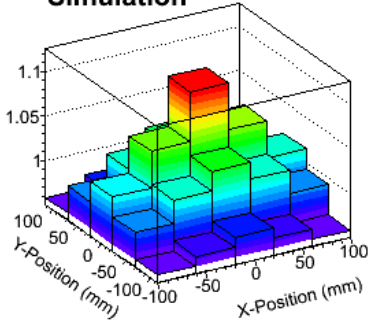


Simulations of large NEMO-3 scintillators agree with measurements

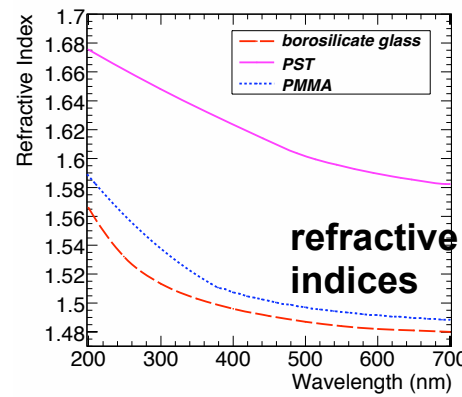
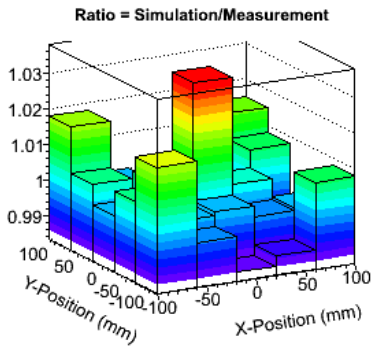
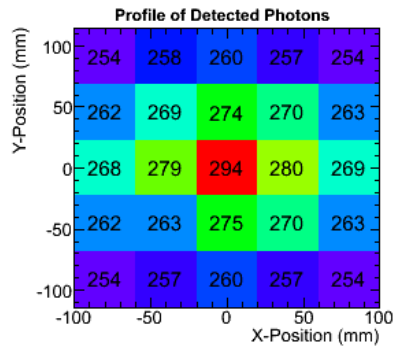
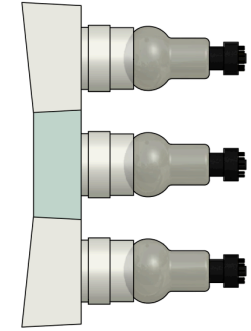
1 MeV electrons on the block face

Simulation

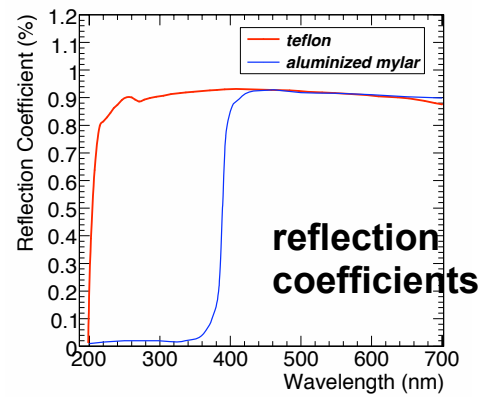
Measurement



polystyrene and scintillator absorption



refractive indices



reflection coefficients

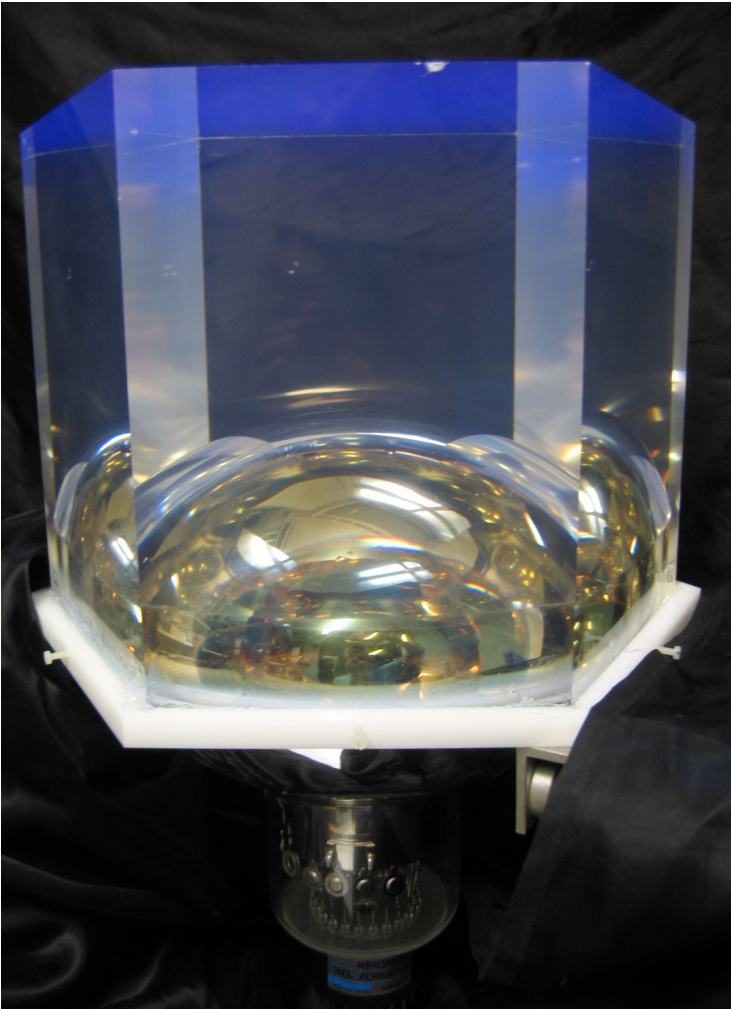
Comparison of measurement and simulation for a NEMO-3 external wall block.

(Published in NIM, Nov. 2010)

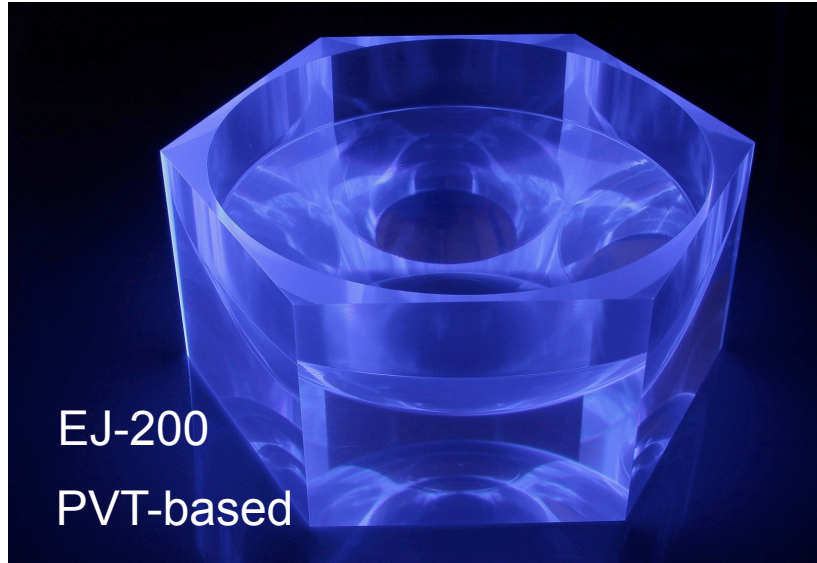
Results: 14.4% FWHM @ 1 MeV simulation
13.8% FWHM @ 1 MeV measurement



SuperNEMO Calorimeter Blocks

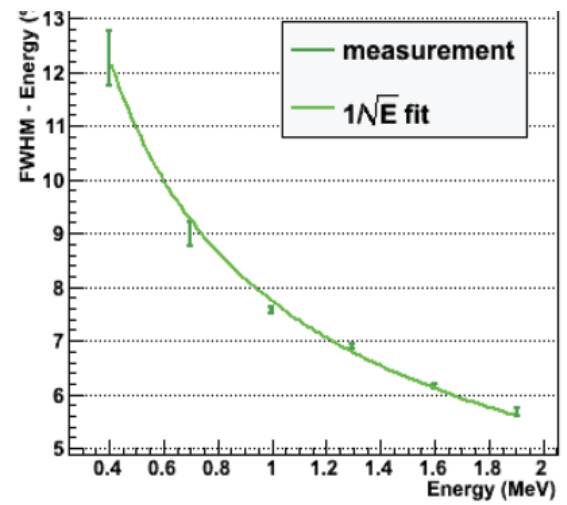


8" Hamamatsu R5912-MOD Super-Bialkali PMT with 276 mm diameter block



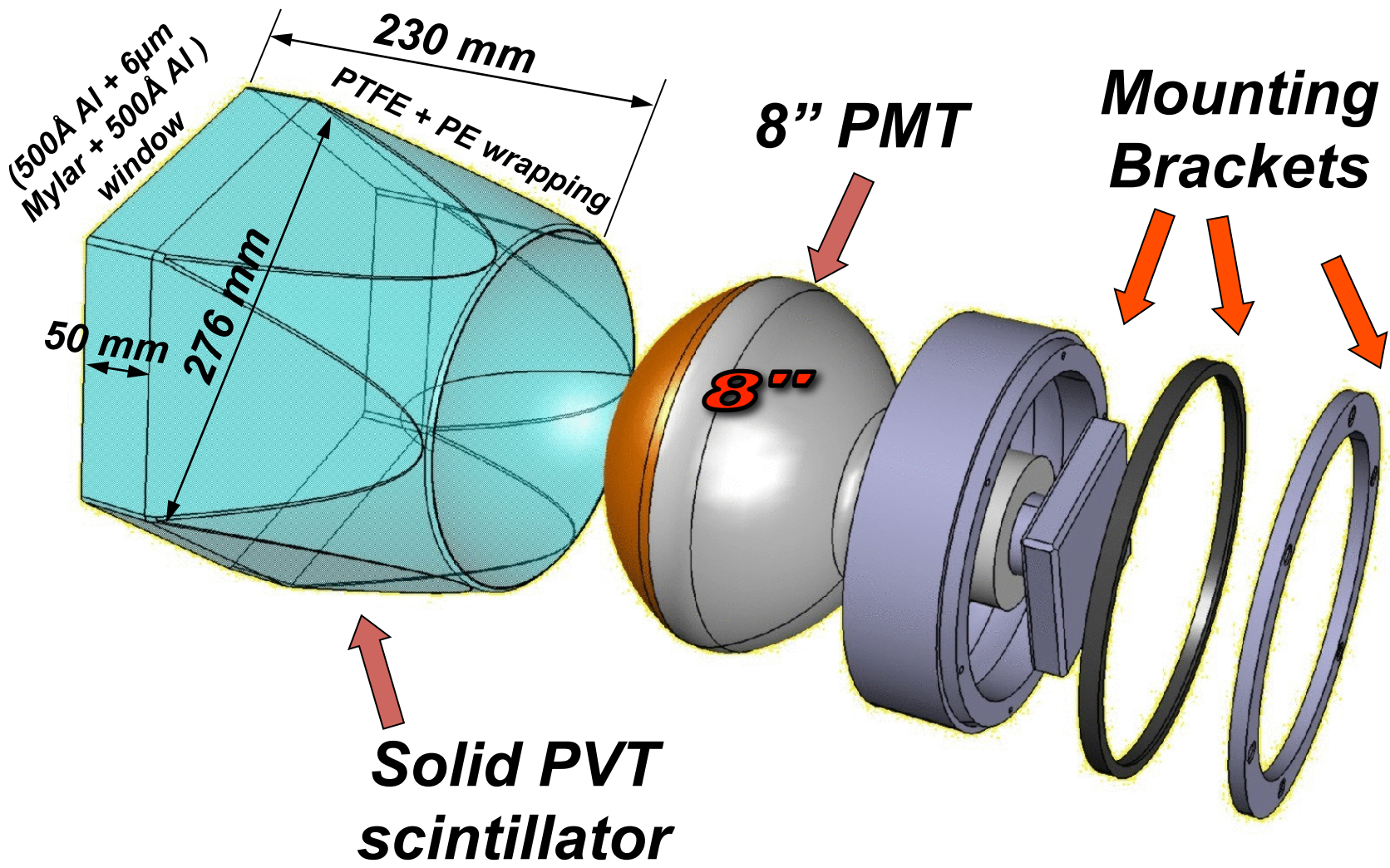
EJ-200
PVT-based

$\Delta E/E \sim 7.2\%$ (FWHM) at 1 MeV (corrected)





A SuperNEMO Module

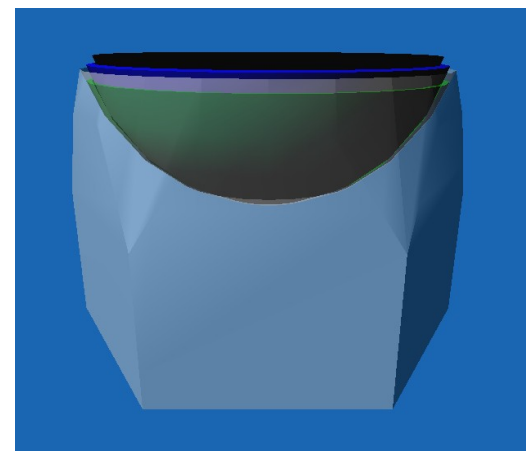
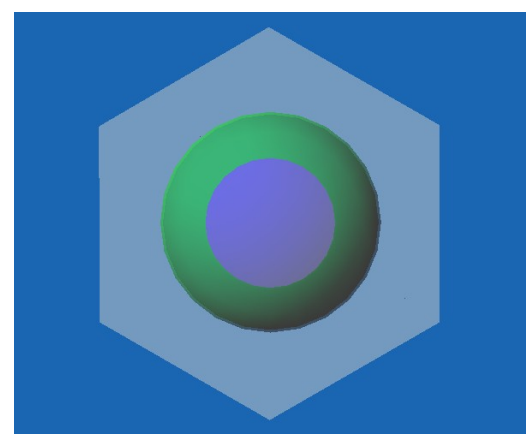
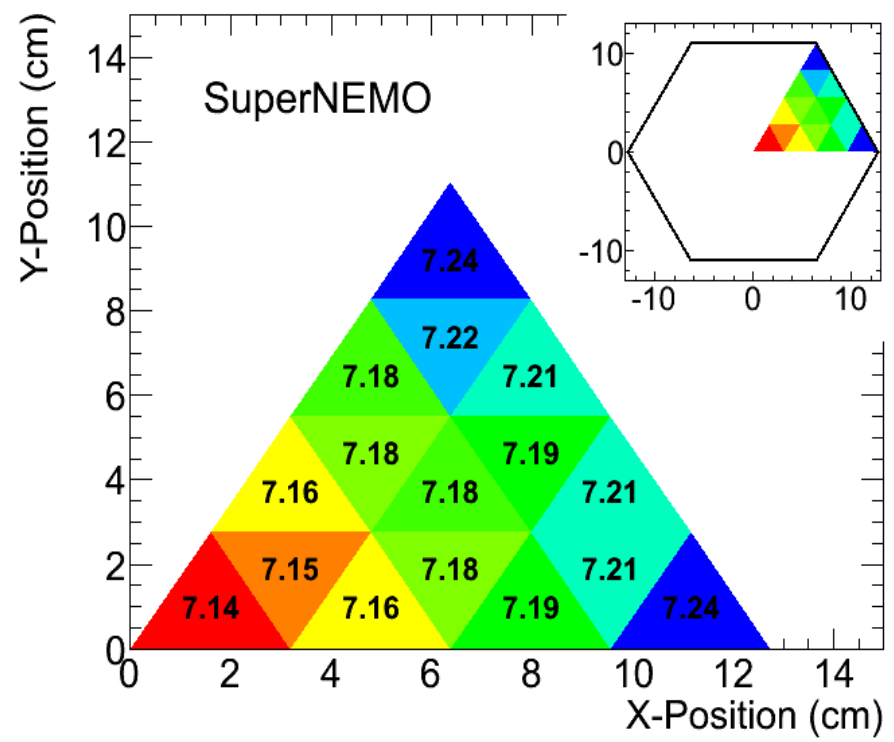




SuperNEMO Block Simulations



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 $7.5 \pm 0.5\%$ FWHM @ 1 MeV have recently been obtained.

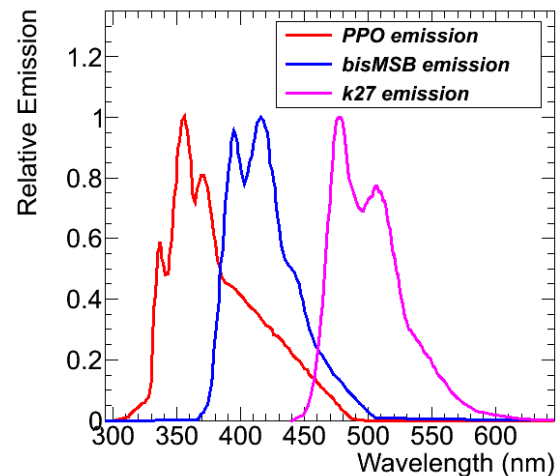


Optical Photon Model Ingredients

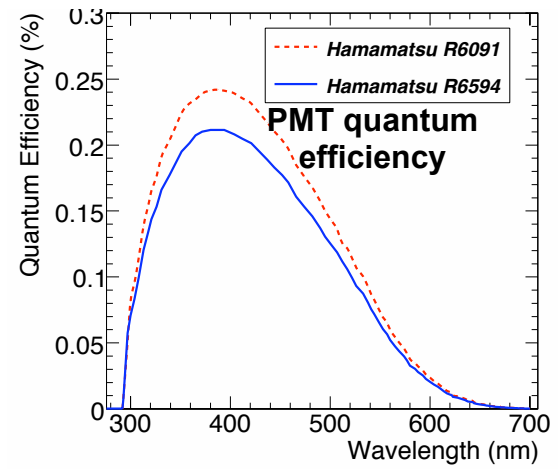
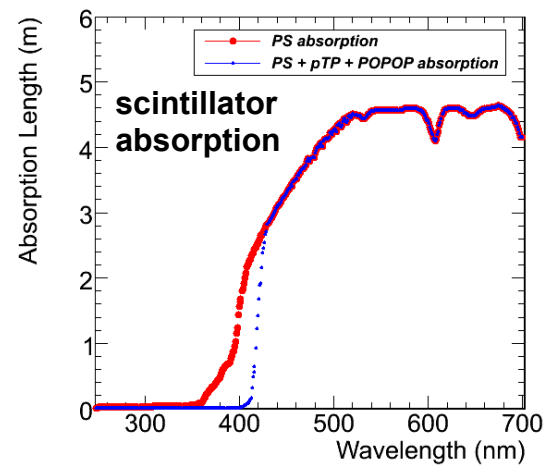
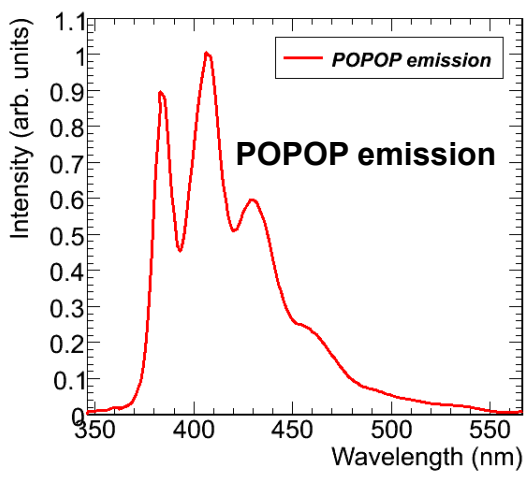


- ◆ Emission and absorption spectra
 - base scintillator
 - primary and secondary fluors
 - Stokes shifting and fluorescent quantum yield
- ◆ Spectral reflectivity of all relevant materials
- ◆ Spectral indices of refraction
- ◆ Spectral QE of photodetector

GEANT4 + ROOT framework



Example input data for optical simulations:





LED Measurements



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

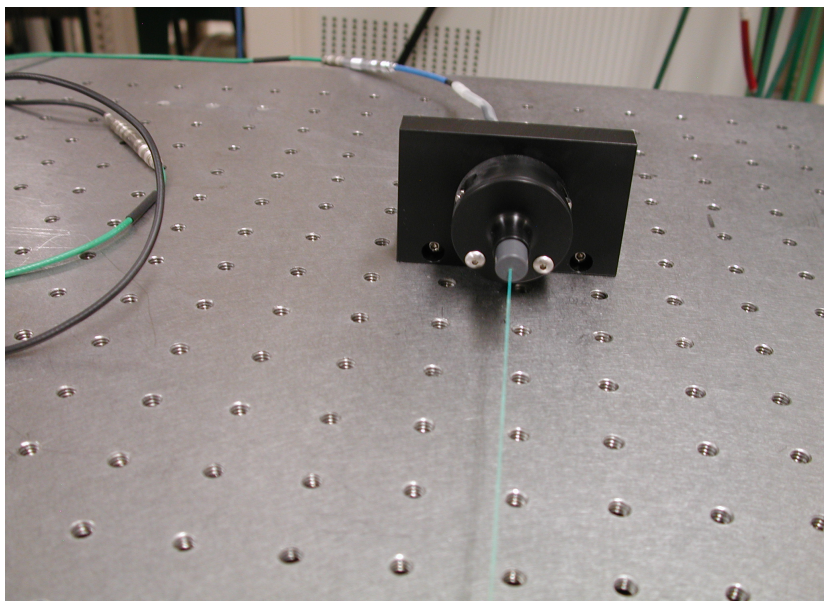
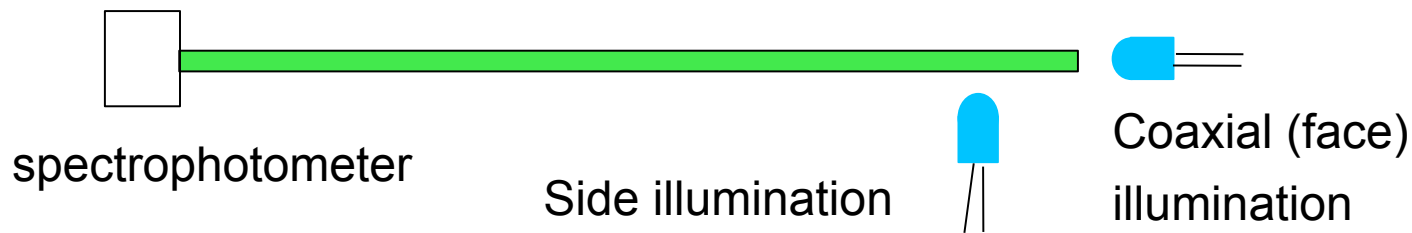


Photo of face illumination jig to align LED and fiber.

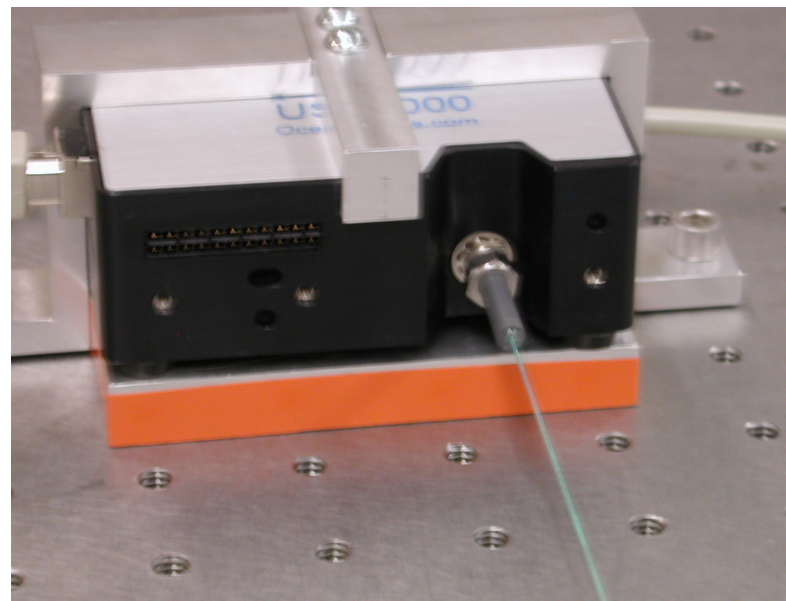
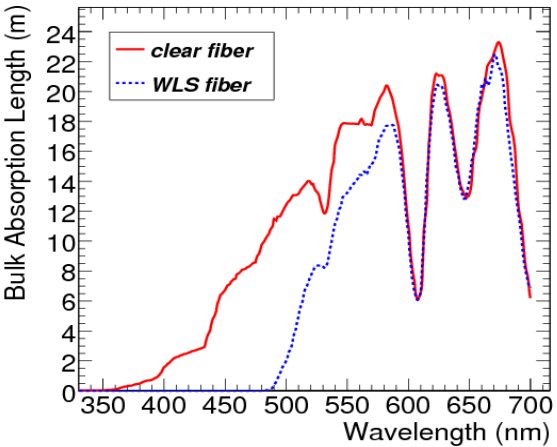
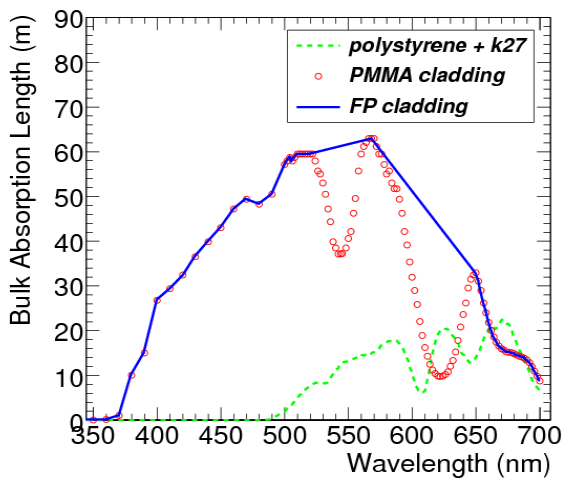


Photo of fiber coupling to an Ocean Optics 2000 spectrophotometer.

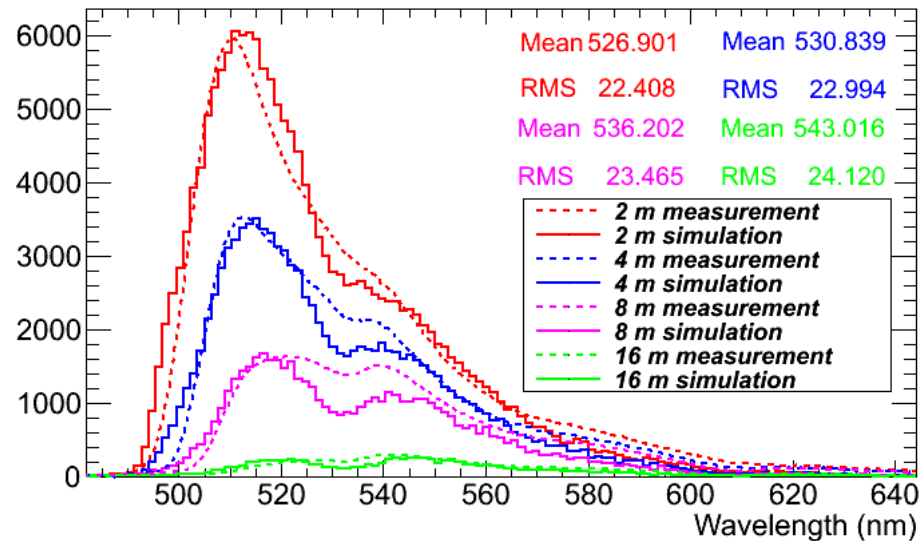


Fiber Simulations

Compare fiber simulations to fiber measurements



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



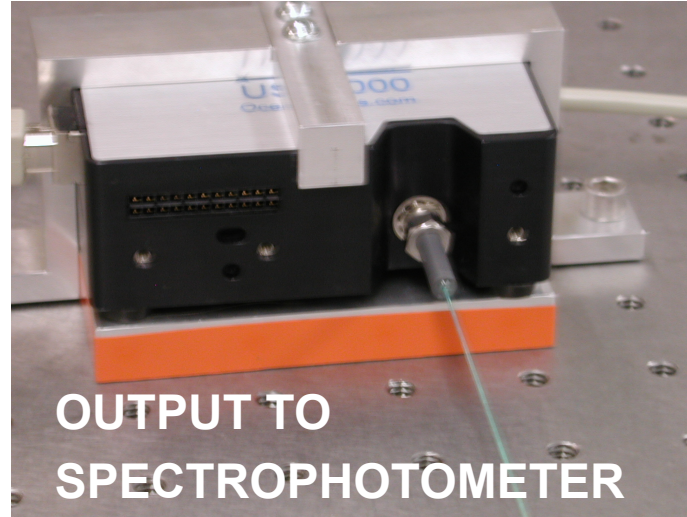
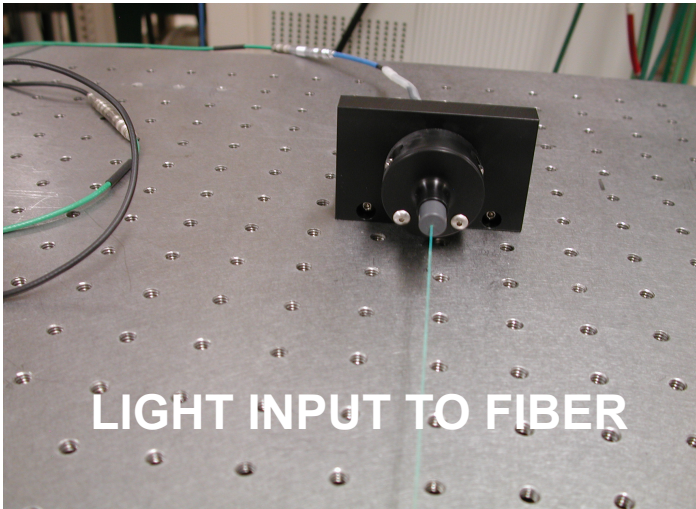
- Y11 and clear fiber data from Kuraray*
- Absorption in WLS is for 200 ppm
- Account for k27 wavelength shifting
- Account for dual cladding interaction
- Face and side simulations yield same results

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

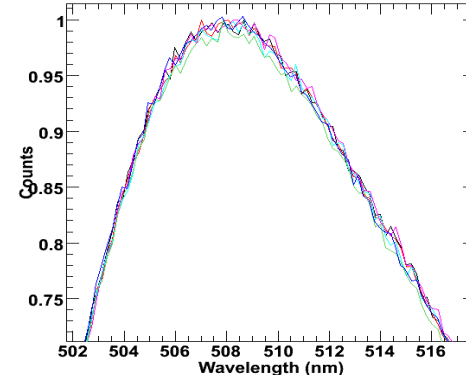
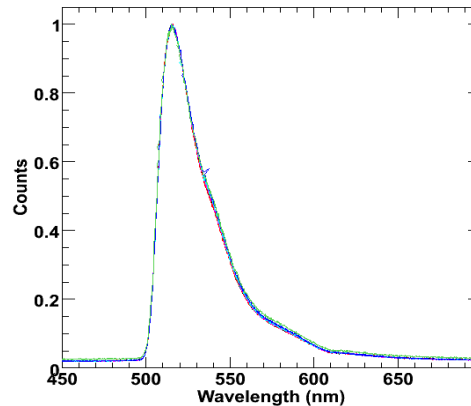
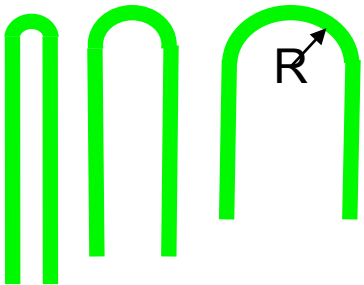


Effect of Fiber Bending

- ◆ 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

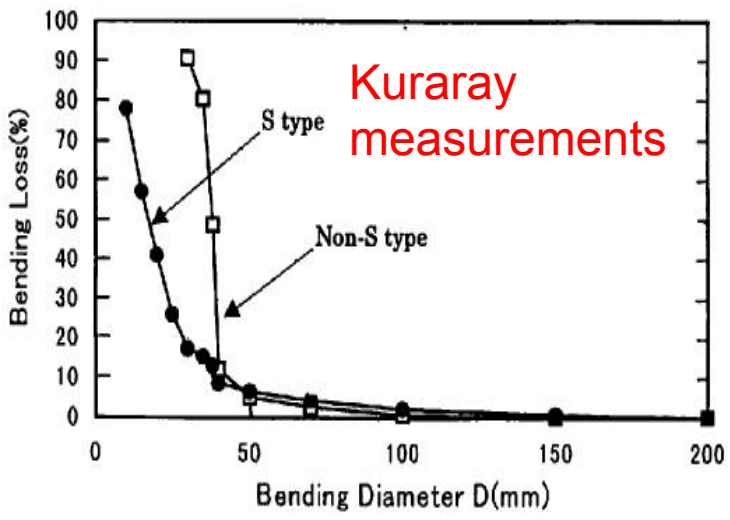
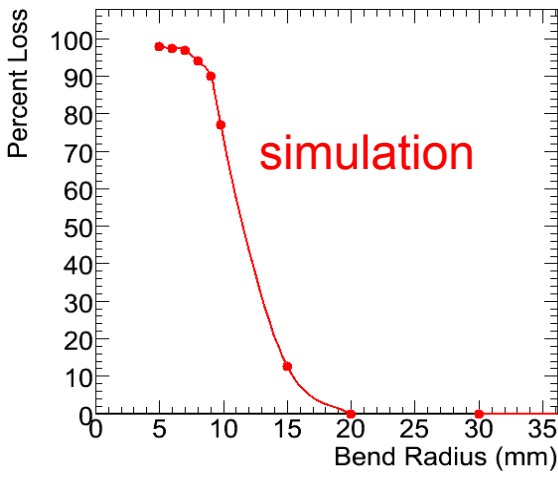
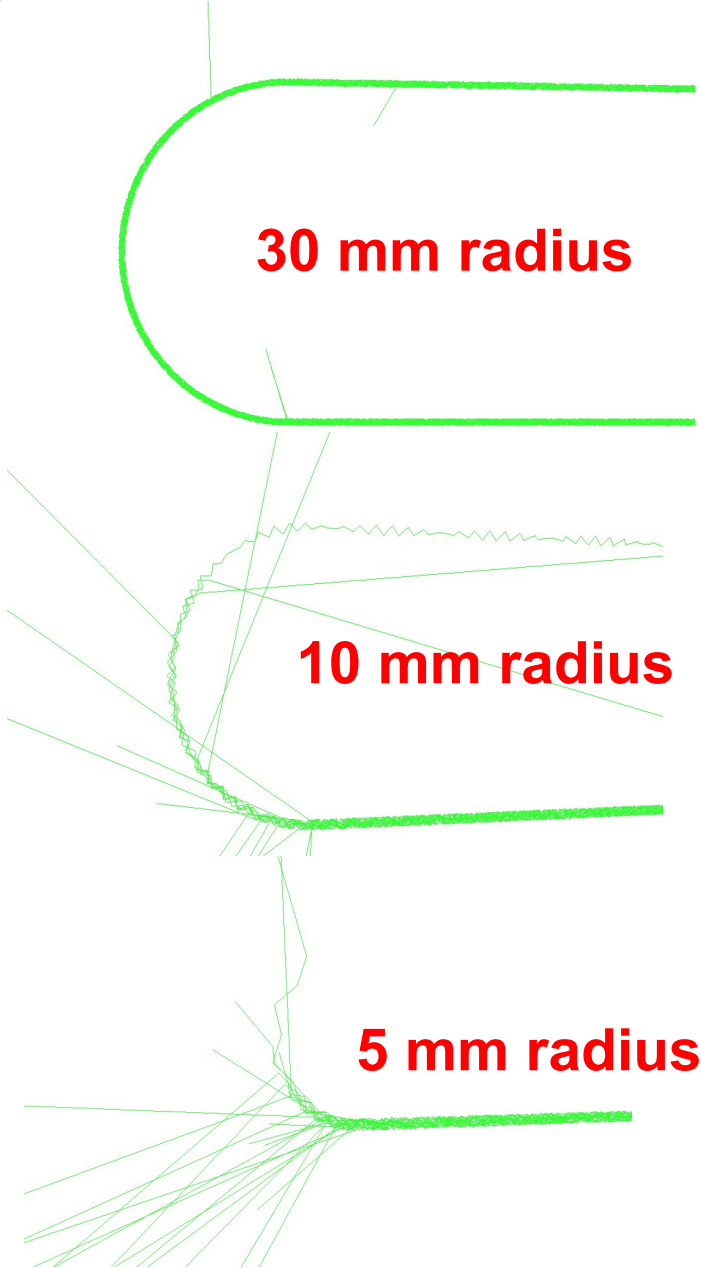


Measurement Results: No light loss at all up to 1.5 cm





Fiber Curvature Studies



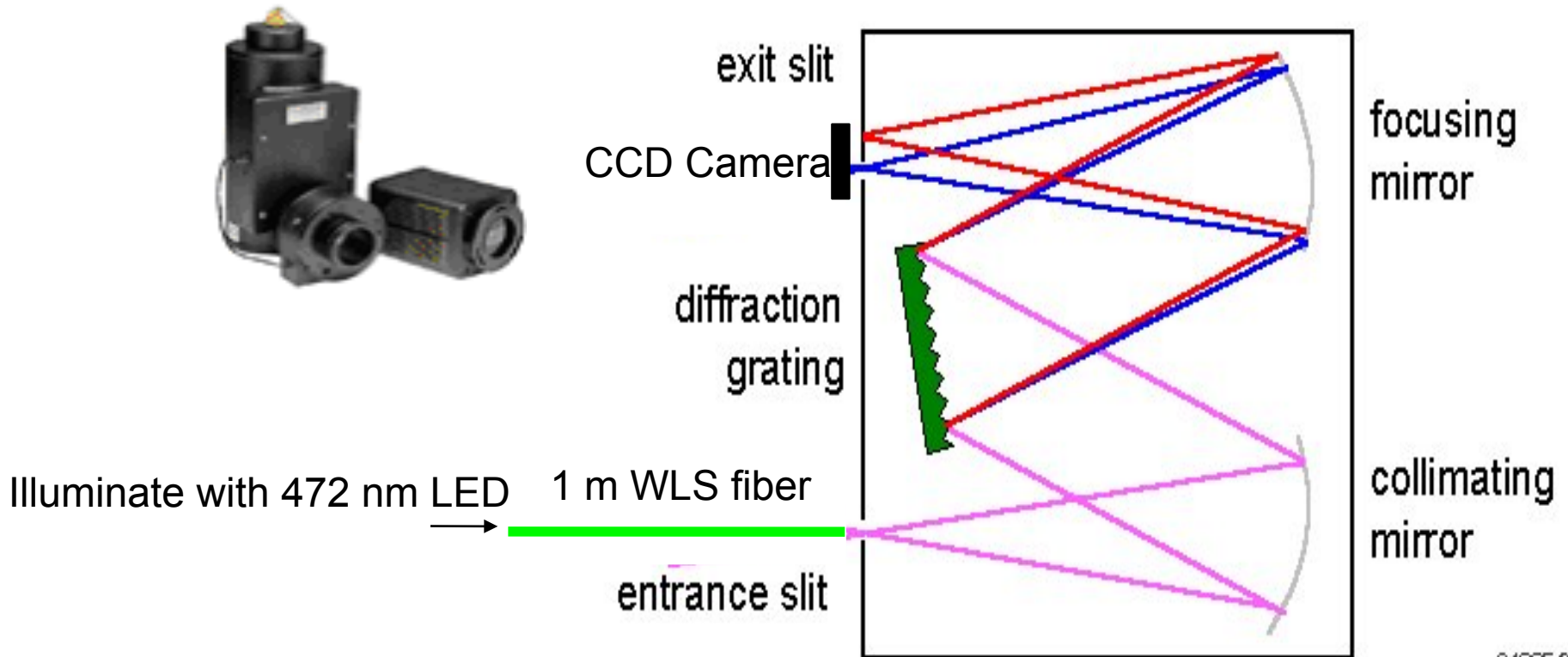
Comparison of simulations and Kuraray measurements for the bending radius.



Fiber Imaging

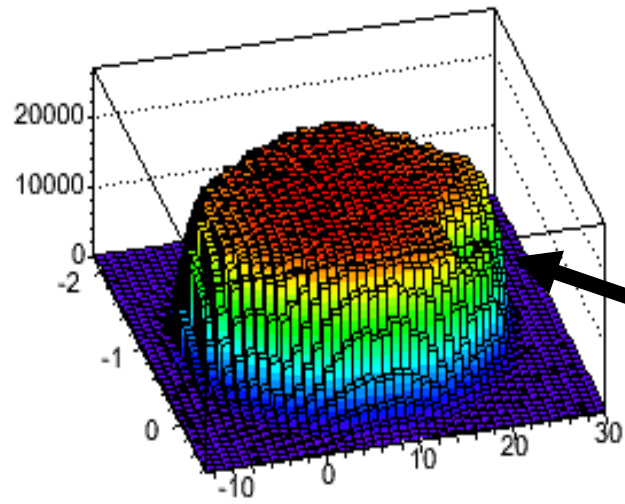
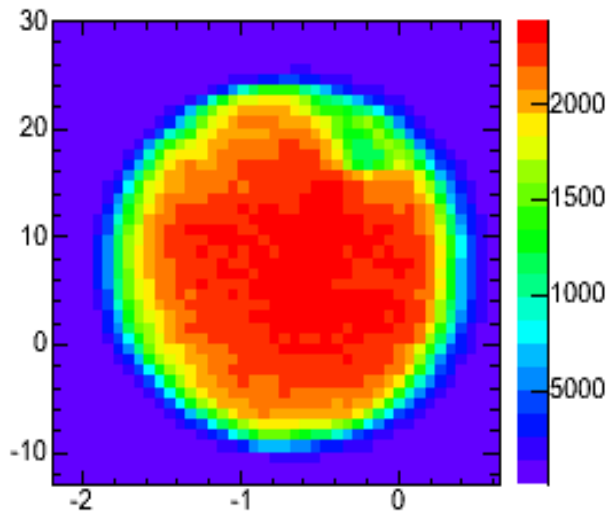


- ◆ Princeton Instruments SPEC-10 CCD (liquid nitrogen cooled)
- ◆ 1340 X 1340 pixels
- ◆ Coupled to spectrometer, illuminate fiber with 472 nm LED
- ◆ Observe light output profile and/or wavelength



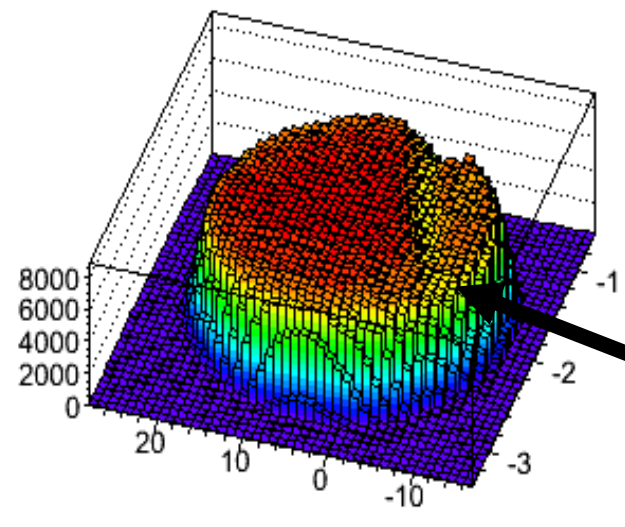
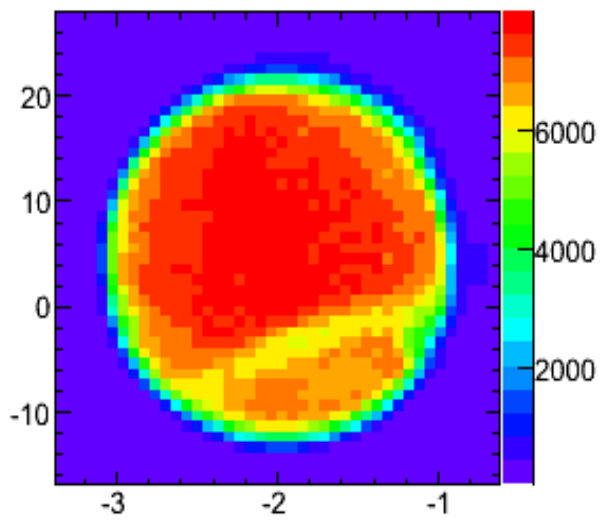


0.7 mm Diameter Fiber



- ◆ 1 m fiber
- ◆ Polished by hand

CHIP IN CLADDING

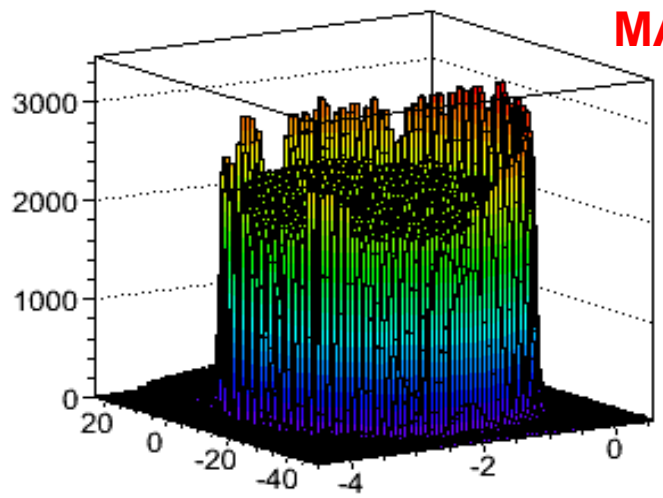
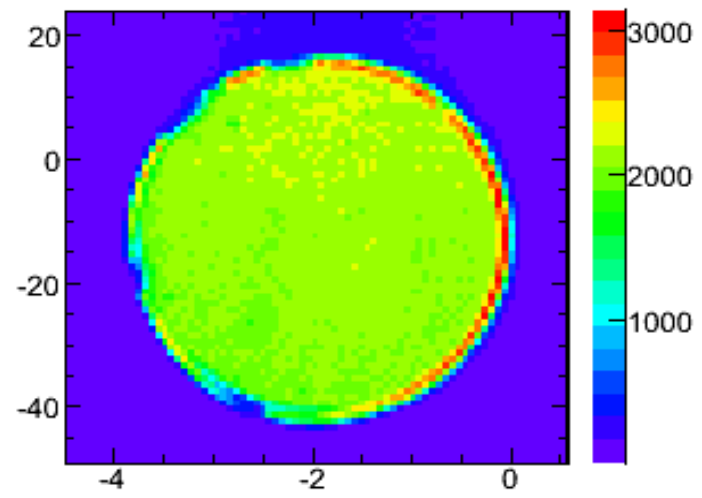


- ◆ 32 m fiber
- ◆ Polished by hand

SCRATCH ON FACE

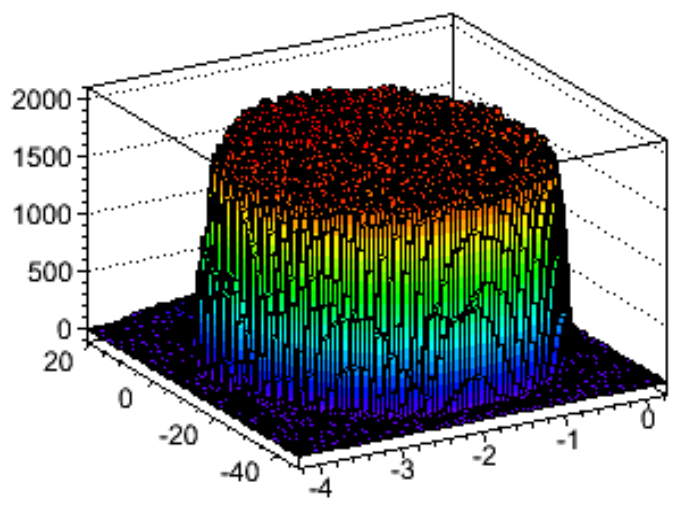
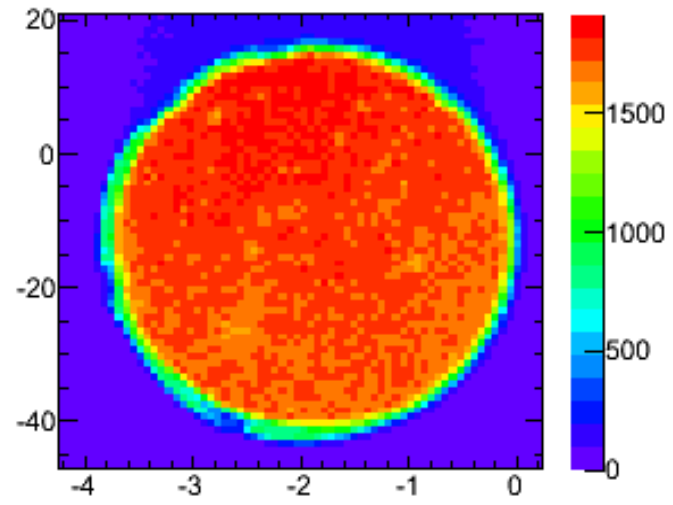


1.2 mm Diameter Fiber



MACHINE POLISHED

Ring on right edge due to small amount of ambient light



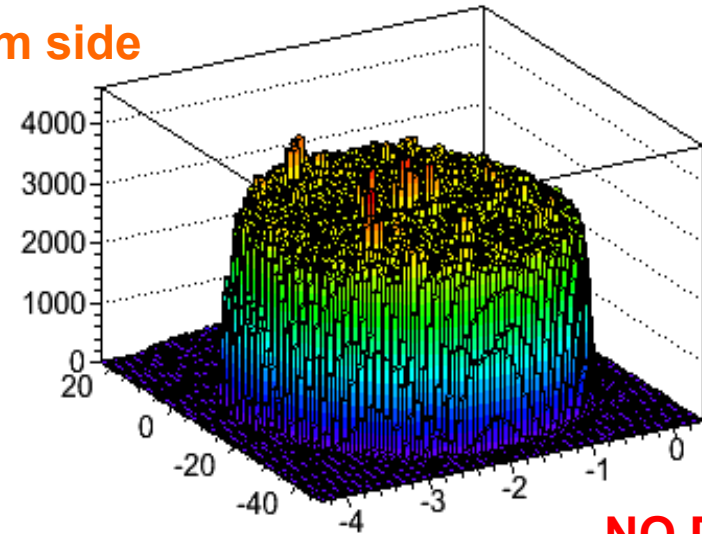
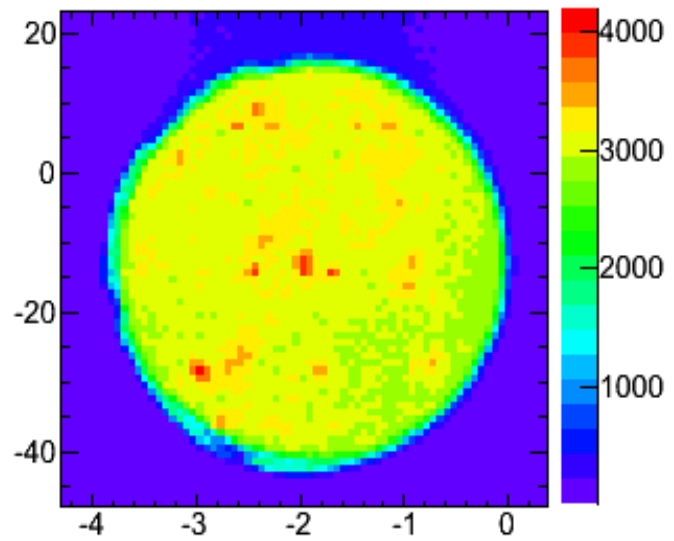
After removal of ambient light



Side vs. Face Illumination

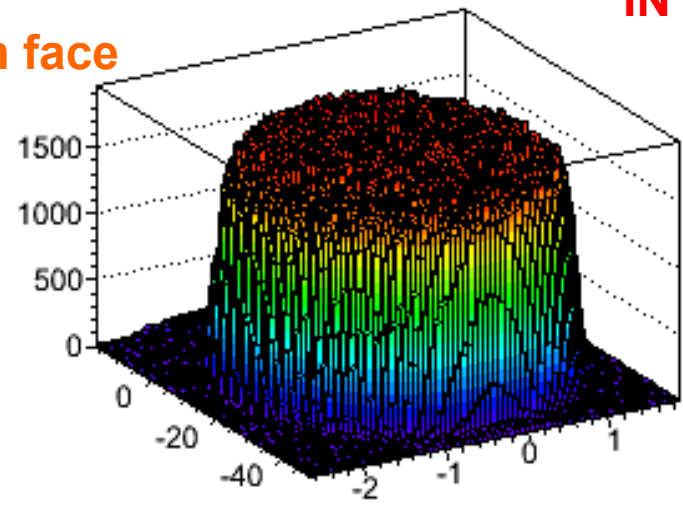
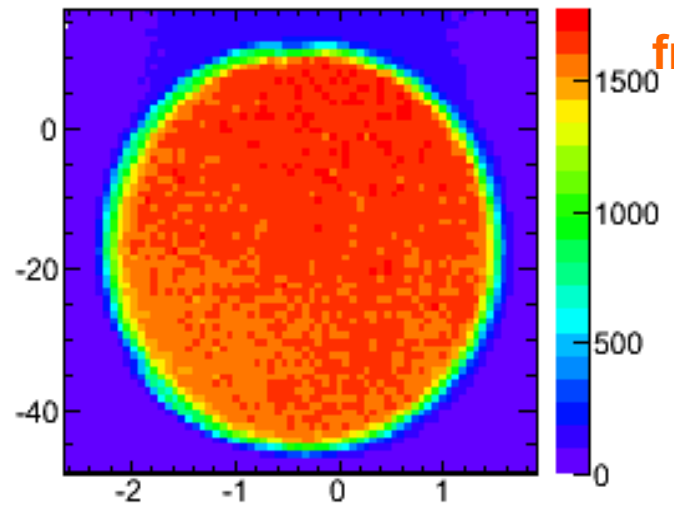


Illuminated from side



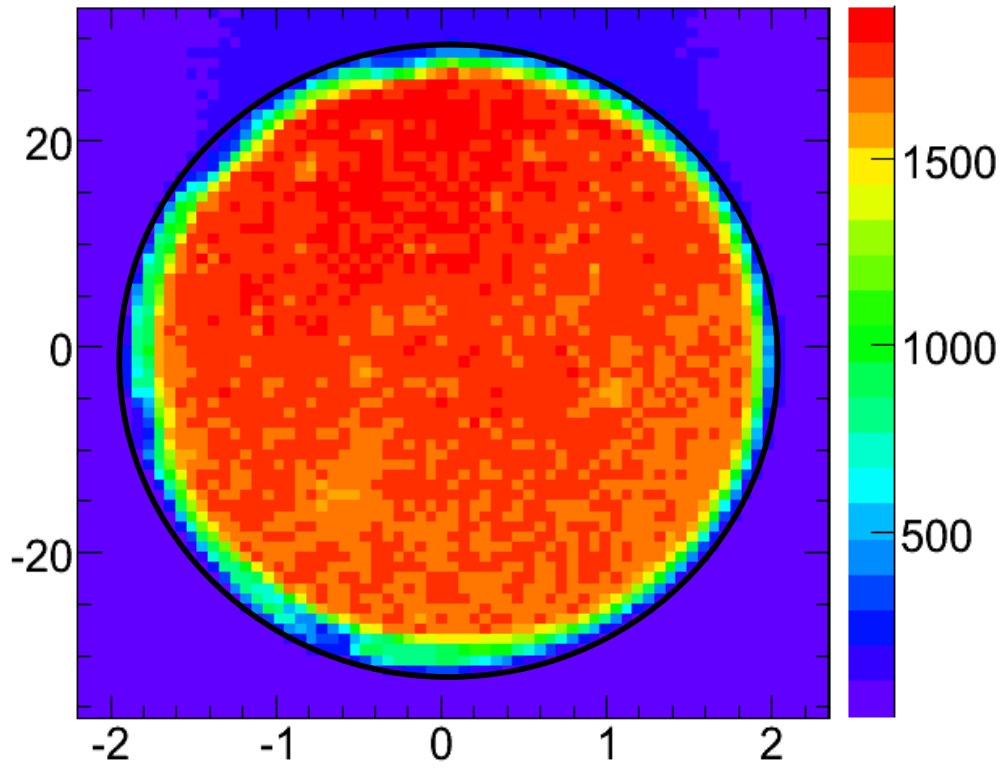
NO DIFFERENCE IN UNIFORMITY!

Illuminated from face





Light Output Profile: 1.2 mm Fiber

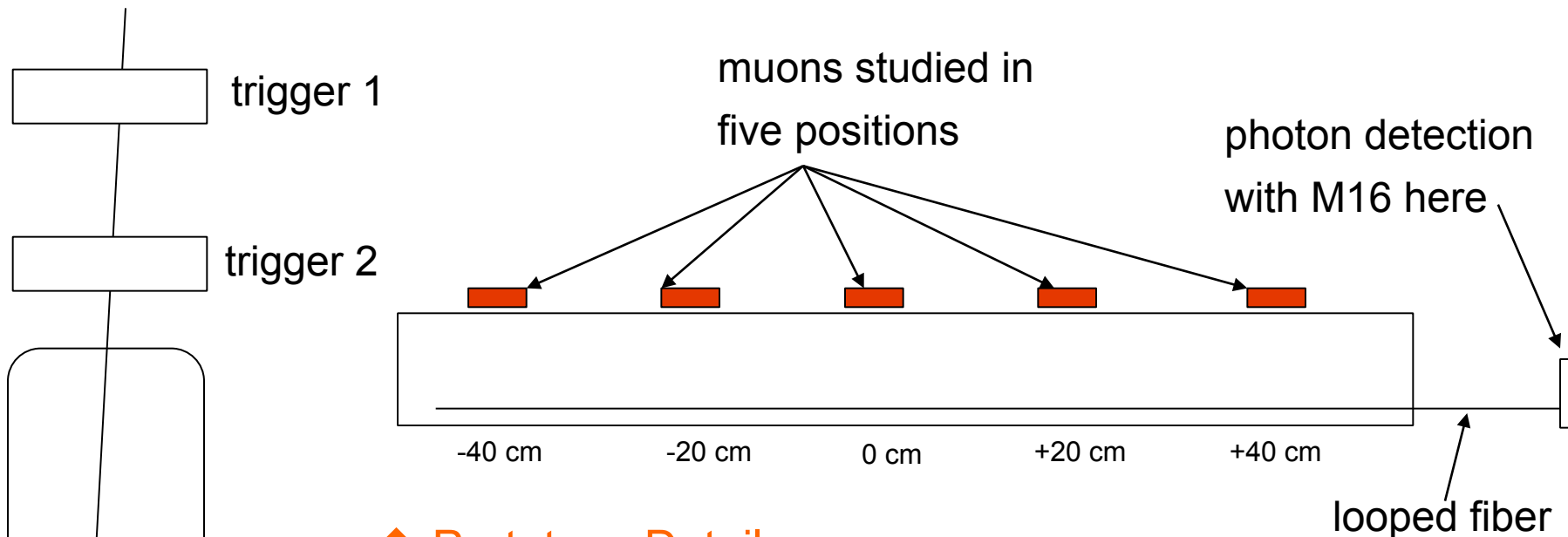


- ◆ 20 microns/pixel
- ◆ 60 pixels across
- ◆ black ring is exactly 1.2 mm



Prototype NOvA Cell Setup

A simple setup with triple coincidence using scintillator paddles

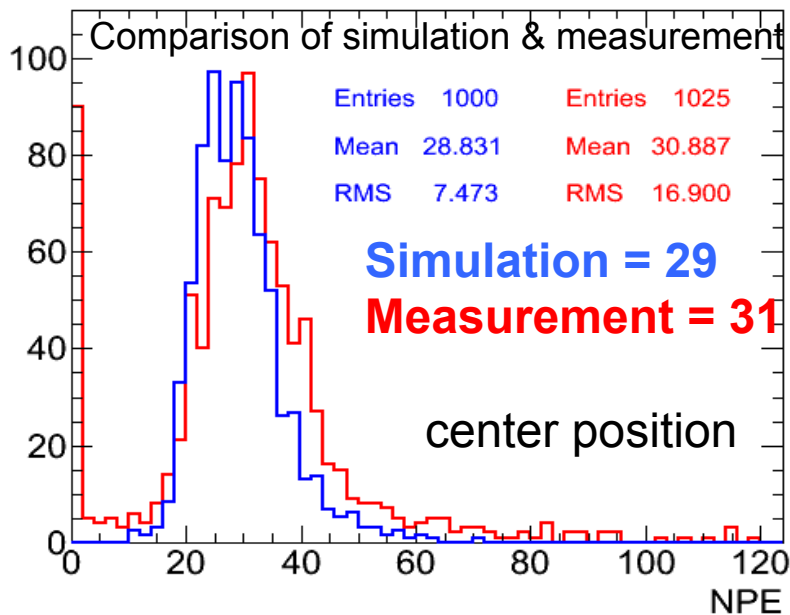
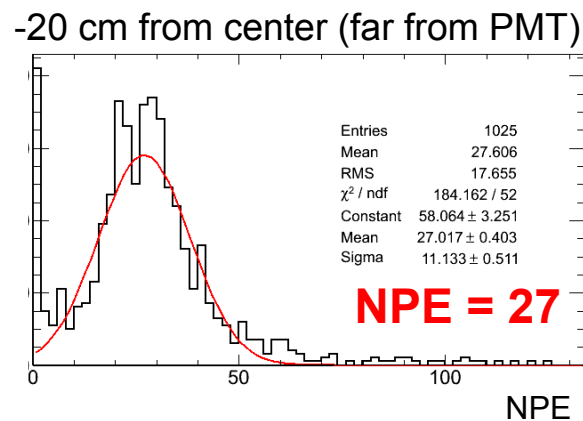
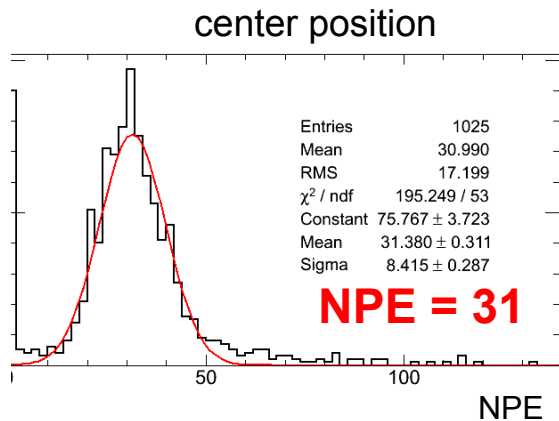
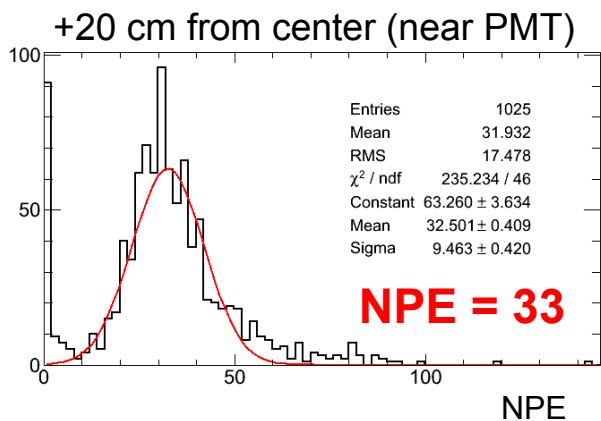


- ◆ Prototype Details:
- ◆ NOvA 27A PVC extrusion – length = 1.2 m
- ◆ NOvA liquid scintillator (2007)
- ◆ 200 ppm 0.7 mm diameter looped fiber to M16 PMT
- ◆ M16 readout at two opposite pixel corners
- ◆ Positions are center, ± 20 cm and ± 40 cm off center



Prototype Measurements

Results for three positions and a comparison with simulations



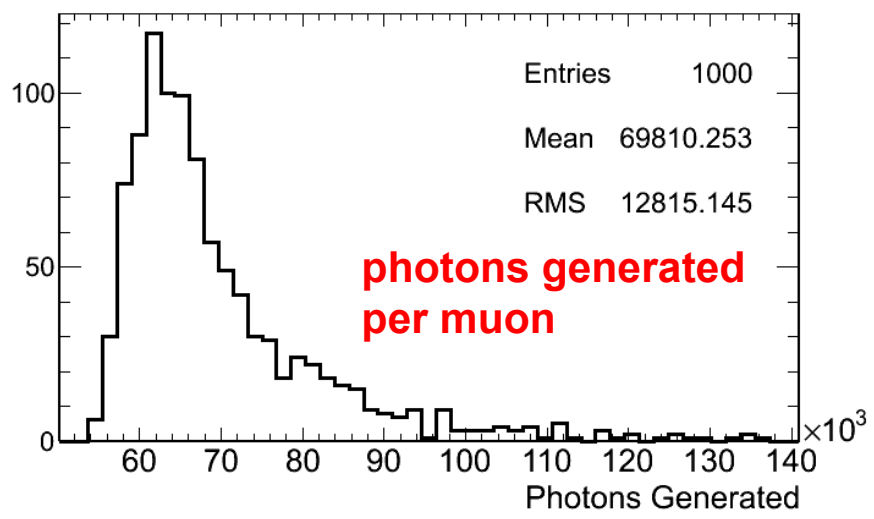
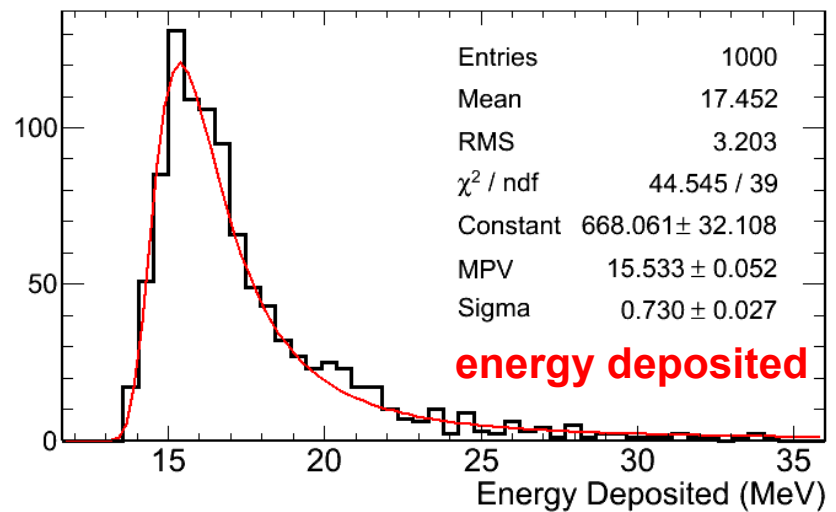
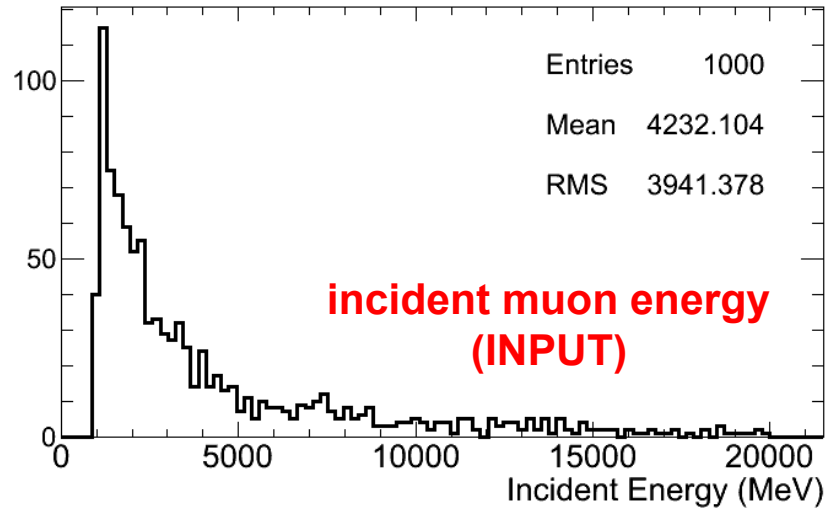
Details:

- ◆ 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



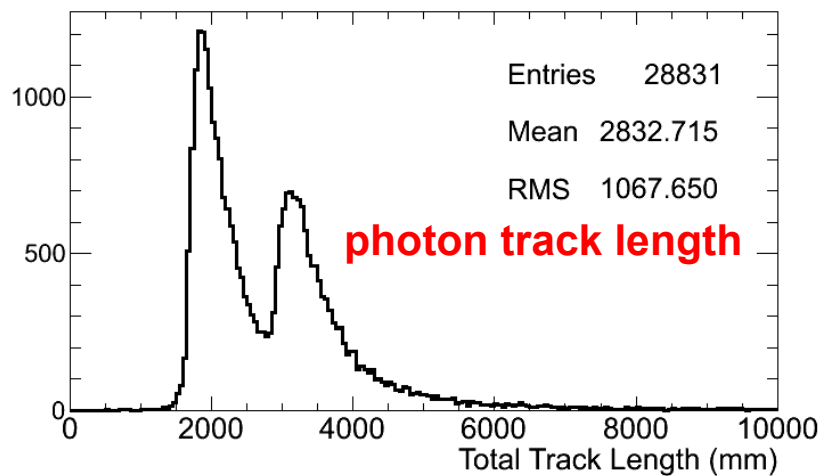
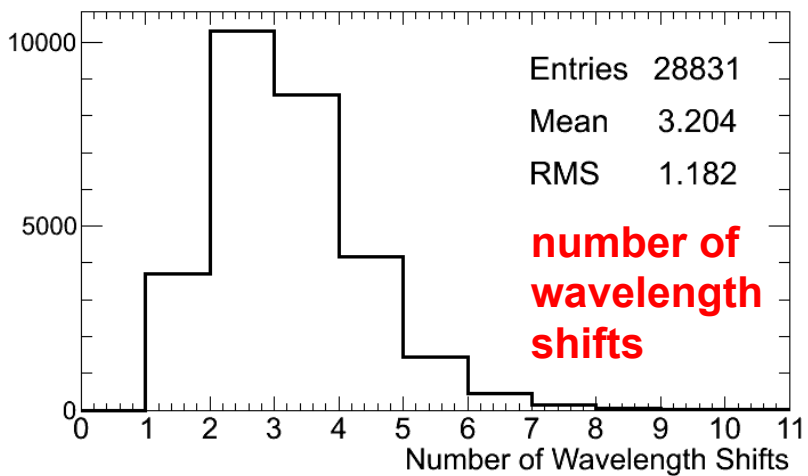
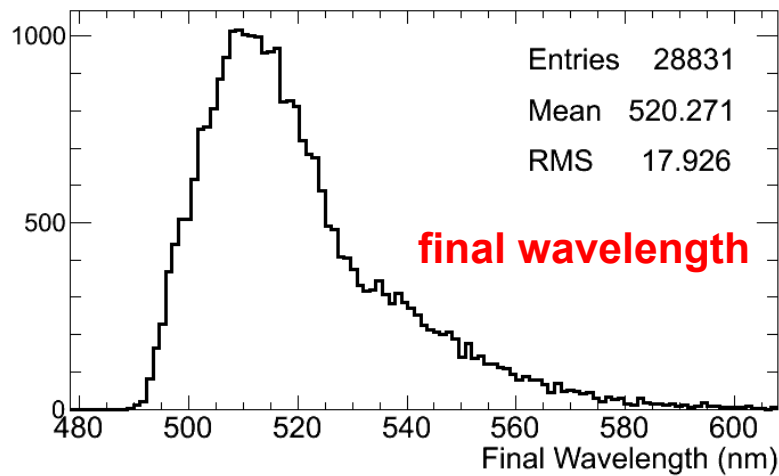
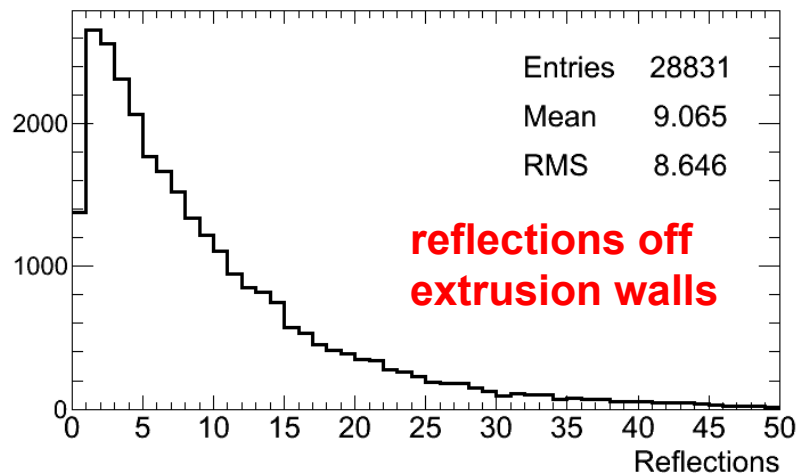
Details:

- ◆ 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)

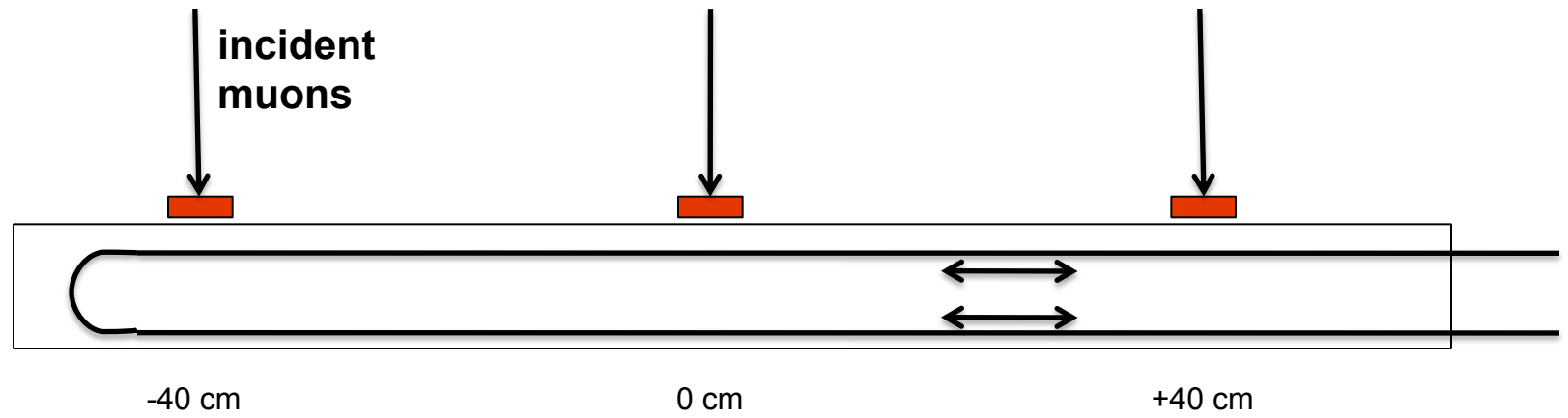
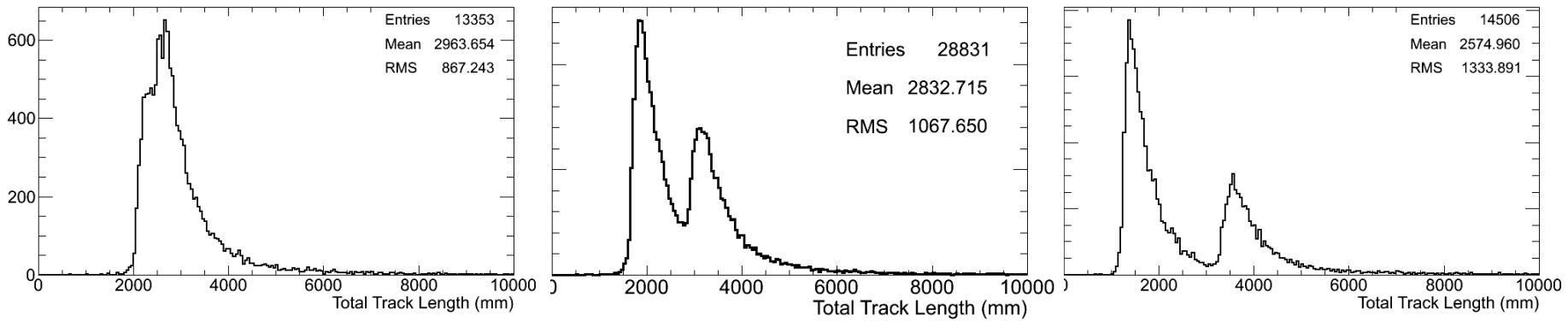




Simulation Results



Comparison of track lengths for three positions



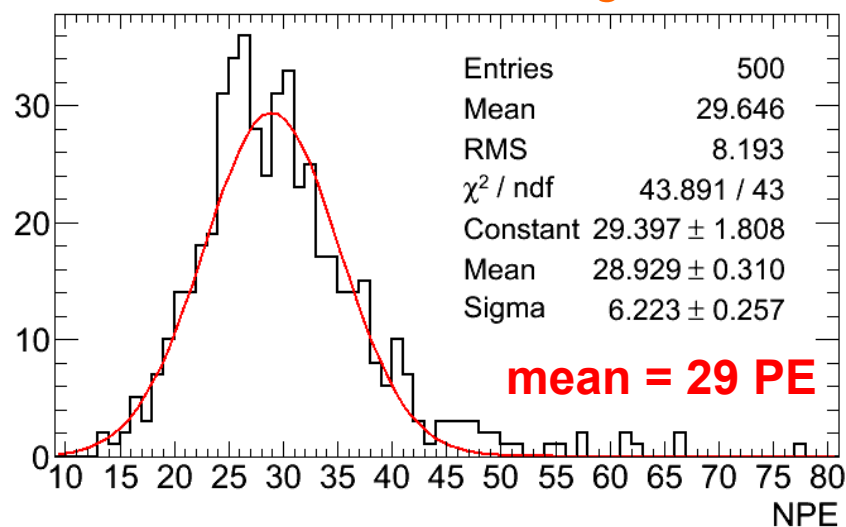
Demonstrates propagation in curved fiber



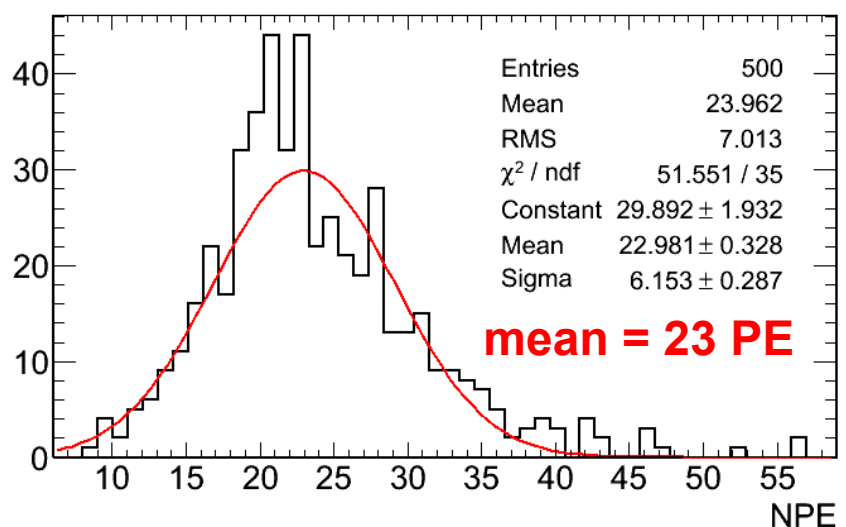
Simulation Results



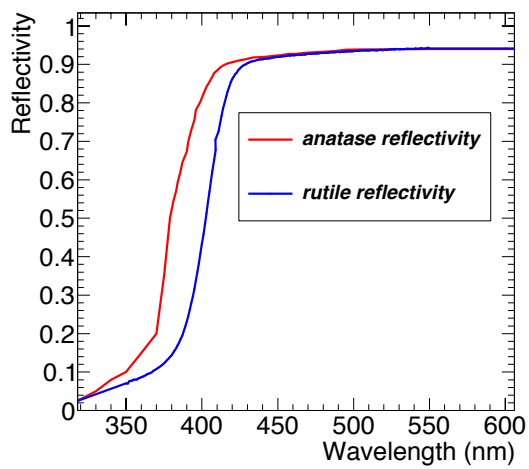
Simulations show a large difference between anatase and rutile!



Photons detected using anatase
(anatase reflectivity Ref. NOvA TDR)

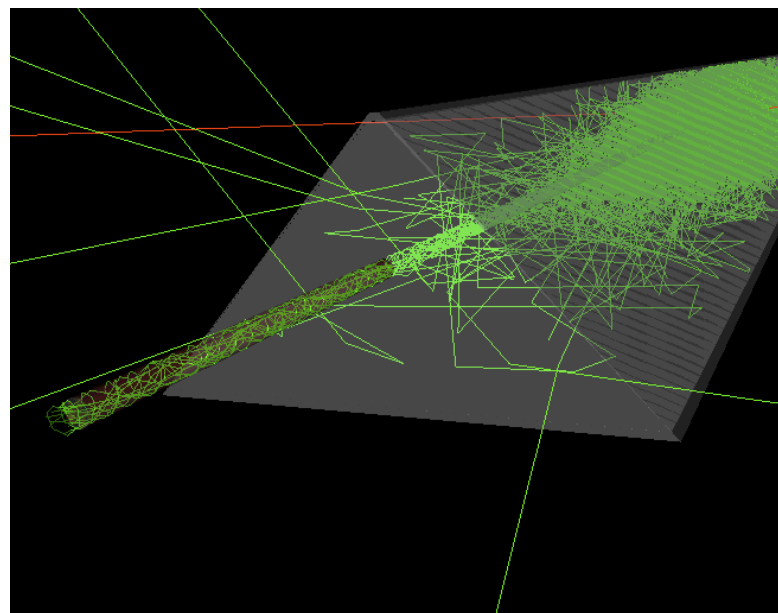
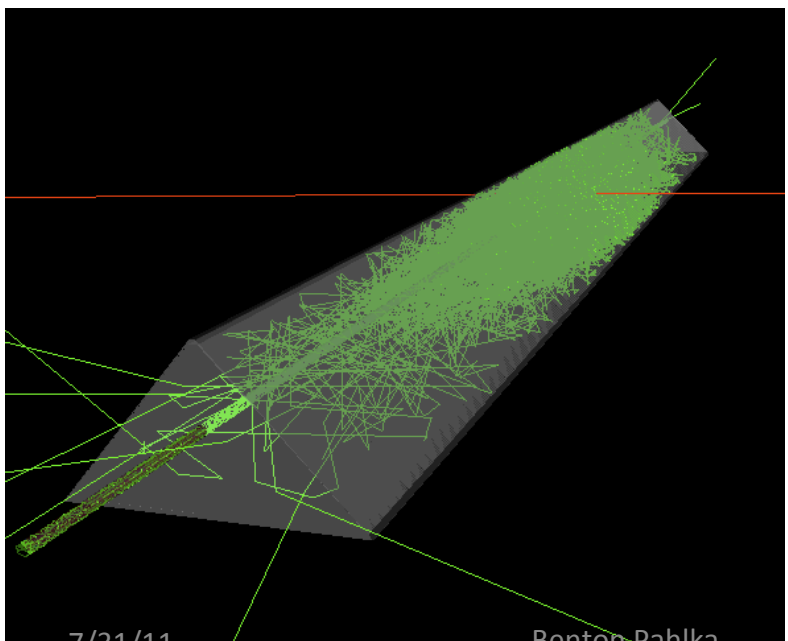
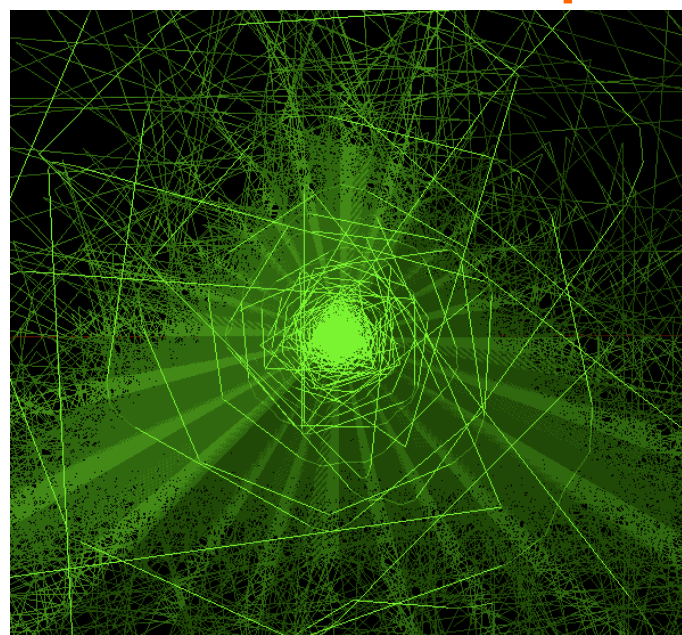
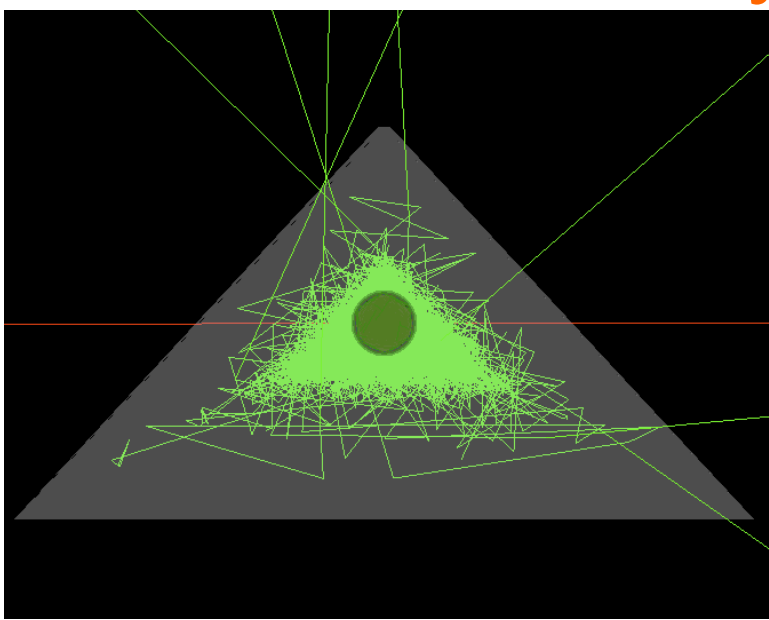


Photons detected using rutile
(rutile reflectivity Ref. Ana Pla-Dalmau, 2008)





Preliminary MINERvA Setup





Single Strip MC Comparison



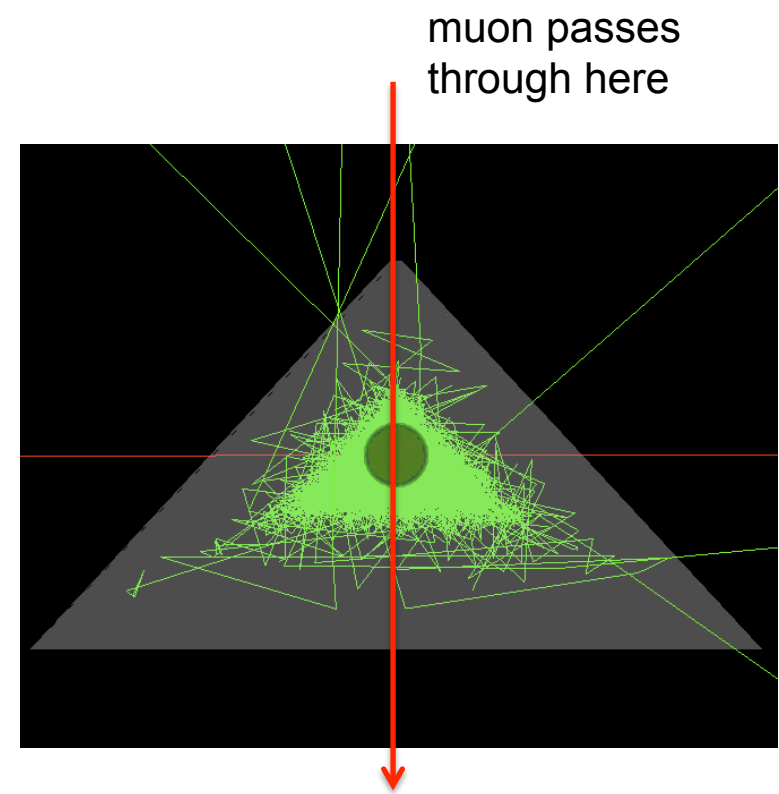
Compare energy deposition profiles (neglect photon generation)

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

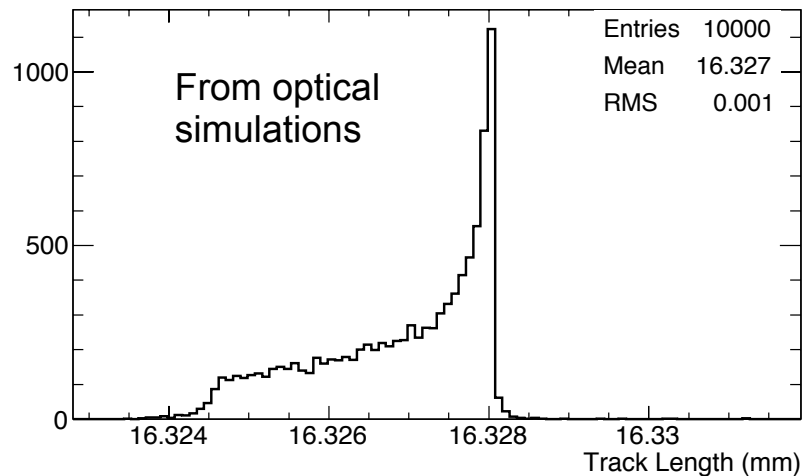
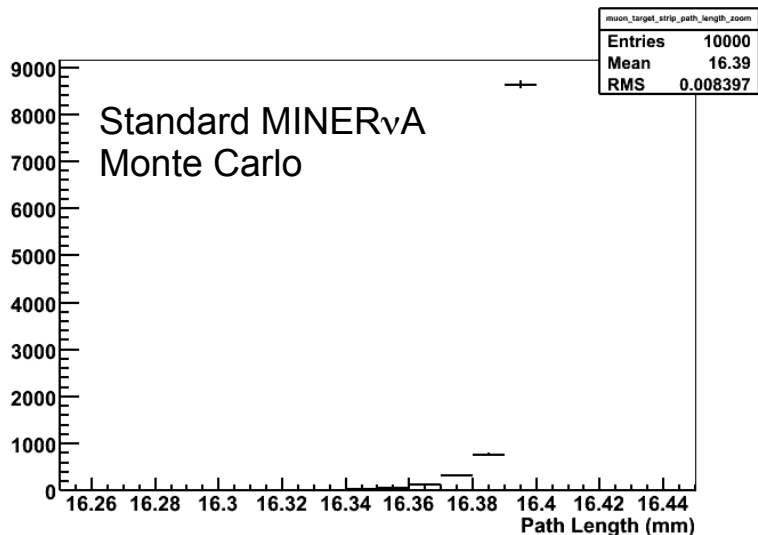
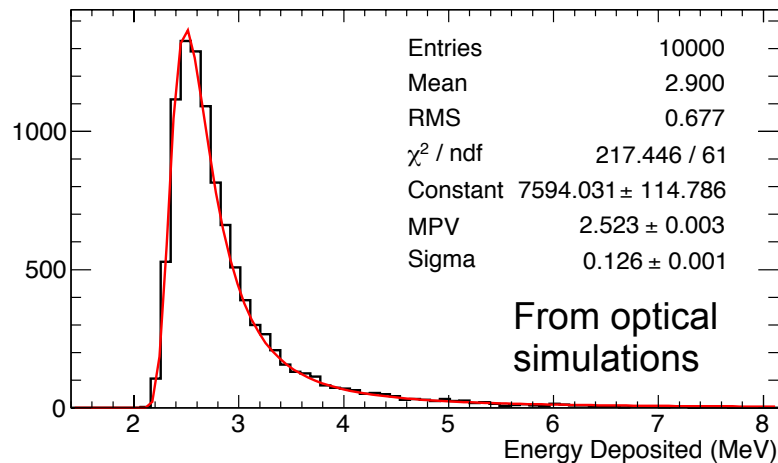
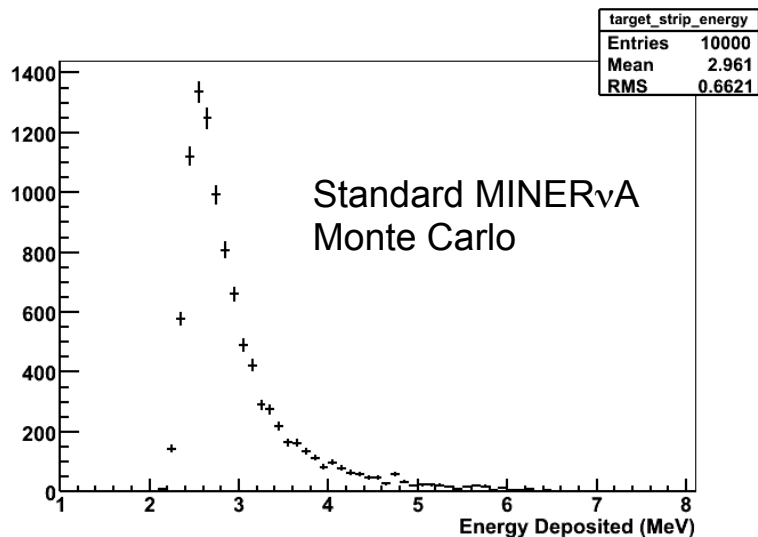
From our detector geometry description:

- ◆ 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:

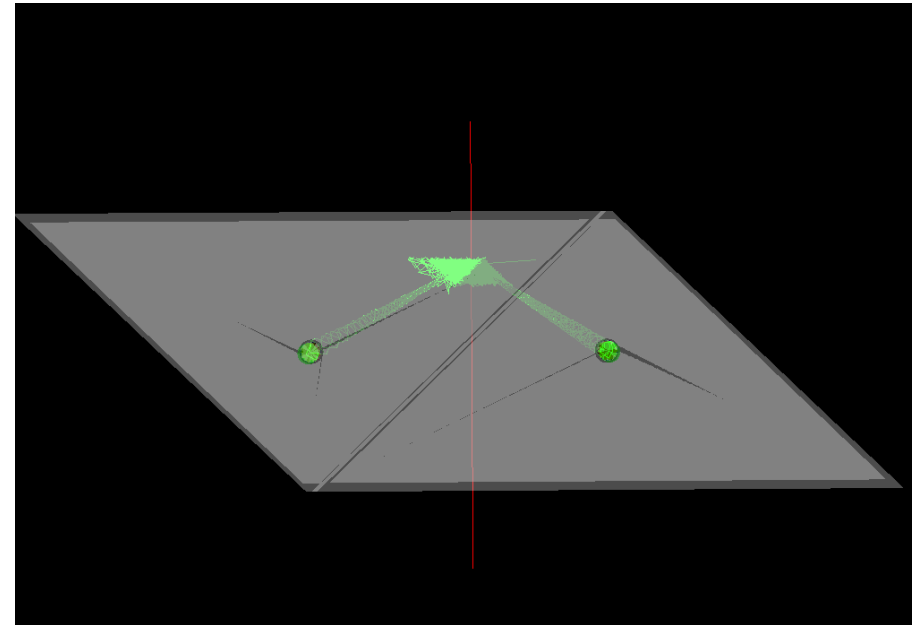
- ◆ Avg. scintillator strip length = 2.33 m
- ◆ Only extrusions with:
 - WLS baggie length = 0.775 m
 - Clear fiber length = 1.067 m
- ◆ Simulation input details seen previously

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

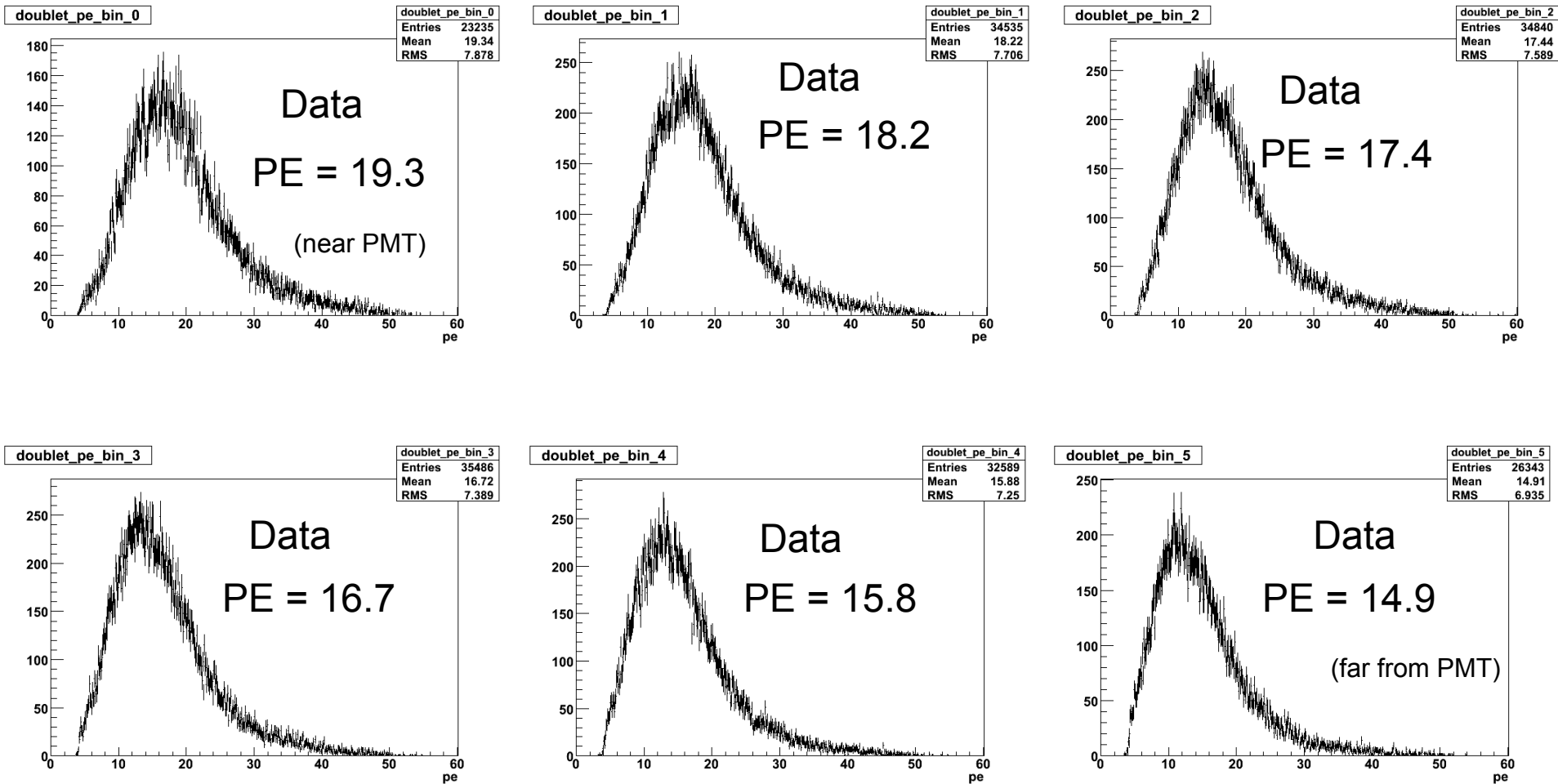
Details of optical simulations:

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



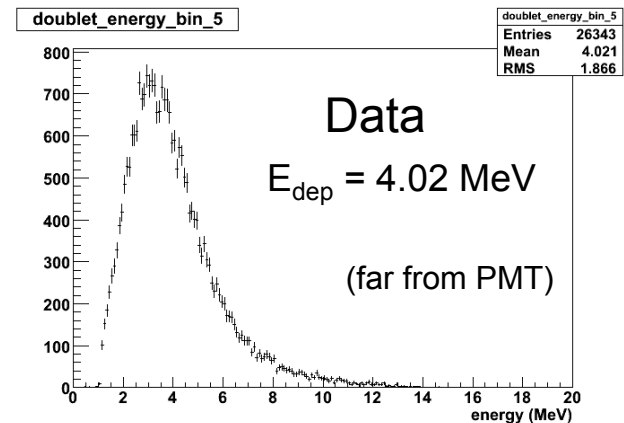
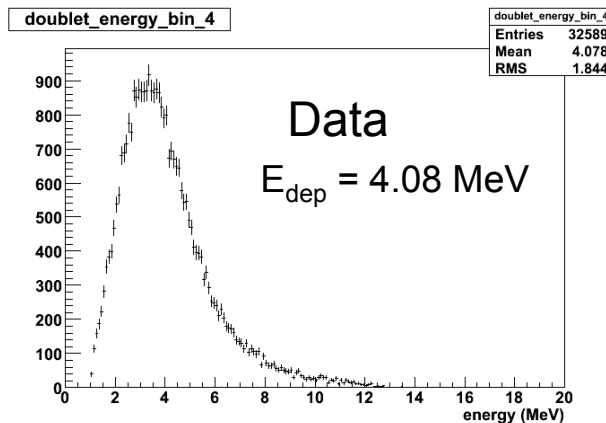
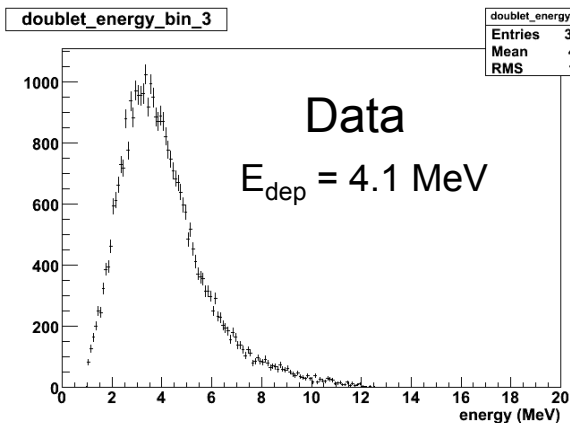
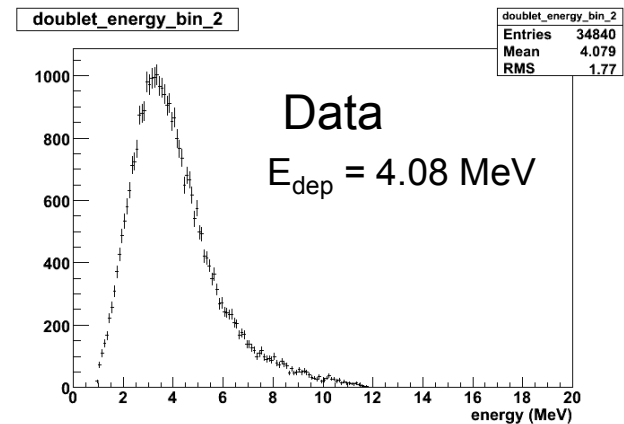
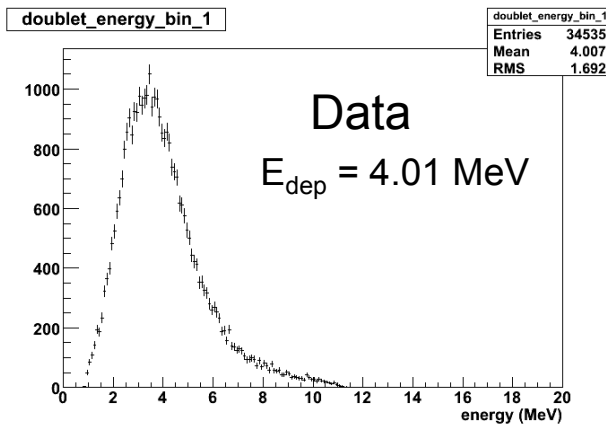
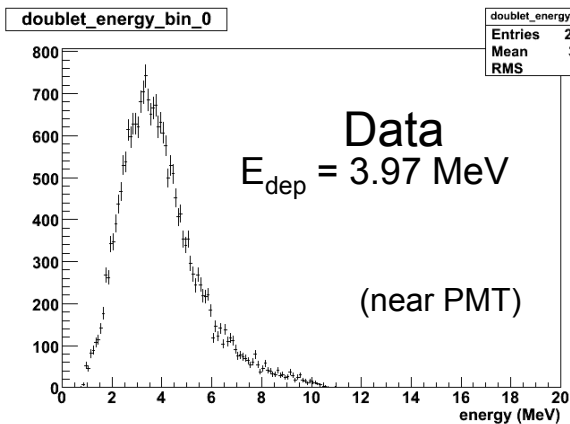


Results from Data





Results from Data

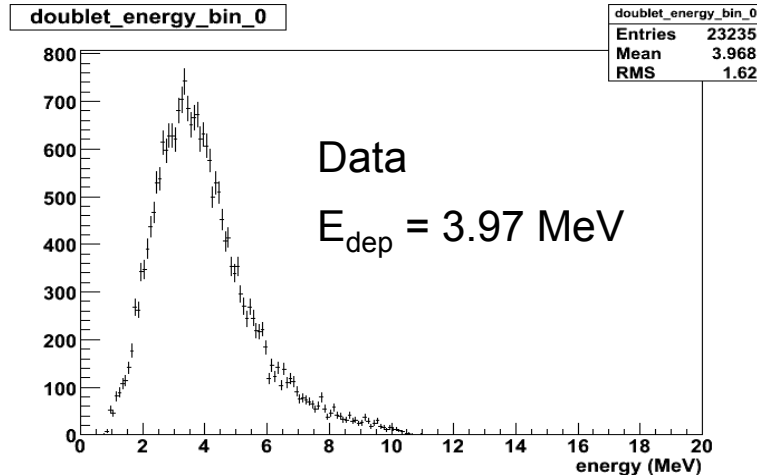
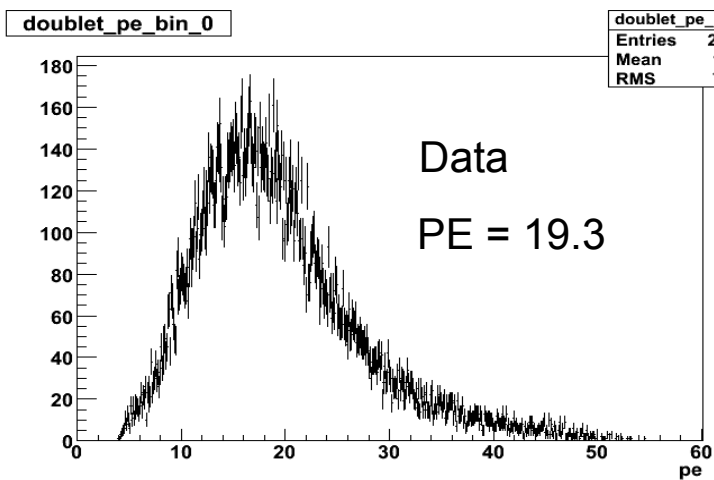
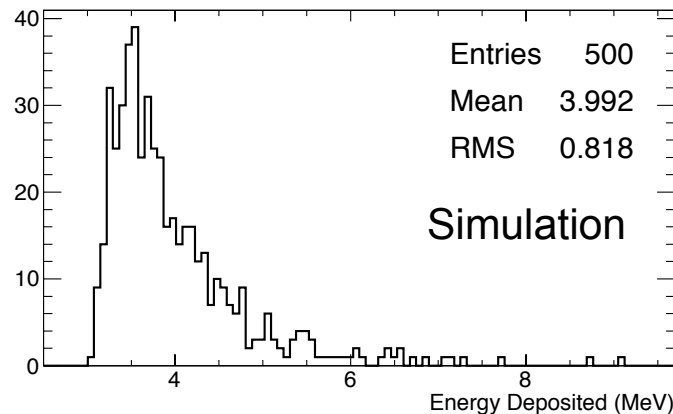
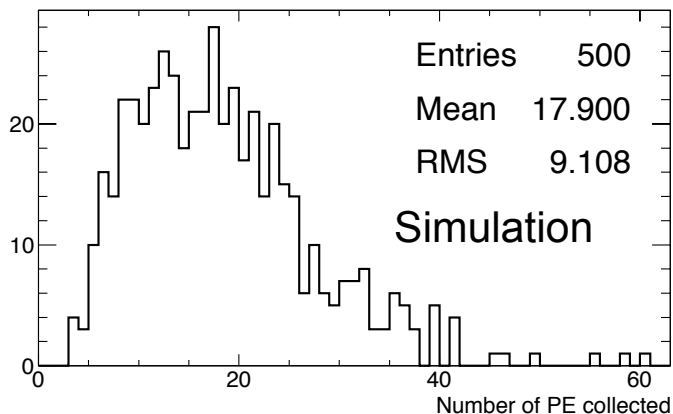


Energy deposition is back-corrected from PE count and attenuation



Results from Optical Simulation

Results for the bin nearest the PMT



...more results very soon



Timing Simulations



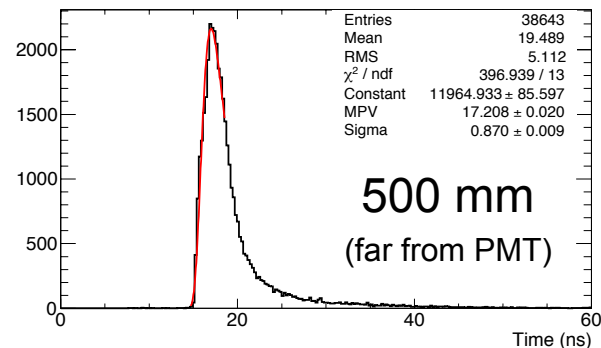
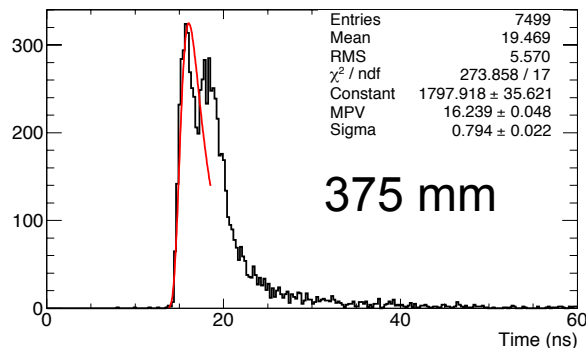
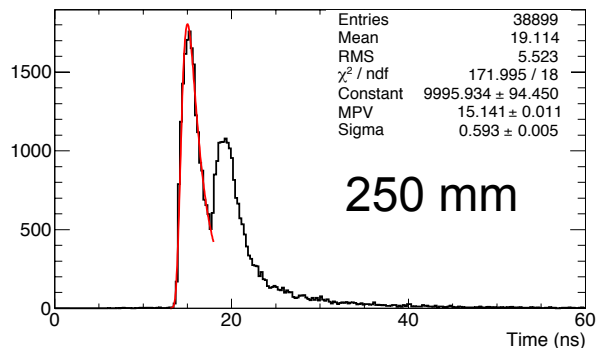
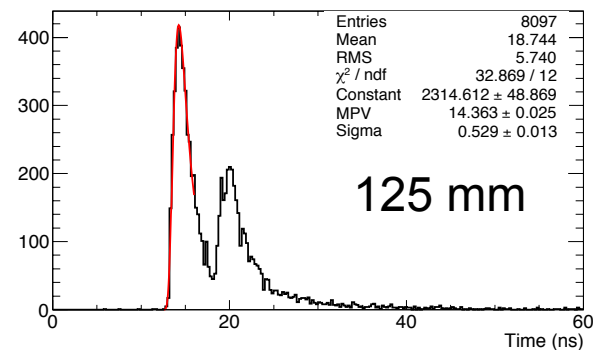
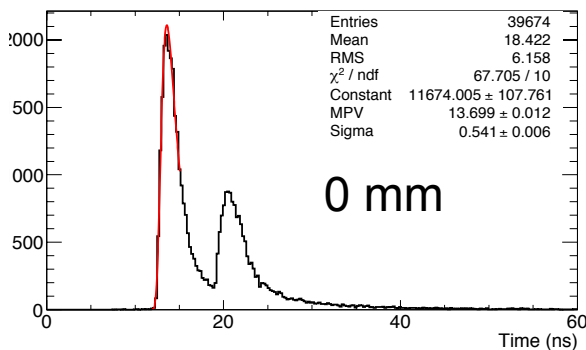
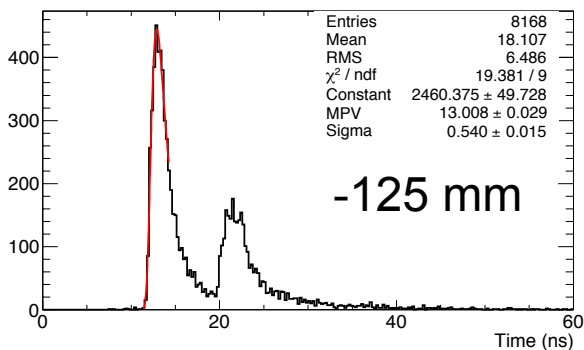
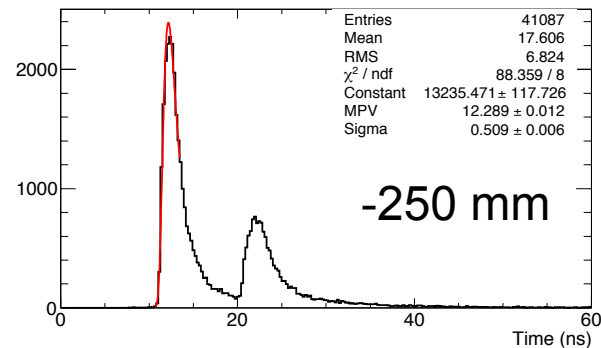
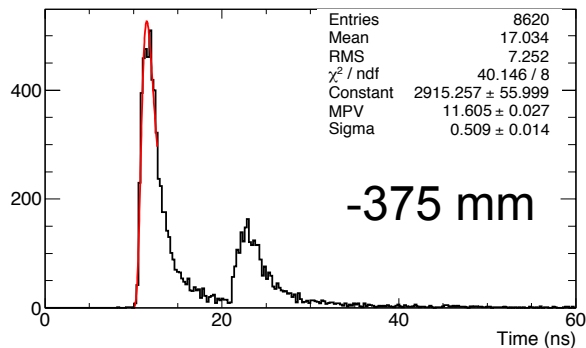
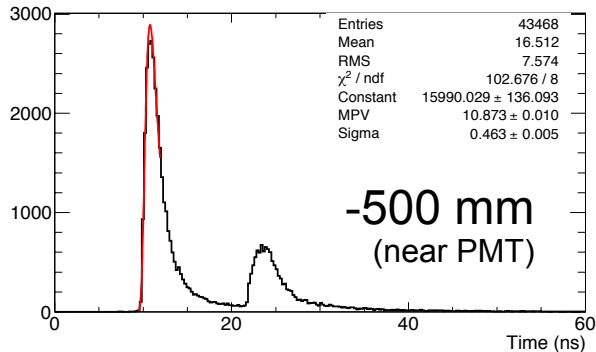
Analysis details:

- ◆ 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





Parametrization Thoughts



Response is (could be) a function of:

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

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

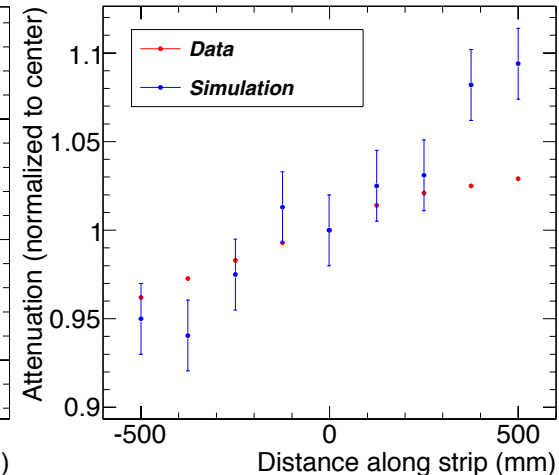
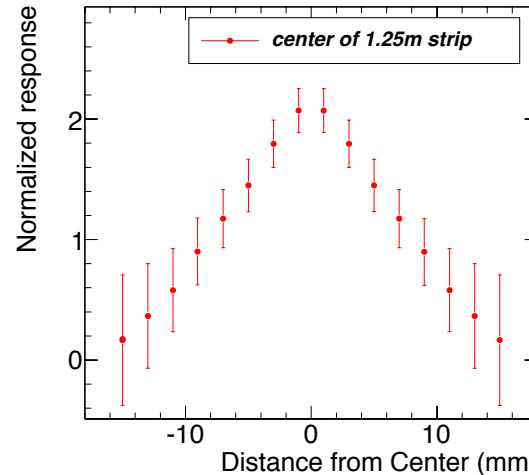
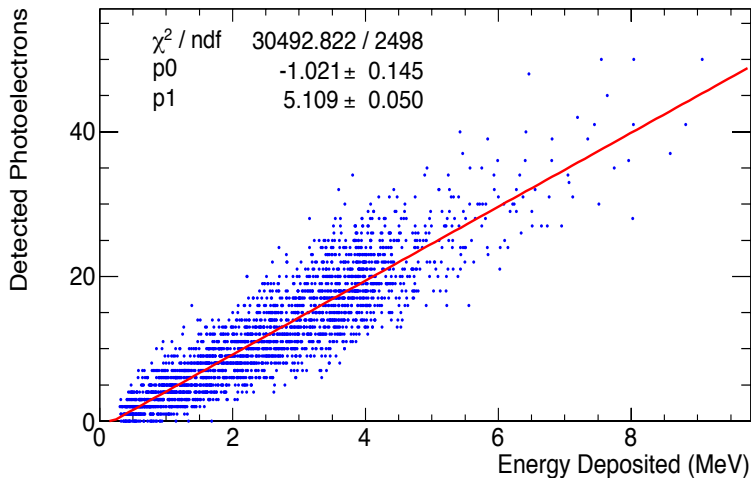
$$R = R(E_{dep}) \times R(x) \times R(z)$$

where

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

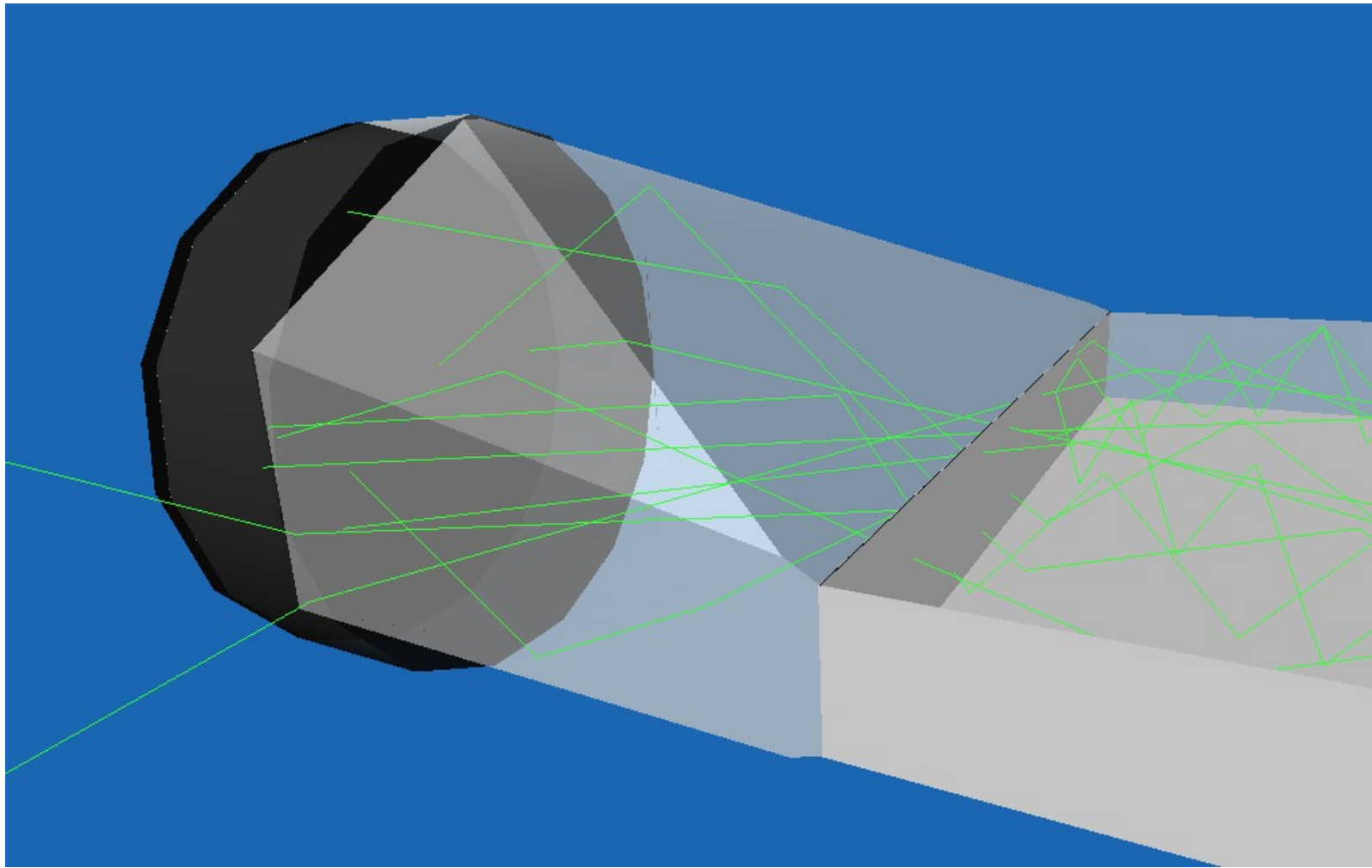
for each strip...

then interpolate between strips





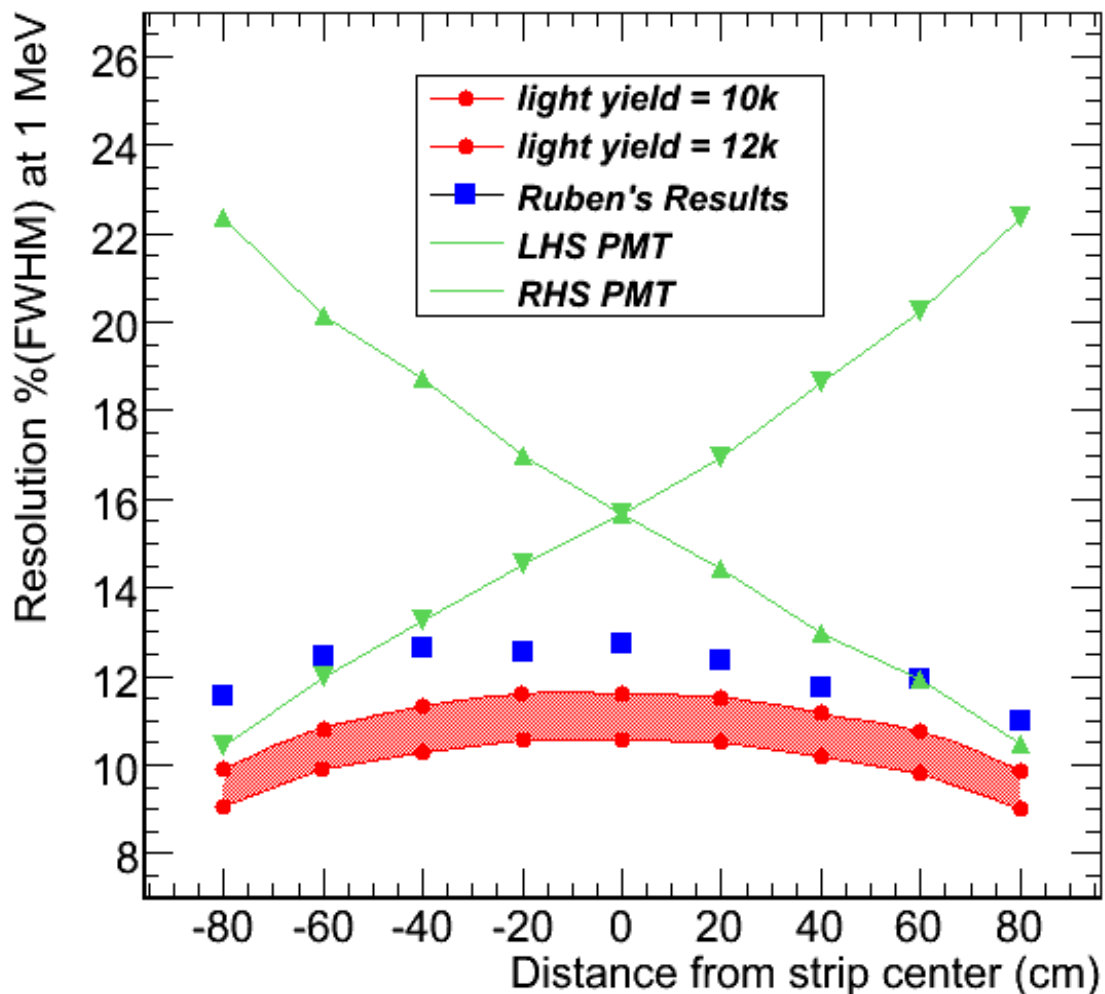
Simulations of a Thin Scintillator Bar



Large Eljen scintillator bar. 10 cm x 2 cm x 2 meters with light guide coupling. Tested wrapping with and without an air gap in simulation.



Bar Simulations: 10 cm x 2 cm x 2 m



Sim/measurement from 2007

Cross section 10 cm x 2 cm
Two PMTs : ETL 9390B
Optical grease coupling
Mylar wrapping (with air gaps)

Simulations are for 200k photons per data point

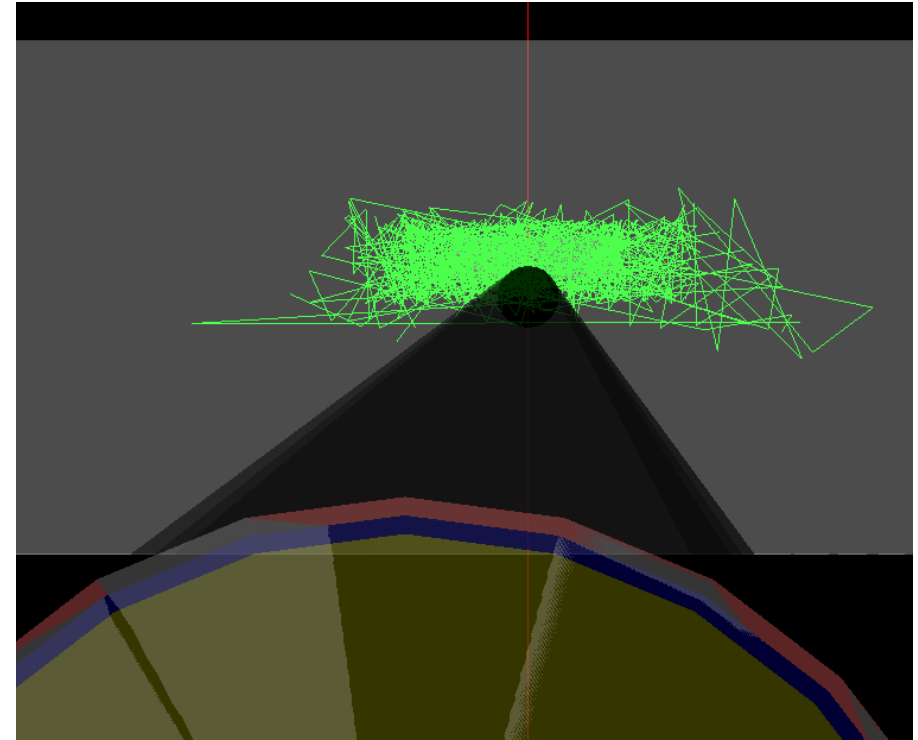
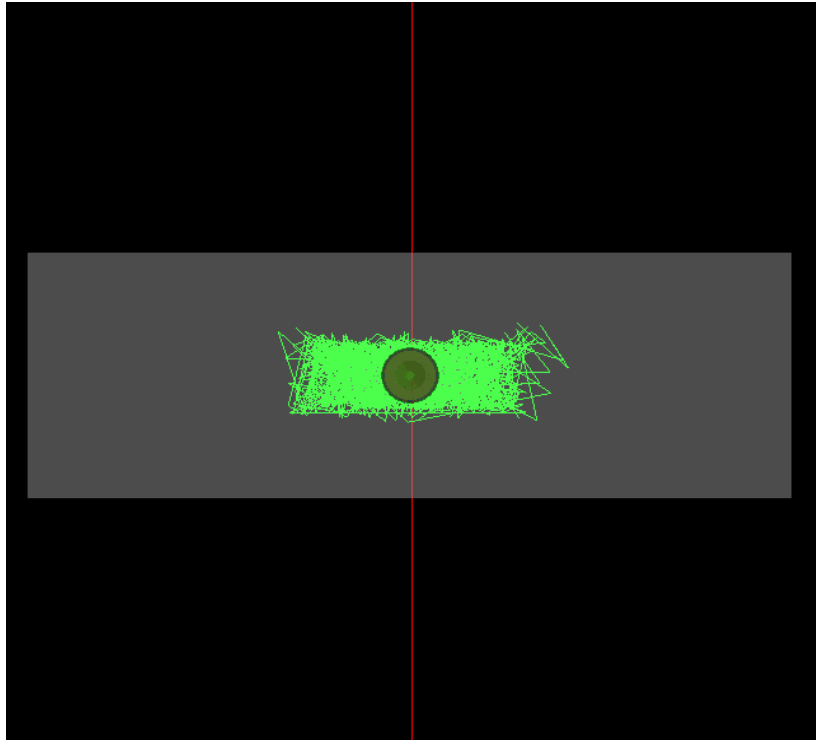
Resolution is calculated as $2.35 \cdot \sqrt{\text{counts}}$

no mylar gap, center of bar: R = 31%

With mylar gap, center of bar: R = 11%



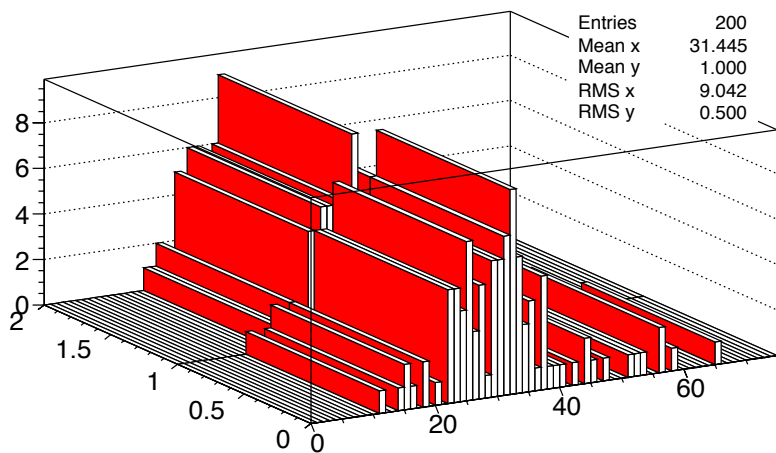
Simulations of a 30 mm x 10 mm Extrusion



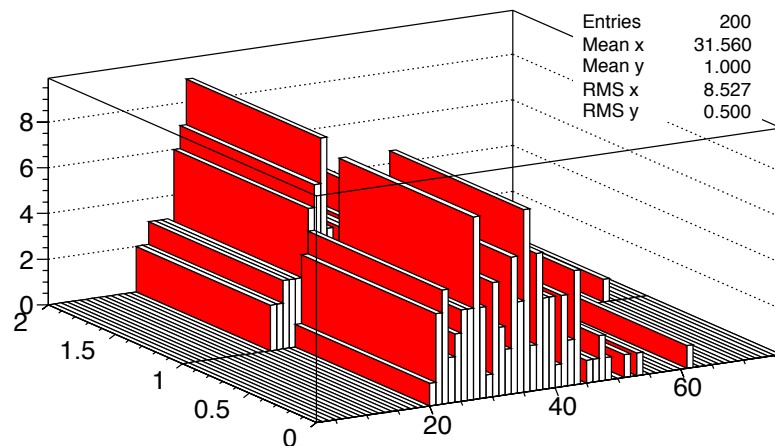
1.5 meter x 30 mm x 10 mm extrusion, 1.0 mm diameter WLS fiber. TiO₂ reflectivity. 1 GeV muons fired at 4 points along the bar from center in 20 cm increments.



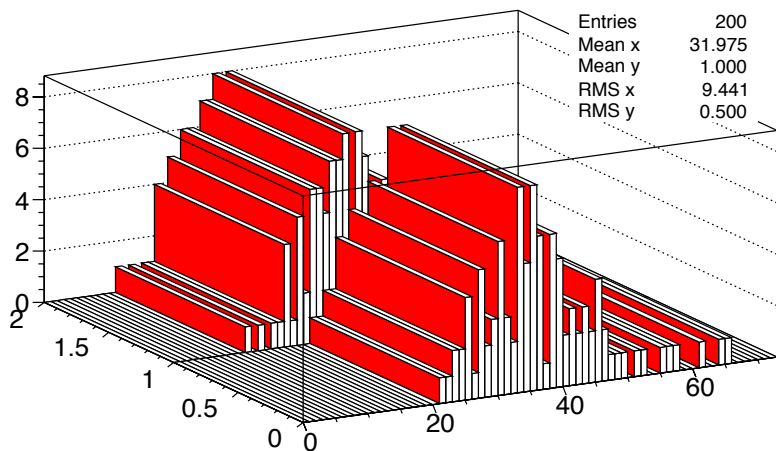
30 mm x 10 mm Extrusion



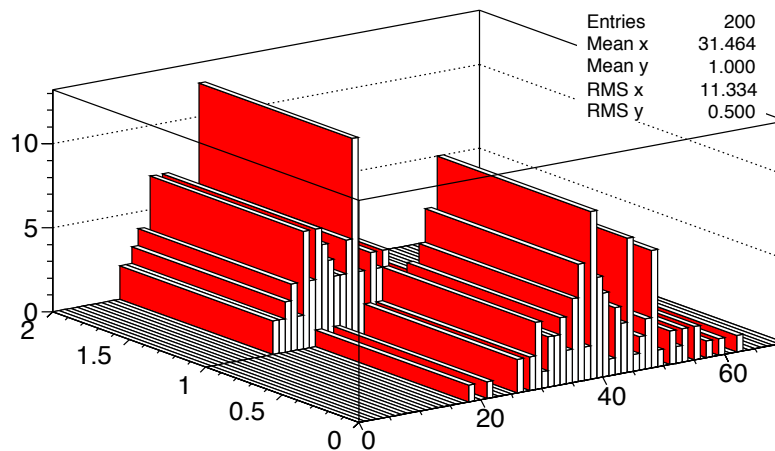
center



20 cm away from center



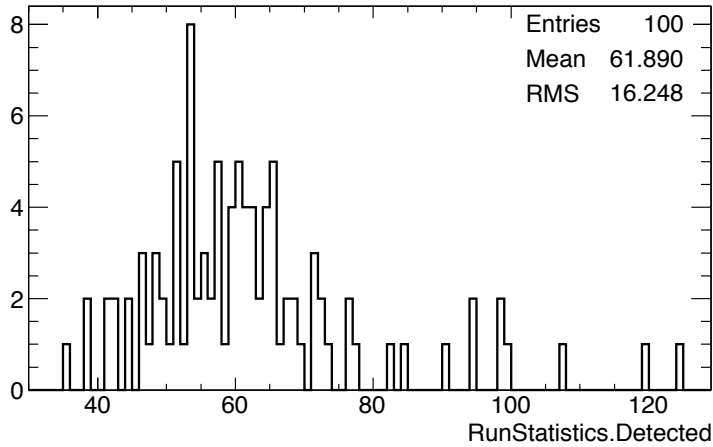
40 cm away from center



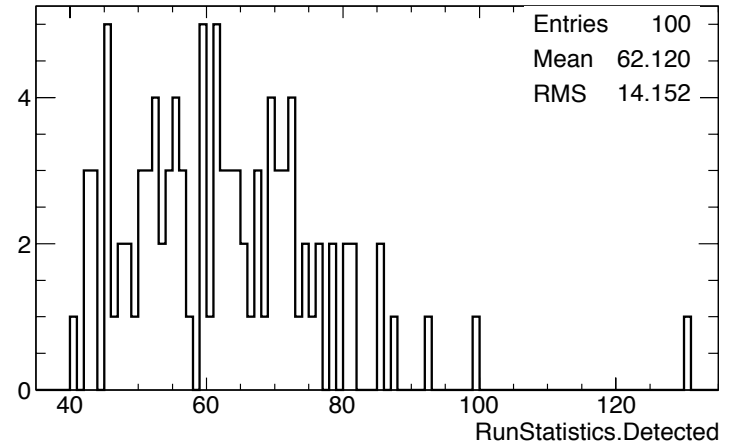
60 cm away from center



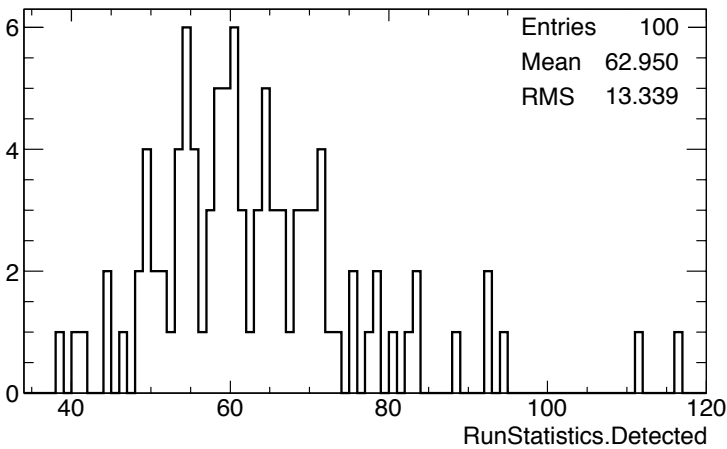
30 mm x 10 mm Extrusion



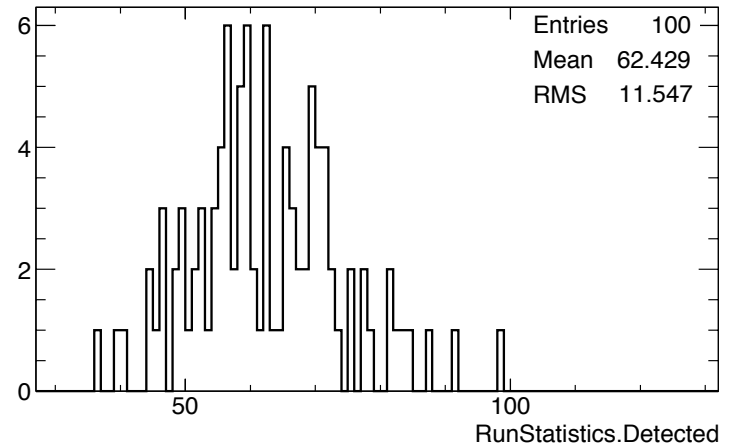
center



20 cm away from center



40 cm away from center



60 cm away from center



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 measurements
- ◆ MINERvA extrusion studies agree with measurements
- ◆ This is a general model for a wide range of applications

Current Plans

- ◆ Complete the studies suggested by Roumen
- ◆ Consider possible improvements for:
 - Fiber co-extrusion
 - Reflective coating/wrapping
- ◆ Consider a possible parametrization of the response
- ◆ **NEW results from fiber measurements/simulations coming soon**



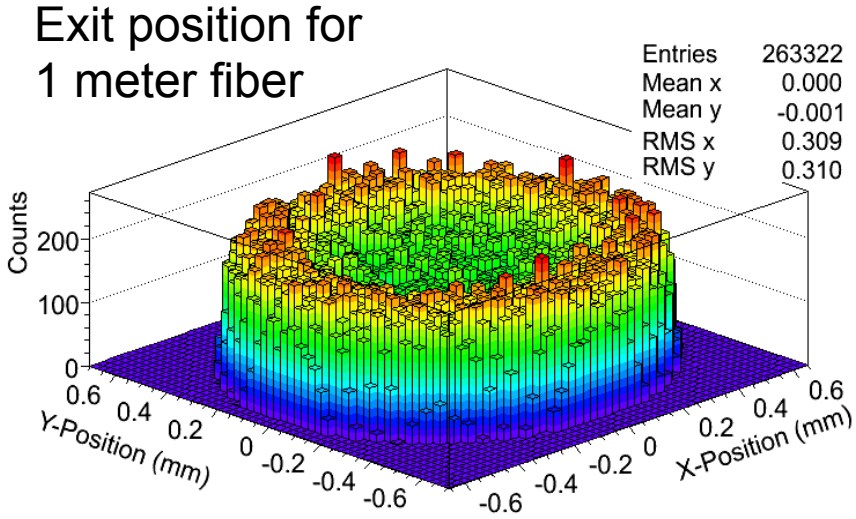
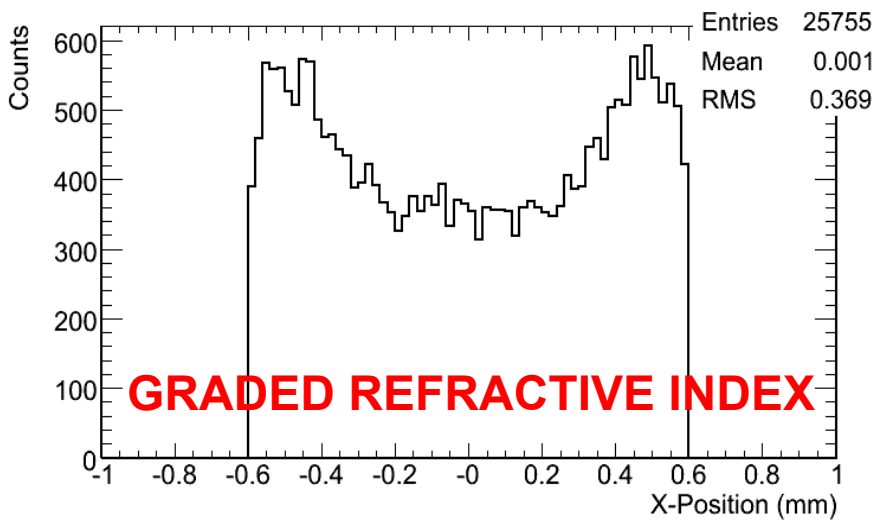
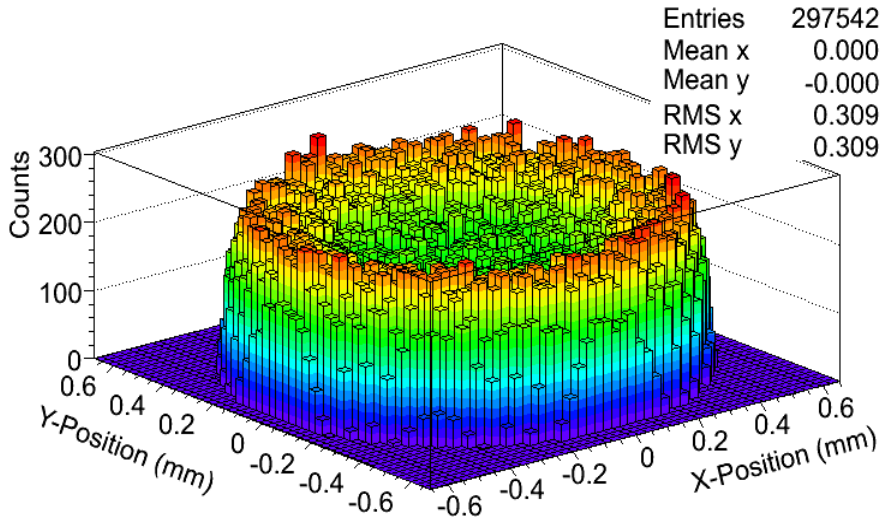
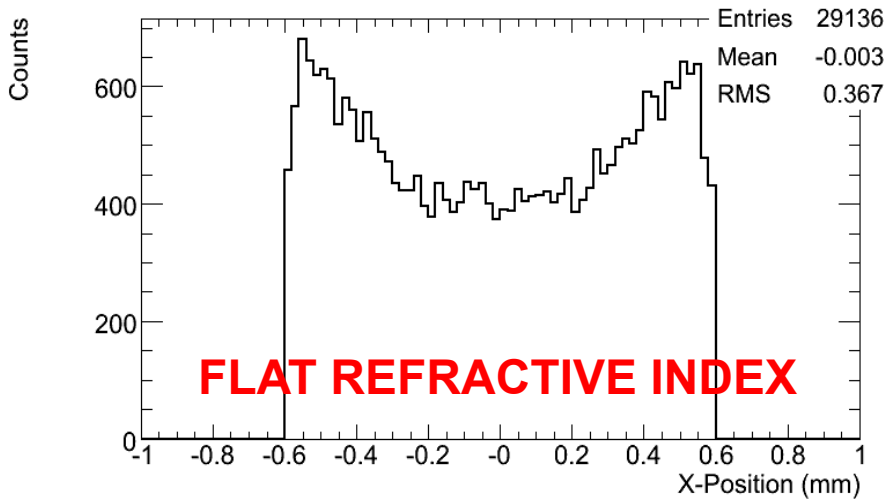
Backup Slides



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

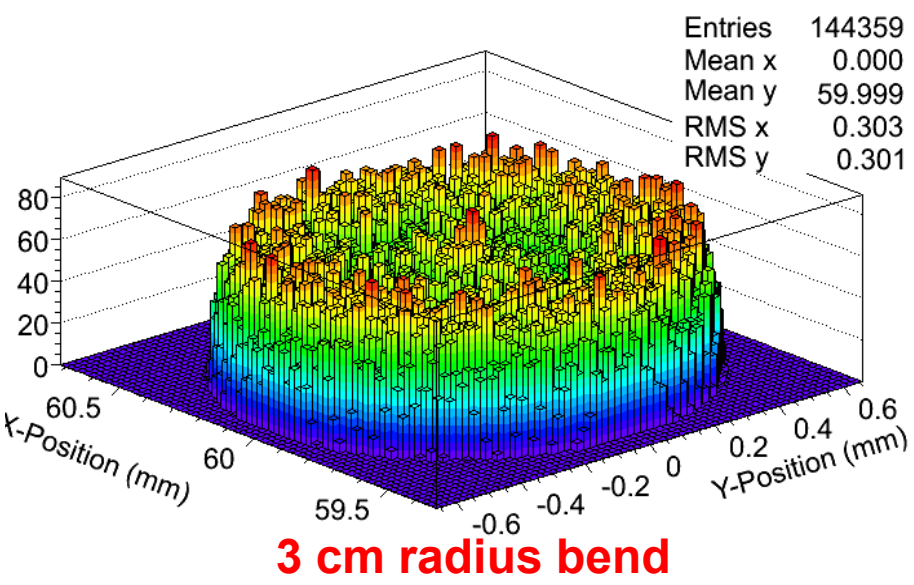
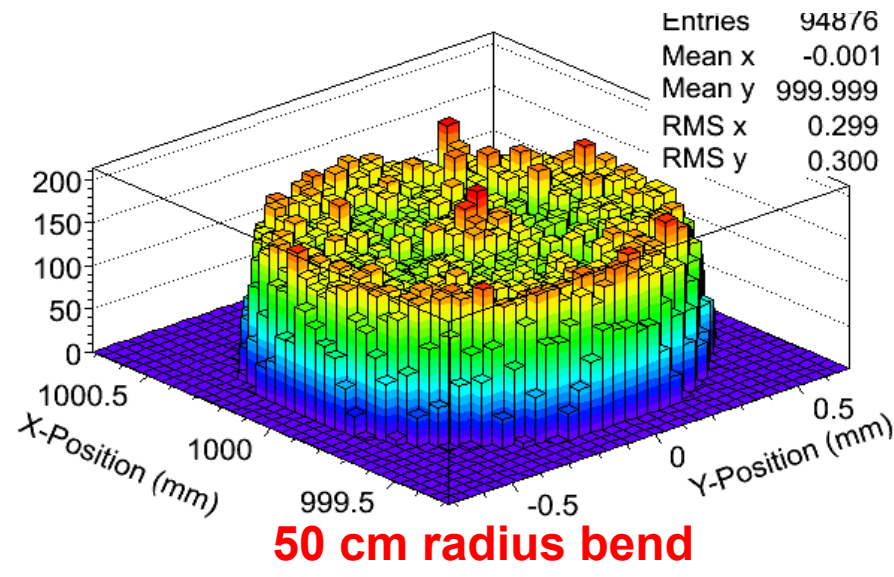
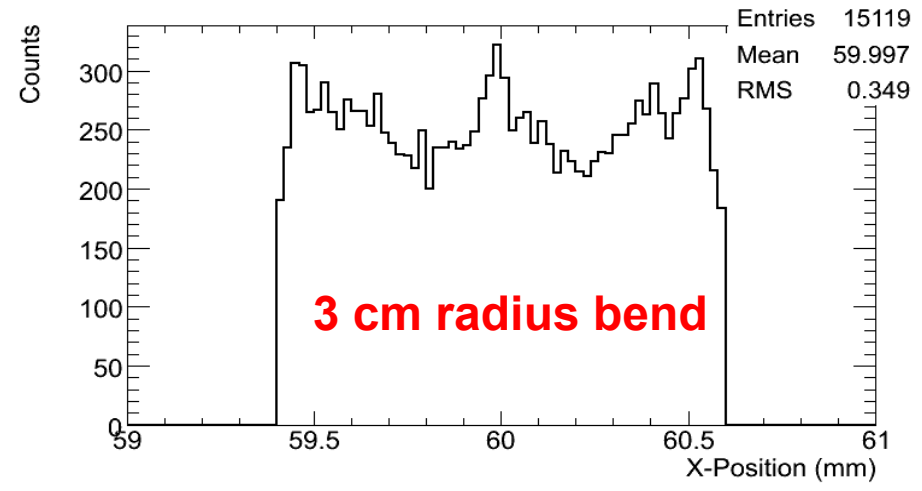
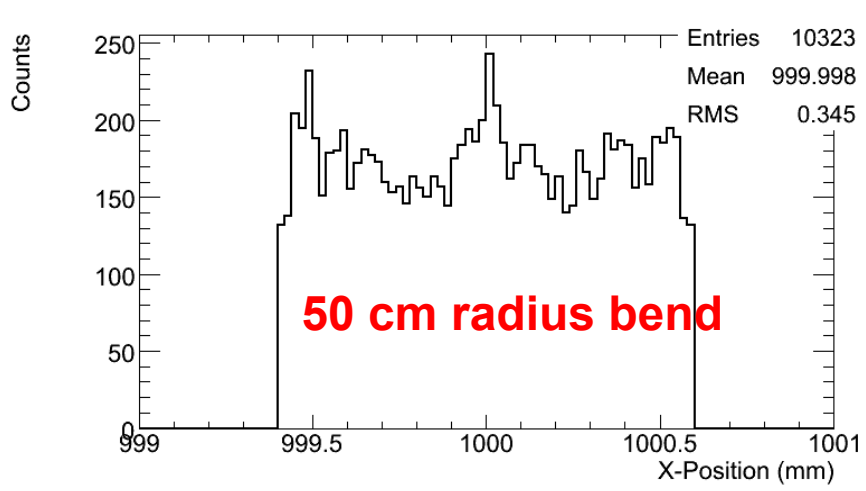




Exit Position for Bent Fiber

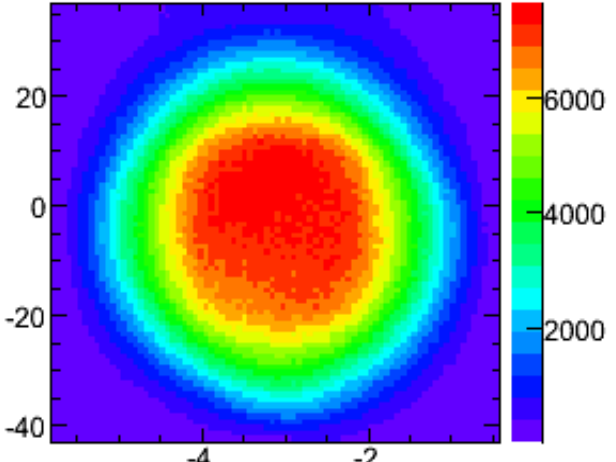


- ◆ Results are for 50 cm and 3 cm radius bends.
- ◆ Light input is a pencil beam centered on the side of the fiber.

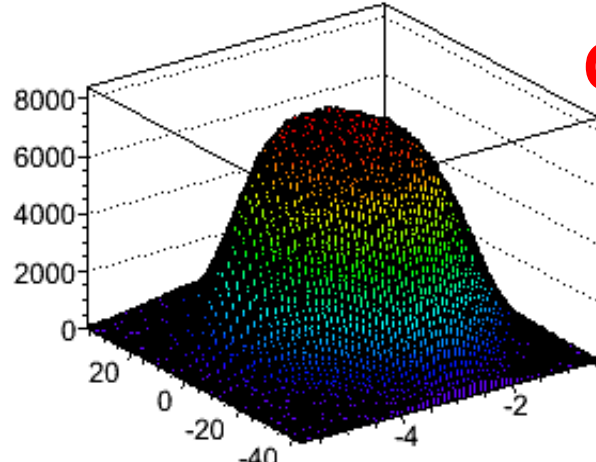




First Try: 1.2 mm Fiber

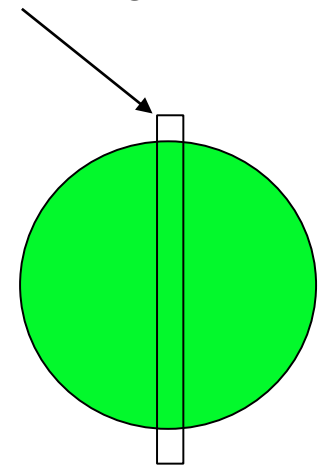
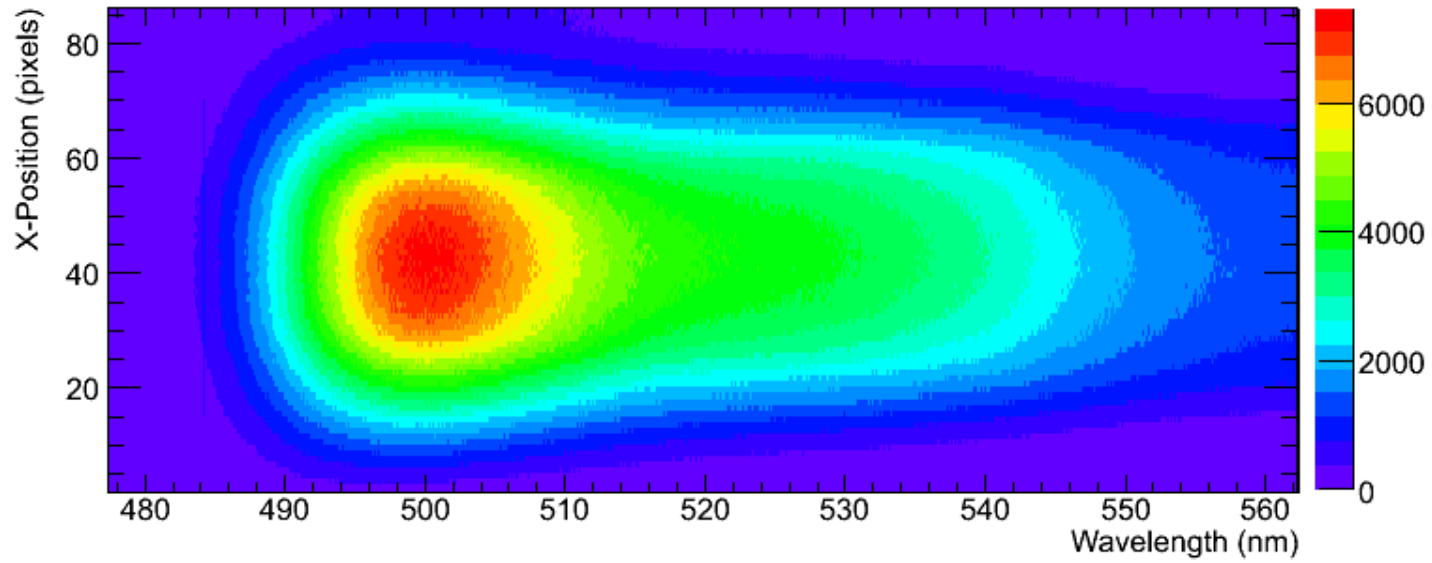


arbitrary units (pixel position)



OUT OF FOCUS!

Narrow exit slit for center position vs. wavelength

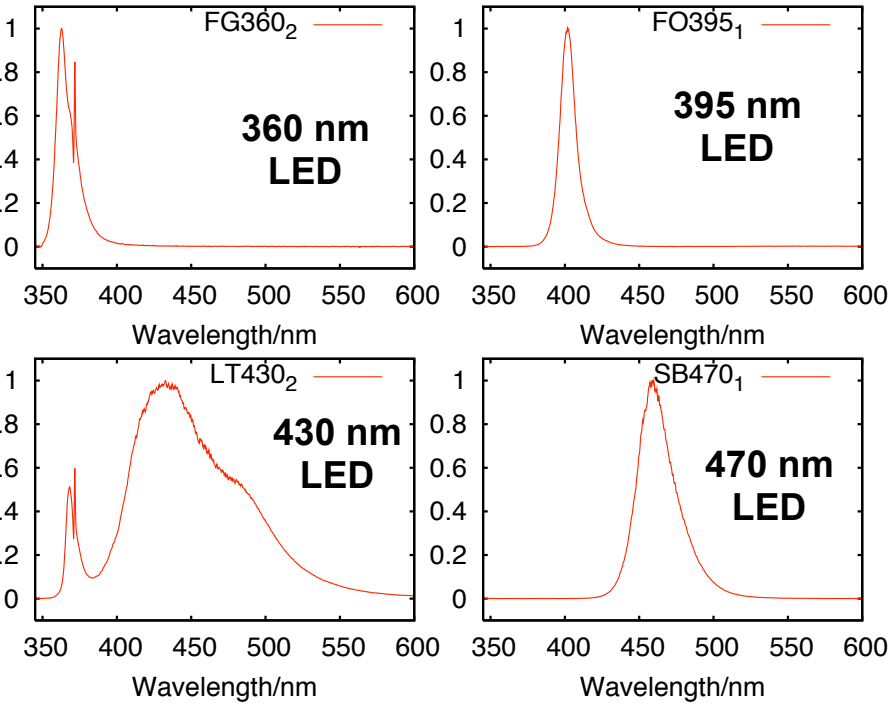




Long-distance light transport LED Measurements

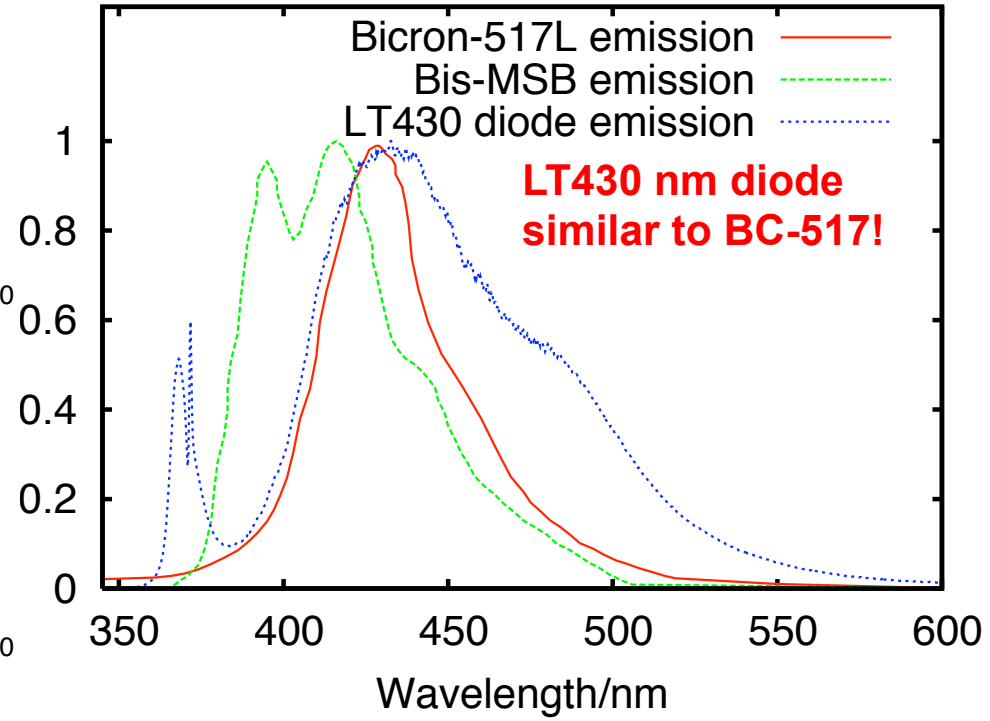


Use LEDs to study fiber attenuation...and test the simulation



Spectra of select LEDs used to illuminate fibers.

Measurements by Gabriel Elpers



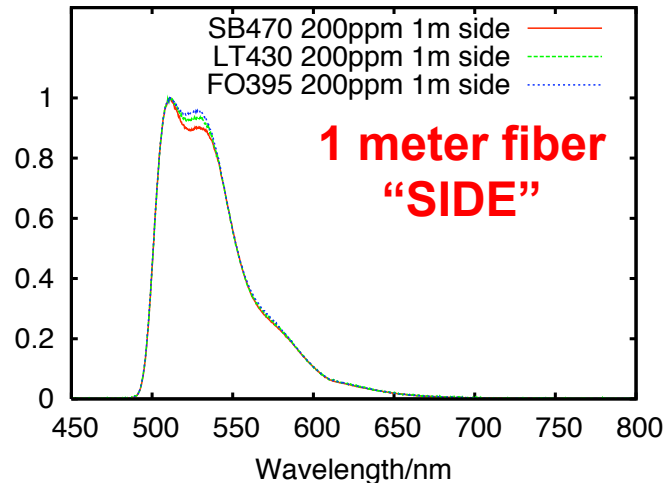
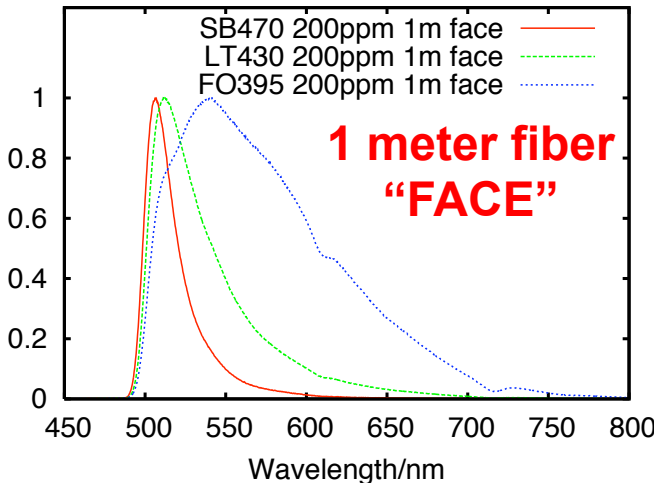
Comparison of LT430 diode with 517L scintillator and bis-MSB fluor.



Fiber Measurements (1)

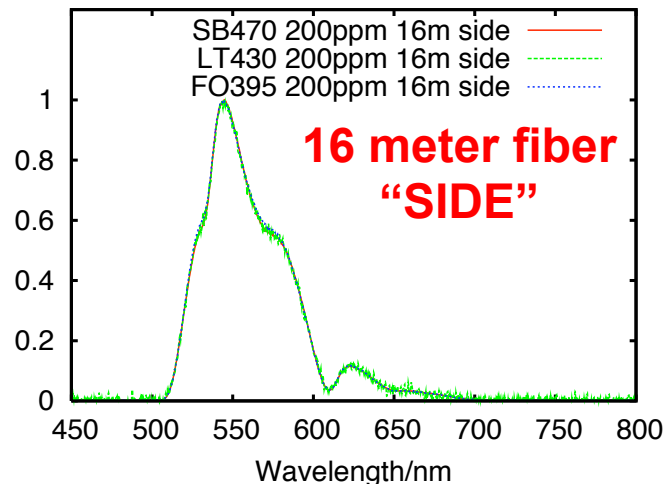
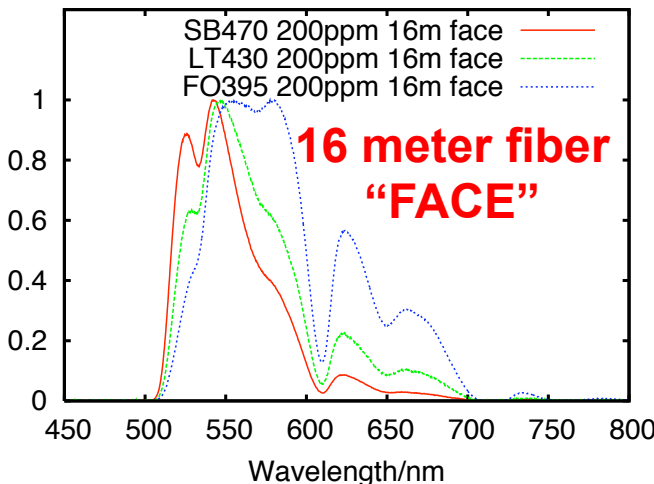


Illumination on the face shows large difference in spectra



1 meter "face" illumination with three LEDs

1 meter "side" illumination with three LEDs



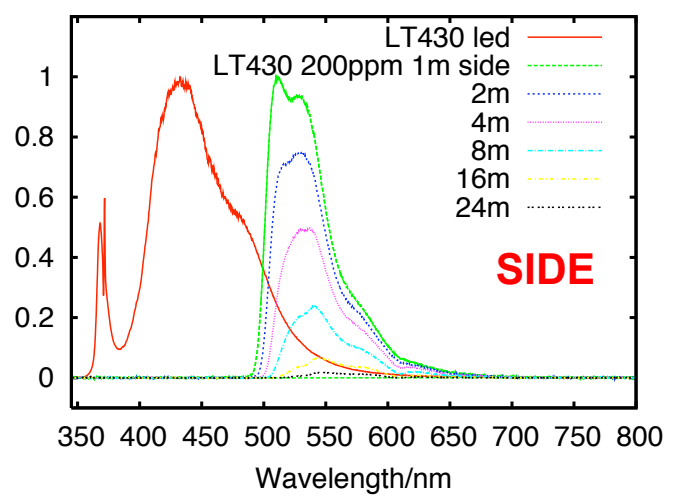
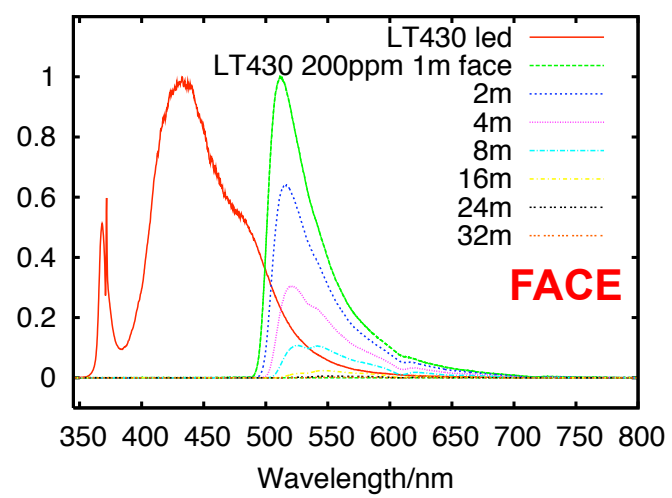
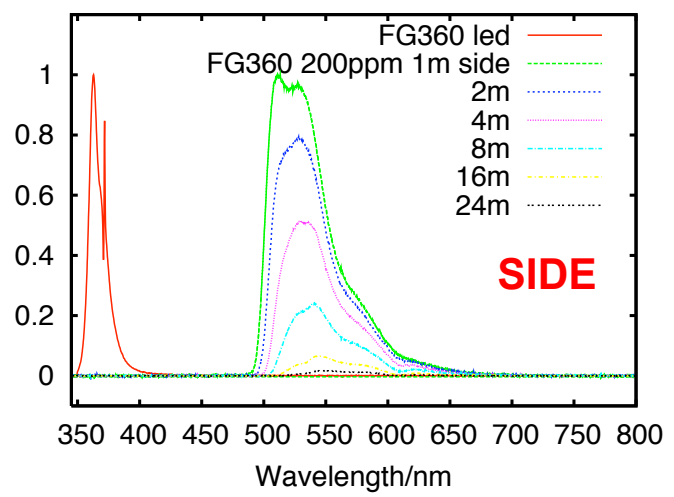
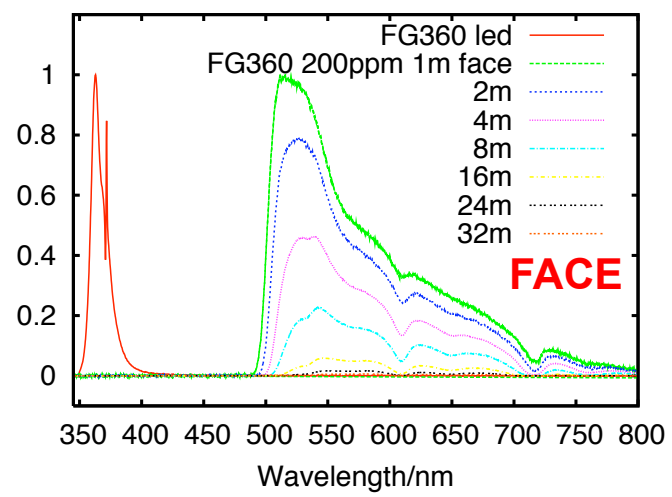
16 meter "face" illumination with three LEDs

16 meter "side" illumination with three LEDs



Fiber Measurements (2)

Results for two full sets of measurements for two LEDs

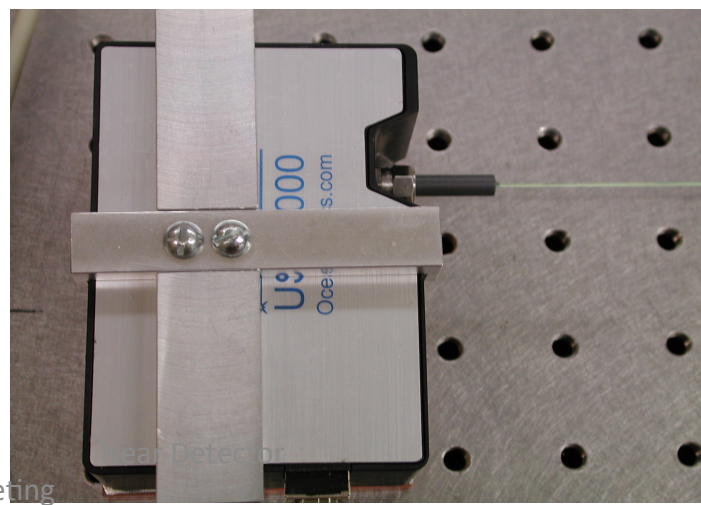
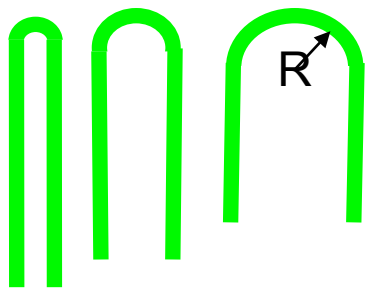
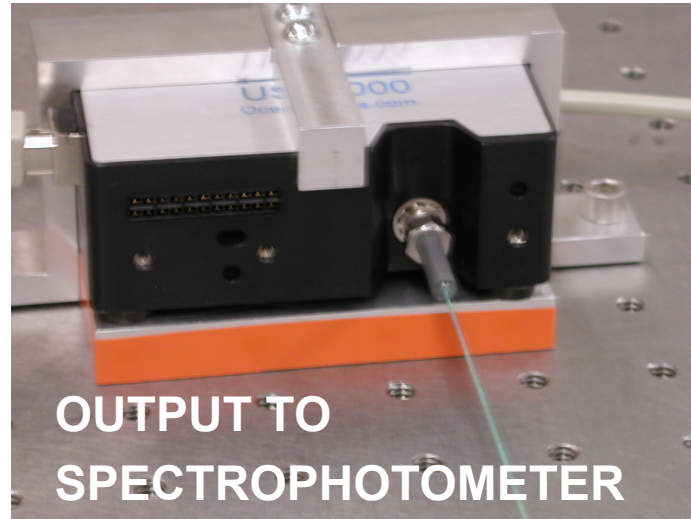
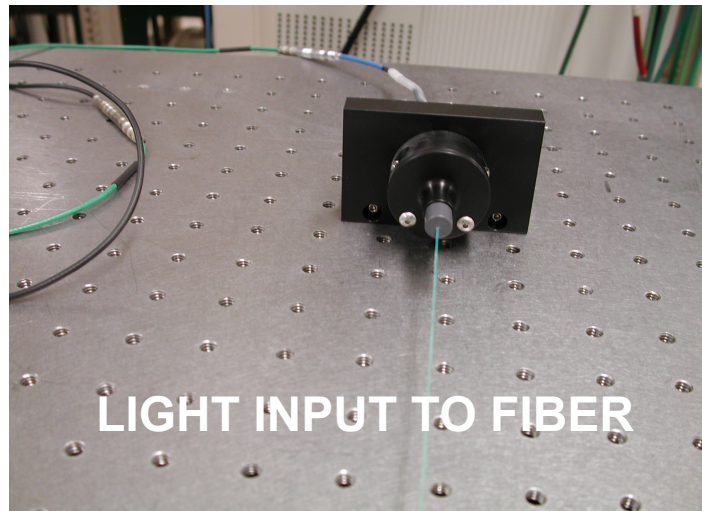




Effect of Fiber Bending

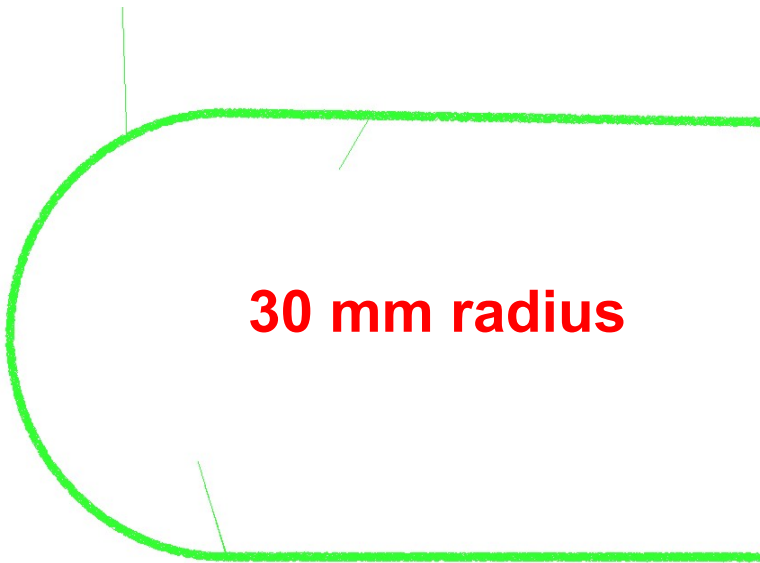


- ◆ 2.0 m 0.7 mm diameter Kuraray Y-11 WLS (200 ppm) coupled to 400 nm LED
- ◆ Measurements taken at bending radius of 13.5 cm to 1.5 cm in 2 cm increments

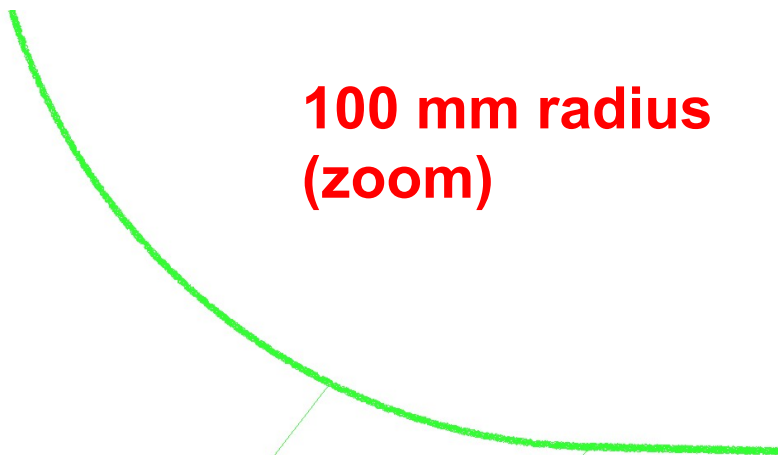




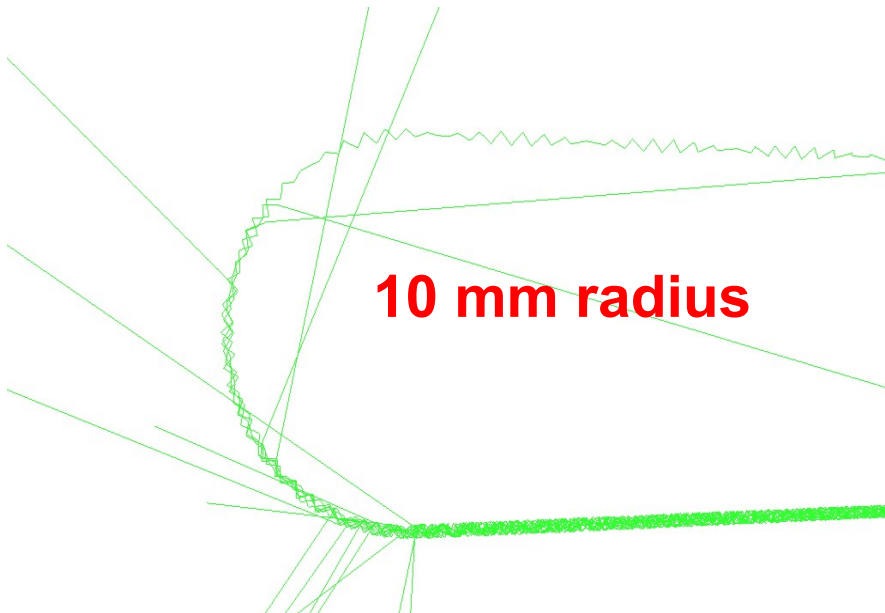
Bending Radius Studies: Images



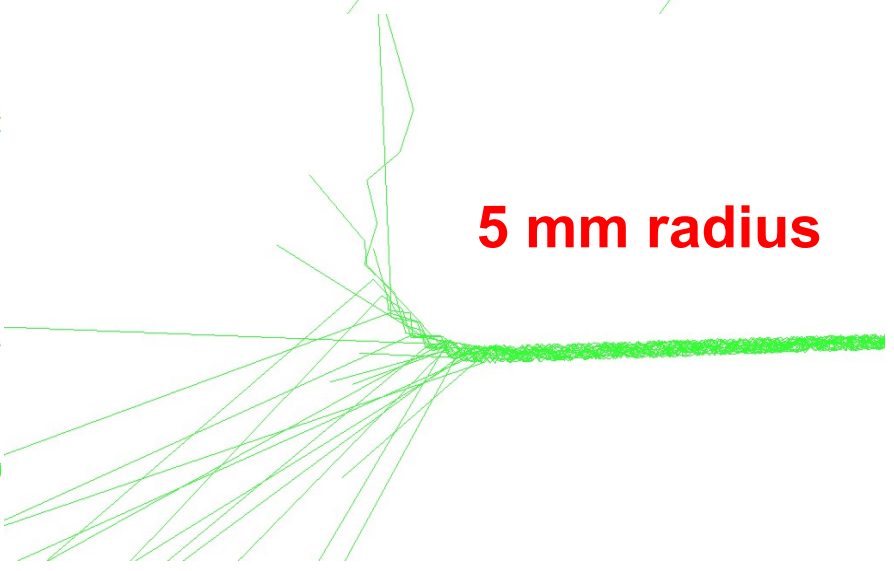
30 mm radius



**100 mm radius
(zoom)**



10 mm radius



5 mm radius

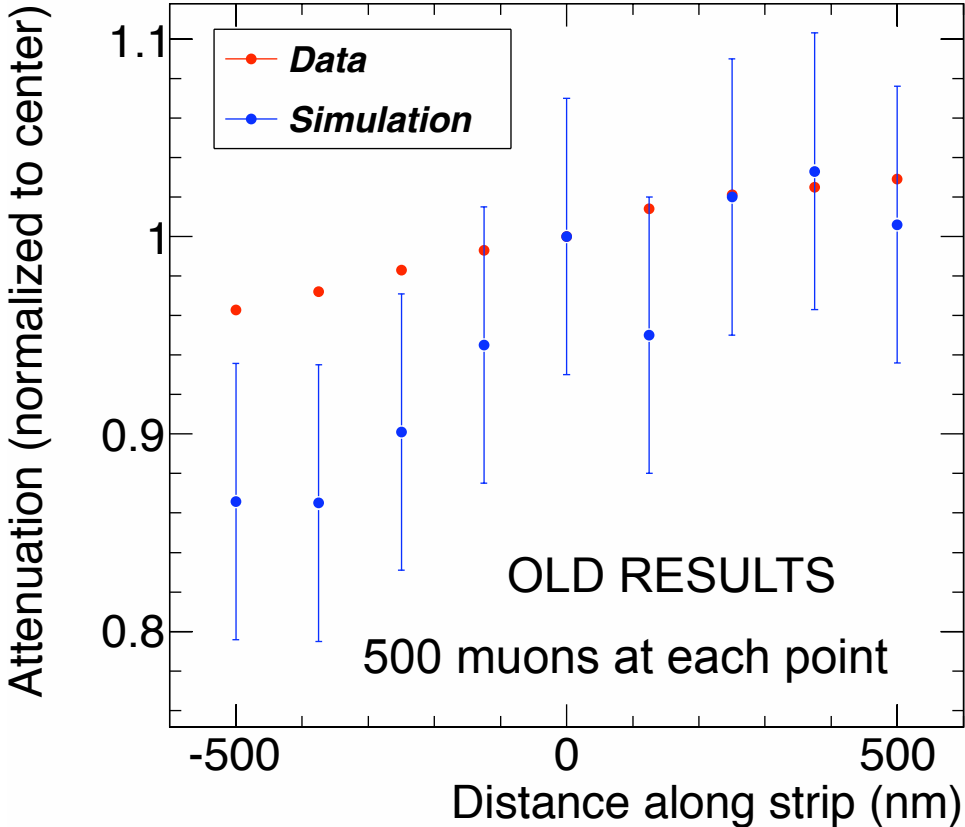
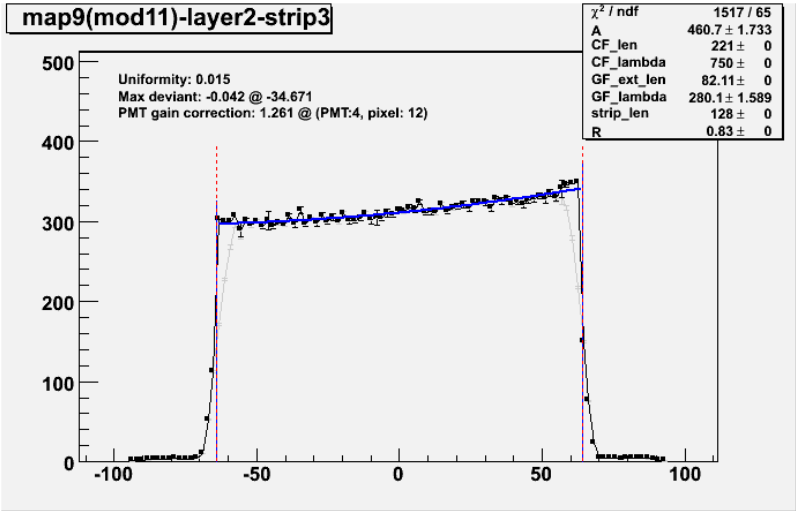


Preliminary MINERvA Setup



Return to the 1.25 m extrusion: Add more statistics

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



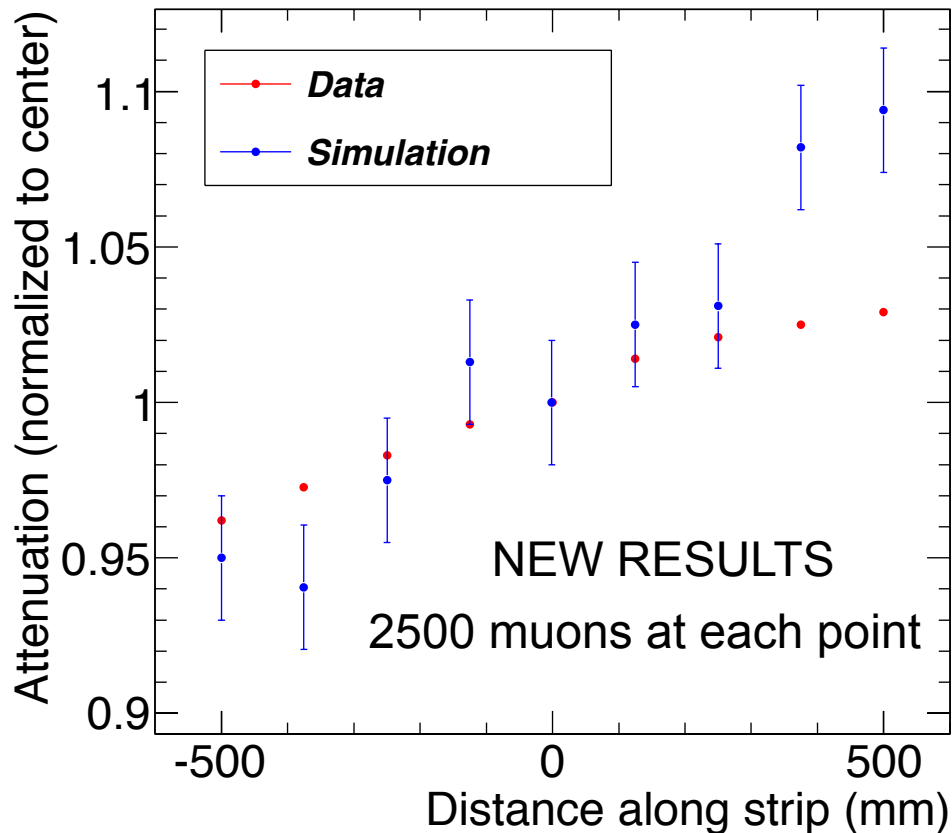
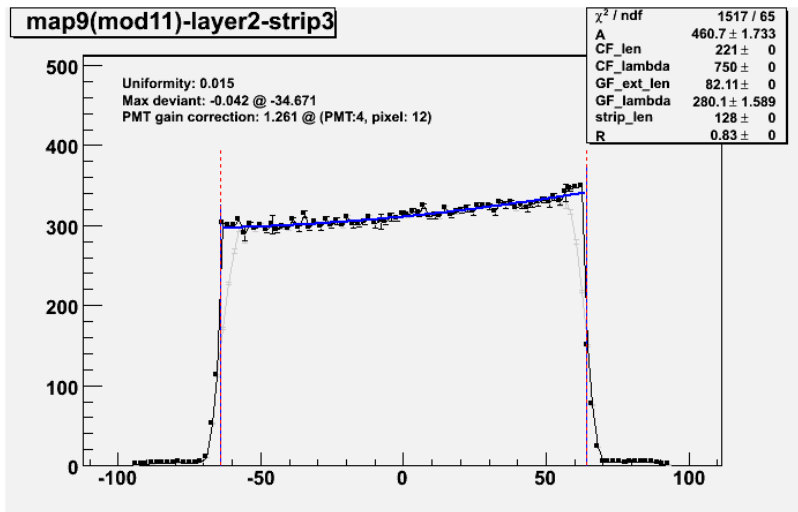
Clearly need more statistics. Normalization to center may skew this plot. Data was scanned “crudely” with a plot digitizer. Room for improvement!



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?



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%