Studies of radiation effects on the hadronic calorimeters at CMS

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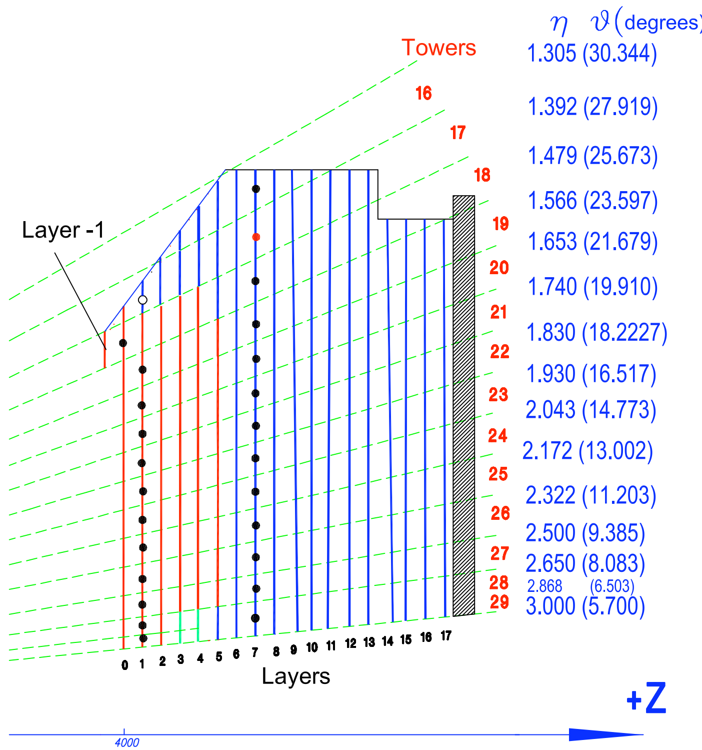
On behalf of the CMS Collaboration

CALOR 2018 @ University of Oregon – 2018/05/24

Outline

- Overview on CMS HCAL ageing
- Introduction of a new R&D approach
  - Motivation
  - Real measurements assisting GEANT4 simulation
  - Example extracting oxygen diffusion model parameters
- Procedures
- Summary



HCAL Ageing

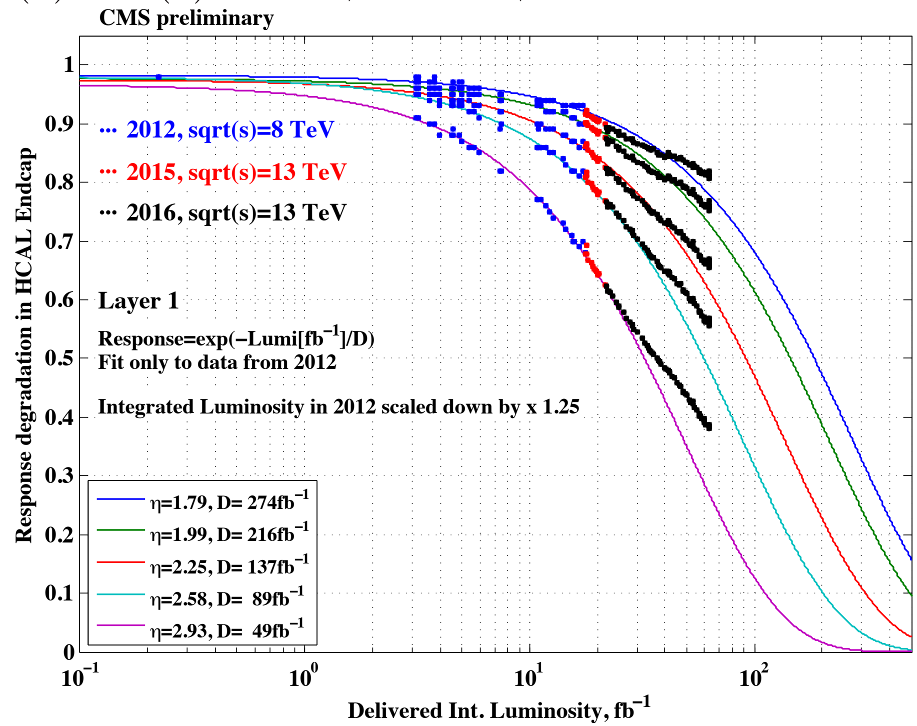
Larger than expected light-yield reduction observed in 2012

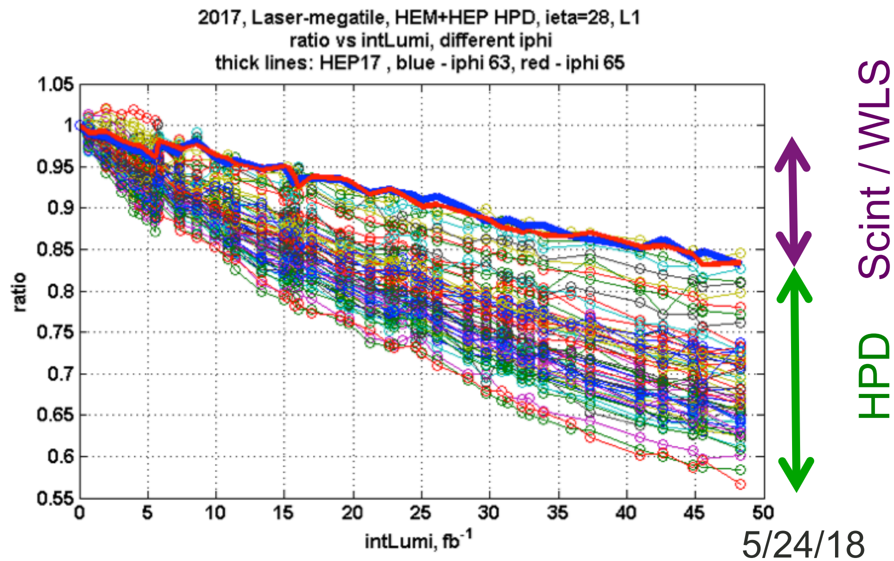
- CMS Hadronic calorimeter uses plastic scintillator as active material
  - Susceptible to radiation
  - Dose rate dependence

JINST **11**, T10004 (2016)

- HPD degradation turns out also contribute significantly to lager than expected darkening
  - HPDs show signs of various degrees of inhomogeneous damages
  - Suboptimal results biased by ill-behaved HPDs

$$L(d) = L(0) \times e^{-\frac{d}{D}}; d: \text{ dose}; \; D: \text{ dose constant}$$



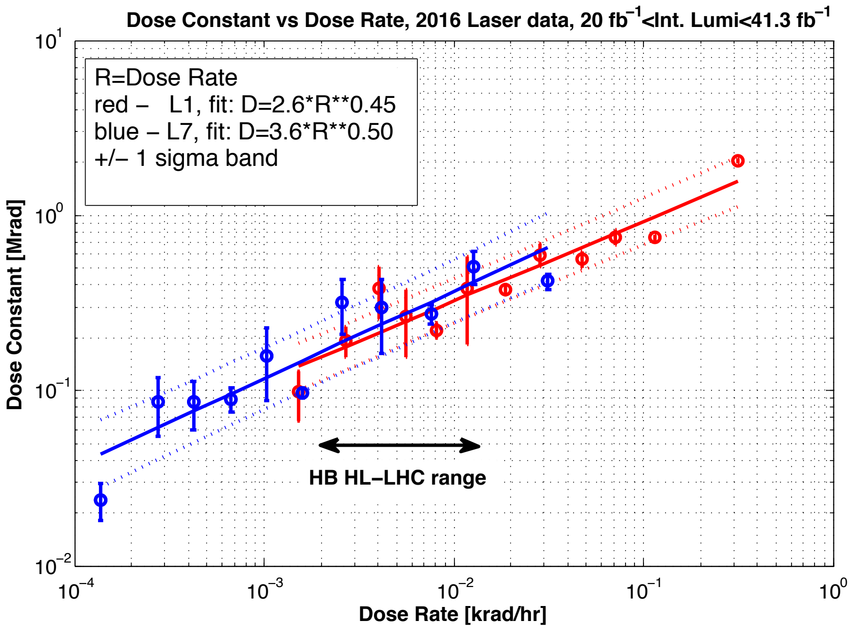


See Federico's slides on Tue

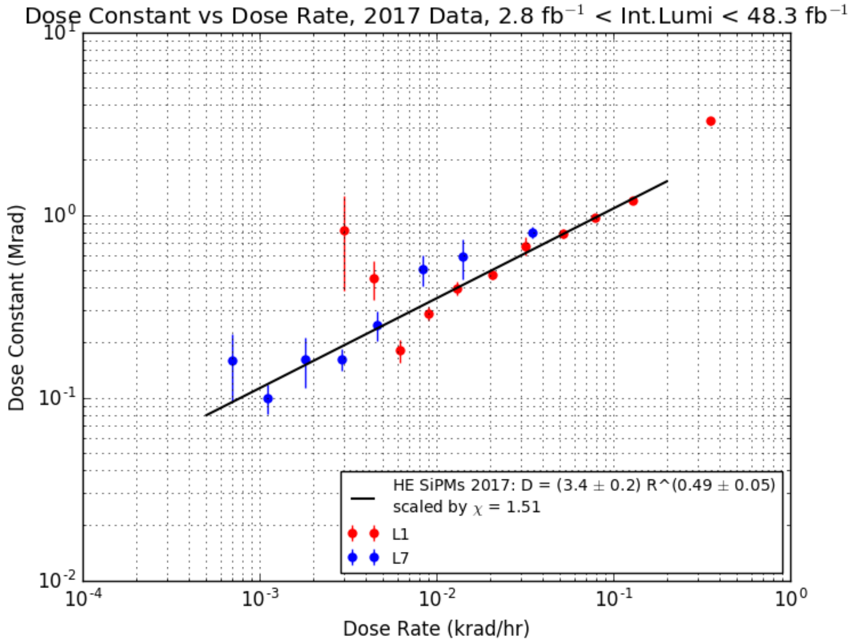
HPD vs. SiPM

$$L(d) = L(0) \times e^{-\frac{d}{D}}; d: \text{ dose}; \; D: \text{ dose constant}$$

- HEP17 replaced with SiPM for 2017 data taking (more details in Federico's slides on Tue)
- Comparing 2016 results from 10 best HPDs with 2017 of SiPM allows studying "nominal" ageing
  - Confirming active material system (scint+WLS) light reductions are consistent



10 best HPDs

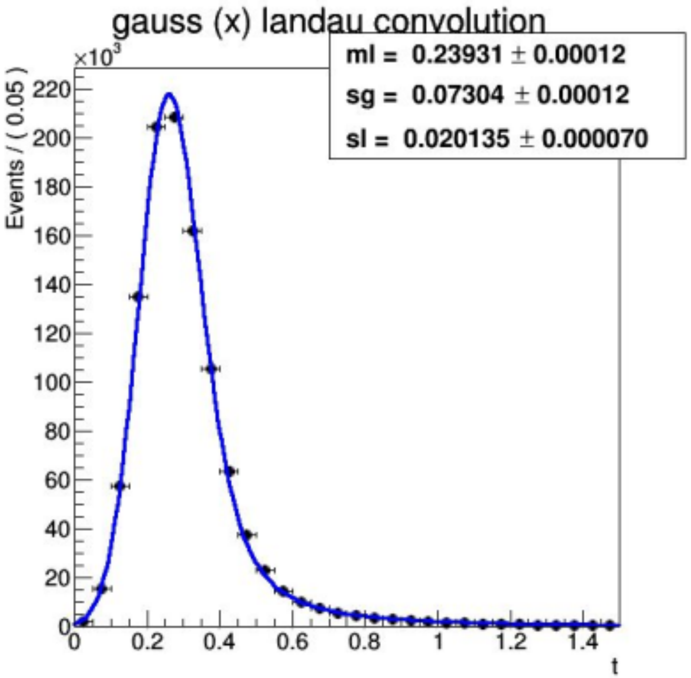


SiPM

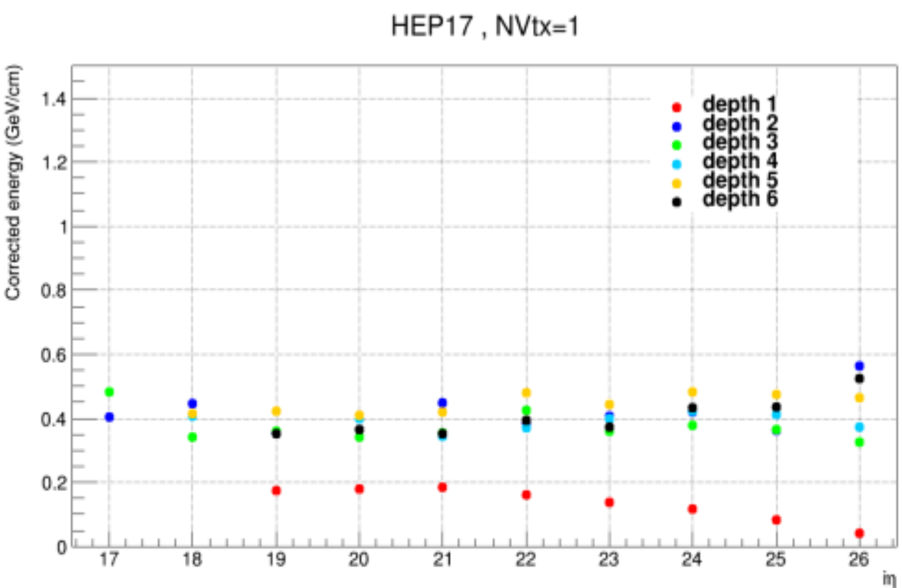
Used to predict HB performance in HL-LHC

Other Methods for Ageing Studies

- Isolate muons in HE
  - MIP energy loss fitted by Landau convoluted with Gaussian
- In-situ calibration with inclusive hadrons in HE
- High dose rate irradiation

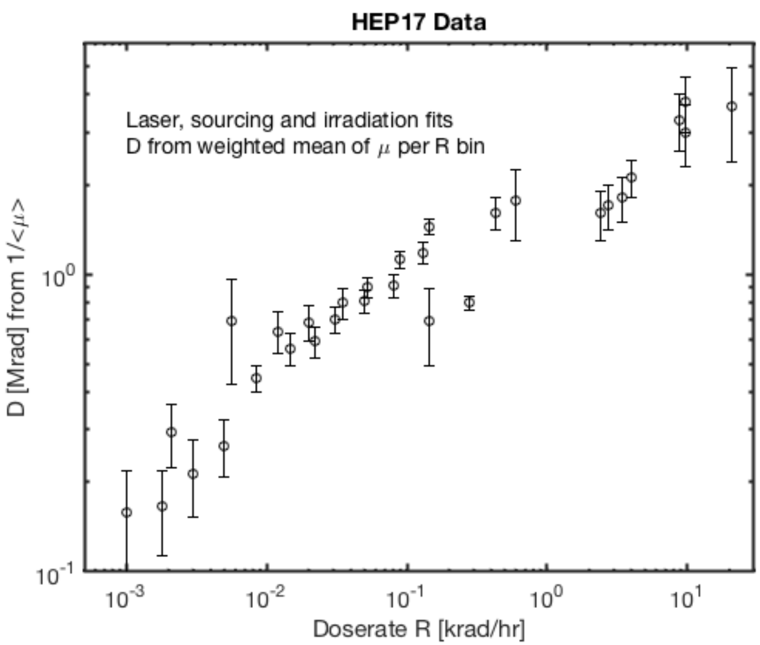


Iη = 1 , RunB
Most Probable Value ~ 0.26

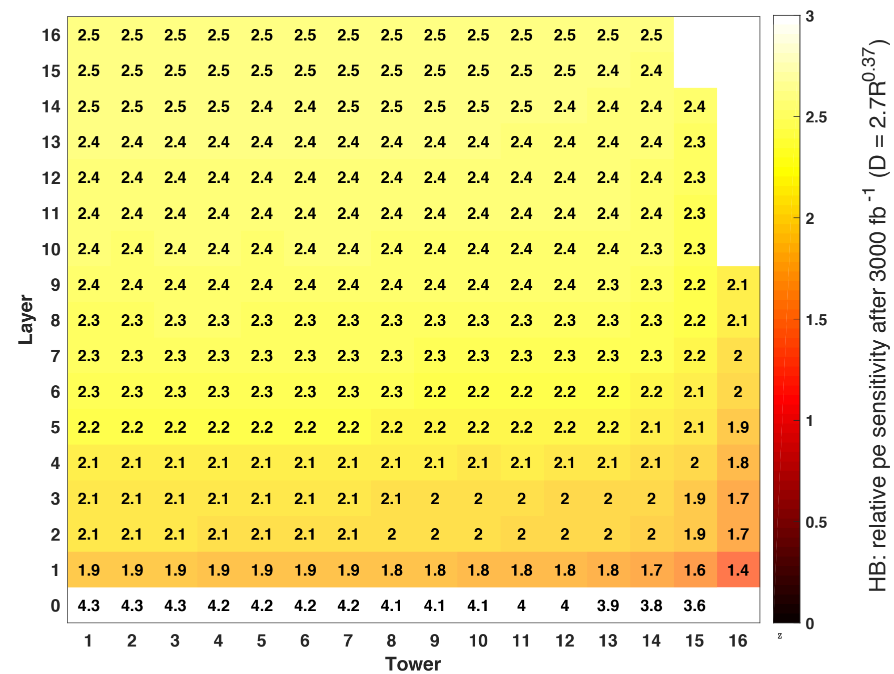


Ageing Model for HCAL Barrel (HB)

- Predicted ratio of mip signal to dark current in HB for 14 TeV and 3000 fb^{-1}



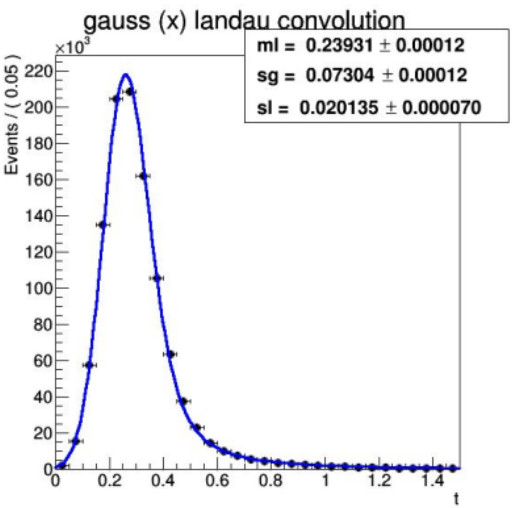
Laser+source calibration+CRF



HB will survive through HL-LHC

Many Types of Measurements

- What can we do with these to better understand radiation damage



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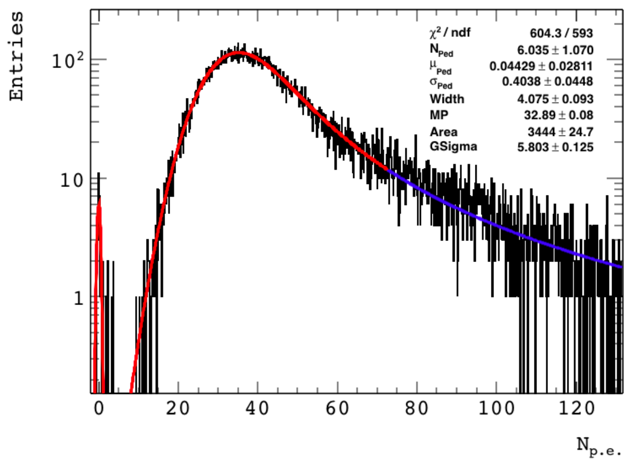
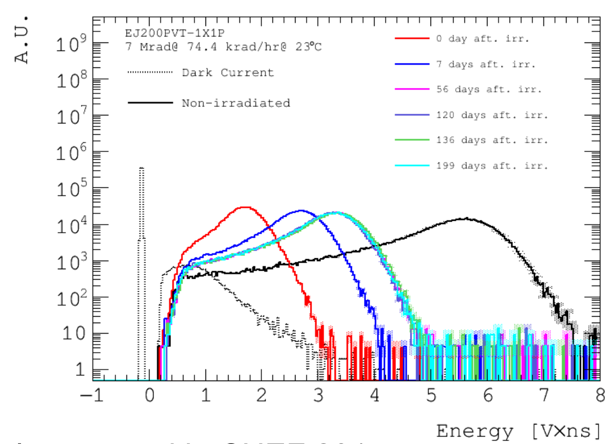
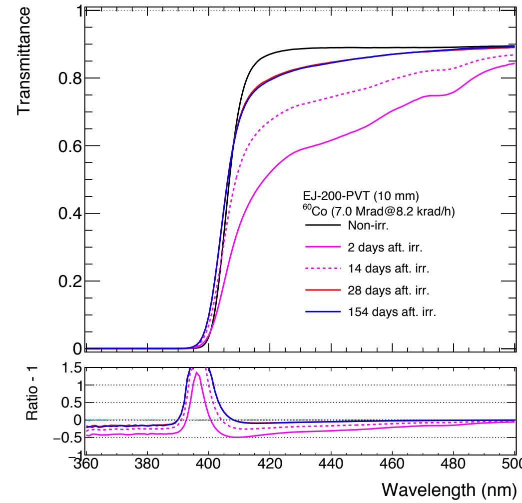
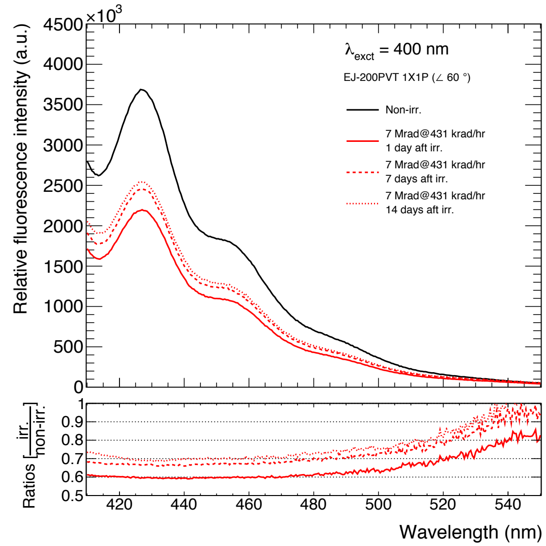


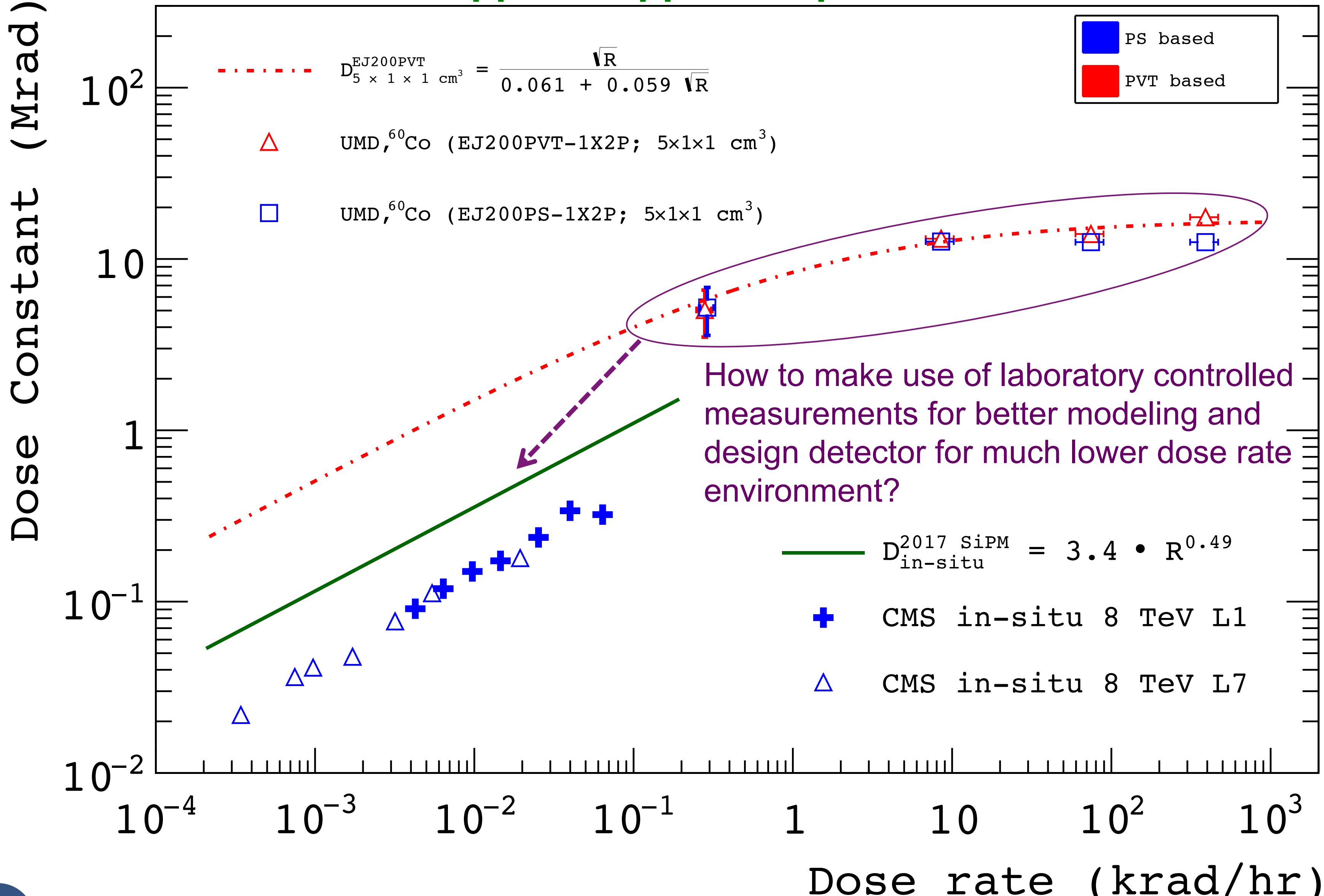






Many results reported in CHEF 2017: https://indico.cern.ch/event/629521/contributions/2703006/attachments/1536233/2406727/RicciTam_ScintillatorPerformance.pdf)

Something is clearly missing
Not apple to apple comparison



CMS in-situ SCSN81 tiles are 3.7 mm thick

Motivation

$$L = L_0 \times e^{-d/D_{\mathrm{eff}}};\ 1/D_{\mathrm{eff}} = \sum_i 1/D_i$$

- Dose rate effect published in *JINST* **11**, T10004 (2016)
  - Oxygen diffusion model for dose rate dependence
- Dose constants from measurements of Rods (5x1x1 cm^3) and Tiles (LxLx0.4 cm^3; L varies from 10 to 20; trapezoidal in CMS HE) appear disconnected on the D vs. dose rate plots
  - Discovery of large HPD contribution introduces further complication
    - **Absolute dose constant vs. effective dose constant**
    - Effective Dose Constant
      - Compounding several contributing absolute dose constants: base material, WLS, clear fiber, photodetector…
    - Absolute dose constant (model parameters)
  - All the results shown so far are effective dose constants, which depend on active material geometry/size, signal detection mechanism…, while the oxygen diffusion model parameters do not
    - The plan is to demonstrate how geometry impacts the effective dose constant by setting up a systematic procedure for GEANT4 simulation based on oxygen diffusion model (or else if available) to compare and validate with real measurements (absorption, emission, alpha source, cosmic ray, and in-situ), and provide basis for extrapolation for future design

Oxygen Diffusion Model

JINST **11**, T10004 (2016)

R: dose rate
V: diffusion constant
S: solubility constant of O_2
P: oxygen pressure
Φ: specific rate constant of active site formation
Y: density of color centers
σ: absorption cross section of the color center
t: thickness
g: chemical yield
Q: density of scintillator

$$z_0^2 = \frac{G}{R}$$

$$G = \frac{2VSP}{\Phi}$$

$$L = L_0 \exp(-\mu_1(2z_0) - \mu_2 t)$$

$$\mu = Y\sigma$$

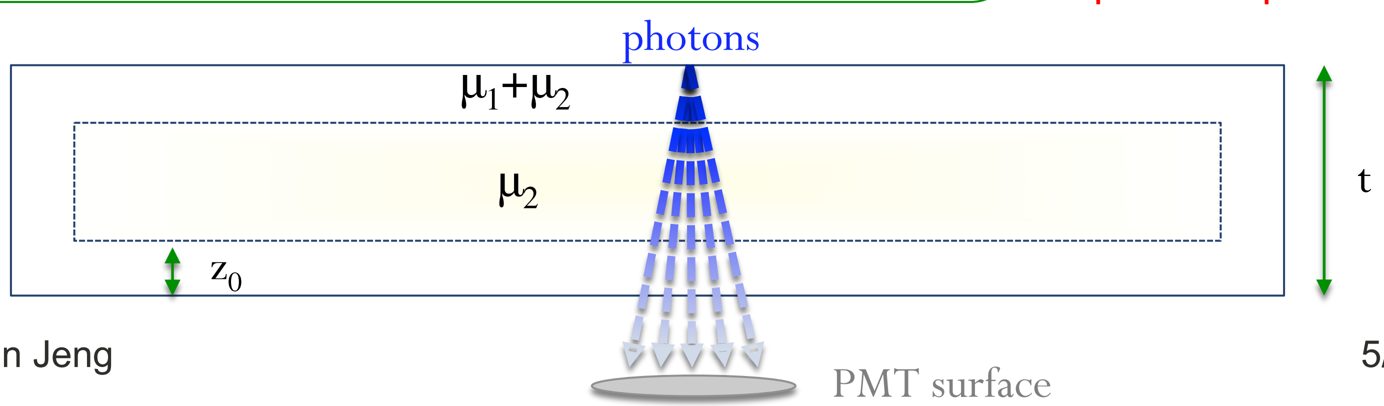
$$Y = \mathrm{g}Qd$$

$$L(d) = L_0 \exp\Big(-\Big(\mathrm{g}_1 Q_1 \sigma_1 2\frac{\sqrt{G}}{\sqrt{R}}\Big)d - (\mathrm{g}_2 Q_2 \sigma_2 t)d\Big)$$

$$D = \frac{\sqrt{R}}{A + B\sqrt{R}};\ A = 2\mathrm{g}_1 Q_1 \sigma_1 \sqrt{G} \text{ and } B = \mathrm{g}_2 Q_2 \sigma_2 t$$

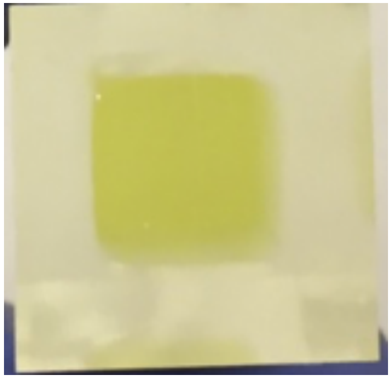
$D \propto \sqrt{R}$ for small R

Note: the $R^{0.5}$ applies for similar cases depicted below (small spread of path lengths)



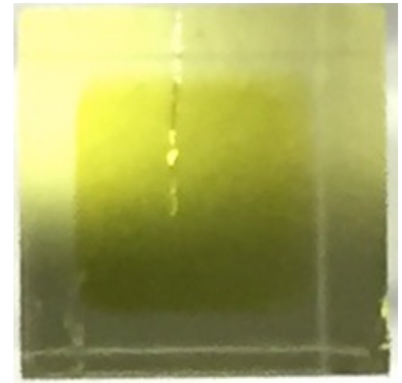
EJ200 overdoped on primary fluors

8.53 krad/h; 1 hr aft. irradiation

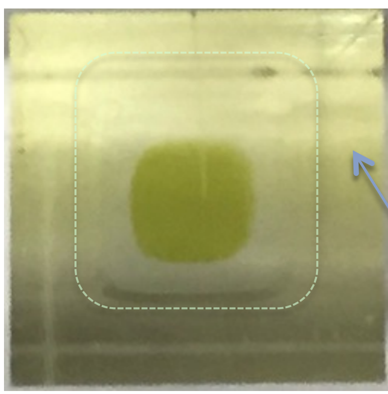


Still some temp damage at this dose rate

390 krad/h; 3 days aft. irradiation

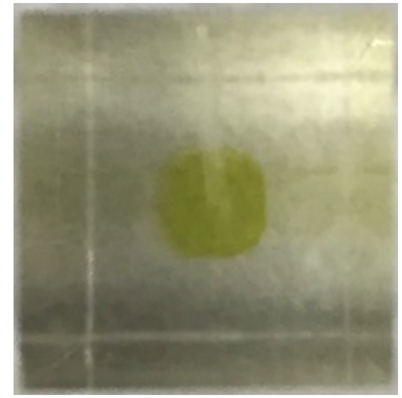


8.53 krad/h; 8 days aft. irradiation



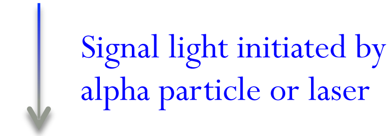
Region (outside the dashed shape) appears for dose rate low enough (depth >2mm each side); Note that there is a clear boundary (enclosed in the dashed line for displaying reason) which is not seen for high dose rates

390 krad/h; 14 days aft. irradiation

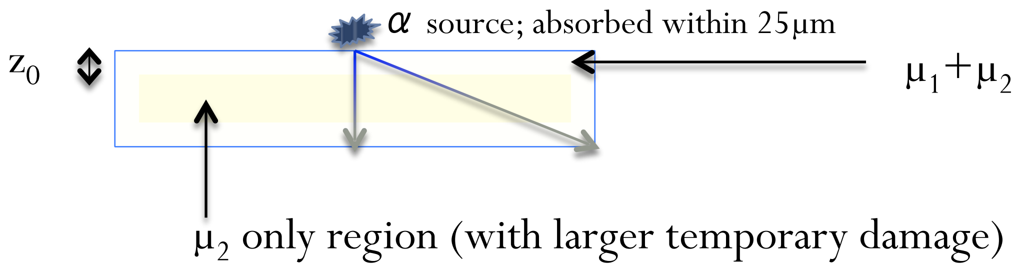


Fast recovery for the temporary damage for high dose rate

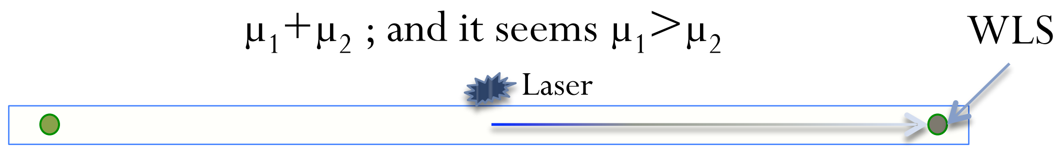
$$L = L_0 \times e^{-\mu_1 (2z_0) - \mu_2 t} \qquad \text{t=1 cm}$$



Rod:



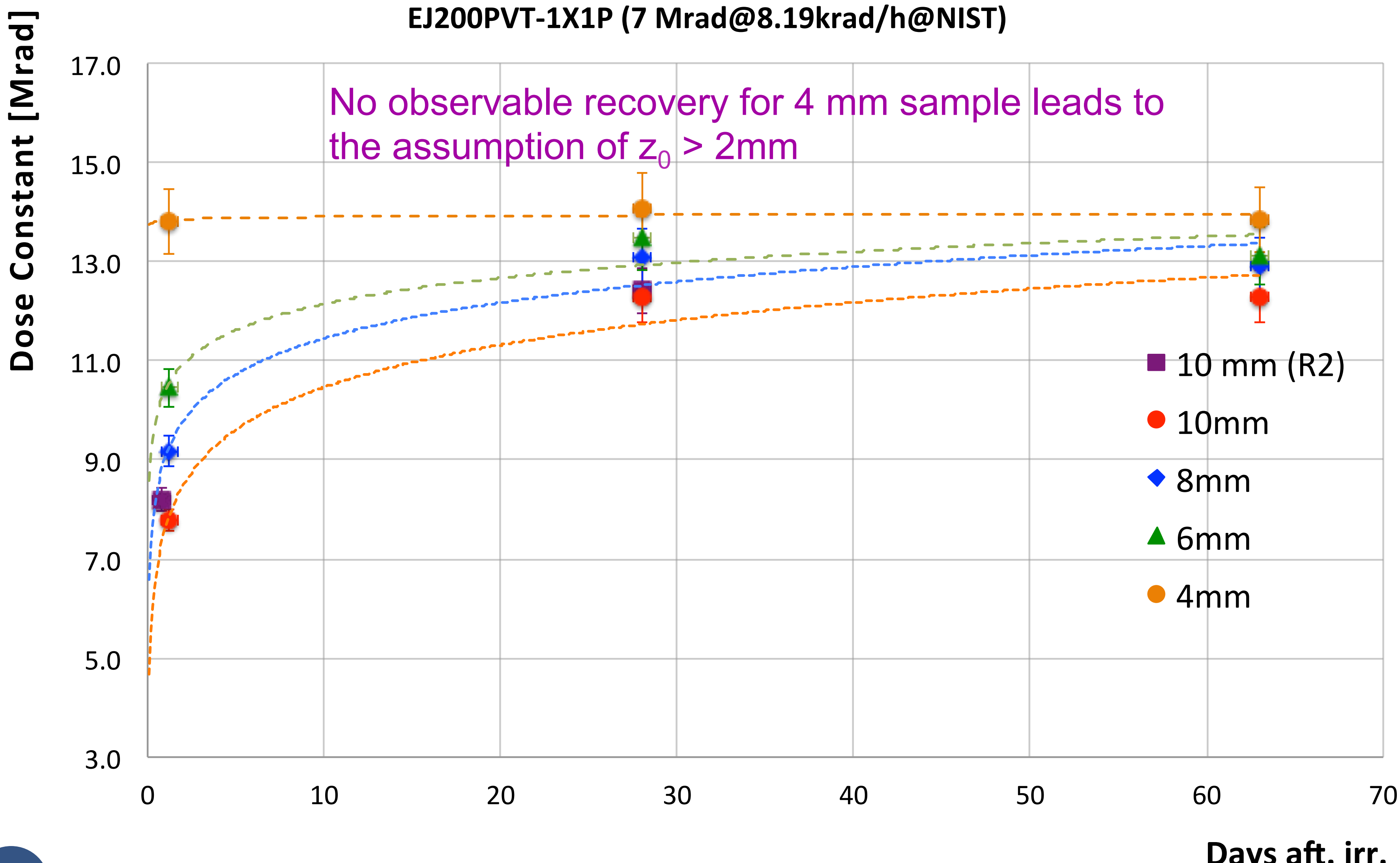
Tile:



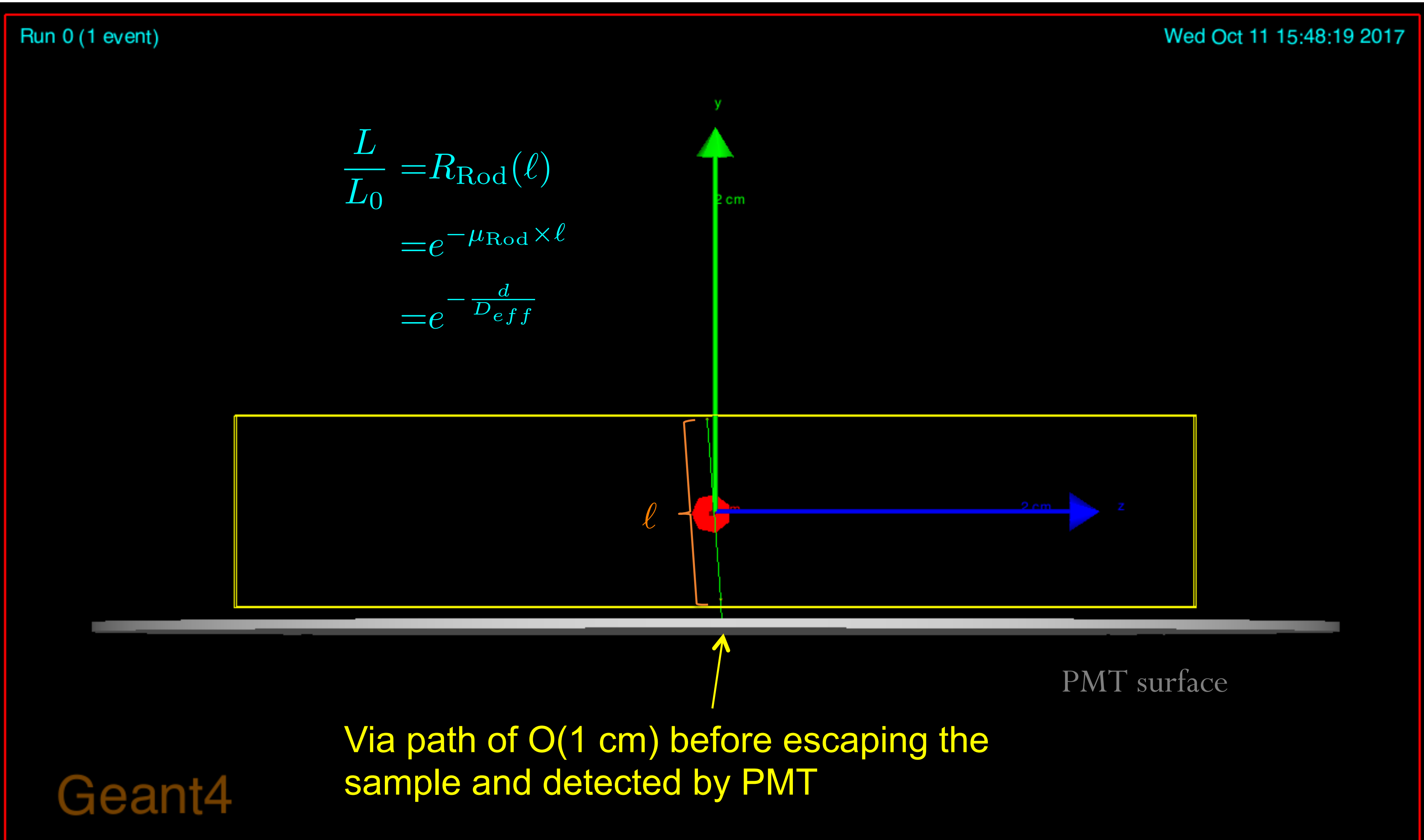
$$L = L_0 \times e^{-(\mu_1+\mu_2)T} \qquad T_{min} \approx 5 \text{ cm}$$

- Rudimentary first order estimation and ignoring attenuation of matrix itself
- z_0 > 2 mm for R ≲ 10 krad/h (next slide)
- μ_2 is the attenuation characteristic independent of oxygen concentration, while μ_1 affects the region where more damage to base matrix and less temporary color centers due to oxygen diffusion.

$D_{eff}(t)$ of Variant Thickness Samples

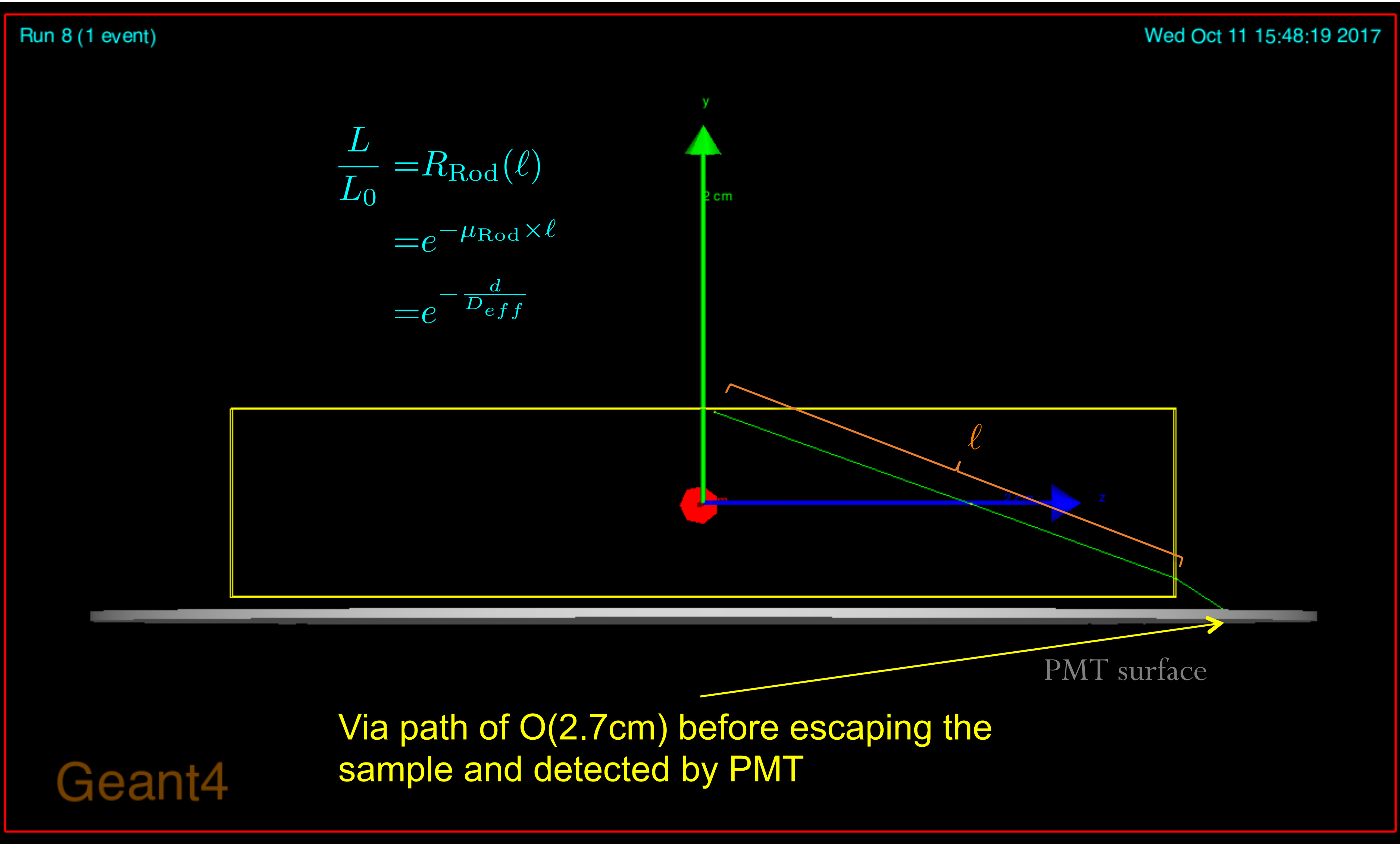


This is an example (1 photon)



Note: flat absorption spectrum used in these example

This is an example (1 photon)



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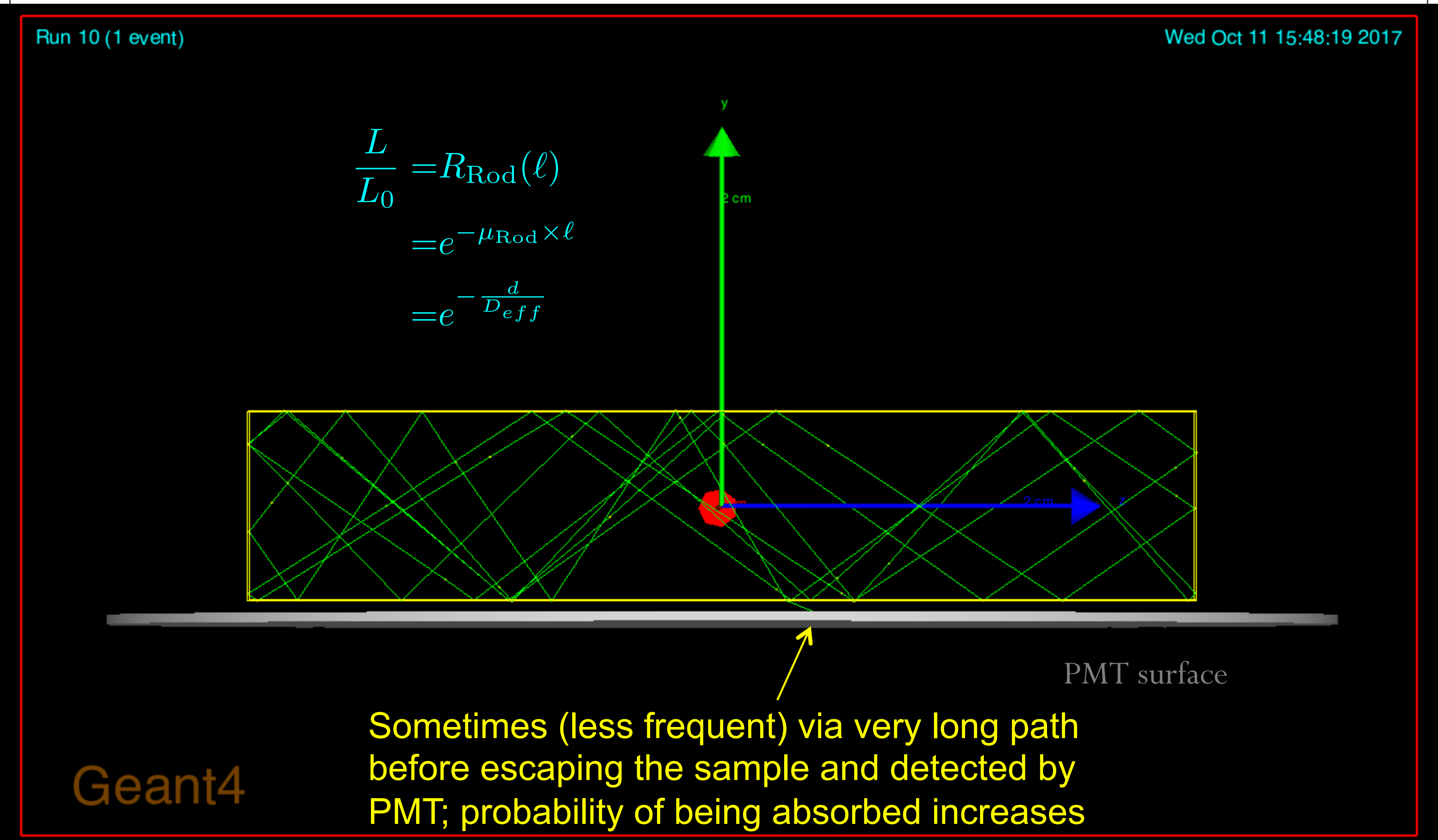
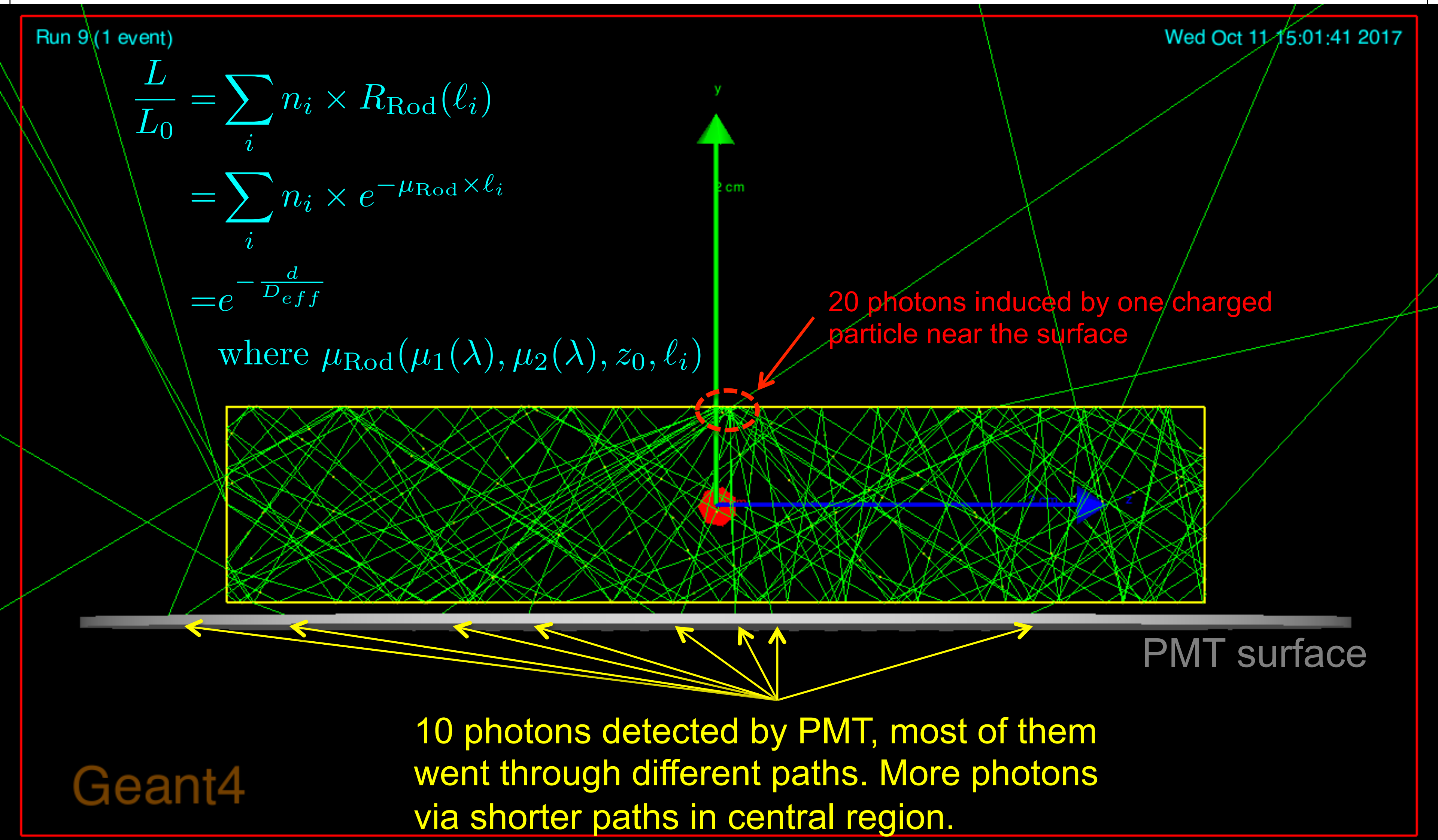


This is an example (20 photons)

$$\frac{L}{L_0} = \sum_i n_i \times R_{\text{Rod}}(\ell_i) = \sum_i n_i \times e^{-\mu_{\text{Rod}} \times \ell_i} = e^{-\frac{d}{D_{eff}}}$$

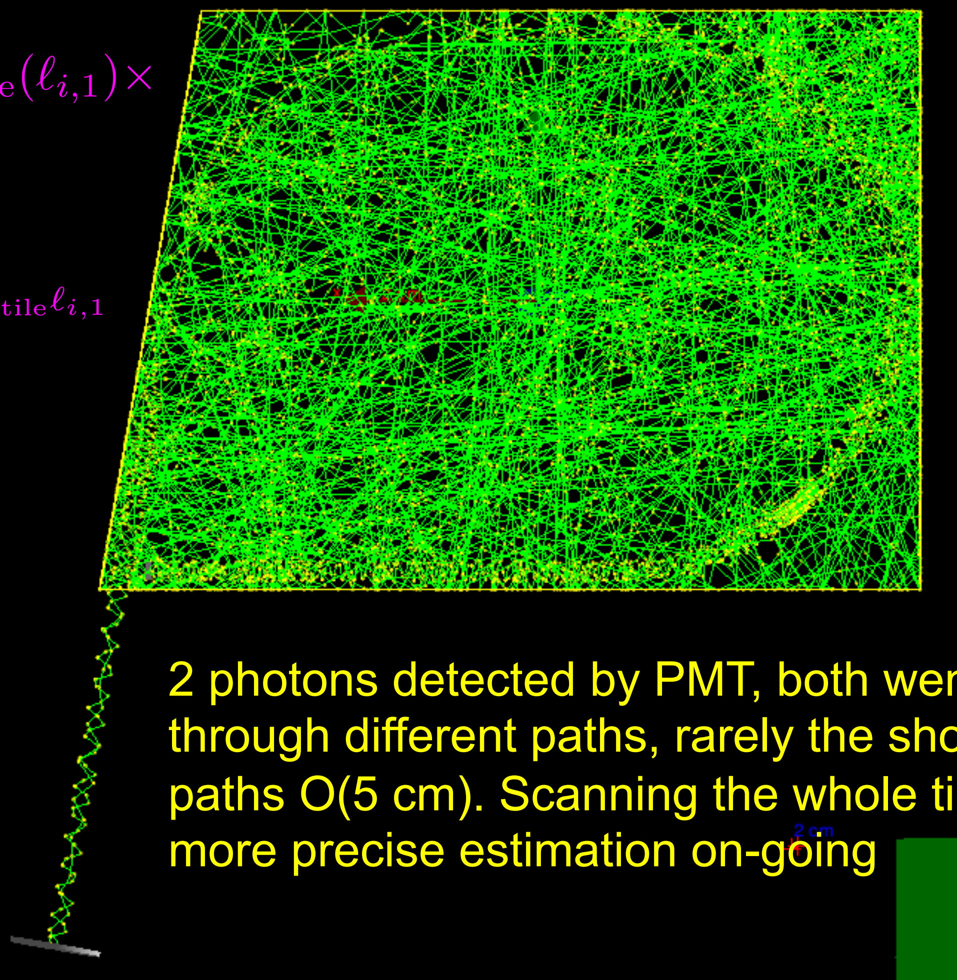
where $\mu_{\text{Rod}}(\mu_1(\lambda), \mu_2(\lambda), z_0, \ell_i)$



This is an example (20 photons)

μ_{tile} weakly depends on path length for low dose rate

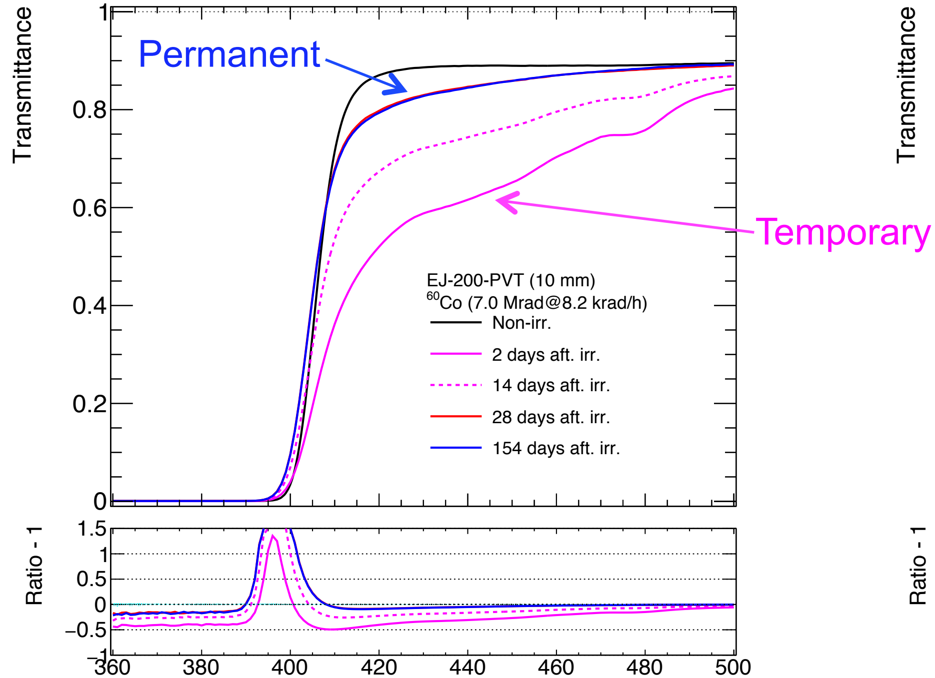
$$\frac{L}{L_0} = \sum_i n_i \times \left(R_{\text{tile}}(\ell_{i,1}) \times R_{\text{WLS}}(\ell_{i,2}) \right) = \sum_i n_i \times \left(e^{-\mu_{\text{tile}}\ell_{i,1}} e^{-\mu_{\text{WLS}}\ell_{i,2}} \right) = e^{-\frac{d}{D_{eff}}}$$

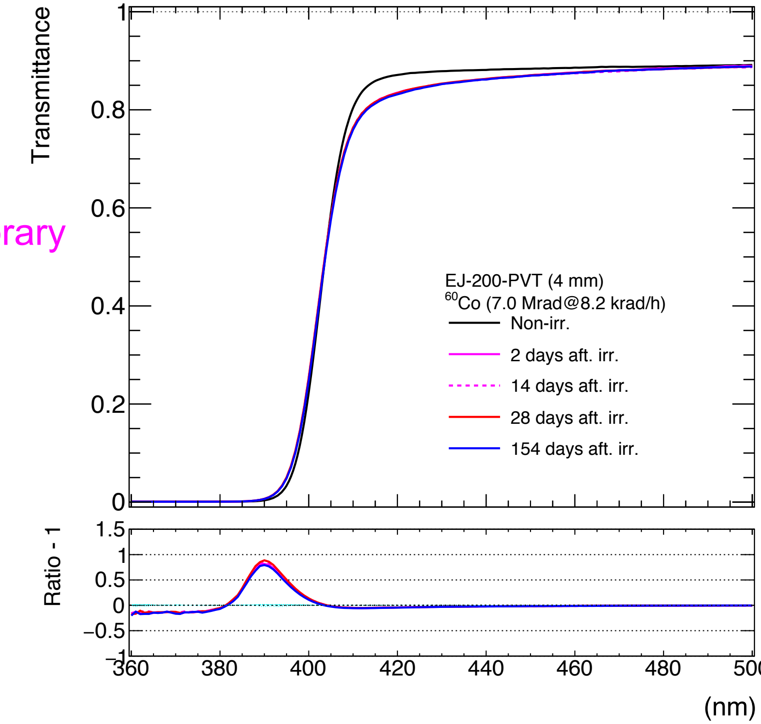


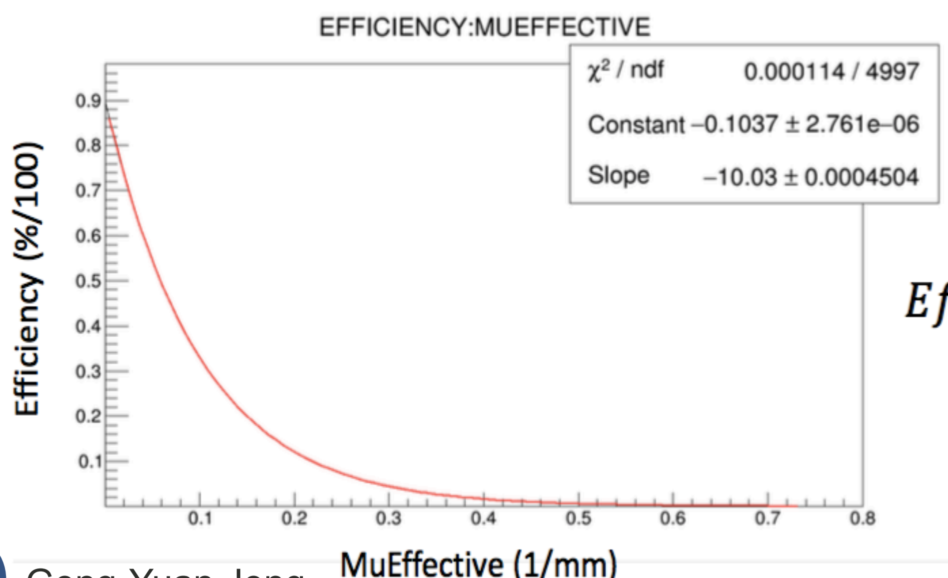
2 photons detected by PMT, both went through different paths, rarely the shorter paths O(5 cm). Scanning the whole tile for more precise estimation on-going

Simulation Procedures

- Extraction of model parameters from absorption measurements of variant thickness samples
- Implement material absorption behavior by the derived parameters
  - Validate with alpha source measurements of different thickness samples (rods)
- Compare to rod (tile) measurements using alpha source (cosmic ray) stand







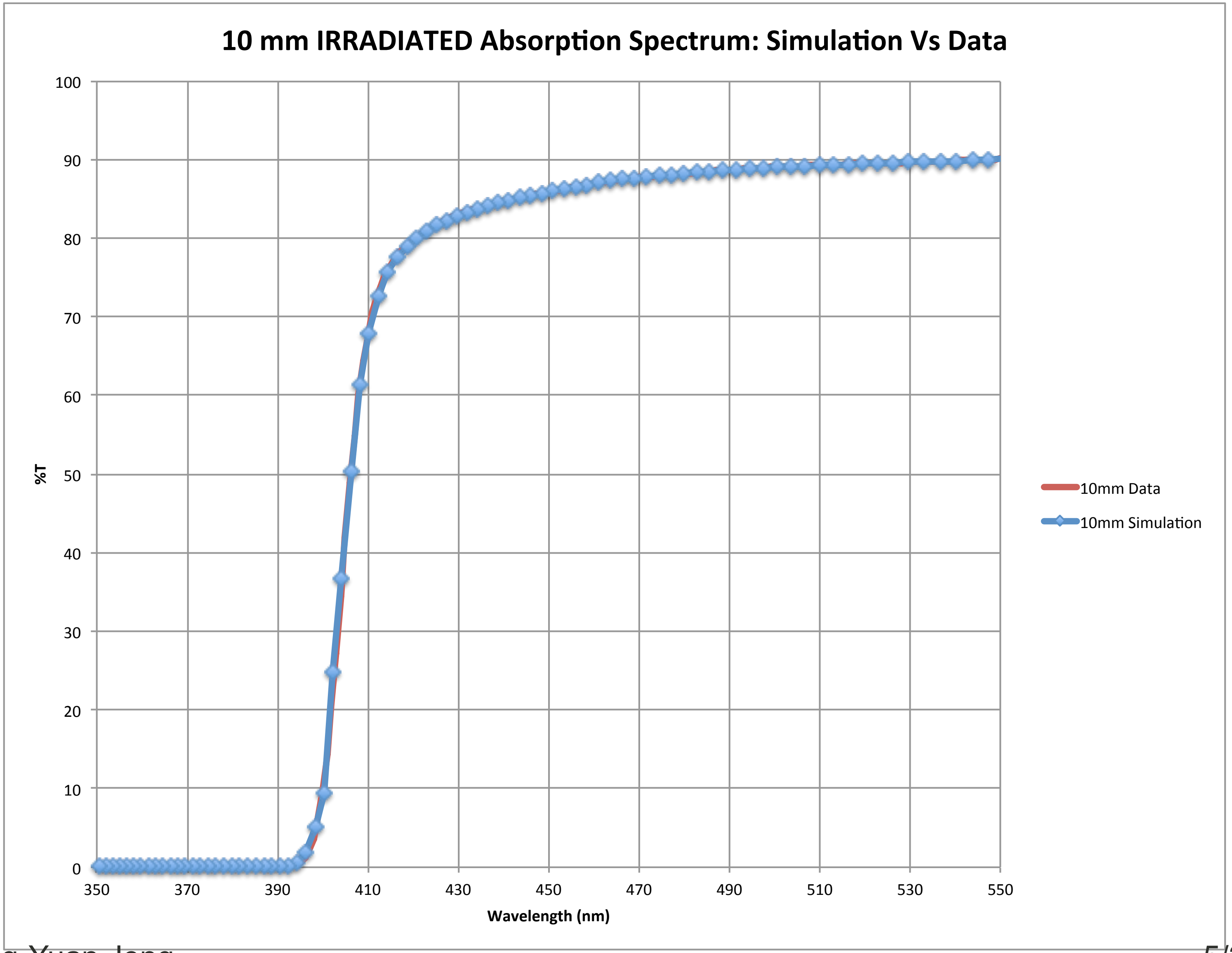
Example steps:

1. Derive photon detection efficiency for chosen input absorption lengths
2. Fit efficiency by function $\varepsilon = e^{a+b\times\mu_{\text{eff}}}$

$$Efficiency = \ e^{(-10.03-0.1037*\mu_{eff})}$$

Each function for each thickness
→ Compared with transmittance spectrum of real measurement to calculate μ_{eff} as a function of wavelength

Validation on Transmittance



Solving System of Equations

$$\mu_{\text{eff},i}(\lambda) = \mu_2(\lambda) + \frac{2z_0}{t_i}\Big(\mu_1(\lambda) - \mu_2(\lambda)\Big);\ \text{for } t_i > 2z_0$$

$t_1 = 4\ mm$

$t_2 = 6\ mm$

$t_3 = 10\ mm$

- Note: since z_0 > 2 mm, derive $\mu_1(\lambda) = \mu_{\text{eff},1}(\lambda)$ from irradiated 4 mm sample transmittance measurements
  - Calculate z_0 and $\mu_2(\lambda)$ in two iterations:

$$\mu_1 = \mu_{\text{eff},1}$$

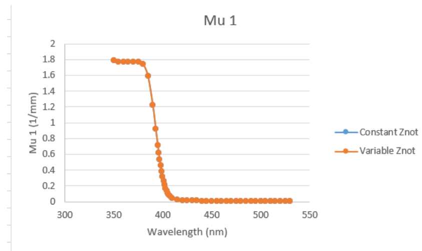
$$\mu_2 = \frac{\mu_{\text{eff},3}t_3 - \mu_{\text{eff},2}t_2}{t_3 - t_2}$$

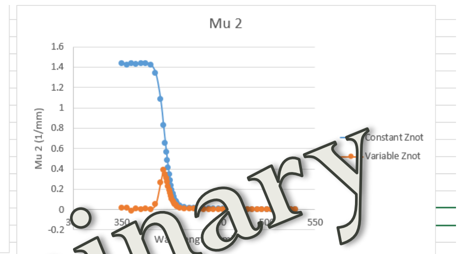
$$z_0 = \frac{t_2 t_3(\mu_{\text{eff},3} - \mu_{\text{eff},2})}{2[t_3(\mu_{\text{eff},3} - \mu_{\text{eff},1}) - t_2(\mu_{\text{eff},2} - \mu_{\text{eff},1})]}$$

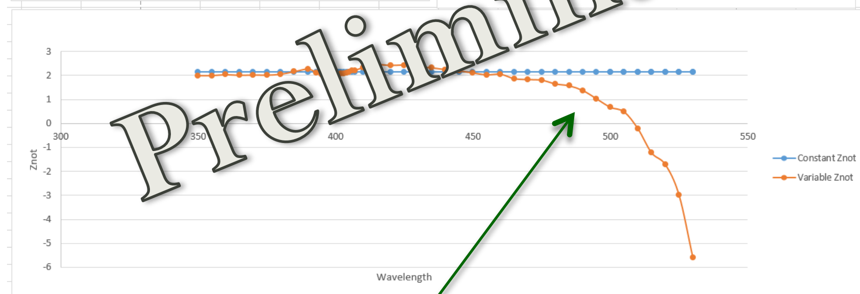
    - Fixed z_0 (not a function of λ) by averaging the range when solutions are stable for second iteration in deriving $\mu_2(\lambda)$:

$$\mu_2 = \frac{\mu_{\text{eff},2}t_2 - 2z_0\mu_1}{t_2 - 2z_0} = \frac{\mu_{\text{eff},3}t_3 - 2z_0\mu_1}{t_3 - 2z_0}$$

Cross check each other







Breakdown due to real measurements uncertainty too large for longer wavelengths

Summary

- HE ageing studied by several methods
  - Consequently as input ageing model for HB in HL-LHC regime
    - Positive results indicating HB will remain usable throughout the runs
- Systematic procedures utilizing GEANT4 simulation established
  - Real measurement assisting
  - First steps of extracting oxygen diffusion model parameters done
    - Inputs of property table to construct radiated scintillators for further comparison
    - Cross checking with other (high dose rate) measurements on-going
      - Alpha source and cosmic ray measurements
    - Eventually to cross check with results from methods using collision data

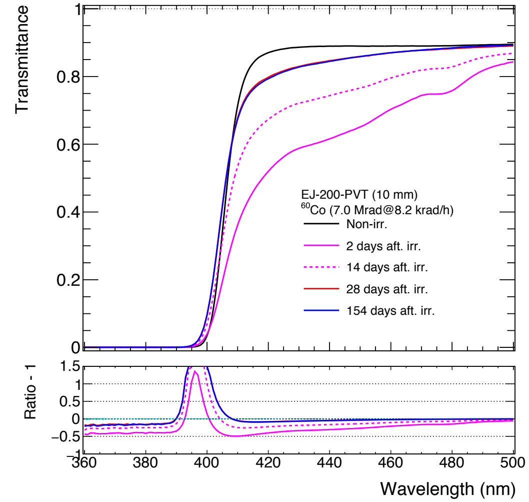
Backup

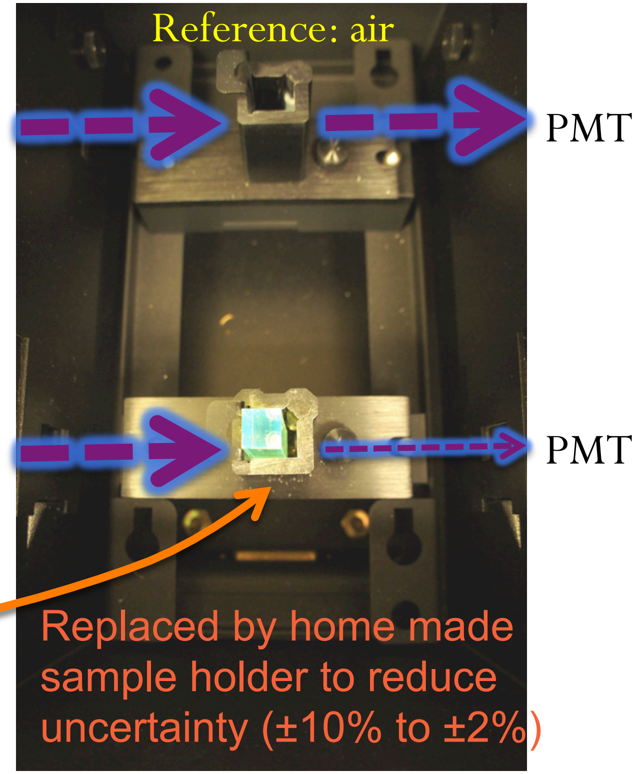
Measurement Setups

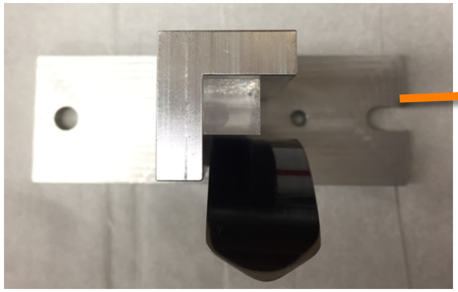
- Absorption
- Emission
- Alpha Source
- Cosmic

Absorption Measurements

- **CARY 300 Bio UV-Visible Spectrophotometer**
- Operated in double beam mode using double choppers.
- The first beam chopper separated the incident light into two optical paths through the sample compartment which houses two sample holders.
- One holder filled with the sample while the other left empty as the reference.
- The sample and reference light outputs measured by a photomultiplier (Hamamatsu R928) in turn via the second chopper (in sync with the first chopper) and the transmittance of the sample was then calculated by taking the ratio with respect to the reference.

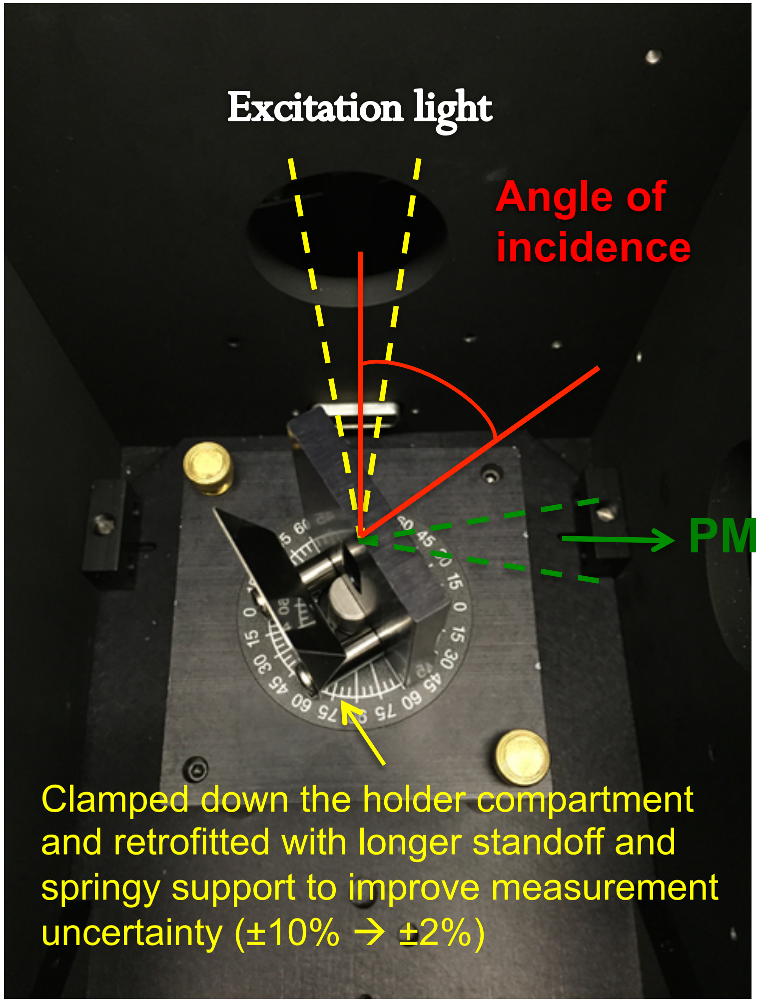






Fluorescence Measurements

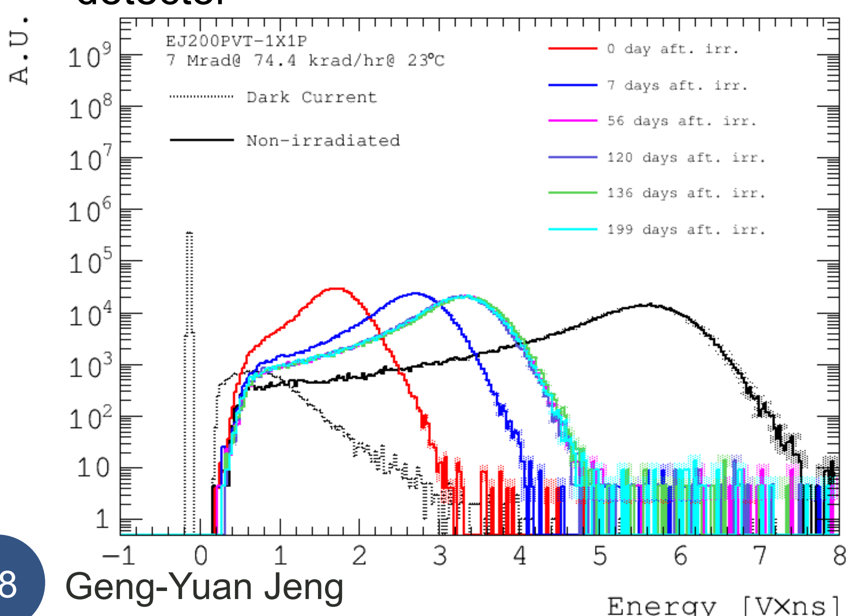
- Instrument: Horiba FluoroMax-4P
  - PMT: Hamamatsu R928P
- EJ-200:
  - Excitation wavelengths: 285 nm, 350 nm, and 400 nm
    - 285 nm is ~max. absorption peak of primary fluors
    - 400 nm is ~max. abs. peak of secondary (WLS) fluors
- EJ-260:
  - Excitation wavelengths: 310 nm and 425 nm
    - 310 nm is ~max. absorption peak of primary fluors
    - 425 nm is ~max. abs. peak of secondary (WLS) fluors

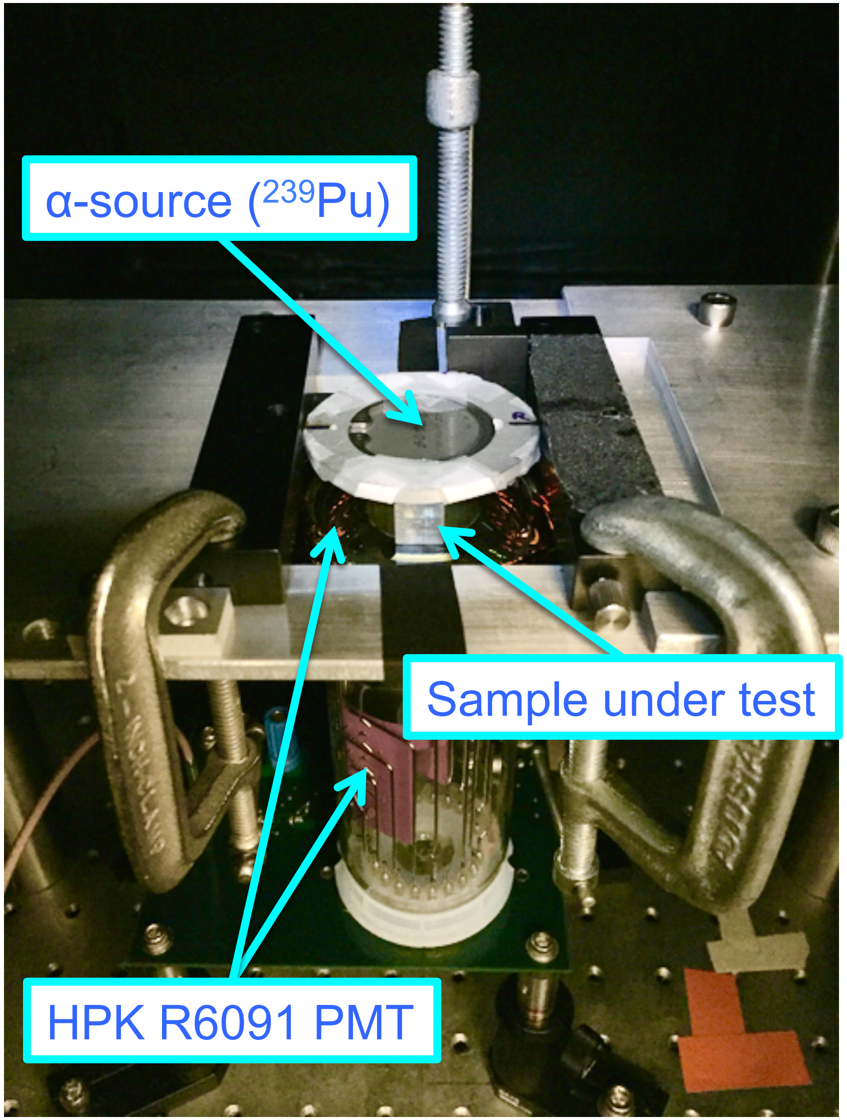


Utilize front face configuration to better study energy transfer processes by minimizing effects due to bulk absorption behavior.

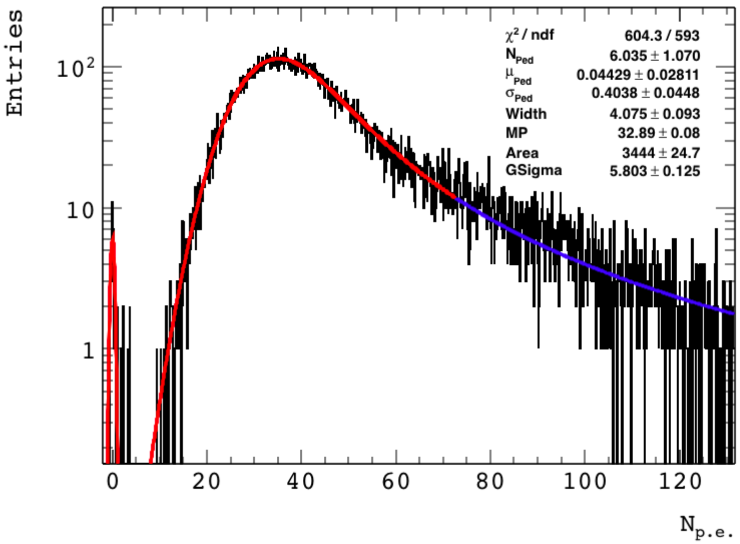
Alpha Source Measurement

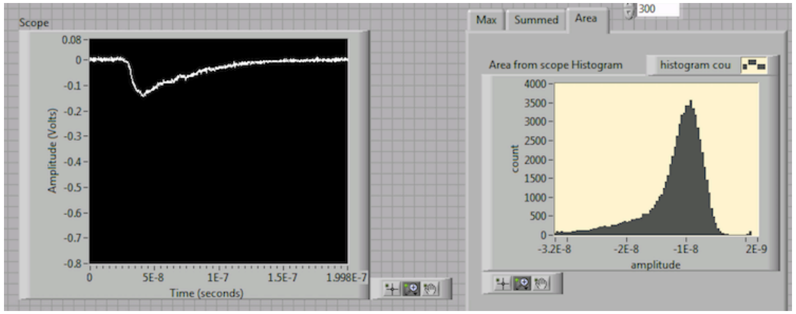
- Sensitive to complete chain of light-production
  - Source releases complete energy in the base, and the whole chain of dopants and energy transfers is exercised
- Provides complementary measurement to transmission and emission spectra
  - Most precise measurement (<±1% @23°C)
  - Closer to actual operation of scintillator in detector

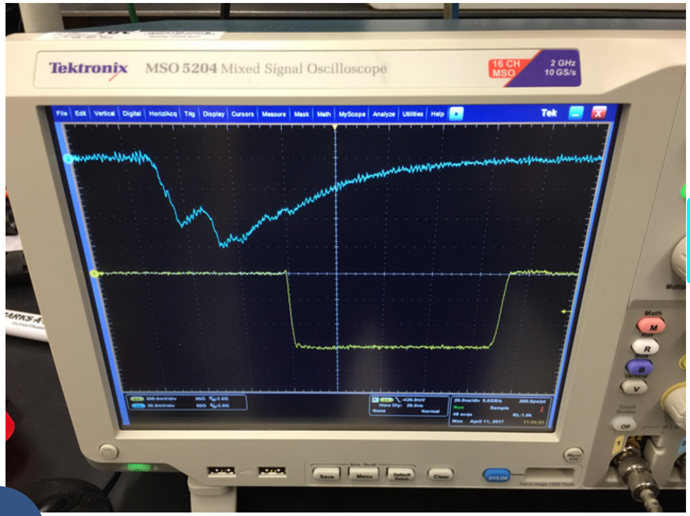


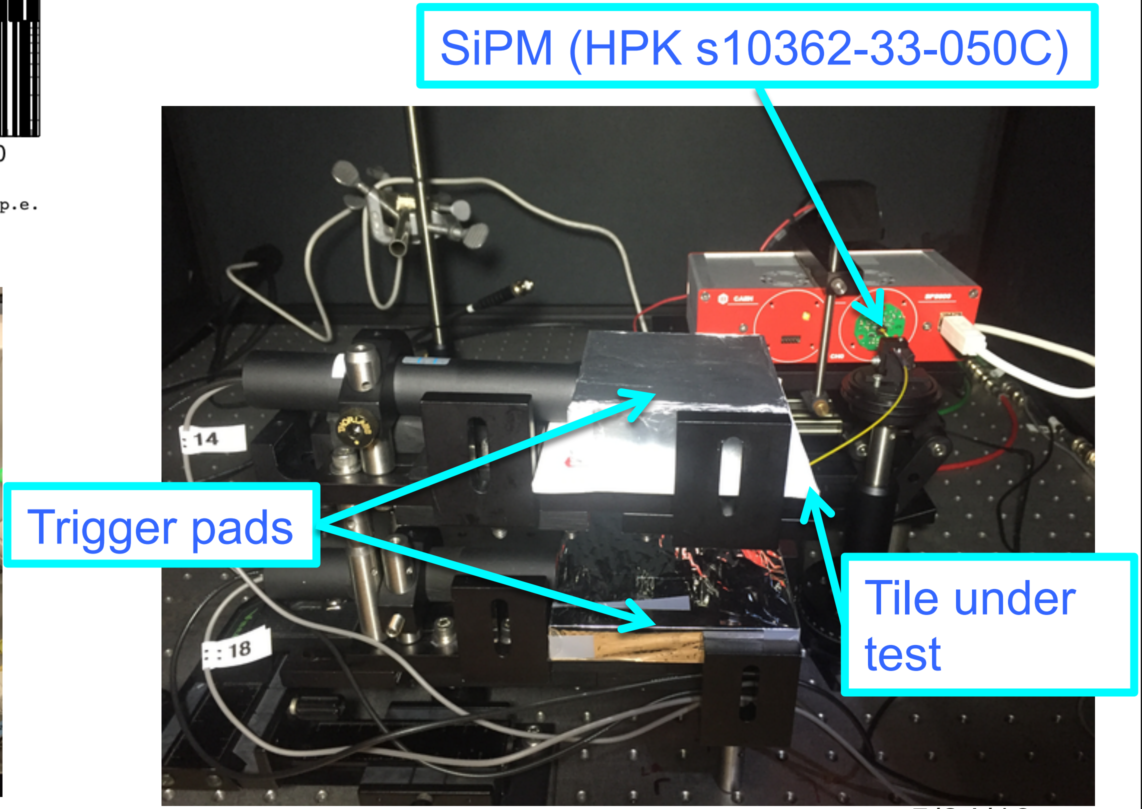


Cosmic Stand Measurement

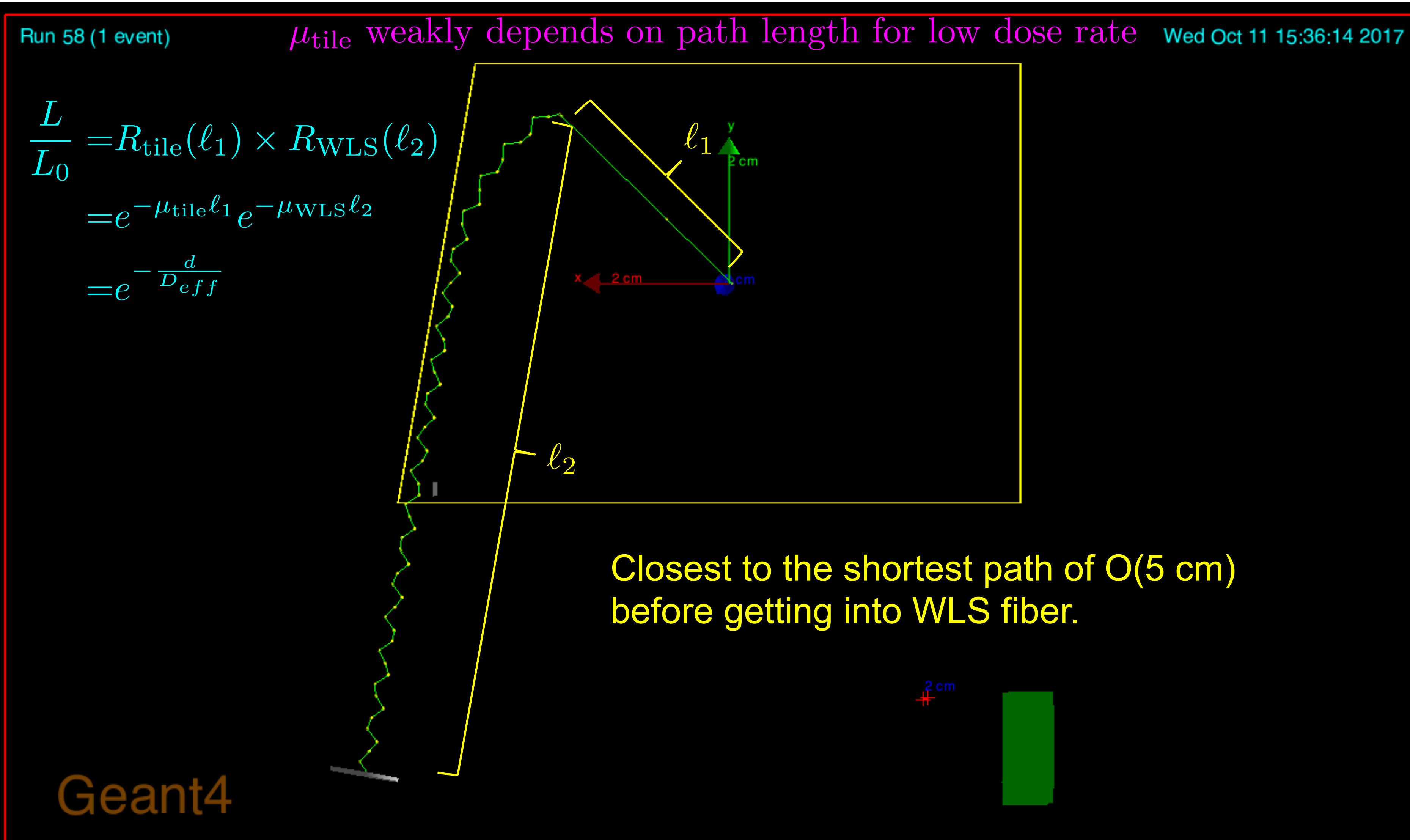








This is an example (1 photon)



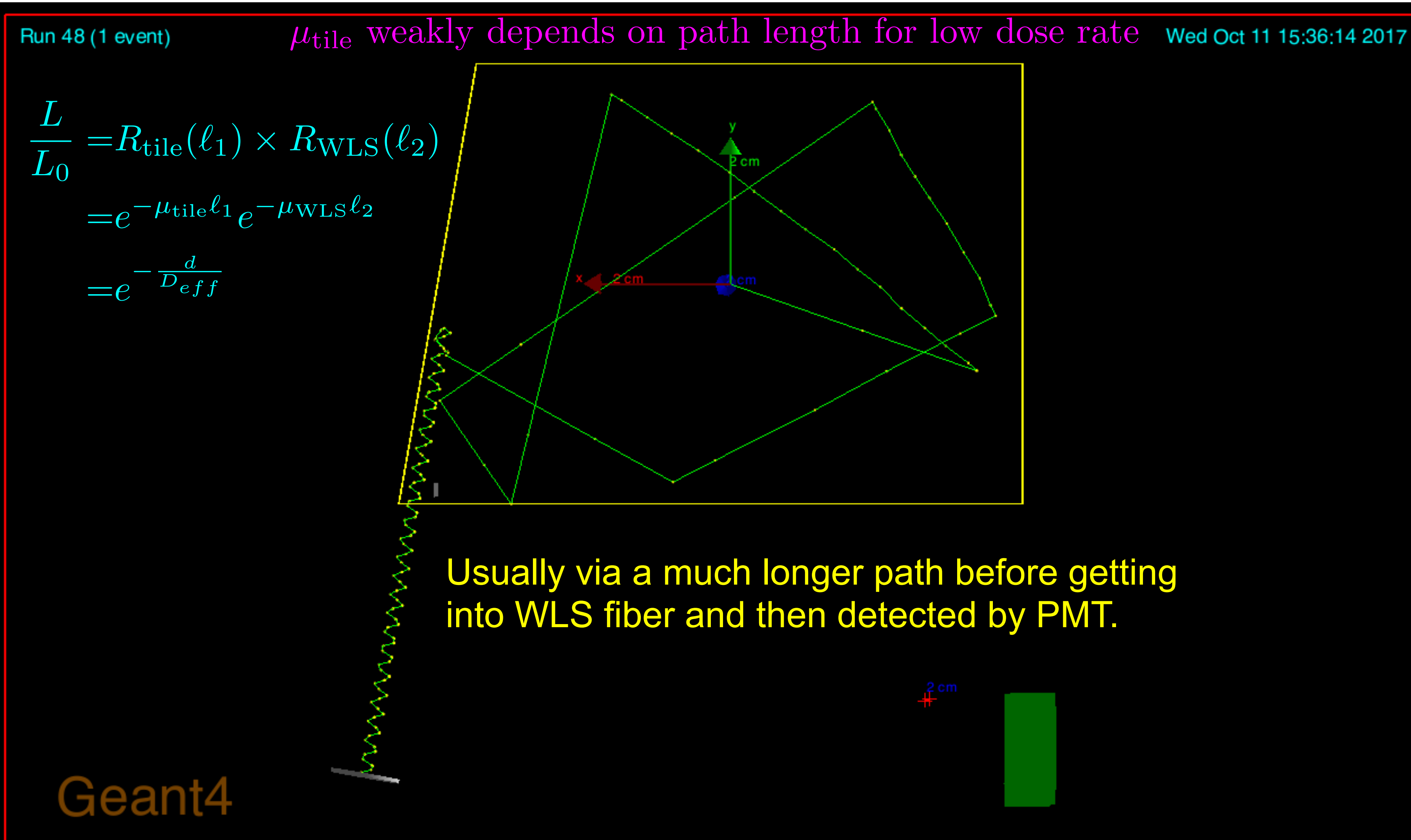
$$\frac{L}{L_0} = R_{\rm tile}(\ell_1) \times R_{\rm WLS}(\ell_2)$$
$$= e^{-\mu_{\rm tile}\ell_1} e^{-\mu_{\rm WLS}\ell_2}$$
$$= e^{-\frac{d}{D_{eff}}}$$

Closest to the shortest path of O(5 cm) before getting into WLS fiber.

This is an example (1 photon)

μ_{tile} weakly depends on path length for low dose rate

$$\frac{L}{L_0} = R_{\text{tile}}(\ell_1) \times R_{\text{WLS}}(\ell_2)$$
$$= e^{-\mu_{\text{tile}}\ell_1} e^{-\mu_{\text{WLS}}\ell_2}$$
$$= e^{-\frac{d}{D_{eff}}}$$

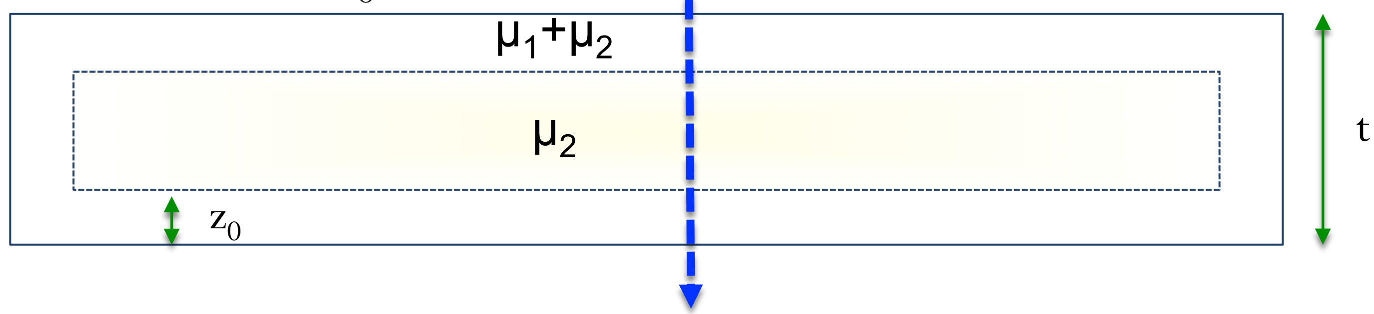


Usually via a much longer path before getting into WLS fiber and then detected by PMT.

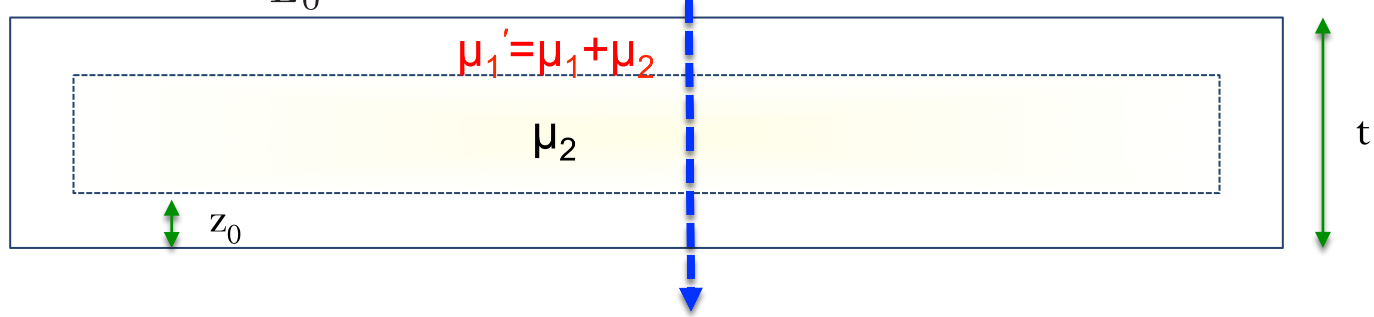
Extracting Parameters

- Extracting parameters from absorption measurements
  - Underlying model: oxygen diffusion model

Original parameterization: $$\frac{L}{L_0} = R(t) = e^{-\mu_{eff}t} = e^{-\mu_1(2z_0)-\mu_2 t}$$



New parameterization: $$\frac{L}{L_0} = R(t) = e^{-\mu_{eff}t} = e^{-\mu_1'(2z_0)-\mu_2(t-2z_0)}$$



From now on we will call μ_1' simply μ_1 but keep in mind its real characteristic