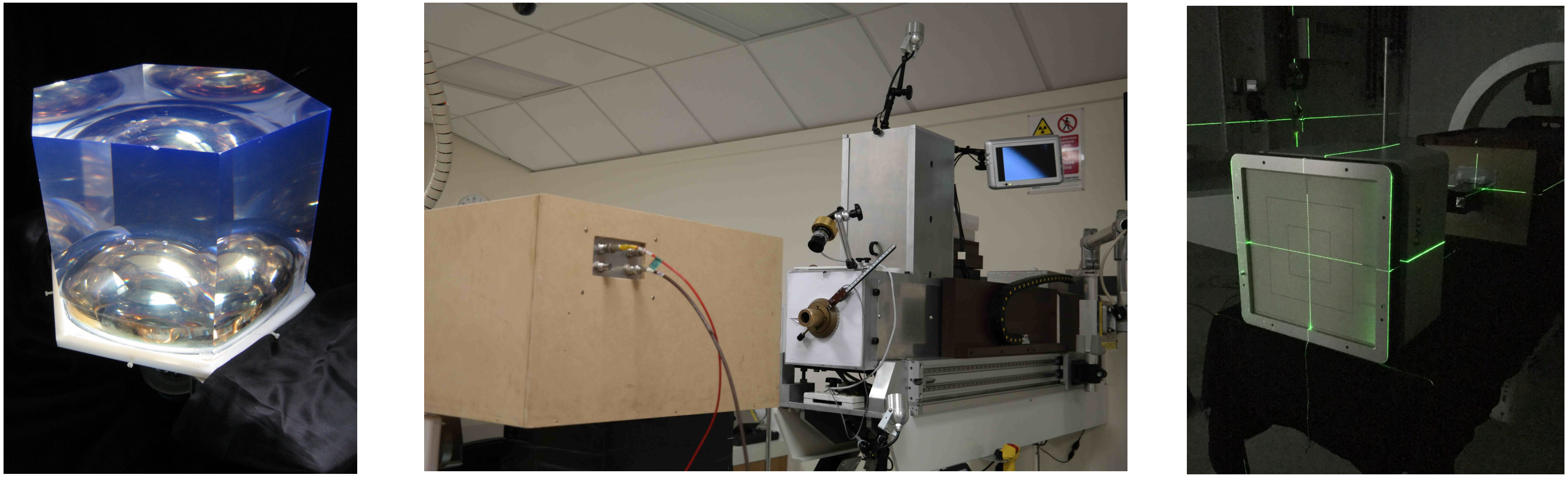
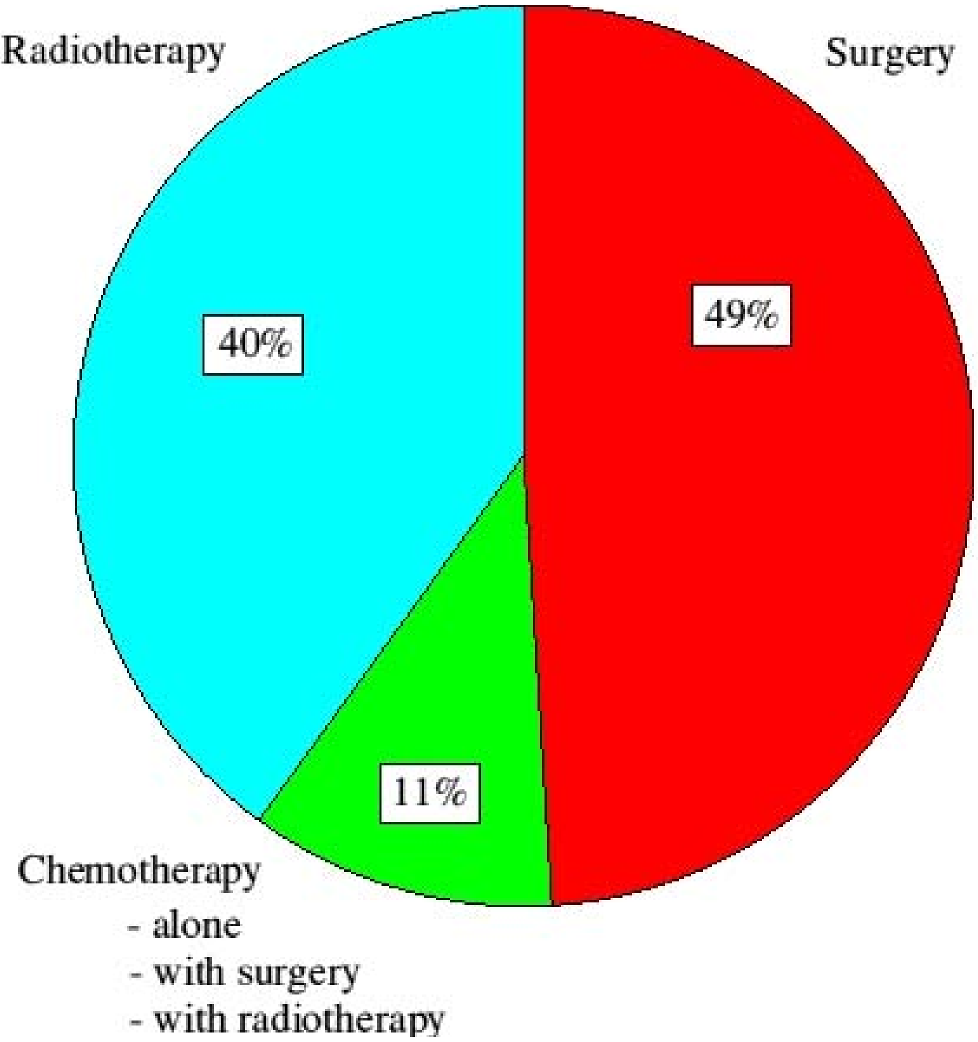


# From SuperNEMO to Proton Therapy: Adapting SuperNEMO Calorimeter Technology for Proton Therapy QA

Anastasia Basharina-Freshville

(University College London)

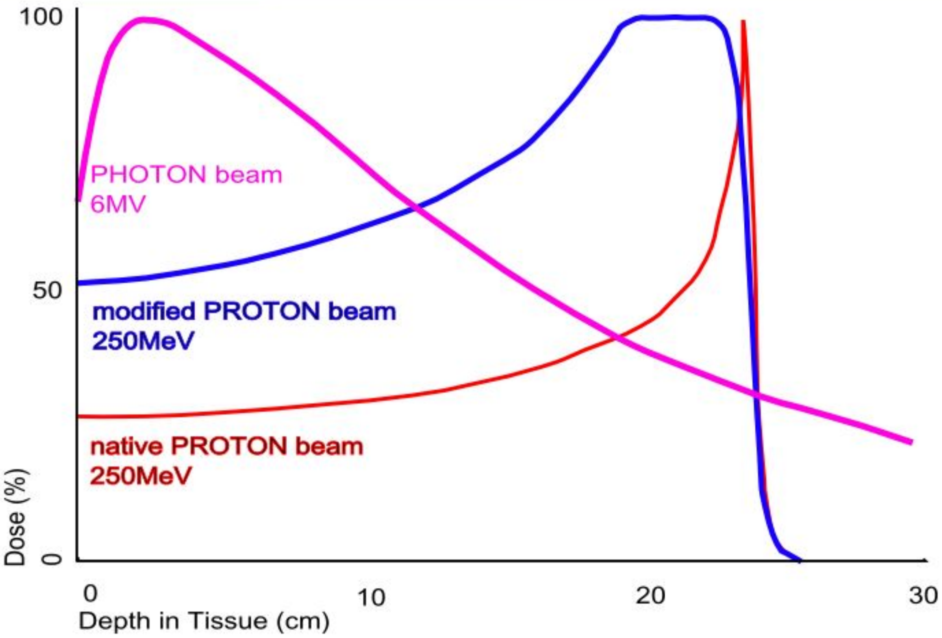
# Cancer Treatment



- Cancer is treated with 3 different modalities:
  - Surgery
  - Chemotherapy
  - Radiotherapy
- Each has advantages and disadvantages
- Surgery is the most successful
- If you can't remove it with surgery, radiotherapy is the next best option
- Also cost effective

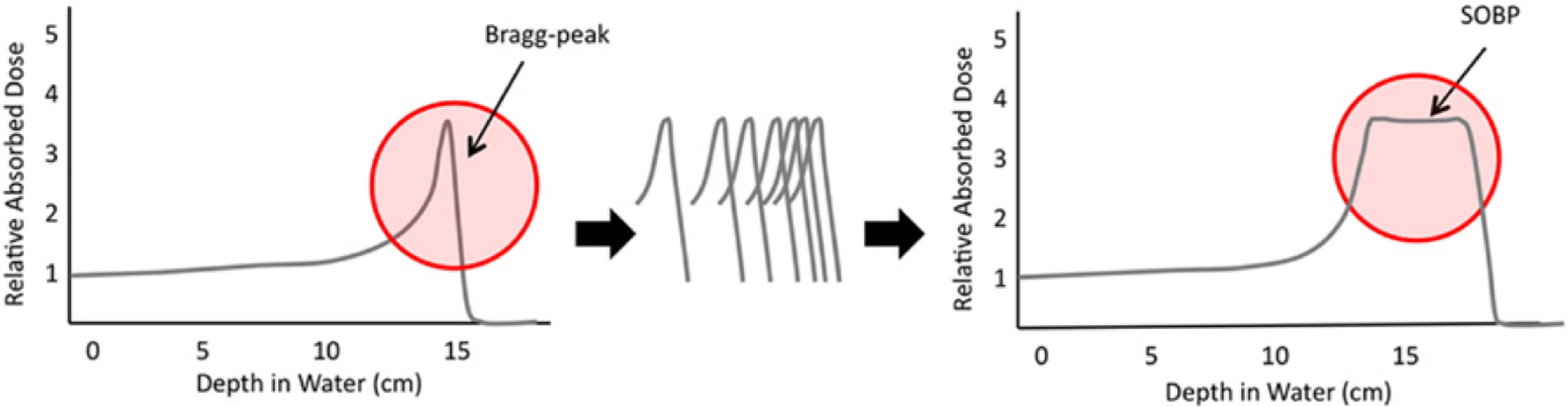
# Why Proton Therapy?

- More precise form of radiotherapy
- Precise tuning of the delivered dose to the patient through careful selection of proton beam energy
  - Due to energy loss profile of protons
  - And much smaller beam spot sizes
- Important for areas where we particularly want to avoid large doses of radiation to healthy tissue:
  - Head and neck
  - Central nervous system
  - In children



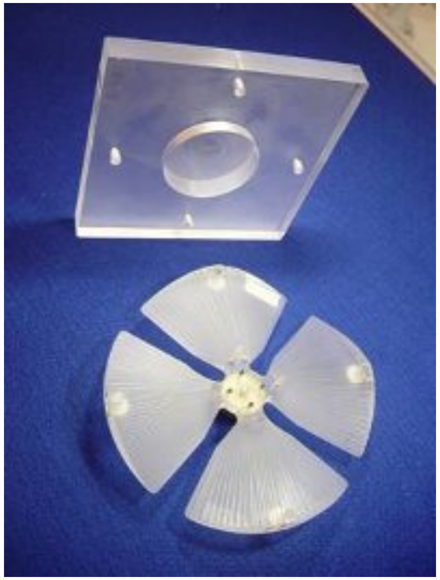
http://samhs.org.au/Virtual%20Museum/xrays/Braggs-peak-rxth/braggpeakrxth.htm

# Why Proton Therapy?



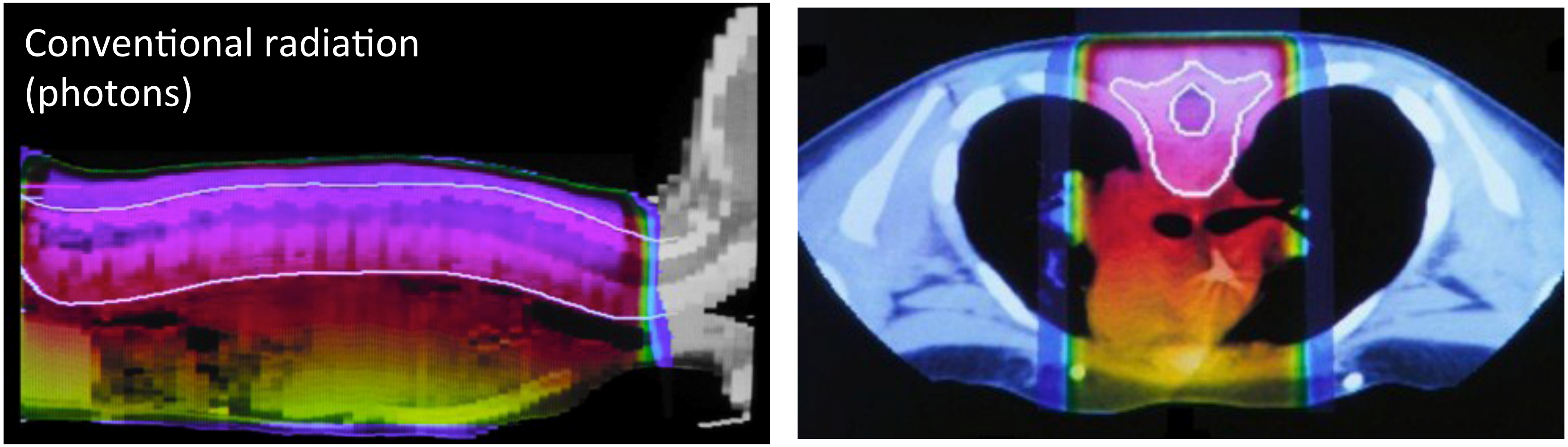
Front. Oncol., 06 September 2011 | doi: 10.3389/fonc.2011.00024

- Range shifter and modulator used for a Spread Out Bragg Peak
- Alters beam energy to provide a uniform dose over the depth of the tumor

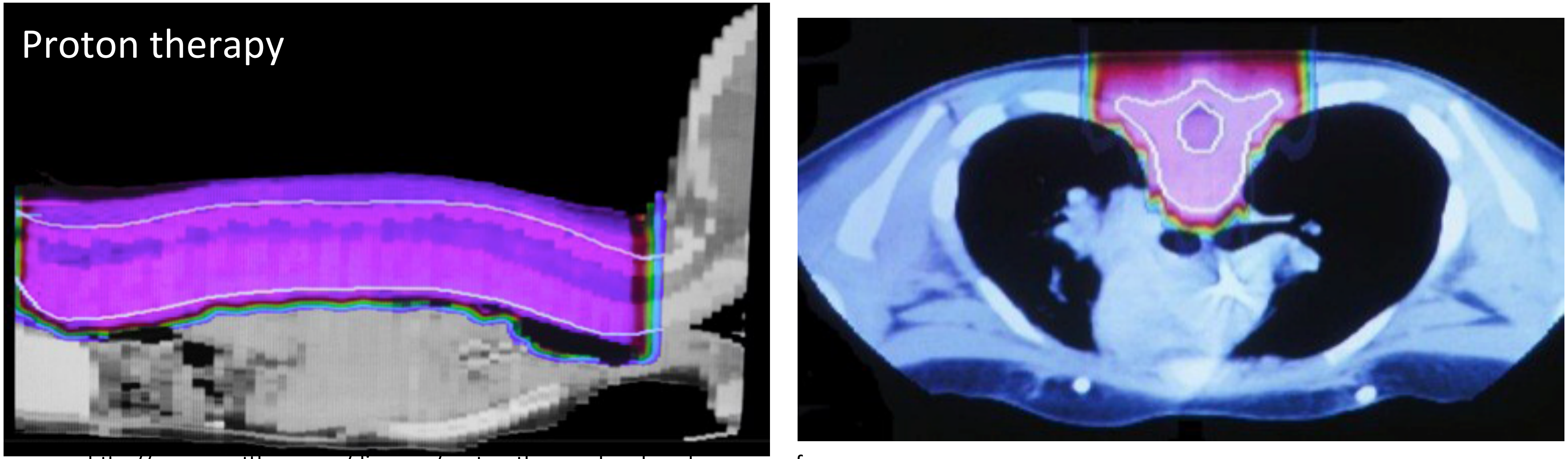


http://www.clatterbridgecc.nhs.uk/professionals/physicsdepartment/cyclotron/

# Photons vs Protons: Medulloblastoma



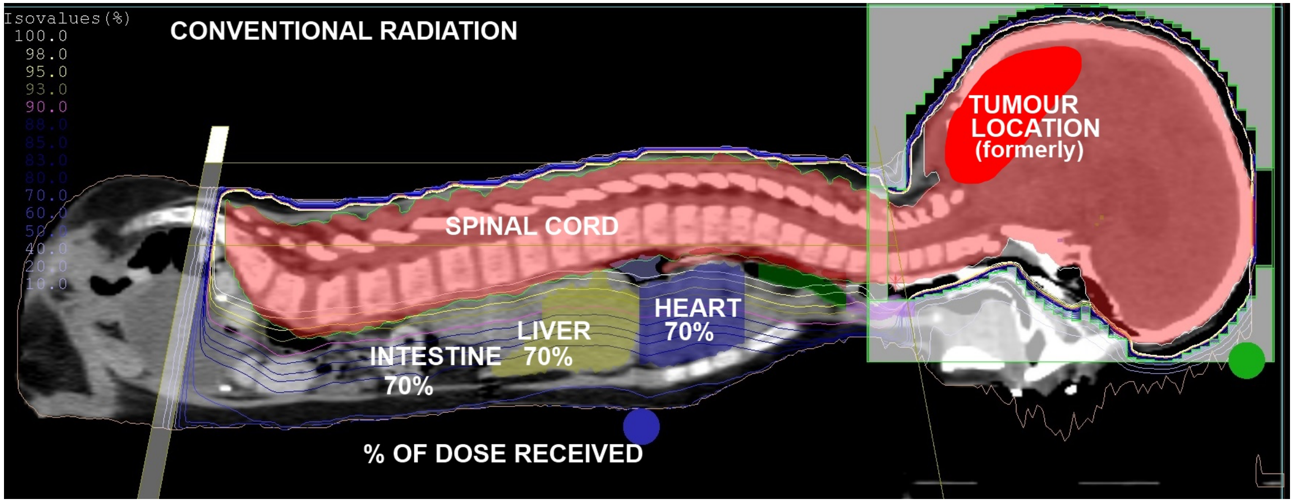
Conventional radiation (photons)

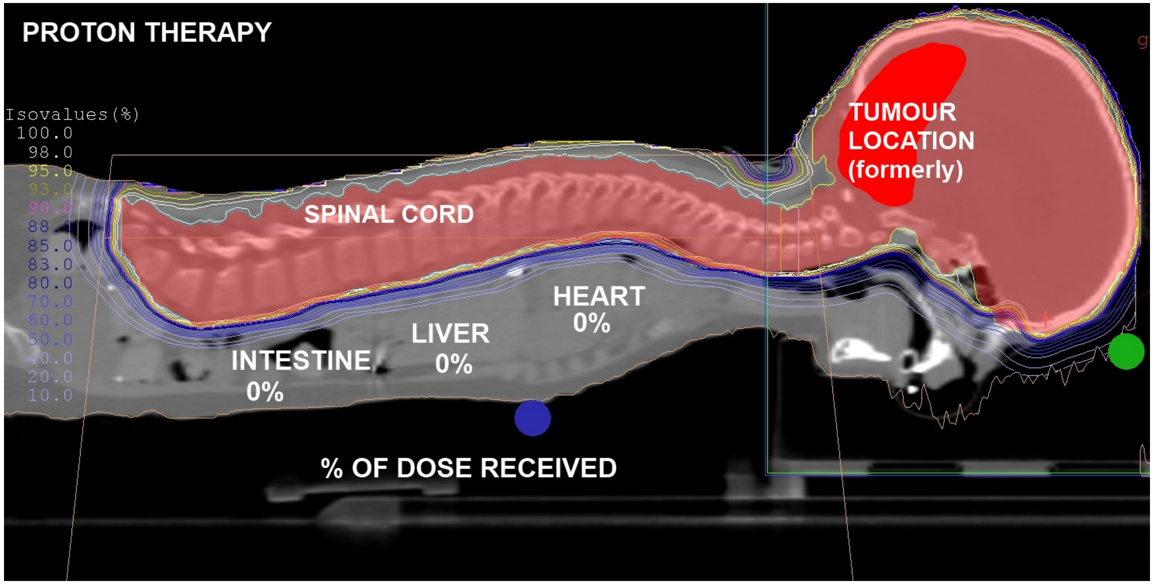


Proton therapy

http://www.seattlecca.org/diseases/proton-therapy-head-neck-cancers.cfm

# Photons vs Protons: Medulloblastoma

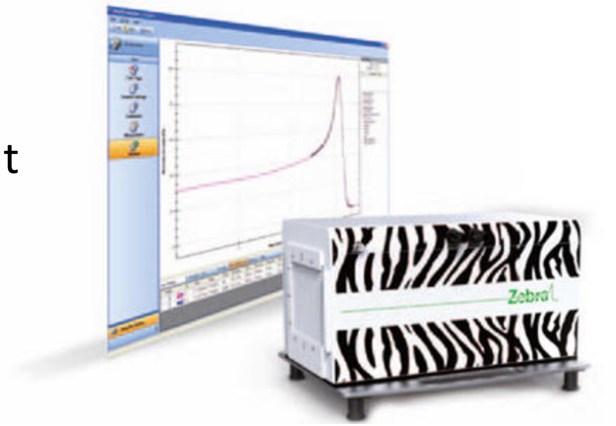




# Proton Therapy Challenges (1)

- Quality Assurance (QA):
  - A number of QA checks are necessary for safe PT treatment:
    - Daily, weekly and monthly
  - Daily checks carried out before treatment:
    - Verifying that the range is correct for a given energy takes most time
  - Two methods currently used:
    - A single dose monitor to look at 3-5 different beam ranges/energies, >1 hour daily
    - “Zebra”: a multi-layer ionisation chamber, <1 minute to acquire data

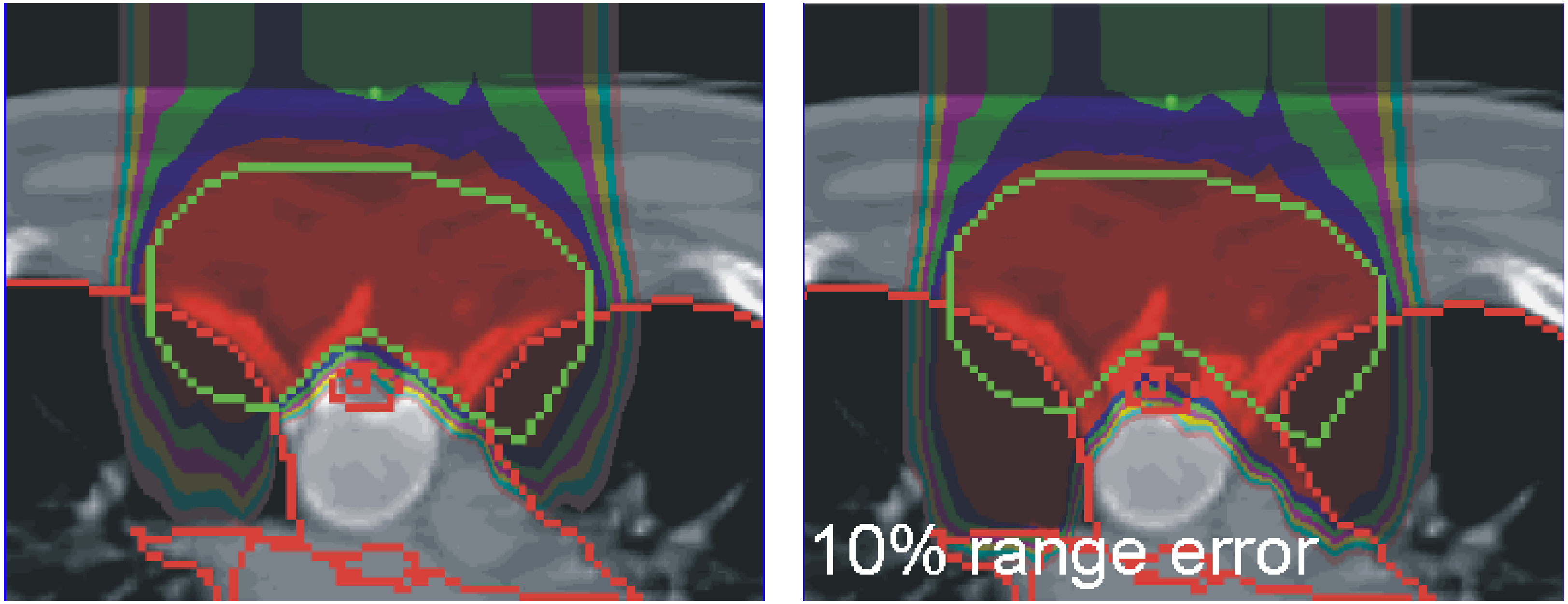
    BUT: expensive, bukly and long setup times



http://www.iba-dosimetry.com/complete-solutions/radiotherapy/particle-therapy-dosimetry/zebra-with-omnipro-incline

# Proton Therapy Challenges (2)

- Proton imaging
  - Requires an increase in imaging resolution compared to X-ray based systems due to localisation of proton dose delivery
  - Currently use a conversion factor to convert from X-Ray to proton therapy treatment plans → imprecision and range uncertainty
  - Currently, the patient is imaged away from the treatment – any movement of the patient's anatomy introduces further imprecision



# Proposed Solutions

- Calorimetry approach for:
  - Measuring range for QA:
    - measure energy and convert to range using a single scintillator + PMT
    - measure range directly using a segmented scintillator with a readout on every slice
    - Both methods aim to reduce QA times to 2-3 minutes, are affordable and can have short setup times

- Proton imaging:
  - Image with > 300 MeV proton beam, which will emerge from the body without significant energy deposition
  - Tomography approach:
    - A series of tracking layers upstream and downstream of the patient
    - Accurate calorimeter for energy measurements
    - Target energy resolution: ~1% σ for 300 MeV imaging protons

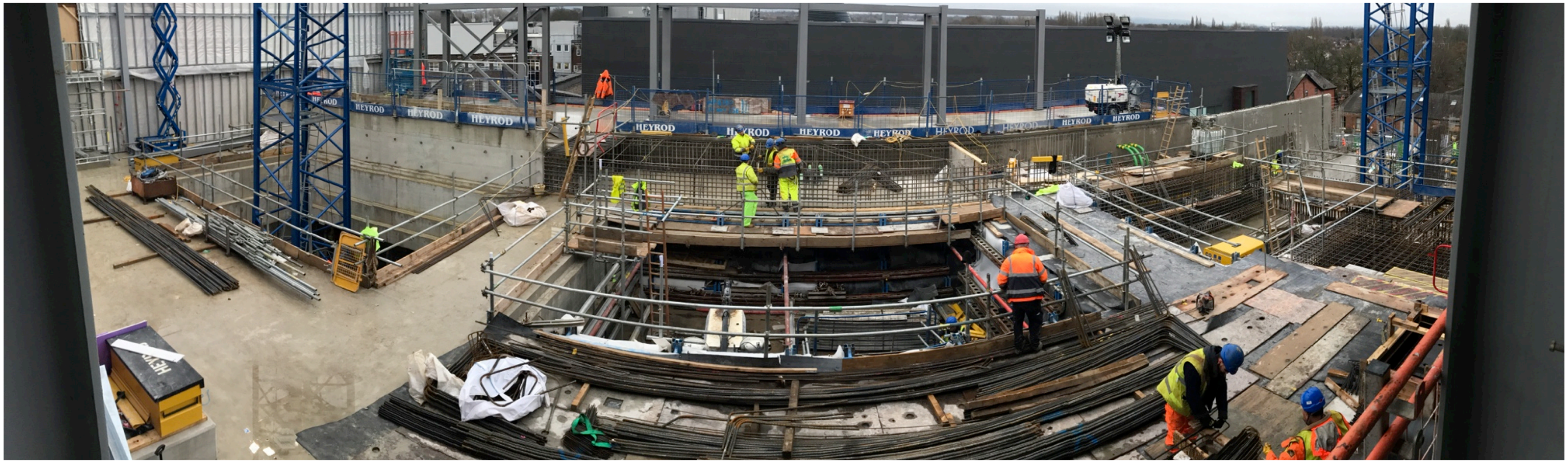
# Proton Therapy in the UK

- One currently operational proton therapy centre:
  - Clatterbridge Cancer Centre: treatment of ocular melanomas with 60 MeV proton beam

- Two new high energy centres currently under construction:
  - The Christie (Manchester)
  - UCLH (London)

- £250 million joint project - the largest single project the NHS has ever attempted!

- The Christie will open in August 2018 and UCLH a couple of years later.



# UCLH Proton Therapy Centre

- Use a particle accelerator (cyclotron) to get a 250 MeV proton beam
- Delivered to the patient through a gantry, which has to be big enough to deliver the beam from any angle: must be 3 stories tall!
- Three gantries
- Construction in progress (summer 2015)
- First patient treatment: 2020

Can we work on some of the challenges before then?

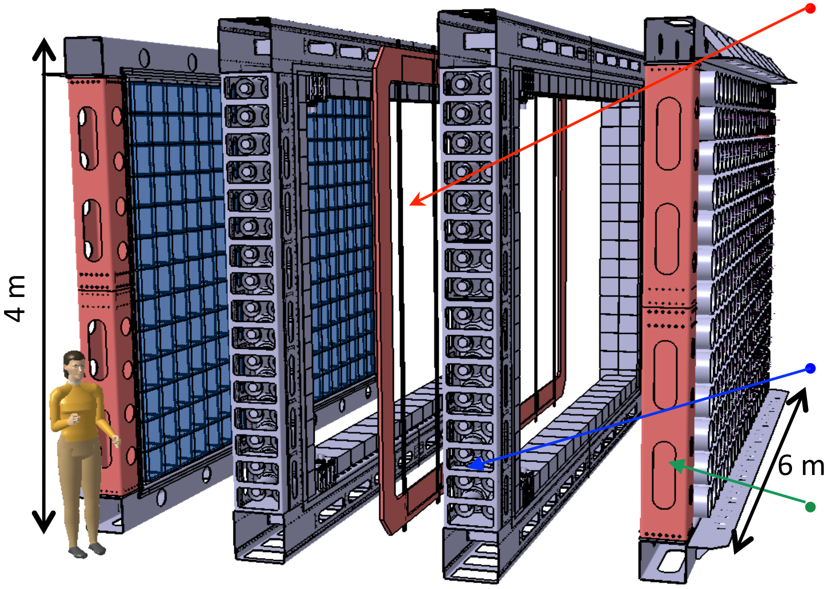
# SuperNEMO

supernemo
collaboration

- Neutrinoless double beta decay detector using NEMO3's tracker-calorimeter technique
  Target sensitivity: $T_{1/2} > 10^{26}$ years → $\langle m_\nu \rangle < 0.04 – 0.1$ eV

- Modular detector with a planar geometry

**1 module** (of 20) consists of:



2 m (assembled, ~0.5 m between source and calorimeter)

- Source foil:
  - 5 kg (total of 100 kg) of 40 mg/cm$^2$ (4 x 2.7 m$^2$)
  - $^{82}$Se (high $Q_{\beta\beta}$, long $T_{1/2}^{2\nu\beta\beta}$, proven enrichment technology): starting baseline
  - $^{150}$Nd and $^{48}$Ca being considered depending on enrichment possibilities

- Tracker: ~2000 drift cells in Geiger mode
  → particle identification (for background suppression)

- Calorimeter: ~550 scintillator blocks + PMTs
  → energy and time of flight measurements of particles

- Passive shielding surrounding each module

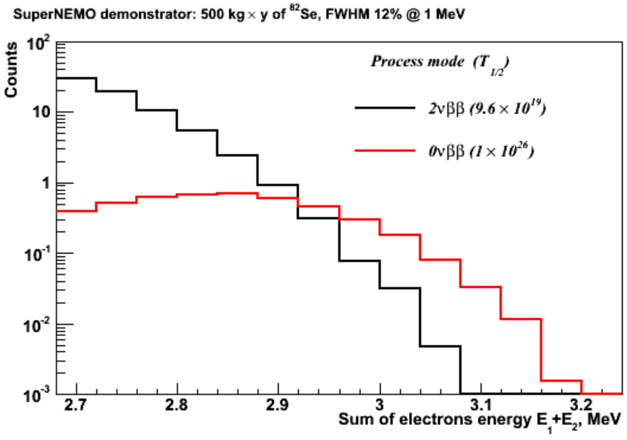
# From NEMO3 to SuperNEMO

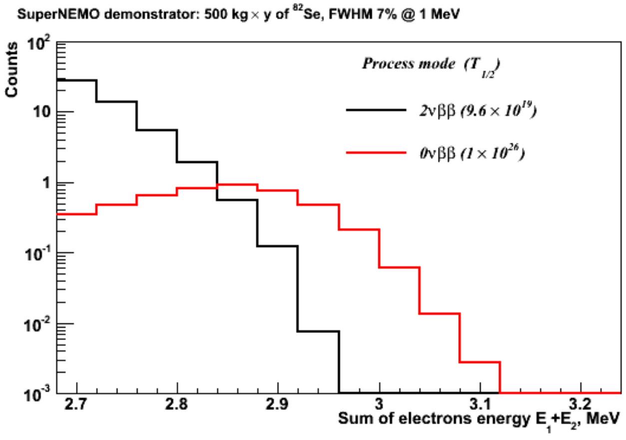
- Energy resolution is one of the main challenges (factor of 2 improvement):

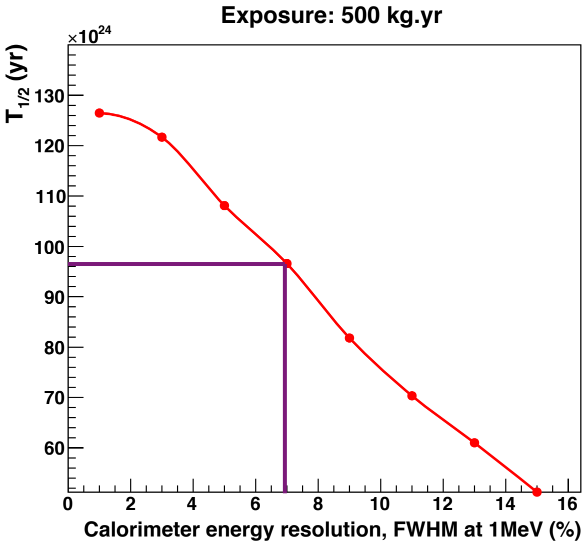
NEMO3: $\frac{6-7\%}{\sqrt{E(MeV)}}$ $\longrightarrow$ SuperNEMO: $\frac{3\%}{\sqrt{E(MeV)}}$

- SuperNEMO scintillator has to be organic plastic scintillator
  (high light yield, low electron back-scattering, high radiopurity, fast timing)
  → Can 3% σ at 1 MeV be reached for organic solid plastic scintillator?

- First step in SuperNEMO R&D: secured STFC funding for energy resolution R&D


SuperNEMO demonstrator: 500 kg × y of $^{82}$Se, FWHM 12% @ 1 MeV


SuperNEMO demonstrator: 500 kg × y of $^{82}$Se, FWHM 7% @ 1 MeV


Exposure: 500 kg.yr

# Energy Resolution

$$\frac{\Delta E}{E} = \frac{2.35\sigma}{E} = \frac{2.35}{\sqrt{N_{pe}}}$$

Three experimental objectives:

$$\frac{N_{ph}}{E_e} \cdot \epsilon_{col}^{light} \cdot \left(QE^{PMT} \cdot \epsilon_{col}^{PMT}\right) = N_{pe}$$

scintillator light output

| | |
|---|---|
| **$\sigma$** | sigma of distribution |
| **$E$** | mean of distribution |
| **$N_{pe}$** | number of photo-electrons |
| **$N_{ph}/E_e$.** | number of photons per unit energy |
| **$\varepsilon^{light}$** | light collection efficiency |
| **$QE^{PMT}$** | quantum efficiency of the photo-cathode |
| **$\varepsilon^{PMT}$** | PMT collection efficiency |

Physically translates to:

- Scintillator: material, surface treatment, geometry
- Reflector: material, reflectivity coefficient, specular/diffusive
- Optical coupling quality: material, geometry, light guides
- Photomultiplier Tubes (PMTs): quantum efficiency (QE), collection efficiency, gain of the first dynode

Combined in an "optical module":

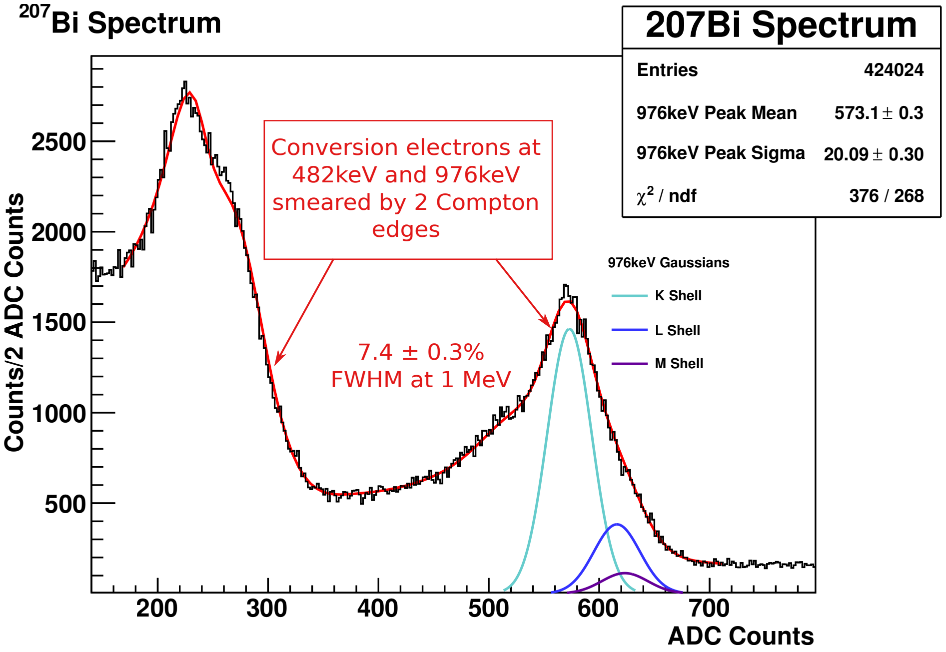
scintillator wrapped in reflective material coupled to a PMT

# SuperNEMO Calorimeter Test Bench

Excite scintillator with a monochromatic electron source (approximates the delta function)
→ any smearing of distribution is due to detector properties

## UCL:

- $^{207}$Bi source: 976 keV and 482 keV K-shell conversion electrons
- Fit: deconvolution of X-rays, γs, L-shell and M-shell conversion electrons

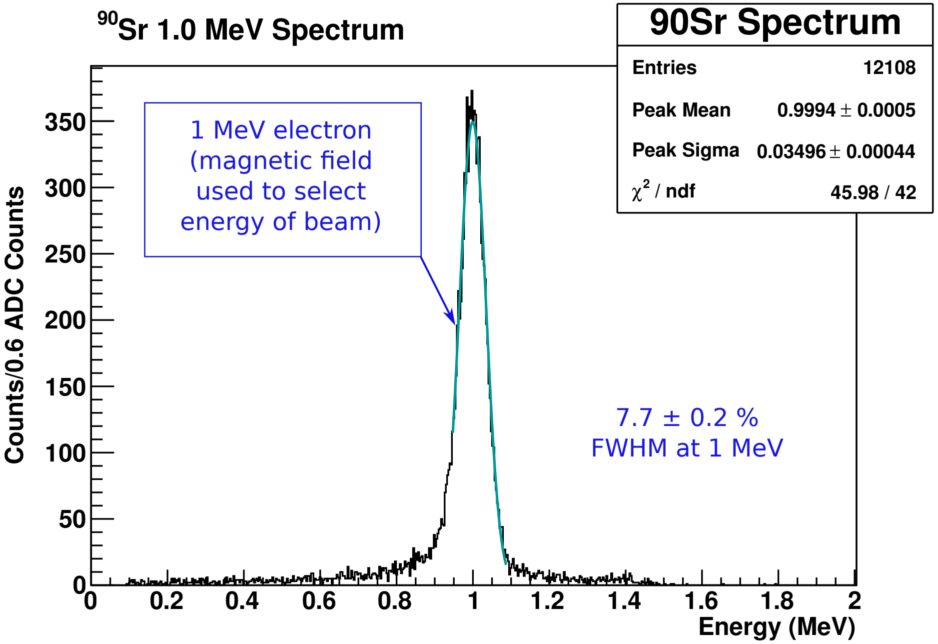


Conversion electrons at 482keV and 976keV smeared by 2 Compton edges

7.4 ± 0.3% FWHM at 1 MeV

## Bordeaux:

- $^{90}$Sr spectrometer: $^{90}$Sr beam passed through a magnetic field to select monochromatic electrons of known energy
- Fit: Gaussian

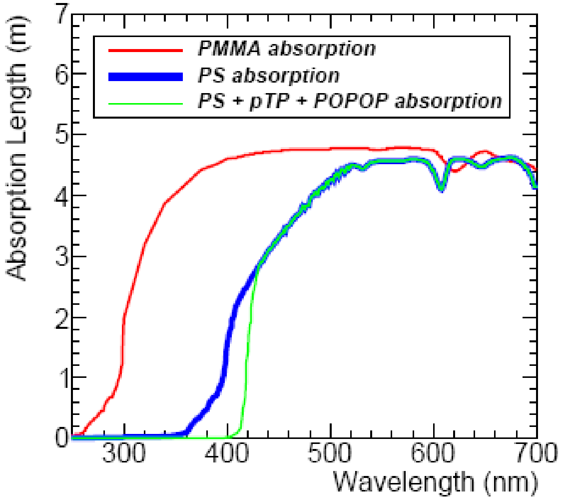


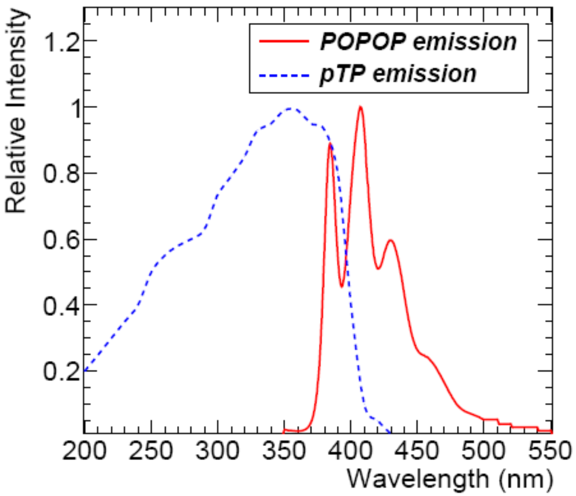
1 MeV electron (magnetic field used to select energy of beam)

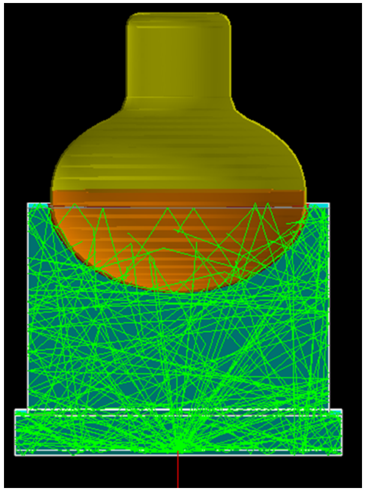
7.7 ± 0.2 % FWHM at 1 MeV

# SuperNEMO Calorimeter R&D: Simulations

- Full calorimeter simulations:
  - GENBB event generator
  - Physics simulations with GEANT4 (optical photon transport in scintillator detectors)
- The model accounts for wavelength dependence of optical properties, all of which have been experimentally measured, of the:
  - scintillators (self absorption and re-emission)
  - reflective wrappings
  - photomultipliers (QE)
  - optical coupling materials
  - refractive index of optical materials



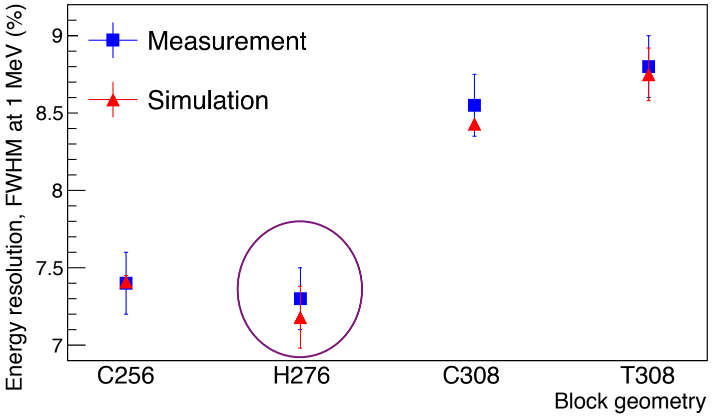




- For further details see: “Spectral modeling of scintillator for the NEMO-3 and SuperNEMO detectors” https://doi.org/10.1016/j.nima.2010.09.027

# SuperNEMO Calorimeter R&D: Scintillators

- Block shape studies:



**C256:** cubic $256^2$ x 190 $mm^2$
**H276:** hexagonal 276 mm diameter with 12 mm minimum depth
**C308:** cubic $308^2$ x $190mm^2$
**T308:** cubic $308^2$ x $190mm^2$ with tapered sides

- Material: polystyrene (PST) vs. polyvinyl toluene (PVT)

| Material | $\Delta E/E(\%)$ | $f_{\mathrm{FWHM}}$ |
|---|---|---|
| JINR NEMO-3 PS | $8.9 \pm 0.2$ | 1 |
| Eljen-200 PVT | $8.3 \pm 0.2$ | $1.07 \pm 0.03$ |
| Eljen-204 PVT | $7.8 \pm 0.2$ | $1.14 \pm 0.03$ |

| Material | $\Delta E/E(\%)$ | $f_{\mathrm{FWHM}}$ |
|---|---|---|
| NUVIA PS | $7.9 \pm 0.2$ | 1 |
| Enhanced NUVIA PS | $7.6 \pm 0.2$ | $1.04 \pm 0.03$ |

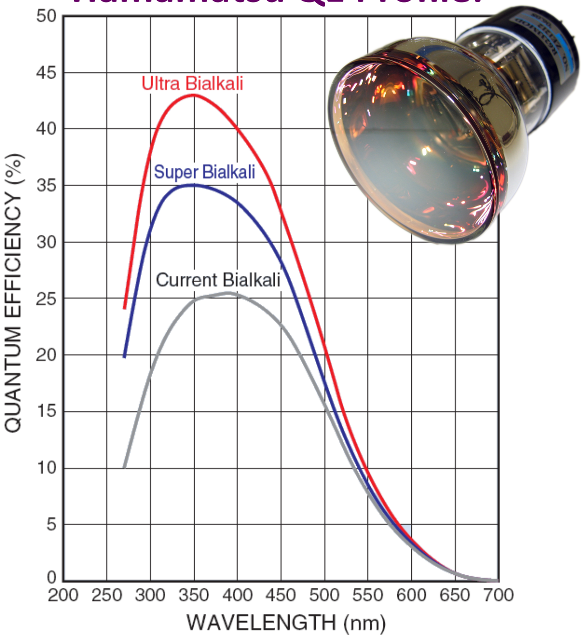
- Close collaboration with manufacturers (JINR Dubna, ISM Kharkiv, NUVIA, ELJEN) for contents of:
  - PPO scintillating agent
  - POPOP wavelength shifter

- Surface finishing: polished vs. depolished
  - All surfaces depolished (machine finish), with the face with the hemispherical cutout polished

# SuperNEMO Calorimeter R&D: PMTs

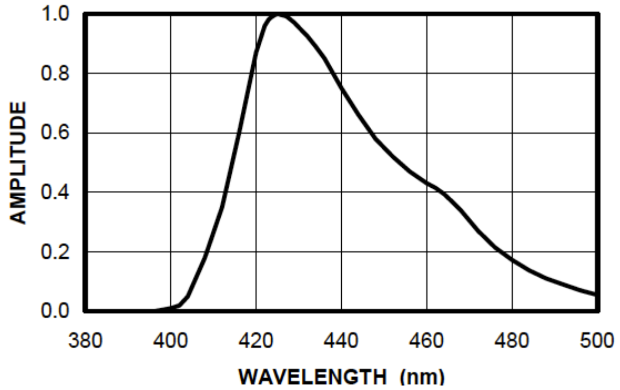
- Photocathode QE:

**Hamamatsu QE Profile:**

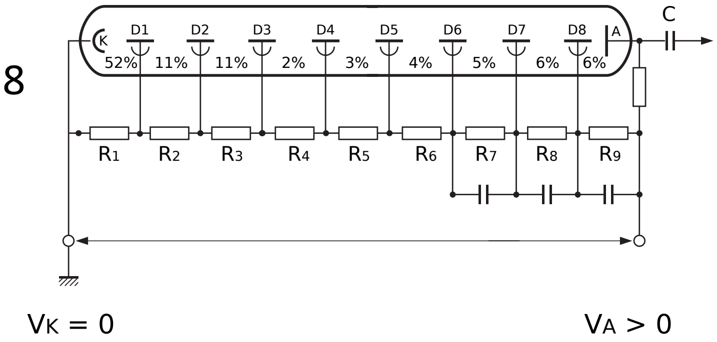


  - Bi-alkali alloy development for photocathode material has achieved QE > 40%
  - Selection of PMT to optimise QE to the emission spectra of the scintillator

EJ-200 EMISSION SPECTRUM

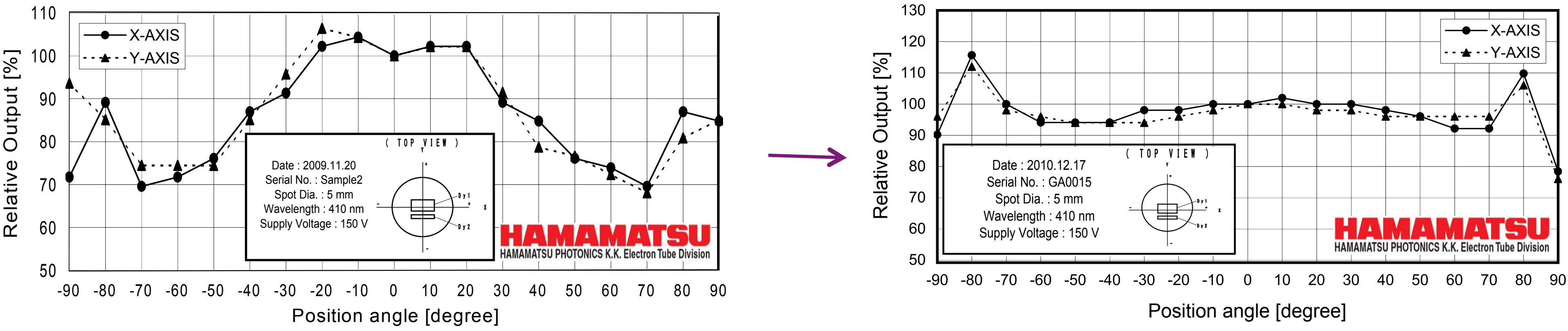


- Collection efficiency (close collaboration with Hamamatsu on 8” R5912-MOD tube):
  - Number of dynode stages reduced from 10 to 8
  - Voltage divider optimisation
  - Improved from <70% to ~80%



# SuperNEMO Calorimeter R&D: PMTs

- Photocathode uniformity:
  - Close collaboration with Hamamatsu to improve photocathode uniformity across the entire surface of the R5912-MOD PMT



Date : 2009.11.20
Serial No. : Sample2
Spot Dia. : 5 mm
Wavelength : 410 nm
Supply Voltage : 150 V

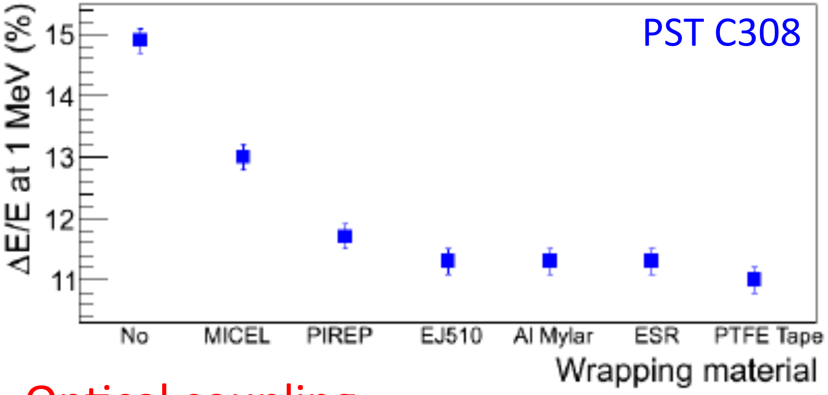
Date : 2010.12.17
Serial No. : GA0015
Spot Dia. : 5 mm
Wavelength : 410 nm
Supply Voltage : 150 V

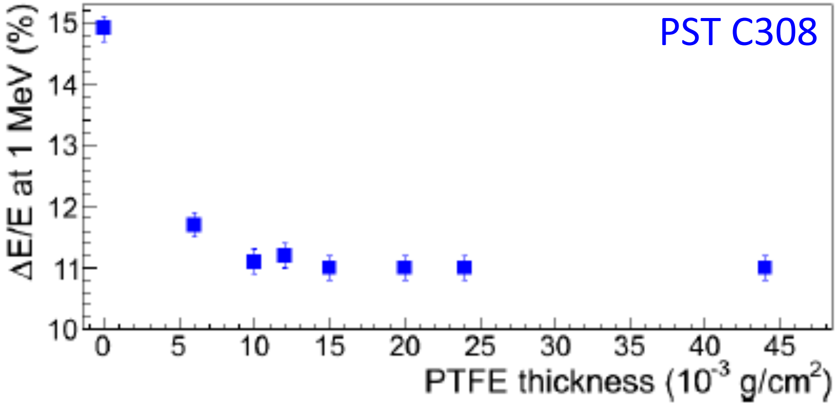
- Timing:
  - Reducing the number of dynode stages improves the timing of the PMT by reducing the time transition spread (TTS)

- Gain and Linearity (a big achievement!):
  - Reducing the number of dynode stages and optimising the voltage divider decreases the gain: ~1 x $10^5$
    → Good linearity (< 2% for very high light levels – 50 mA peak current) whilst good gain of the 1st dynode and therefore high collection efficiency

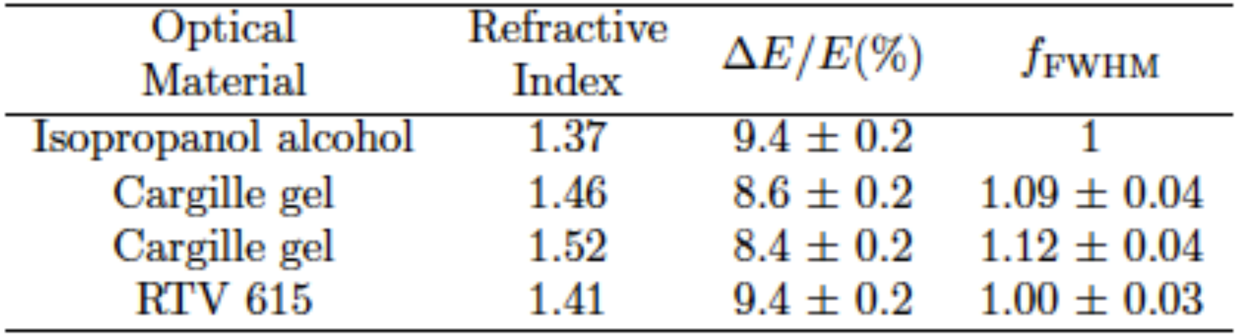
# SuperNEMO Calorimeter R&D: Reflective Material & Coupling

- Reflective material:
  - High reflectivity, radiopure, low Z and low density (to reduce backscattering)





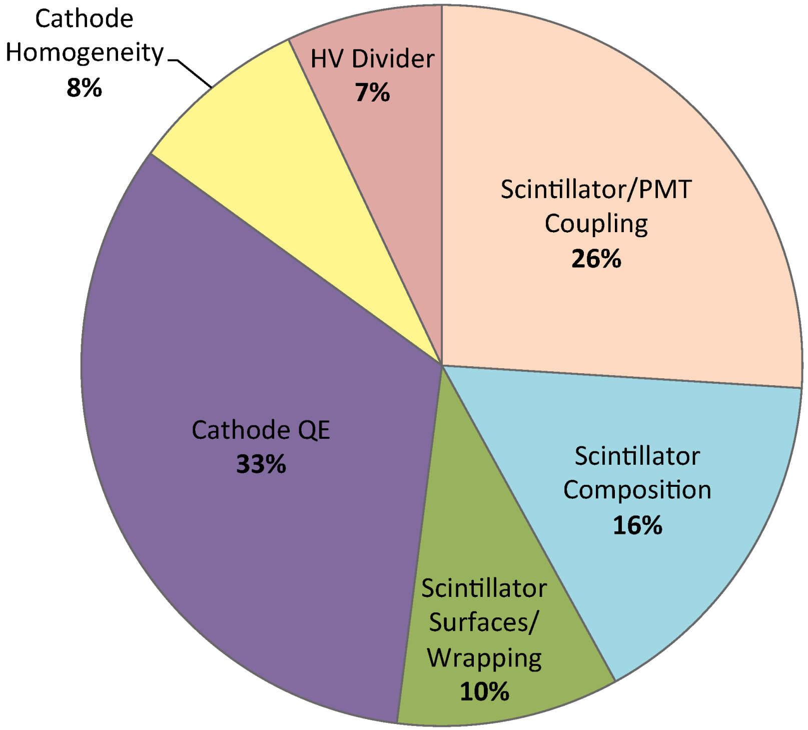
- Optical coupling:
  - Good optical coupling between scintillator and PMT essential for uniform and complete light collection

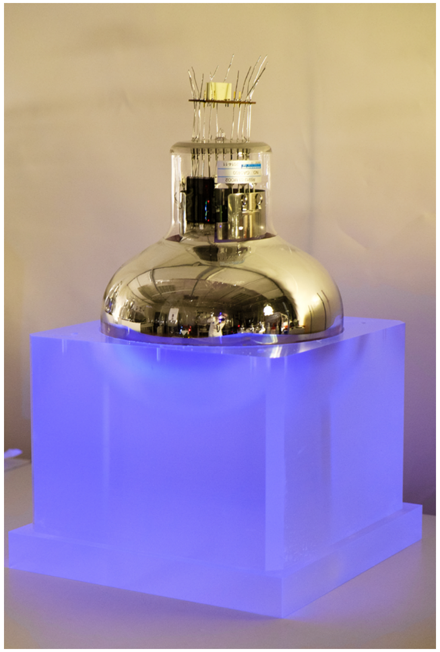


| Optical Material | Refractive Index | $\Delta E/E(\%)$ | $f_{\mathrm{FWHM}}$ |
|---|---|---|---|
| Isopropanol alcohol | 1.37 | $9.4 \pm 0.2$ | 1 |
| Cargille gel | 1.46 | $8.6 \pm 0.2$ | $1.09 \pm 0.04$ |
| Cargille gel | 1.52 | $8.4 \pm 0.2$ | $1.12 \pm 0.04$ |
| RTV 615 | 1.41 | $9.4 \pm 0.2$ | $1.00 \pm 0.03$ |

  - Direct coupling of PMT to hemispherical cutout in scintillator gave the biggest impact in energy resolution improvement.

# SuperNEMO Calorimeter R&D: Summary

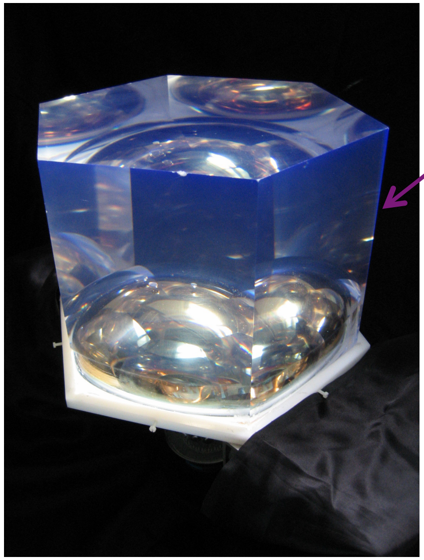




- For further details, see:

“Calorimeter development for the SuperNEMO double beta decay experiment”
https://doi.org/10.1016/j.nima.2017.06.044

# Optimised SuperNEMO Optical Module Design



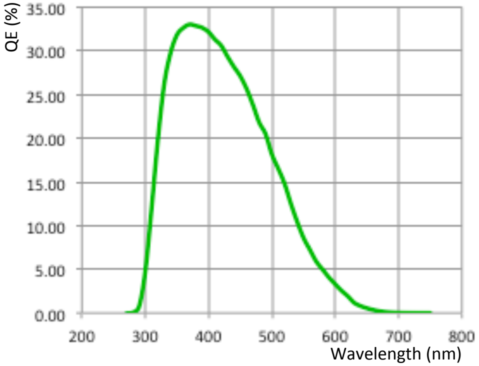
$$\frac{3.2\%(\sigma)}{\sqrt{E(MeV)}}$$

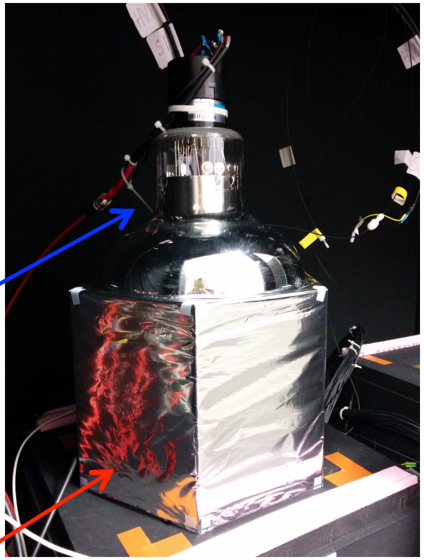
**EJ-200 hexagonal PVT block**:

276 mm diameter
193 mm deep, minimum thickness between PMT and scintillator: 100 mm

**R5912-MOD Hamamatsu 8” PMT**:

Maximum quoted QE: 33%
32% QE at 400 nm





**Wrapping:**

Sides: 75 µm of PTFE (Teflon) ribbon
Sides and entrance face: 12 µm of Mylar

# Back to Proton Therapy…

- With this fantastic energy resolution of 3.2% σ at 1 MeV can we apply the SuperNEMO optical module technology to proton therapy beam monitoring and proton imaging?

**Challenges**: from SuperNEMO (electrons) to a proton beam

- Very high intensity of events at a proton beam (~10 GHz):
  - Random number of protons per bucket from beam, we require 1 proton per bucket
  - Pile up!
- Scintillator quenching for protons:
  - For a plastic scintillator, the scintillator response is nonlinear with the amount of energy deposited in it
  - Amount of deviation → "quenching"
  - Characterised by Birk's law:

$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

| | |
|---|---|
| **dY/dx** | light yield per unit path length |
| **dE/dx** | energy lost by particle per unit path length |
| **kB** | relates density of ionisation to energy loss<br>= 0.207 mm/MeV |
| **S** | absolute scintillation efficiency |

  - Becomes important for large dE/dx and ionisaion density → important for protons, which have a large dE/dx when they slow down

- Energy range:
  - SuperNEMO optimised for electrons from 0.5 – 4 MeV for double beta decay
  - For proton therapy we require ~O(100 MeV)

# Step 1: GEANT4 Simulations

- A 60 MeV proton beam simulated, positioned 30 cm before the entrance face of the scintillator block
  - Proton beam has been run through the Clatterbrdige beamline

- Scintillator geometry and composition fully described

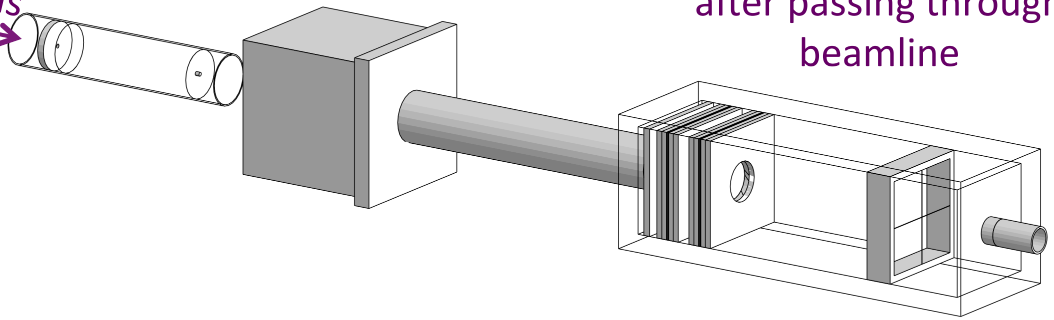
- Quenching of scintillation light in plastic scintillator for protons

- Energy deposited smeared according to Poissonian fluctuations in the number of generated photo-electrons

- The number of photo-electrons per MeV taken from test bench data (SuperNEMO calorimeter R&D): 982 photo-electrons per MeV
  (for an energy resolution of 3.2% σ at 1MeV)

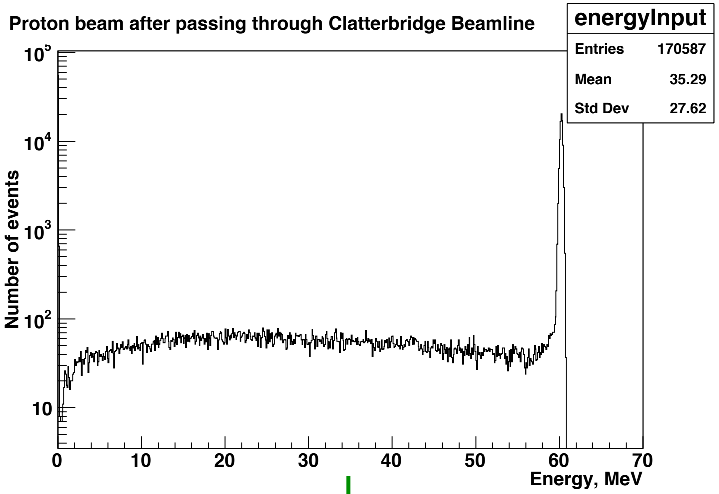
# Step 1: GEANT4 Simulations

protons

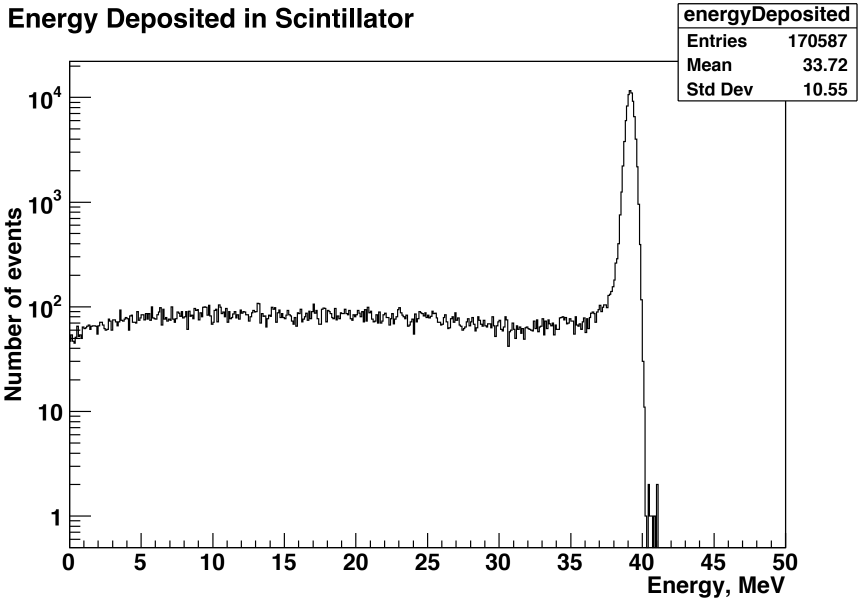


resulting proton beam

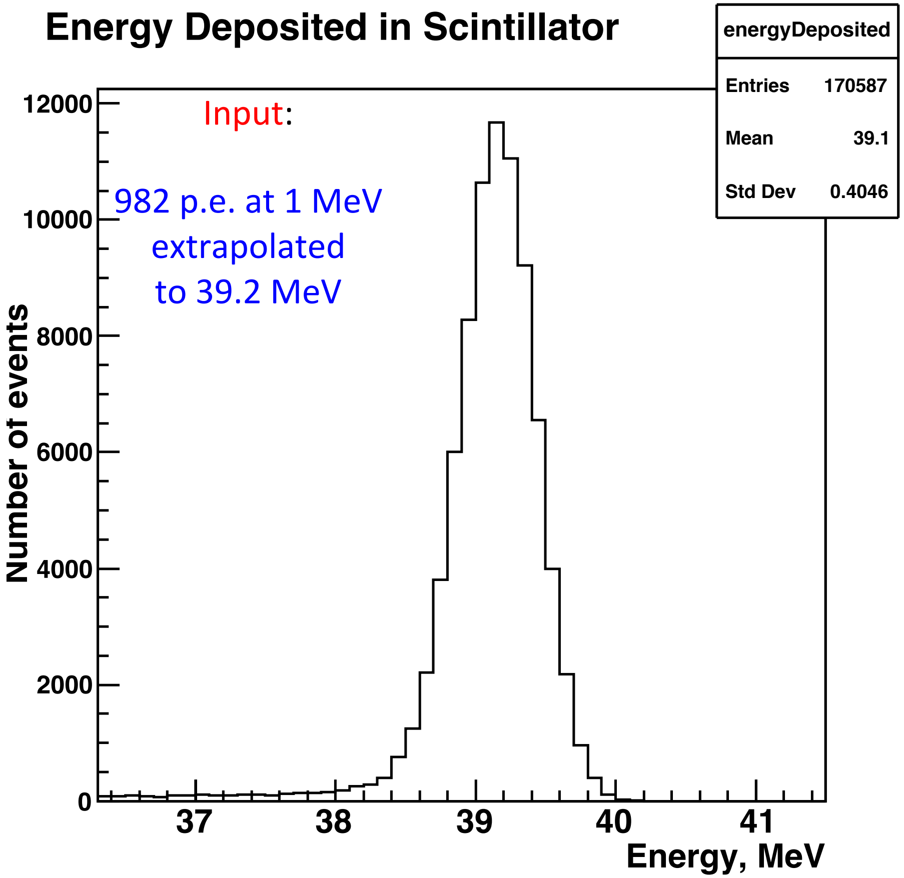
after passing through beamline



Energy deposited in scintillator after beam passes through detector

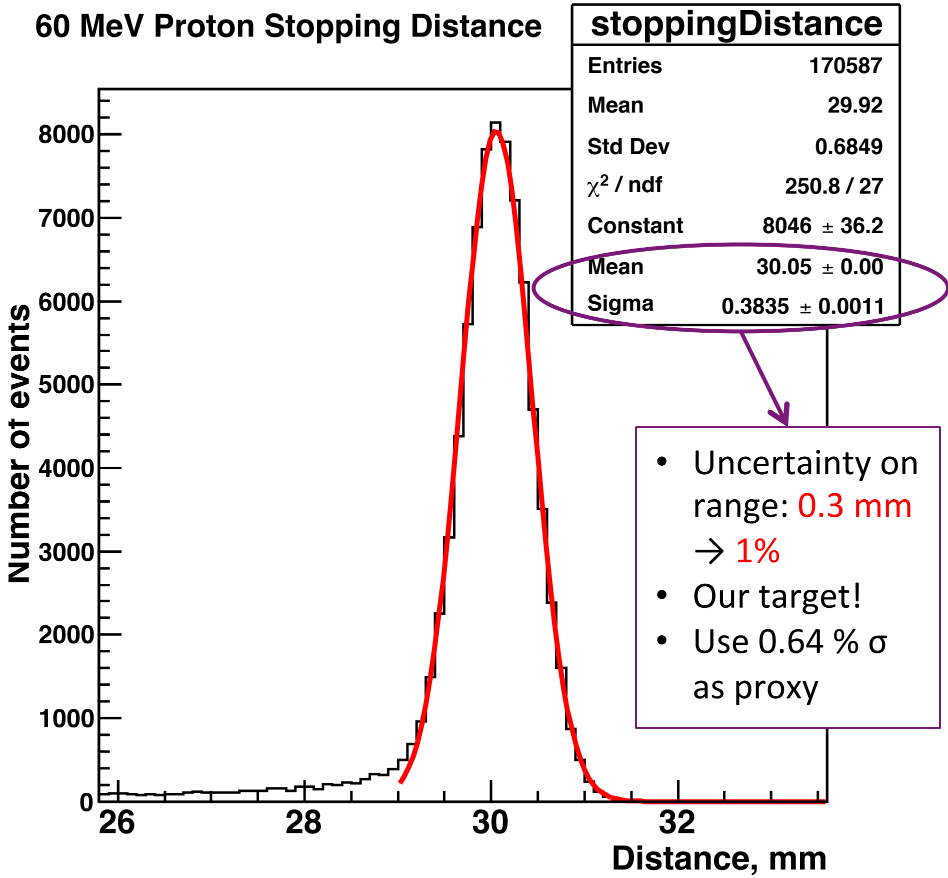


# Step 1: GEANT4 Simulations



Input:

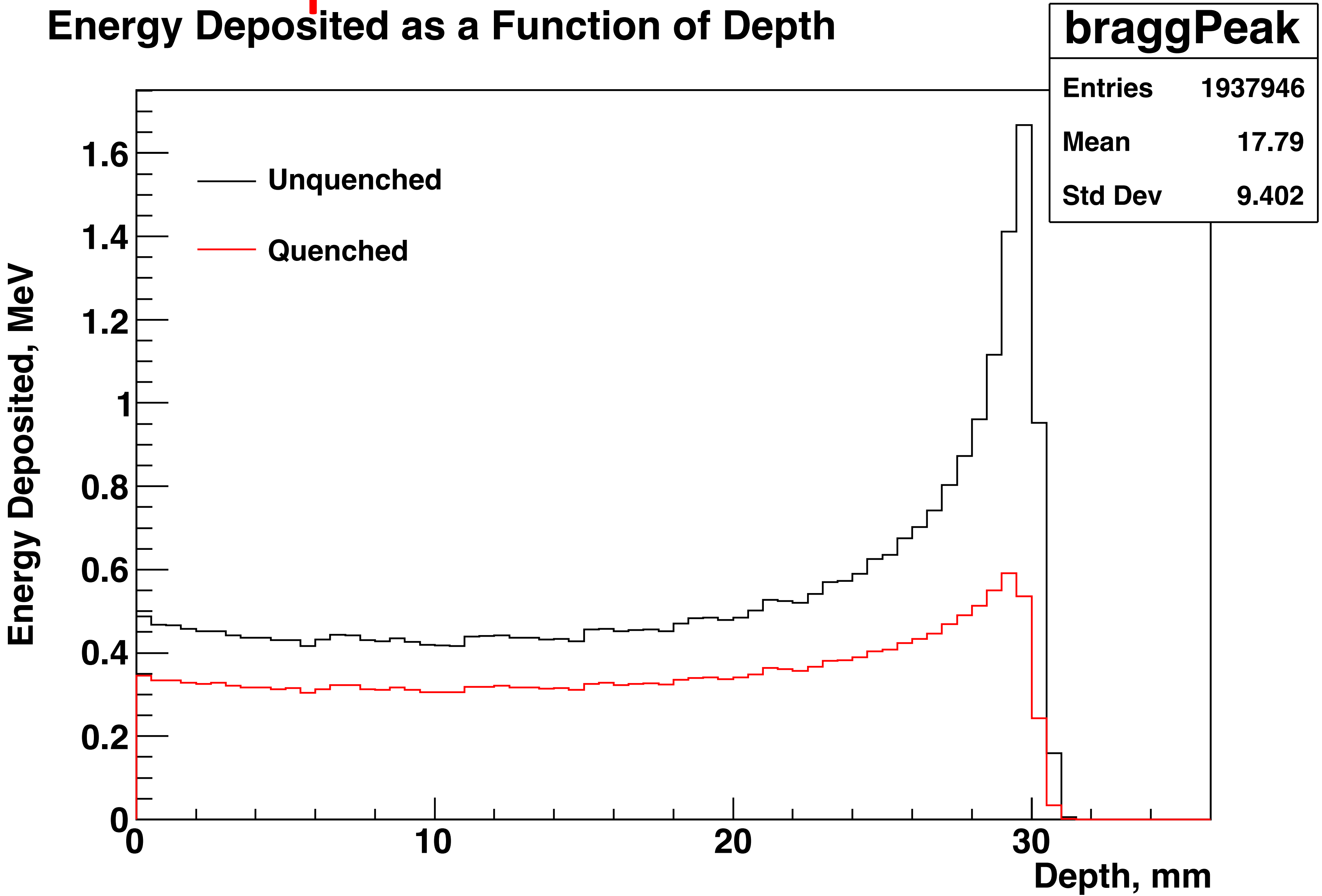
982 p.e. at 1 MeV extrapolated to 39.2 MeV



- Uncertainty on range: 0.3 mm → 1%
- Our target!
- Use 0.64 % σ as proxy

- Quenching from simulations:
  - Simulated mean: 39.2 MeV
  - Quenching: 35% for 60 MeV protons
- Energy resolution from simulations:
  - σ: 0.252, μ: 39.21
  - **σ/E: 0.64 % σ**

# Step 1: GEANT4 Simulations



60 MeV protons range out at 30 mm in the scintillator

# Step 1: GEANT4 Simulations

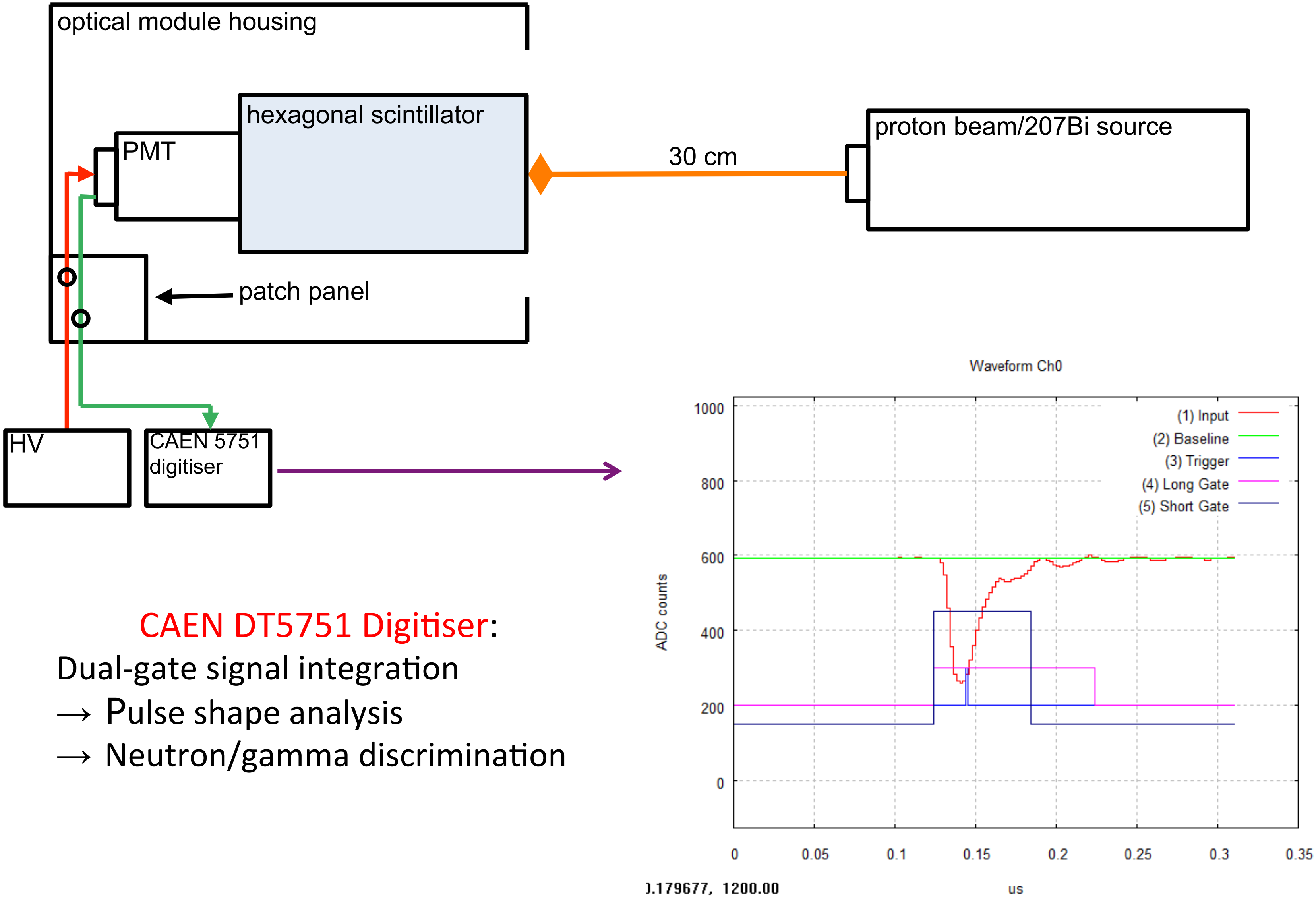
## Proton Stopping Distance

- Simulations of SuperNEMO scintillator vs Water Equivalent
  - Pencil beam simulations

| Proton Beam Energy, MeV | Mean stopping distance, SCINT (mm) | Mean stopping distance, WATER (mm) | σ stopping distance, SCINT (mm) | σ stopping distance, WATER (mm) |
|---|---|---|---|---|
| 60 | 30.21 | 30.54 | 0.33 | 0.33 |
| 200 | 255.4 | 257.1 | 2.48 | 2.44 |
| 300 | 505.9 | 509.9 | 4.64 | 4.78 |

- The SuperNEMO scintillator is water equivalent for stopping distance and spread
  - One to one conversion for water phantoms used in medical physics
  - An advantage for direct range verification using the “segmented” design

# Step 2: Equipment Setup

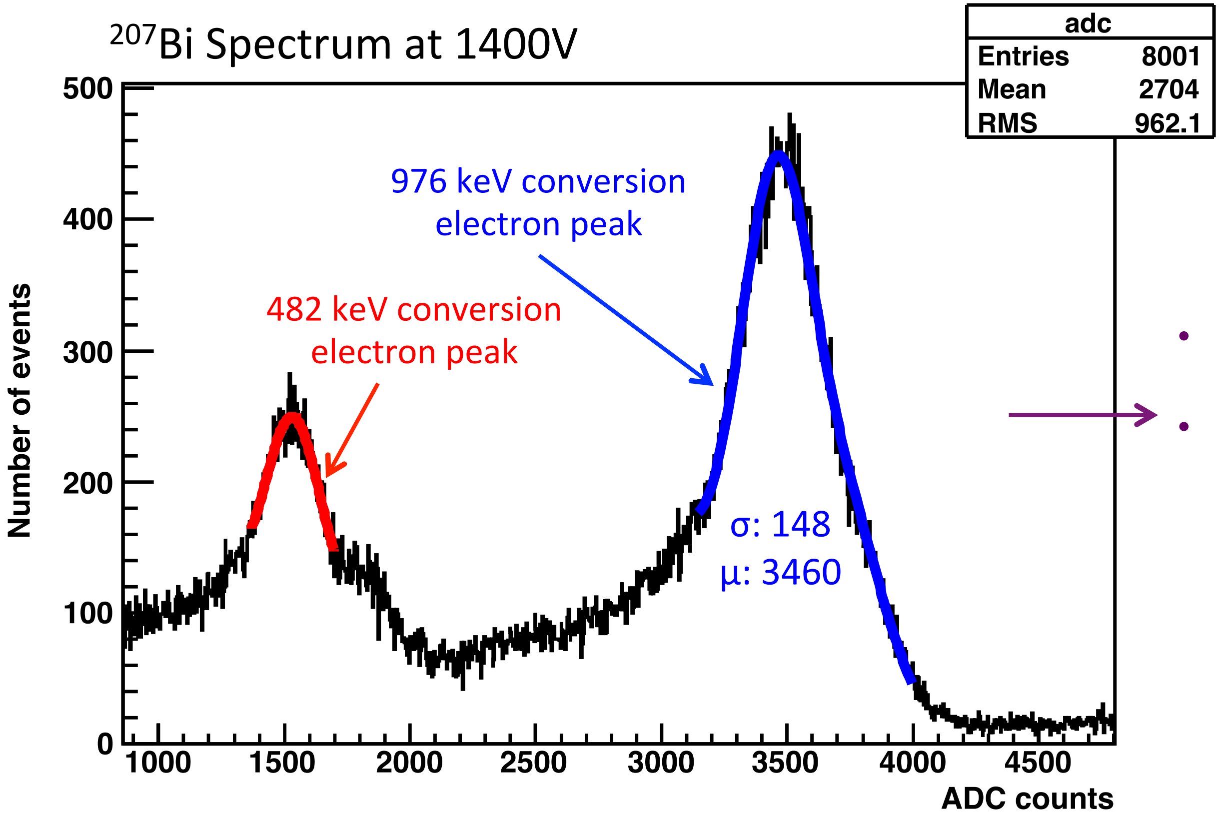


**CAEN DT5751 Digitiser**:
Dual-gate signal integration
→ Pulse shape analysis
→ Neutron/gamma discrimination

# Step 3: $^{207}$Bi Test at UCL

- Optical module resurrected after some years: re-measure energy resolution!
  - New test bench at UCL: a thin scintillator introduced into set up, which triggers DAQ only when an electron passes through it

→ Gammas removed, fit simplified to triple Gaussian of 976 keV and 482 keV peaks



After:
- correction for energy lost in thin scintillator
- conversion to MeV

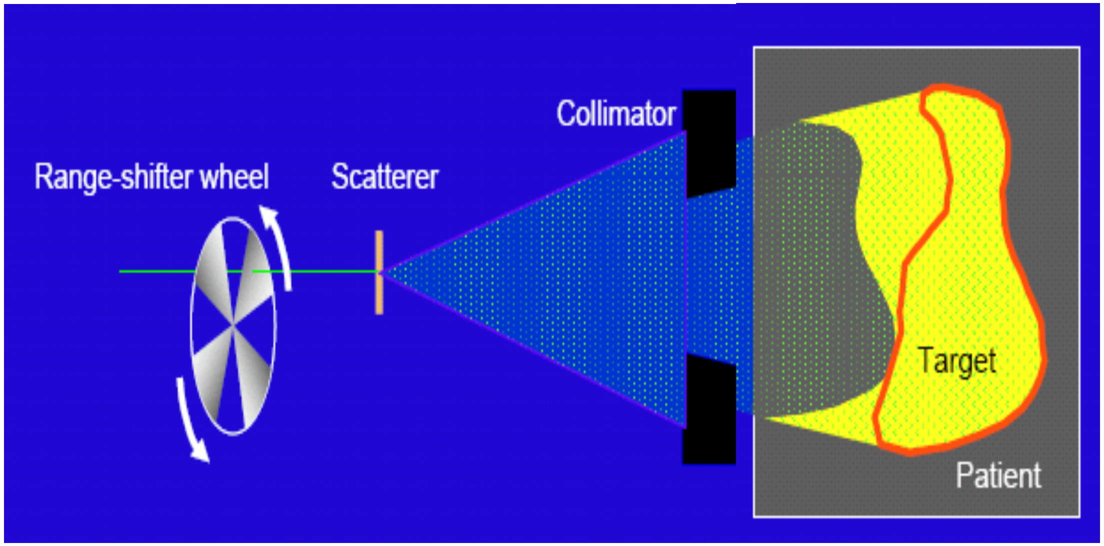
σ/E: **3.6 ± 0.2 % σ** at 1 MeV

# Step 4: Clatterbridge Cancer Centre

- Only currently operational proton beam treatment centre in the UK

- Home to the Douglas Cyclotron → produces 60 MeV proton beam for the treatment of ocular melanomas (penetration of 60 MeV protons: 30.5 mm in water)

- Double scattering beam technique:

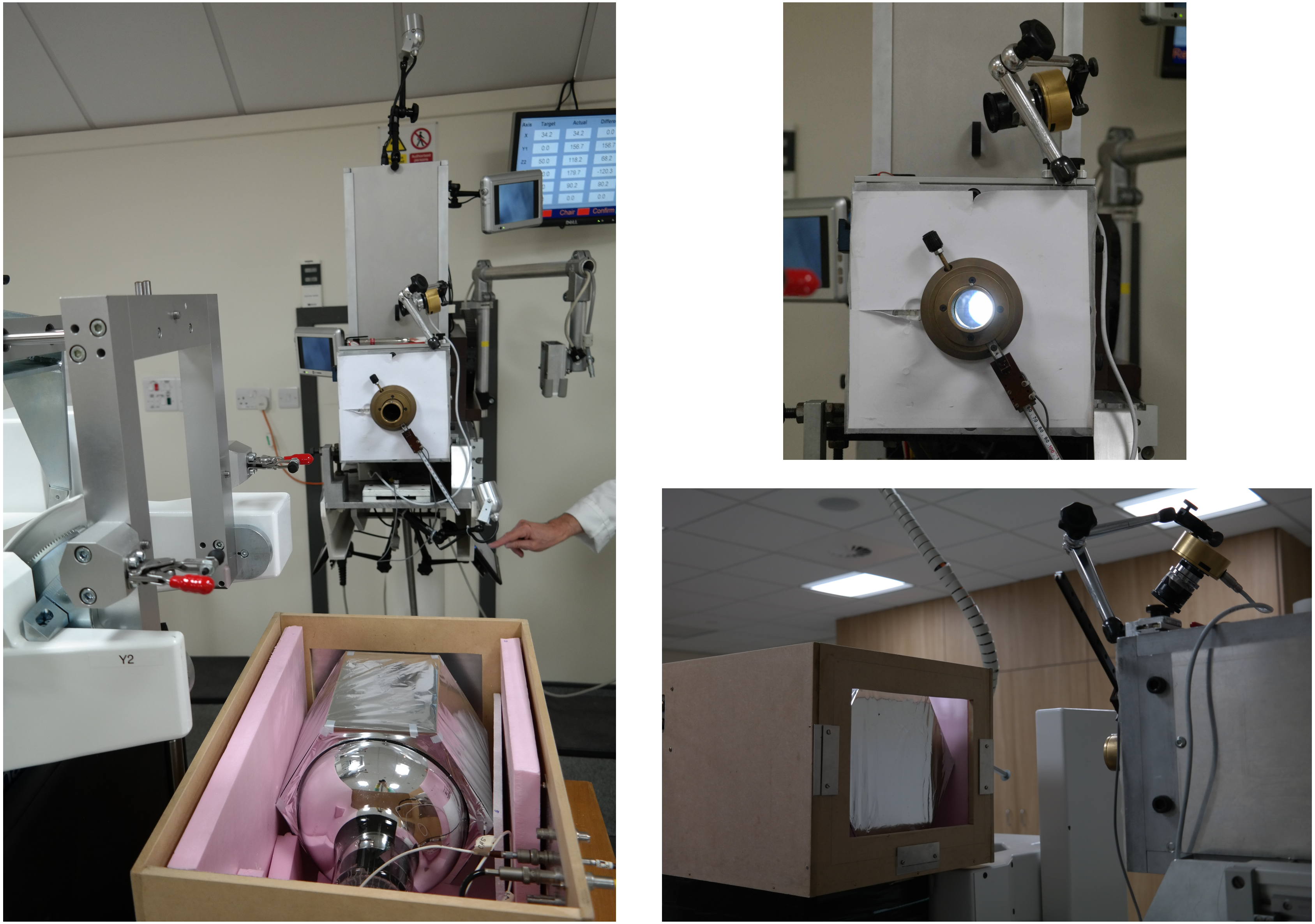


- Beam accelerated to single energy
- Beam passes through range-shifter wheel that modulates the proton beam energy to reach front/back of target volume
- Scatterer enlarges beam to cover whole volume
- Collimator shapes outer edge of beam to target area

# Step 4: Clatterbridge Cancer Centre

- Eight full days in total of proton beam access granted to UCL from 2013 - 2016

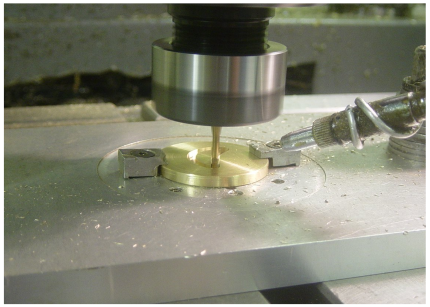
# Step 4: Clatterbridge Cancer Centre



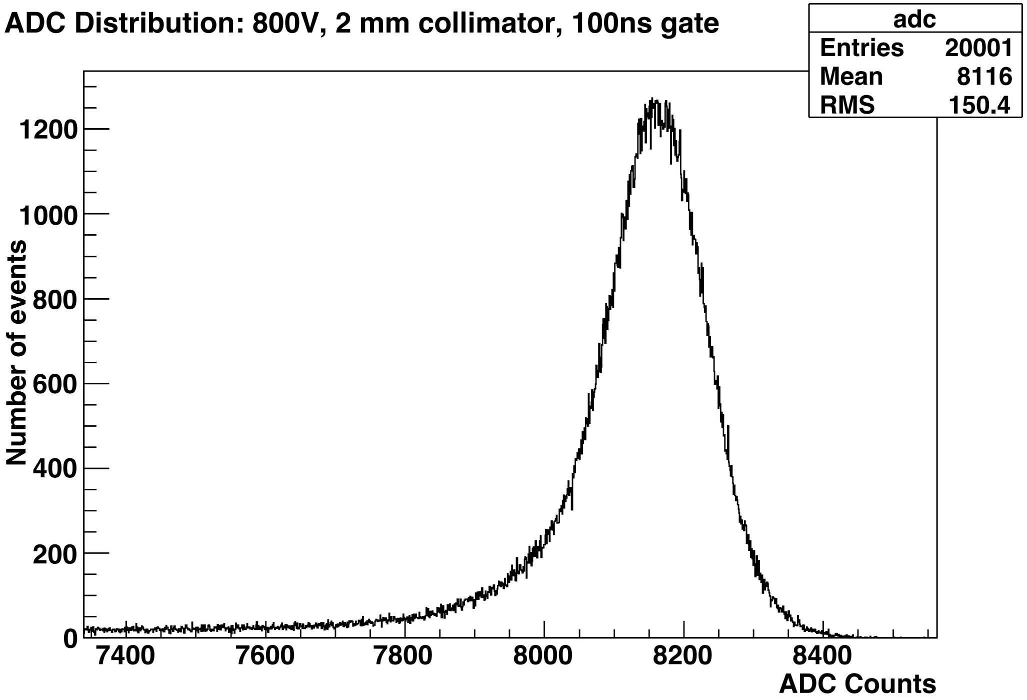
# Step 4: Clatterbridge Cancer Centre

# Step 4: Clatterbridge Cancer Centre

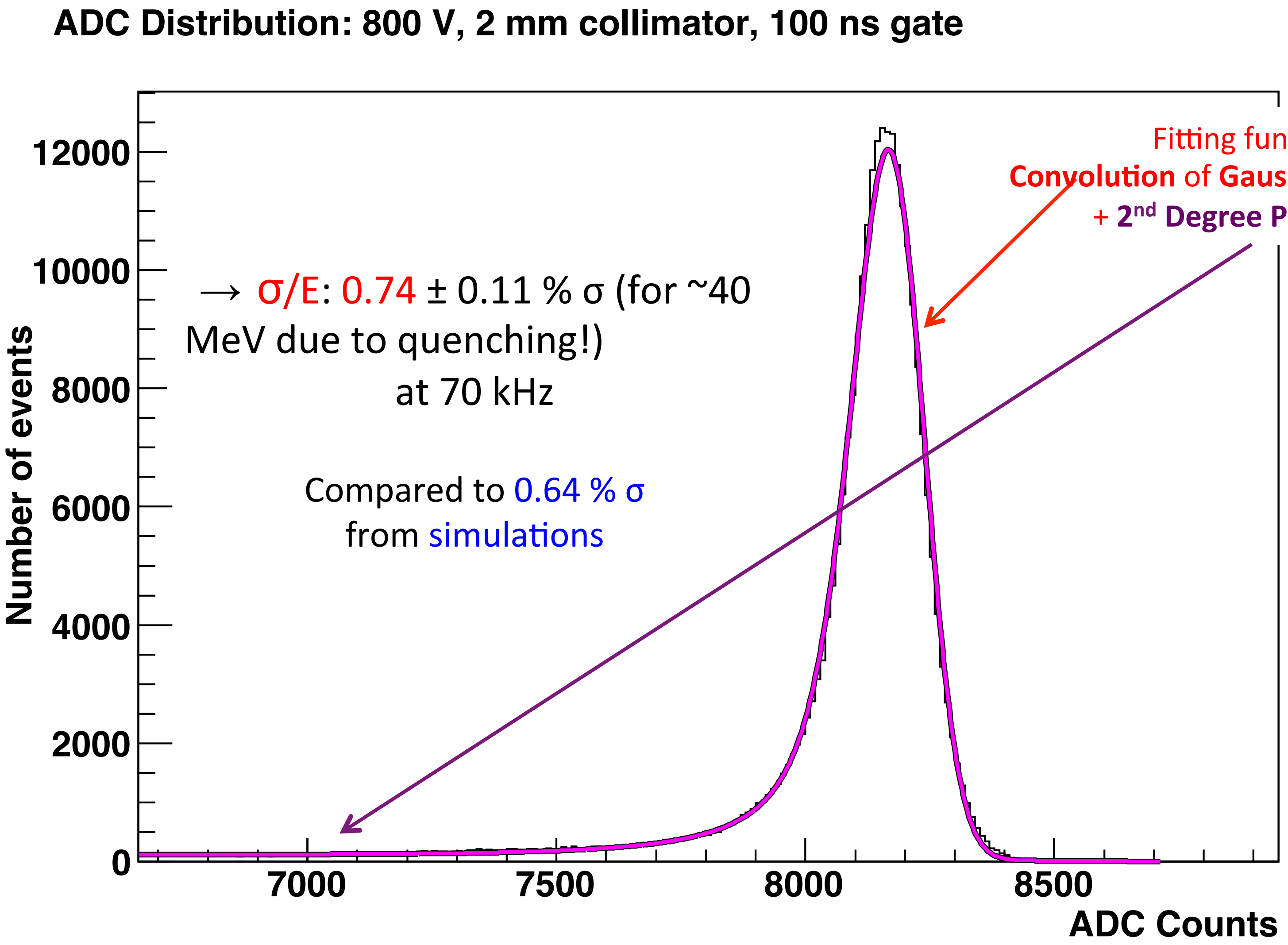
- The proton rate from the beam was carefully controlled by
  - Inserting brass collimators with varying diameters (0.5 mm – 10 mm) into the beam nozzle (~30 cm upstream of the optical module)
  - Adjustment of the ion source gas supply
  - Adjustment of the cyclotron RF phase



- Resulting distribution:



# Step 4: Clatterbridge Cancer Centre

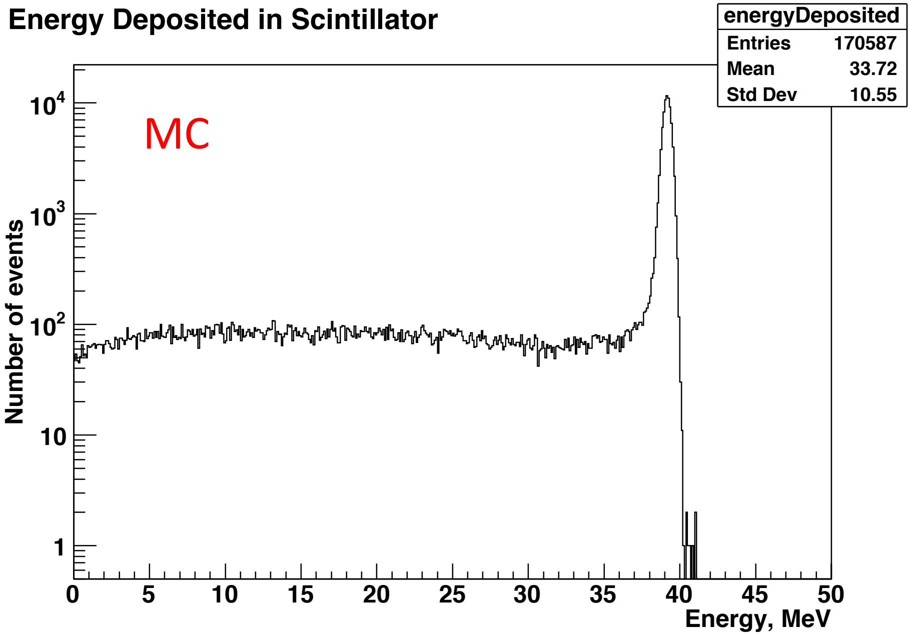


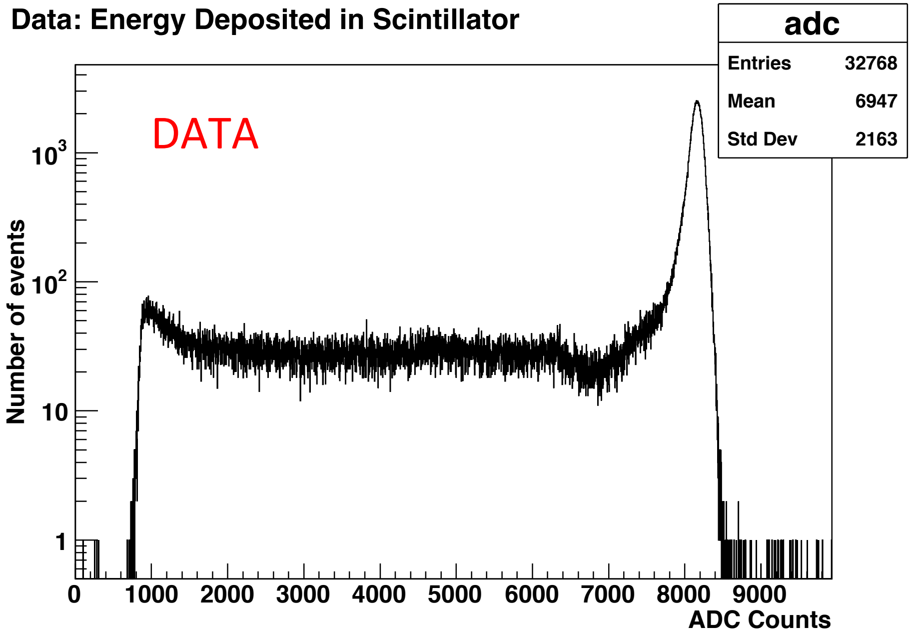
Fitting function:
**Convolution** of **Gaussian** and **Landau**
+ **$2^{nd}$ Degree Polynomial**

→ σ/E: 0.74 ± 0.11 % σ (for ~40 MeV due to quenching!)
at 70 kHz

Compared to 0.64 % σ
from simulations

# Step 4: Clatterbridge Cancer Centre





- Our simulations accurately represent our data!

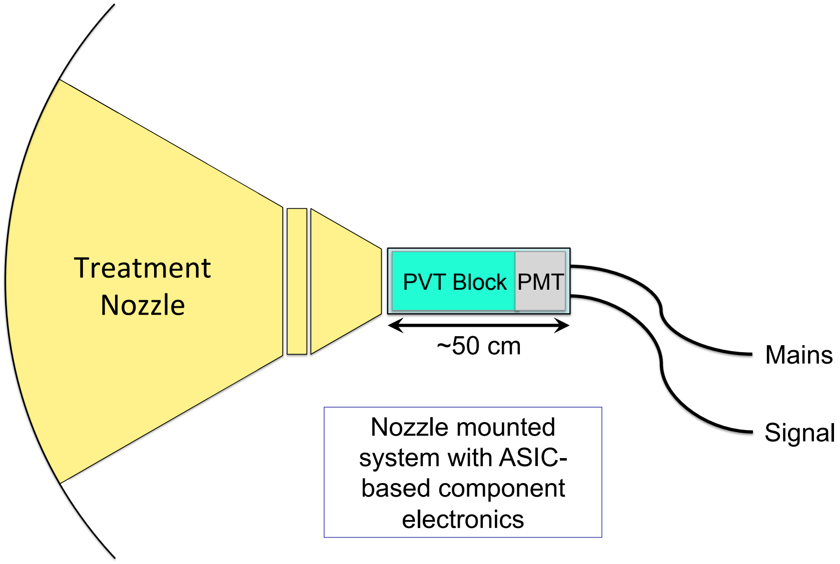
# Step 5: Make the Technology Smaller & Faster

- We have already achieved the target energy resolution: 0.7 % σ
- But, at rates > 250 kHz we start to see pile up
- The next step is to do this for very high rates of 1 – 10 MHz with a compact design:
  - Reduce the size of the PMT and the scintillator to improve timing and make the design nozzle-mountable
  - -VE HV PMT base to remove decoupling capacitor (not fast enough discharge)

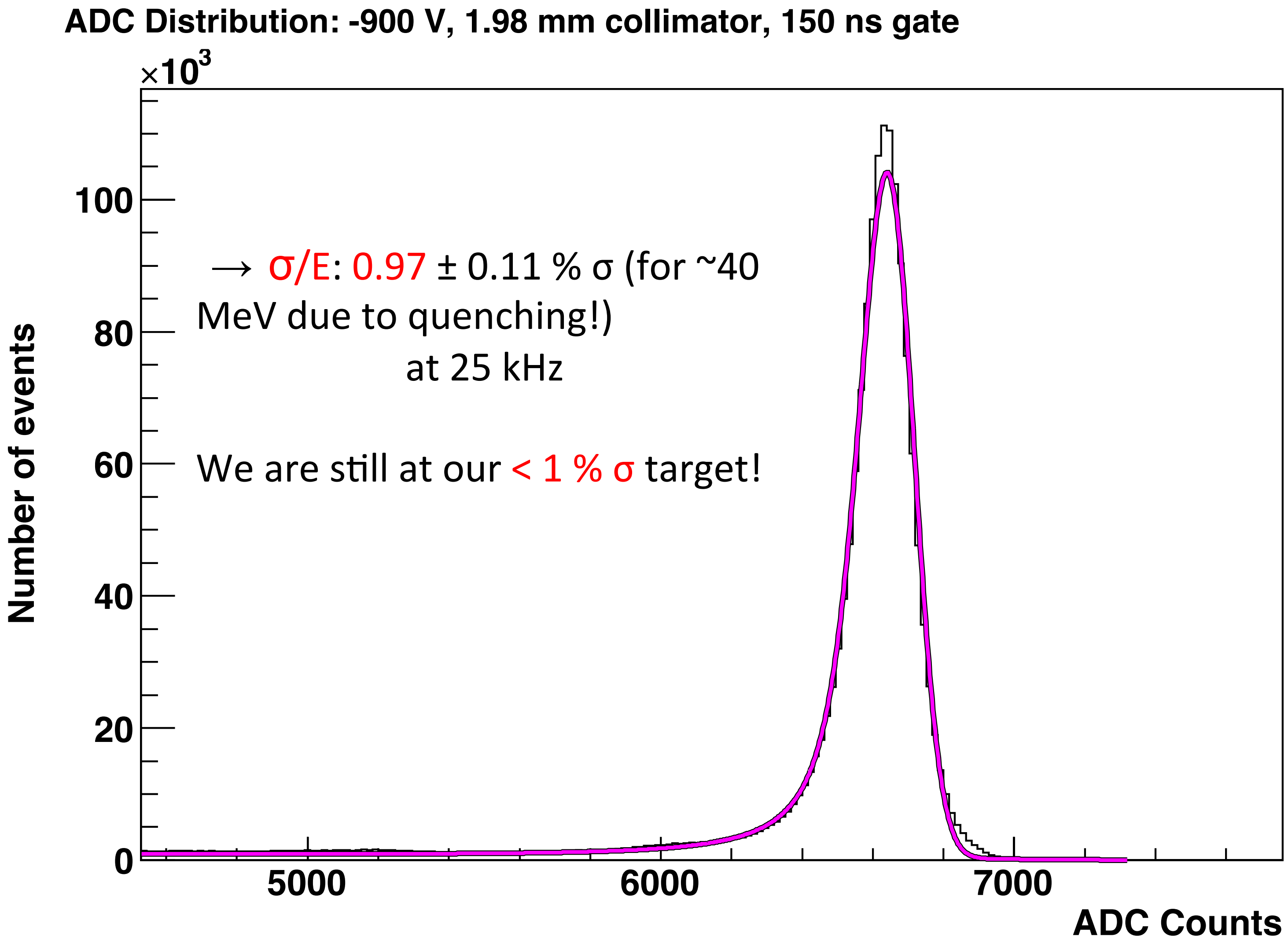
2" Hamamatsu R13089-100-11 PMT with negative HV active divider base

3 cm x 3 cm x 5 cm cuboid ENVINET/NUVIA PS scintillator

- Coupled with BC-630 Saint Gobain silicone optical gel
- Wrapped in 75 μm of PTFE (Teflon) ribbon on the sides and 12 μm of Mylar on the sides and entrance face



# Step 5: Make the Technology Smaller & Faster

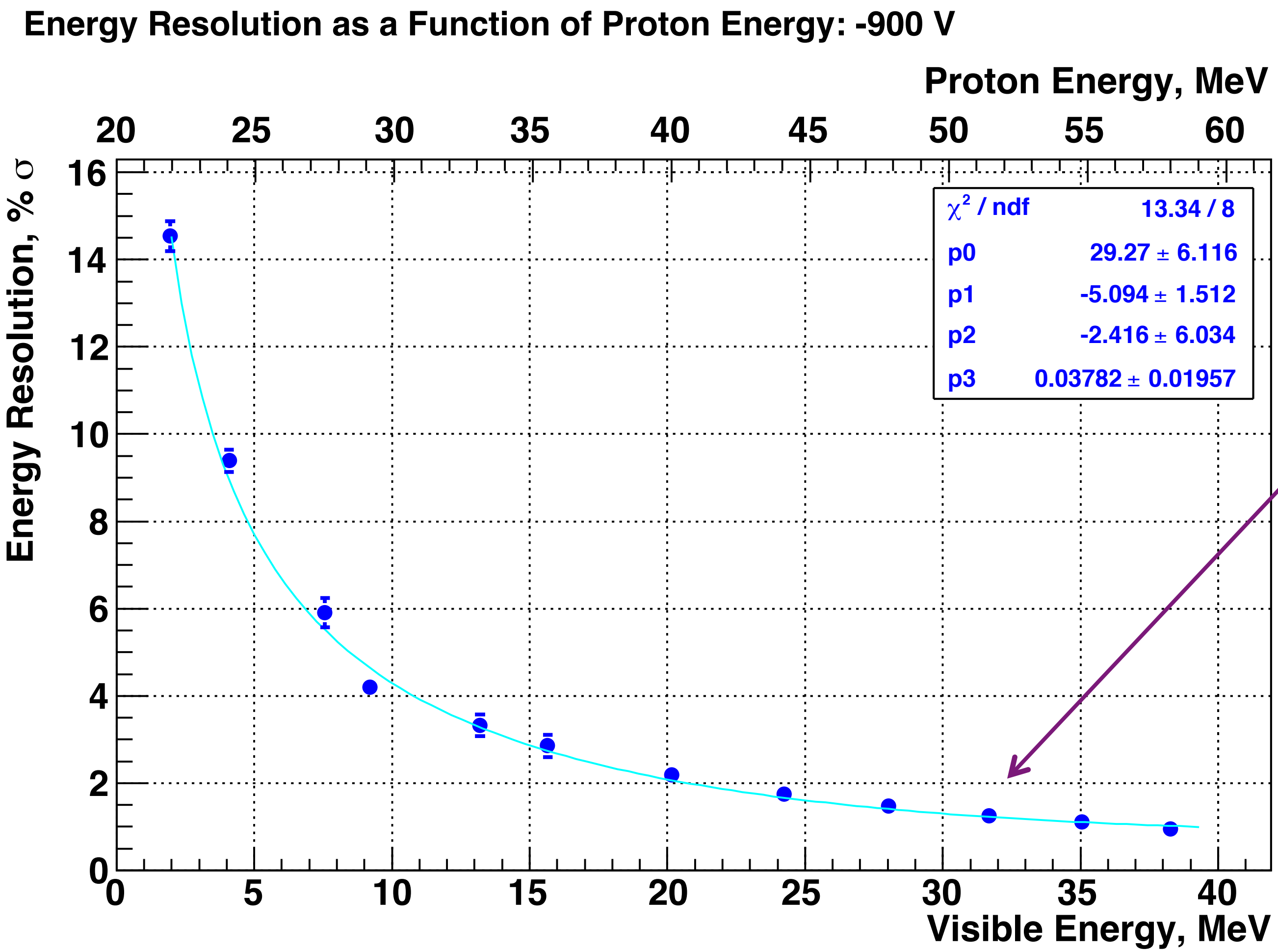


→ σ/E: 0.97 ± 0.11 % σ (for ~40 MeV due to quenching!)
at 25 kHz

We are still at our < 1 % σ target!

# Energy Dependence on Resolution

- Energy of protons incident on scintillator varied by placing absorbers (PMMA plates and calibration wheel) of known thickness ~1.8 m upstream of the optical module



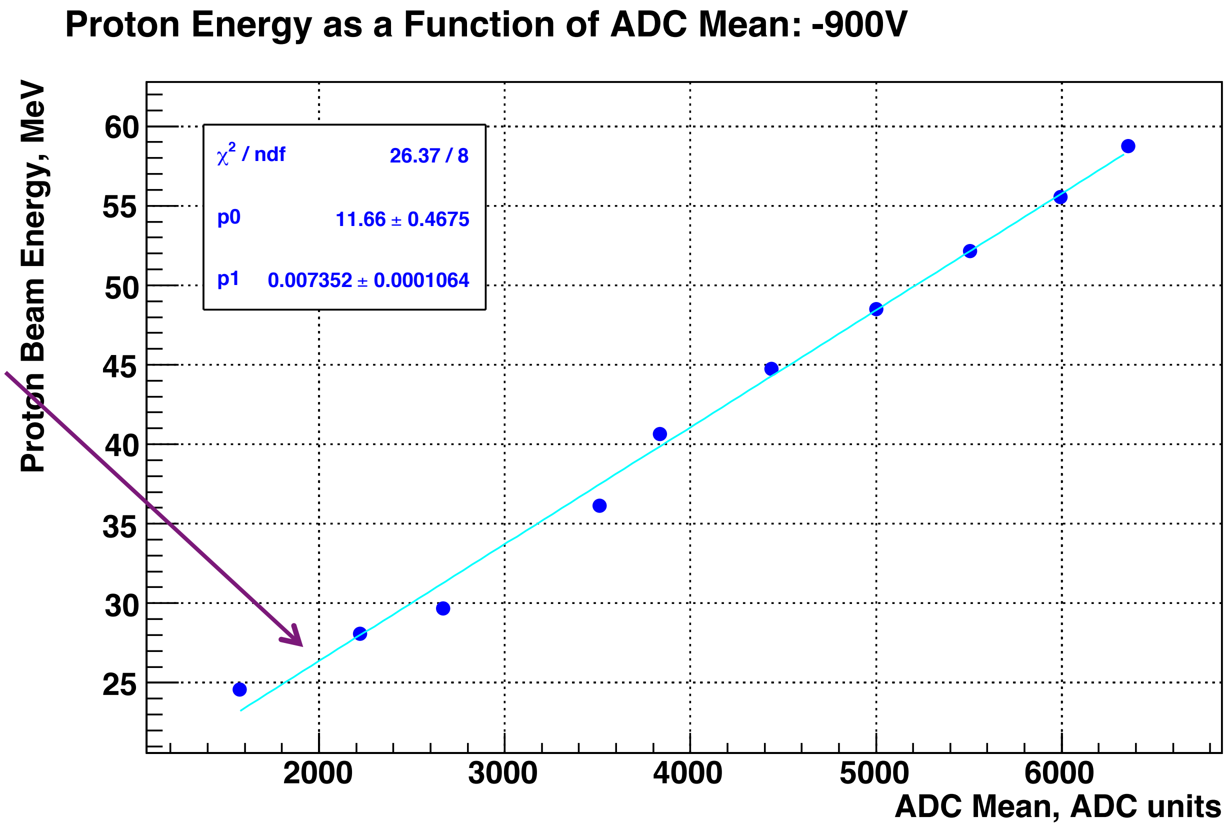
$$y = p0 + \frac{p1}{\sqrt{x}} + \frac{p2}{x} + p3 \cdot x$$

$\sqrt{E}$ dependence!

# Linearity: -900 V

- We want to run the PMT at higher voltages (can run at up to 1500V) as this will increase the PMT's collection efficiency and will improve the energy resolution

- BUT we have a LOT of light (tens of thousands of photo-electrons) so we need to make sure we are not saturating the PMT
  - Look at linearity

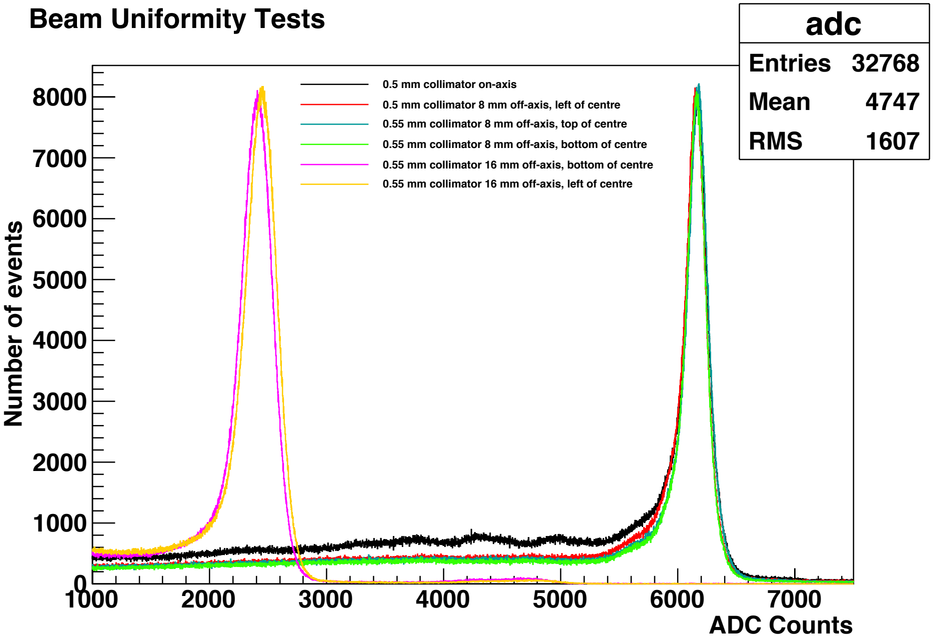


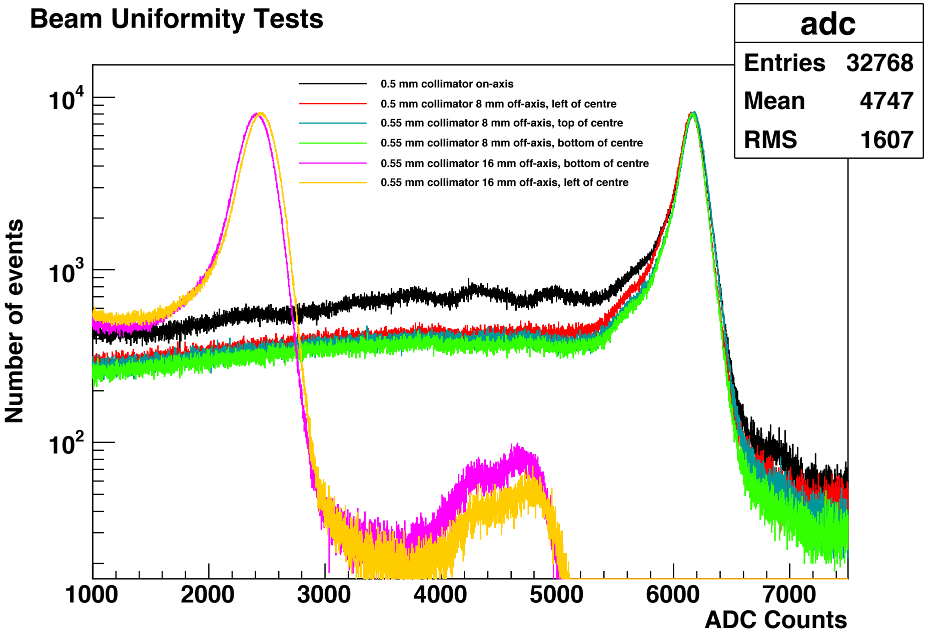
$y = p0 + (p1 \cdot x)$

For - 900V:
Deviation from linearity < 2%!

# Beam Uniformity Measurements

- 0.5 mm Ø collimator





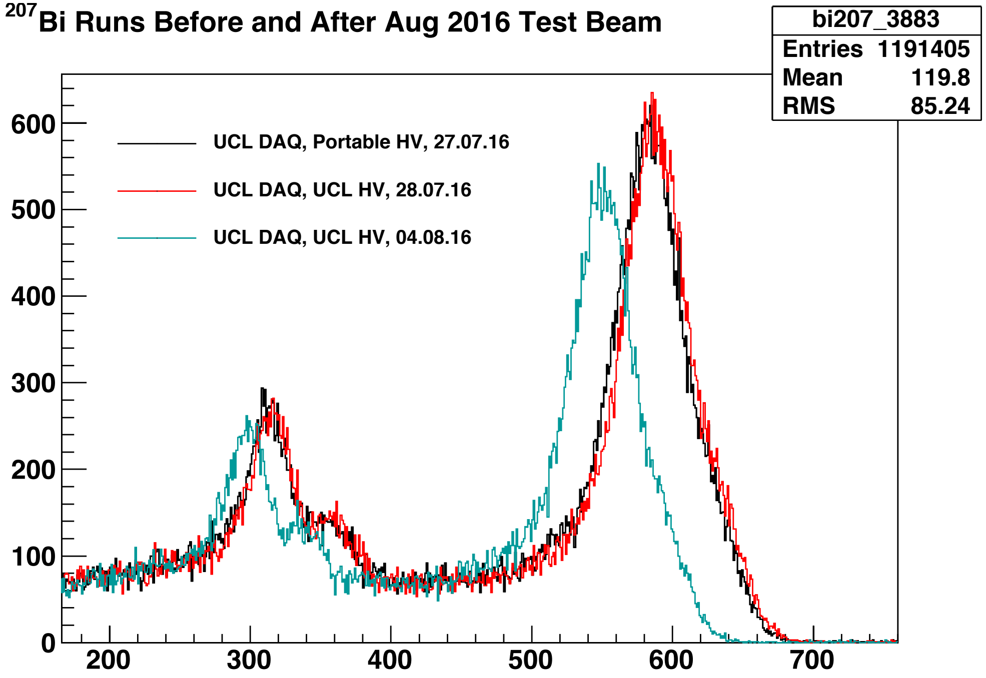
- Uniform 8 mm away from the centre

- 16 mm away from the centre is 1mm away from the beam edge
  - Currently trying to understand these edge effects

- Okay to use collimators to reduce rates!

# Radiation Damage Assessment

- Total estimated radiation dose received by 2” OM: 0.25 Gy

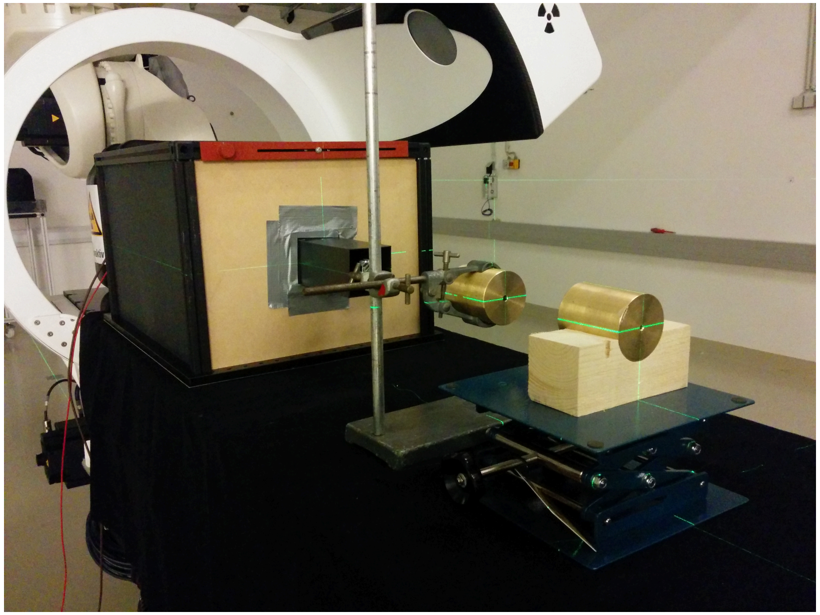


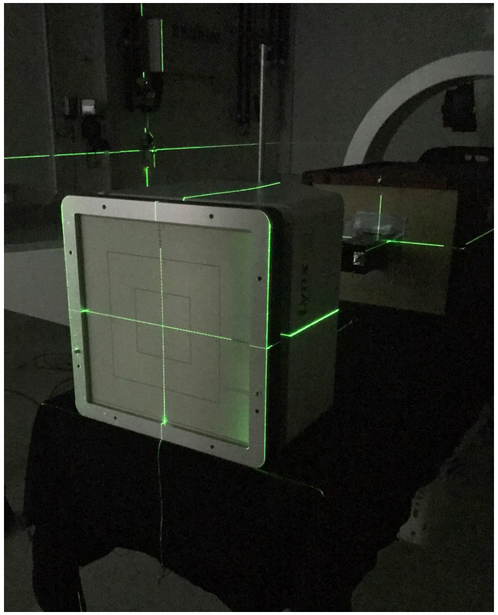
| Date | HV Supply | DAQ | σ/E (%) |
|---|---|---|---|
| 27/07/16 | Portable | UCL | 3.16 ± 0.03 |
| 28/07/16 | UCL | UCL | 3.14 ± 0.03 |
| Clatterbridge Test Beam: 02-03/08/16 | | | |
| 04/08/16 | UCL | UCL | 3.08 ± 0.03 |

- No noticeable difference in resulting energy resolution so far.

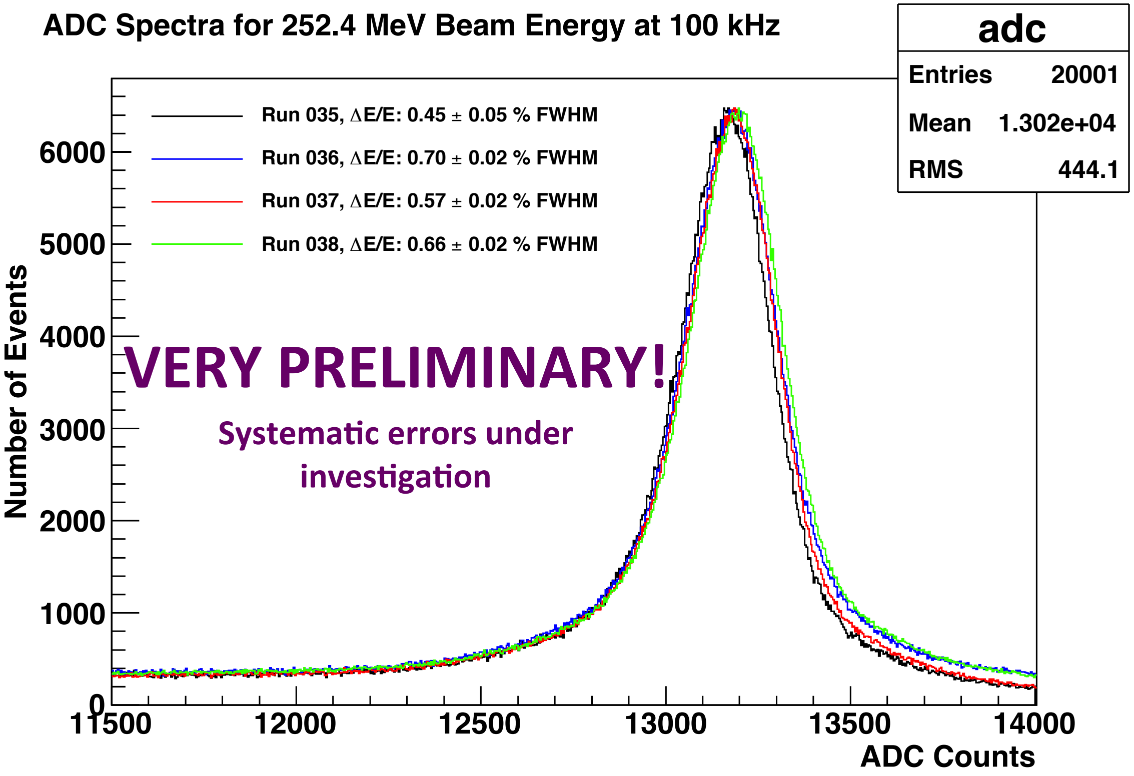
# Step 6: 250 MeV Beam at medAustron

- First external collaborators to use research room at the medAustron proton beam therapy centre in Austria!
- Two nights of tests:
  - Scintillator length increased to 45 cm to contain 250 MeV beam
  - 62 – 252 MeV beam
  - Rate adjusted down with chopper magnet
    - 1 kHz–1 MHz
  - Custom collimators to reduce intensity and beam size





# Step 6: 250 MeV Beam at medAustron



ADC Spectra for 252.4 MeV Beam Energy at 100 kHz

**VERY PRELIMINARY!**

Systematic errors under investigation

- Still seeing excellent energy resolution up to 252 MeV!
- Best resolution 0.2% σ
- But also still seeing rate issues:
  - PMT current limit from too much light!
  - Detector not fast enough for $10^{10}$ p/s clinical rate

- In close collaboration with Hamamatsu to develop a new kind of light detector:
  - High QE (photocathode) of PMT
  - Lower gain of $10^3$
  - Low noise
  - Currently experimenting with bases

# Summary for Single Module Measurements

- An optical module inspired by the SuperNEMO experiment has measured the 60 MeV proton beam at Clatterbridge with an energy resolution of:

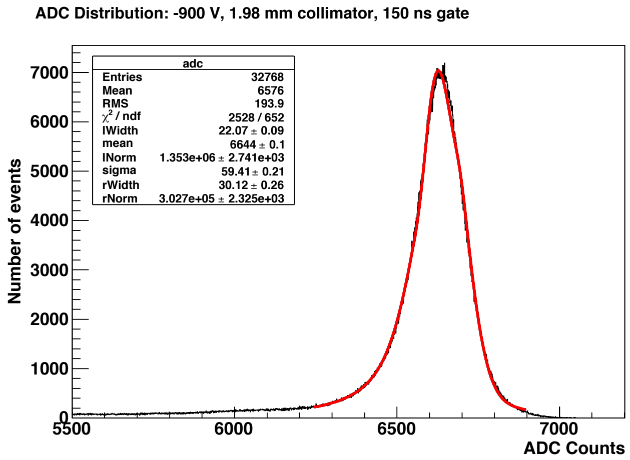
0.97 ± 0.11 % σ

(for 40 MeV "visible" energy)

↓

This has reached the target energy resolution of

< 1 % σ

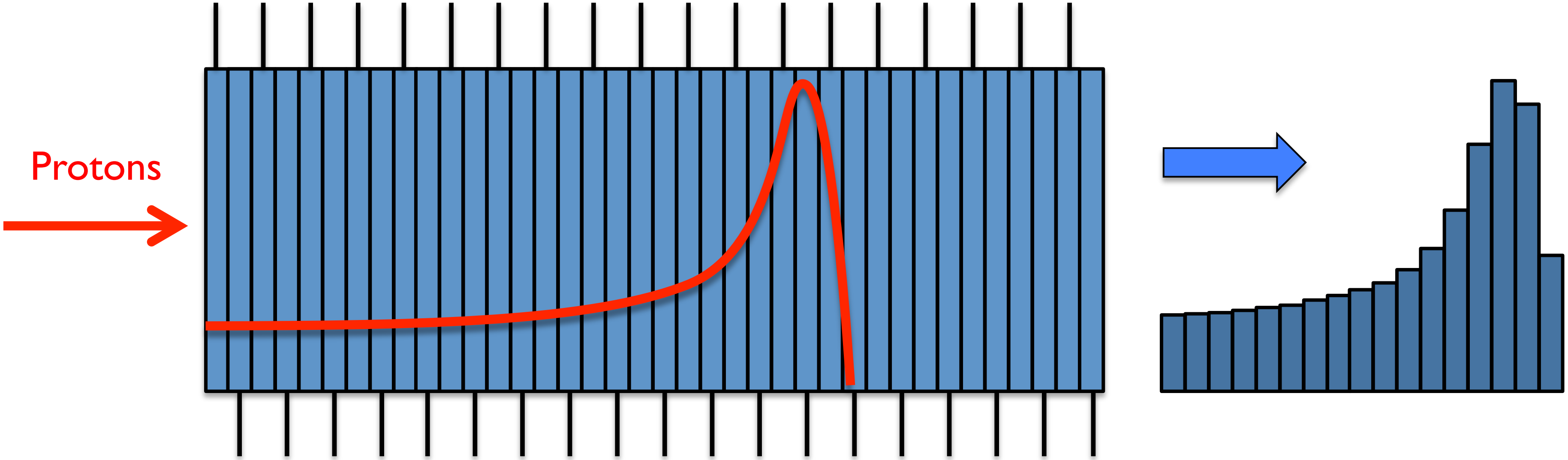


- And a 250 MeV proton beam at medAustron with an energy resolution of 0.2 % σ
- A great result for protonCT
- But this single module isn't fast enough to handle clinical proton rates and therefore is not currently suitable for QA range verification
- Ongoing work to improve timing in collaboration with Hamamatsu
- Goal to reach 10 MHz

⟶ Design a segmented calorimeter to be used as a range telescope!

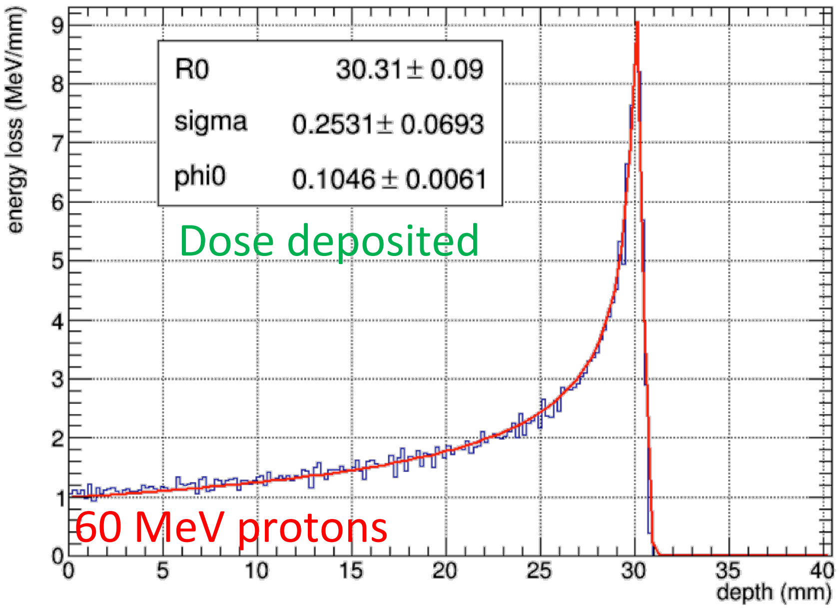
# Segmented Calorimeter: Range Telescope

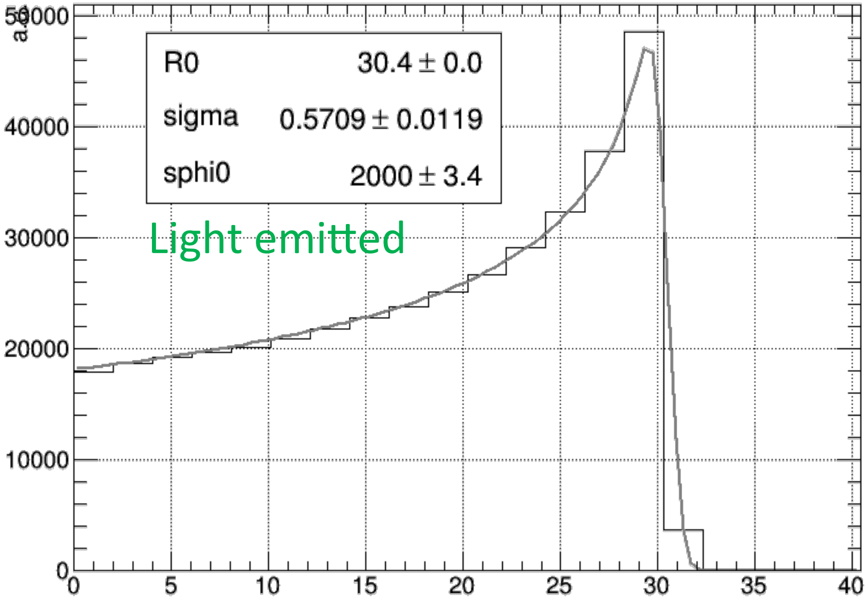
- Clinical facilities operate at much higher rates of ~ $10^9 - 10^{10}$ protons/sec
- We need to reach these rates for a feasible QA system
- R&D for a new multi-layer scintillator design to verify the range directly:
  - Segment block into slices and read out light from entire spill (not single proton) from each slice individually
  - Map out the Bragg Peak
  - No need for energy-range conversion, measure range directly
  - Our plastic scintillator is water equivalent!
  - Minimum slice width will depend on manufacture: aiming for < 3 mm
  - Use simple, stable light detection: photodiodes/pixel sensors



# Segmented Calorimeter: Range Telescope

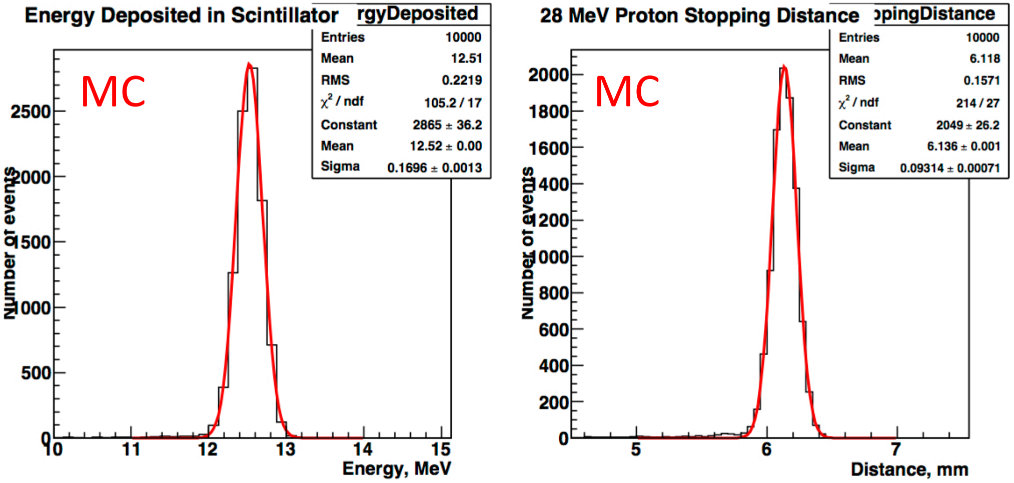
- Current R&D:
  - Collaboration with NUVIA in Czech Republic to manufacture 2 − 3 mm scintillator sheets. Challenging due to uniformity!
  - Testing and researching best detector to couple scintillator sheets to
  - Simulations to characterise light quenching to reconstruct Bragg curve carried out by Laurent
    - Quenching included in Bortfeld formula
    - Fit to light output



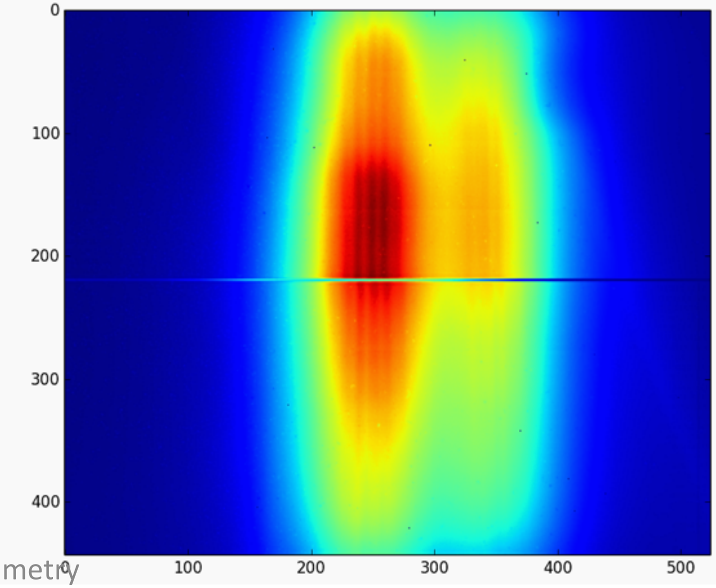


# Segmented Calorimeter: First Tests

- Fist tests carried out using the Birmingham cyclotron:
  - 28 MeV proton beam, range of protons ~ 6 mm
  - Clinical rates



  - 2 sheets of 3 mm and 4 mm NUVIA scintillator used to
  - PRaVDA Priapus MAPS pixel sensor (10 cm x 5 cm)



protons

# Current Work & Future Plans

- Construct 60 MeV prototype using:
  - 20 x 3 mm and 30 x 2 mm scintillator sheets obtained from NUVIA

  - Tests ongoing to determine the best method to isolate sheets from each other and reduce light output (we have too much light!)
  - Clinical beamline tests lined up for the near future:
    - Birmingham, Clatterbridge and medAustron
  - Look at overall performance, radiation hardness and quenching at high rates

# Acknowledgements

- UCL participation in this work:

Simon Jolly, Ruben Saakyan, Derek Attree,
Anastasia Basharina-Freshville, Laurent Kelleter, Matthieu Hentz

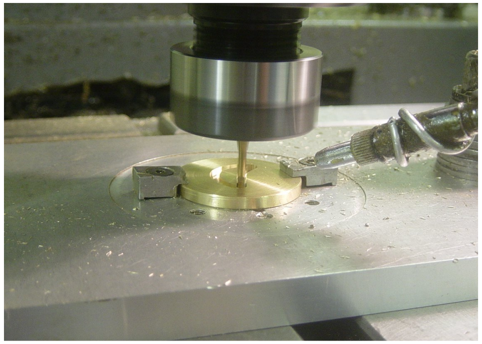
- A HUGE thank you to Andrzej Kacperek and the fantastic team at Clatterbridge, the medAustron team and the Birmingham team for all of their expertise and help!

# Back Up Slides

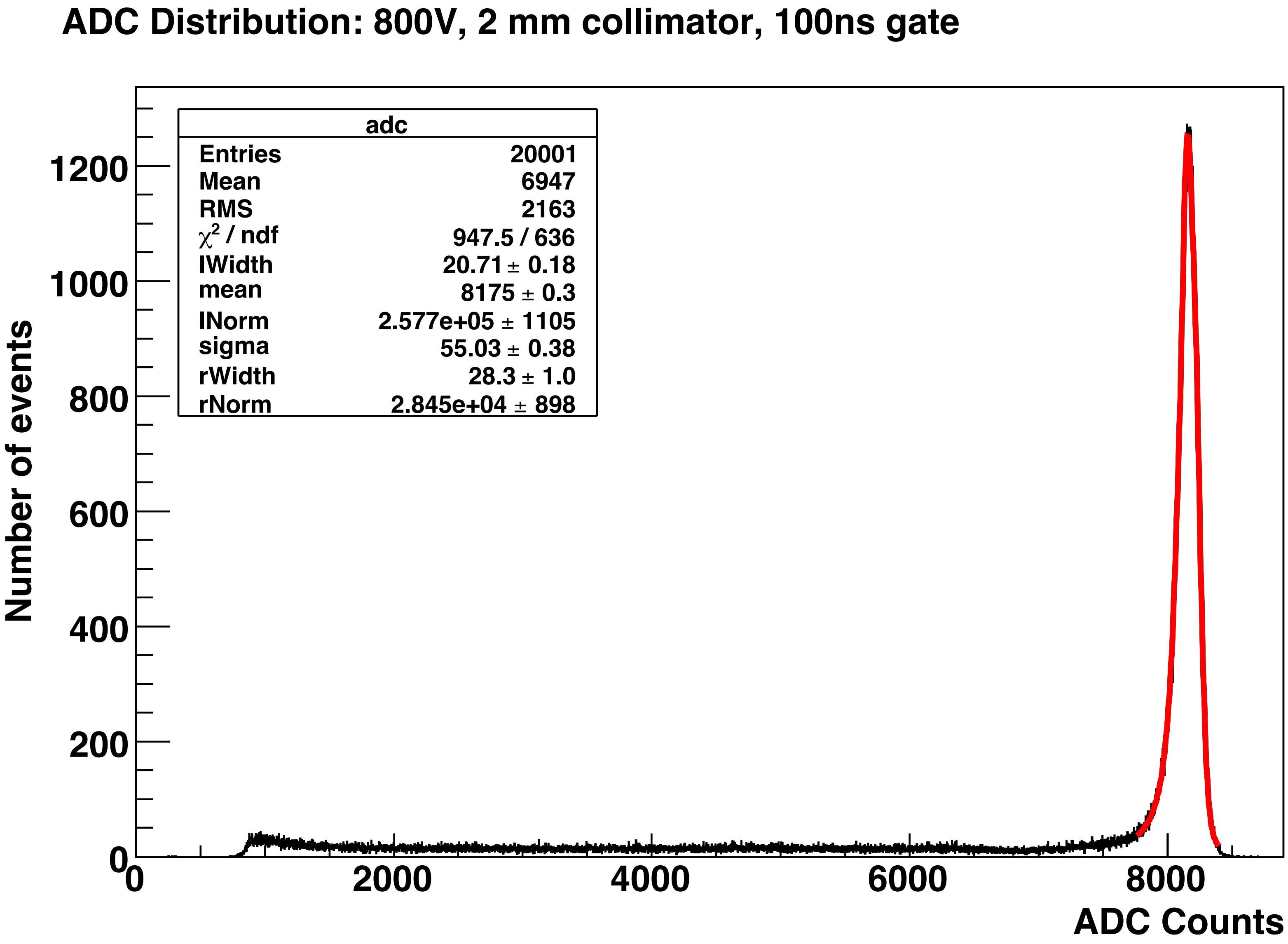
# First Test Beam Details

- The proton rate from the beam was carefully controlled by:
  - Inserting brass collimators with varying diameters (0.5 mm – 10 mm) into the beam nozzle (~30 cm upstream of the optical module)
  - Adjustment of the ion source gas supply
  - Adjustment of the discharge current
  - Adjustment of the cyclotron RF phase

- Over the four days of test beam the dependence of measurements on the following parameters was studied:
  - Collimator diameter size (0.5 mm – 10 mm)
  - Beam settings
  - Operating voltage of the PMT (800 V, 900 V)
    - Increasing HV increases collection efficiency of the PMT and therefore achieves a better energy resolution
    - Note: standard operating HV for this PMT is 1500V, but due to such high light levels ( 100,000 photons → 30,000 photo-electrons) reduce HV
  - Integrating window of acquisition on the CAEN digitiser (50 ns, 100 ns, 200 ns): sensitive to pile up effects



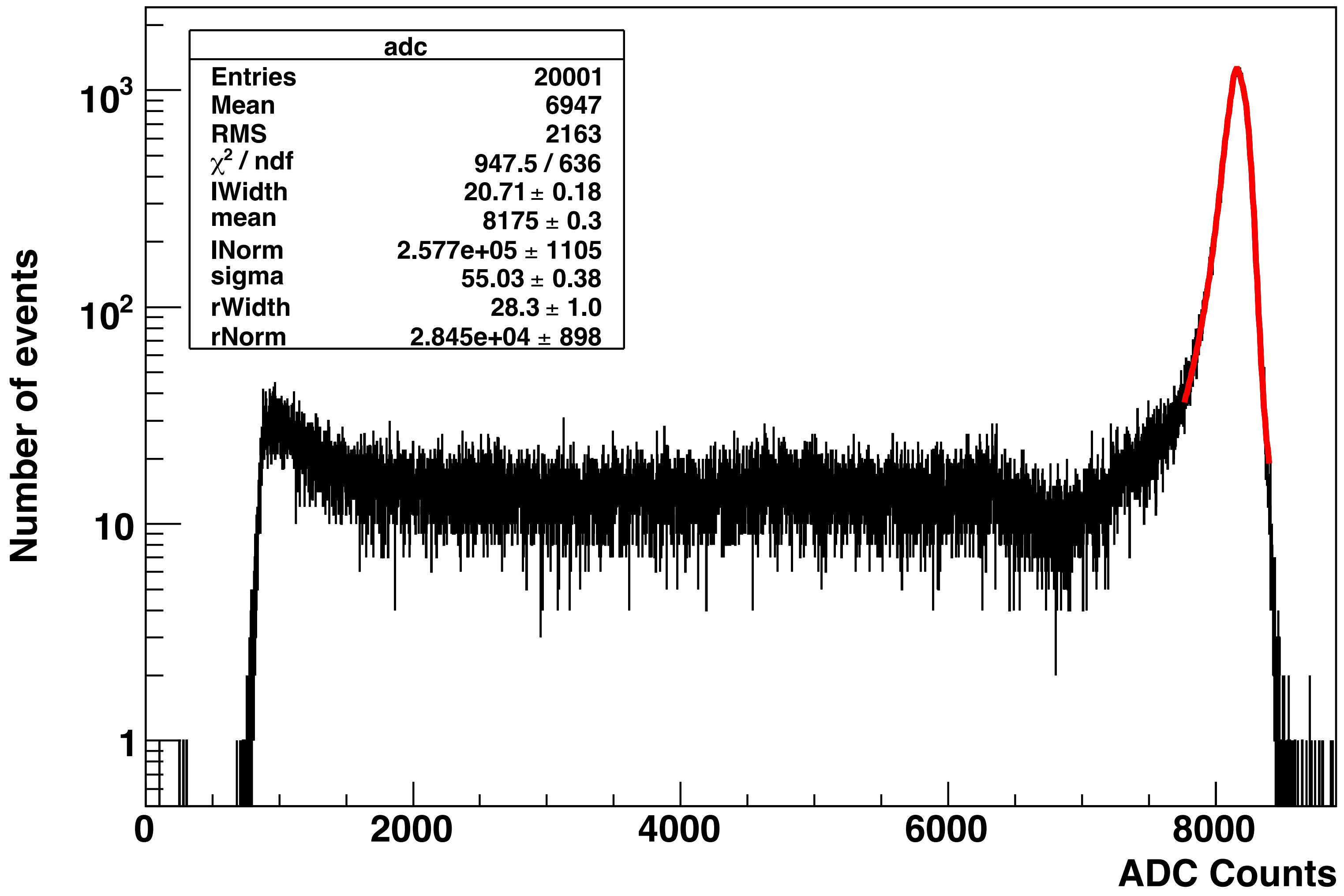
# 8” PMT + Hexagonal Scintilator: 0.67 ± 0.11 % σ



ADC Distribution: 800V, 2 mm collimator, 100ns gate

| adc | |
|---|---|
| Entries | 20001 |
| Mean | 6947 |
| RMS | 2163 |
| $\chi^2$ / ndf | 947.5 / 636 |
| lWidth | 20.71 ± 0.18 |
| mean | 8175 ± 0.3 |
| lNorm | 2.577e+05 ± 1105 |
| sigma | 55.03 ± 0.38 |
| rWidth | 28.3 ± 1.0 |
| rNorm | 2.845e+04 ± 898 |

# 8” PMT + Hexagonal Scintilator: 0.67 ± 0.11 % σ



ADC Distribution: 800V, 2 mm collimator, 100ns gate

| adc | |
|---|---|
| Entries | 20001 |
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| lWidth | 20.71 ± 0.18 |
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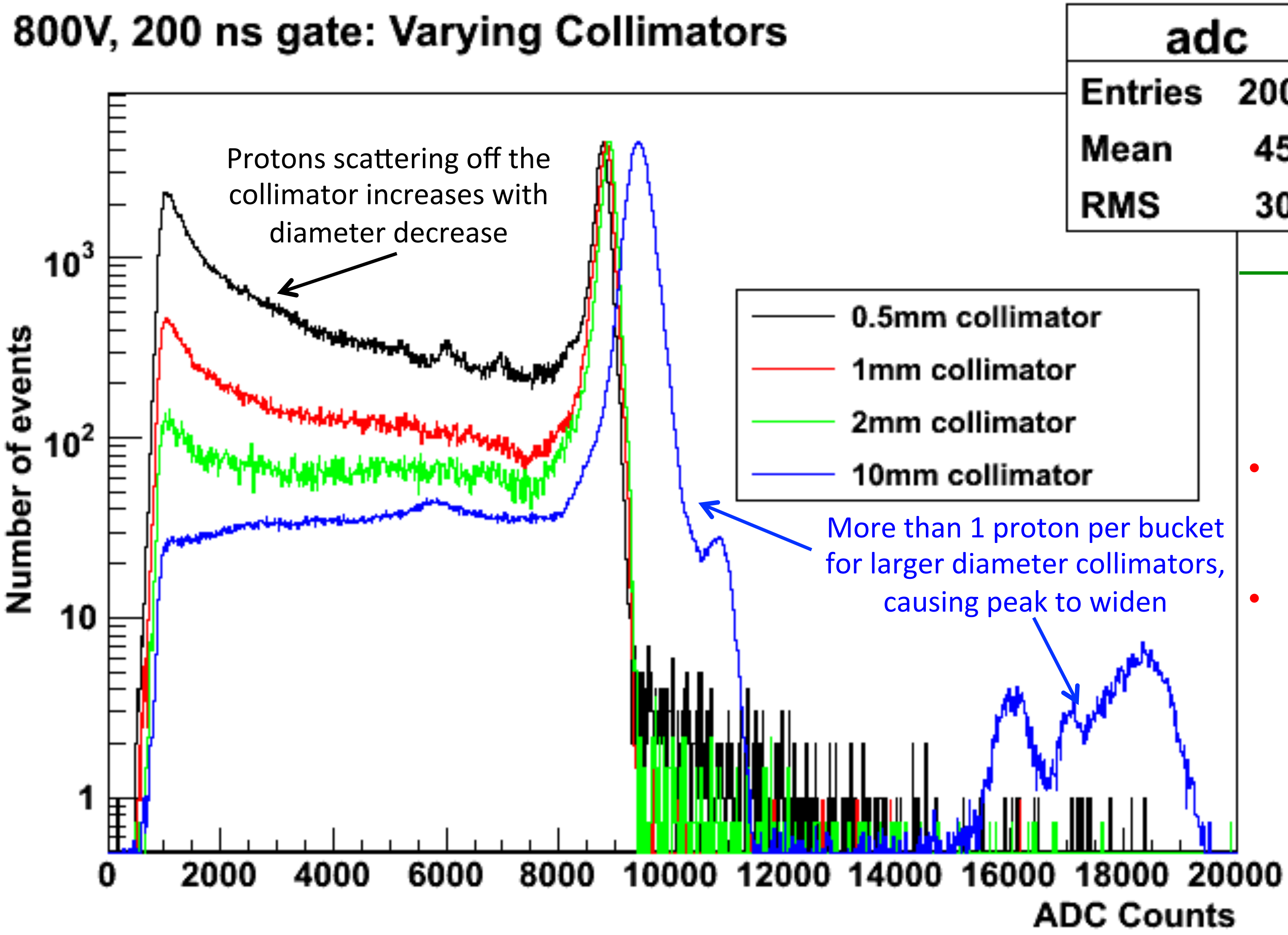
| lNorm | 2.577e+05 ± 1105 |
| sigma | 55.03 ± 0.38 |
| rWidth | 28.3 ± 1.0 |
| rNorm | 2.845e+04 ± 898 |

# Pile Up: Varying Collimators



800V, 200 ns gate: Varying Collimators

Protons scattering off the collimator increases with diameter decrease

More than 1 proton per bucket for larger diameter collimators, causing peak to widen

To avoid pile up:

- Optimal collimator: 2mm diameter
- Keep integrating window small to only collect 1st proton pulse

# Considering Measuring Parameters

| PMT HV (V) | Acquisition window (ns) | Collimator diameter (mm) | Energy resolution, % FWHM |
|---|---|---|---|
| 800 | 50 | 2 | 1.6 ± 0.18 |
| 800 | 100 | 2 | 1.58 ± 0.27 |
| 800 | 200 | 2 | 2.11 ± 0.42 |
| 900 | 50 | 2 | 1.1 ± 0.13 |
| 900 | 100 | 2 | 0.97 ± 0.16 |
| 900 | 200 | 2 | 1.27 ± 0.19 |
| 800 | 200 | 3 | 2.32 ± 0.43 |
| 800 | 200 | 4 | 2.16 ± 0.41 |

Reducing the acquisition gate from 200ns to 100ns shows considerable improvement (ensures we only look at 1 proton).
But we don't win anything with a 50ns gate.

At 900 V:
Improved energy resolution but are we linear at 900 V?
(See later)

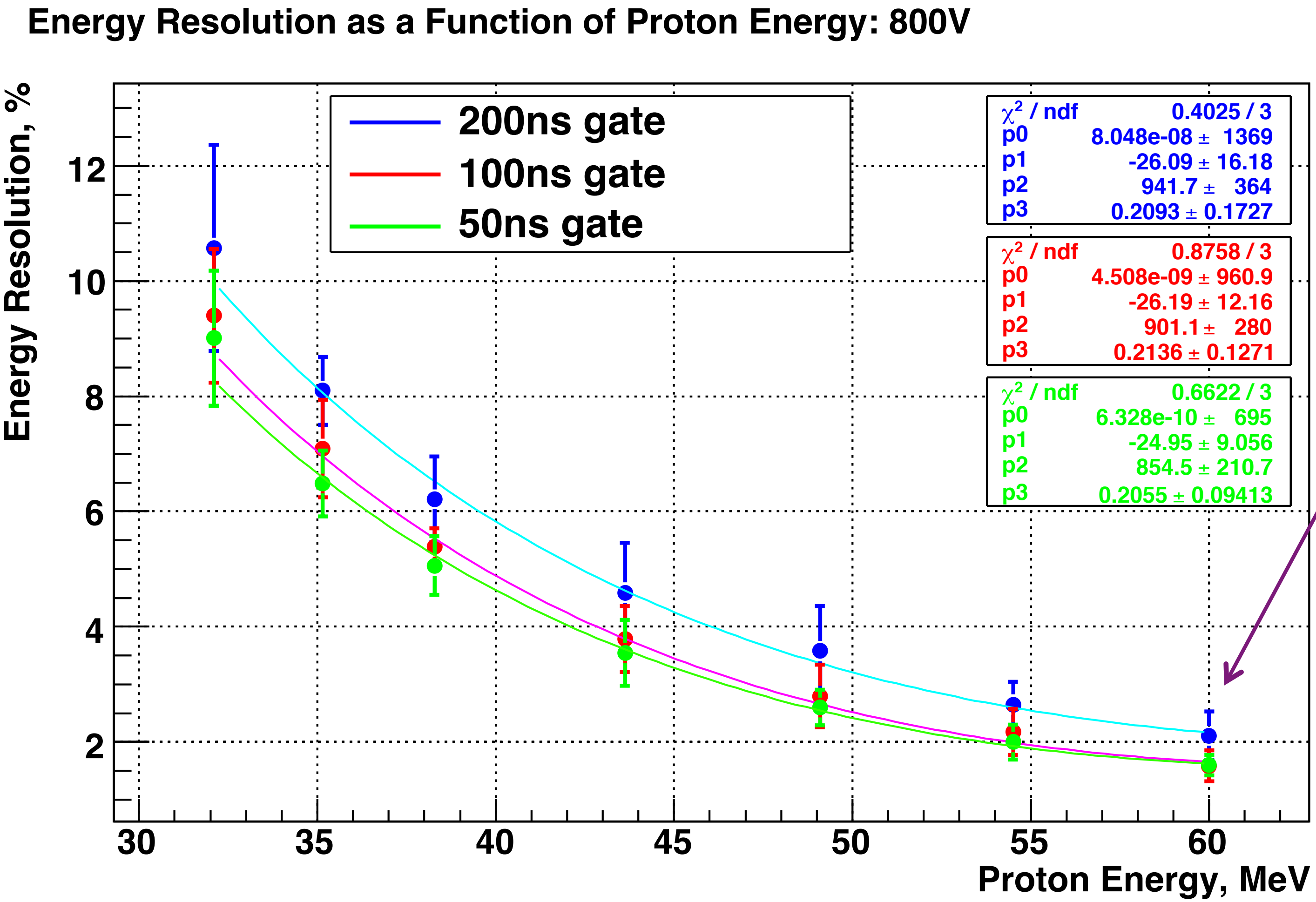
Further confirmation that 2mm diameter collimator is optimal for reducing intensity

Our optimal parameters for measurements are:

PMT HV: 800 V
Acquisition window: 100 ns
Collimator diameter: 2 mm

# Energy Dependence on Resolution

- Energy of protons incident on scintillator varied by placing absorbers (PMMA plates) of known thickness ~1.8 m upstream of the optical module



$$y = p0 + \frac{p1}{\sqrt{x}} + \frac{p2}{x} + p3 \cdot x$$

$\sqrt{E}$ dependence!

# Intrinsic Energy Resolution of Optical Module

- How much of the measured energy resolution is due to the proton beam and how much is due to the "intrinsic" energy resolution of the detector?

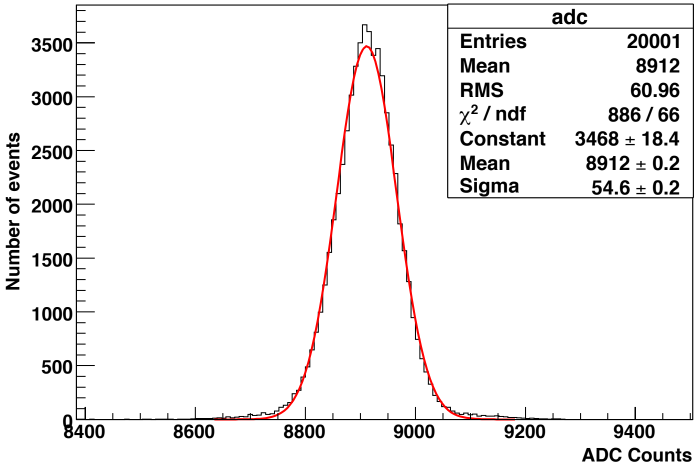
- From MC (1.48%) we already know that most of the energy resolution measured with the proton beam (1.58 ± 0.27) is from the intrinsic resolution of detector:
  - Use MC and data to put a limit on the energy spread of the 60 MeV Clatterbridge beam:

Proton energy spread: 0.65 ± 0.66 % FWHM

or limit on spread: **FWHM (60 MeV): <1.56% at 90% CL**

- Also tests carried out at UCL:
  - Pulse PMT with a 400nm LED at an amplitude and width that will give a peak at the same ADC counts as the proton beam spectra
  - Fit the acquired spectra with a Gaussian and extract energy resolution

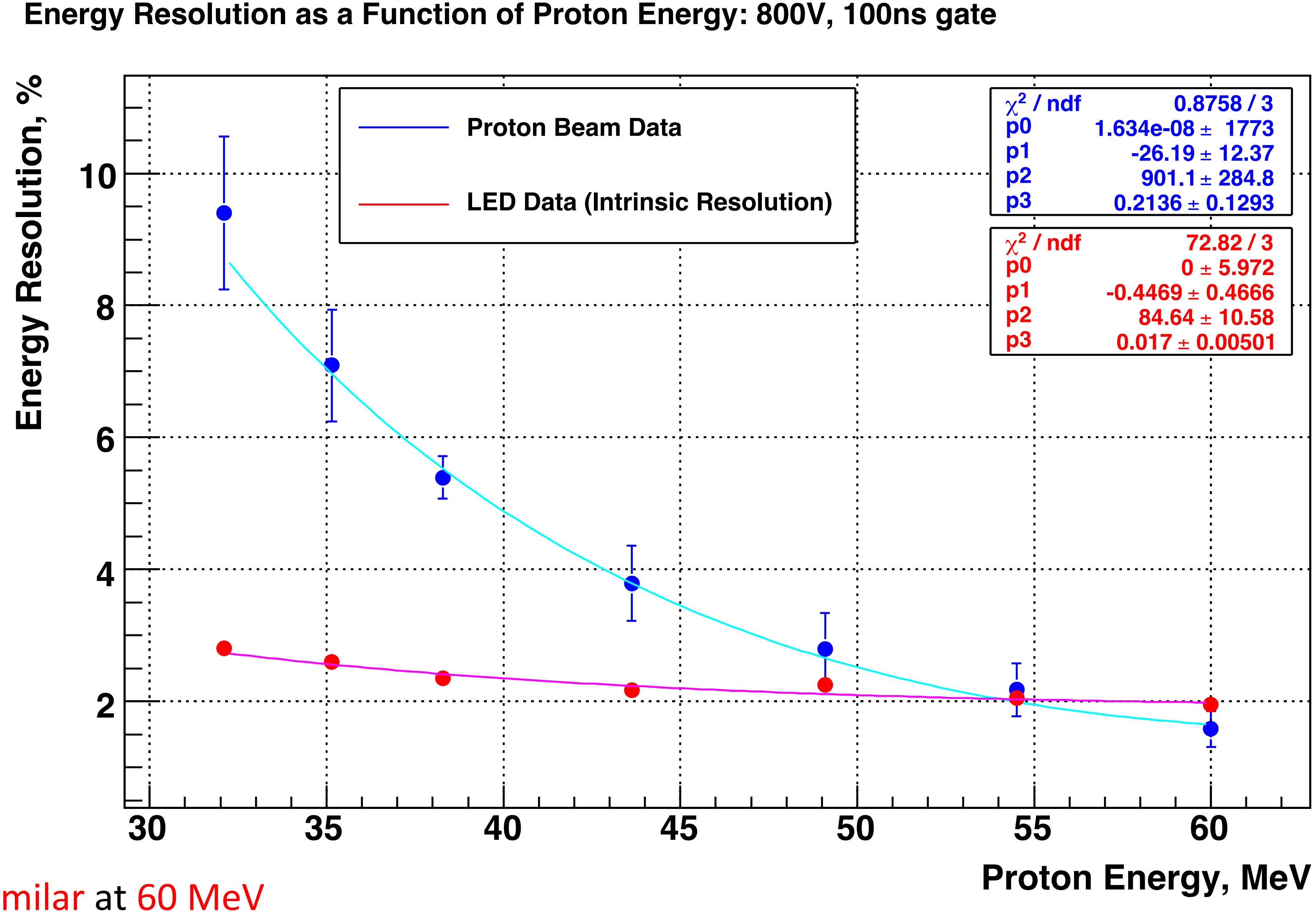
LED Pulsed Distribution for 800V, 200 ns and 60 MeV Proton Beam



BUT: LED is operating at very "high" parameters (~8V and 40ns width), therefore the width is very sensitive to noise and the LED distribution would be better monitored with a device such as a pin diode

→ future measurement!

# Intrinsic Energy Resolution of Optical Module



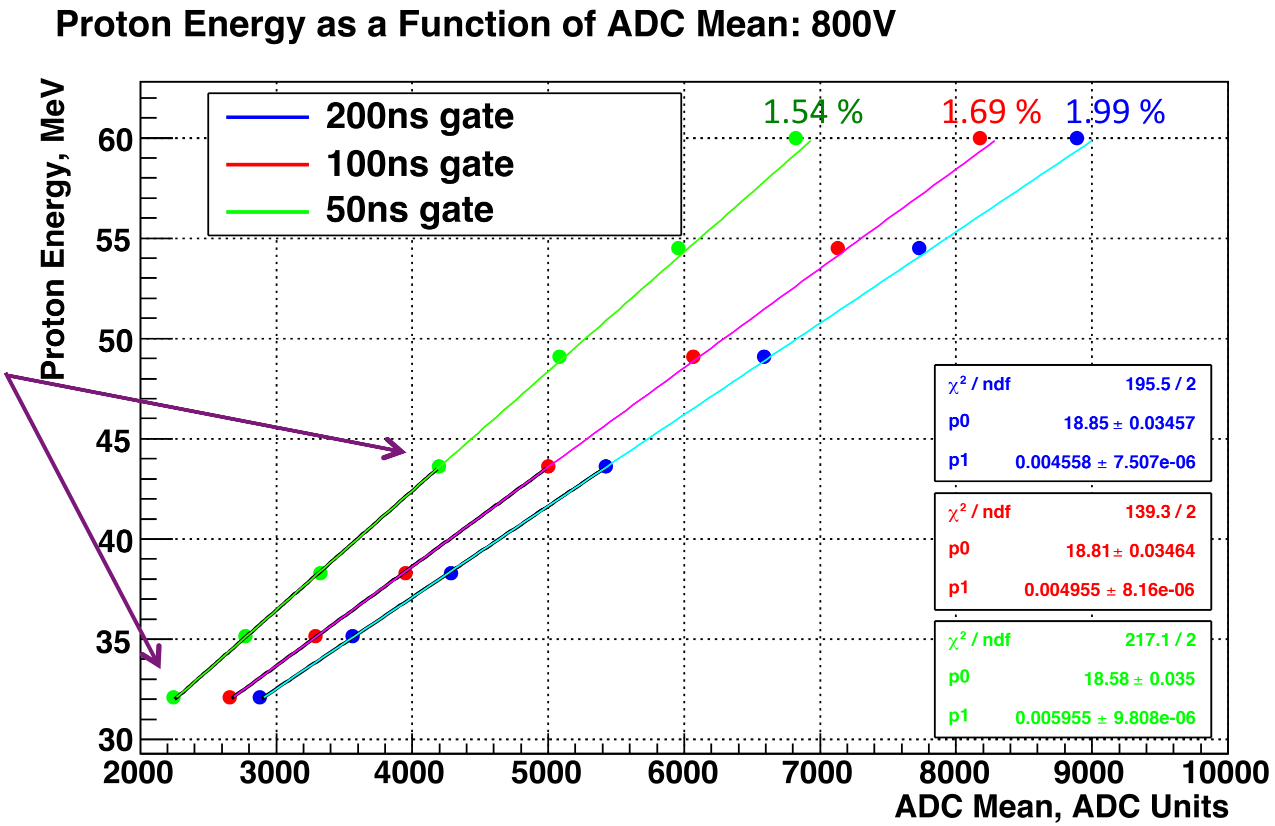
- Similar at 60 MeV
- Proton beam energy resolution much worse than intrinsic energy resolution at lower energies due to scattering of protons

# Linearity: 800 V

- We want to run the PMT at higher voltages (can run at up to 1500V) as this will increase the PMT's collection efficiency and will improve the energy resolution: 0.97 ± 0.16 % FWHM from measurements (900V, 100 ns gate)

- BUT we have a LOT of light (tens of thousands of photo-electrons): can we trust this result?
  - Look at linearity

$$y = p0 + (p1 \cdot x)$$

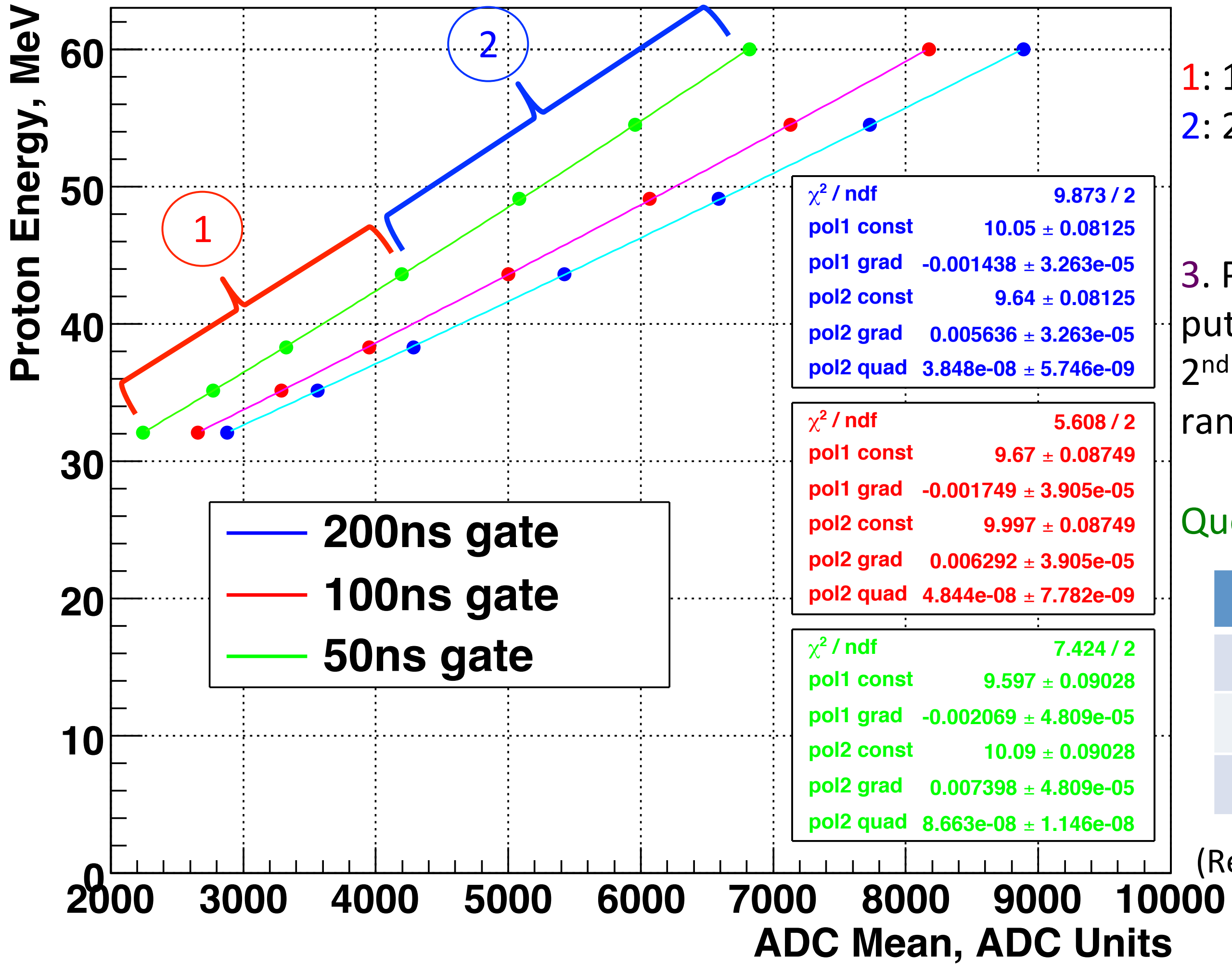


For 800V:
Deviation from
linearity < 2%!

# Measuring Quenching

- Fitting linearity curves gives us a measurement of scintillator quenching:

**Proton Energy as a Function of ADC Mean: 800V**



| $\chi^2$ / ndf | 9.873 / 2 |
|---|---|
| pol1 const | 10.05 ± 0.08125 |
| pol1 grad | -0.001438 ± 3.263e-05 |
| pol2 const | 9.64 ± 0.08125 |
| pol2 grad | 0.005636 ± 3.263e-05 |
| pol2 quad | 3.848e-08 ± 5.746e-09 |

| $\chi^2$ / ndf | 5.608 / 2 |
|---|---|
| pol1 const | 9.67 ± 0.08749 |
| pol1 grad | -0.001749 ± 3.905e-05 |
| pol2 const | 9.997 ± 0.08749 |
| pol2 grad | 0.006292 ± 3.905e-05 |
| pol2 quad | 4.844e-08 ± 7.782e-09 |

| $\chi^2$ / ndf | 7.424 / 2 |
|---|---|
| pol1 const | 9.597 ± 0.09028 |
| pol1 grad | -0.002069 ± 4.809e-05 |
| pol2 const | 10.09 ± 0.09028 |
| pol2 grad | 0.007398 ± 4.809e-05 |
| pol2 quad | 8.663e-08 ± 1.146e-08 |

Fitting procedure:

1: 1st degree polynomial (32-44 MeV)
2: 2nd degree polynomial (44-60 MeV)

↓

3. Parameters extracted from 1 and 2 put into "combined" 1st degree and 2nd degree polynomial over entire range

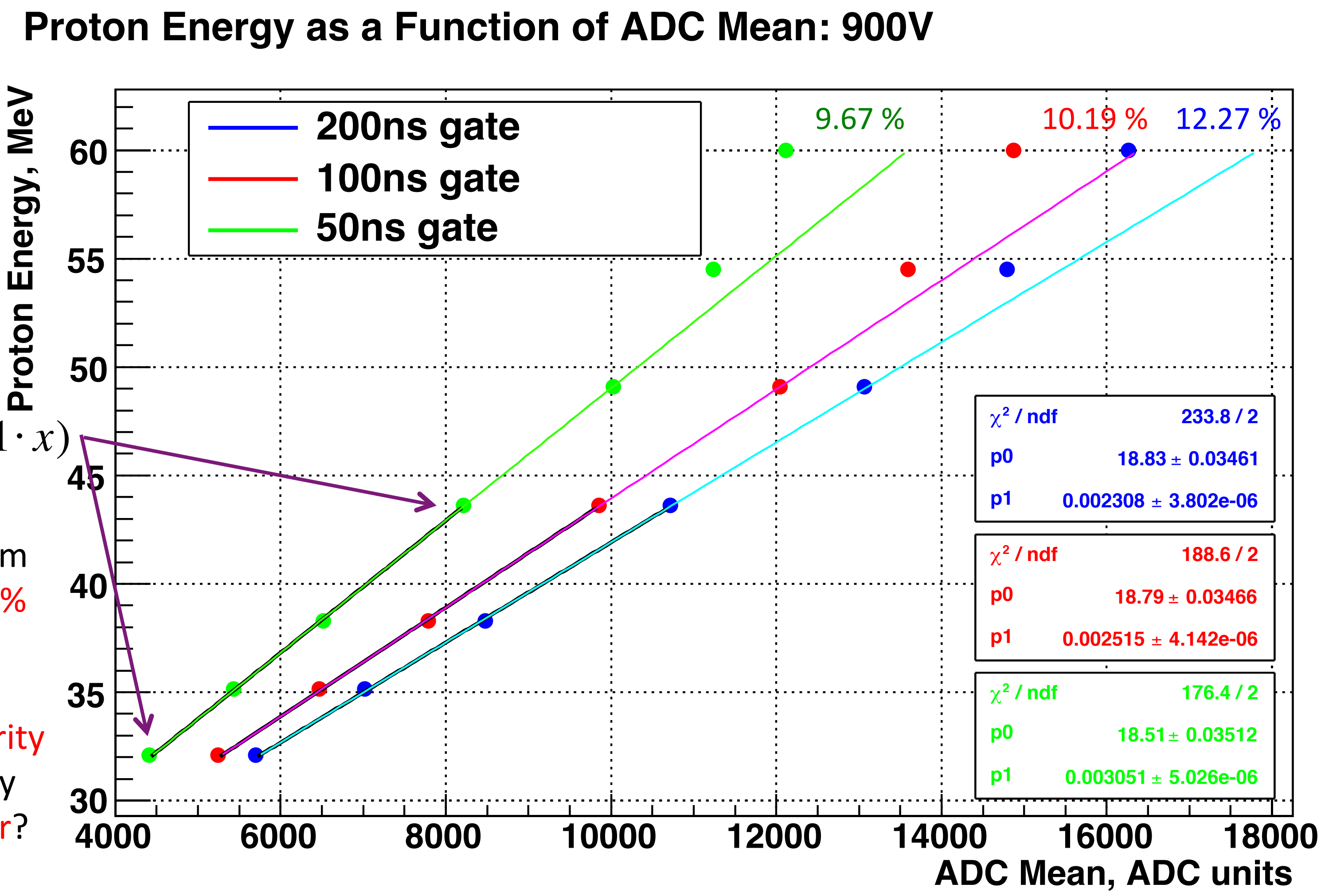
↓

Quenching = pol1 const + pol2 const

| Gate (ns) | Quenching (MeV) |
|---|---|
| 50 | 19.69 ± 0.12 |
| 100 | 19.67 ± 0.12 |
| 200 | 19.69 ± 0.13 |

(Remember: 20.57 MeV from simulations)

# Linearity: 900 V



$$y = p0 + (p1 \cdot x)$$

For 900V:
Deviation from
linearity > 10%

↓

Can non-linearity
be accurately
accounted for?

# “Unfolding”: Getting a Grip on Non-Linearity

- For our 900 V data we see non-linearity > 10 %
- BUT can we take into account non-linearity of our equipment to “unfold” the true energy resolution?
- We want to be able to do this:
  - To potentially increase HV even further (to 1000 V or above) to increase collection efficiency and hence improve the energy resolution
  - For proton imaging: requires protons > 300 MeV, which will give a huge amount of light and non-linearity will be inevitable
- Work currently on-going to determine the best way to:
  - Convert the data from ADC counts to MeV (“visible energy” due to quenching)
  - Fit the visible energy data to extract the “unfolded” energy resolution (with non-linearity taken out)
  - Compare results for 800 V and 900 V