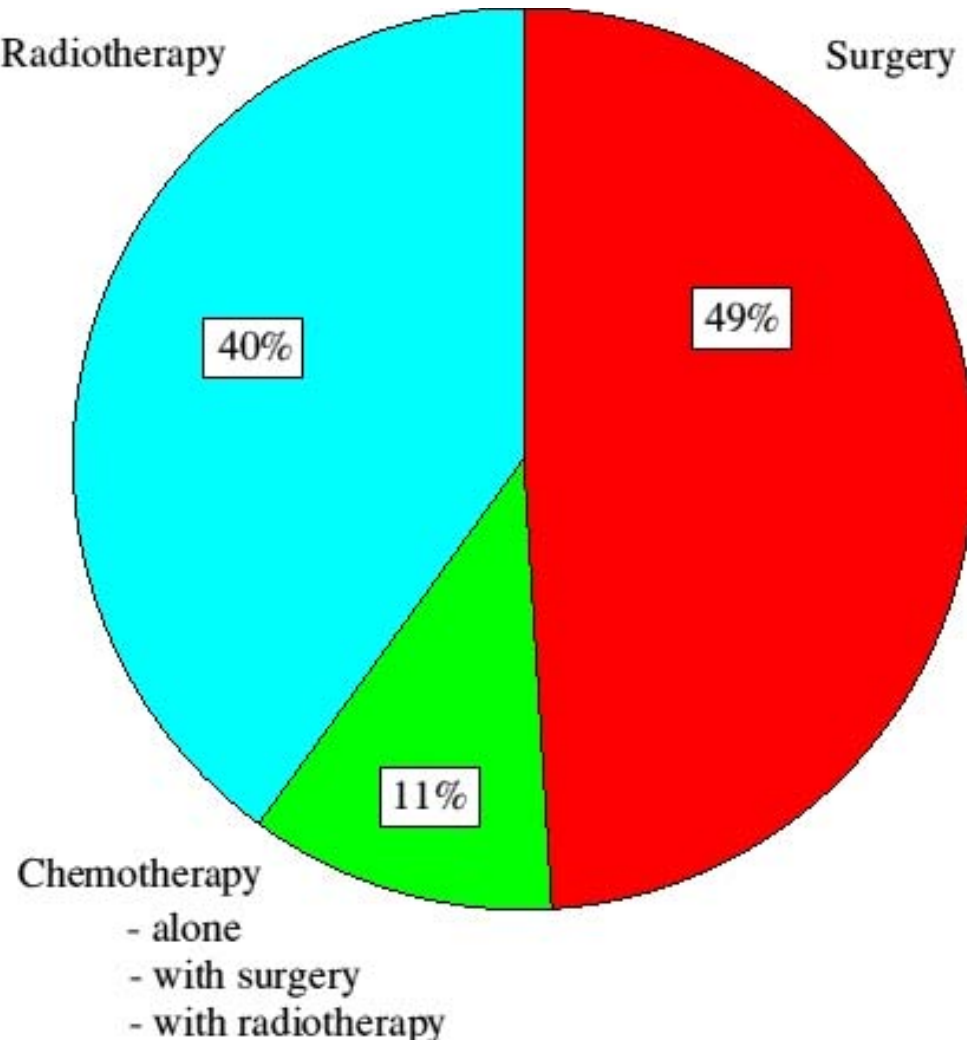# From SuperNEMO to Proton Therapy: Adapting SuperNEMO Calorimeter Technology for Proton Therapy QA

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
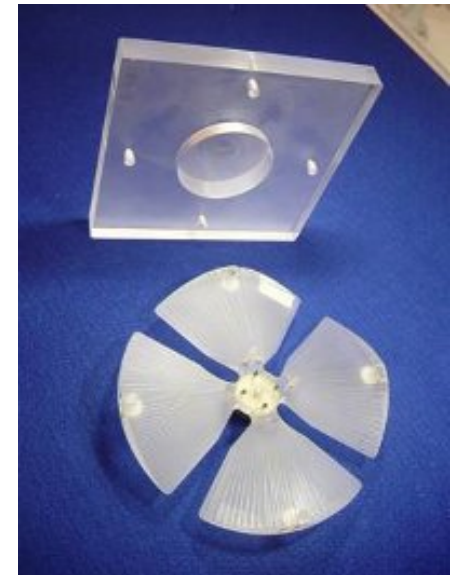 - Central nervous system
  - In children

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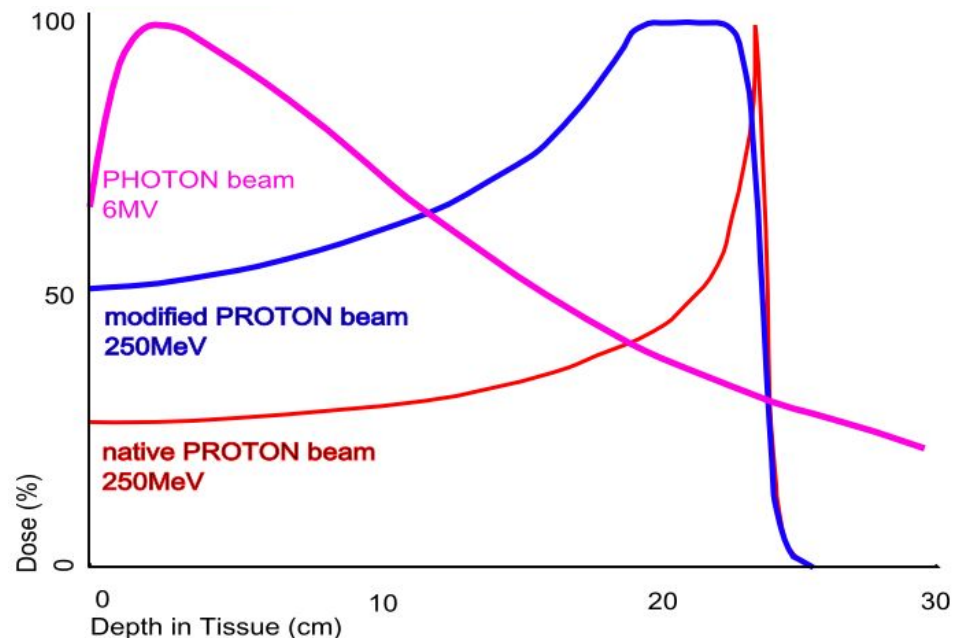
Why Proton Therapy?
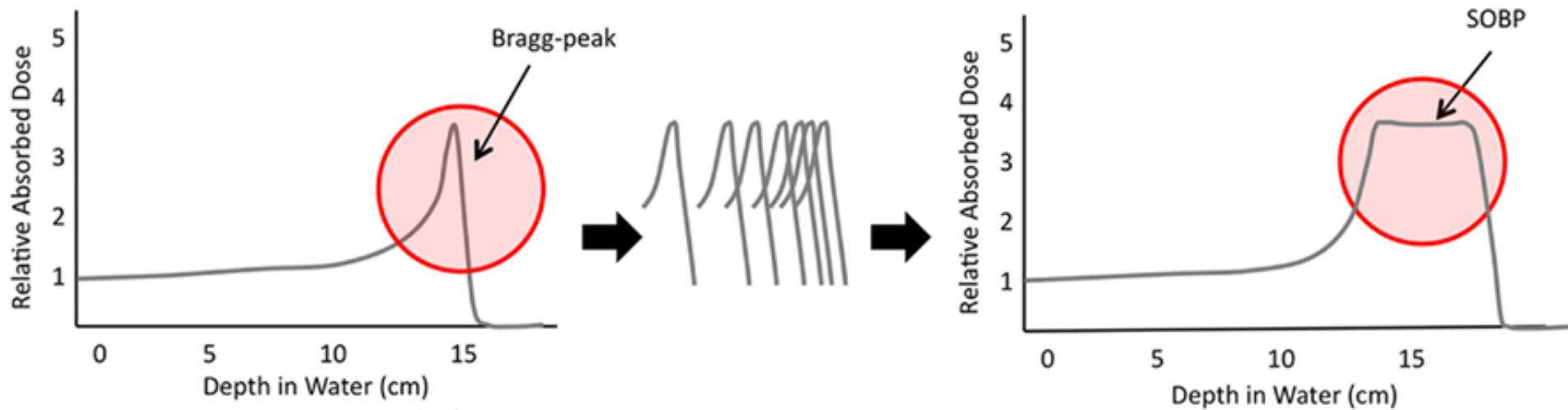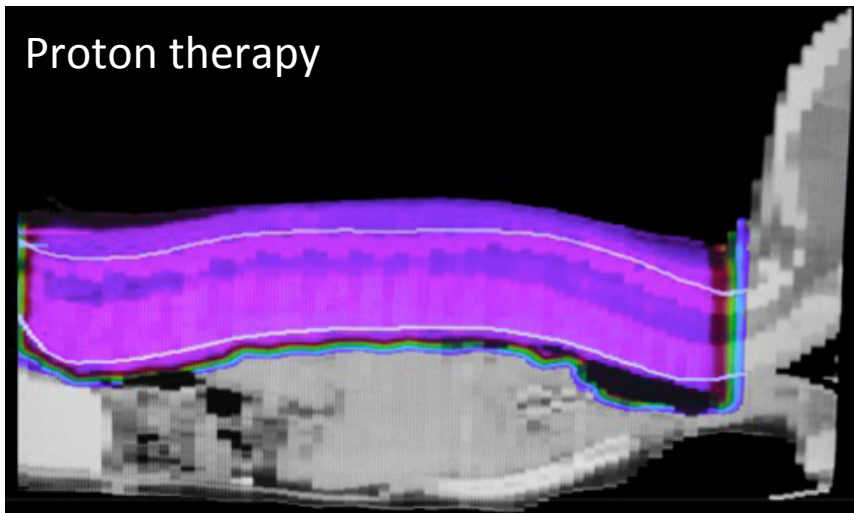

Front. Oncol., 06 September 2011 | doi: 10.3389/fonc.2011.00024

- 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
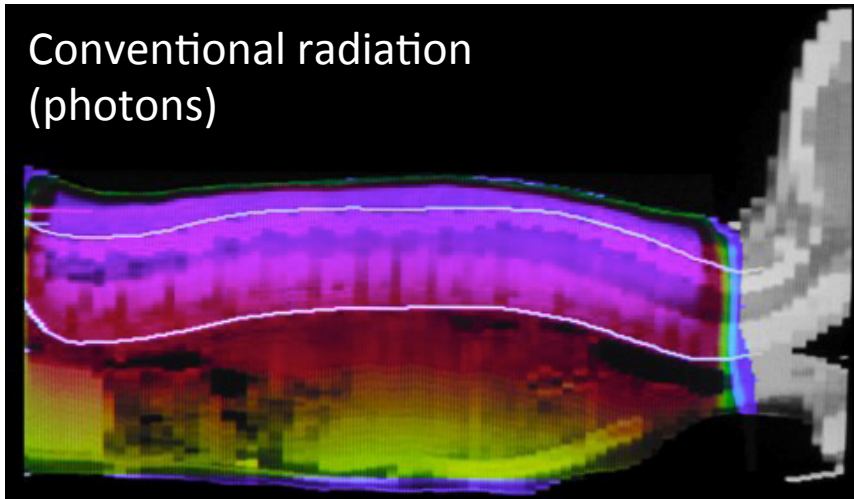
Photons vs Protons: Medulloblastoma

Proton Therapy Challenges (1)

- Quality Assurance (QA):

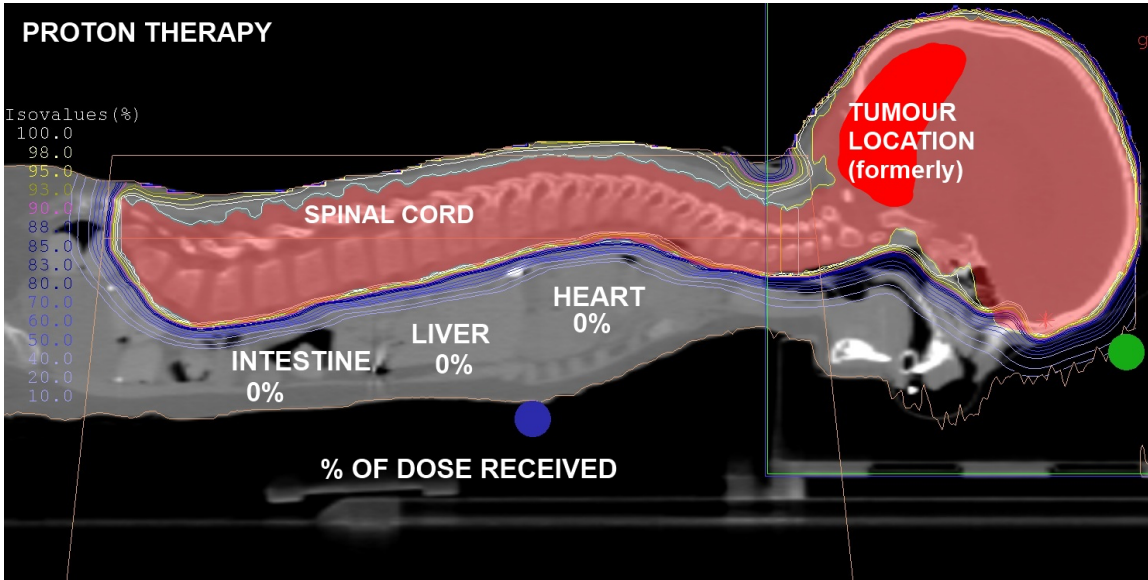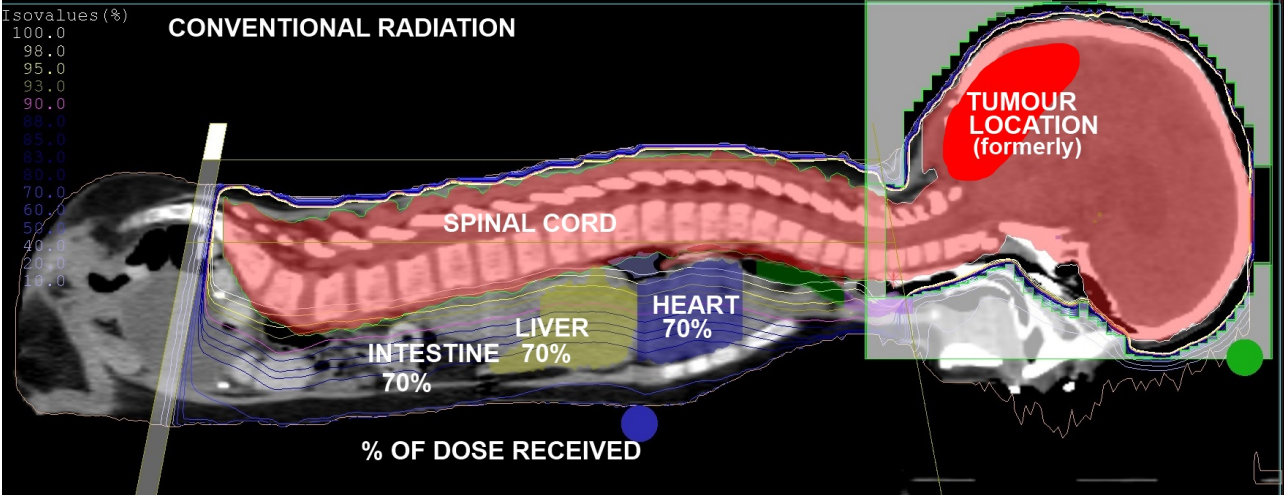 - A number of QA checks are necessary for safe PT treatment:
    - Daily, weekly and monthly

  - 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

10% range error
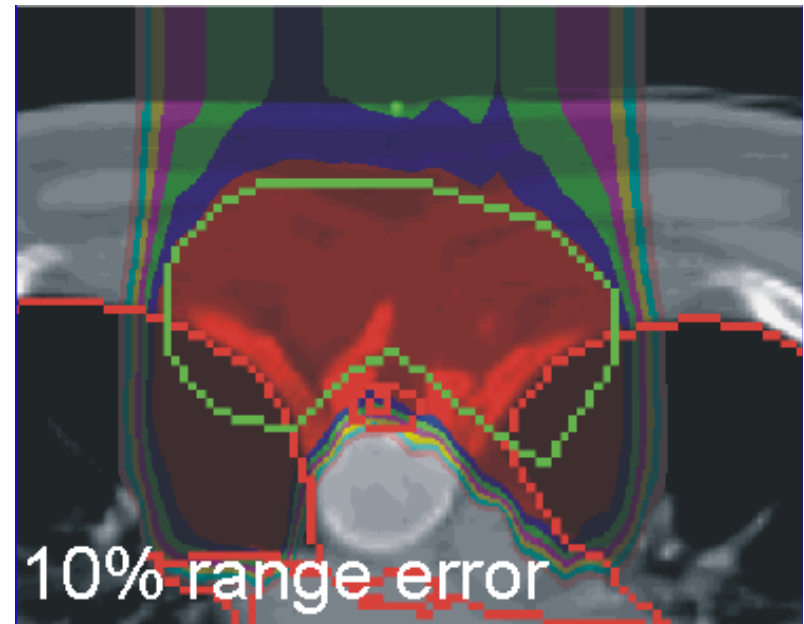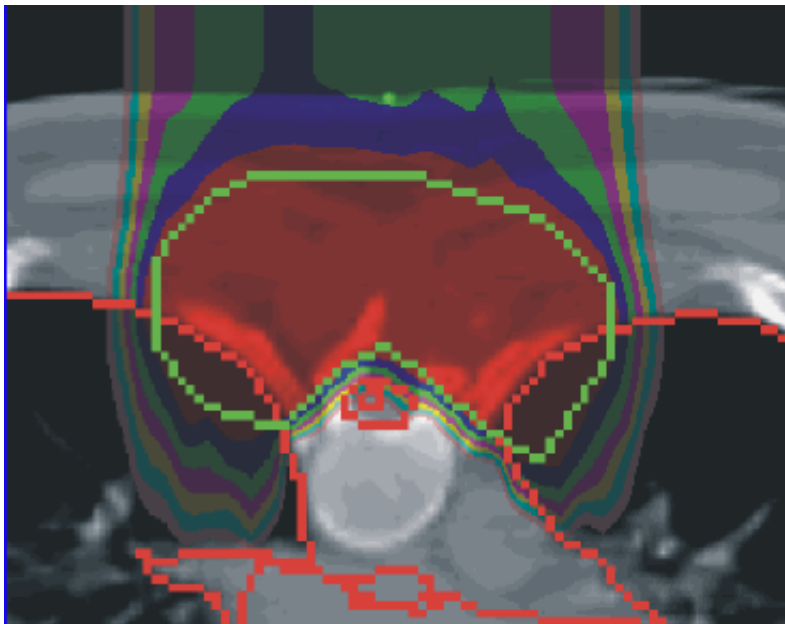
Proposed Solutions

- 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.
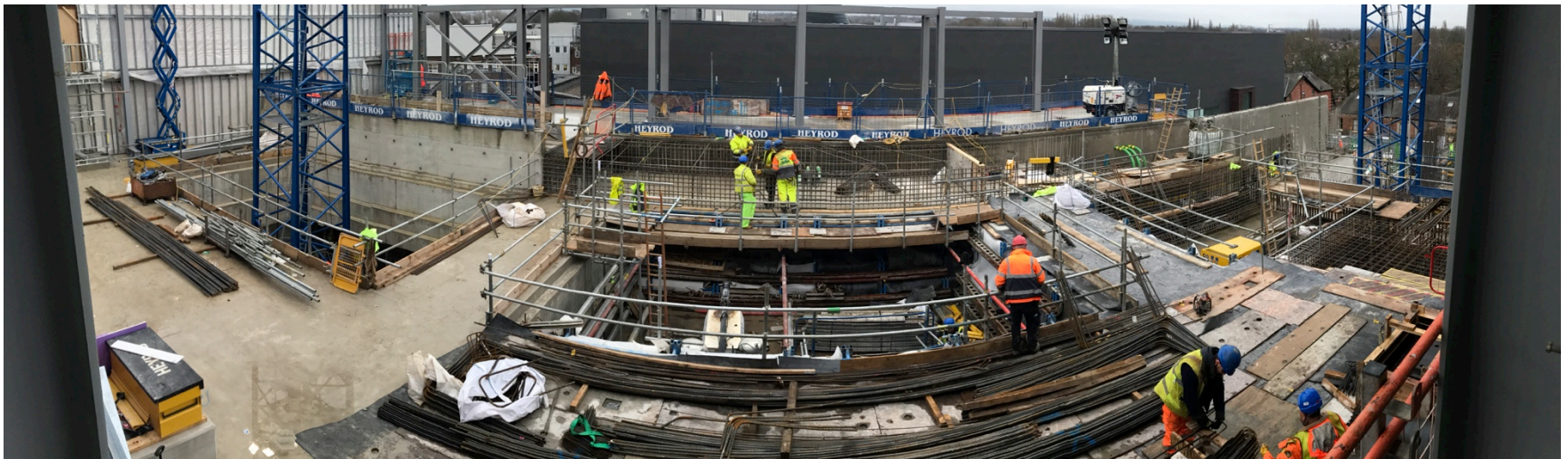
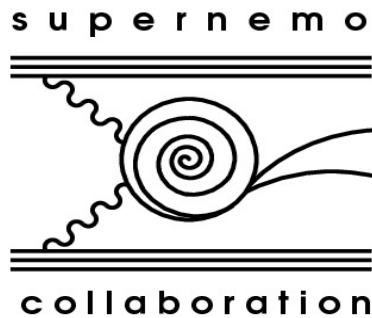# UCLH Proton Therapy Centre

- 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

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

- Modular detector with a planar geometry

1 module (of 20) consists of:
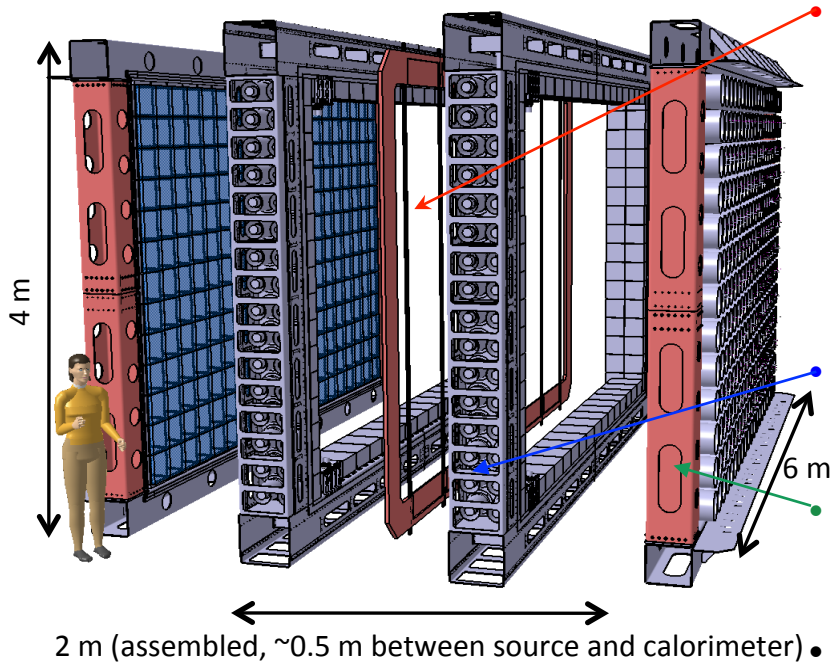
Source foil:
- 5 kg (total of 100 kg) of 40 mg/cm^2 (4 x 2.7 m^2)
- ^{82}Se (high $Q_{\beta\beta}$, long $T_{1/2}^{2\nu\beta\beta}$, proven enrichment technology): starting baseline
- ^{150}Nd and ^{48}Ca being considered depending on enrichment possibilities

Tracker: ~2000 drift cells in Geiger mode
$\rightarrow$ particle identification (for background suppression)

Calorimeter: ~550 scintillator blocks + PMTs
$\rightarrow$ 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):

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

- 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
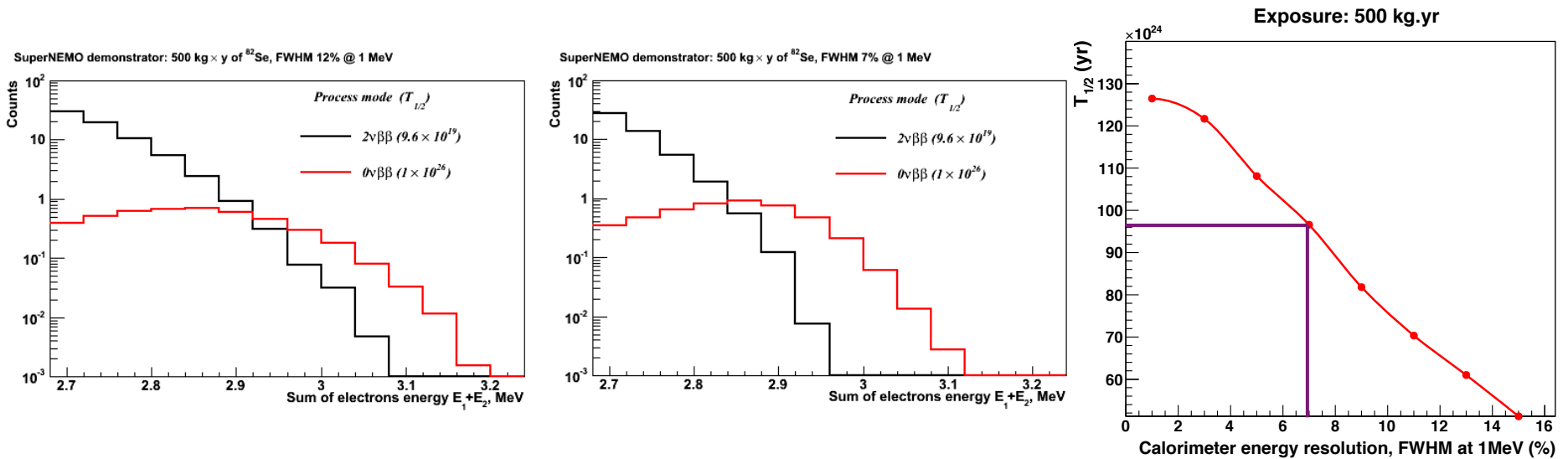
Energy Resolution

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

σ	sigma of distribution
E	mean of distribution
N_{pe}	number of photo-electrons
$N_{ph}/E_{e.}$	number of photons per unit energy
ϵ^{light}	light collection efficiency
QE^{PMT}	quantum efficiency of the photo-cathode
ϵ^{PMT}	PMT collection efficiency

Three experimental objectives:

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

scintillator light output

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
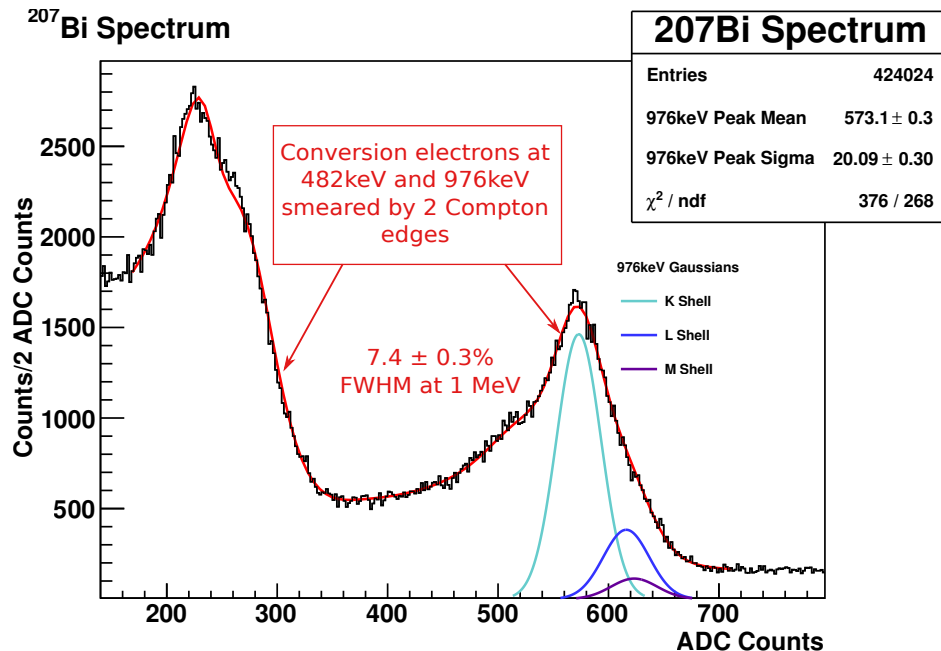
Bordeaux:

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

- Fit: Gaussian

^{207}Bi Spectrum

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

7.4 ± 0.3% FWHM at 1 MeV

976keV Gaussians
K Shell
L Shell
M Shell

207Bi Spectrum	
Entries	424024
976keV Peak Mean	573.1 ± 0.3
976keV Peak Sigma	20.09 ± 0.30
χ^2 / ndf	376 / 268

^{90}Sr 1.0 MeV Spectrum

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

7.7 ± 0.2 % FWHM at 1 MeV

90Sr Spectrum	
Entries	12108
Peak Mean	0.9994 ± 0.0005
Peak Sigma	0.03496 ± 0.00044
χ^2 / ndf	45.98 / 42

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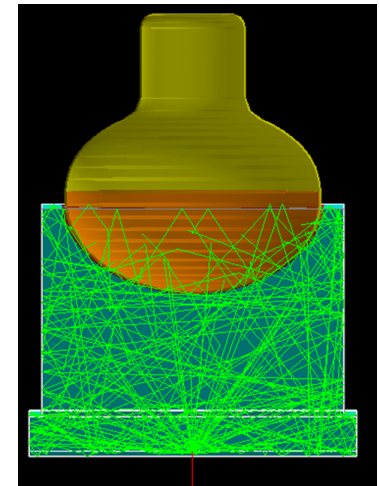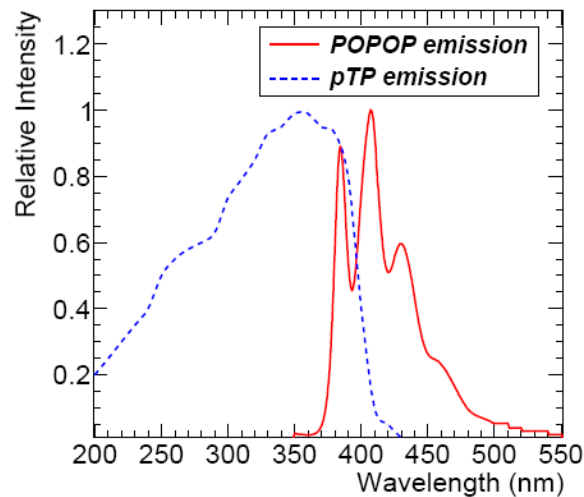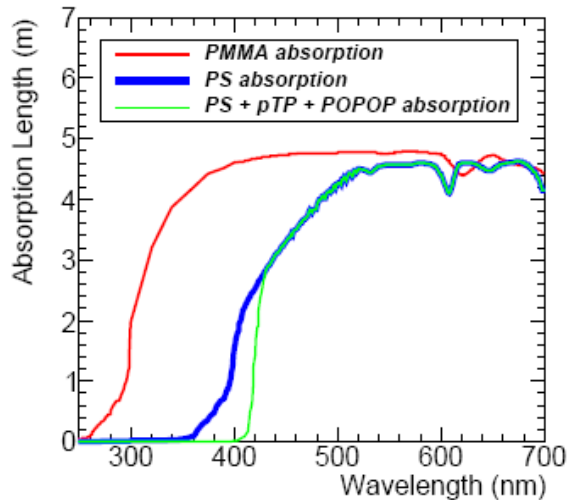
- For further details see: "Spectral modeling of scintillator for the NEMO-3 and SuperNEMO detectors" https://doi.org/10.1016/j.nima.2010.09.027

SuperNEMO Calorimeter R&D: Scintillators

- Block shape studies:
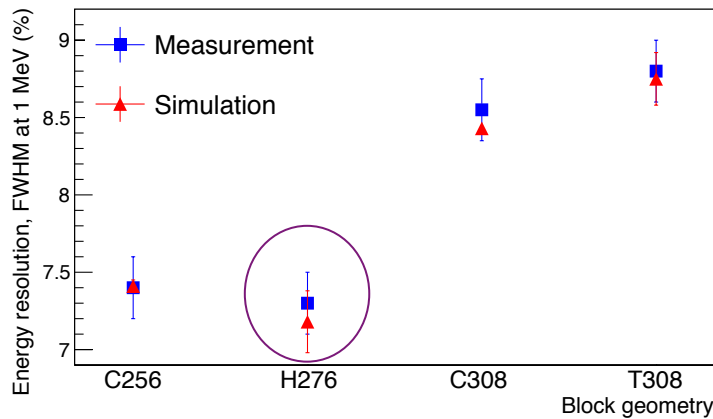
C256:	cubic 256^2 x 190 mm^2
H276:	hexagonal 276 mm diameter with 12 mm minimum depth
C308:	cubic 308^2 x 190mm^2
T308:	cubic 308^2 x 190mm^2 with tapered sides

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

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

Material	$\Delta E/E(\%)$	f_{FWHM}
NUVIA PS	7.9 ± 0.2	1
Enhanced NUVIA PS	7.6 ± 0.2	1.04 ± 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:
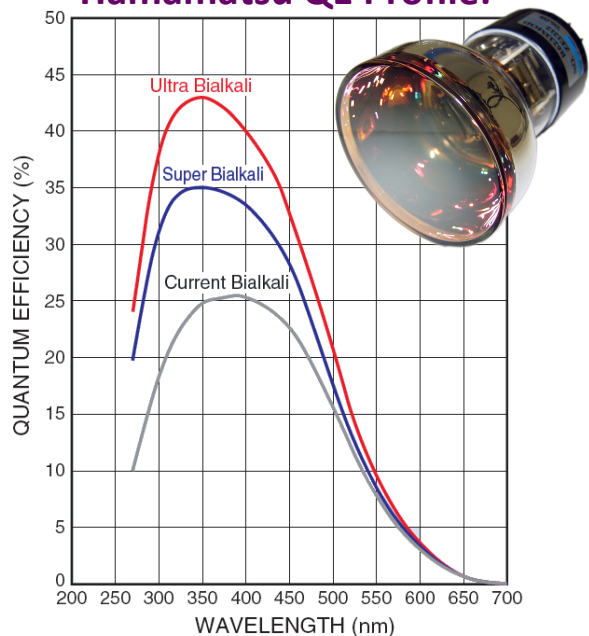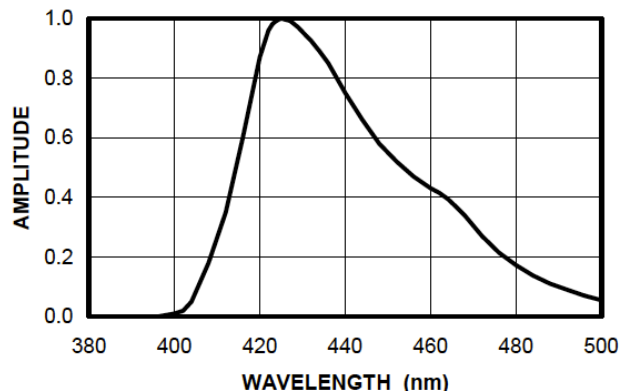

- – **Bi-alkali alloy** development for photocathode material has achieved **QE > 40%**

- – Selection of PMT to **optimise QE to the emission spectra of the scintillator**

- **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%
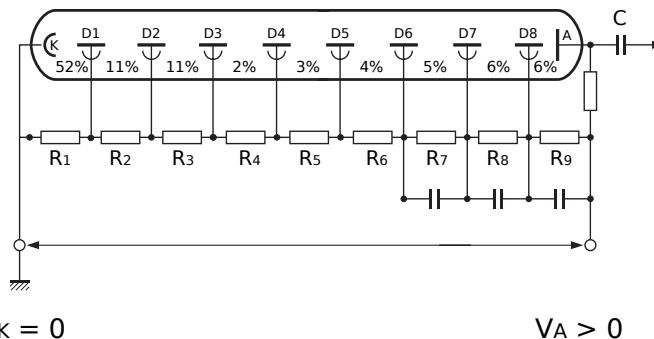
SuperNEMO Calorimeter R&D: PMTs

- Photocathode uniformity:
  - Close collaboration with Hamamatsu to improve photocathode uniformity across the entire surface of the R5912-MOD PMT
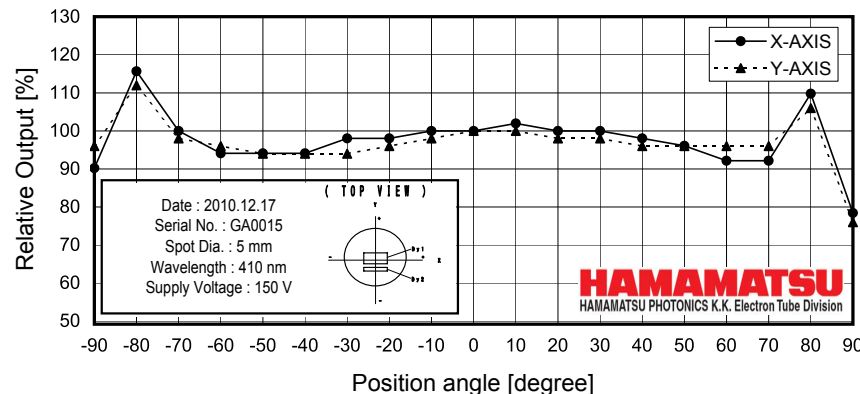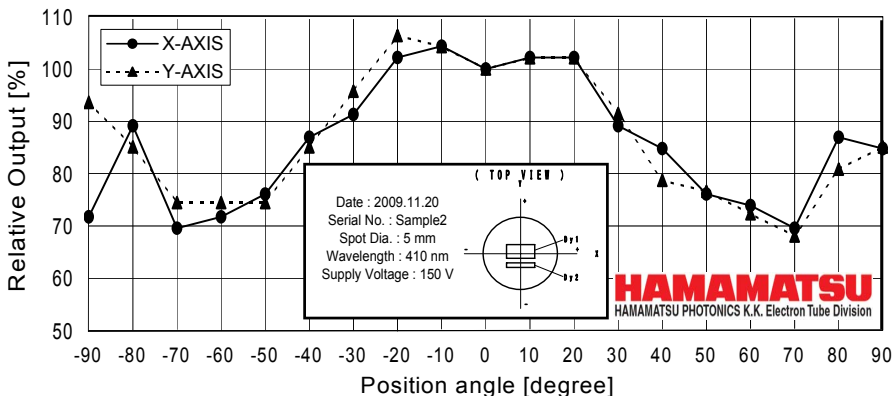
- Timing:
  - Reducing the number of dynode stages improves the timing of the PMT by reducing the time transition spread (TTS)

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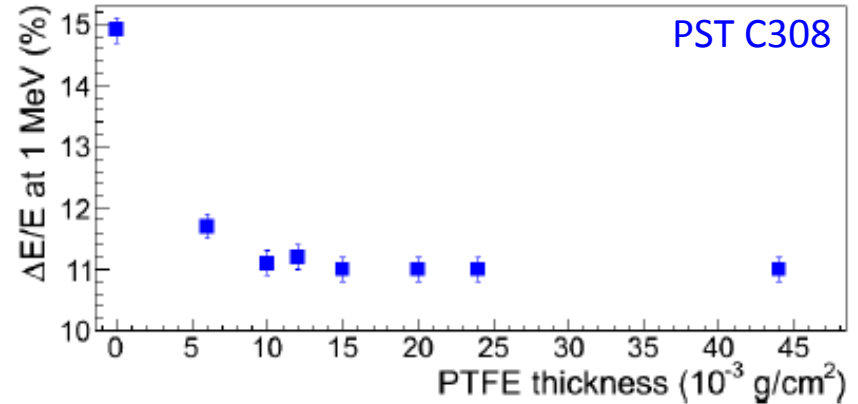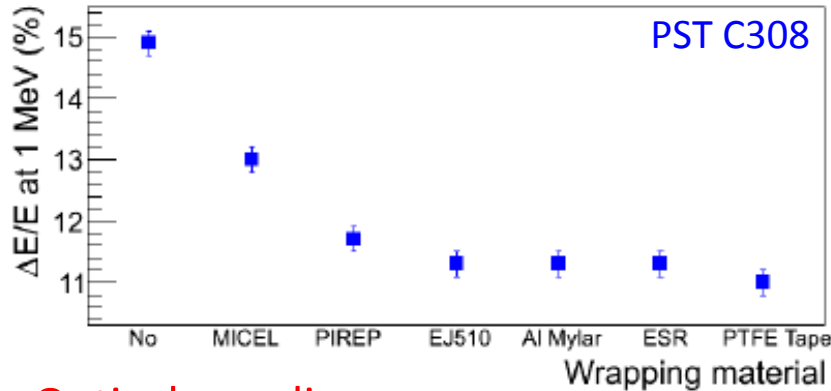
- **Optical coupling**:
  - Good optical coupling between scintillator and PMT essential for uniform and complete light collection

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

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

SuperNEMO Calorimeter R&D: Summary
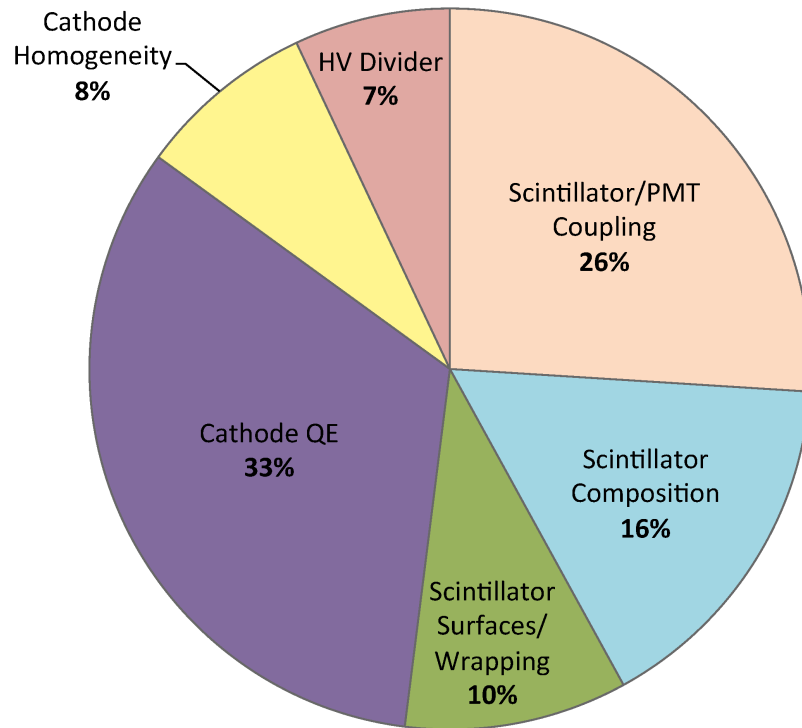
- For further details, see:

 "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
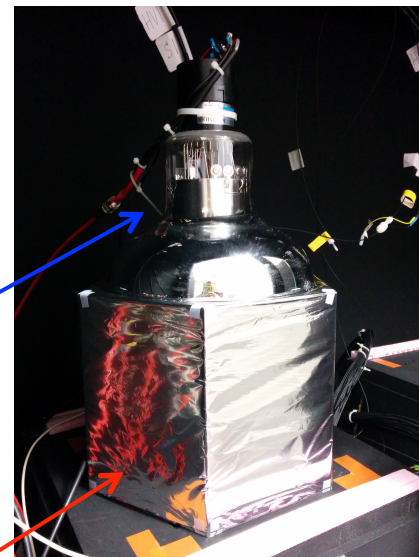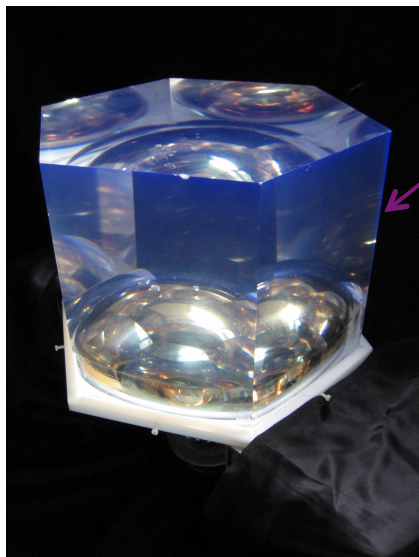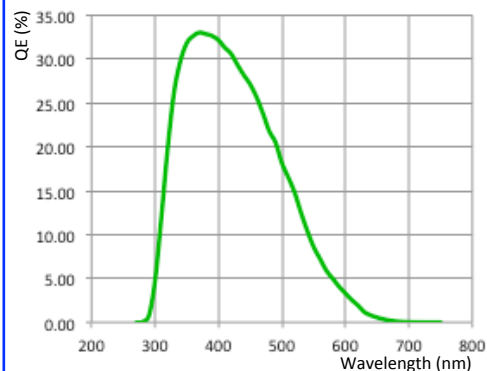
Wrapping:

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 = 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

Proton beam after passing through Clatterbridge Beamline

energyInput	
Entries	170587
Mean	35.29
Std Dev	27.62

Energy deposited in scintillator after beam passes through detector

Energy Deposited in Scintillator

energyDeposited	
Entries	170587
Mean	33.72
Std Dev	10.55

Step 1: GEANT4 Simulations

Energy Deposited in Scintillator

Input:

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

energyDeposited	
Entries	170587
Mean	39.1
Std Dev	0.4046

60 MeV Proton Stopping Distance

stoppingDistance	
Entries	170587
Mean	29.92
Std Dev	0.6849
χ^2 / ndf	250.8 / 27
Constant	8046 ± 36.2
Mean	30.05 ± 0.00
Sigma	0.3835 ± 0.0011

- 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

Energy Deposited as a Function of Depth

60 MeV protons range out at 30 mm in the scintillator
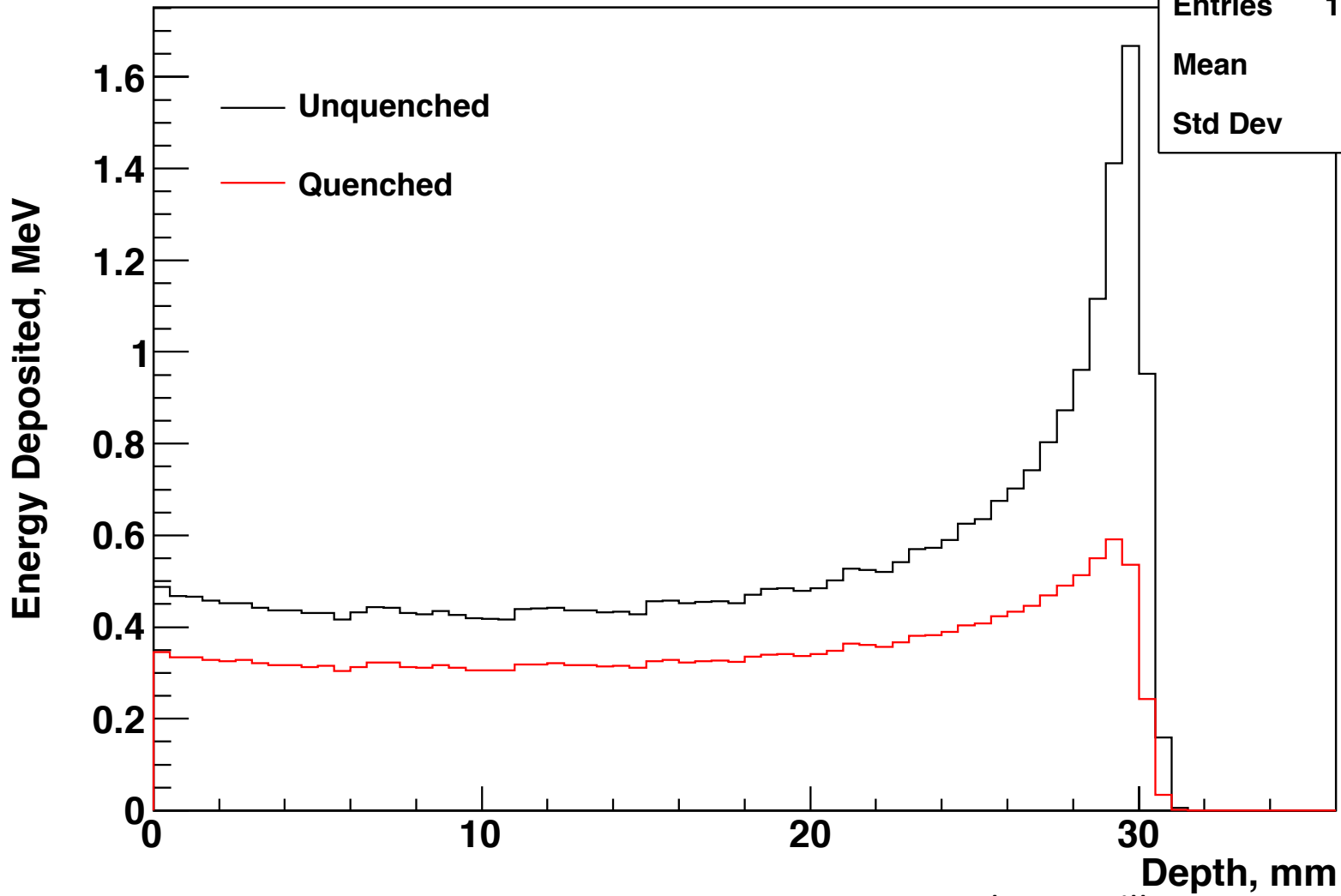
Step 1: GEANT4 Simulations
Proton Stopping Distance

- 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
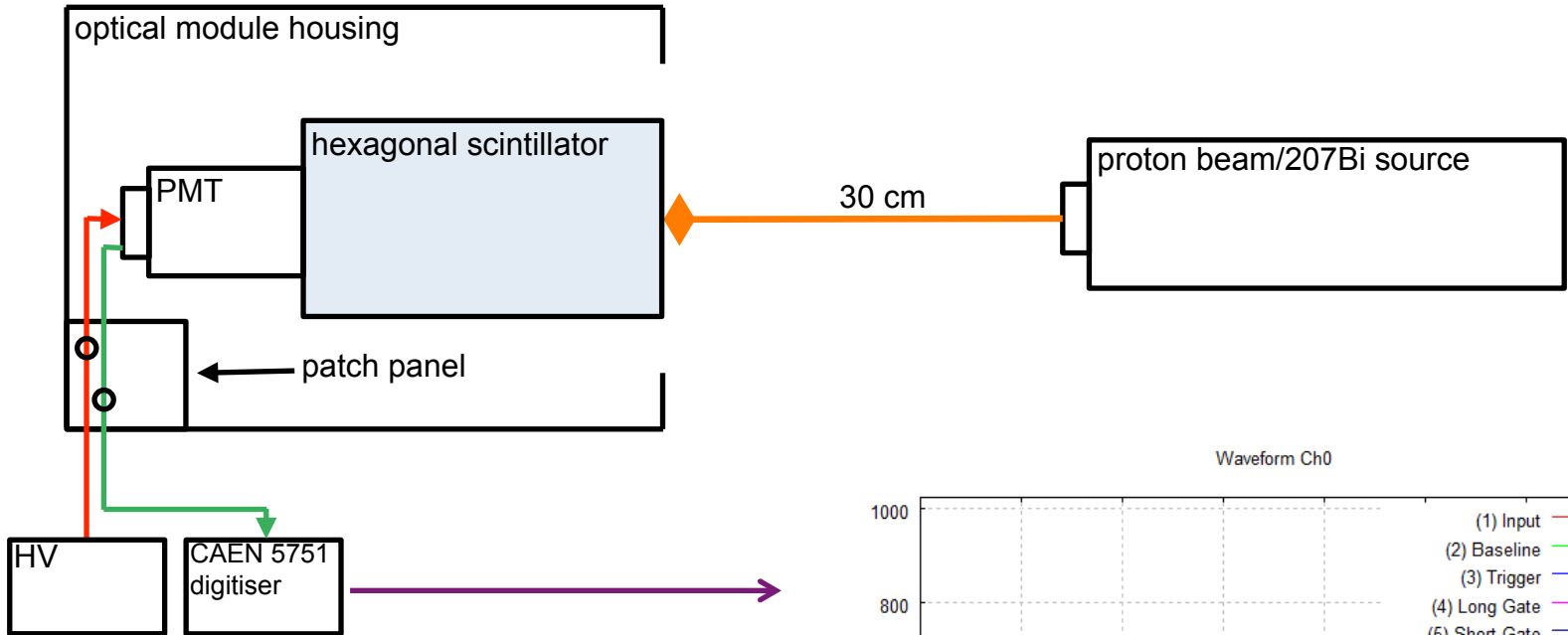
CAEN DT5751 Digitiser:

Dual-gate signal integration
→ Pulse shape analysis
→ Neutron/gamma discrimination
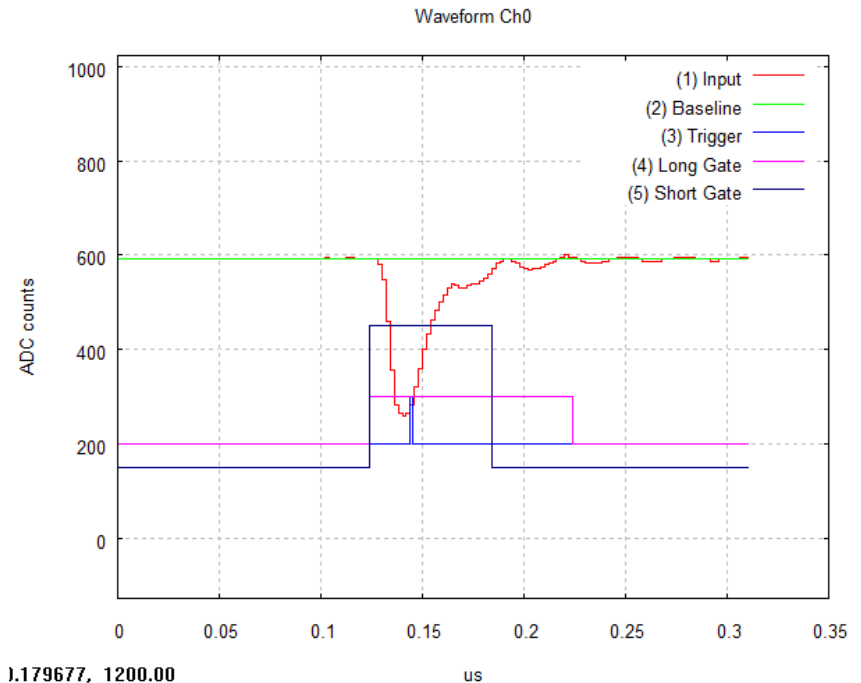
Step 3: ^{207}Bi Test at UCL

- 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

^{207}Bi Spectrum at 1400V

adc	
Entries	8001
Mean	2704
RMS	962.1

976 keV conversion electron peak

482 keV conversion electron peak

σ: 148
μ: 3460

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

σ/E: **3.6 ± 0.2 % σ** at 1 MeV
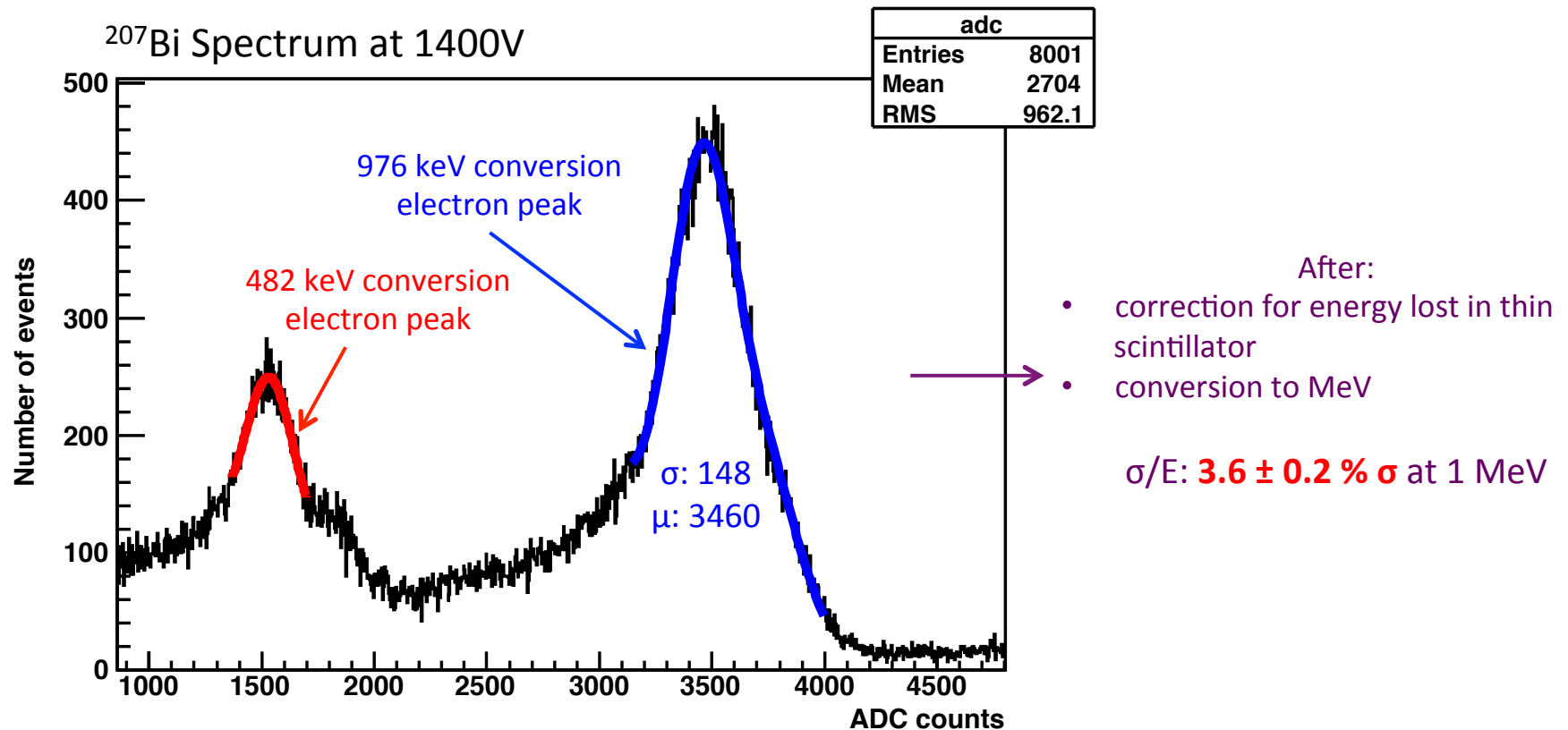
Step 4: Clatterbridge Cancer Centre

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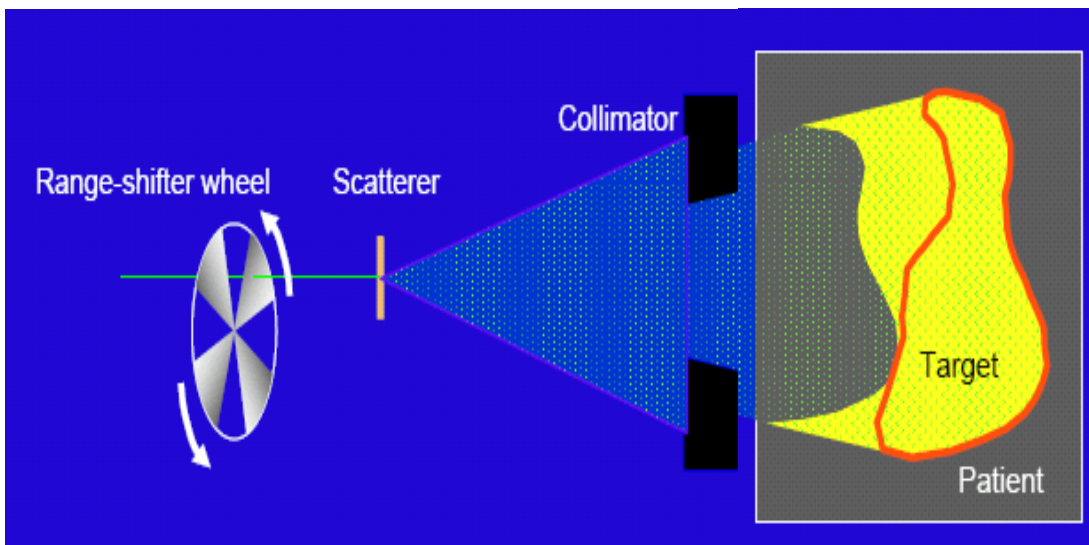
- Beam accelerated to single energy
- Beam passes through range-shifter wheel that modulates the proton beam energy to reach front/back of target volume
- Scatterer enlarges beam to cover whole volume
- Collimator shapes outer edge of beam to target area

Step 4: Clatterbridge Cancer Centre

- Eight full days in total of proton beam access granted to UCL from 2013 - 2016
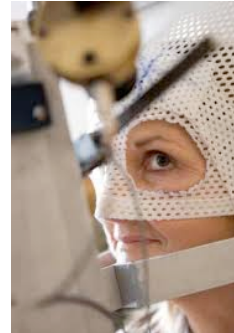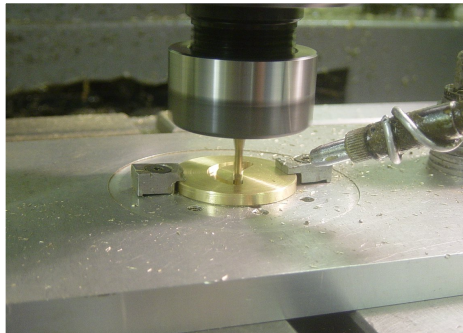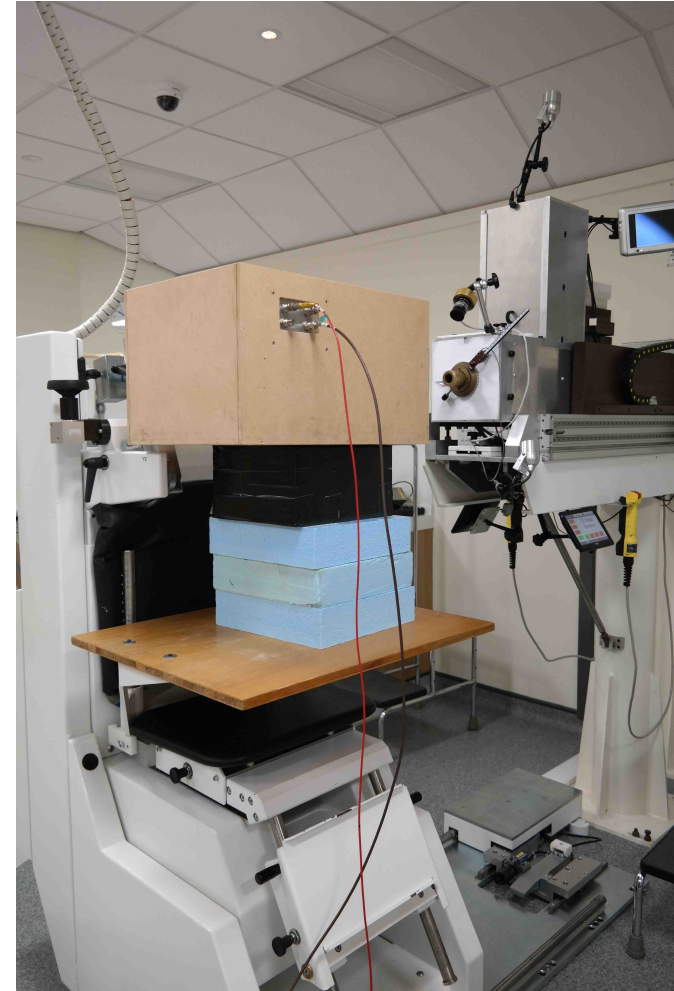
Step 4: Clatterbridge Cancer Centre
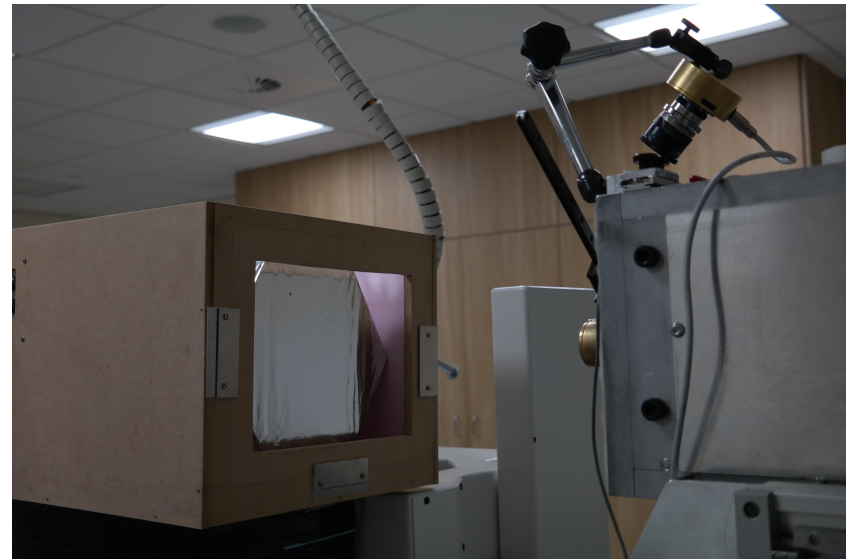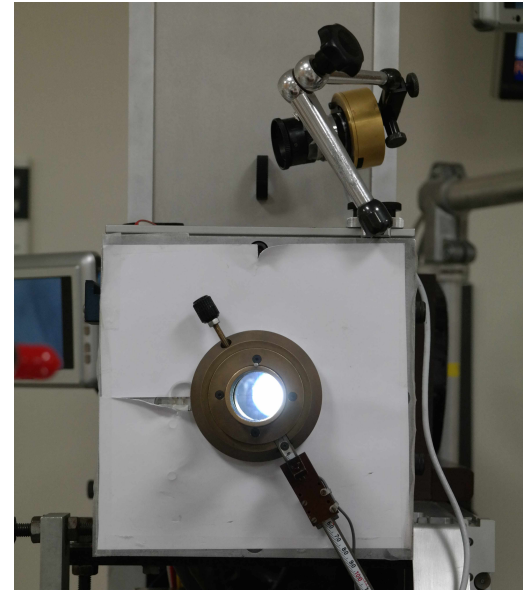
Step 4: Clatterbridge Cancer Centre

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
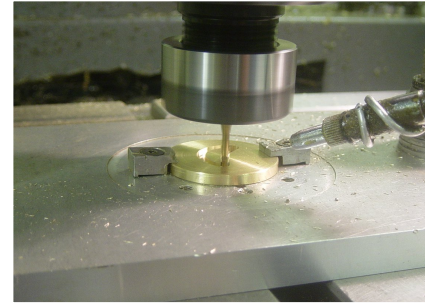
    - Adjustment of the cyclotron RF phase
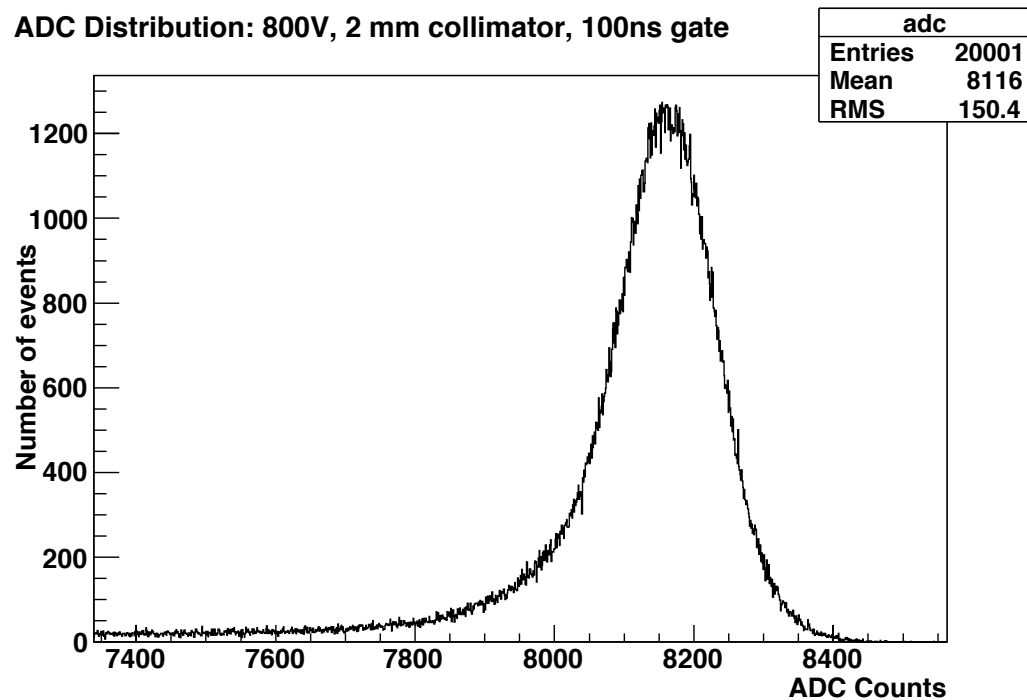
- Resulting distribution:

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

adc	
Entries	20001
Mean	8116
RMS	150.4

Step 4: Clatterbridge Cancer Centre

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

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

Compared to 0.64 % σ from simulations

Fitting function:
Convolution of **Gaussian** and **Landau** + **2nd Degree Polynomial**

Number of events

ADC Counts
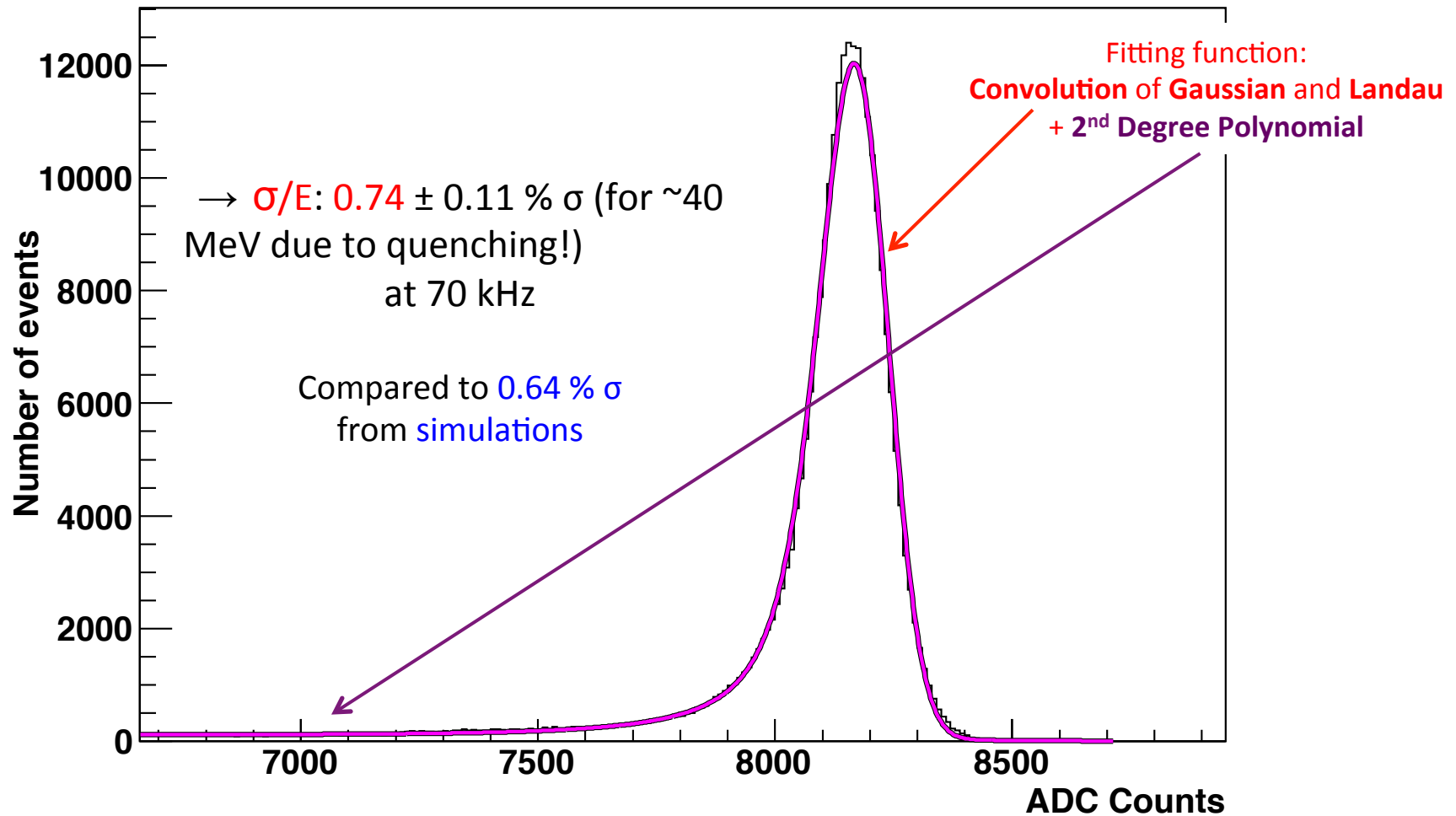
Step 4: Clatterbridge Cancer Centre

Energy Deposited in Scintillator

MC

energyDeposited	
Entries	170587
Mean	33.72
Std Dev	10.55

Data: Energy Deposited in Scintillator

DATA

adc	
Entries	32768
Mean	6947
Std Dev	2163
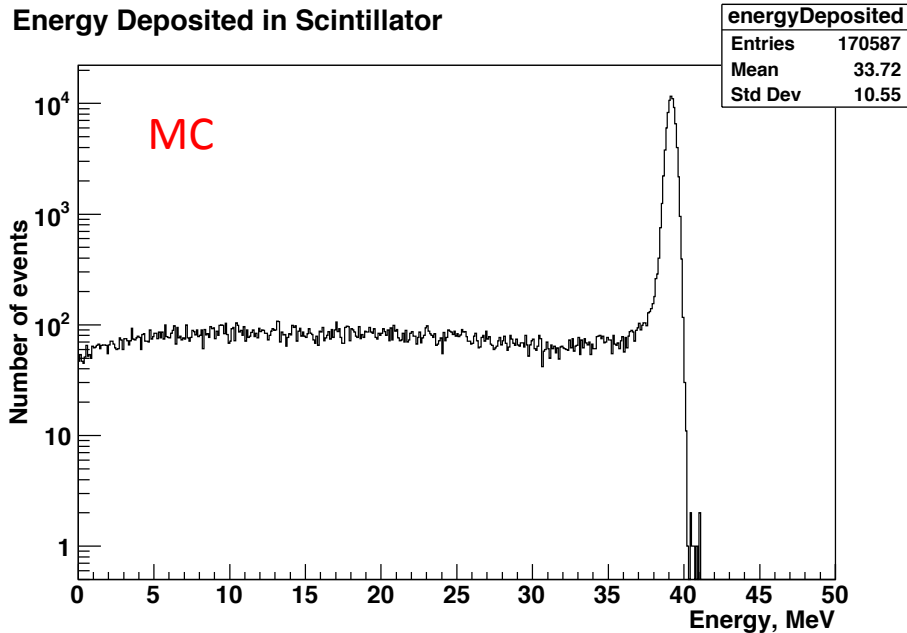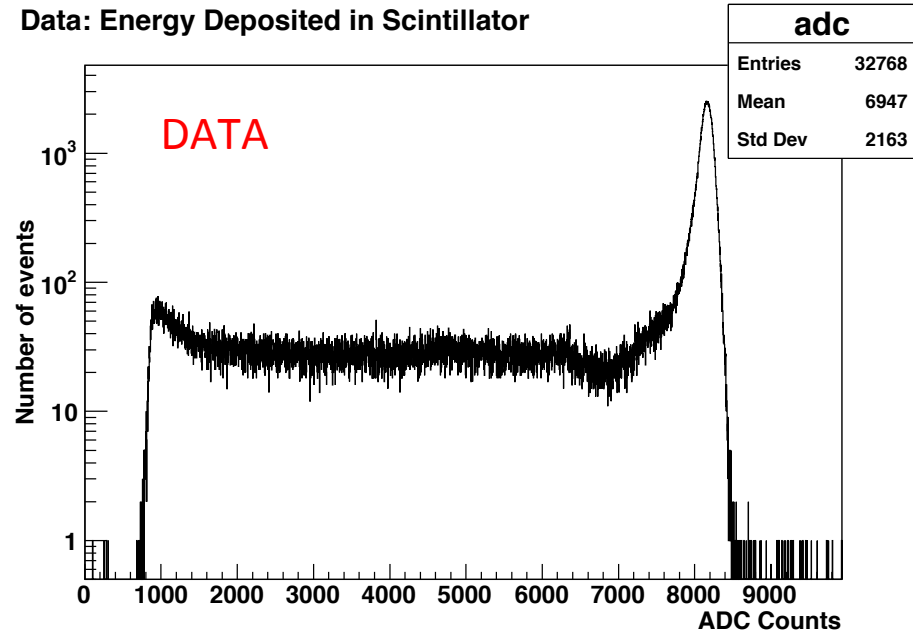
- Our simulations accurately represent our data!

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

Treatment Nozzle

PVT Block | PMT

~50 cm

Mains

Signal

Nozzle mounted system with ASIC-based component electronics
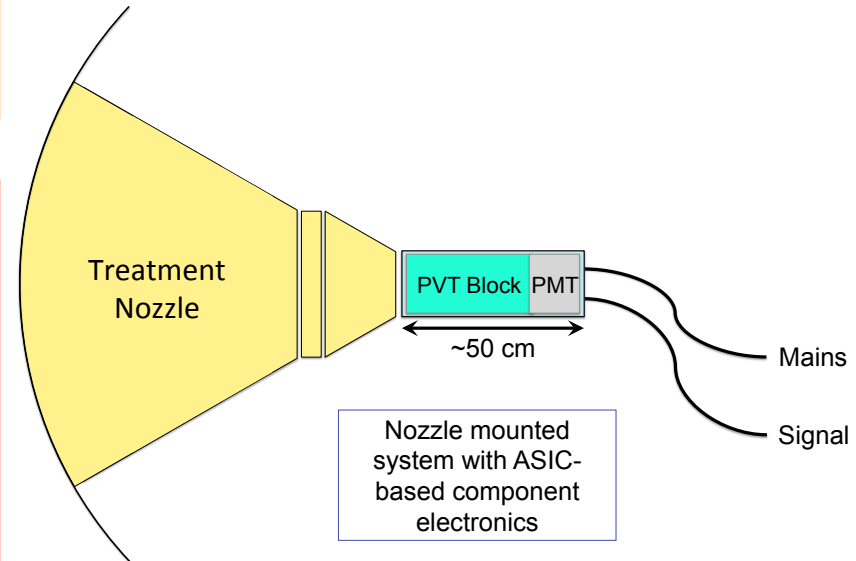
Step 5: Make the Technology Smaller & Faster

ADC Distribution: -900 V, 1.98 mm collimator, 150 ns gate
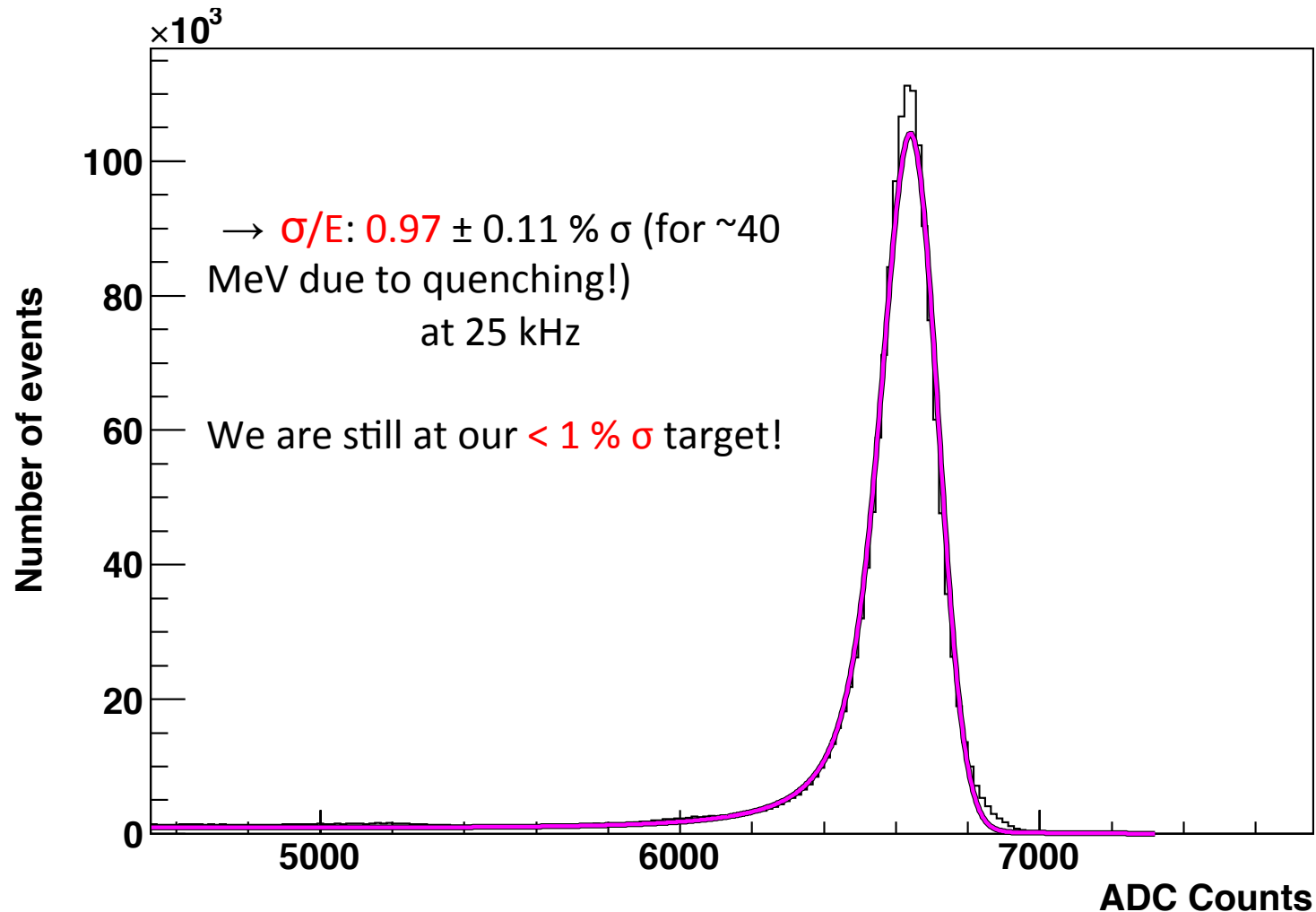
$\rightarrow$ σ/E: 0.97 ± 0.11 % σ (for ~40 MeV due to quenching!) at 25 kHz

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

Energy Resolution as a Function of Proton Energy: -900 V

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

χ^2 / ndf	13.34 / 8
p0	29.27 ± 6.116
p1	-5.094 ± 1.512
p2	-2.416 ± 6.034
p3	0.03782 ± 0.01957
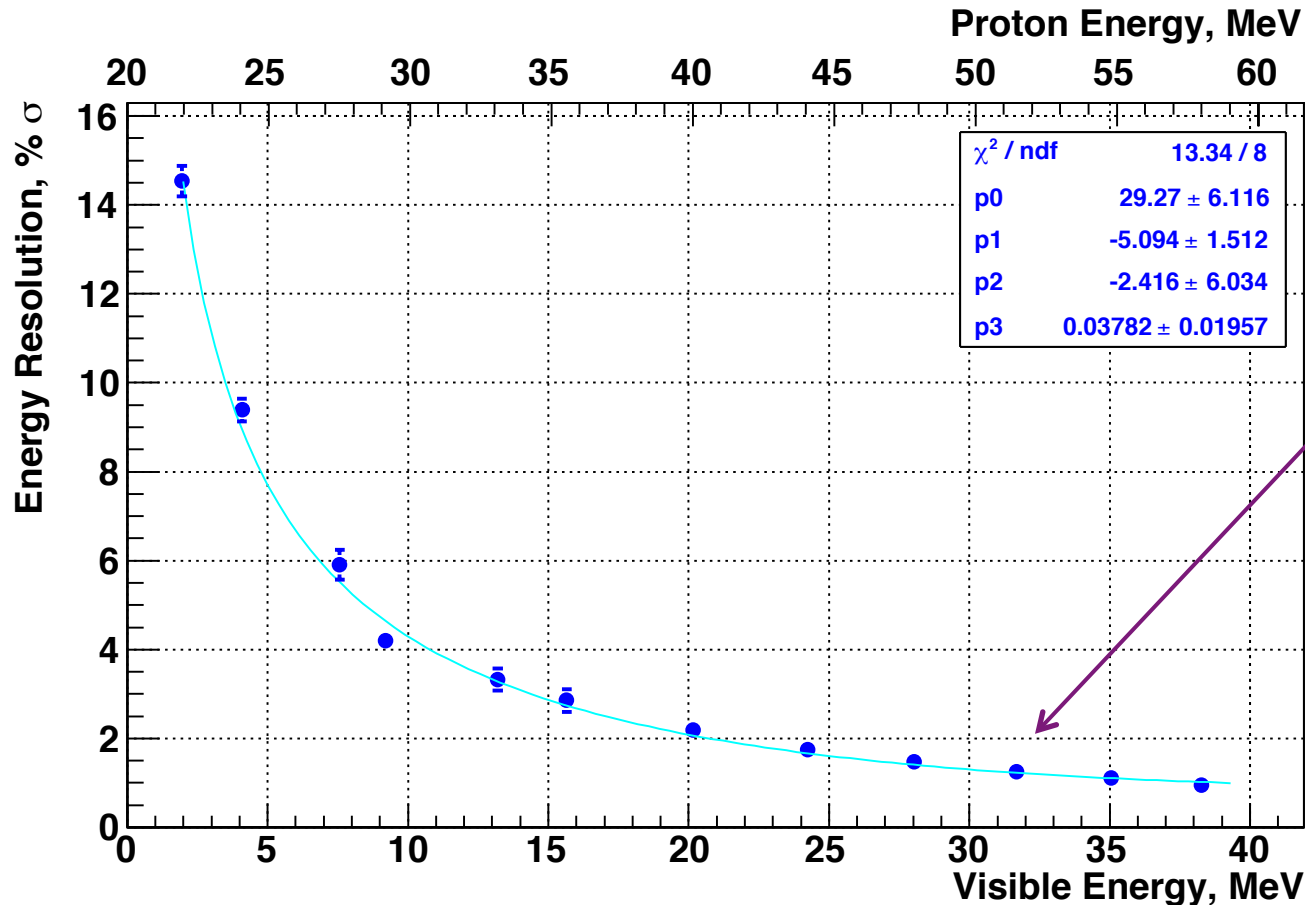
$\sqrt{E}$ dependence!

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

Proton Energy as a Function of ADC Mean: -900V

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

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

Chart details:
- Y-axis: Proton Beam Energy, MeV
- X-axis: ADC Mean, ADC units
- χ^2 / ndf: 26.37 / 8
- p0: 11.66 ± 0.4675
- p1: 0.007352 ± 0.0001064
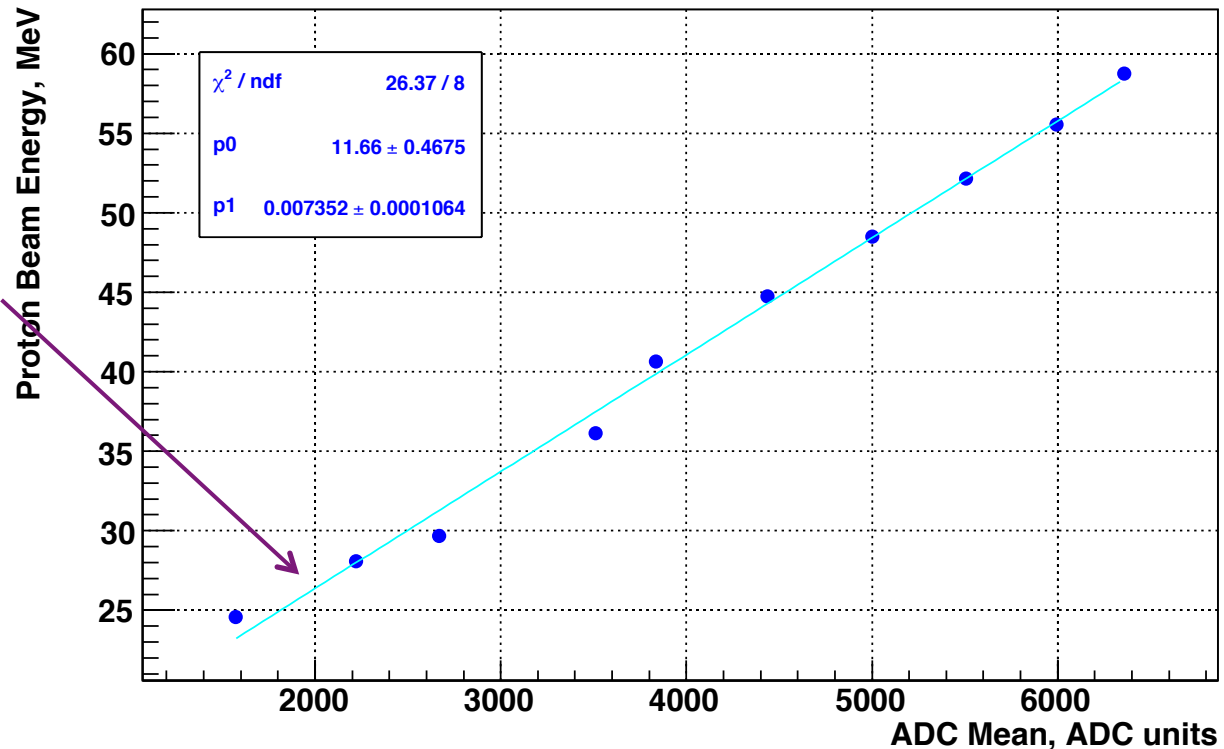
Beam Uniformity Measurements

- 0.5 mm Ø collimator
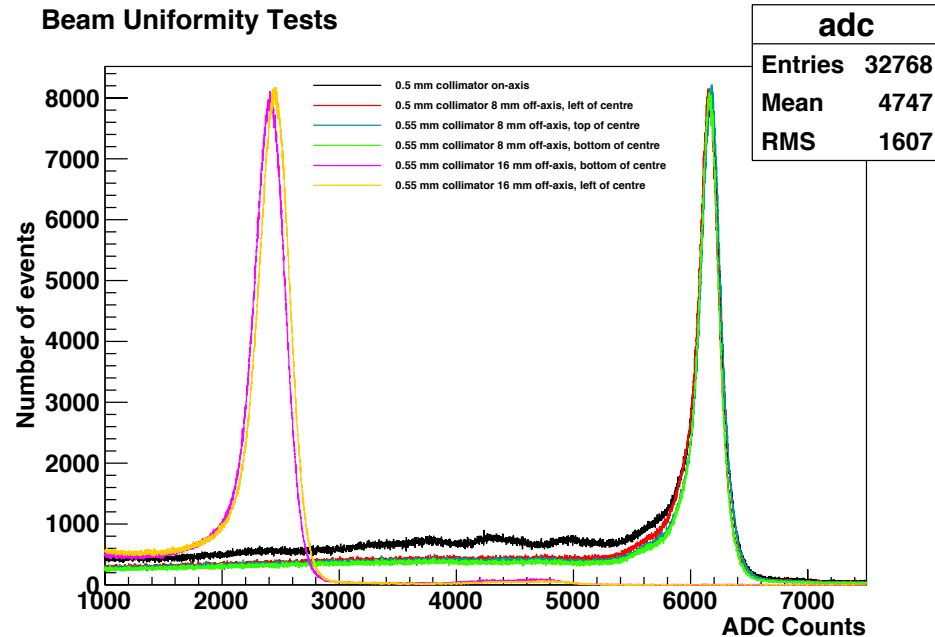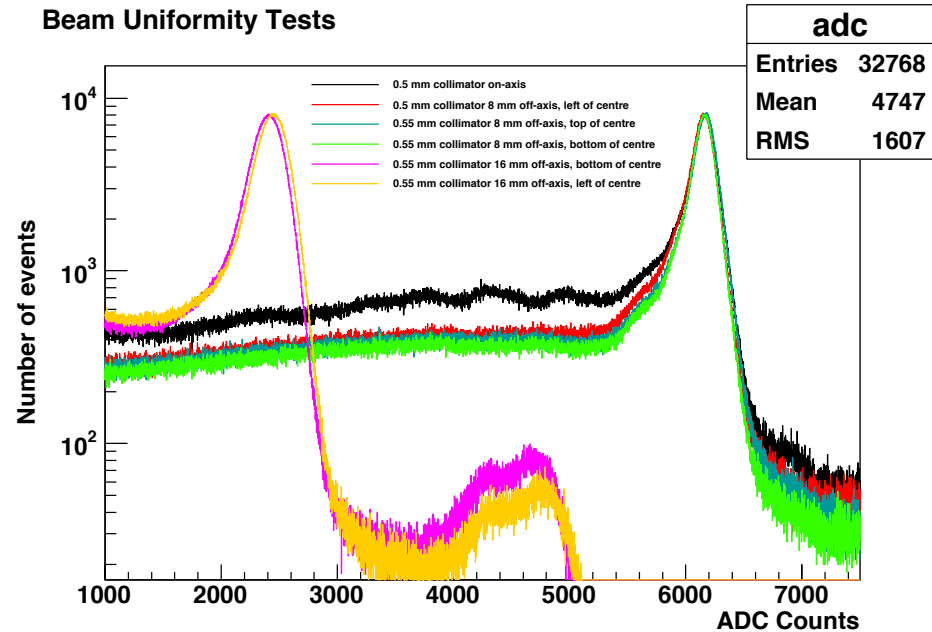
- Uniform 8 mm away from the centre

- 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

^{207}Bi Runs Before and After Aug 2016 Test Beam

bi207_3883	
Entries	1191405
Mean	119.8
RMS	85.24

- UCL DAQ, Portable HV, 27.07.16
- UCL DAQ, UCL HV, 28.07.16
- UCL DAQ, UCL HV, 04.08.16
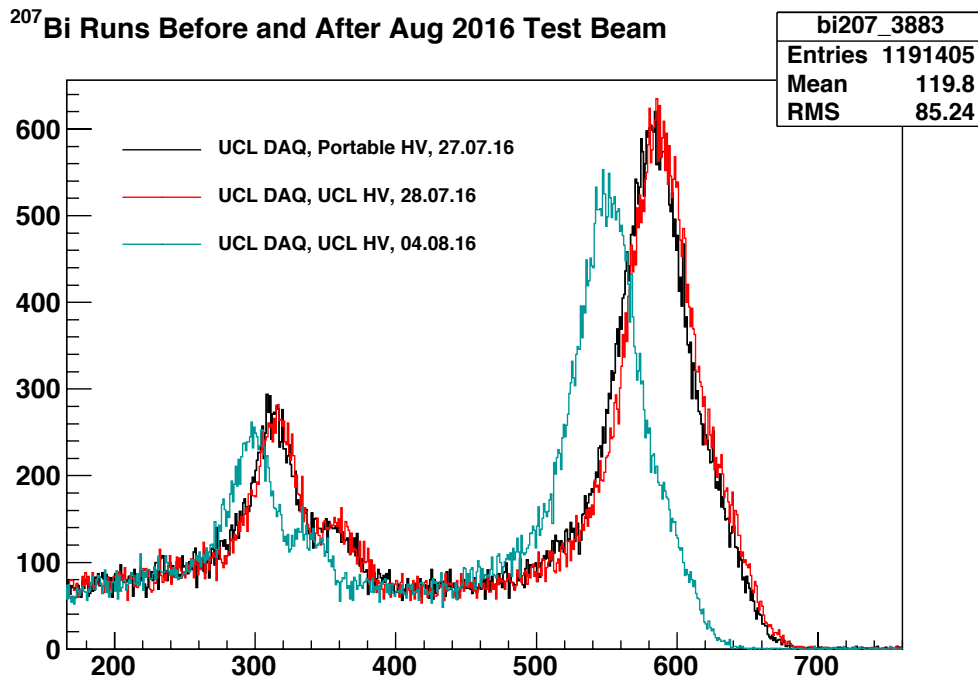
Date	HV Supply	DAQ	σ/E (%)
27/07/16	Portable	UCL	3.16 ± 0.03
28/07/16	UCL	UCL	3.14 ± 0.03
Clatterbridge Test Beam: 02-03/08/16			
04/08/16	UCL	UCL	3.08 ± 0.03

- 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
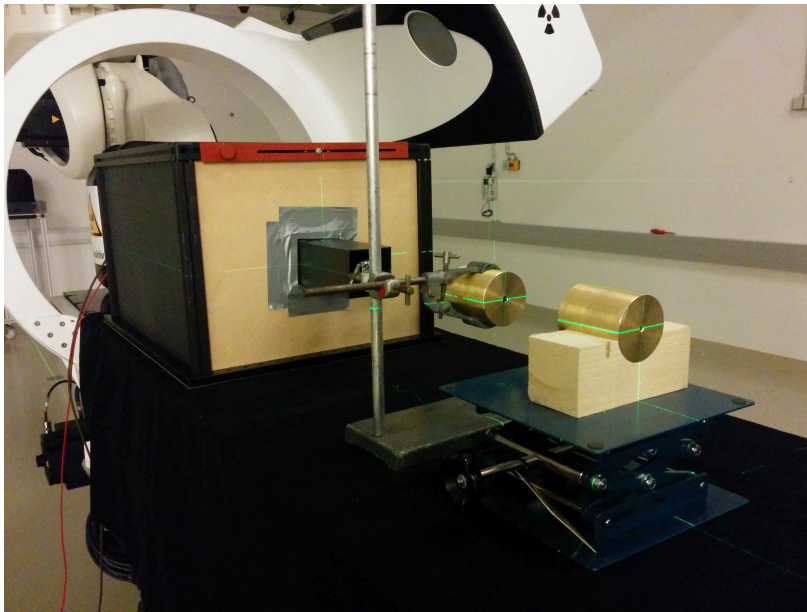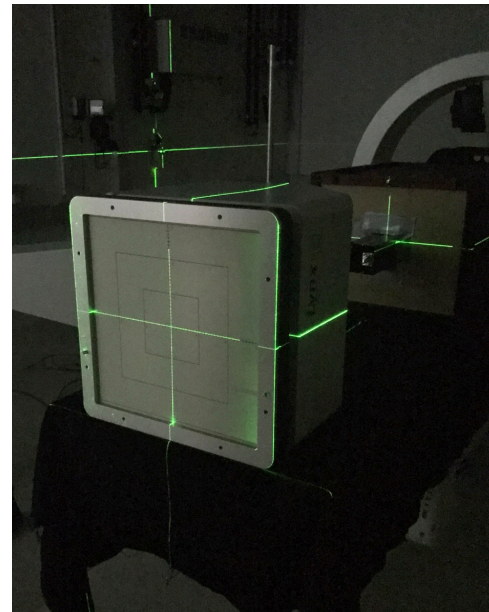
Step 6: 250 MeV Beam at medAustron

ADC Spectra for 252.4 MeV Beam Energy at 100 kHz

- Run 035, $\Delta E/E$: 0.45 ± 0.05 % FWHM
- Run 036, $\Delta E/E$: 0.70 ± 0.02 % FWHM
- Run 037, $\Delta E/E$: 0.57 ± 0.02 % FWHM
- Run 038, $\Delta E/E$: 0.66 ± 0.02 % FWHM

adc	
Entries	20001
Mean	1.302e+04
RMS	444.1

VERY PRELIMINARY!

Systematic errors under investigation
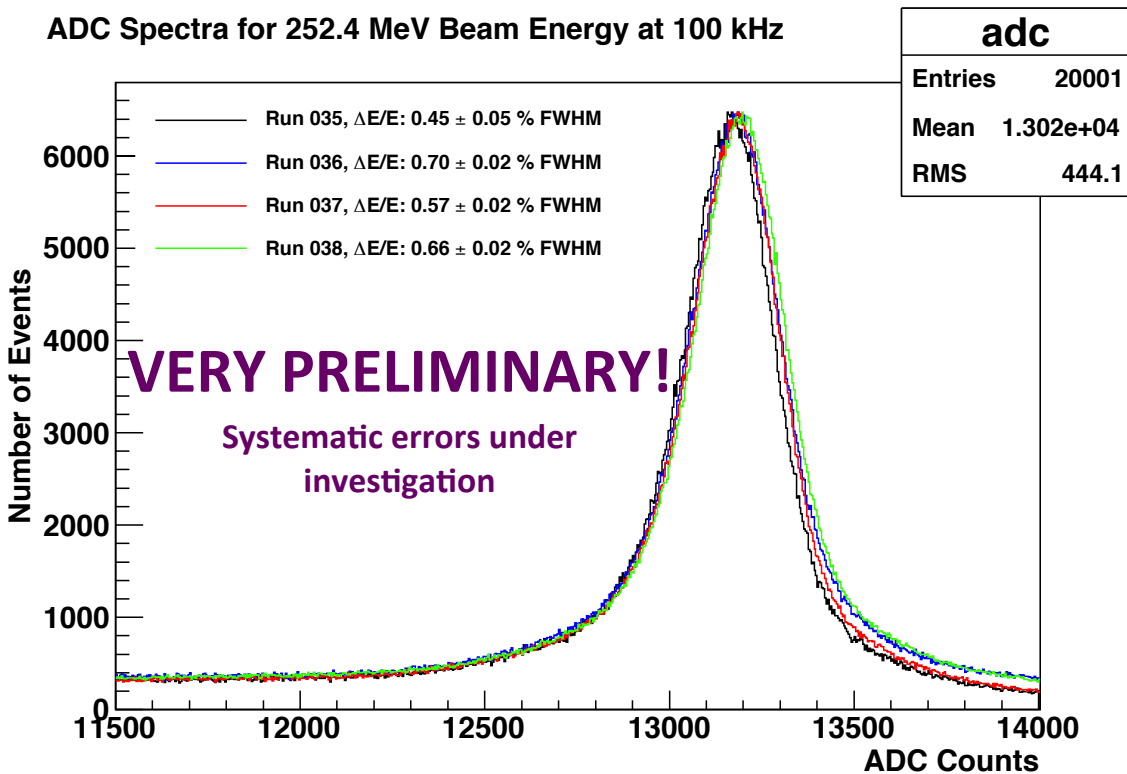
- Still seeing excellent energy resolution up to 252 MeV!

- 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:

<div align="center">

0.97 ± 0.11 % σ

(for 40 MeV "visible" energy)

↓

This has reached the target energy resolution of < 1 % σ

</div>

ADC Distribution: -900 V, 1.98 mm collimator, 150 ns gate

adc	
Entries	32768
Mean	6576
RMS	193.9
χ^2 / ndf	2528 / 652
lWidth	22.07 ± 0.09
mean	6644 ± 0.1
lNorm	1.353e+06 ± 2.741e+03
sigma	59.41 ± 0.21
rWidth	30.12 ± 0.26
rNorm	3.027e+05 ± 2.325e+03
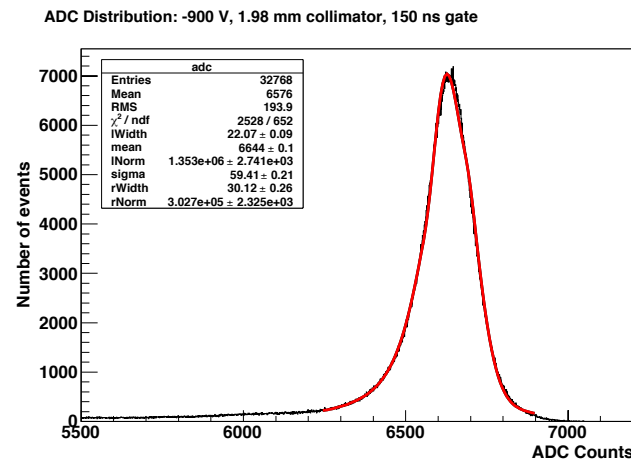
- And a 250 MeV proton beam at medAustron with an energy resolution of 0.2 % σ

- 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

Protons
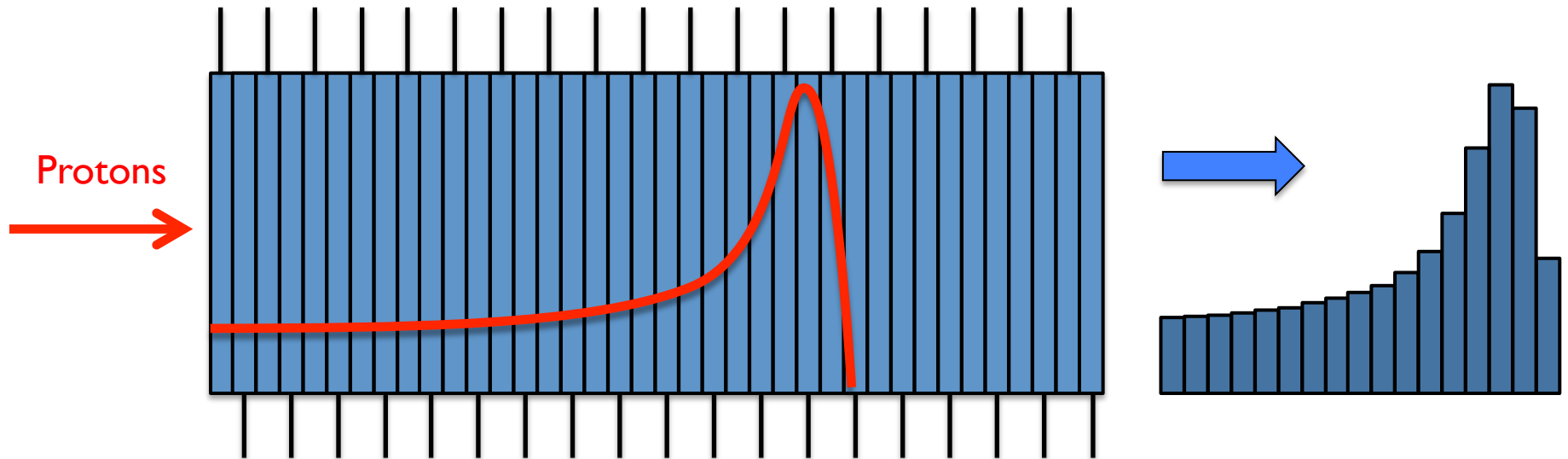
Segmented Calorimeter: Range Telescope

- 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
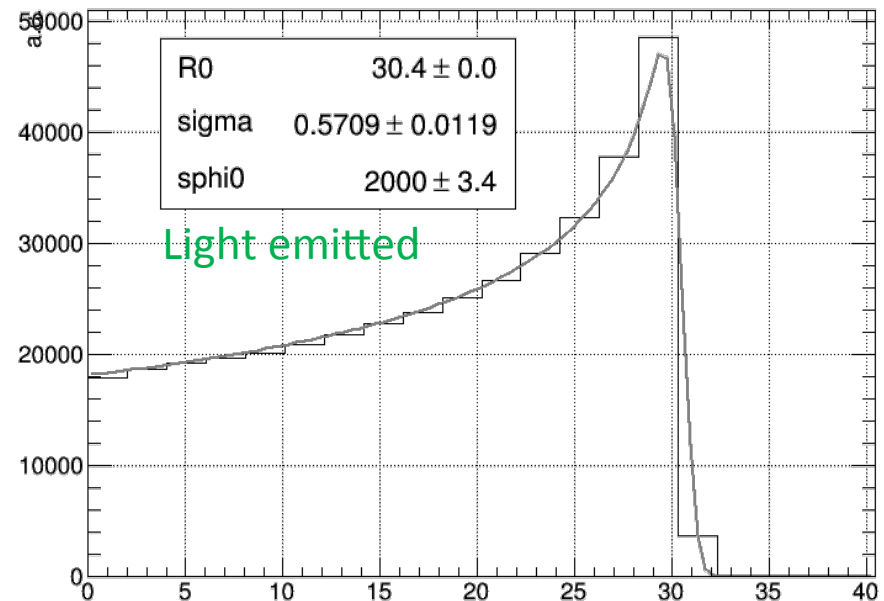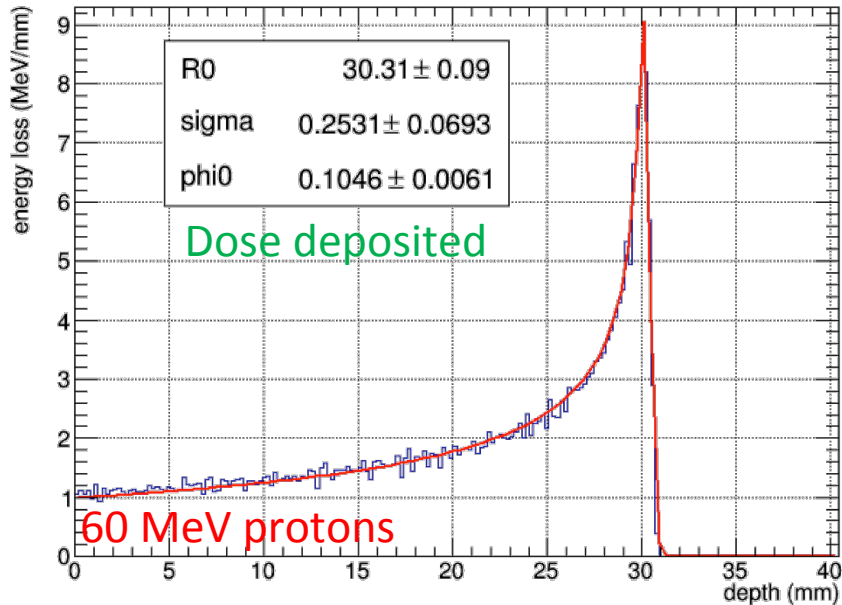
Segmented Calorimeter: First Tests

- Fist tests carried out using the Birmingham cyclotron:

  - 28 MeV proton beam, range of protons ~ 6 mm
  - Clinical rates
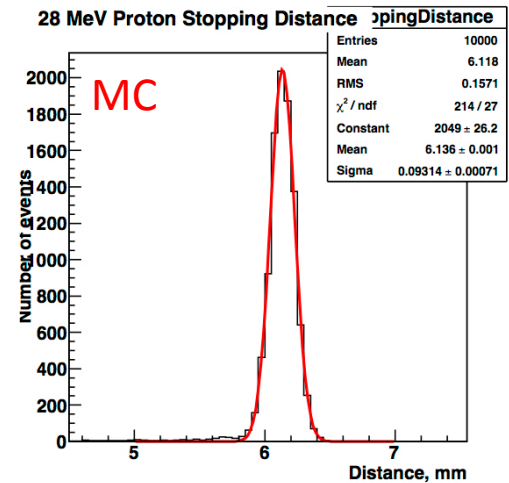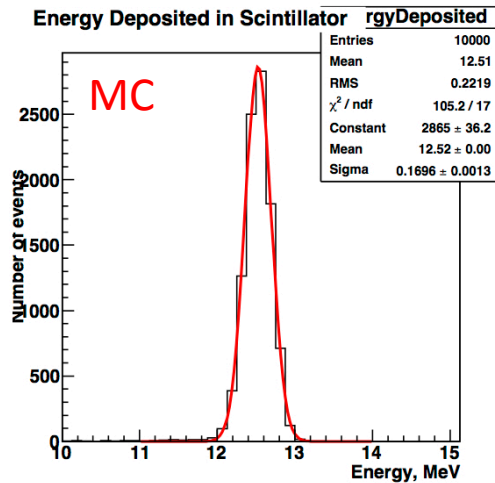
  - 2 sheets of 3 mm and 4 mm NUVIA scintillator used to
  - PRaVDA Priapus MAPS pixel sensor (10 cm x 5 cm)

protons
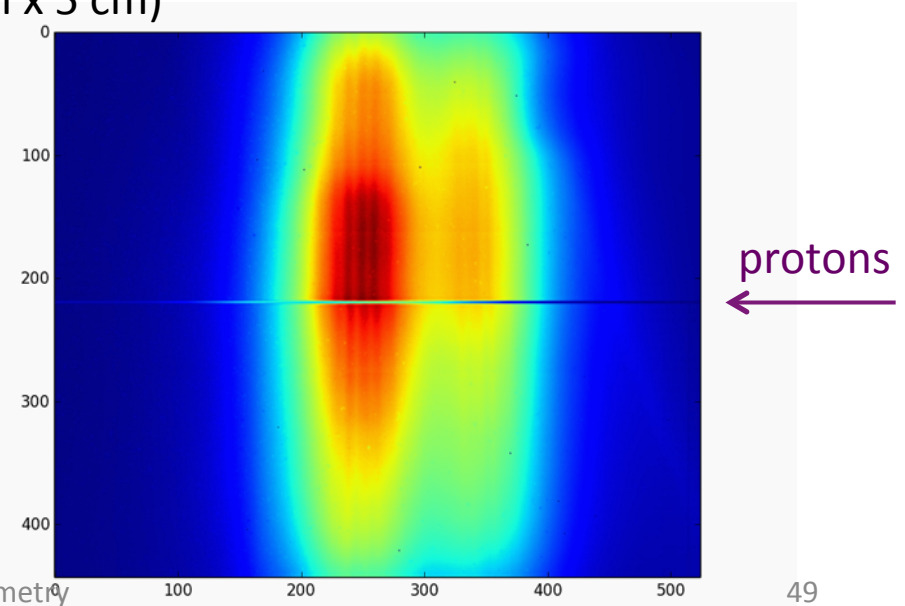
Current Work & Future Plans

- 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
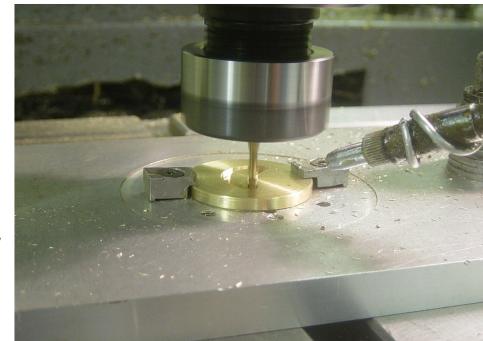
8" PMT + Hexagonal Scintilator: 0.67 ± 0.11 % σ
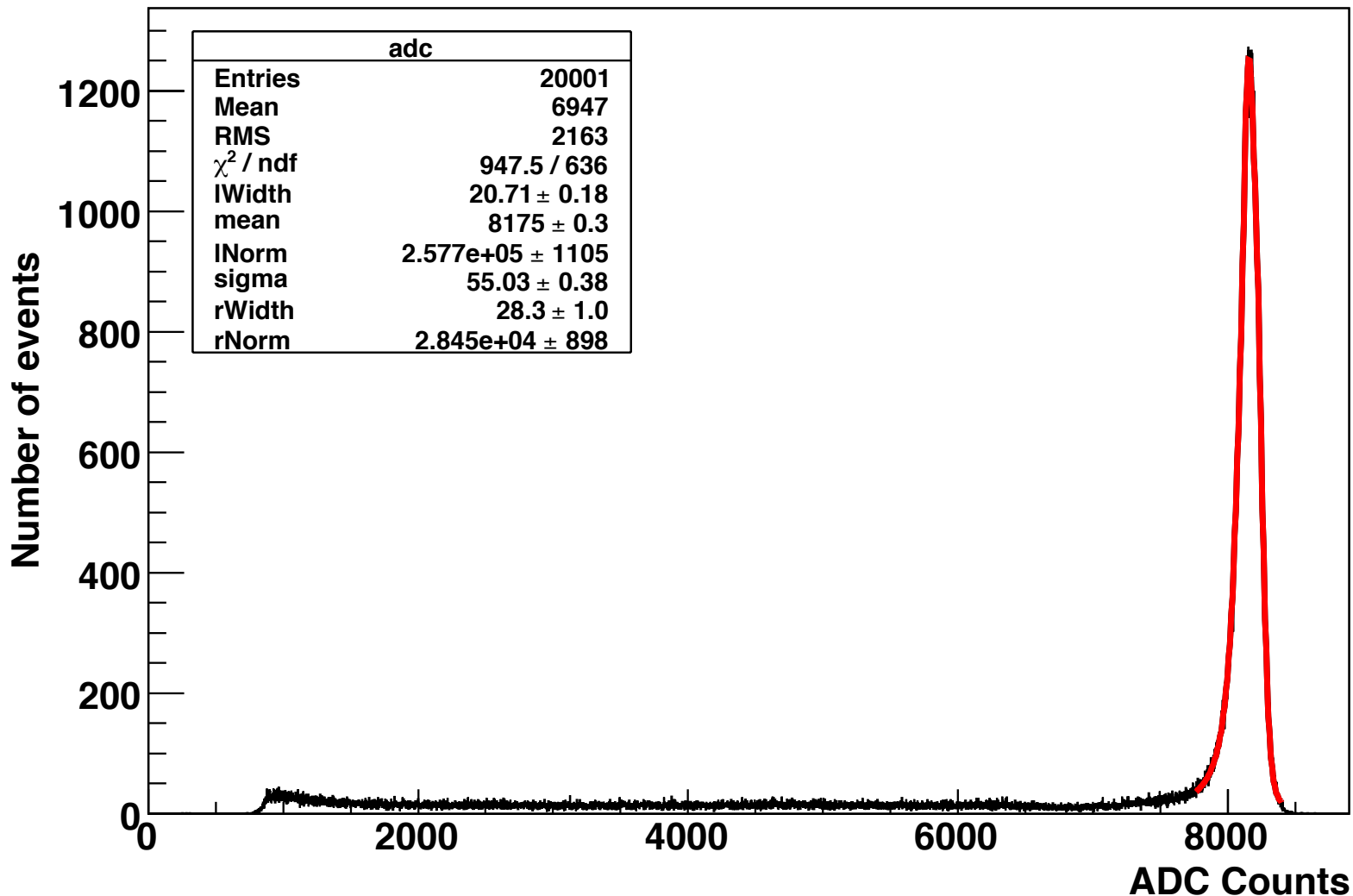
ADC Distribution: 800V, 2 mm collimator, 100ns gate

adc	
Entries	20001
Mean	6947
RMS	2163
χ^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
Mean	6947
RMS	2163
χ^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
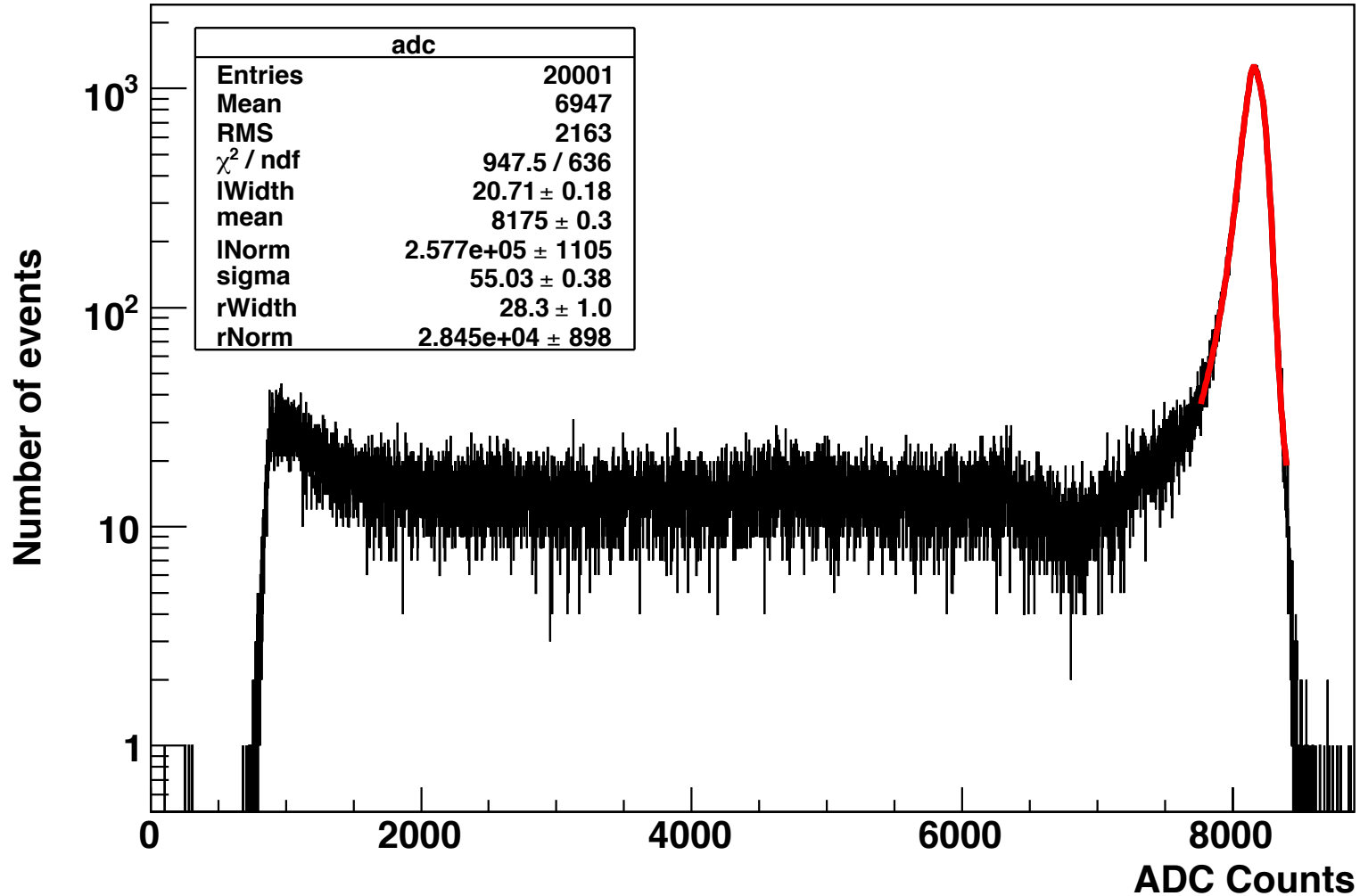
Pile Up: Varying Collimators

800V, 200 ns gate: Varying Collimators

Protons scattering off the collimator increases with diameter decrease

adc	
Entries	20001
Mean	4568
RMS	3020

— 0.5mm collimator
— 1mm collimator
— 2mm collimator
— 10mm collimator

More than 1 proton per bucket for larger diameter collimators, causing peak to widen
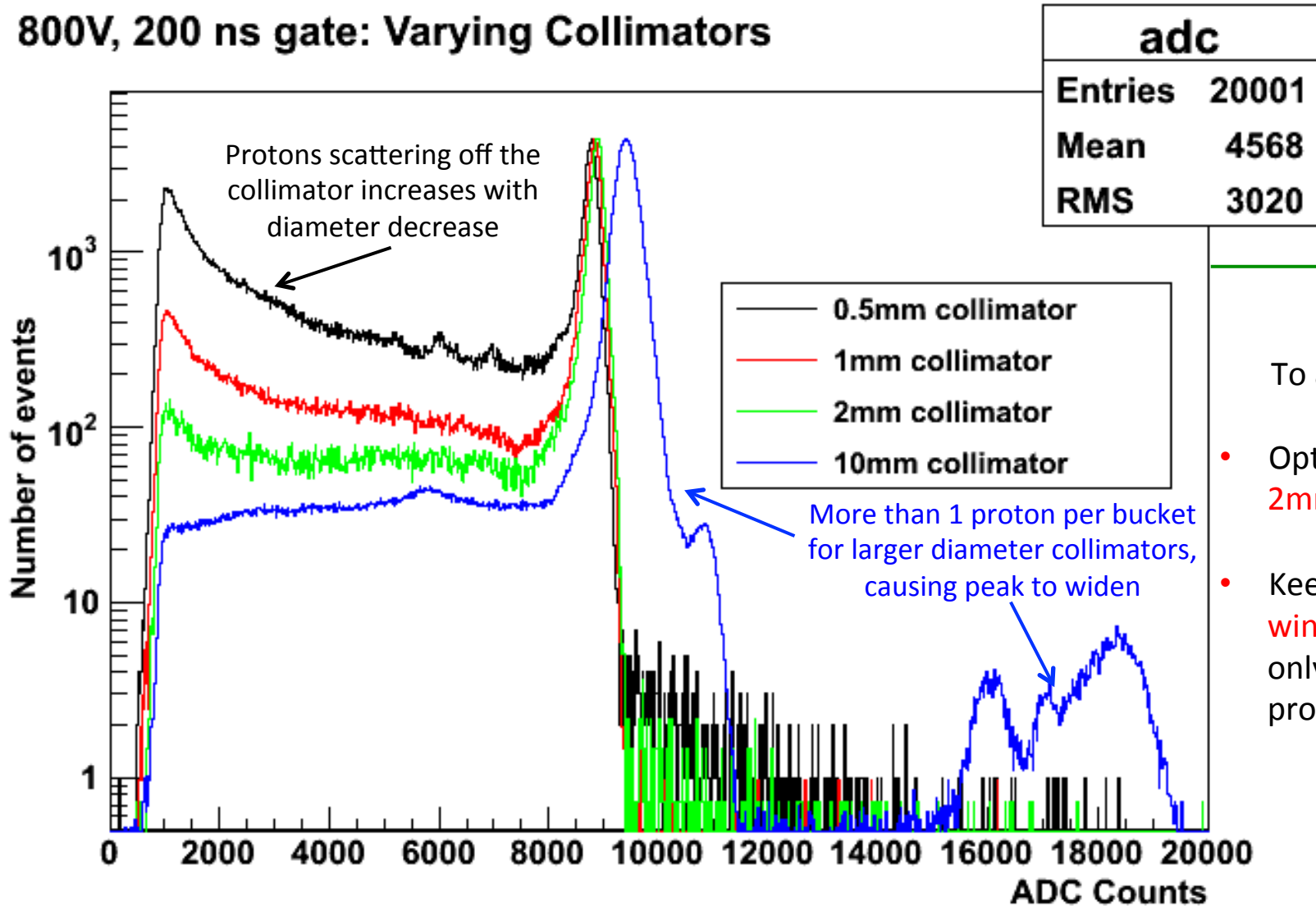
To avoid pile up:

- 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

Energy Resolution as a Function of Proton Energy: 800V

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

$\sqrt{E}$ dependence!
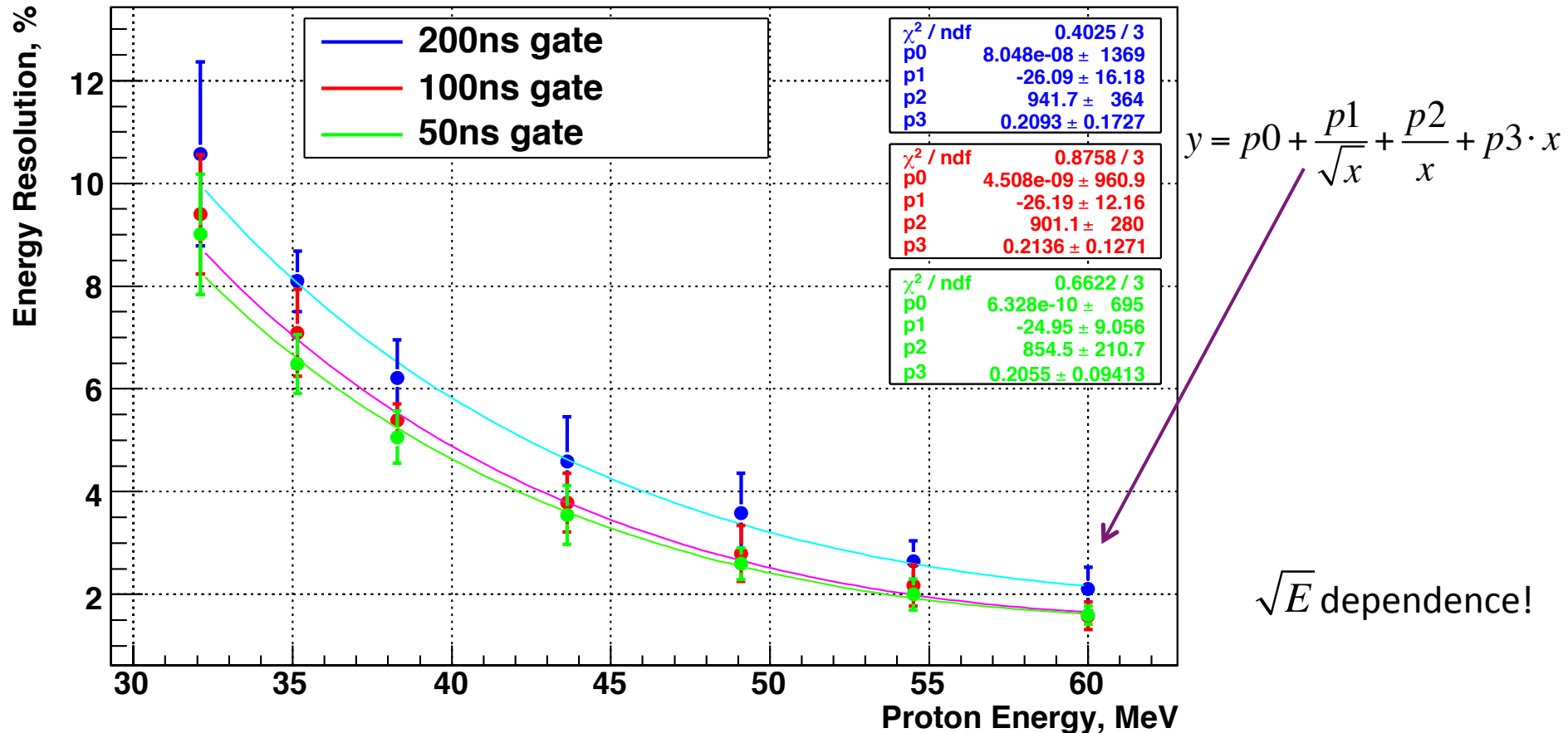
Intrinsic Energy Resolution of Optical Module

- 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

adc	
Entries	20001
Mean	8912
RMS	60.96
χ^2 / ndf	886 / 66
Constant	3468 ± 18.4
Mean	8912 ± 0.2
Sigma	54.6 ± 0.2
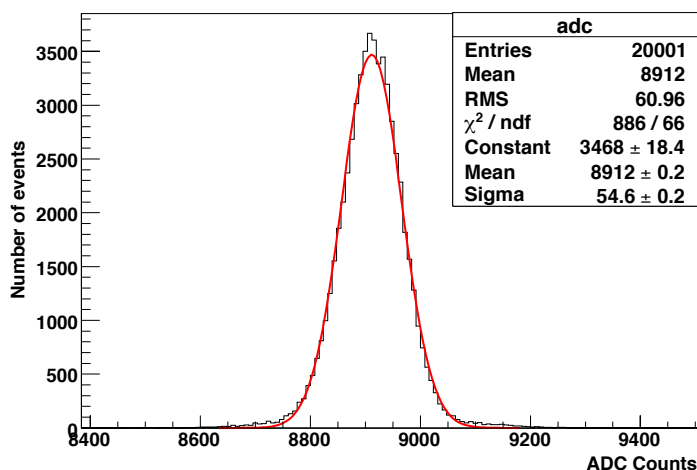
BUT: LED is operating at very "high" parameters (~8V and 40ns width), therefore the width is very sensitive to noise and the LED distribution would be better monitored with a device such as a pin diode

→ future measurement!

Intrinsic Energy Resolution of Optical Module

Energy Resolution as a Function of Proton Energy: 800V, 100ns gate
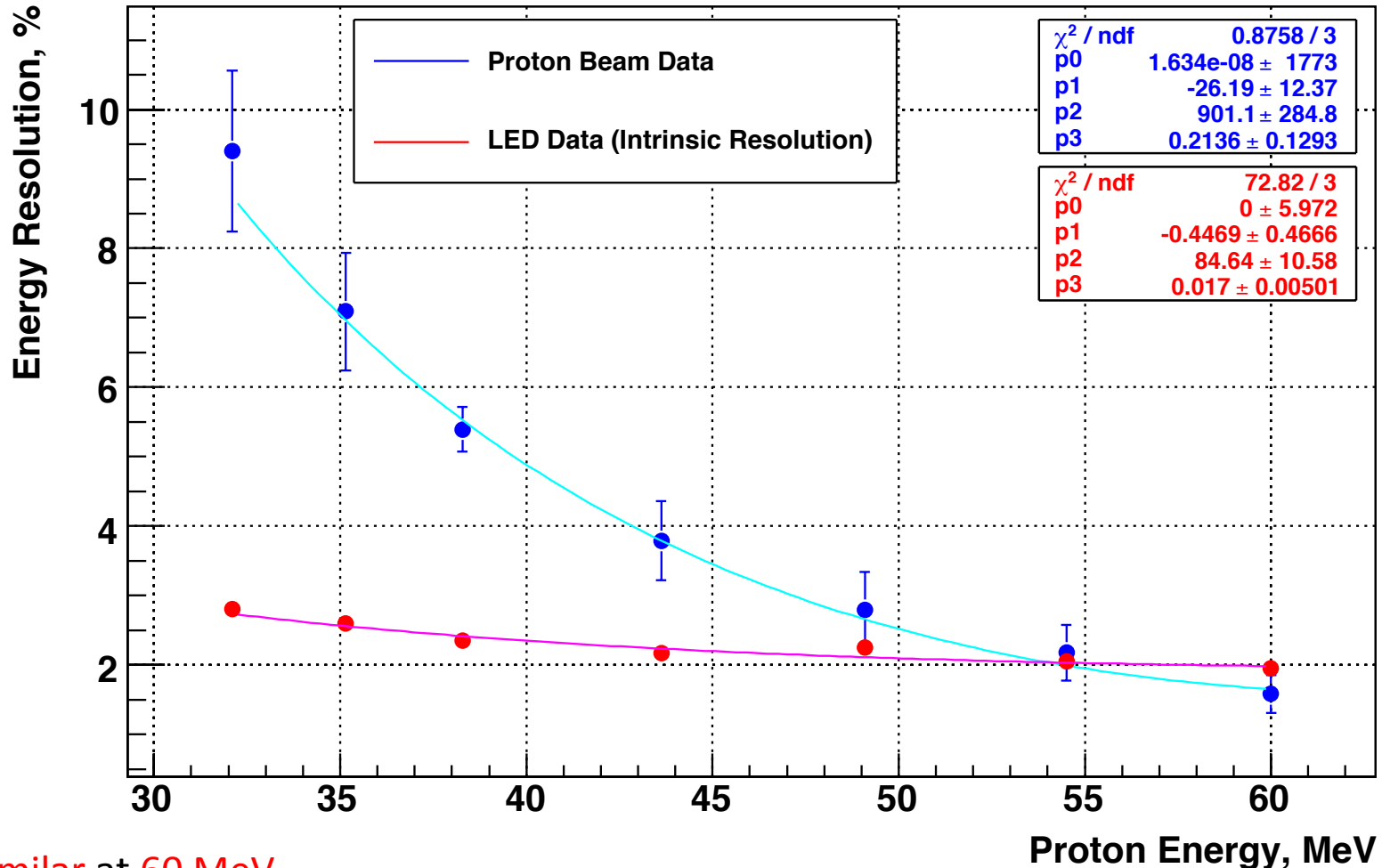
- Similar at 60 MeV
- Proton beam energy resolution much worse than intrinsic energy resolution at lower energies due to scattering of protons

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

Proton Energy as a Function of ADC Mean: 800V

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

For 800V: Deviation from linearity < 2%!

	200ns gate		100ns gate		50ns gate	

| | 1.54 % | 1.69 % | 1.99 % |

χ^2 / ndf	195.5 / 2
p0	18.85 ± 0.03457
p1	0.004558 ± 7.507e-06

χ^2 / ndf	139.3 / 2
p0	18.81 ± 0.03464
p1	0.004955 ± 8.16e-06

χ^2 / ndf	217.1 / 2
p0	18.58 ± 0.035
p1	0.005955 ± 9.808e-06
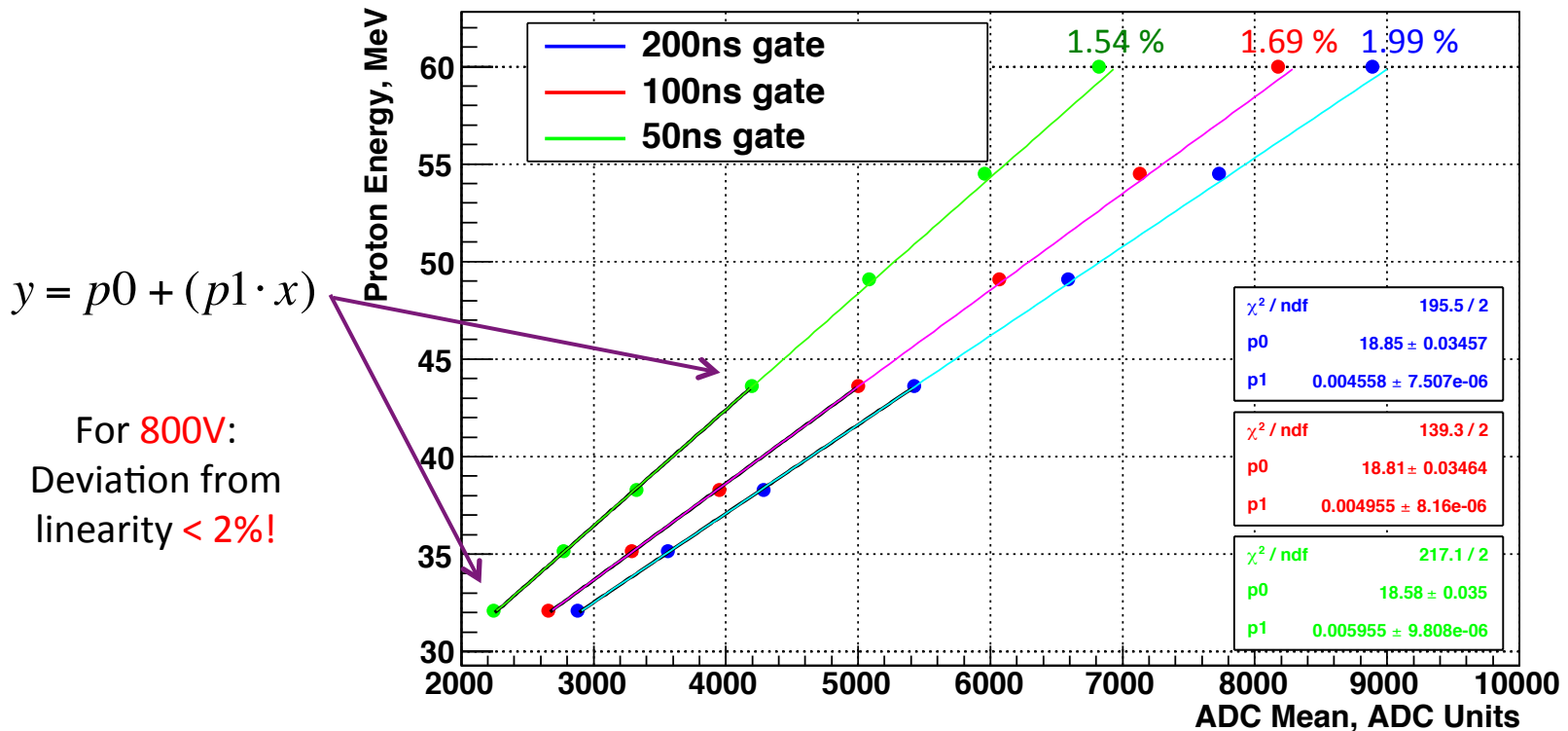
Measuring Quenching

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

Proton Energy as a Function of ADC Mean: 800V
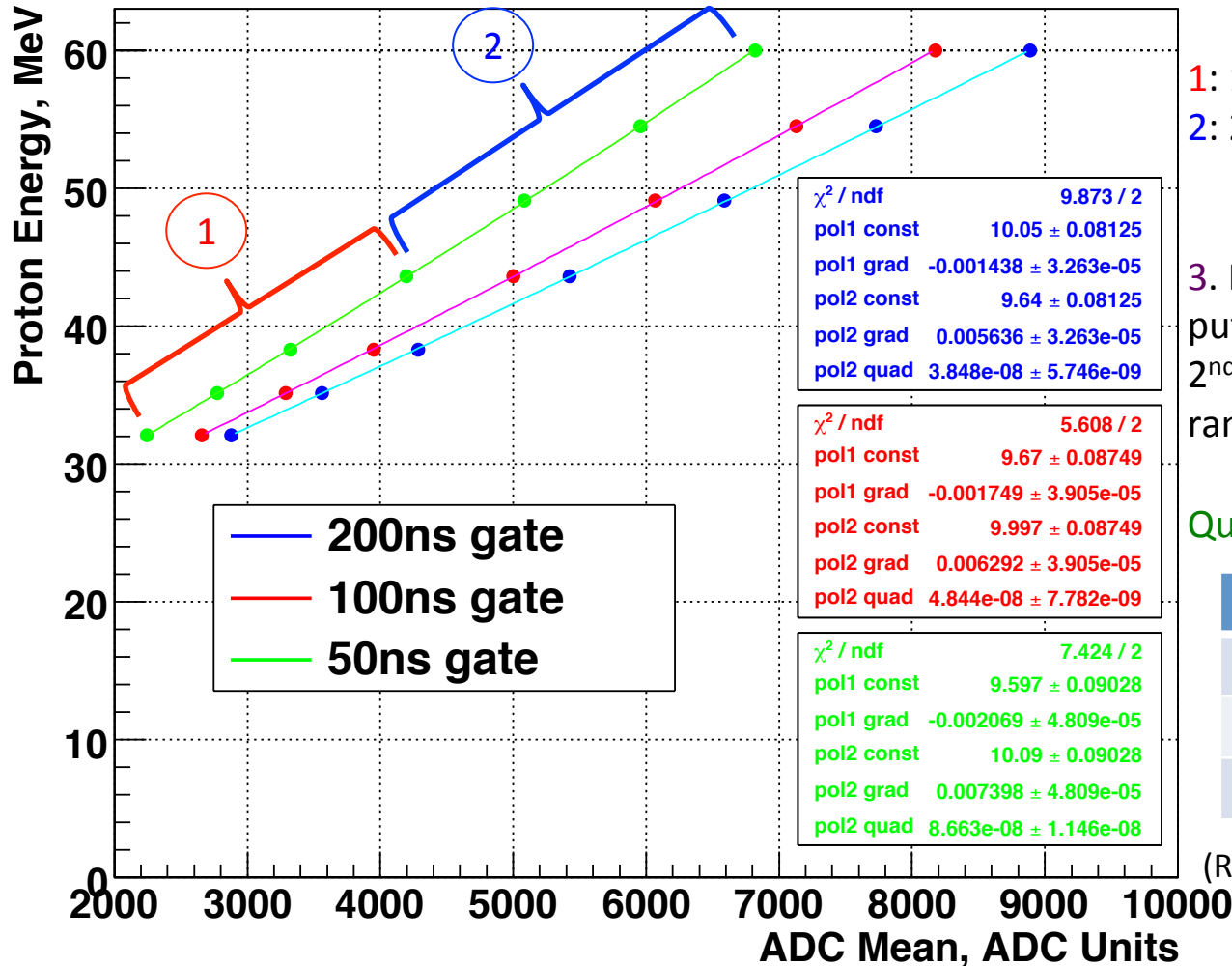
Fitting procedure:

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)

Legend (plot):
- 200ns gate
- 100ns gate
- 50ns gate

Blue fit box:
χ^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

Red fit box:
χ^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

Green fit box:
χ^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

Linearity: 900 V

Proton Energy as a Function of ADC Mean: 900V

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

For 900V:
Deviation from
linearity > 10%

Can non-linearity
be accurately
accounted for?

9.67 %   10.19 %   12.27 %

	200ns gate
	100ns gate
	50ns gate

χ^2 / ndf	233.8 / 2
p0	18.83 ± 0.03461
p1	0.002308 ± 3.802e-06

χ^2 / ndf	188.6 / 2
p0	18.79 ± 0.03466
p1	0.002515 ± 4.142e-06

χ^2 / ndf	176.4 / 2
p0	18.51 ± 0.03512
p1	0.003051 ± 5.026e-06
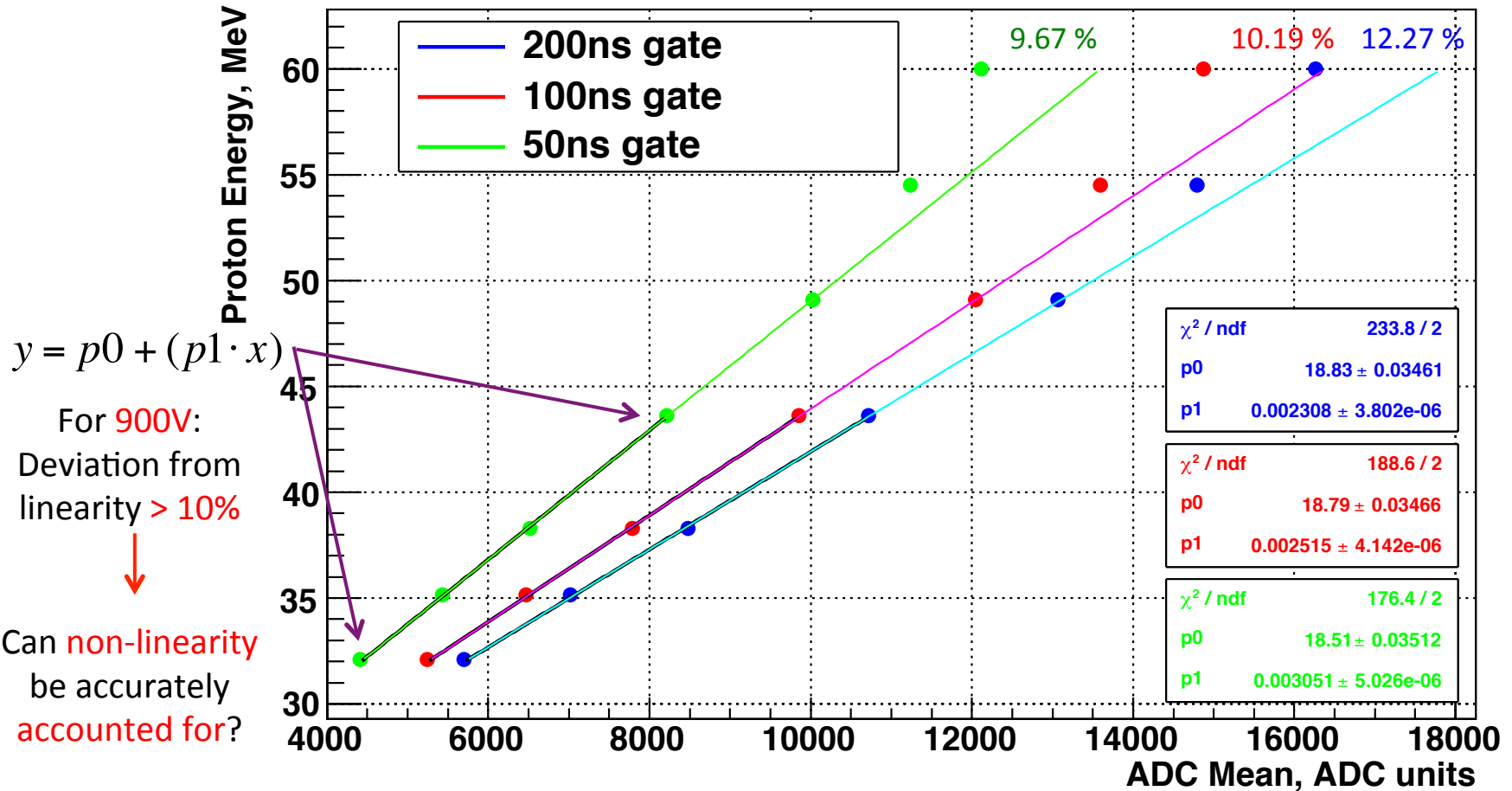
"Unfolding": Getting a Grip on Non-Linearity

- 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