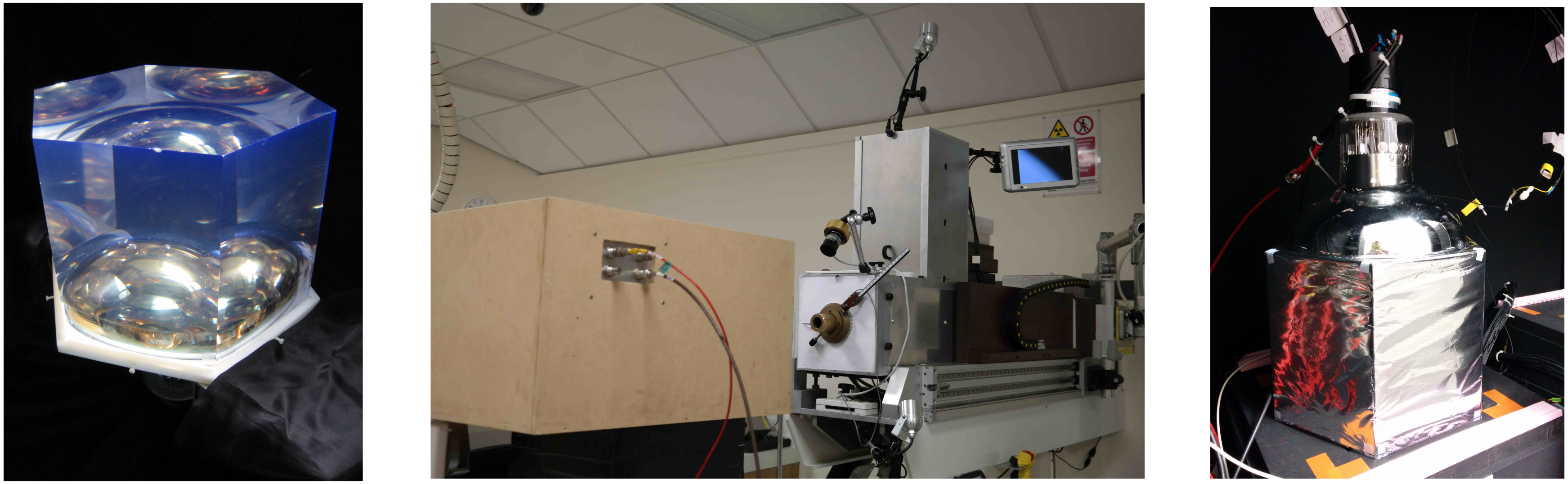


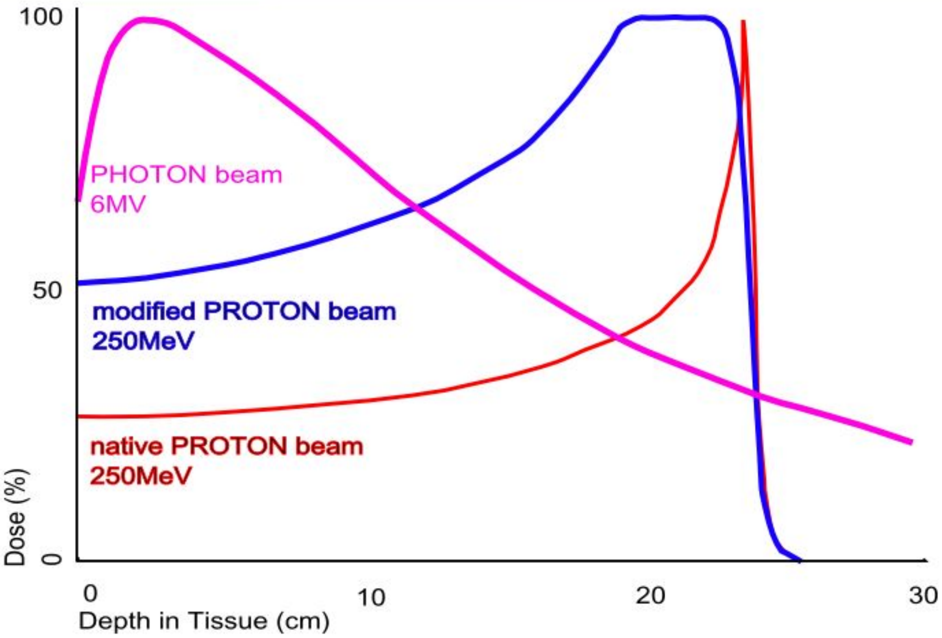
Calorimetry for Cancer Proton Therapy – Can We Help?

Anastasia Basharina-Freshville

(University College London)

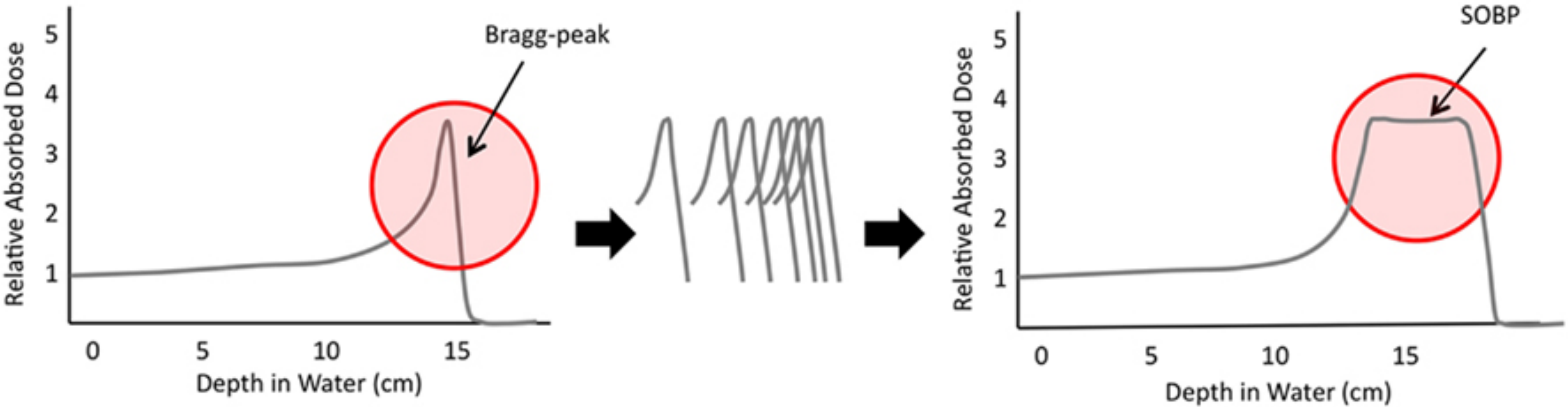
Why Proton Therapy?

- 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



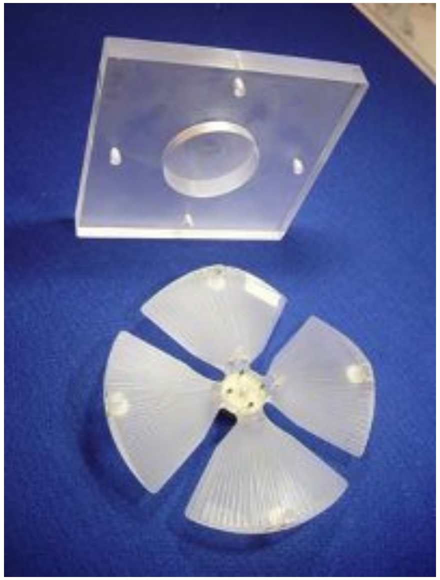
http://samhs.org.au/Virtual%20Museum/xrays/Braggs-peak-rxth/braggpeakrxth.htm

Why Proton Therapy?

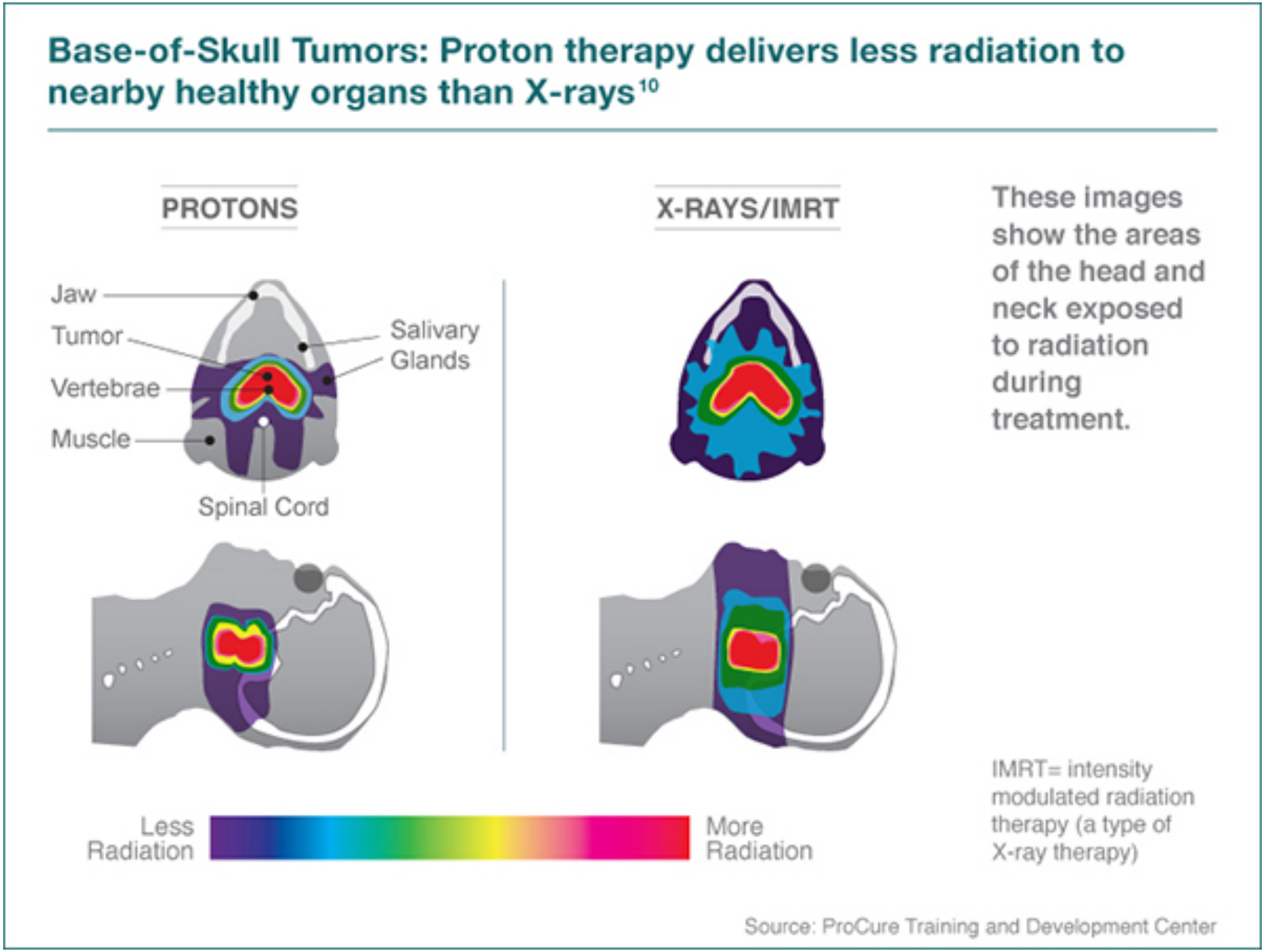


Front. Oncol., 06 September 2011 | doi: 10.3389/fonc.2011.00024

- 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/



Base-of-Skull Tumors: Proton therapy delivers less radiation to nearby healthy organs than X-rays[10]

These images show the areas of the head and neck exposed to radiation during treatment.

IMRT= intensity modulated radiation therapy (a type of X-ray therapy)

Source: ProCure Training and Development Center

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

Proton Therapy Challenges

- Precise measurements of beam energy and energy spread
  - Target: ~1% level

Our starting point!

- 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 based imaging systems to proton therapy treatment plans, which introduces imprecision
  - Currently, the patient is imaged away from the treatment – any movement of the patient’s anatomy introduces further imprecision

- Neutron background
  - Neutron background flux at proton therapy facilities is poorly known
  - Must be measured to avoid adverse biological effects to the patient

Proposed Solutions

- Calorimetry approach for beam energy and spread measurements

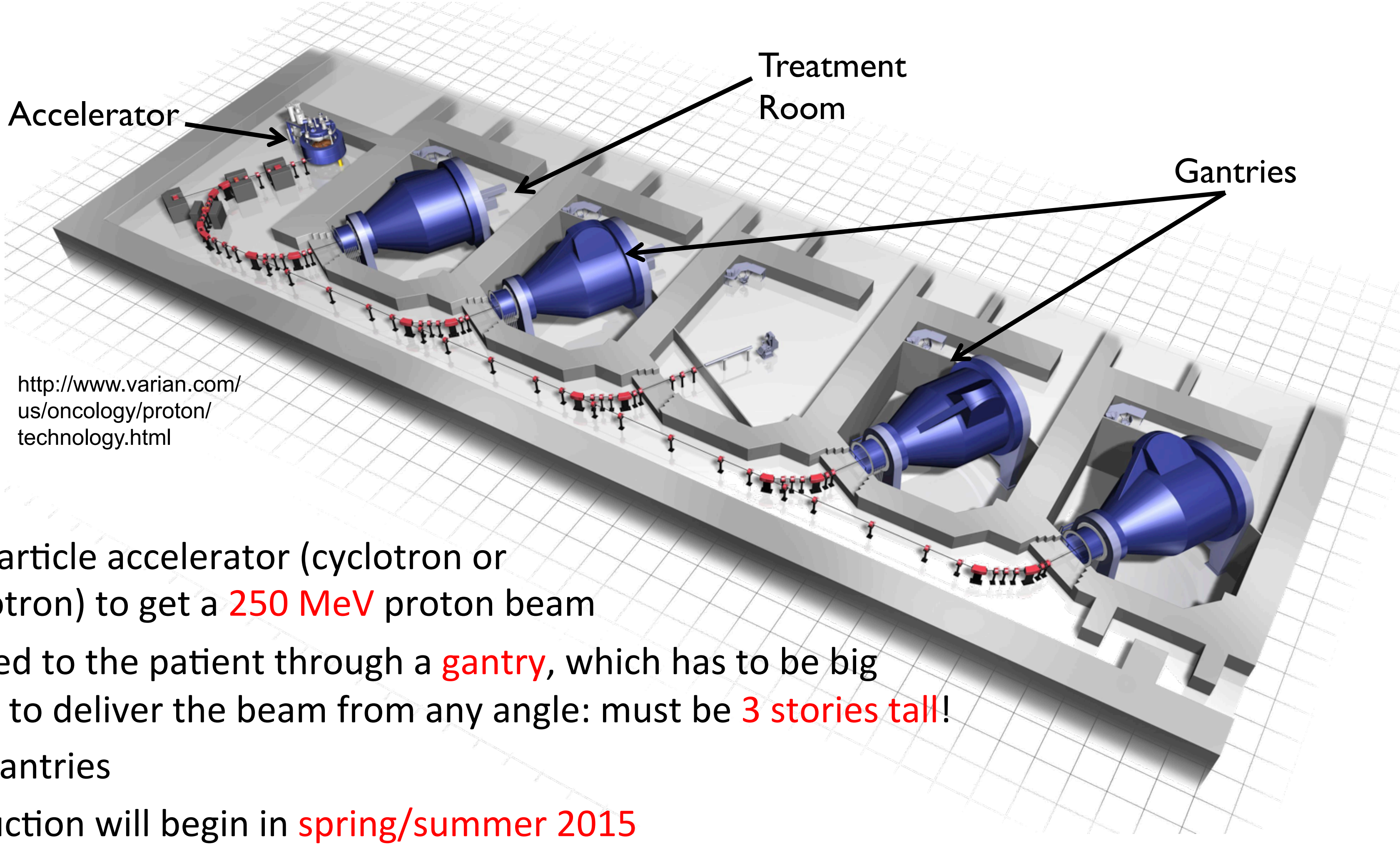
↑

The focus of this seminar

- 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: ~0.5 – 1% for 300 MeV imaging protons

- Neutron background:
  - Calorimetry approach (discussed in “Future Plans”)

UCLH Proton Therapy Centre



http://www.varian.com/us/oncology/proton/technology.html

- Use a particle accelerator (cyclotron or synchrotron) 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 will begin in spring/summer 2015
- First patient treatment: three years from start of construction

↑

Can we work on some of the challenges before then?

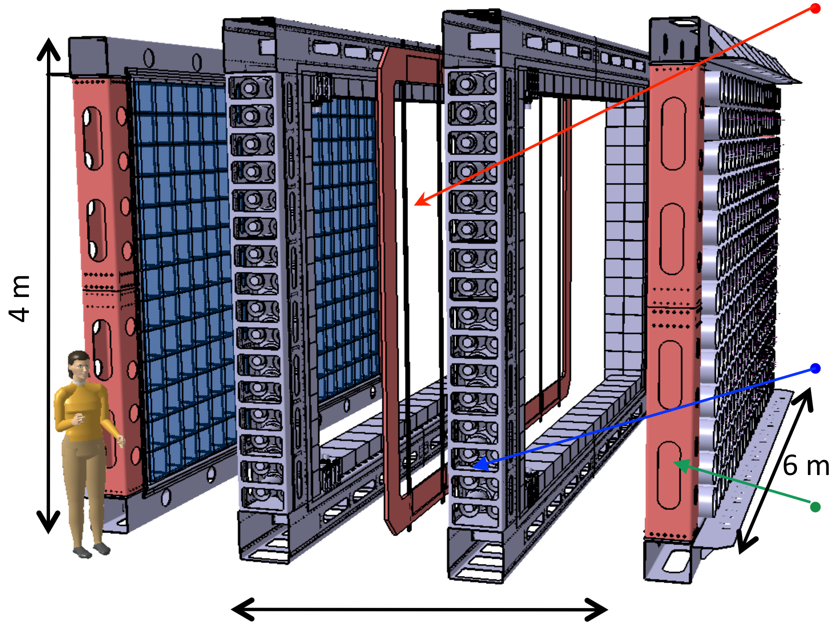
SuperNEMO

supernemo
collaboration

- Neutrinoless double beta decay detector using NEMO3's tracker-calorimeter technique
  Target sensitivity: $T_{½} > 10^{26}$ years → $\langle m_\nu \rangle < 0.04 – 0.1$ 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
  → particle identification (for background suppression)

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

- Passive shielding surrounding each module

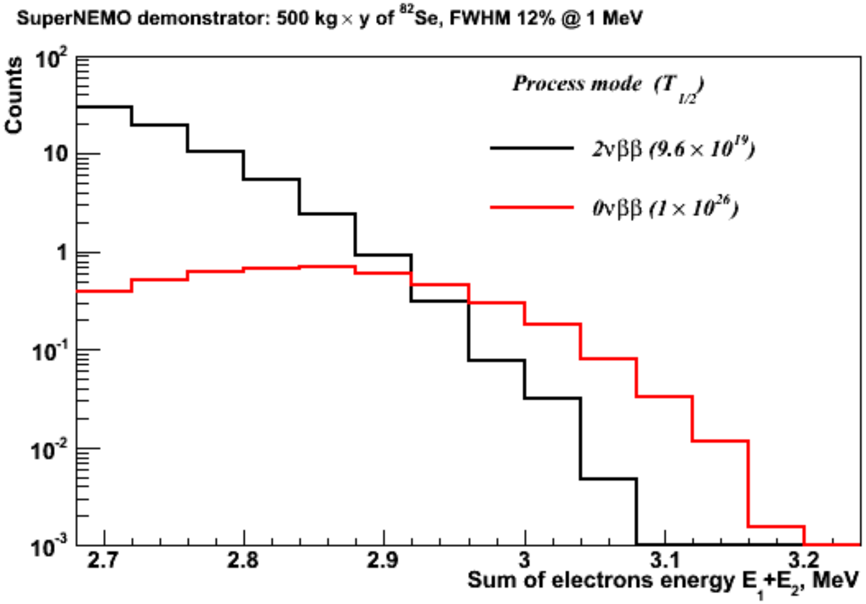
From NEMO3 to SuperNEMO

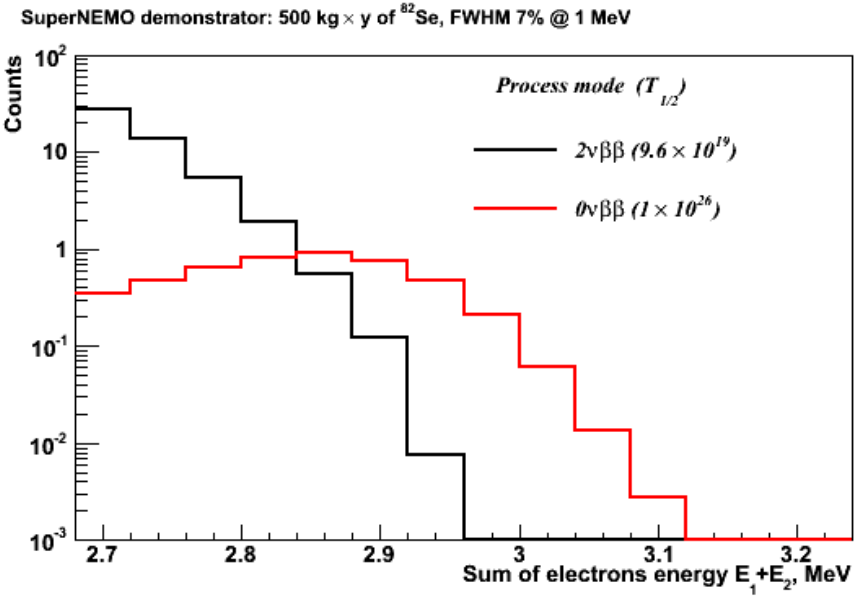
- Energy resolution is one of the main challenges (factor of 2 improvement):

$$\text{NEMO3: } \frac{14-17\%}{\sqrt{E(MeV)}} \longrightarrow \text{SuperNEMO: } \frac{7\%}{\sqrt{E(MeV)}}$$

- SuperNEMO scintillator has to be organic plastic scintillator
  (high light yield, low electron back-scattering, high radiopurity, fast timing)
  → Can 7% FWHM 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

Energy Resolution

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

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

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

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":

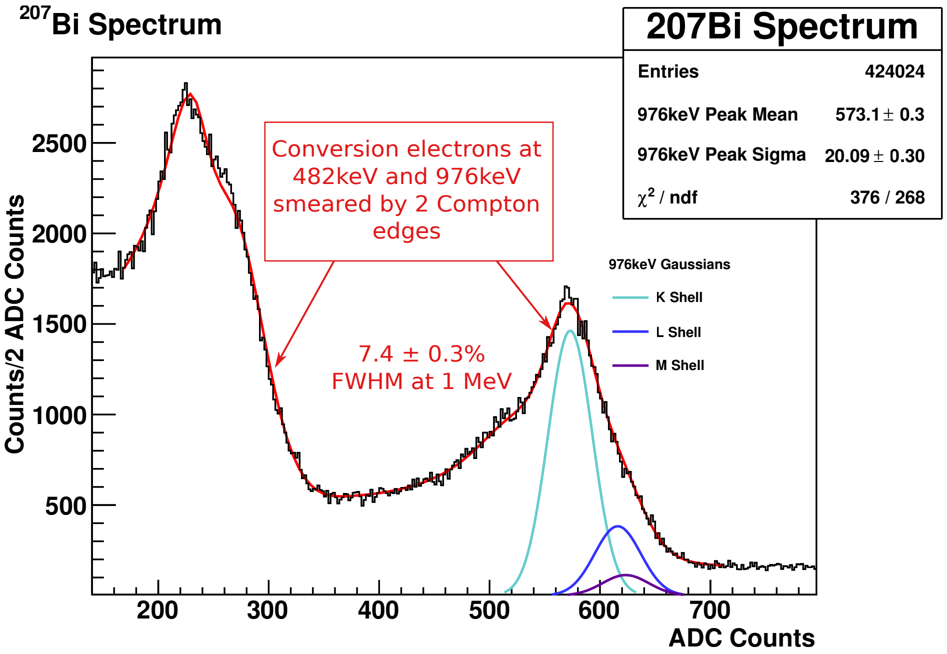
scintillator wrapped in reflective material coupled to a PMT

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

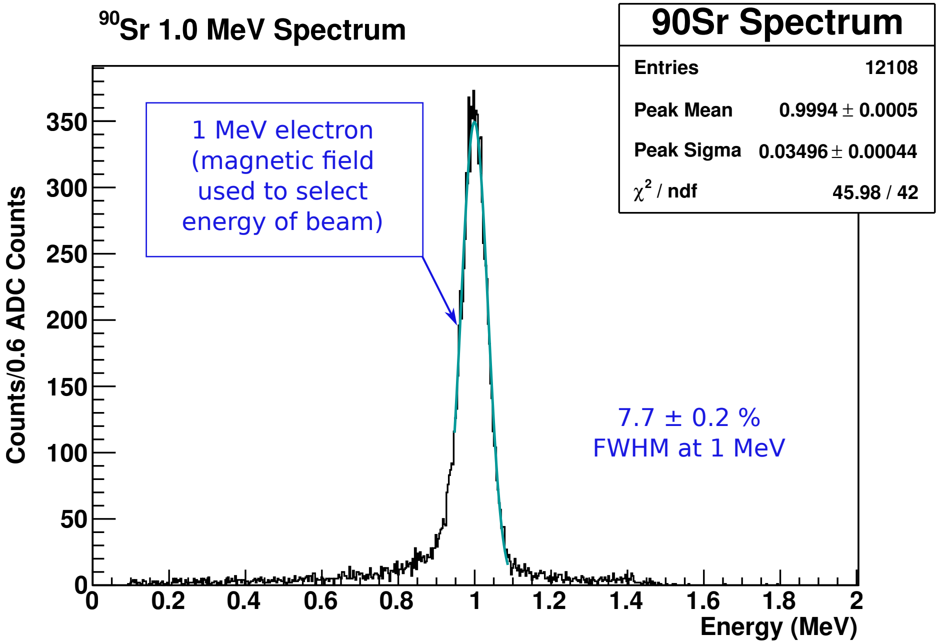


Conversion electrons at 482keV and 976keV smeared by 2 Compton edges

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



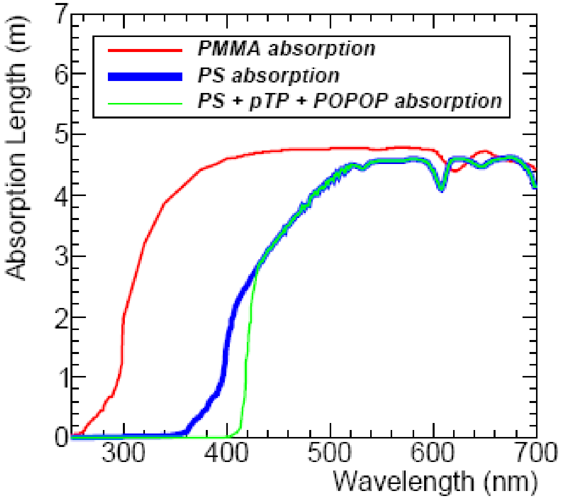
1 MeV electron (magnetic field used to select energy of beam)

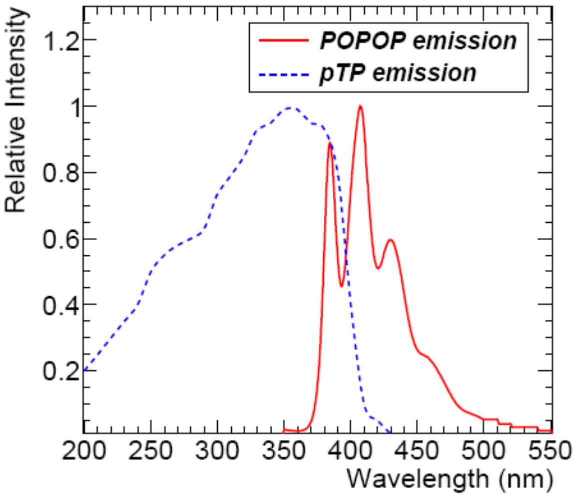
7.7 ± 0.2 % FWHM at 1 MeV

SuperNEMO Calorimeter R&D: Simulations

- Full calorimeter simulations:
  - GENBB event generator
  - Physics simulations with GEANT4 (optical photon transport in scintillator detectors)

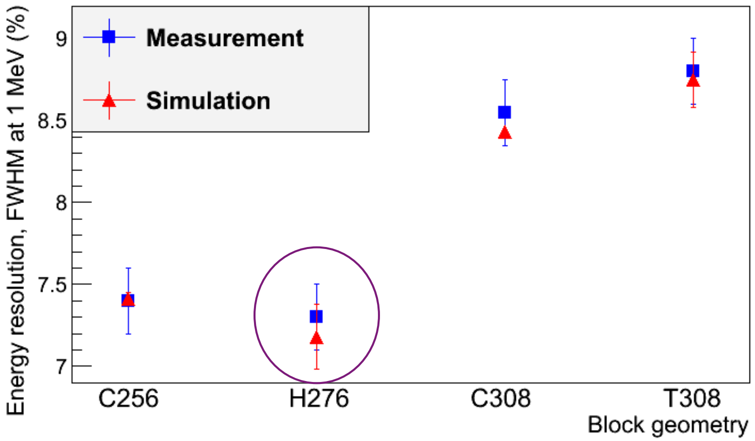
- The model accounts for wavelength dependence of optical properties, all of which have been experimentally measured, of the:
  - scintillators (self absorption and re-emission)
  - reflective wrappings
  - photomultipliers (QE)
  - optical coupling materials
  - refractive index of optical materials





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	$\frac{\Delta E}{E}(\%)$	f_{FWHM}
NEMO-3 PST	8.9 ±0.2	1.
EJ-200 PVT	8.3 ±0.2	1.07 ±0.03
EJ-204 PVT	7.8 ±0.2	1.12 ±0.03

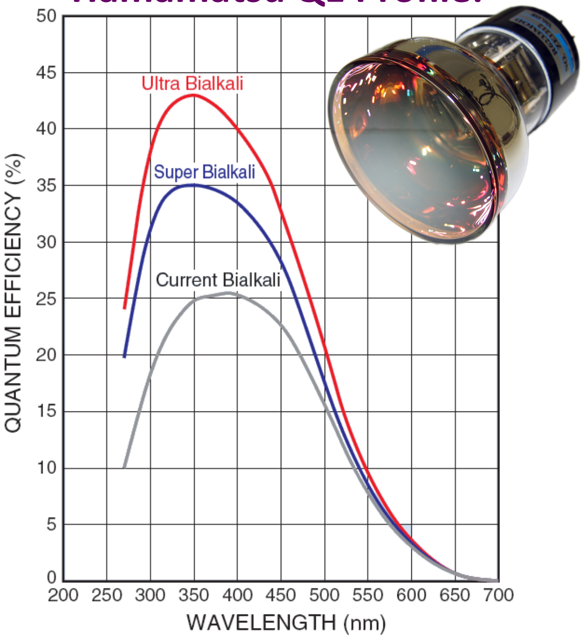
- Close collaboration with manufacturers (JINR Dubna, ISM Kharkiv, ENVINET, ELJEN) for contents of:
  - PPO scintillating agent
  - POPOP wavelength shifter

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

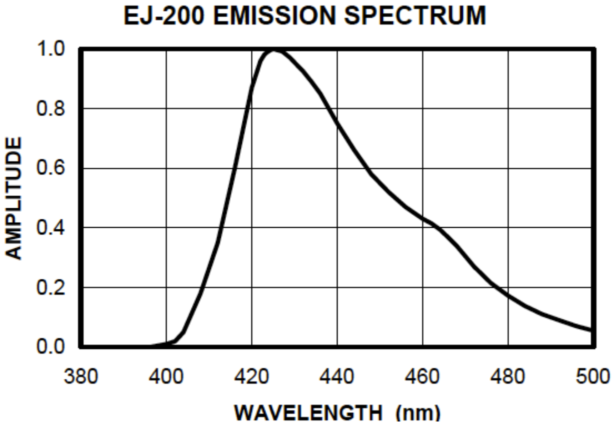
SuperNEMO Calorimeter R&D: PMTs

- Photocathode QE:

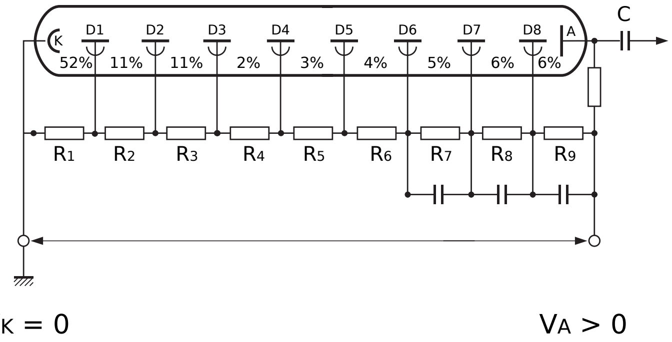
Hamamatsu QE Profile:



  - Bi-alkali alloy development for photocathode material has achieved QE > 40%
  - Close collaboration with Hamamatsu to optimise QE to the emission spectra of the scintillator

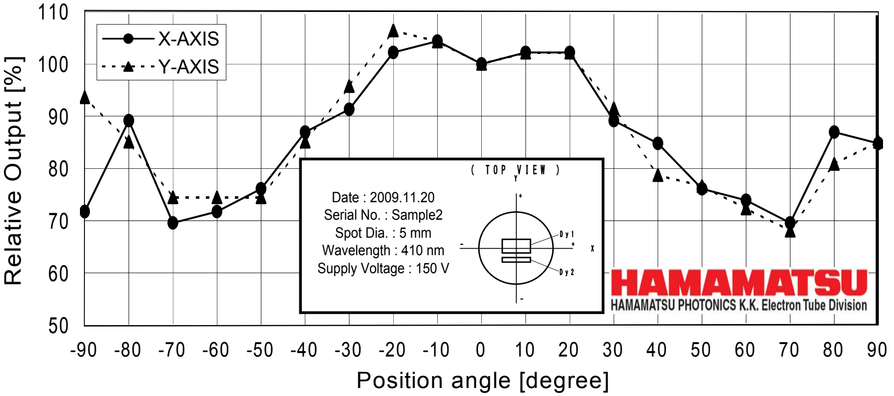


- Collection efficiency (close collaboration with Hamamatsu on 8” R5912-MOD tube):
  - Number of dynode stages reduced from 10 to 8
  - Voltage divider optimisation
  - Improved from <70% to ~80%

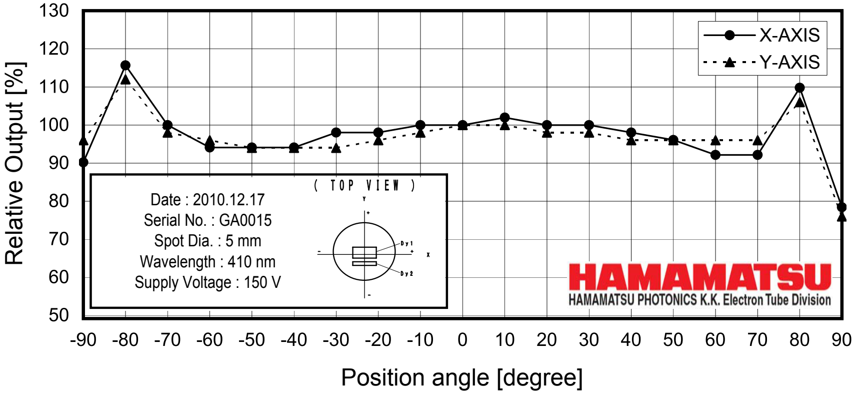


SuperNEMO Calorimeter R&D: PMTs

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



→

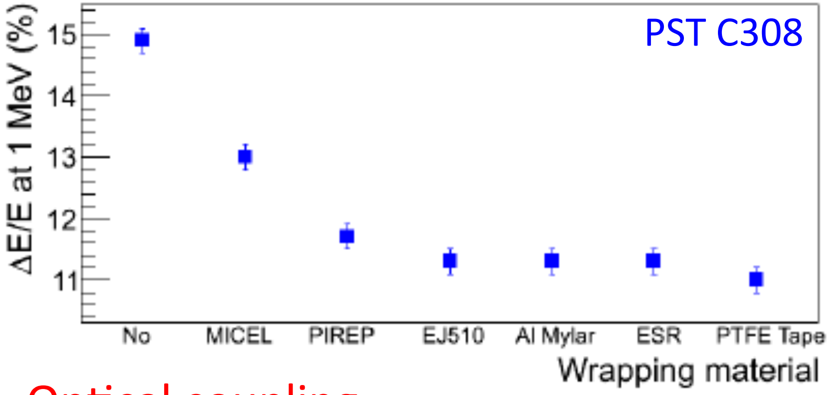


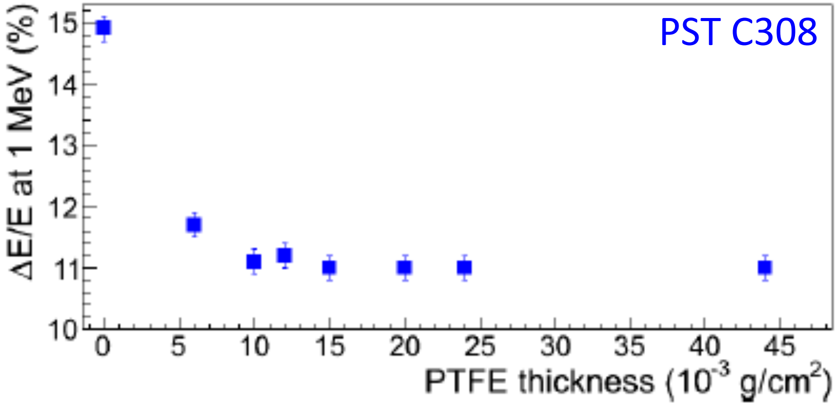
- Timing:
  - Reducing the number of dynode stages improves the timing of the PMT by reducing the time transition spread (TTS)

- Gain and Linearity (a big achievement!):
  - Reducing the number of dynode stages and opitmising the voltage divider decreases the gain: ~1 x 10^5
    → Good linearity (< 2% for very high light levels) 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)



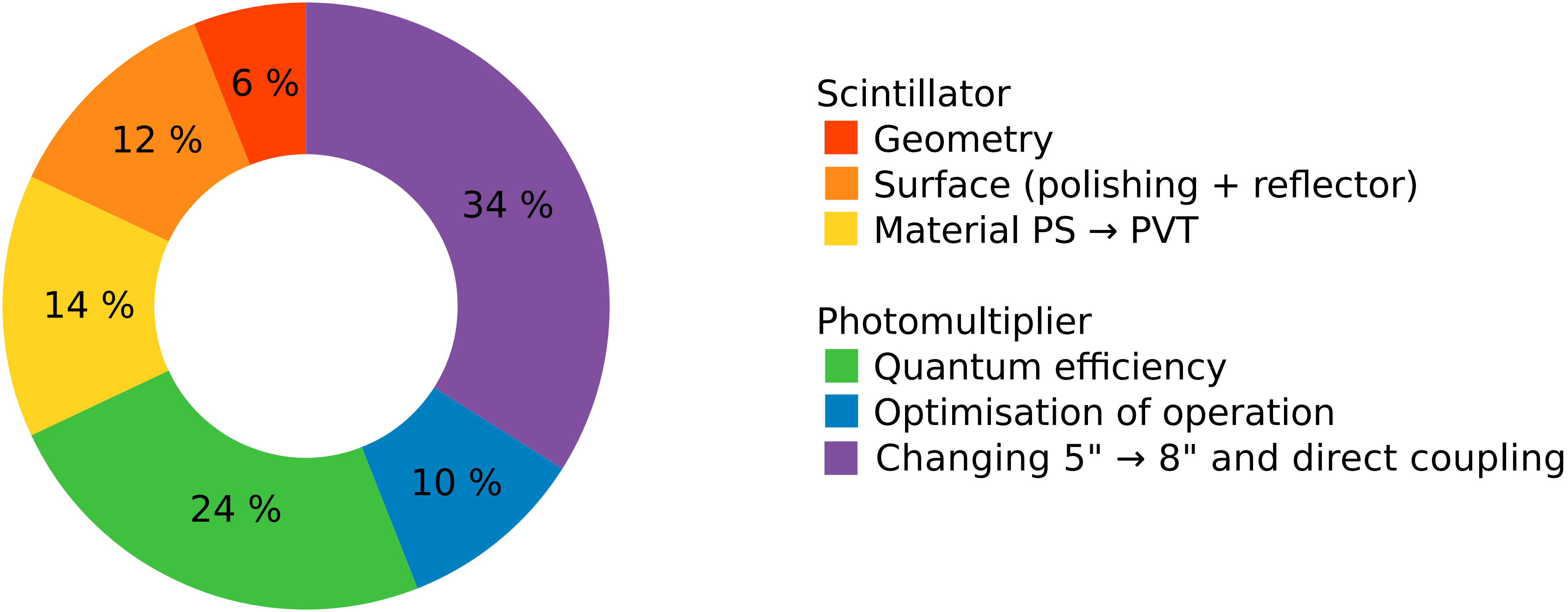


- Optical coupling:
  - Good optical coupling between scintillator and PMT essential for uniform and complete light collection

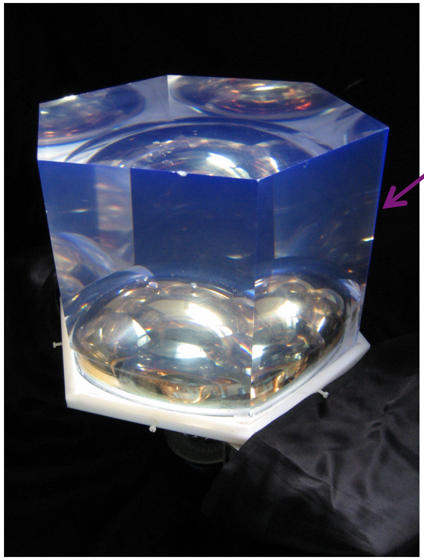
Optical Material	Refractive Index	$\frac{\Delta E}{E}$ (%)	f_{FWHM}
Alcohol	1.37	9.4 ± 0.2	1.
Gel	1.46	8.6 ± 0.2	1.08 ± 0.3
Gel	1.52	8.4 ± 0.2	1.11 ± 0.3
RTV 615	1.41	9.4 ± 0.2	1.00 ± 0.3

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

SuperNEMO Calorimeter R&D: Summary



Optimised SuperNEMO Optical Module Design



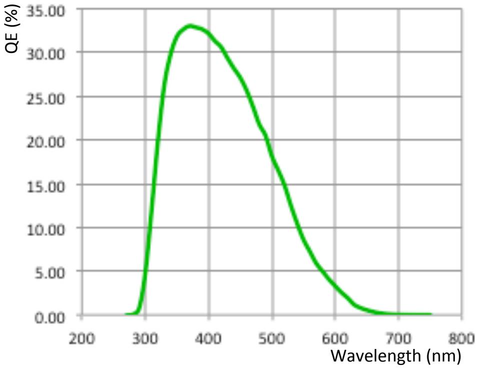
$$\frac{7.5\%}{\sqrt{E(MeV)}}$$

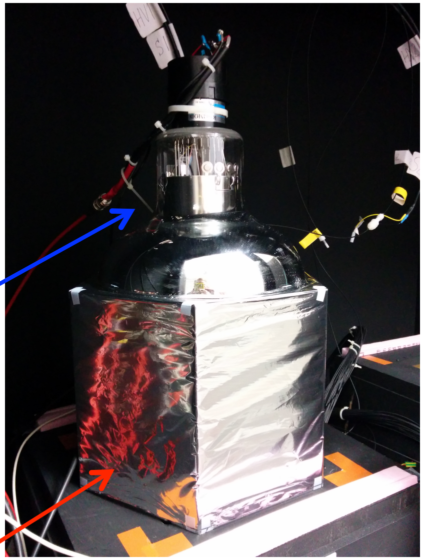
EJ-200 hexagonal PVT block:

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 7.5% FWHM 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 (~25 MHz):
  - A proton beam delivers a random number of protons per bucket, which will worsen the energy resolution measured
  - We require 1 proton per bucket for a good detector response
- 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 pencil proton beam (60 MeV) simulated, positioned 70 cm underneath the entrance face of the scintillator block

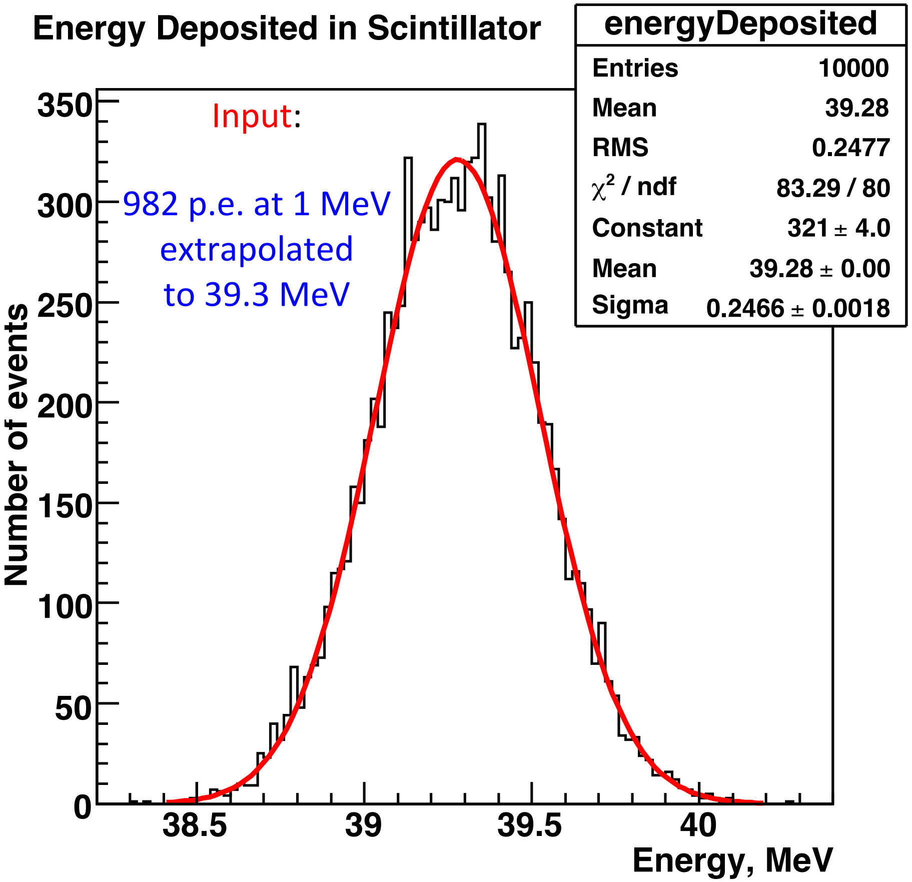
- Scintillator modeled as a square block (256 mm x 256 mm x 120 mm) with scintillator composition fully described

- Quenching of scintillation light in plastic scintillator for protons

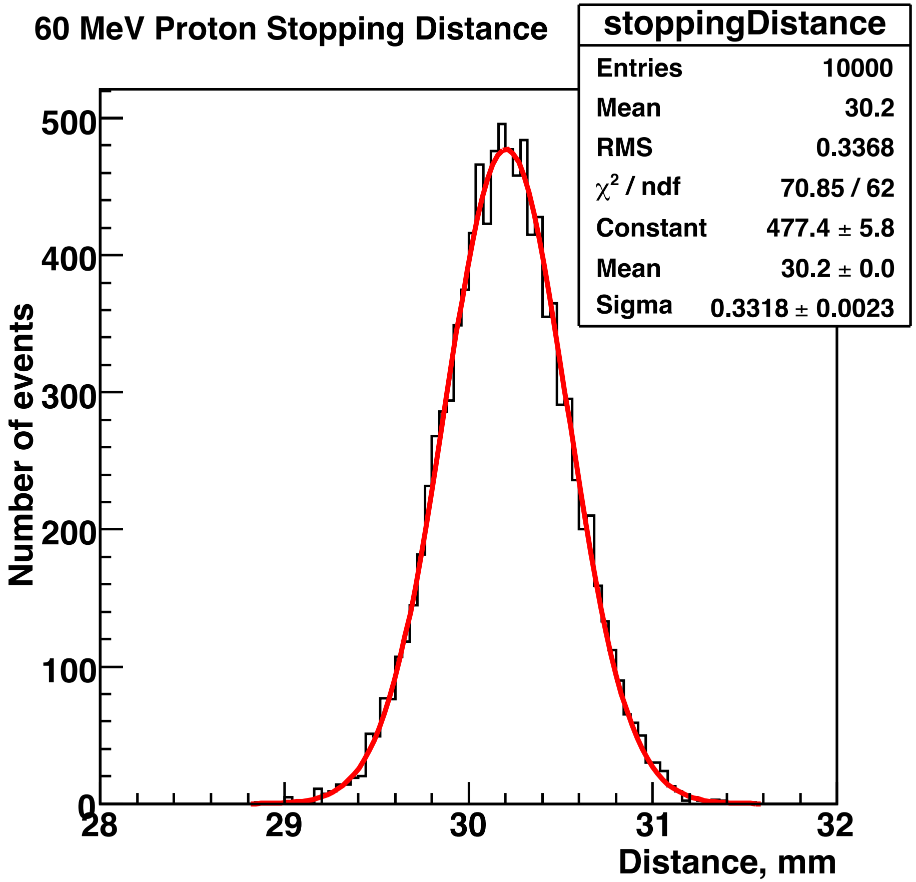
- Energy deposited smeared according to Poissonian fluctuations in the number of generated photo-electrons

- The number of photo-electrons at per MeV taken from test bench data (SuperNEMO calorimeter R&D): 982 photo-electrons per MeV
  (for an energy resolution of 7.5% FWHM at 1MeV)

Step 1: GEANT4 Simulations


Energy Deposited in Scintillator

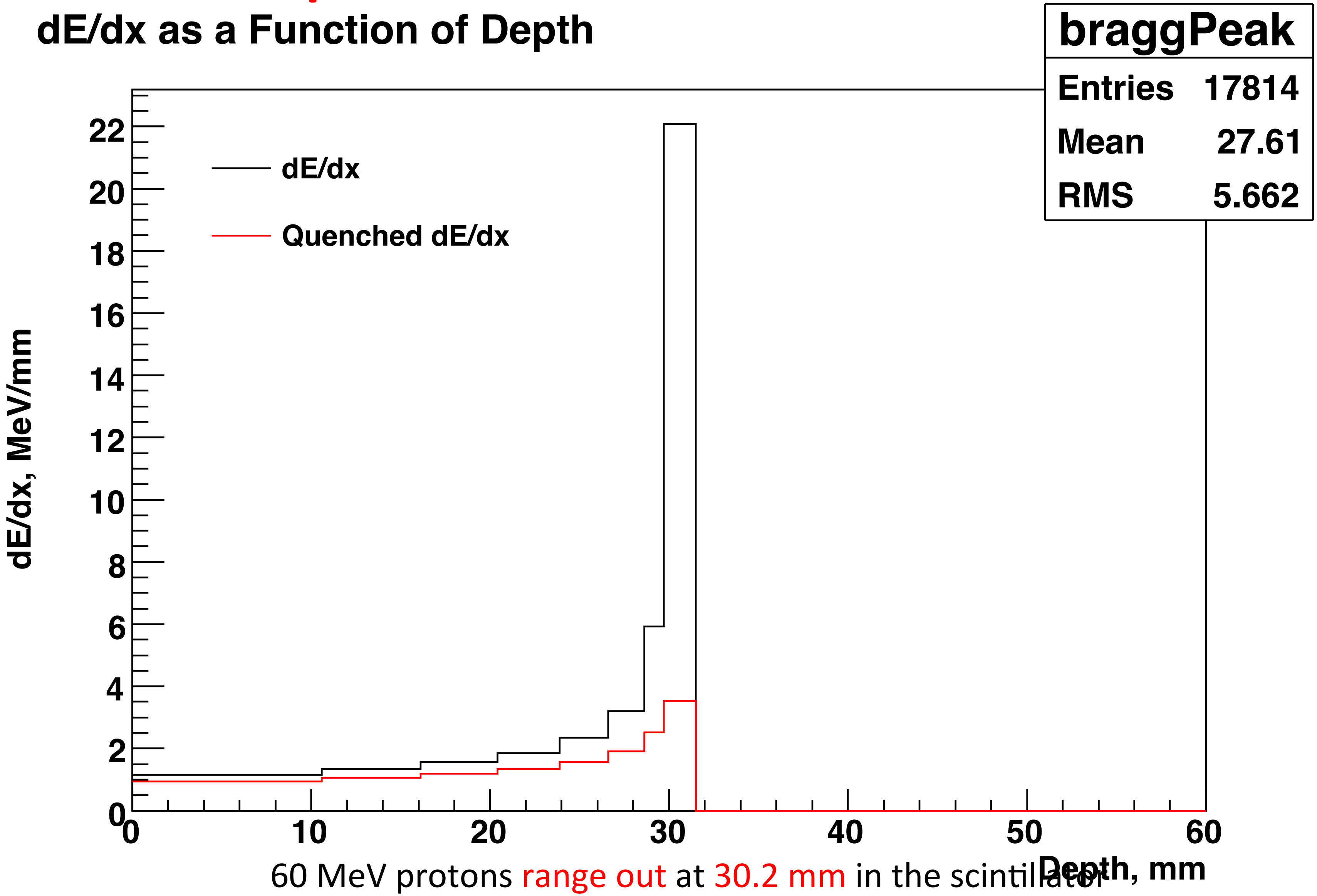
Input:
982 p.e. at 1 MeV
extrapolated
to 39.3 MeV


60 MeV Proton Stopping Distance

- Quenching from simulations:
  - Simulated mean: 39.3 MeV
  - Quenching: 35% for 60 MeV protons
- Energy resolution from simulations:
  - σ: 0.247, μ: 39.28
  - ΔE/E: 1.48 % FWHM

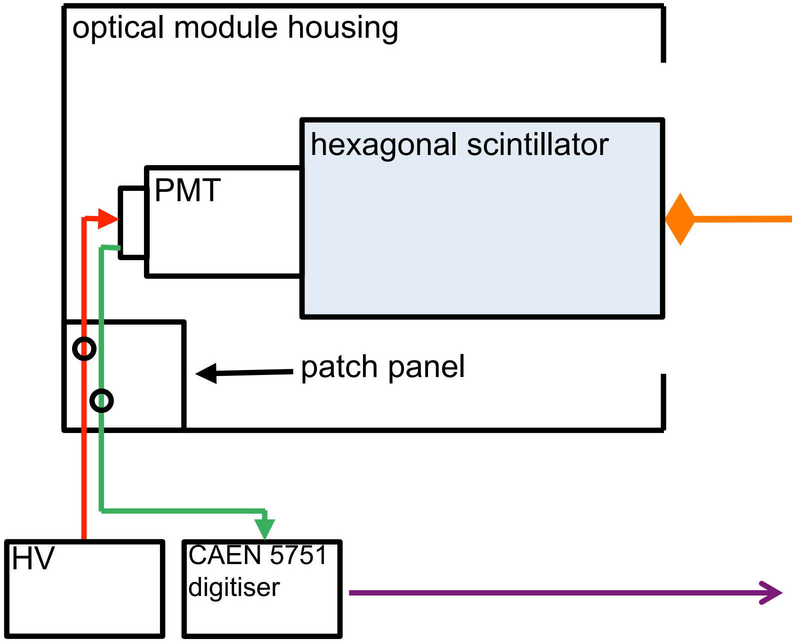
$$\frac{\Delta E}{E} = \frac{2.35\sigma}{E}$$

Step 1: GEANT4 Simulations



60 MeV protons range out at 30.2 mm in the scintillator

Step 2: Equipment Setup



optical module housing

hexagonal scintillator

PMT

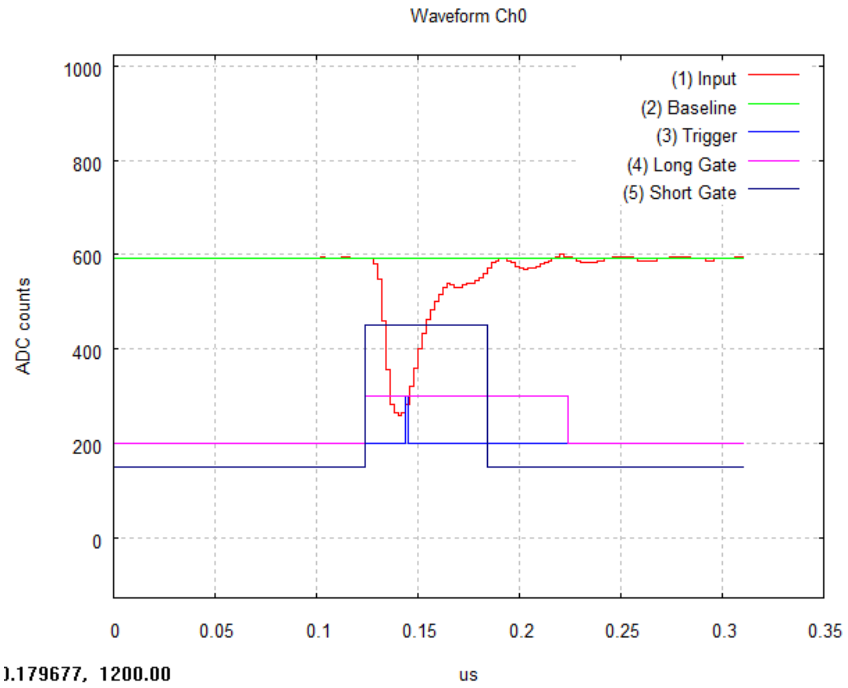
30 cm

proton beam/207Bi source

patch panel

HV

CAEN 5751 digitiser



CAEN DT5751 Digitiser:

Dual-gate signal integration

→ On-the-fly pulse shape analysis

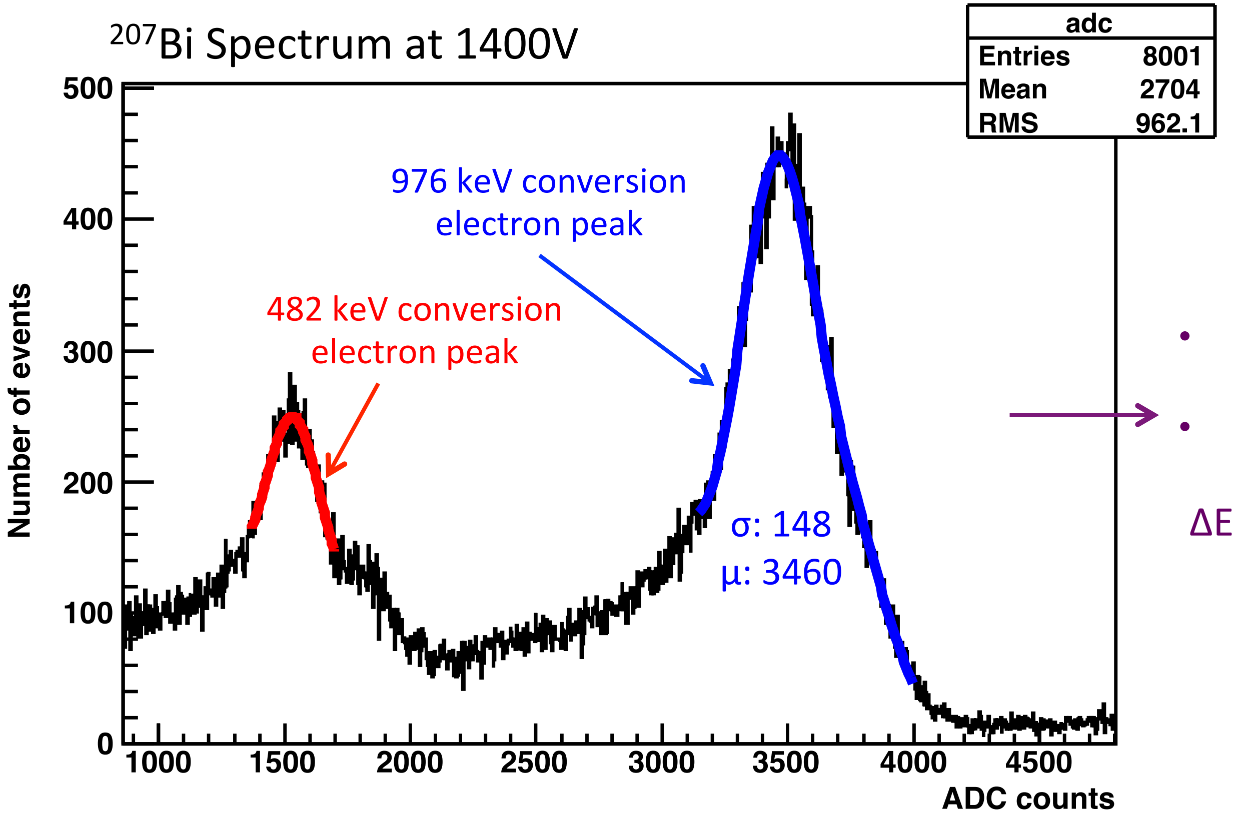
→ Neutron/gamma discrimination

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



976 keV conversion electron peak

482 keV conversion electron peak

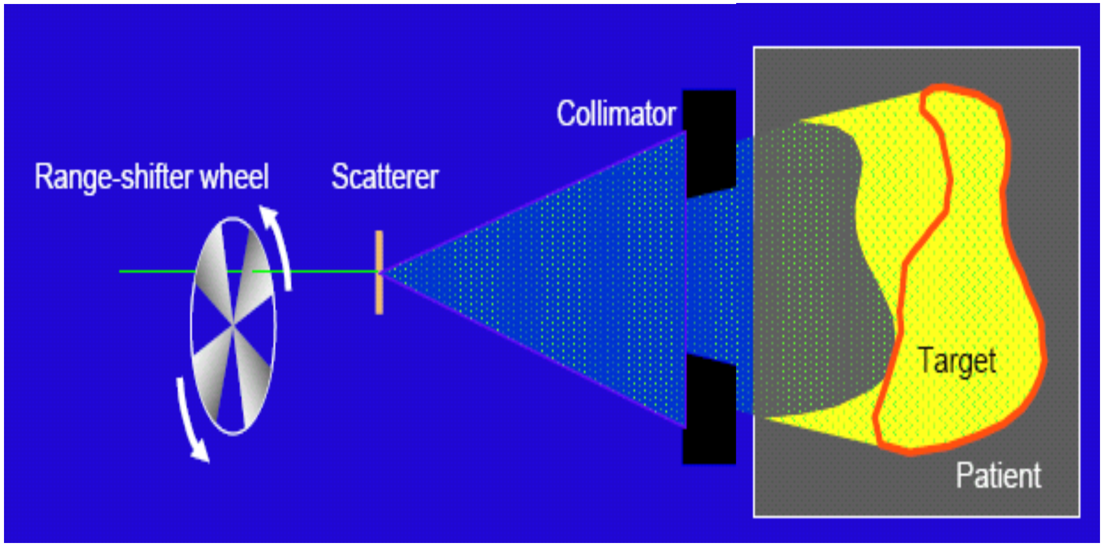
σ: 148
μ: 3460

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

ΔE/E: **8.5 ± 0.5 % FWHM** at 1 MeV

Step 4: Clatterbridge Cancer Centre

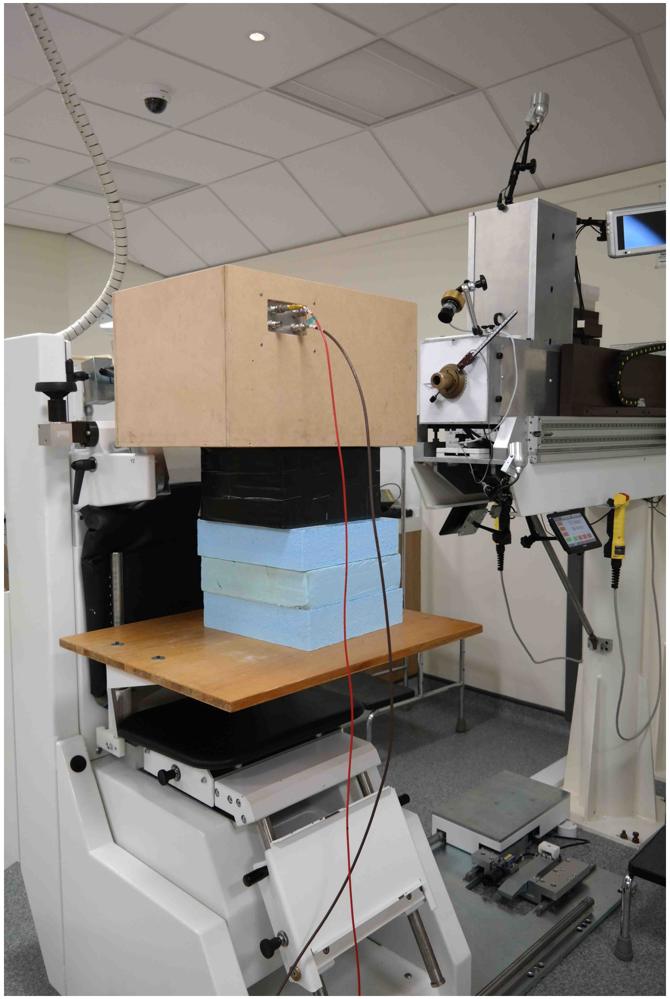
- Only currently operational proton beam treatment centre in the UK
- Home to the Douglas Cyclotron → produces 60 MeV proton beam for the treatment of ocular melanomas (penetration of 60 MeV protons: 31 mm in water)
- Double scattering beam technique:



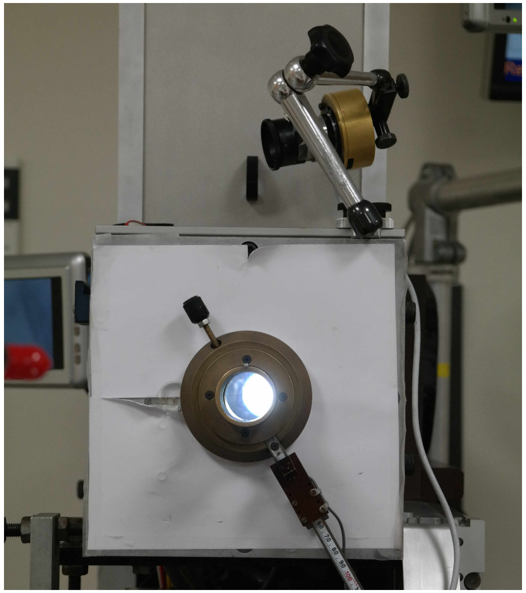
- Beam accelerated to single energy
- Beam passes through range-shifter wheel that modulates the proton beam energy to reach front/back of target volume
- Scatterer enlarges beam to cover whole volume
- Collimator shapes outer edge of beam to target area

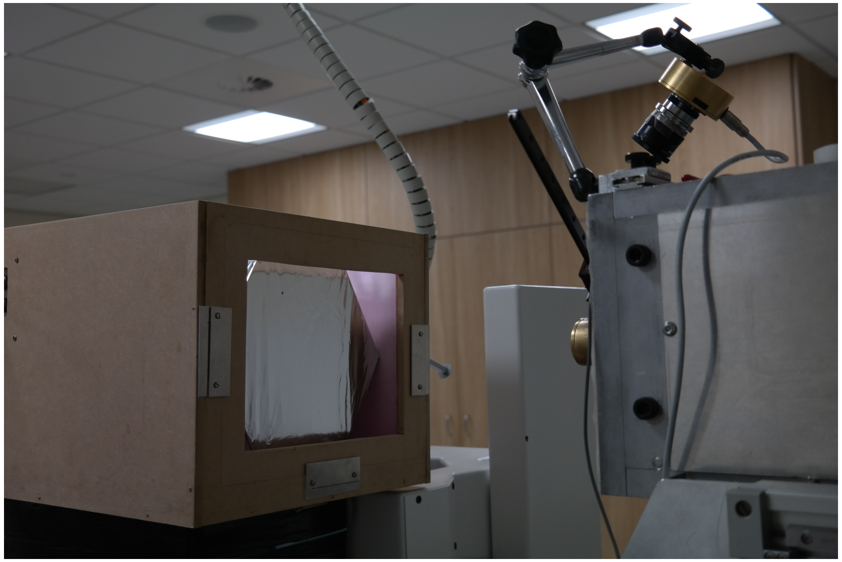
Step 4: Clatterbridge Cancer Centre

- Four full days in total of proton beam access granted to UCL in December 2013 and December 2014



Step 4: Clatterbridge Cancer Centre

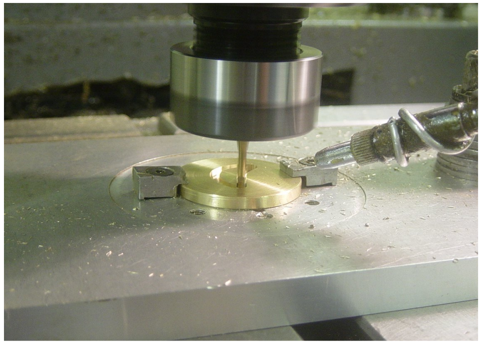




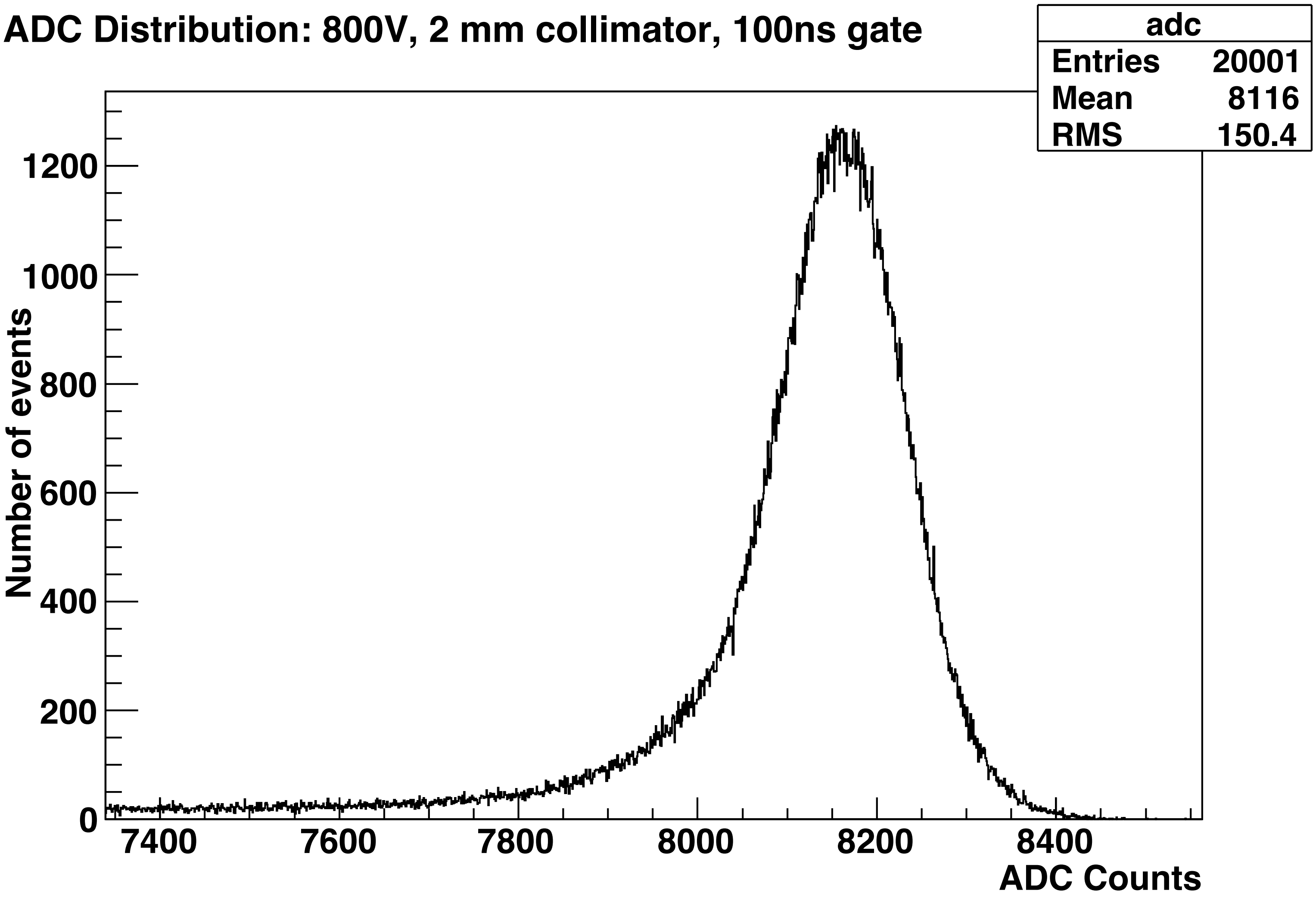
Step 4: Clatterbridge Cancer Centre

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 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)
  - Integrating window of acquisition on the CAEN digitiser (50 ns, 100 ns, 200 ns): sensitive to pile up effects

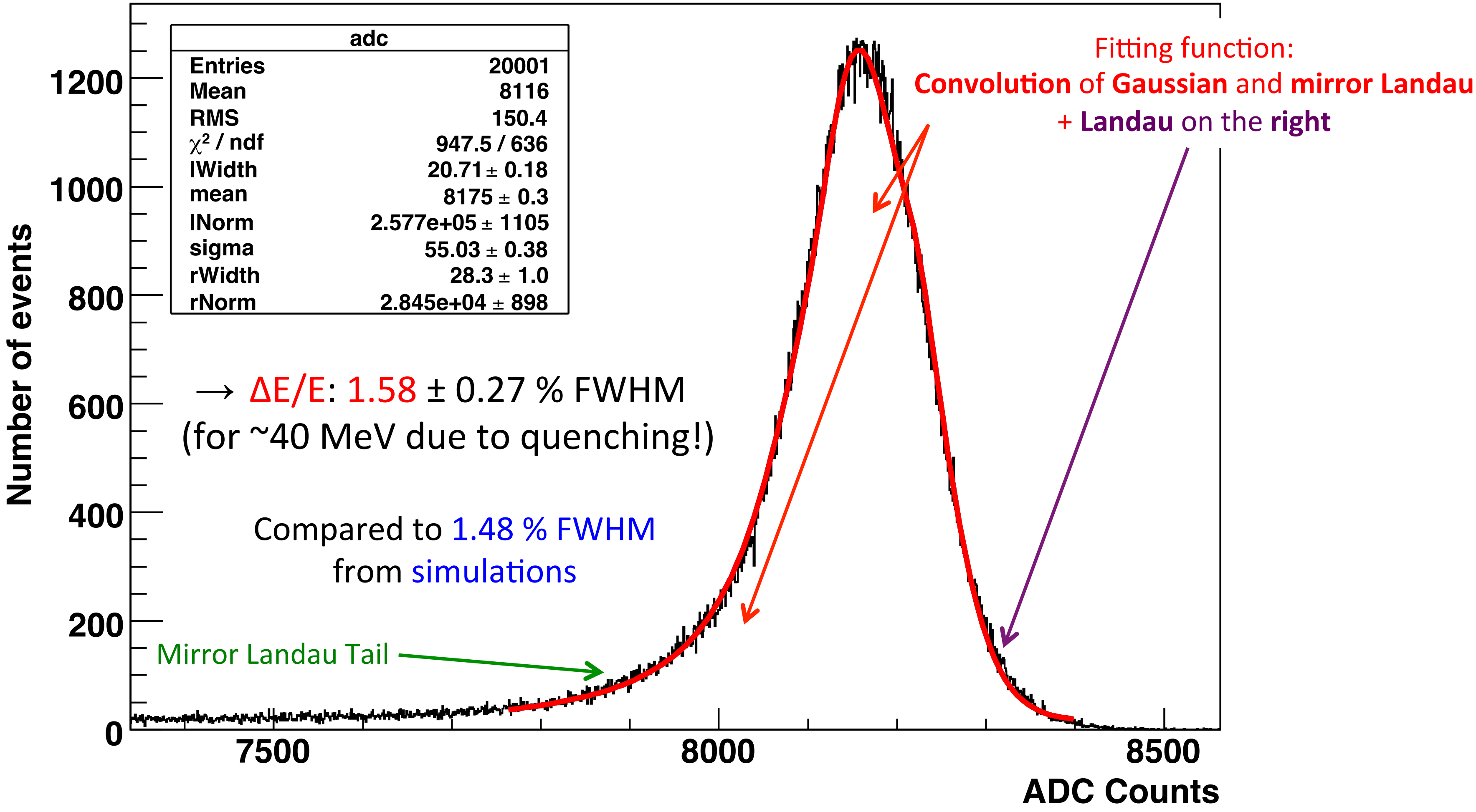


Step 4: Clatterbridge Cancer Centre



Step 4: Clatterbridge Cancer Centre

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



adc	
Entries	20001
Mean	8116
RMS	150.4
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

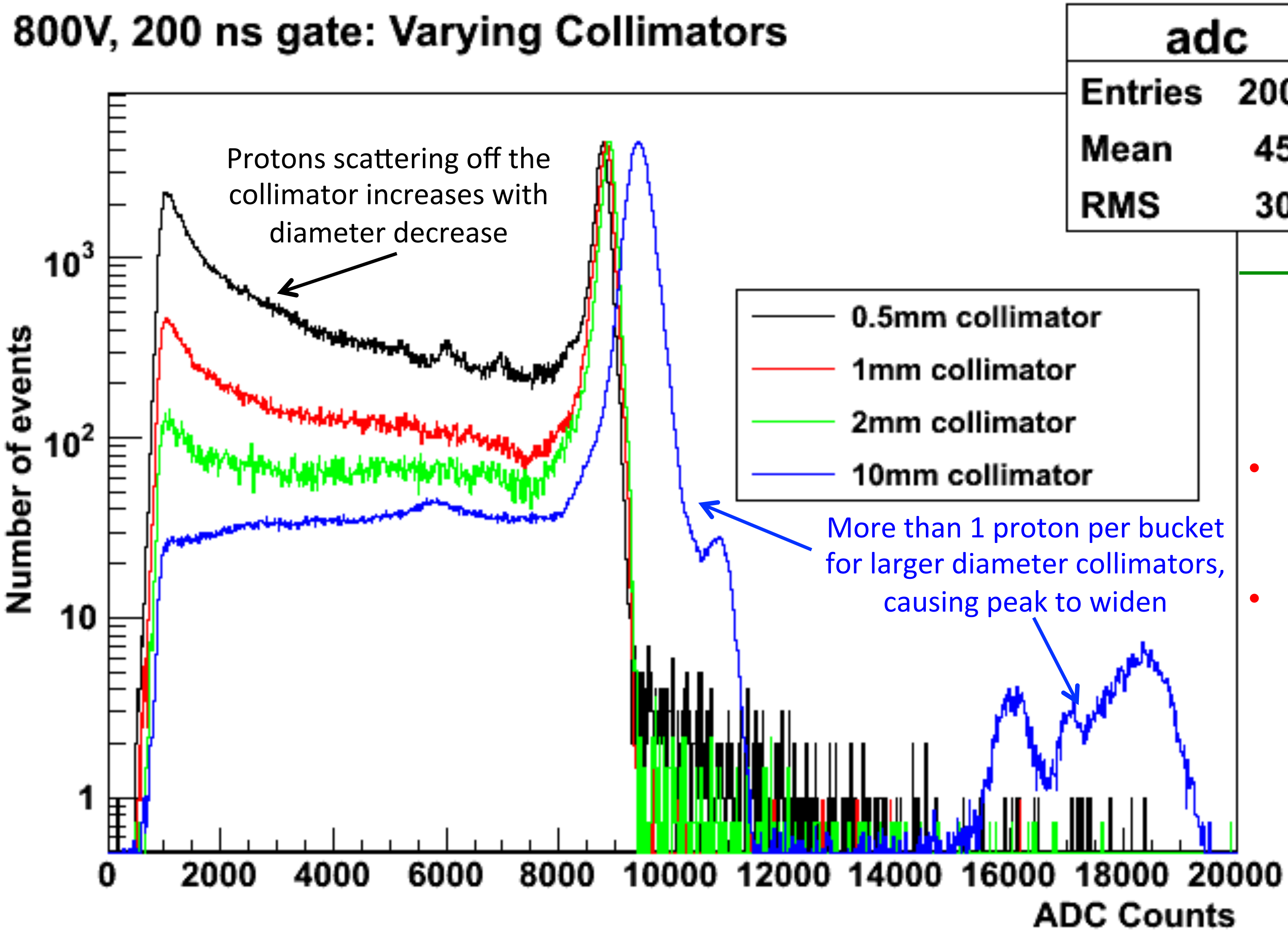
Fitting function:
Convolution of **Gaussian** and **mirror Landau**
+ **Landau** on the **right**

→ ΔE/E: 1.58 ± 0.27 % FWHM
(for ~40 MeV due to quenching!)

Compared to 1.48 % FWHM
from simulations

Mirror Landau Tail

Pile Up: 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

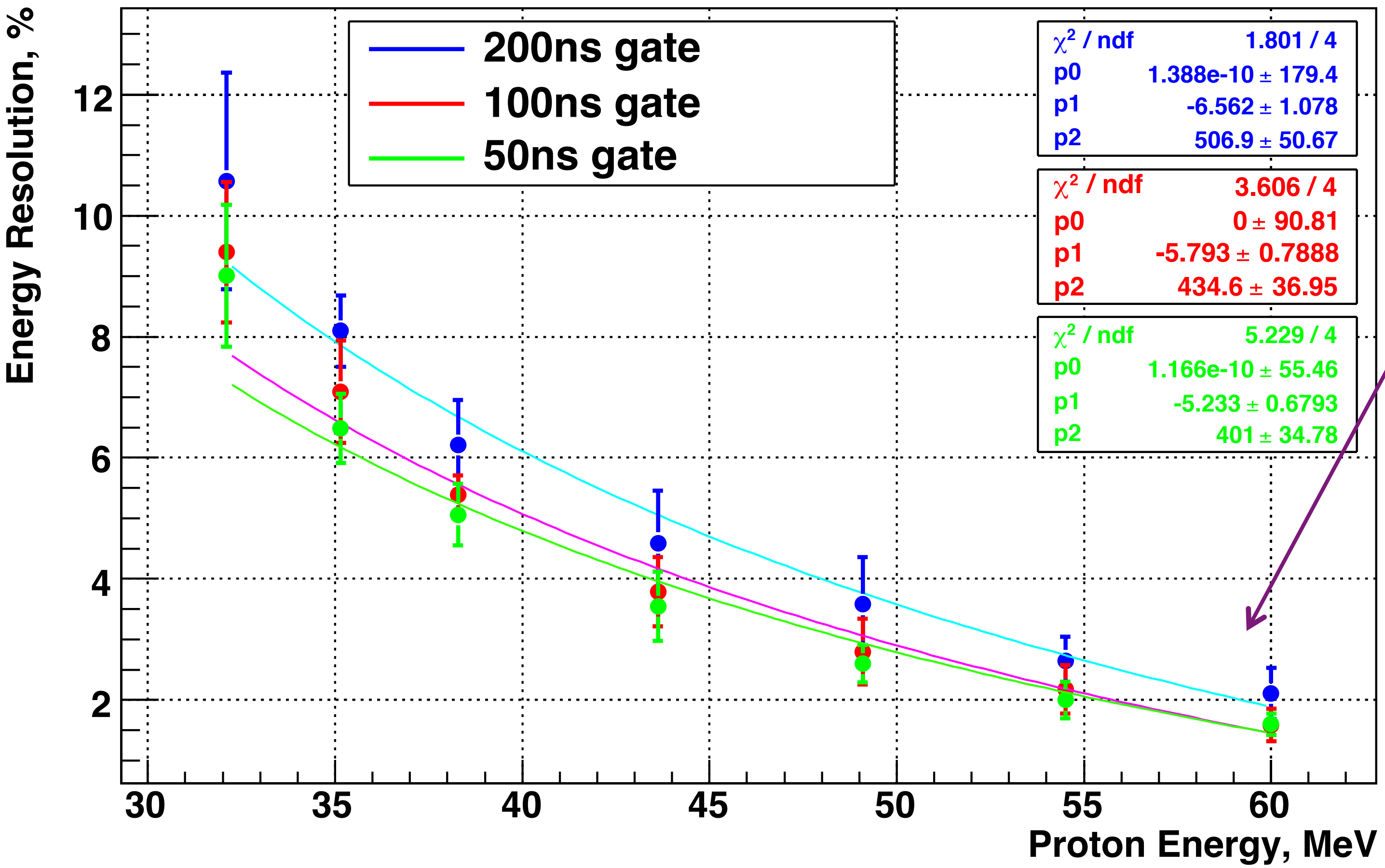
Our optimal parameters for measurements are:

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

Energy Resolution as a Function of Proton Energy: 800V



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

$\sqrt{E}$ dependence!

Intrinsic Energy Resolution of Optical Module

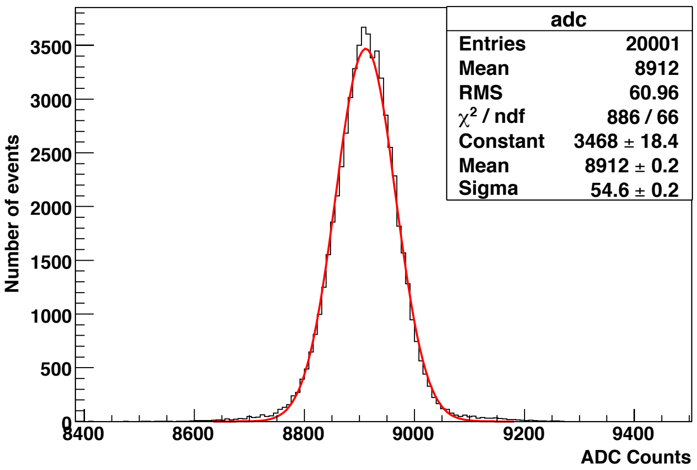
- How much of the measured energy resolution is due to the proton beam and how much is due to the "intrinsic" energy resolution of the detector?

- 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**

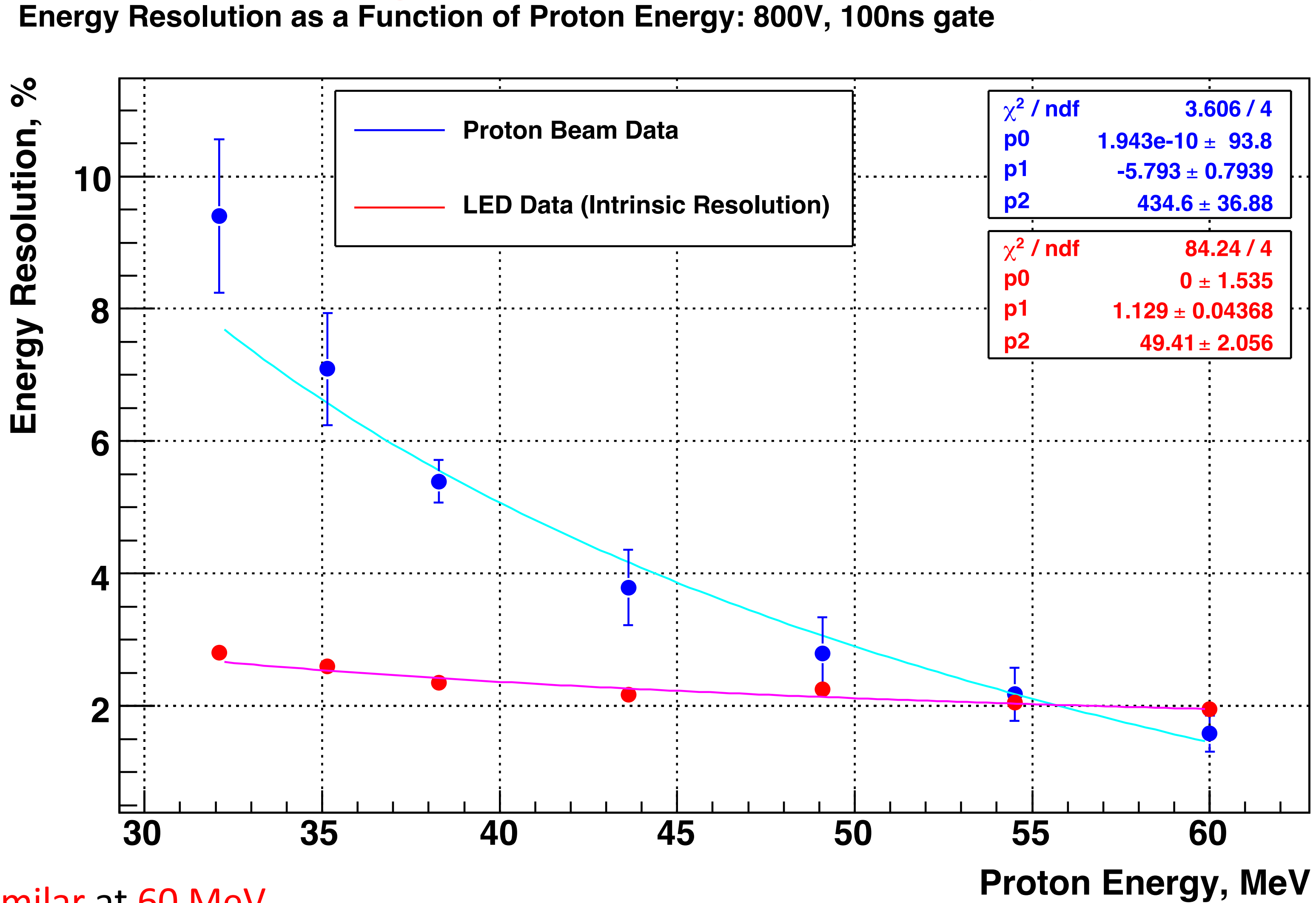
- Also tests carried out at UCL:
  - Pulse PMT with a 400nm LED at an amplitude and width that will give a peak at the same ADC counts as the proton beam spectra
  - Fit the acquired spectra with a Gaussian and extract energy resolution


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



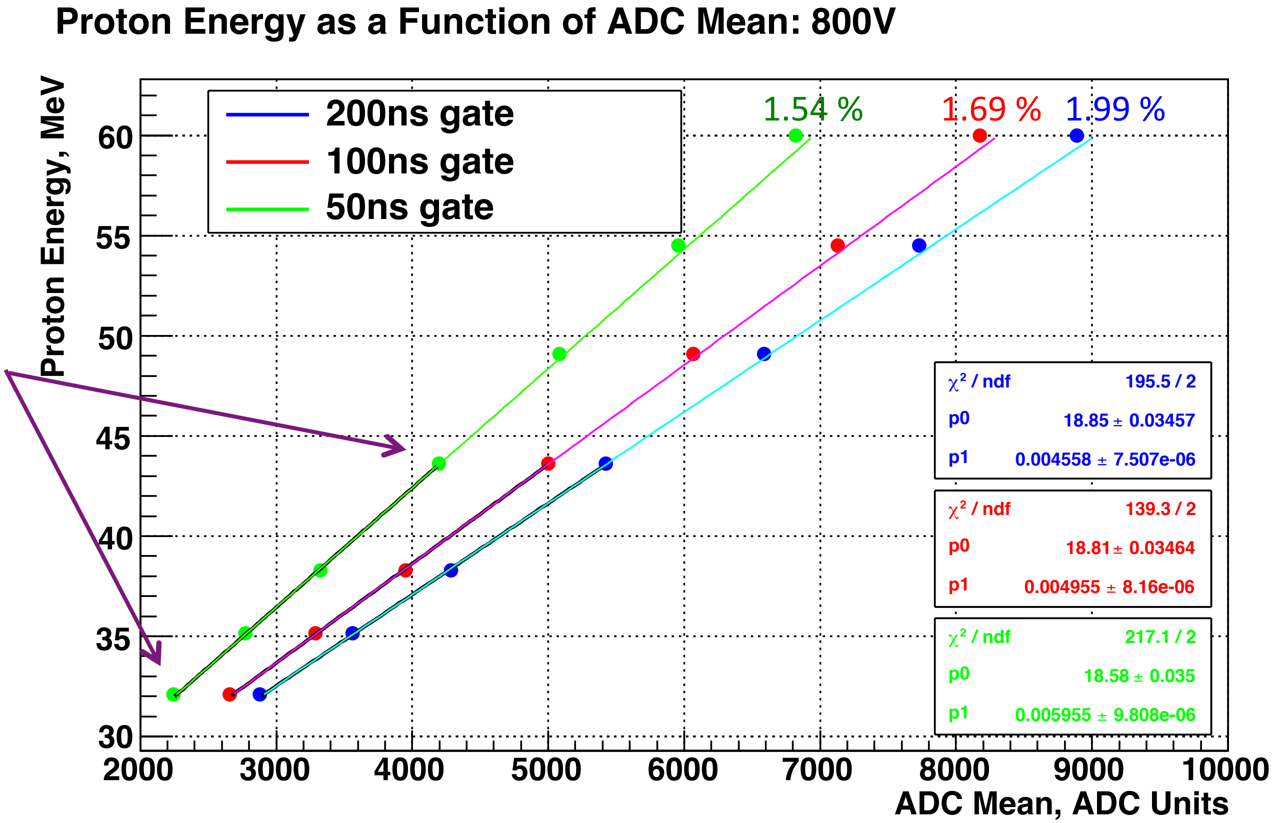
- Similar at 60 MeV
- Proton beam energy resolution much worse than intrinsic energy resolution at lower energies due to scattering of protons

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

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

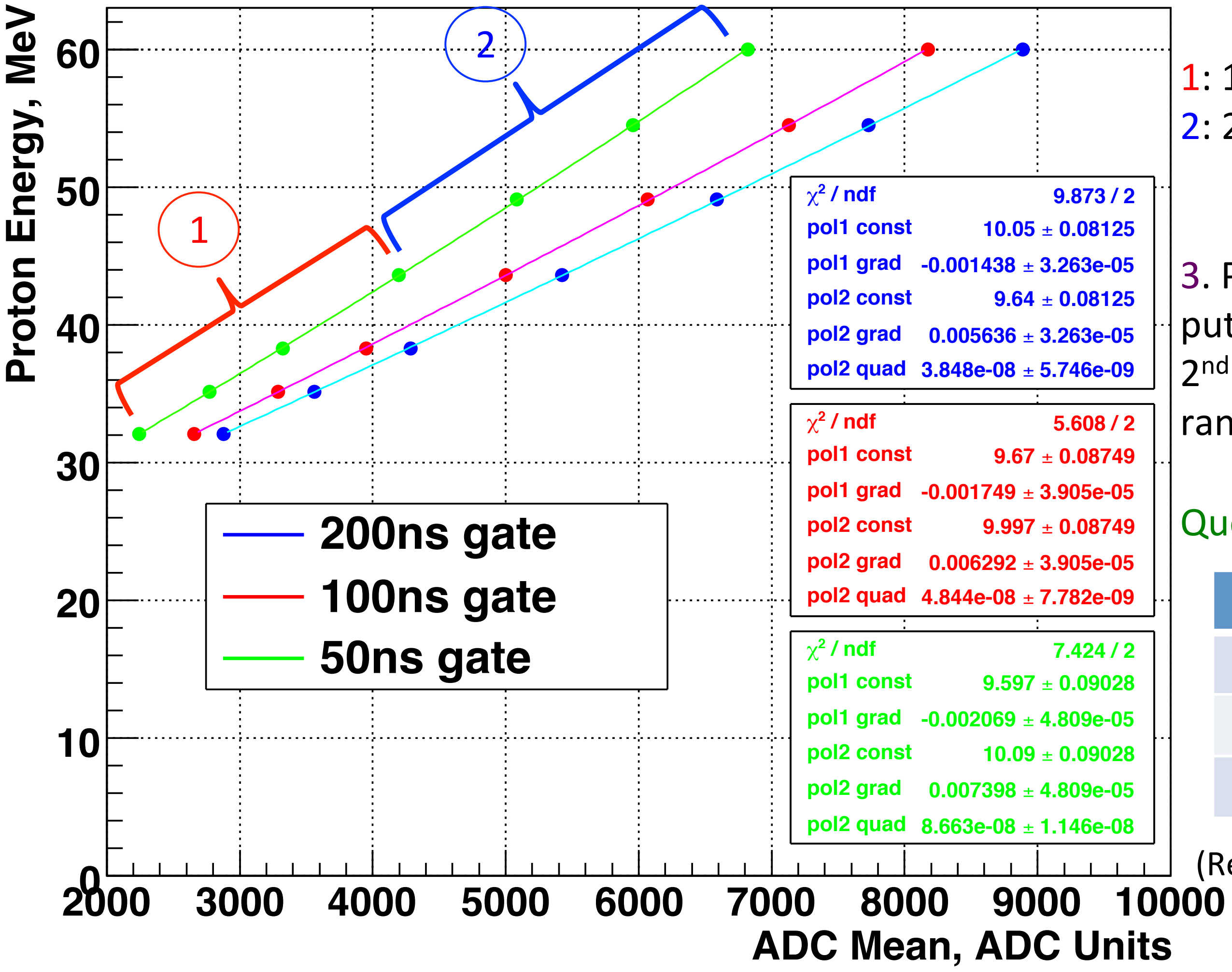


For 800V:
Deviation from
linearity < 2%!

Measuring Quenching

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

Proton Energy as a Function of ADC Mean: 800V



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

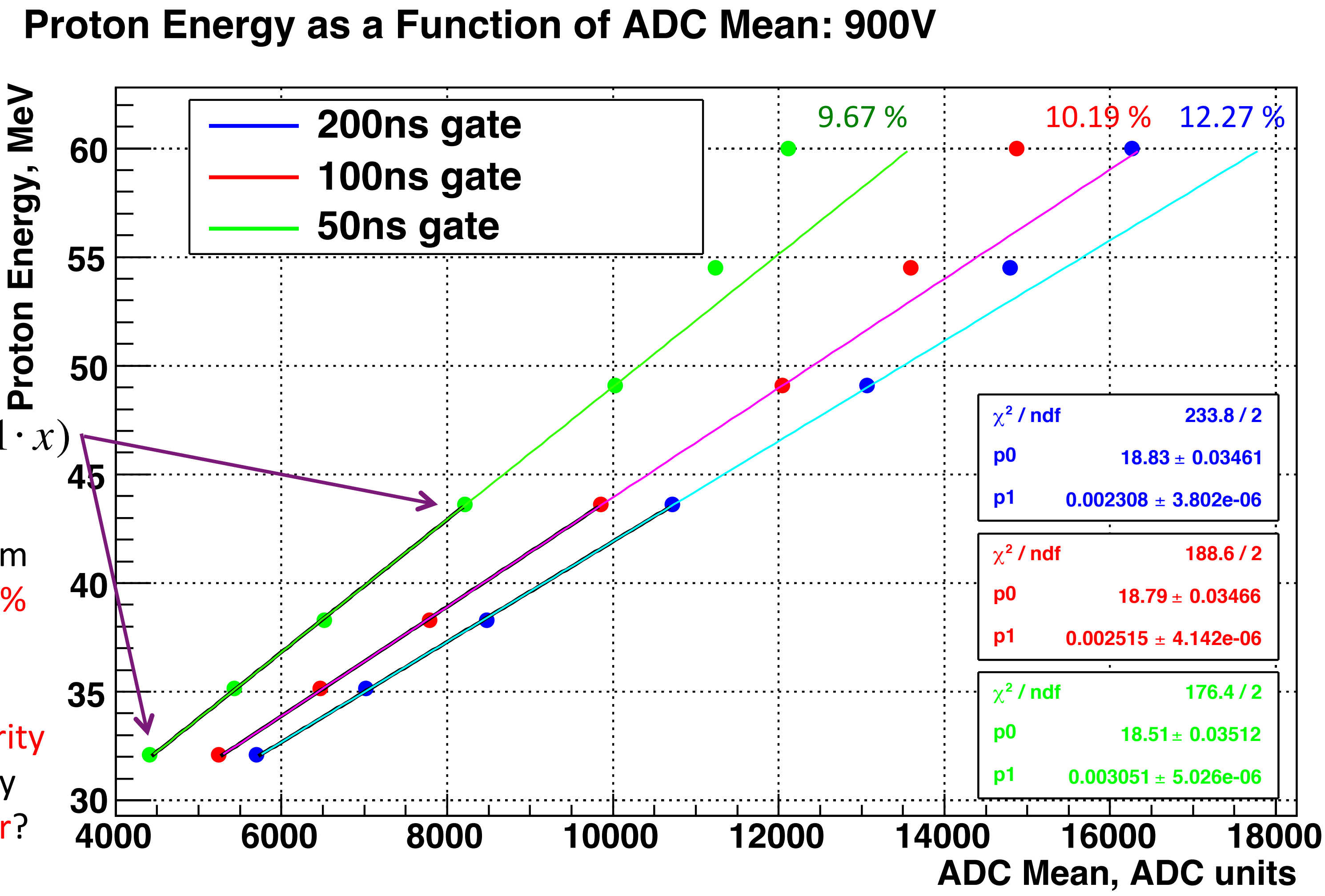
↓

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

Future Plans

1. We already have a great result for energy resolution, but can we push it any further?

   - Use the same technology, but reduce in size to allow us to collect more light
   - Use 3” UBA (43% QE) Hamamatsu PMTs used for SuperNEMO calorimeter R&D coupled to small EJ-200 scintillator. Two scintillators ordered:

Block: 4 cm x 4cm x 5 cm

Cylindrical: 4 cm diameter x 5 cm

Entrance face area chosen to fully fit the 3” diameter PMT

   - Test at UCL with ^{207}Bi and in the 60 MeV proton Clatterbridge beam

2. Given the amount of light we have (~30,000 photo-electrons), consider using alternative photo-detectors:

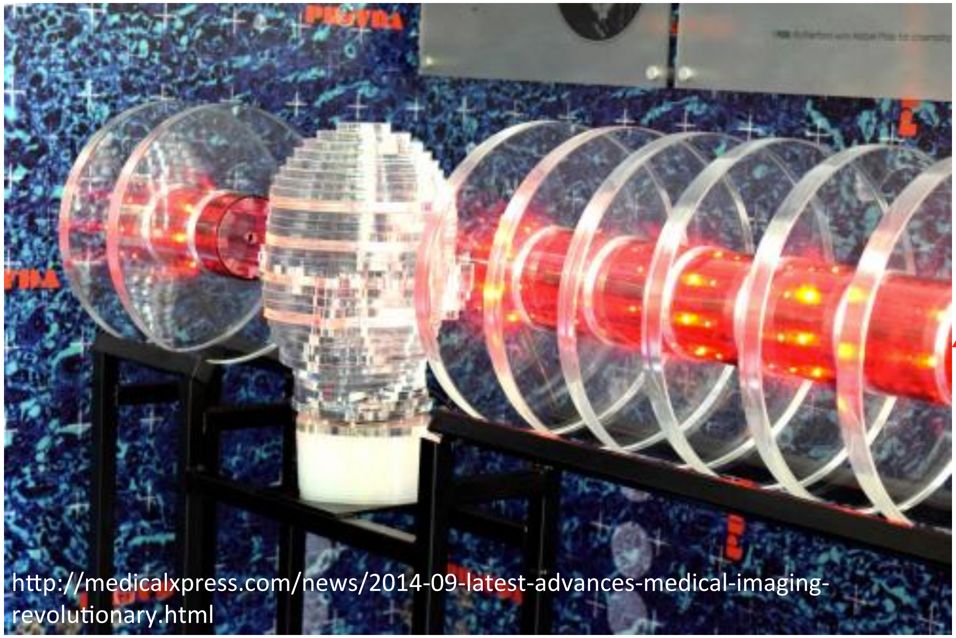
   - High QE, low gain
   - Removes any non-linearity
   - CCD, SiPM, etc.

Future Plans

3. We need to think about practical arrangements for beam monitoring and proton imaging:

   - Talk to clinical scientists and medical physicists at UCLH for specific design constraints needed to produce a deliverable product
   - Collaborate with the PRaVDA (Proton Radiotherapy Verification and Dosimetry Applications) Consortium funded by the Wellcome Trust:

"The world's first silicon-based detector system that will allow in-situ monitoring of the incident dose, in terms of its fluence, energy and distribution both prior to and during treatment."



http://medicalxpress.com/news/2014-09-latest-advances-medical-imaging-revolutionary.html

Silicon radiation hard detectors used for accurate tracking → from PRaVDA

Calorimetry with optical modules → from UCL

Future Plans

4. Neutron background simulations and measurements:

   - Protons create secondary fast neutrons from interaction with the beam pipe etc.
   - This neutron background flux and spectra at proton therapy facilities is poorly known
   - Must be measured to avoid adverse biological effects to the patient
   - Try to use the same SuperNEMO technology to measure neutron flux and spectra

1. Collaborate with dark matter colleagues at UCL for neutron simulations
2. Calibrate the detector with a spectrum of known neutrons at the National Physical Laboratory (NPL) to get detector response

   - Radionuclide sources for broad energy spectra or
     3.5 MV Van de Graaf accelerator for monoenergetic neutrons
   - Use pulse shape analysis provided by the CAEN DT5751 digitiser
   - Make any modifications if necessary
   - Apply detector response in simulations

3. Measure the neutron rate and spectrum at Clatterbridge

http://www.npl.co.uk/measurement-services/neutron-measurements/

Summary & Conclusions

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

1.58 ± 0.27 % FWHM
(for 40 MeV "visible" energy)

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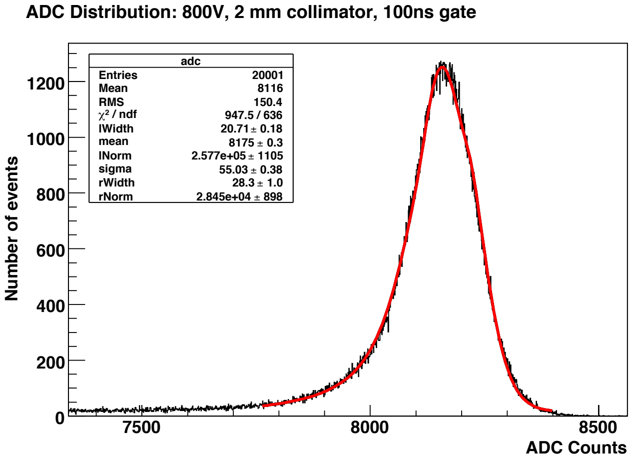
simple extrapolation:
0.7 % FWHM @ proton imaging energy (300 MeV)

Limit on energy spread of Clatterbridge beam:
FWHM (60 MeV) < 1.66% @ 90% CL


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

- An important result for the future of proton beam monitoring and proton imaging

- Lots to do!!!
  - Ongoing data analysis from four days of Clatterbridge test beam data in December 2013 and December 2014
  - Can we do better with the same technology reduced in size?
  - Alternative photo-detector technologies
  - Lots of collaboration with colleagues coming up!

Acknowledgements

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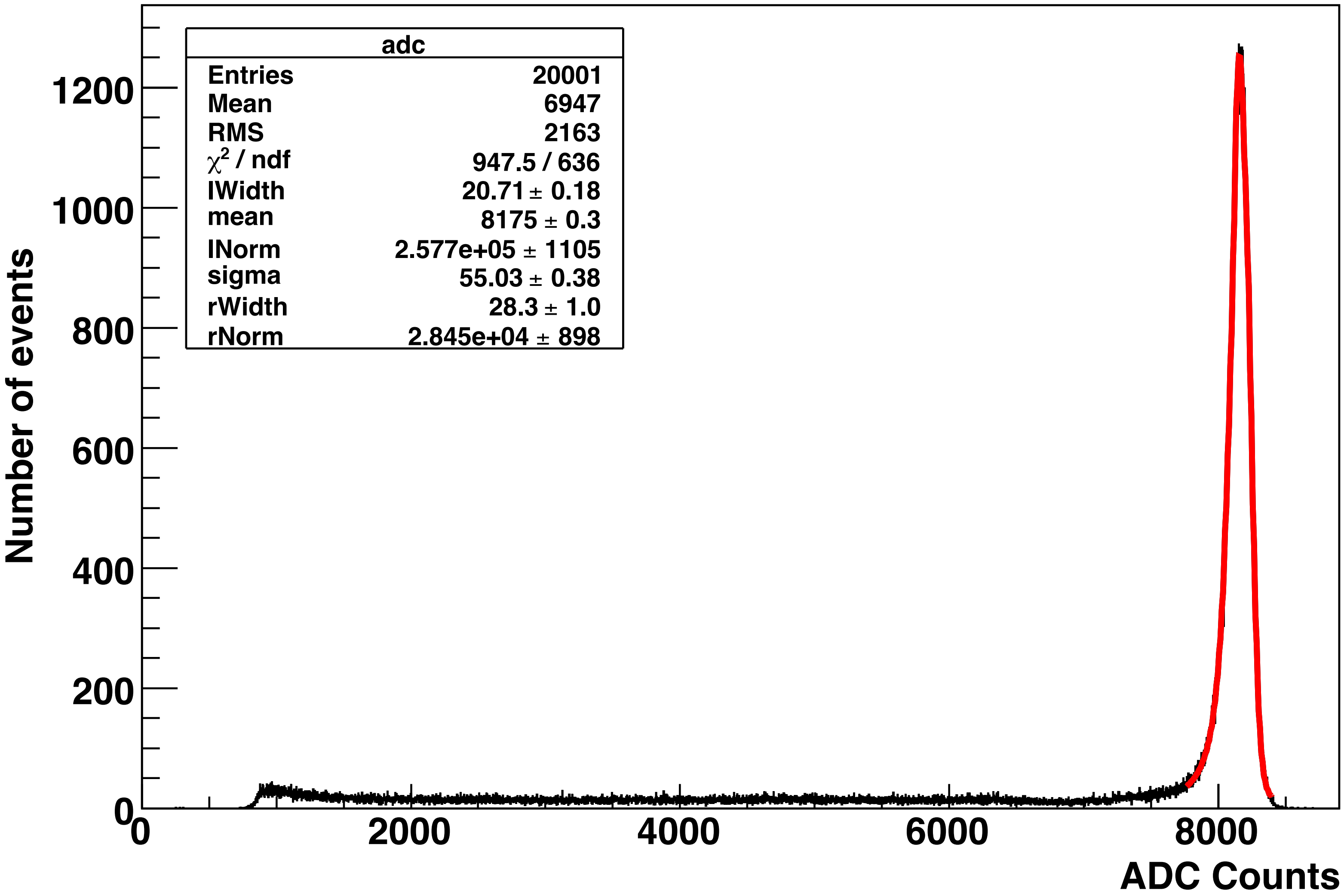
Anastasia Basharina-Freshville and Sophie Neal

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

Backup Slides

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



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