Initial Studies in Proton Computed Tomography

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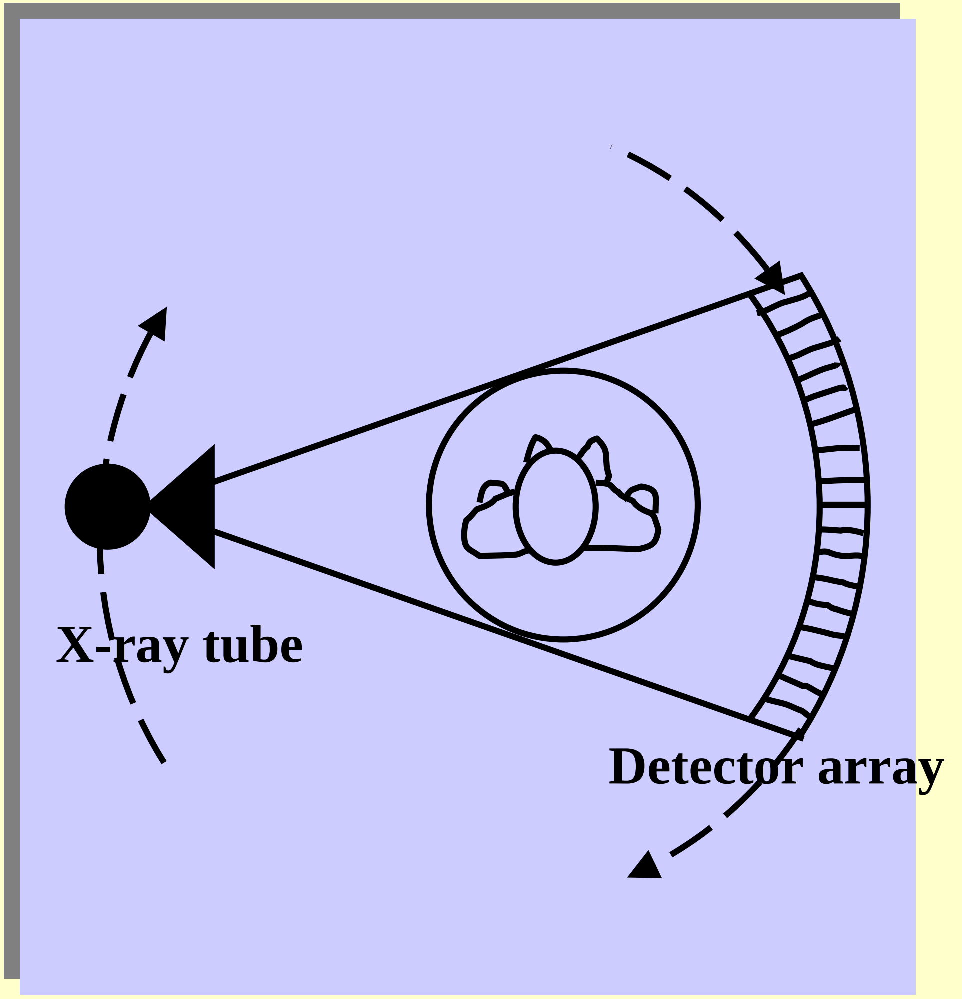
- **Proton Energy Loss in Matter**
- **Proton Tomography / Proton Transmission Radiography**
- **Proton Transmission Radiography Data**
- **Proton Transmission Radiography MC Study**

Computed Tomography (CT)

- Based on X-ray absorption
- Faithful reconstruction of patient's anatomy
- Stacked 2D maps of linear X-ray attenuation
- Coupled linear equations
- Invert Matrices and find (hopefully) non-malignant structures
- Proton CT replaces X-ray absorption with proton energy loss



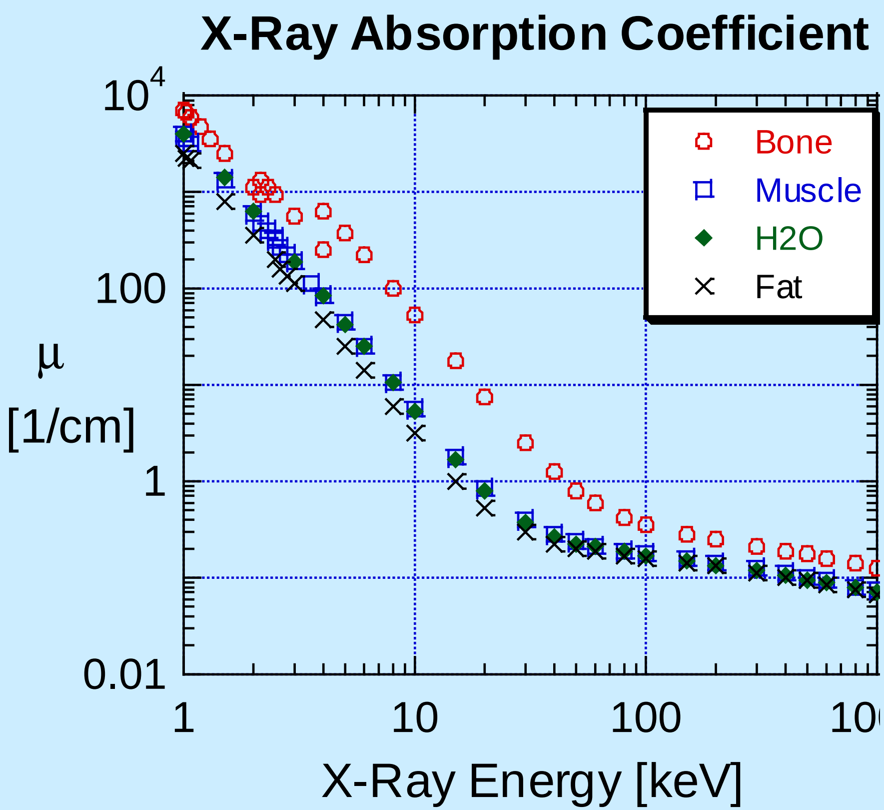
Radiography: X-rays vs. Protons

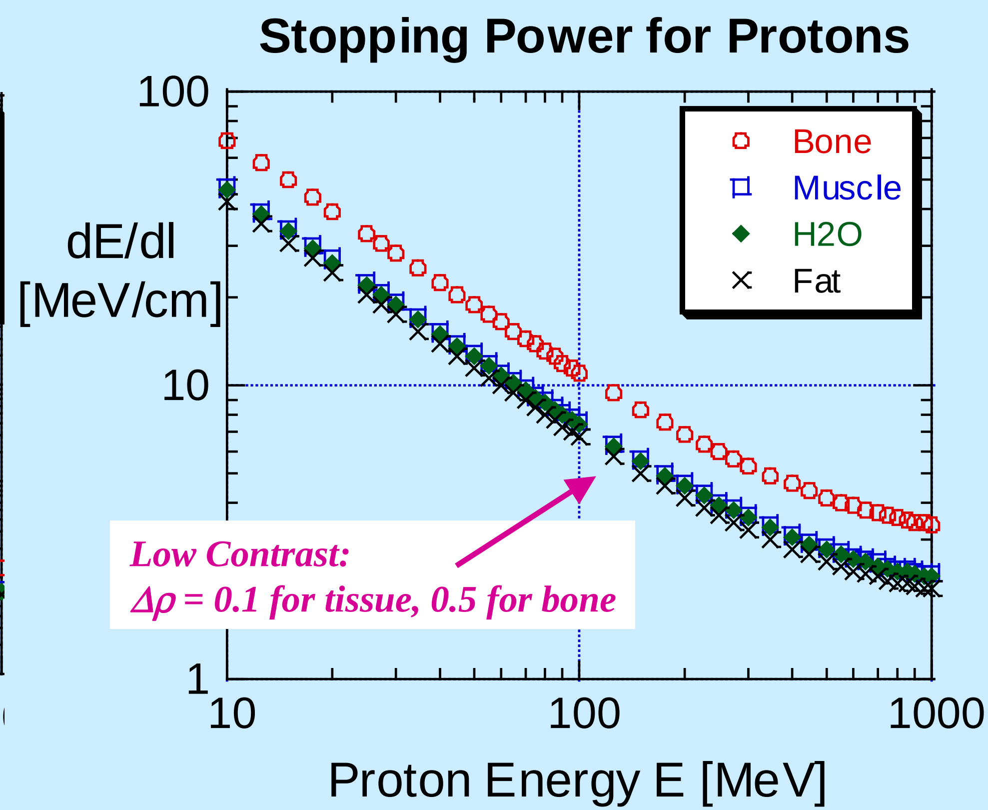
Attenuation of Photons, Z

$$N(x) = N_o e^{-\mu x}$$

Energy Loss of Protons, ρ

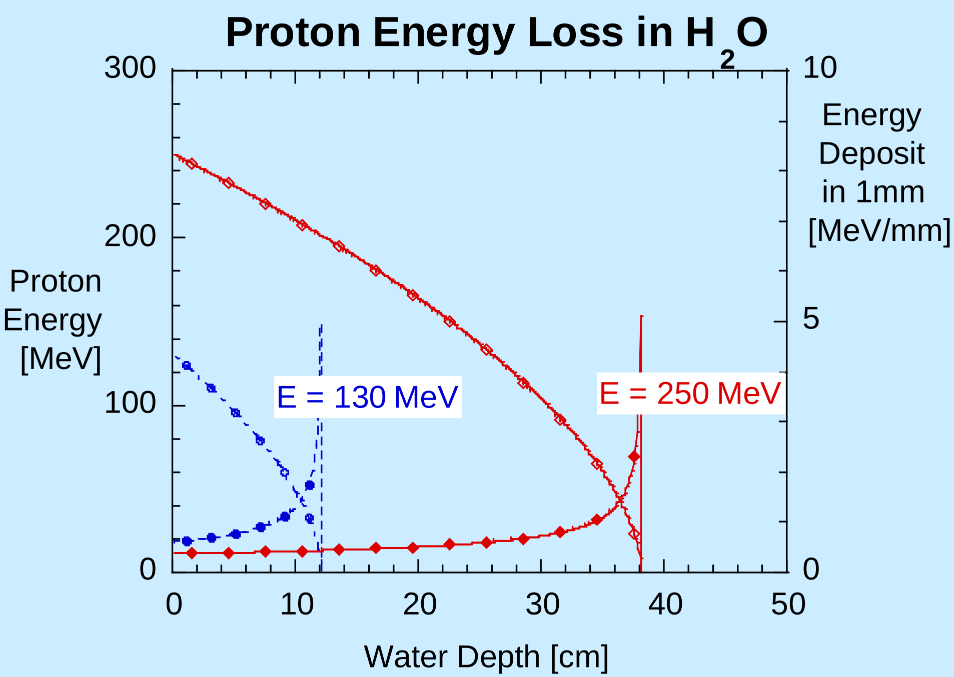
$$\Delta E = \int \frac{dE}{dx} dx \approx \sum \rho \frac{dE}{dx} \Delta l$$

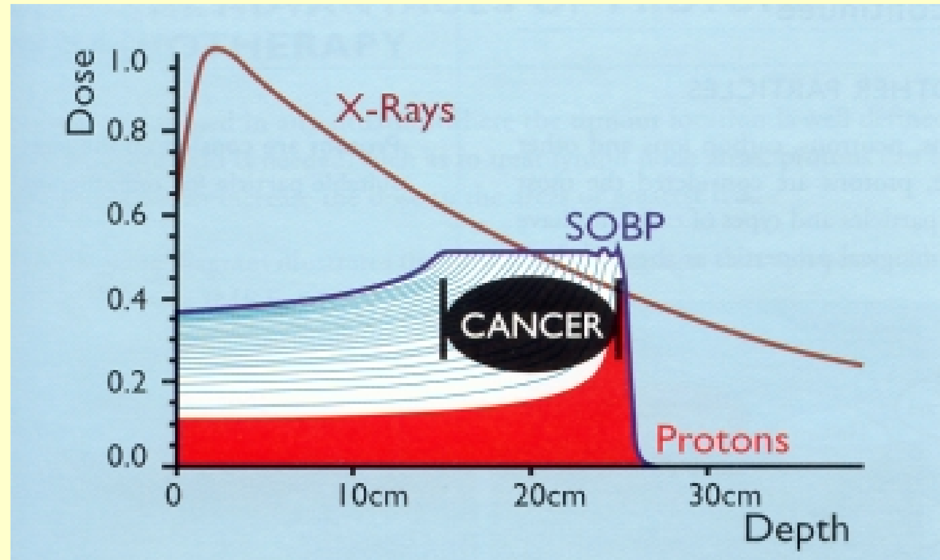


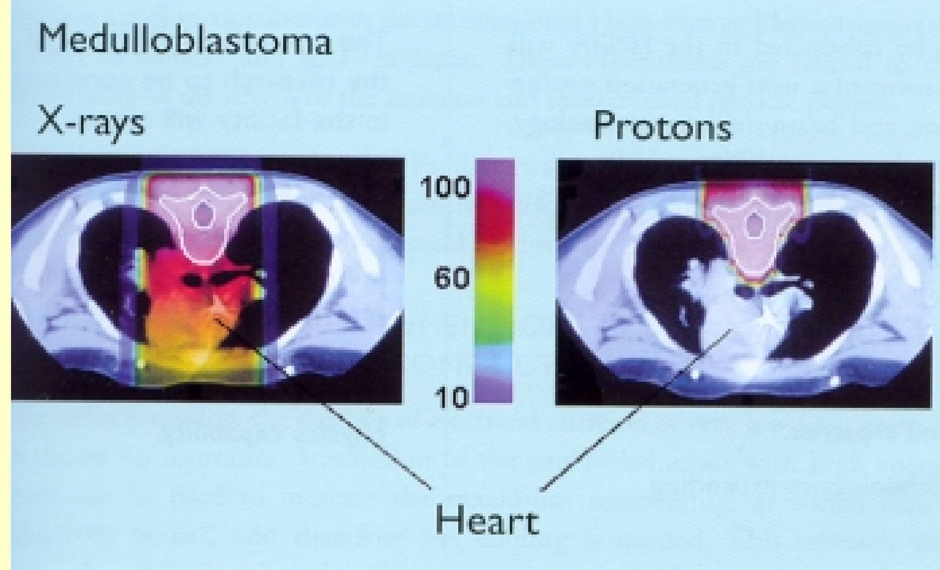


NIST Data

Advantages of Protons in Therapy







- **Relatively low entrance dose (plateau)**
- **Maximum dose at depth (Bragg peak)**
- **Rapid distal dose fall-off**
- **Energy modulation (Spread Bragg peak)**
- **RBE close to unity**

Use of Proton Beam CT: Treatment Planning

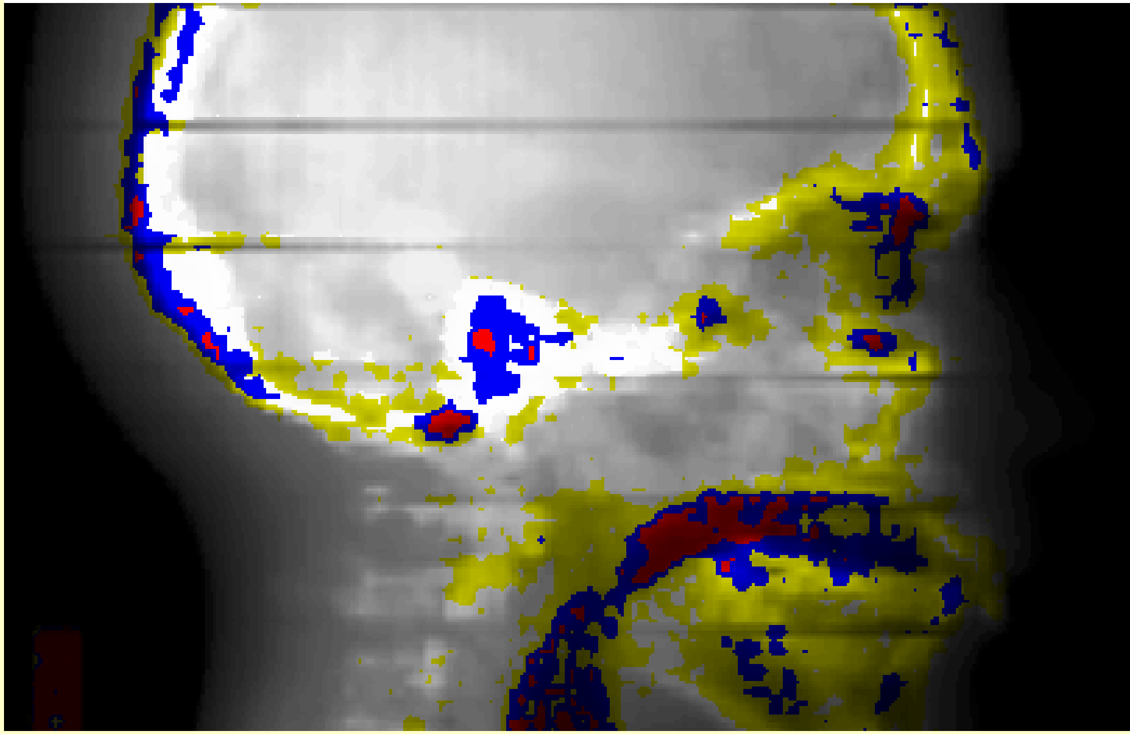
X-ray CT use in Proton Cancer Therapy can lead to large Uncertainties in Range Determination

Range Uncertainties

(measured with PTR)

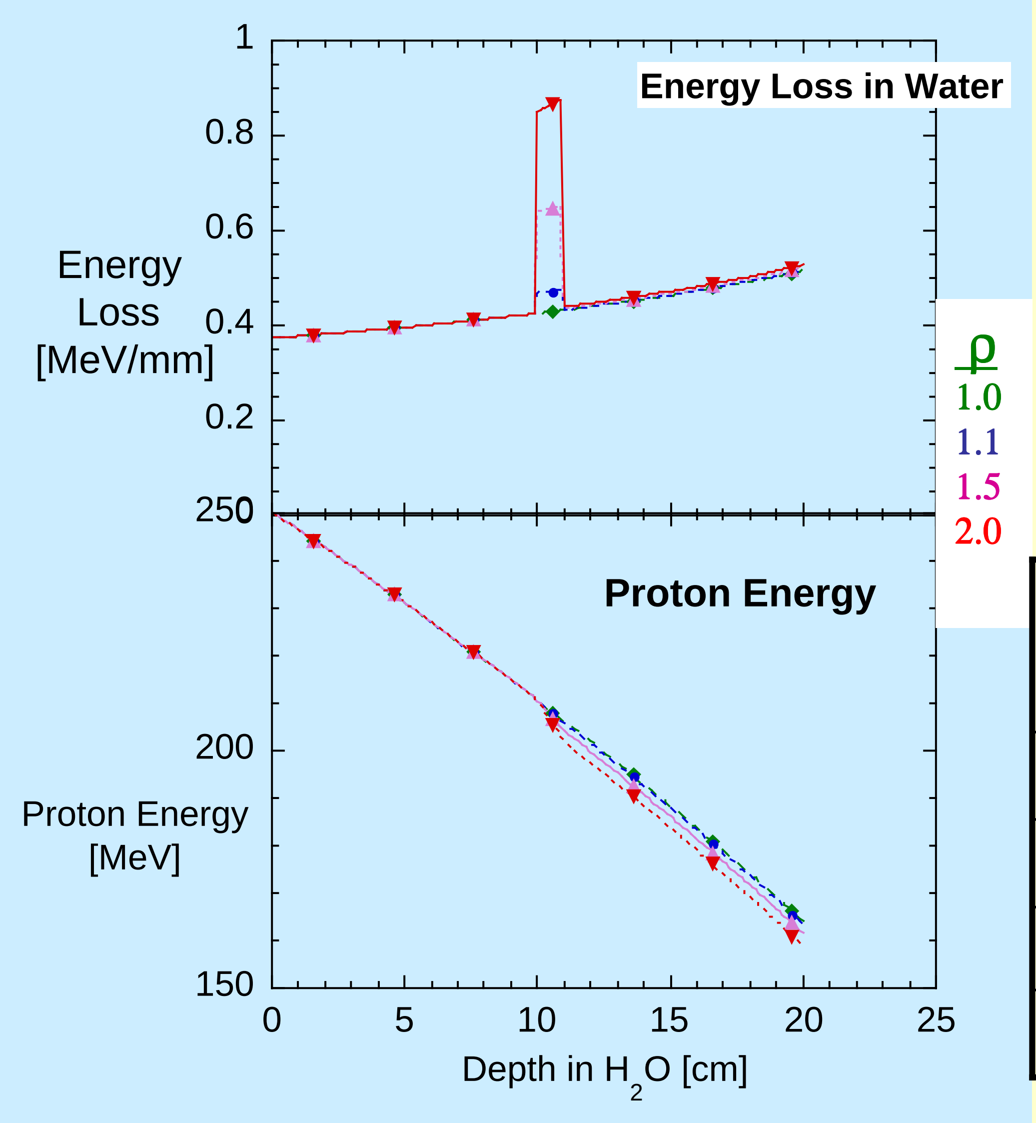
- Black: > 5 mm
- Blue: > 10 mm
- Red: > 15 mm

Schneider U. & Pedroni E. (1995), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.

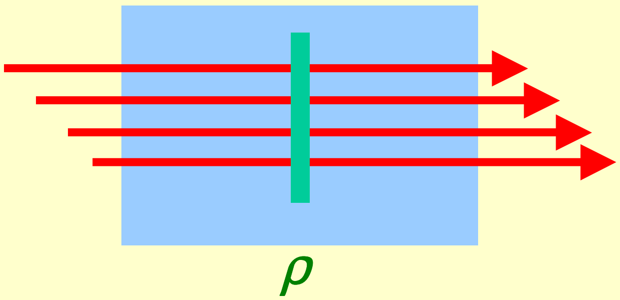


Alderson Head Phantom

Low Contrast in Proton CT



Inclusion of 1cm depth at midpoint of 20cm H_2O



ρ [g/cm²]	Energy [MeV]	Range [cm]	TOF [ps]
1.0	164.1	38.2	1309
1.1	163.6	38.1	1311
1.5	161.5	37.7	1317
2.0	158.9	37.2	1325

Proton CT Measurements

Requirements:

- Proton location to few hundred um
- Proton angle to a degree

$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

- Average Proton Energy <E> to better than %

$$\sigma_{<E>} = \frac{\sigma_E}{\sqrt{N}}$$

- Improve energy determination with statistics?

- Problem: Dose D = Absorbed Energy / Mass
  Voxel with diameter d = 1mm
  10^6 protons of 200 MeV = 7.2 [cGy]

$$D = \frac{N}{A} \cdot \frac{dE}{dx}$$

$$D \sim \frac{\sigma_E^{\,2}}{\Delta^2 \rho \cdot d^5}$$

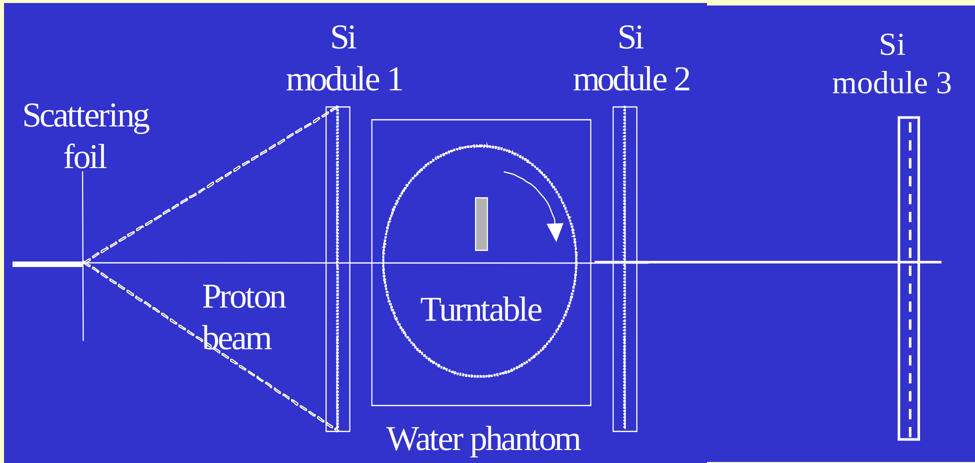
- In order to minimize the dose, the final system needs to employ the best energy resolution!

$$\sigma_E \approx 1\%$$

Development of Proton Beam Computed Tomography

Collaboration
Loma Linda University Medical Center – UC Santa Cruz

- Exploratory Study in Proton Radiography
  - two x-y detector modules
  - Crude phantom in front
- Theoretical Study
  - GEANT4 MC simulation
  - influence of MCS and range straggling
  - importance of angular measurements
  - Optimization of energy
- Experimental Study in pCT
  - Three or four x-y Si planes
  - water phantom on turntable



Proton Energy Measurement with LET in Si

Simple 2D Silicon Strip Detector Telescope built

for Nanodosimetry (based on GLAST Design)

2 single-sided SSD

194um Pitch

400um thick

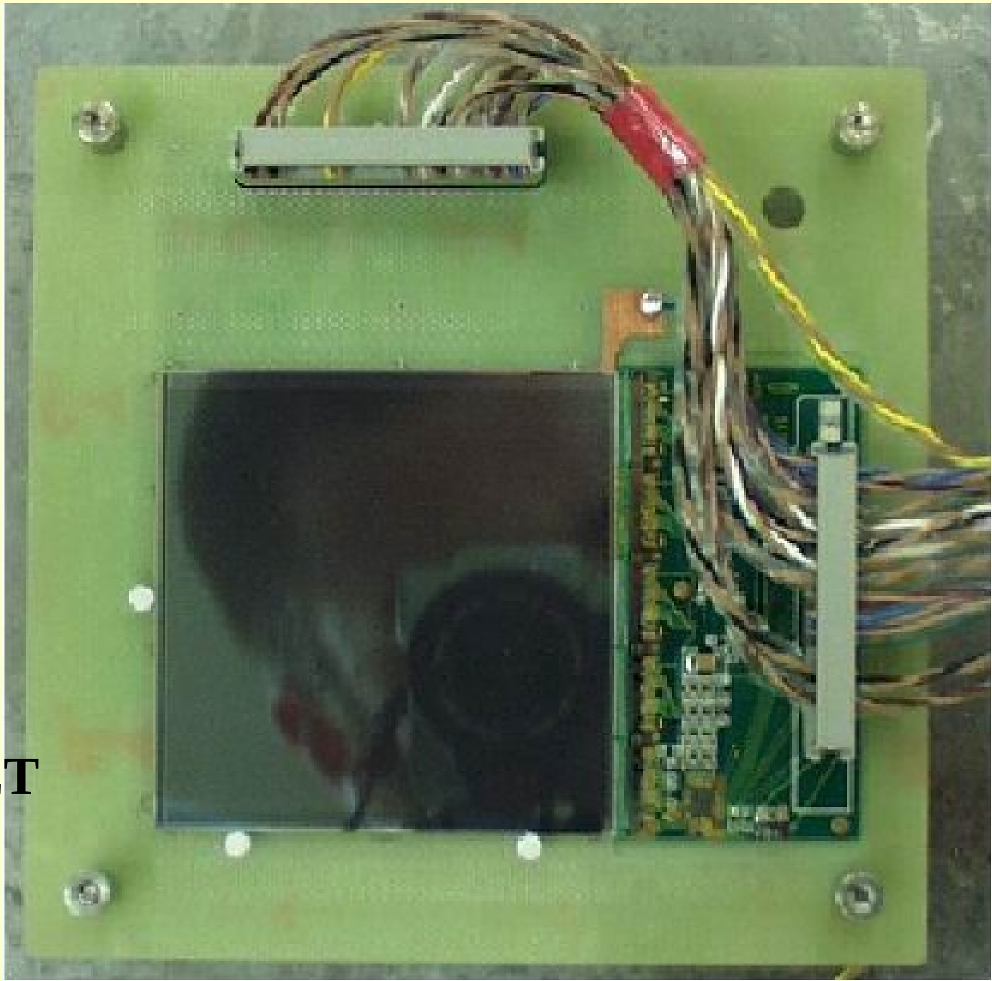
1.3us shaping time

Binary readout

Time-over-Threshold TOT

Large dynamic range

Measure particle energy via LET



GLAST Front-End Electronics ASIC

Binary Readout:

•Low-power (~200uW/channel)

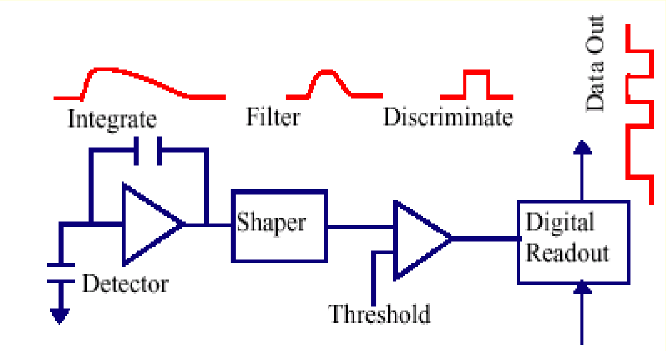
•Peaking time ~ 1.3 ms

•Low noise (Noise occupancy <10^{-5})

•Threshold set in every ASIC

•Separate Masks for Trigger and Readout in every Channel

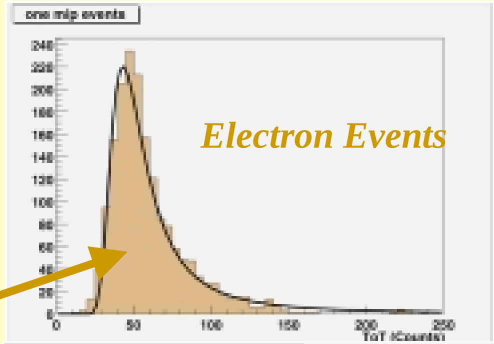
•Self - Trigger = OR of one Si plane (1536 channels)

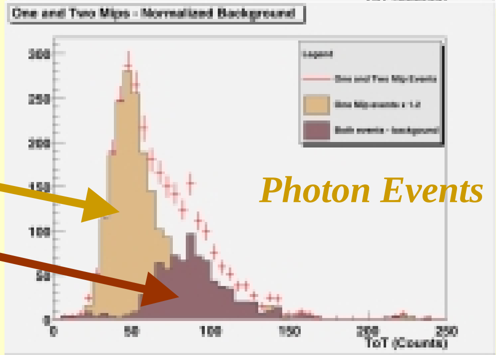


Pulse Charge:

Time – over-Threshold on the OR of every Si plane

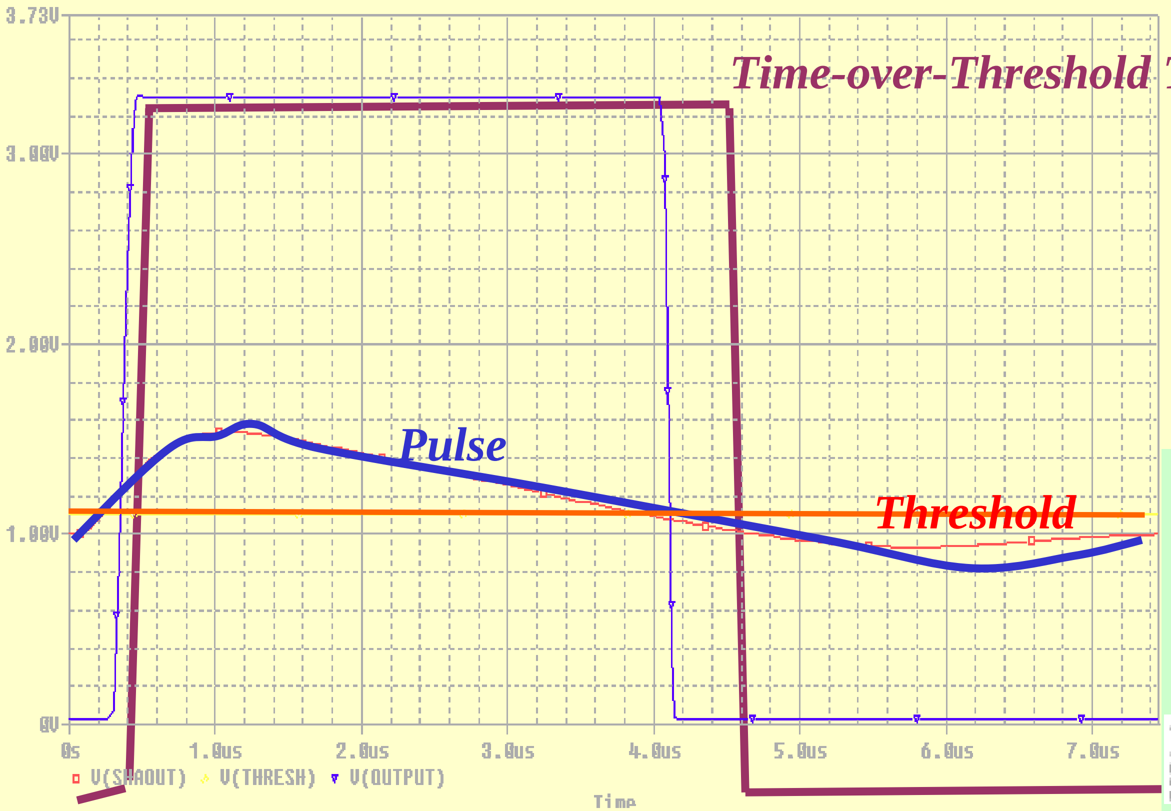
Distinguish single tracks from two tracks in one strip



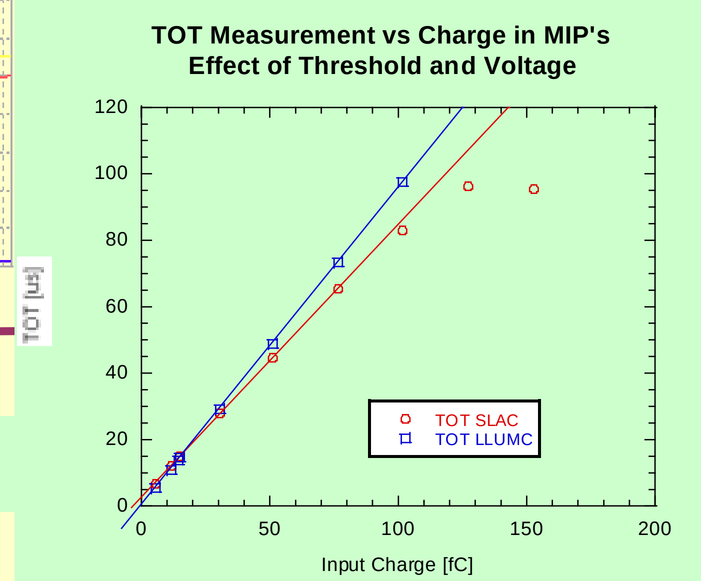


Charge ~ Time-Over-Threshold (TOT):

Digitization of Position and Energy Deposit with large Dynamic Range

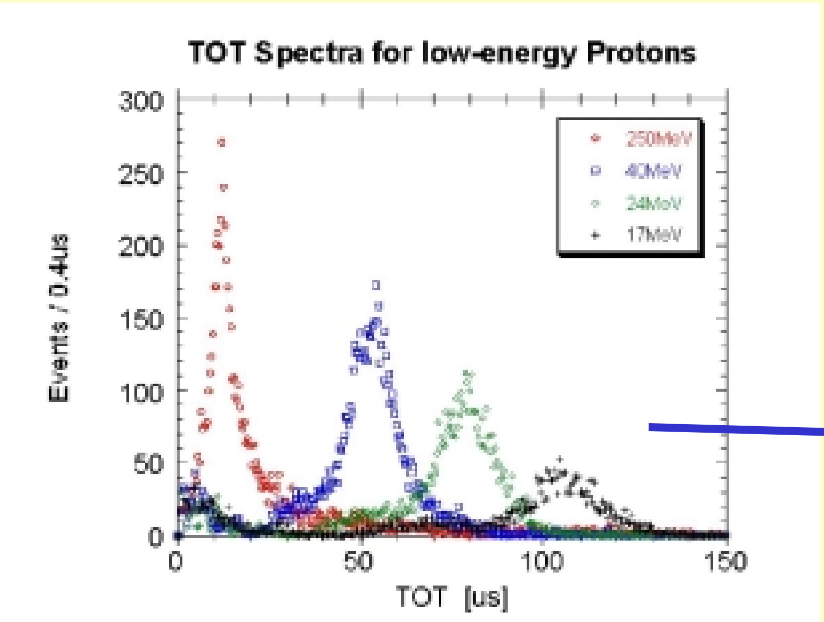


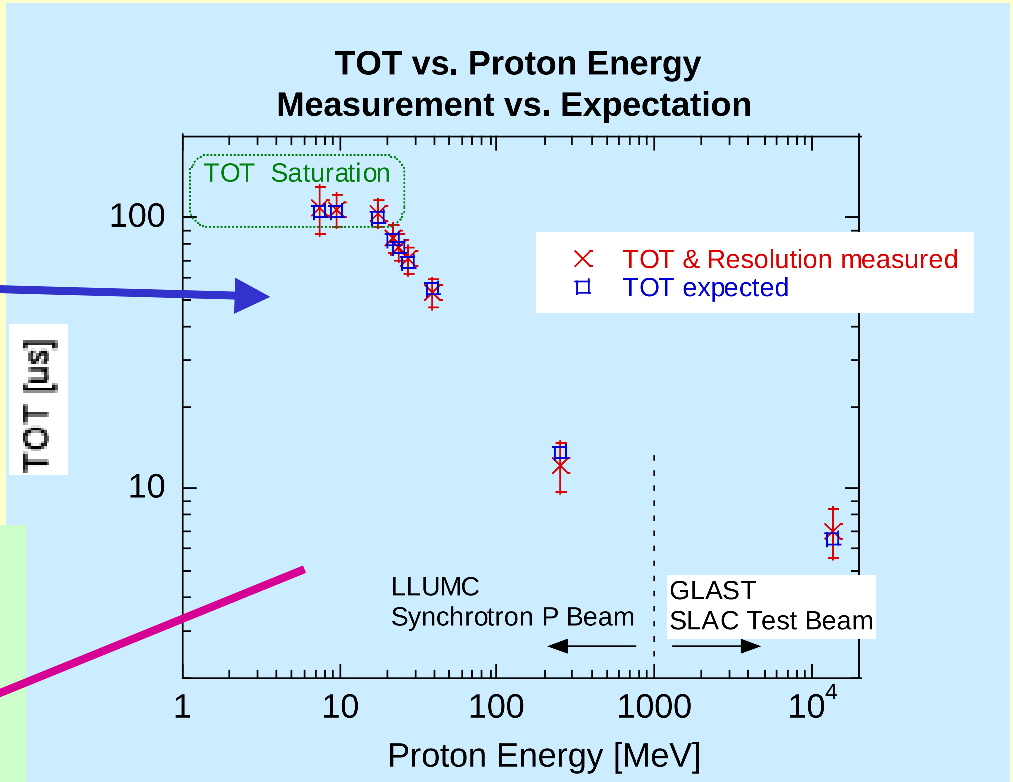
TOT ∝ charge ∝ LET

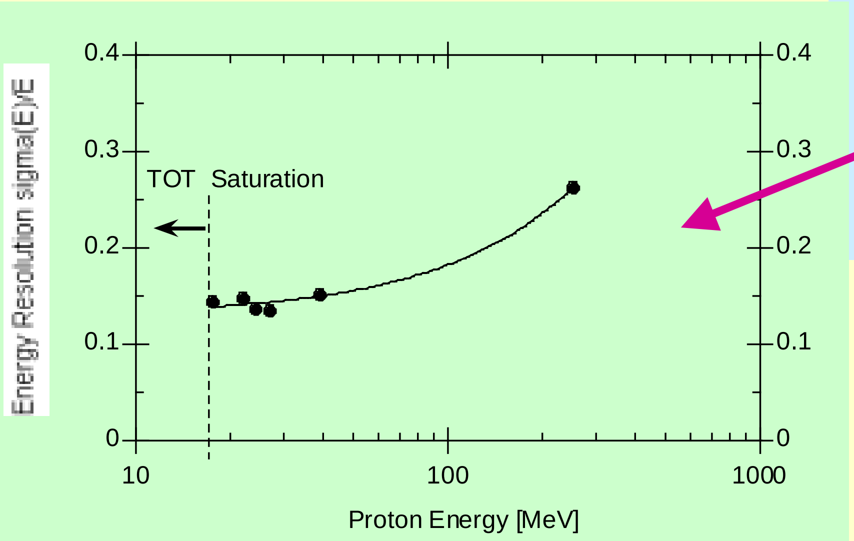


Proton Energy Measurement with LET

Good agreement between measurement and MC simulations







Derive Energy Resolution from TOT vs. E Plot

Exploratory Proton Radiography Set-up

Use Loma Linda University Medical Ctr 250 MeV Proton Beam
Degraded down to 130 MeV by 10” Wax Block
Object is Aluminum pipe 5cm long, 3cm OD, 0.67cm ID
Very large effects expected, but beam quite non-uniform
Silicon detector telescope with 2 x-y modules

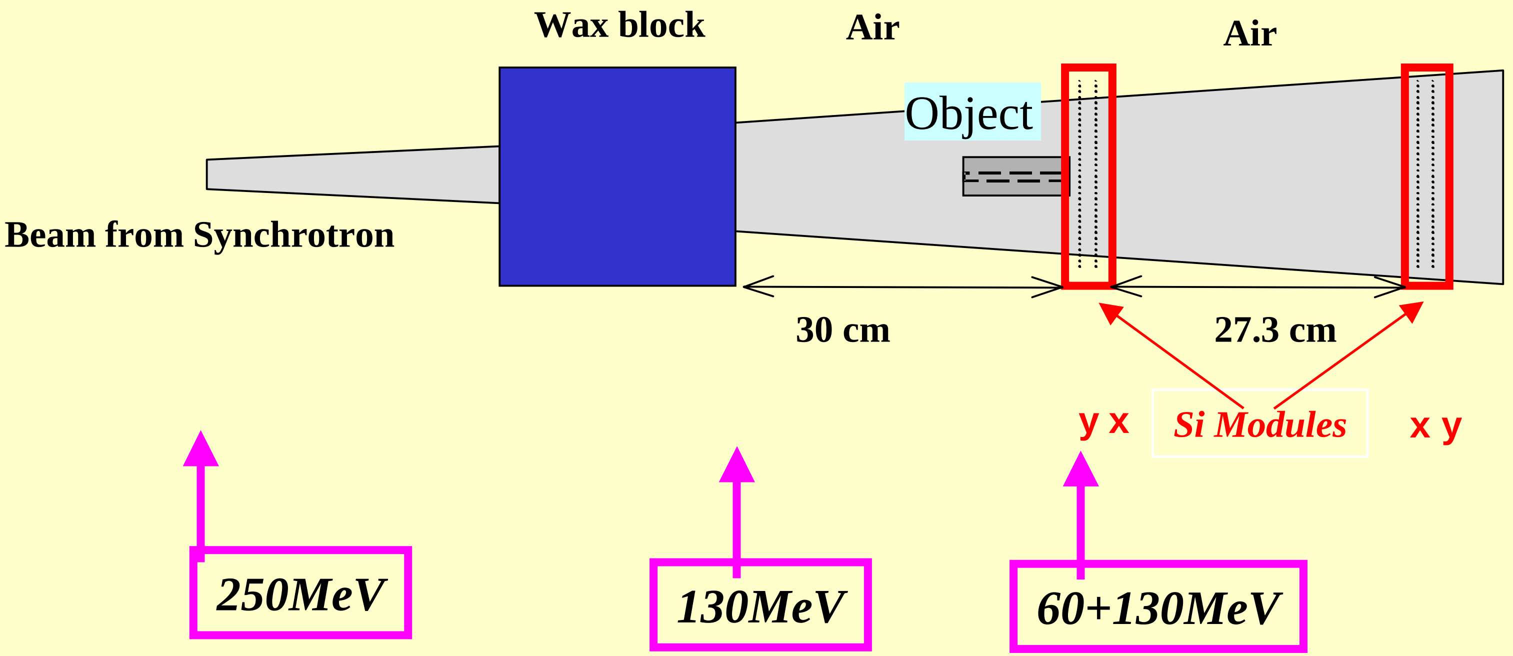
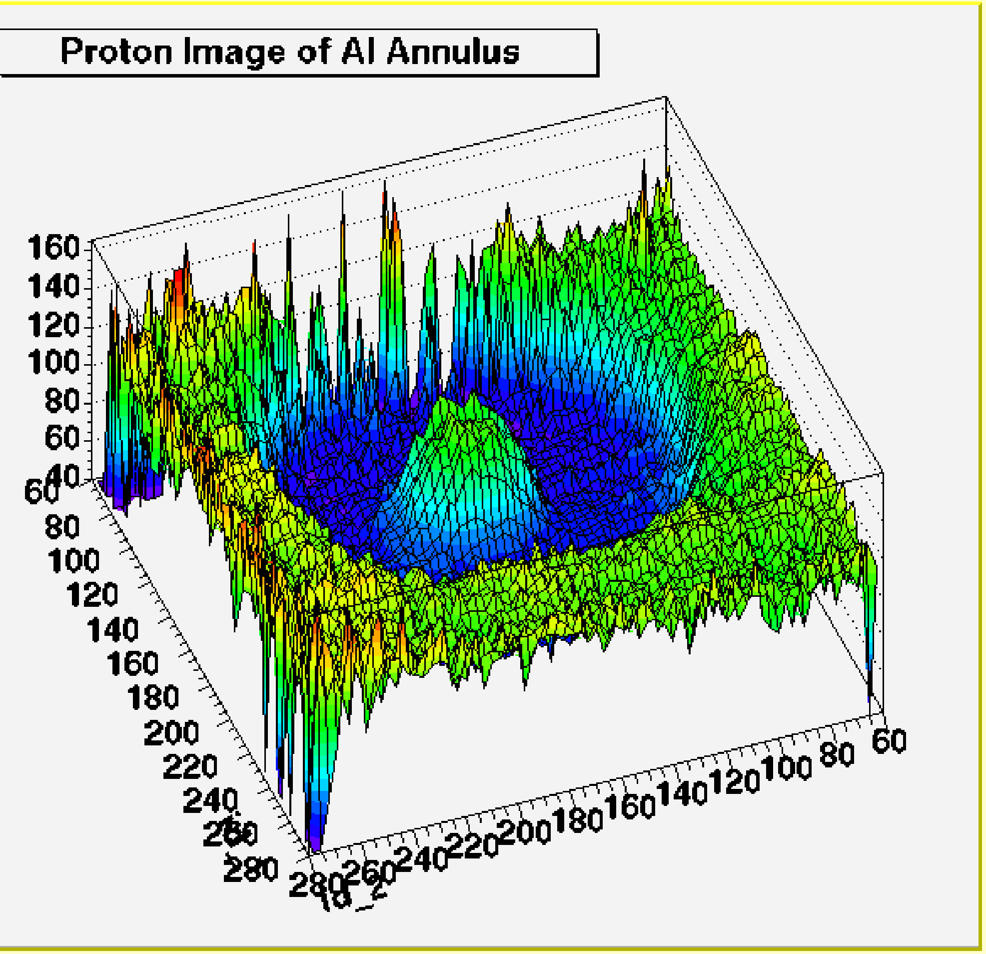


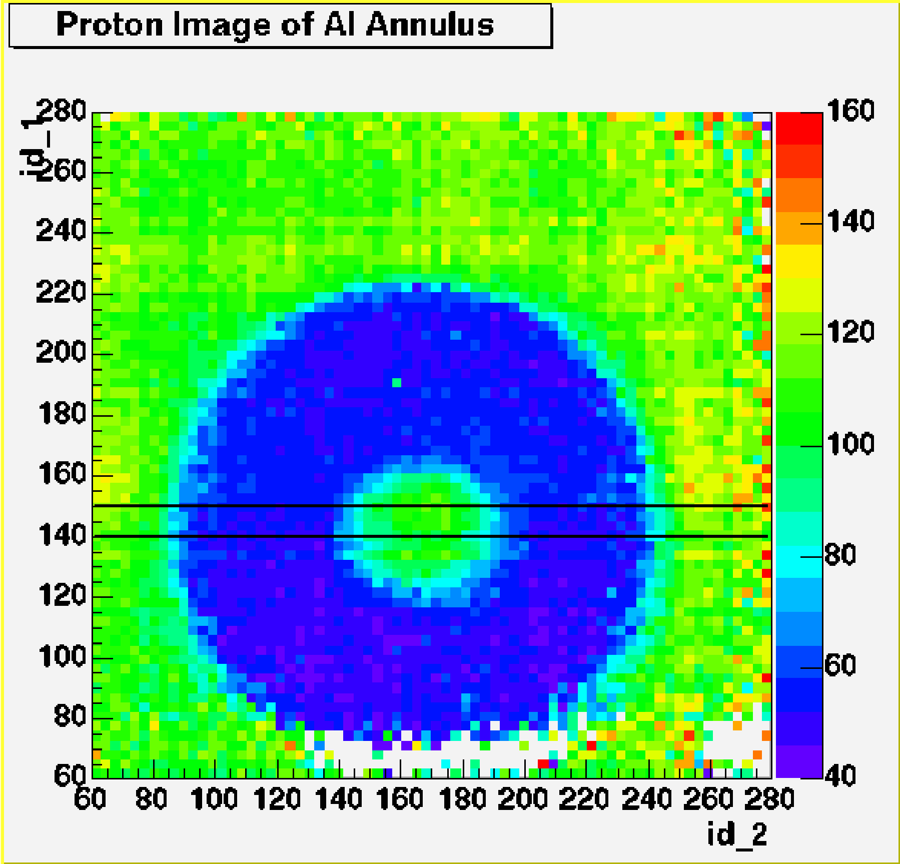
Image !



Subdivide SSD area into pixels

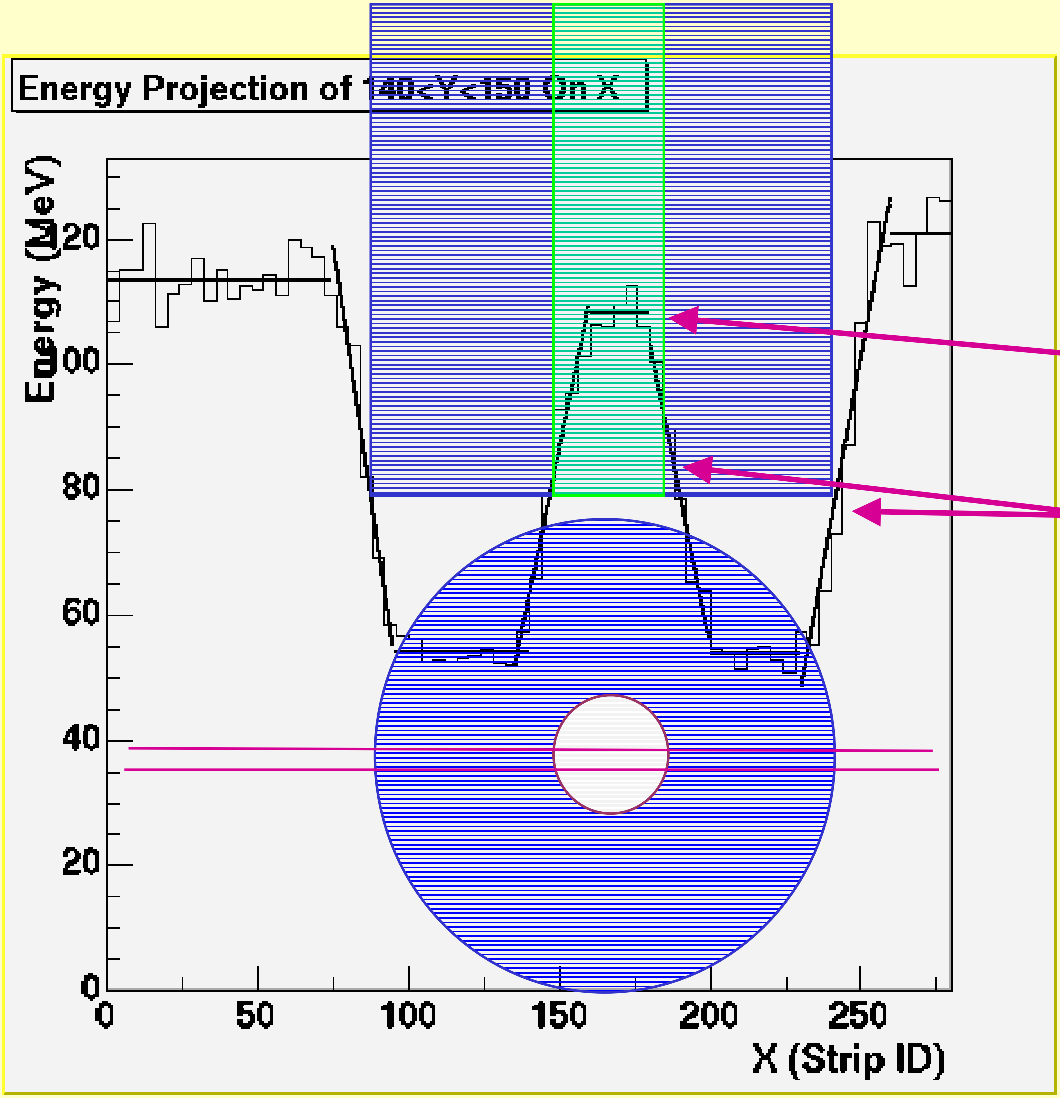
1. **Strip x strip 194um x 194um**
2. **4 x 4 strips (0.8mm x 0.8mm)**

Image is average energy in pixel



Energy Resolution = Position Resolution

Slice of 4x4 pixels

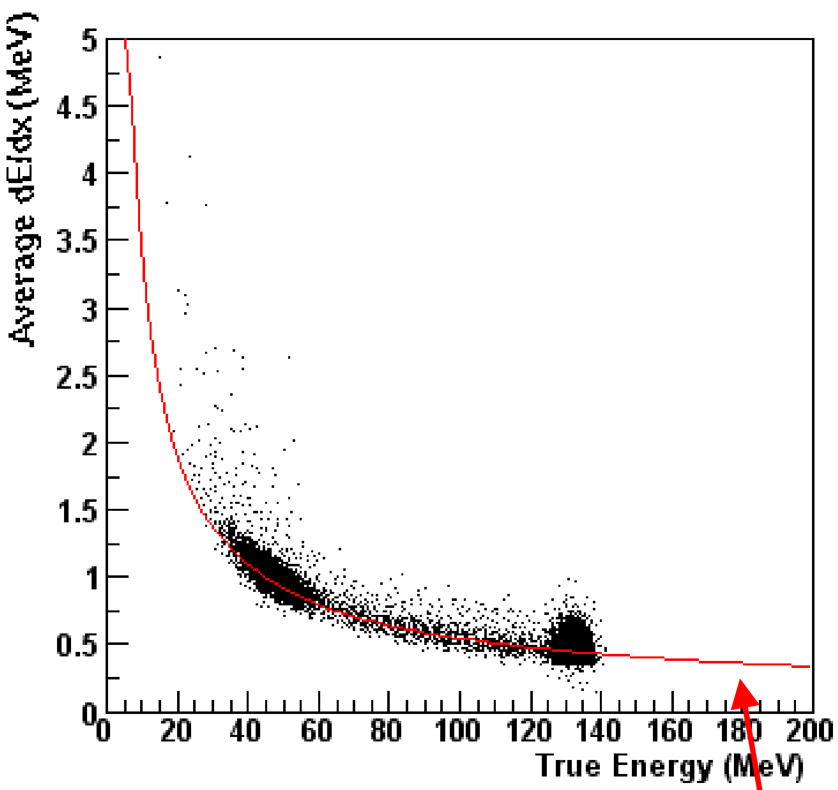


Hole “filled in”

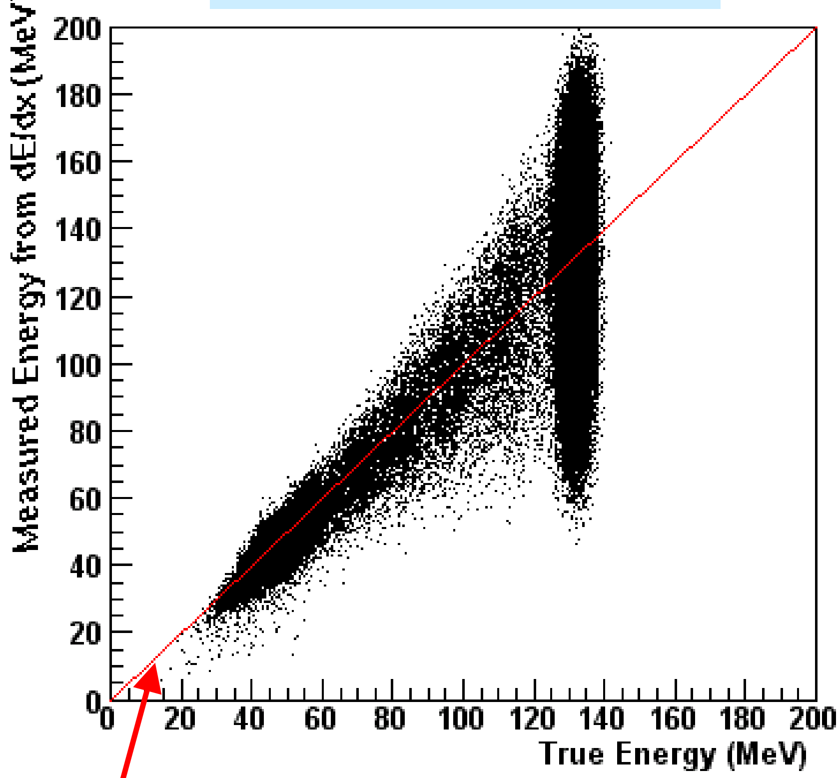
“Fuzzy” Edges

GEANT4 MC: Energy Reconstruction

Energy Loss in Si

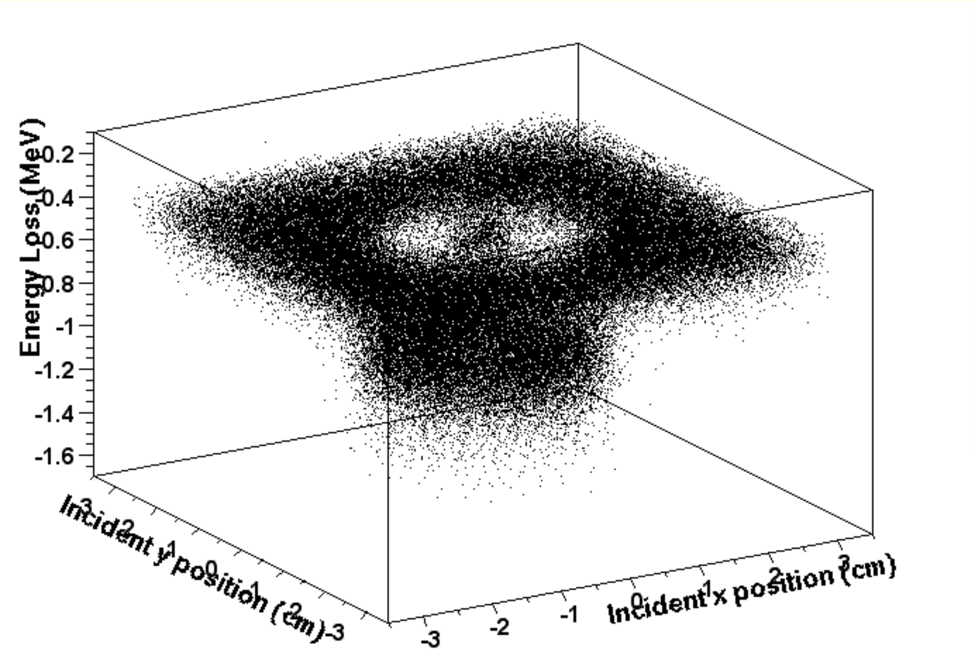


Energy Reconstructed from Energy Loss in Si

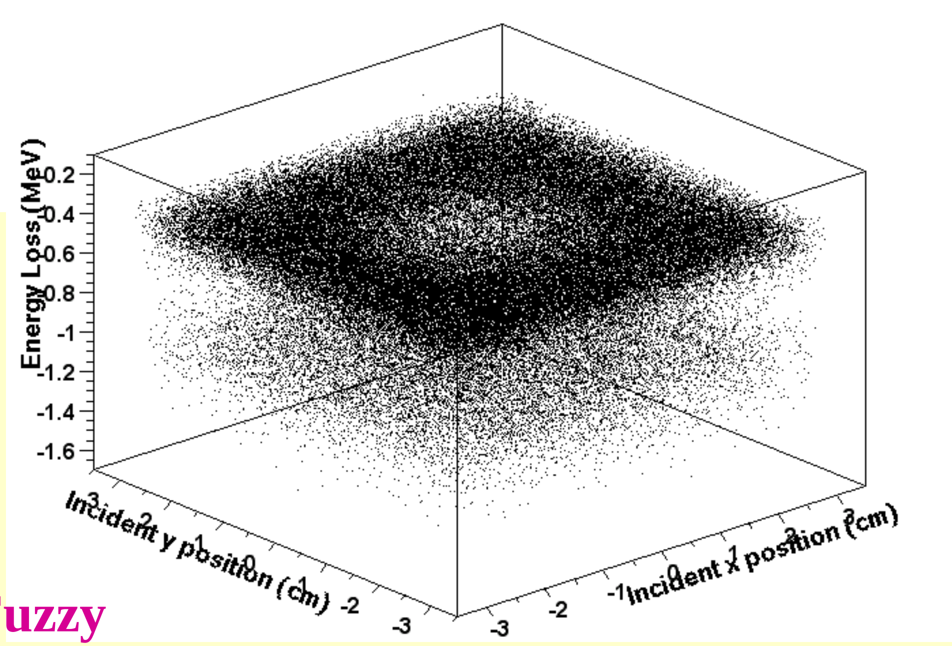


NIST Data

MC: Loss of Resolution in Back



First Plane, 2cm behind Object



Second Plane, 30cm behind Object: Fuzzy

Multiple Scattering: Migration

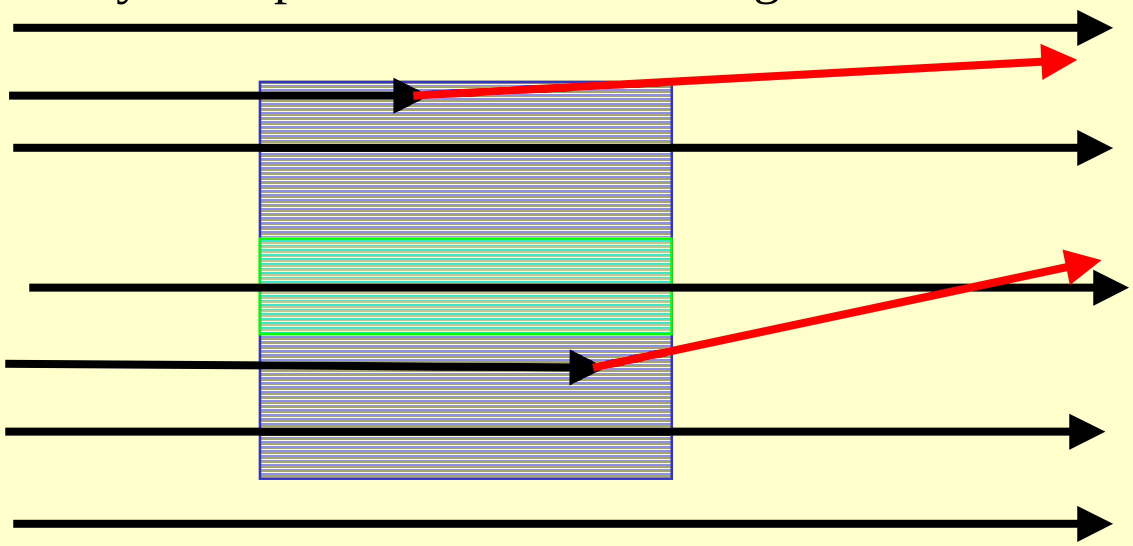
Features:

Washed out image in 2nd plane (30cm downstream)

Energy diluted at edges and in hole (Fuzzy edges,Hole filled partially)

Migration of events

are all explained by Multiple Coulomb Scattering MCS



Protons scatter OUT OF Target (not INTO).

Those have larger energy loss, larger angles, fill hole, dilute energy

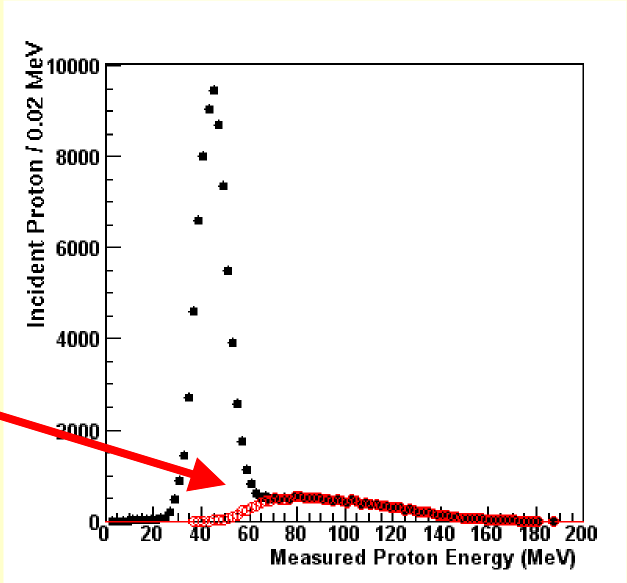
Migration: MC

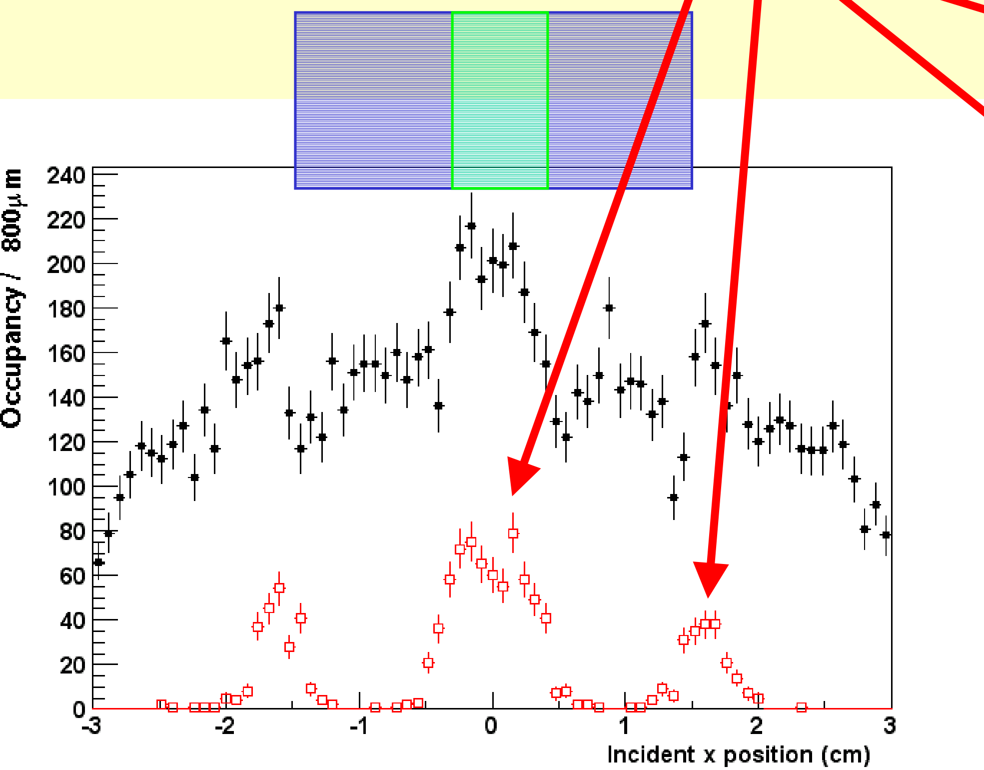
Dilution:

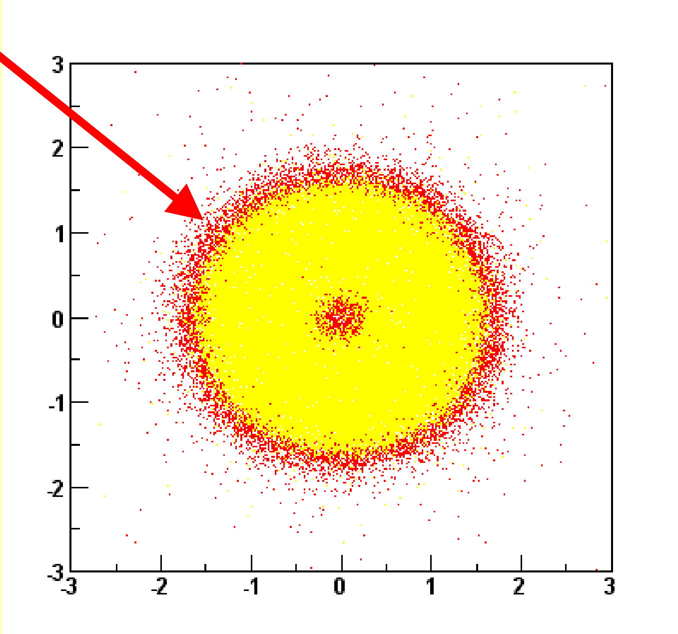
Protons

entering the Object in Front Face

but leaving it before the Rear Face

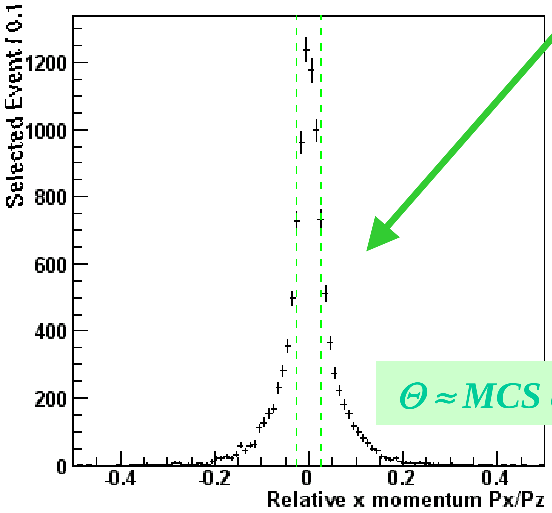






MC: Use Angular Information

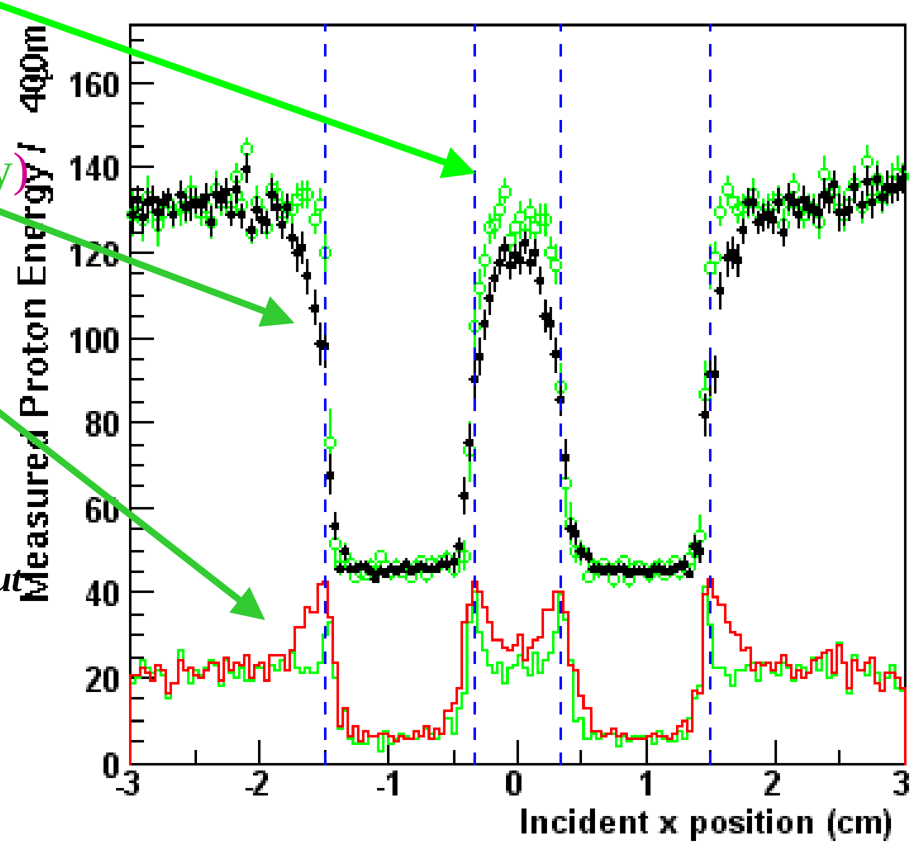
Effect of Angular Cut: Energy more uniform

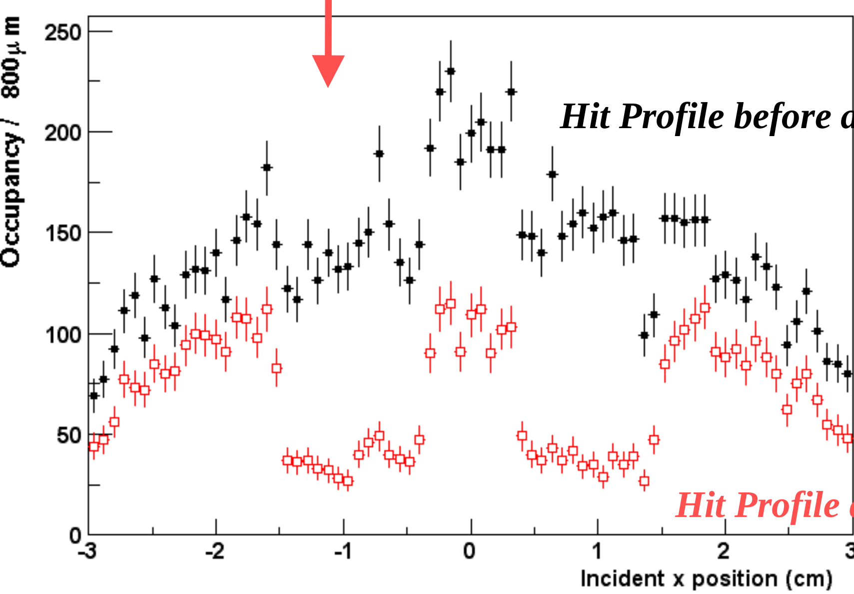


Θ ≈ MCS angle

Less Migration

Sharp edges
(RMS and Energy)





Hit Profile before angle cut

Hit Profile after angle cut

Imaging with MCS Angle?

Conclusions

Imaging with protons is working!

GEANT4 program describes the data well

(energy and position resolution, migration)

Issues:

- **Energy needs Optimization depending on Target**
- **Improve Resolution with cut on exit angle** √
- **Investigate independent Energy Measurement**
- **Dose – Contrast - Resolution Relationship**

Next steps: pCT