Geant4 based Monte Carlo simulations for proton beam radiation therapy

an experimentalist's view of Geant4

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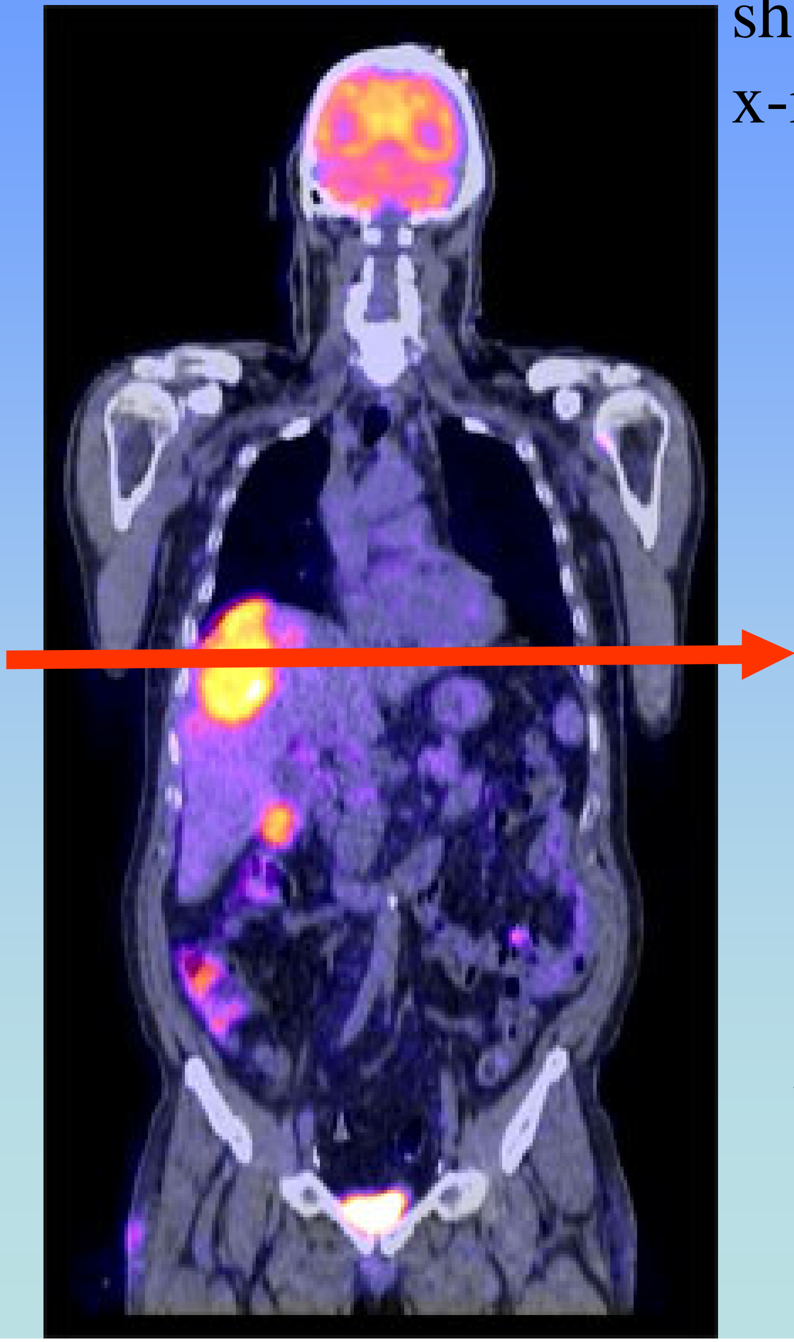
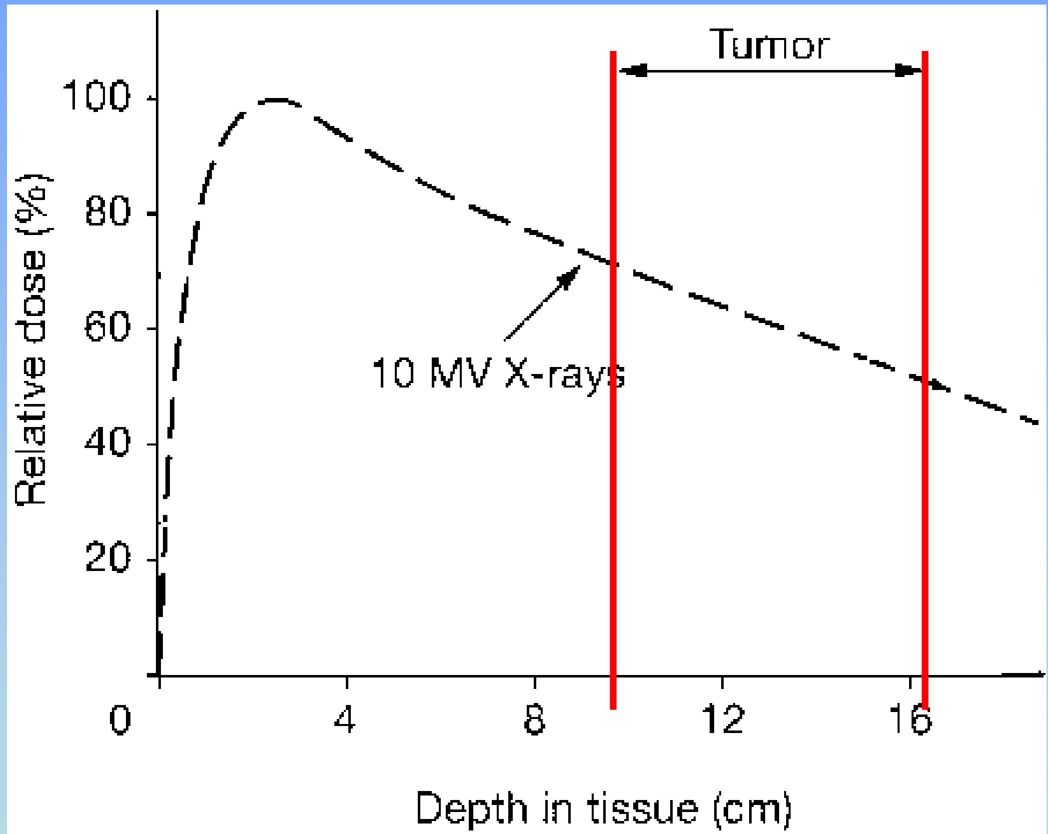
definition of the problem

x-ray beam treatment



shoot x-rays through cancer to kill cells
x-rays go through alot of healthy tissue too

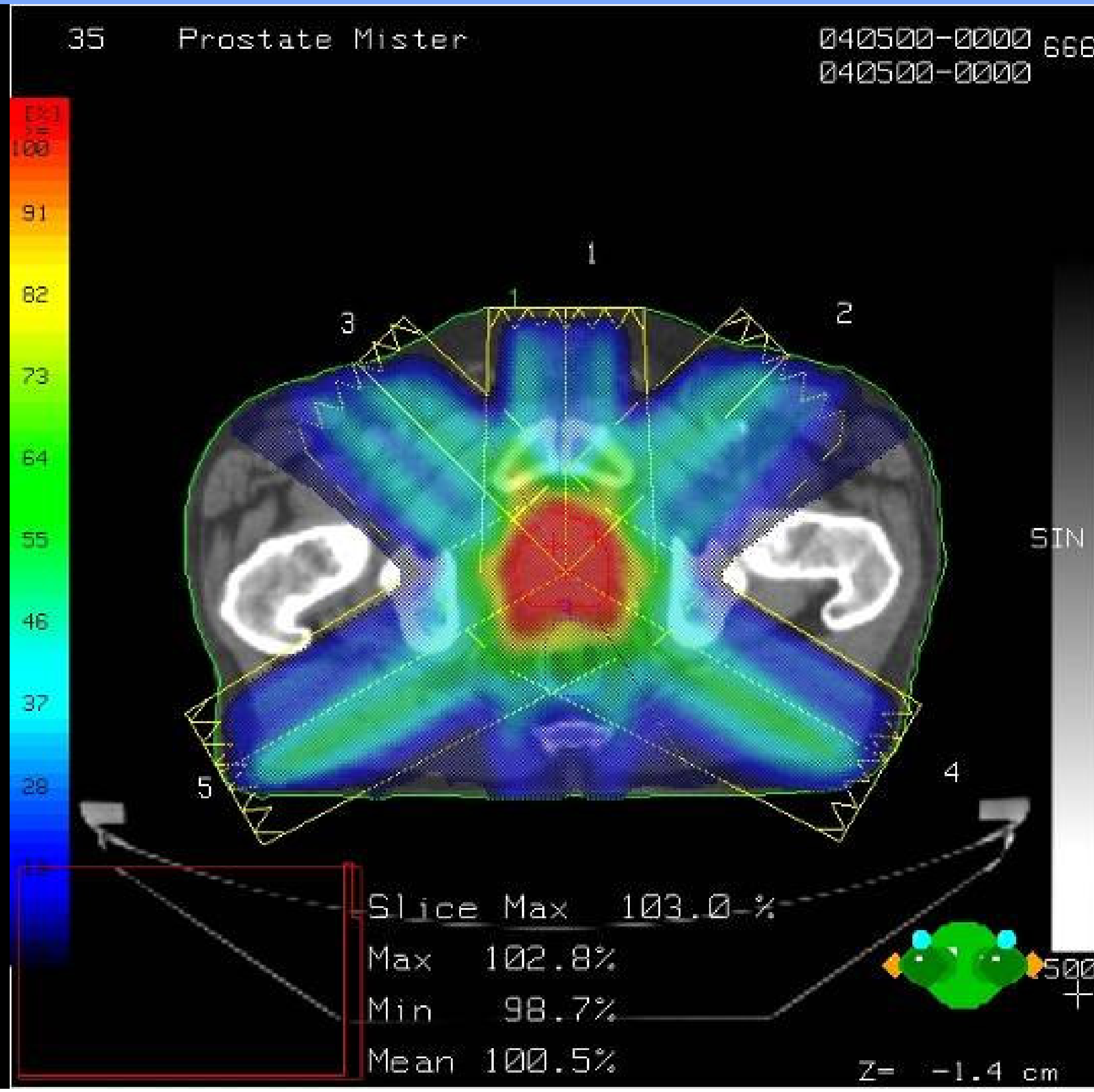


x-ray intensity $I=I_0e^{-\mu x}$
energy transferred to tissue (dose)
by electrons knocked out by x-rays.

minimize damage to healthy tissue

hit tumor from several angles

dose to healthy tissue spread out



What else? Protons!

Avoid healthy tissue, esp.: brain, spinal chord...

Pediatric cancer–>long life ahead of them, high risk of secondary cancer

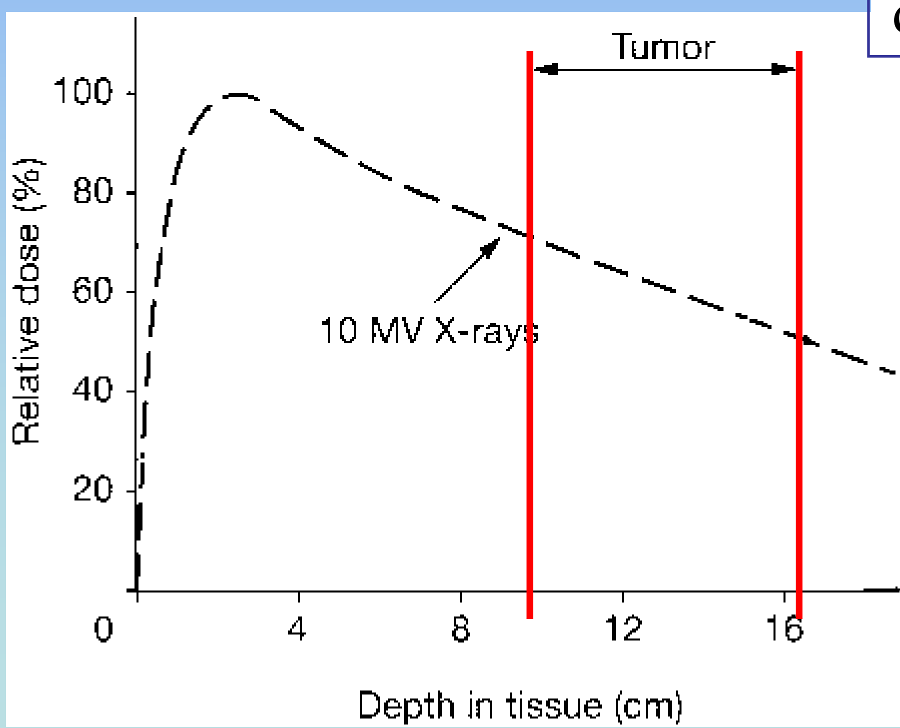
X-ray beam:
high dose to healthy tissue
large entrance/exit dose

proton beam:
small entrance dose
approx. no exit dose

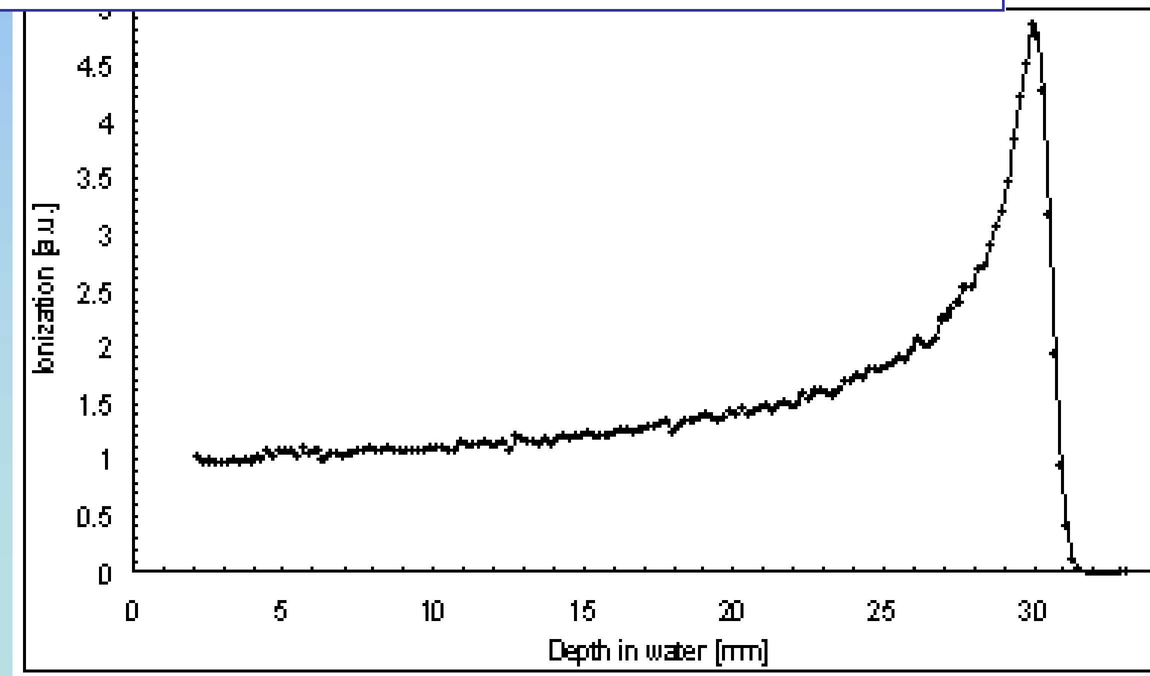
x-ray intensity $I=I_0 e^{-\mu x}$

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

different beam energies = different depths



adapted from Nature Clin. Prac. Onc. **1**, 97 (2004).



http://www.lns.infn.it/CATANA/latest.htm

Geometric considerations

Avoid Organs At Risk (OAR), sensitive tissue which should not receive dose.
Examples:
Spinal chord and bladder in prostate cancer treatment.

- Crucial geometric advantage to proton beams.
- Lowers weighting of single beamlets, reducing dose uncertainty.

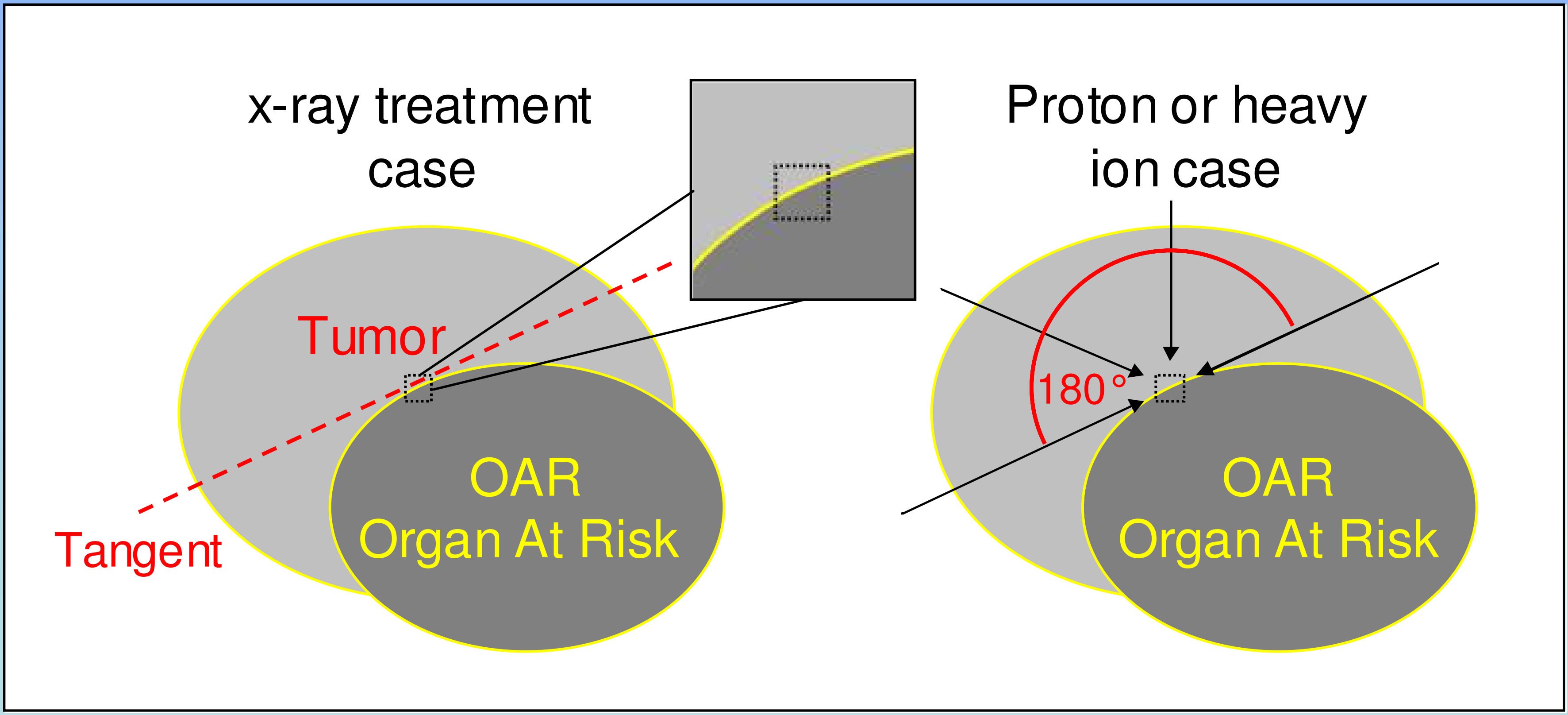


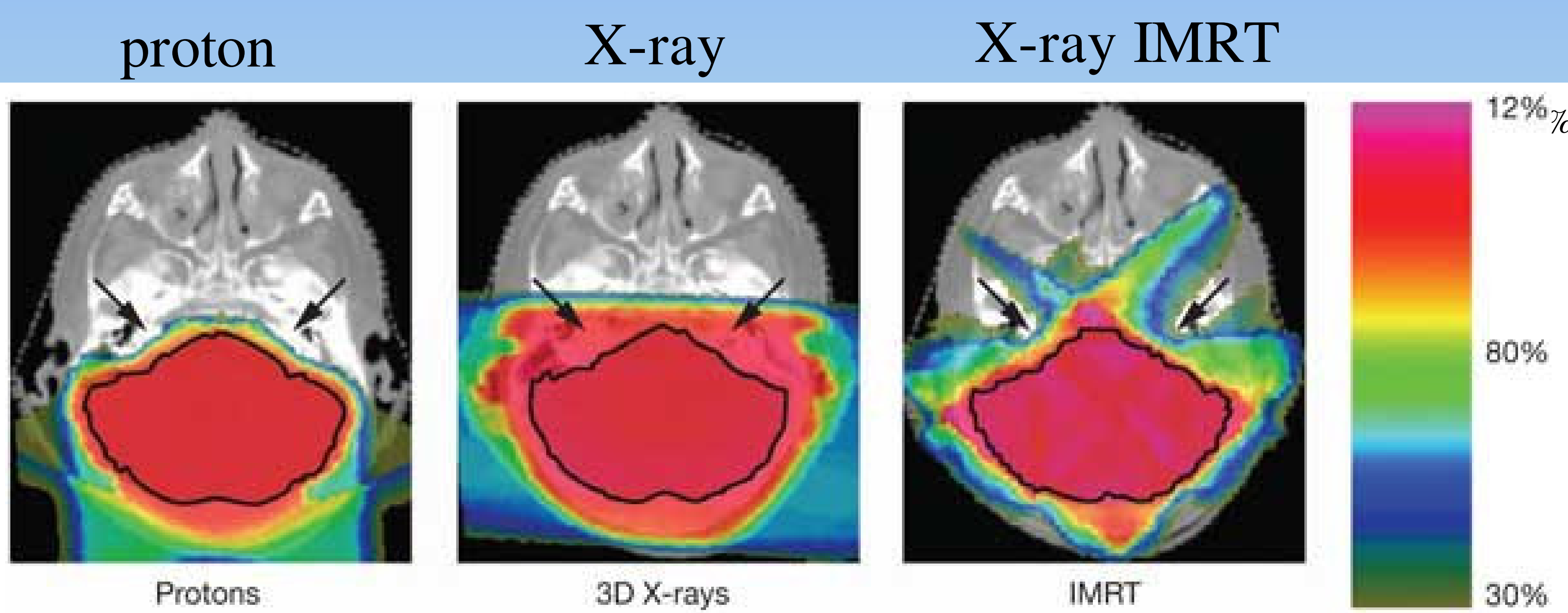
Illustration concept courtesy of Prof. T.R. Mackie

Minimize damage to surrounding tissue using several angles

State of the art treatment:

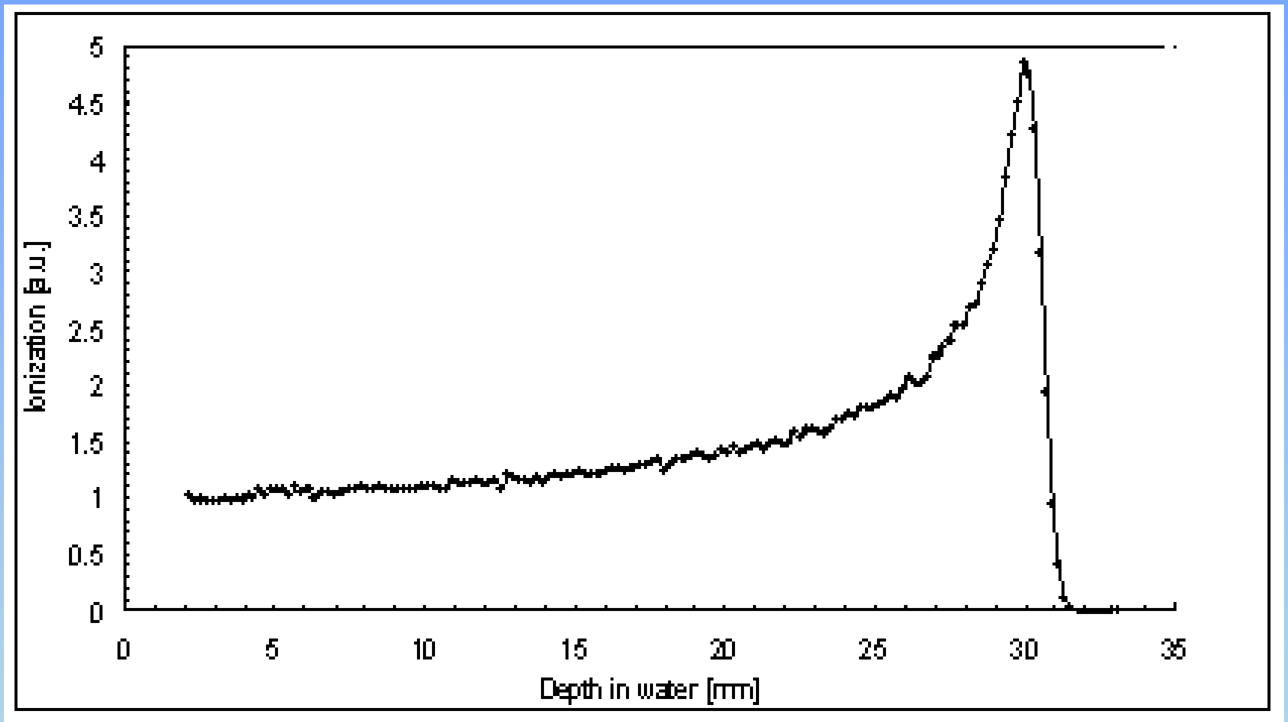
- Intensity Modulated Radiation Treatment (IMRT):
 total dose according to Rx, individual beams of different intensities

can get better conformity to Rx with protons.



TI Yock and NJ Tarbell, Nat Clin Pract Oncol **1**: 97 (2004)

need to fill volume of tumor with radiation dose



need to spread
longitudinally ↔

hot spot

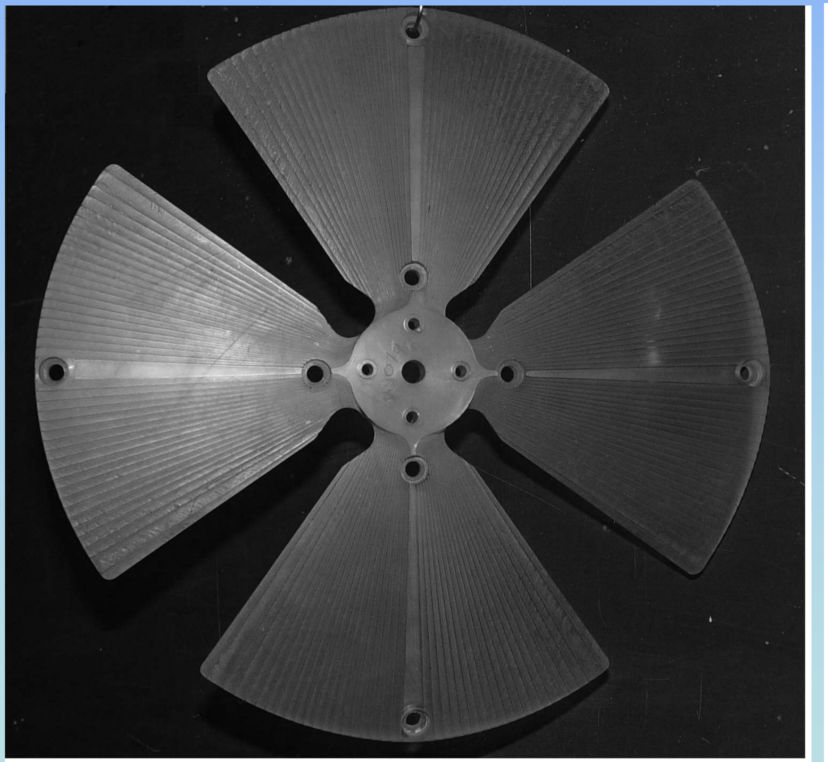
laterally ↕

Specifics of Treatment: Spread Out Bragg Peak

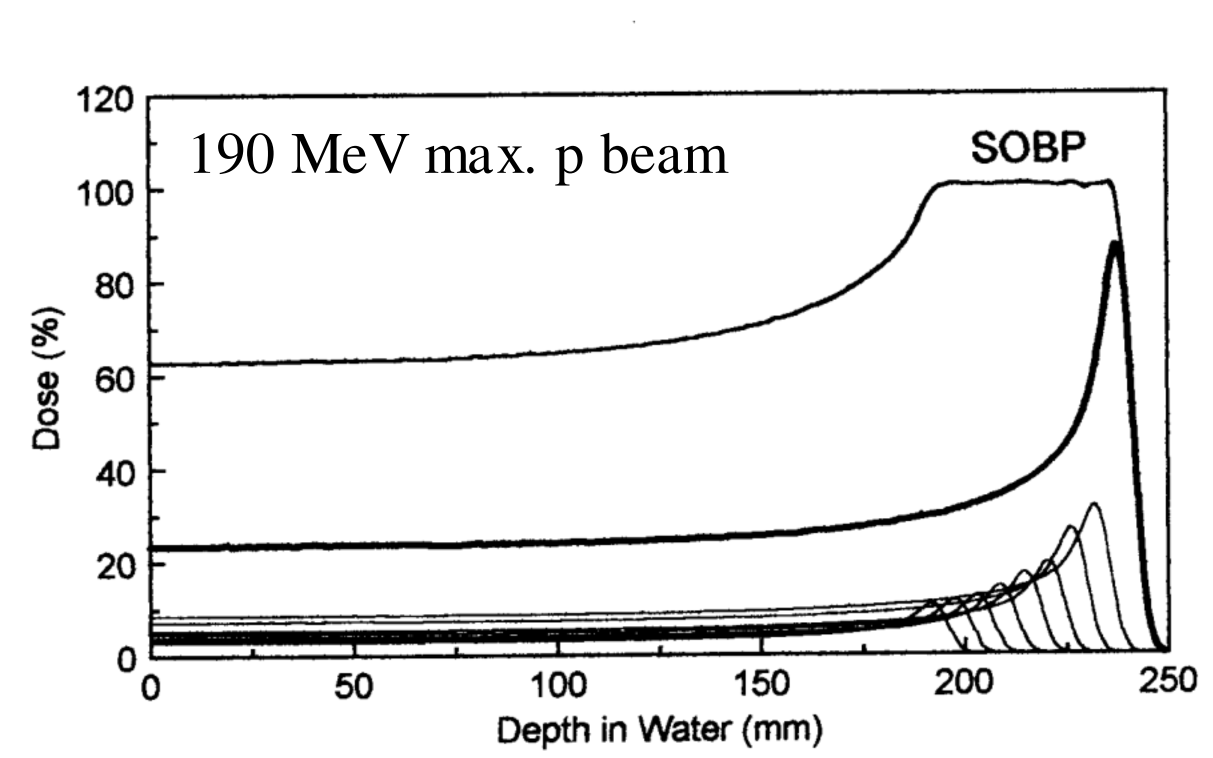
For depth dose distribution use different energy beams...

or

vary treatment energy after production with variable thickness range shifter to spread out Bragg peaks



PolyMethylMethAcrylate range shifter from Laboratori Nazionali del Sud CATANA, Italy



http://www.canberra.edu.au/irps/archives/vol15no34/mempap.html

Secondary radiation from proton beam radiotherapy

start with narrow beam "pencil beam"

spread laterally and longitudinally

lateral: put through material far from target

small angle --- large spread

need collimation - nozzle

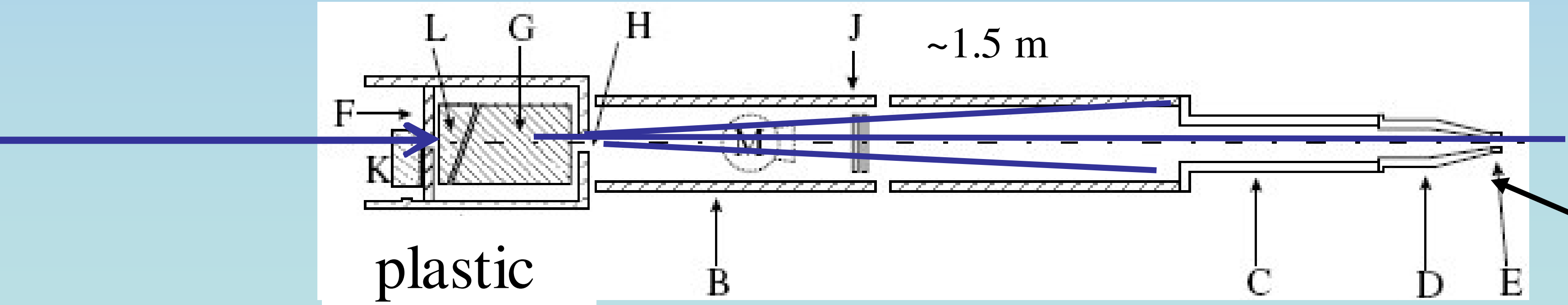
longitudinal: use range shifter

but...produce neutrons

Neutrons especially bad.

Production is set up dependent.

Must model.



W. Newhauser *et al. Phys. Med. Biol.* **50** 5229 (2005).

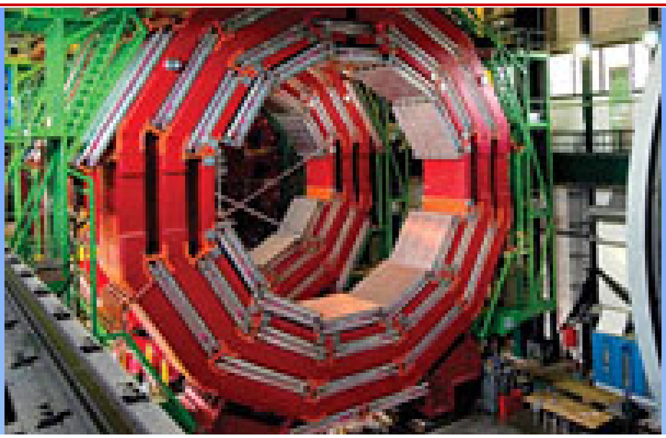
Radiation therapy is used to kill cells.
kill cancerous cells
spare healthy tissue

need to model proton pencil beam in matter
compare with experiment

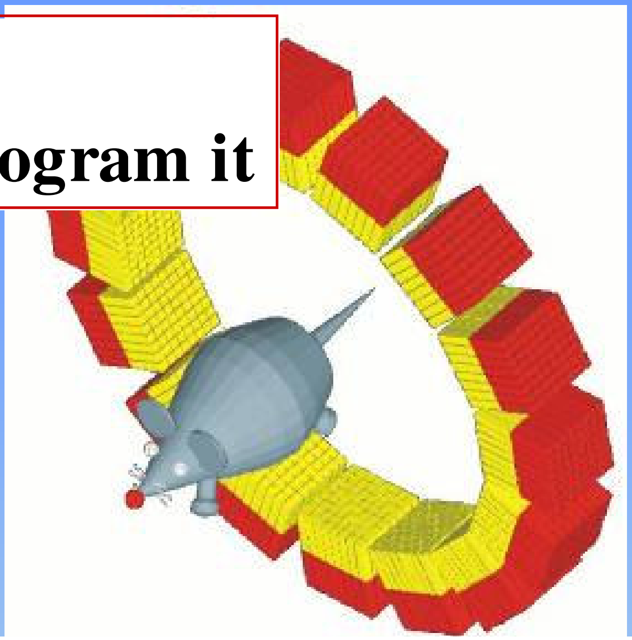
Secondary radiation from broad beam not well studied.
Model to understand what to expect.

Geant4 simulation to study secondary radiation

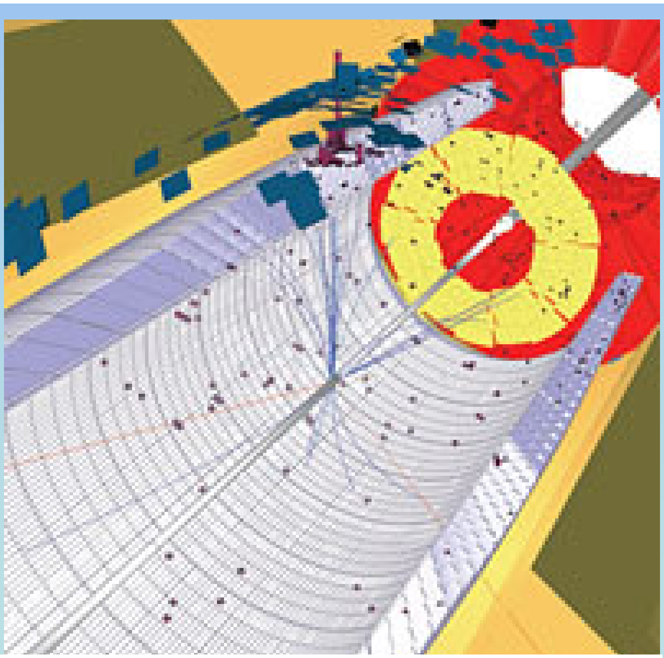
Geant4:
anything is possible but you have to program it



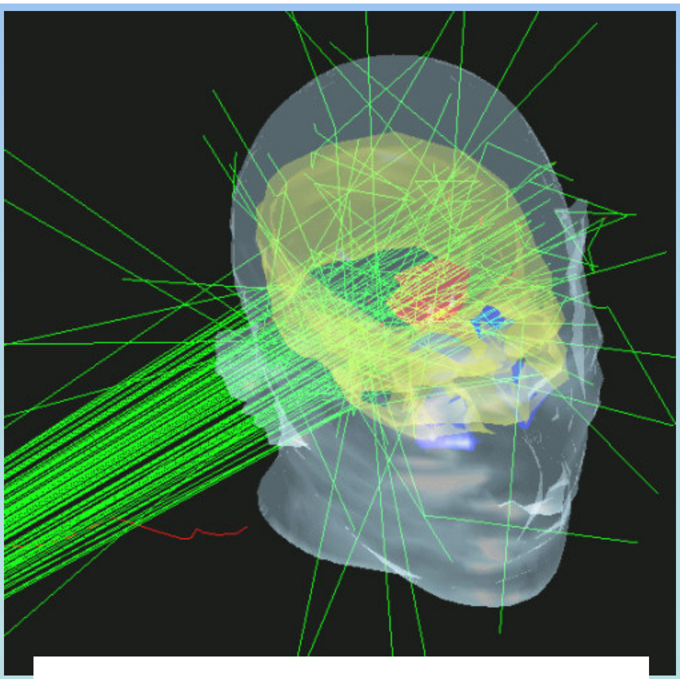
CMS (Compact Muon Solenoid), CERN



CMS (Compact Mouse Scanner)



simulated Higgs particle decay



simulated CT photon beam

figures: geant4.cern.ch

Geant4 background and functionality

Geant4 - GEometry ANd Tracking

- developed, supported, maintained by Geant collaboration, CERN
- Object oriented ***toolkit*** for the simulation of radiation in matter
- Offers set of complementary and alternative physics models based on
  - experimental data
  - theory
  - parameterizations

The take-away message:

- Geant 4 not a Monte Carlo code but a “toolkit”
  - can’t run “out of box”
  - write application in C++
  - no defaults
  - choose which Geant4 tools to use

- particle by particle tracking

must

- describe experimental set-up
- provide the primary particles
- decide which particles and physics models to include, and precision (step size)

may

- visualize – DAWN, WIRED, RayTracer, OpenGL,...
- create histograms, tuples
- G4xxx classes, can define own

example structure

- main program
  - refers to subprograms, header files
- geometry and materials
  - world, detector
- physics
  - particle interactions with matter
- step and tracking management
  - step size, tracking properties in target volume
- event management
  - define beam
  - per primary particle tracked
- run management
  - for entire run
- must define visualization, persistency

geometry and materials

- define elements
- define compounds/materials
  - components, densities
  - interactions will be as if materials are ***amorphous soup***

    no crystal effects, surface effects, emergent properties, band gaps
    - that is, modeling not recommended below 250 eV
- define world boundaries
- define geometry of inert and tracking volumes

defining materials

```
#include "G4Isotope.hh"
#include "G4Element.hh"
#include "G4Material.hh"
#include "G4UnitsTable.hh"

int main() {
G4String name, symbol;
G4double A, Z, density;
G4int natoms, ncomponents;

G4Element* elO = new G4Element(name="Oxygen", symbol="O", Z=8., A=16.00*g/mole);
G4Element* elH = new G4Element(name="Hydrogen", symbol="H", Z=1., A=1.01*g/mole);

..............

density = 1.00 *g/cm3
G4Material* H2O = new G4Material(name="water", density, ncomponents=2);
H2O->AddElement(elH, natoms=2);
H2O->AddElement(elO, natoms=1);

..........
```

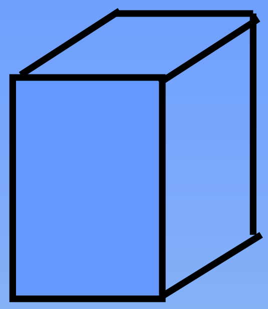
note G4int, G4double...

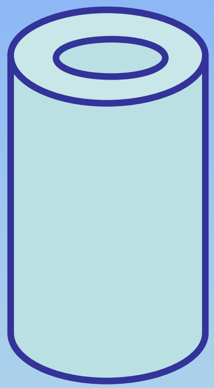
Geant4 understands basic units

can define by atomic proportions, mass ratios

defining geometry

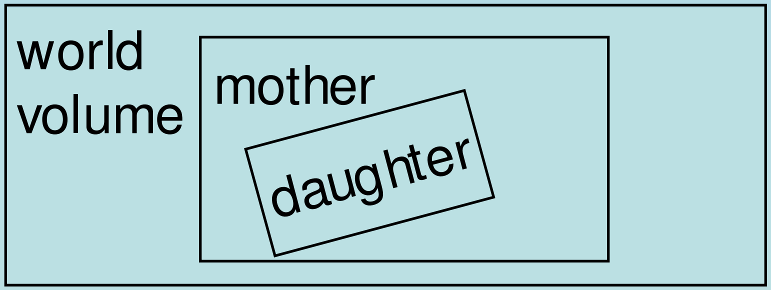
```
//defining a box
solidObject1 = new G4Box(const G4String& TheBoxVolumeName,
        G4double 20*cm, //box x-size from center (half length)
        G4double 20*cm, //box y-size from center (half length)
        G4double 20*cm) //box z-size from center (half length)

..............

//defining a cylindrical section or tube
solidObject2 = new G4Tubs(const G4String& TheTubeVolumeName,
        G4double 5*cm, //max radius
        G4double 4*cm, //min radius
        G4double 20*cm, //Z length
        G4double 0*deg, //start angle
        G4double 360*deg) //end angle

..........
```





relate objects to a mother volume (world, specific detector, etc)

place them relative to the (0,0,0) position of mother volume rotate, etc



defining geometry

conceptual layers:

G4VSolid	shape, size
G4LogicalVolume	material, magnetic field, etc
G4VPhysical Volume	position, rotation

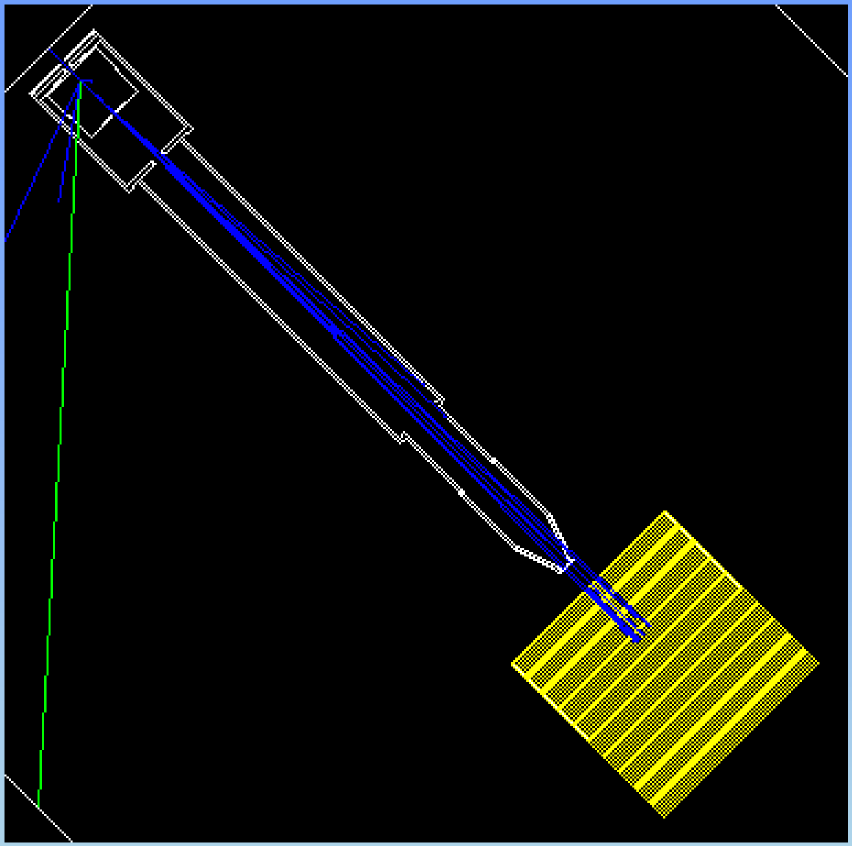
```
solidBox1 = new G4Box("thebox",20*cm,20*cm,20*cm);

logicBox1 = new G4LogicalVolume(solidBox1, H2O, "thebox",0,0,0);

physicalBox1 = new G4PVPlacement(45*deg,G4ThreeVector(0,0,0),
                                 logicBox1,"thebox",logicWorld,false,0);
```

..., mother volume, Boolean operations, fields)

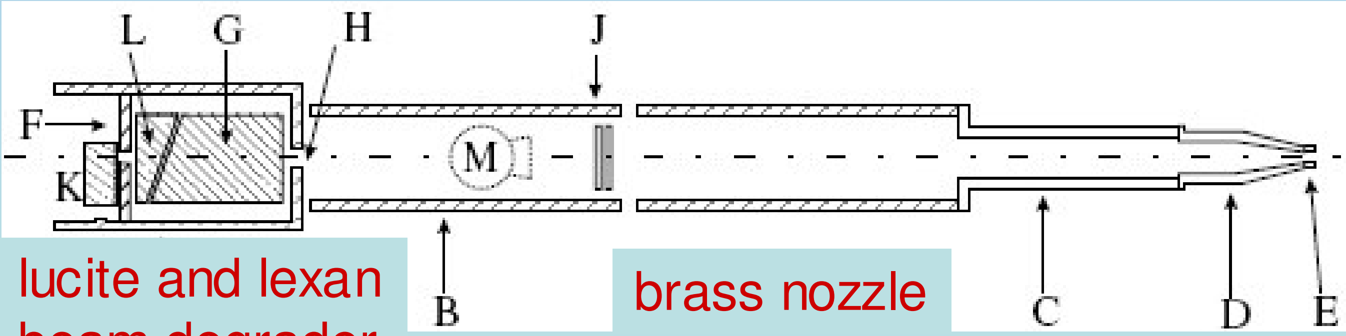
placement relative to mother volume
but can't extend beyond mother volume

example geometry and materials

note tracks
blue + (proton)
red – (electron)
green neutral
(photon, neutron)



40x40 cm water block
“phantom”
1 mm slices



lucite and lexan
beam degrader
range shifter

brass nozzle

physics interactions

- electromagnetic – down to 250 eV (lower with caveats)
  - Compton scattering
  - Rayleigh scattering
  - Pair production
  - Photoelectric effect
  - ionization
  - Cerenkov
  - etc
- hadronic
  - elastic
  - inelastic
    - fusion-evaporation
    - photonuclear
- also: decay, optical, photolopton_hadron, transportation

physics models

- models
  - some use data libraries/interpolation, some theory driven
  - alot of data at “low energies”, approx. few hundred eV to few hundred MeV
- electromagnetic
  - standard – e^-, e^+, γ, hadron EM ----- keV to TeV
  - low energy – extend to lower energy
  - muons
  - X-rays
  - optical photons
- hadronic - many choices
  - Bertini model hadron interactions: only p and n
  - Binary collision – can handle heavier particles

    low energy binary collision – invoke Shen and Tripathi models
  - etc
  - alot of detail, choose what you think is appropriate and what you think works

```
#include "G4eplusAnnihilation.hh"
#include "G4StepLimiter.hh"
#include "G4ionIonisation.hh"
#include "G4hIonisation.hh"
```

physics: electromagnetic interactions

```
PHYS_EM_Standard::PHYS_EM_Standard(const G4String& name):
G4VPhysicsConstructor(name){}

PHYS_EM_Standard::~PHYS_EM_Standard()
{}

void PHYS_EM_Standard::ConstructProcess()
{

 theParticleIterator -> reset();
  while( (*theParticleIterator)() ){
   G4ParticleDefinition* particle = theParticleIterator -> value();
   G4ProcessManager* pmanager = particle -> GetProcessManager();
   G4String particleName = particle -> GetParticleName();

   if (particleName == "gamma"){
     pmanager->AddDiscreteProcess(new G4PhotoElectricEffect());
     pmanager->AddDiscreteProcess(new G4ComptonScattering());
     pmanager->AddDiscreteProcess(new G4GammaConversion());
   }

    if (particleName == "e-"){
     pmanager->AddProcess(new G4MultipleScattering,-1, 1,1);
     pmanager->AddProcess(new G4eIonisation,       -1, 2,2);
     pmanager->AddProcess(new G4eBremsstrahlung,   -1, 3,3);
     pmanager->AddProcess(new G4StepLimiter(),     -1,-1,4);
   }
```

goes through list of particles

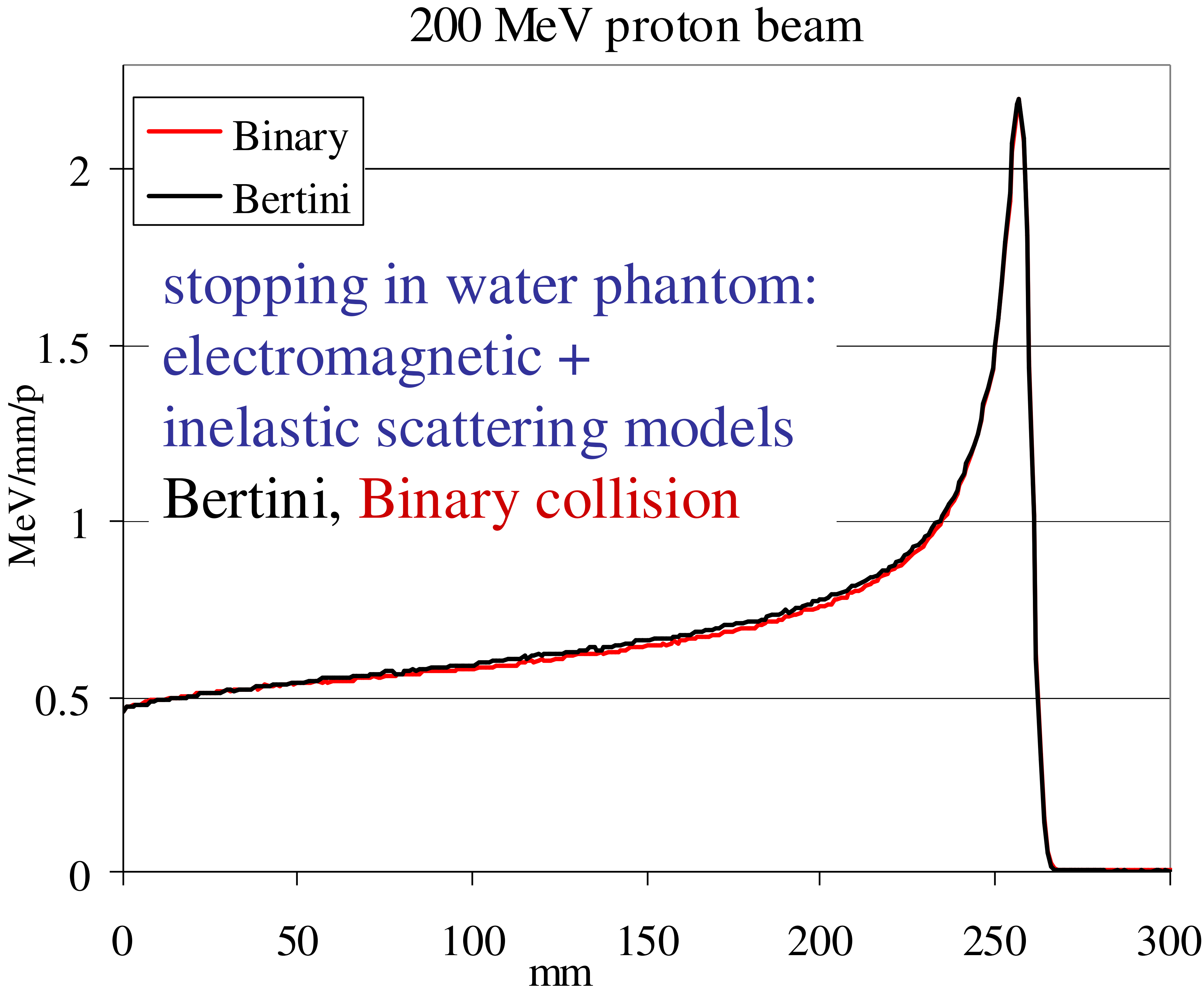
photon:
catastrophic processes
only one can happen

e-
undergoes many processes
vertical order is priority
(rest, along step, post step)

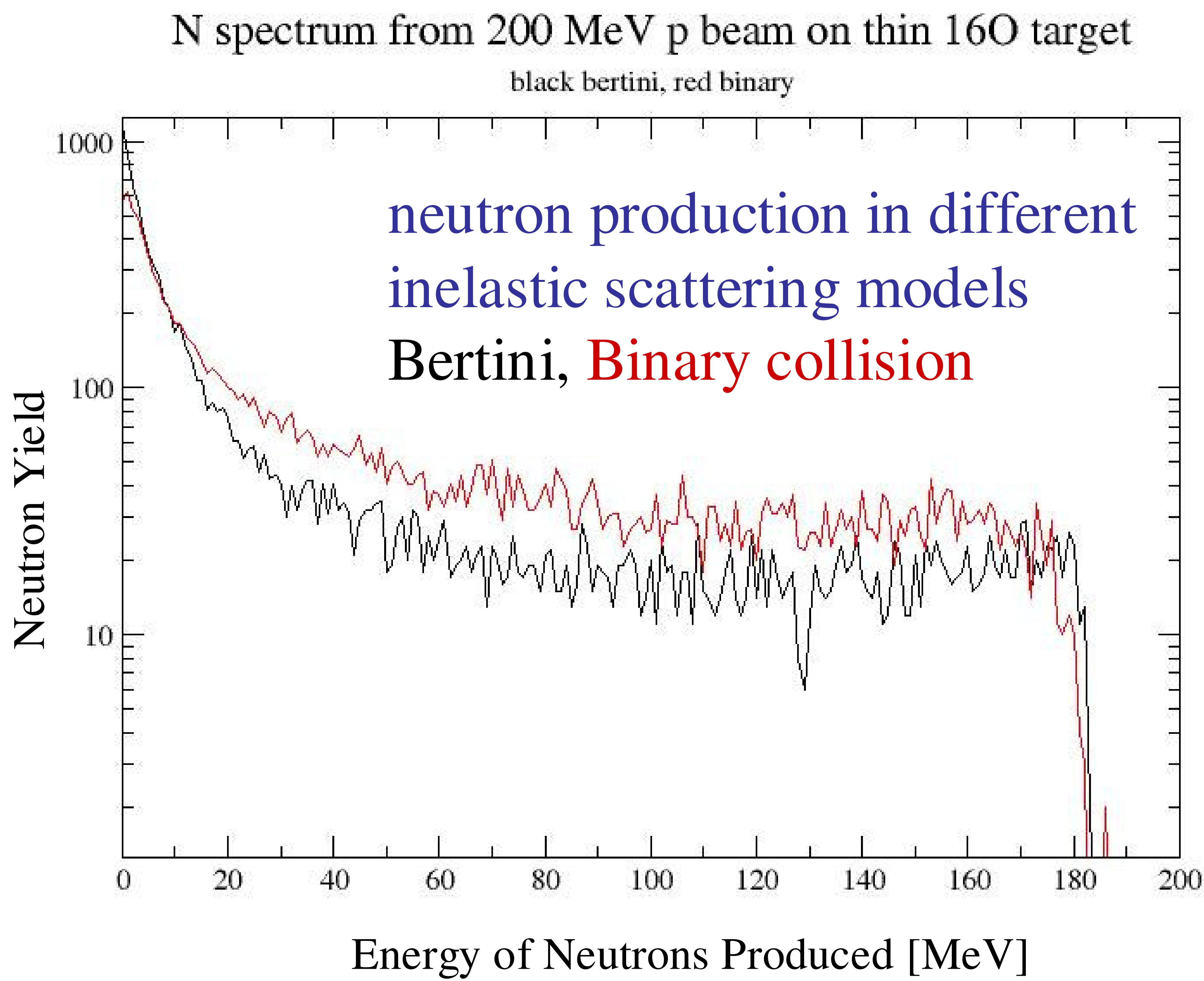
hadronic physics models

- For hadronic processes Russian Dolls structure – levels and sublevels of framework
  - level 1: elastic, inelastic processes
  - level 2: cross sections, isotope production, final states
  - level 3: precompound modeling, partial final states
  - level 4: quark-gluon and subnucleon scale monsters
  - level 5: Feynman field, string fragmentation...

medical physics uses low enough energy (< GeV) focus just on 1,2, some 3.

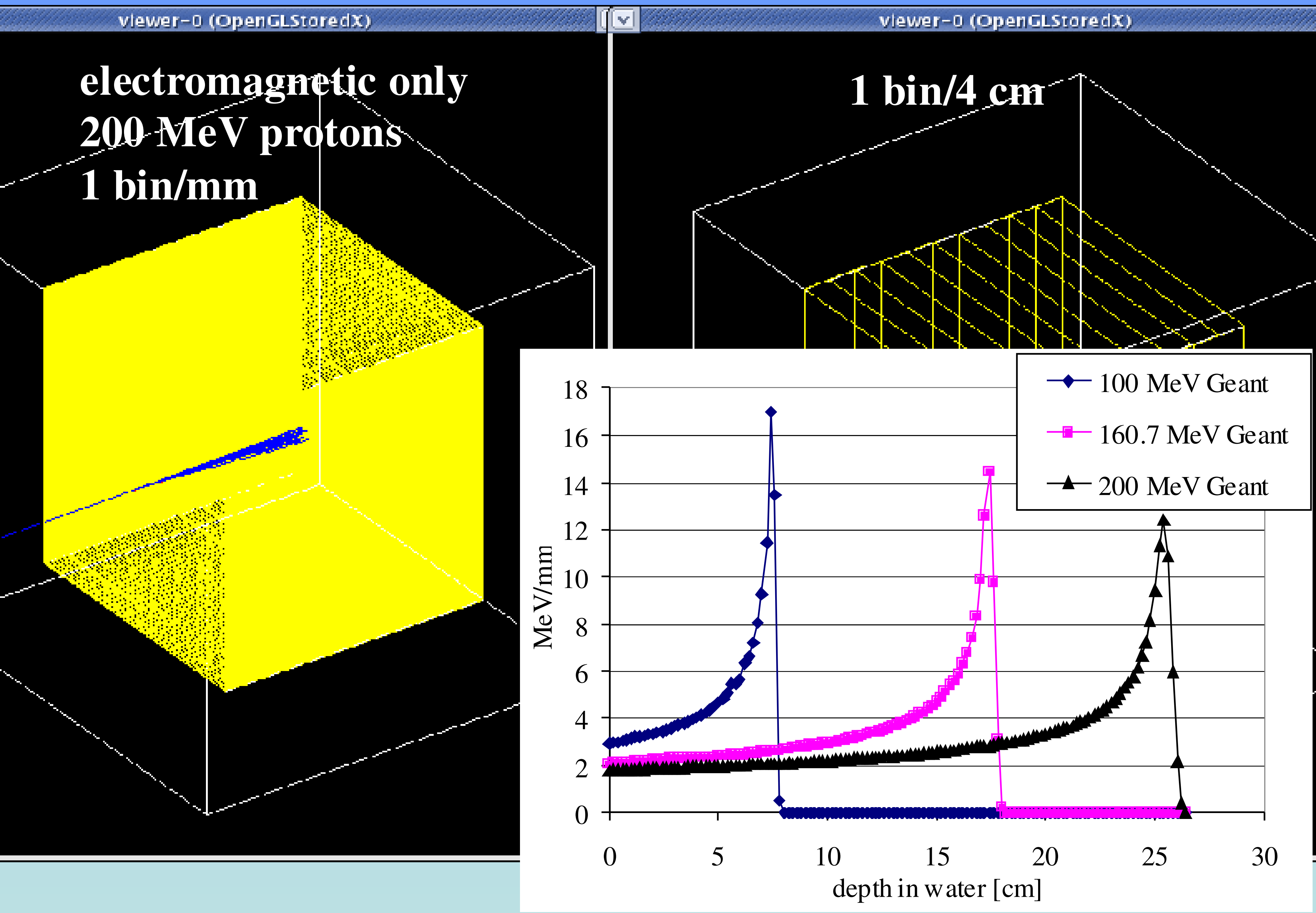


200 MeV proton beam
Binary
Bertini
stopping in water phantom:
electromagnetic +
inelastic scattering models
Bertini, Binary collision
MeV/mm/p
mm
0
0.5
1
1.5
2
0
50
100
150
200
250
300

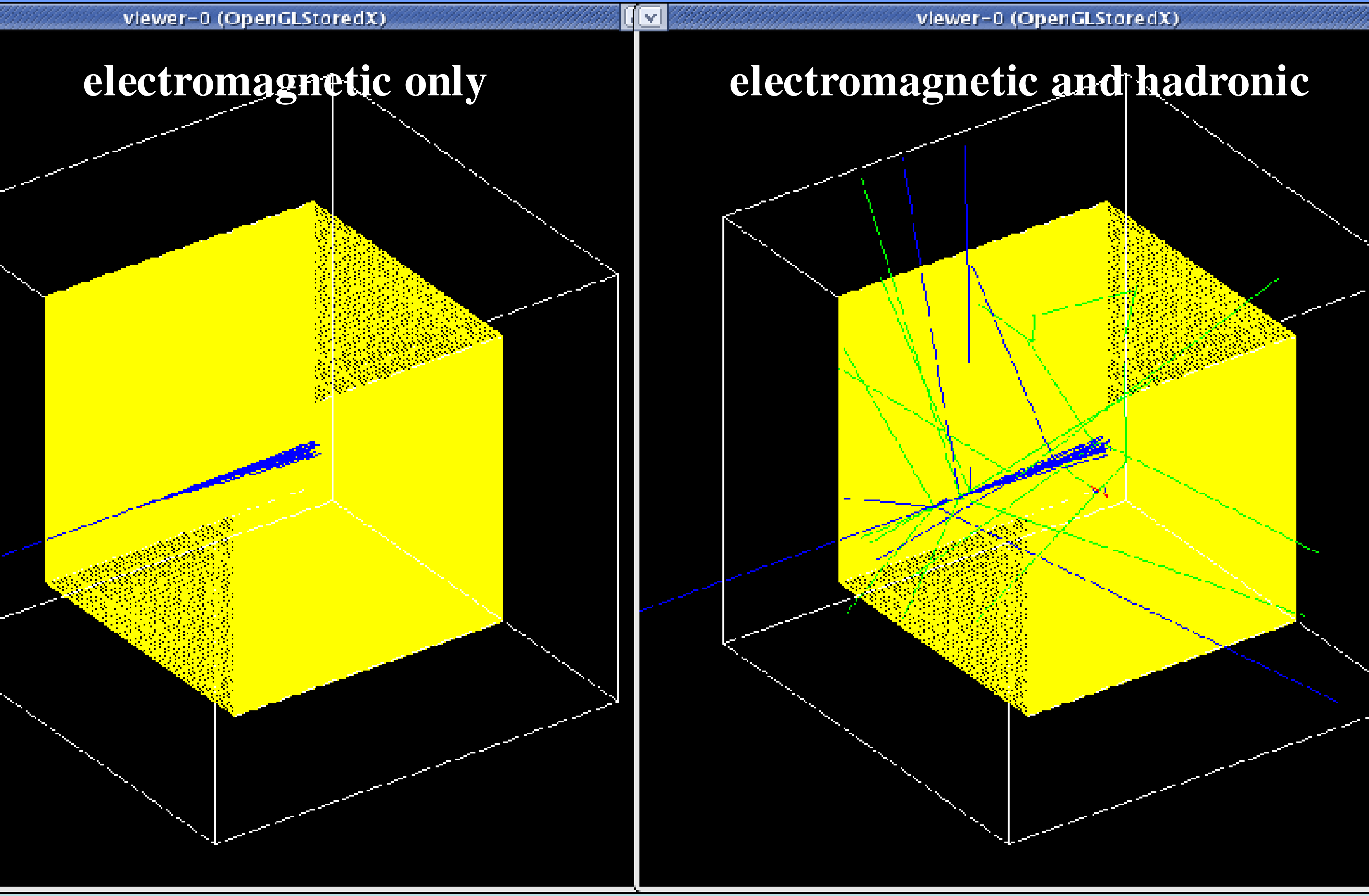

N spectrum from 200 MeV p beam on thin 16O target
black bertini, red binary
neutron production in different
inelastic scattering models
Bertini, Binary collision
Neutron Yield
1000
100
10
0
20
40
60
80
100
120
140
160
180
200
Energy of Neutrons Produced [MeV]

stepping and tracking

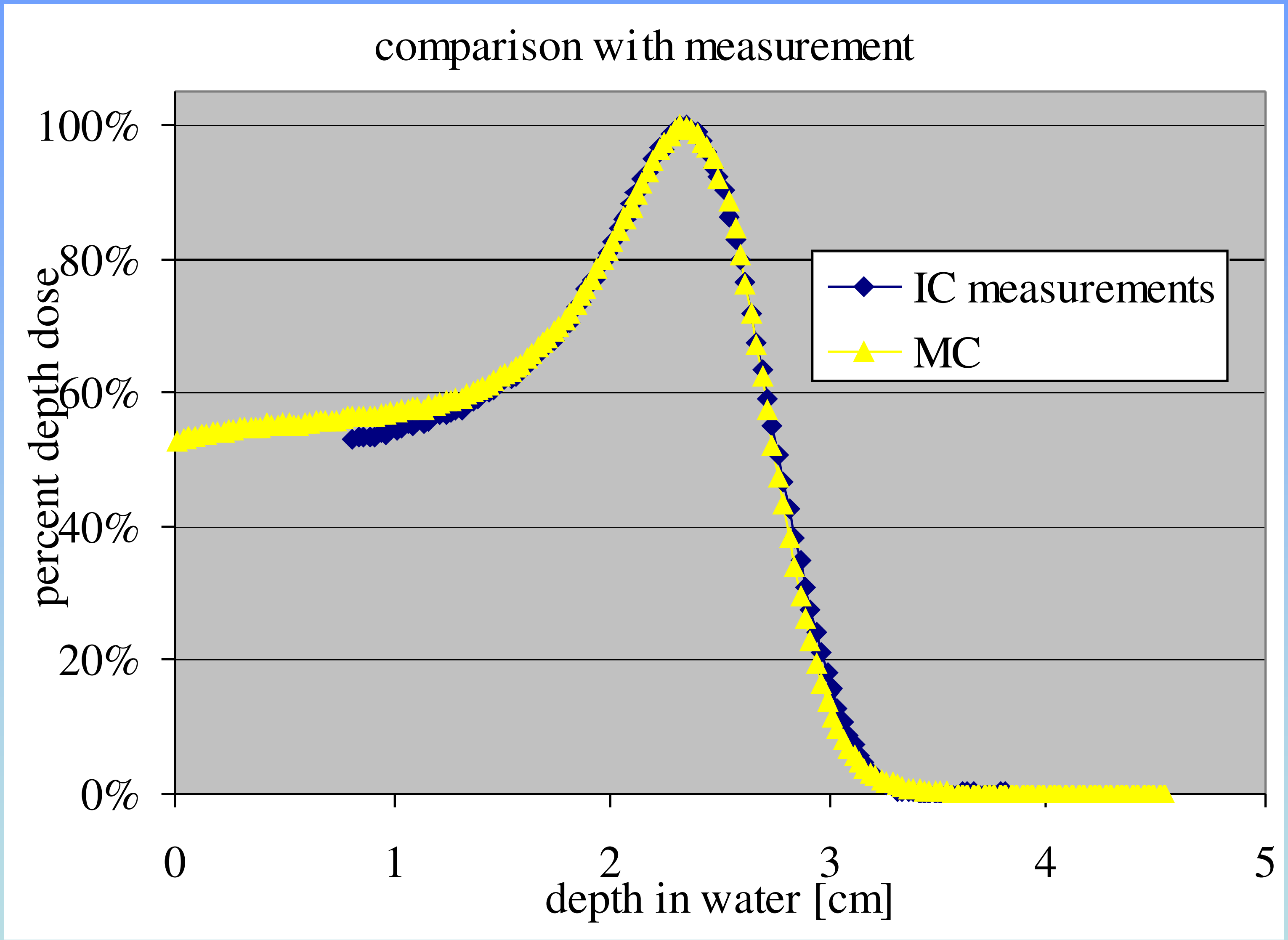
- you define max. step size
  - actual particle motion
- tracks for each step
- automatic step at each geometry boundary
- active target area
  - send energy, particle ID, momentum, ...
    to variables read in event manager
  - gather statistics and at end send to run manager
  - run manager outputs to file, histogram, ...



viewer-0 (OpenGLStoredX)
viewer-0 (OpenGLStoredX)
electromagnetic only
200 MeV protons
1 bin/mm
1 bin/4 cm
100 MeV Geant
160.7 MeV Geant
200 MeV Geant
MeV/mm
depth in water [cm]
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
30

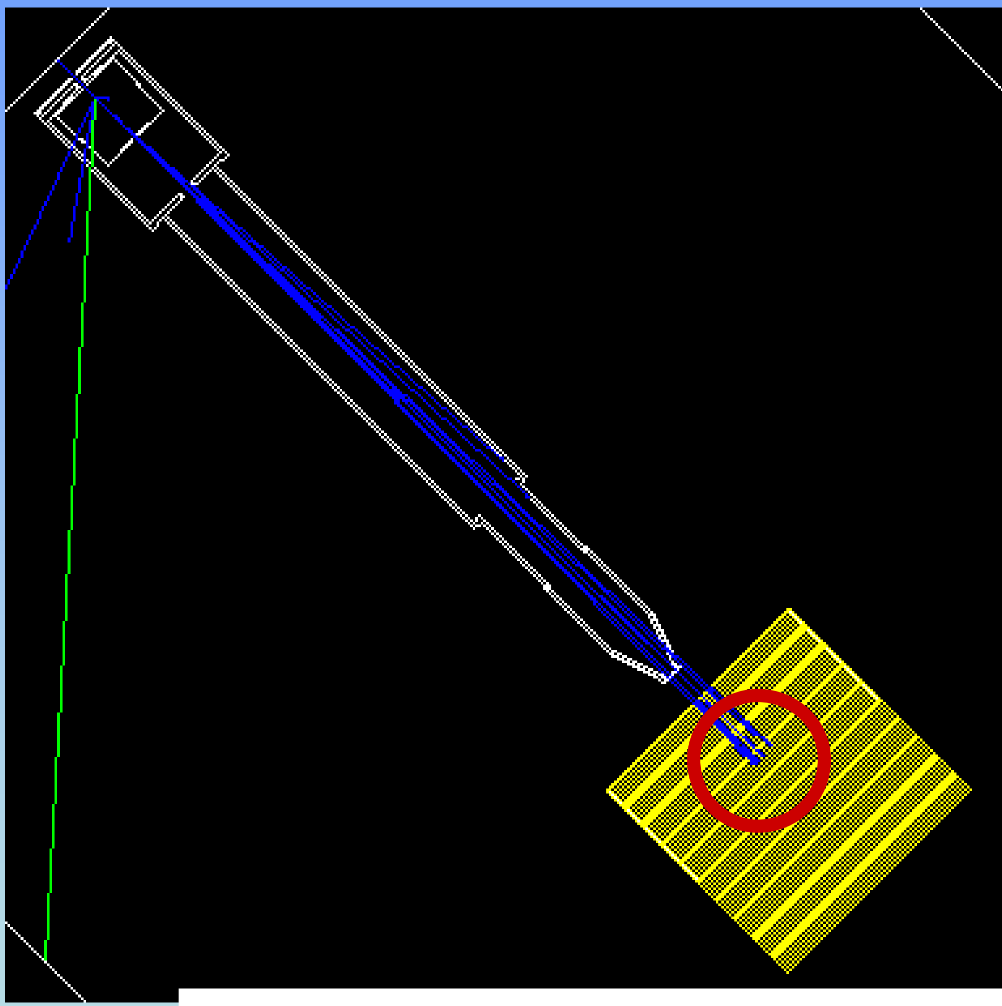

viewer-0 (OpenGLStoredX)
electromagnetic only
viewer-0 (OpenGLStoredX)
electromagnetic and hadronic

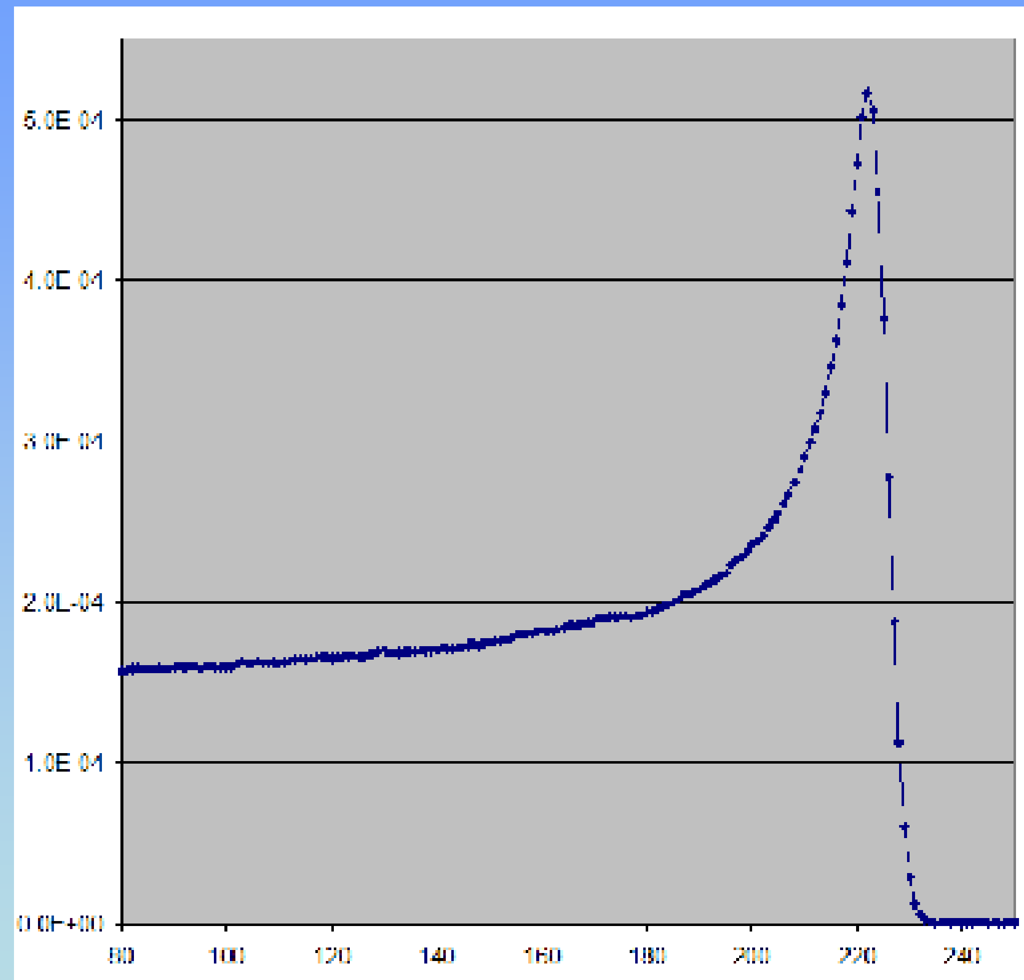
narrow beam validation



private communication Wayne Newhauser, MD Anderson/U Texas

broad beam
using degrader and beam nozzle

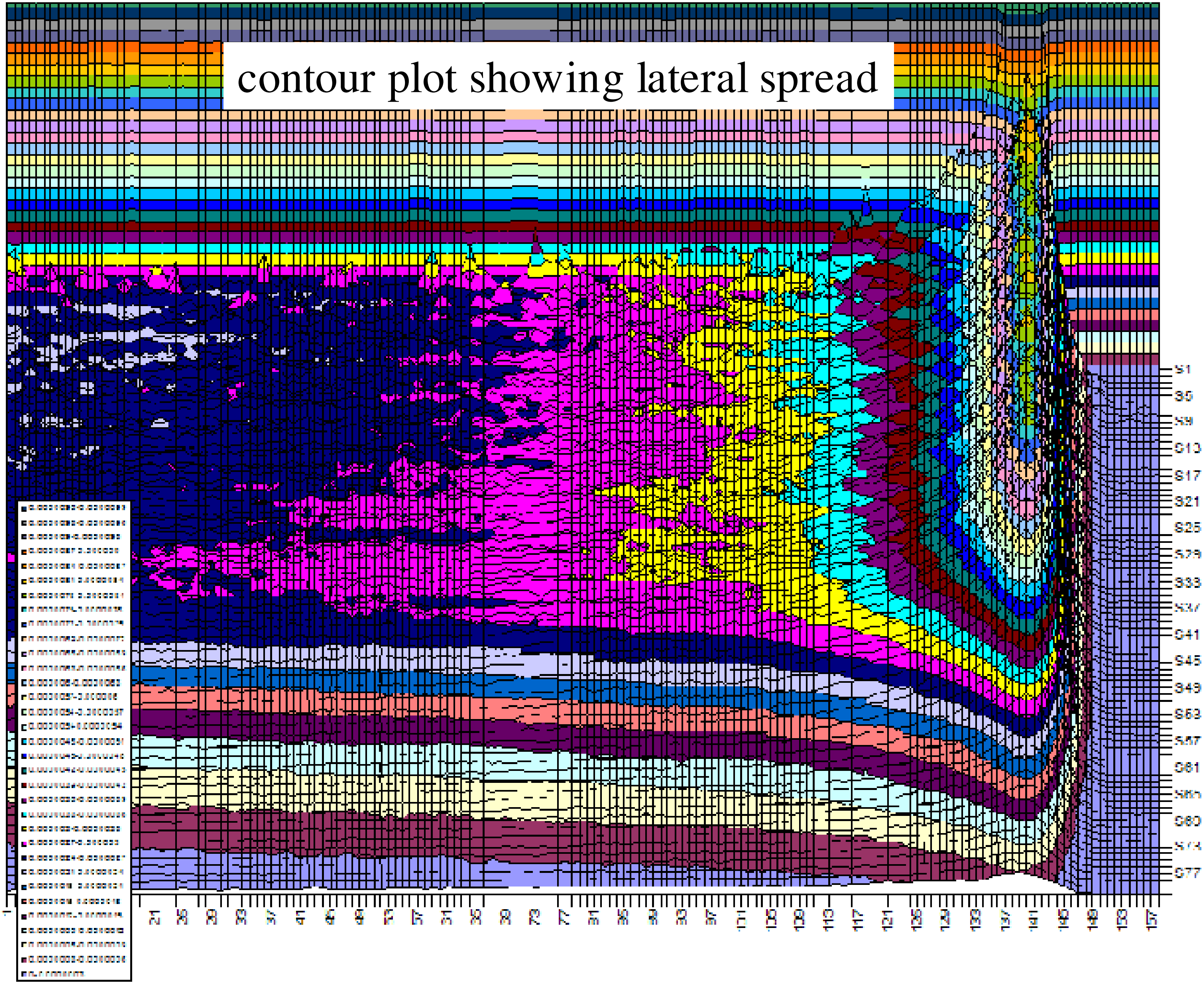




depth in water [mm]

need to paint tumor volume
beam has width – lateral spread
need longitudinal spread

contour plot showing lateral spread

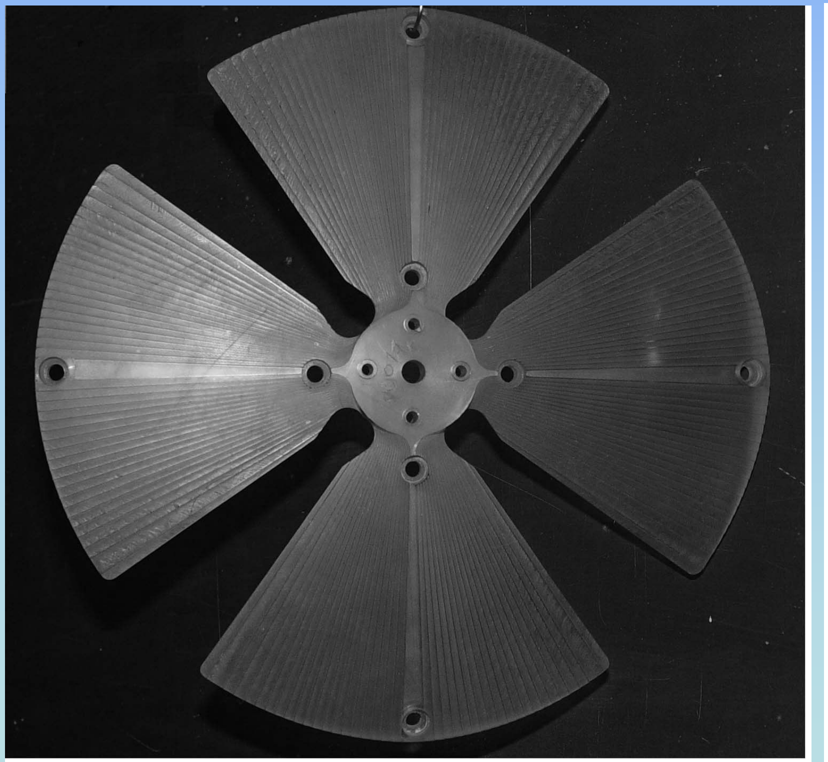


Remember: Spread Out Bragg Peak

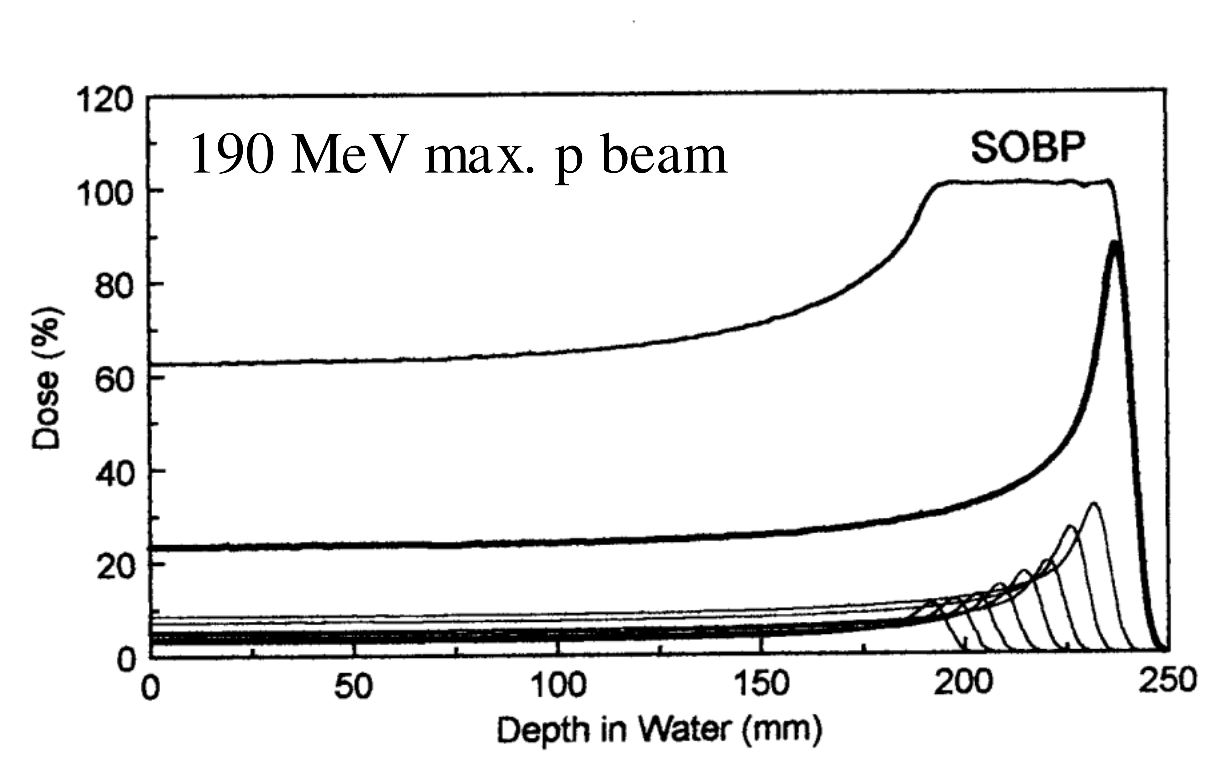
For depth dose distribution use different energy beams...

or

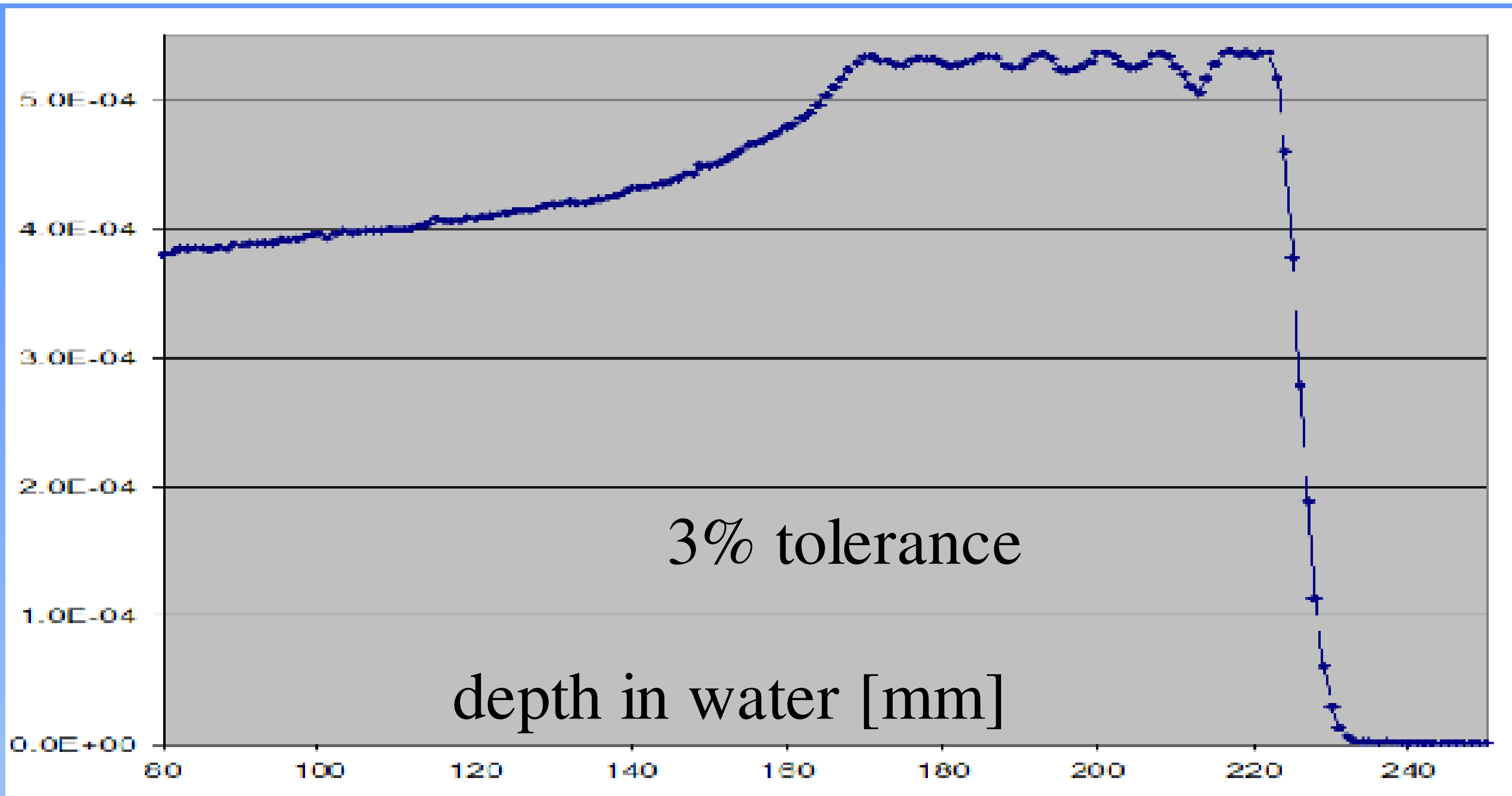
vary treatment energy after production with variable thickness range shifter to spread out Bragg peaks

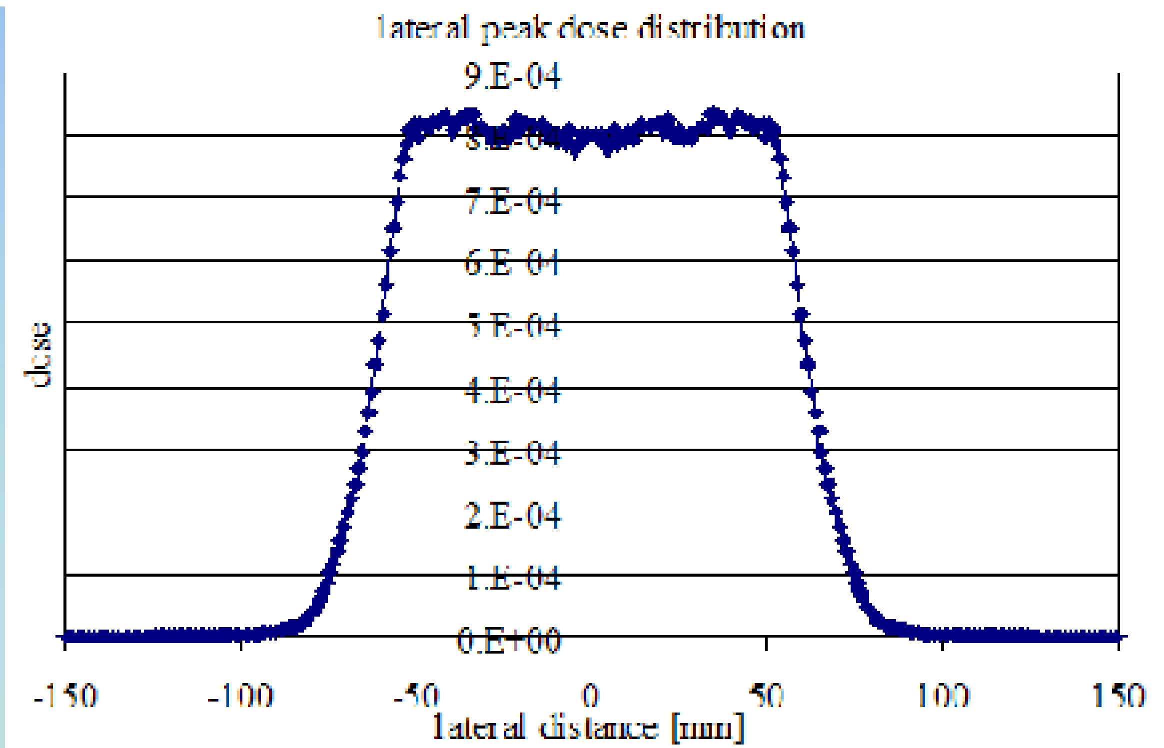


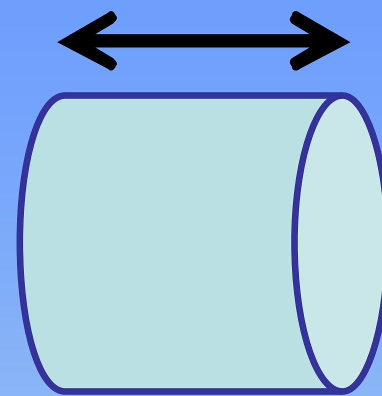
PolyMethylMethAcrylate range shifter from Laboratori Nazionali del Sud CATANA, Italy

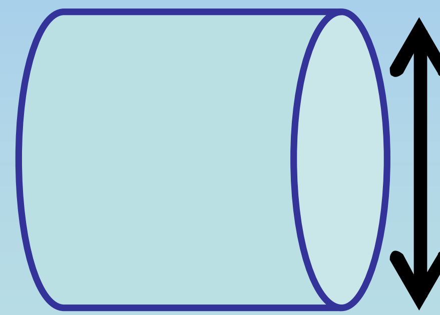


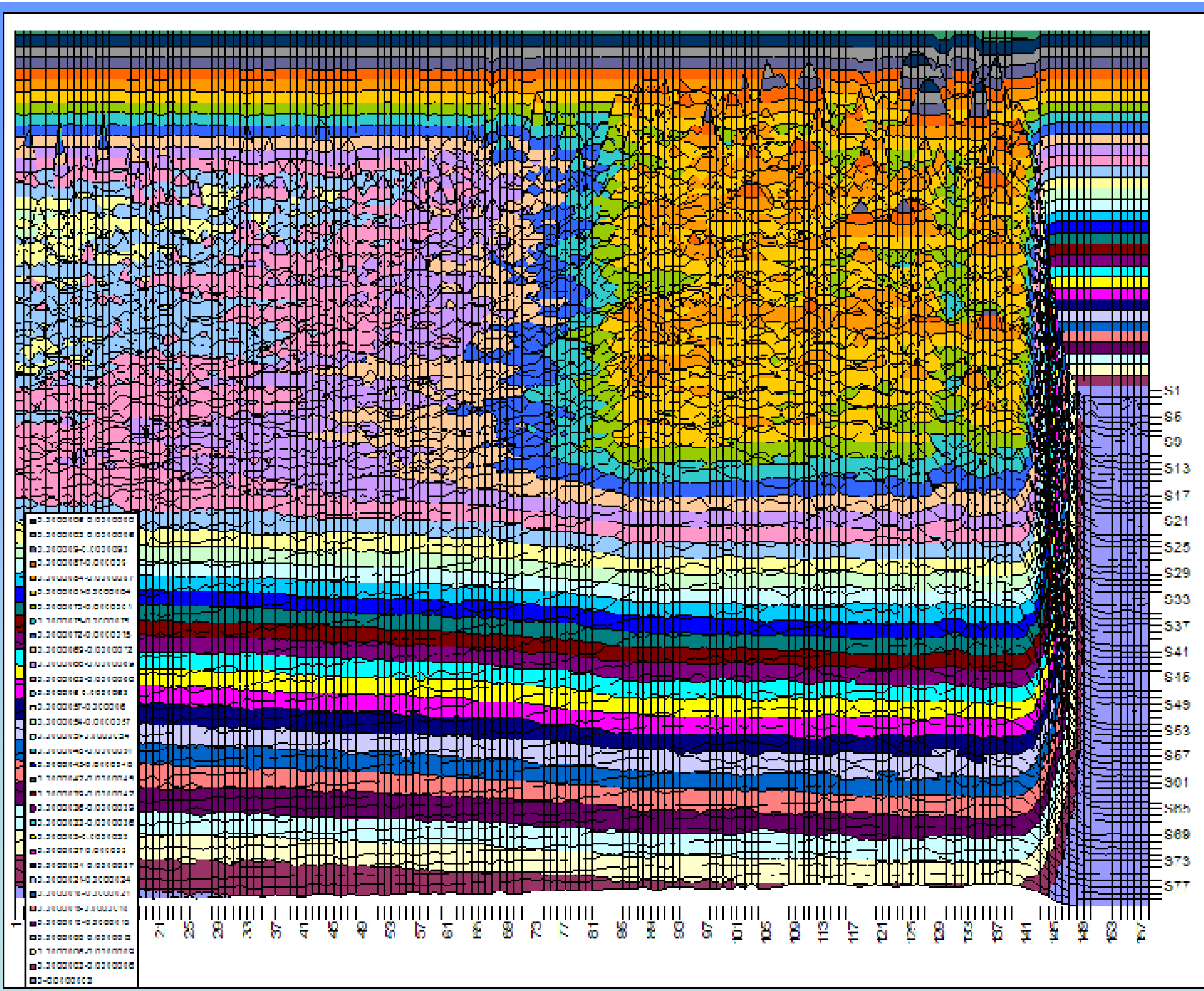
http://www.canberra.edu.au/irps/archives/vol15no34/mempap.html

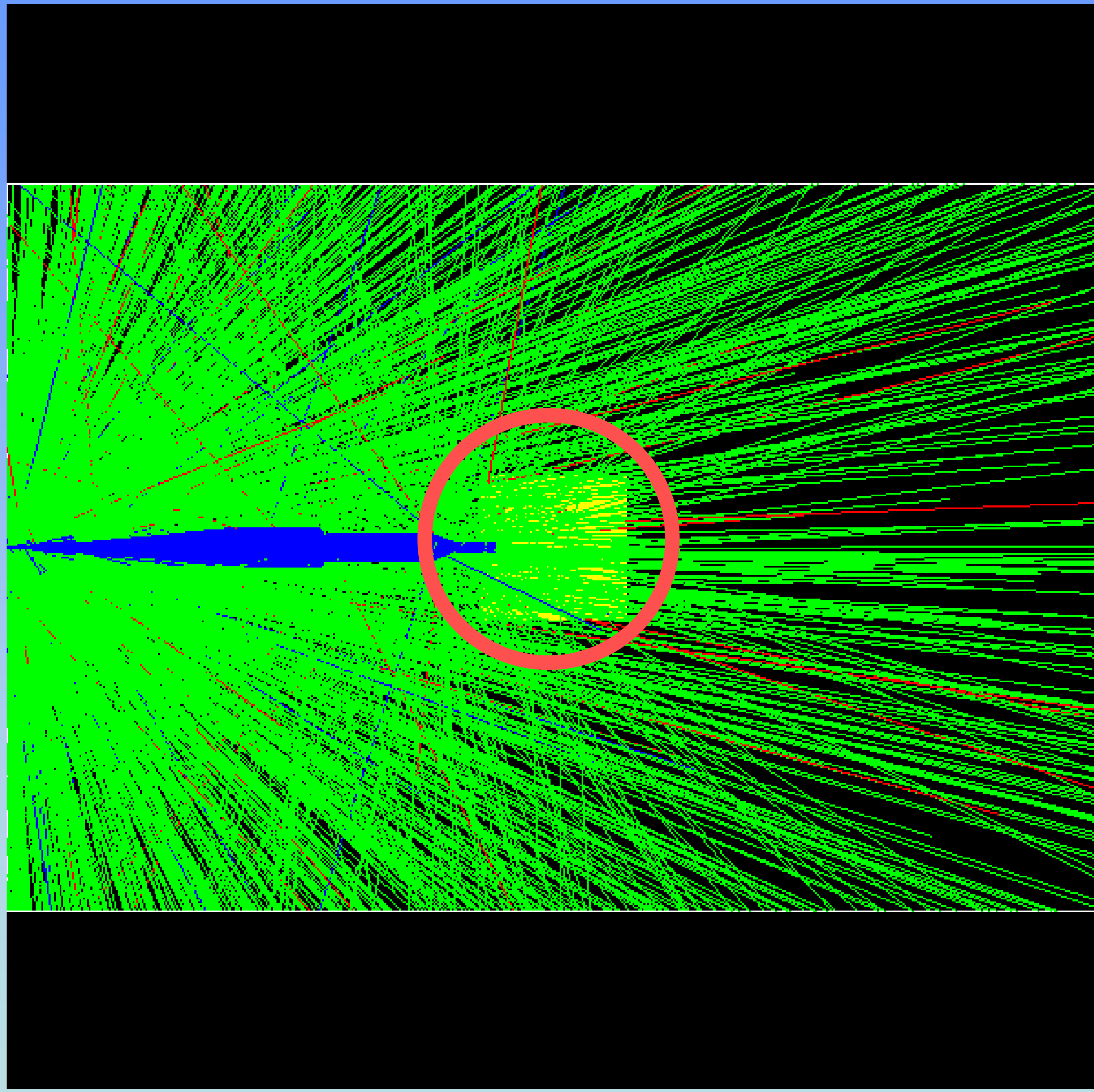

5.0E-04
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
80
100
120
140
160
180
200
220
240
3% tolerance
depth in water [mm]


lateral peak dose distribution
9.E-04
8.E-04
7.E-04
6.E-04
5.E-04
4.E-04
3.E-04
2.E-04
1.E-04
0.E+00
dose
-150
-100
-50
0
50
100
150
lateral distance [mm]

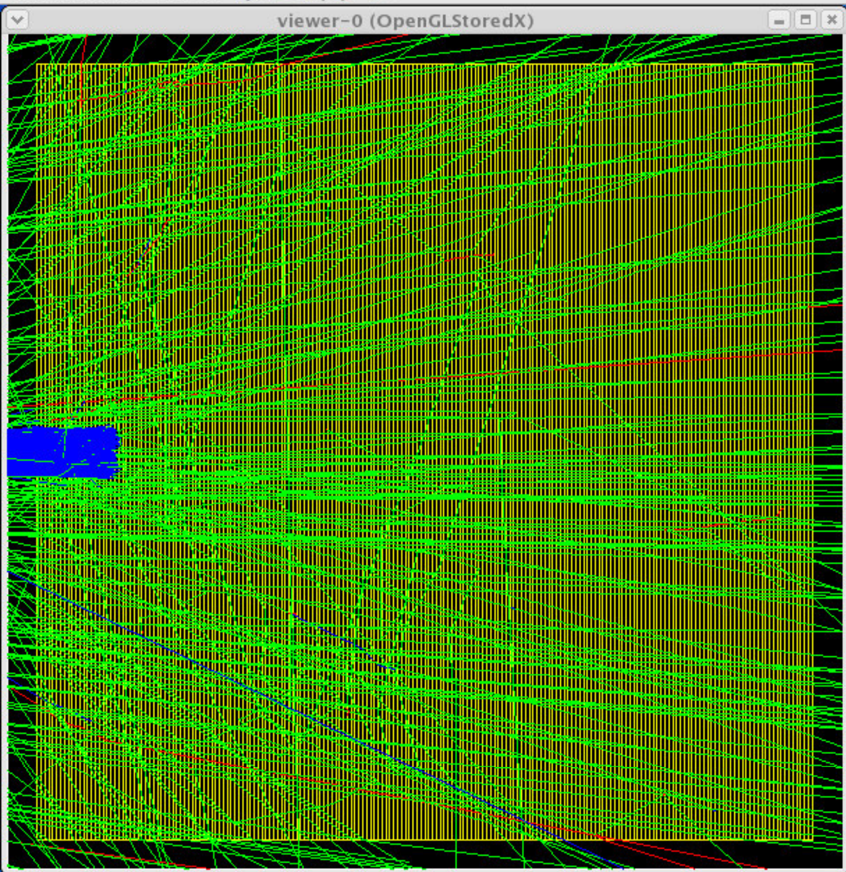





S1
S5
S13
S17
S21
S25
S29
S33
S37
S41
S49
S53
S57
S73
S77



Applications Actions Fri Jan 25, 2:3



hecht@mpded:~/g4work/mySimAdam

File Edit View Terminal Tabs Help

* Bin * -	Av-Dose per-p-(MeV)	Sigma-(MeV) using-Ntotal	No-Events in-Bin	Sigma-using No-in-Bin * *
0	0.087992101	0.54452654	9986	0.54489814
1	0.083799305	0.4792516	9986	0.47957715
2	0.081627831	0.4342347	9986	0.43452822
3	0.083680324	0.4484653	9986	0.44876861
4	0.088722138	0.50718348	9986	0.50752799
5	0.090285446	0.50173182	9986	0.50207201
6	0.09121346	0.49661282	9986	0.49694906
7	0.092723482	0.50591847	9986	0.50626106
8	0.095332218	0.53810921	9986	0.53847444
9	0.098366031	0.52954433	9986	0.52990258
10	0.10308547	0.56330292	9986	0.56368441
11	0.10688175	0.58093528	9986	0.58132857
12	0.11090939	0.6197377	9986	0.62015804
13	0.1153703	0.62596492	9986	0.62638864
14	0.12447816	0.68493243	9986	0.68539652
15	0.13708817	0.74865341	9986	0.74916041
16	0.15577188	0.84641247	9986	0.84698547
17	0.19445275	1.0868077	9986	1.0875448
18	0.25277576	1.4565446	9986	1.4575345
19	0.19762203	1.3529682	9986	1.353896
20	0.076119822	0.8267217	9966	0.82811874
21	0.010649387	0.30576904	9966	0.30628955
22	0.0018555242	0.13531089	8033	0.15096765
23	0.00097360879	0.078599251	4790	0.11355713
24	0.00029853889	0.023677821	7366	0.027587575
25	0.000435402	0.037135396	4790	0.053652236
26	0.00043866014	0.036392266	9419	0.03749771
27	0.0005506549	0.042615052	9419	0.043909489
28	0.00033608268	0.02783324	4790	0.040212546
29	0.00040726271	0.034637775	4790	0.050043719
30	0.00020384722	0.015083365	4790	0.021791511
31	0.00027356961	0.019341863	4790	0.027943661
32	0.00034348416	0.024631192	4790	0.03558539
33	0.00035209253	0.024538957	9419	0.025284301
34	0.00024260501	0.017608509	4790	0.025439583
35	0.00020628734	0.020627702	4790	0.029802965
36	0.00018414937	0.018226464	9419	0.018780132
37	0.00028903217	0.018456424	9419	0.019016994
38	6.4551069e-05	0.0060498328	9419	0.0062336075
39	0.00014886469	0.010259646	9419	0.010571269
40	0.00019533493	0.014370471	9419	0.014806968
41	0.00010830927	0.0095831402	9419	0.0098742412
42	6.2487494e-05	0.006248437	4790	0.0090277602
43	0.00010083328	0.0099976322	9419	0.010301332
44	0.00014104799	0.0096989507	9331	0.010040547
45	5.8306566e-05	0.0056913705	4790	0.0082228867
46	7.0859966e-05	0.0070856423	4790	0.010237357
47	8.561219e-05	0.0085607909	4790	0.012368656
48	0.00011867052	0.0085283229	7366	0.0099364841
49	8.7885766e-05	0.0065113351	9335	0.0067392267
50	7.2391805e-05	0.0063560156	9419	0.0065490879
51	7.2054031e-05	0.0071428298	9335	0.0073928444
52	6.5473673e-05	0.0065470399	4790	0.0094591826
53	8.3329646e-05	0.0068976915	9335	0.0071391145
54	6.371692e-05	0.0062804638	9335	0.0065002935
55	6.515138e-05	0.0065148122	4790	0.0094126199
56	8.257836e-05	0.0082574231	4790	0.011930349
57	0.00013191916	0.0088471545	9419	0.0091158723
58	9.4145767e-05	0.0069625348	9419	0.0071740191
59	8.3972509e-05	0.0077184065	9335	0.0079885628
60	0.00010122015	0.010121509	4790	0.014623586
61	7.5984237e-05	0.0075980437	4790	0.010977676

- comparing neutrons produced in optics for different tumor depths (beam energies) and different beam particles

- More info? Talk to me

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