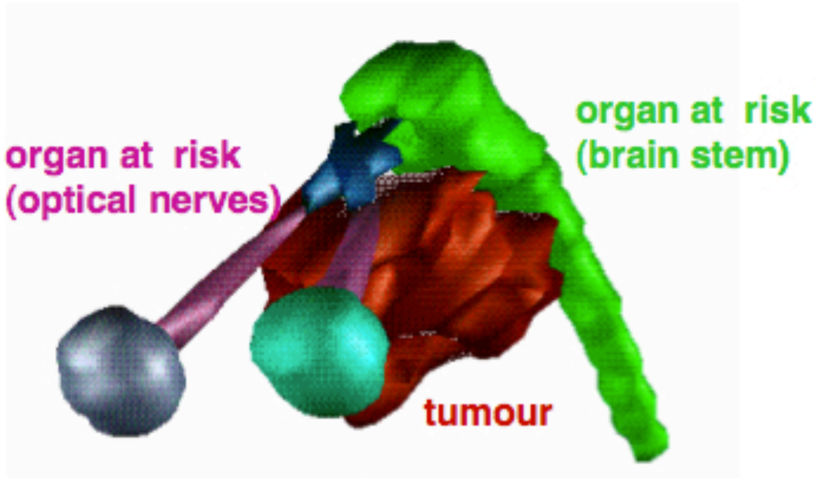
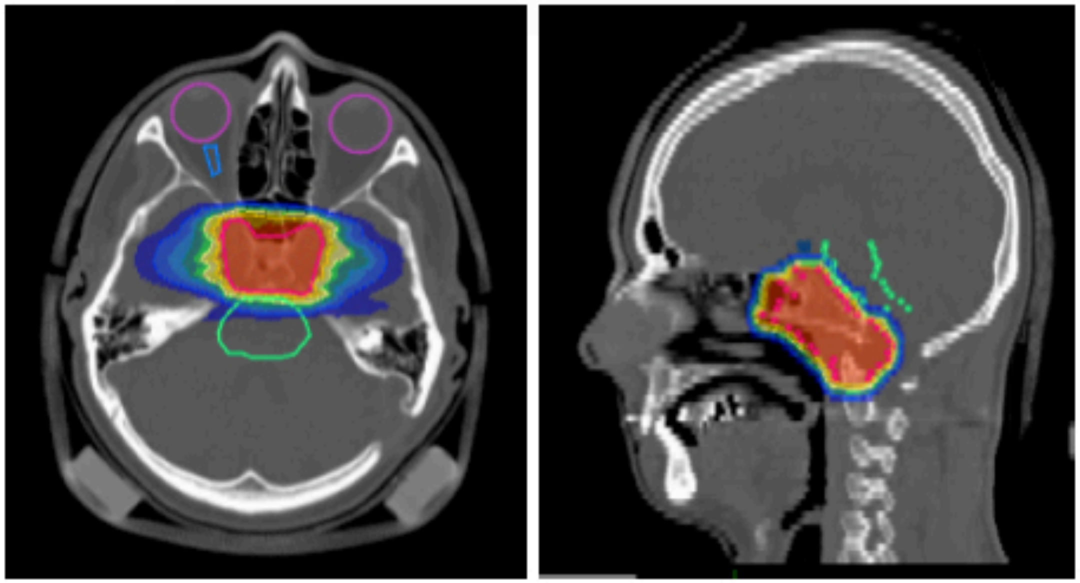
Dose measurements in hadrontherapy

F. Collamati, A. Didomenico, **R. Faccini**, F. Ferroni, S. Fiore, P. Gauzzi, I. Mattei, C. Voena
"Sapienza" Dip Fisica, INFN Roma
E. Iarocci, V. Patera. L. Piersanti, A. Sarti, A. Sciubba
"Sapienza" Dip SBAI, INFN LNF
E. De Lucia
LNF
M. Marafini
Centro Fermi

Introduction to hadrontherapy

- **Goal**
  - Deliver a high radiation dose to the target area to kill all tumour cells.
  - Spare out healthy tissue and organs at risk.
  - Tumour conformal dose distribution.
- **Radiation type**
  - Conventional therapy: electrons, photons
  - Hadron therapy: protons, light ions
  - More exotic: neutrons, pions





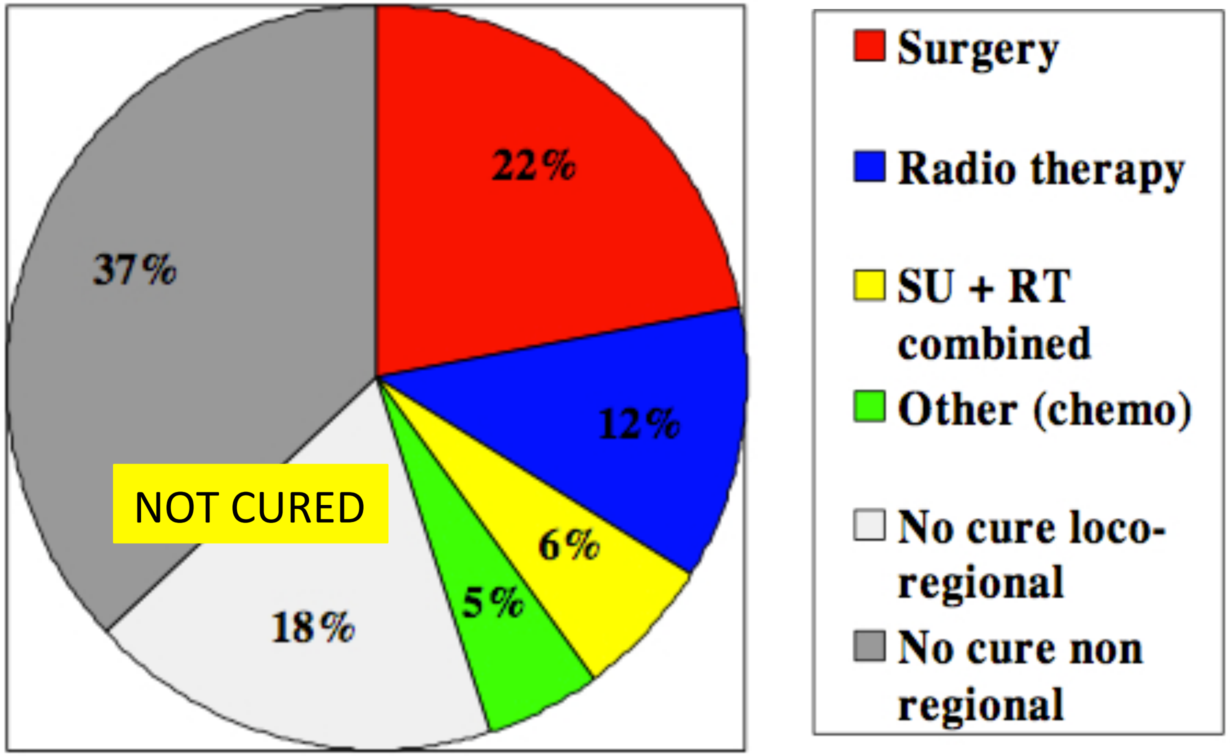
Courtesy GSI

Tumor treatment in Europe

Percentage of cure ~ 45% (EU report 2000)

Main problems:

- Anatomy does not permit surgery
- RadioResistant tumours or close to organs at risk (OAR)



Hadrontherapy can be a viable solution to increase cure to 60-65%: allows for better localised dose distribution

POTENTIAL PATIENTS

X-ray therapy (5 – 20 MeV)

20'000 pts/year every 10^6 inhabitants

Protontherapy

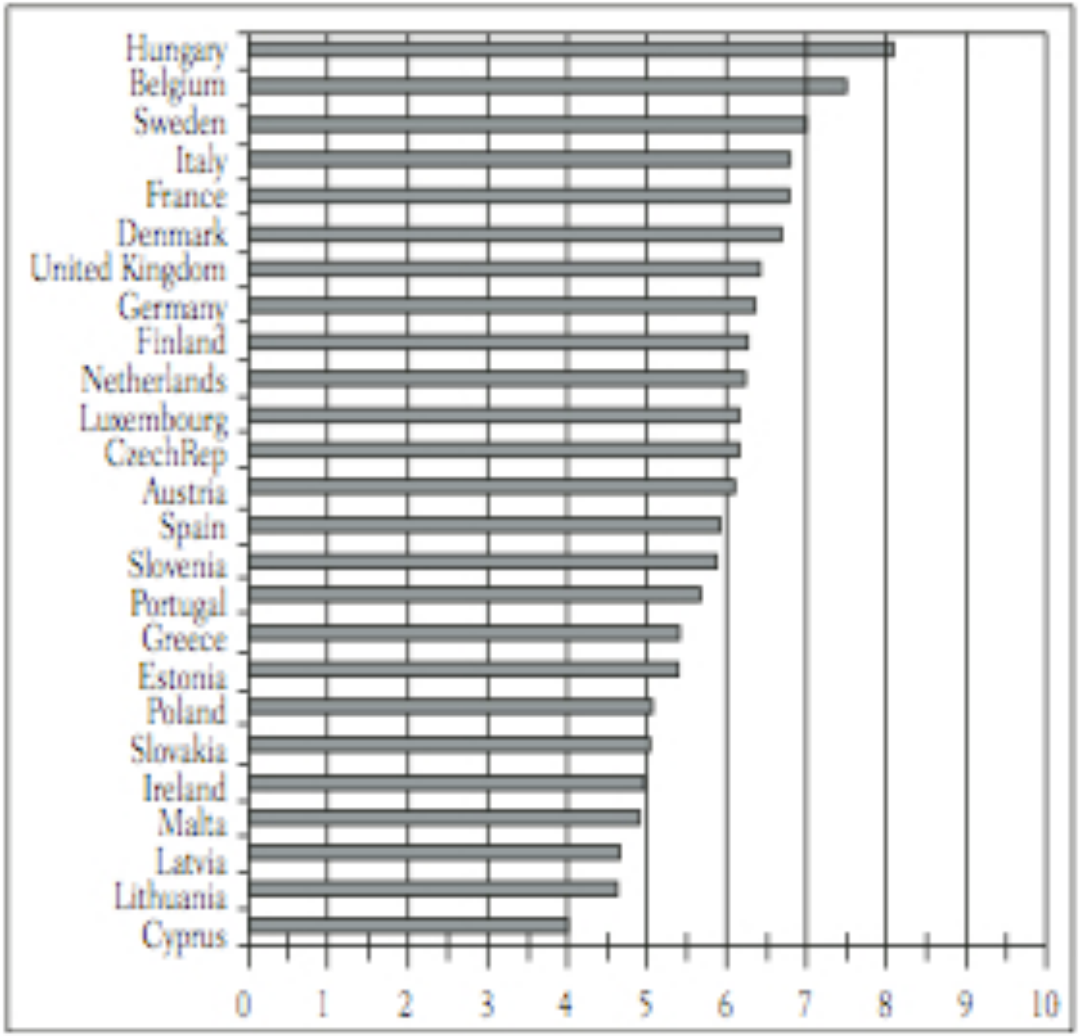
10% of X-ray patients

2'000 pts/year every 10 M

Carbon ions for radioresistant tumours
10% of X-ray patients

2'000 pts/year every 10 M

By TERA foundation

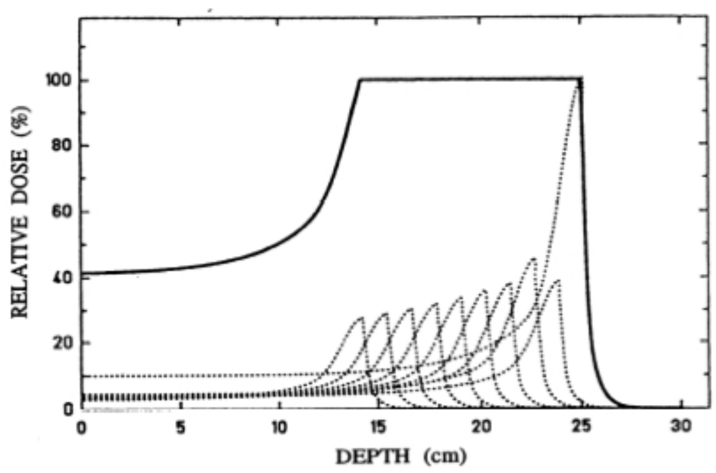


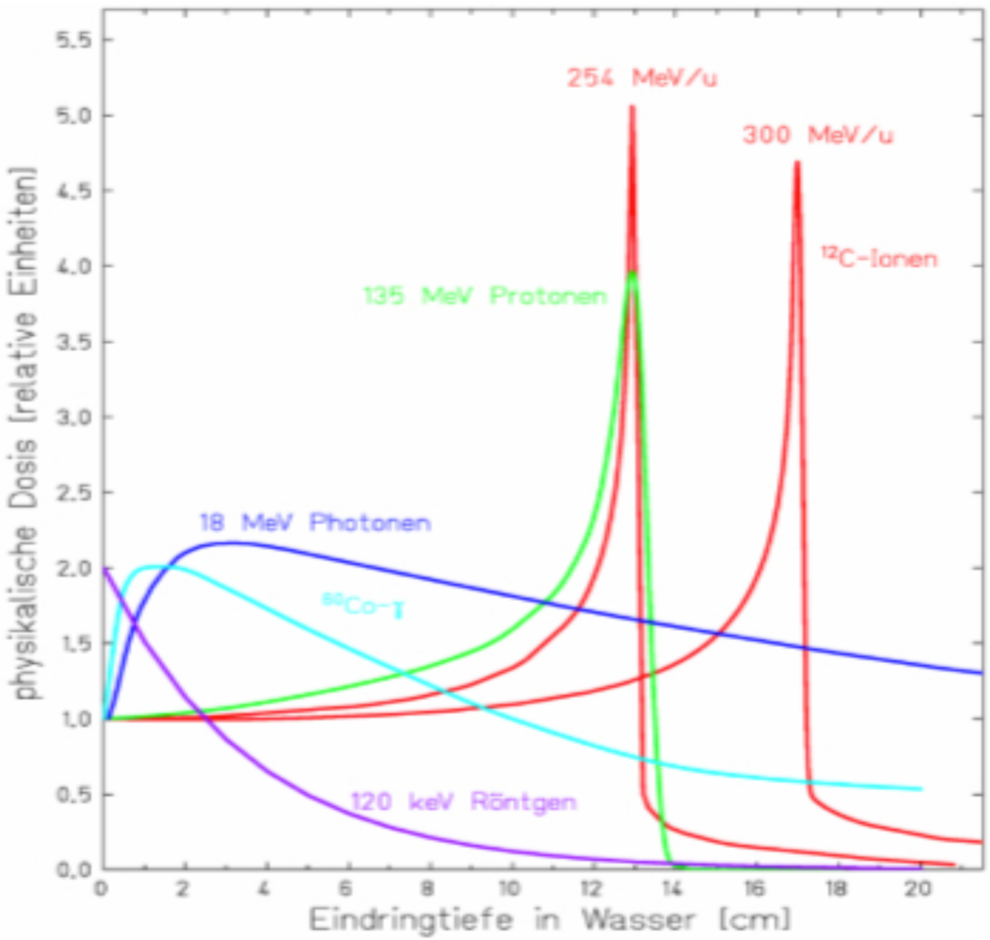
EU Report : LINAC needed per 10^6 inhabitants

Hadrontherapy vs Photon RT

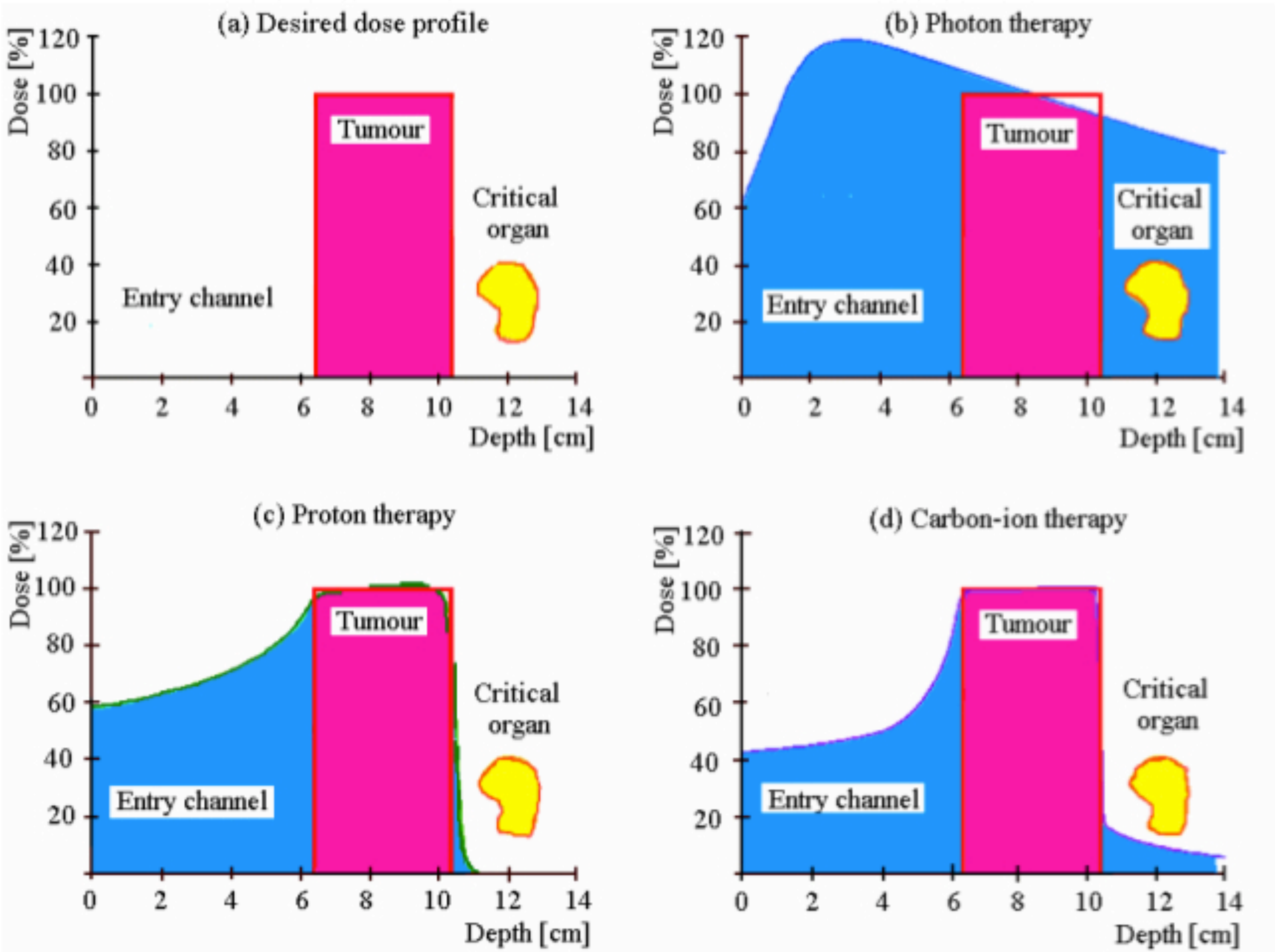
The highest dose released at the end of the track, sparing the normal tissue

- Length of track function of the beam energy
- Dose decrease rapidly after the BP.
- Accurate conformal dose to tumour with Spread Out Bragg Peak

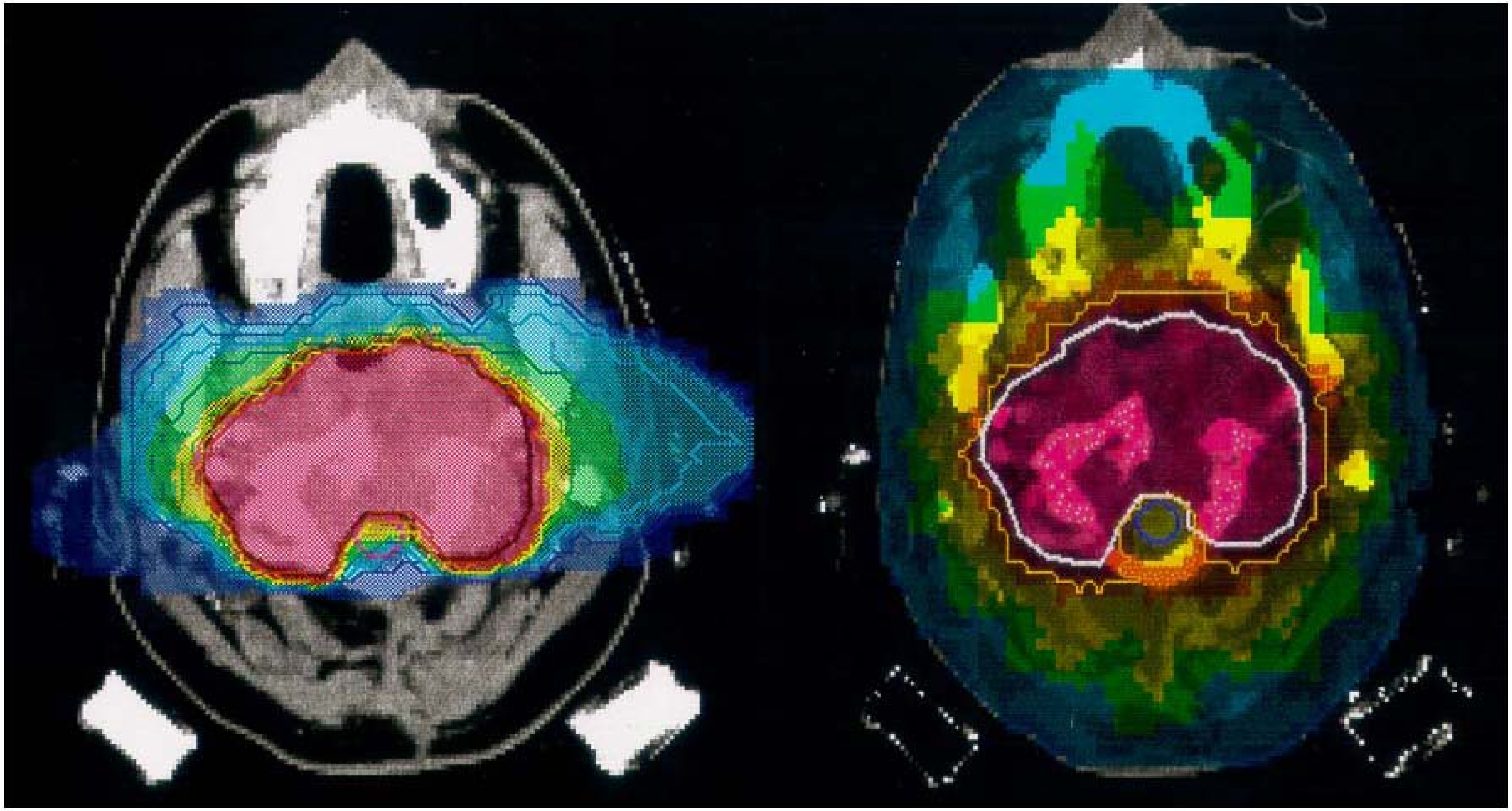




Single Field Dose comparison



Comparison ^{12}C vs IMRT



C-12, 2 fields

IMRT, 9 fields

Courtesy of M.Durante, GSI

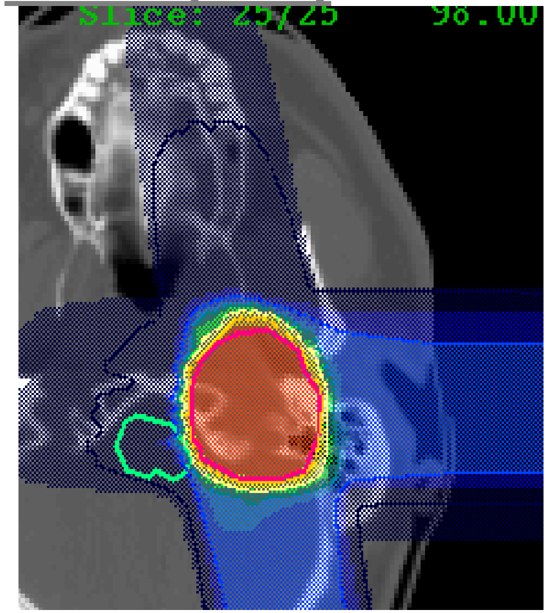
Protons vs ^{12}C

No absolute best:

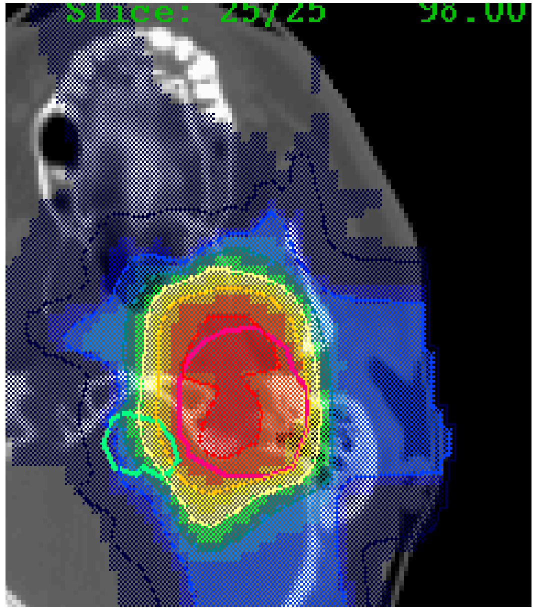
(if you exclude that the proton facilities are less expensive..). For example…

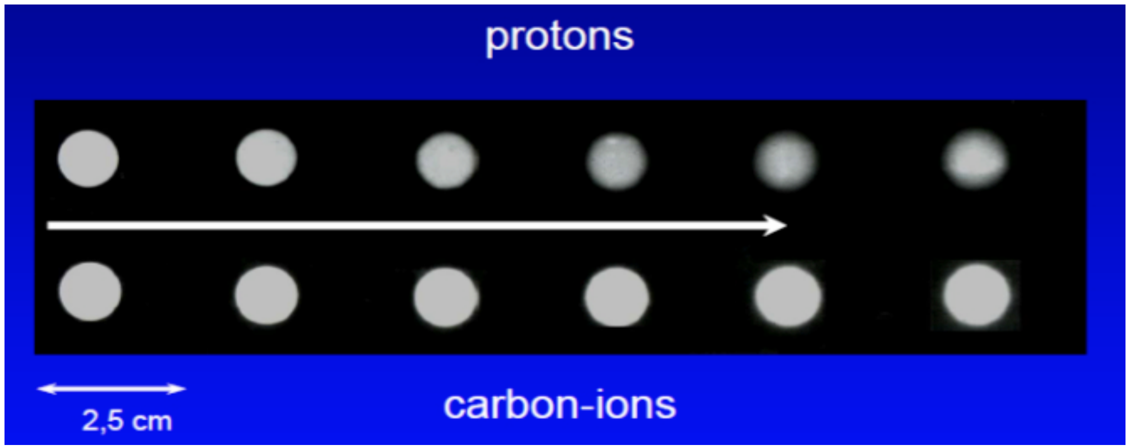
- ^{12}C has better peak to plateau dose ratio
- ^{12}C has less multiple scattering

C-ions (GSI)



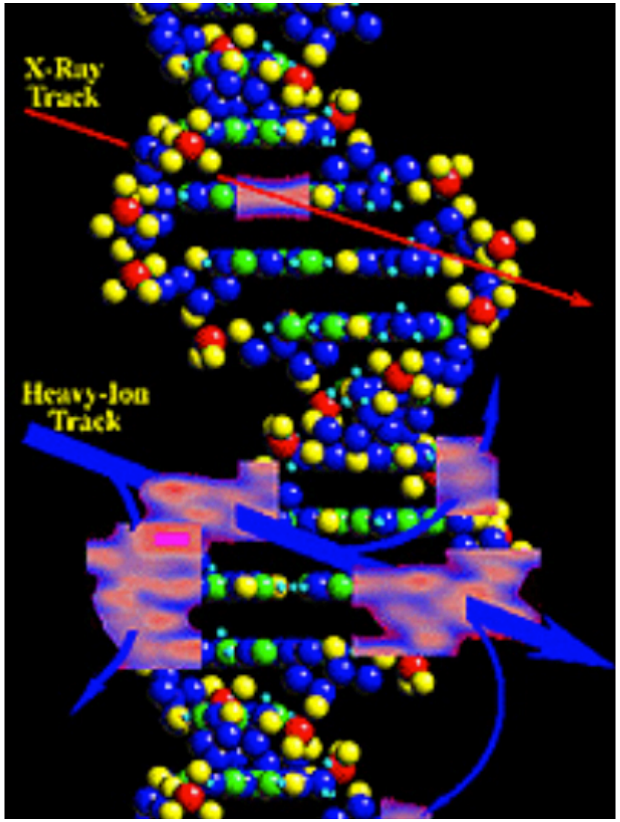
H-ions (CapeTown, SA)

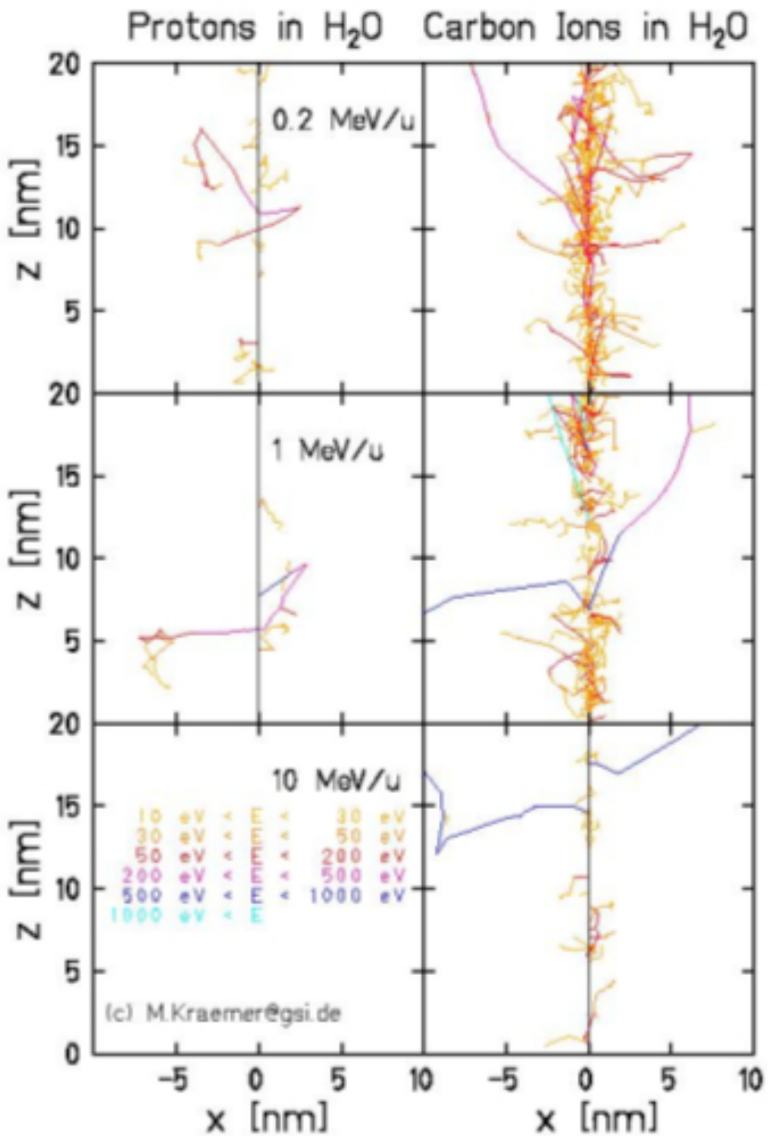




Why same dose induces different survival?

The high ionization density of ^{12}C induces easily DSB in DNA helix



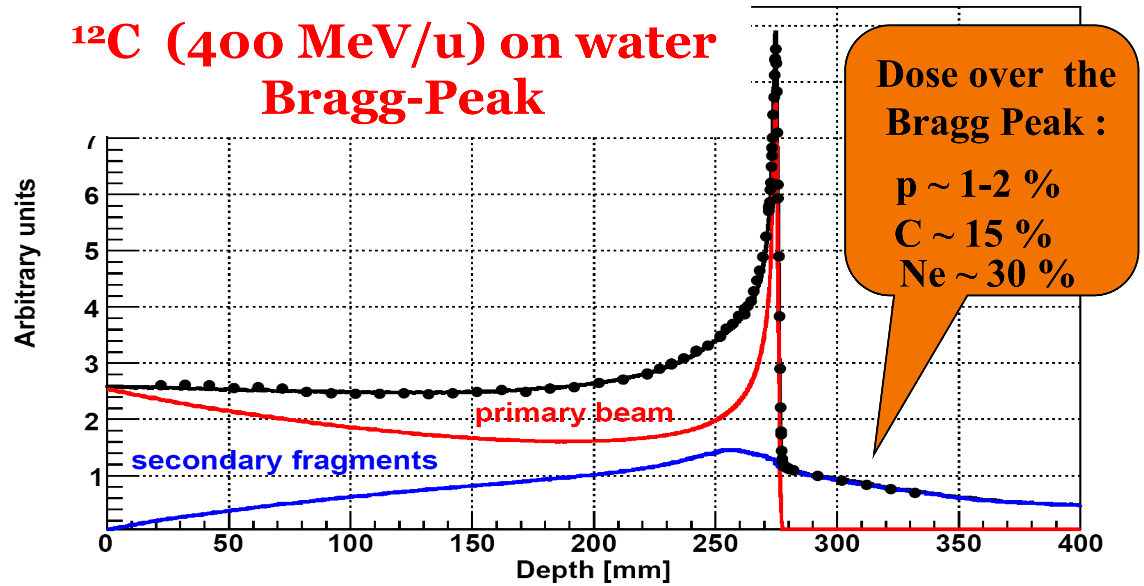


BUT .... ^{12}C fragments on the path to tumour

Dose release in healthy tissues with possible long term side effects, in particular in treatment of young patients ➔ must be carefully taken into account in the Treatment Planning System

- ✓ Production of fragments with higher range vs primary ions
- ✓ Production of fragment with different direction vs primary ions

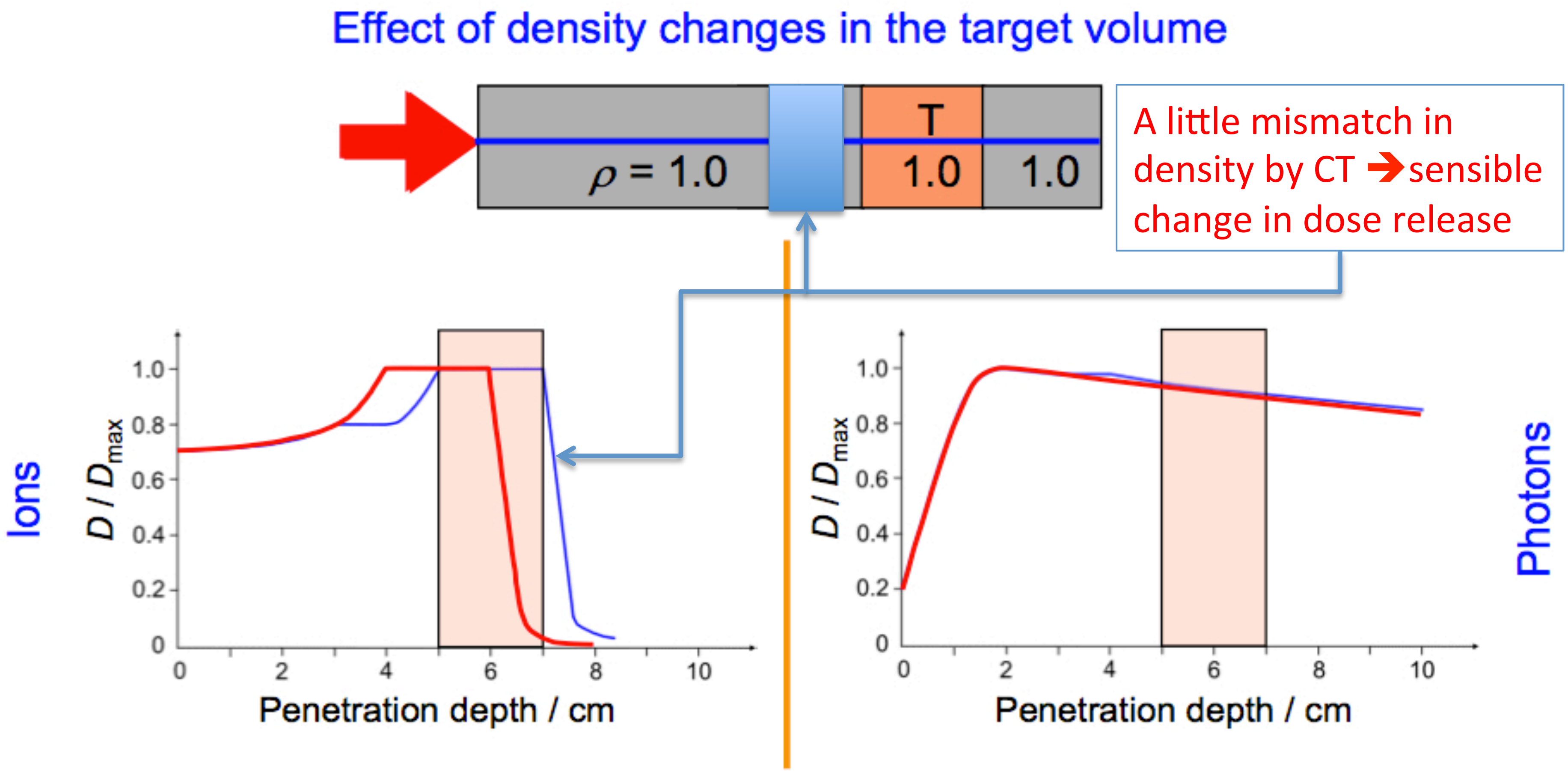
- ✓ *Mitigation and attenuation of the primary beam*
- ✓ *Different biological effectiveness of the fragments wrt ^{12}C*



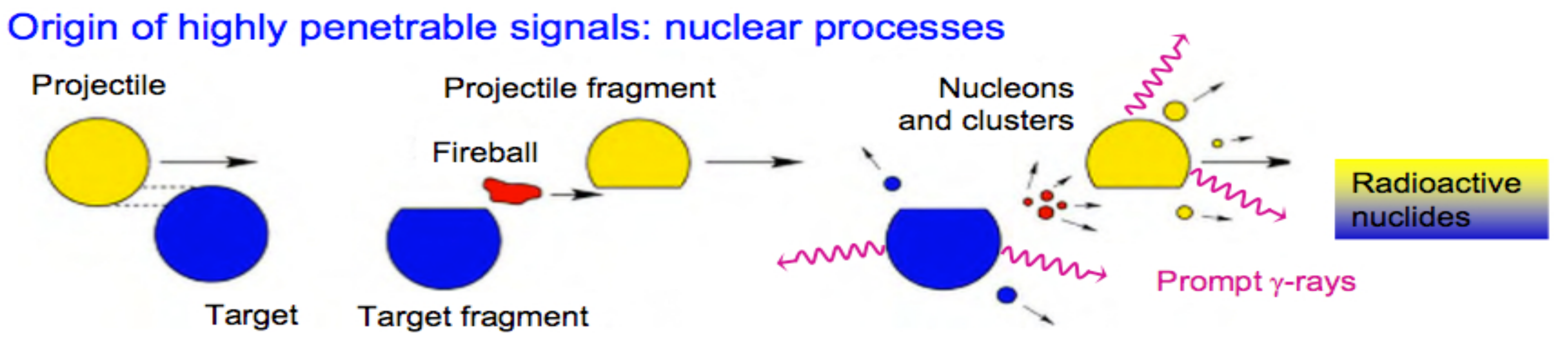
Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Monitoring the dose

- Why is so crucial to monitor the dose in hadrontherapy ? Is like firing with machine-gun or using a precision rifle..



Measuring the dose



- Measure shape and absolute value of dose to check the agreement between the planned target volume and the actually irradiated volume
- The measurement should be done during the treatment (in-beam)
- Must rely on a given secondaries generated by the beam that comes out from the patient, to spot the position of the dose release
- Must be able to deal with the other secondaries that come out that acts like background

baseline dose monitoring in HT : PET

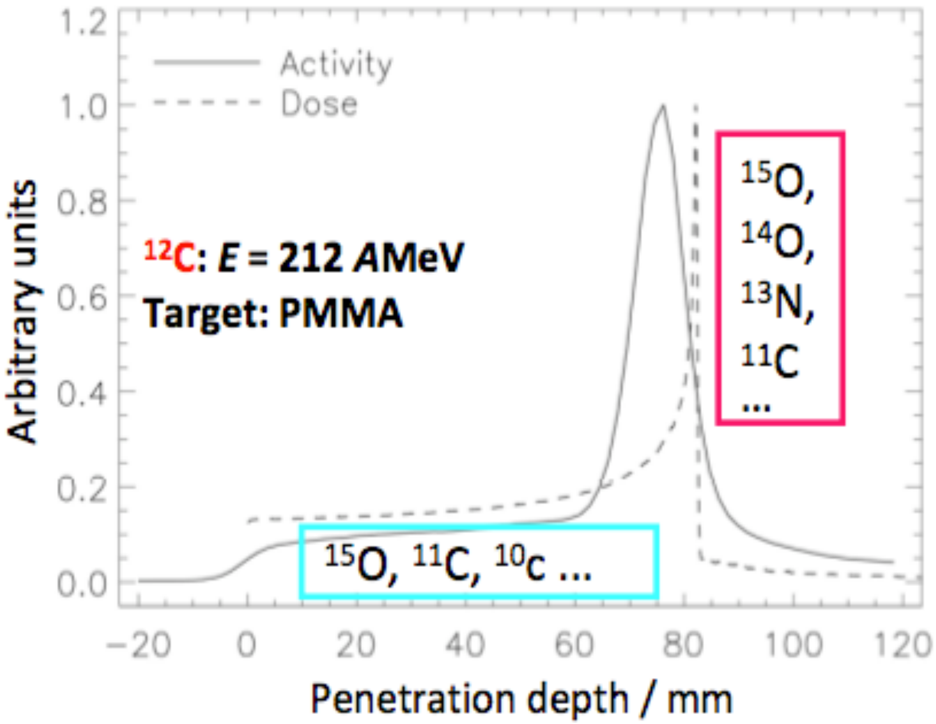
Baseline for monitor in HT is PET : autoactivation by p & ^{12}C beam that creates β^+ emitters.

- Isotopes of short lifetime ^{11}C (20 min), ^{15}O (2 min), ^{10}C (20 s) wrt conventional PET (hours)
- Low activity in comparison to conventional PET need quite long acquisition time (few minutes)
- Metabolic wash-out, the β^+ emitters are blurred by the patient metabolism
- No direct space correlation between β^+ activity and dose release (but can be reliable computed by MC)

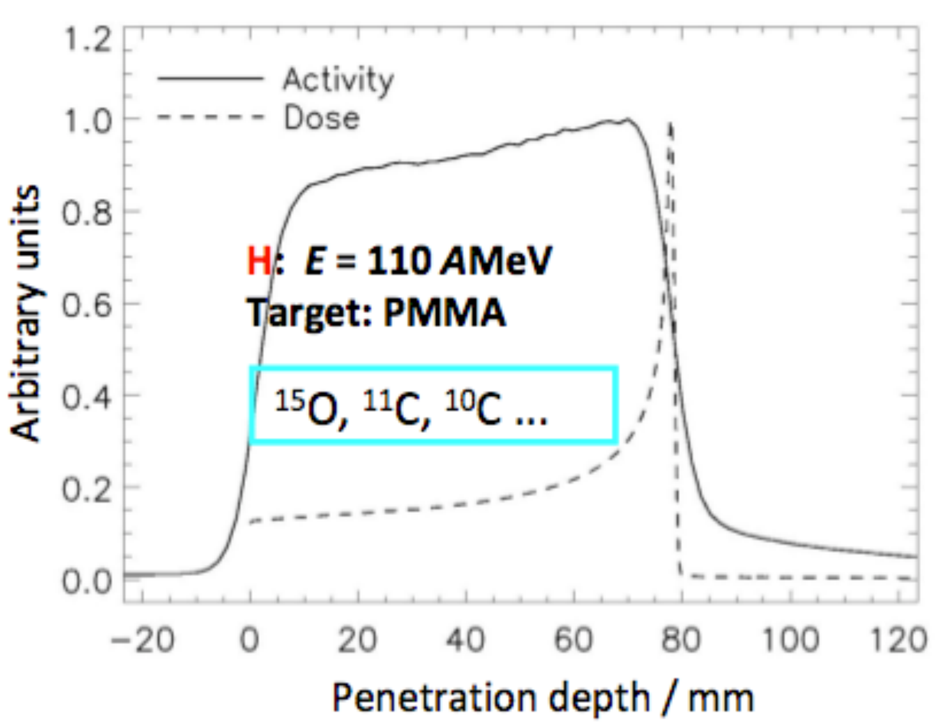
Correlation between β^+ activity and dose

Therapy beam	^{1}H	^{3}He	^{7}Li	^{12}C	^{16}O	Nuclear medicine
Activity density / Bq cm^{-3} Gy^{-1}	6600	5300	3060	1600	1030	10^4 – 10^5 Bq cm^{-3}

Projectiles & target fragmentation



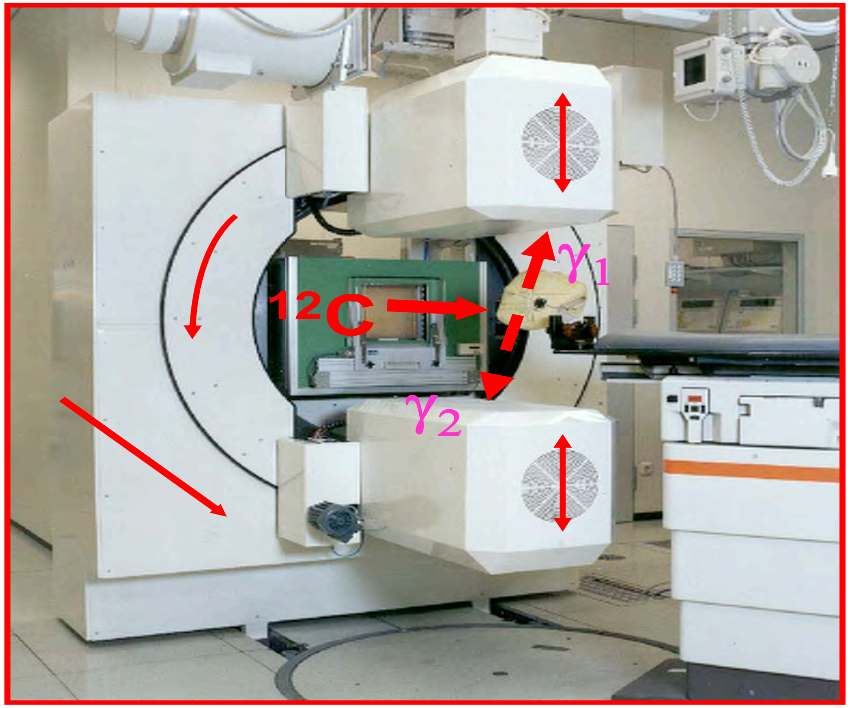
Target fragmentation



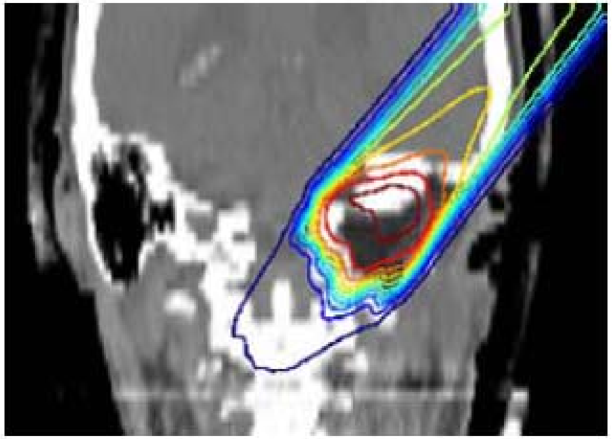
In -beam PET @GSI

CARBON BEAM: 2 heads x 64 crystals

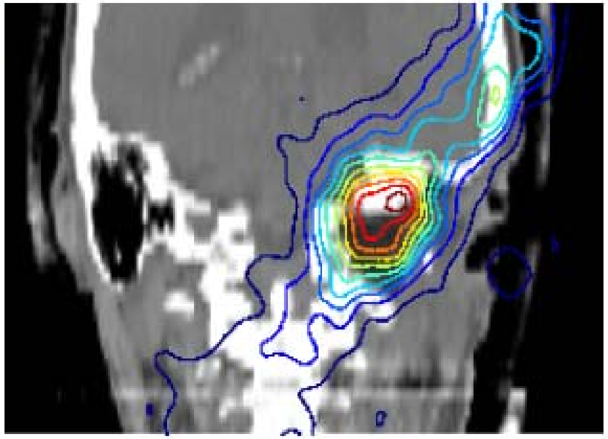
- Less acceptance
- No patient movement
- Less methabolic washout
- Background from the beam



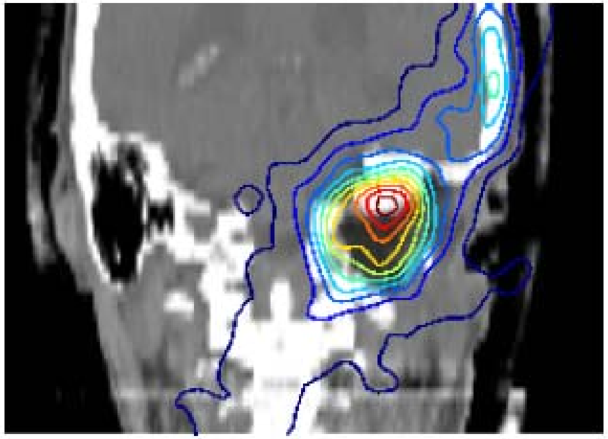
279, W. Enghardt et al.: Nucl. Instr. Meth. A525 (2



Treatment plan



Predicted β⁺-activity

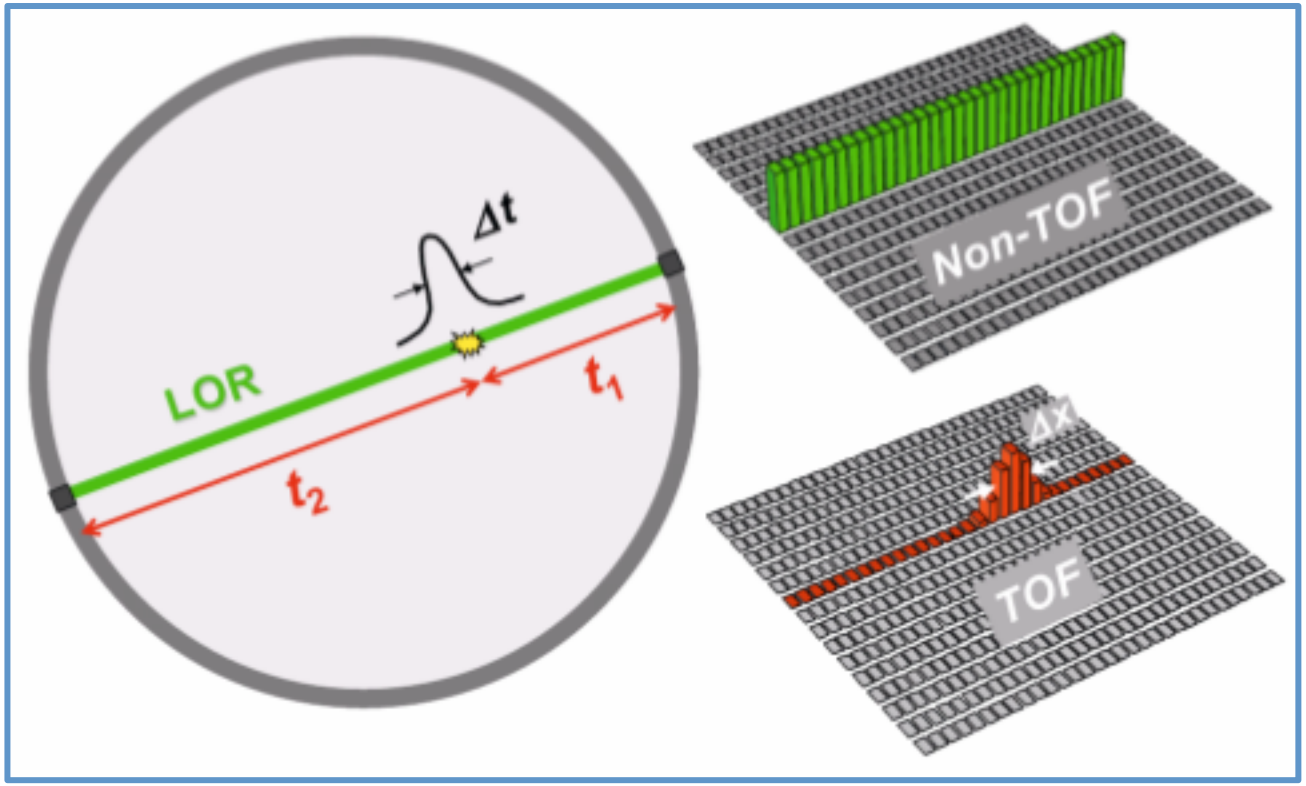


Measured β⁺-activity

Possible developments: in-beam TOF-PET

Improving the reconstruction and reducing background using the time difference between the Time Of Flights of the 2 collinear γ

- Improvement in the S/B ratio
- Better accuracy with less statistic
- Easier events reconstruction
- O(200ps) time resolution on 511 keV γ needed



Possible developments: MC tuning

Balance of promptly emitted particles outside the target:

G4

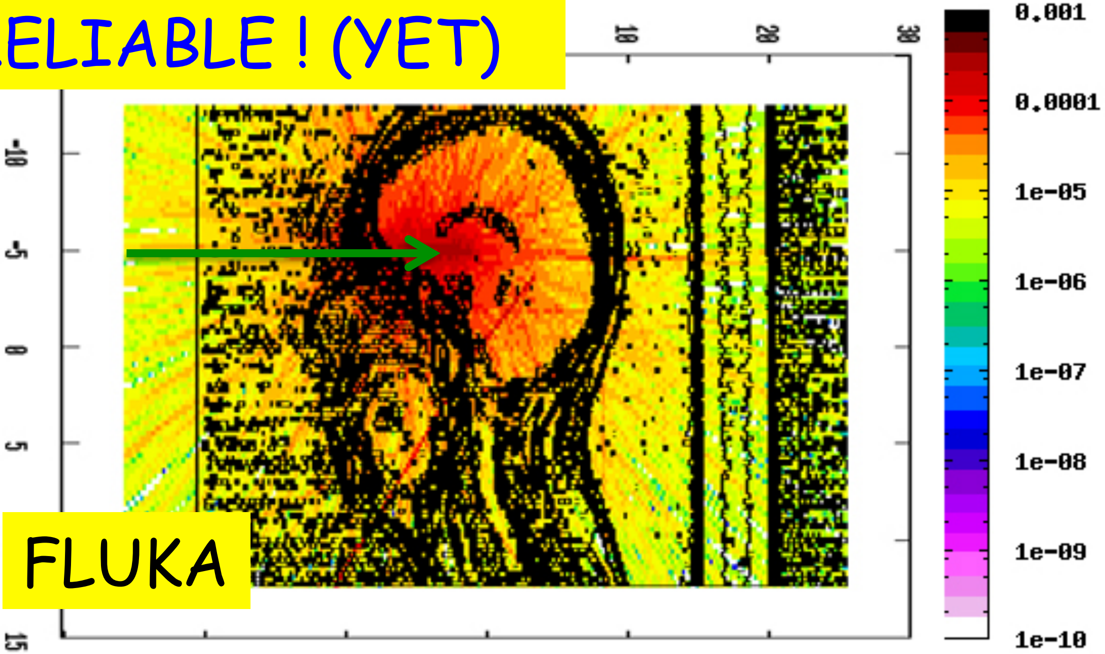
Incident protons:	1.0	($\sim 10^{10}$)
γ-rays:	0.3	($3 \cdot 10^{9}$)
Neutrons:	0.09	($9 \cdot 10^{8}$)
Protons:	0.001	($1 \cdot 10^{7}$)
α-particles:	$2 \cdot 10^{-5}$	($2 \cdot 10^{5}$)

The p, ^{12}C beams generate a huge amount of secondaries.. expecially prompt single γs. and neutrons in the 1-10 MeV range. Can be used to track the beam inside the patient

NOT RELIABLE ! (YET)

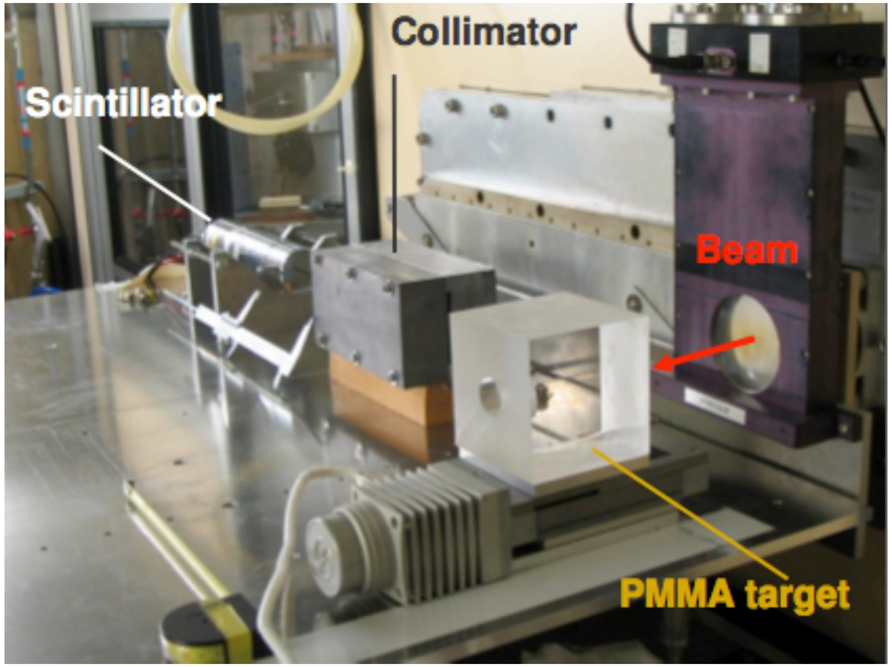
The nuclear models inside MC (FLUKA&G4) not yet able to fully describe this physics

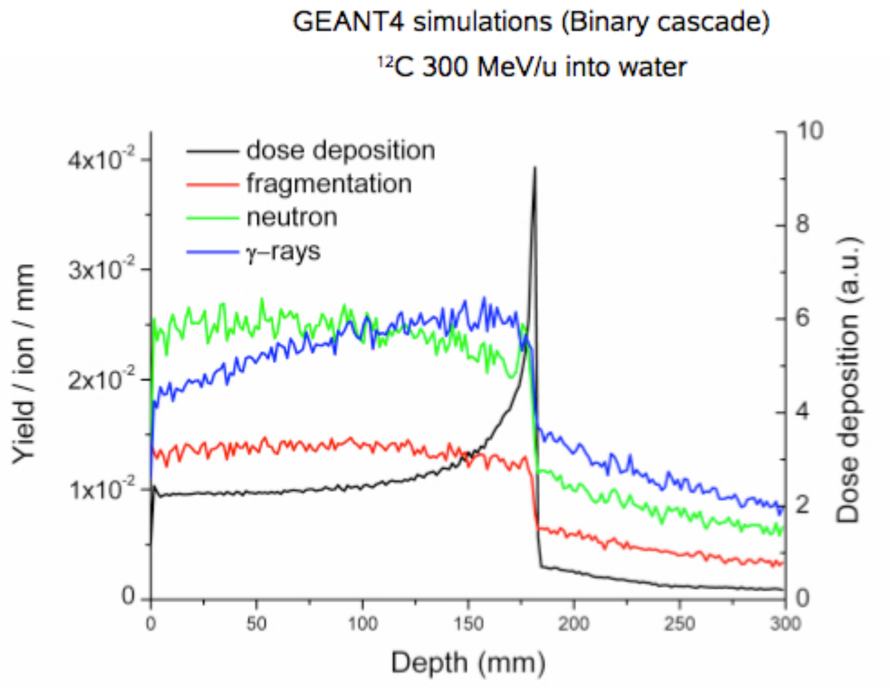
➔ huge development effort ongoing

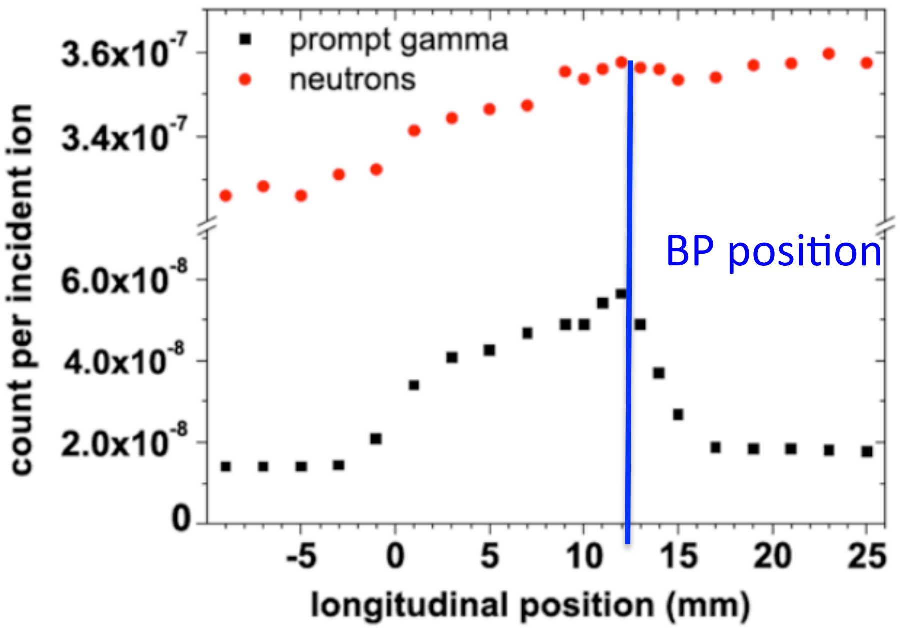


Possible developments: prompt γs

- 73 AMeV carbon beam
- γ peak correlated with BP
- MC one order of magnitude off (more..)
- Neutrons background (TOF rejection ?)

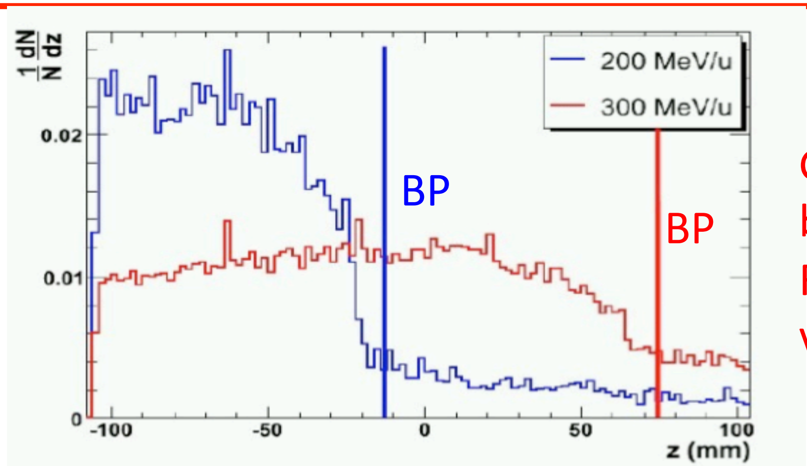




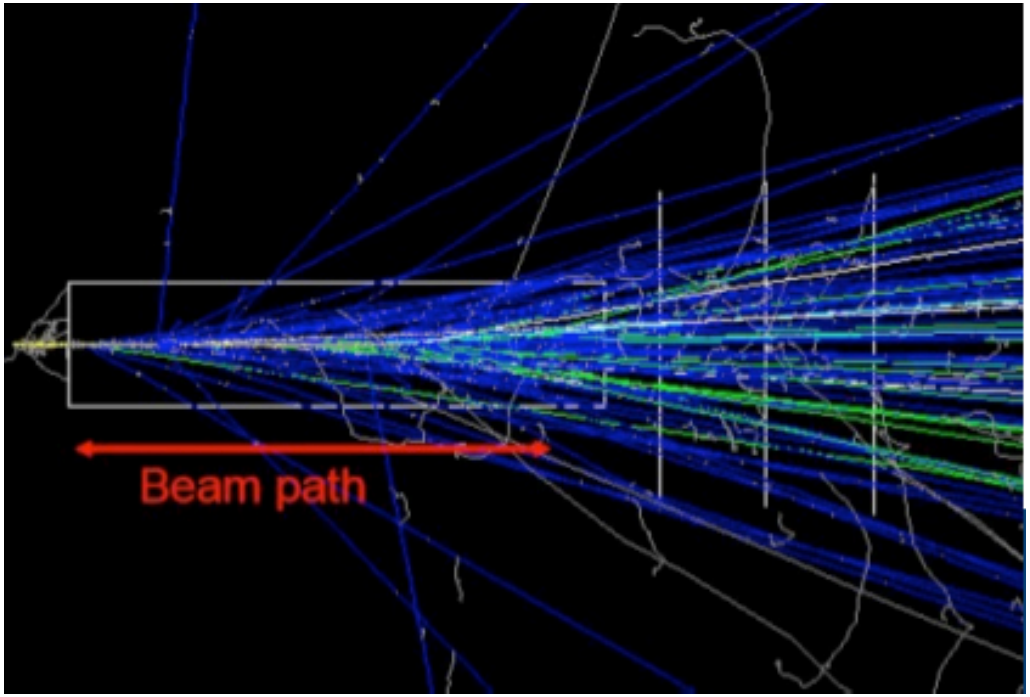


Possible developments: charged products

- Low energy p emitted also near BP (Fermi motion). Enough energy to be useful?
- Best space resolution for large angle emission → low statistic
- MC highly unreliable, probing the very tail of the angular distribution of secondary



G4 : proton beam. Reconstructed vertex



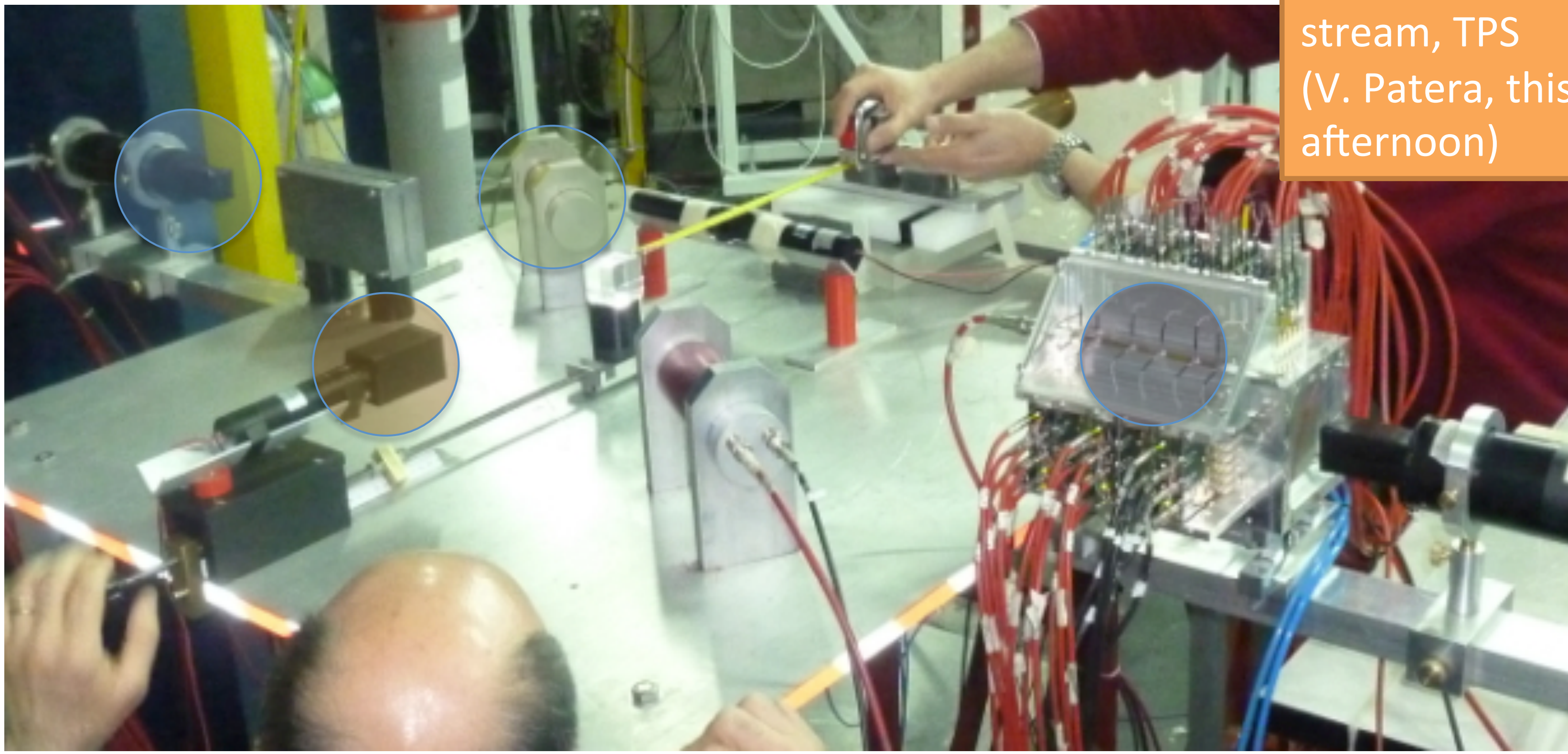
Envision WP2 2011 Report

A first TB of the newly formed group

RM1, LNF,LNS : Measurement of β^+, γ, p, n & charged sec fluxes induced by the ^{12}C 80AMeV @LNS on PMMA phantom

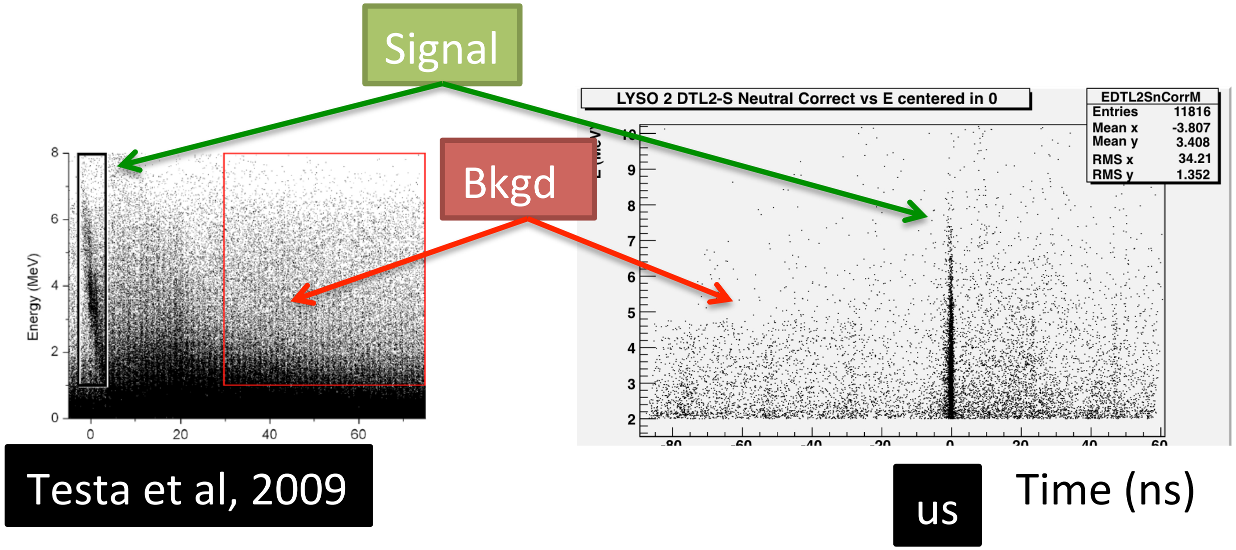
NAI counter ➔ β^+ ; LYSO counter➔ γ,n ; Drift Chamber➔Charged ; PLASTIC counter➔low angle frags

Still out of main stream, TPS (V. Patera, this afternoon)



Research directions (1)

- Clean measurement of prompt photon γs using lyso for the time resolution (wrt NaI of previous measurents)

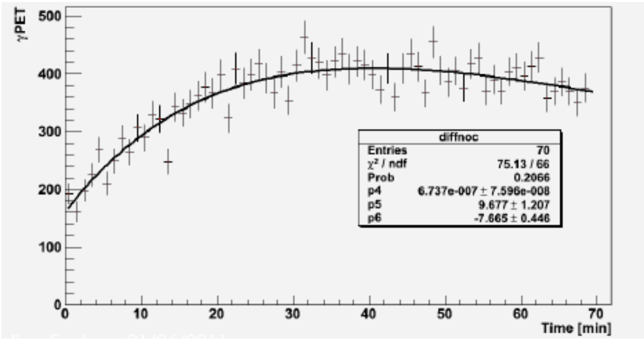


➔Energy spectrum measurement and comparison with MC

➔Evaluate correlation between the number of measured prompt photons and the dose

Research directions (2)

- Study of β+ decays (coincidences in NaI detectors) of ^{11}C and ^{14}N decays (different lifetimes)



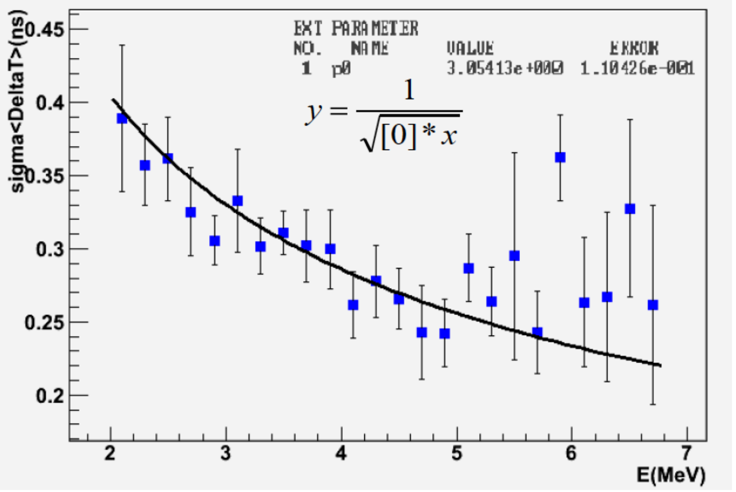
$$n_{dec} = \alpha_2 e^{-\frac{t}{\tau_2}} + \alpha_3 e^{-\frac{t}{\tau_3}} + \alpha_1 e^{-\frac{t}{\tau_1}} \left(\frac{A_2}{\frac{1}{\tau_2} - \frac{1}{\tau_1}} + \frac{A_3}{\frac{1}{\tau_3} - \frac{1}{\tau_1}} \right)$$

→ Understanding time dependence

→ Evaluate correlation between the number of measured NaI and the dose → lifetime correction for high intensity treatments

Research directions (3)

- Use of time of flight to study the neutron spectrum
  - Exploit high resolution of LYSO
- Use drift chamber for charged products
  - Tune MC
  - Evaluate dose measurement feasibility
- Fragmentation rates studies



Considerations

- A frequent path: particle physicists reusing competences in medical physics:
  - "recommended path": education as particle physicists and then move to applied physics?
  - Need to change mindset: from the "search of the optimal" to the "search of the best cost/performance compromise".
- Group formed in a few months, including now 2 postdocs and 2 laurea students → large interest
- Diverse funding sources: Centro Fermi, IIT (on a related topic), … more difficult "coordination"
- Relatively few groups working on PET detectors around the world, but big companies also involved. Hopeless competition or different roles?