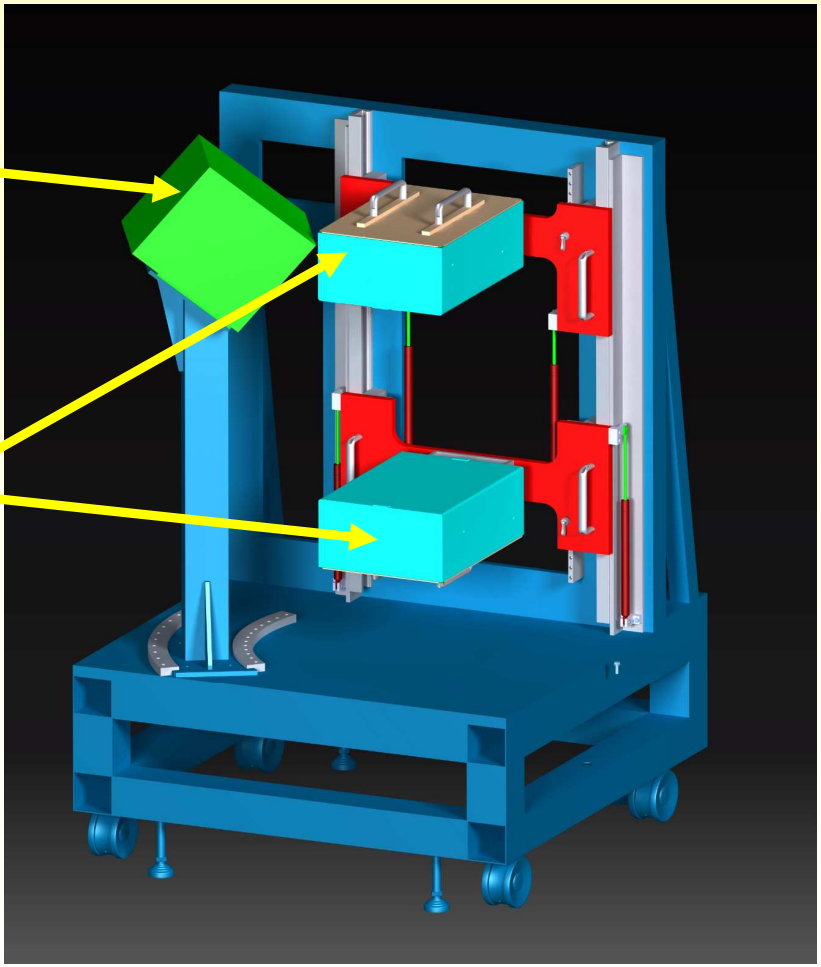
A study of monitoring performances with the INSIDE system

Francesco Pennazio on behalf of
the INSIDE collaboration

INSIDE Hadrontherapy monitoring system

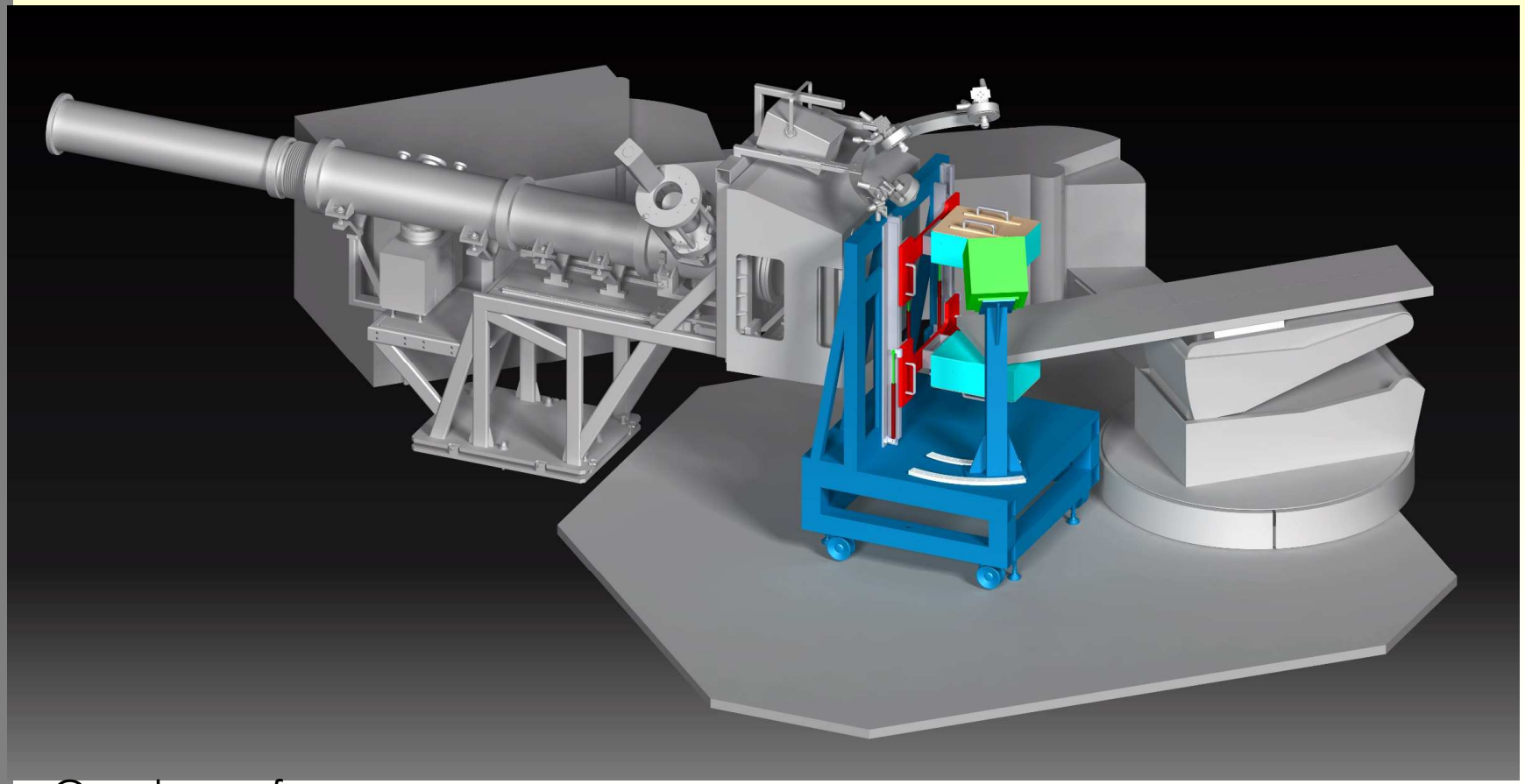
TRACKER

PET heads



Courtesy of G. Giraudo

INSIDE Hadrontherapy monitoring system



Courtesy of
G. Giraudo

Choice of the MC code

FLUKA (INFN-CERN property) **is the baseline choice for this project**

(http://www.fluka.org)

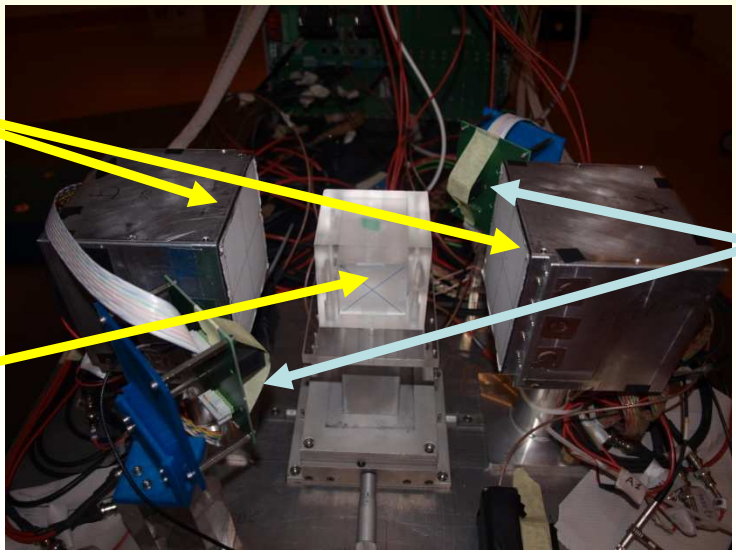
- Includes sound physical models
- Capability of being coupled to CT scans to import geometry, to import volume/organ definitions
- Possibility to be coupled to a radiobiological model
- A long history of applications and developments for hadrotherapy
- Now used at CNAO for TPS database generation, patient plan verification, forward calculation of patient plans, eye treatment studies, radio-biology related studies…etc
- At HIT for TPS database generation, patient plan verification, forward calculations of patient plans, imaging related studies…etc

FLUKA code validation

- Data acquired during a test beam at CNAO – Pavia by the INSIDE and RDH-DOPET collaboration

DOPET heads

PMMA phantom

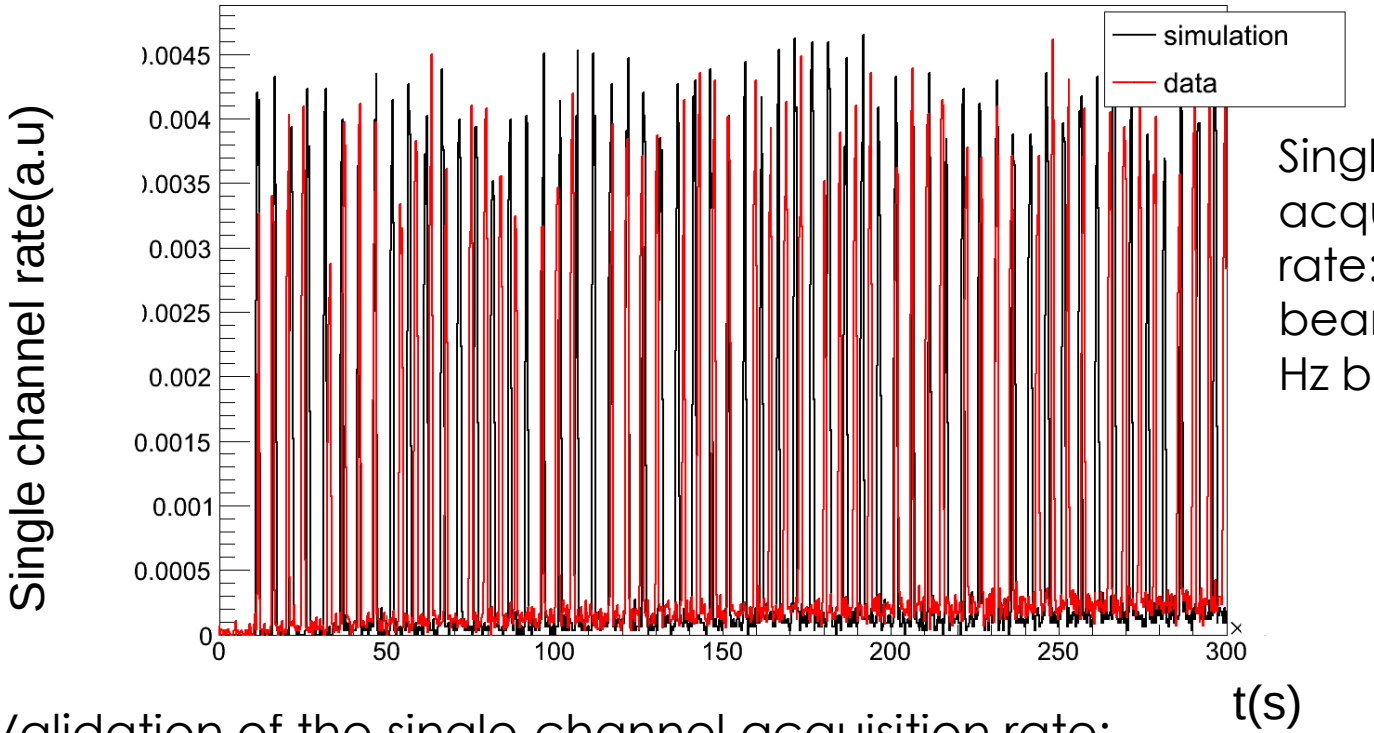


INSIDE PET test modules

Courtesy of RDH(DOPET)

FLUKA code validation

- Beam test at CNAO – single channel acquisition
- 95 MeV protons, PMMA phantom
- $2 \cdot 10^9$ pps (protons), 300 s, ~ 60 spills

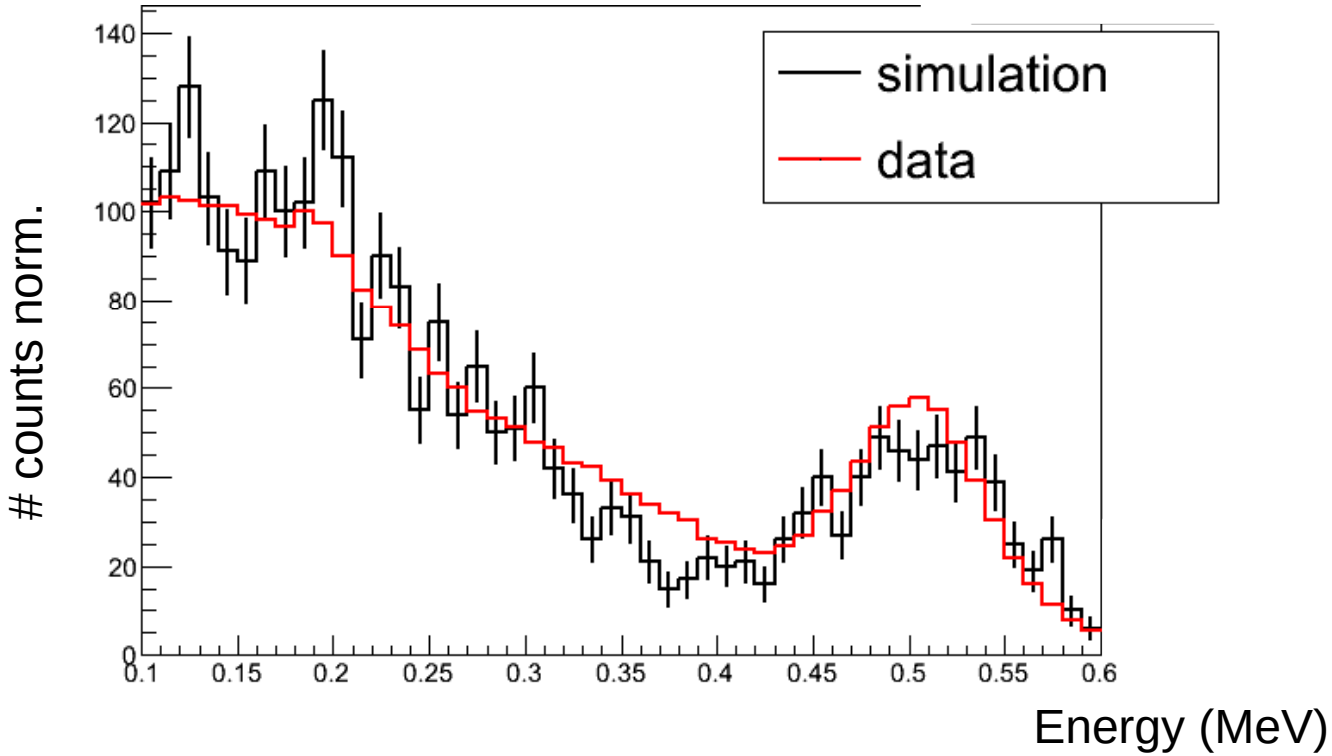


Single-channel acquisition rate: ~1.2 kHz beam on, 100 Hz beam off

- Validation of the single-channel acquisition rate:
  - same trend in inter-spill (β^+activity rising) and in-spill (prompt signal)
  - limitations due to irregular beam repetition (only in the case of test beams)

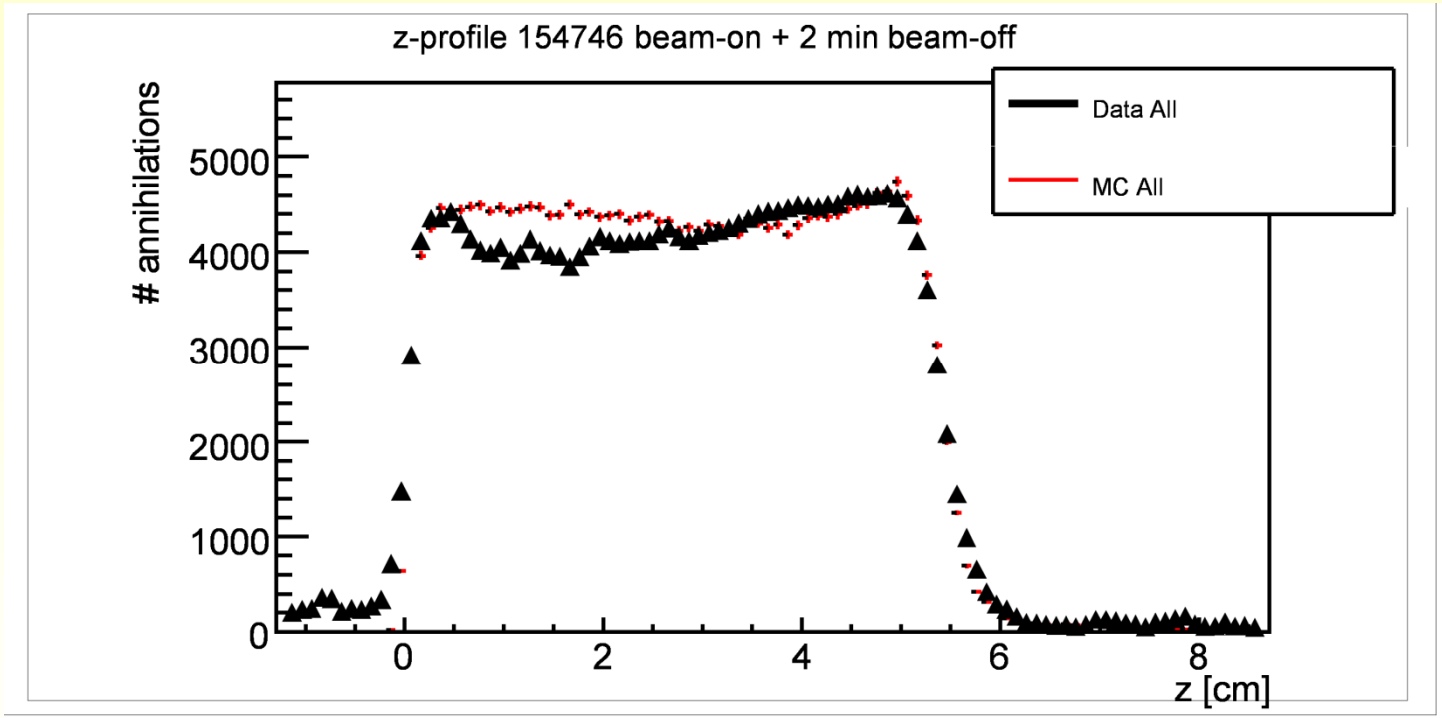
FLUKA code validation

- Beam test at CNAO – single channel acquisition
- 95 MeV protons, PMMA phantom
- $2 \cdot 10^9$ pps (protons), 300 s, ~ 60 spills



- Validation of the inter-spill energy spectrum.

FLUKA code validation



120 s 95 MeV protons on uniform PMMA + 120 s after-treatment

Courtesy of A. Kraan and DOPET (RDH INFN experiment)

in-beam PET simulations

Preliminary steps faced by means of a FLUKA Monte Carlo simulation:

- Evaluation of the expected **number of coincidence events** acquired by the scanner:
  - →Evaluation of monitoring feasibility and geometrical acceptance requirements
- Synchrotron beam is not continuous:
  - →**Inter-spill acquisition vs in- and inter- spill acquisition**

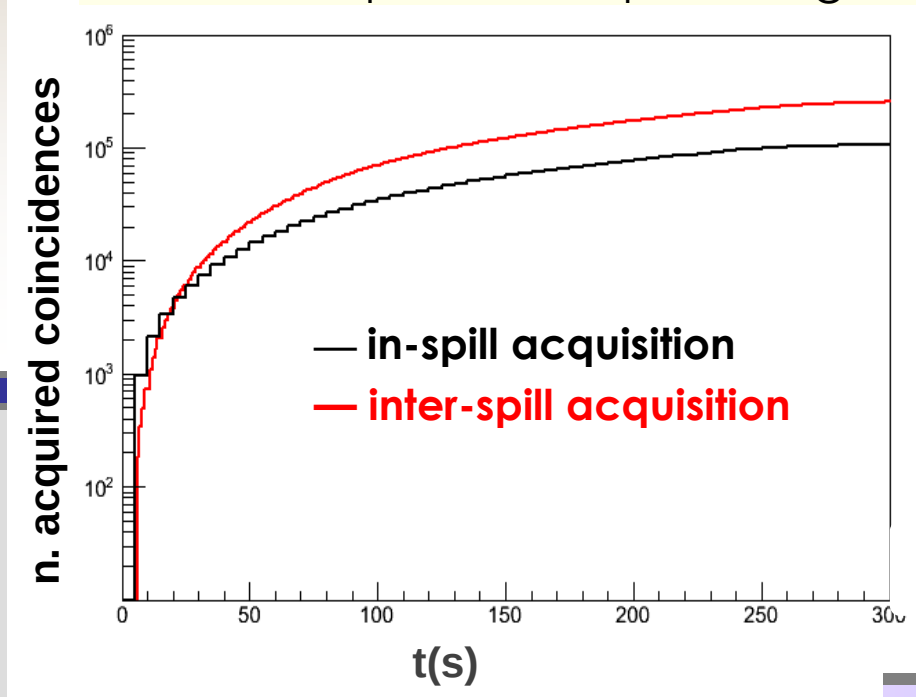
PET: Number of events

- A typical (proton) treatment involves 4 .0·10^{10} primary particles.
- Patient activation is (thankfully) limited: ~1/163 primaries produce a β^+ emitter
- Low geometric scanner acceptance

  → low number of coincidences acquired during the treatment (need of special effort in image reconstruction)
- Full treatment simulation not (yet) feasible
- Problem: **estimate the total number of coincidences which will be acquired by the scan**

PET: Number of events

- Method:
  - FLUKA simulation of the 100% of particles of 20 ms of treatment
  - post-processing to simulate detector behavior:
    - merge of hits in the same element if $\Delta t < 3\tau_{LFS}$
    - energy and time smearing application to simulate E, t resolution
    - coincidence identification (true and random)
  - Geometrical acceptance filtering and superposition of the coincidence rate found to simulate the full treatment
  - Inter-spill and in-spill time gating



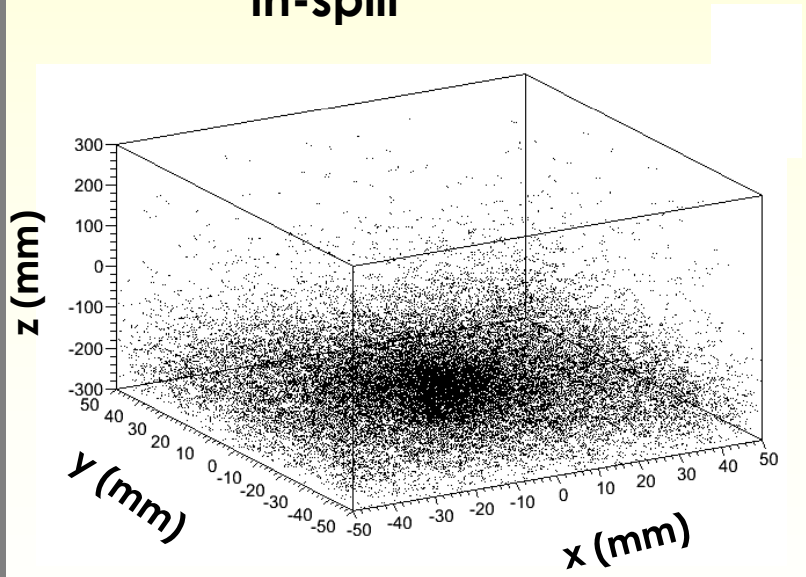
Expected number of **coincidences** (**interspill only, no after treatment acquisition**) evaluated on an **input treatment plan**, taking the detector acceptance/efficiency into account: **$3.09 \cdot 10^5$**

In-spill and inter-spill acquisition

Analysis of the annihilation position :

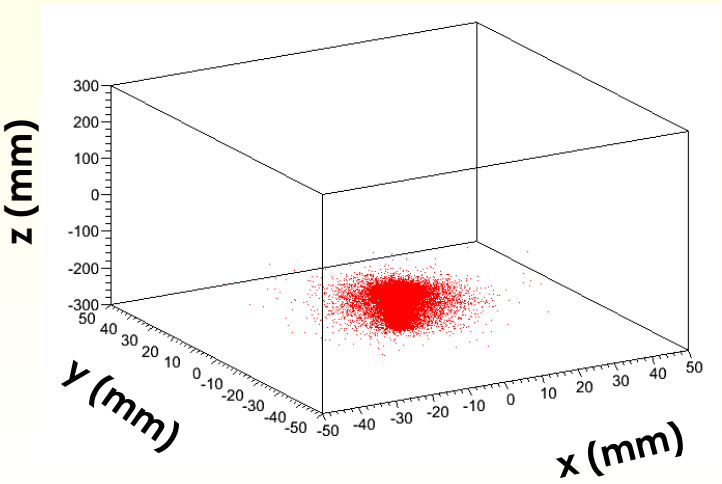
- 2 ms beam on + 300 s beam off (no pile-up to build spills)
- plot of the annihilation positions with beam on (**black**) and off (**red**)
  -> in-spill coincidences are more related to beam position

in-spill



prompt-induced annihilations and β⁺ decays

inter-spill

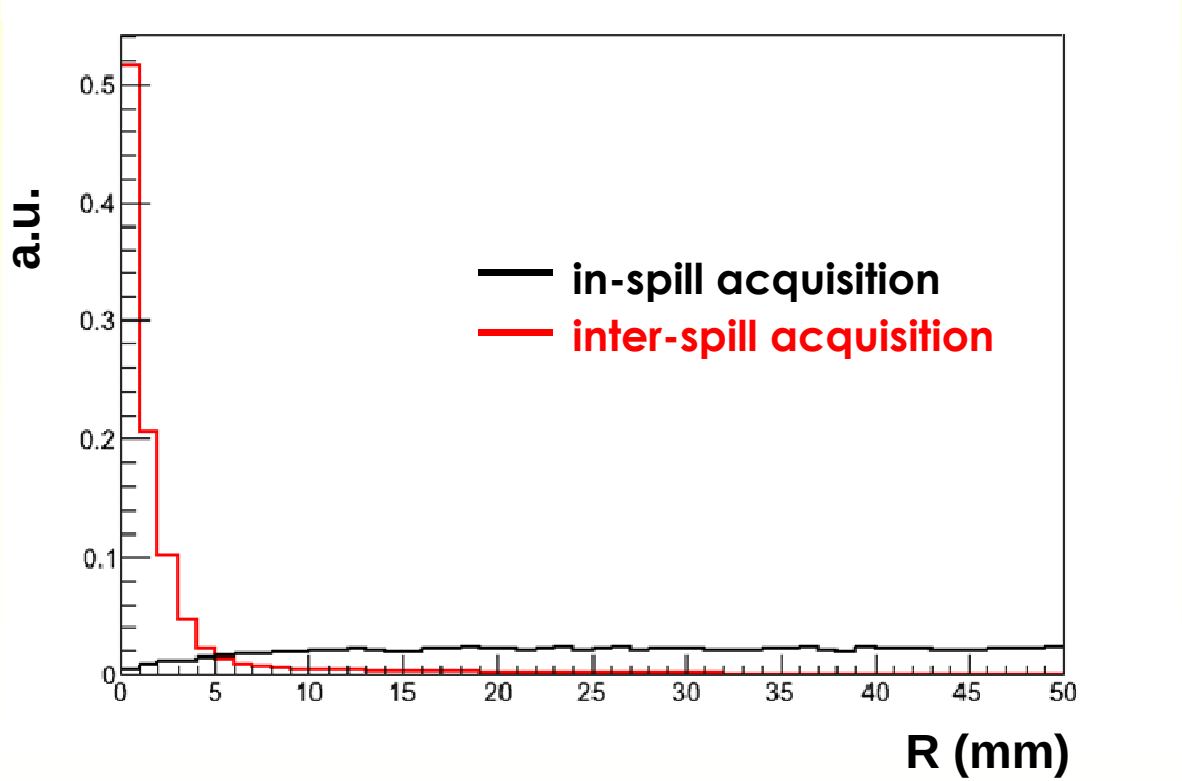


β⁺ decays only

In-spill and inter-spill acquisition

Analysis of the annihilation position :

- 2 ms beam on + 300 s beam off (no pile-up to build spills)
- plot of the annihilation positions in-spill (**black**) and inter-spill (**red**)
  -> in-spill coincidences are more related to beam position



Tracker simulations

Preliminary steps faced by means of a FLUKA Monte Carlo simulations

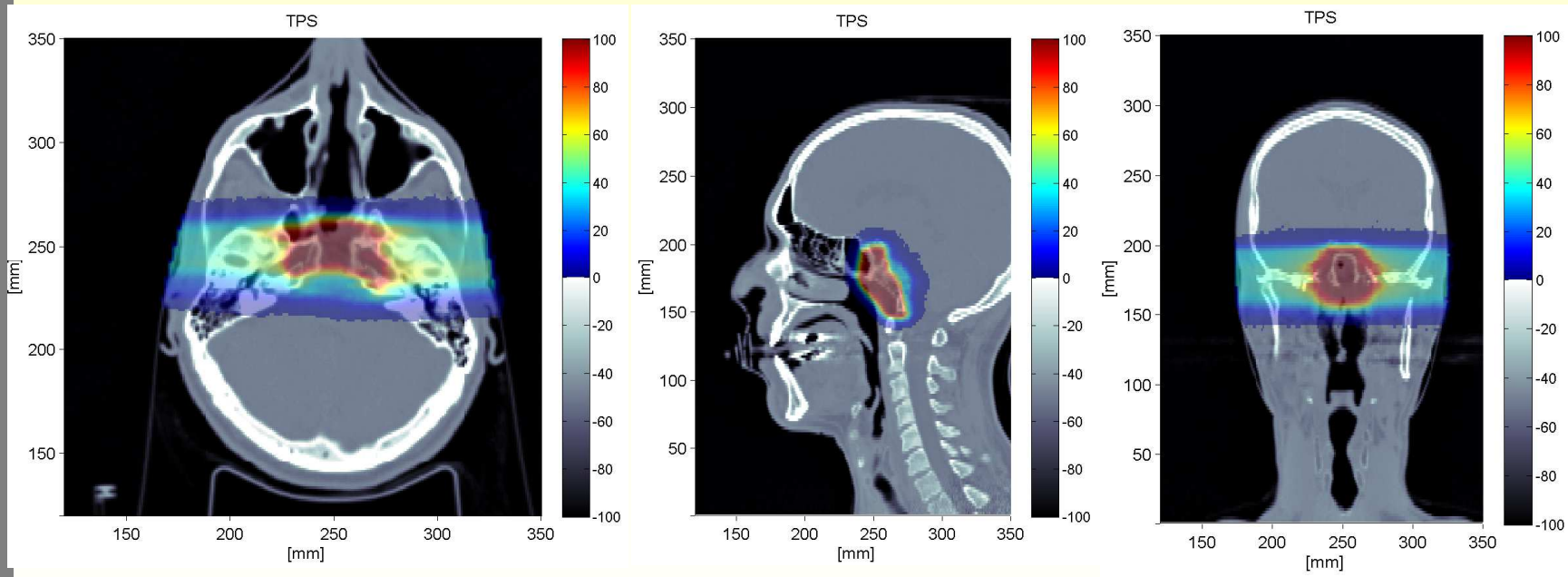
- Radiation type study and momentum analysis for **carbon ions** treatment

  →**Tracker optimal positioning**

- Expected resolution and sensibility assessment

Carbon Example: Treatment Description

The complete plan is composed by 2 opposed fields, ^{12}C.



Dose prescription as calculated by Syngo TPS

Beam1 = 272 571 648 particles

Beam2 = 239 598 608 particles

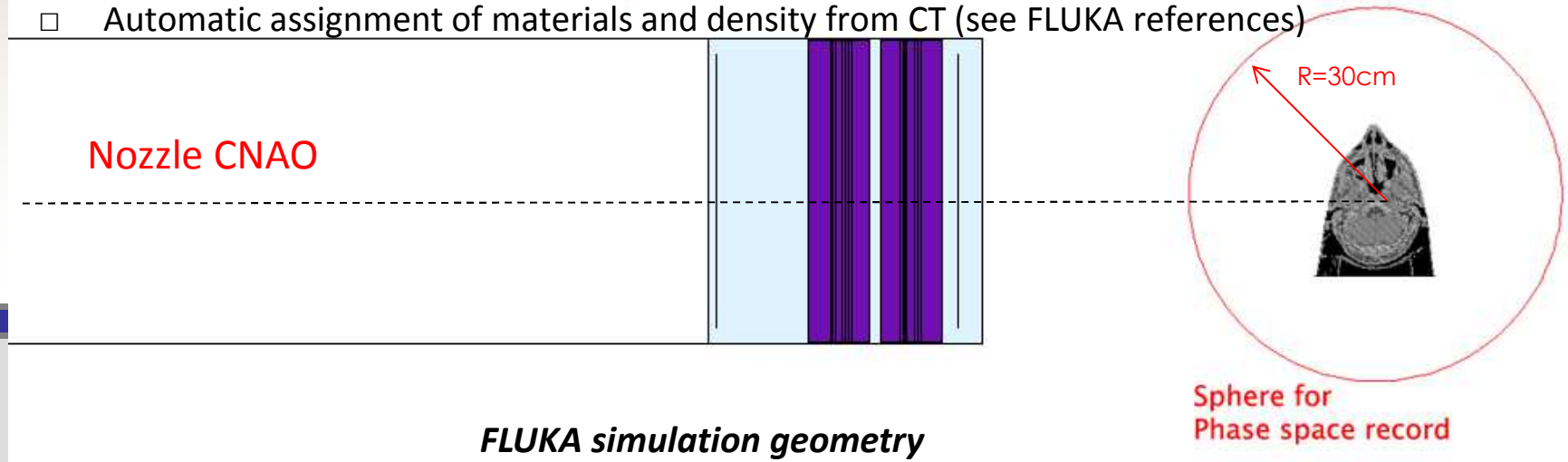
Carbon Example: Treatment Description Beam 1

Energy Slice [n]	Nominal Beam Energy [MeV/u]	Spots per Slice [n]:
1	137.28	2
2	140.72	2
3	144.10	3
4	147.43	3
5	150.71	5
6	153.94	7
7	157.12	8
8	160.26	10
9	163.35	15
10	166.41	28
11	169.43	71
12	172.41	103
13	175.37	163
14	178.28	219
15	181.17	249
16	184.03	236
17	186.86	234
18	189.66	235
19	192.43	231
20	195.18	229
21	197.91	232
22	200.61	228
23	203.29	193
24	205.95	181
25	208.58	174
26	211.19	186
27	213.79	180
28	216.36	172
29	218.91	166
30	221.45	154
31	223.96	135
32	226.46	123
33	**228.94**	**105**
34	231.34	88
35	233.79	72
36	236.22	49
37	238.63	33
38	241.03	14
39	243.42	4

Total no. of spots: 4542

Simulation set up

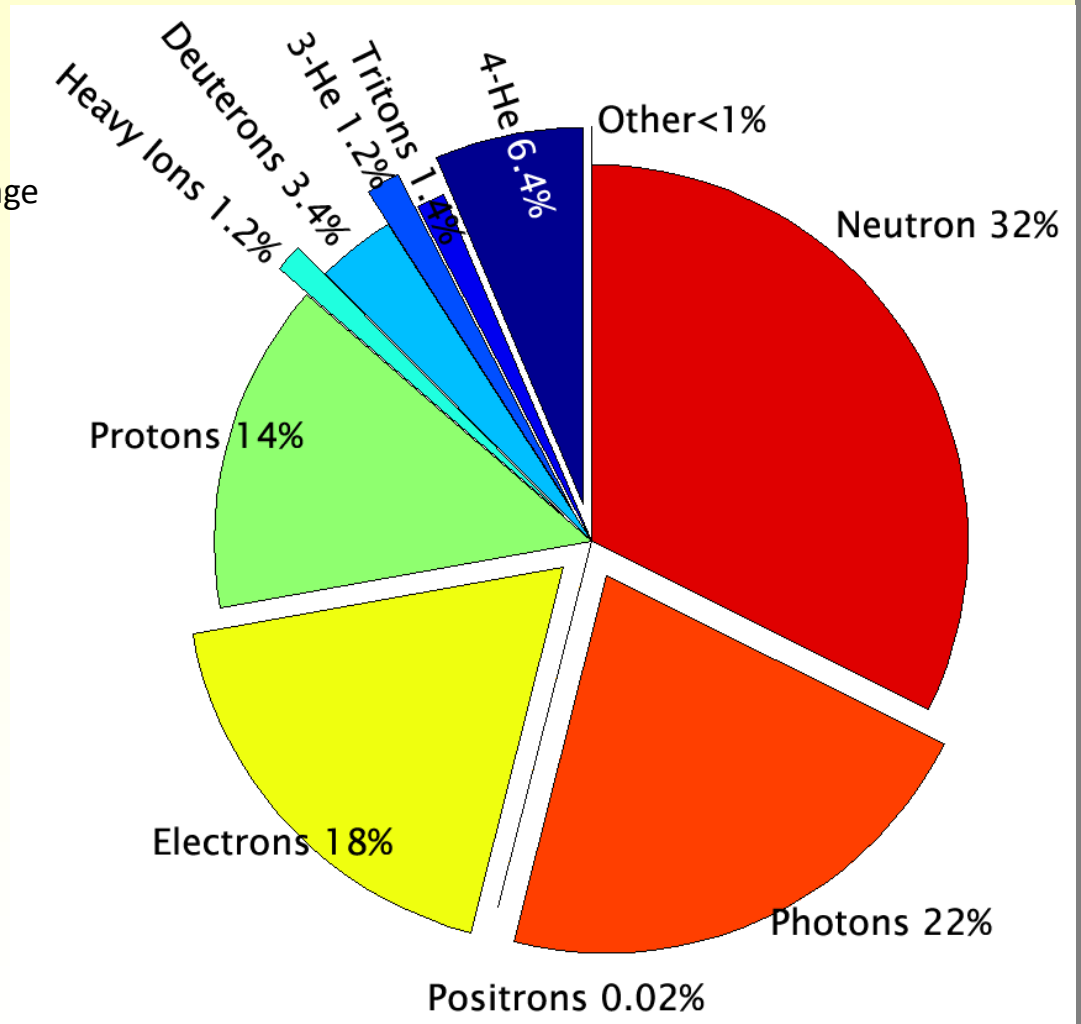
- Slice 33 contains 12×10^6 particles, i.e. ≈1/20 (5%) of the total planned number for Beam1,
- Simulated 5×10^5 primary particles, (≈ 4% of the total slice particles, uniform sampling on spots).
- Simulation time 8h on single core -> simulation of entire plan would require 20 days on 24-cores.
- Scoring on a spherical surface (boundary crossing), record of phase space file around patient head.
- Air around the patient skin
- Beam parameters optimized at CNAO
- Voxel geometry of patient from CT
- Automatic assignment of materials and density from CT (see FLUKA references)



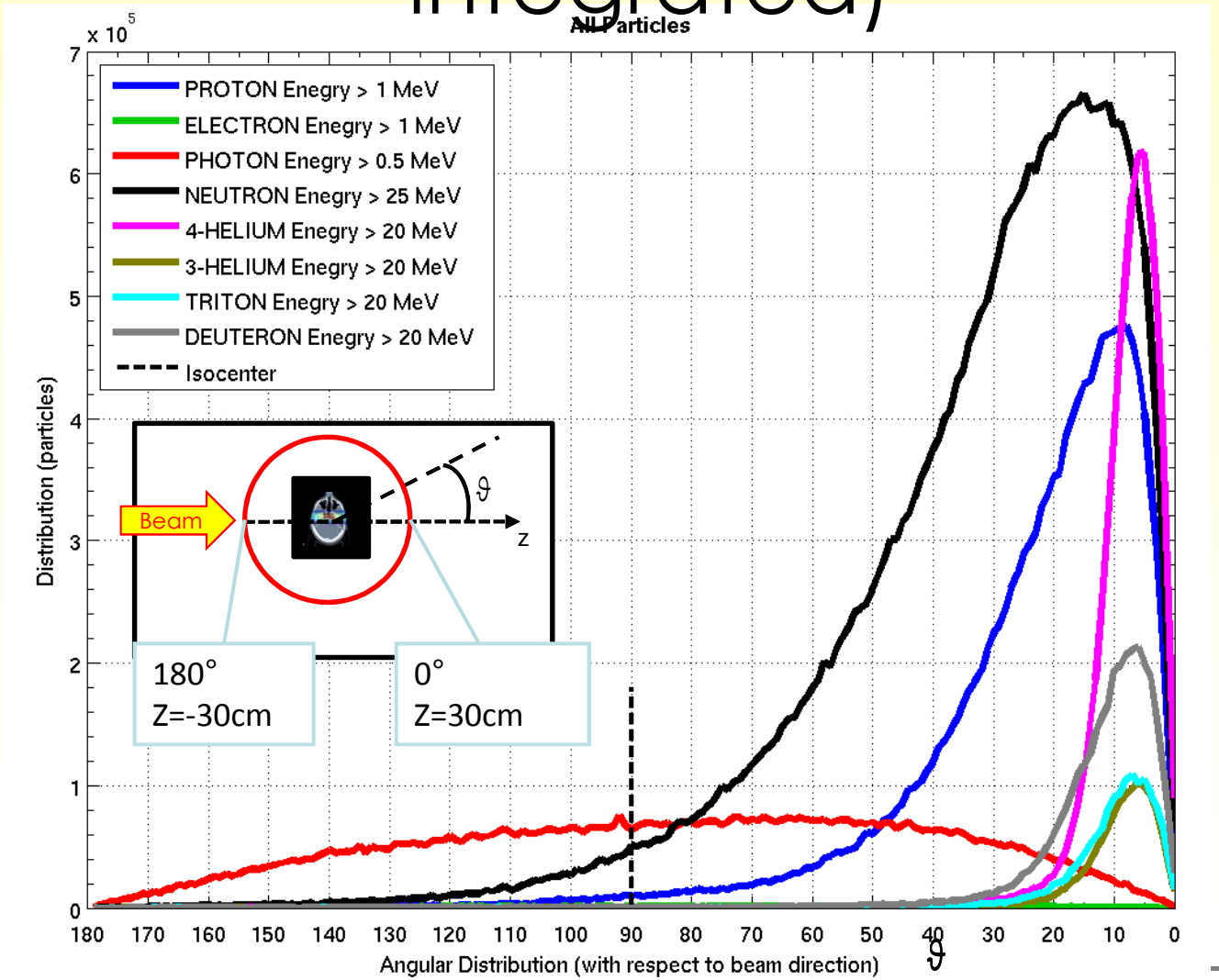
FLUKA simulation geometry

Emitted Radiation Flavor

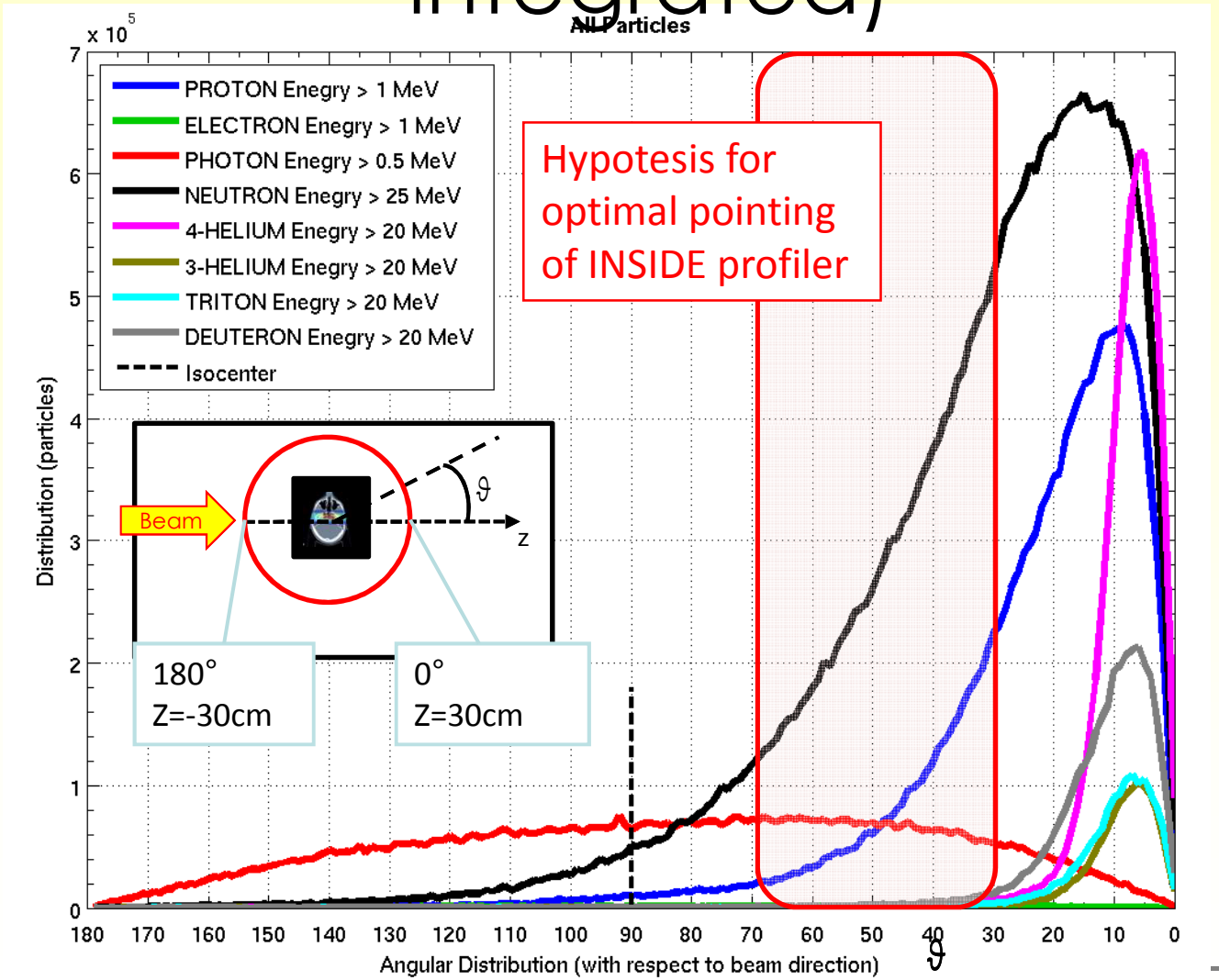
Number of crossing particles	Particle name	Percentage
6e+06	4-HELIUM	6 %
1e+06	3-HELIUM	1 %
1e+06	TRITON	1 %
3e+06	DEUTERON	3 %
1e+06	HEAVYION	1 %
1e+07	PROTON	10 %
2e+07	ELECTRON	20 %
2e+04	POSITRON	0.02 %
2e+07	PHOTON	20 %
3e+07	NEUTRON	30 %
2e+02	MUON+	0.0002 %
3e+02	MUON-	0.0003 %
3e+03	PION+	0.002 %
2e+03	PION-	0.002 %



Angular Distribution (azimuthally integrated)



Angular Distribution (azimuthally integrated)



Tracker Simulations

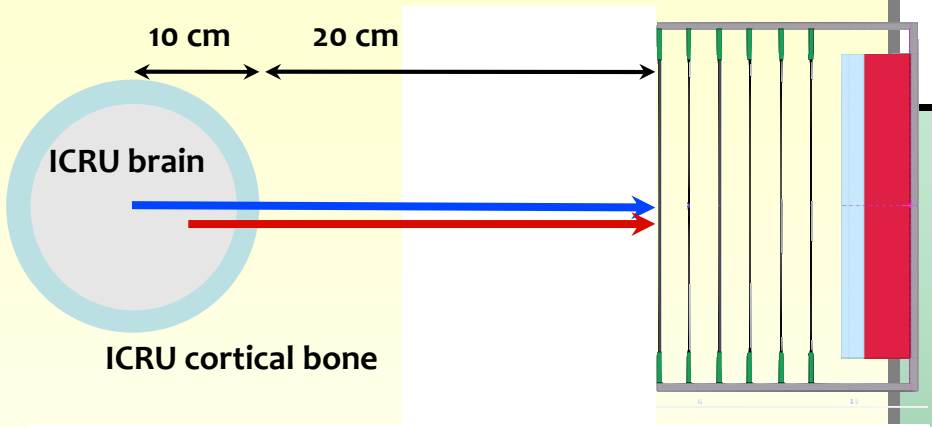
Simulation of a "spherical patient" with ICRU materials, with proton source placed at different depths:

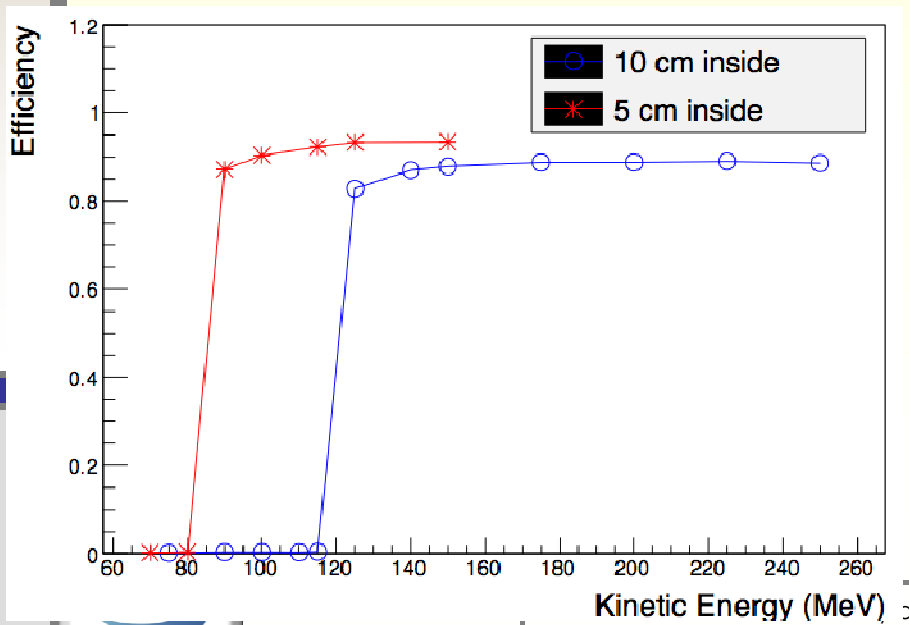
10 cm and 5 cm

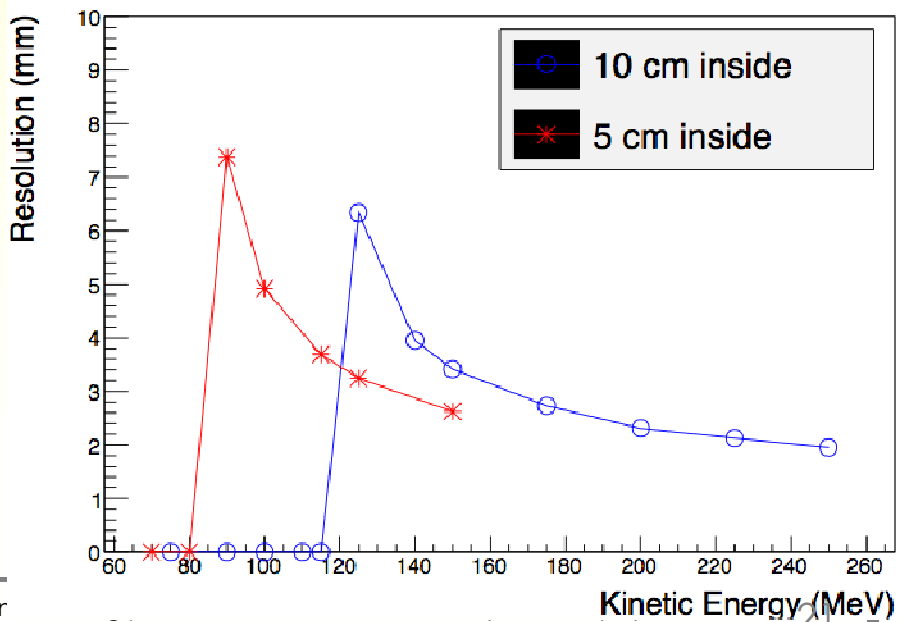
Energy Threshold

Single Track Spatial resolution

~ few mm







Conclusions (to date)

FLUKA-based simulations were validated on CNAO and GSI test data

PET

- the PET detector can operate full beam/in beam
- single Channel Trigger rate under control
- photopeak well identified, even on single channel triggers
- O(10^5) expected coincidences on a typical treatment plan
  - simulations suggest avoiding full beam acquisition (i.e., only inter-spill coincidences in the analysis) will provide better data quality

Tracker

- the Tracker can operate full beam
  - It must do so, as it exploits information from prompt events!
- GSI testing confirms the expected spatial resolution

Simulation and reconstruction work in progress

- Monte Carlo simulation speed up:
  - PET two-step simulation method:
    - Activity scoring with **time tagging** by means of a complete simulation of 1/100 of the full treatment
    - A custom activity-based generator is written
    - Preliminary result: full-treatment image reconstruction on a desktop PC within few hours

Simulation and reconstruction work in progress

- Monte Carlo simulation speed up:
  - Optimization of production and transport thresholds
  - Inelastic interaction biasing
  - Further "tuning" as a function of particle energy
  - Multiple "replicas" of radioactive decays
  - Direction biasing of annihilation photons
  - Multiple "replicas" of final (gamma) de-excitation
  - Direction biasing of de-excitation photons (work in progress)

Simulation and reconstruction work in progress

- Monte Carlo simulation speed up:
  - Optimization of production and transport thresholds
  - Inelastic interaction biasing
  - Further "tuning" as a function of particle energy
  - Multiple "replicas" of radioactive decays
  - Direction biasing of annihilation photons
  - Multiple "replicas" of final (gamma) de-excitation
  - Direction biasing of de-excitation photons (work in progress)

- **Preliminary result: full-treatment image reconstruction on a desktop PC within few hours**

Acknowledgments

The INSIDE collaboration: Giuseppe Battistoni, Maria Giuseppina Bisogni, Niccolò Camarlinghi, Piergiorgio Cerello, Alberto Del Guerra, Elisa Fiorina, Giuseppe Giraudo, Aafke Kraan, Ben Liu, Michela Marafini, Cristoforo Marzocca, Ilaria Mattei, Matteo Morrocchi, Vincenzo Patera, Francesco Pennazio, Cristiana Peroni, Luca Piersanti, Maria Antonietta Piliero, Giovanni Pirrone, Valeria Rosso, Alessio Sarti, Adalberto Sciubba, Giancarlo Sportelli, Richard Wheadon

From CNAO: Mario Ciocca and Andrea Mairani (who also provided assistance and beam delivery MC setup for FLUKA)

FLUKA collaboration for the assistance in the use of the code

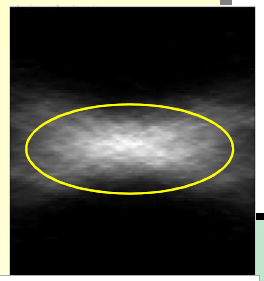
This work has been supported by the European Community in the framework of the ENVISION FP7 project.

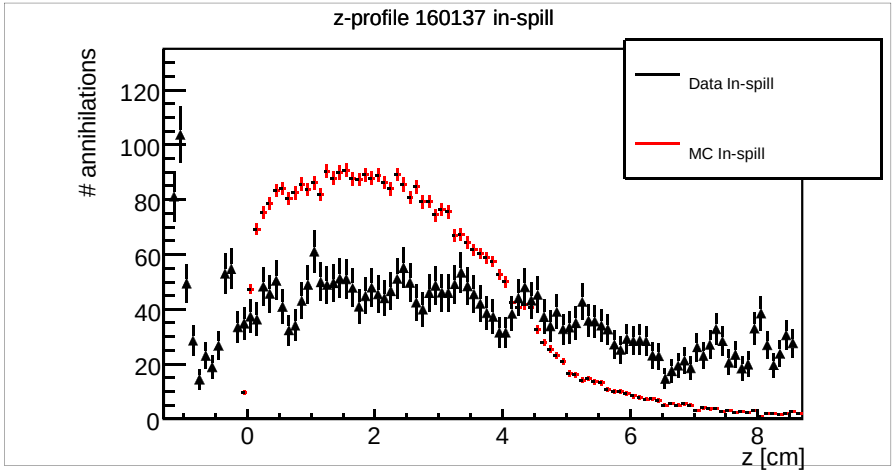
Backup slides

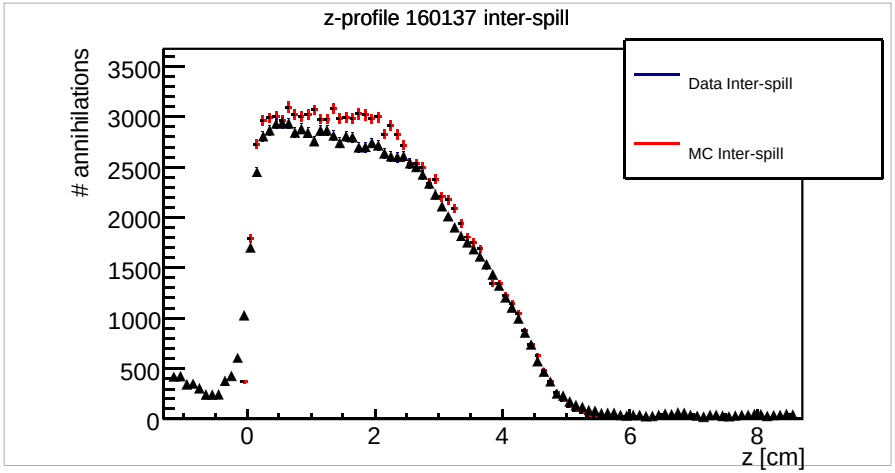
Data 1601: 2 Gy plan on homogeneous PMMA

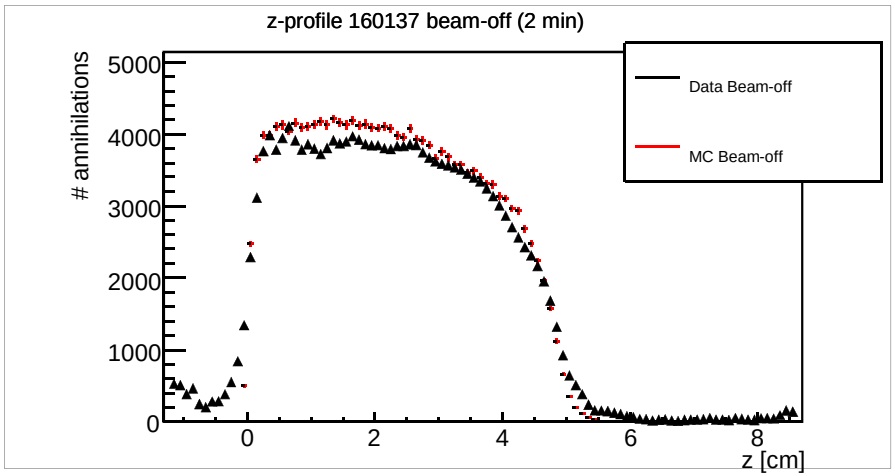
2 Gy plan on uniform PMMA
3x3x3 cm³
located at z=2.5->5.5 cm
1-D z-profile for DATA and MC

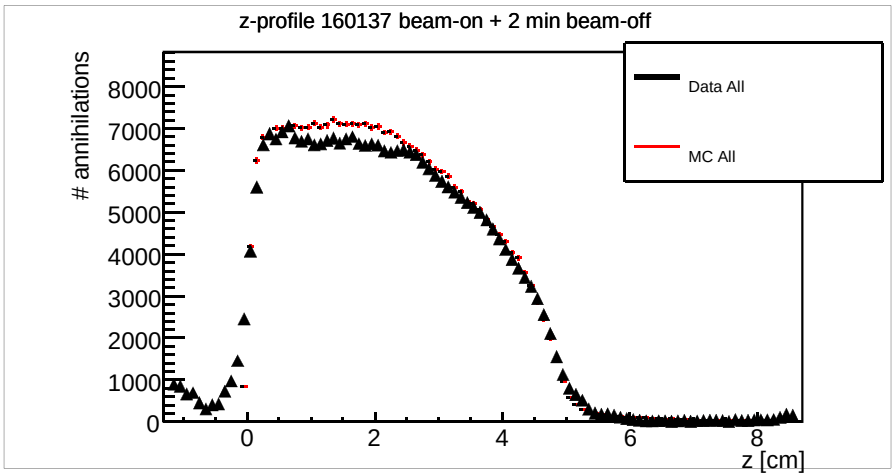
Nr events:
In-spill =9349
Inter-spill=181422
2 min beam-off =278171
BON+2min beam-off



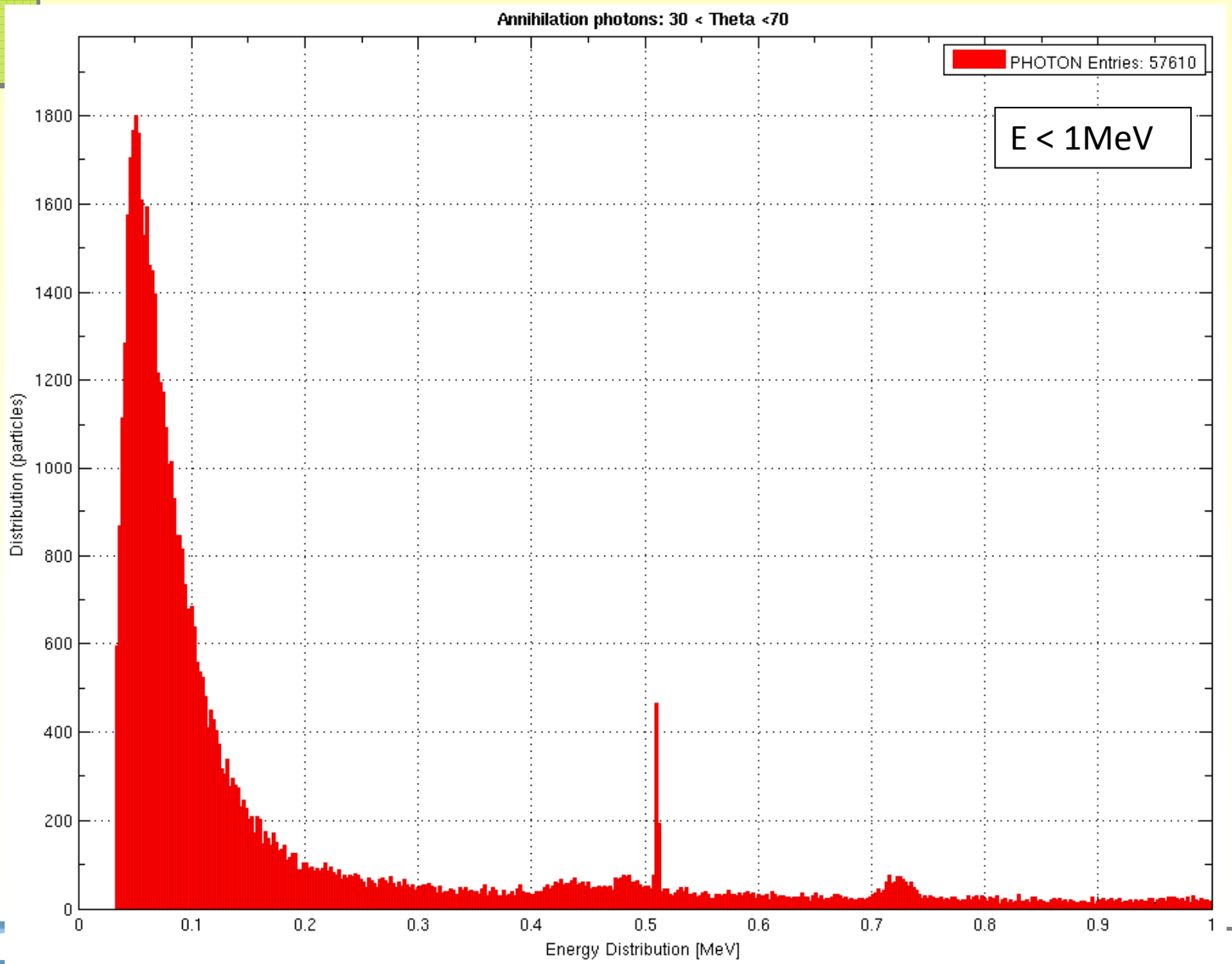




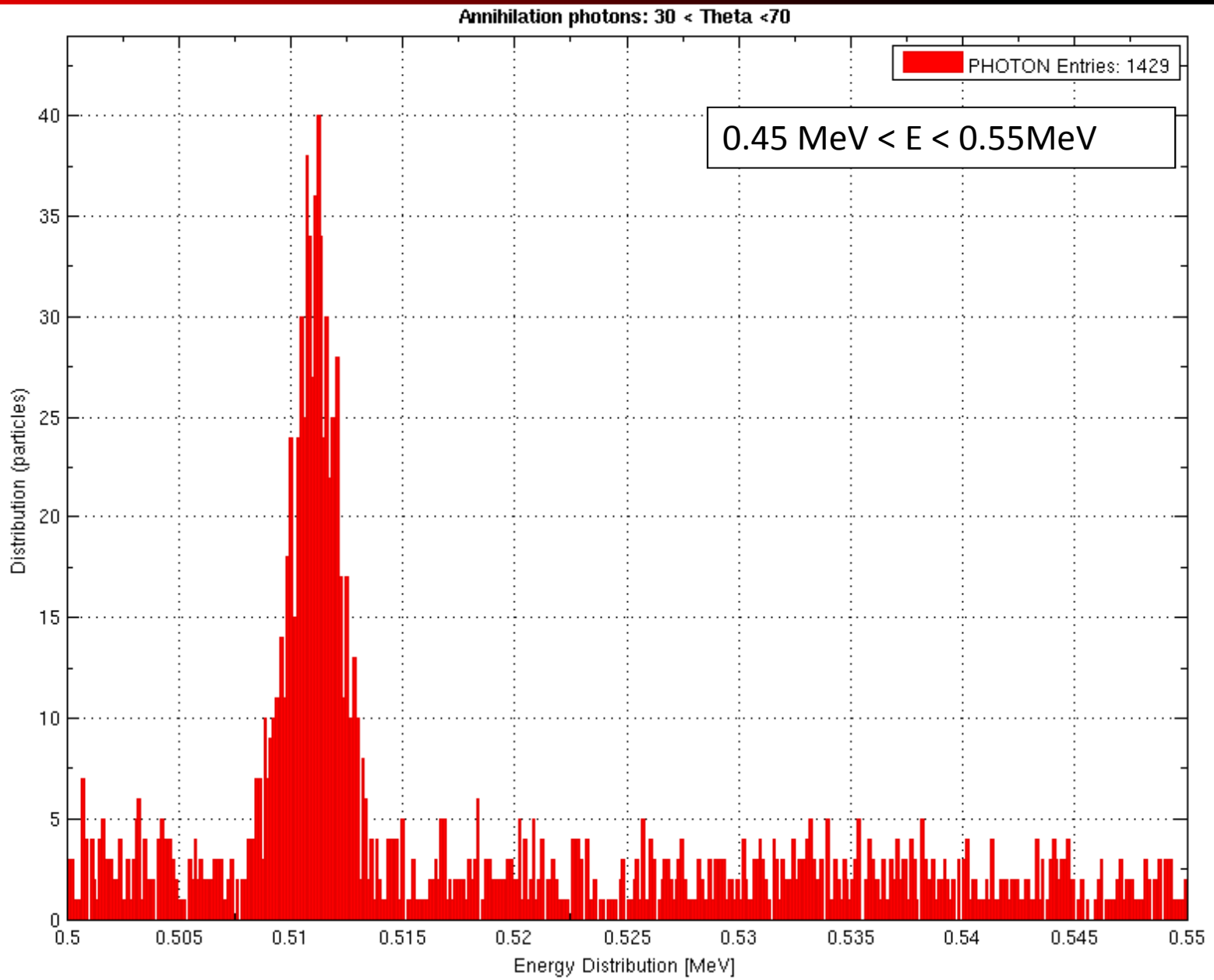




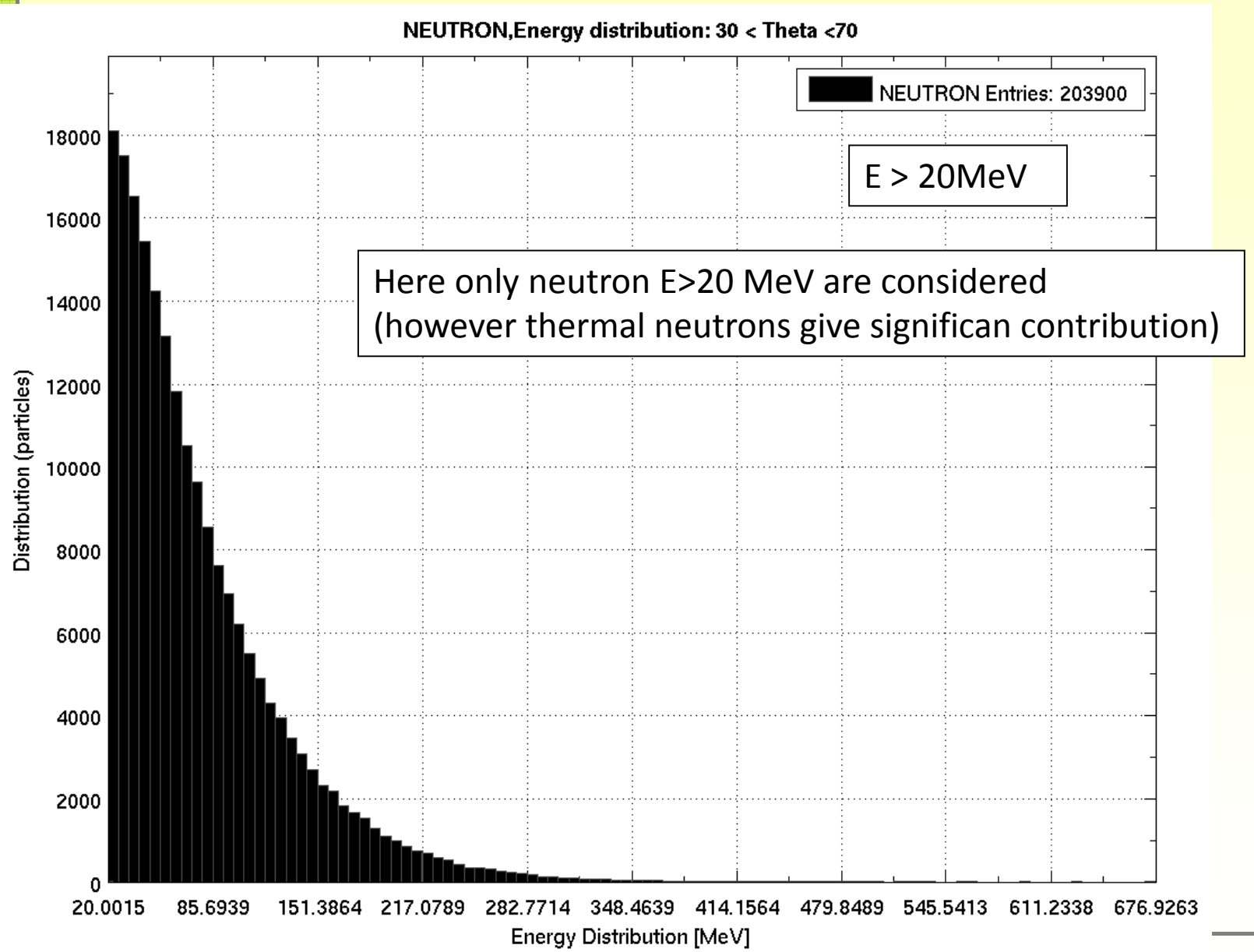
Energy Distribution PHOTONS



Energy Distribution PHOTONS



Energy Distribution NEUTRONS



Energy Distribution PROTONS