Neutrons with the FOOT detector (or with few modifications)

Questions:

- **How many neutrons produced in target**
- **« » and are in the scintillator acceptance**
- **« » make elastic scattering**
- **How many background neutrons produced**
- **« » and are in the scintillator acceptance**
- **« » make elastic scattering**

Measure Goal:

- **Total neutron cross section**
  - **differential cross sections: $d\sigma/d\theta$ and $d\sigma/dE$**
    - **Double differential cross section $d^2\sigma/d\theta\, dE$**

Detector Goal:

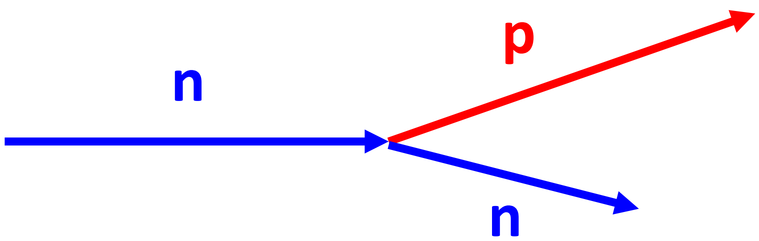
- **Use a detector as similar as possible to FOOT**

Neutrons with the FOOT detector (or with few modifications)

measure neutron ToF

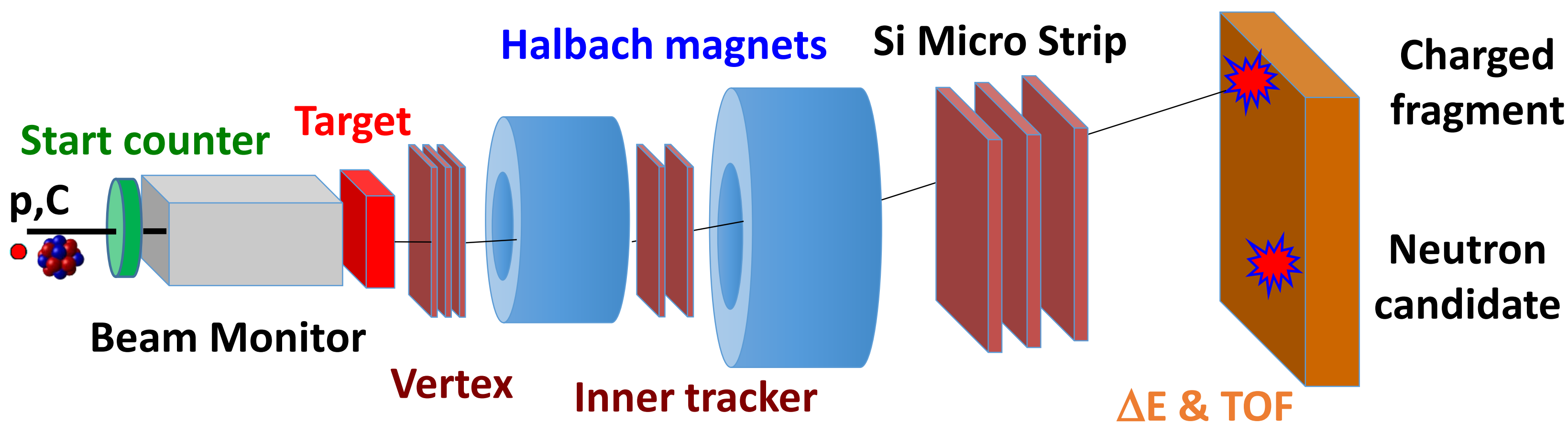
Projective tower (as calo) of deeper plastic scintillator (variable granularity)

np elastic scattering



Directly measurement of dσ/dθ

Exclusion of calo to decrease bkg contribution



Neutron definition: signal in SCN without a combined track in tracker

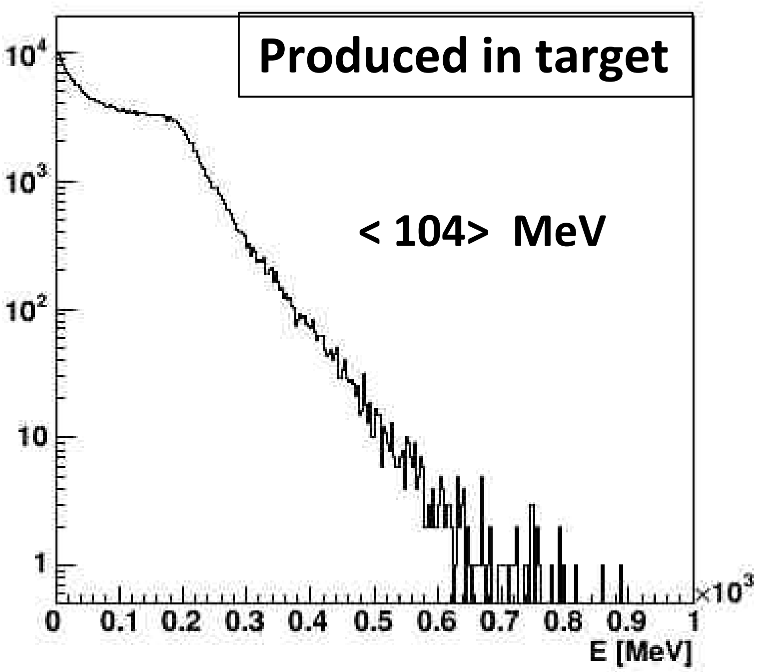
Neutrons kinetic energy

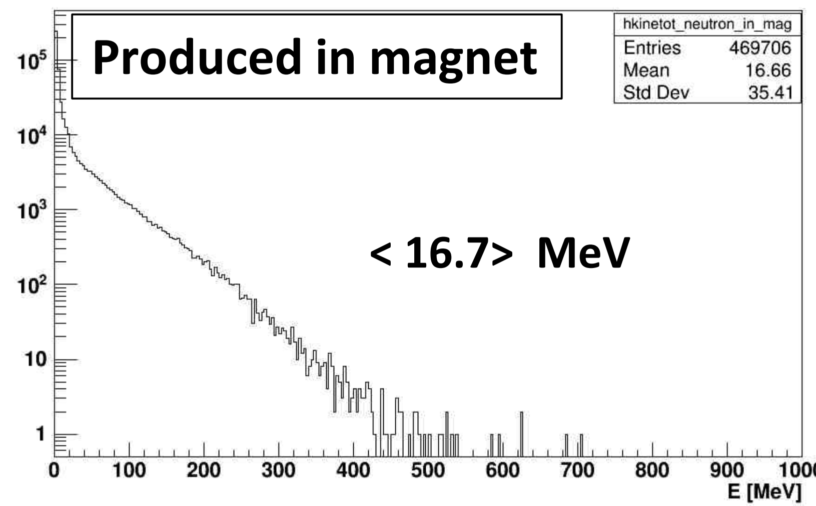
Input: /gpfs_data/local/foot/Simulation/V13.1.1/16O_C2H4_200_1.root

10^7 primary particles → 115,3 k fragmentation (1.15%)

Selected 295.8 kneutrons produced in target → 2.56 neutrons/ev

Selected 469.7 kneutrons produced in magnet → 4.07 neutrons/ev





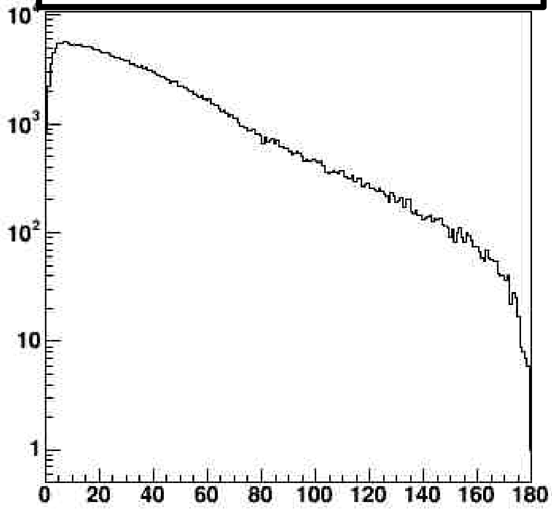
2% emitted with E< 2 MeV
10% « » 10 MeV
54% « » 100 MeV
87% « » 200 MeV

36% emitted with E< 2 MeV
73% « » 10 MeV
96% « » 100 MeV
99% « » 200 MeV

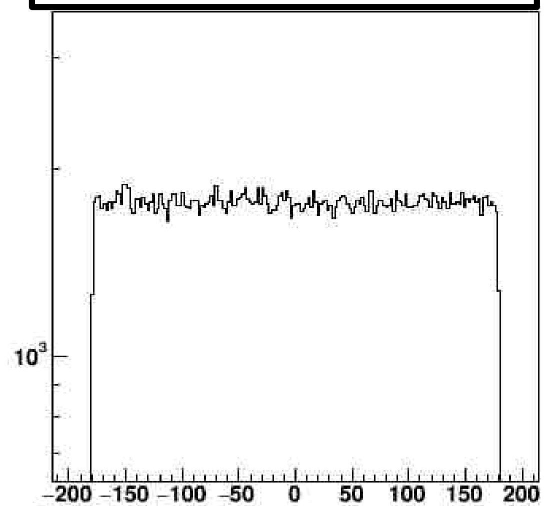
Neutrons produced in Target

Neutrons direction

Theta (degrees)

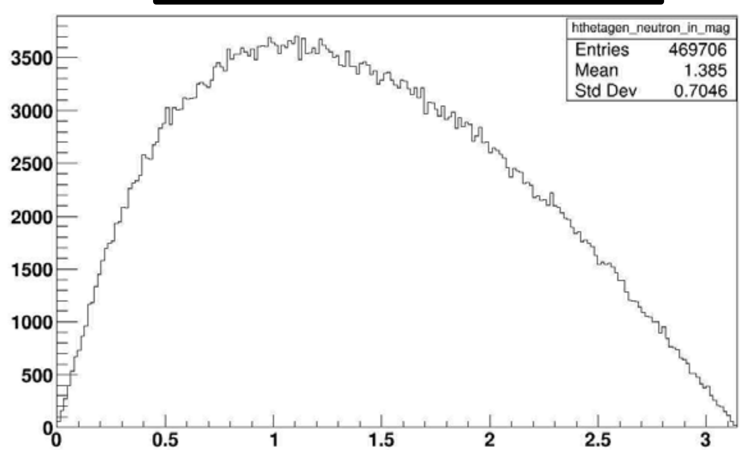


Phi (degrees)

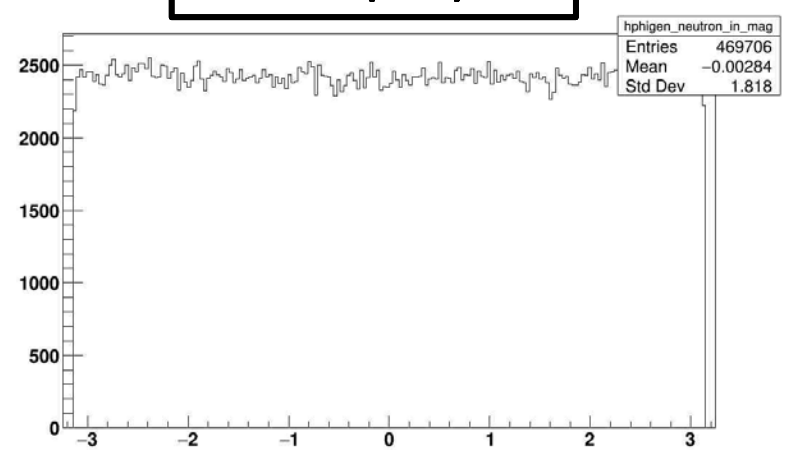


Background Neutrons

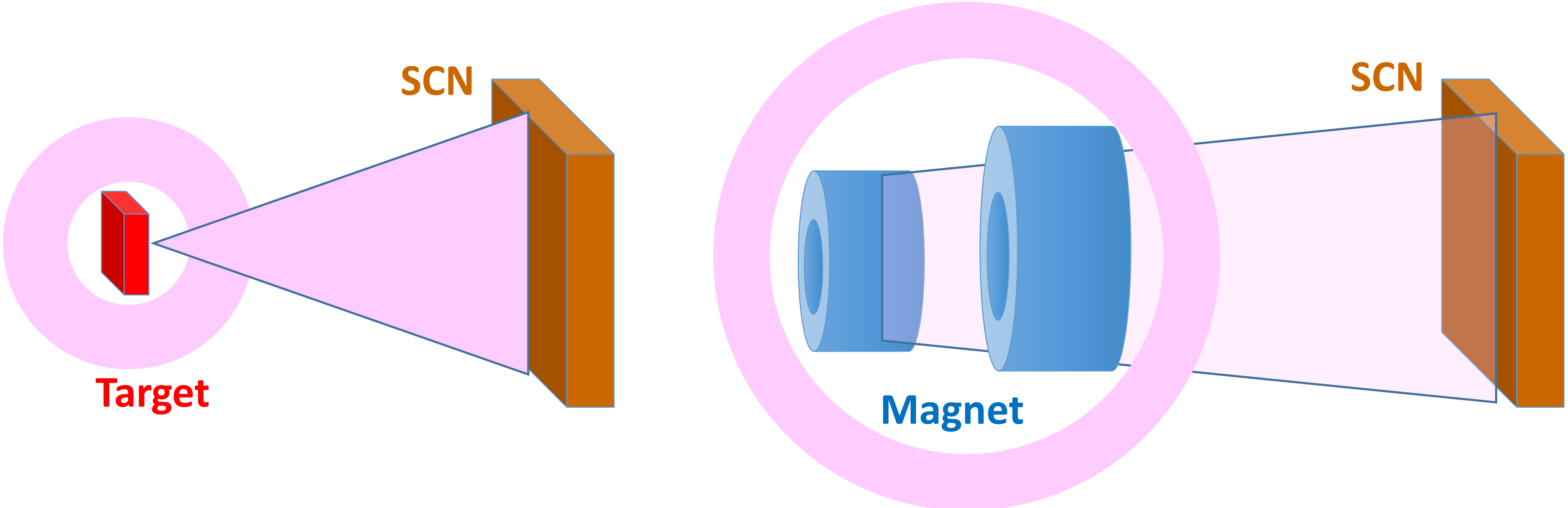
Theta (rad)



Phi (rad)



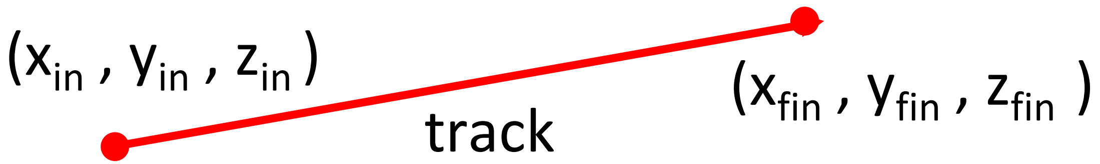
SCN Geometrical acceptance



Definition of neutrons hit the SCN

- $Tr_{fin} > 100$
- $fabs(x_{SCN}) < 20$
- $fabs(y_{SCN}) < 20$

$$\begin{cases} x_{SCN} = x_{in} + (x_{fin} - x_{in})\dfrac{(z_{SCN} - z_{in})}{(z_{fin} - z_{in})} \\ y_{SCN} = y_{in} + (y_{fin} - y_{in})\dfrac{(z_{SCN} - z_{in})}{(z_{fin} - z_{in})} \\ z_{SCN} = 100 \end{cases}$$



SCN Geometrical acceptance, 2

^{16}O with 200 MeV/u

neutrons prod in target

- 295826
- hit the SCN: 56806

→ Geometrical acceptance **19.2%**

0.49 n/ev

neutrons prod in magnet

- 469706
- hit the SCN: 7371

→ Geometrical acceptance **1.6%**

6.4×10^{-2} n/ev

Geometrical acceptance of bkg neutrons << neutrons from target

With ^{16}O of 700 MeV/U (4×10^6 primary → 24011 fragmentations (0.6%)

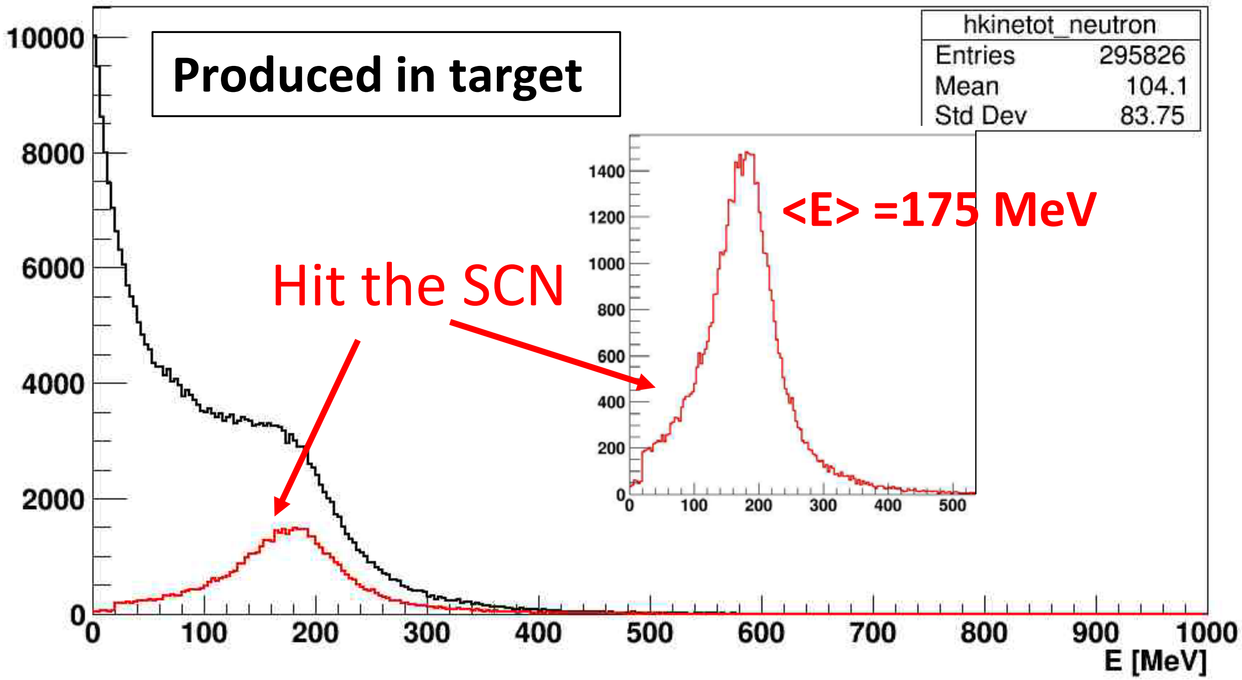
- **Neutron in target: 92129**
- **« » hit SCN: 26542**

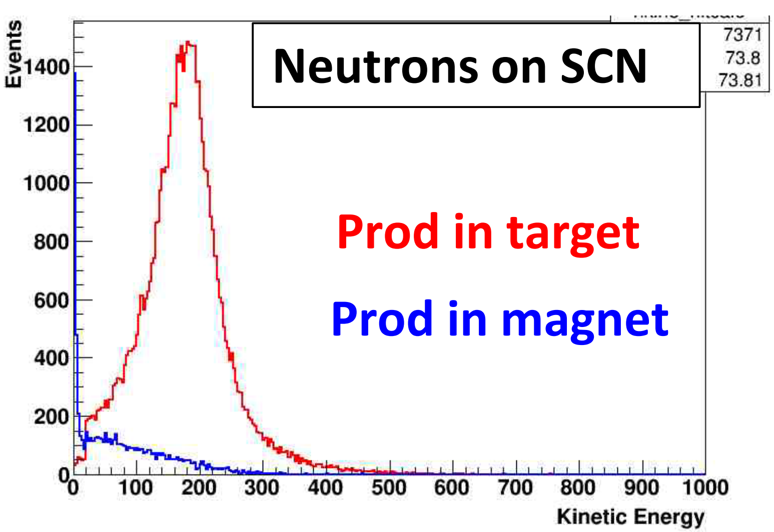
→ **Geom acc 28.8%** **1.10 n/ev**

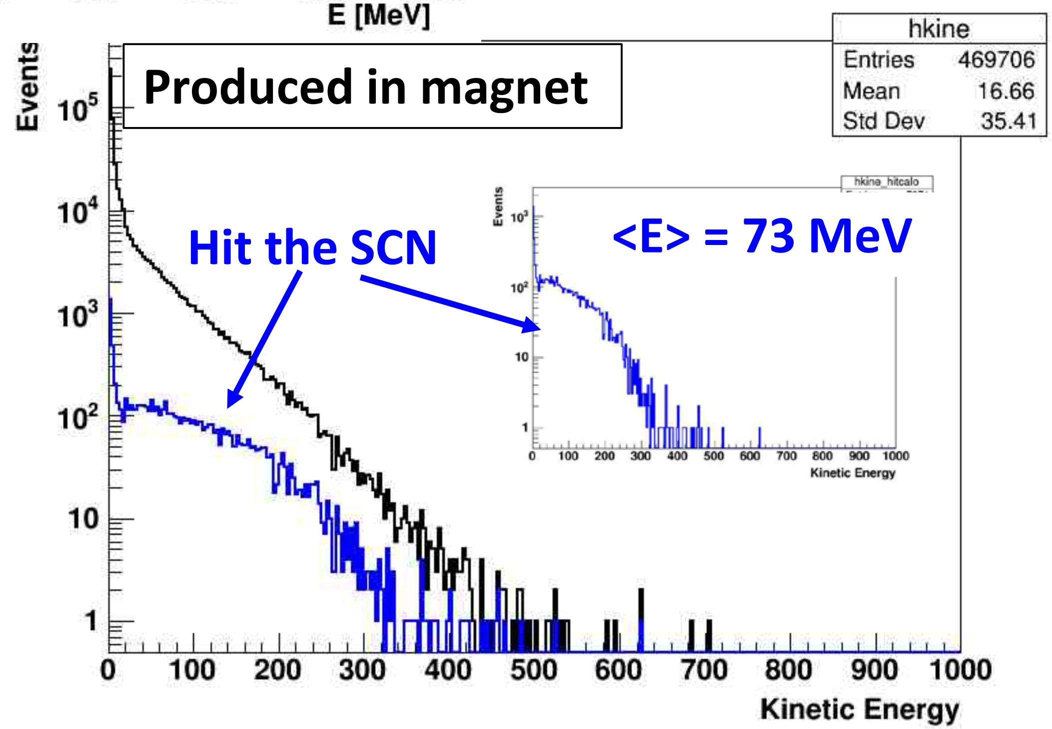
- **Neutron in Magnet: 219477**
- **« » hit SCN: 3310**

→ **Geom acc 1.5%** **0.14 n/ev**

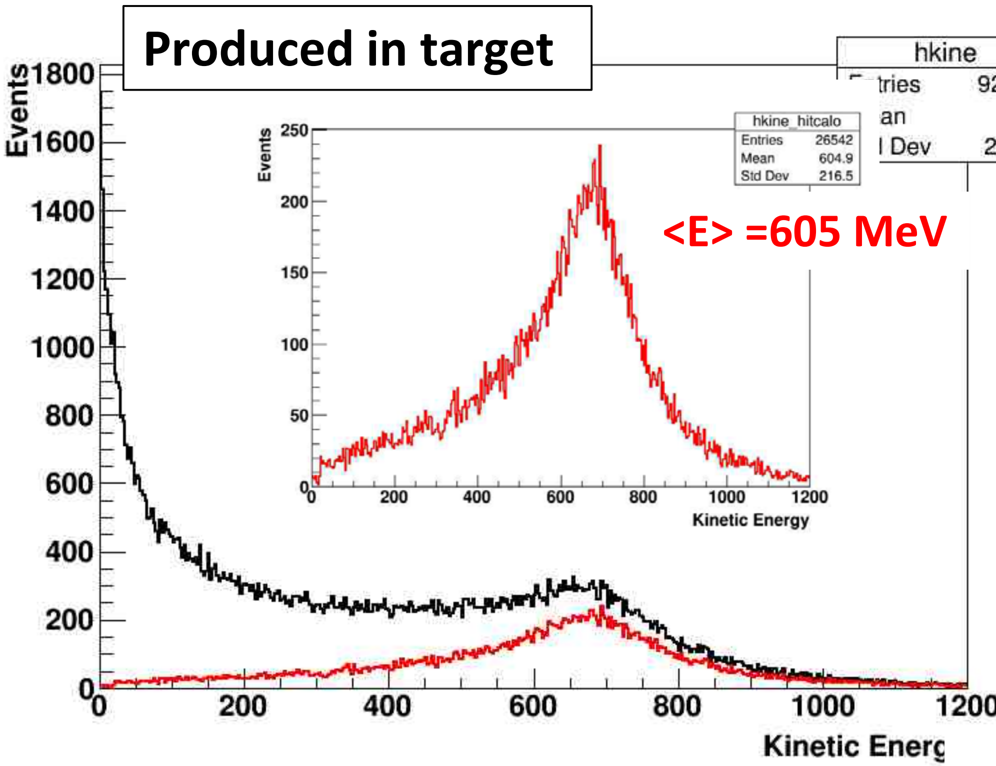
Neutrons on SCN, 200 MeV

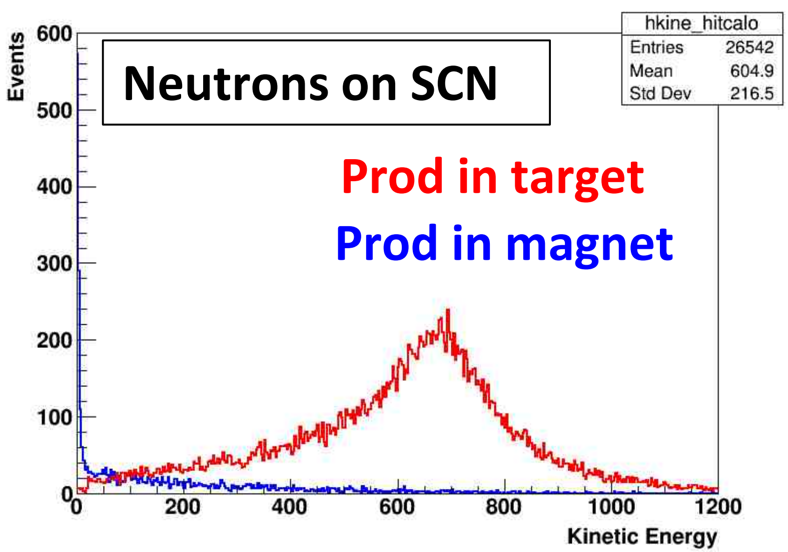


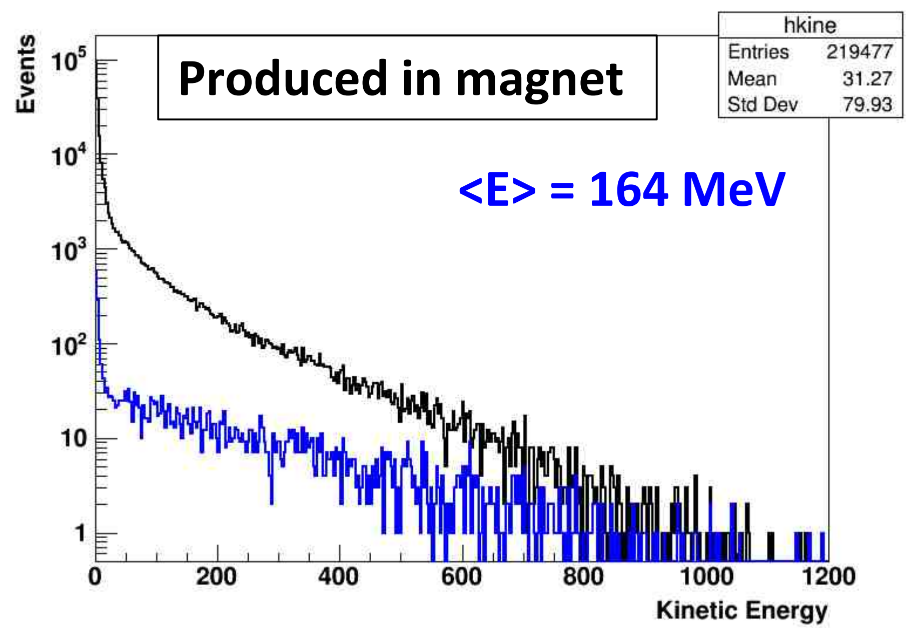




Neutrons on SCN, 700 MeV







Neutrons elastic scattering

$$N = N_0 \, e^{-(\sigma_{el} \, n_p)}$$

N	Number of survived neutrons after travelling a material
N_0	Number of incident neutrons
σ_{el}	n + p elastic cross section (barn)
n_p	Number of hydrogen nuclei in the material

$$n_p = \frac{\rho \;\; dx \;\; N_{AV} \;\; N_H}{W_{atomic} \;\; 1_{barn}}$$

ρ	Material density (gr/cm^3)
dx	Depth of travelled material (cm)
N_{AV}	Number of Avogadro
W_{atomic}	Atomic weight (gr)
N_H	Number of hydrogens
1_{barn}	10^{-24} cm^2

SCN characteristics

Supposing to use the current scintillator: C_9H_{10}

- ρ = 1.3 gr/cm^3
- W_{atomic} = 9 x 12 + 10 = 118
- N_H = 10
- N_{AV} / barn = 0.6

$$n_p = dx \times 6.6 \times 10^{-2}$$

Percentage of interacting neutrons

$$(1 - N) \times 100 = \left(1 - N_0\, e^{-(\sigma_{el}\, n_p)}\right) \times 100$$

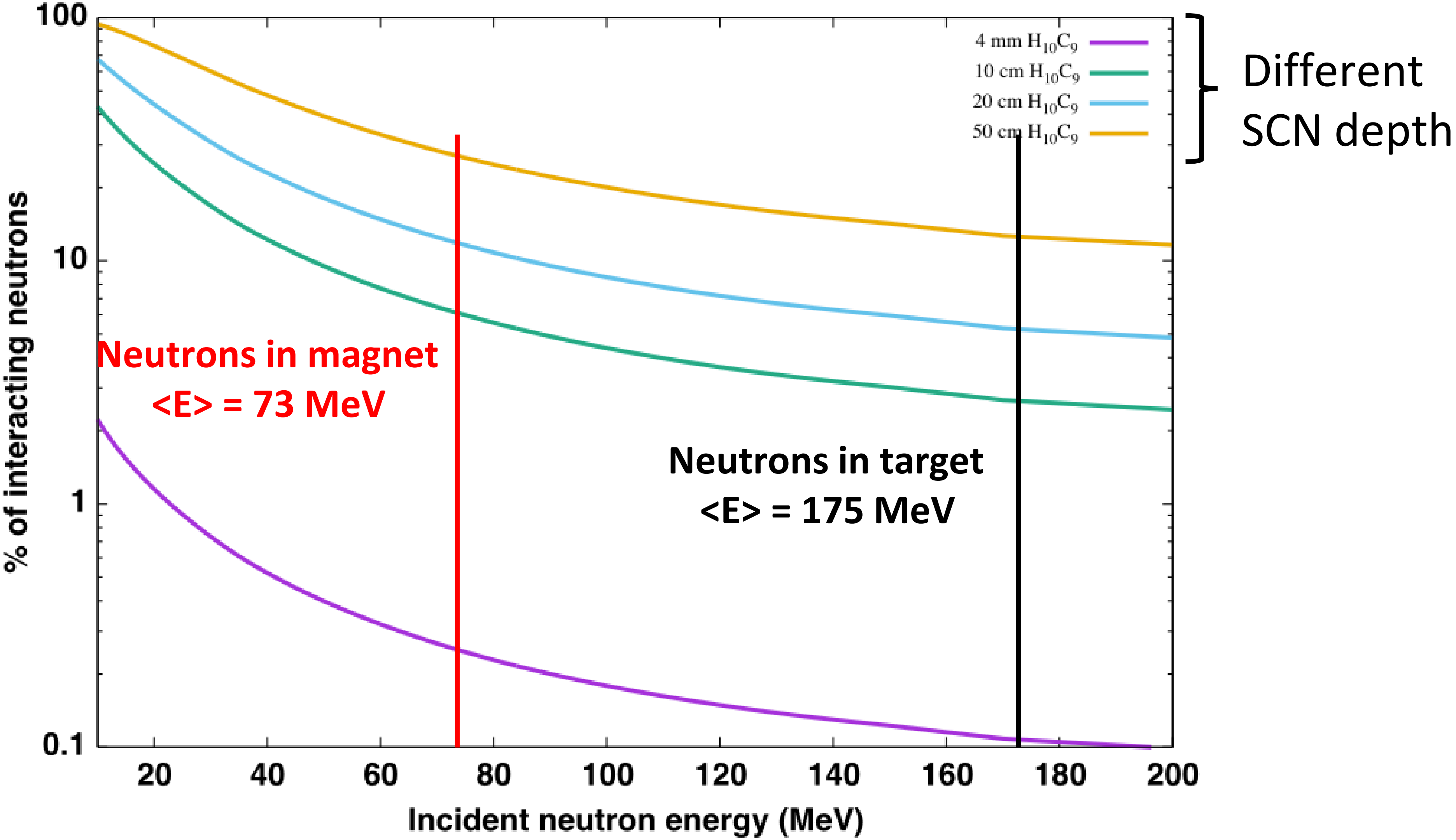
Neutrons elastic cross section

E (ev)	σ (barn)	E (ev)	σ (barn)	E (ev)	σ (barn)	E (ev)	σ (barn)
1000000.	4.258634	6000000.	1.424436	2.4000000E+07	0.3968942	8.0000000E+07	9.5312953E-02
1100000.	4.047134	6200000.	1.389067	2.5000000E+07	0.3795238	8.2000000E+07	9.2661671E-02
1200000.	3.862534	6400000.	1.355657	2.6000000E+07	0.3634735	8.4000000E+07	9.0174548E-02
1300000.	3.699234	6500000.	1.339636	2.7000000E+07	0.3478769	8.5000000E+07	8.8982753E-02
1400000.	3.553334	6600000.	1.323678	2.8000000E+07	0.3331329	8.6000000E+07	8.7822869E-02
1500000.	3.421934	6800000.	1.293022	2.9000000E+07	0.3194632	8.8000000E+07	8.5598052E-02
1600000.	3.302534	7000000.	1.263935	3.0000000E+07	0.3067523	9.0000000E+07	8.3492503E-02
1700000.	3.193434	7500000.	1.195935	3.2000000E+07	0.2837656	9.2000000E+07	8.1501983E-02
1800000.	3.093134	8000000.	1.134534	3.4000000E+07	0.2637287	9.4000000E+07	7.9618230E-02
1900000.	3.000334	8500000.	1.078634	3.5000000E+07	0.2547208	9.5000000E+07	7.8712352E-02
2000000.	2.914234	9000000.	1.027733	3.6000000E+07	0.2463217	9.6000000E+07	7.7830680E-02
2100000.	2.833934	9500000.	0.9810930	3.8000000E+07	0.2310516	9.8000000E+07	7.6139249E-02
2200000.	2.758835	1.0000000E+07	0.9381926	4.0000000E+07	0.2174195	1.0000000E+08	7.4532203E-02
2300000.	2.688335	1.0500000E+07	0.8986022	4.2000000E+07	0.2051533	1.0500000E+08	7.0844941E-02
2400000.	2.621935	1.1000000E+07	0.8619718	4.4000000E+07	0.1940759	1.1000000E+08	6.7572080E-02
2500000.	2.559235	1.1500000E+07	0.8279614	4.5000000E+07	0.1889184	1.1500000E+08	6.4671740E-02
2600000.	2.499935	1.2000000E+07	0.7963111	4.6000000E+07	0.1839921	1.2000000E+08	6.2092088E-02
2700000.	2.443635	1.2500000E+07	0.7667906	4.8000000E+07	0.1747990	1.2500000E+08	5.9774552E-02
2800000.	2.390235	1.3000000E+07	0.7391802	5.0000000E+07	0.1664175	1.3000000E+08	5.7691999E-02
2900000.	2.339336	1.3500000E+07	0.7133200	5.2000000E+07	0.1587586	1.3500000E+08	5.5816911E-02
3000000.	2.290736	1.4000000E+07	0.6890298	5.4000000E+07	0.1517245	1.4000000E+08	5.4121610E-02
3200000.	2.199936	1.4500000E+07	0.6661794	5.5000000E+07	0.1484164	1.4500000E+08	5.2582111E-02
3400000.	2.116636	1.5000000E+07	0.6446490	5.6000000E+07	0.1452254	1.5000000E+08	5.1181000E-02
3600000.	2.039836	1.5500000E+07	0.6243186	5.8000000E+07	0.1391786	1.7000000E+08	4.5181000E-02
3800000.	1.968636	1.6000000E+07	0.6050983	6.0000000E+07	0.1336154	2.0000000E+08	4.1181000E-02
4000000.	1.902436	1.6500000E+07	0.5868316	6.2000000E+07	0.1285076		
4200000.	1.840636	1.7000000E+07	0.5696374	6.4000000E+07	0.1237658		
4400000.	1.782836	1.7500000E+07	0.5531932	6.5000000E+07	0.1215146		
4600000.	1.728636	1.8000000E+07	0.5376673	6.6000000E+07	0.1193363		
4800000.	1.677536	1.8500000E+07	0.5227802	6.8000000E+07	0.1151904		
5000000.	1.629436	1.9000000E+07	0.5086862	7.0000000E+07	0.1113139		
5200000.	1.583581	1.9500000E+07	0.4951463	7.2000000E+07	0.1077032		
5400000.	1.540675	2.0000000E+07	0.4822960	7.4000000E+07	0.1043276		
5500000.	1.520236	2.1000000E+07	0.4581755	7.5000000E+07	0.1027133		
5600000.	1.499882	2.2000000E+07	0.4360451	7.6000000E+07	0.1011443		
5800000.	1.461022	2.3000000E+07	0.4156746	7.8000000E+07	9.8141886E-		

Thanks to Cristian Massimi

Neutrons elastic cross section

Thanks to Cristian Massimi



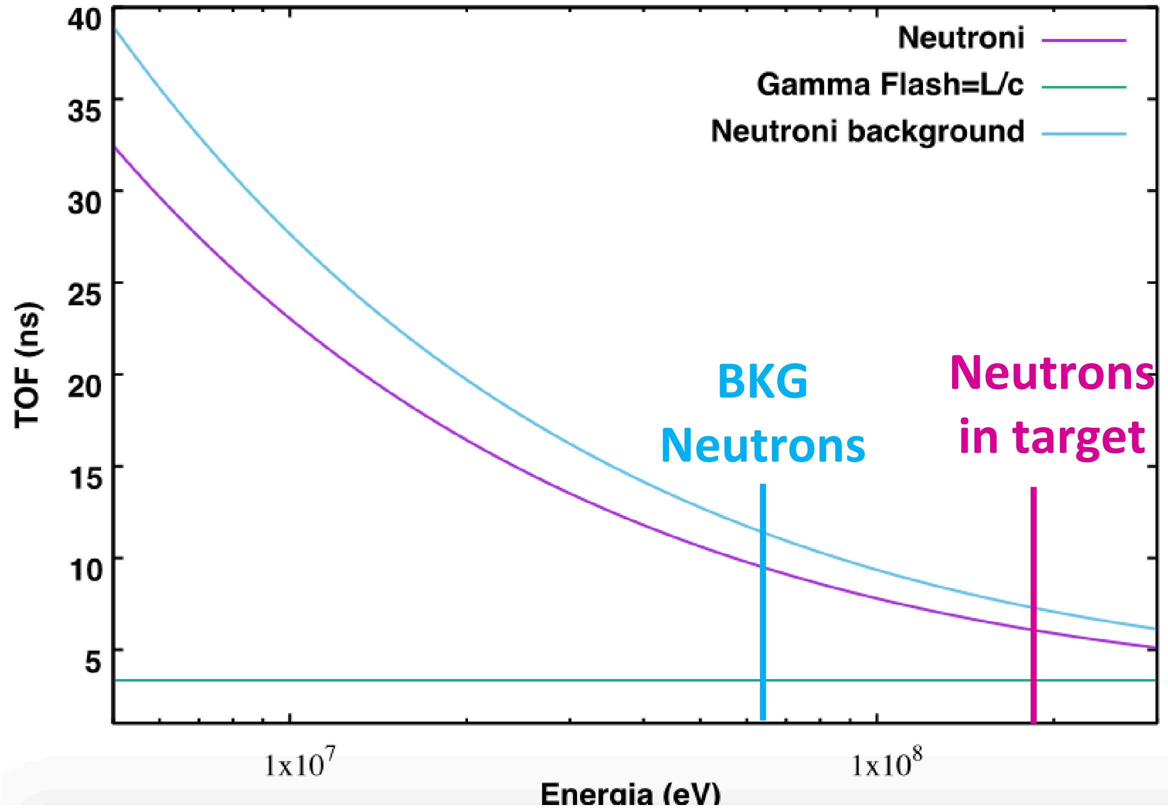
Percentage and Rate of interacting neutrons (200 MeV)

SCN depth (cm)	% interacting n from target <E> = 175 MeV	% interacting background n <E> = 73 MeV
0.4	0.12	0.29
10	2.95	6.90
20	5.82	13.32
50	13.92	30.04

Rate Hz	Rate Hz n from target	Rate Hz Background n	Sign/Bkg
DAQ (supposing to use FOOT)	1000	1000	
Fragmentation (1%)	10	10	
Produced neutrons	25.6	40.7	
Geometrical acceptance	4.9	0.64	
Interacting neutron on SCN 0.4 cm	$5.9\ 10^{-3}$	$1.9\ 10^{-3}$	3.1
Interacting neutron on SCN 10 cm	$1.4\ 10^{-1}$	$4.4\ 10^{-2}$	3.2
Interacting neutron on SCN 20 cm	$2.9\ 10^{-1}$	$8.5\ 10^{-2}$	3.4
Interacting neutron on SCN 50 cm	$6.8\ 10^{-1}$	$1.9\ 10^{-1}$	3.6

Supposing a SCN of 10 cm → **500 n/hour** with 30% of bkg

Neutrons Tof, 200 MeV



Thanks to Cristian Massimi

- neutrons from target travel 100 cm (<E> = 175 MeV) → Tof = 6.2 ns
- Background neutrons « » = 73 MeV) → Tof = 8.9 ns
- « » 120 cm 73 MeV) → Tof = 10.7 ns

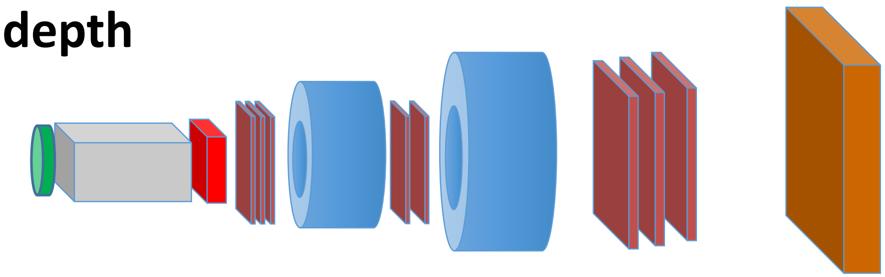
$<\Delta_{tof}>$ = 3-4 ns

Different Tof but not possible to disentangle signal from the bkg → bkg neutrons are mismatched for low energy neutrons from target

Conclusion

Studied a quasi-FOOT detector to measure the neutrons tof

- Take away the calorimeter
- Use the same scintillator with 10 cm depth



Neutrons/ ev

- 2.56 n/ev from fragmentation in target
  - 0.49 n/ev hit SCN (ε_{ACC} = 19.2%)
    - 0.014 n/ev make elastic scattering (ε_{INT} = 2.95%)

→ **500 n/h**

- 4.07 background neutrons expecially from the target
  - 0.064 n/ev hit SCN (ε_{ACC} = 1.6%)
    - 0.0044 n/ev make elastic scattering (ε_{INT} = 6.9%)

→ **160 n/h**

neutrons tof

- Neutrons from target: $\langle tof_f \rangle$ = 6.2 ns
- Bkg neutrons : $\langle tof_f \rangle$ = 8.9 ns

→ **Different tof but Not possible to disentangle**

Next step to analyze the data at 700 MeV/u

FOOT General Paper

First paper in FOOT (to be sent to NIM): «*Development and Characterization of a ΔE-TOF detector prototype for the FOOT experiment*» signed by all the collaboration

Important to have a general paper to be extracted from the CDR

Proposal: 1 paper from the CDR (hadrontherapy range energy 200 MeV/u)

- **the FOOT experiment:**
  - **Introduction;**
  - **Motivation;**
  - **Design criteria**
    - **Detectors description**
  - **Reconstruction Software;**
  - **Performances;**

- **Another paper at the radioprotection energies (700 MeV/U)**

Giuseppe contacted Marzio Nessi for JINST (Journal of Instrumentation) that allows to publish a very long article (40-50 pages)

FOOT General Paper

God new: we have the first paper in FOOT (to b sent to NIM):
«*Development and Characterization of a ΔE-TOF detector prototype for the FOOT experiment*» signed by all the collaboration

Important to have a general paper to be extracted from the CDR

Same possibility for **JINST** (Journal of Instrumentation), but better to contact Marzio Nessi

Giuseppe contacted the **Journal of Physics G** and **European Journal of Physics C** → possibility to publish paper of order of 40 pages

FOOT Papers from CDR

Possibility to extract two papers from the CDR:

- The FOOT detector
  - Detector description meaning :
    - chapter 3: Design criteria;
    - Chapter 4: Electronic detector Setup;
    - Chapter 5: Emulsion Chamber;
    - Chapter 6: DAQ and Trigger;
- The FOOT experiment
    - Chapter 1: Introduction;
    - Chapter 2: Motivation;
    - Chapter 7: Reconstruction Software;
    - Chapter 8: Performances;

Persons involved are at least the ones involved for the CDR