

Measurement of the neutron detection efficiency of the KLOE calorimeter

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Why neutrons at KLOE ?

- Detection of neutrons of 10^1 - 10^2 MeV traditionally performed with organic scintillators: efficiency scales with thickness \Rightarrow 1%/cm
- Use of high-Z material improves neutron efficiency

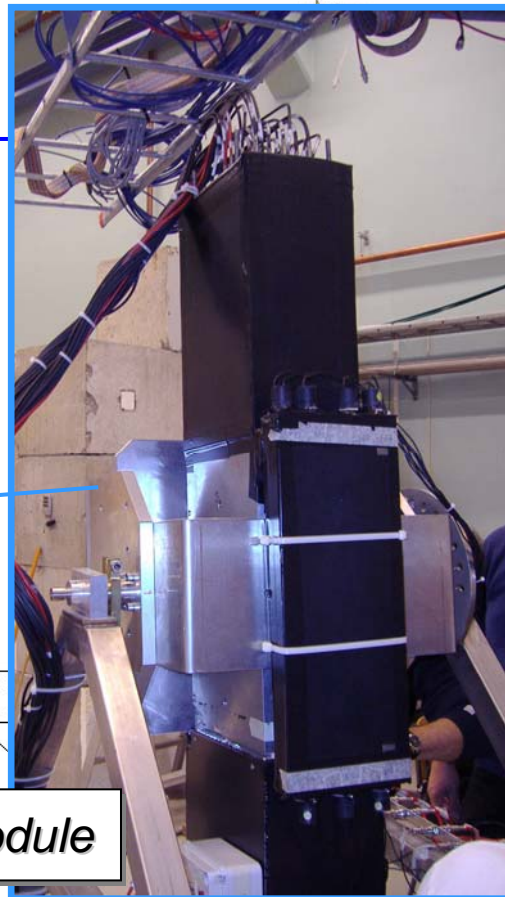
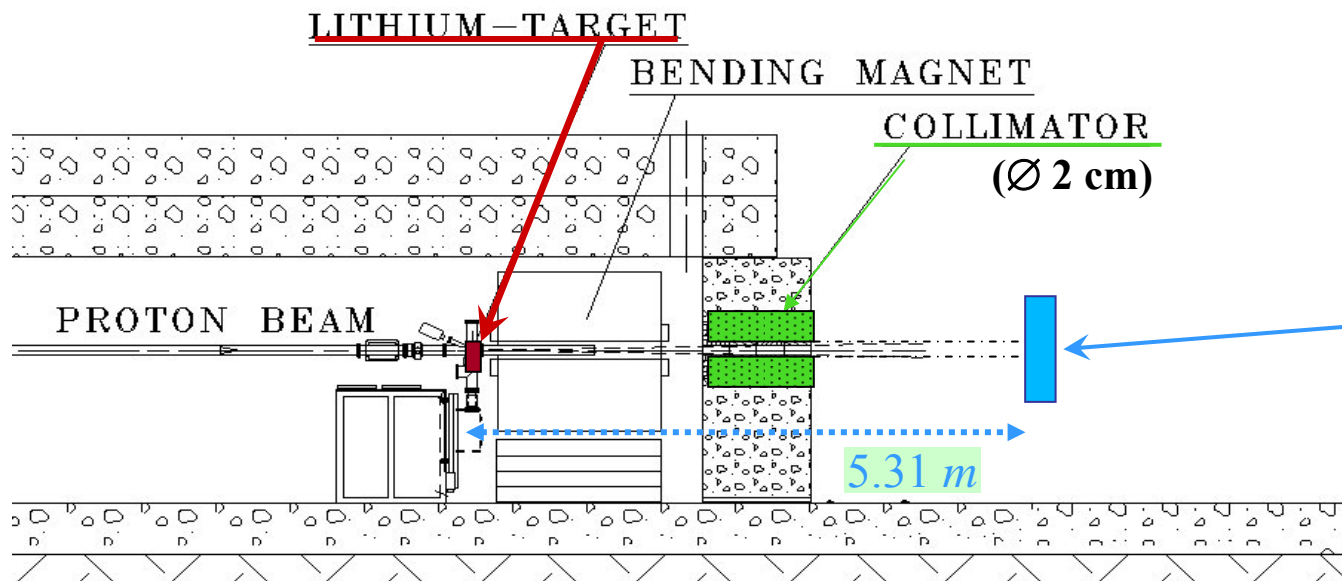
(C.Birattari et al., NIM A297 (1990) and NIM A338 (1994)

T.Baumann et al., NIM B192 (2002))

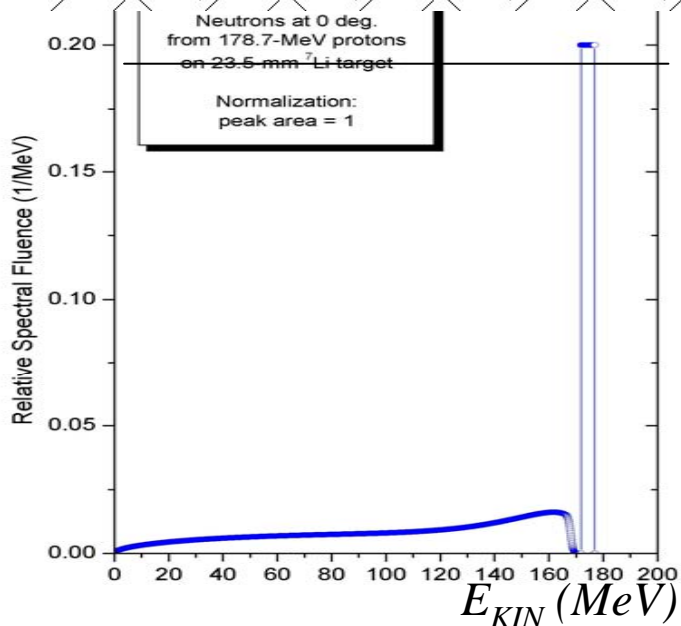
- Preliminary estimate with **KLOE data** (n produced by K^- interactions in the apparatus) showed **high efficiency (~40%)** for neutrons with $E_n < 20$ MeV, **confirmed by the KLOE MC**
- n detection is relevant for the **DAΦNE-2 program at LNF**; two proposals:
 - search for deeply bounded kaonic nuclei (AMADEUS)
 - measurement of the neutron time-like form factors (DANTE)

Tests have been performed with the neutron beam of the The Svedberg Laboratory in Uppsala (October 2006 and June 2007)

The neutron beam @ TSL

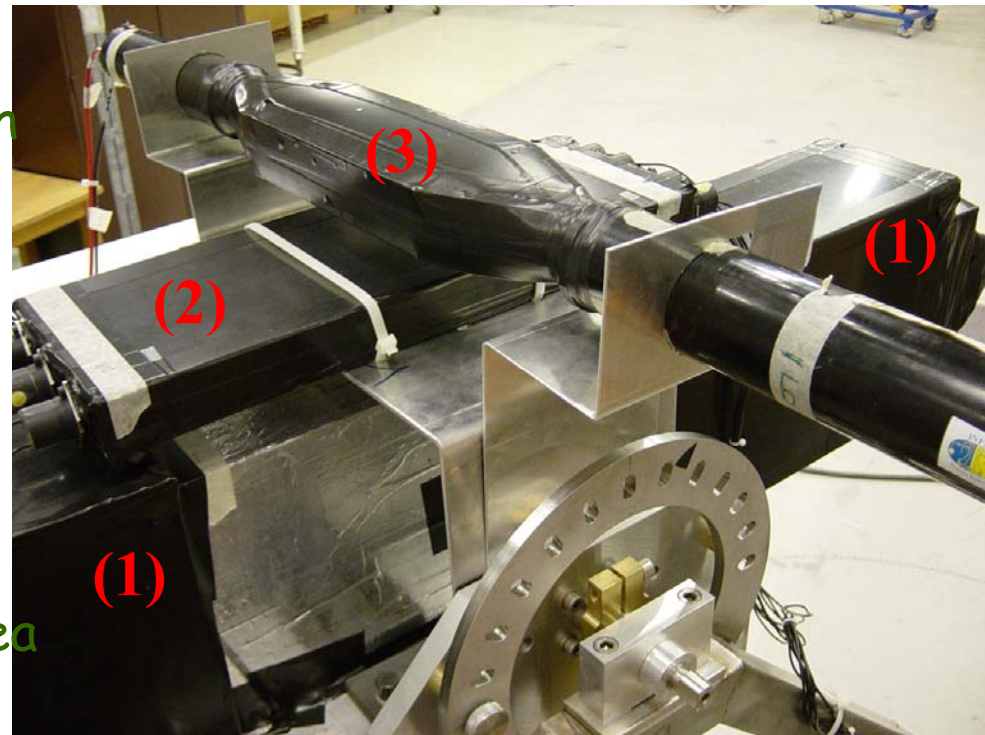


KLOE calorimeter module



- Neutrons produced in the reaction ${}^7\text{Li}(p,n){}^7\text{Be}$
- Proton beam energy from 180 MeV to \sim 20 MeV
- Neutron energy spectrum peaked at max energy (at 180 MeV \Rightarrow $f_p=42\%$ of n in the peak)
- Tail down to thermal neutrons

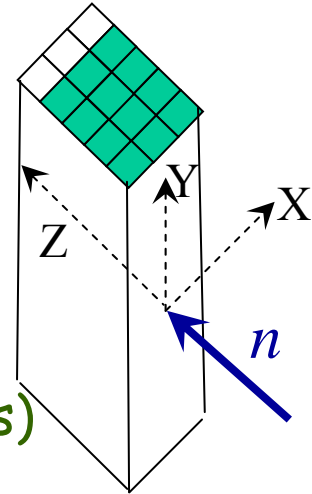
1. **KLOE EMC prototype:**
total length ~60 cm, 3×5 cells
(4.2 cm × 4.2 cm) read out at both
ends by Hamamatsu/Burle PMT's
2. **Beam Position Monitor:**
array of 7 scintillating counters
1 cm thick (removed in June '07)
3. **Reference counter :**
NE110; 5 cm thick; 10×20 cm² area
(June 2007 ⇒ two other NE110
counters 2.5 cm thick)



Everything is mounted on a rotating frame allowing for vertical (data taking with n beam) and horizontal (for calibration with cosmic rays) positions

Trigger:

- No neutron tagging available: self-triggering required
- **Scintillator trigger:** Side 1 - Side 2 overlap coincidence
- **Calorimeter trigger:** analog sum of the signals of the cells (4 or 5 planes out of 5) $\Rightarrow \Sigma_A \cdot \Sigma_B$ overlap coincidence
- Trigger signal is phase-locked with the RF signal (45 - 54 ns)



Acquired Data:

- For each configuration/energy: scans with different trigger thresholds
- Three data-sets:
 - $E_{\text{peak}} = 174 \text{ MeV}$ -- October 2006 - two weeks
 - $E_{\text{peak}} = 46.5 \text{ MeV}$ -- June 2007
 - $E_{\text{peak}} = 21.8 \text{ MeV}$ -- " } 4 days h24
- Typical run: 10^6 events - Max DAQ rate : 1.7 kHz (Simplified version of the KLOE experiment DAQ system (VME standard))

Global efficiency measurement: integrated over all the energy spectrum

$$\varepsilon = \frac{\text{Rate(trigger)}}{\text{Rate}(n) \cdot f_{\text{live}} \cdot \alpha}$$

f_{live} = fraction of DAQ live time

α = acceptance (assuming beam fully contained in the calorimeter surface $\Rightarrow \alpha \approx 1^*$)

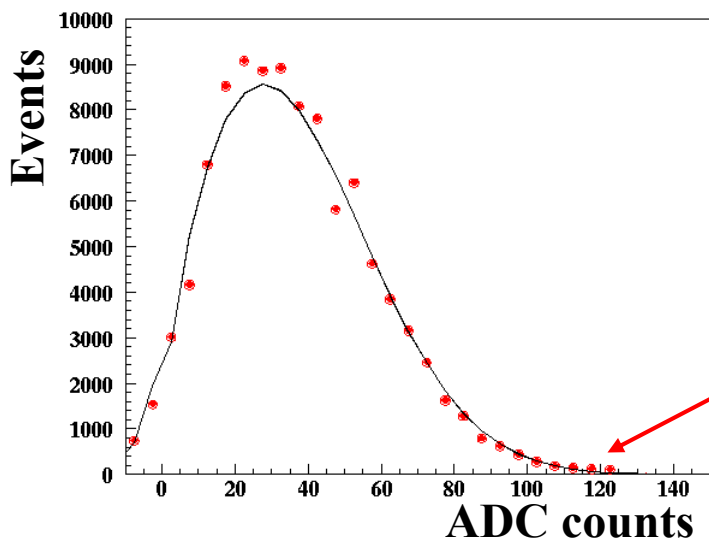
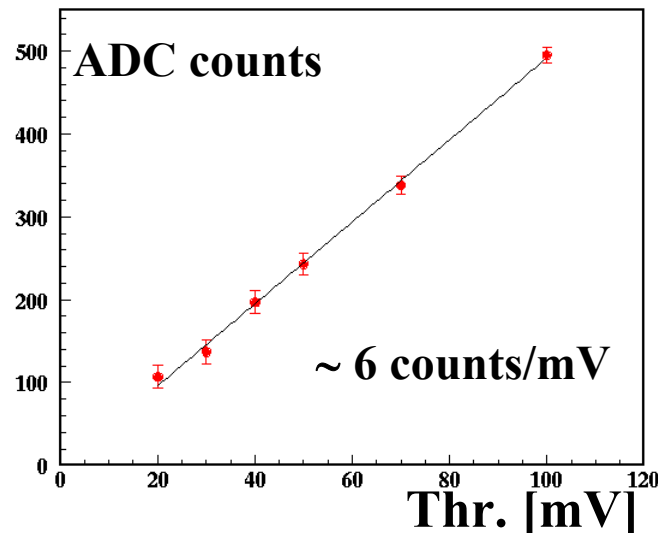
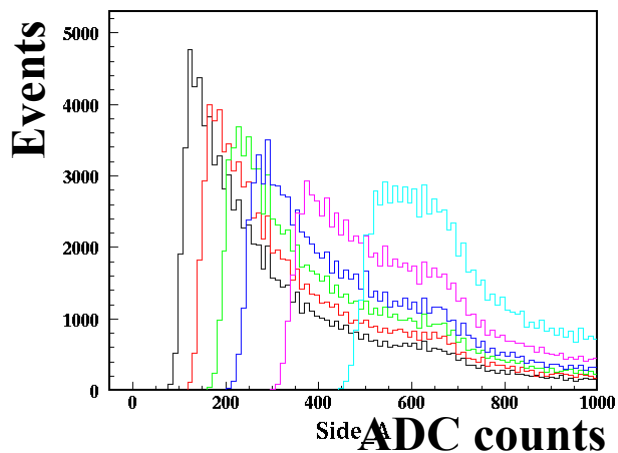
*At low energies: presence of Beam halo!
Evaluated through TSL off-beam counters

Absolute flux of neutrons measured after the collimator

- **2 monitors of beam intensity** (A.Prokofiev et al., PoS (FNDA2006)016):
 - Ionization Chamber Monitor (7 cm \varnothing): online monitor, not position sensitive
 - Thin-Film Breakdown Counter (1 cm \varnothing): offline monitor; used to calibrate the ICM by measuring the neutron flux at the collimator exit
- $\text{Rate}(n) = \text{Rate(ICM)} \cdot K \cdot \pi r^2 / f_p$
 - r = collimator radius (1 cm)
 - K = calibration factor (TFBC to ICM)
 - f_p = fraction of neutrons in the peak

\Rightarrow accuracy: 10% at higher peak energy (174 MeV)
20% at lower peak energy (22 - 46 MeV)

- Trigger threshold calibration in equivalent electron energy (MeV):



β source to set the energy scale in MeV:

^{90}Sr β^- endpoint = 0.56 MeV

^{90}Y β^- endpoint = 2.28 MeV

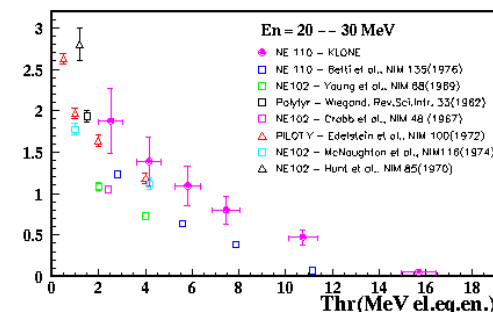
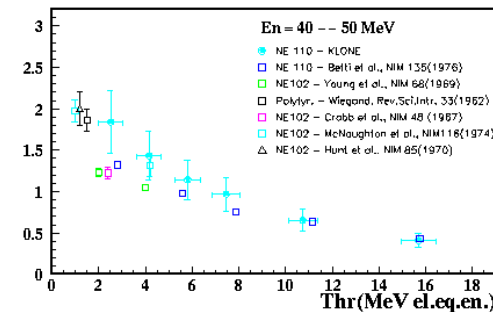
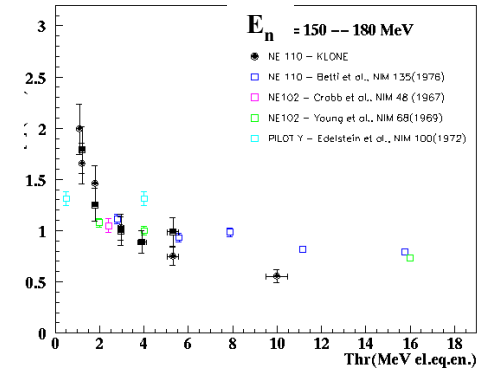
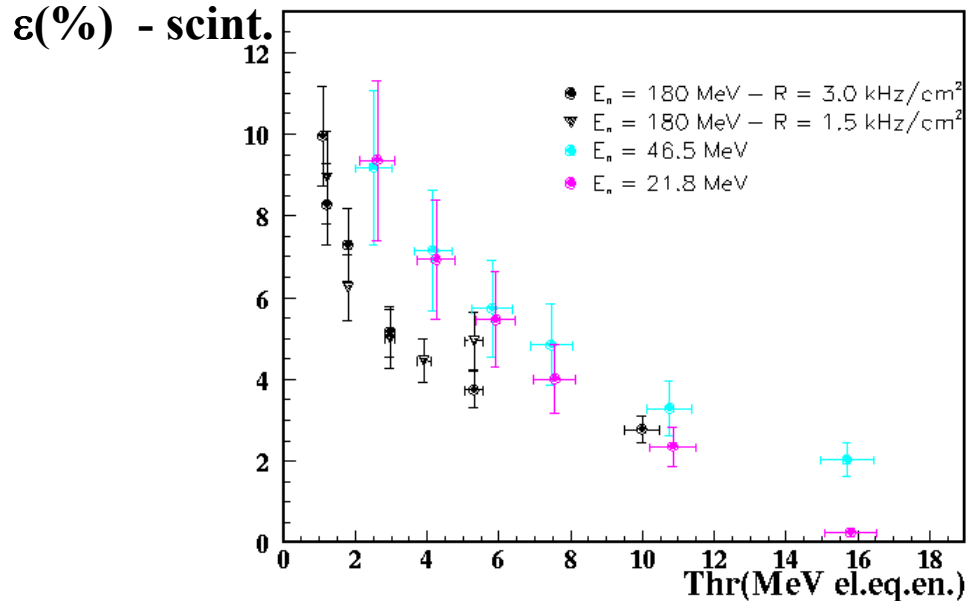
25 keV/ADC count

Thr. [mV]	20→100
Thr. [MeV]	2.5→15

Scintillator efficiency

- Agrees with the "thumb rule" (1%/cm) at thresholds above 2.5 MeV el.eq.en.

$\epsilon(\%)/\text{cm}$ of scintillator



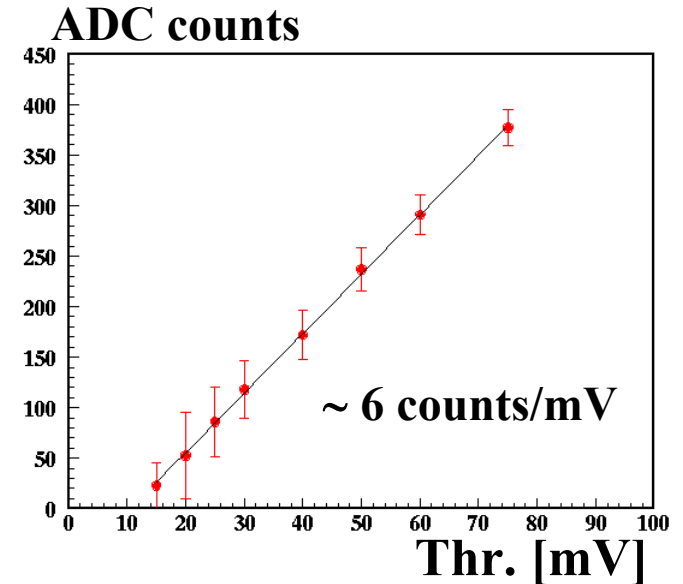
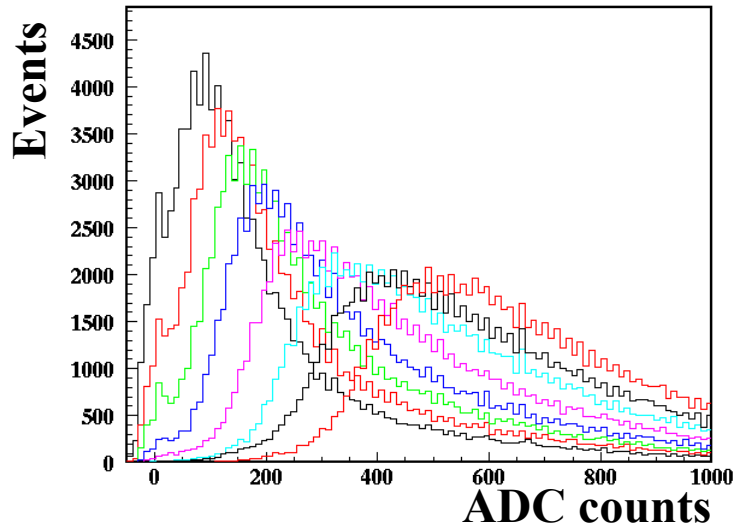
- Agrees with previous measurements in the same energy range after rescaling for the thickness

Larger errors at low energies due to:

- big uncertainty in the beam halo evaluation
- worse accuracy of the beam monitors

Correction factor for beam halo $\approx 0.9 \pm 0.1$

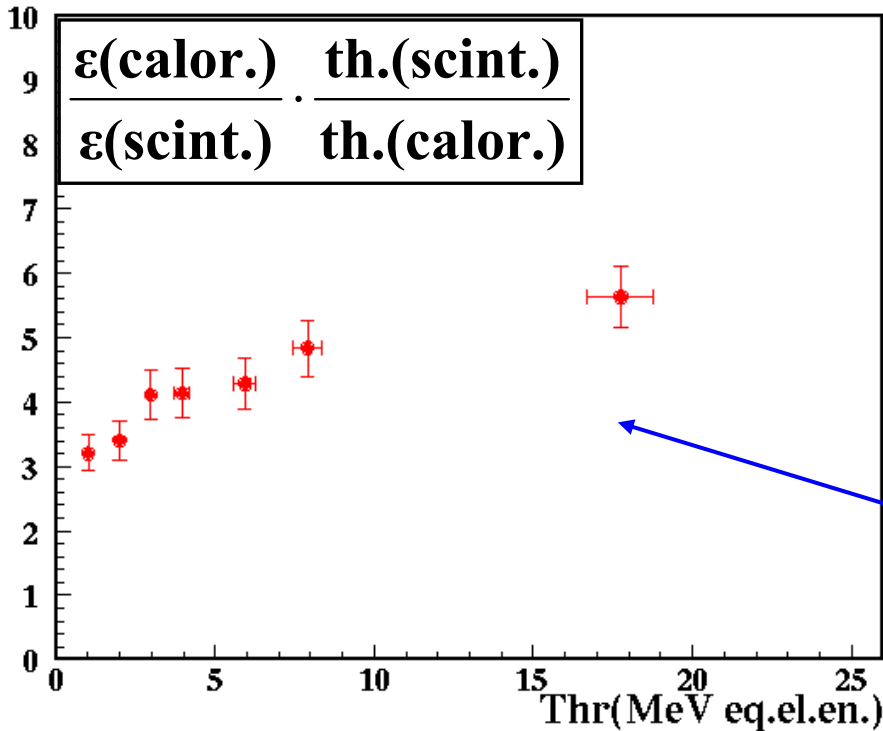
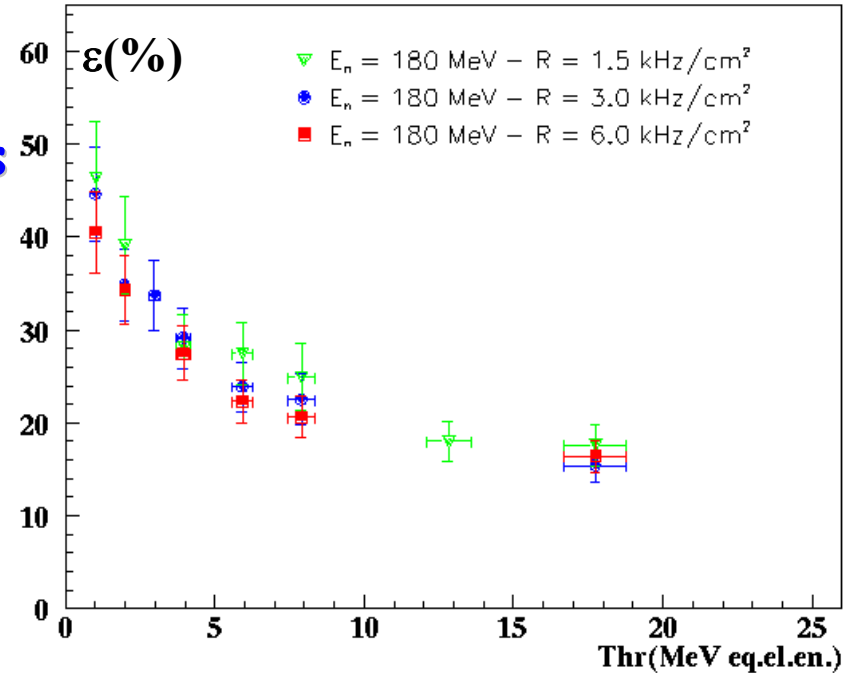
- Cell response equalization: MIP peak at ~ 550 ADC counts
- Trigger threshold calibration



Energy scale calibration with the MIP/MeV conversion factor from KLOE (1 MIP in one calorimeter cell ≈ 35 MeV eq. en.)
(KLOE Collaboration, NIM A354 (1995),352)

Thr. [mV]	15 \rightarrow 75
Thr. [MeV]	1.5 \rightarrow 23

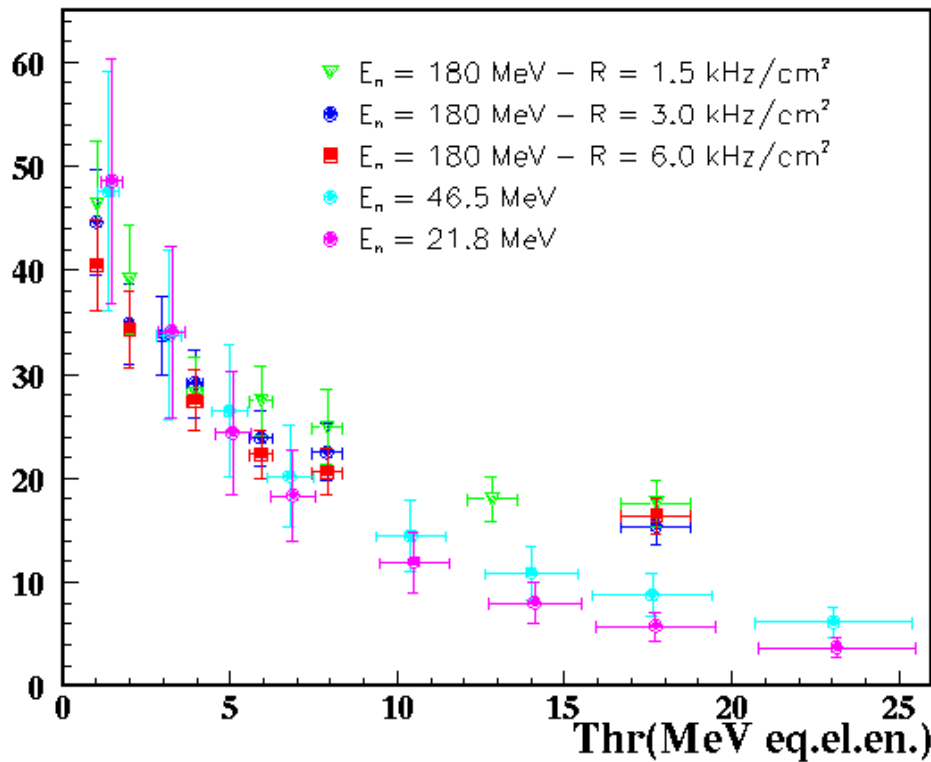
- **Very high efficiency** w.r.t. the naive expectation ($\sim 10\%$ @ 2 MeV thr.)
- **Stable for different run conditions**



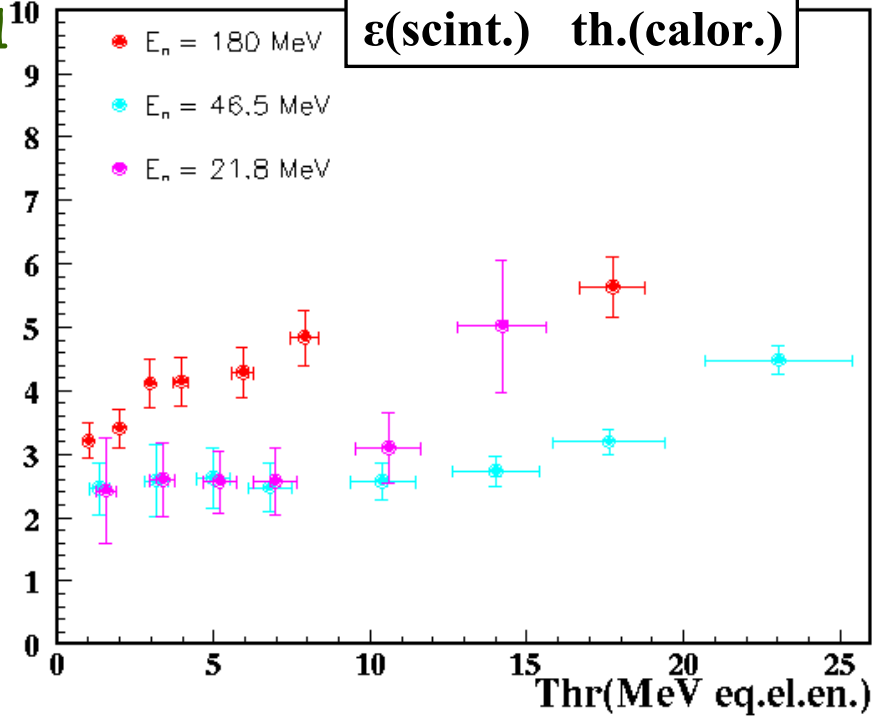
Comparison with our scintillator normalized to the same active material thickness

- **Very high efficiency**
- Agreement with the high energy measurements
- Correct. factor for beam halo $\approx 0.8 \pm 0.1$

$\epsilon(\%)$ - calorimeter



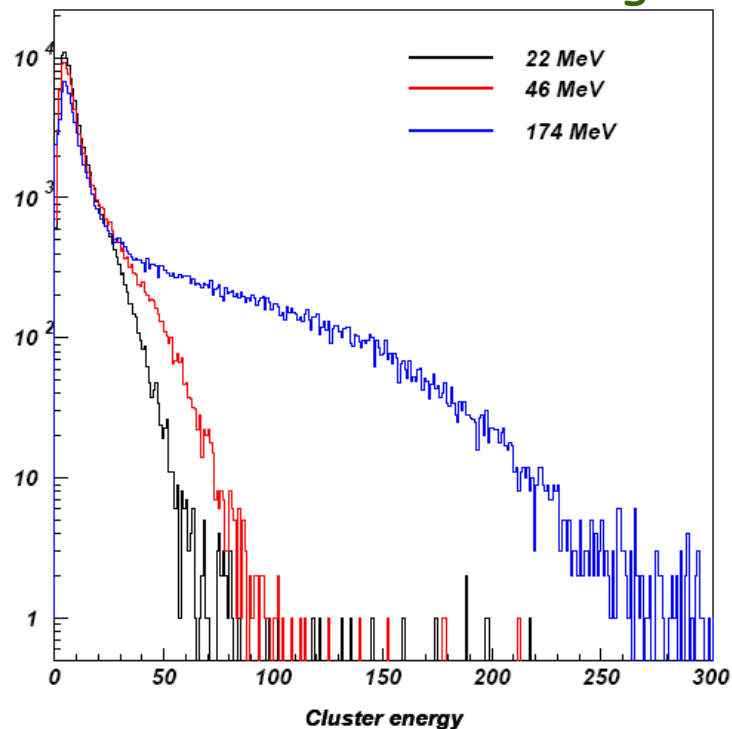
$$\frac{\epsilon(\text{calor.})}{\epsilon(\text{scint.})} \cdot \frac{\text{th.}(\text{scint.})}{\text{th.}(\text{calor.})}$$



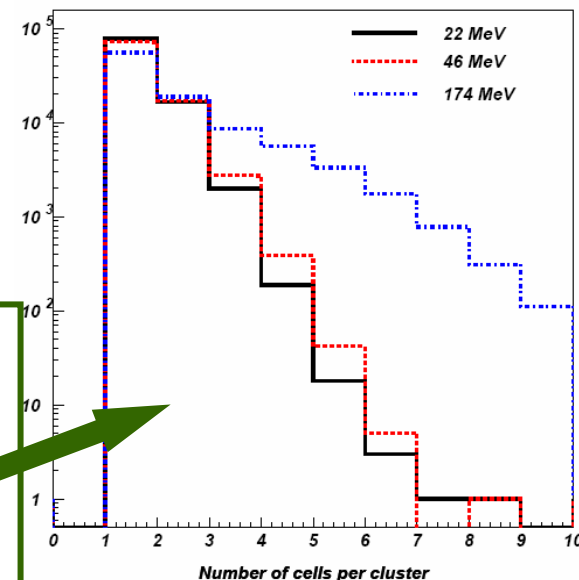
The ratio is almost independent from the halo
 (Ratio normalized to the same active material thickness)

Events' anatomy

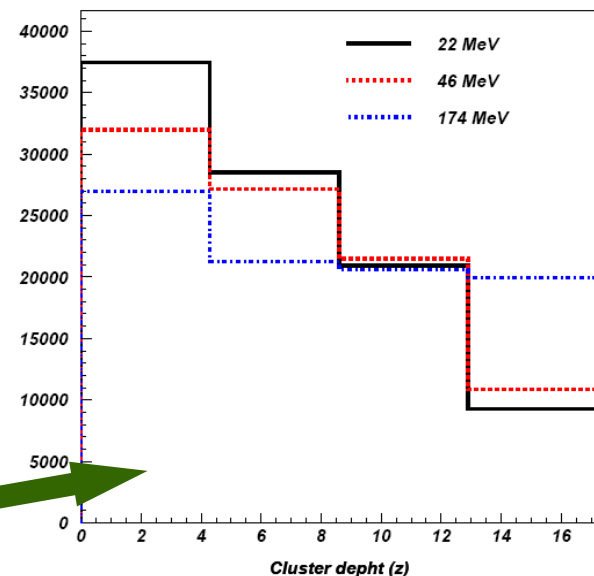
Energy deposited by neutrons for the three beam energies

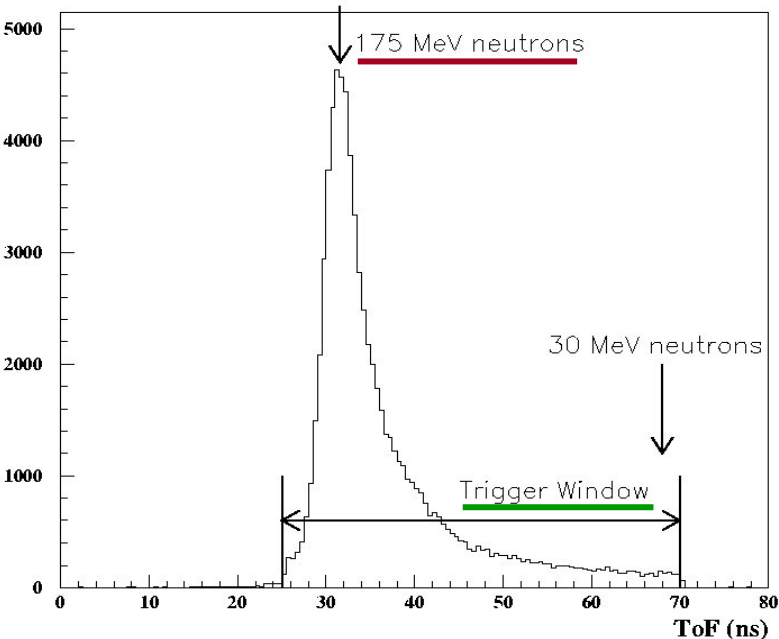


Number of cells per neutron cluster increases with beam energy



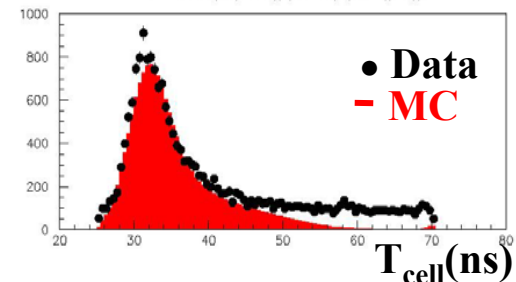
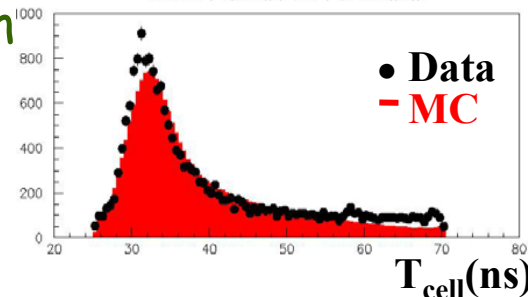
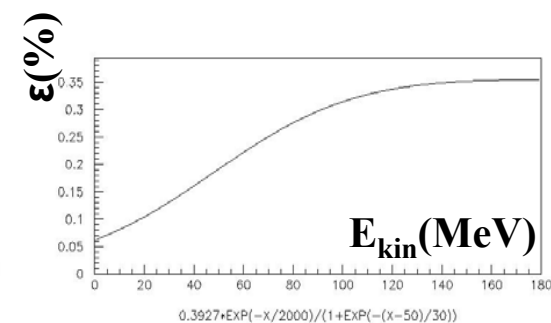
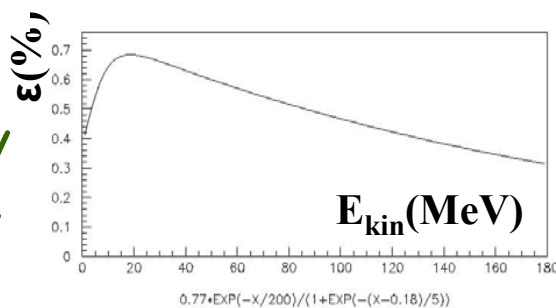
Position of neutron clusters in the calorimeter along the forward direction



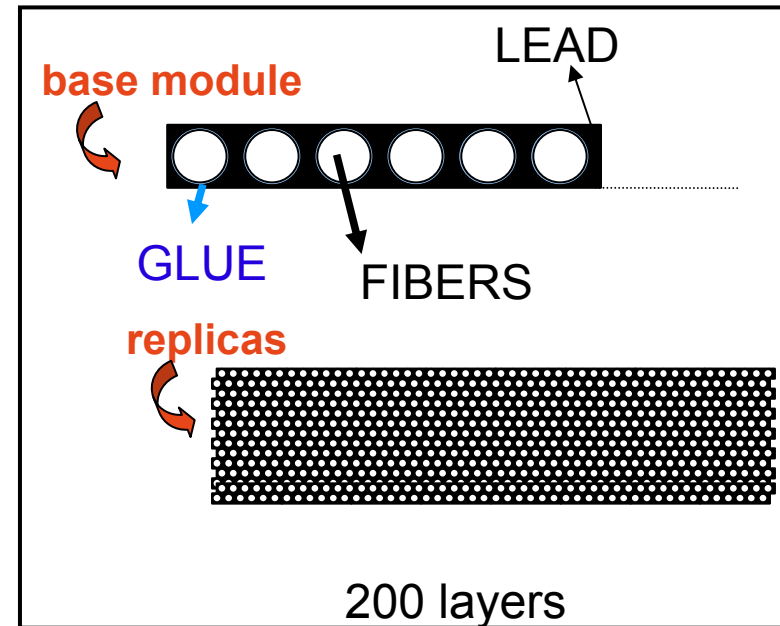


Energy spectrum can be related to Time Of Flight

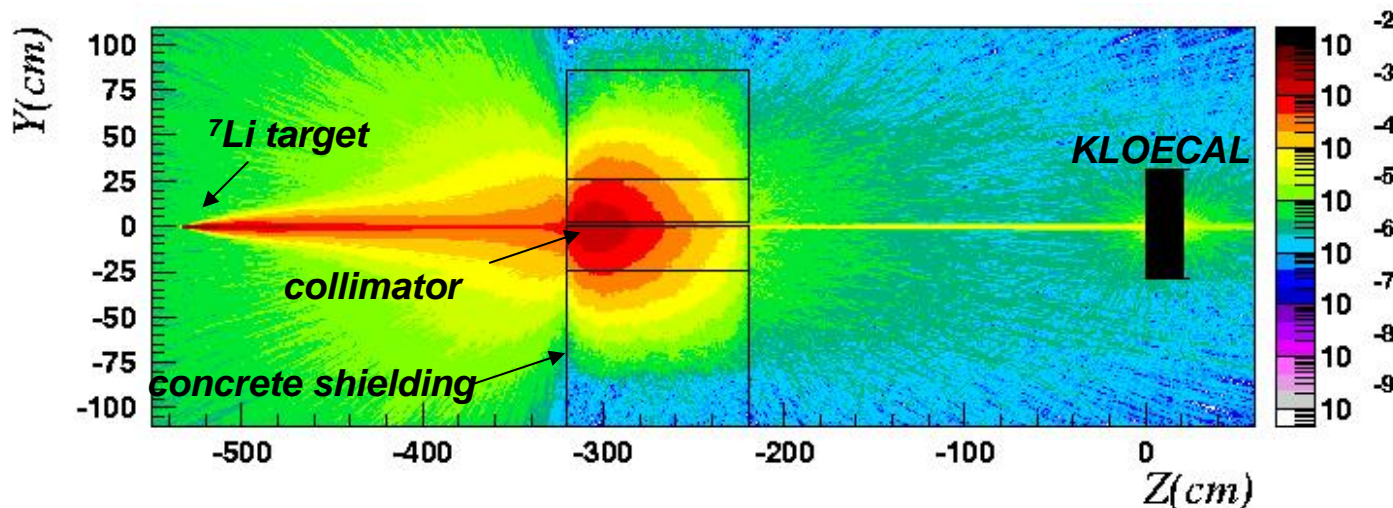
Fast MC to test the sensitivity of the time distribution to the shape of the efficiency curve shows better agreement with an efficiency decreasing with energy

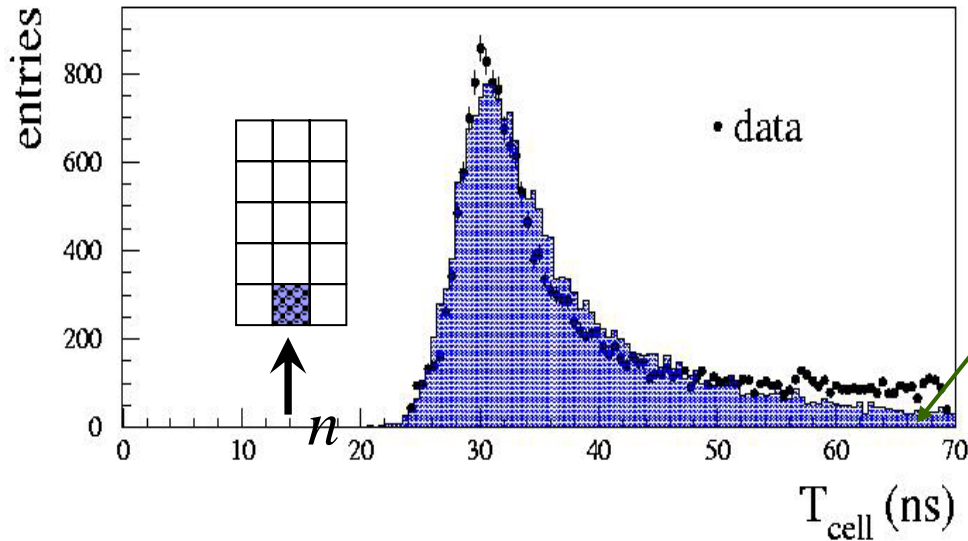


A detailed simulation of the calorimeter structure and of the beamline (source, collimator and concrete shielding) has been carried out with the **FLUKA Code**



Neutron fluence along the beamline ($n/cm^2/29000n$)

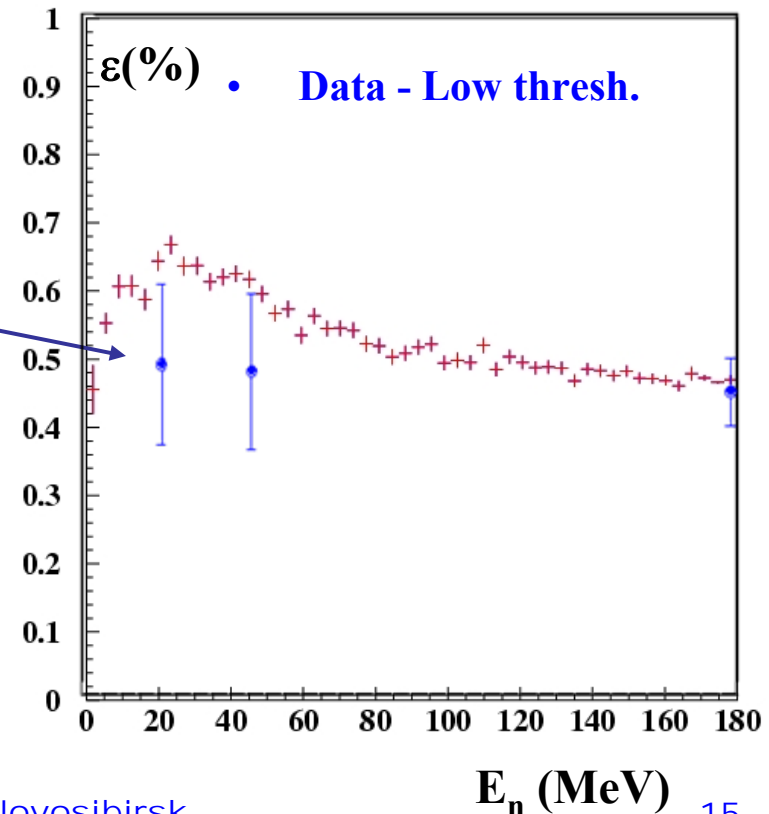




Some discrepancy in the low energy part of the spectrum

- No cut in released energy
 - No trigger simulation
- ⇒ Upper limit on ε

Efficiency enhancement appears to be due to the large inelastic production of secondary neutrons in Pb.



- The first measurement of the detection efficiency for neutrons of 20 - 180 MeV of a high sampling Pb-sci.fi. calorimeter has been performed at the The Svedberg Laboratory in Uppsala.
- Measurement of the n efficiency of a NE110 scintillator agrees with published results in the same energy range.
- The KLOE calorimeter efficiency, integrated over the whole neutron energy spectrum, ranges between 30-50 % at the lowest trigger threshold.
- Estimate of beam halo, the main source of uncertainty at low energies, is being carried on, also with further tests at TSL which are foreseen to better understand the halo.

Spares

Preliminary results of MC

- Simulated neutron beam: $E_{kin} = 180 \text{ MeV}$
- Each primary neutron has a high probability to have elastic/inelastic scattering in Pb



target	$P_{el}(\%)$	$P_{inel}(\%)$
Pb	32.6	31.4
fibers	10.4	7.0
glue	2.3	2.2

- On average 5.4 secondaries per primary neutron are generated, counting only neutrons above 19.6 MeV.

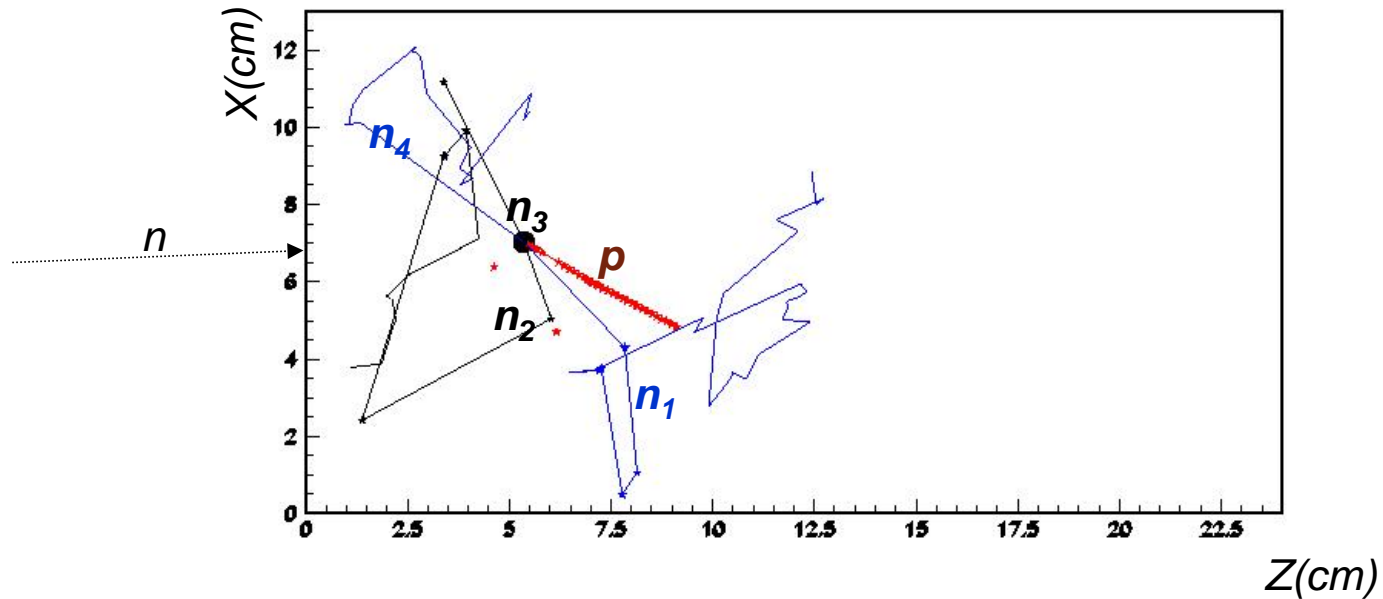


Neutrons above 19.6 MeV	62.2%
photons	26.9%
protons	6.8%
He-4	3.2%
deuteron	0.4%
triton	0.2%
He-3	0.2%

- Secondaries created in interactions of low energy neutrons (below 19.6 MeV) are - on average - 97.7 particles per primary neutron.



neutrons	94.2%
protons	4.7%
photons	1.1%



- The enhancement of the efficiency appears to be due to the large inelastic production of neutrons in Pb. These secondary neutrons:
 - are produced isotropically;
 - are associated with a non negligible fraction of e.m. energy and of protons, which can be detected in the nearby fibers;
 - have low energy and then have a large probability to do new interactions in the calorimeter with neutron/proton/ γ production.

- TSL beam experts measured a sizeable beam halo at low peak energy (21.8 and 46.5 MeV):
 - TFBC scan of the area near the collimator
 - integrated flux over the ICM area ~ 5% of the "core" flux (with large uncertainty)
 - halo shape also measured
- Confirmed by our background counters
- Our calorimeter is larger than the projection of ICM area
- By integrating over the calorimeter we obtain an estimate of the halo contribution to the trigger rate of $(20 \pm 10)\%$
- Only 10% on the reference scintillator due to the smaller area