



SATIF-17

17th Workshop on Shielding Aspects of Accelerators, Targets, and Irradiation Facilities
IBS Science Culture Center of Daejeon, South-Korea



Performances of the novel "TetraBall" single moderator neutron spectrometer at CMS from the analysis of 2025 and 2026 data

Marco Costa

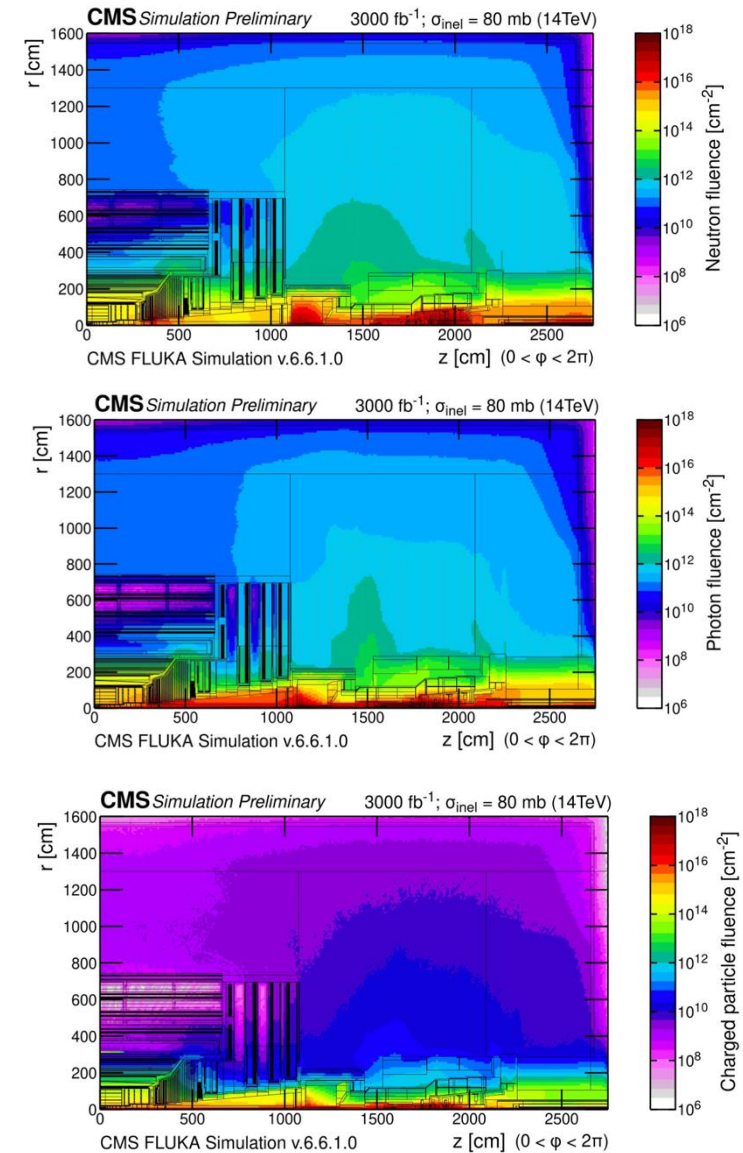
(University of Turin and INFN)
on behalf of **CMS Collaboration**

October 21-st, 2026

Neutron Radiation Monitoring (NRM) at CMS is coordinated by **BRIL- Beam Radiation, Instrumentation, and Luminosity group**

Main goals of Phase II Neutron Radiation Monitoring for the CMS cavern

- Provide real time measurements in the HL-LHC radiation environment
- Validation of the FLUKA estimates that are used to predict damage to electronics; activation; background in detectors
- Central CMS regions are well modelled and benchmarked in Phase-1 FLUKA, while uncertainties increase in the more coarsely modelled **outer cavern**
- The outer cavern (OC) radiation field is dominated by neutrons covering a large energy range (**thermal–GeV**)
- General strategy OC: Compare simulations with measurements from a network of monitors with differing response functions allowing discrepancies to be linked to specific neutron energy ranges
- **A dedicated CMS-maintained neutron monitoring system that provides broad energy range and spatial coverage is needed** to complement fixed monitors maintained by the CERN radiation protection groups



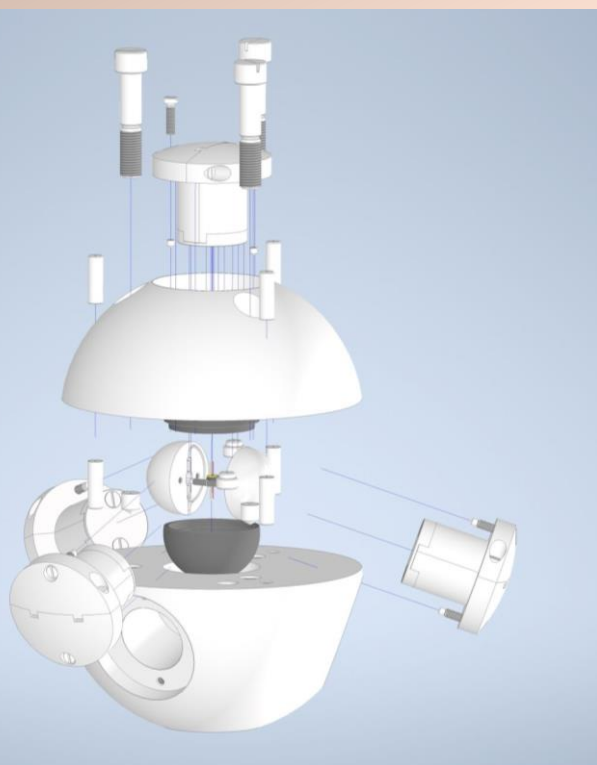
- Sensitive to **neutrons from meV to GeV**
- Able to operate in **single exposure mode**
- **Insensitive to gammas and to charged hadrons**
- **Tolerant to radiation and magnetic field**
- **Portable** in order to map different locations in UXC

Need for a Novel Design of a
Single Moderator Neutron Spectrometer:
“THE TETRABALL” (*)

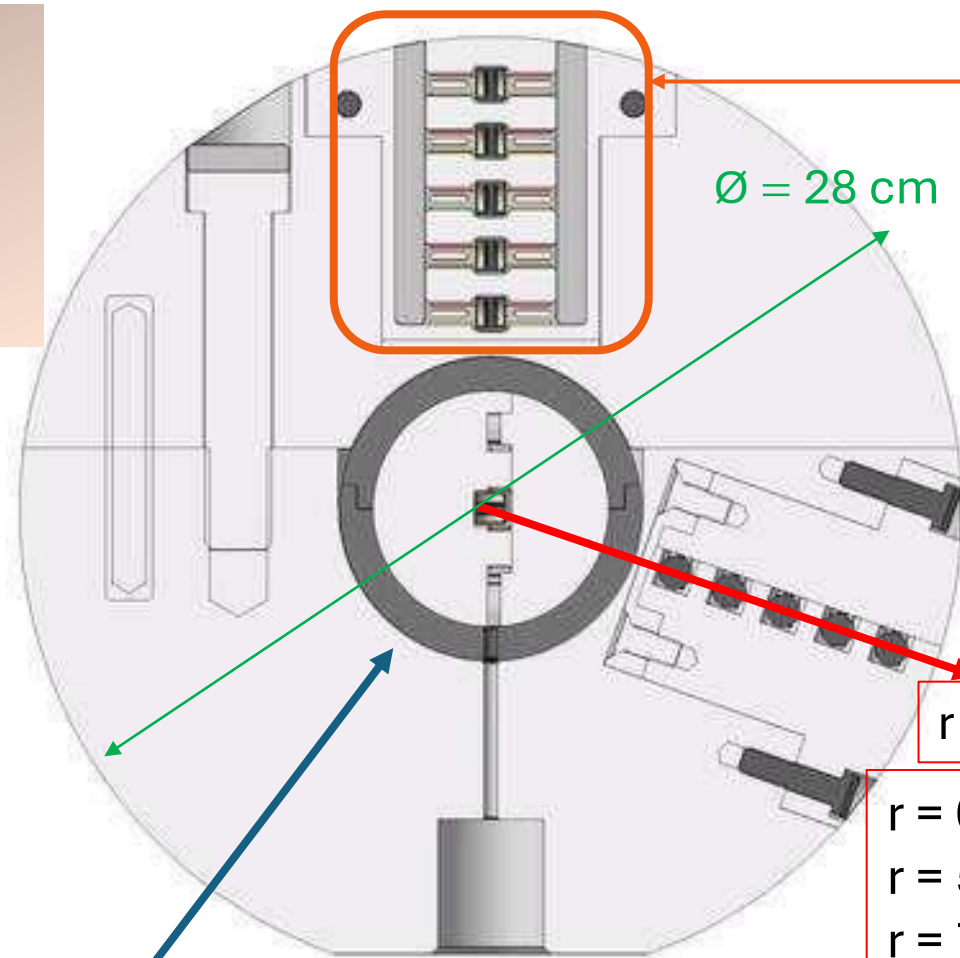
(*) <https://doi.org/10.1140/epjp/s13360-024-05949-8>

(*) <https://doi.org/10.1016/j.nima.2024.169805>

It condenses the property of several Bonner Sphere Spectrometer in a single moderator with tetrahedral geometry



(@credits INFN-LNF Mech. service)



HDPE moderator with **a one-cm lead insert** for high-energy neutrons

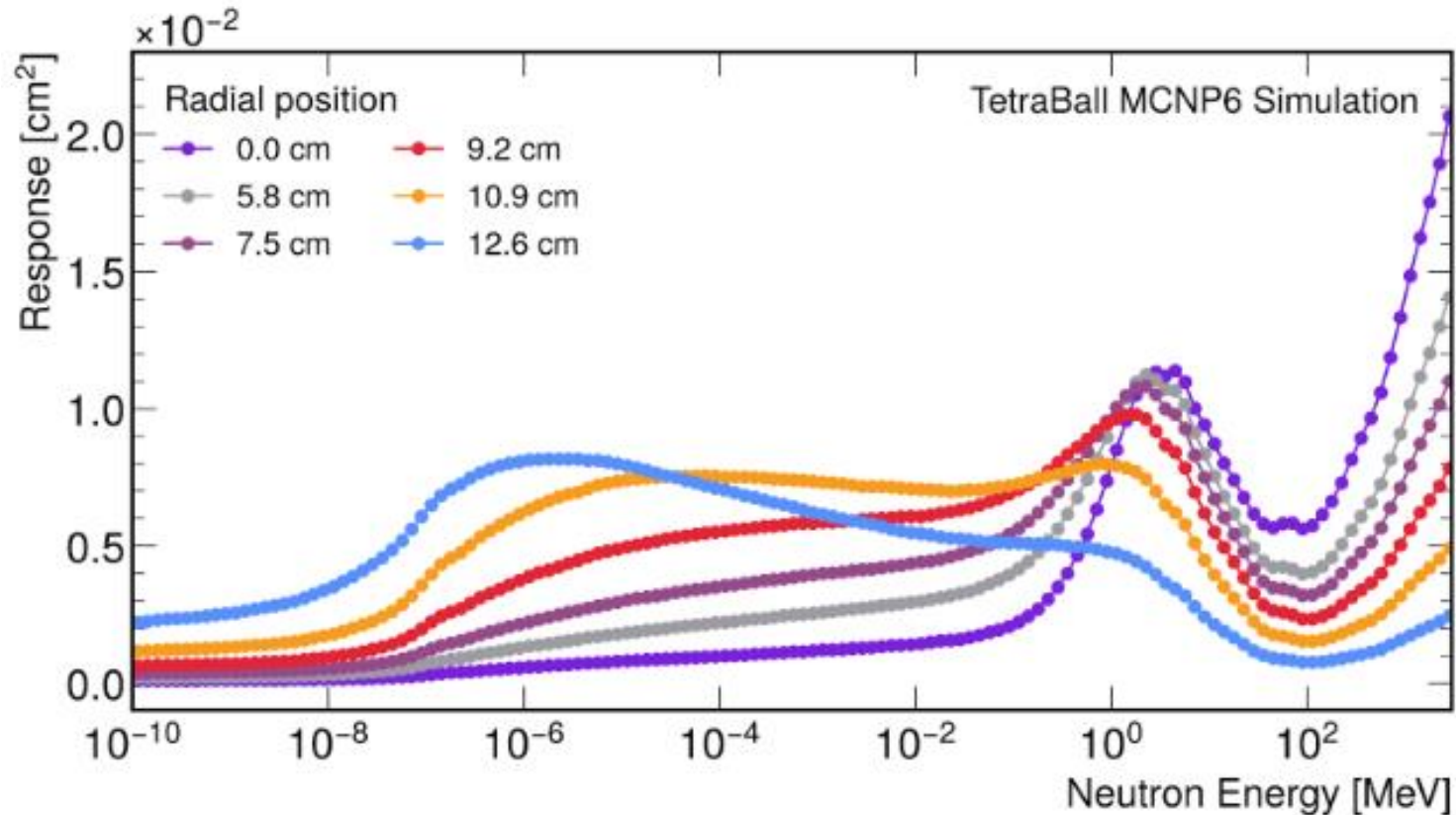
- Detectors allocated in 4 identical “ARMS” (5 pairs each) + 1 central pair
- **Isotropic response** by averaging detectors at the same radius
- Unfolding process to infer the spectrum starting from:
 - Det count
 - Response matrix
 - Guess spectrum

$r = 0 \text{ cm}$
 $r = 5.5 \text{ cm}$
 $r = 7.25 \text{ cm}$
 $r = 9 \text{ cm}$
 $r = 10.75 \text{ cm}$
 $r = 12.5 \text{ cm}$

Detector radial positions optimized with MCNP simulations (<https://mcnp.lanl.gov>)

MCNP Simulations to define the TetraBall Response Matrix

Proving that TetraBall responds from thermal to GeV



- Every irradiation geometry has (virtually) a different response matrix
- This plot: isotropic irradiation

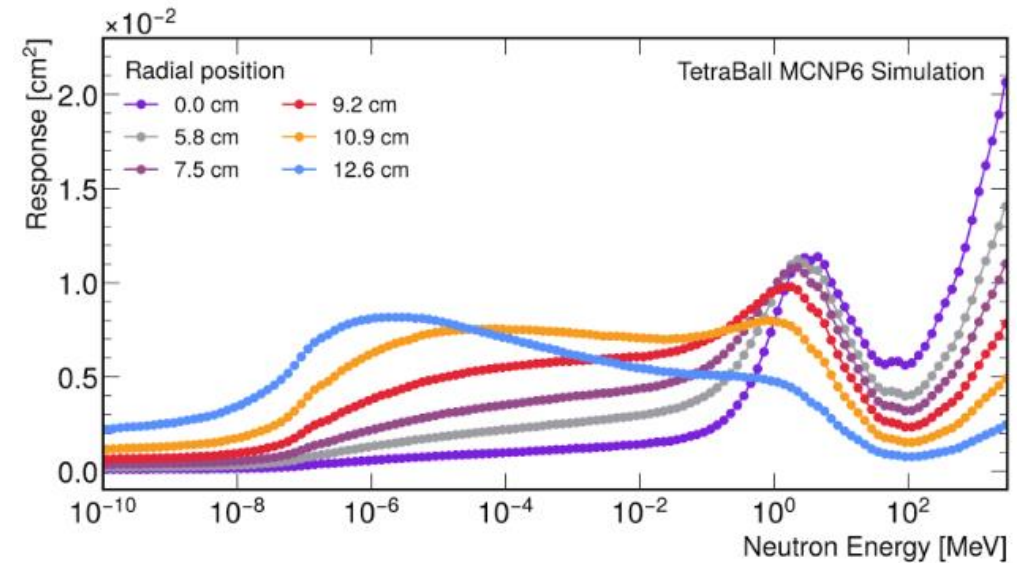
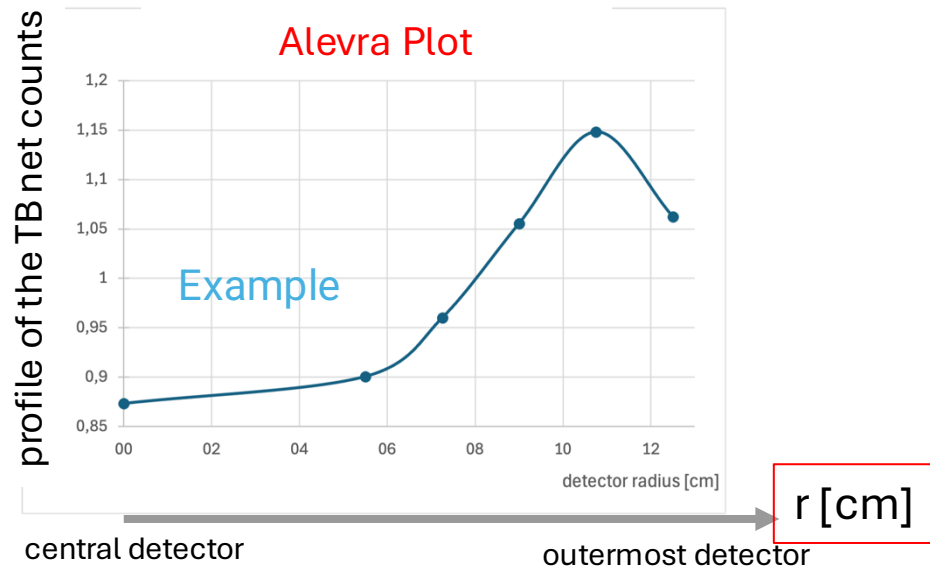
Response Matrix to be validated in a reference field (calibration)

TetraBall energy response functions, one for each radial position. Each point represents the response of the detectors at a specific radial position to neutrons of specific original incident energy, and it is given in units of detected neutrons per unit incident neutron fluence. The radial position at 0.0 cm corresponds to the central detector pair. The other response functions are obtained averaging the response of detector pairs at the same radial positions.

TetraBall SMNS working principles

to infer the neutron spectrum

TetraBall Measurement provide radial counts profile



Average detector
counts at a given
radial position

$$C_i = \sum_{j=0}^n R_{ij} \Phi_j$$

Response matrix

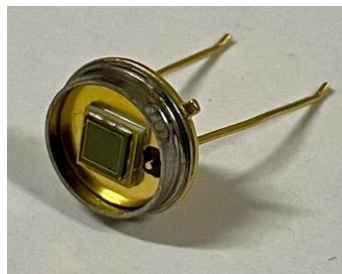
i = detector radial position
 j = energy bin ($n = 140$)

Φ_j = neutron fluence in the bin j

“UNFOLDING” → “trial and error” process or by a priori information (guess spectrum)

It consists of 42 SiC detectors organized in 21 pairs (4x5+1), 1 pair = (1 ^6LiF -coated SiC) & (1 uncoated SiC)

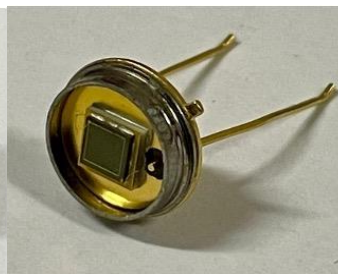
SiC



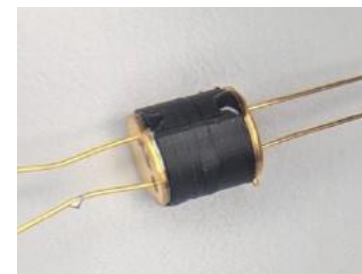
^6LiF coating



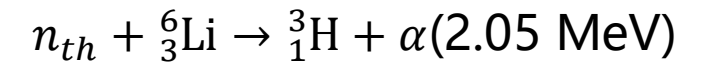
SiC



SiC "pair"



Conversion reaction:



Enriched 95% ^6Li powder by Sigma-Aldrich

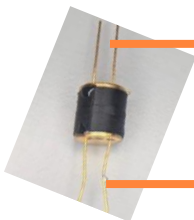
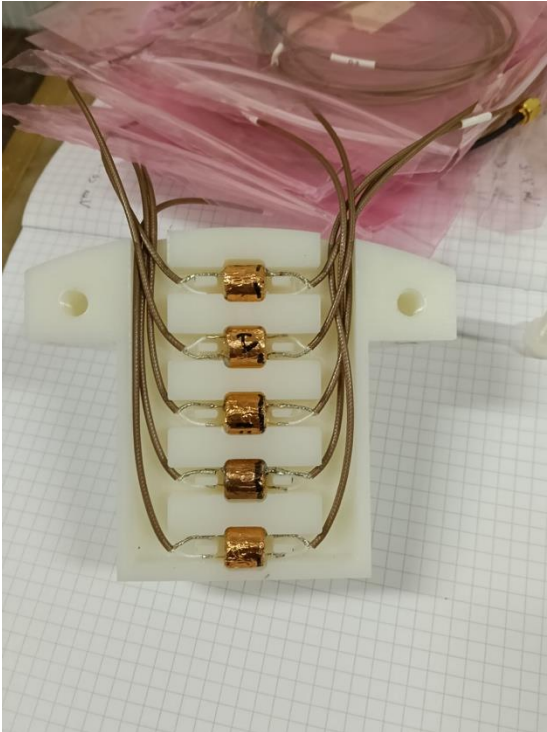
- SiC diodes chosen for their radiation hardness
 - tested @ TRIGA reactor (LENA, Pavia) up to $5\text{E}+13 \text{ cm}^{-2}$
 - **7.6 mm²** sensitive area (expected SiC rate @LHC few to 10 Hz)
 - Dual detector to work in a mixed field
- Net counts = ^6LiF coated SiC counts - bare SiC counts**
- 12V reverse bias: 3 μm depletion layer
(intrinsically insensitive to gamma and charged hadrons)

Detector quality control:

- Diode characterization in Torino with probe station (CV-IV curves) -> extremely uniform
- **SiC+ ^6LiF** characterized at LNF (Hotnes AmB – ENEA)
-> they work as single TND
- “ARM” Characterization in thermal neutron field in Torino (LINAC based)

Cabled SiC pairs are tested in a thermal neutron field and then assembled in the TetraBall arms at INFN

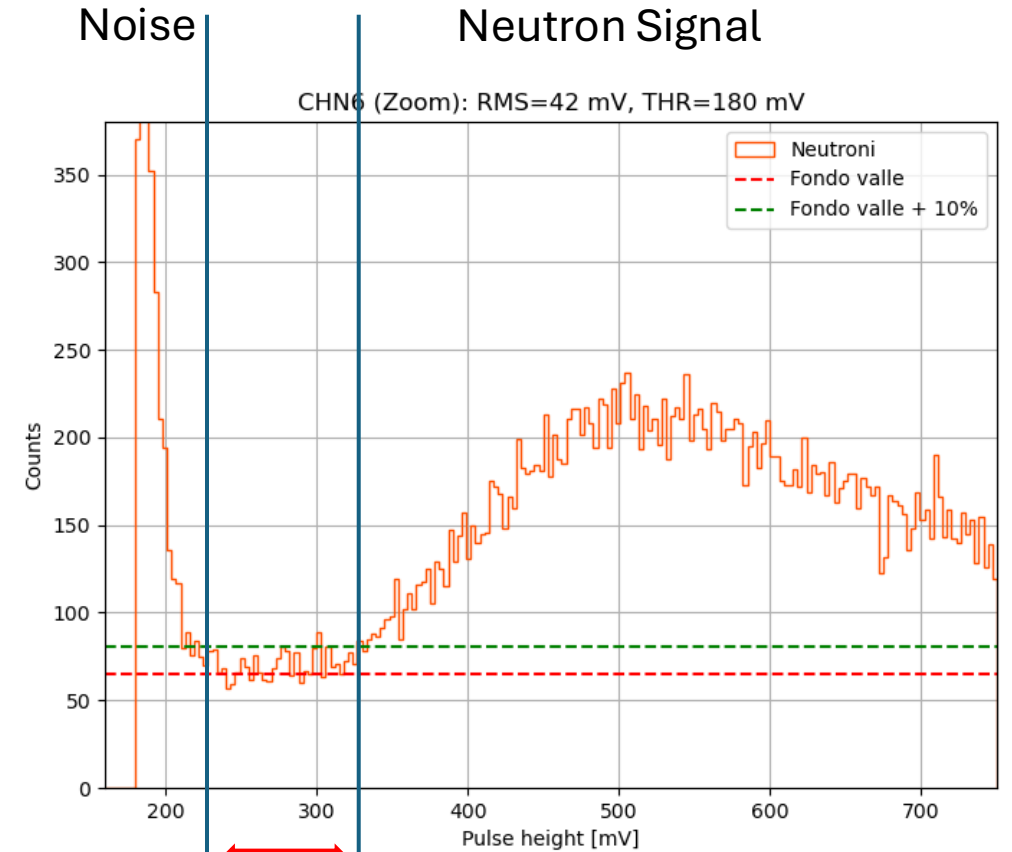
single arm



Coax cables RG178B/U,
1.8mm, 50ohm

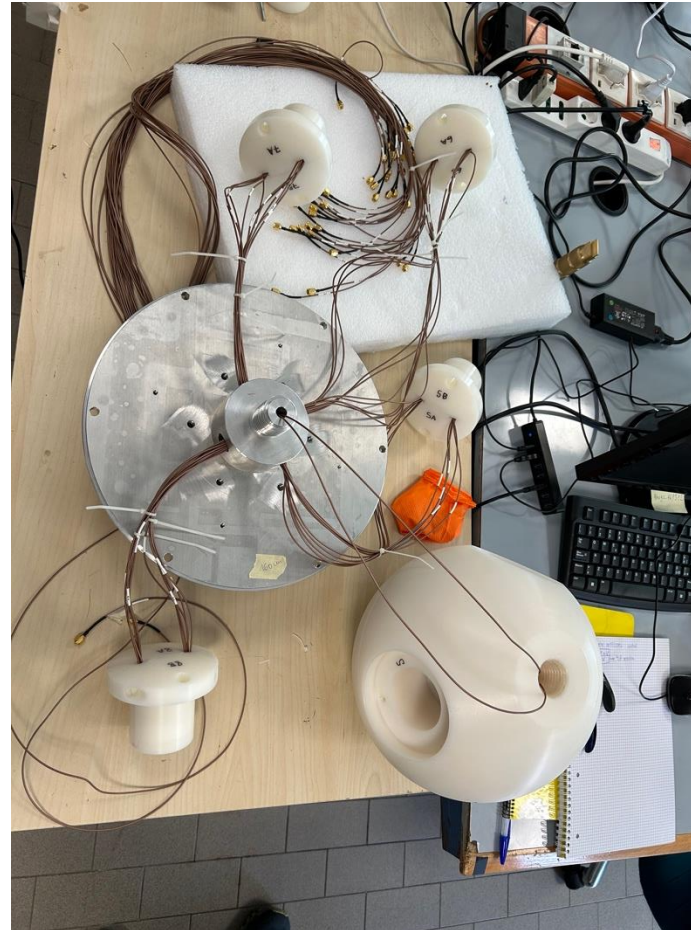
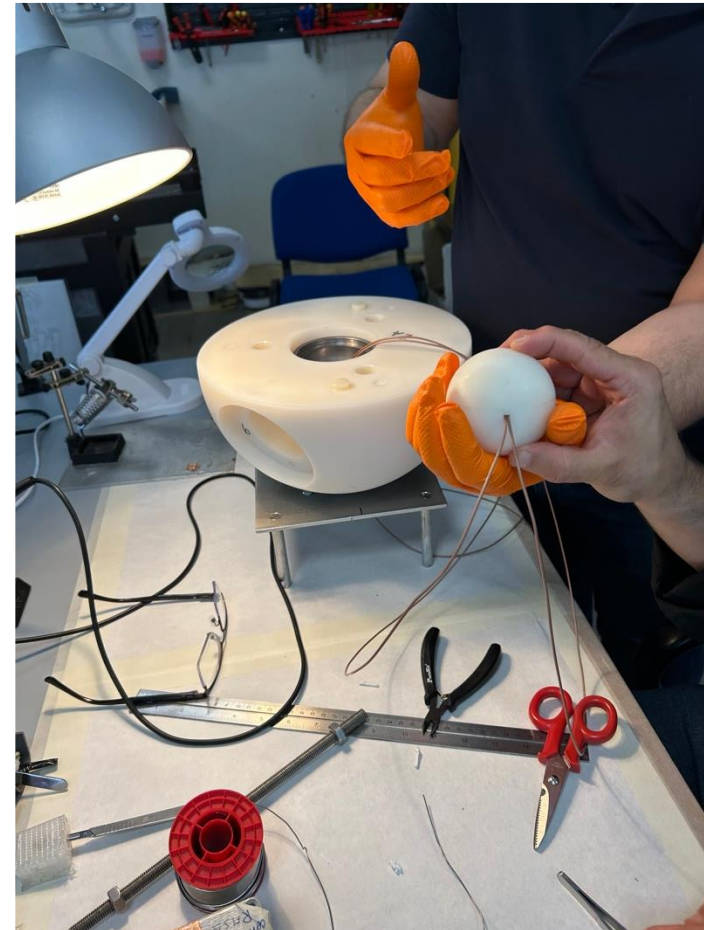


analog electronics



Expected operational Threshold range: 220-320 mV

Easy assembly and maintenance due to its modular structure

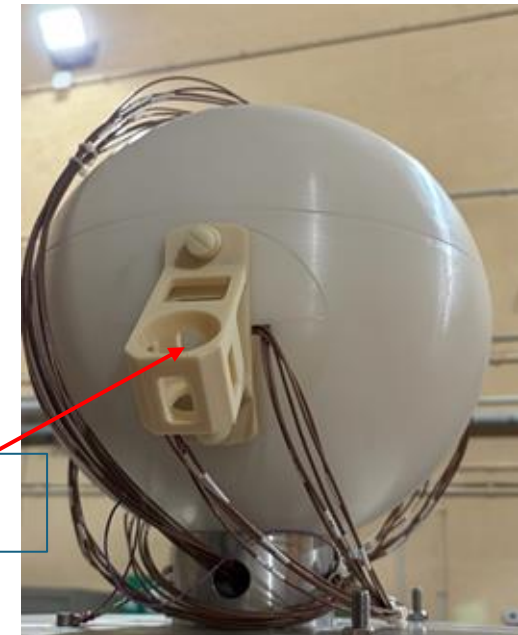
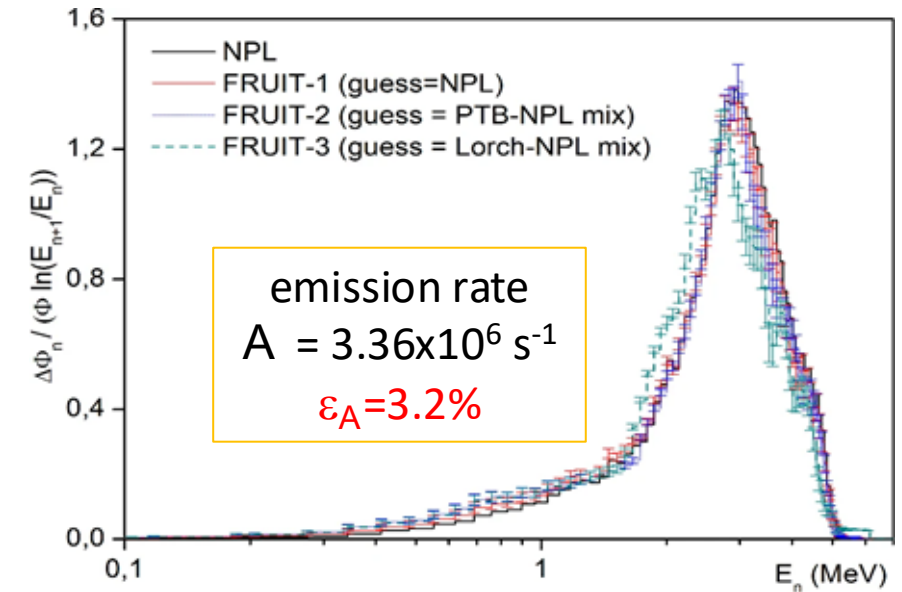


- It allows to determine an overall proportionality factor f between MCNP simulation and the measured data
- It can be repeated every Long Shutdown to monitor radiation damage
- Each TetraBall arm is exposed in sequence to the same source
- The result should not depend on the detector radial position

$$f = \frac{\text{DATA}}{\text{MCNP}}$$

- The MCNP simulation takes into account the specific **irradiation setup at ENEA** and it includes:
 - ✓ The TetraBall geometry
 - ✓ the "braccetto" geometry
 - ✓ $^{241}\text{Am-B}$ source
 - ✓ floor/room scattering

$^{241}\text{Am-B}$ source support: the "braccetto"



radius [cm]	axis A	axis B (vertical)	axis C	axis D	<f>	σ(%)
0.0	0.171 (±0.005)	0.164 (±0.005)	0.172 (±0.005)	0.171 (±0.005)	0.169 (±0.003)	2.2
5.8	0.166 (±0.005)	0.160 (±0.005)	0.164 (±0.005)	0.170 (±0.005)	0.165 (±0.002)	2.4
7.5	0.167 (±0.005)	0.166 (±0.005)	0.167 (±0.005)	0.169 (±0.005)	0.167 (±0.003)	0.7
9.2	0.159 (±0.005)	0.158 (±0.005)	0.162 (±0.005)	0.168 (±0.005)	0.162 (±0.002)	2.6
10.9	0.167 (±0.005)	0.162 (±0.005)	0.172 (±0.005)	0.172 (±0.005)	0.168 (±0.002)	2.9
12.6	0.171 (±0.005)	0.166 (±0.005)	0.179 (±0.005)	0.178 (±0.005)	0.173 (±0.003)	3.6
<f>	0.167 (±0.002)	0.163 (±0.002)	0.169 (±0.002)	0.171 (±0.002)	0.167 (±0.001)	
σ (%)	2.5	1.9	3.7	2.1		2.2

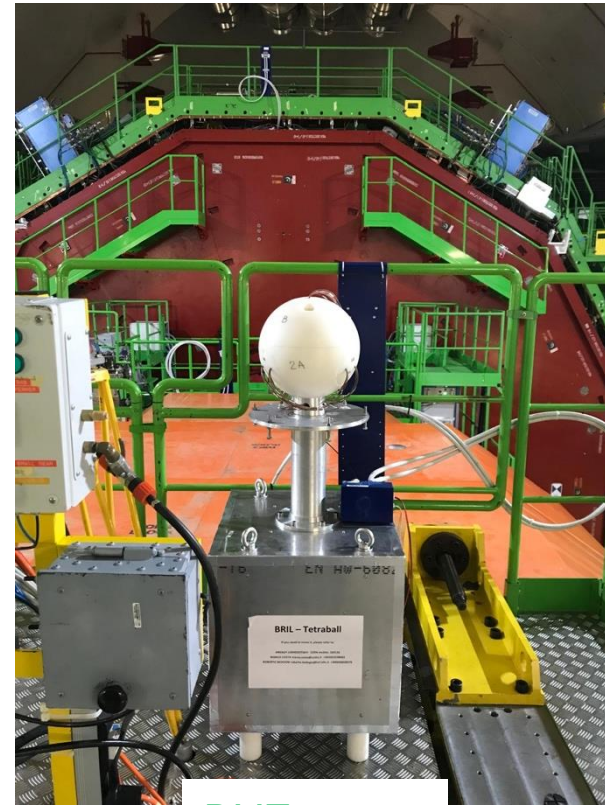
$$f = \frac{\text{DATA}}{\text{MCNP}}$$

Good uniformity is verified both as a function of radius and arm!

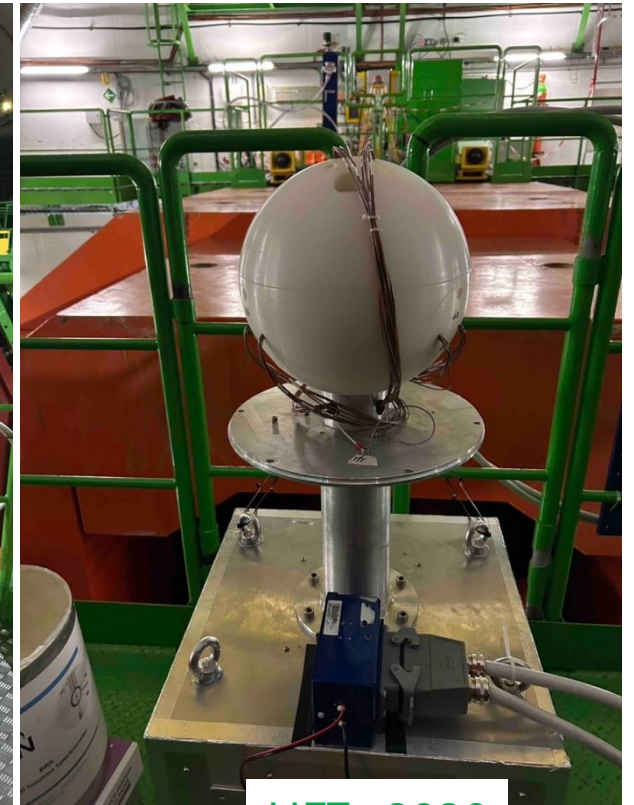
Mean Calibration factor: <f> = **0.167(3) ± 0.005(5)**

(incl. 3.2% uncertainty on the emission rate)

Tetra Ball Operation at CERN in the CMS outer cavern during 2025 and 2026 LHC running period



BHT+ 2025



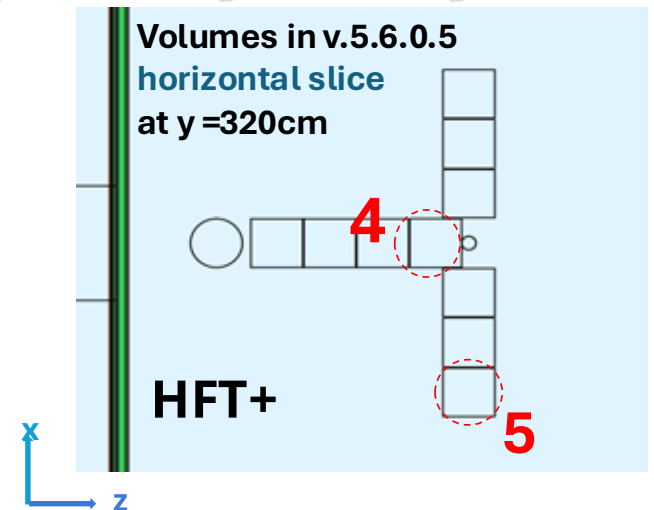
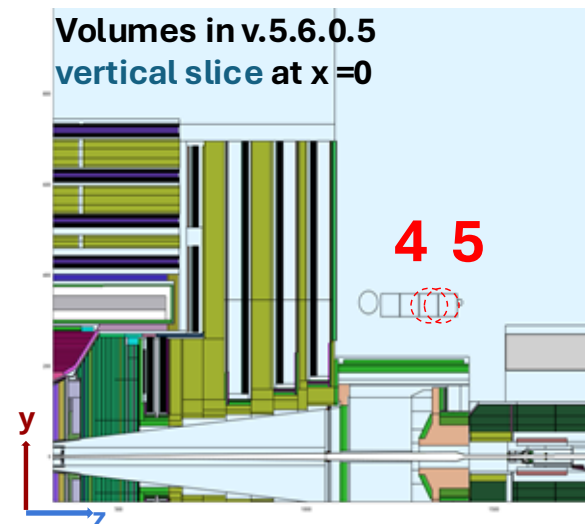
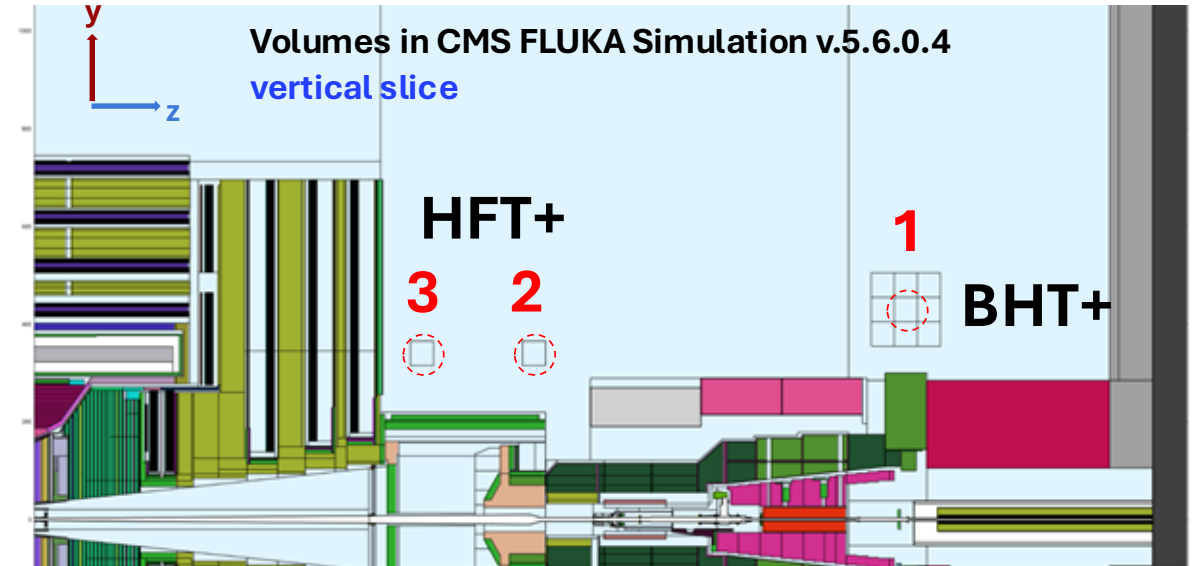
HFT+ 2026

During 2025 and 2026 data taking different Estimation Regions for Energy Spectra have been considered

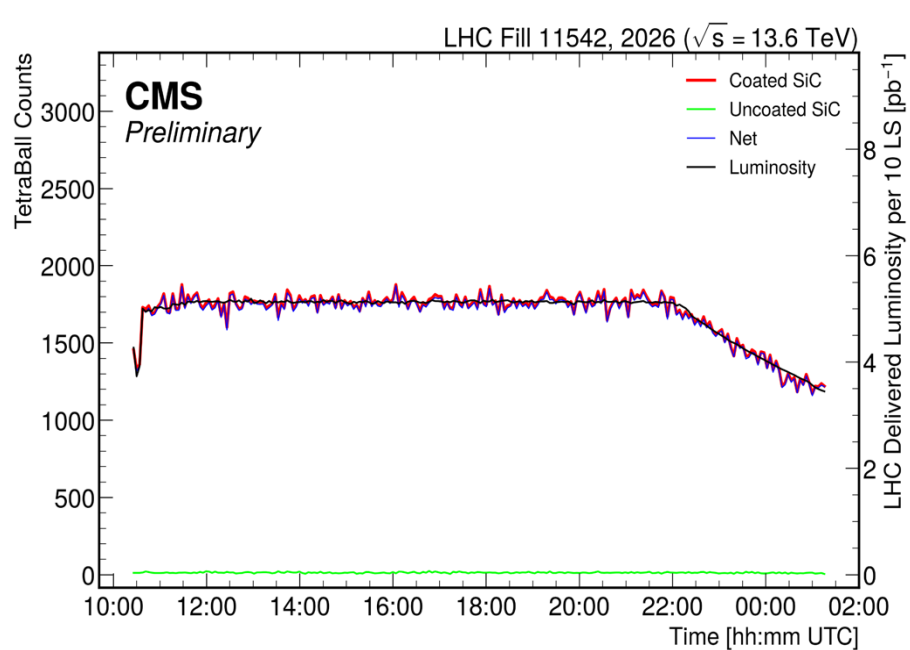
- Energy spectra cannot be recorded in a model-independent mesh
- Specific volume based estimators to match various TetraBall locations on Blockhouse Top (BHT+) and Hadron Forward Top (HFT+) positive ends were added in two Run 3 simulations.
- The black solid lines show some of the volumes in which the neutron energy spectra were recorded.
- The red dotted lines indicate those that correspond to actual measurement locations
- The CMS FLUKA coordinate system uses a right handed cartesian frame where $x=y=z=0$ at the Interaction Point; $+x$ is towards the near side, $+y$ to the ceiling and $+z$ to the positive end.

1. $35 < x < 85 \text{ cm}; 405 < y < 455 \text{ cm}; 2189 < z < 2239 \text{ cm} (*)$
2. $-25 < x < 25 \text{ cm}; 315 < y < 365 \text{ cm}; 1383 < z < 1433 \text{ cm} (*)$
3. $-25 < x < 25 \text{ cm}; 315 < y < 365 \text{ cm}; 1140 < z < 1190 \text{ cm}$
4. $-25 < x < 25 \text{ cm}; 309 < y < 359 \text{ cm}; 1351 < z < 1401 \text{ cm}$
5. $-178 < x < -128 \text{ cm}; 304 < y < 354 \text{ cm}; 1383 < z < 1433 \text{ cm}$

(*) this talk

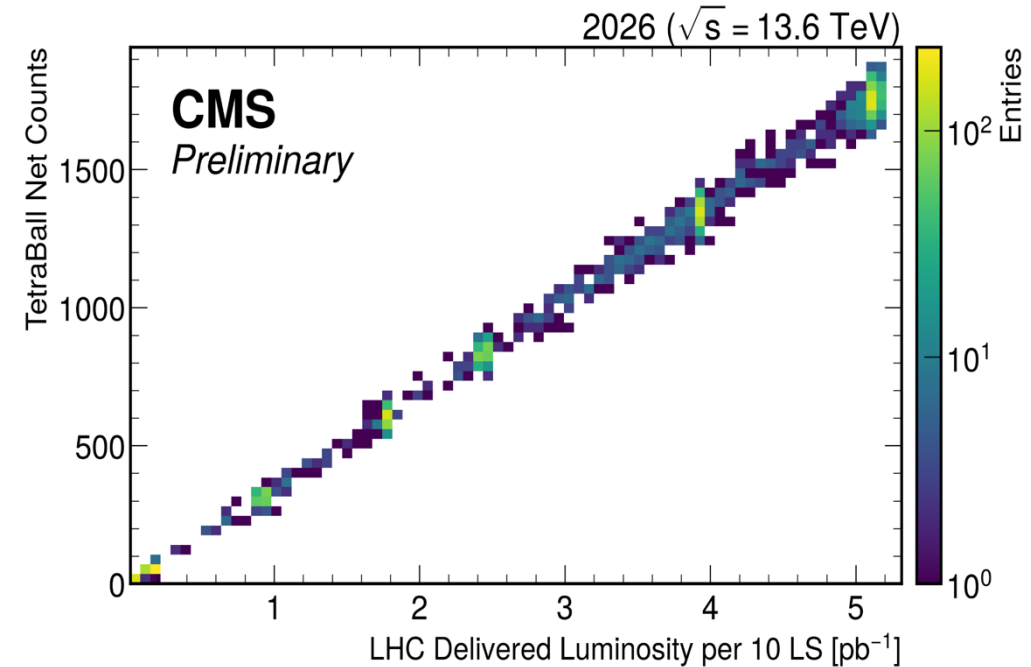


TetraBall net counts versus delivered LHC luminosity



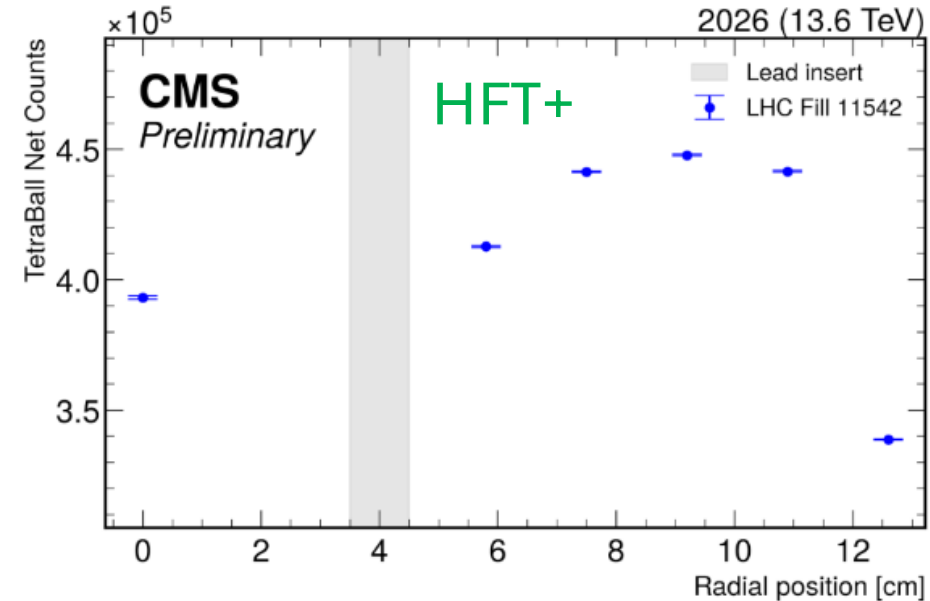
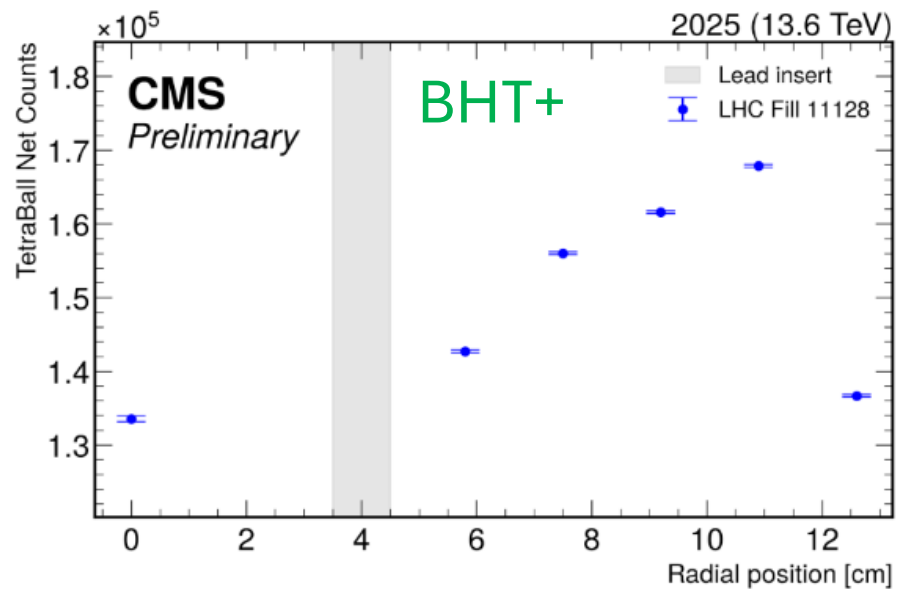
Example profile of one TetraBall detector pair counts (arm C, radial position 9.2 cm) and LHC p-p luminosity versus time. All quantities are integrated over ~ 230 -second interval.

The “Net” contribution corresponds to the subtraction between the coated SiC and uncoated SiC counts



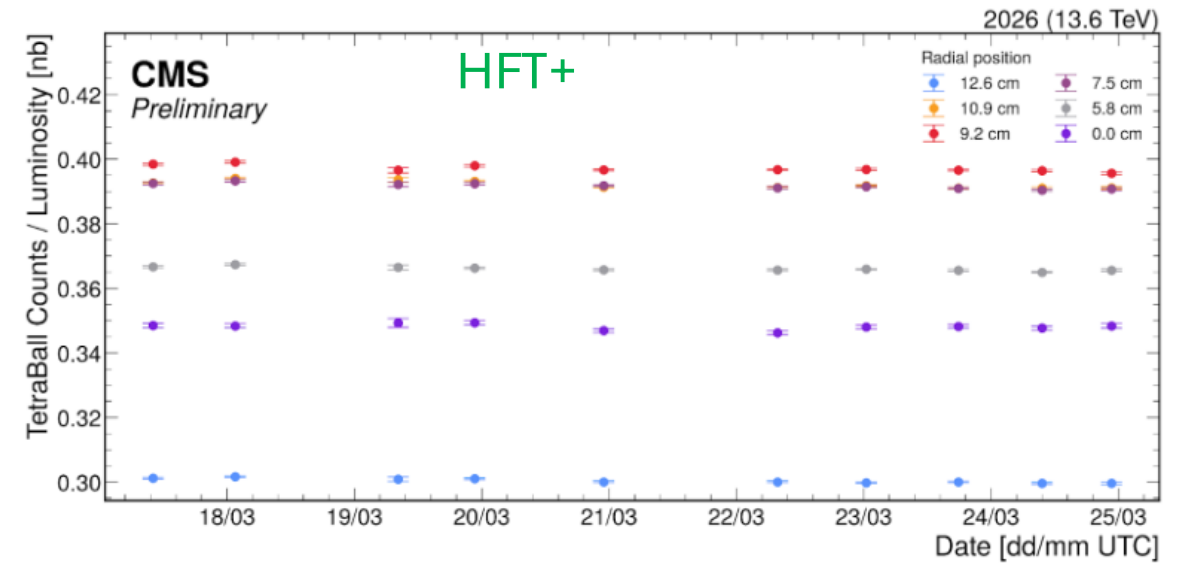
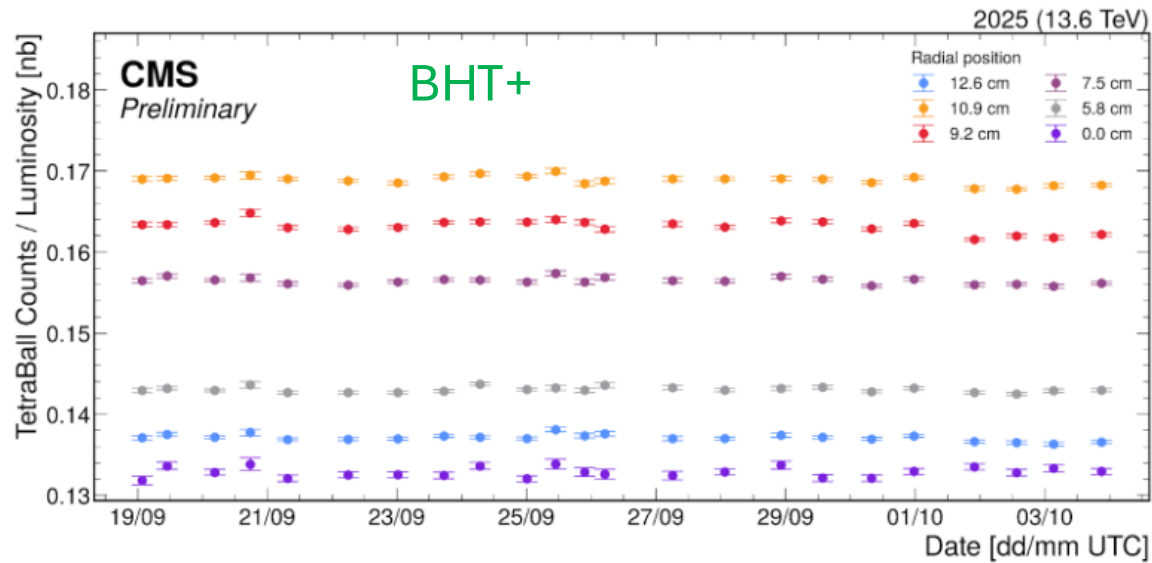
TetraBall net counts vs. LHC p-p luminosity 2D histogram for one detector pair (arm C, radial position 9.2 cm), acquired during 2026 luminosity ramp-up when the number of bunches for each proton beam increased from 12 to the standard 2460. Both TetraBall counts and luminosity data are integrated over ~ 230 -second intervals. The denser regions correspond to instantaneous luminosity leveling periods.

→ **TetraBall response linearity is well evident**



TetraBall net counts profile as a function of detector radial position inside the HDPE moderator. Data points have been obtained by performing a subtraction between the integrated counts read by the ^6LiF -coated SiC detectors and the uncoated ones, and they thus represent net neutron counts. Error bars include only statistical uncertainties on the integrated counts and are obtained through standard error propagation. The shape of the counts profile reflects the neutron energy spectrum at the specific TetraBall location in the CMS cavern: Block House Top (left), Hadron Forward Top (right). The counts profile is used as an input to unfold the neutron spectra at the specific TetraBall location in the CMS cavern.

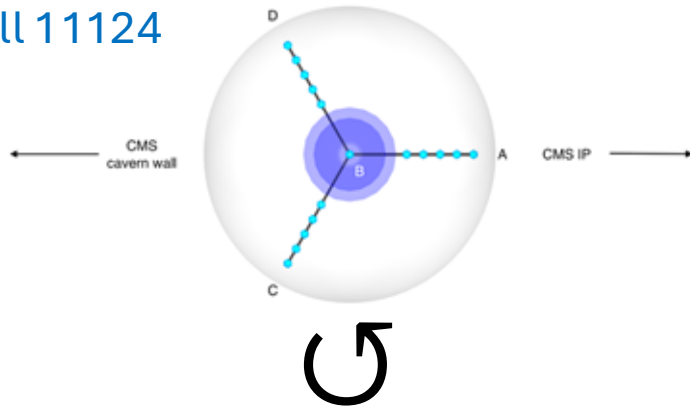
*<https://doi.org/10.1093/oxfordjournals.rpd.a006388>



Different colors refer to different radial positions inside the HDPE moderator, as specified in the plot legend. Each vertical set of points corresponds to data acquired during one LHC p-p fill and has been normalized to the online integrated luminosity for the specific fill. The data were acquired on the Block House Top (left) and Hadron Forward Top (right) positions during standard pileup conditions.

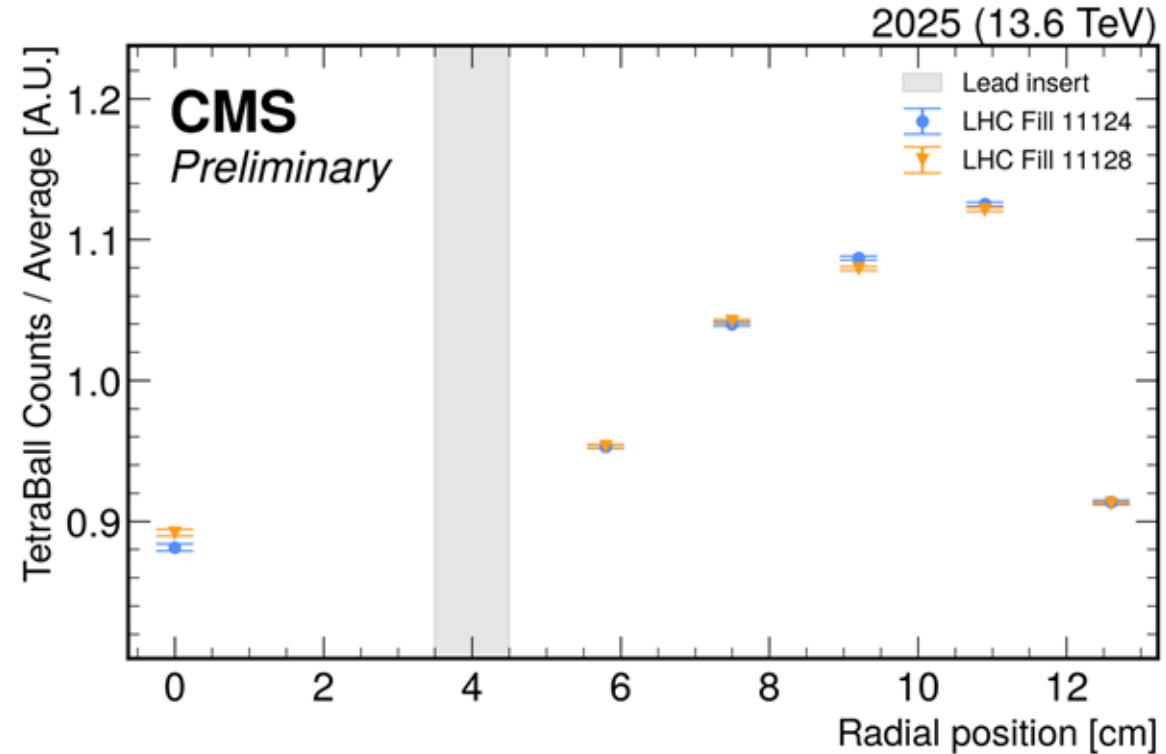
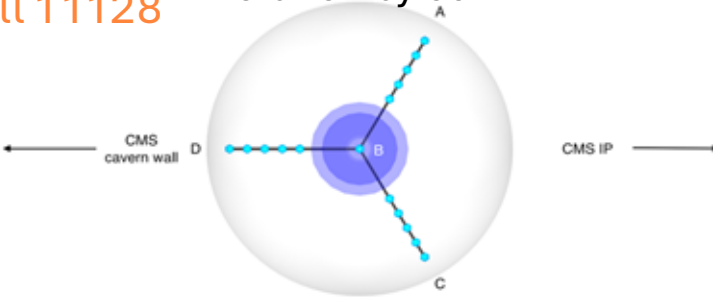
➔ **System Response Stability within 2%**

LHC Fill 11124

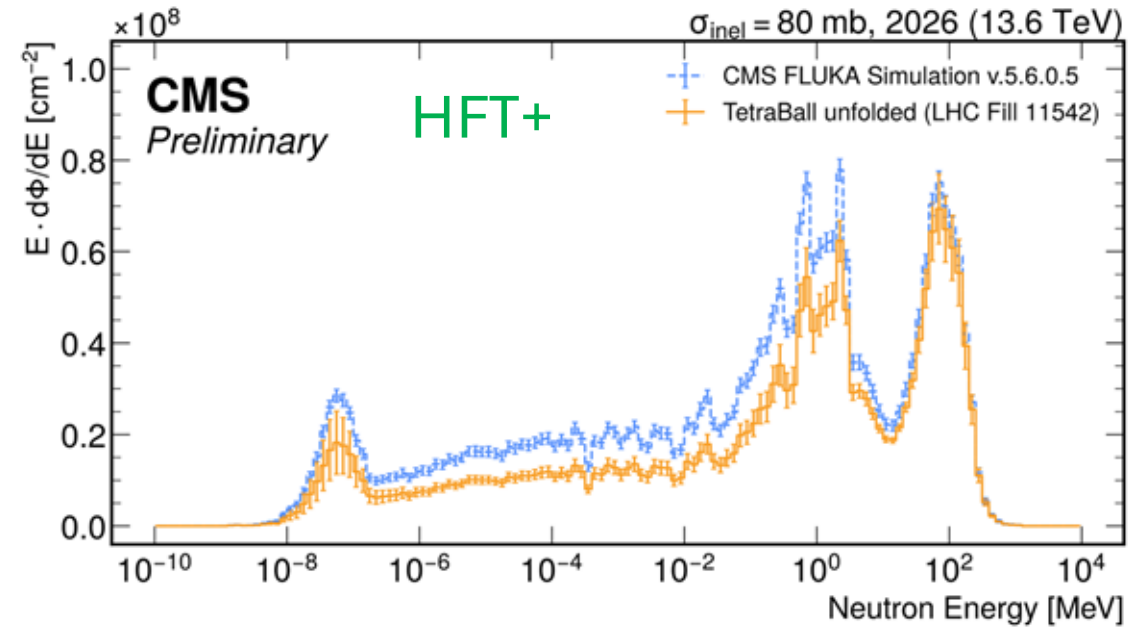
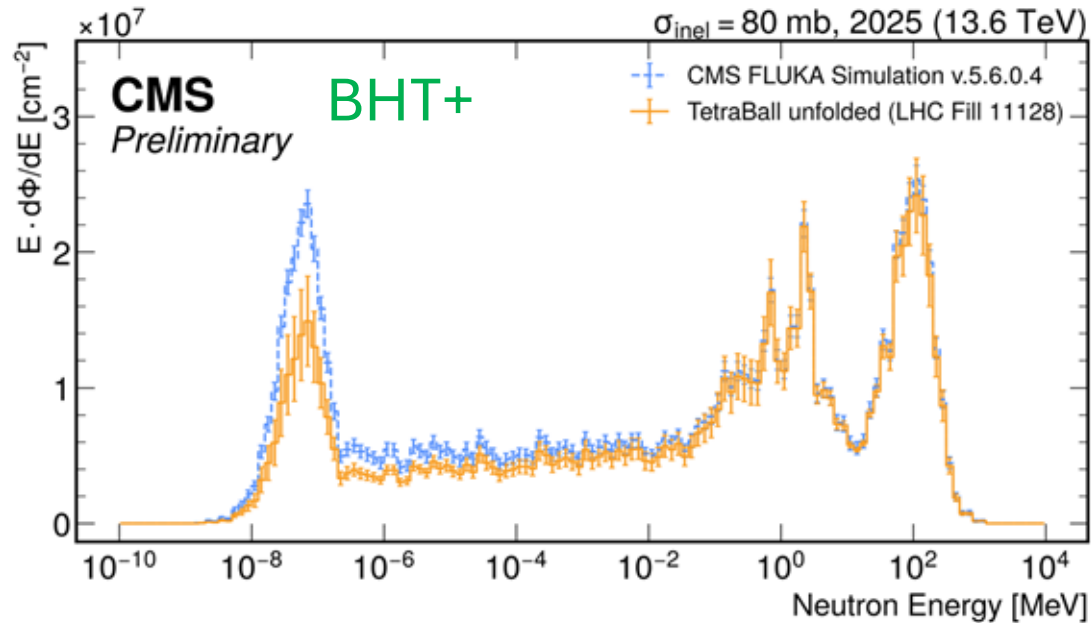


LHC Fill 11128

Rotation by 60°



To prove the isotropic response of the TetraBall system a study of the net count profiles as a function of detector radial position inside the HDPE moderator at the BHT+ location has been performed. The differences between counts at the same radial position before and after a TetraBall rotation by 60° around its vertical axis are below 2%, proving the isotropic response of the system.



The blue curve is the output of CMS FLUKA simulations. The orange curve is obtained by unfolding TetraBall counts profile (acquired during LHC Fill 11128 and 11542 respectively). The FRUIT* unfolding tool has been used with CMS FLUKA spectrum as input a priori information.

For direct comparison both spectra are expressed as integrated neutron fluences: the TetraBall unfolded spectrum gives an absolute measurement, while the FLUKA spectrum, originally normalized to single p-p collision, has been rescaled by both the canonical p-p inelastic cross section ($\sigma_{\text{inel}} = 80 \text{ mb}$) and the specific LHC Fill integrated luminosity. The error bars for the FLUKA spectrum represent only the statistical uncertainty. For the TetraBall unfolded spectrum the error bars are obtained by Monte Carlo Gaussian perturbation of the TetraBall counts profile used as input for the unfolding procedure. These error bars account for both statistical uncertainty on the TetraBall counts and the systematic uncertainty associated with the TetraBall calibration procedure. **A general good agreement can be found between the two spectra, with indications of FLUKA overestimating the neutron fluence in certain energy regions. More detailed studies are ongoing.**

*[10.1016/j.nima.2007.07.033](https://doi.org/10.1016/j.nima.2007.07.033)

TetraBall Total fluence [cm⁻²]	1.91E+08	±4.66% ^(*)		Using TB calibration factor: <f> = 0.1673 ± 0.0055
FLUKA Total fluence [cm⁻²]	2.22E+08	±0.67% ^(†)		Calculated from fluence per pp collision assuming $\sigma_{pp} = 80\text{mb}$ and rescaled to the specific fill luminosity

FLUENCE FRACTIONS				
	E < 0.4 eV	0.4 eV ≤ E < 10 keV	10 keV ≤ E ≤ 20 MeV	E > 20 MeV
TetraBall [cm⁻²]	2.93E+07	4.37E+07	7.16E+07	4.62E+07
relative error^(*)	±7.14%	±3.71%	±3.93%	±4.55%
FLUKA[cm⁻²]	4.63E+07	5.38E+07	7.39E+07	4.83E+07
relative error^(†)	±1.47%	±1.37%	±1.17%	±1.44%

^(*) It includes the calibration factor uncertainty (3.2%)

^(†) Includes only FLUKA statistical uncertainty

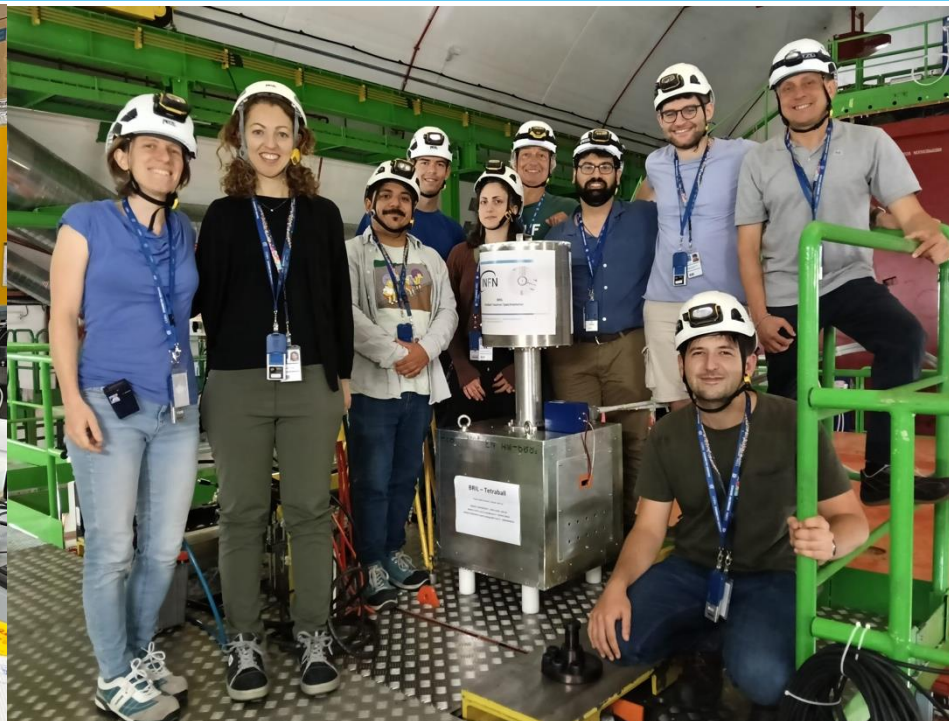
TetraBall total fluence [cm ⁻²]	4.88E+08	±4.40%(*)		Using TB calibration factor: <f> = 0.1673 ± 0.0055
FLUKA total fluence [cm ⁻²]	6.65E+08	±0.51%(†)		Calculated from fluence per pp collision assuming σ _{pp} = 80mb and rescaled to the specific fill luminosity
FLUENCE FRACTIONS				
	E < 0.4 eV	0.4 eV ≤ E < 10 keV	10 keV ≤ E ≤ 20 MeV	E > 20 MeV
TetraBall [cm⁻²]	3.68E+07	1.05E+08	2.19E+08	1.27E+08
relative error(*)	±10.38%	±3.60%	±3.73%	±4.57%
FLUKA [cm⁻²]	5.78E+07	1.70E+08	2.99E+08	1.38E+08
relative error(†)	±1.72%	±1.01%	±0.76%	±1.14%

(*) It includes the calibration factor uncertainty (3.2%)

(†) Includes only FLUKA statistical uncertainty

- TetraBall 2025 and 2026 data taking has been successful.
- TetraBall response is isotropic and the system stability in time has been demonstrated
- Count rates are proportional to instantaneous lumi and we can accumulate $\sim E+5$ counts/fb⁻¹, i.e. enough statistics to produce a spectrum with 1 fb⁻¹
- TetraBall calibration with metrological qualified ²⁴¹Am-B source was demonstrated
- The ²⁴¹Am-B source "braccetto" measurement can be used to quantify the radiation damage
- A total integrated fluence integrate over 2025-2026 was 2.39×10^{10} n/cm²
- The unfolded spectra from TetraBall confirm a general good agreement with FLUKA simulation with indications of FLUKA overestimating the neutron fluence in certain energy regions.
- The TetraBall measurement allows to benchmark the FLUKA prediction on the total fluence at the level of 4.7%, and the single fluence fractions at the level of 10%-20%

**• The TetraBall single moderator neutron spectrometer
fullfills the CMS BRIL NMR requirements**



Roberto Bedogni, Matteo Marchisio Caprioglio , Ivàn Castro Campoy, Marco Costa, Domenico Dattola, Elisabetta Durisi, Jose Maria Gomez Ros , Deborah Iantorno, Valeria Monti, Tommaso Napolitano, Antonino Pietropaolo, Francesco Rotondo, Luigi Russo, Ivan Valinotto (INFN-LNF & INFN-TO) and CMS BRIL colleagues including Olena Karacheban (CERN), Arkady Lokhovitskiy (University of Debrecen), Sophie Mallows (CERN), Gabriella Pasztor (Eotvos Lorand University), Alice Svärdström (CERN)

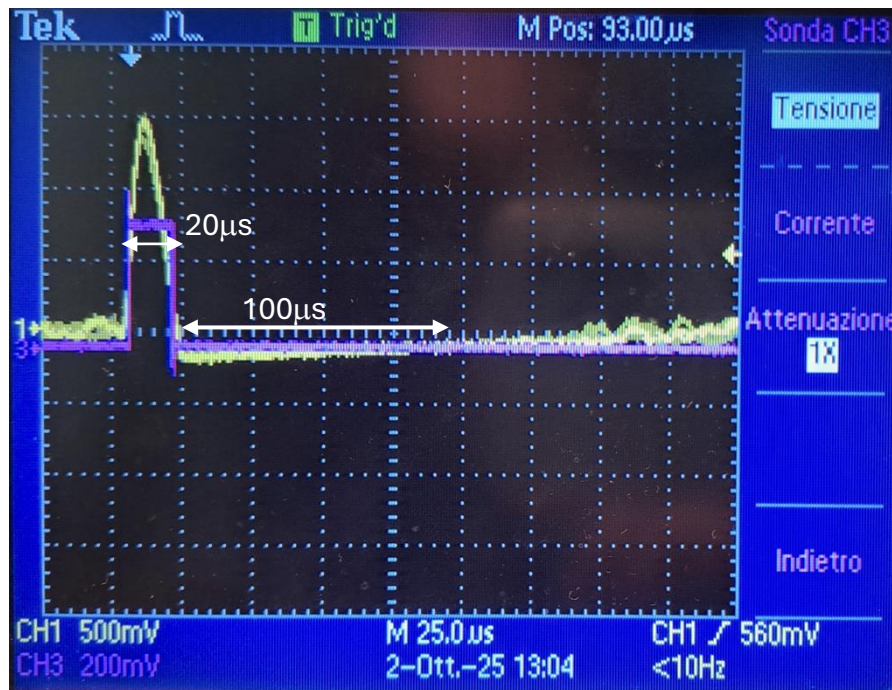
THANK
YOU!

Backup

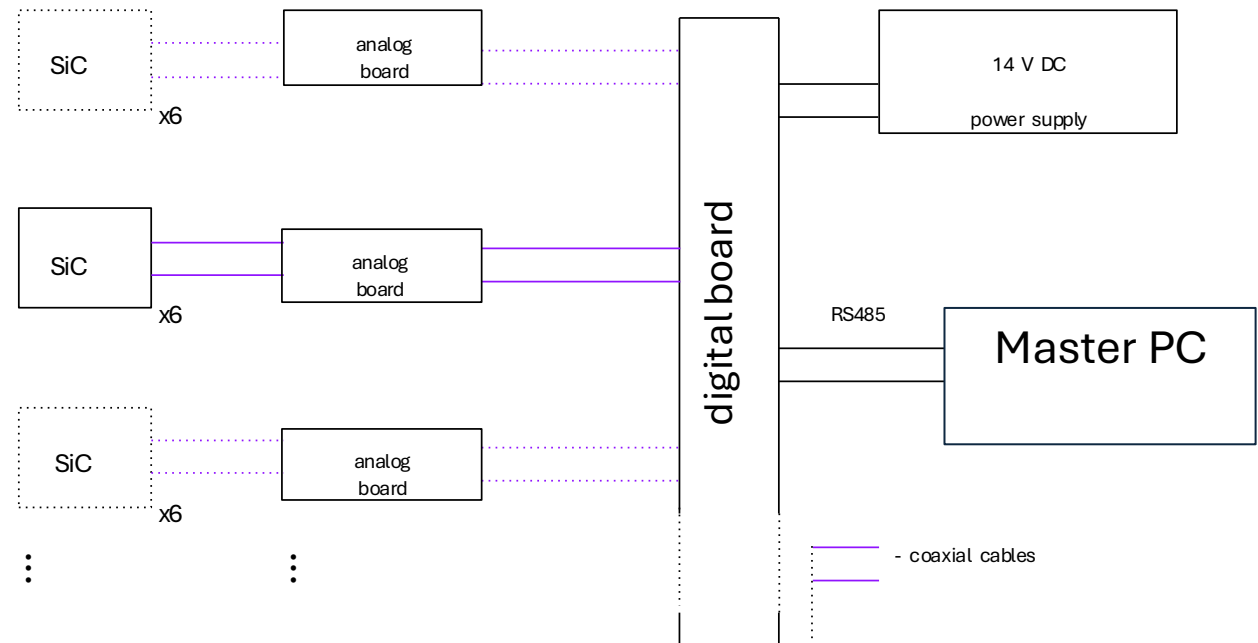
TetraBall Readout electronics

- 42 SiC detectors are readout independently. It is a low rate application with typical count rate ~few Hz per channel
- We implement a Master/Slave logic where the PC in USC is the Master and each TB is identified by a unique Slave_id address
- Digitized data output have the format : **DDMMYY \t HHMMSS \t CH1 \t ... CH48 \t STATUS**

Analog and Digital signal



Schematic (42 SiC readout separately)



Analog Board (5V, 0.07A)

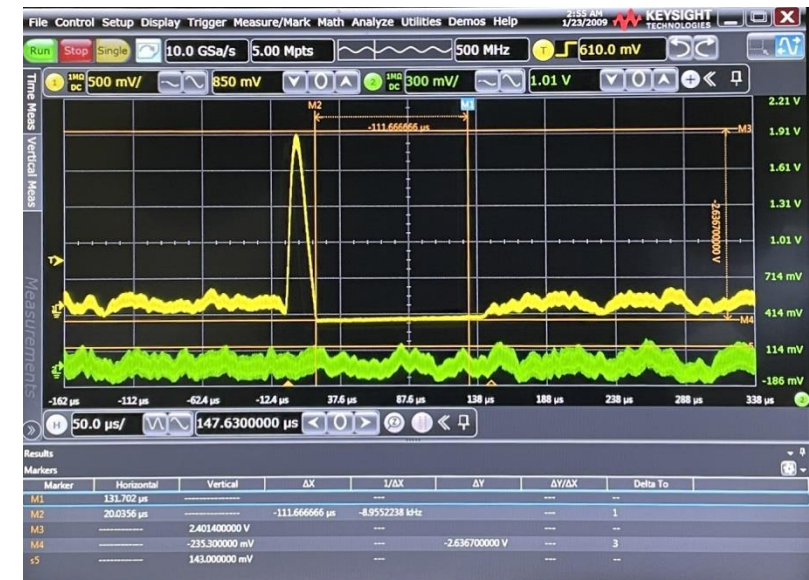
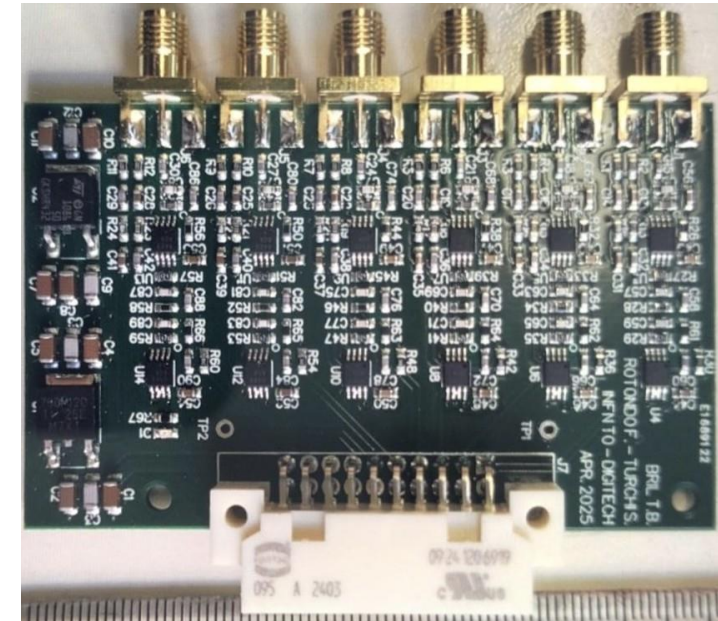
@credits INFN-Torino Electronic service

The analog electronic boards are responsible for **amplifying the signal** from the SiC detectors.

Their characteristics include:

- **6 input channels** per board
- **2 amplification stages** per channel (with $-0.15 \div 4.85\text{V}$ output saturation range)
- connector with digital board for signal output and 14V power input.
- Linear voltage regulators to produce 12V **DC reverse bias voltage** to each SiC detector and 5V to power the analog chain

The amplified signals, with mpv of $\sim 0.5\text{ V}$ (Landau-like peak), and rms noise $\sim 40\text{ mV}$ are sent to the digital board for thresholding and digitization.



Digital Electronic Board (3.3V, 0.2A)

The Digital electronic board (designed in collaboration with DIGITECH srl) is responsible for **thresholding the amplified signals** against electronic noise for neutron counting.

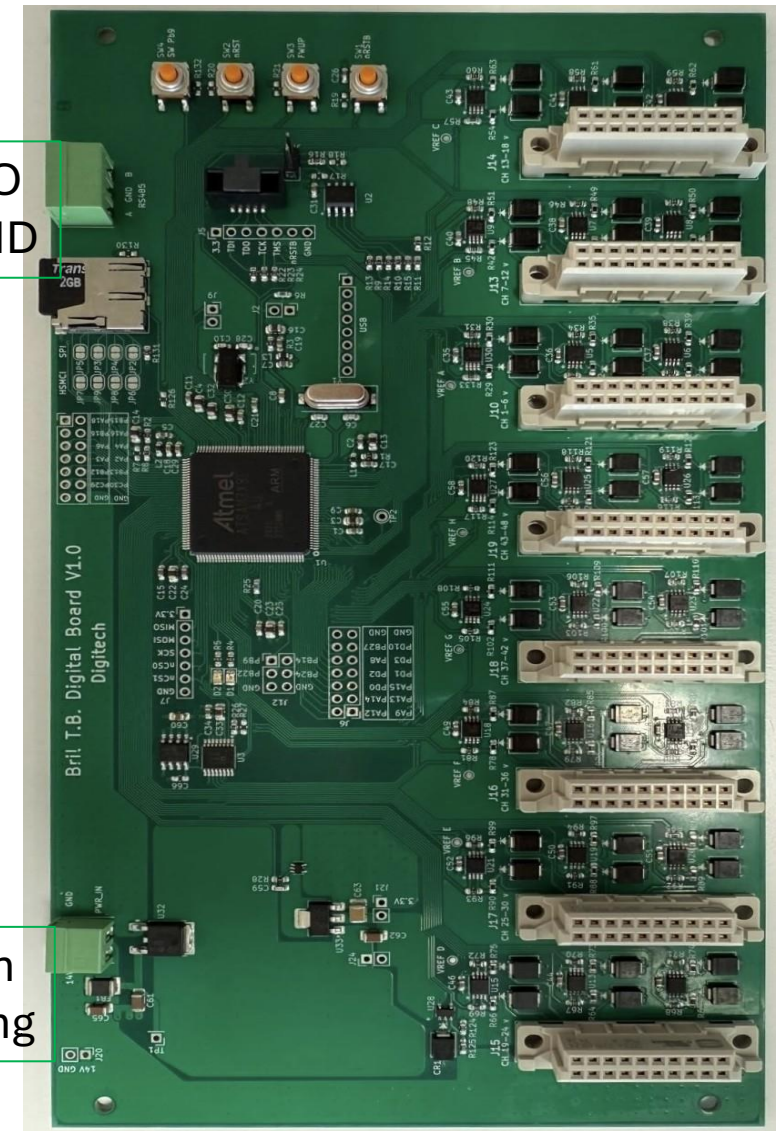
Its characteristics include:

- **1 ATMEL^a microcontroller** for counting and board control (rad-tolerant, many I/O channels)
- **1 RS485 serial connection** to a DAQ miniPC
- **8 analog board connectors (6x8 channels)**
- **1 thresholding circuit** for each analog input channel
- **14V DC supply** to power the board itself, the analog boards and to bias the SiC detectors
- A common reference GND referred to USC GND

^aAtmel ATSAM3X8EA-AU

RS485 I/O
D+D-,GND

14 V in
floating



8

A

N

A

L

O

G

B

O

A

R

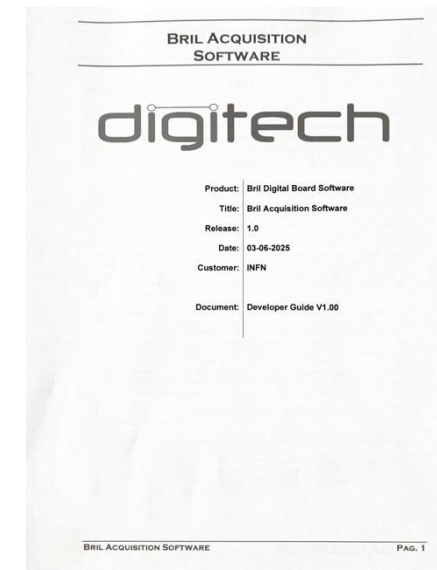
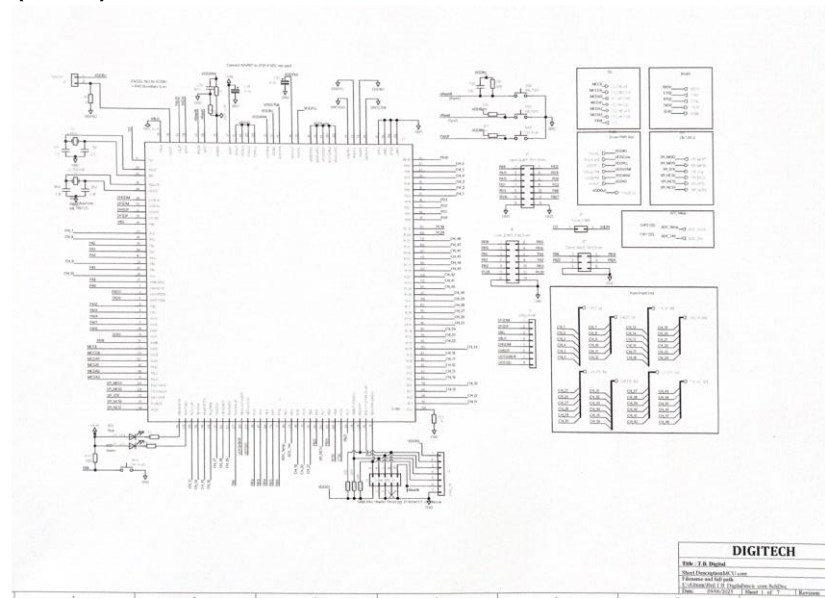
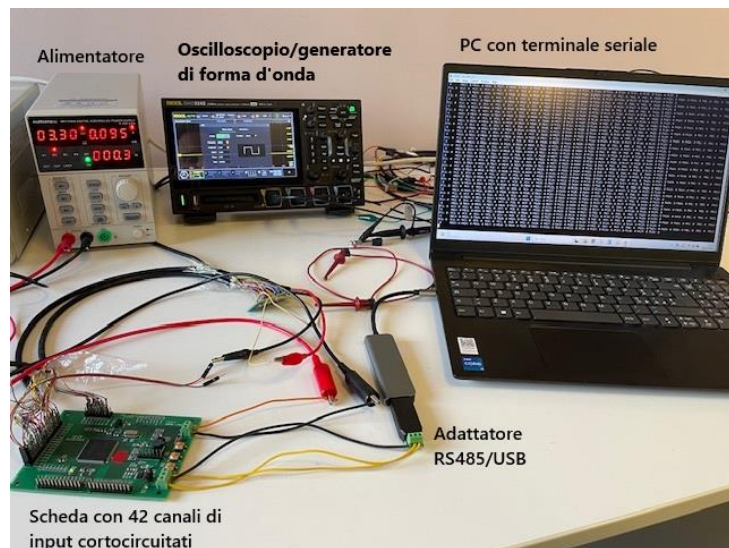
D

S

32-bit ARM Cortex-M3 microcontrollers running at 84MHz with 512KB Flash and 100KB SRAM.

Rad-tolerant technology (not certified)

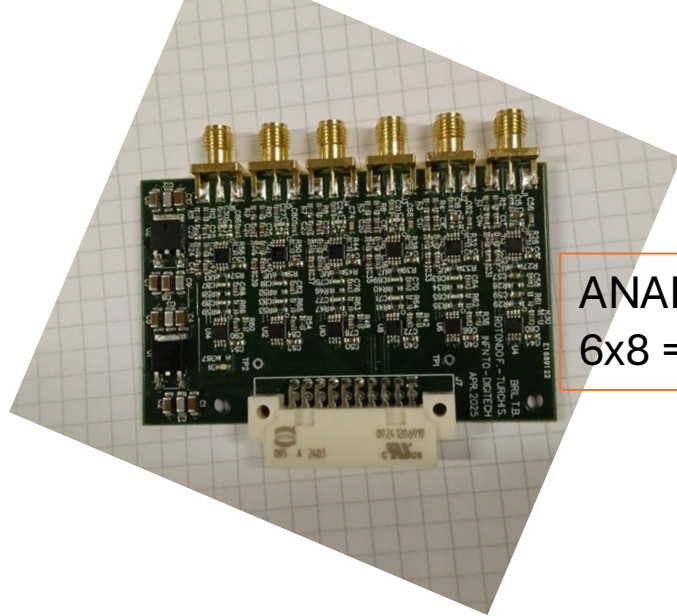
- Up to 103 I/O lines with external interrupt capability (edge or level sensitivity), debouncing, glitch filtering and on die Series Resistor Termination
- Up to four 32-bit Parallel Input/Outputs (PIO)



→no communication loss occurred during 2025 and 2026 data taking

NO Need for Active Cooling

Temperature of microcontroller: from 33.5 °C up to 35.5°C and then stabilized



ANALOG Boards
6x8 = 48 ch

Atmel-11057-32-bit-Cortex-
M3-Microcontroller-SAM3X

1 Digital Board

