MUonE

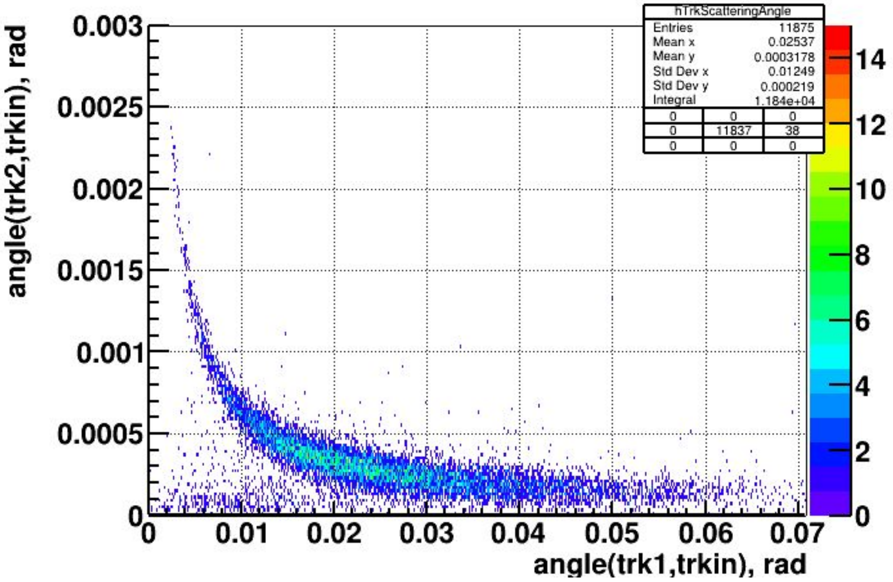
U. Marconi,
On behalf of the proponents
Liverpool, 2023 November 8th

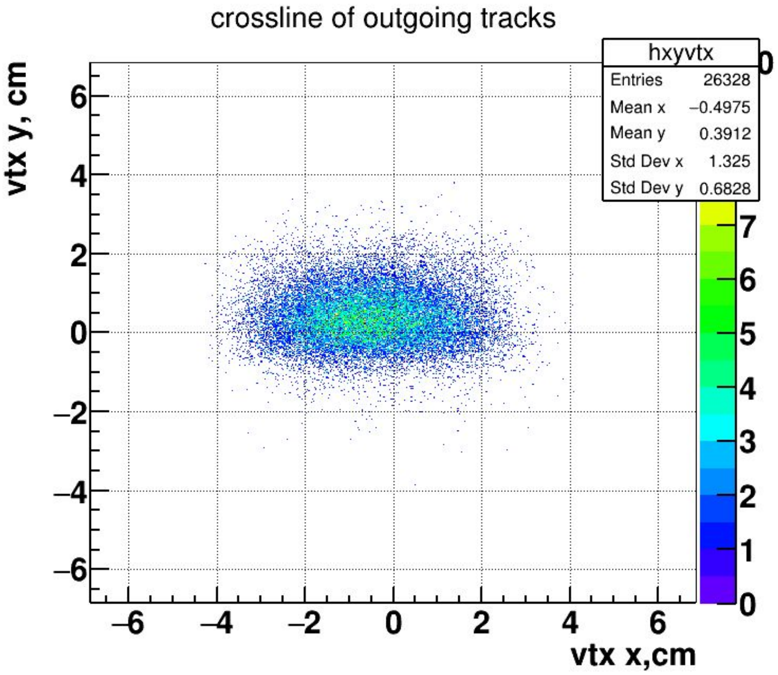
Introduction

- Detailed reports on selected topics concerning MUonE tomorrow: DAQ, software, mechanics, BMS, 1S modules.
- Status of the theory follows, in Fulvio's presentation
- I discuss here some of the achievements and limits we've discovered, with simulations, and by means of tests we made this summer.
- Developments of MUonE has been so far mainly driven by the availability of the silicon strip detectors, the 2S modules, we borrow/purchase from CMS.
- Future developments of MUonE are constrained by the CERN's plans for the upgrade of the accelerator complex, which foresees the LS3 shut down in 2026.

Elastic collisions

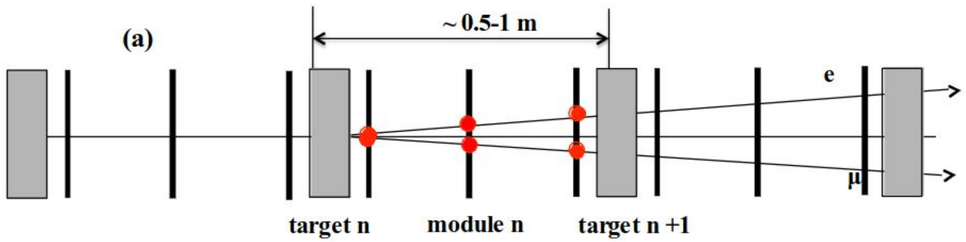
- We do see elastic collisions at 40 MHz
- High intensity muon hitting a 3 cm Carbon target





The tracking station and the 2S modules

- We have been using modules made of two sensors, with a total thickness of 2 × 320 um
- We have assumed a module efficiency for a MIP ~99%

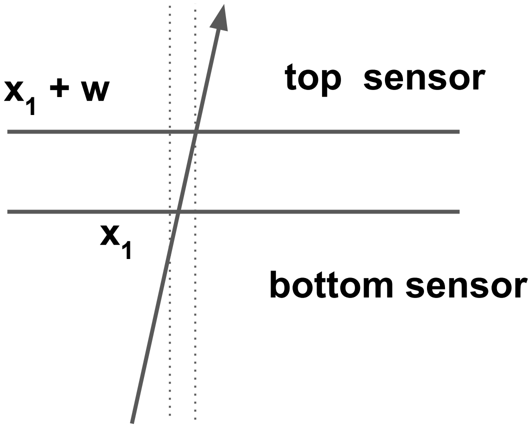


- Minimum number of planes per view to limit the effects of MSC
- Tilting of the XY modules to improve their spatial resolution
- Use of rotated UV planes to build up 3D tracks
- Extremely precise detector geometry known by construction, to be refined by means of software alignment

2S modules

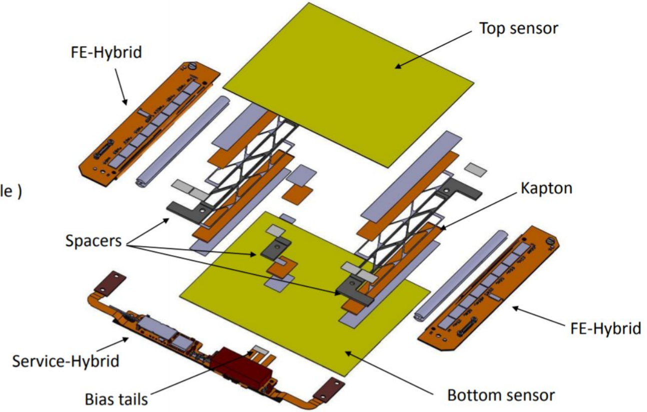
Designed for the CMS upgrade
Operating at 40 MHz
Digital binary strip readout
with and expected resolution 22 μm

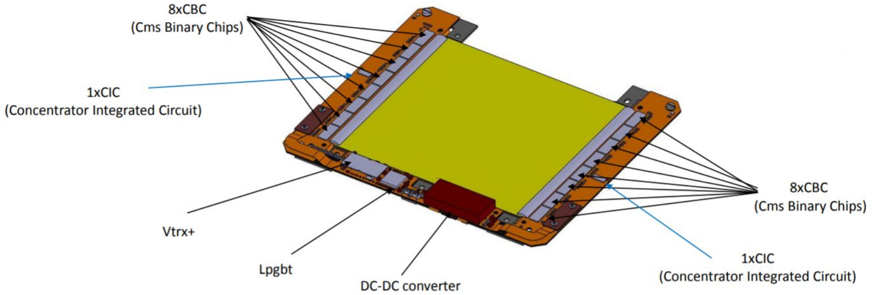
N.B. We use stubs, i.e. trigger primitives for the CMS L1 trigger



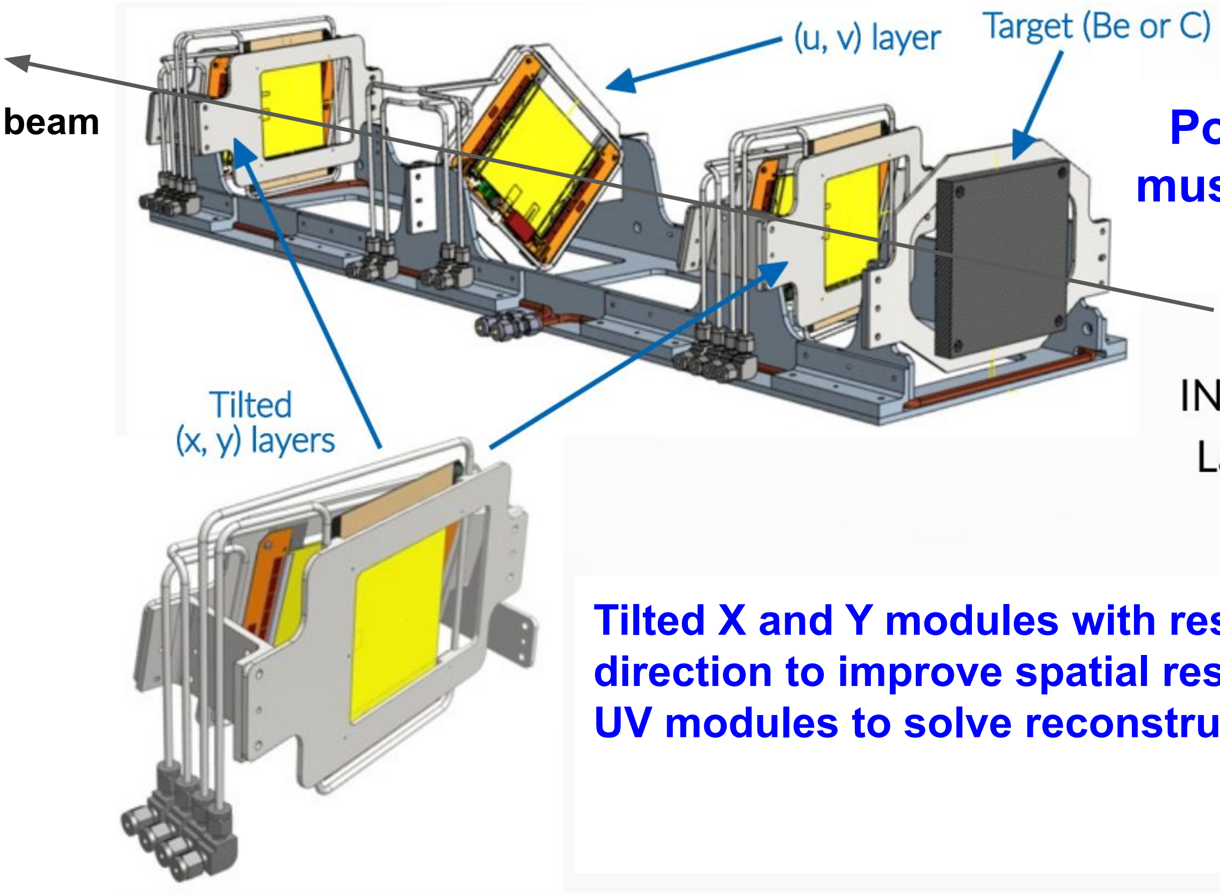
Components to be assembled:

- **Strip sensors** (2)
- **Kapton isolators** (4 long, 2 short)
- **Backplane bias tails** (1 double, 1 single)
- **Al-CF bridges** (2 main, 1 stump)
- **Front-end Hybrid** (1 Left, 1 right)
- **Service Hybrid + VTRX+** (1)





The tracking station at present



Positions of the modules must stable within a few μm

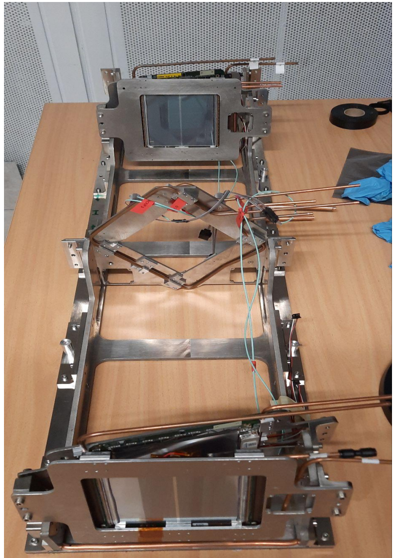
Low CTE material:
INVAR (CTE ~ 1.2×10^{-6} K^{-1})

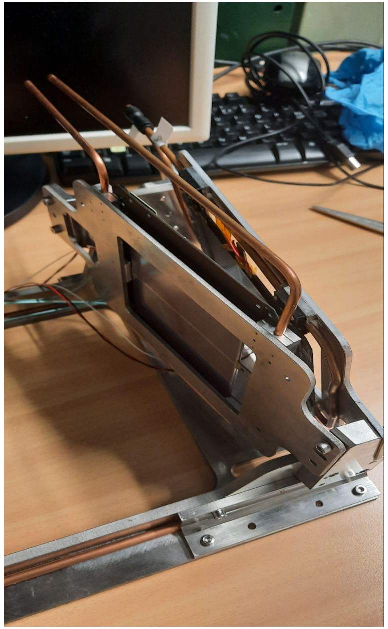
Laser holographic system to monitor stability.

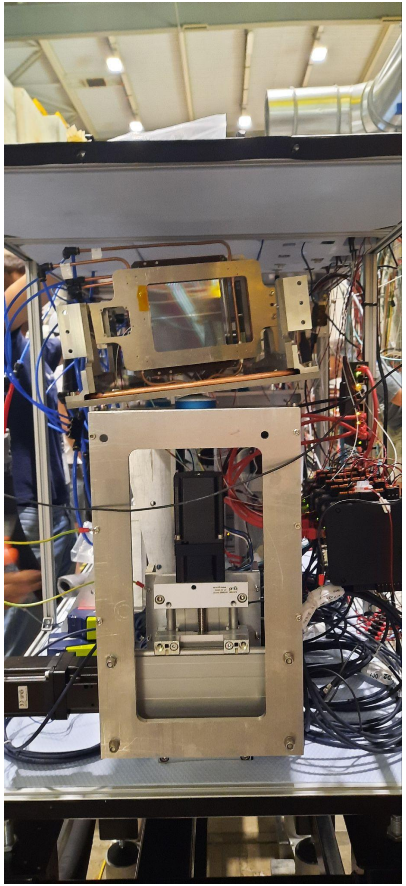
Tilted X and Y modules with respect the strip direction to improve spatial resolution
UV modules to solve reconstruction ambiguities

A real tracking station

- Support
- Frame and a module in place
- Movable support to be optimally aligned to the beam

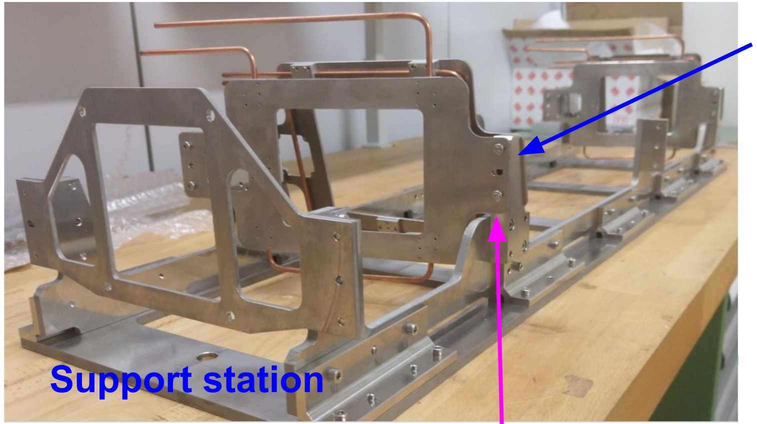




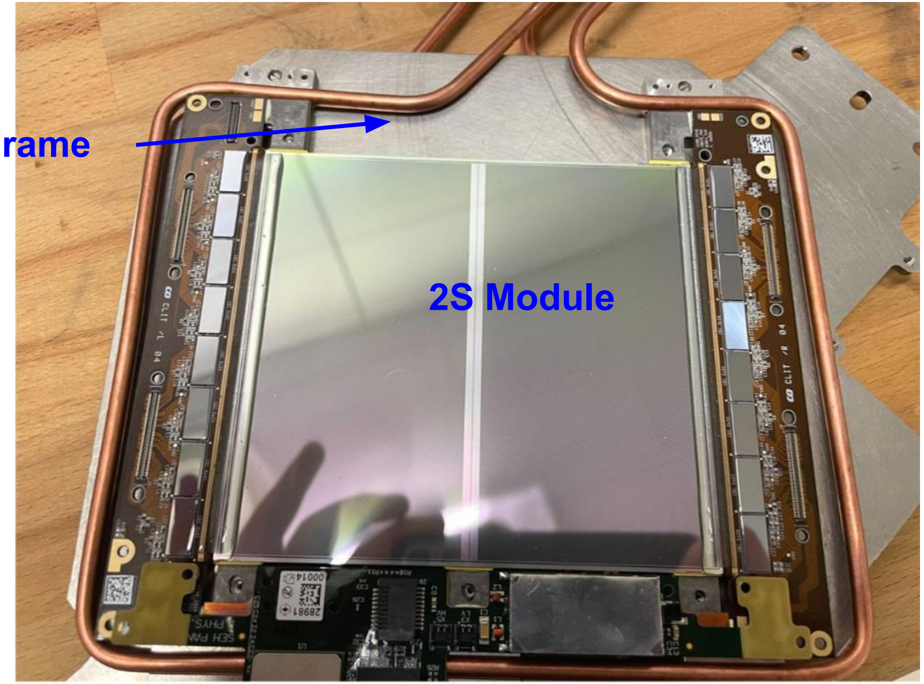


2S module on its frame and supporting structure

Station mechanics in INVAR



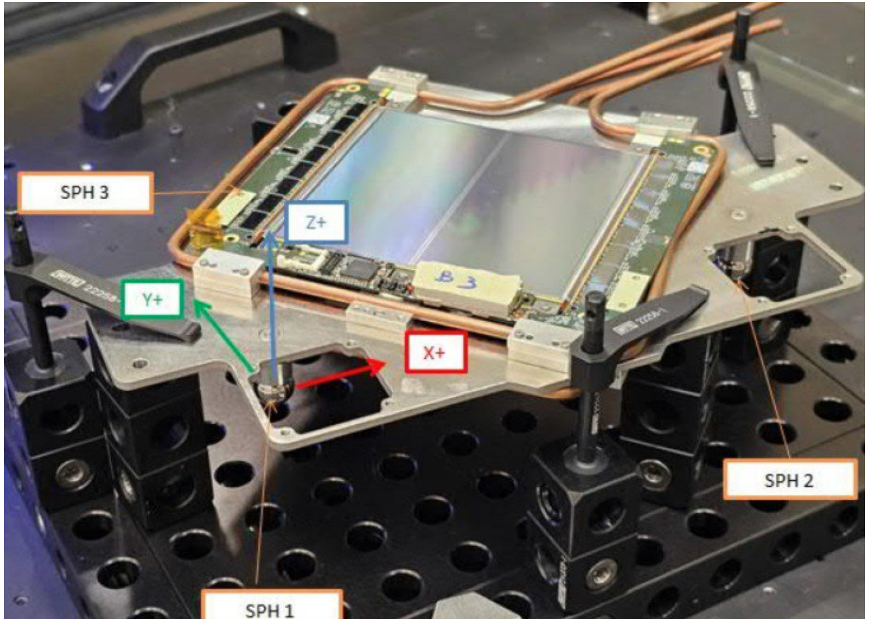
Frame



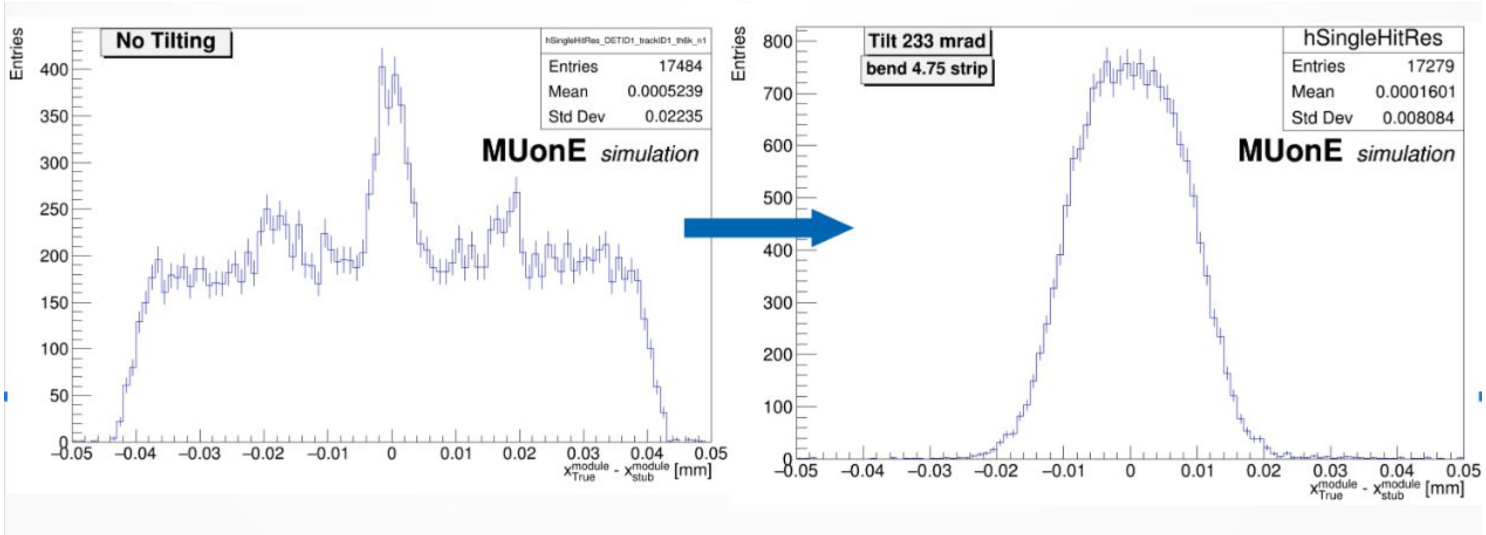
Mounting modules with the required precision quite difficult

Metrology

- Position and shape of a module on its frame can be measured precisely
- Position of the frame in the support station can be poorly established
- It may be we could improve the precision with the software alignment, but it has not been proved yet.



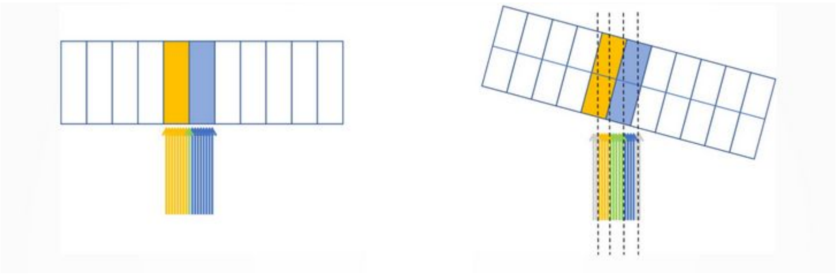
Tilting the XY modules



By tilting the module we do expect to improve the resolution:

22 μm →10 μm

The tilting angle is 14 degrees



Charge sharing

Recent results

- **Riccardo's presentation https://indico.cern.ch/event/1344029/**

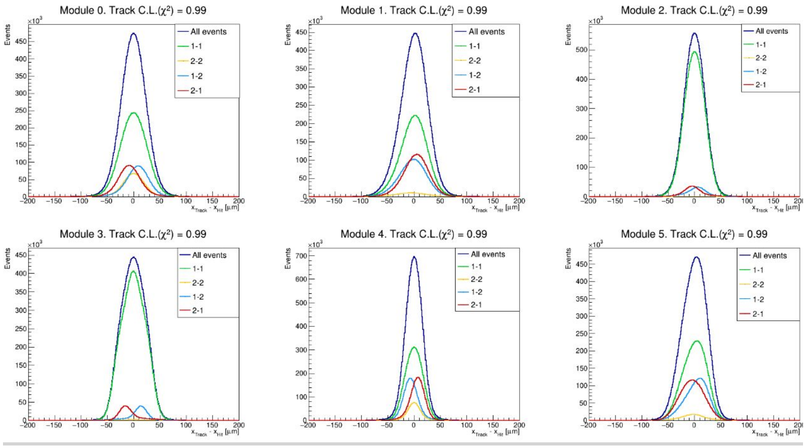
- **Tilting the modules seems to improve the resolution.**
- **Using the bend information improves the resolution.**

Results

- Average values from the last 6 iterations of all the 4 series of points to get the final estimate on the resolutions.

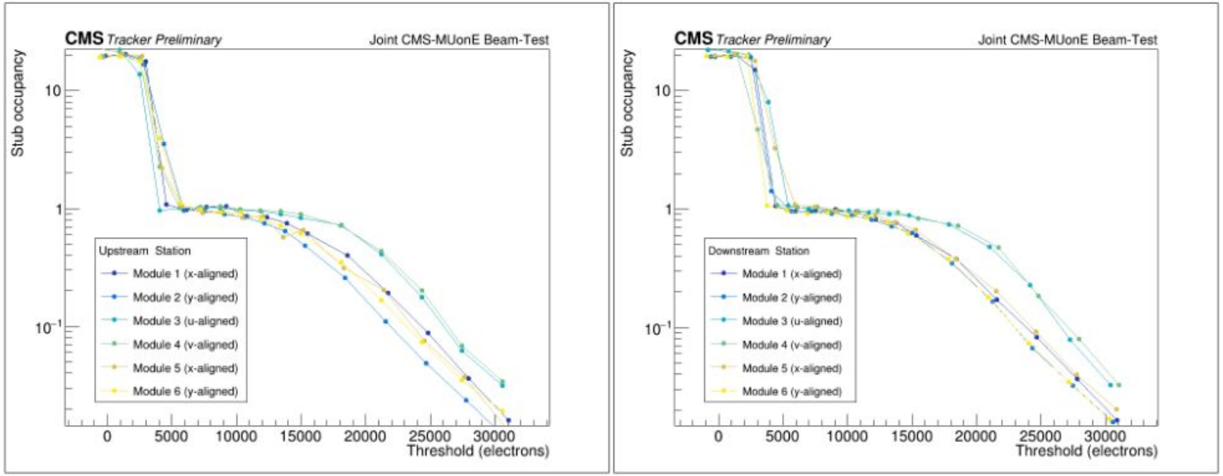
LinkID	σ_{Hit}, Bend [µm]	σ_{Hit}, without Bend [µm]
0	14.4	19.5
1	13.2	23.1
2	17.2	24.7
3	22.7	28.9
4	13.8	19.5
5	22.1	26.4
6	13.6	19.9
7	10.7	18.3
8	23.0	24.8
9	24.6	25.3
10	16.0	20.2
11	21.9	23.1

- On average, σ_{Hit} for tilted modules is better than non-tilted.
- Modules 5 and 11 (last Y in both stations) have a bad resolution (since they are tilted).
- Resolution improves using bend.



Occupancies vs threshold

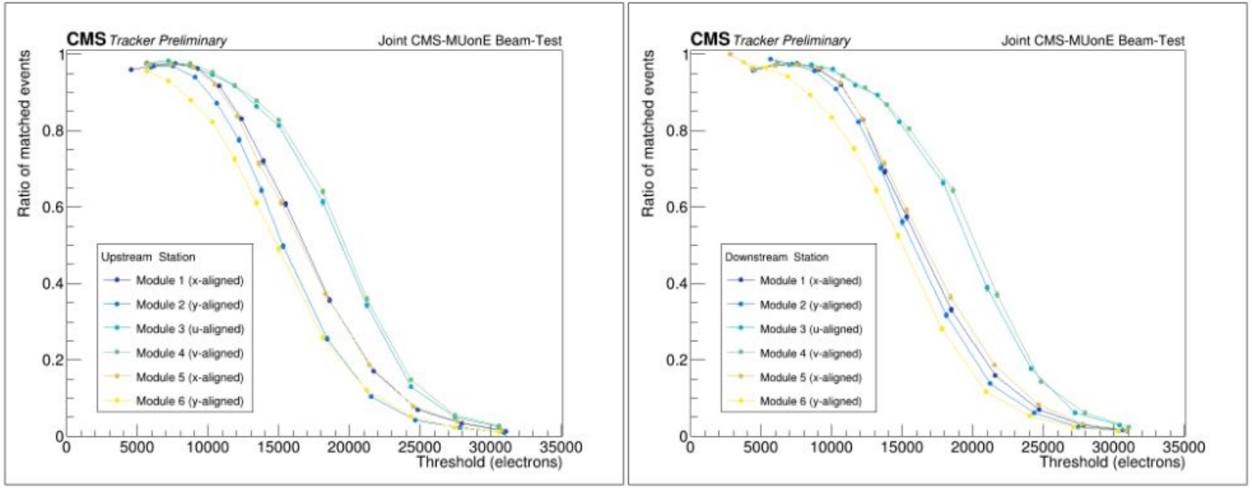
M. Delcourt for the CMS-TK group



Module stub occupancy as a function of applied comparator threshold for events where a single stub is observed in all other modules. Modules were scanned one at a time with the others being set at a nominal threshold of around 7500 electrons. The sharp increase at low threshold is caused by noise contribution, while the decrease at higher thresholds is due to the gradual efficiency loss.

Efficiency vs threshold

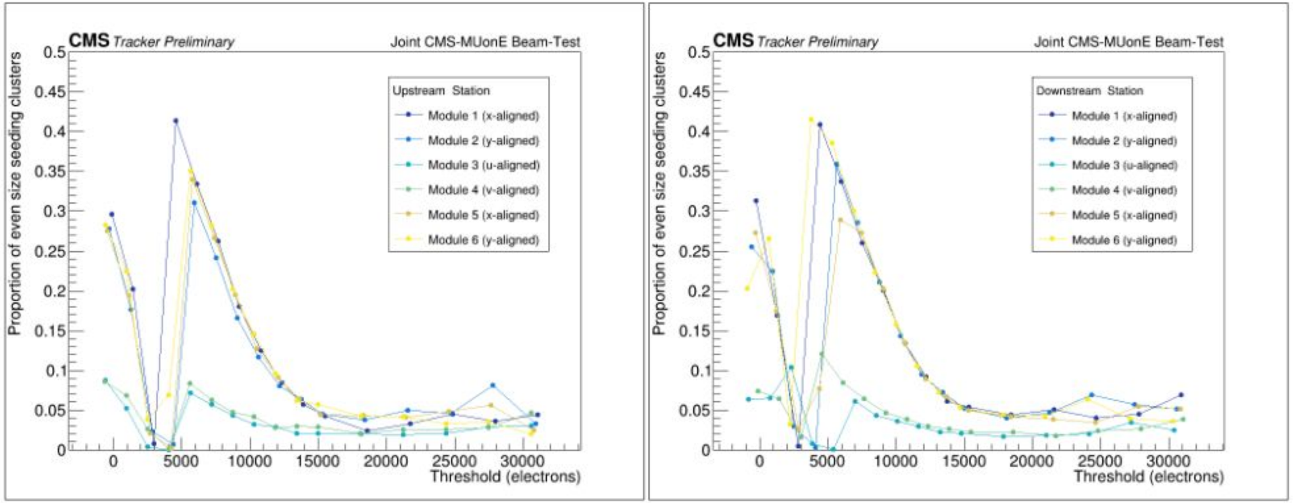
M. Delcourt for the CMS-TK group



Ratio of events with at least a stub in a given module when all other modules have measured a single stub, as a function of comparator threshold. Modules were scanned one at a time with the others being set at a nominal threshold of around 7500 electrons. The modules aligned in the “u-v” directions exhibit a higher efficiency at high thresholds due to the absence of tilting angle with respect to the beam, and therefore a reduced charge sharing between strips.

Proportion of stubs of given size

M. Delcourt for the CMS-TK group

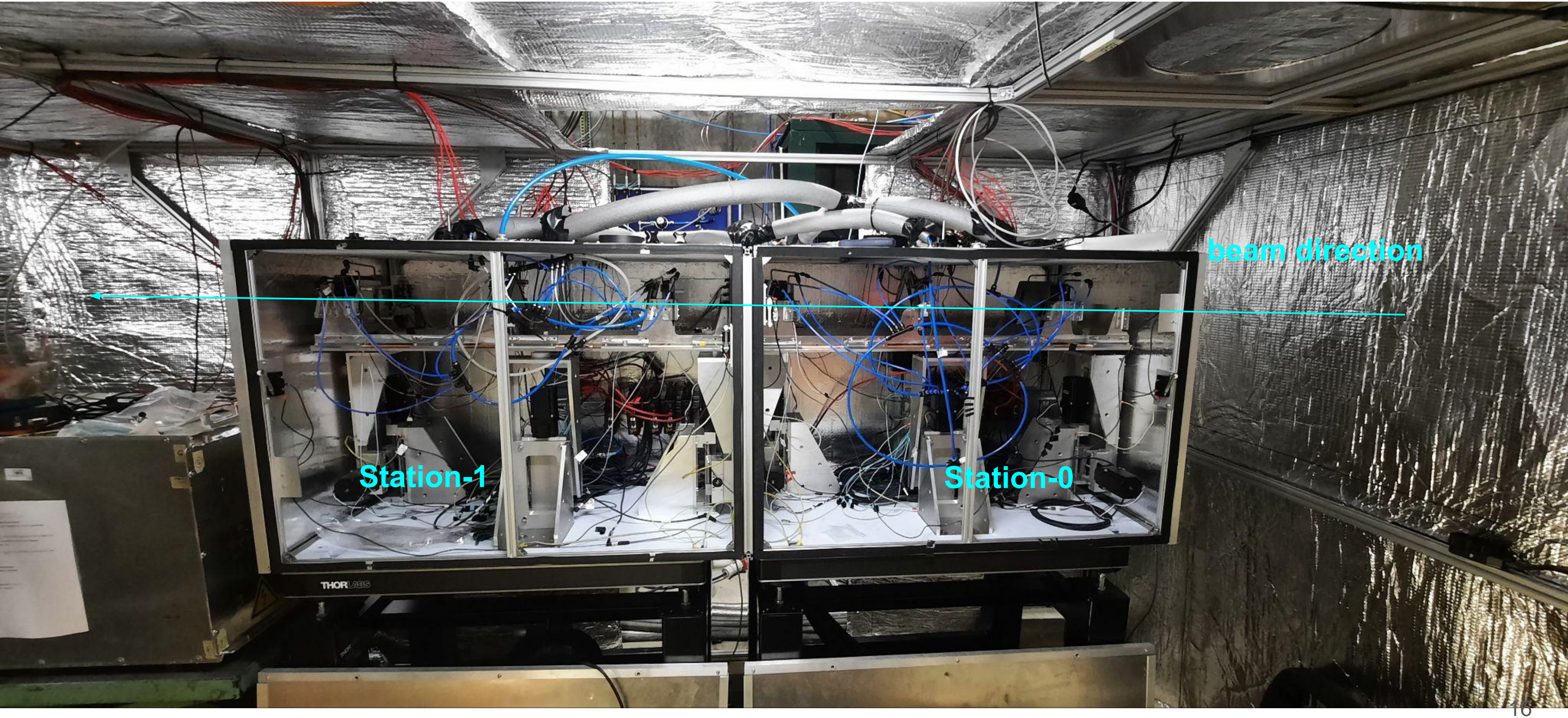


Proportion of stubs with seeding cluster of even size as a function of threshold. The gradual increase when lowering the threshold is caused by the appearance of clusters of size 2 due to charge sharing, while the abrupt changes at very low thresholds are caused by the appearance of noise stubs.

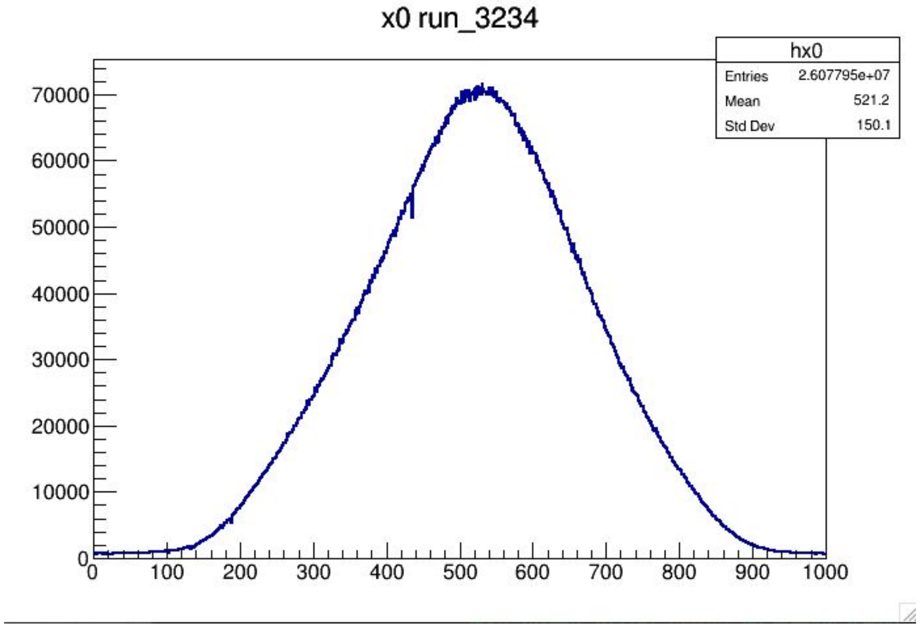
Trying to measure the detection efficiency

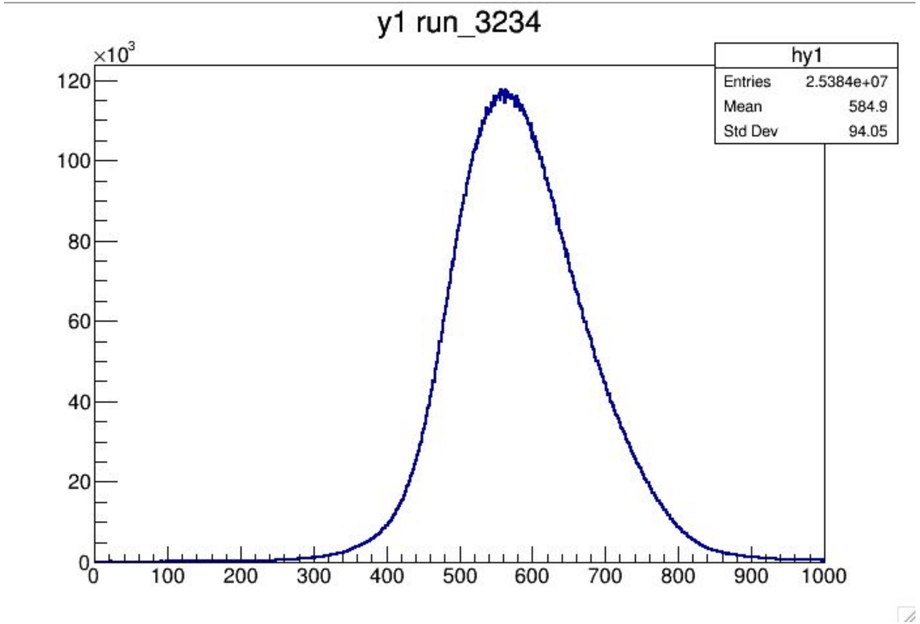
- How many muons have entered the detector in a given run?
- How many of them can be exploited for the analysis?
- High intensity run used for the analysis.

The two tracking stations



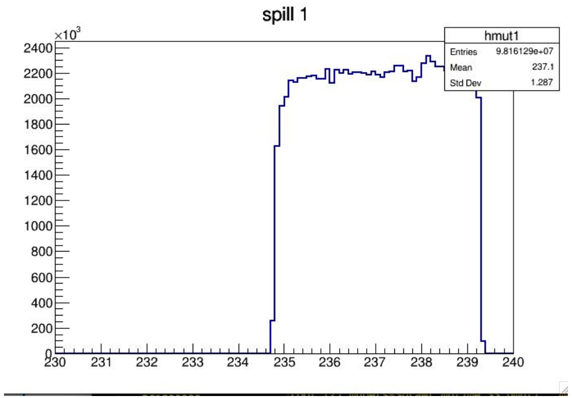
Run 3234. Beam profile

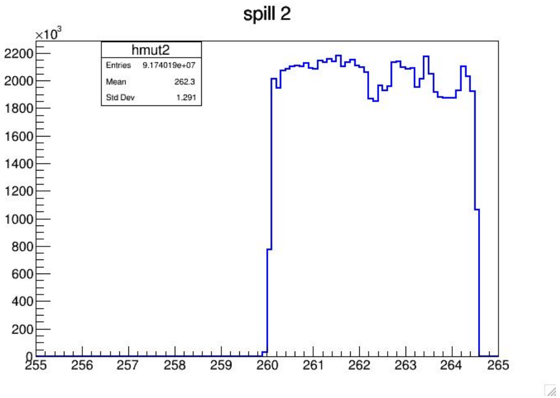


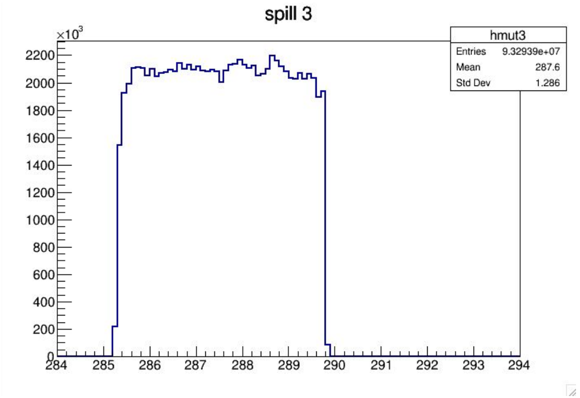


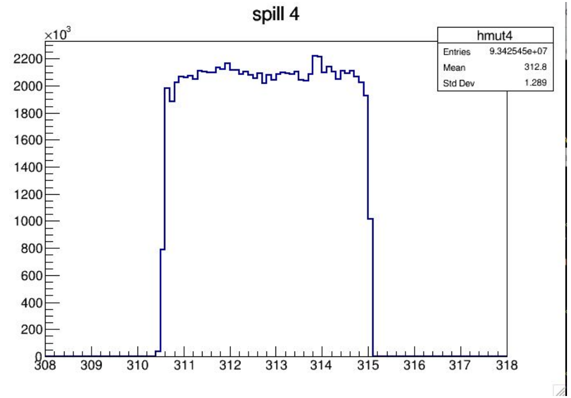
The beam is entirely in the detector acceptance

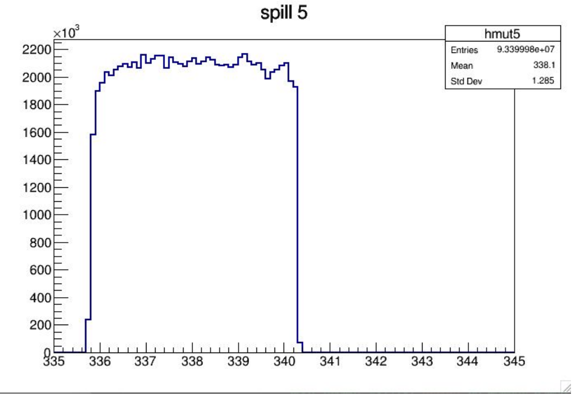
Run 3234. Event time distribution: spills





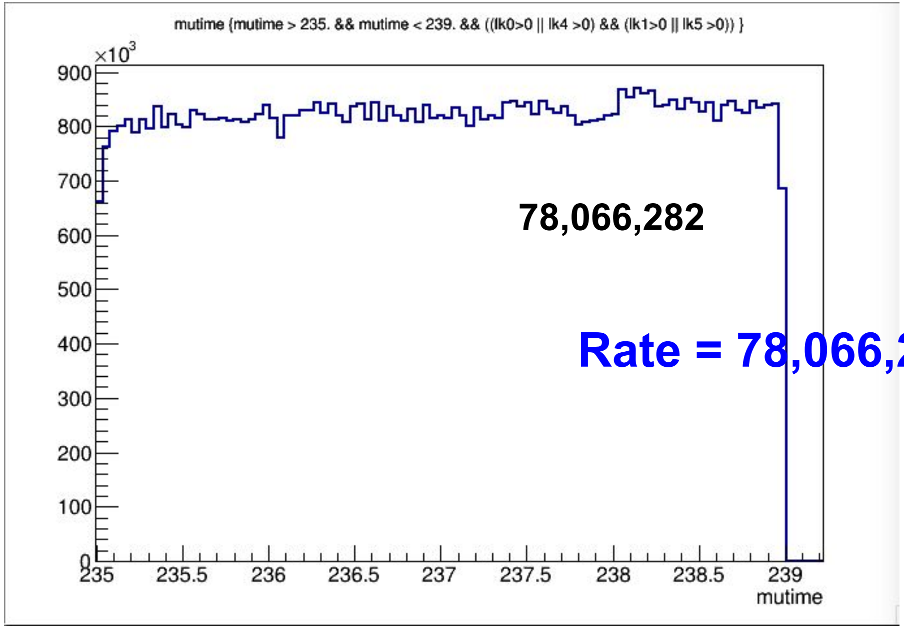






Run 3234. How to measure the muon rate?

- **Entries that satisfies the conditions:**
  (lk0>0 || lk4 >0) && (lk1>0 || lk5 >0) = stub in X AND stub in Y



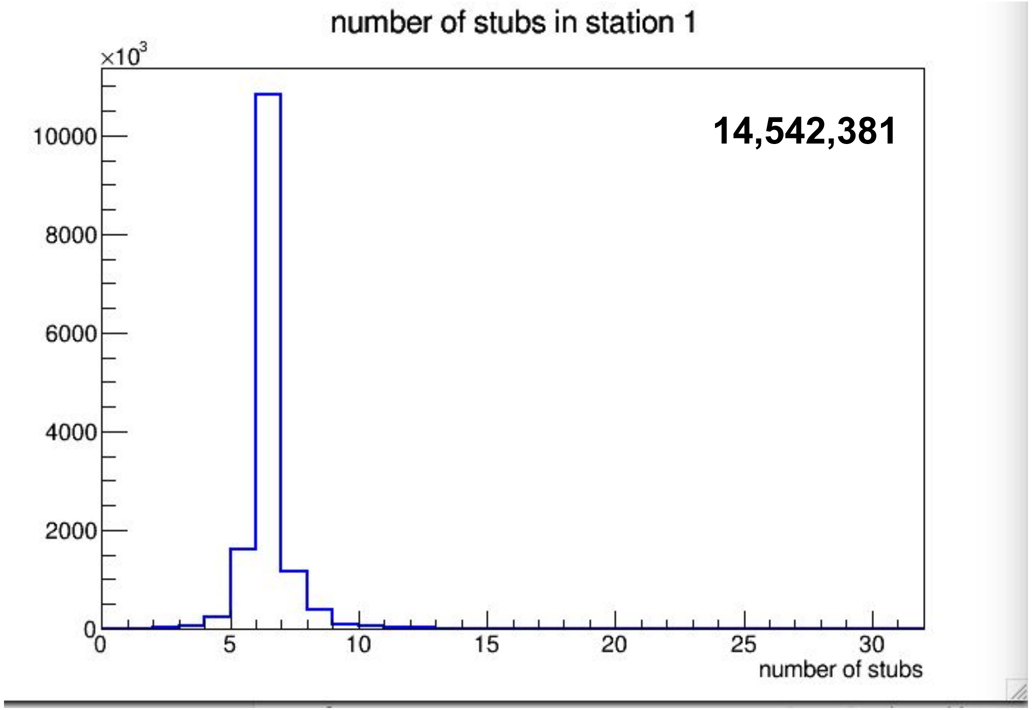
Rate = 78,066,282. (entries) / 4. (s)= 19.5 MHz

Entries to count muons in the detector

- Entries in a spill: 93,167,353
  The cut ns0 >=2, to get rid of what could be accidentals.
- Double muons candidates: 24,171,402
  ns0 >=10 && ns0 <= 15
- Triple muons candidates: 8,593,523
  muns0 >=16 && muns0 <= 22
- Muons in total:
  93167353. (total as single) + 24171402. (double correction) +
  2. * 8593523. (triple correction) = 1.3452580e+08 = 1.3E+8/spill
- Considering the dead time and the efficiency of 0.9,
  the M2 muon per spill ~ 150 M /spill = 1.5E+8 muons/spill
- From the M2 accelerator expert:
  " I checked the beamline settings from 4th to 5th September and comparing with what we had last year what I can say is the rate will be more than > 1.4E8 per spill. As we had the number of units slightly less this year the rate must have been between 1.4 to about 1.6E8 per spill."

Run 3234, HI, merged, station-1

n. of stub in station-1 when a golden muon is detected in station-0.



They are 14,896,292 if lk5>=1

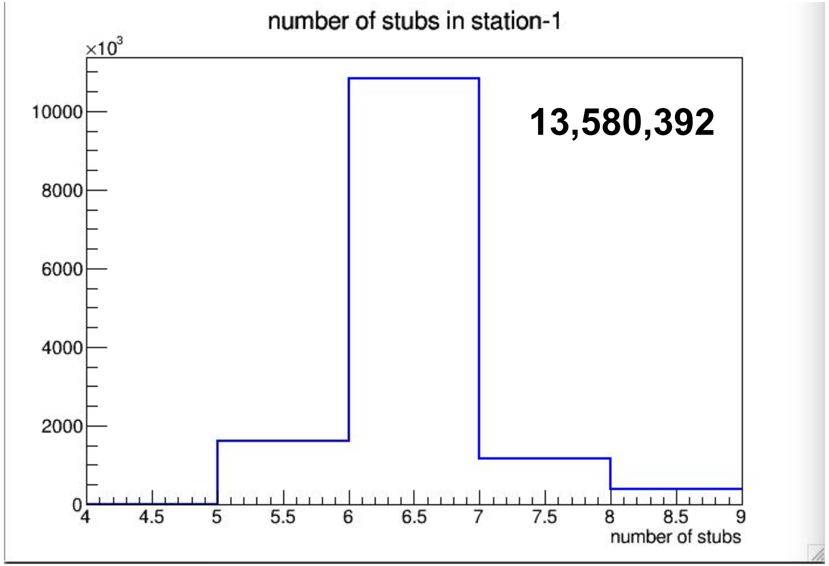
ns1	counts
0	0
1	1804
2	19685
3	43,696
4	237,962
5	1,617,138
6	10,824,266
7	1,157,675
8	389,170
9	95,856
10	66392

There is a muon in station-0

A muon candidate is in 5 <= ns1 <=8

Run 3234, HI, merged, station-1

- Golden muons selected in station-0
- Single muons candidates detected in station-1, with 5 <= ns1 <= 8.
- To be reconstructed there must be at least one stub in U OR V modules.
  TCut lk56 = "(lk5>=1 && lk6>=1) || (lk5>=1 && lk6==0) || (lk5==0 && lk6 >=1)"

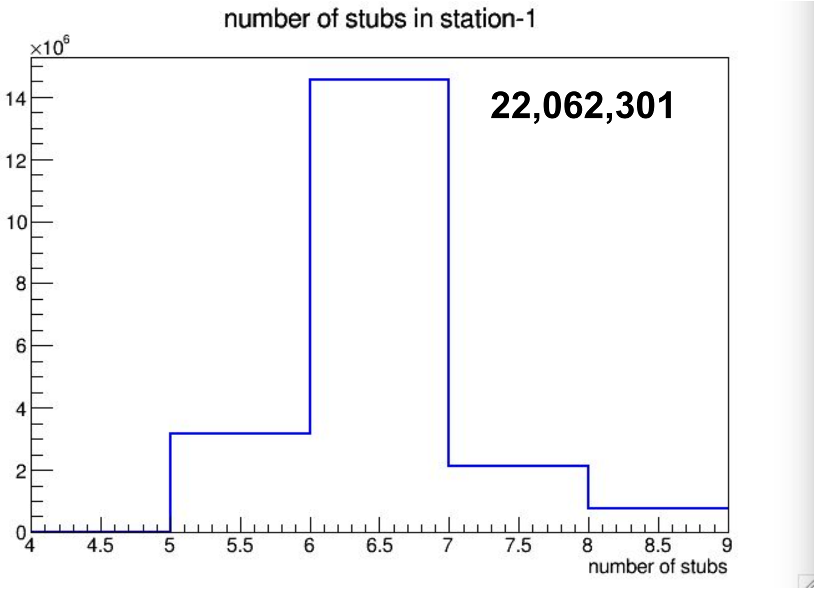


The detection efficiency of a single muon candidate in station-1, for a golden muon in station-0:
13,580,392 / 14,542,381 = 0.934

They are:
14,301,002/14,896,292 = 0.960
allowing lk5>=1

Run 3234, HI, merged, station-1

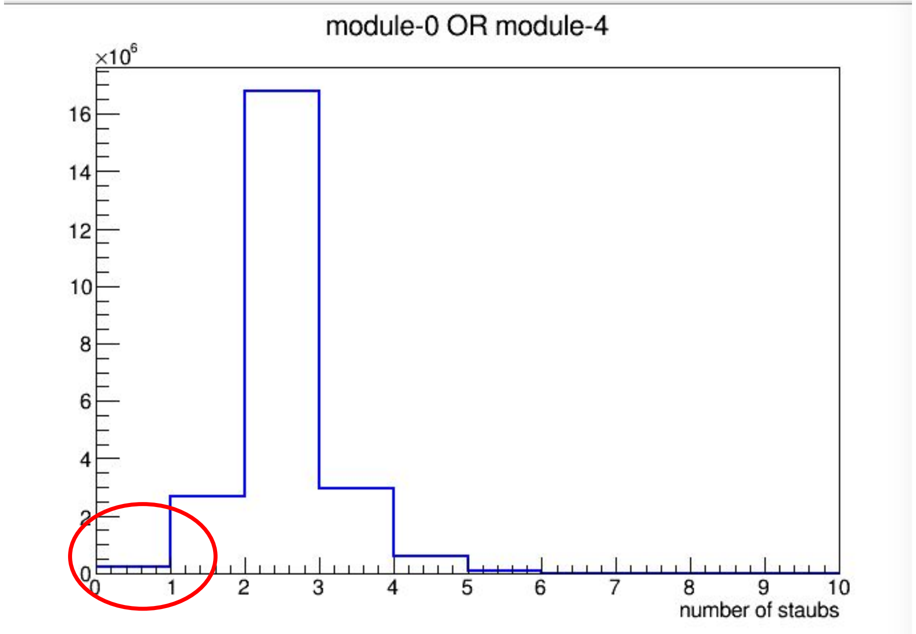
- Single muon candidate reconstructable in station-0: 24,923,478
- Single muon candidate reconstructable in station-1: 22,062,301



The efficiency muon-1 / muon-0 is:
22,062,301 / 24,923,478 = 0.885
muon-0 / entries
24,923,478 / 54,751,115 = 0.455

OR of the modules

- Considering the OR of the X modules in station-0, for reconstructable muons in stations-1 one gets:
- #(single muon in station-1) = 25,160,221
  #(lk0 == 0) =
  1,294,330 no stubs in module-0, 5.1% of the cases
  #(lk4 == 0) =
  2,092,825 no stubs in module-4, 8.3% of the cases
  #(lk0 + lk1 == 0) =
  219,806, no stubs in both of them 0.8% of the cases



Towards an improved detector geometry

- **We should test a redundant configuration with the 2S before 2025**
  S10 = XY(XYUVXY)XY
  It should improve efficiency and pattern recognition.
- **We know there are drawbacks, due to the material budget.**
- **It brings to the concept of 1S**
  With a constant material budget we could get 6 hits per projection.

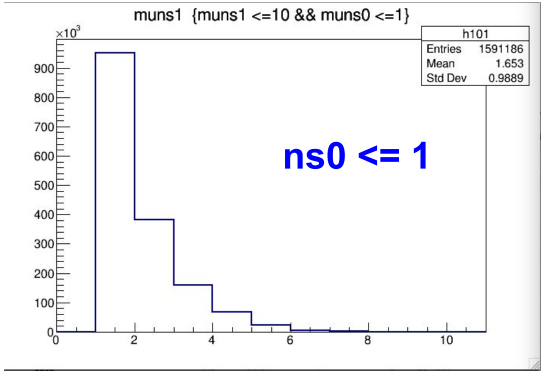
Conclusions

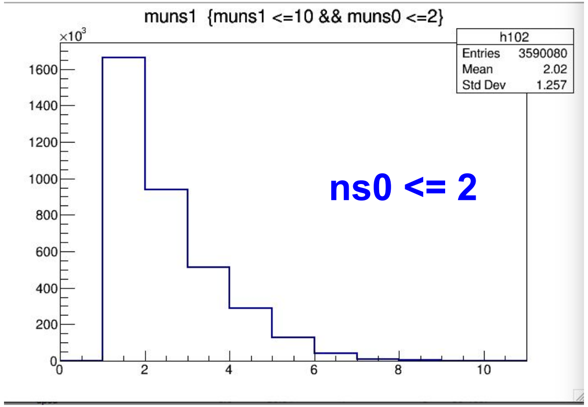
- **We proved that elastic processes can be detected at high rate, with an asynchronous beam.**
- **We have to improve the detector design in several aspects**
- **Two phases for the experiment have to be considered:**
  - Short term plan, to improve the detector and possibly make a first measurements before the LS3;
  - Long term plan, looking beyond the LS3, to get the final result.

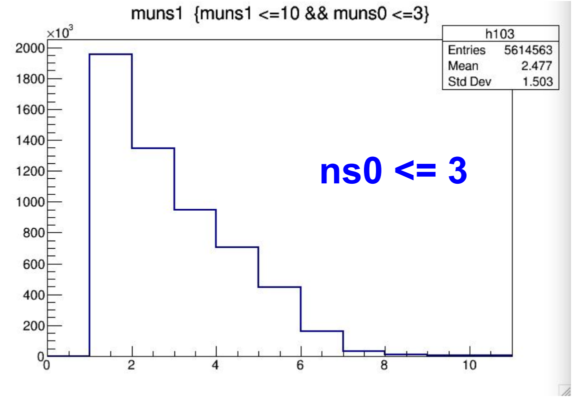
The end

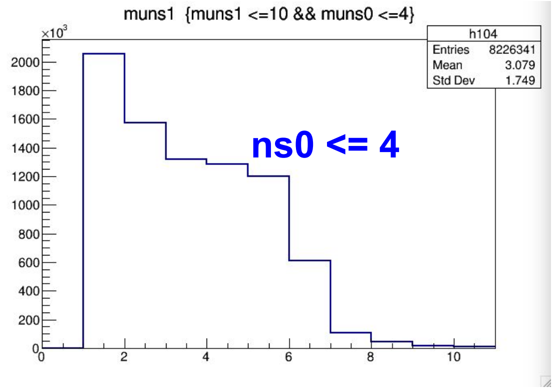
Run 3234, HI, merged, station-1

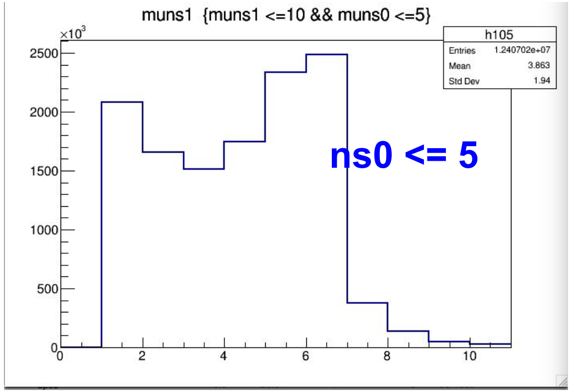
Are they muons? Let's look at the distributions in station-1

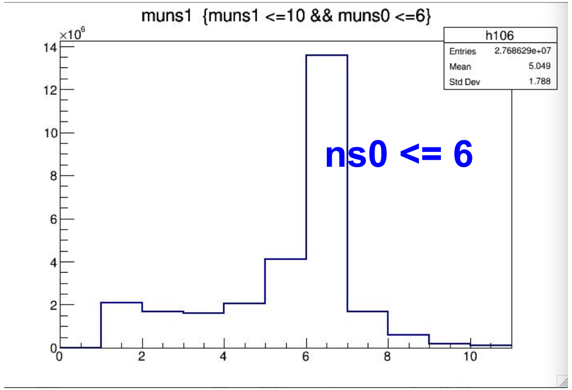




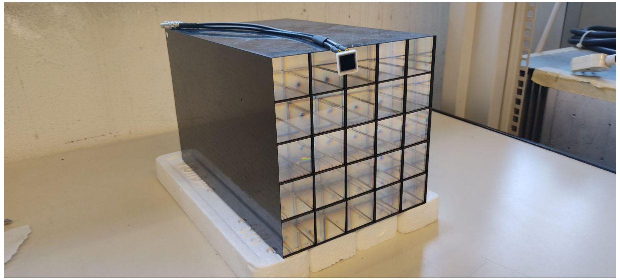


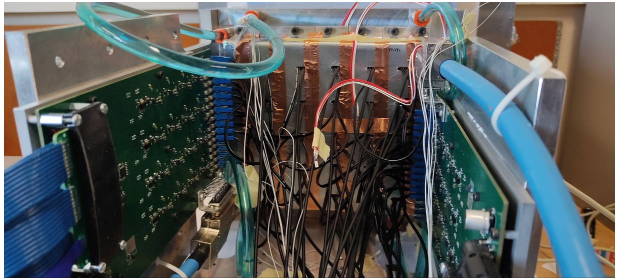


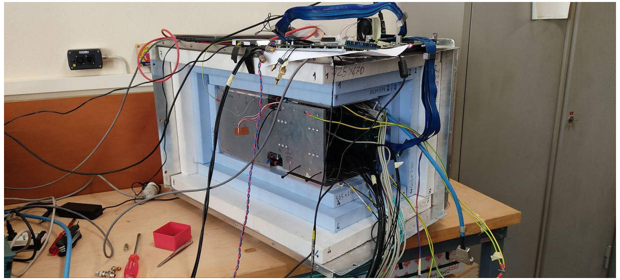


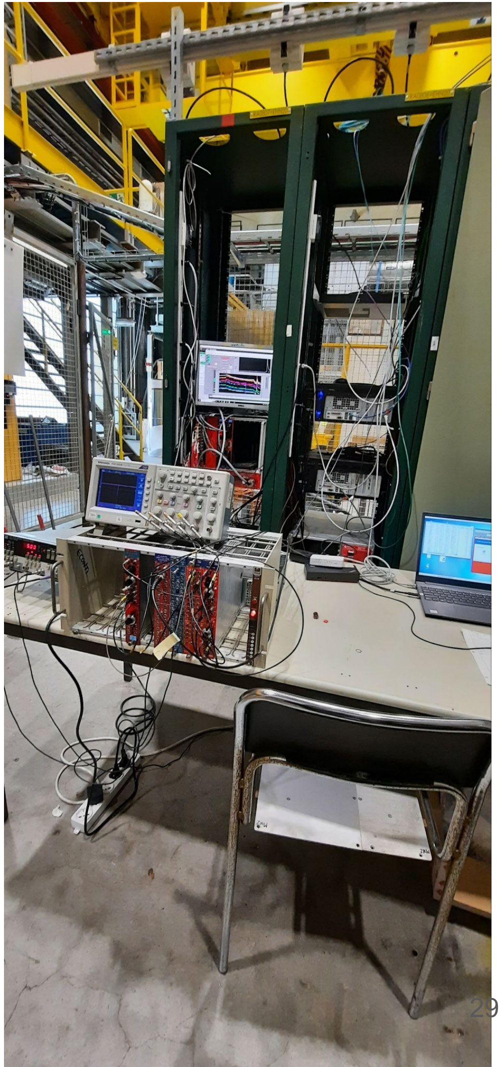


The calorimeter





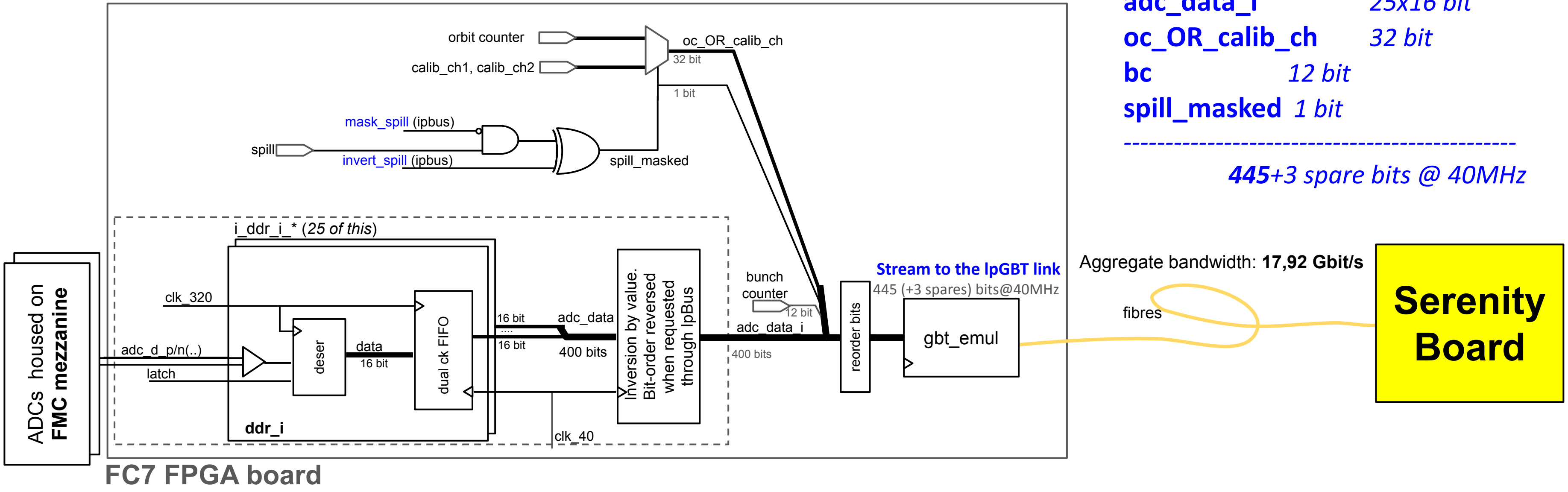




25 $PbWO_4$ crystals
FE uses MPGA by CMS

Streaming ADC samples to the Serenity at 40 MHz

All 25 ADCs connected to the Crystal's APT are streamed with a unique time reference via an optical link toward the TRACKER Serenity board



Data serialized over the fiber

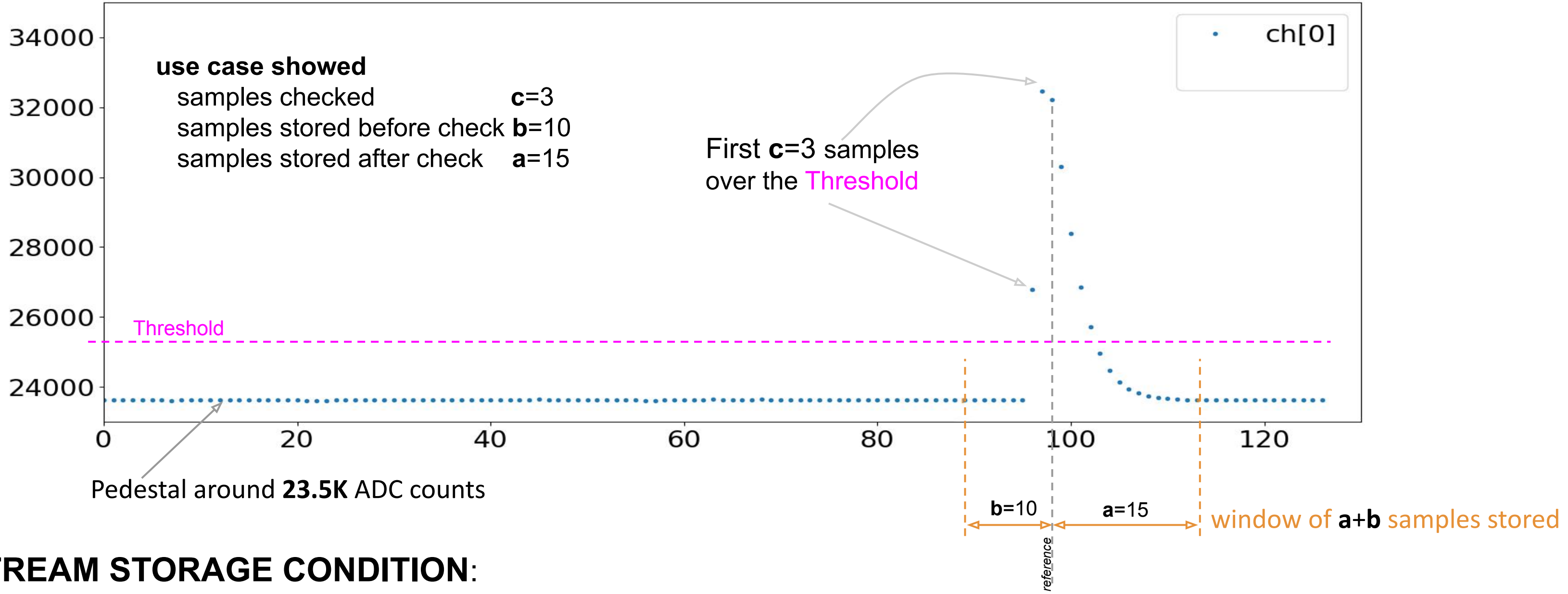
adc_data_i	*25x16 bit*
oc_OR_calib_ch	*32 bit*
bc	*12 bit*
spill_masked	*1 bit*

445*+3 spare bits @ 40MHz*

Fabio Montecassiano INFN - Padova

ECAL Zero Suppression module: how it works

The picture shows the real ADC samples (blue dots) streamed on channel[0] after a laser test pulse



STREAM STORAGE CONDITION:

*For each channel, when **c** consecutive samples exceed the channel threshold, a window of (**a**+**b**) samples for a selected group of channels - even all - will be stored on the hard disk*.

The *reference* for the window is the last sample that satisfy the above condition, where

- **b** sets the no. of samples stored before the *reference*
- **a** sets the no. of samples stored after the *reference*

A downscale of the bandwidth is possible by introducing a **DEADTIME** between 2 consecutive storage requests.

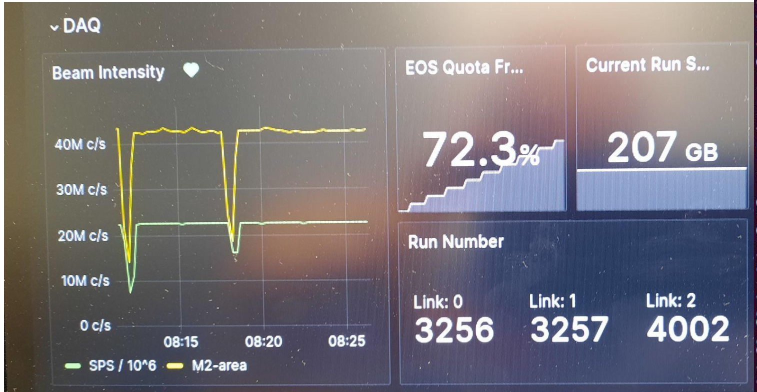
Data volumes

bash> du -h

- Data are stored on CERN's EOS
- We collected RAW data for about 200 TB
- DECODED data generates 200 TB
- Size of the RAW data can be reduced by compression by a factor 2.
  It costs CPU but save TAPE space.

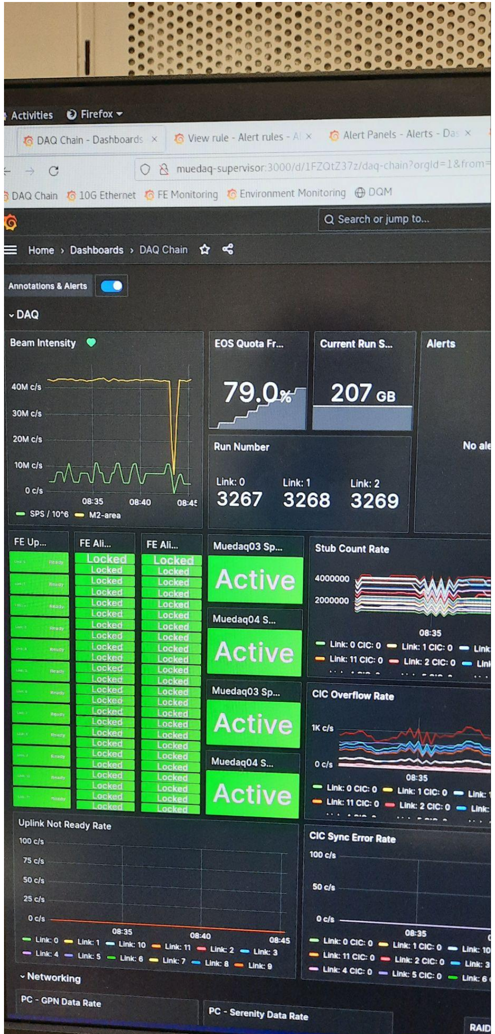
```
1,9T	./commissioning/run_3233
1,3T	./commissioning/run_3234
989G	./commissioning/run_3235
183G	./commissioning/run_3236
490G	./commissioning/run_3237
25T	./commissioning/run_3238
26T	./commissioning/run_3239
135G	./commissioning/run_3240
122G	./commissioning/run_3241
11T	./commissioning/run_3242
15T	./commissioning/run_3243
1,6T	./commissioning/run_3244
1,6T	./commissioning/run_3245
19T	./commissioning/run_3246
19T	./commissioning/run_3247
18T	./commissioning/run_3248
26T	./commissioning/run_3249
74G	./commissioning/run_4001
579G	./commissioning/run_4002
694G	./commissioning/run_4003
68G	./commissioning/run_4004
34G	./commissioning/run_4005
27G	./commissioning/run_4006
337G	./commissioning/run_4007
99G	./commissioning/run_4008
17G	./commissioning/run_4009
3,4G	./commissioning/run_4010
10G	./commissioning/run_4011
10G	./commissioning/run_4012
991G	./commissioning/run_4013
990G	./commissioning/run_4014
27G	./commissioning/run_4015
32G	./commissioning/run_4016
89G	./commissioning/run_4017
89G	./commissioning/run_4018
200T	./commissioning
```

EOS quota 72.3%



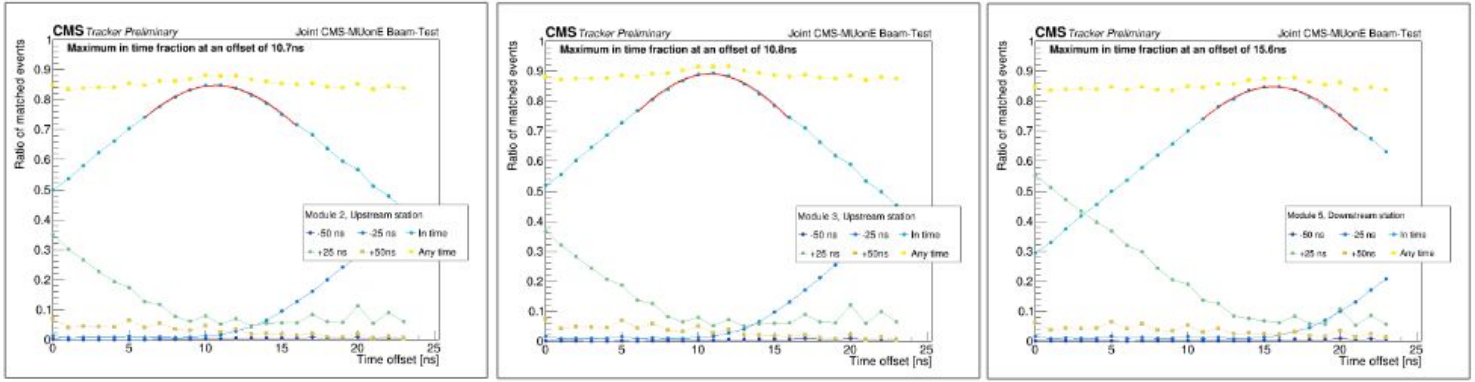
Disk space available in EOS

We have consumed 80% of the disk space available



2S module synchronisation

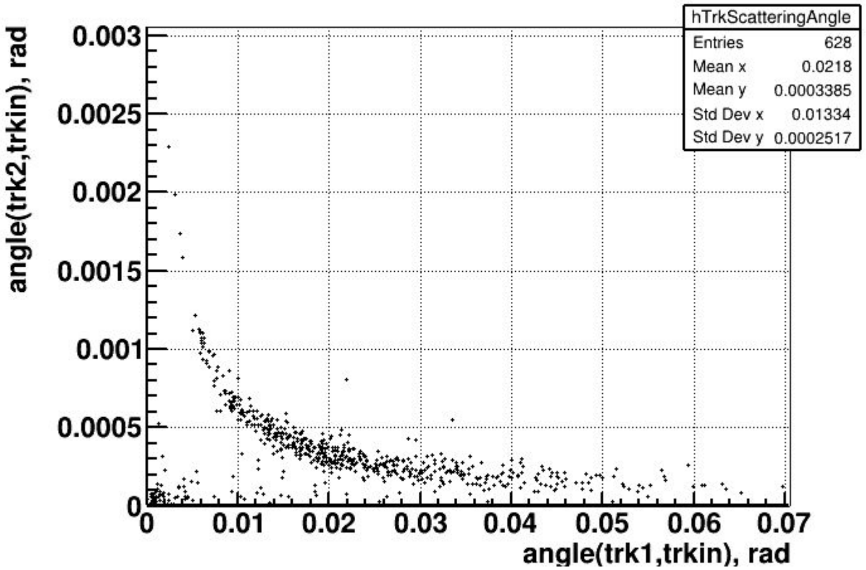
M. Delcourt for the CMS-TK group

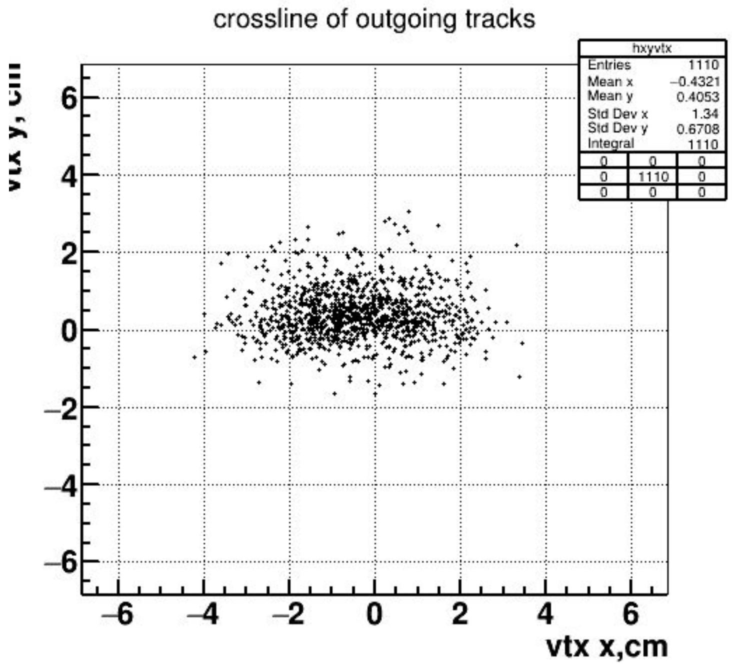


Ratio of events with a stub in a given module when a single stub is seen in the first module of the corresponding station, split by assigned timing and combined, as a function of module internal time offset. The 25ns granularity in the timing assigned to events corresponds to the bunch crossing frequency of the Large Hadron Collider. The reference module has an internal delay set to 12ns, and the ideal offset is obtained by measuring the maximum in-time ratio through a gaussian fit.

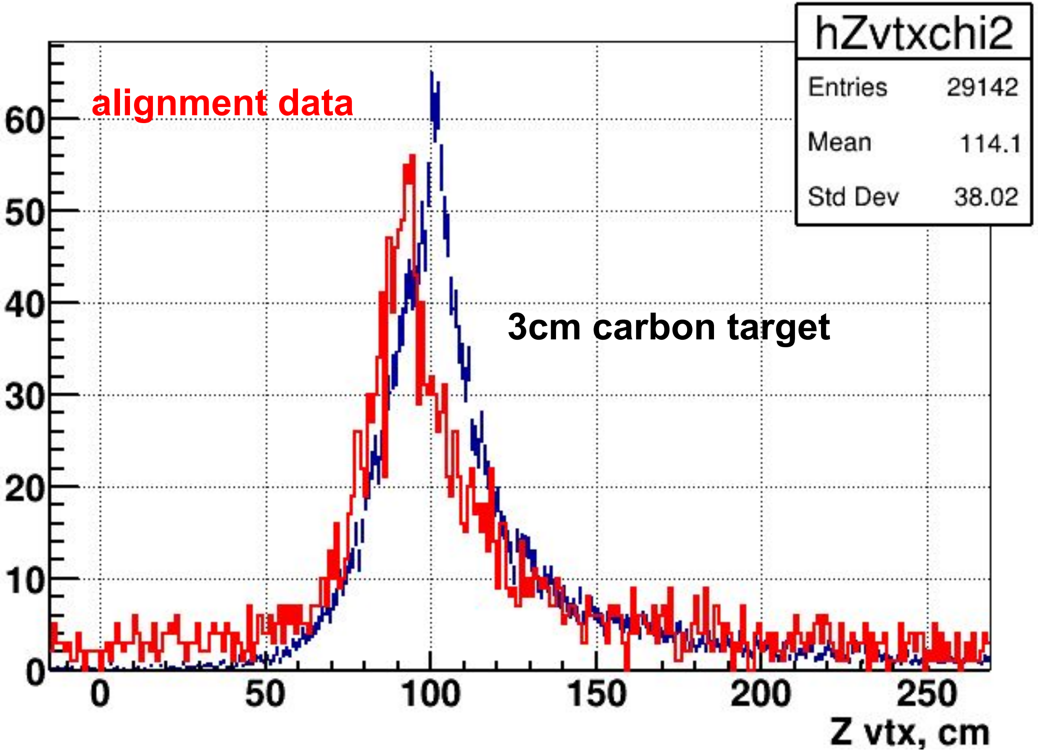
First 2D plots of the elastic collisions

- **High intensity muon beam alignment data**





Z positions of the vertices

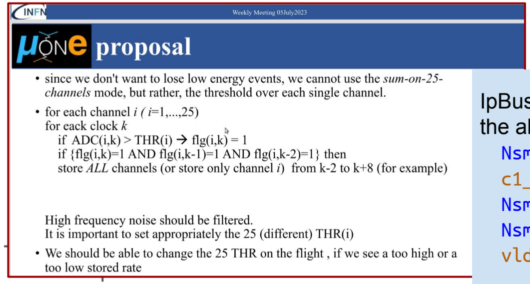


The End

ECAL Zero Suppression module: Firmware integrated on the TK SERENITY board

A proposal for the algorithm has been presented during MUonE Wednesday Weekly July 5, 2023.

Here a proposal for an efficient FPGA implementation, much more general than requested by the algorithm specified the July 5th ====>


INFN Weekly Meeting 05July2023

μONe proposal

- since we don't want to lose low energy events, we cannot use the *sum-on-25-channels* mode, but rather, the threshold over each single channel.
- for each channel *i* (*i*=1,...,25)
  for each clock *k*
  if ADC(i,k) > THR(i) → flg(i,k) = 1
  if {flg(i,k)=1 AND flg(i,k-1)=1 AND flg(i,k-2)=1} then
  store *ALL* channels (or store only channel *i*) from k-2 to k+8 (for example)

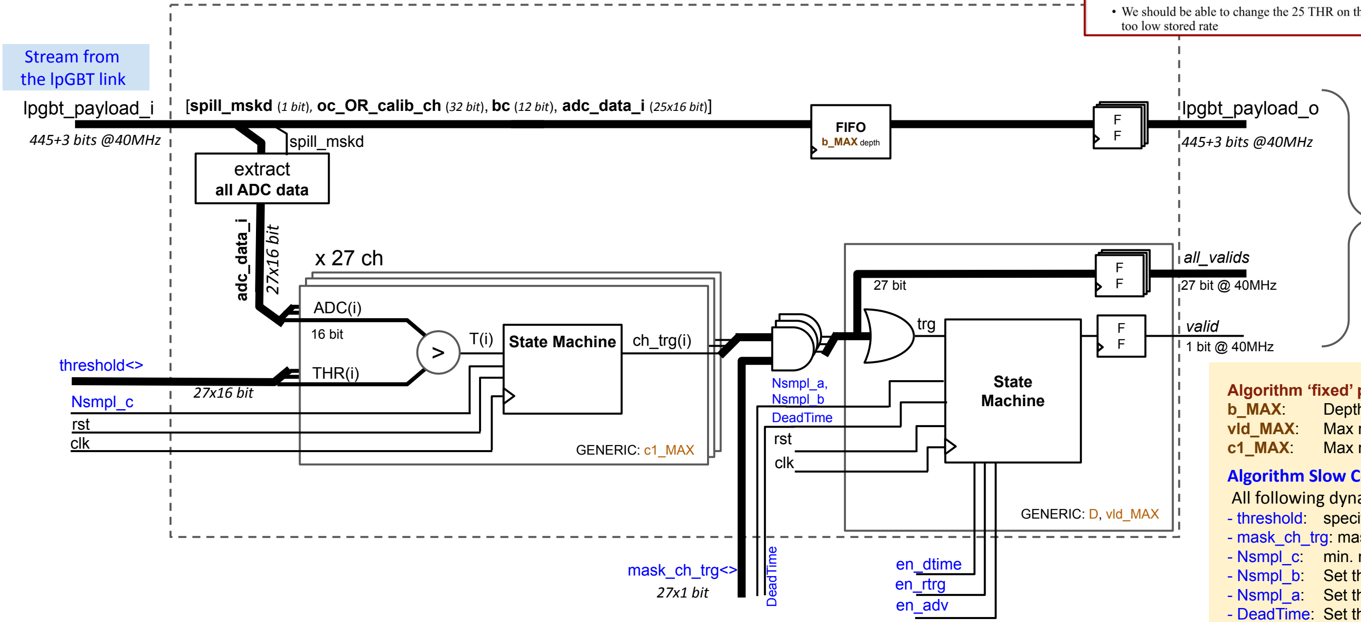
High frequency noise should be filtered.
It is important to set appropriately the 25 (different) THR(i)

- We should be able to change the 25 THR on the flight , if we see a too high or a too low stored rate

IpBus parameters satisfying the algorithm proposed:

```
Nsmpl_c = 3
c1_MAX  = 5 (must be >= Nsmpl_c)
Nsmpl_b = 3
Nsmpl_a = 8
vld_MAX = 11

mask_ch_trg = 0x07FFFFFF
en_rtrg = '0'
en_dtime = '0'
DeadTime = 0
```



to the STORAGE manager that can decide whether to store all the channels or just a subgroup

Algorithm 'fixed' parameters

b_MAX: Depth of the FIFO
vld_MAX: Max no. of clocks after which the deassertion of **valid** is forced
c1_MAX: Max no. of clocks with T(i)='1' after that deassertion of **ch_trg(i)** is forced

Algorithm Slow Control via Serenity IpBus

All following dynamic parameters must be sync with the module clock

- threshold: specifies the *threshold* value for each channel (array 27x 16 bit)
- mask_ch_trg: mask specific channels (array 27x 1 bit)
- Nsmpl_c: min. nr. of consecutive samples whith T(i)='1' required for ch_trg(j) assert.
- Nsmpl_b: Set the nr. samples to be stored BEFORE the assertion of **trg** signal
- Nsmpl_a: Set the nr. samples to be stored AFTER the assertion of **trg** signal
- DeadTime: Set the no. of clocks during which the trg is masked
- en_dtime: Flag activating DeadTime counter [1bit]
- en_rtrg: Flag enabling re-triggering [1bit]
- en_adv: Flag enabling advanced mode [1bit]

A bank of 32x 32bits IpBus registers would be enough

Fabio Montecassiano / INFN - Padova