Dose profiler: status and prospects

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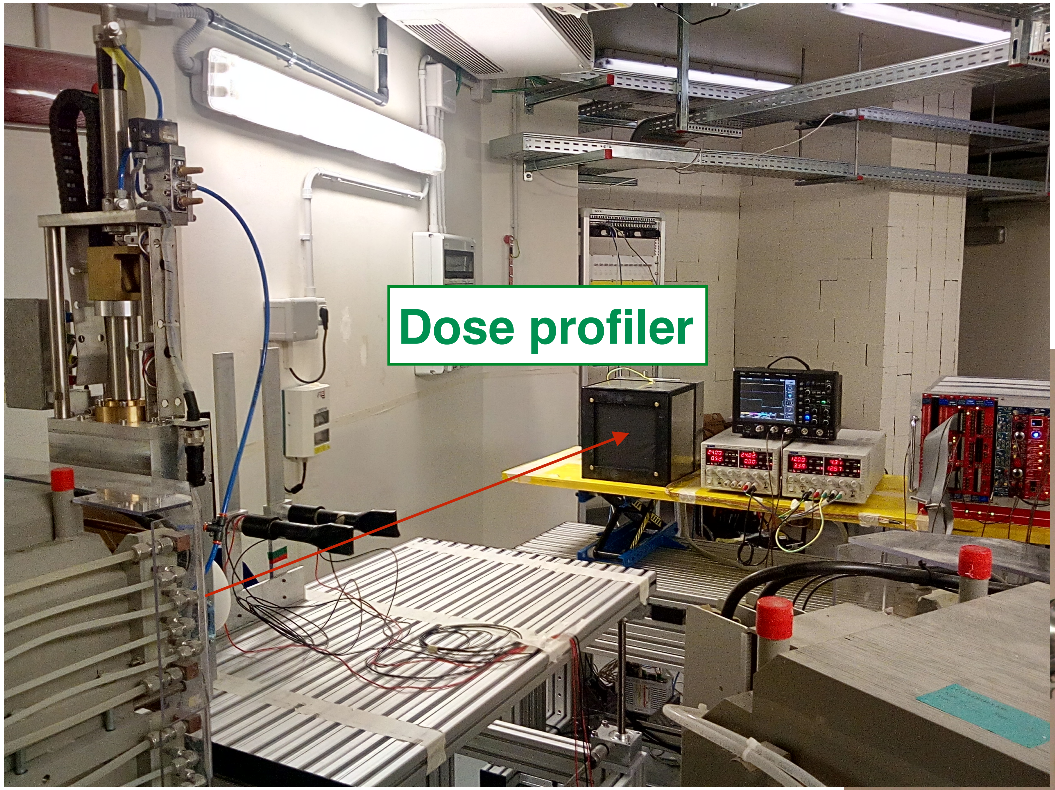
Where do we stand

- Time line (2017)
  - **May: the birth of DP**
  - June: a first test using protons @Trento
    - Hardware check performed → Improved mechanical assembly of boards, alignment of SiPMs with fibres
  - July: collected a lot of data @Trento and CNAO
  - September - October: HW and SW development to address some issues spotted in the July data taking
  - **November: additional data taken @ CNAO.**
- A large amount of data that is currently being digested / understood.. and a detector that is nearly newborn….
  - [these have been 7 crazy months for us :D !!!]

The final question

- What will be the resolution on the BP position during a treatment?
  - The answer is far from trivial! Many factors that are 'treatment-patient dependent' have to be addressed
- All the work done so far and the data taken has been devoted to answer properly this question.. We are currently:
  - benchmarking our resolution in clinical conditions → How many events we can integrated and what is the final 'single track resolution'….
  - studying the hardware response (efficiency, dead time)
  - developing the software tools needed for the online deconvolution of the matter effects
- **No final / conclusive answer ye**t… But we learned a lot and managed to have a clear path for improvements in the near future.
- Details in the next slides….

Data taking conditions

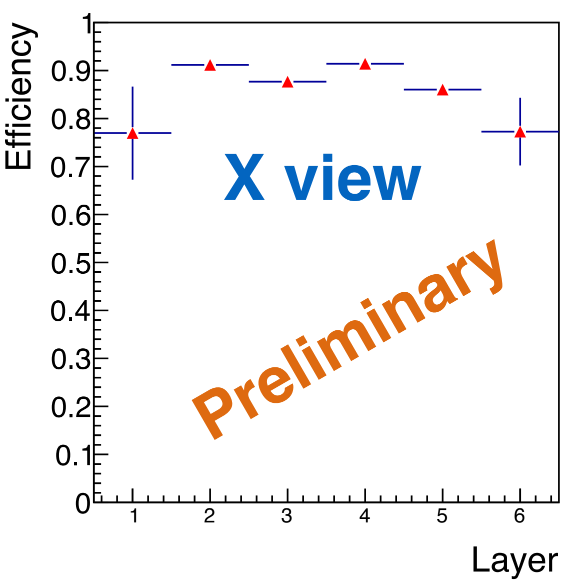


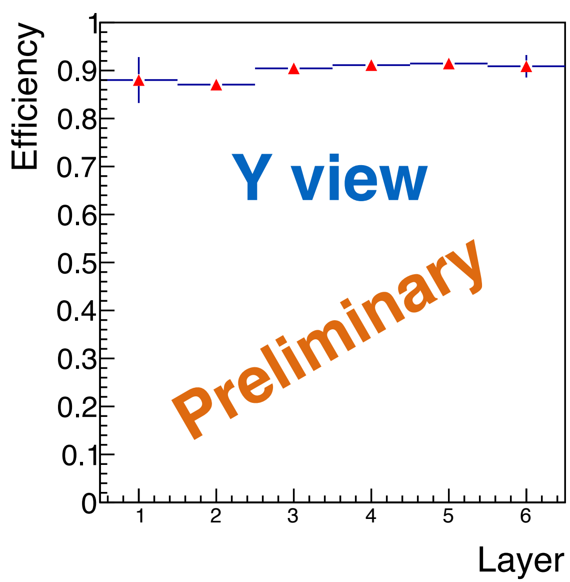
The hardware response

- How is the detector doing?
  - The design rate has been reached (10 kHz).
  - The single layer efficiency is well above 80% in all detection planes and views.
  - Operation at 14°C has proven to be stable and the DAQ was smooth even at clinical intensities with very large backgrounds.
- In the meanwhile, we discovered that:
  - we have an unstable behaviour of some BASIC cards (currently being investigated)
  - We have a dead time that is much larger wrt the one expected

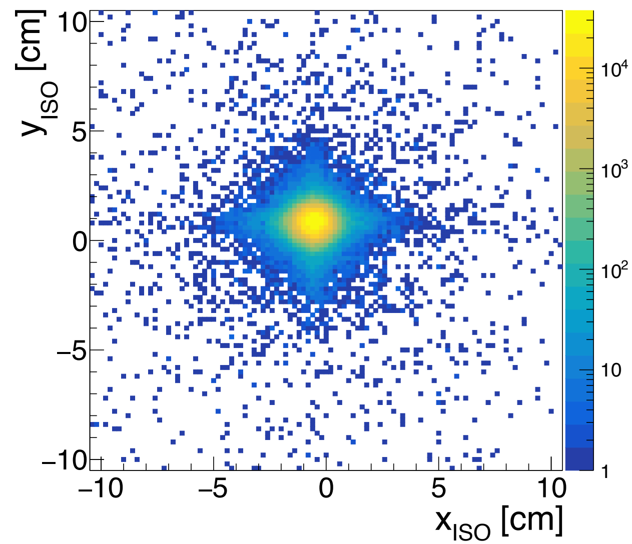
DP tests @ Trento

- Used protons from Trento to measure the detector performance.



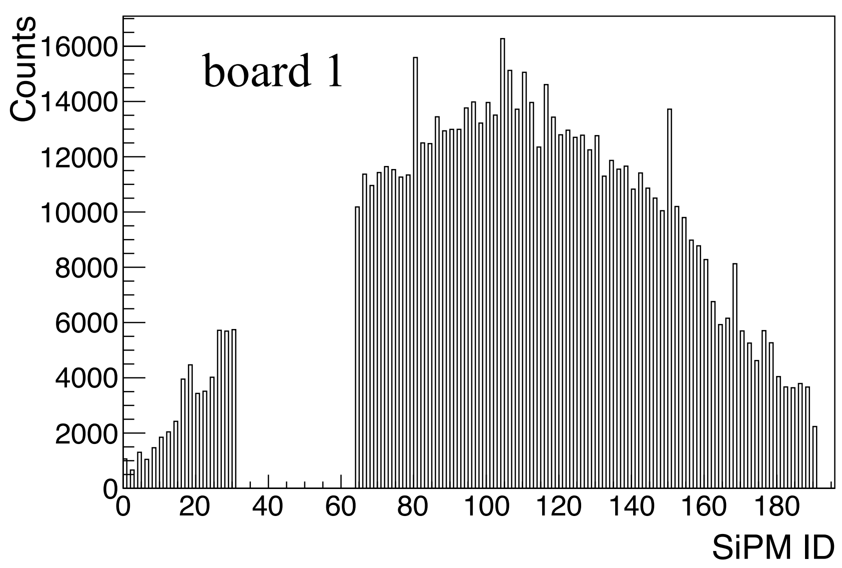


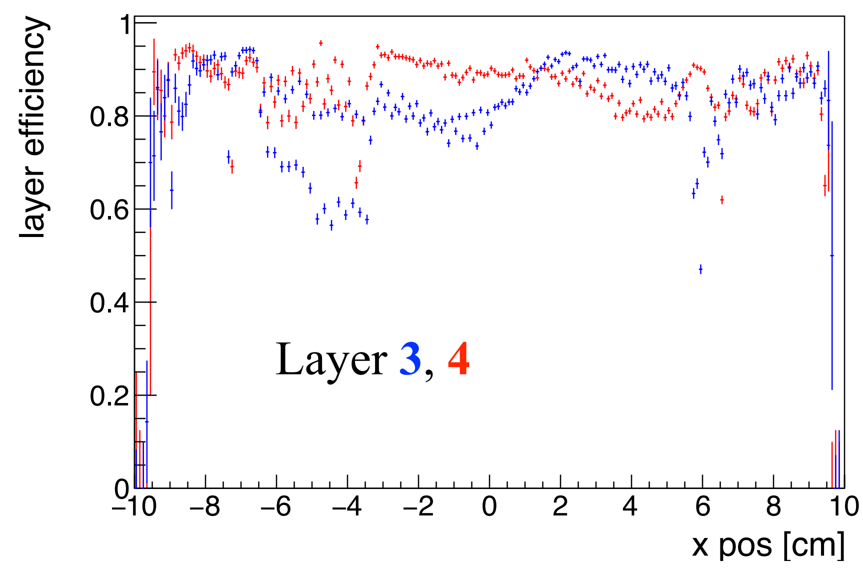
Proton beam as seen from dose profiler



Unstable basics

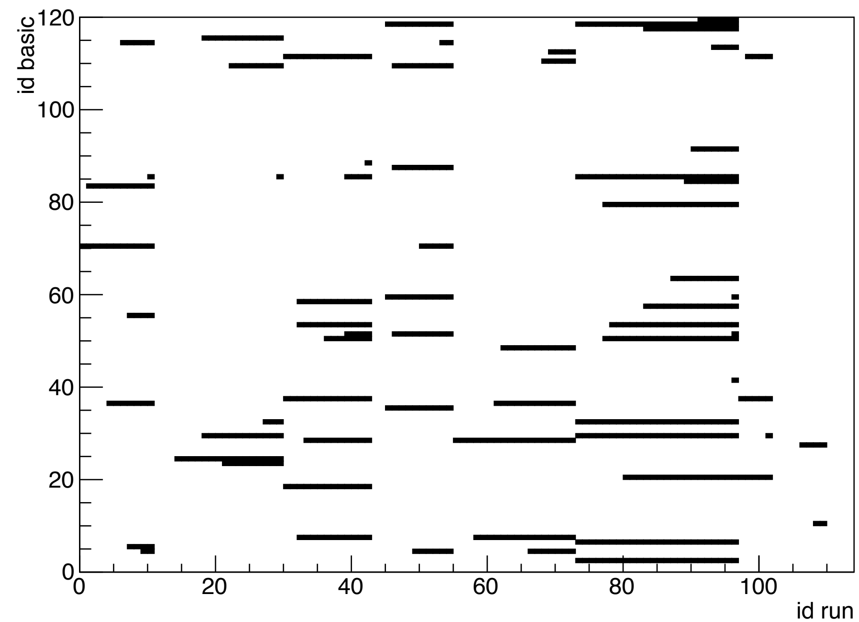
- From time to time, at the beginning of the DAQ, a (few) card(s) of a single board (32 channels → 32 SiPMs in two consecutive planes) fails to configure properly and stops working.
  - Given the high light cross talk among the fibers (resulting in a cluster multiplicity of ~ 2 pixels tuned on for each plane traversed by a track) this effect is not easily spotted by 'eye' as the tracking efficiency remains high.





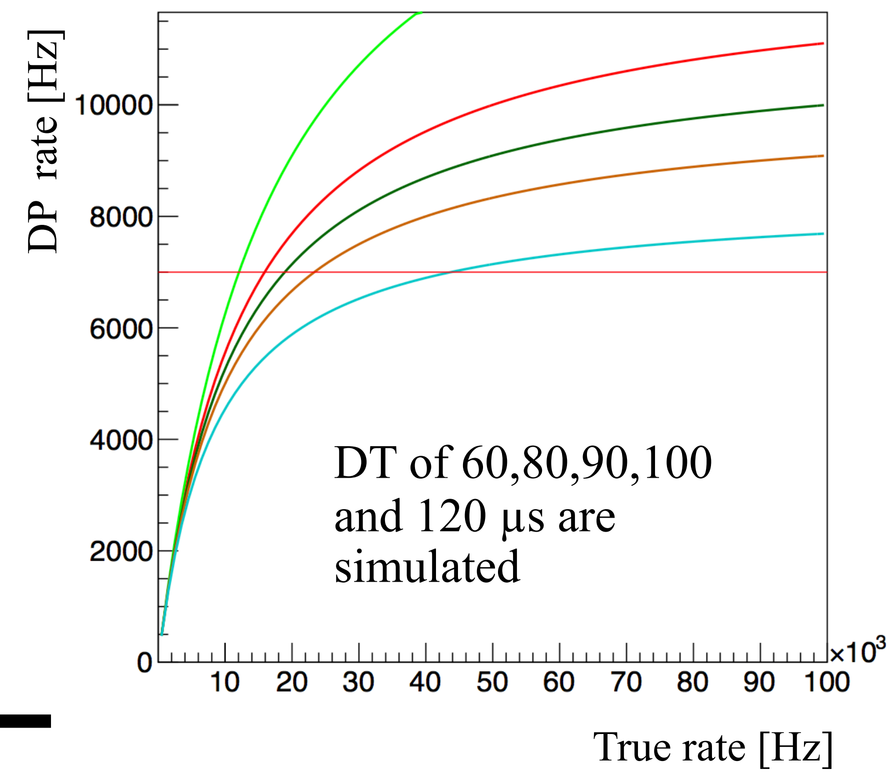
BASICs instability: diagnosis

- We studied the effect as a function of time: it appears randomly and we still have to figure out if it appears during a run or only at the beginning..
- It seems that re-configuring the DAQ every time, at the start of each run, helps in keeping under control the problem (this re-configuration takes 1 ms and will be routinely applied from now on).
  - The DAQ now implements a panel that allows to understand if all the basics are providing data or not
- The source of the problem is still unknown: we are currently debugging the problem and looking for
  - a) known basic feature that we thought was solved (if the trigger window is too small, from time to time the BASIC is not properly reset by the 'standard' reset procedure and needs extra clock counts to work again)
  - b) problem in applying the initial configuration to all the boards in parallel



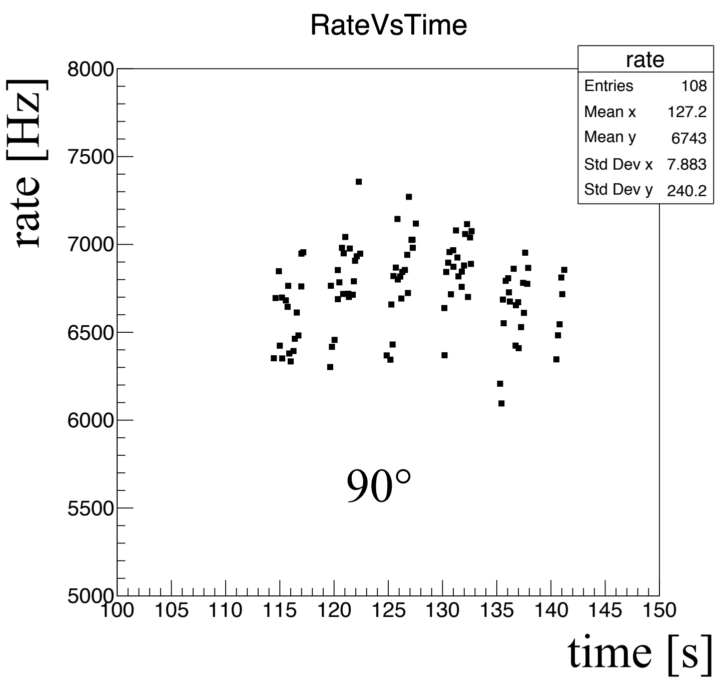
Dead time (part I)

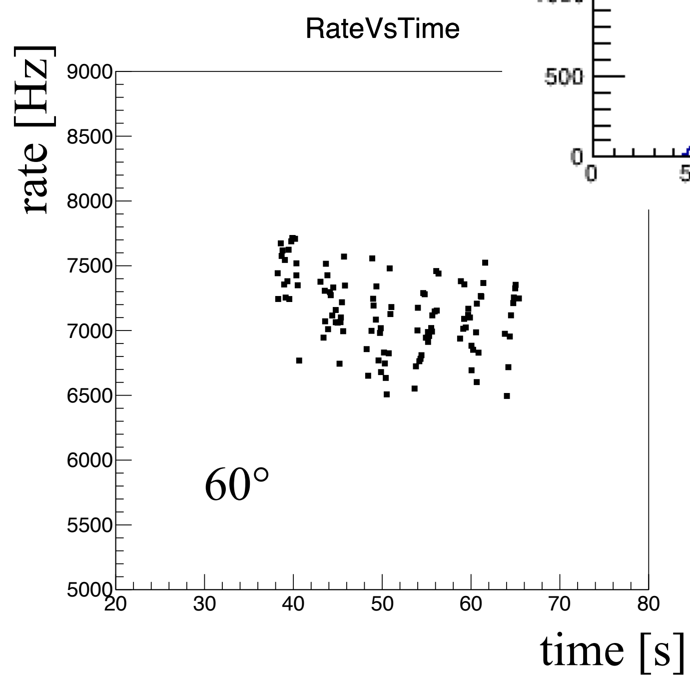
- The statistics that can be collected and used to monitor the BP is heavily affected, in clinical conditions with very high intensities, by the detector dead time.
- Taking into account the specifics of the HW (BASICs readout time, routing among the readout FPGAs and the 'master' FPGA, aka 'il concentratore') the estimated dead time is ~20 μs.
- We measured something really different!
  - Dead time always larger than 50 μs, average of 80 μs, as large as 120 μs in some cases!
  - When computing the real incoming particle rate, given the known (measured) rate and the DT, rates as large as 100 kHz are observed!

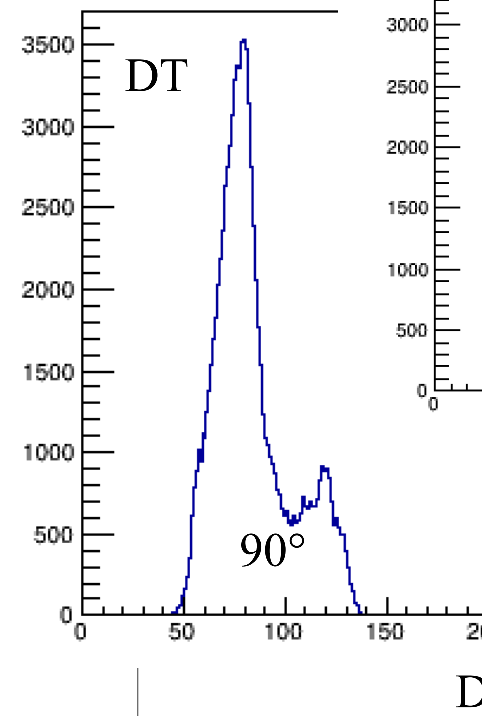


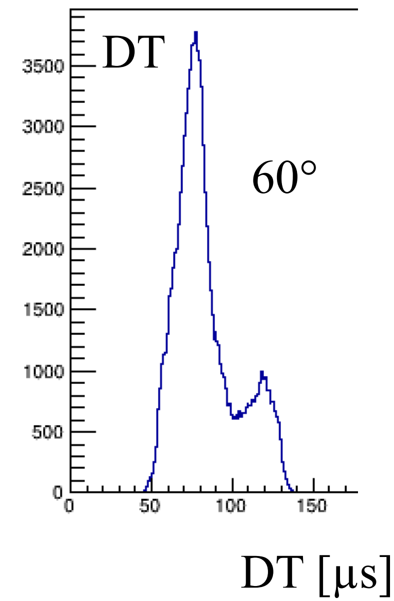
DT, data @ 90° (part II)

- The measured DT in the 90° and 60° run is, in average, **83 μs with very similar spectra in both cases**.
- Average **DP rates are 6.7 kHz and 7.1 kHz in the two cases**



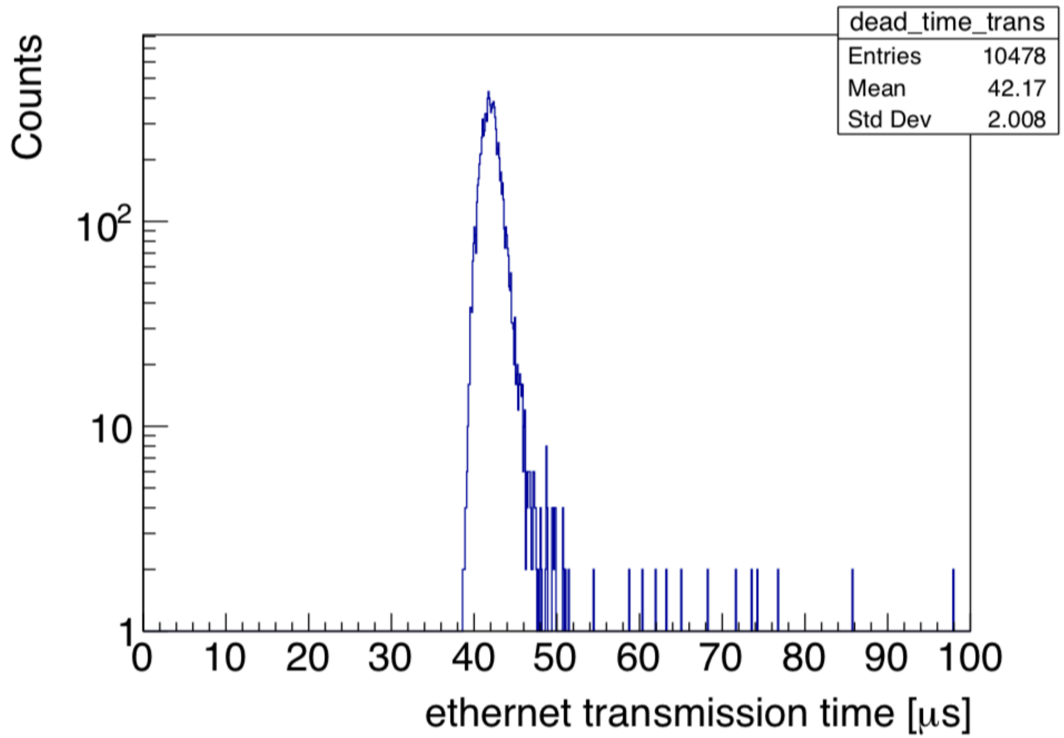






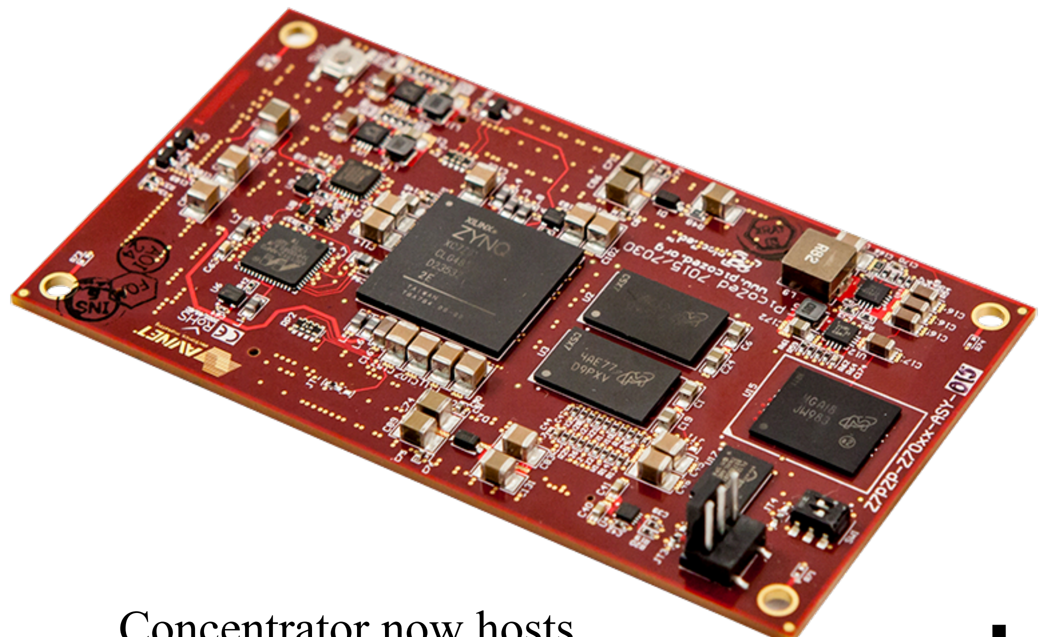
Dead time (part III)

- Since mid October a careful review of all the contributions to the dead time has started and the causes of such large amount of DT have been identified and are currently being fixed:
  - Incorrect sleep time allocated for basics (window of 10 μs instead of 1 μs, to ensure the sync. of the BASICS boards reading). This (easy) firmware fix will save us 9μs of DT
  - All the FPGAs data transfer times have been checked and are consistent with what expected
  - All the remaining DT (difference btw 20 and 50-120 μs) has been tracked down and is caused by the TCP-IP transfer protocol!
- The huge data transfer overhead is currently being addressed…



Data transfer strategies

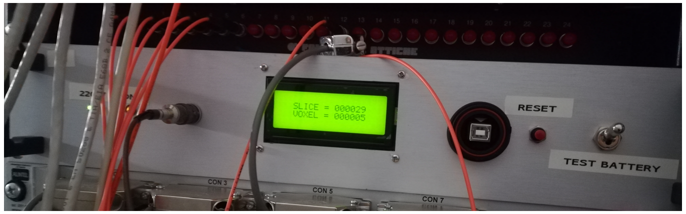
- Protocols smarter than TCP-IP will be investigated (UDP is claimed to perform much better)
- The possibility to store the data on a local memory and to transfer them when the spill/beam is off, is also on the table and is being studied. Requires
  - Proper study of the memory dimensions needed to store interactions from 2x10^8 primary ions (maximum that can be provided in a single spill). If larger memory is needed → new concentrator will be needed
  - Implementation of a data transfer driven from the DDS (next slide).

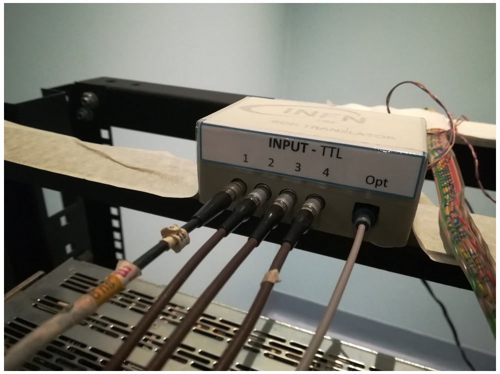


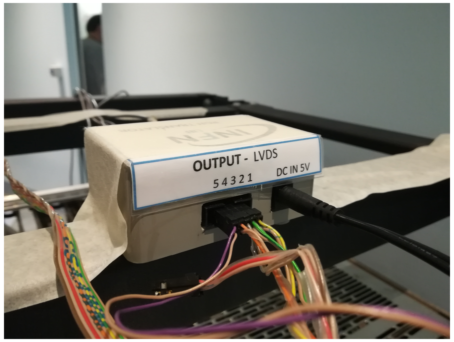
Concentrator now hosts
4 GB eMMC memory

Exploiting the DDS

- In the latest TB we had the chance to test the LEMO - Fiber → LVDS translator that we're going to use to convert the DDS signals into something readable by the concentrator FPGA. The 'voxel-slice' (4 μs frequency, ~70 bit) & a beam on (level) signals will be used to sync. the data transfer with the 'spill switch'
  - currently each slice is painted in a given spill: there's not chance _yet_ to have an energy change within a given spill.







What about SW?

- The HW path for the next months is clear:
  - Investigate instabilities: small impact on performance
  - Investigate DT: crucial impact. Needs to be done in order to reach online monitoring level capabilities.
  - Embed DAQ DDS driven capabilities
- But… provided that we can collect as many events as provided by the beam.. What can we do with them?
  - It depends on how many they are :) .. Some **super preliminary** estimates are given here..

Position is the nominal DP one in INSIDE 2 config.

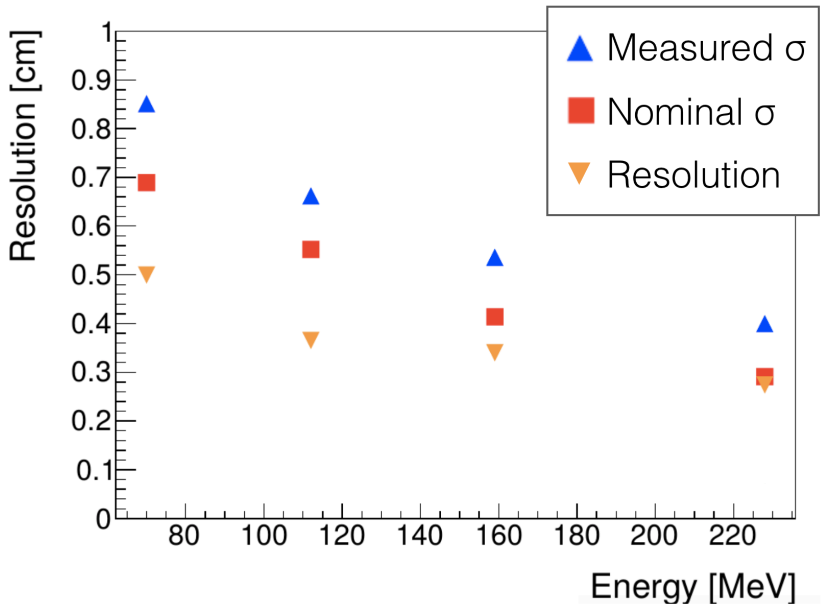
	real TP, PB	real TP, 9PB	real TP, slice
20μs DT, 60°	~40	~350	~5k

No DT scenario → x3

Resolution: the DP detector

- With ~ 1k tracks, what can we expect to do for the BP monitoring?
- Expectation using a DCH: 1k tracks → σ ~ 3 mm on how. target 2.5 mm thick.
- In clinical conditions: larger thickness (MS) + detector effect.
  - The starting point has to be the assessment of the DP resolution for protons of energy of interest for monitoring applications.

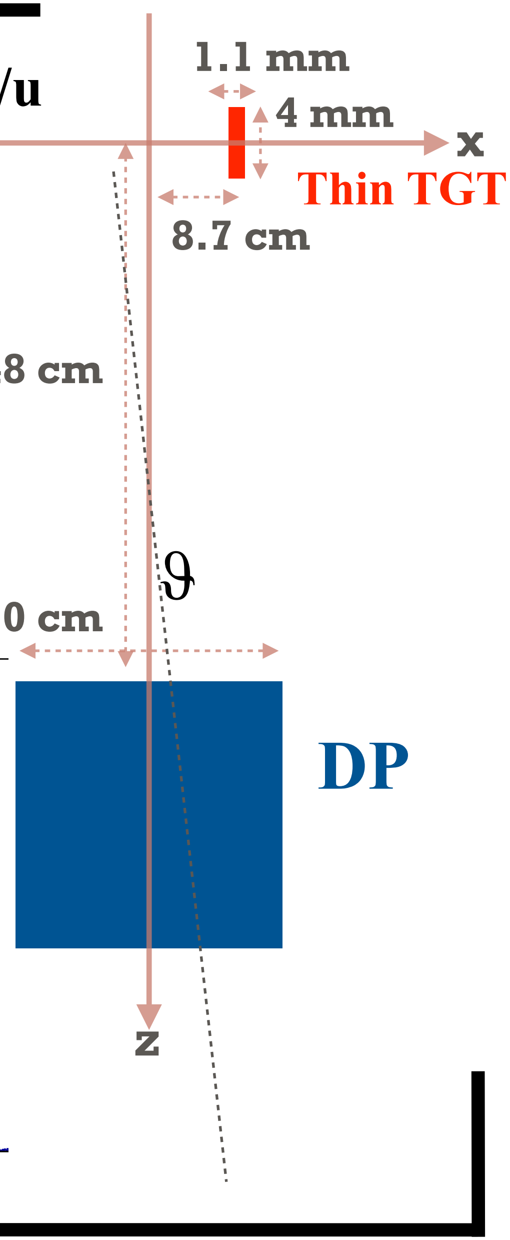
Preliminary results @ Trento were encouraging: @ 50 cm, few mm σ was obtained.
However: keep in mind that the 'clinical' protons are more towards 70 MeV than 220 MeV!
5 mm instead of 3.

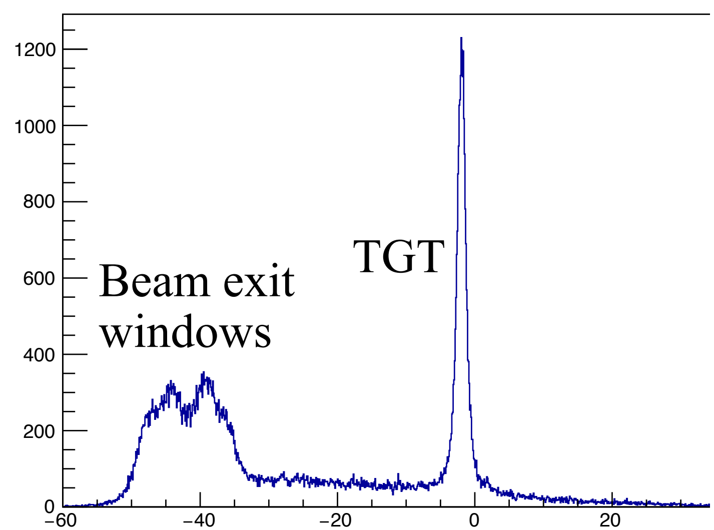


Resolution: secondary protons

InSide

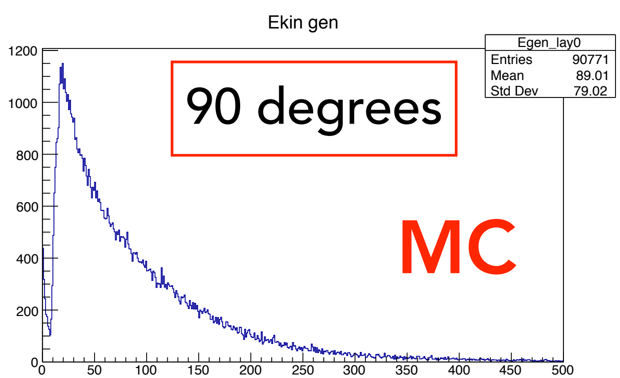
- Trento results were obtained shooting protons of fixed energy inside our detector.
- What if we try to look at secondary protons from a ^{12}C beam? Broad energy spectrum and low energy protons are expected.
- To assess the DP resolution in clinical conditions:
  - Ultra thin targets have been chosen (1.1 mm 'wire' plastic, 2mm 'wire' aluminum, 4mm 'sphere' plastic thickness/diameter)
  - Distance from TGT as in clinical conditions (~50 cm)
  - Different angles (90°, 60°)





E.g. the 'sphere' runs

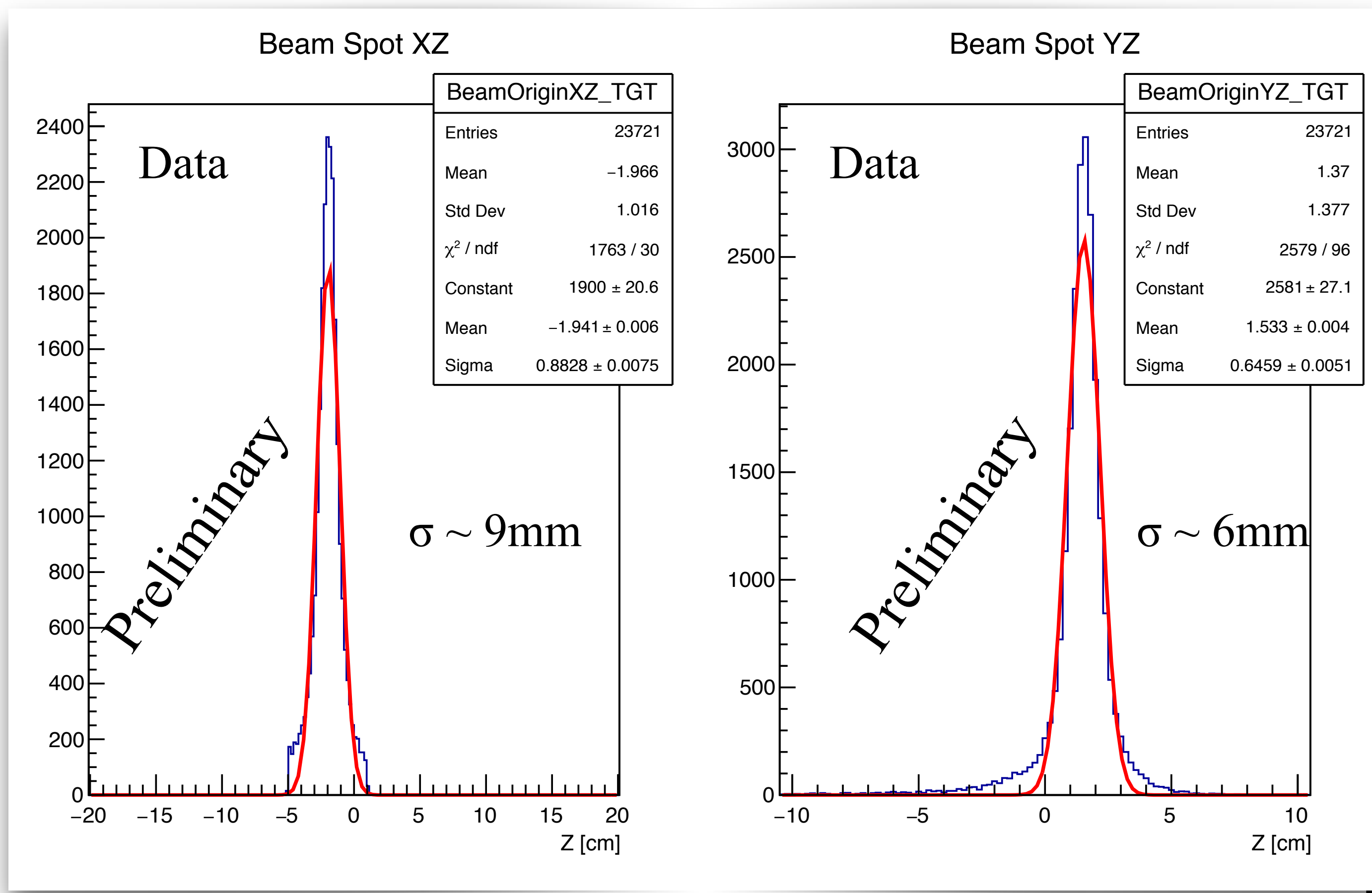
Using as a target a 4mm diameter plastic sphere.



(production) E_{kin}

E_{beam} = 220 MeV/u
distance = 53.5 cm
Trigger = tripla
@ 60° wrt beam

Secondaries Reconstructed Emission Distribution



DP resolution: summary

InSide

- Extensive data and MC effort to assess the DP resolution. Preliminary summary:
  - MC + Al wire + Plastic sphere are ~ in agreement: σx,σy of ~9,7 mm are observed
  - Plastic wire runs are being scrutinised to understand the discrepancy source

Preliminary

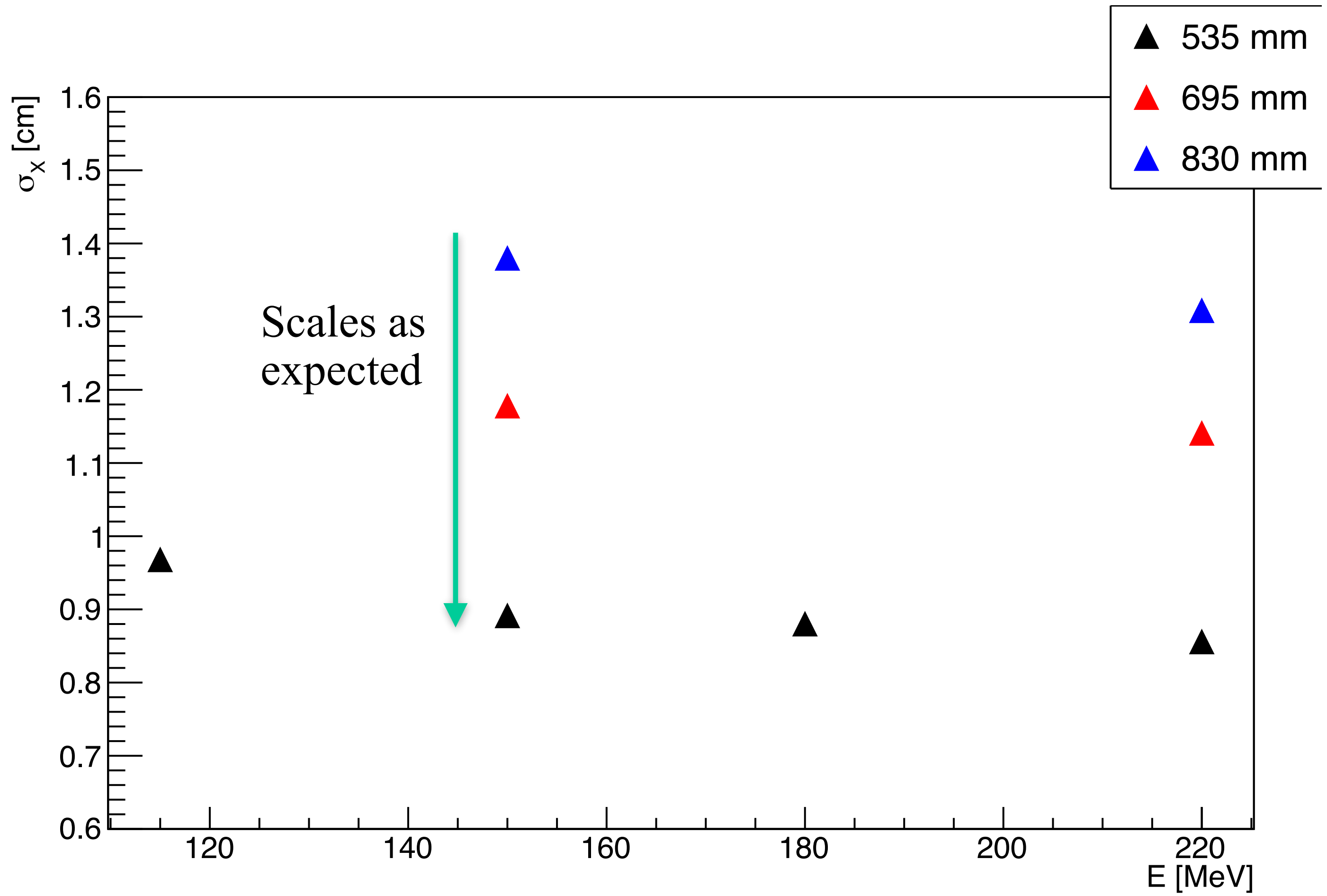
	220 MeV/u	σX	σY
90°	MC Pl wire	8.3mm	7.9mm
90°	Pl wire	1.4cm	8.4mm
60°	Sphere	8.8mm	6.5mm
60°	Al wire	8.6mm	7.4mm

Huge ongoing work

The 5mm from Trento become 8-9mm after: a) **softer E_{kin} spectra**, b) different angular distribution

Dependence on the distance…

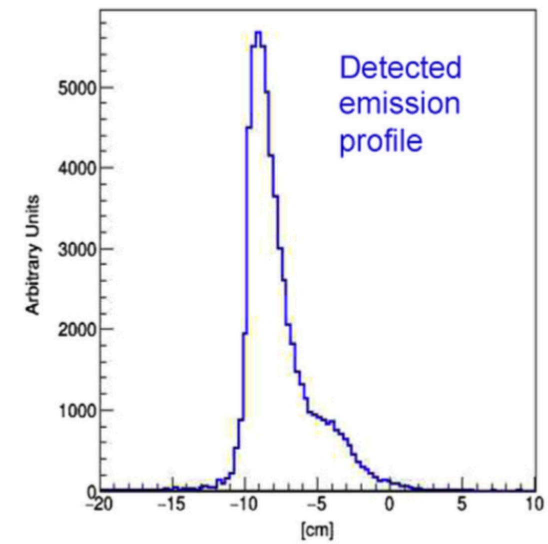
- Took data @ different energies, distances.
- **As expected, ~linear dependence on distance:**
  - The closer the better!

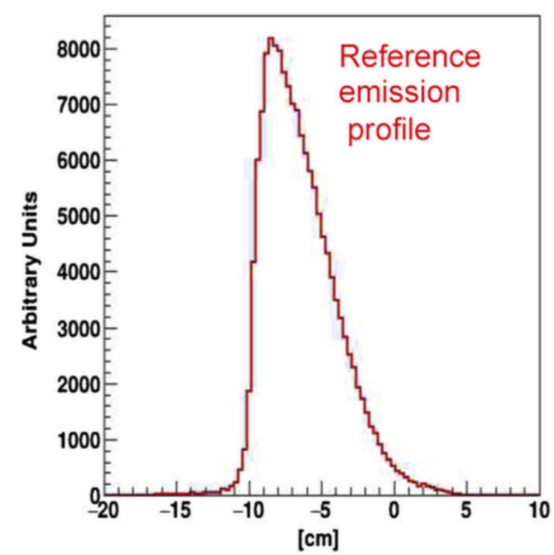


Distance from patient becomes a crucial parameter to be optimised in the future.

Matter effect: going on-line

- If we divide the path of the beam in the patient in N bins, then the emission distribution is a vector where the i-th component gives the number of secondary truly emitted in the bin i of the path
- A charged emitted at bin i (x_i) can be reconstructed in bin j (y_j). The relation between the true emission point x and the reconstructed point y can be written as y = S(x)
- The system operator S include multiple scattering, detection resolution, absorption in matter. It can be represented by a system matrix A with A_{ij}: Probability that emission in bin i results in a detection in bin j. So $y_j = S_i A_{ij} x_i$
- We need to solve the inverse problem: $x = A^{-1}y$. Typical deconvolution problem: is fundamental to evaluate the system matrix S





Strategy: use FRED & M-LEM

InSide

- Initial guess for emission distribution: $x_i^{(0)}$ ← From MC+ Patient CT
- Estimate measurements from system matrix (forward proj.):

$$y_j^{est} = \sum_k A_{kj} x_j^{(0)}$$

- Compare this to actual measurements: $R_j = \frac{y_j}{y_j^{est}}$
- Improve iteratively image estimation (backw. projection):

ML-EM

$$x_i^{(n+1)} = x_i^{(n)} \cdot \frac{1}{\sum_j A_{ij}} \cdot \sum_j A_{ij} \frac{y_j}{\sum_k A_{kj} x_k^{(n)}}$$

Steps towards online implementation

- Need to be fast: FRED
  - A GPU based software that implements MC models relevant for PT applications. Can be really fast.. E.g. TPS re-optimisation that takes 72h on 1 CPU with FLUKA is performed in 1 min using FRED on few GPUs.
- Generator model under development (Mi + Roma)
  - While the validation of the proton interaction description is done and published, the Carbon interactions are being implemented now. A custom generator will be used (btw: the MLEM matrix should be ~ independent on the 'underlying' true spectra of generation provided that the energy spectra covered is 'wide enough')
  - Validation against full MC expected soon afterwards
- Iterative method will be used to process the data offline
  - Full online implementation will happen afterwards

Towards integration

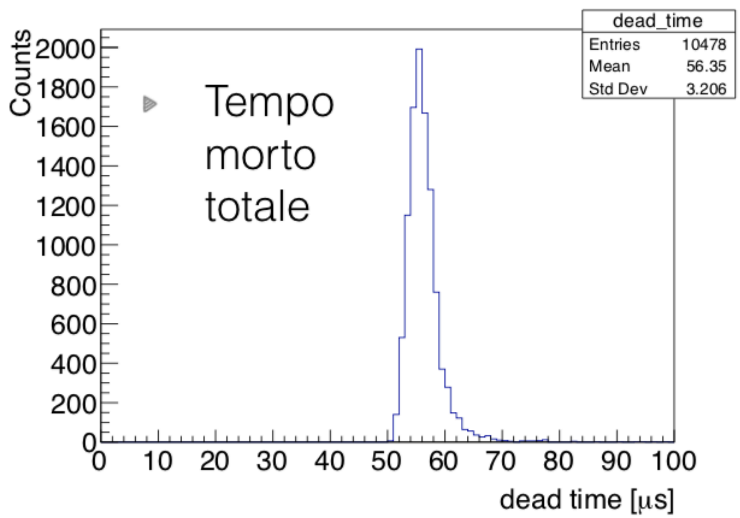
- Before starting the operation in the treatment room we still need to
  - Change the cooling aluminum block + test its tightness against liquid overpressure
  - Close the 'rear end' of the Profiler + beautify "QB"
- The only 'HW' missing part is the integration of the DDS signals inside the concentrator (currently being implemented). Once available the DP will be fully operational within INSIDE.
  - Signal, power and cooling connections are being finalised. All the HW that is needed is already available.
- From the operational point of view the DP system is currently designed to be 'plug and play'.
  - No need to 'calibration runs': a configuration will be applied at the start of DAQ and then the operator will be able to acquire the data.

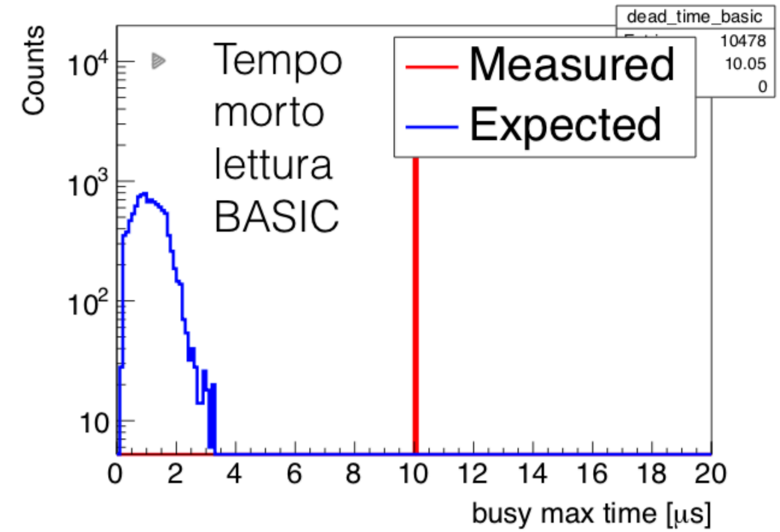
Summary

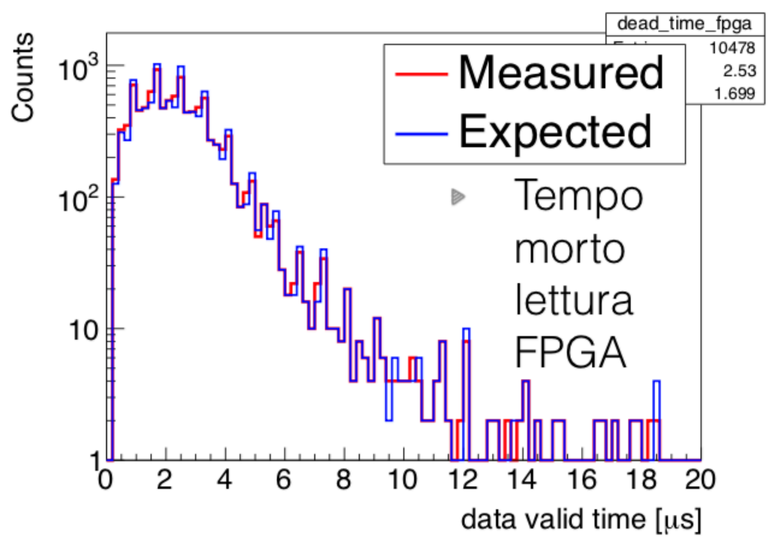
- HW activities in the near future:
  - Investigate BASICs instabilities
  - Improve data transfer DT
  - Implement DAQ DDS driven capabilities
- SW activities in the near future:
  - Finalise the resolution studies, study the detector response in different operating conditions
  - **Study the (BP) resolution capabilities on the data collected @ CNAO using RANDO (other targets).**
  - Implement the full MC matter effect correction
- Integration
  - no show stopper, so far. System is ~ plug and play.. Profited from experience **and huge help from Francesco and Elisa**

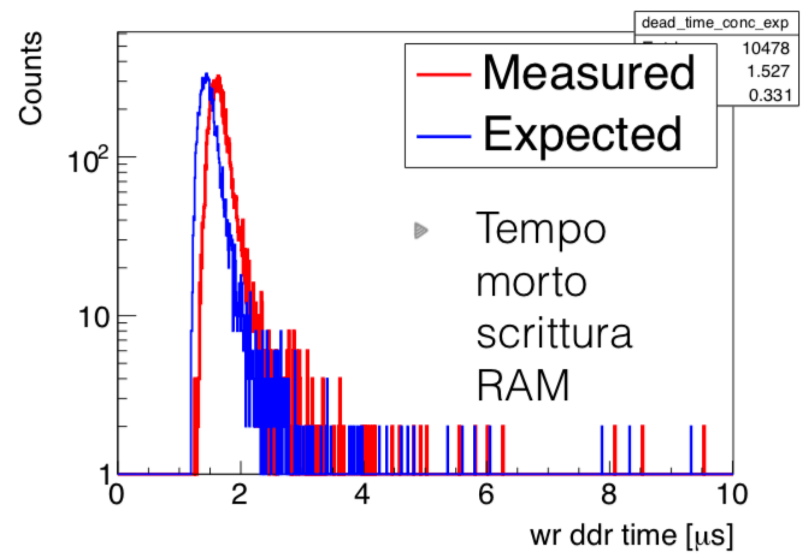
Spares

DT details


dead_time
Entries 10478
Mean 56.35
Std Dev 3.206
Counts
Tempo morto totale
dead time [μs]


dead_time_basic
10478
10.05
0
Counts
Tempo morto lettura BASIC
Measured
Expected
busy max time [μs]


dead_time_fpga
10478
2.53
1.699
Counts
Measured
Expected
Tempo morto lettura FPGA
data valid time [μs]


dead_time_conc_exp
10478
1.527
0.331
Counts
Measured
Expected
Tempo morto scrittura RAM
wr ddr time [μs]