# Overview of activities in the ALFA and AX-PET projects

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On behalf of the AX-PET collaboration
https://twiki.cern.ch/twiki/bin/view/AXIALPET

On behalf of the ALFA community

MC-PAD closing network event
19-22st September 2012 in Frascati

# Outline

- ALFA, Absolute Luminosity For ATLAS
  - Physics goal
  - Detector description
  - Physics analysis
    - Track based alignment
- AX-PET
  - Detector description
  - Test campaign on small animals
  - Using digital SiPM from Philips
- Conclusions
- Future and MC-PAD benefits

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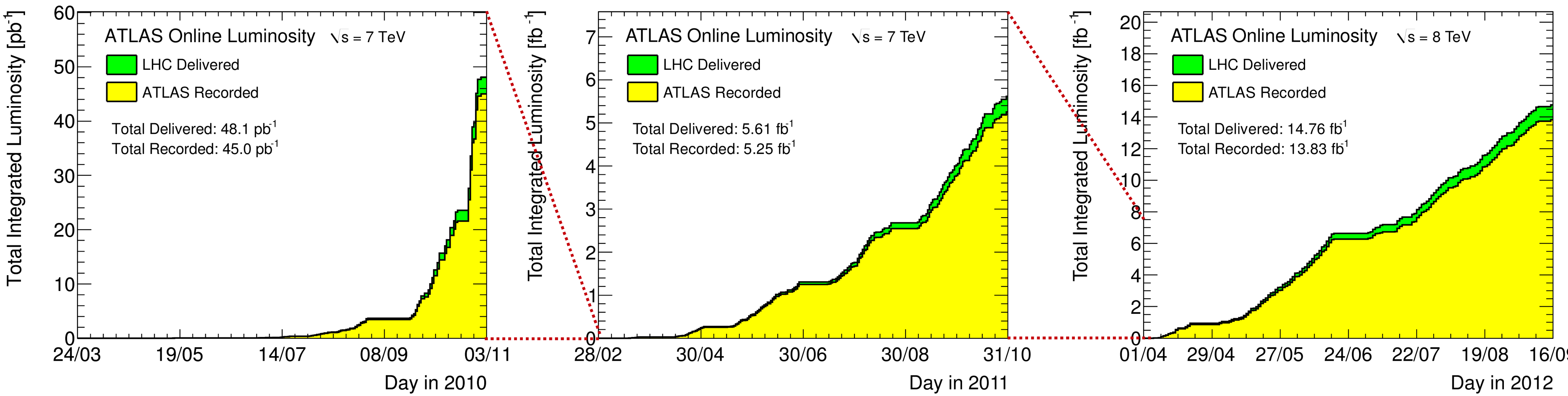
# Context of the ALFA detector

- The LHC has been delivering proton-proton collisions since 24th March 2010
- The energy went from 7 TeV in the center of mass to 8 TeV in 2012
- The efficiency of these collisions, called luminosity, has never stopped improving since then :

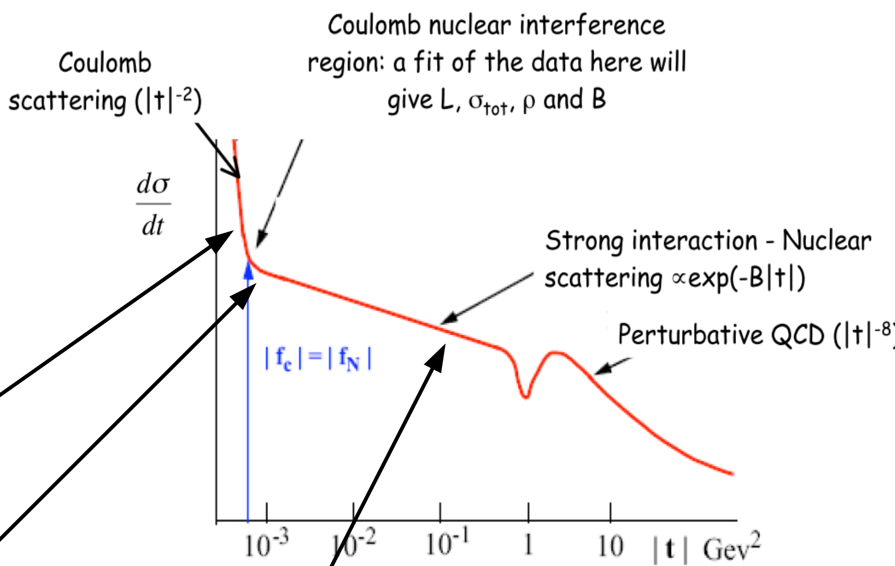



- In order to measure the cross sections of different physics process (e.g. Higgs boson production), one need to know the absolute luminosity :

$$R = \mathscr{L} \cdot \sigma \cdot A \cdot \epsilon \Longrightarrow \sigma \propto \frac{R}{\mathscr{L}}$$

# Physics goal

- The luminosity can be measured in an absolute way via different methods :
  - From the beam parameters : $\mathscr{L} = \frac{f \cdot N_{bunch} \cdot N_1 N_2}{4\pi \sigma_x \sigma_y}$
  - From a well known physics process
- ALFA uses the optical theorem to derive the luminosity, the total cross section and the nuclear slope from the measurement of the differential elastic cross section
- The process is very well described by the Coulomb interaction at very small angle (i.e few μrad) but suffers from uncertainties at larger scattering angles (nuclear interactions)

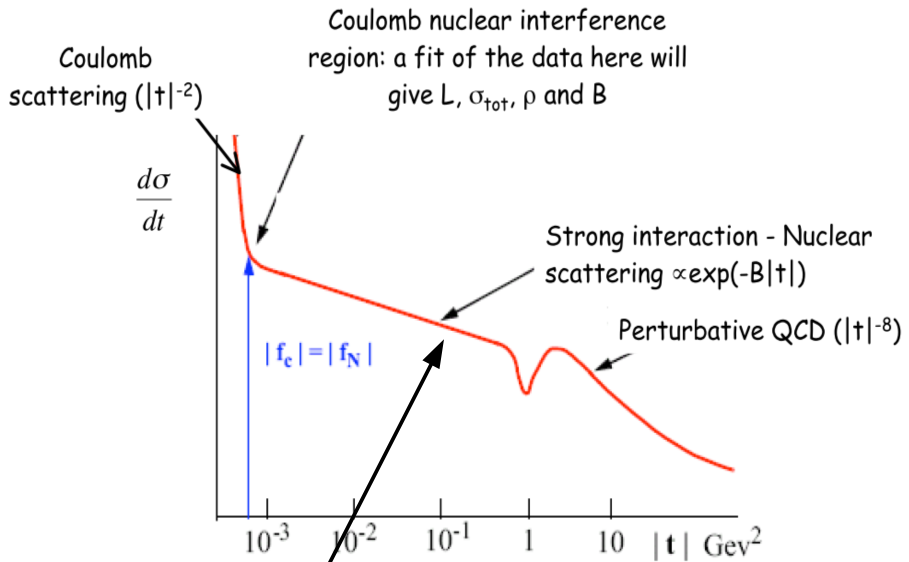



**Goal** ⇒ Measure elastic scattering in the Coulomb region to determine absolute luminosity (2-3 % precision) independently of the total cross section (1-1.5 % precision)

$$\frac{dN_{tot}}{dt} \sim L\,|A_{coulomb} + A_{nuclear}|^2 = L\left[\frac{4\pi\alpha^2}{t^2} - \frac{\alpha\rho\sigma_{tot}}{t}\exp\left(-\frac{B|t|}{2}\right) + \frac{\sigma_{tot}^2}{16\pi}(1+\rho^2)\exp(-B|t|)\right]$$ with $$t = (p_1 - p_3)^2 \qquad t \approx (p\theta)^2$$

# Physics goal

- The measurement of the Coulomb region requires the LHC to run in a special configuration (see next slide). This latter is hard to setup and will only be realised in 2014
- In the meantime, intermediate settings have been used but only allowing to reach the nuclear region
- Probing the nuclear part of the spectrum allows us to determine the total cross section and the nuclear slope
- For this we use the theoretical value of ρ and the luminosity measured using beam parameters (precision ~ 2 %)

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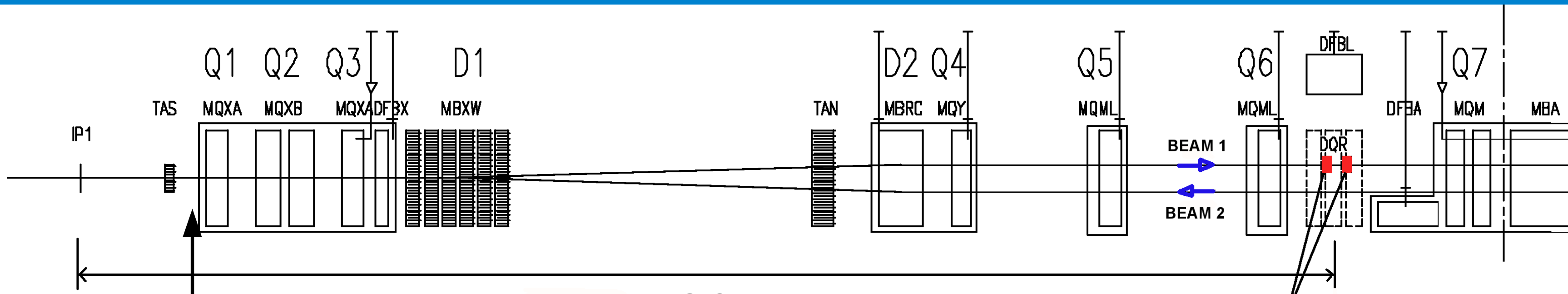
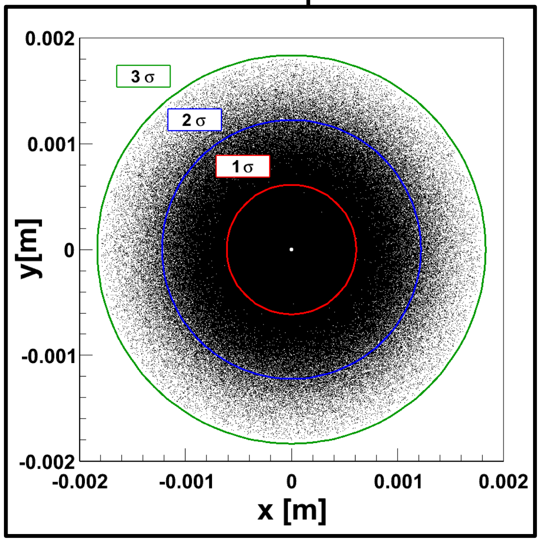
with $t = (p_1 - p_3)^2$, $t \approx (p\theta)^2$

# Optics settings




Scattering picture before the first magnetic element

- Elastically scattered protons are too close to the beam core to be intercepted before the first magnetic element

- Need to install the detectors after in the sequence to increase the separation of these protons

$$u(s) = f(u_{IP}) + \sqrt{\beta(s)\beta_{IP}} \sin(\Delta\mu) u'_{IP}$$

$$\sigma' = \sqrt{\frac{\epsilon}{\beta_{IP}}}$$ Angular dispersion at the interaction point

**Parallel to point focusing and high β* optics**

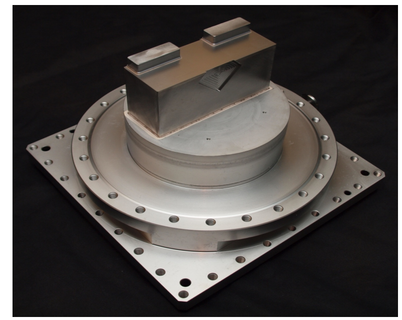
$y_{det} \approx L_{eff,y} \theta_y^{IP}$ and $x_{det} = L_{eff,x} \theta_x^{IP} + f(x_{IP})$

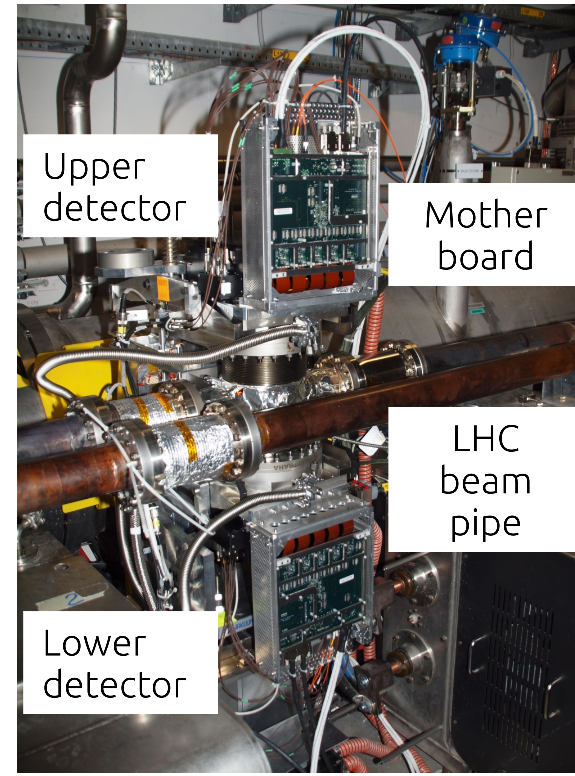
with $L_{eff,y} \approx 270\,m$ and $L_{eff,y} \approx -10\,m$

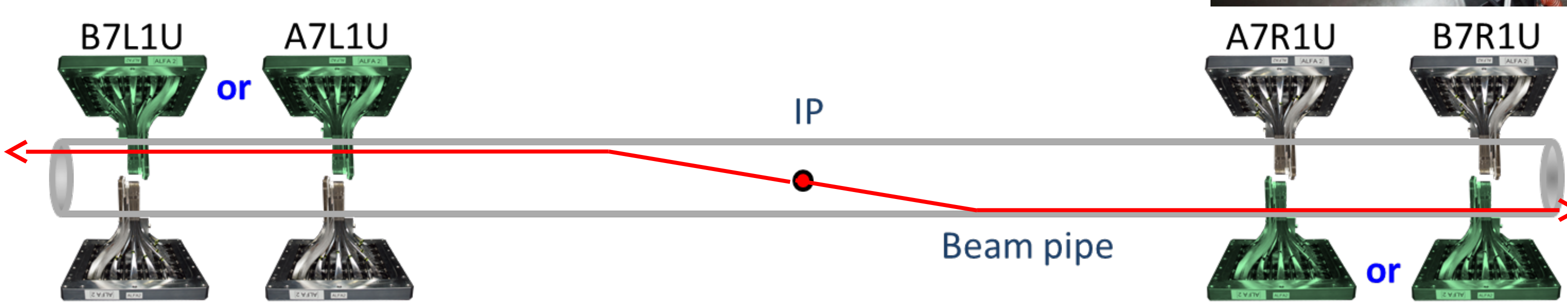
# Detector description

- The detectors still have to be approached very close the circulating beam at ~ mm distance The requirements are then :
  - No dead edge zones
  - Compatibility with operation in vacuum
  - Easy and quick to install and remove
  - Moderate radiation hardness
- A technical solution was already used in the past, the so called Roman Pot. A detector can be installed inside being separated from the pimary vacuum of the accelerator

Roman pot





# Detector description

## Scintillating fiber tracker :

- 20 layers arrange in U-V geometry

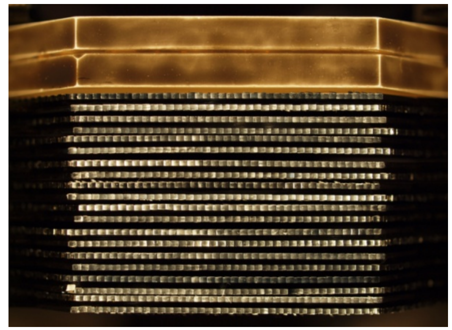
- A staggering of a 1/10th of a fiber → ideal spatial resolution $\sigma_{x,y}$=14.4 μm

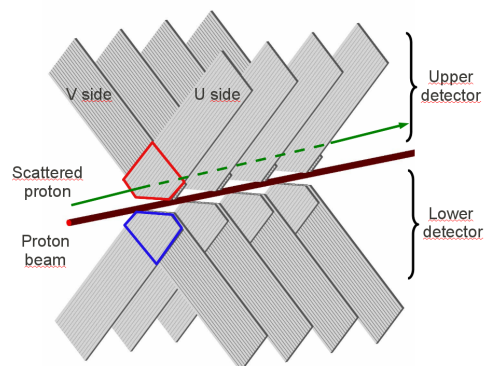
- Each layer is made of 64 scintillating square fibers (0.5 x 0.5 mm$^2$)

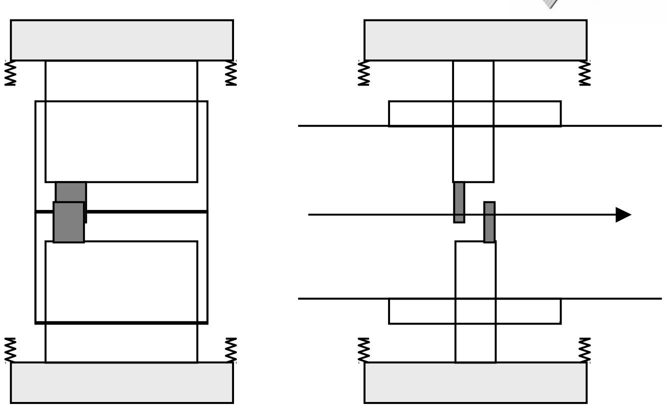
- The 64 fibers are readout by an MAPMT from Hamamastu connected to a compact front end electronics

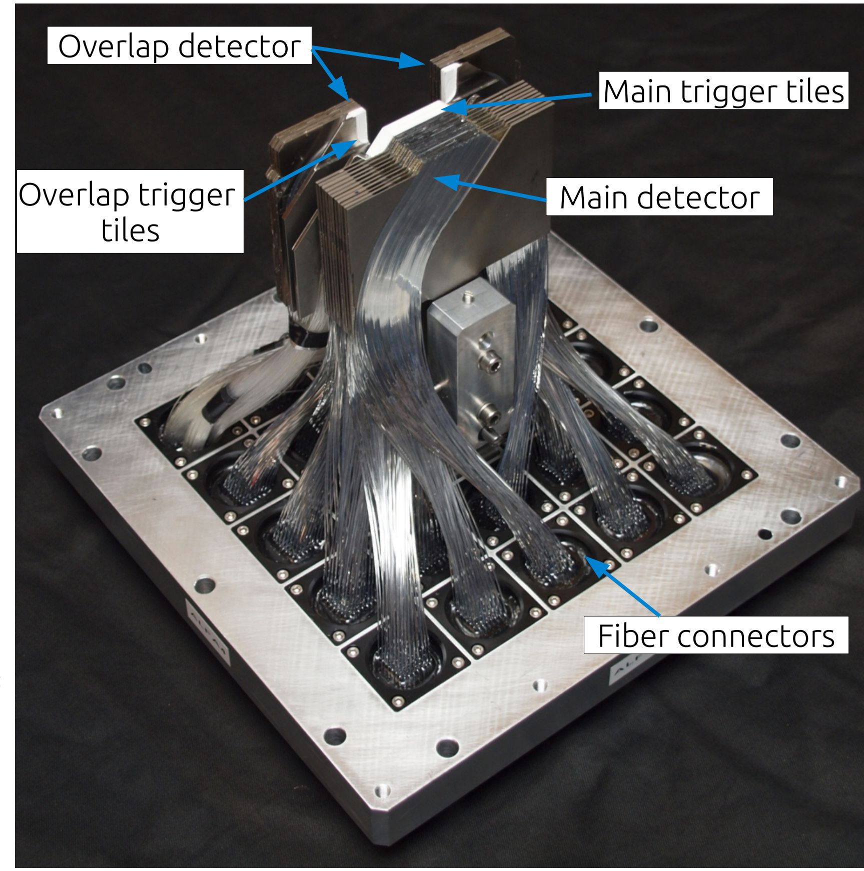
- Overlap detectors to measure the distance between upper and lower detectors

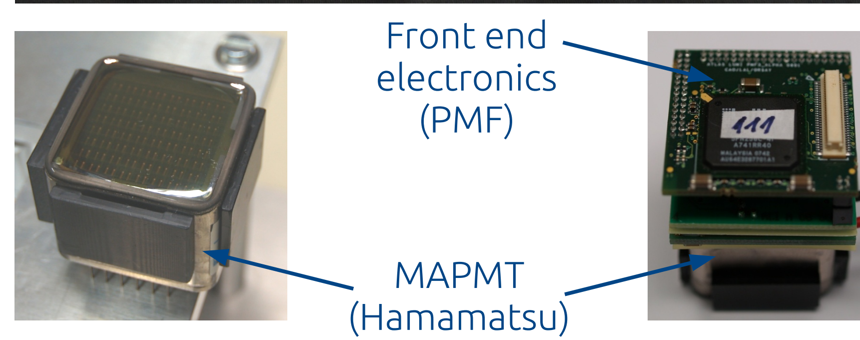
Staggered fiber planes







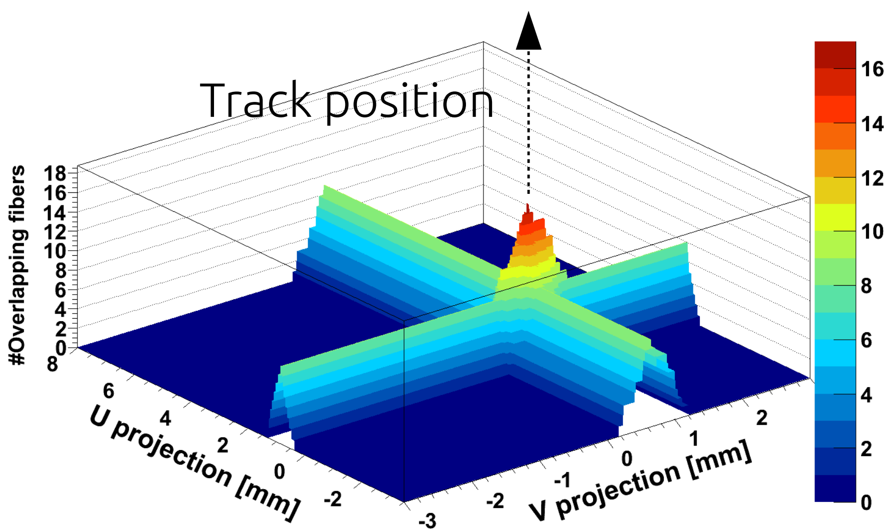



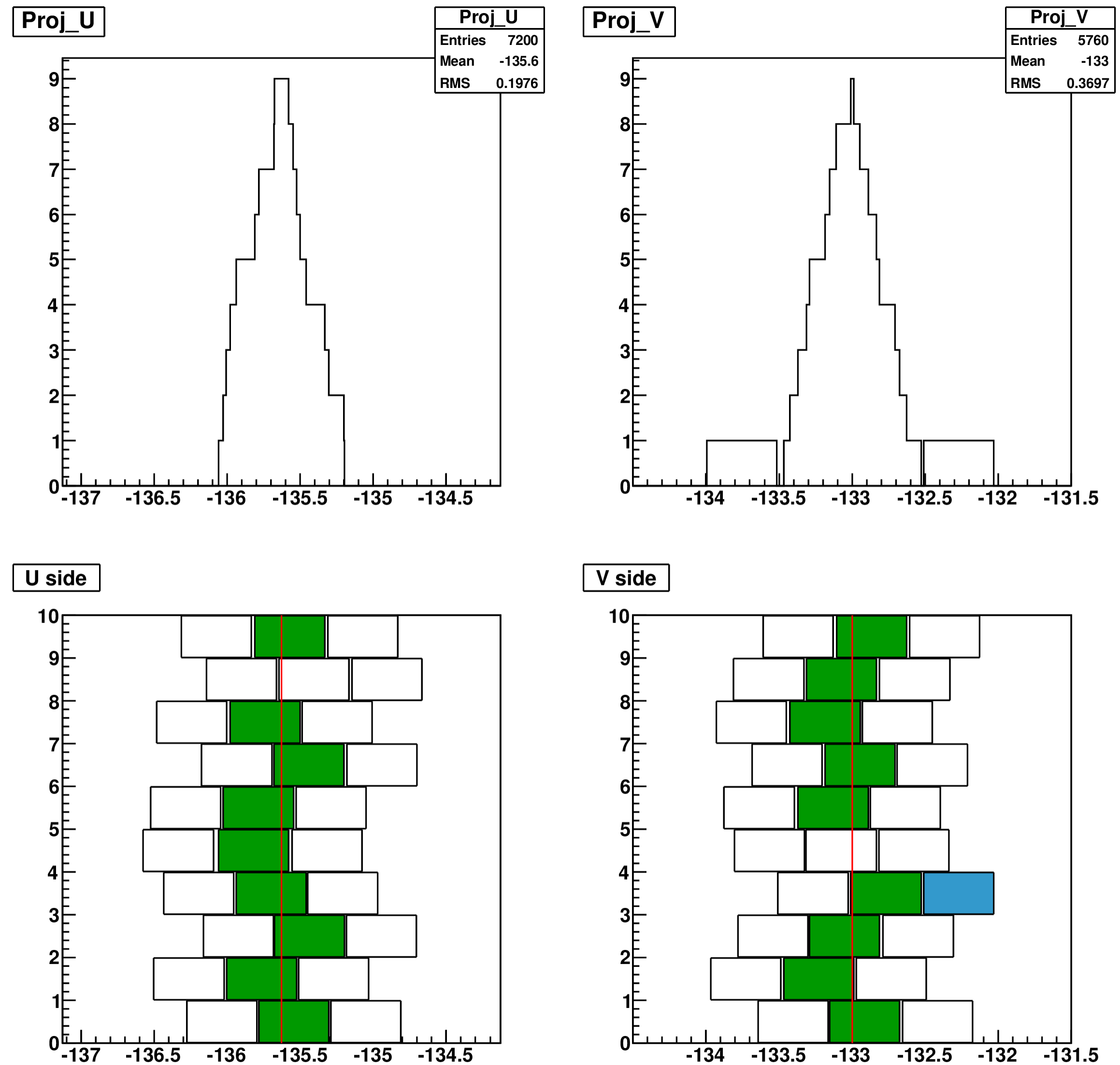
# Track reconstruction

Tracks perpendicular to detector
→ Overlap reconstruction algorithm
→ ~30 µm resolution achieved

Also available :
- Multiple track reconstruction
- Enhanced resolution using gaps
- 3D reconstruction if rotation in transverse plane known

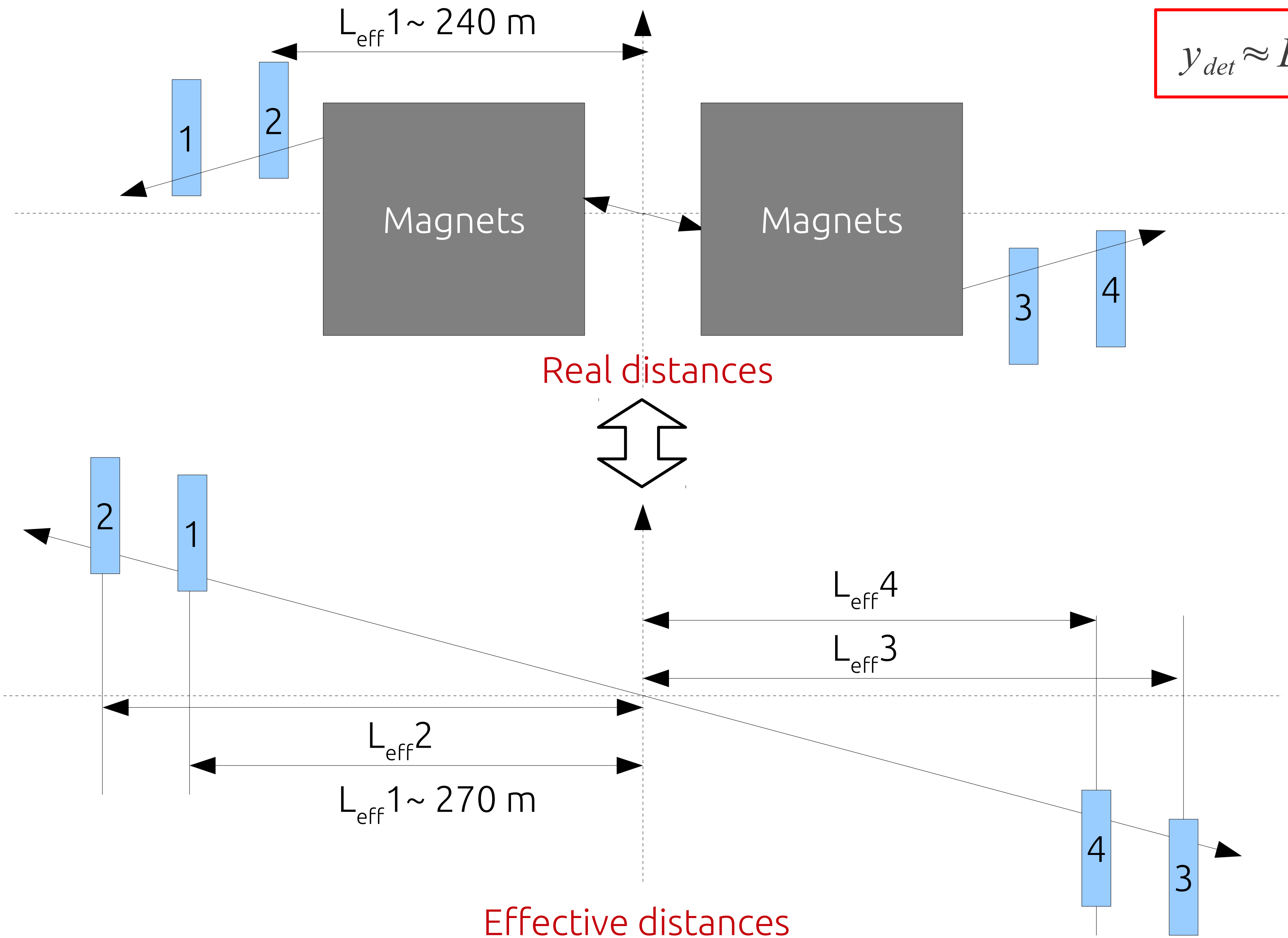
- Very robust, almost insensitive to any noise hit (e.g cross talk)



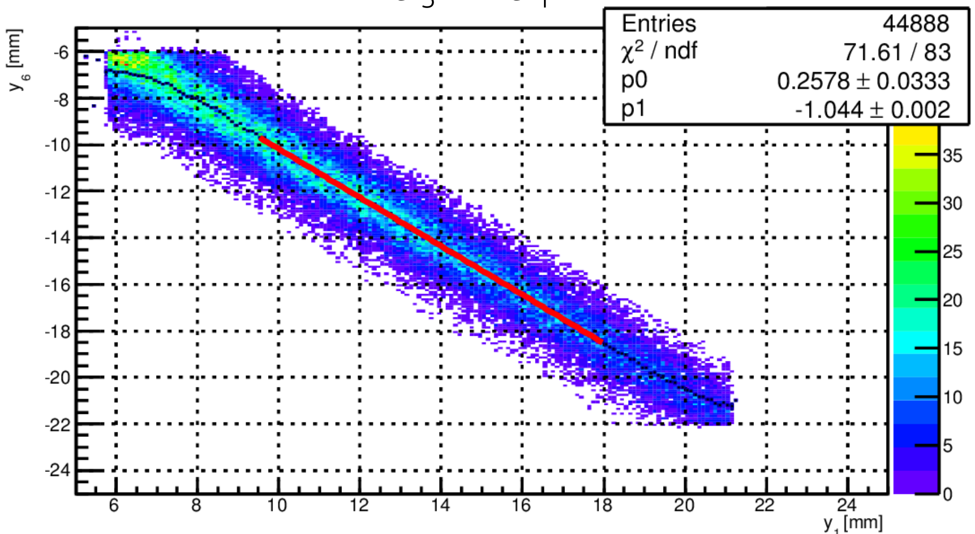
# Track based alignment

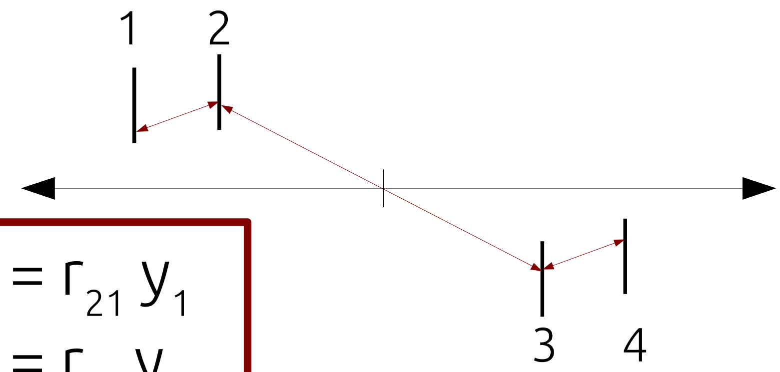
$$y_{det} \approx L_{eff,y} \theta_y^{IP}$$



# Track based alignment

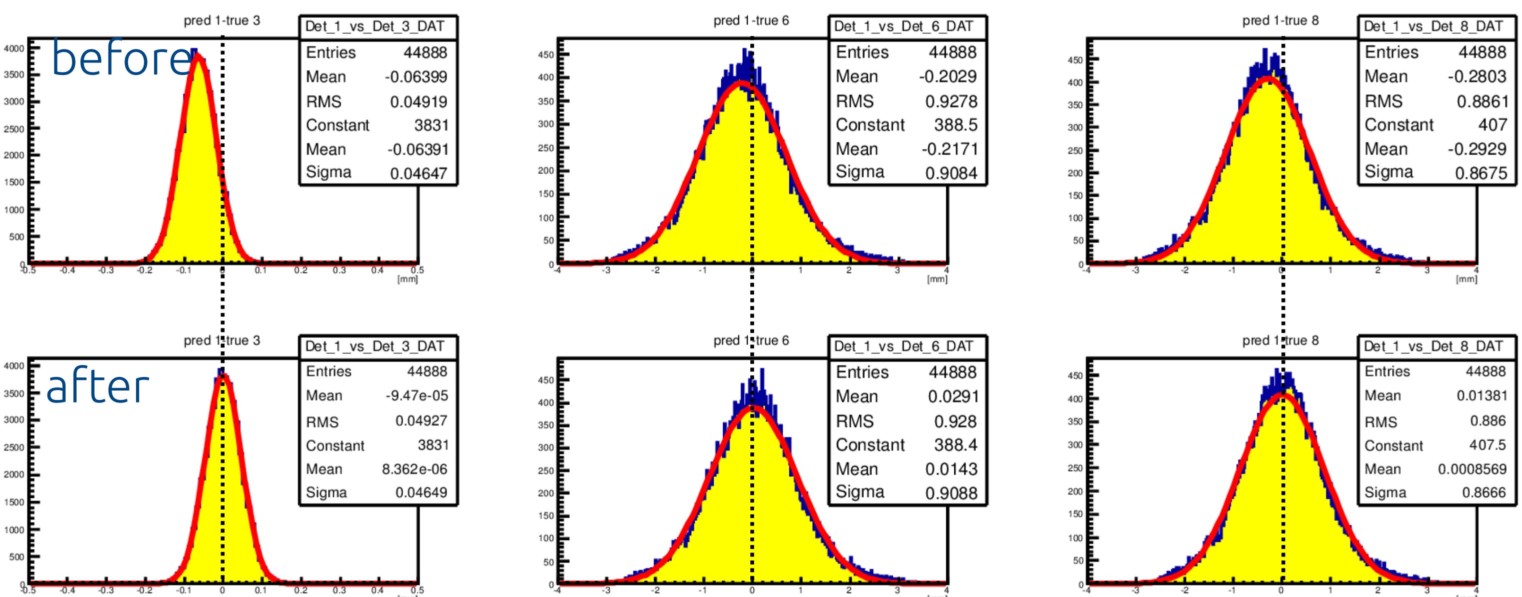
$y_3$ vs. $y_1$




$$y_1 \rightarrow y_2 = r_{21}\, y_1$$
$$\rightarrow y_3 = r_{31}\, y_1$$
$$\rightarrow y_4 = r_{41}\, y_1$$

Example using station 1 as a reference



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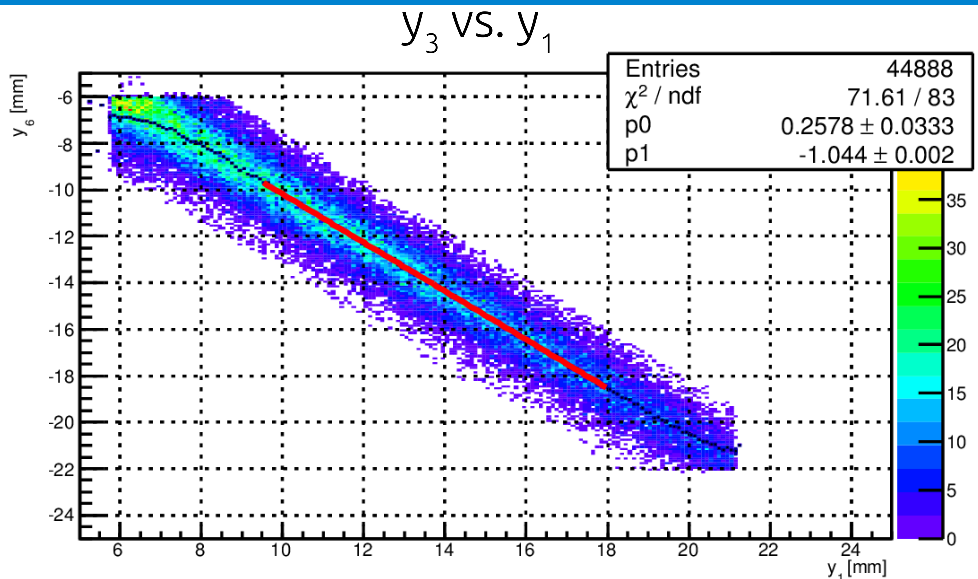


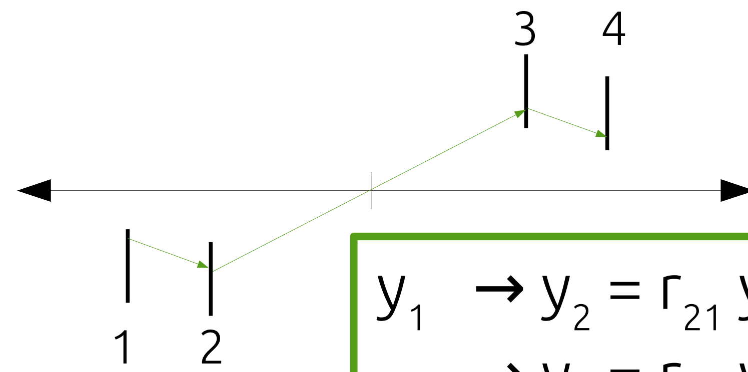


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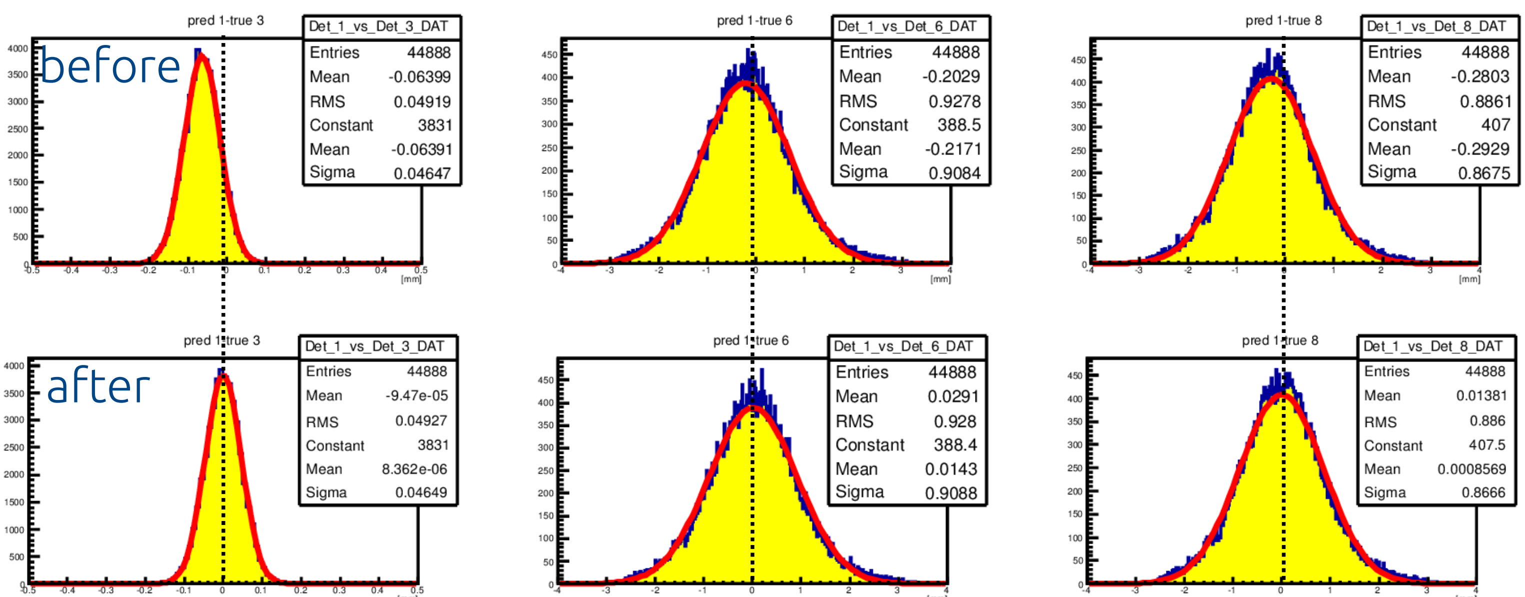
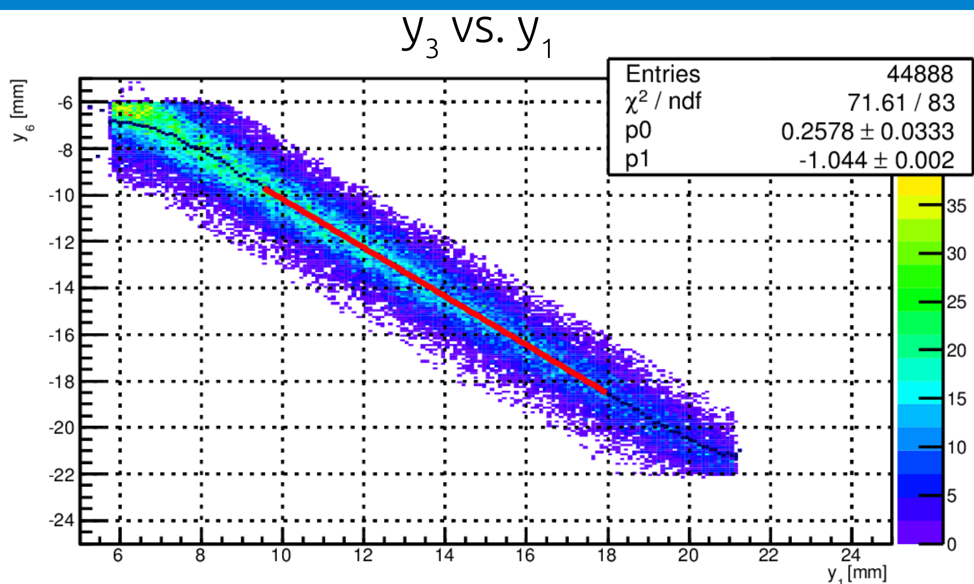
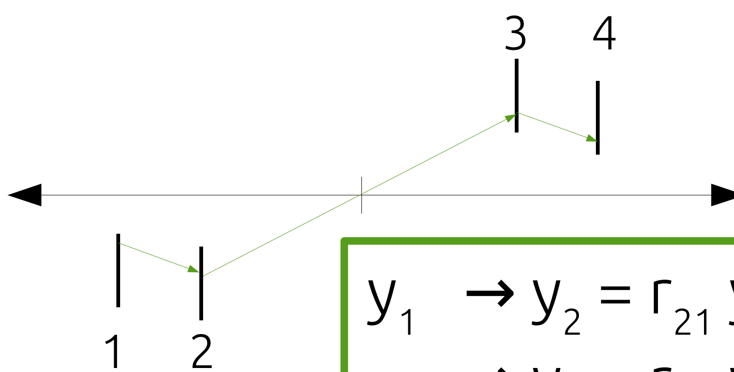



Relative alignment only, need a reference station !

Distance measurement is affected by very different systematical uncertainty depending on the station (calibration, data quality, statistics..)

# Track based alignment

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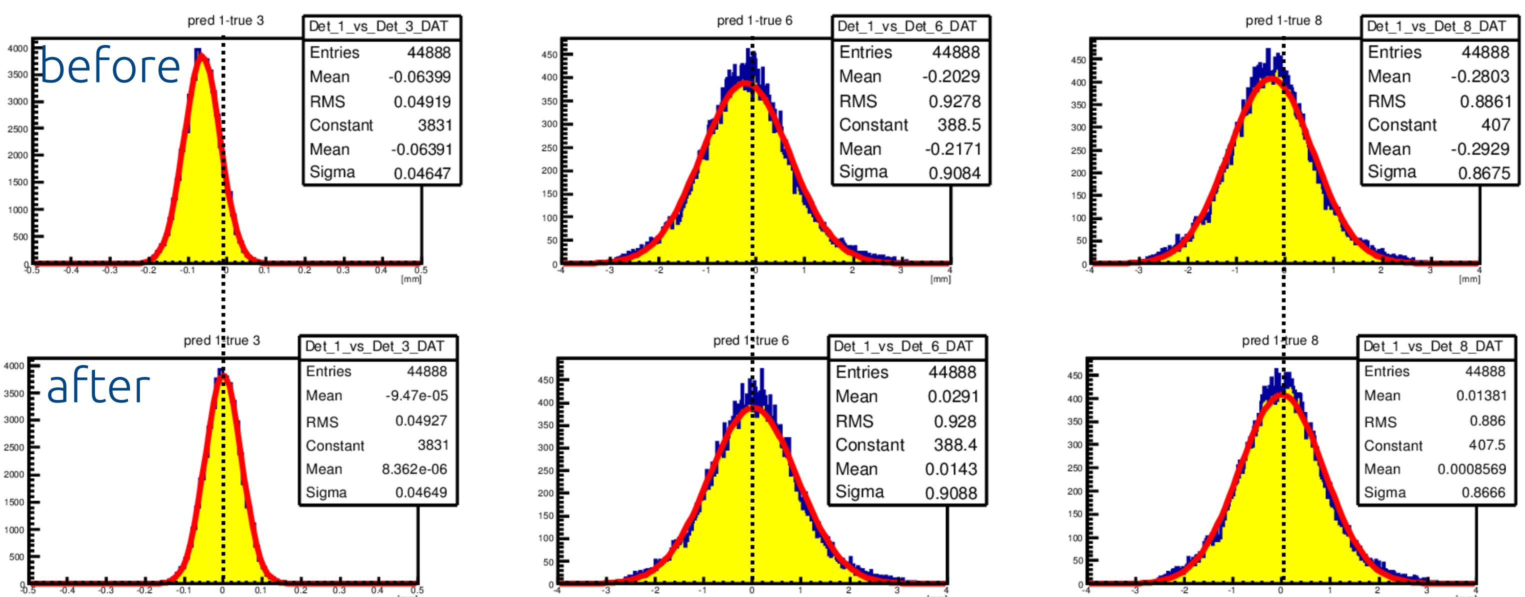
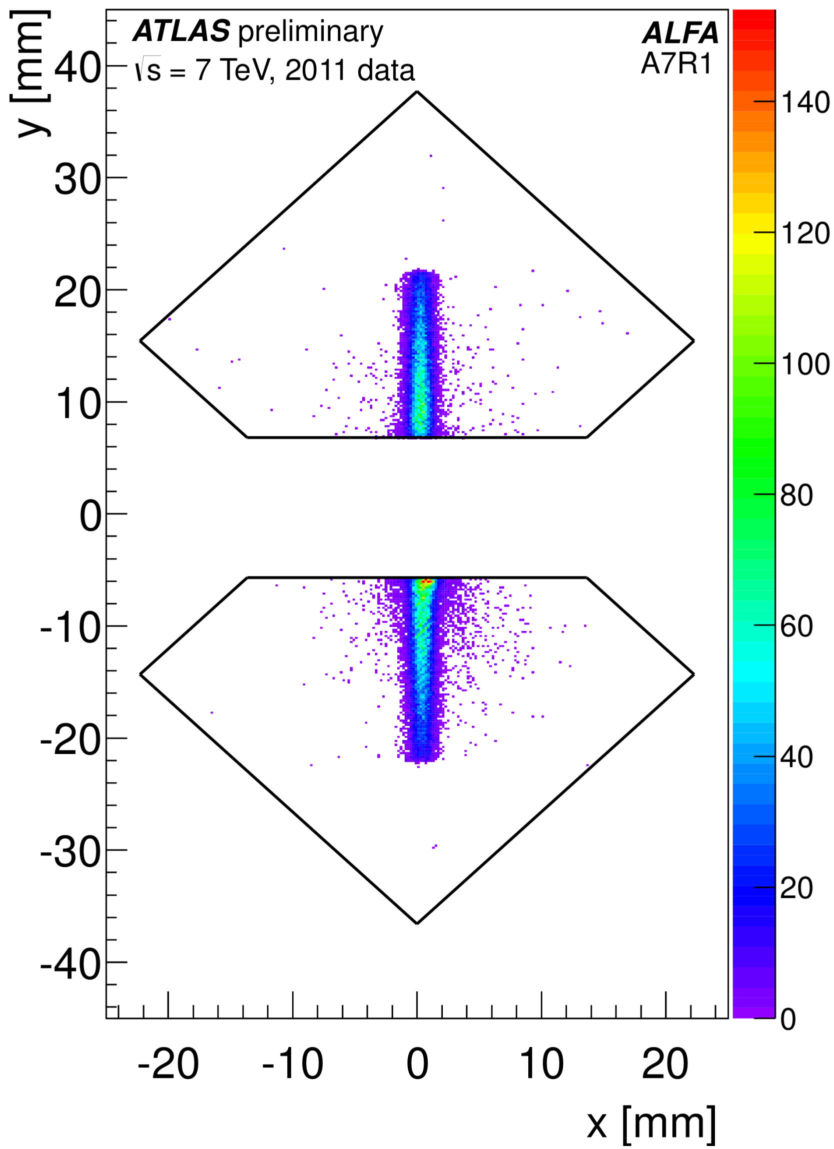



$$\Delta y_{UPPER} = \Delta d/2 - \Delta Off_y$$
$$\Delta y_{LOWER} = -\Delta d/2 - \Delta Off_y$$

⇩

$$\Delta d = \Delta y_{UPPER} - \Delta y_{LOWER}$$
$$\Delta Off_y = \frac{-\Delta y_{UPPER} - \Delta y_{LOWER}}{2}$$

# Physics analysis

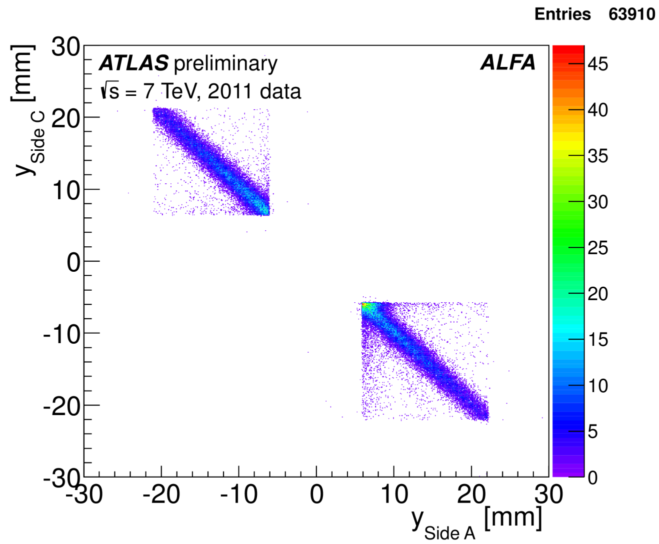


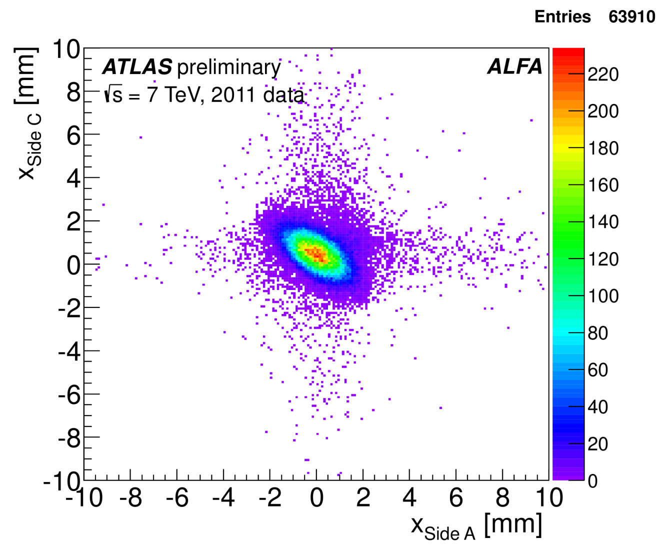

Alignment uncertainty driven by the distance measurement error (~30 µm), relative precision better than 3 µm

Horizontal alignment easier due to absence of acceptance cut

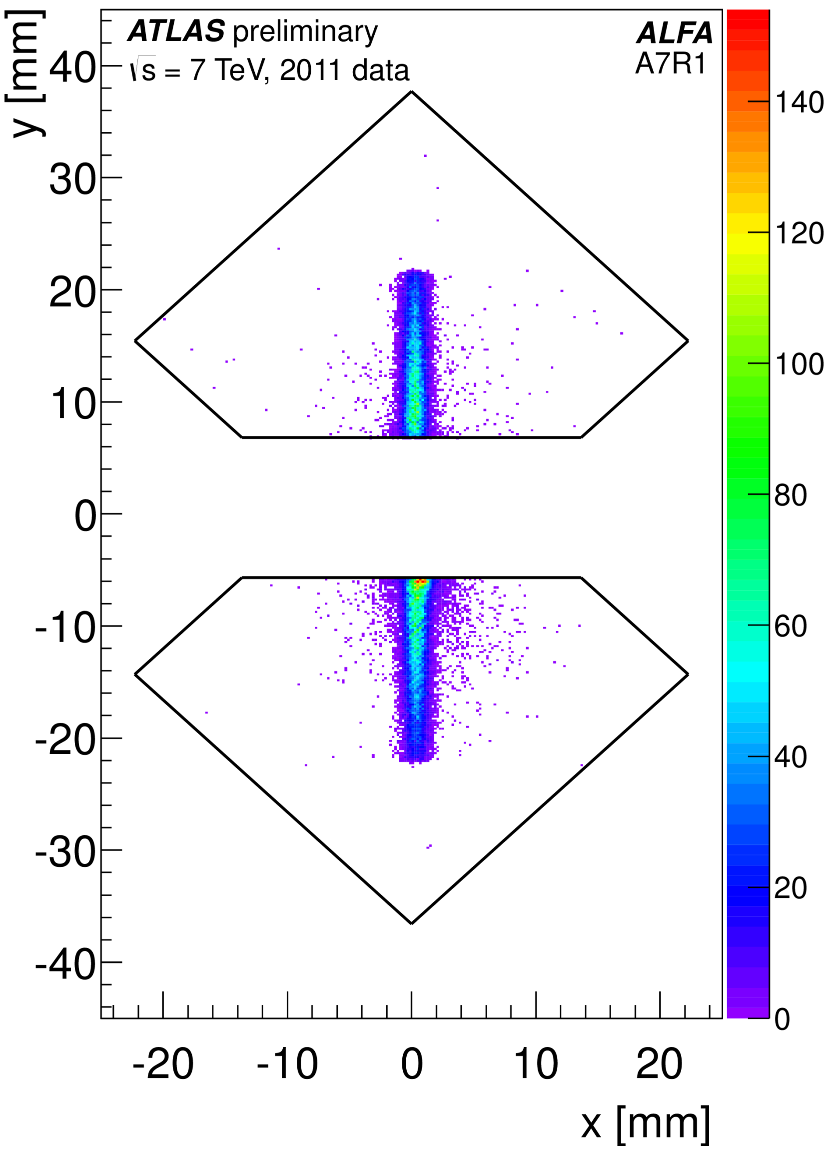
Once the tracks are expressed in the beam coordinate system, the physics analysis can start :

- First look at correlations between the two sides
- Define selection criteriae for elastic events
- Disantangle efficiency from acceptance corrections
- ...



# Physics analysis

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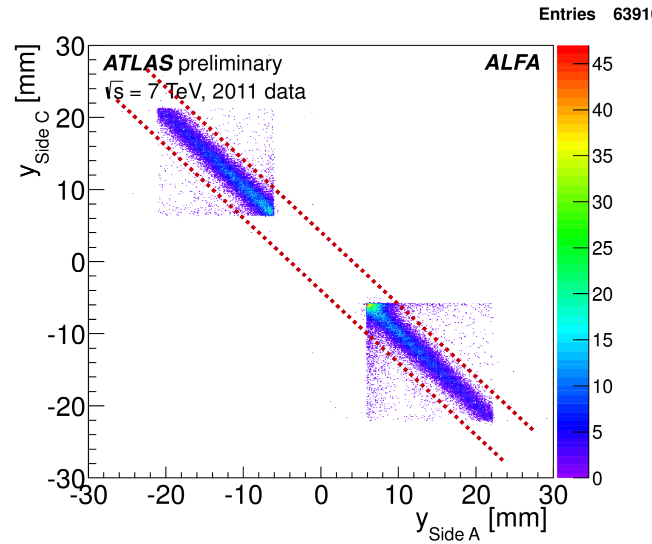


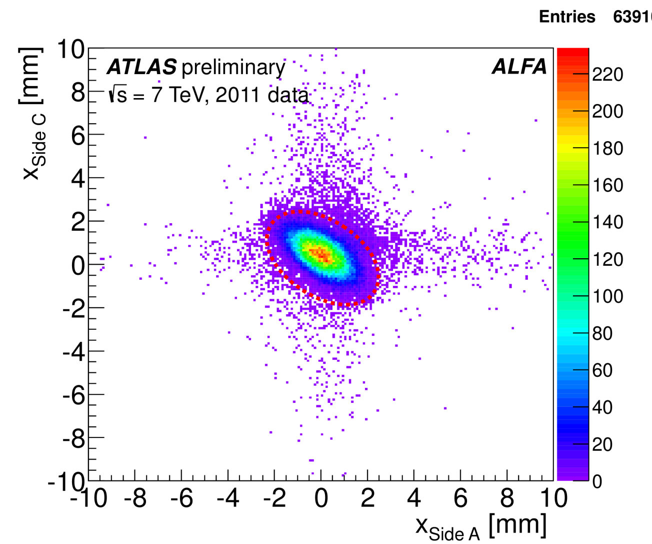

# Conclusion

- The ALFA detector has been fully installed and commissioned since 2011 and has taken so far three major run for physics
- The total cross section and nuclear slope measurement publication is still pending due to inconsistency between different t-reconstruction methods (optics related)
- A week ago, the optics was set such that we could reach the Coulomb-Nuclear interference region
- After the long LHC shutdown, the ultimate optics will be setup and the Coulomb region will be reached allowing the absolute luminosity measurement
- During this two years I have participated to the different commissioning activities, data taking (deputy run coordinator) and physics analysis (deputy conveiner)

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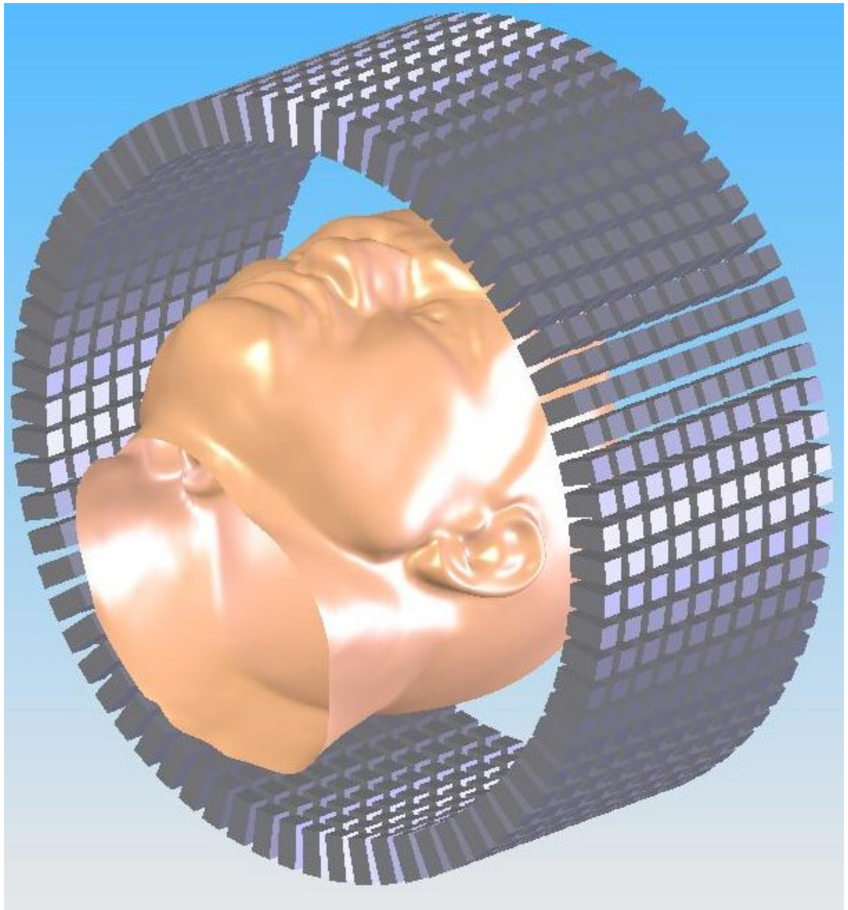
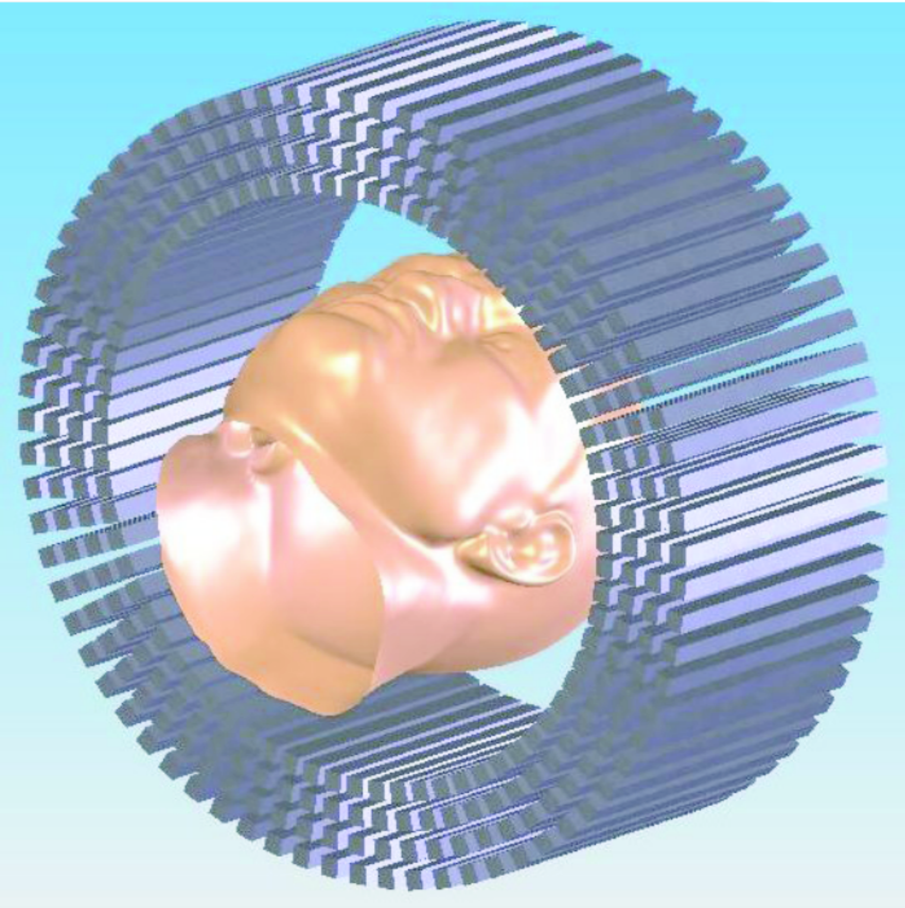
# The AX-PET concept

Standard PET scanners

AX-PET geometry proposal





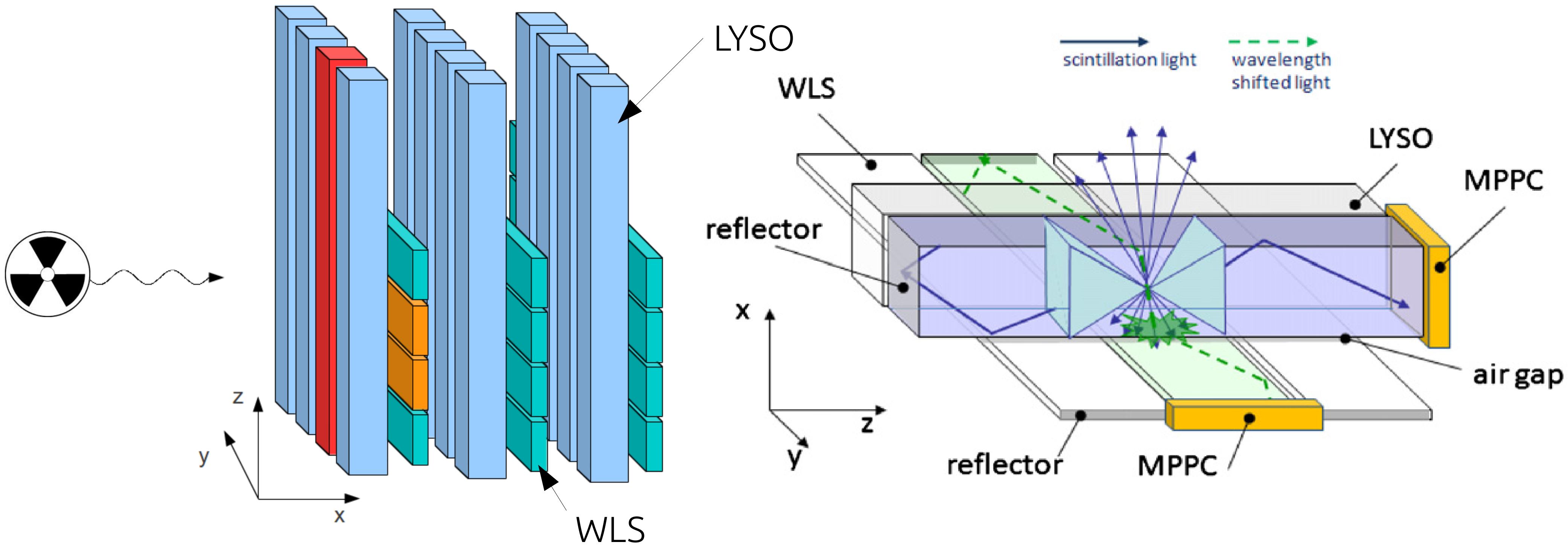
Short crystals radially oriented
Block readout

Long crystals axially oriented
Single crystal readout

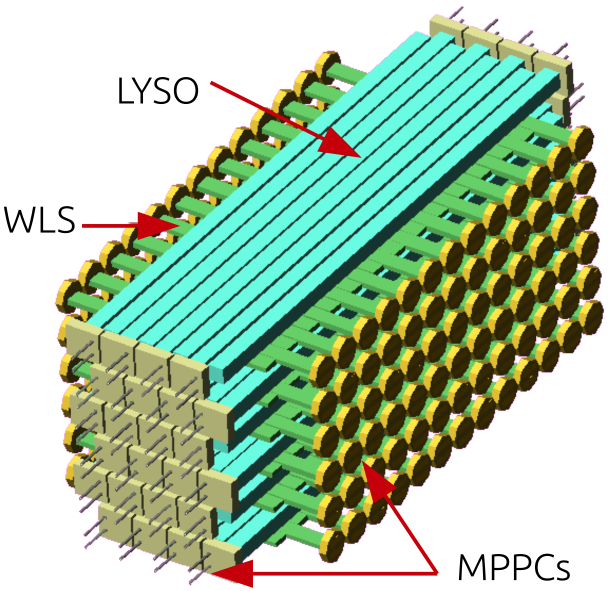
# The AX-PET concept

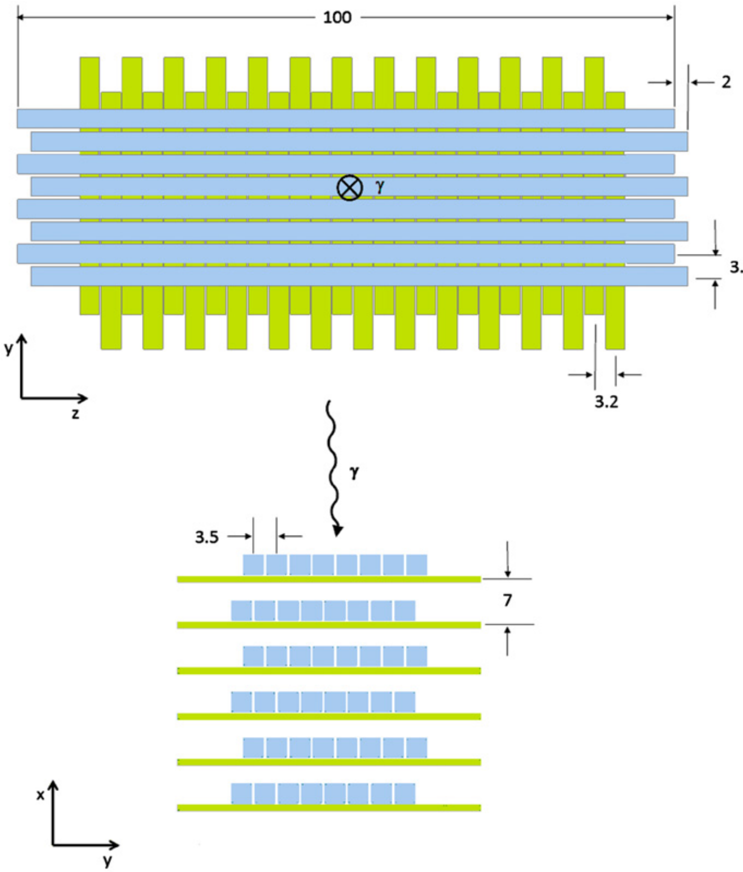
3D measurement of the photon interaction point

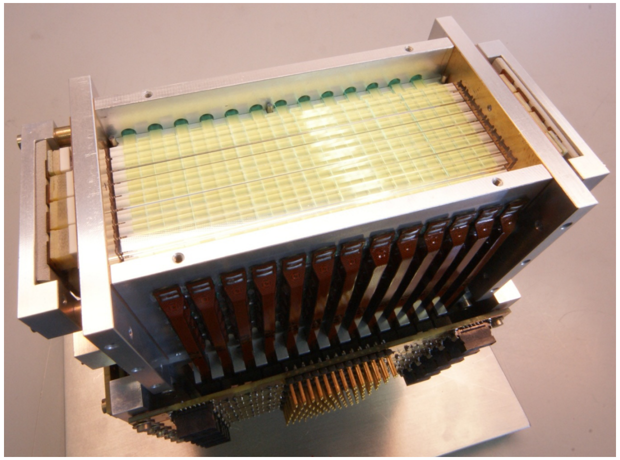
- Transaxial coordinate and energy measurement with thin elongated scintillator LYSO crystals
  - The hit crystals gives the transaxial coordinate (x, y)
- Axial coordinates measured with Wave Length Shifter (WLS) strips



# Module assembly

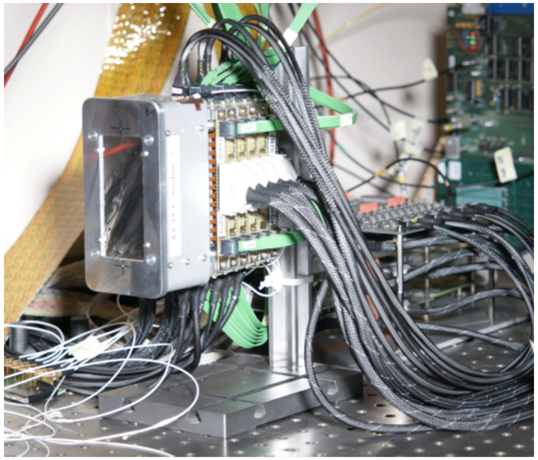


Assembled module

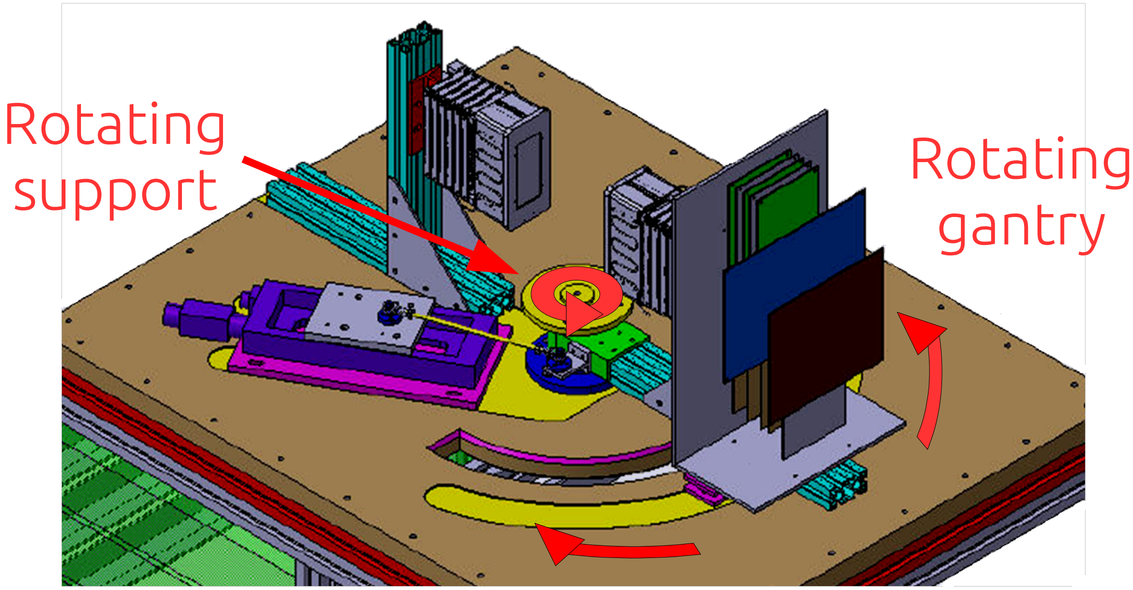
- Each module is composed by six layers
- Each layer is made of 8 LYSOs and 26 WLS both staggered to enable the readout
  - → 204 channels per module
- All layers are optically decoupled

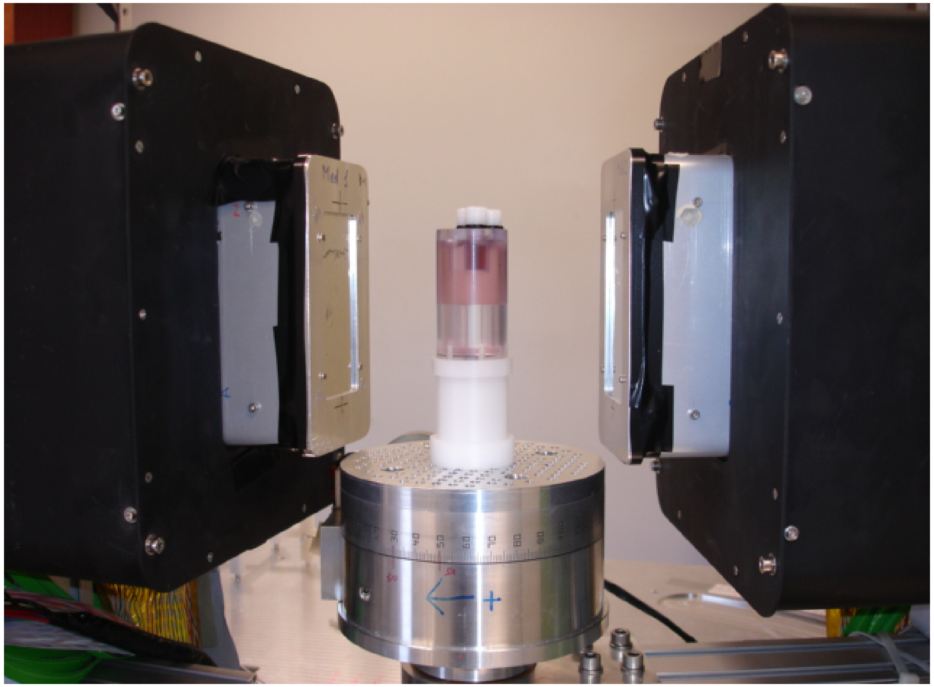


Module housing and services

# Test bench for tomographic reconstruction

- The two modules are mounted on top of a portable platform, which houses also the electronics, power supply, etc...
- A rotating motor can move the source or phantom positioned in the field of view
- One of the modules can rotate wrt 180° position by ±60°



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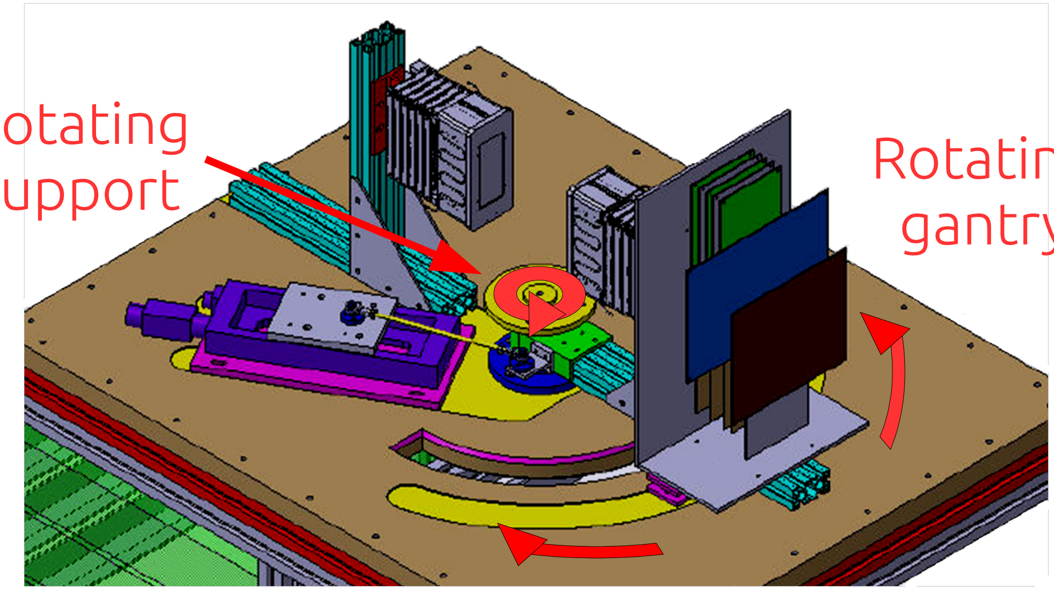
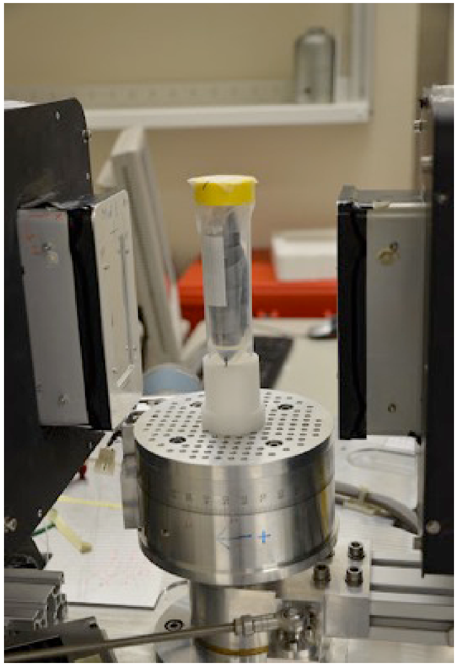
Rotating support

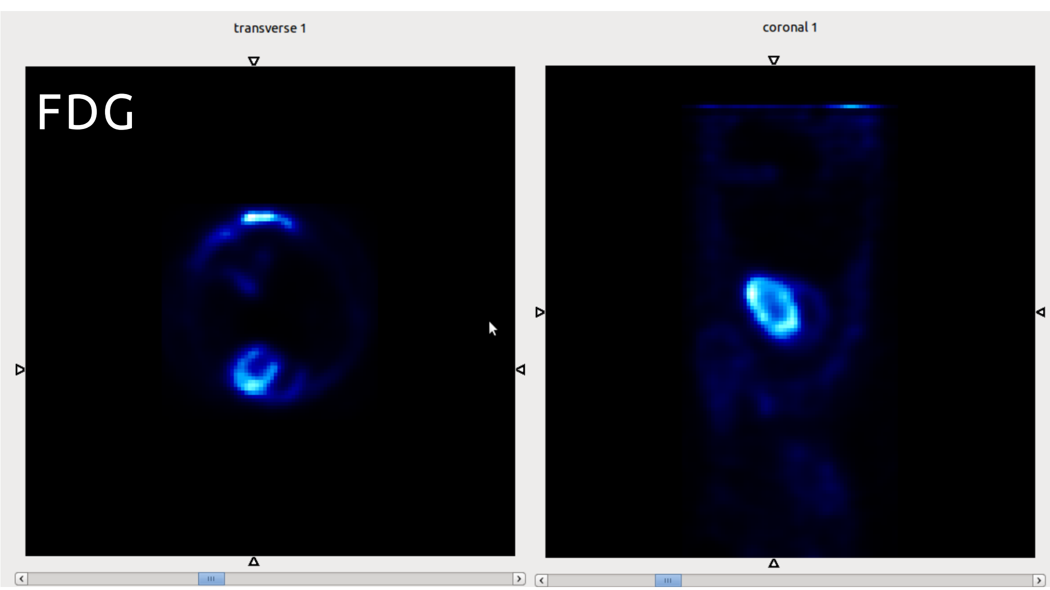


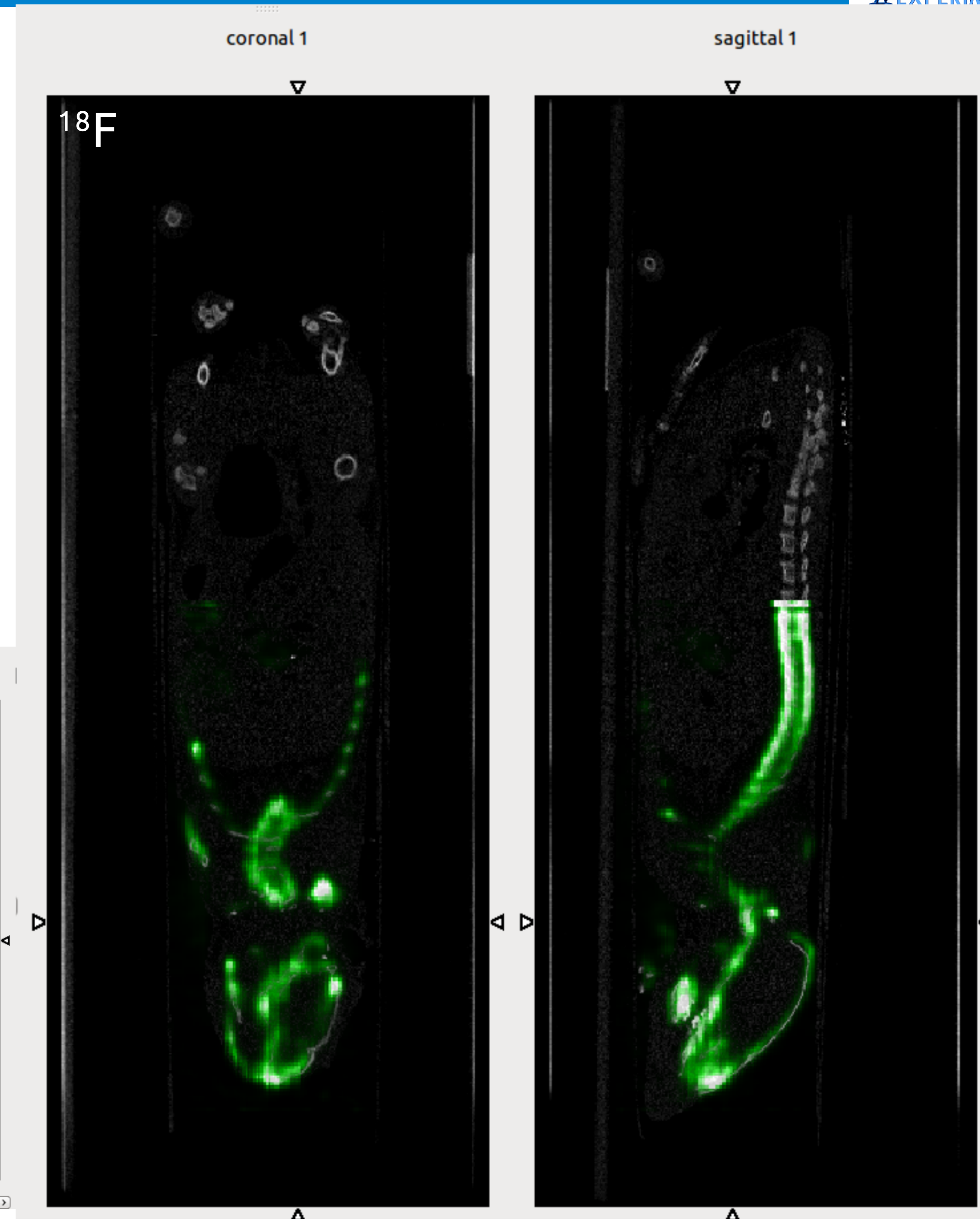
Rotating gantry



# Images from tomographic reconstruction

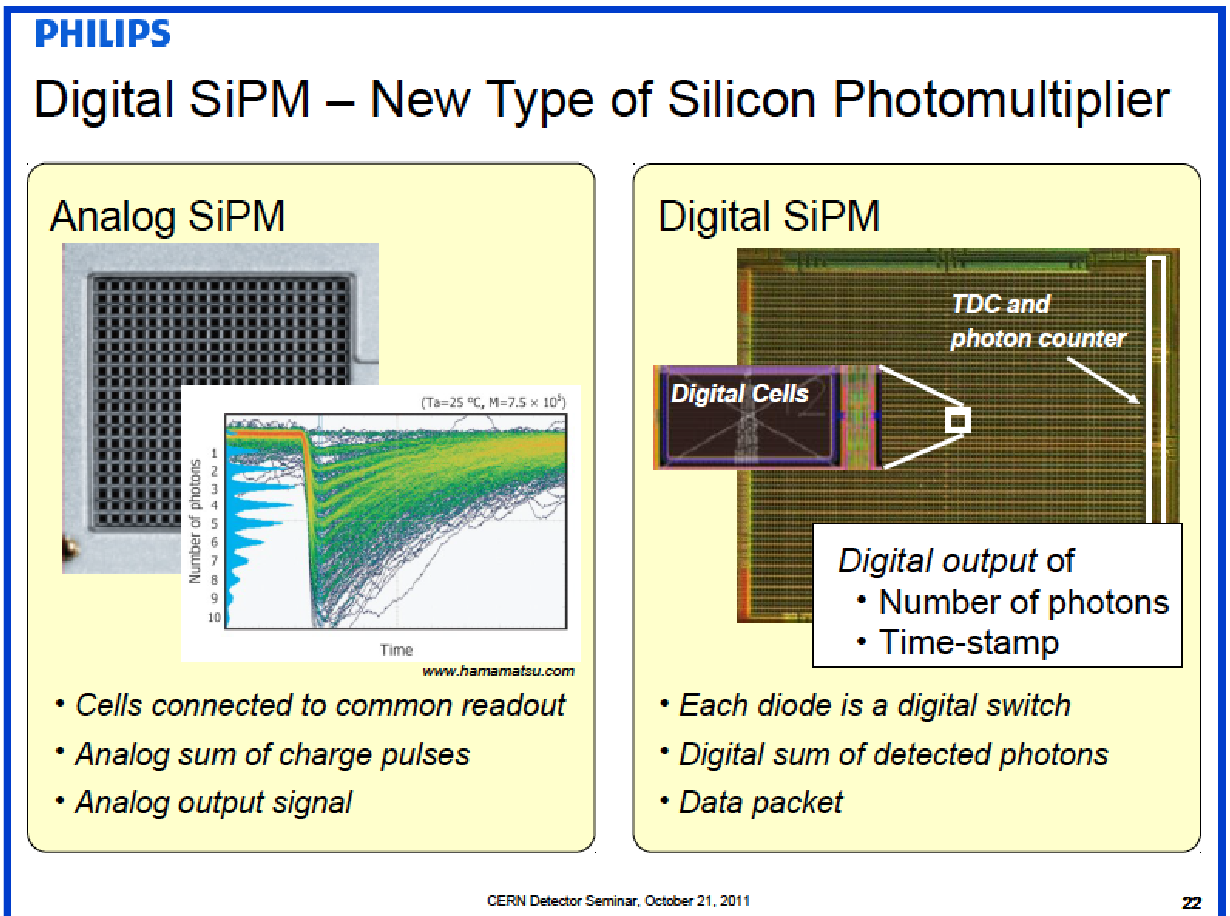
- Last measurement campaign done at ETH zurich on rat and mouse
- Goal : demonstrate that the AX-PET concept is capable of providing images at least as good as standard scanners (e.g ExploreVista)

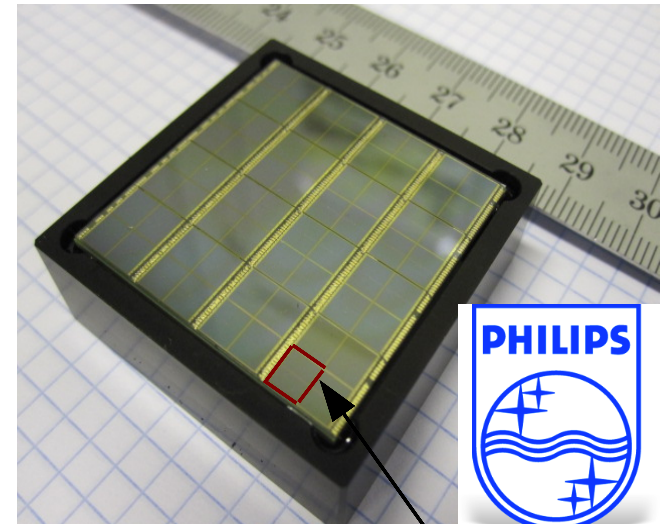


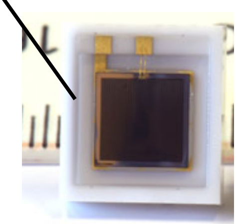



# Using digital SiPM from Philips as alternative photodetectors

- extremely good timing performance
- GOAL : demonstrate the possibility a TOF-PET with the axial concept



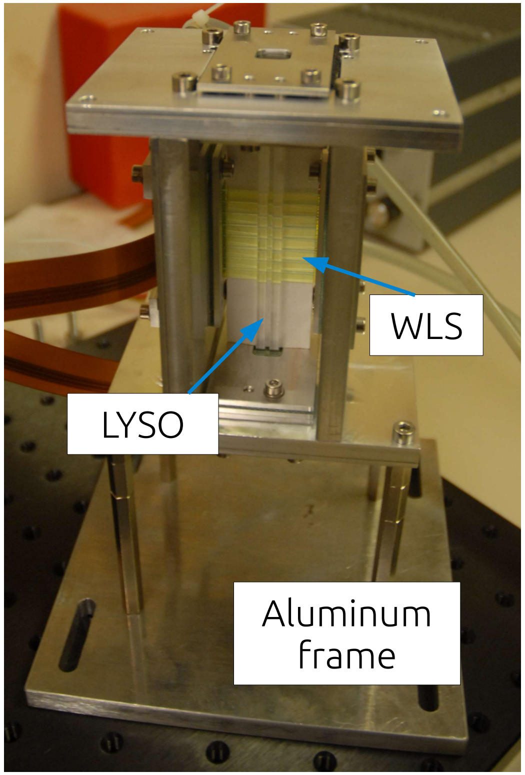


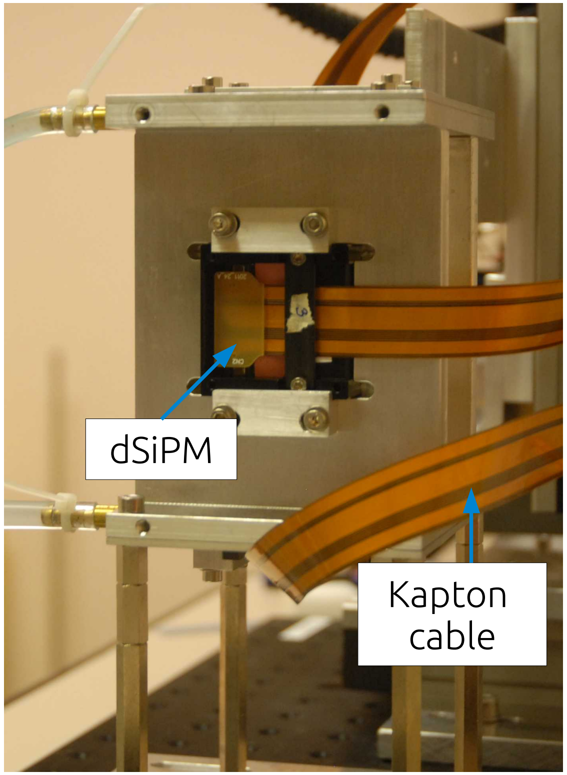
**MPPC :**
3200 cells
3x3 mm$^2$

Still a prototype
Evaluation kit bought :

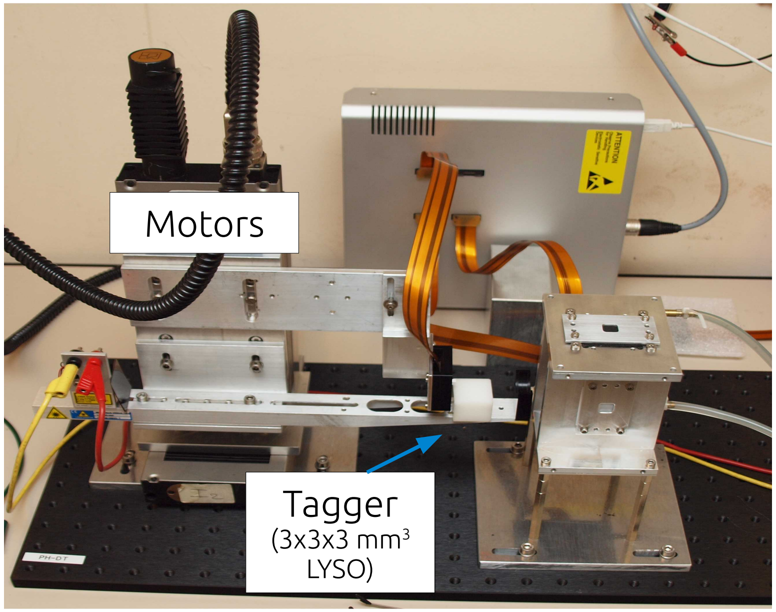
Includes four sensors (2 with 3200 cells per detection unit, 2 with 6400 cells

# The different setup used

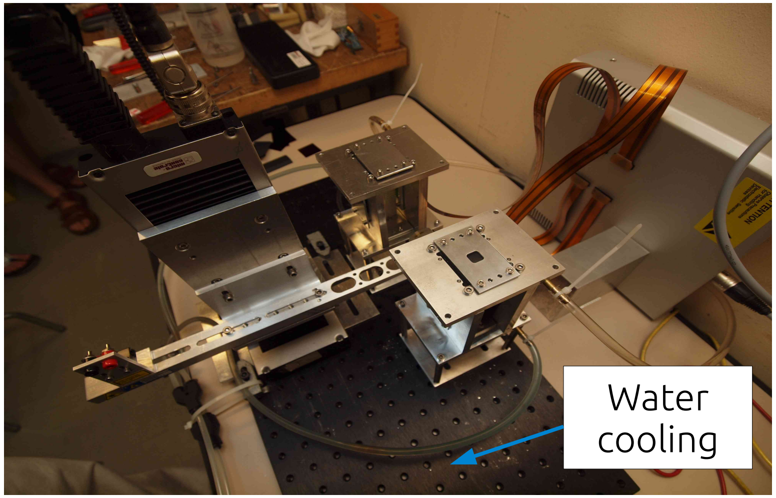



One module setup




Two modules setup




<u>Test module composition :</u>

2 layers made of :
- 2 LYSO 3 x 3 x 100 $mm^3$ (4.6 mm pitch)
- 8 WLS strips 3 x 0.9 x 40 $mm^3$ (4 mm pitch)

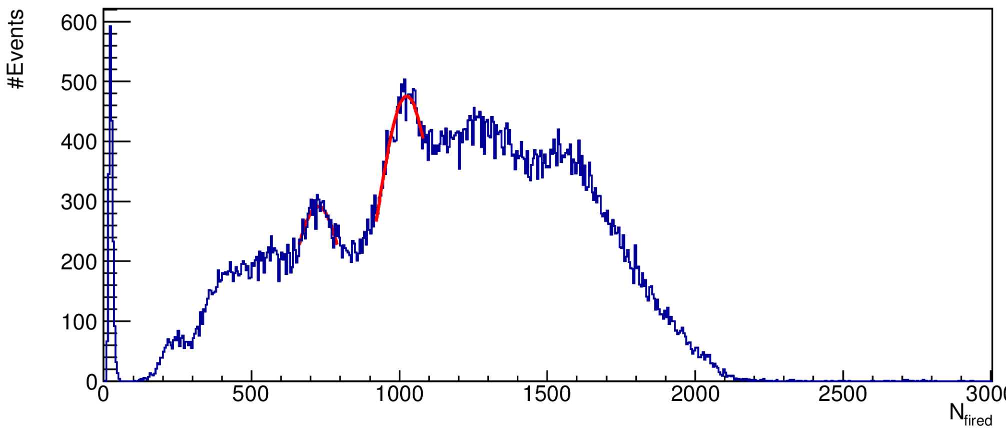
<u>One module setup used for :</u>
- Energy resolution
- Single module spatial resolution

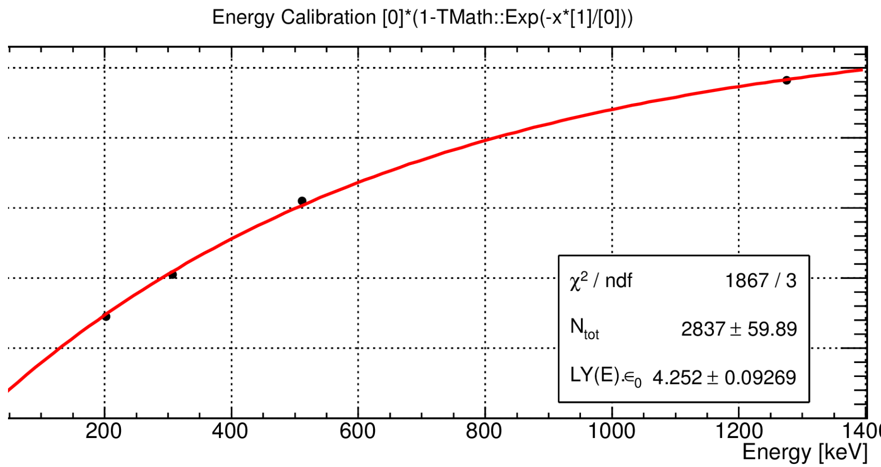
<u>Two module setup used for :</u>
- Spatial resolution for modules in coincidence
- Coincidence time resolution

# Energy resolution

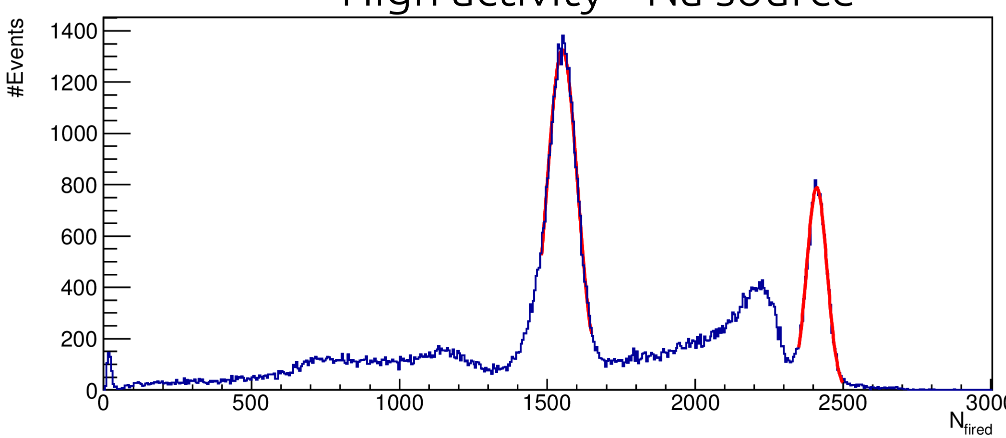
$$E = N_{TOT}\left(1-\exp\left(\frac{-N_{\gamma}LY(E)\epsilon_0(1+XT)}{N_{TOT}}\right)\right) = N_{TOT}\left(1-\exp\left(-\alpha\frac{N_{fired}}{N_{TOT}}\right)\right)$$

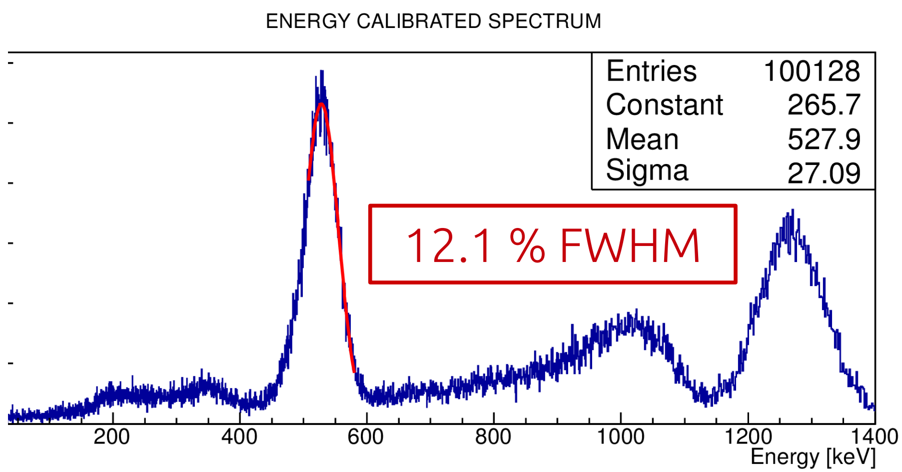
Intrinsic radioactivity



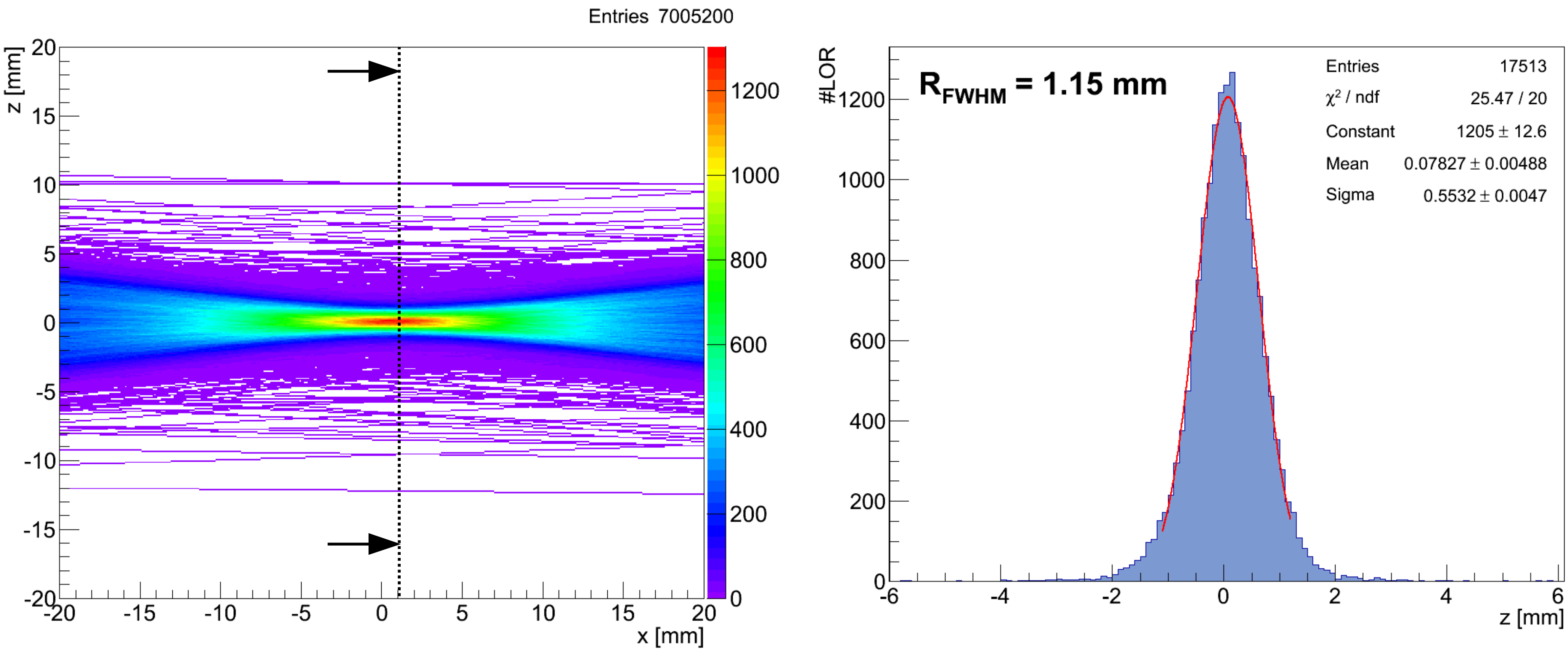

High activity $^{22}$Na source



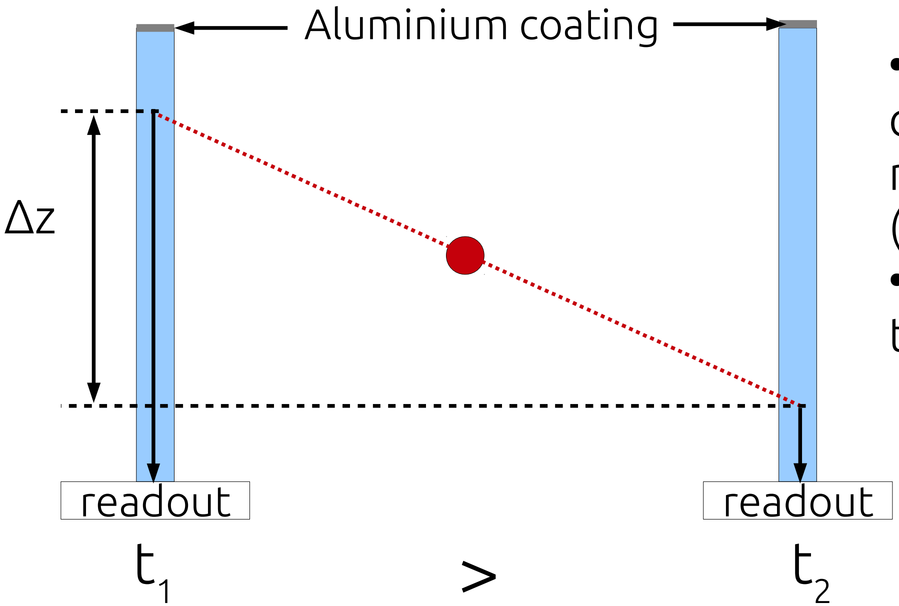
# Spatial resolution

$^{22}Na$ source of 250 microns diameter, 150 mm between the two modules

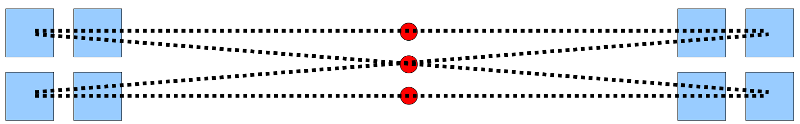



- Single module intrinsic resolution : ~ 1.6 mm FWHM
- Confocal axial resolution : 1.15 mm FWHM
  -> Expected sqrt(2) factor observed between the two measurements

# Coincidence Time Resolution Calibration for long crystals

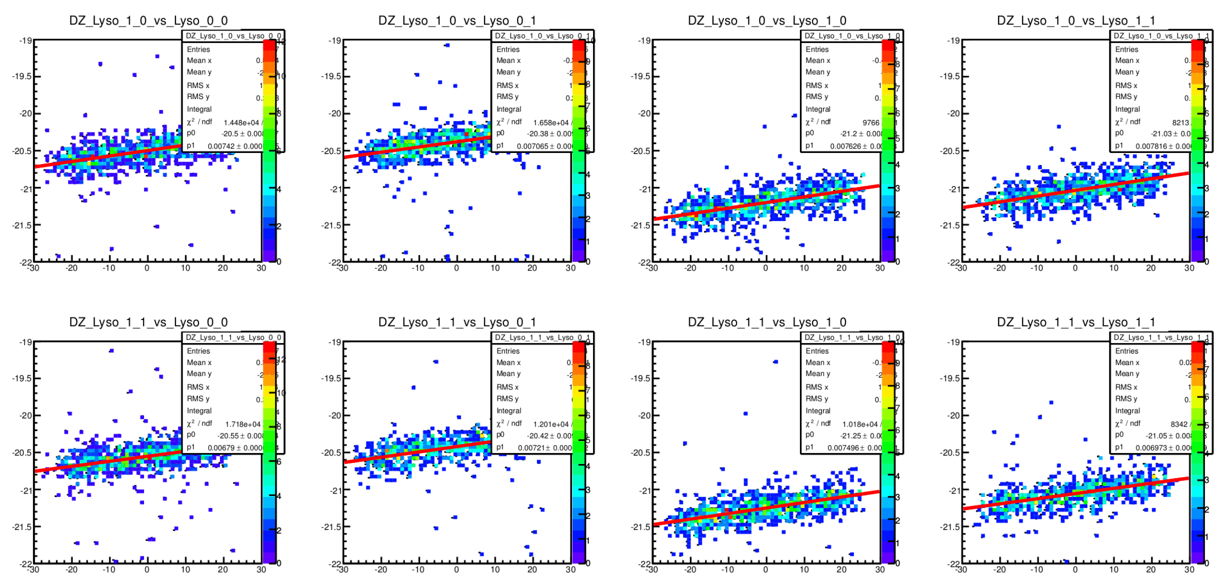



- If the interaction happens at the same height in the crystal, the time difference between the two modules gives directly the position of the interaction (within time resolution)
- If the interaction is asymetric, one has to correct for the light path in the two crystals.

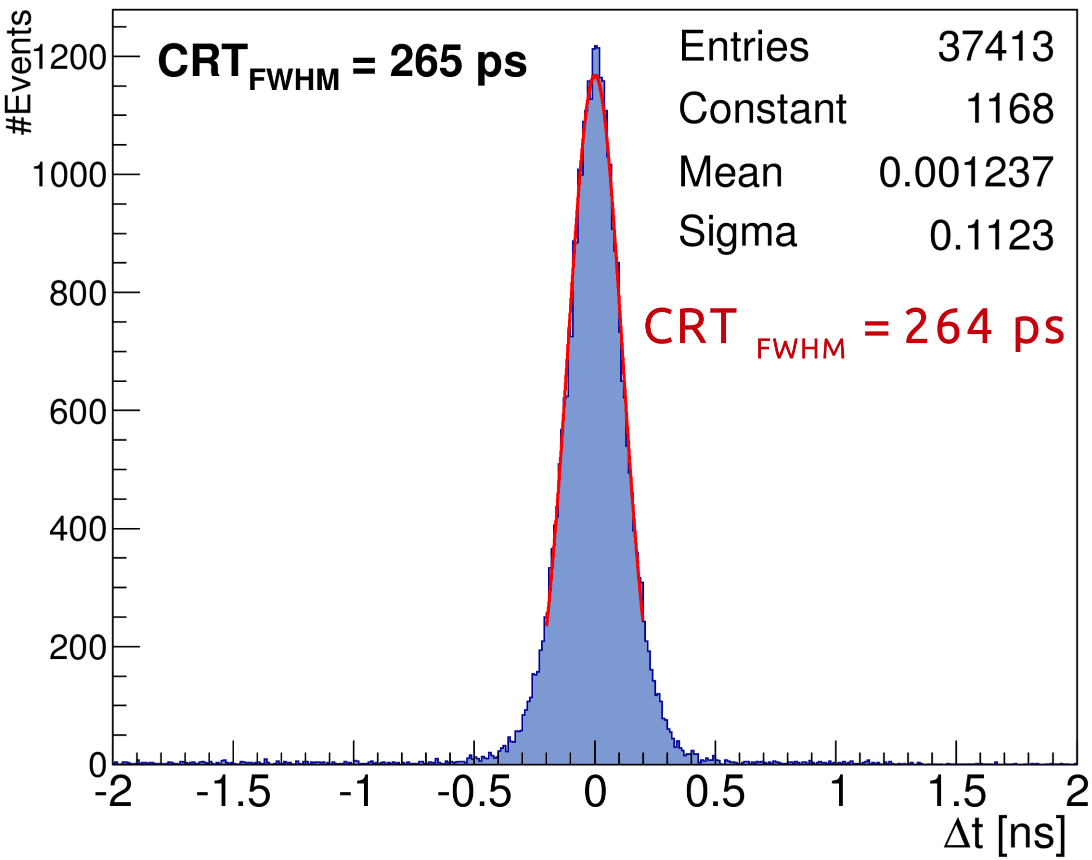


- The parametrization is done fitting the 2D distribution Δt vs. Δz

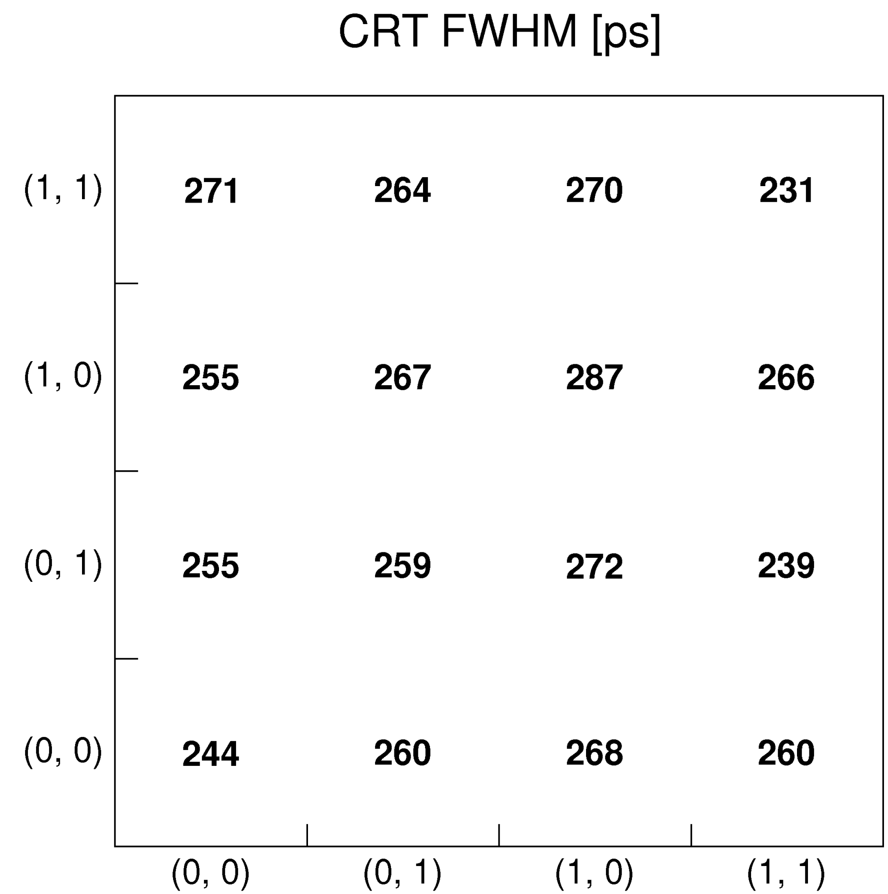
- This parametrization needs to be done for every crystal combination because all trigger networks have their own time offset



# Coincidence Time Resolution

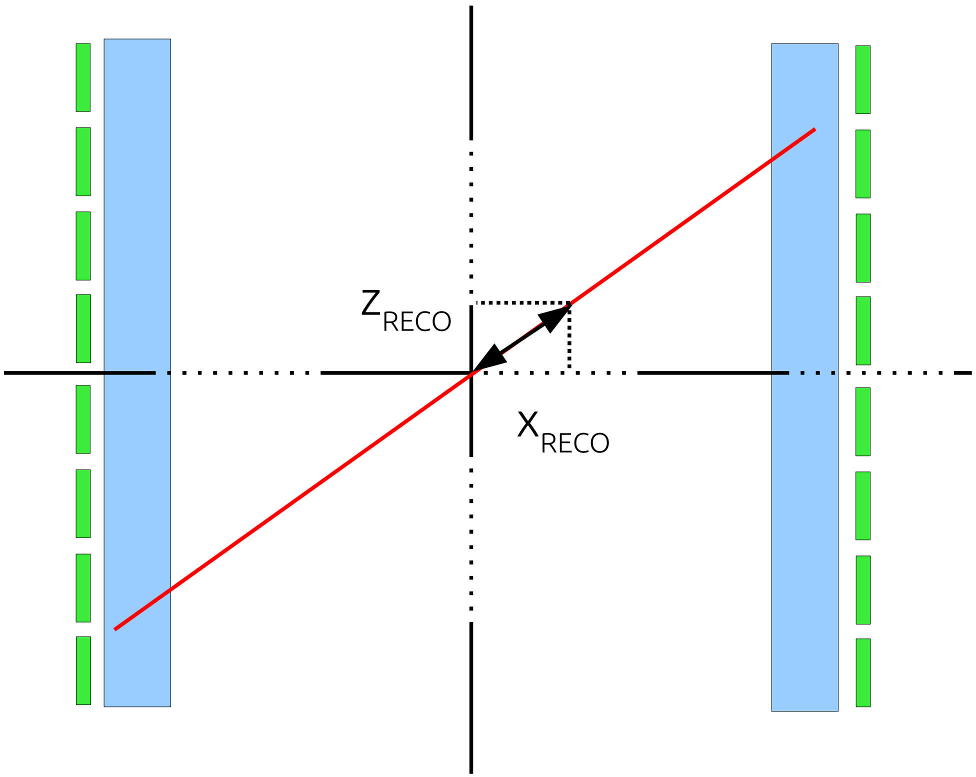



Module resolution

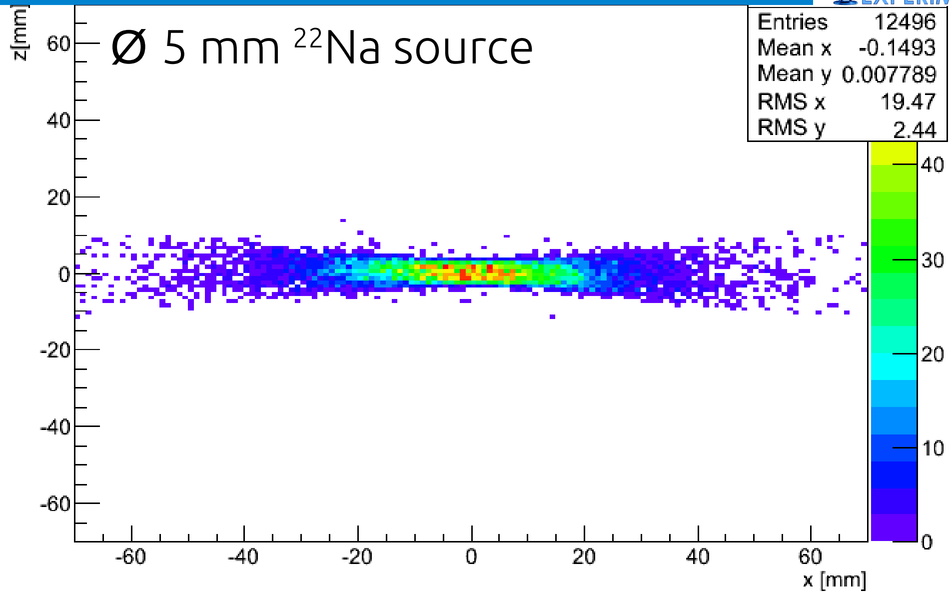


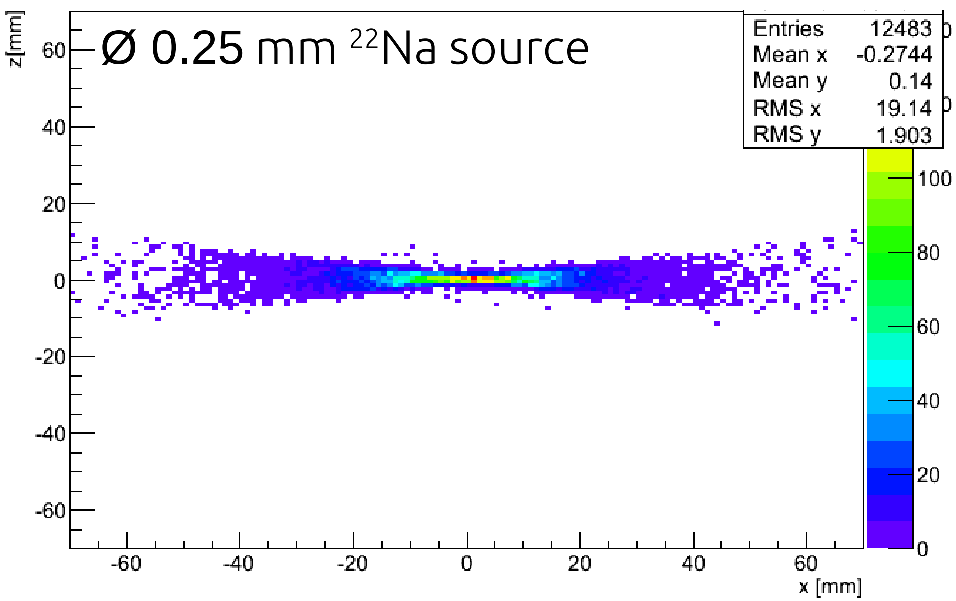

Resolution for all Lyso combinations

# Time Of Flight reconstruction

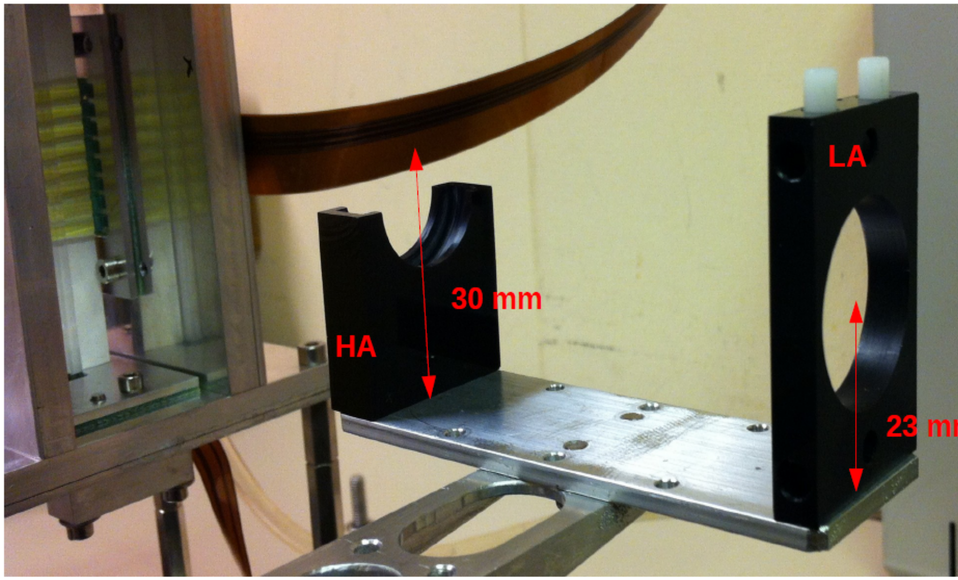


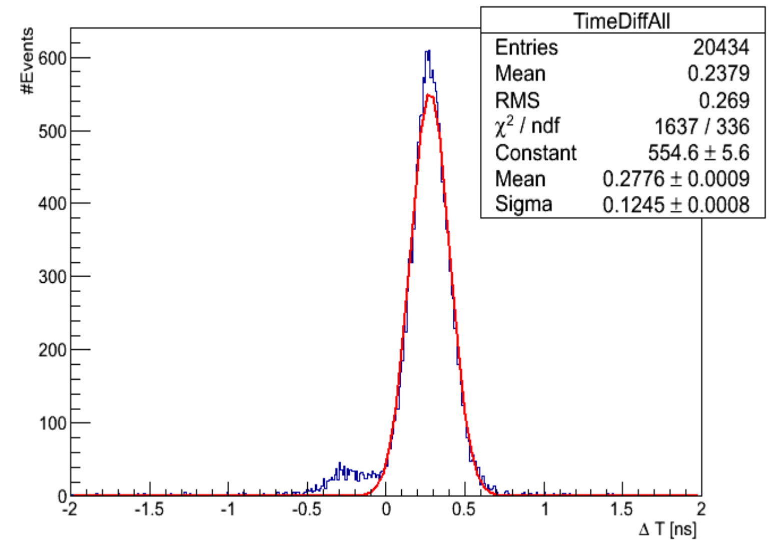

$$\Delta LOR = \frac{\Delta t * c}{2} \quad \begin{cases} x_{reco} = \Delta_{LOR} * \cos(\theta_{LOR}) \\ z_{reco} = \Delta_{LOR} * \sin(\theta_{LOR}) \end{cases}$$

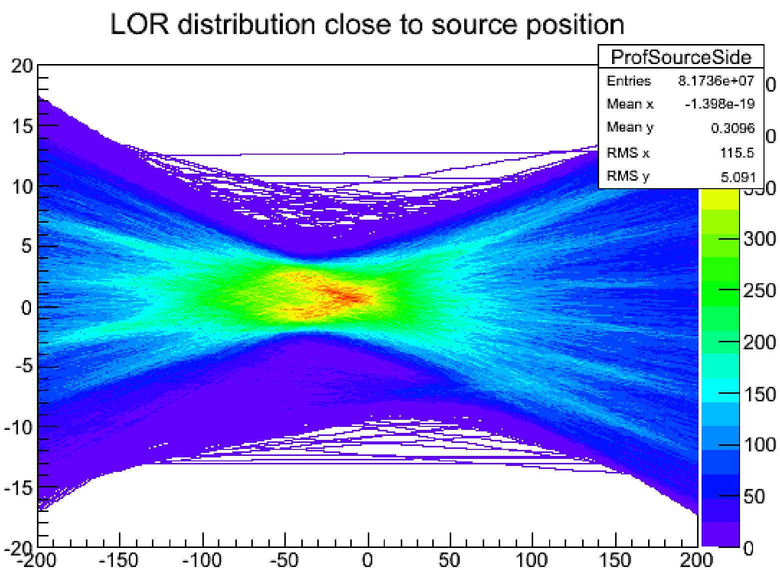


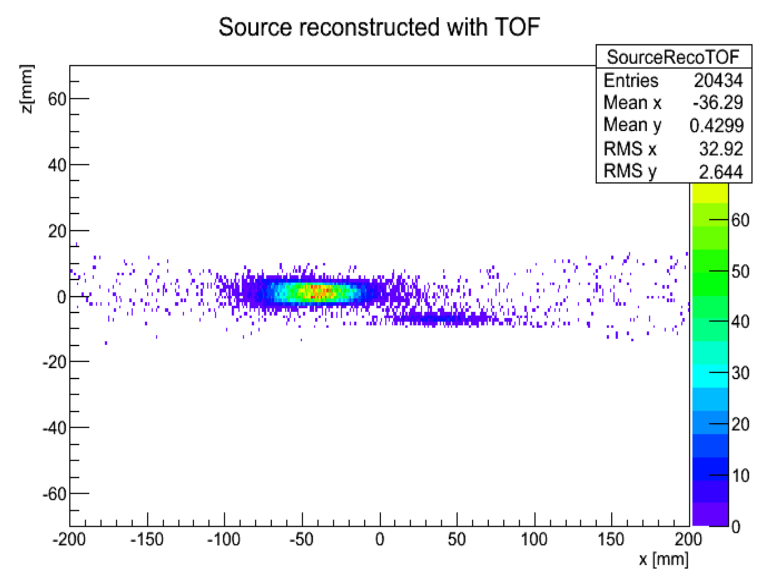
# Time Of Flight reconstruction



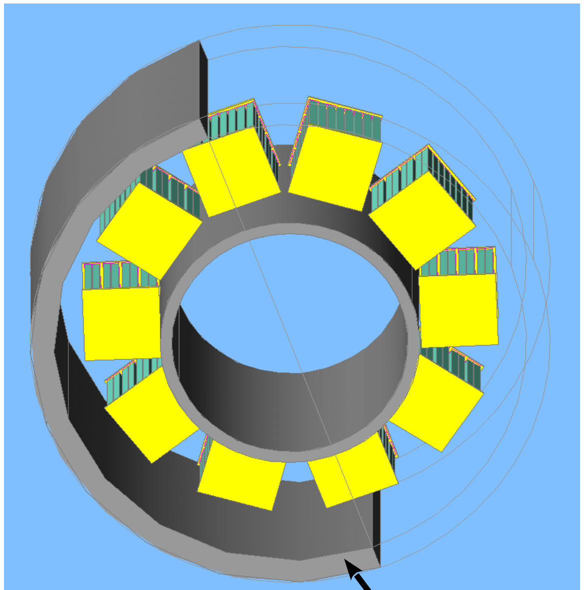

The excellent timing capabilities of the dSiPM allow to identify very clearly the low activity source, while in the simple LOR representation it is hard



# Conclusion

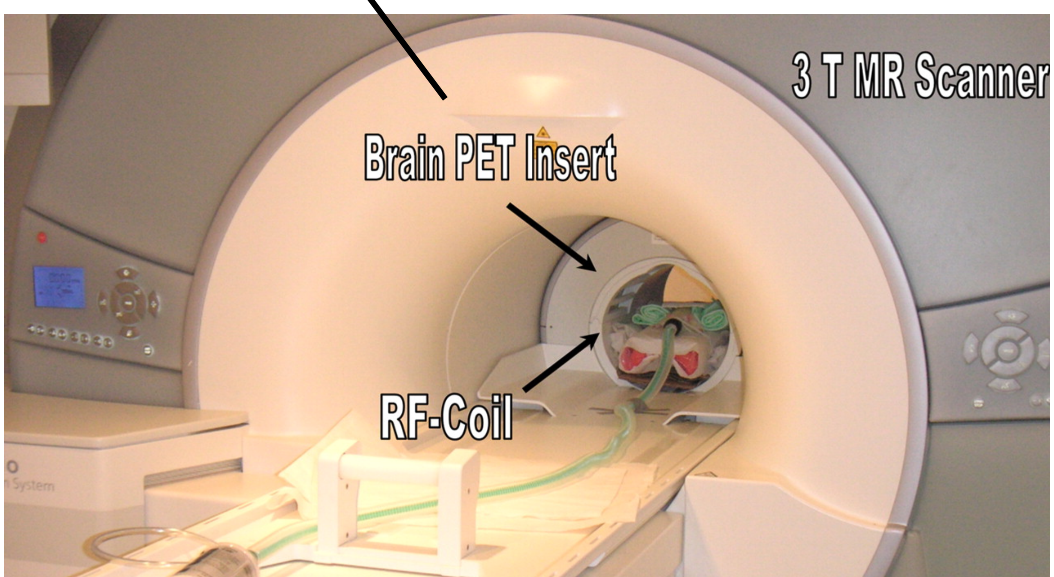
- The AX-PET demonstrator was extensively tested and so far has shown impressive capabilities for tomographic reconstruction despite its limitations
- The ultimate goal of AX-PET is not to build an entire ring. The goal was always to prove its principle and encourage people to use the concept
- Recent collaboration with Philips has opened new horizon, see next slide
- During these two years I have worked on data analysis, test campaign and more recently started at CERN the activities using the dSiPM from Philips (setup, data analysis...)

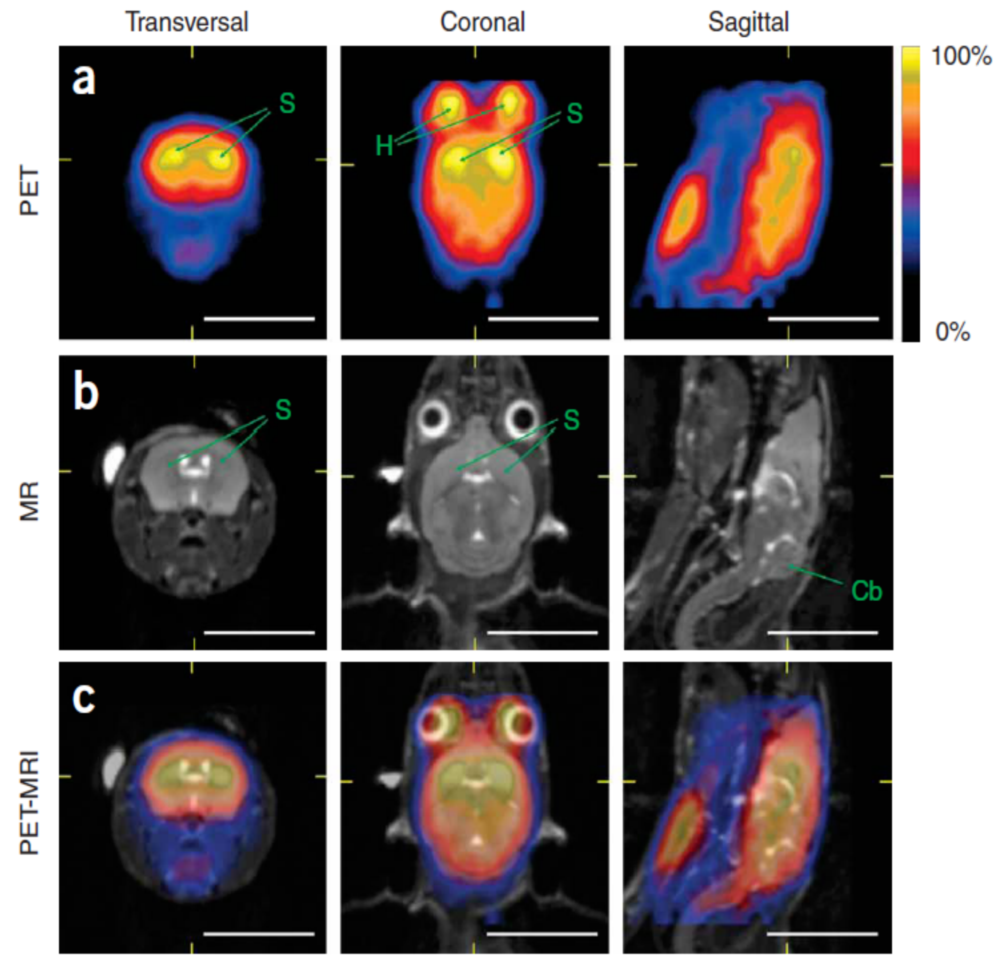
# AX-PET future !!!



The axial concept provides compactness, good sensitivity and spatial resolution. Consequently it is a very good candidate for PET insert in an MRI scanner

Future collaboration with ETH zurich and Philips on the conception of an entire ring for small animal imaging



# MC-PAD benefit and Future

- Wide spectrum covered during the different training events, pity that I was not in  from the very beginning...
- Thanks to training events and collaborators, learnt a lot about detector physics both on a theoretical and experimental point of view
- Unfortunatly no opportunity to exchange with the different members/partners except during the training events (marginal project)
- Hard to combine two very active projects ! However extremely interesting to combine fondamental and applied research, physics analysis and lab work
- Present and near future (Extented till end of February 2013) :
  - to participate to the realization of the new AX-PET project success and fortunatly lead it to success
  - to publish the proton-proton total cross section and nuclear slope measurement

# Thanks for you attention

Thanks to mobility funds I could attend :

- All MC-PAD training events since gaseous and photon detectors at CERN in march 2011
- EIROforum School of Instrumentation 2011 in Grenoble (Presentation of a poster on AX-PET)
- New Development In Photodetectors 2011 in Lyon (Talk on AX-PET)
- Workshop on Digital Counting Photosensors For Extreme Low Light Level in Lisboa (Talk on AX-PET)
- PhotoDET 2012 in Orsay (Talk on AX-PET)
- Chair experimental session in a school (JRJC) for the french PhD students

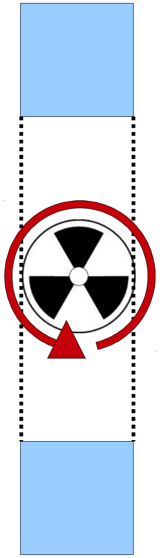
# Measurement with phantoms

## How to mimic a full ring scanner ?

➡ It depends on the Field Of View (FOV)

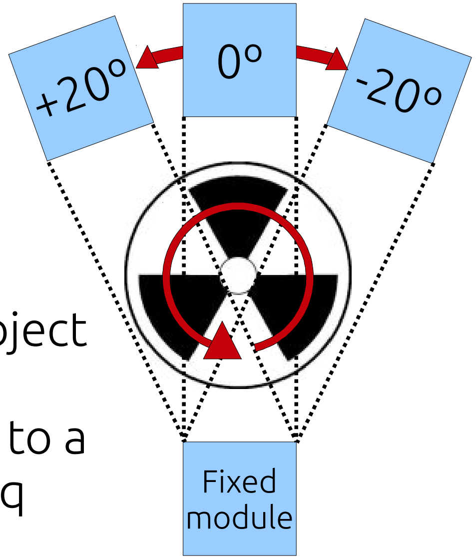
<u>Standard FOV :</u>

- Distance between modules 15 cm
- Modules both fixed : source rotates by 360°



<u>Extended FOV :</u>

- The source rotates by 360° (20° steps)
- One module fixed
- The other rotates by +20°



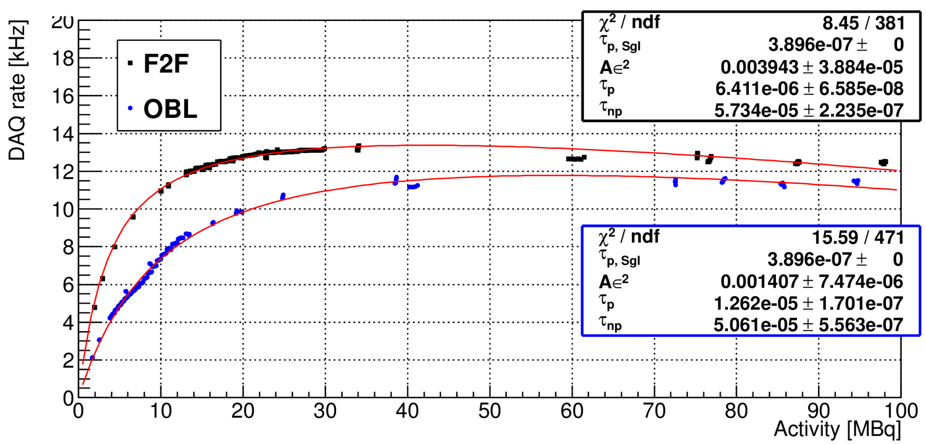

<u>Limitations :</u>

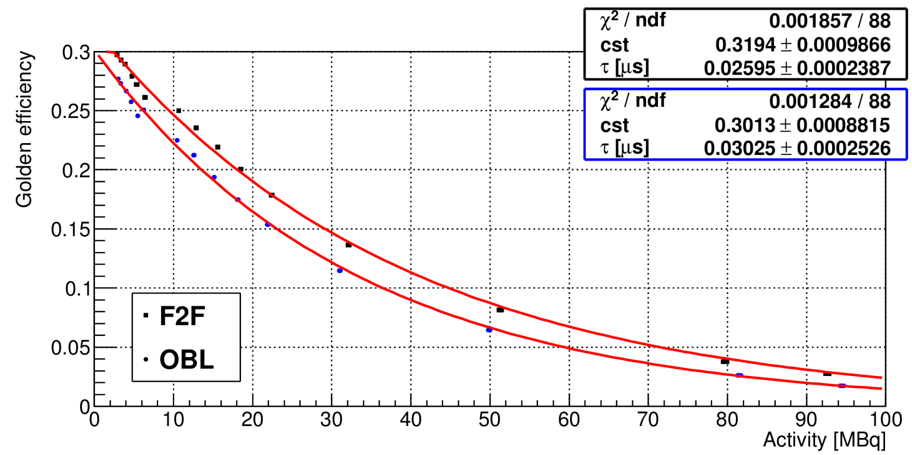
- The entire geometry of the scanned object is not embraced at the same time !
- The activity decay along the scan leads to a non uniform response of the system (daq rates, event selection...)

# Rate prediction

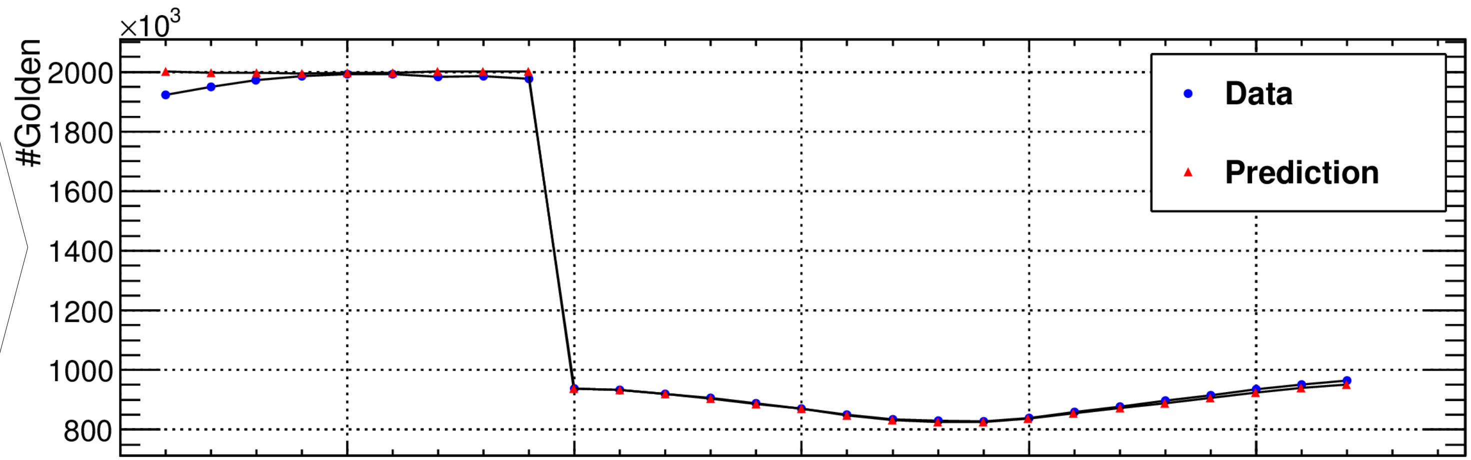
## How to overcome these limitations :

- Correct afterwards for source decay → can lead to lack of statistics
- In case of a performance demonstration campaign, on can anticipate all the different effects



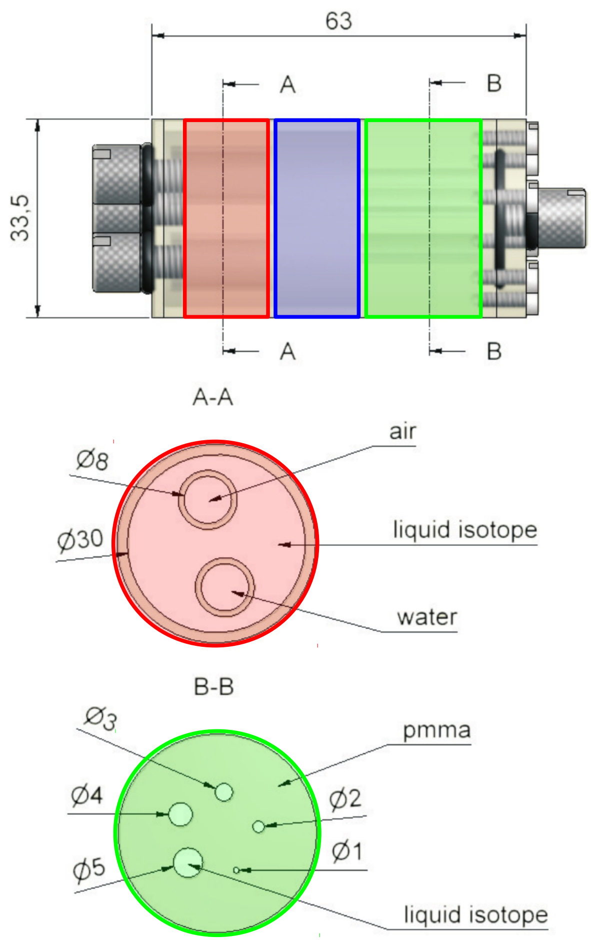

After extacting the geometry of the object in a so-called pre-scan, the number of golden events per position can be computed

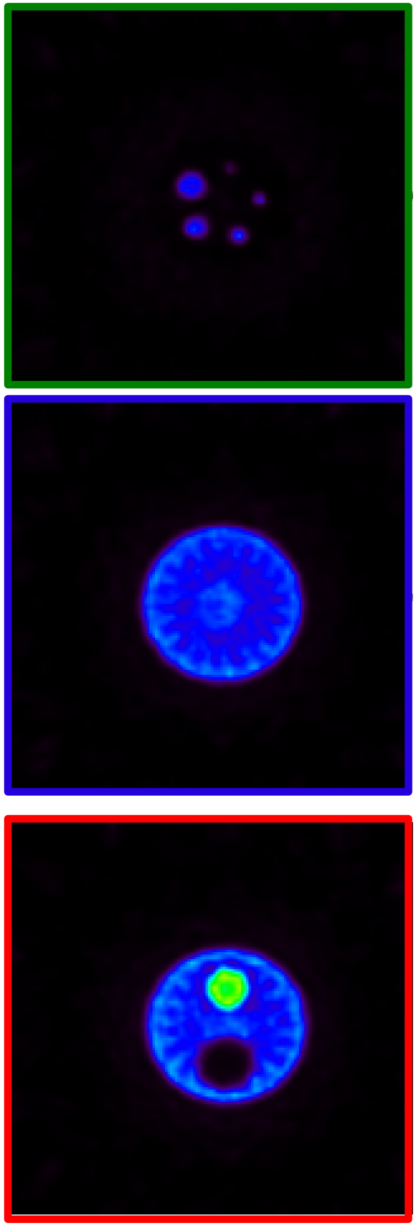


# Images from tomographic reconstruction

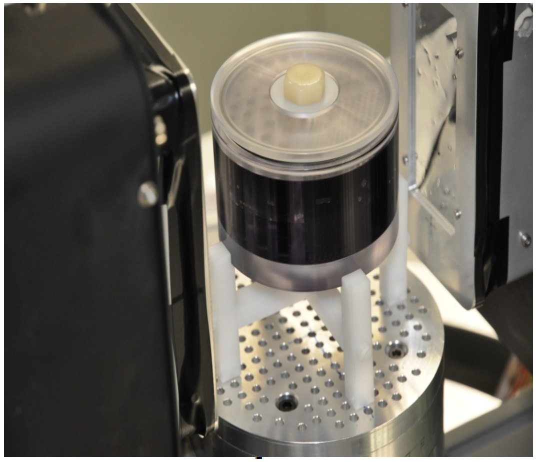
## NEMA NU4

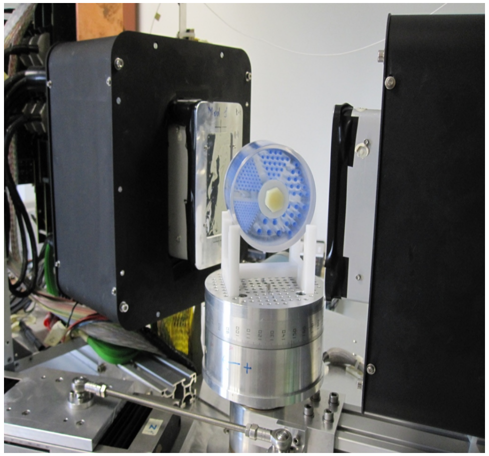
Image Quality
Mouse Phantom

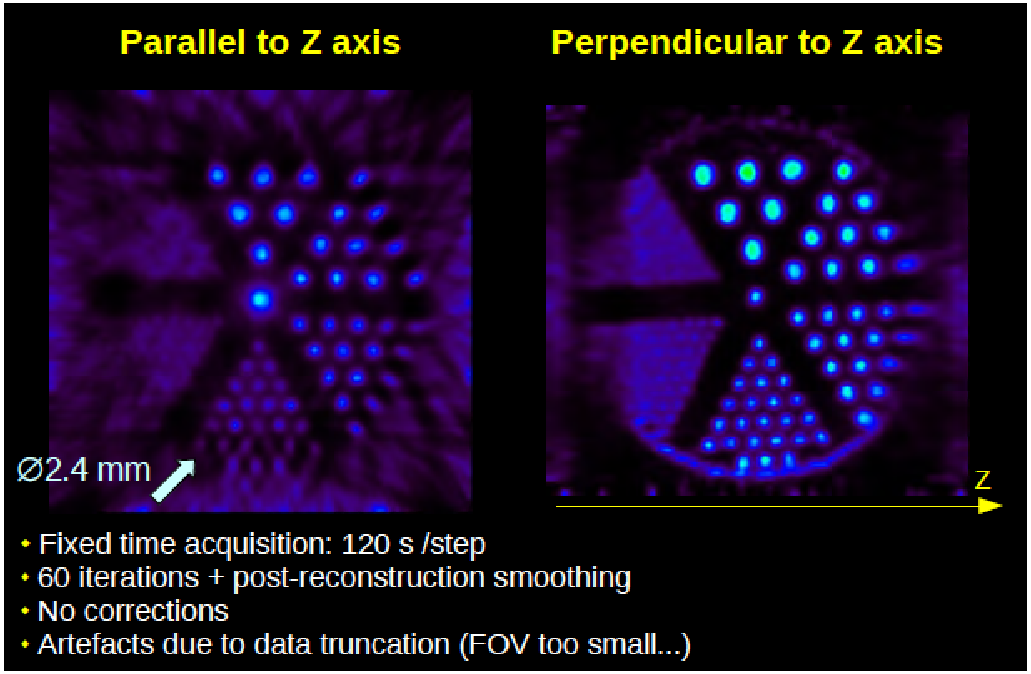


## Mini deluxe

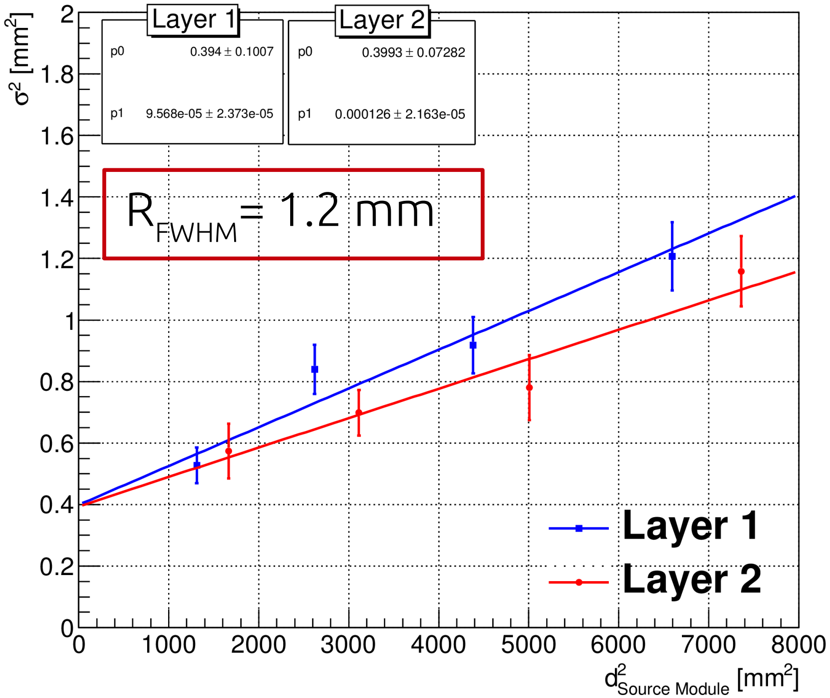




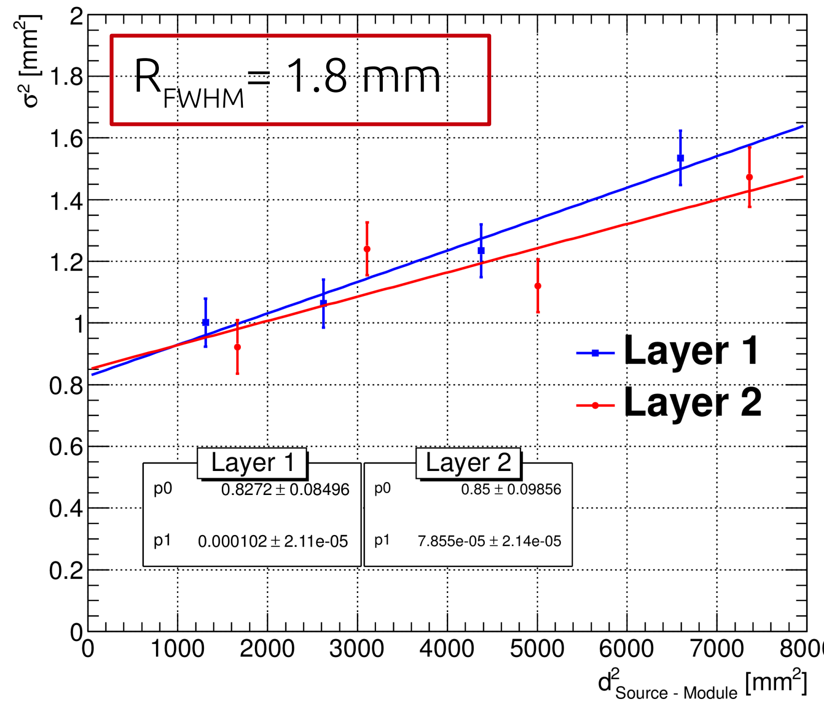


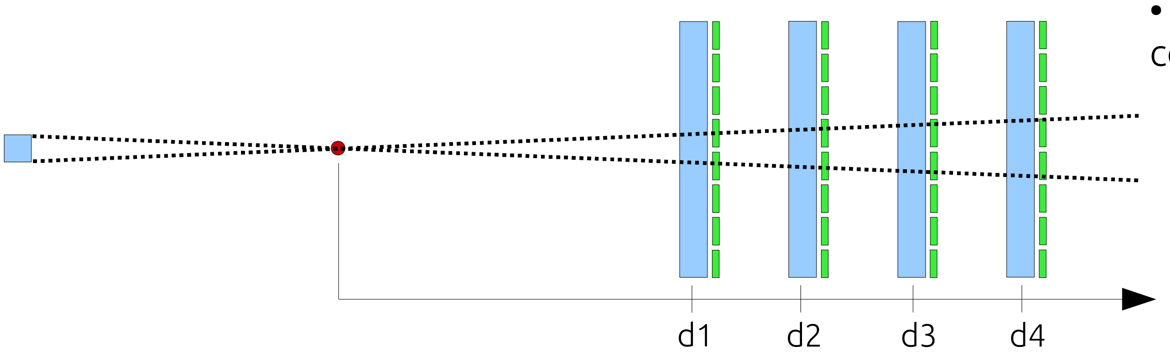
# Spatial resolution

## Beam centered on one WLS strip




## Beam centered between two WLS strips




- At each distances, the measured beam size is the convolution of several contribution :
  - Distance dependant :
    - Beam width
    - Non-collinearity

    } Cancelled by extrapolation to zero distance
  - Distance independant :
    - Intrinsic resolution
    - Source size
    - Finite positron range

    } Quadratically subtracted to intercept value