MUON Spectrometry at forward rapidities with ALICE

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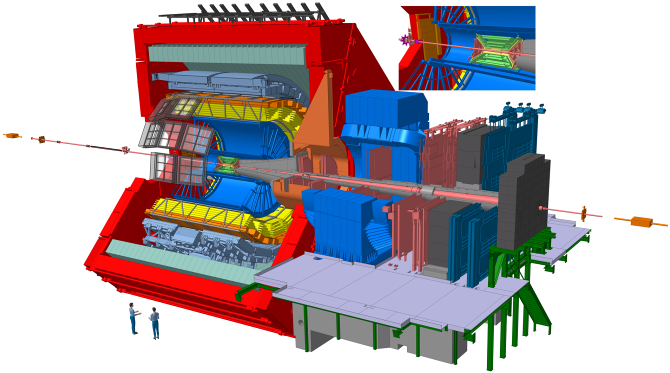
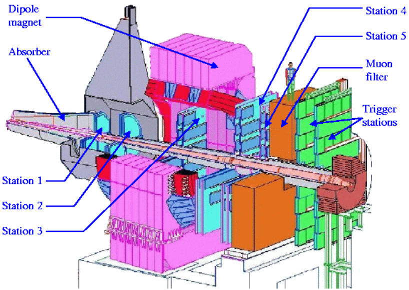
ALICE at CERN–LHC



- ALICE is a multipurpose experiment at the CERN–LHC, mainly designed to study the hot and dense matter produced in heavy-ion collisions
- A **Muon Spectrometer** at forward rapidity allows the detection and reconstruction of muons from low mass vector mesons, quarkonia, open-heavy flavours, Z and W bosons

The Muon Spectrometer is composed of:

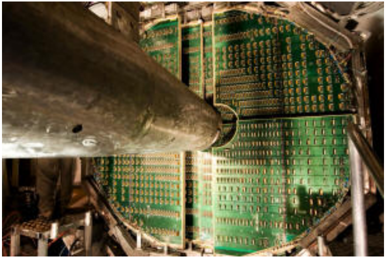
- **Muon Tracking** system
- **Muon Trigger** system
- dipole magnet ($\int Bdz = 3$ T·m)
- front absorber (4.13 m, $\sim$10 λ_{int})
- iron wall (1.2 m, $\sim$7 λ_{int})
- beam shield

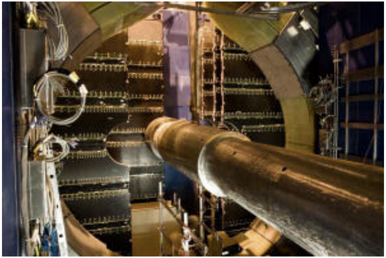


Muons can be detected in the range $-\mathbf{4.0} < \eta < -\mathbf{2.5}$ down to $\boldsymbol{p} \simeq \mathbf{4}$ **GeV**$/\boldsymbol{c}$

Muon Tracking

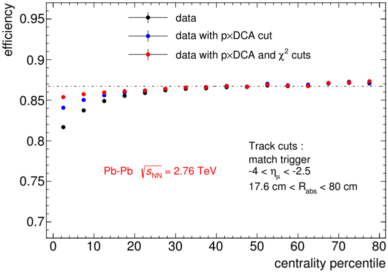
- 5 stations (10 planes) of **Multi-Wired Proportional Chambers** with a high granularity cathode-pad readout on both faces (1M channels)
- First two stations are based on quadrant structure; the other three with slat design
- $\mathcal{O}(100)$ μm detector resolution in the bending plane ($\Delta p/p<1\%$)
- Made of carbon fiber ($0.03X_0$)
- Gas mixture (80% Ar and 20% CO_2) optimised to maximize the probability of gas ionization





Tracking efficiency

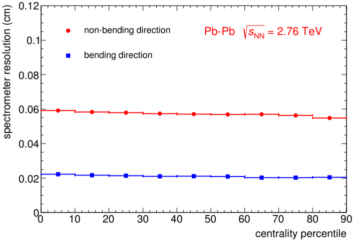
- Tracking algorithm reconstructs particles across the five tracking stations
  - at least 1 cluster in each of the first 3 stations
  - at least 3 clusters in the last 2 stations
- Reconstructed tracks and the redundancy of the detector are exploited to determine the tracking efficiency
- Tracking efficiency close to 90%; cuts are applied to remove fake tracks

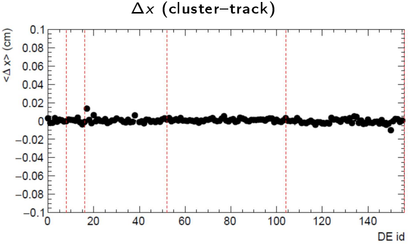


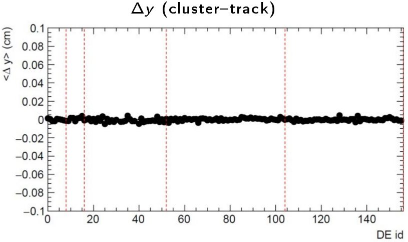
Int J. Mod. Phys. A 29 (2014) 1430044

Muon Tracking alignment

- Muon Spectrometer p resolution depends on the detector alignment
- Alignment method uses reconstructed tracks (w/ and w/o $\vec{B}$) performing **least-square minimization of the cluster-to-track residuals**.
- Overall resolution (cluster res. plus residual misalignment) reaches 200 μm in the bending direction







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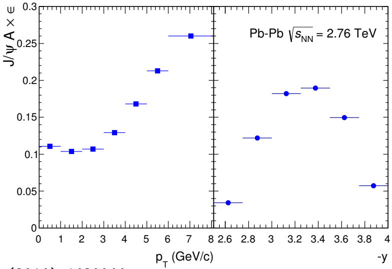
Muon Spectrometer acceptance

- $A \times \varepsilon$ within $-4.0 < \eta < -2.5$ is estimated with MC simulations
- Particles are generated with realistic kinematic distributions
- Detector conditions are taken into account on a run-by-run basis
- Possible effects of high detector occupancy in central heavy-ion collisions are taken into account as well.



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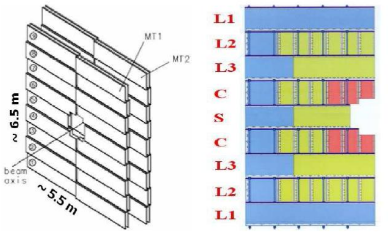
- J/ψ $A \times \varepsilon$ measured with Muon Spectrometer is **sizable down to** $p_T = 0$

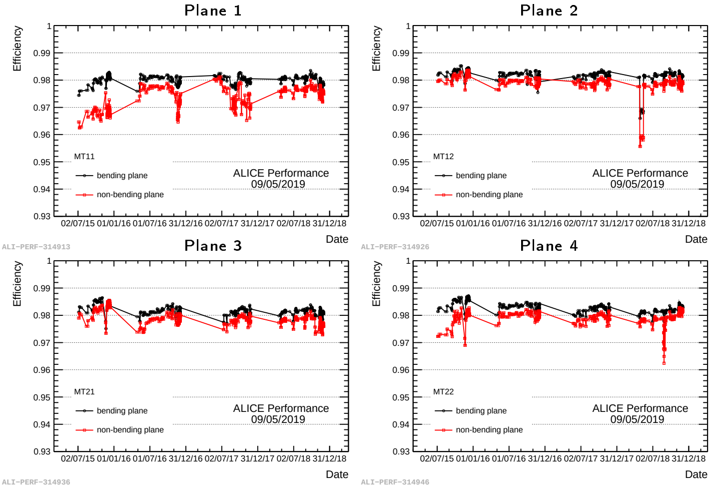
The Muon Trigger

- 72 single-gap low-resistivity bakelite **Resistive Plate Chambers** (RPC) arranged in 4 planes
- Read out by means of ∼21k copper strips of different widths: 1, 2 and 4 cm
- Apparatus delivers two triggers based on muon p_T
- RPC working conditions in 2009–2018:



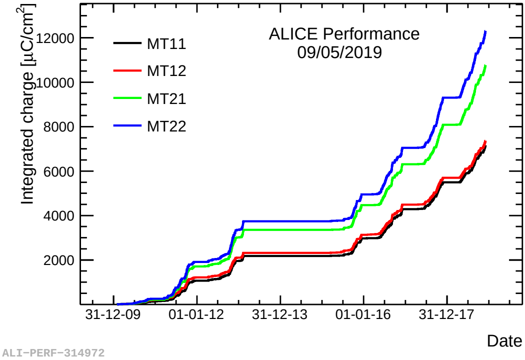
resolution:	few mm, few ns
electrode material:	bakelite ($\rho \sim 10^9$ Ω·cm)
gas mixture:	89.7% $C_2H_2F_4$ – 10% C_4H_{10} – 0.3% SF_6
relative humidity:	37%
working point:	10.1 – 10.4 kV

Muon Trigger efficiency (2015–2018)



- Average efficiency of the four RPC planes stable over time and above 97%
- Small temporary drops (1–2%) essentially due to test and noisy electronics

Muon Trigger integrated charge



- Average integrated charge at the end of 2018 data taking ranges between 7 and 12 mC/cm^2 (20 mC/cm^2 for the most exposed RPC)
- Muon Trigger RPCs were ageing-tested up to 50 mC/cm^2

Data taking with Muon Spectrometer

- Muon Spectrometer participated fruitfully in almost 10 years of data taking (2009–2018)
- It collected data during all types of collisions provided by LHC

System	Years	Energy (TeV)
pp	2009–2013	0.9, 2.76, 7, 8
	2015, 2017	5.02
	2015–2018	13
p–Pb/Pb–p	2013	5.02
	2016	5.02, 8.16
Xe–Xe	2017	5.44
Pb–Pb	2010, 2011	2.76
	2015, 2018	5.02

- **Almost 20%** of total ALICE publications made use of Muon Spectrometer data

Examples of reconstructed (di-)muons

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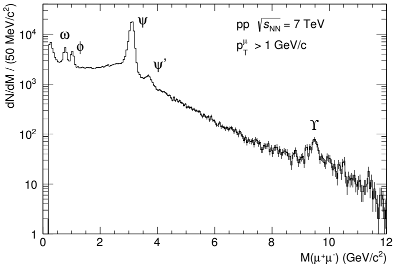
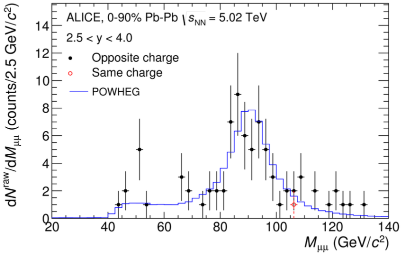
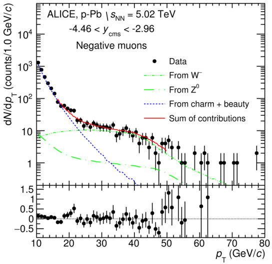


PLB 780 (2018) 372-383



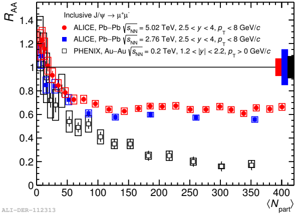
JHEP 02 (2017) 077



Physics highlights

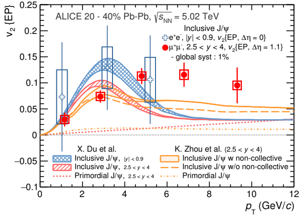
PLB 766 (2017) 212-224

J/ψ suppression in Pb–Pb coll.



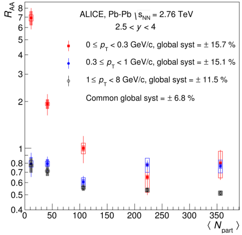
PRL 119 (2017) 242301

J/ψ v_2 in Pb–Pb coll.



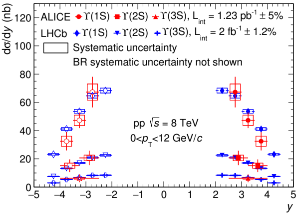
PRL 116 (2016) 222301

J/ψ excess at low-p_T in Pb–Pb coll.



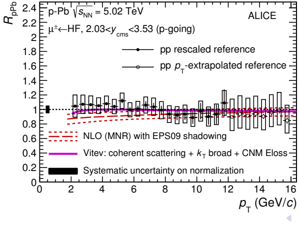
EPJ C 76 (2016) 184

Υ cross section in pp coll.



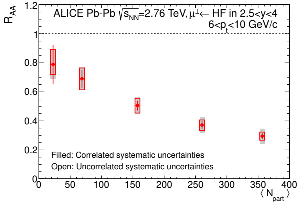
PLB 770 (2017) 459-472

$\mu \leftarrow$ heavy flavours in p–Pb coll.

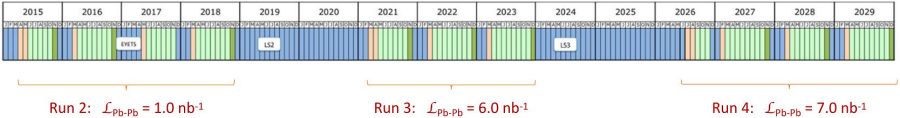


PRL 109 (2012) 112301

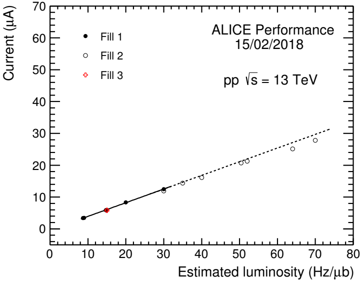
$\mu \leftarrow$ heavy flavours in Pb–Pb coll.



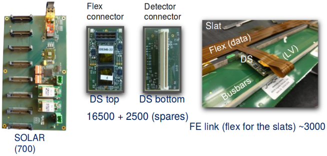
ALICE strategy beyond 2021



- LHC will deliver an instantaneous luminosity ~6 times higher than past years → **50 kHz Pb–Pb interaction rate** (so far <10 kHz)
- The present electronics will not be compatible with such rate
- Both systems are now being upgraded to be ready for these new data taking conditions
- Muon Spectrometer participated in **high luminosity tests** to monitor the behavior of the system in the expected condition beyond 2021
- Example of measured current in Muon Trigger up to an equivalent rate of 50 kHz Pb–Pb



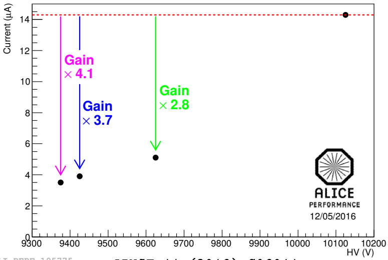
Muon Tracking



- New Front-End ASIC 130 nm CMOS (SAMPA chip) in common with TPC, 4 times faster than current ASIC, with zero suppression
- New concentrator board to read out several PCBs and to transmit data to ALICE DAQ through GBT optical links
- Flex-rigid PCBs to link FEE and RO cards

Muon Trigger (⇒ Muon Identifier)

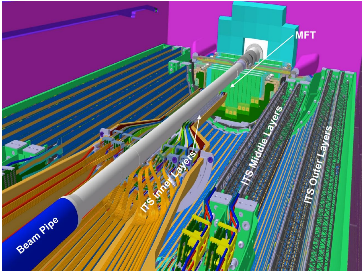
- New Front-End ASIC (FEERIC) with amplification
- New readout electronics with GBT optical links
- Possibility to change discrimination threshold via wireless system
- $\sim$30 RPCs will be replaced

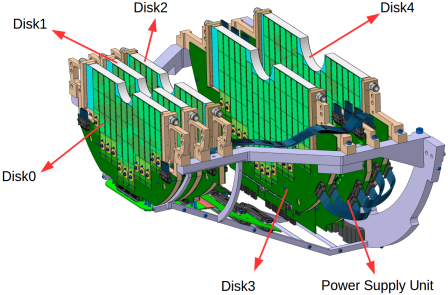


JINST 11 (2016) C06011

Muon Forward Tracker

- **New high resolution Si tracker** upstream of the absorber at forward rapidity will add capabilities for **secondary vertex measurement**



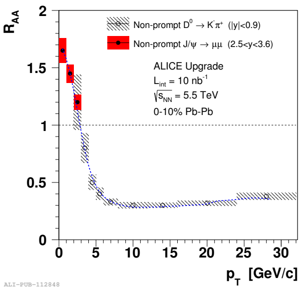


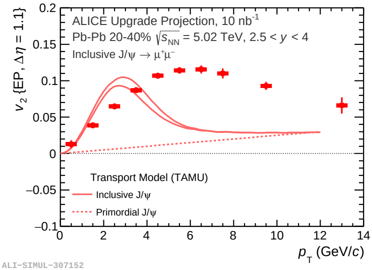
- 10 half-disks, 2 detection planes each
- 280 ladders (Al FPC) of 2–5 sensors each: 920 Si chips (0.4 m^2)
- **ALPIDE**: CMOS Monolithic Active Pixel Sensors (same as new ITS)
  - sensor size 15×30 mm^2
  - pixel pitch 29×27 μm^2
  - low power density $\sim$40 mW/cm^2
  - detection efficiency > 99%
  - 512×1024 pixels per sensor
  - total thickness 50 μm
  - integration time <10 μs
  - fake-hit rate $<10^{-6}$/pixel/event

Summary and outlook

- ALICE Muon Spectrometer showed very good and stable performance since the first collision in LHC
- Very high quality data taking substantially contributing to the ALICE scientific output

Upgraded Muon Spectrometer + MFT + higher luminosity
=
extended physics program and more precise measurements



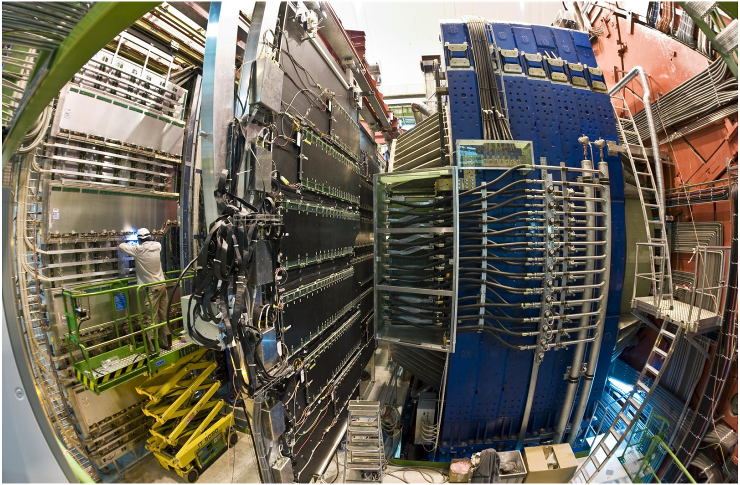


See also J. Norman's talk on Thu – Upgrade session

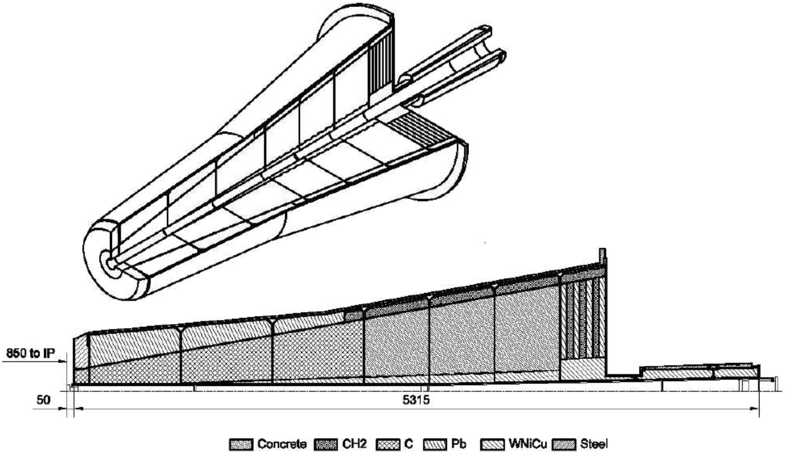
ALICE-TDR-018

Backup

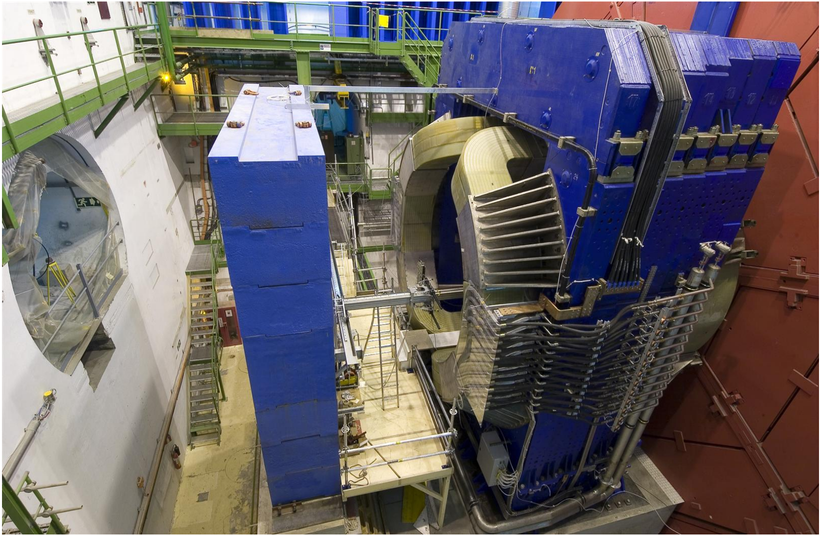
Muon Spectrometer



Front absorber and beam shield



Muon filter and dipole magnet



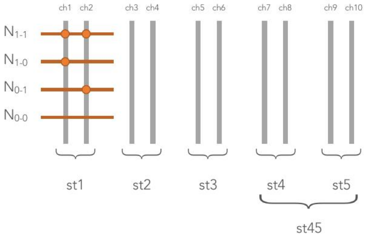
MTK efficiency calculation

Method based on the tracking algorithm properties :
Only tracks for which the examined chamber is not required for the reconstruction are selected

For stations 1, 2 and 3 :
at least 1 cluster per station

$$\epsilon_{ch\ i} = \frac{N_{i-j}}{N_{i-j} + N_{0-j}}$$

$$\epsilon_{st\ 1(2)(3)} = 1 - \left(1 - \epsilon_{ch\ 1(3)(5)}\right)\left(1 - \epsilon_{ch\ 2(4)(6)}\right)$$

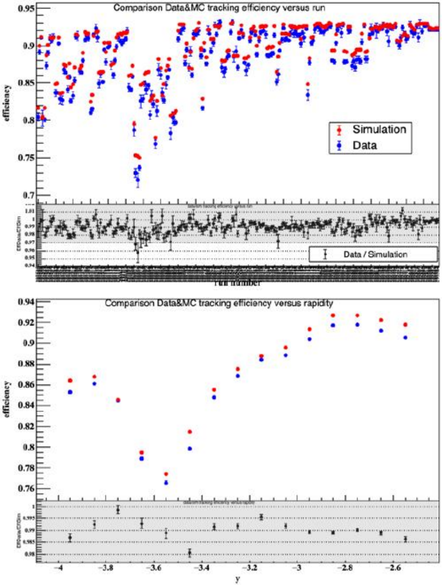


For stations 4 and 5 :
at least 3 clusters in the 4 last chambers

$$\epsilon_{st\ 45} = \prod_{i=7}^{1=10} \epsilon_{ch\ i} + \sum_{i=7}^{i=10}\left((1 - \epsilon_{ch\ i}) \prod_{j=7;j\neq i}^{j=10} \epsilon_{ch\ j}\right)$$

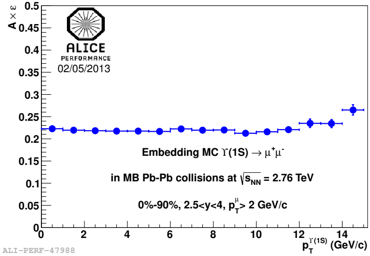
$$\rightarrow \quad \epsilon_{tracking} = \epsilon_{st1}\epsilon_{st2}\epsilon_{st3}\epsilon_{st45}$$

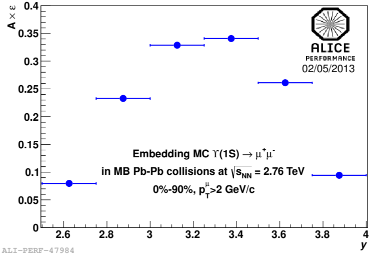
Tracking efficiency (comparison with MC)



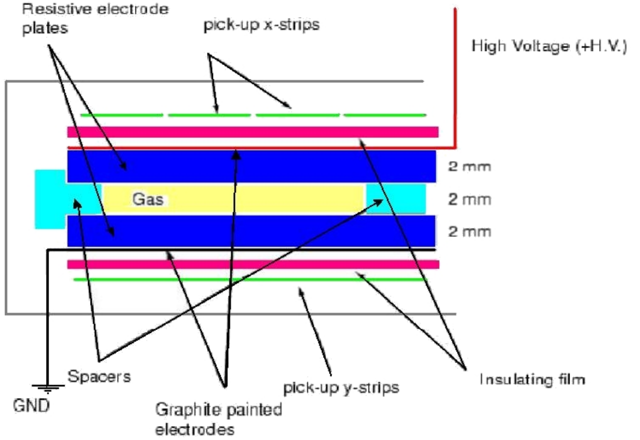
|1-Data/MC| < ~ 3%

Υ $A \times \varepsilon$

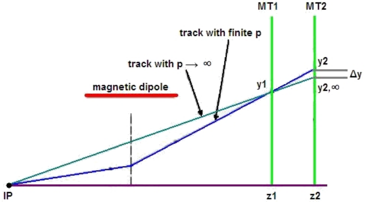




RPC cross section



- The spatial information is used to estimate the p_T via the deviation with respect to a straight track from the I.P.



$$\Delta y = y_2 - y_{2,\infty}$$

$$\Delta y \cong \frac{eBL}{z_1} \cdot \frac{R}{p_T} \cdot (z_2 - z_1)$$

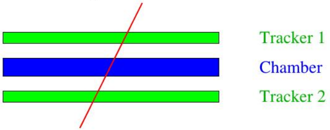
- The cuts are optimized by means of simulations and correspond to an efficiency of 50% at p_T equal to the cut value.
- Single and dimuon trigger signals above two cuts are delivered:

	low-p_T cut	**high-p_T cut**
Pb–Pb 2010	0.5 GeV/c	1 GeV/c
Pb–Pb 2011	1 GeV/c	4 GeV/c

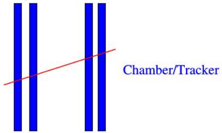
MTR efficiency calculation

$$\varepsilon = \frac{\#\text{ of times chamber gives signal}}{\#\text{ of times a muon crosses the chamber}}$$

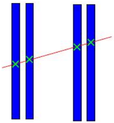
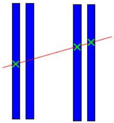
In laboratory:



Muon Spectrometer:



The trigger algorithm searches for hits in at least 3 out of 4 trigger chambers. One can define:

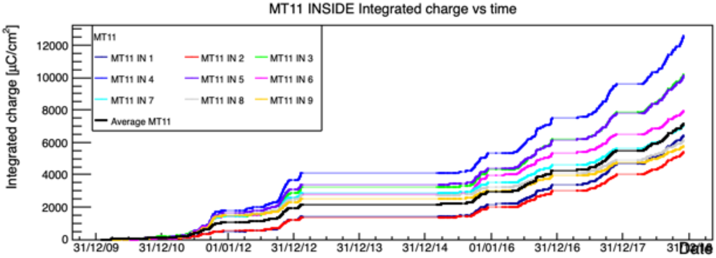
$N_{4/4} =$  $N^{12}_{3/3} =$ 

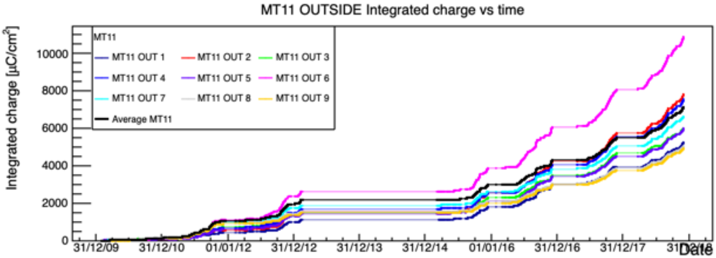
The efficiency for chamber $a = 12$ (for example) is given by:

$$\frac{N_{4/4}}{N^a_{3/3} + N_{4/4}} = \frac{N_{4/4}/N_{tot}}{(N^a_{3/3} + N_{4/4})/N_{tot}} = \frac{\varepsilon_{4/4}}{\varepsilon^a_{3/3} + \varepsilon_{4/4}} = \frac{\varepsilon_{11}\varepsilon_a\varepsilon_{13}\varepsilon_{14}}{\varepsilon_{11}\varepsilon_{13}\varepsilon_{14}} = \varepsilon_a$$

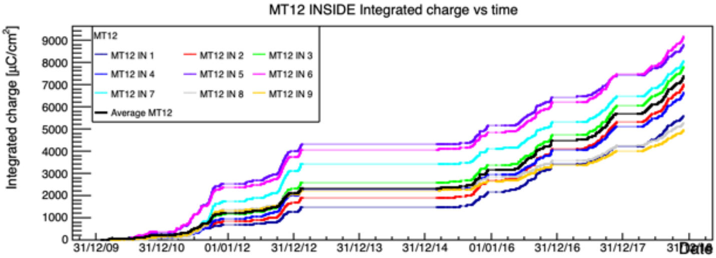
# of triggered tracks if chamber a were switched off.

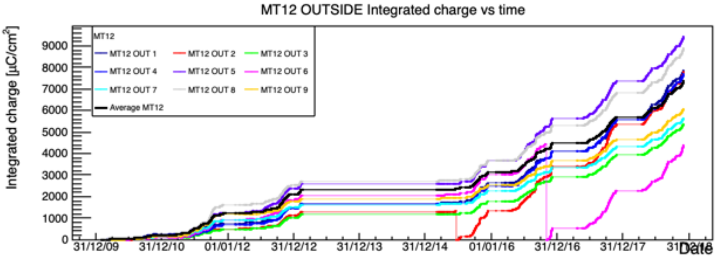
MTR cumulated charge



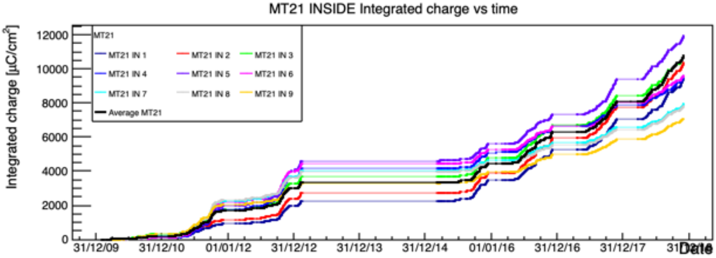


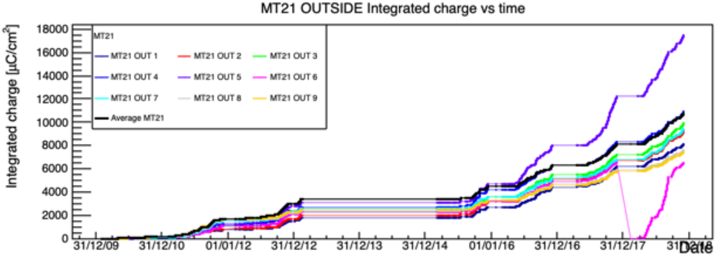
MTR cumulated charge



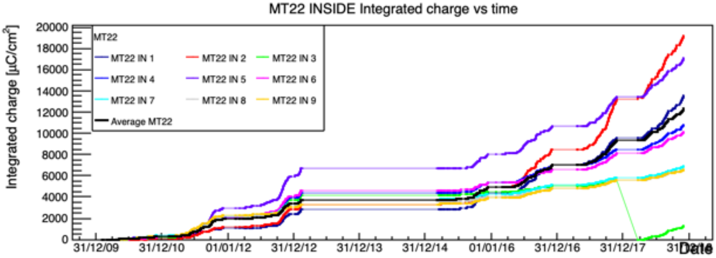


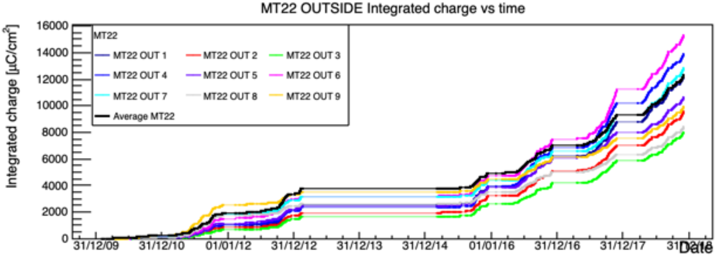
MTR cumulated charge





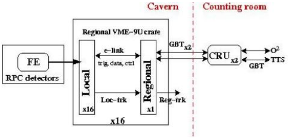
MTR cumulated charge

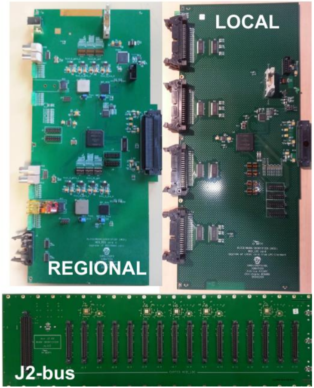




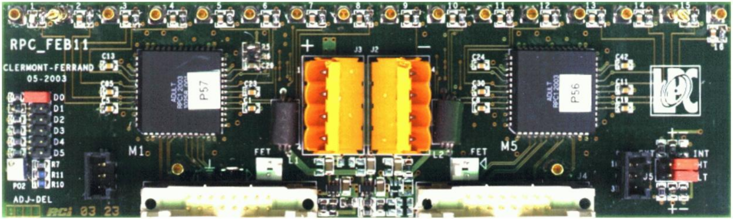
Subatech Nantes, Ithemba lab.

- ***Replacement of the 234 Local cards and of the 16 Regional cards presently in operation***
- ***Readout electronics for continuous mode***
  - Regional card interfaced with CRU via 2 GBTs
- ***Pre-series_v0 readout cards***
  - **Full chain** (with 3 Local and 1 Regional) **validated** in October 2018
- ***Production status, perspectives***
  - Improved (_v1) layouts of Local/Regional
  - **Pre-series_v1 of 20 Local and 3 Regional received early March 2019**
  - **Full crate** (with 16 Local and 1 Regional =>1/16 of total) **validation ongoing**
    - **Preliminary tests very satisfactory**
    - PRR follow-up meeting to be organized, ~end of April, before launching full production
  - Summer 2019 : production completed
    - ~8 months contingency vs. installation
- ***MID CRU specific user logic***
  - Tests in simulation of uplink logic done
  - CRU FPGA code compilation and uploading ongoing
  - Next step: tests connected to MID readout electronics





Present front-end electronics (MTR)



Since the beginning of LHC operations, MTR has been equipped with **ADULT** (**A DUaL T**hreshold) front-end electronics:

- no amplification of the signal, only discrimination;
- symmetric threshold set at 7 mV (for most of the data taking);
- possibility to work in avalanche and streamer mode with the same FEE;
- in these conditions the average charge per hit is $\gtrsim 100$ pC.

Rate limitations and upgrade of the muon trigger

- Safe operation limits in the present conditions (from R&D):

Max counting rate	Cumulative charge[1]
50 hits/s/cm^2	50 mC/cm^2

- Values foreseen for LHC–Run3 (from 2020 onwards) in Pb–Pb collision at an interaction rate of 50 kHz (times a safety factor of 2):

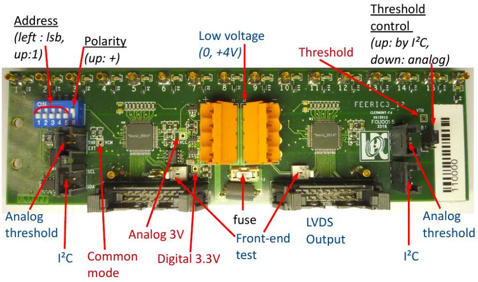
Mean counting rate	Max counting rate	Cumulative charge
75 hits/s/cm^2	125 hits/s/cm^2	100 mC/cm^2

- To guarantee safe operation in the new scenario, the charge per hit must be reduced. Target reduction is a factor $3 \div 5$.
- Possible solution: operate the RPC in avalanche mode lowering the gain $\Rightarrow$ FEE with amplification.
- An upgrade of the read-out system is also foreseen in order to deal with the increased event rate (not discussed here).

[1] Maximum charge reached in aging tests.

New front-end electronics: specifications

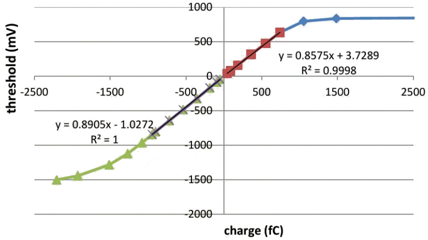
- **FEERIC** (**F**ront-**E**nd **E**lectronics **R**apid **I**ntegrated **C**ircuit).
- R&D started in 2012: 3 different versions developed at LPC of Clermont-Ferrand (France).
- Main functions: amplification, discrimination, LVDS output.
- Possibility to set thresholds remotely.



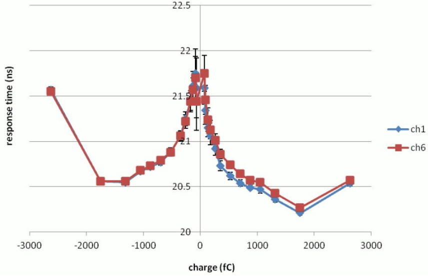
ASIC technology	0.35 µm CMOS
Number of ch.	8
Input polarity	±
Dynamic range (linear gain)	q < 1 pC
Input noise (rms)	< 2 fC
Power cons.	< 100 mW/ch
Power supply	3 V
One-shot	100 ns
Time jitter (rms)	< 1 ns for q > 100 fC
Time walk	< 2 ns for q > 100 fC
Output format	LVDS, 23±2 ns
Gain	1 mV/fC

New front-end electronics: performance

- Direct gain of ~ 0.86 mV/fC in the range ± 1 fC.



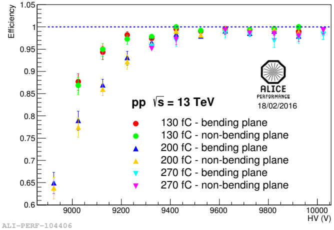
- Response time $20 \div 22$ ns, with a jitter of < 200 ps for $q = 200$ fC.
- Cross-talk $< 2\%$.

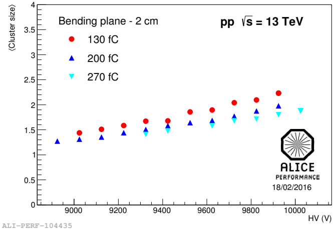


FEERIC specifications

	FEERIC ASIC	FEERIC board (with RPC strips)
ASIC technology	AMS CMOS 0,35 μm	=
Number of ch.	8	=
Polarity	$\pm$	=
Electronics noise (rms) Thresh. above noise	q $<$ 2 fC	= q $<$ 100 fC
Cross talk	$q_{thr}/q < 2$ % for q_{thr}=100 fC	=
Amplifier	trans-impedance	=
Discriminator	zero crossing	=
One-shot (monostable)	yes (100 ns)	=
Output format	LVDS 23 ns width	=
Gain in (linear) range	$\sim$1 mV/fC q $<$ 1 pC	$\geq$ 0.5 mV/fC =
Time jitter (rms)	$<$ 1 ns for 100 fC $<$ q $<$ 1 pC	=
Time walk	$<$ 1 ns for 100 fC $<$ q $<$ 1 pC	=
ch/ch max delay	$<$ 1 ns	=
ASIC/ASIC max delay	$<$ 2 ns	=
Power cons.	$<$ 100 mW/ch	=
Power supply	3 V	4 V

- HV and threshold scan with early pp collisions.

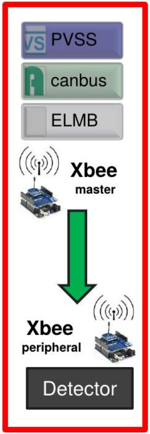




- Full efficiency reached by all thresholds and both polarities.
- Cluster size slightly larger than the one measured with ADULT at higher HV ($\sim$ 1.6 vs $\sim$ 1.4).
- Working point at 9375 V and 130 fC (-750 V w.r.t. ADULT).
- No noise observed for threshold $>$ 60 fC for both polarities.
- Results are in full agreement with measurements made with cosmic rays in Turin.

ALICE

- **Why go to wireless threshold distribution ?**
  - Threshold setting per FEERIC card (vs. per RPC side in the present setup)
  - Possibility of minimizing RPC operating HV, by tuning thresholds locally => optimize FEERIC goal to reduce RPC ageing
- **Zigbee technology used**
  - High level protocol
  - Suitable for required data bandwidth and speed
  - Bandwidth 2.4 Ghz/Radio Communication
  - Based on Microcontroller Atmel SAMD21 core Cortex M0+
  - SoftWare based on Arduino libraries (I2C, SD cards and Xbee)
  - API mode used, checksum for guaranteeing data transmission
  - One full line has been installed during YETS 2017 on the RPC already equipped with FEERIC cards in the cavern, 2018 will be devoted to long term stability tests.



Xbee peripheral card (24 peripheral + 2 master cards needed in total)

Subatech Nantes, Ithemba lab.

- **_Replacement of the 234 Local cards and of the 16 Regional cards presently in operation_**
- **_Readout electronics for continuous mode_**
  - Regional card interfaced with CRU via 2 GBTs
- **_Pre-series_v0 readout cards_**
  - **Full chain** (with 3 Local and 1 Regional) **validated** in October 2018
- **_Production status, perspectives_**
  - Improved (_v1) layouts of Local/Regional
  - **Pre-series_v1 of 20 Local and 3 Regional received early March 2019**
  - **Full crate** (with 16 Local and 1 Regional =>1/16 of total) **validation ongoing**
    - **Preliminary tests very satisfactory**
    - PRR follow-up meeting to be organized, ~end of April, before launching full production
  - Summer 2019 : production completed
    - ~8 months contingency vs. installation
- **_MID CRU specific user logic_**
  - Tests in simulation of uplink logic done
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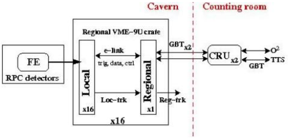
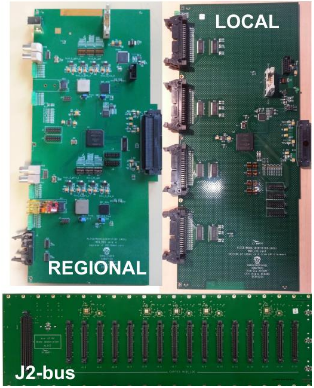
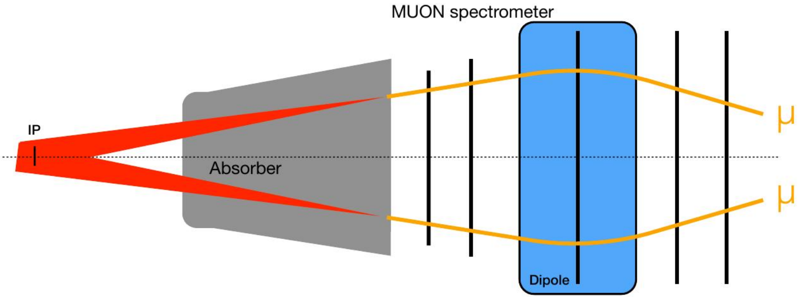




Muon Forward Tracker: concept



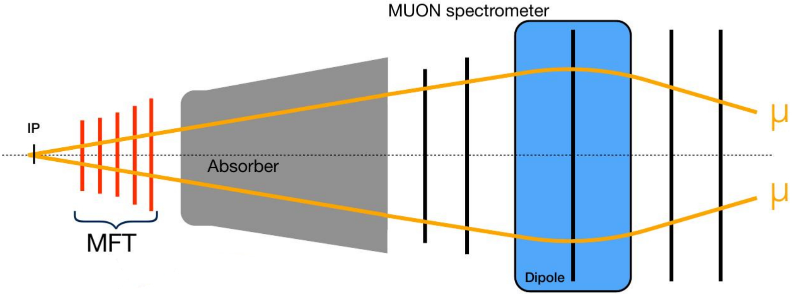
Muon spectrometer only:

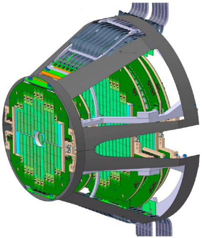
- degradation of muon p_{T} due to the absorber;
- no constraint in the primary vertex region.

MFT+Muon spectrometer:

- charm/beauty separation possible;
- improved mass resolution.

Muon Forward Tracker: concept





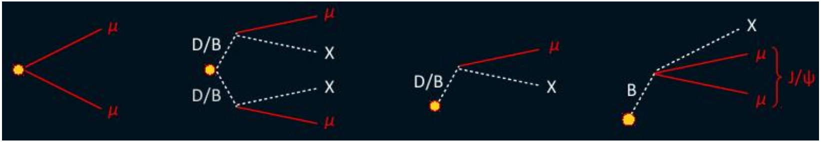
Muon spectrometer only:

- degradation of muon p_T due to the absorber;
- no constraint in the primary vertex region.

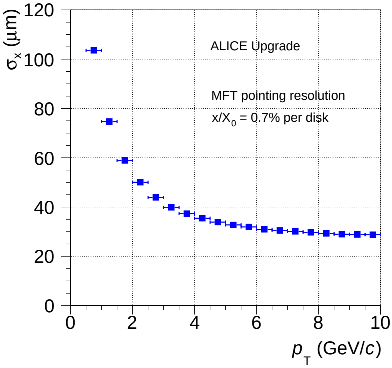
MFT+Muon spectrometer:

- charm/beauty separation possible;
- improved mass resolution.

- Prompt and displaced (di)muons can be distinguished by measuring the distance between primary vertex and the muon track: open charm ($c\tau \cong 150\ \mu$m) and open beauty ($c\tau \cong 500\ \mu$m) can be disentangled.
- The reduced uncertainty on the opening angle can significantly improve the mass resolution for low mass mesons and ψ resonances, especially at low p_T.

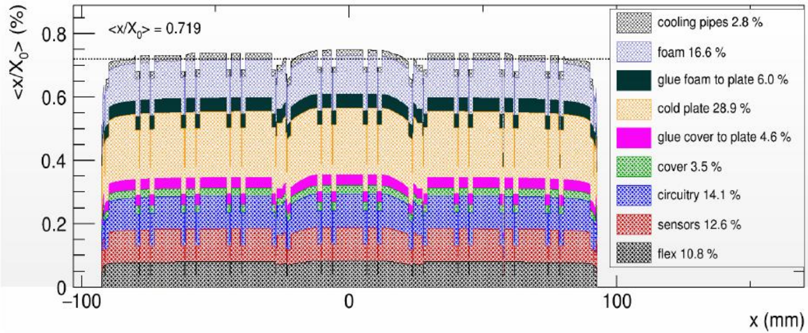


- Muon tracks offset resolution ∼50-100 μm at $p_T < 2$ GeV/c, better at higher p_T: *c* and *b* can be distinguished.
- Extrapolated muon tracks are matched:
  - either with lowest-χ^2 combination of MFT clusters;
  - or with the lowest-χ^2 MFT standalone track.



MFT design goals

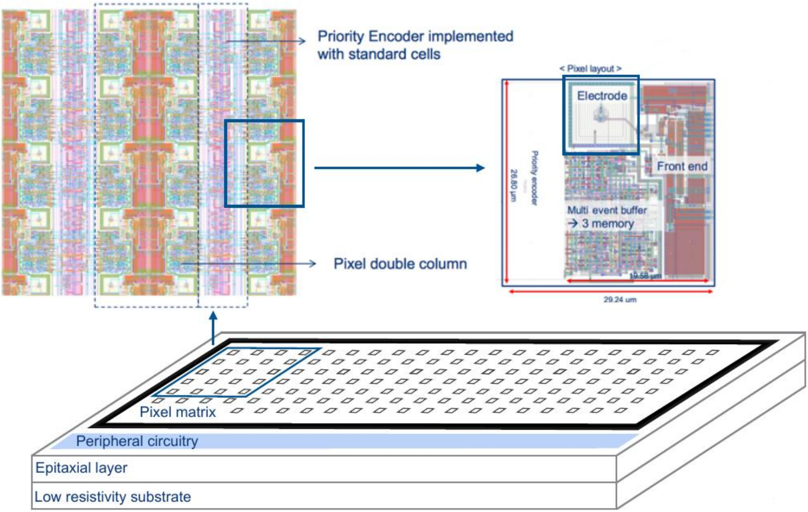
- **Vertexing for the Muon spectrometer at forward rapidity**:
  - 5 detection disks with detection on both side, O(5μm) spatial resolution;
  - 0.7% of X_0 per disk;
  - $-3.6 < \eta < -2.45$;
  - disk 0 at $z = -460$ mm, $r_{in} = 25$ mm (limited by the beam-pipe radius).
- **Good matching efficiency between MFT and Muon spectrometer**:
  - disk 4 at $z = -768$ mm (limited by the frontal absorber).
- **Fast electronics read-out**:
  - Pb–Pb interaction rate up to 50 kHz, pp interactions up to 200 kHz;
  - Integration time and dead-time < 20 μs.



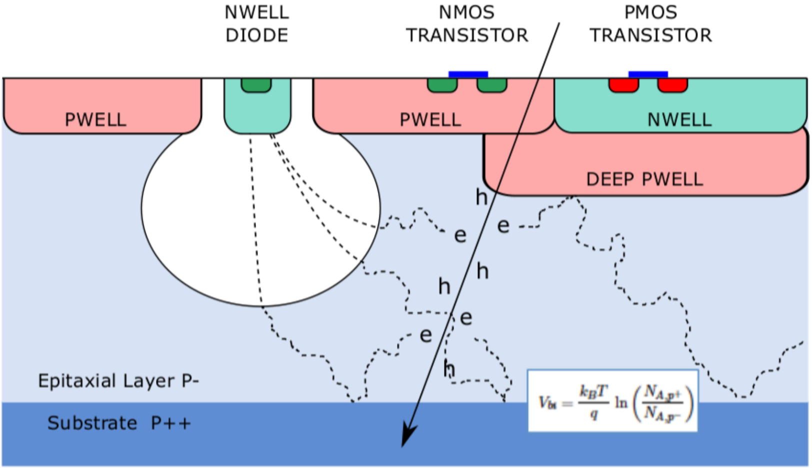
Ladder contribution (two sides): 0.3%

- Sensor: 0.09%
- Flex substrate: 0.08%
- Al circuitry: 0.1%

Total Disk: 0.7%


Priority Encoder implemented
with standard cells
< Pixel layout >
Electrode
Priority encoder
26.80 µm
Front end
Multi event buffer
→ 3 memory
19.58 µm
29.24 um
Pixel double column
Pixel matrix
Peripheral circuitry
Epitaxial layer
Low resistivity substrate

Chip layout

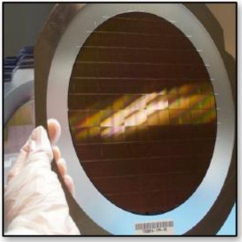


NWELL
DIODE
NMOS
TRANSISTOR
PMOS
TRANSISTOR
PWELL
PWELL
NWELL
DEEP PWELL
h
e
e
h
h
e
e
h
Epitaxial Layer P-
Substrate P++
$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_{A,p^+}}{N_{A,p^-}}\right)$

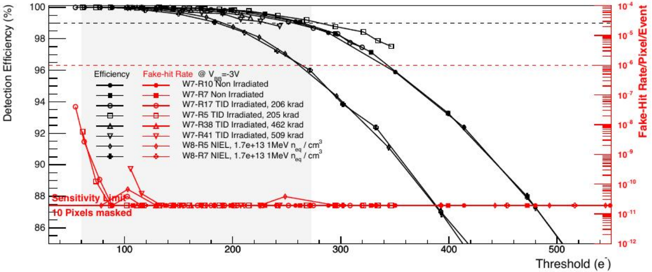
ALice PIel DEtector characteristics

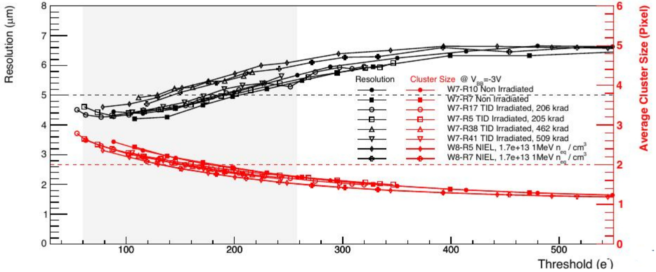
ALPIDE is the chip used in the MFT and in the new ITS.

- CMOS Monolithic Active Pixel Sensor (Si)
- Sensor thickness 50 μm
- Sensor size 15×30 mm^2; pixel pitch 29×27 μm^2
- Spatial resolution of 5 μm
- Time resolution 2 μs
- Low power consumption 40 mW/cm^2
- In-pixel amplification/discrimination/multi-event buffering
- In-matrix zero suppression
- Triggered or continuous acquisition
- High speed serial data output up to 1.2 Gb/s



ALPIDE test beam results





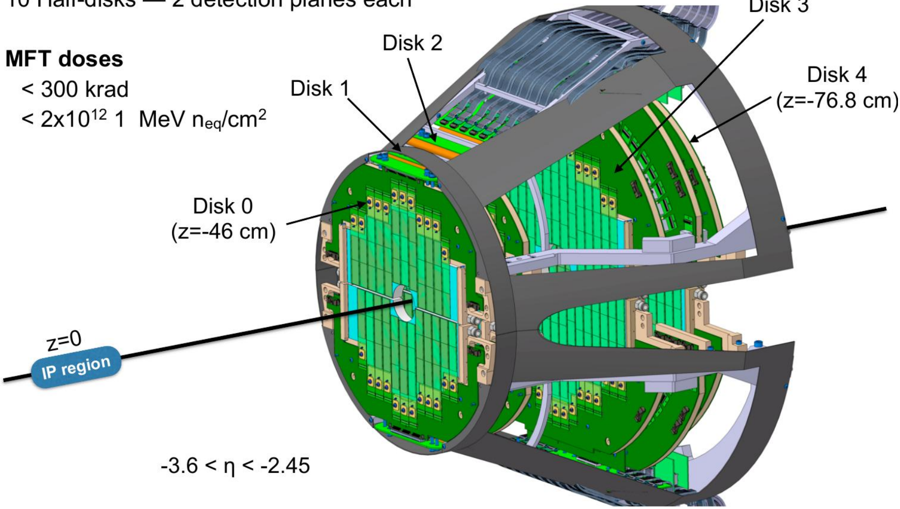
- Very high detection efficiency ($> 99\%$)
- Very low fake hit rate

- Spatial resolution 5-6 μm, as specifications
- Cluster size 2-3 pixels

10 Half-disks — 2 detection planes each

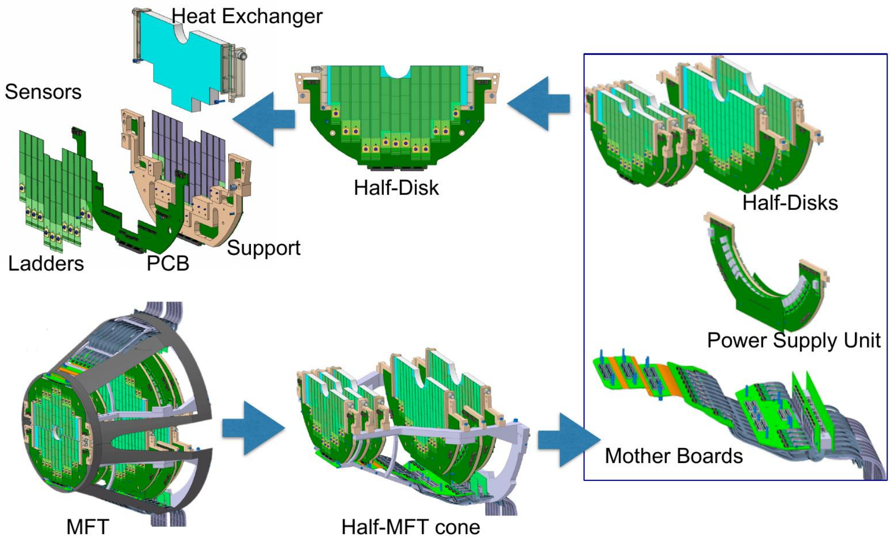
MFT doses

- < 300 krad
- < 2×10^{12} 1 MeV n_{eq}/cm^2

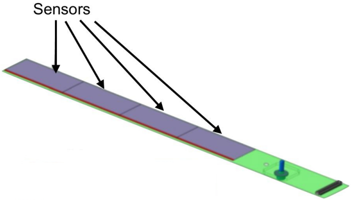


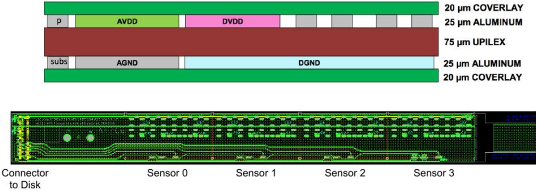
$-3.6 < \eta < -2.45$

MFT layout


Heat Exchanger
Sensors
Ladders
PCB
Support
Half-Disk
Half-Disks
Power Supply Unit
Mother Boards
MFT
Half-MFT cone

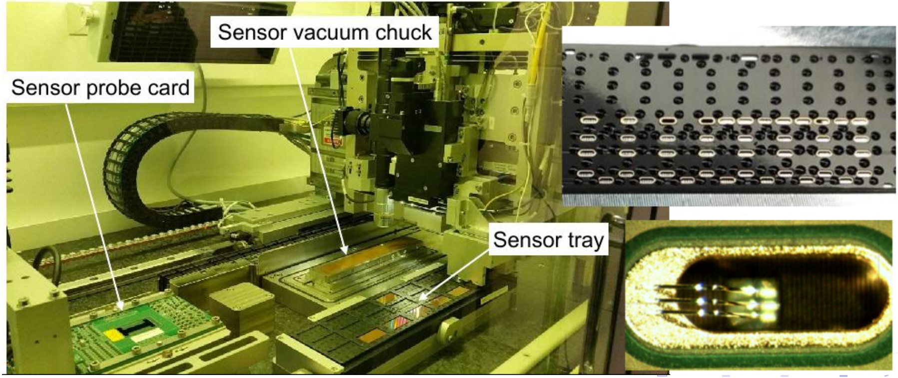
- Ladders are the base element of the MFT detector.
- Transport data to the detector periphery and slow control to the sensors.
- Provide proper power supply and reverse back bias to the chips.
- Ensure adequate stiffness for handling and protect the sensors.
- Sensors are interconnected to a Al Flexible Printed Circuit (FPC).



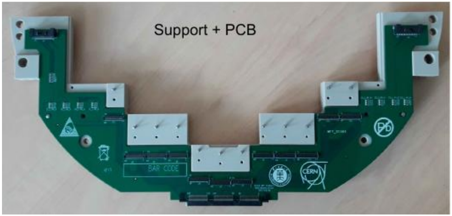


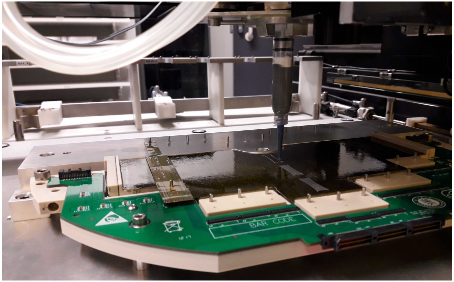
Ladder assembly

- Automatic chip picking from the tray.
- Precise and automatic alignment on the chip.
- If needed, electrical test of the chip.
- Visual inspection of chip quality and alignment.

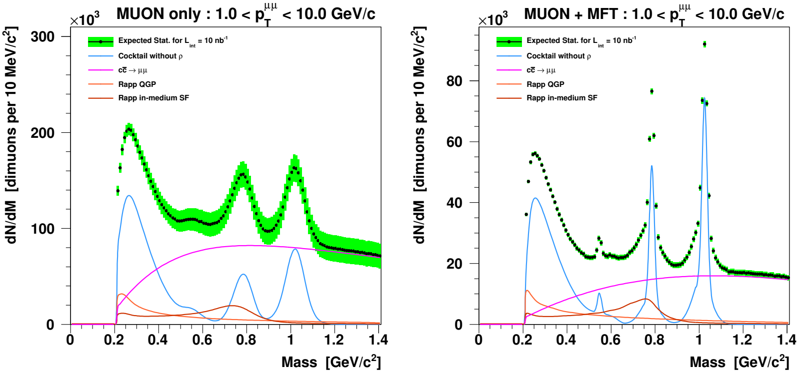


- Ladders are automatically glued on both sides of the heat exchanger.
- They are also connected to PCBs for data transfer.



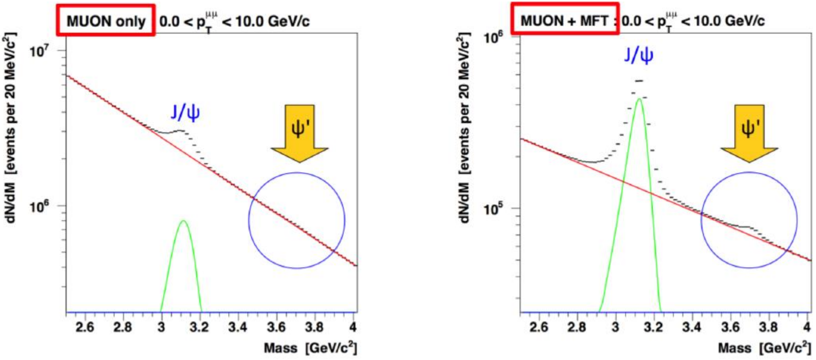


Improvement in low-mass region



- Low-mass region: mesons below $m_{J/\psi} \cong 3.1$ GeV/c^2.
- Mass resolution improved with the MFT. ρ peak now visible.

Improvement in the J/ψ region



- $\psi(2S)$ is another $c\bar{c}$ state, similar to J/ψ.
- $\psi(2S)$ S/B improved by a factor 6-7, visible now even in central Pb–Pb collisions.