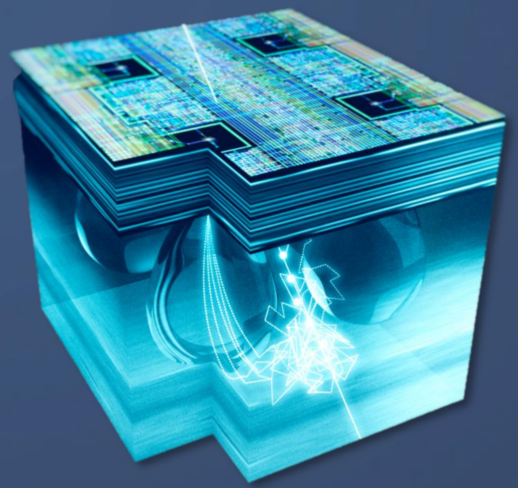
CERN – EP Department

CMOS Pixel Sensor Development For the ALICE Inner Tracking System

Luciano Musa – CERN

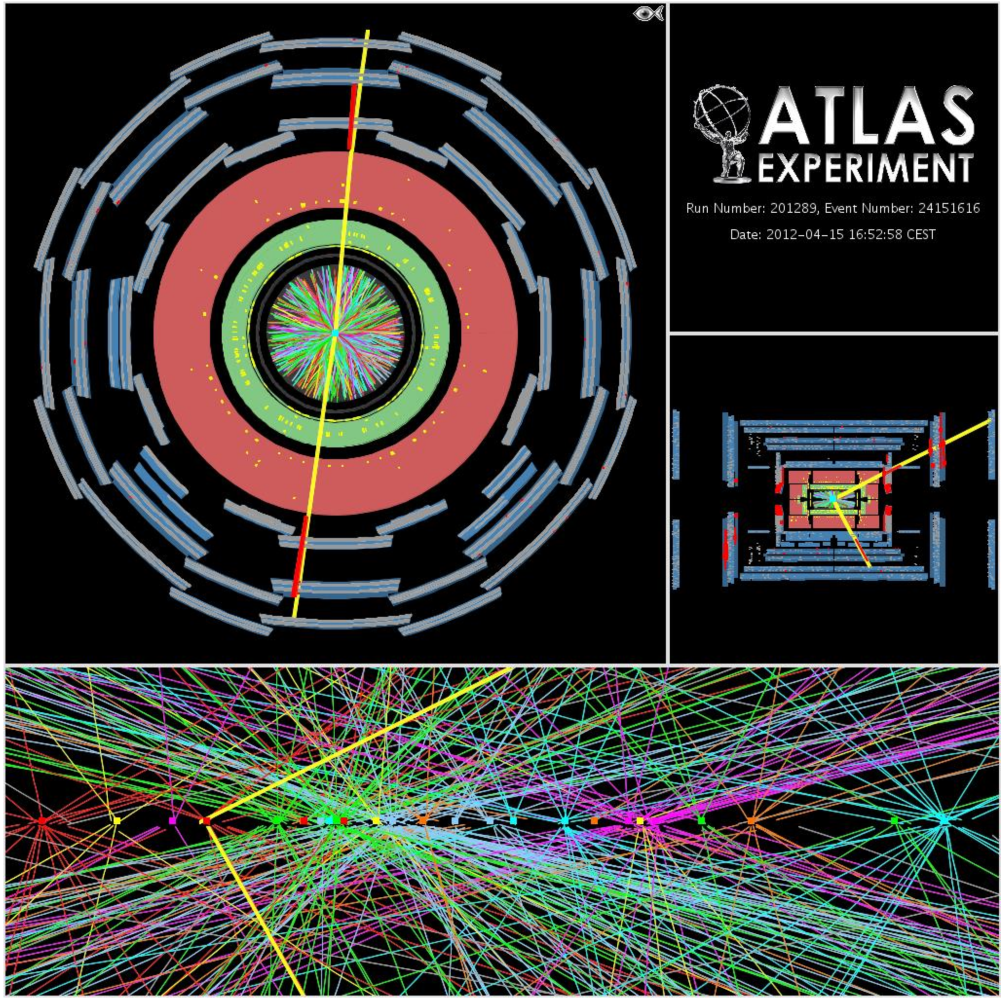


2018 EIROforum Topical Workshop: CMOS sensors, CERN, 27 May, 2018

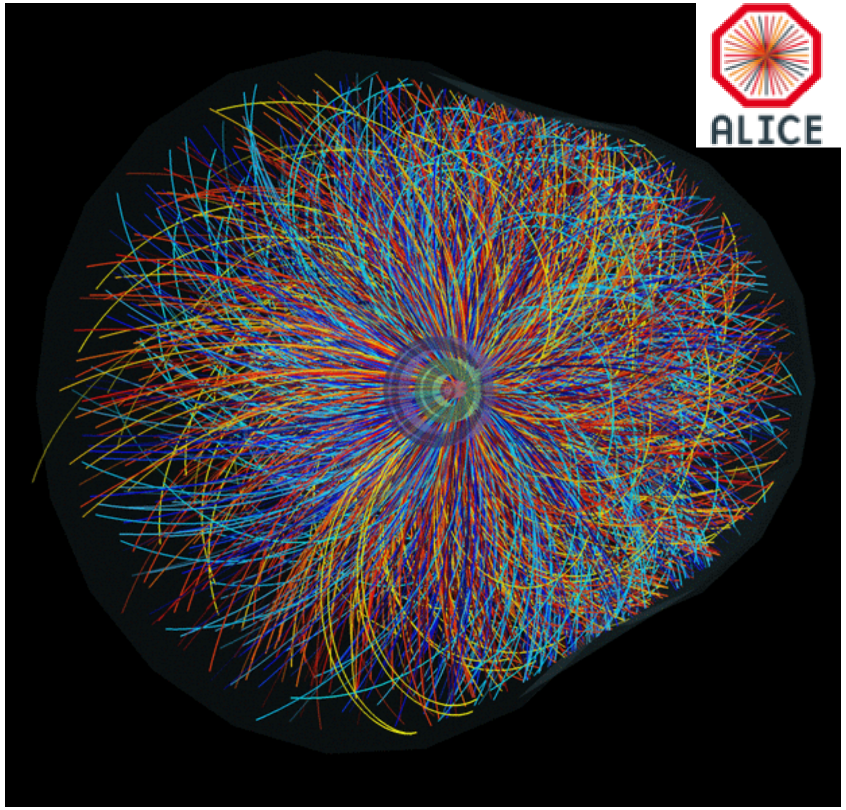
Outline

- Introduction and Motivations
- First applications of CMOS APS in HEP
- ALICE Inner Tracking System
- ALPIDE Chip: a Novel CMOS Active Pixel Sensor
- System Integration and Performance
- Conclusions

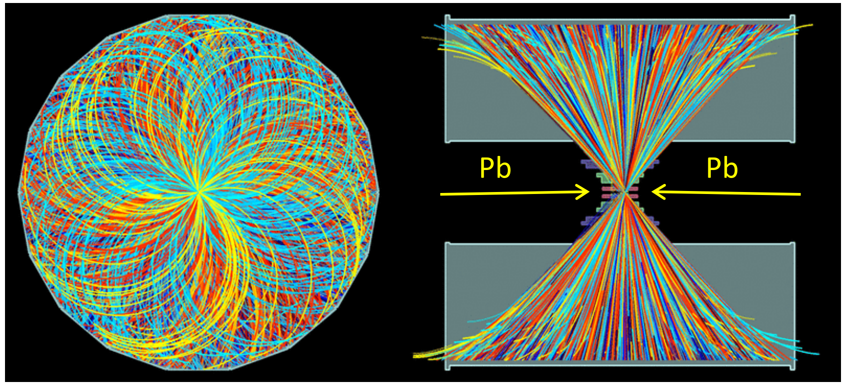
Silicon Trackers – Key to solve complex events close to IP



LHC pp collisions: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices (ATLAS, April 2012)

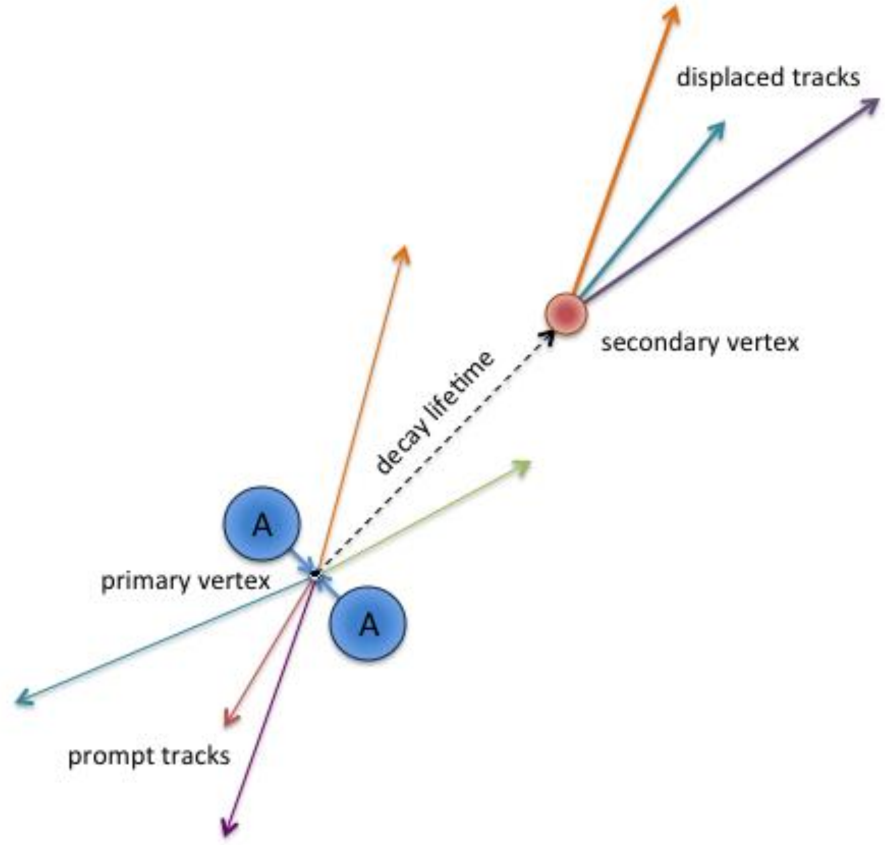


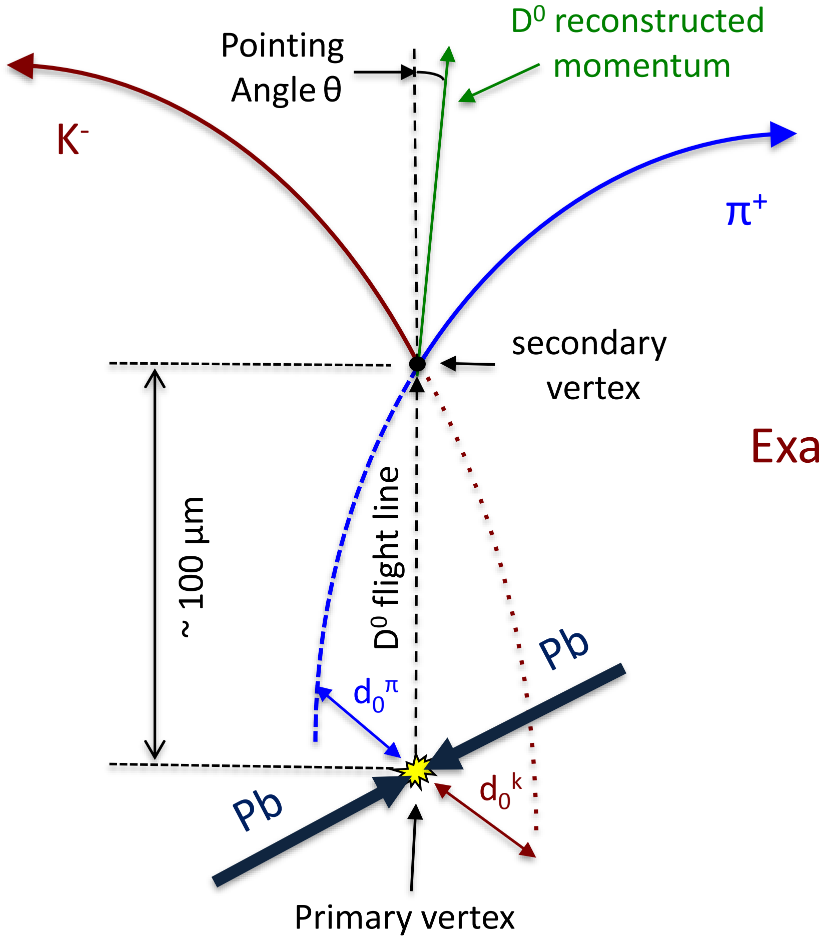
LHC Pb-Pb collision (ALICE, Sep 2011)



Measurement of the decay topology of short-lived particles

The first detection layer, the closest to the IP (r ≥ 20mm), are crucial for the measurement of the interaction vertex (primary vertex) and the decay vertex of short-lived particles (secondary vertex)





Example: D^0 meson

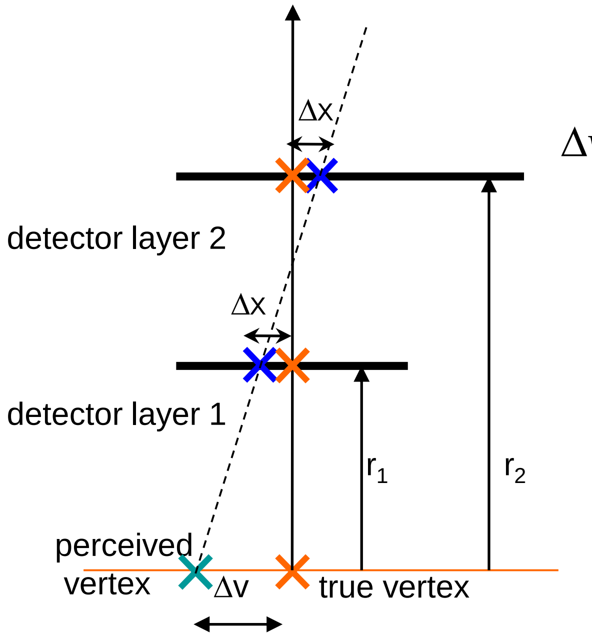
typical (proper) decay length of charm and beauty hadrons: ≈100μm and ≈500μm respectively

What determines the Impact parameter Resolution

Vertex projection from two points: a simplified approach (telescope equation)

expectations for the ITS upgraded ➡ pointing resolution = $(5 \oplus 22 GeV/p \cdot c)\ \mu m$

From detector position error | From Coulomb scattering



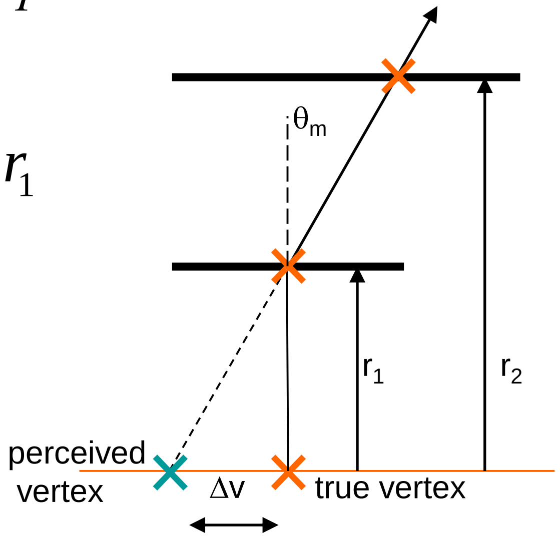
$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

first pixel layer

$$X / X_0 = 0.3\%$$

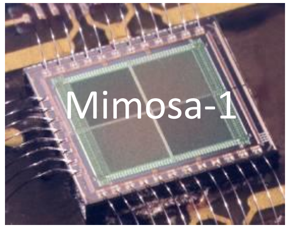
$$q_m = \frac{13.6 Mev}{b \times c \times p} \times \sqrt{X / X_0}$$

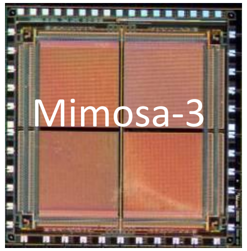
$$\Delta v = \theta_m \cdot r_1$$



Monolithic Pixel Detectors in HEP

Owing to the industrial development of CMOS imaging sensors and the intensive R&D work (IPHC, RAL, CERN)





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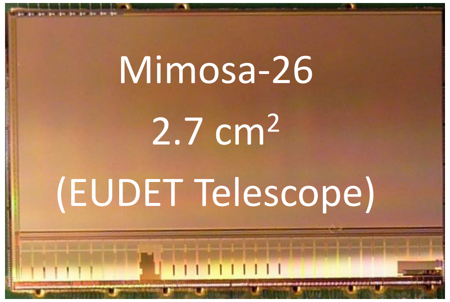
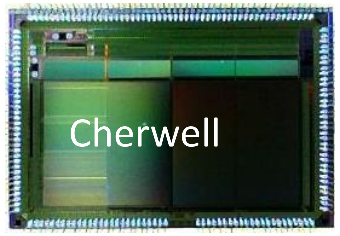
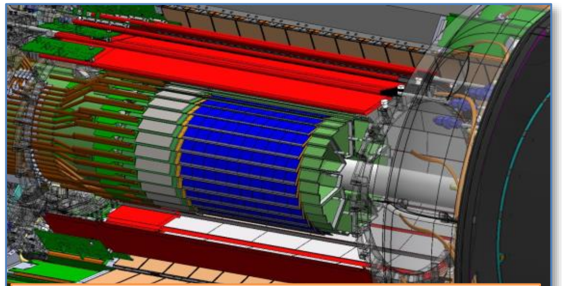




1999

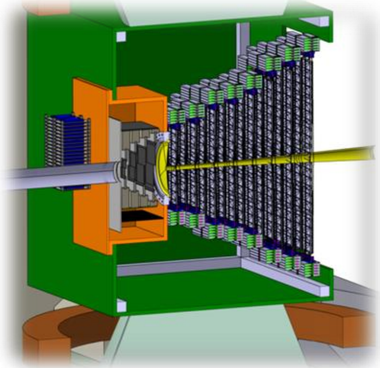
2016

… several HI experiments have selected CMOS pixel sensors for their inner trackers

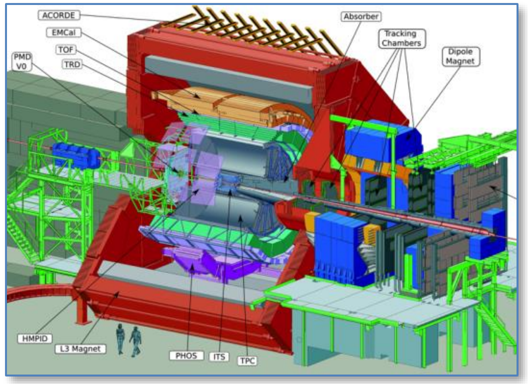


2014 - First CPS Detector

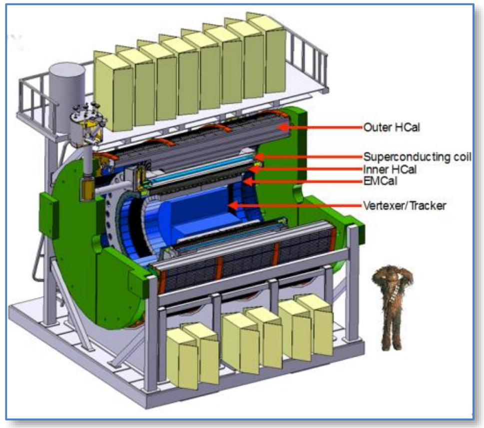
STAR HFT
$0.16\ m^2$ – 356 M pixels



CBM MVD
$0.08\ m^2$ – 146 M pixel



ALICE ITS Upgrade (and MFT)
$10\ m^2$ – 12 G pixel



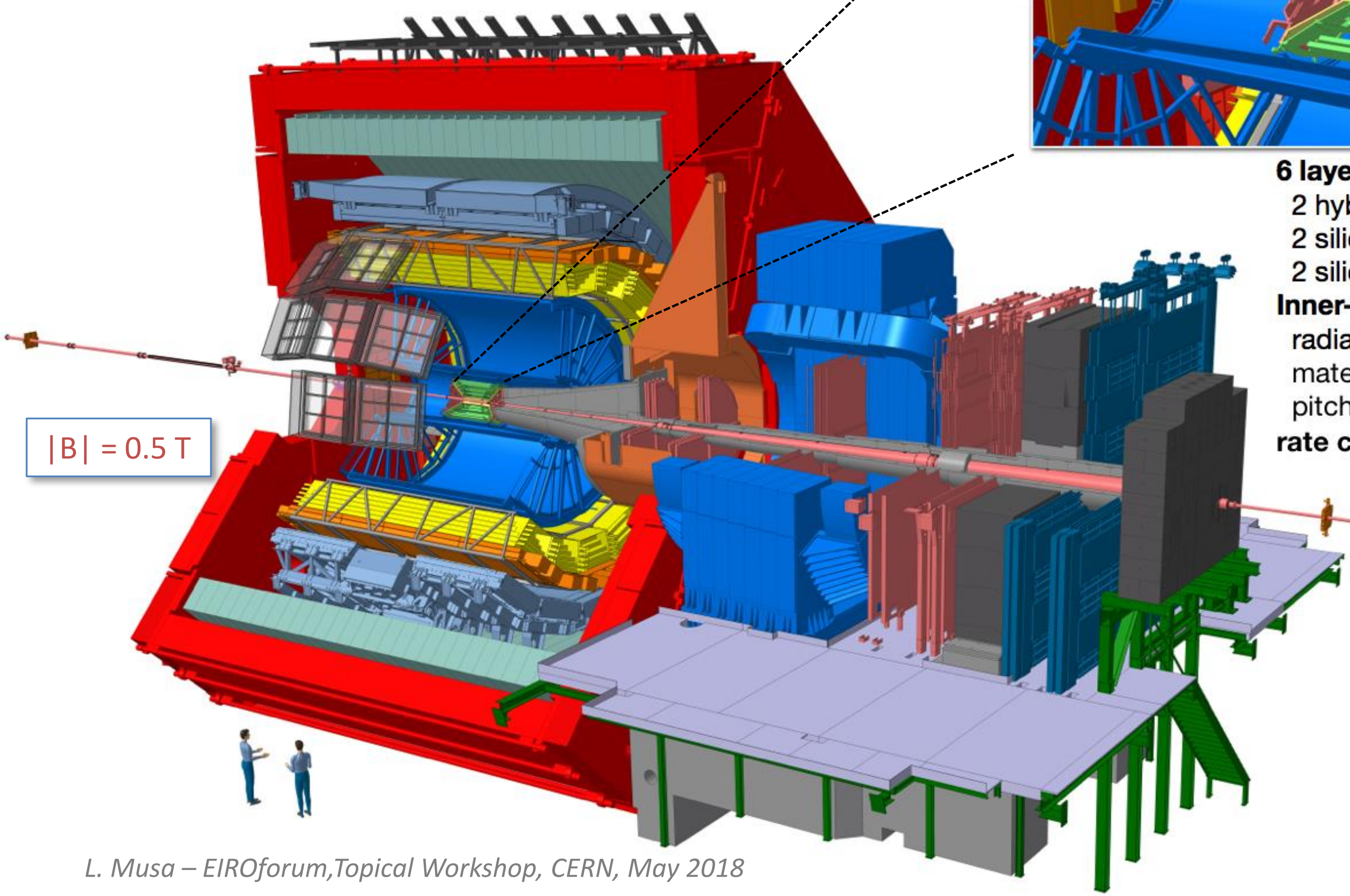
sPHENIX
$0.2\ m^2$ – 251 M pixel

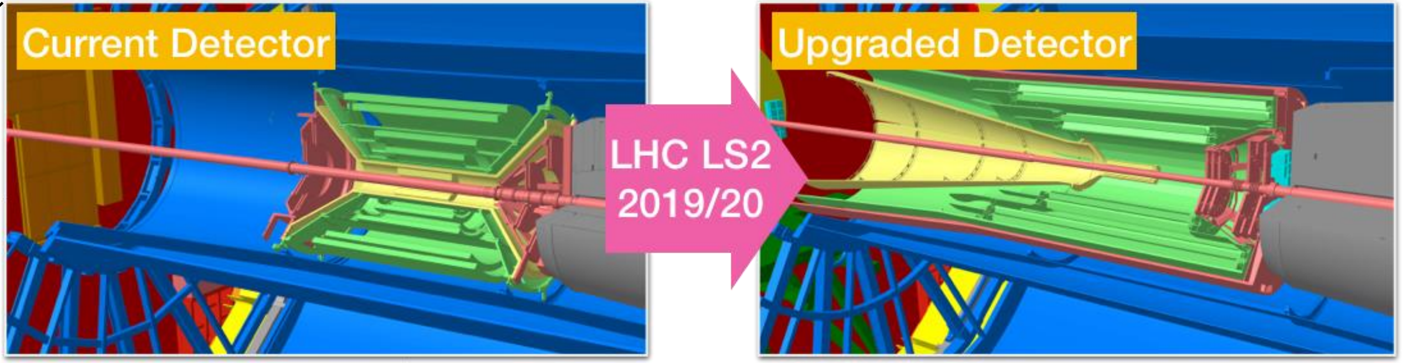
New Inner Tracking System based on CMOS sensors for ALICE

New Inner Tracking System (ITS)

- CMOS Pixels

→ improved resolution, less material, faster readout

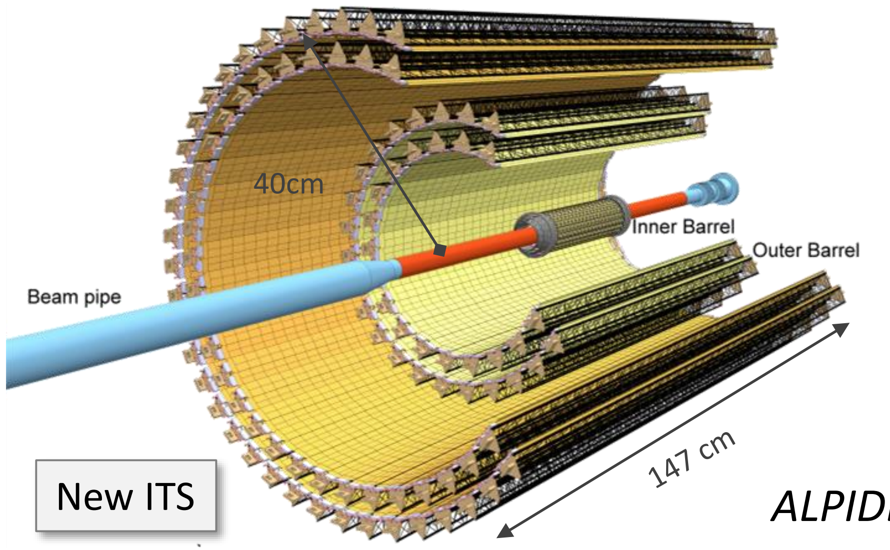




Current Detector	Upgraded Detector
6 layers: 2 hybrid silicon pixel, 2 silicon drift, 2 silicon strip	**7 layers:** all Monolithic Active Pixel Sensors
Inner-most layer:	**Inner-most layer:**
radial distance: 39 mm	radial distance: 23 mm
material: $X/X_0 = 1.14\%$	material: $X/X_0 = 0.3\%$
pitch: $50 \times 425\ \mu m^2$	pitch: $O(30 \times 30\ \mu m^2)$
rate capability: 1 kHz	**rate capability:** 100 kHz (Pb-Pb)

ALICE LOI: https://doi.org/10.1088/0954-3899/41/8/087001
ITS TDR: https://doi.org/10.1088/0954-3899/41/8/087002

A new ITS: closer to IP, thinner, higher position resolution



New ITS

$1.5 \leq \eta \leq 1.5$

Closer to IP: 39mm ➡ 22mm

Thinner: ~1.14% ➡ ~ 0.3% (for inner layers)

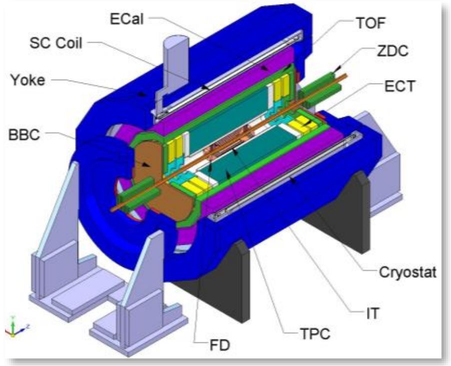
Smaller pixels: 50μm x 425μm ➡ 27μm x 29μm

Increase granularity (x 10^3): 20 chan/cm^3 ➡ 2k pixel/cm^3

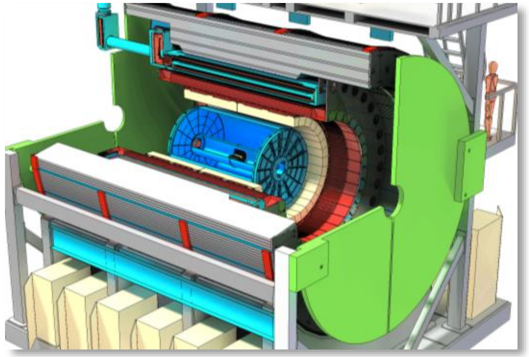
10 m^2 active silicon area: 12.5 G-pixels, $\sigma \approx 5\mu m$

*ALPIDE (**AL**ICE **Pi**xel **De**tector) - Developed for the ALICE upgrade (ITS and MFT) will be used (or it is proposed) for several other HEP detectors and non HEP applications*

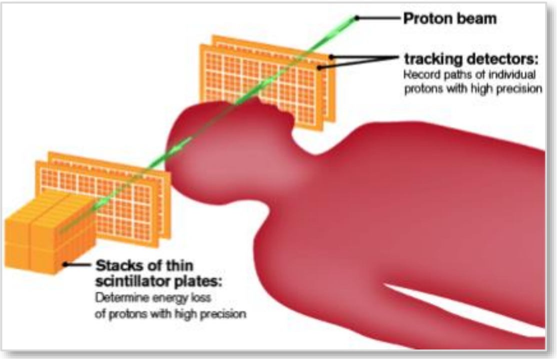
NICA MPD (@JINR)



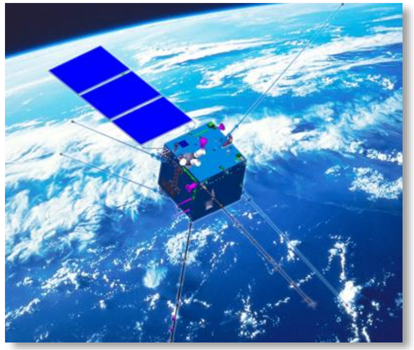
sPHENIX (BNL)



proton CT (tracking)



CSES – HEPD2



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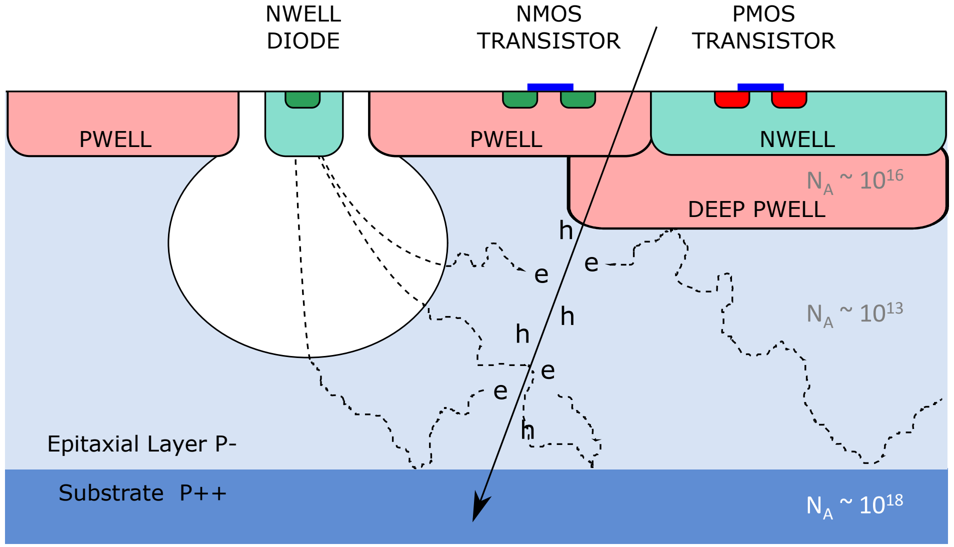
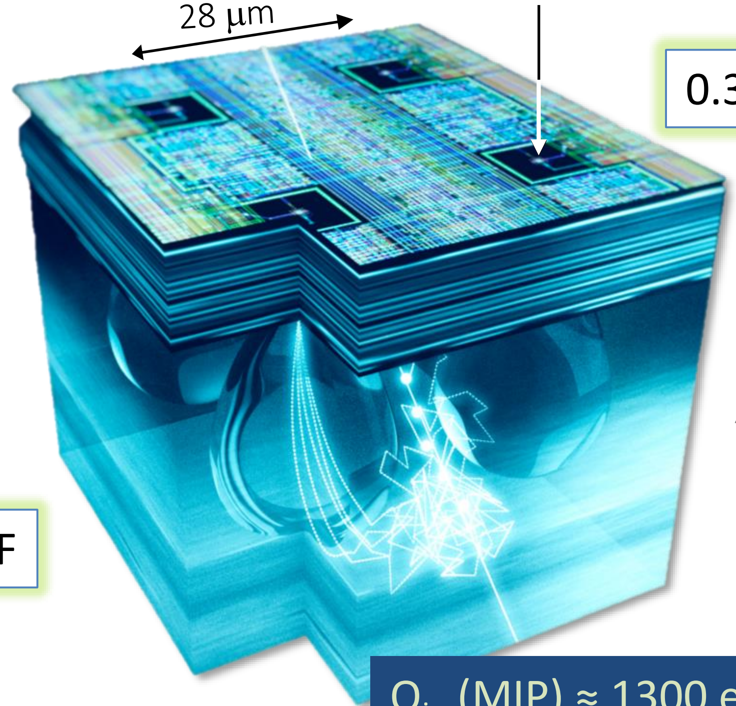
ALICE CMOS Pixel Sensor

CMOS Pixel Sensor using 0.18μm CMOS Imaging Process



pixel capacitance ≈5 fF (@ V_{bb} = -3 V)



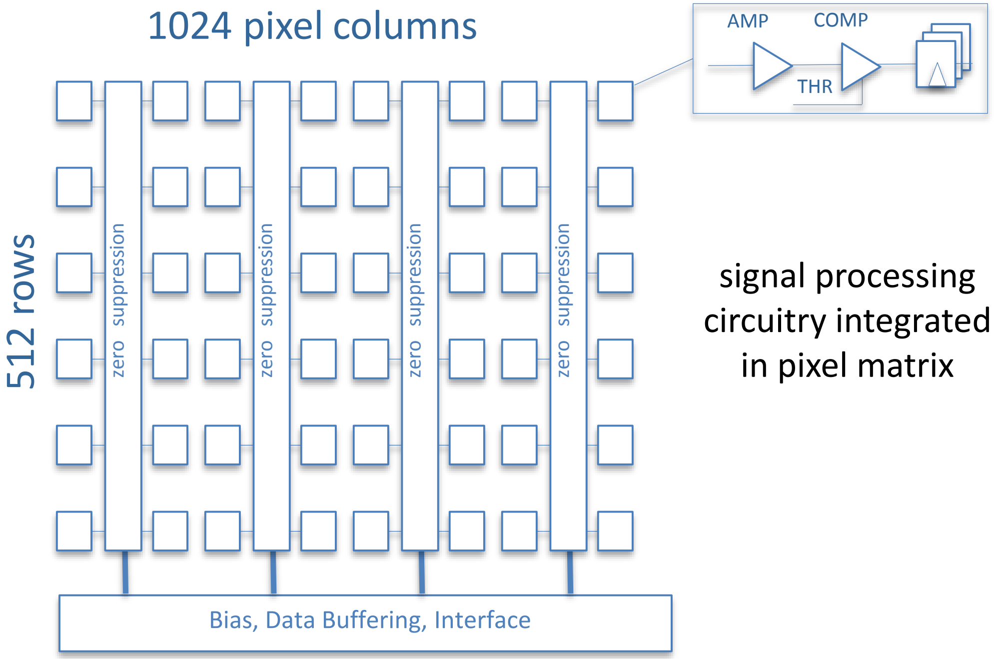
Artistic view of a SEM picture of ALPIDE cross section

Q_{in} (MIP) ≈ 1300 e ⇨ V ≈ 40mV

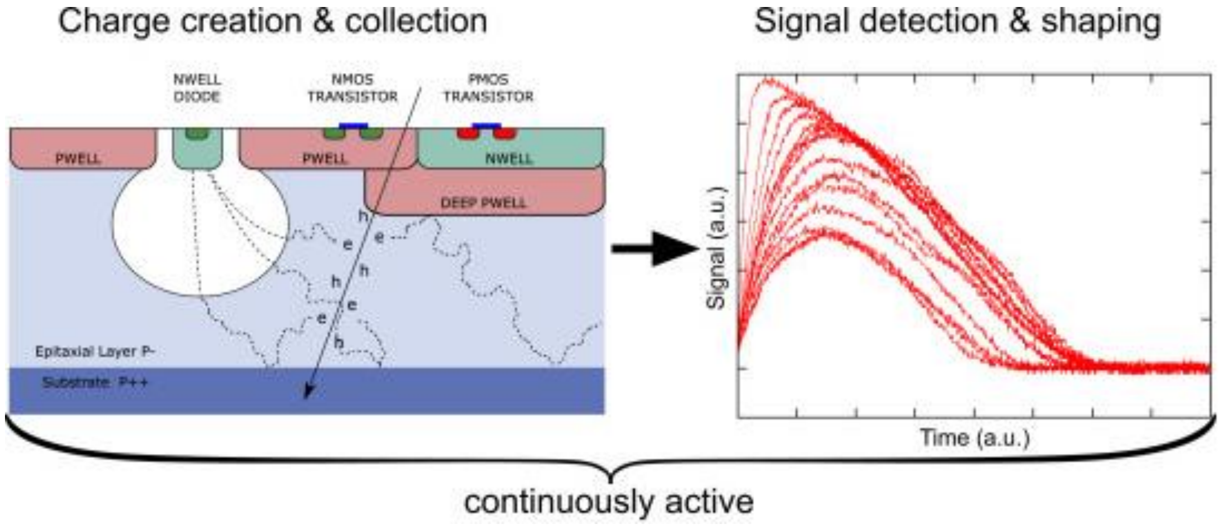
- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

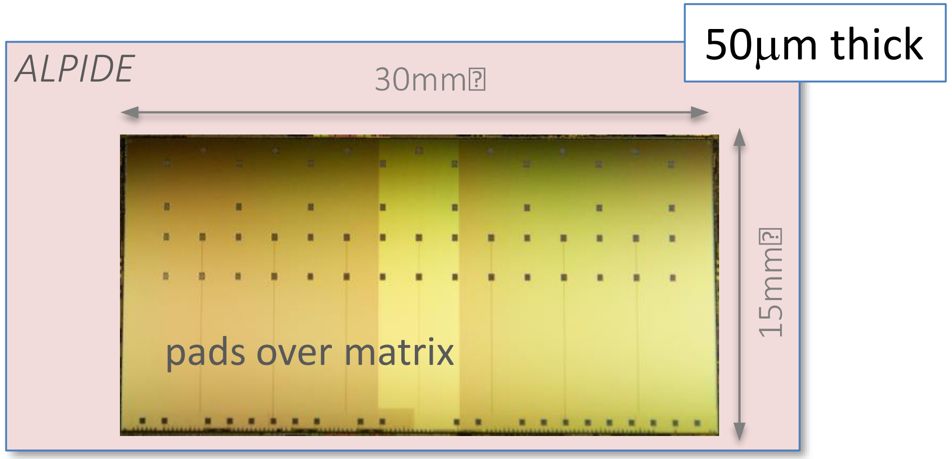
➔ full CMOS circuitry within active area

ALICE CMOS Pixel Sensor



signal processing circuitry integrated in pixel matrix





130,000 pixels / cm^2 27x29x25 µm^3

charge collection time <30ns (V_{bb} = -3V)

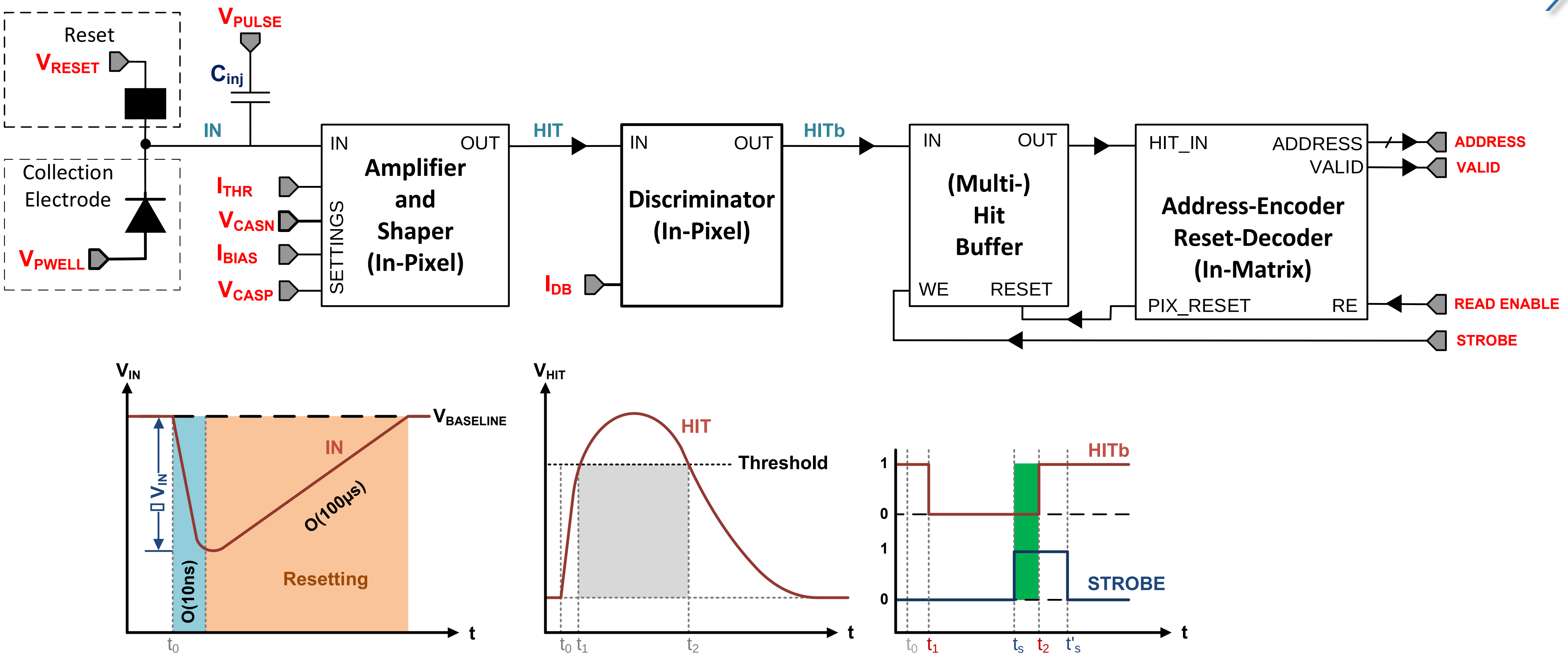
spatial resolution ~ 5 µm

max particle rate ~ 100 MHz / cm^2

fake-hit rate: < 10^{-9} pixel / event

power : ≈300 nW /pixel

ALPIDE Principle of Operation



Front-end acts as delay line

- Sensor and front-end continuously active: upon particle hit front-end forms a pulse with ~1-2μs peaking time
- Threshold is applied to form binary pulse and hit latched into memory

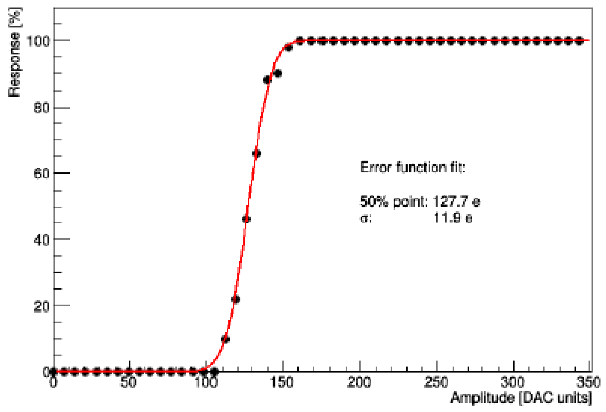
ALICE CMOS Pixel Sensor

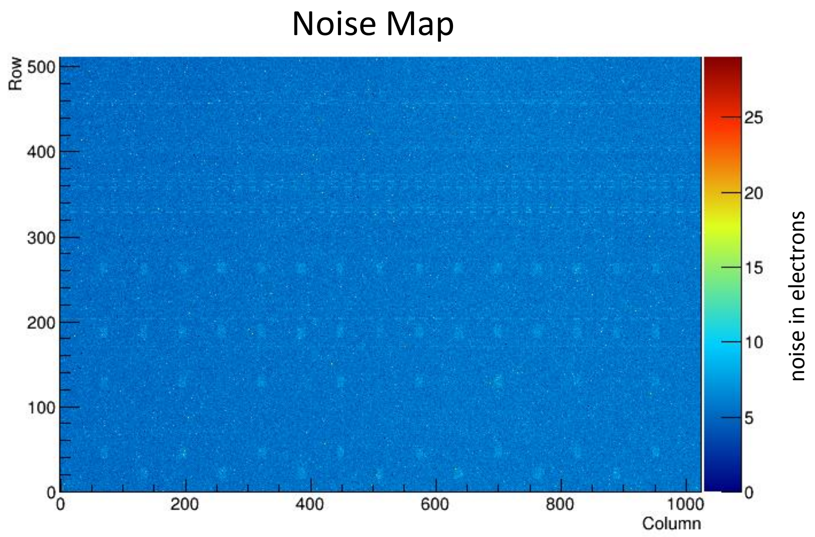
Thresholds and Noise

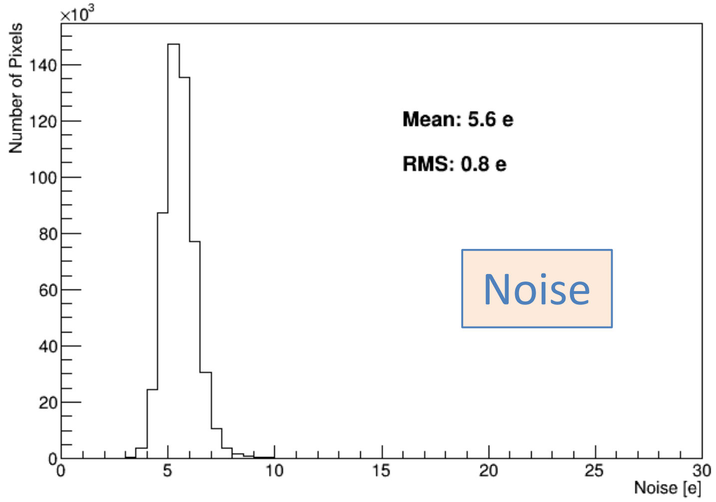
S-curve scan using internal charge injection circuit

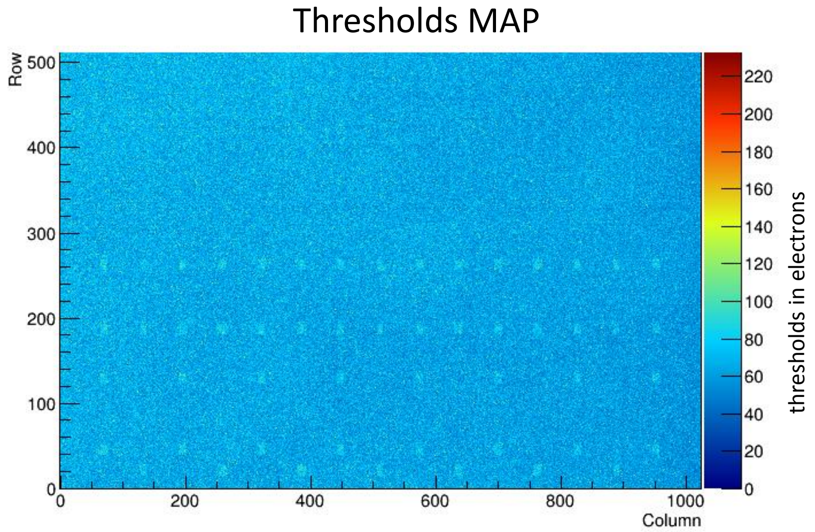
- keep comparator threshold fixed
- inject varying charges
- extract threshold and noise from error-function fit

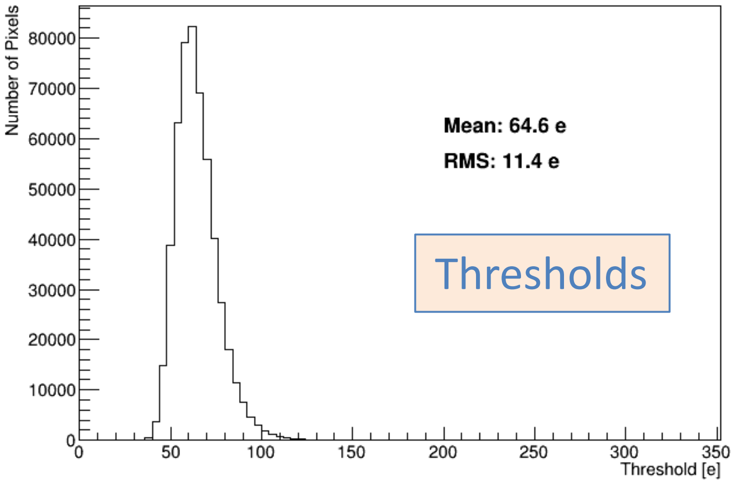
$$P_{HIT}(q) = \frac{1}{2} \cdot Erf\left[\frac{q - \mu}{\sqrt{2} \cdot \sigma}\right]$$



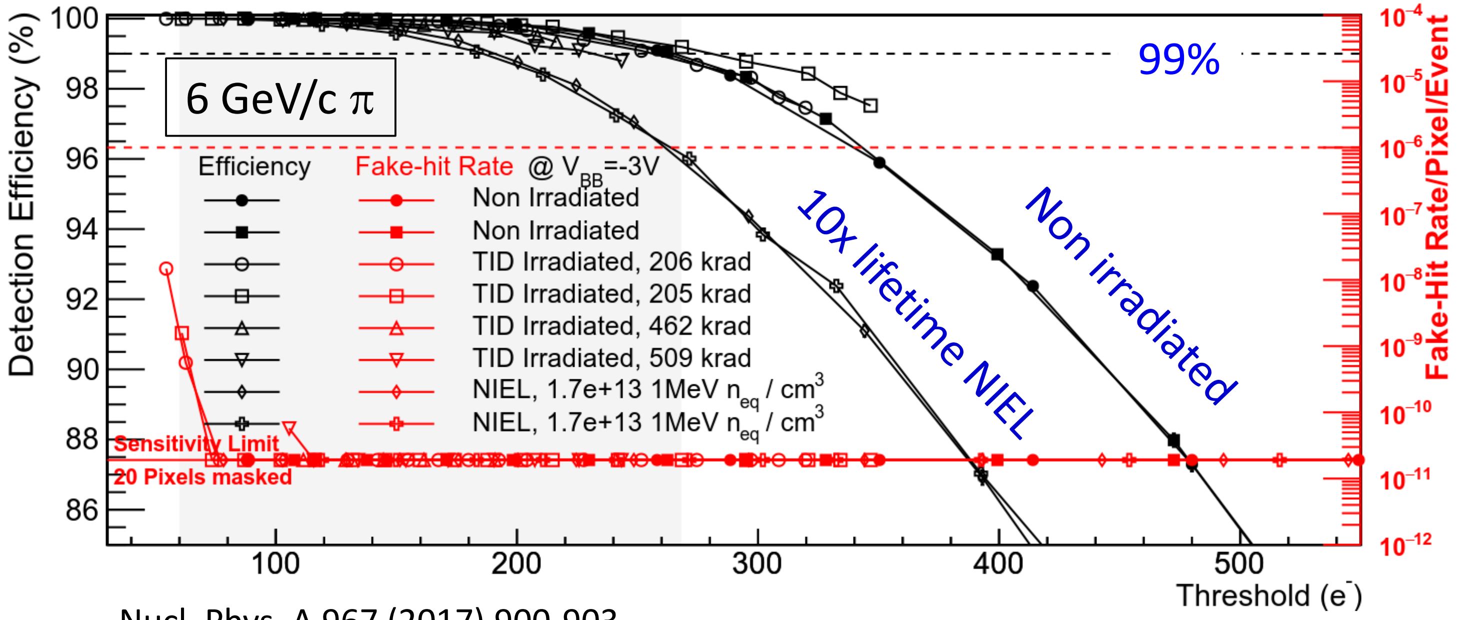








ALICE CMOS Pixel Sensor

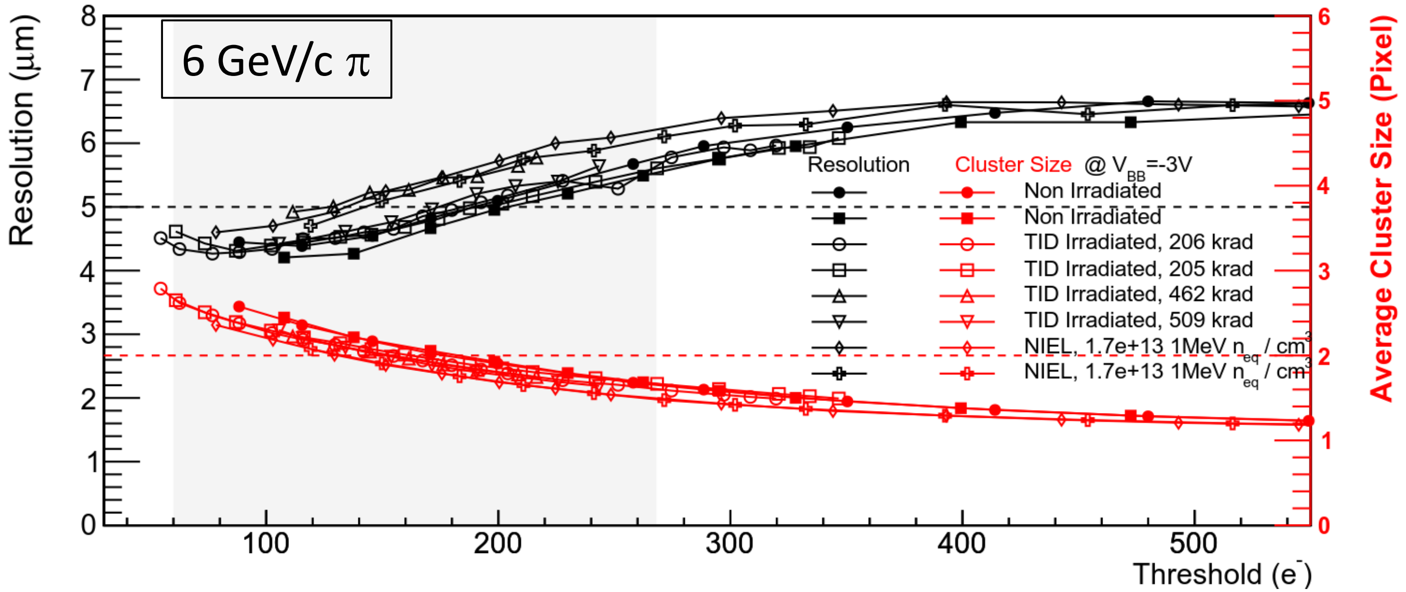


Nucl. Phys. A 967 (2017) 900-903

Large operational margin with only 10 masked pixels (0.002%), fake-hit rate < 10^{-10} pixel/event

Non irradiated and TID/NIEL chips similar performance

Nucl. Phys. A 967 (2017) 900-903

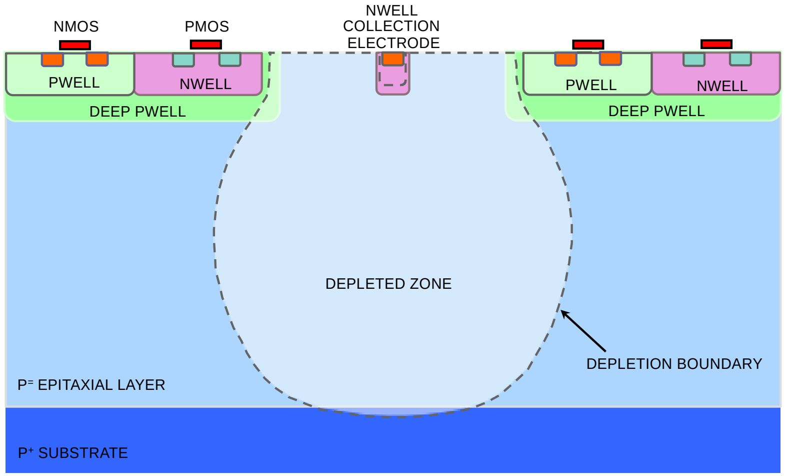


5 μm resolution @ 200 e^- threshold

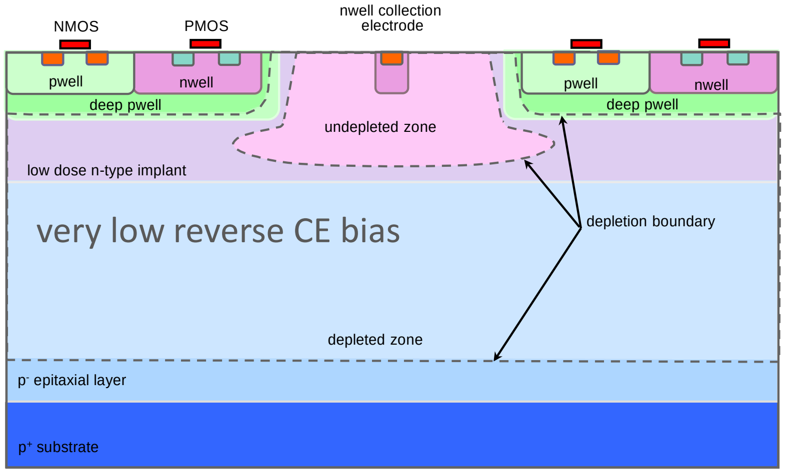
Chip-to-chip negligible fluctuations

A process modification for CMOS APS for full depletion

A process modification for CMOS Active Pixel Sensors for enhanced depletion, timing performance and radiation tolerance



Standard Process (+DEEP PWELL)



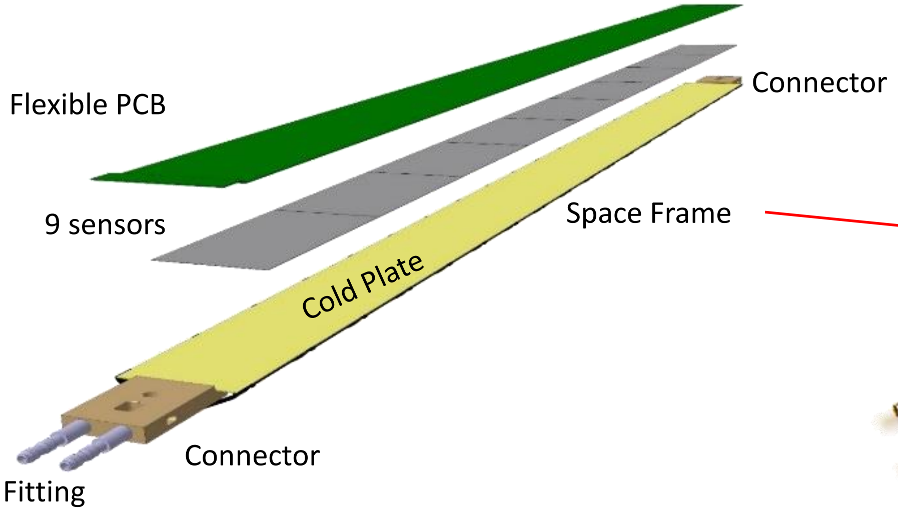
Modified Process with low-dose n-type implant (+DEEP PWELL)

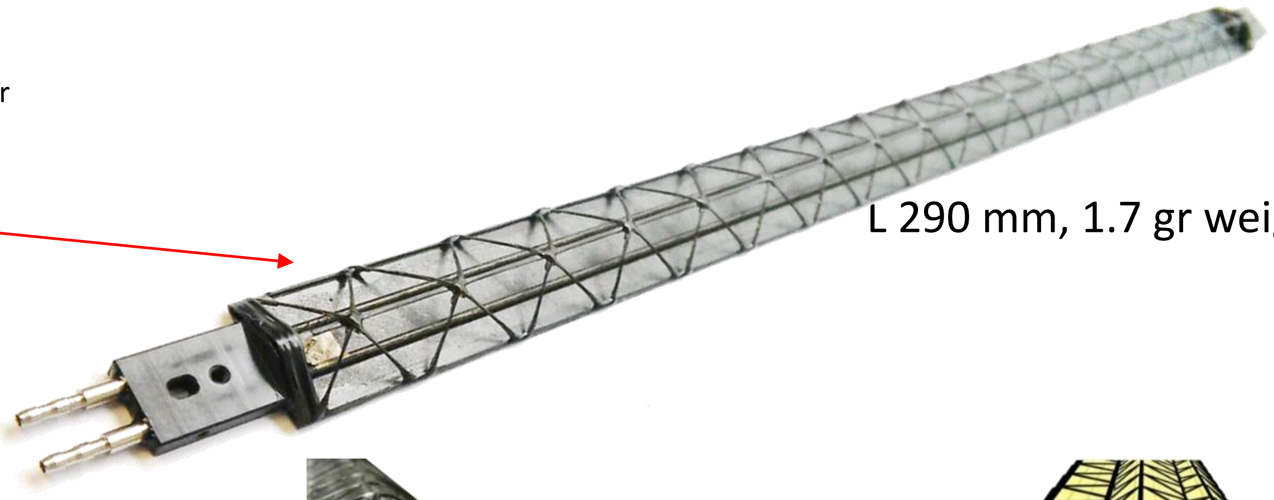
The process modification requires a single additional process mask with no changes on the sensor and circuit layout

For details on process modification and experimental results see: NIM, A 871C (2017) pp. 90-96 (CERN/Tower)

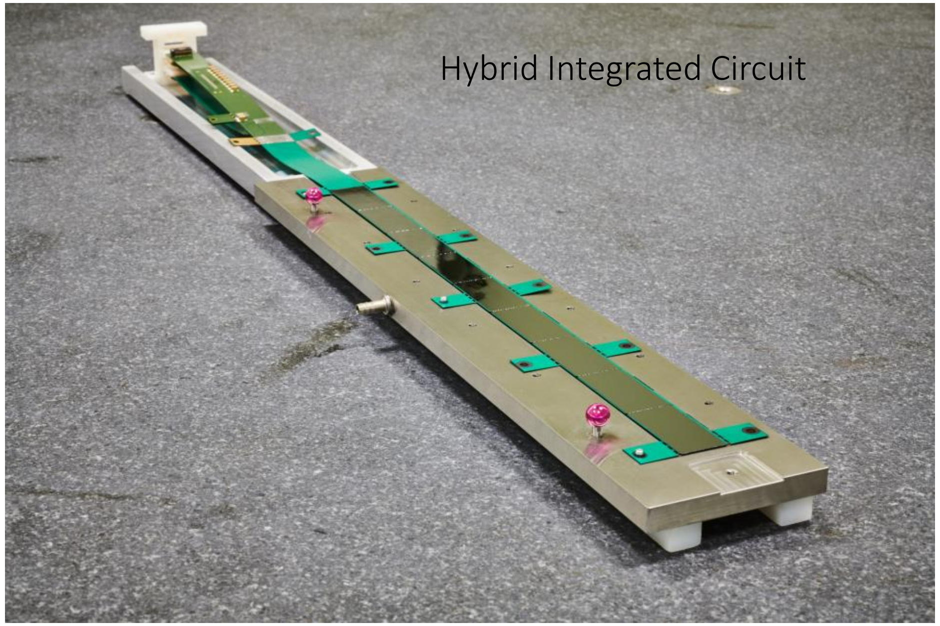
The ALICE test vehicle chip (investigator) and prototype ALPIDE chips exist with both flavors

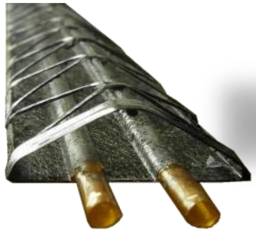
Inner Barrel Stave



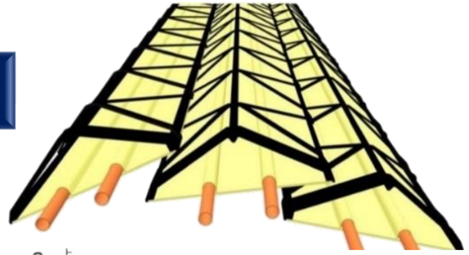


L 290 mm, 1.7 gr weight

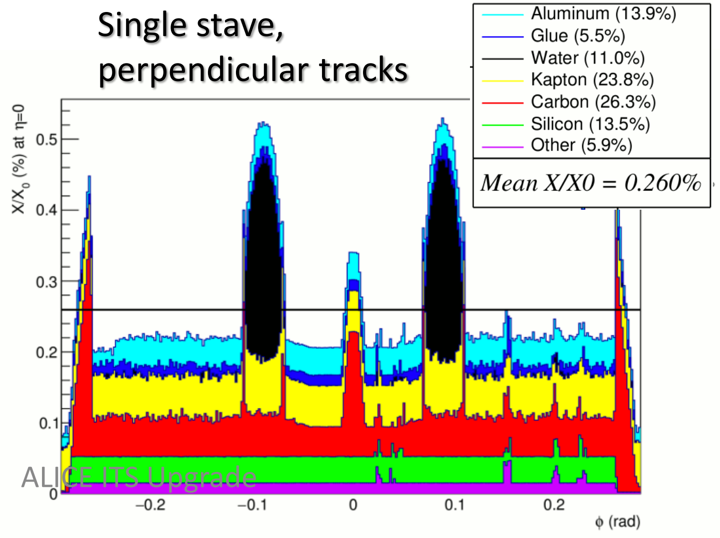




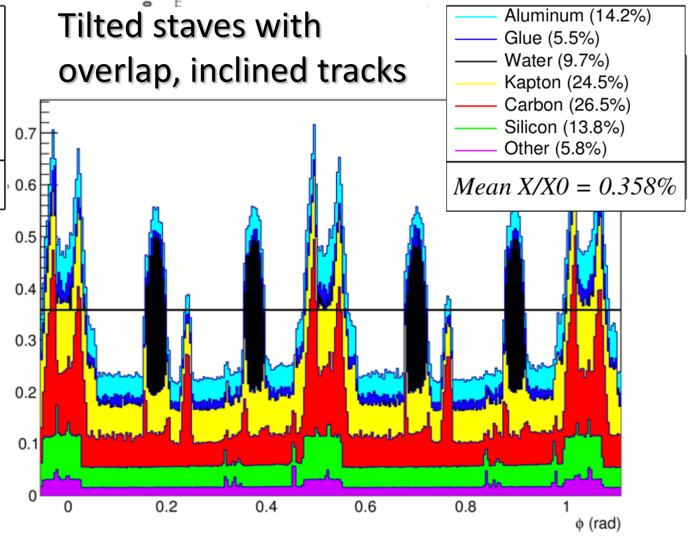
Material budget



Single stave, perpendicular tracks

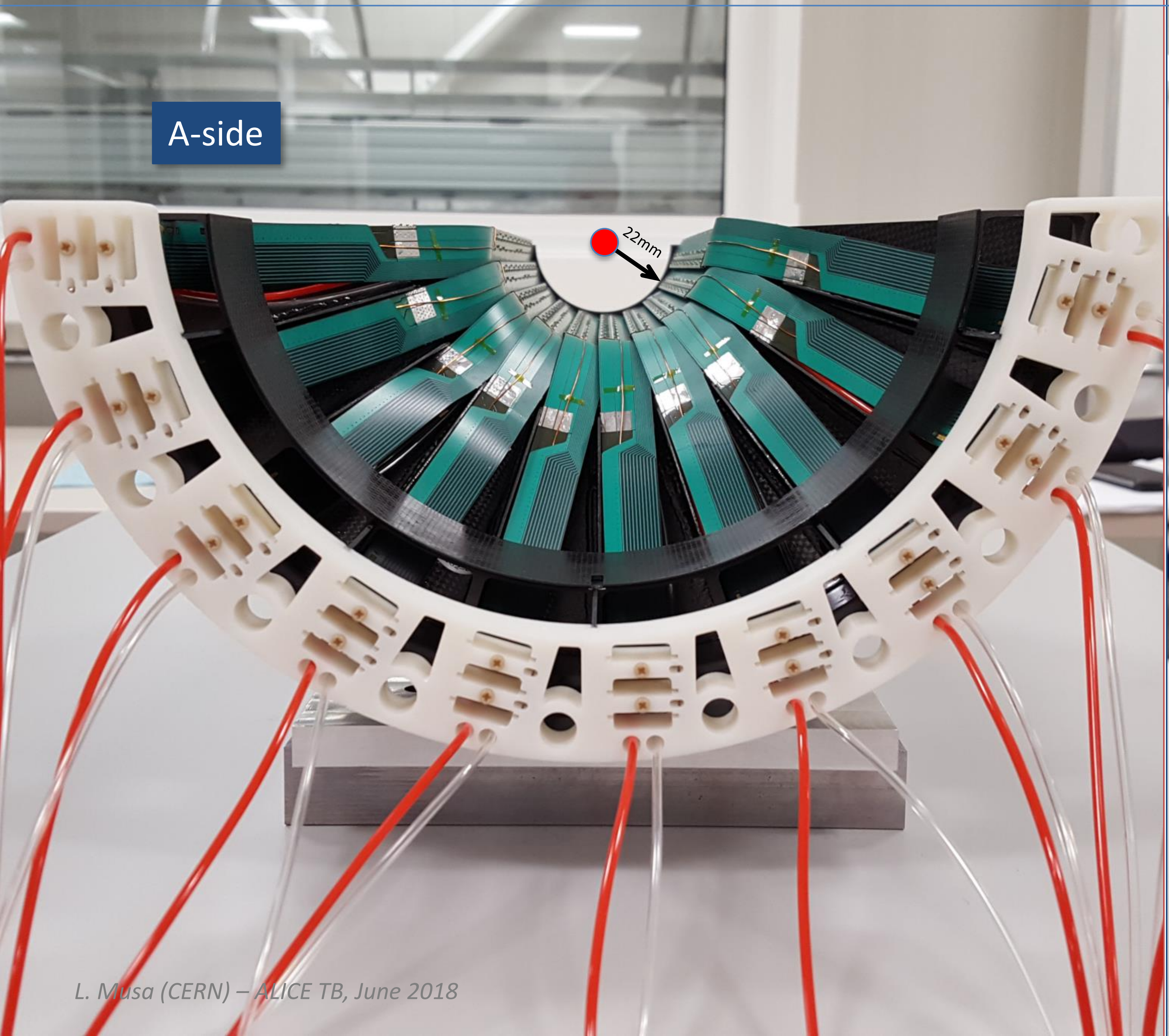


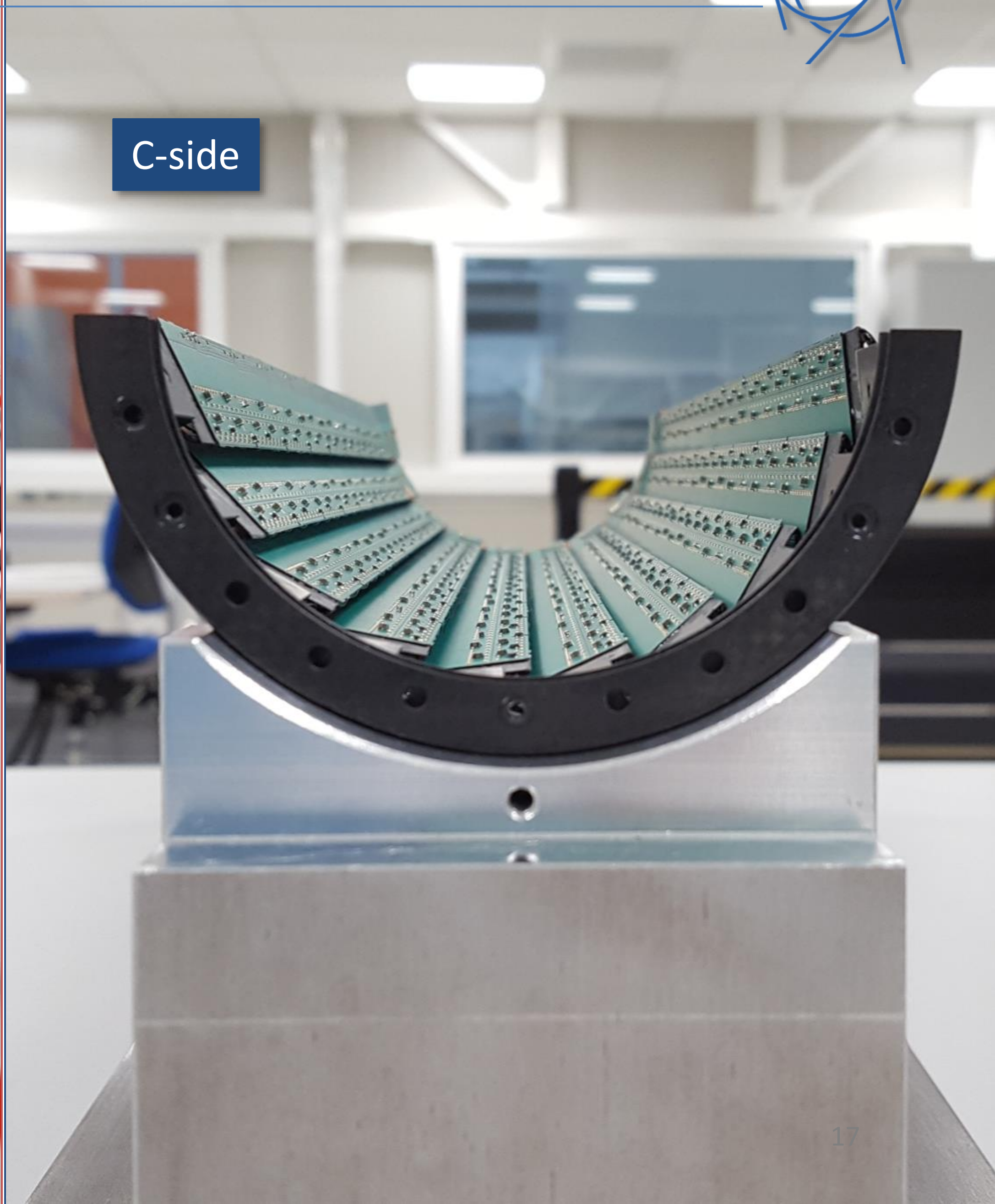
Tilted staves with overlap, inclined tracks



Assembly of First Inner Half-Barrel

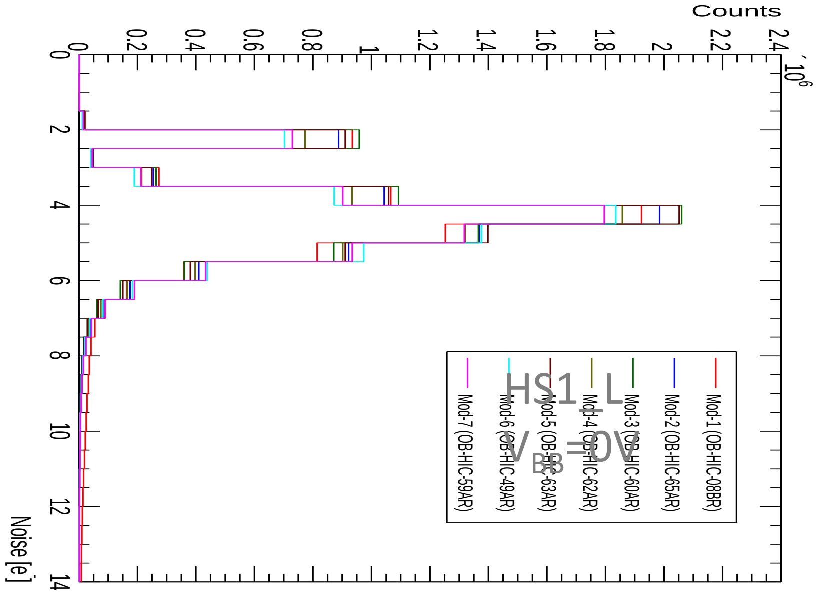
Inner Barrel – Half-Layer 2

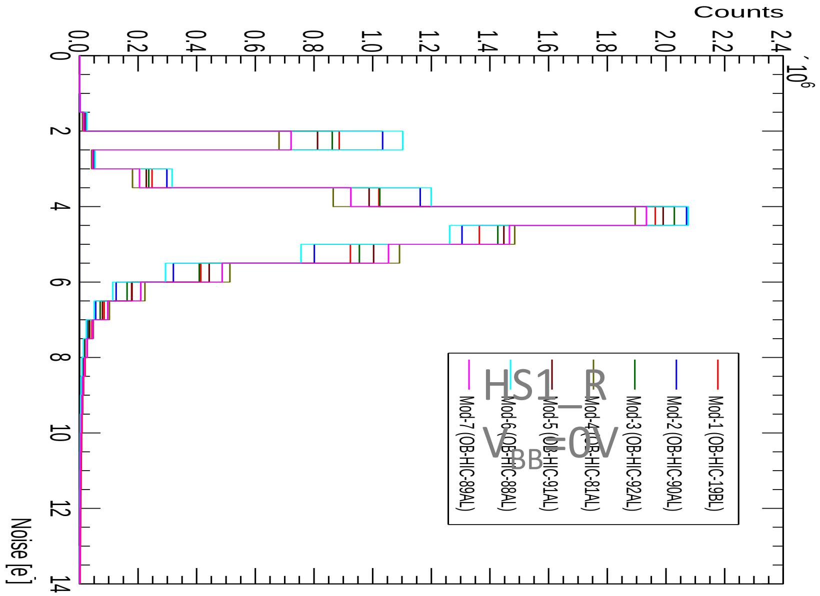




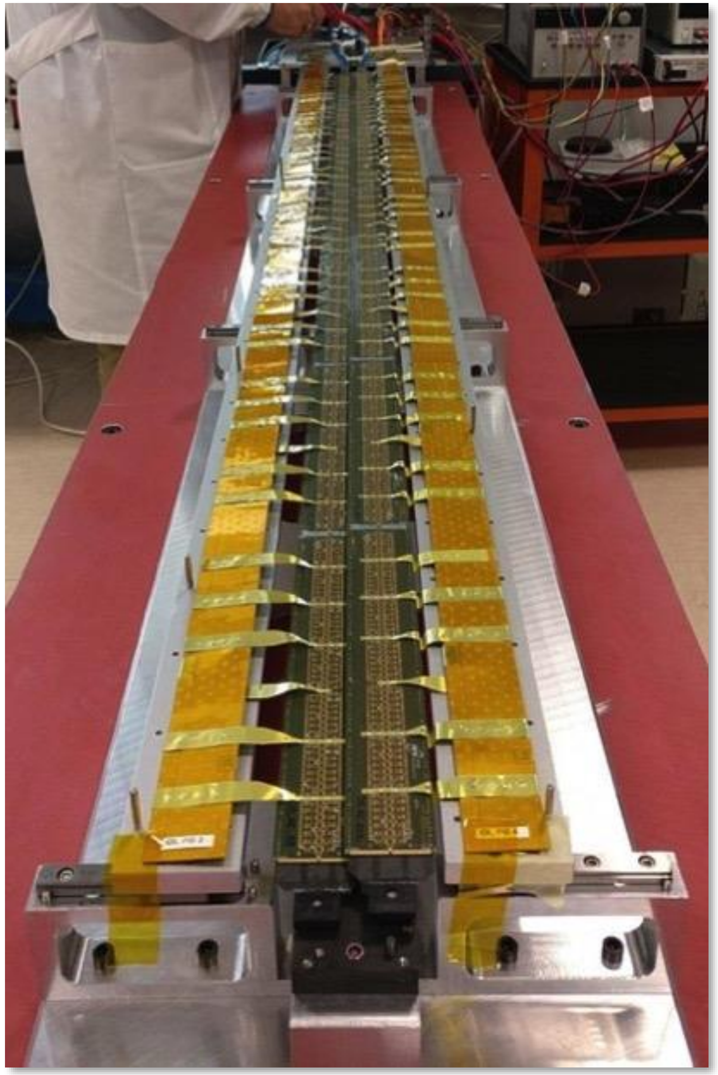
Stave Prototypes

102 Million pixel, average noise uniform ~ 5e





Noise distribution



Conclusion

- After 15 years of intensive R&D, CMOS Active Pixel Sensor have reached a level of performance and maturity to be used in High Energy Physics experiments, the first examples being STAR (2014) and ALICE (2020)
- The ALPIDE chip, developed for the ALICE Inner Tracking System, for the first time integrates the full CMOS circuitry inside the pixel matrix allowing a fast processing and readout of the pixel signals
- Charge is collected by diffusion and (mostly) drift in the "standard process" or entirely by drift ("modified process")
- ALPIDE features a charge collection time below 30ns, a spatial resolution of 5μm, a pixel fake hit rate below 10^{-8} per frame, a power density of 40mW/cm^2 and can cope with particle rates of up to 100MHz/cm^2.
- The production of the sensors has been completed and the construction of the detector is well advanced and will be ready for installation in ALICE in 2020