Achievements and Perspectives of CMOS Pixel Sensors for HIGH-PRECISION Vertexing & Tracking Devices

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http://www.iphc.cnrs.fr/-PICSEL-.html

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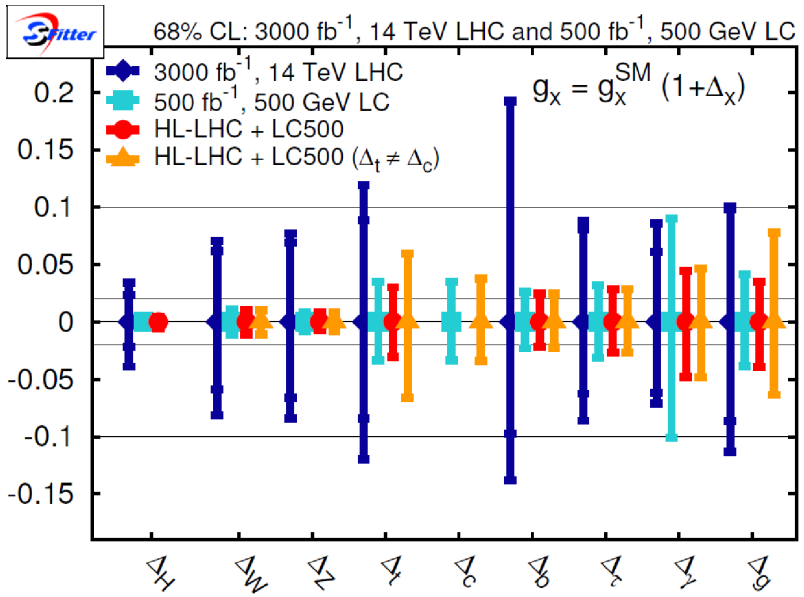
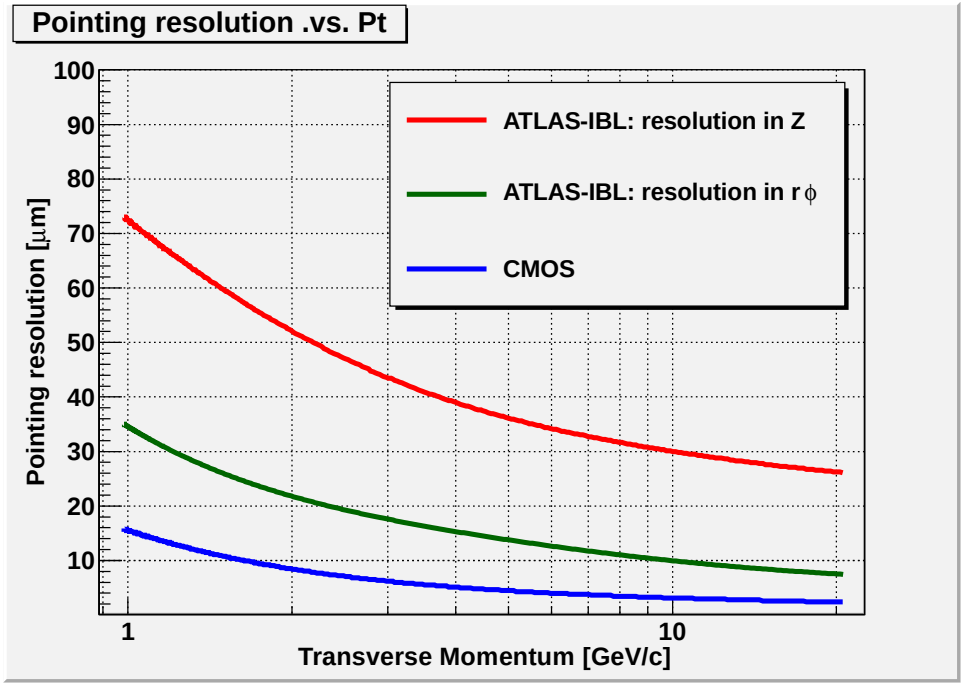
Contents

Original Motivation for the R&D: Vertexing at the ILC

- CMOS PIXEL SENSORS **(CPS) pioneered for the vertex detector requirements :**
  - ⁕ unprecedented granularity & material budget (very low power)
  - ⁕ much less demanding running conditions than at LHC
    - ⇛ alleviated read-out speed & radiation tolerance requests
  - ⁕ ILC duty cycle $\sim$ 1/200
    - ⇛ power saving by power pulsing sub-systems



- **Vertexing goal:**
  - ⁕ achieve high efficiency & purity flavour tagging
    - ⟼ charm & tau, jet-flavour !!!
  - ↪ $\sigma_{R\phi,Z} \leq 5 \oplus 10/p \cdot sin^{3/2}\theta \ \ \mu m$
    - ▷ LHC: $\sigma_{R\phi} \simeq 12 \oplus 70/p \cdot sin^{3/2}\theta$
  - ▷ Comparison: $\sigma_{R\phi,Z}$(ILD) with VXD made of ATLAS-IBL or ILD-VXD pixels ⟼

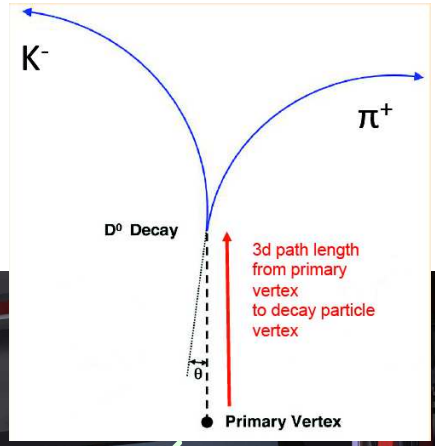


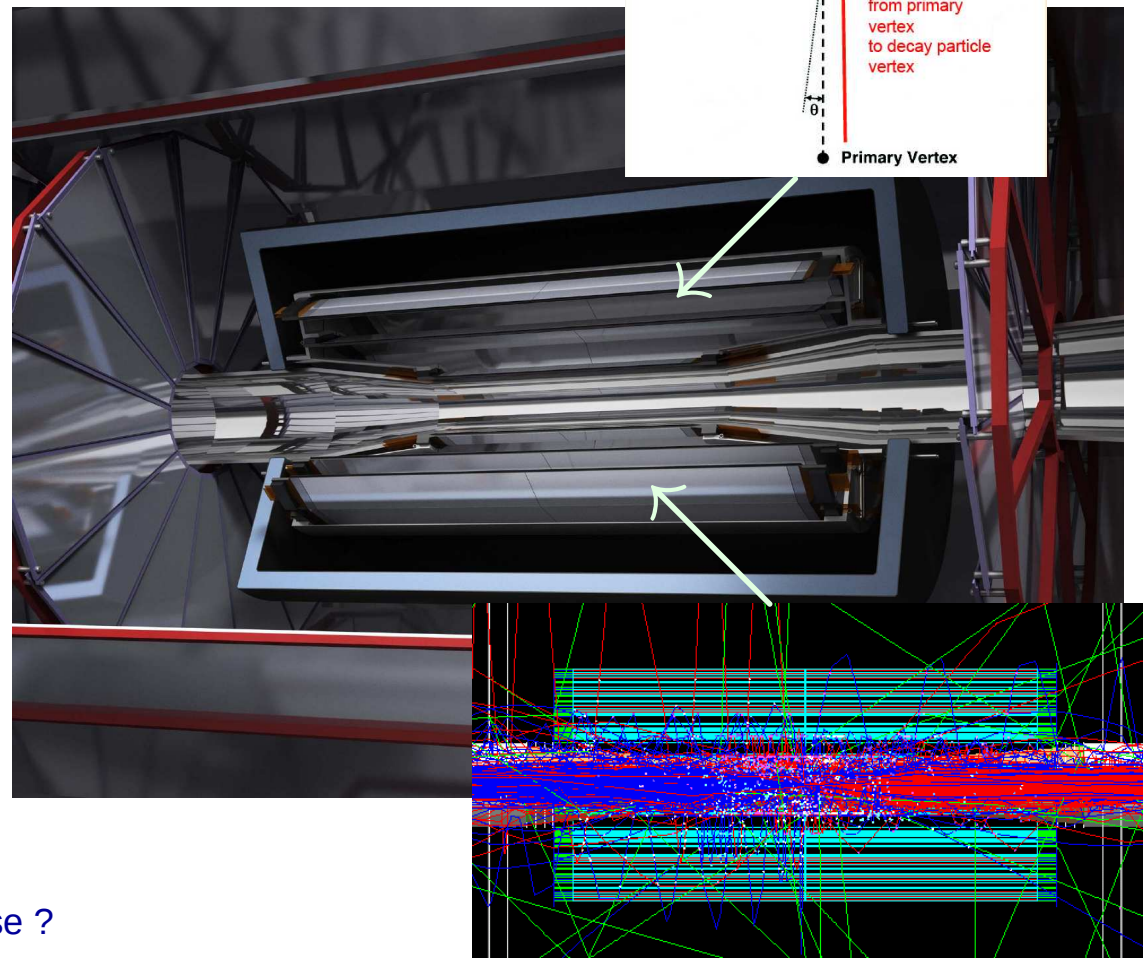
The Central Conflict of Vertexing

- A COMPLEX SET OF STRONGLY CORRELATED ISSUES :

  - **Charged particle sensor technology :**
    - highly granular, thin, low power, swift pixel sensors
  - **Micro-electronics :**
    - highly integrated, low power, SEE safe, r.o. μcircuits
  - **Electronics :**
    - high data transfer bandwith (no trigger), some SEE tol.
    - low mass power delivery, allowing for power cycling
  - **Mechanics :**
    - rigid, ultra-light, heat but not electrically conductive, mechanical supports, possibly with $C_{\Delta t} \simeq C_{\Delta t}^{Si}$
    - very low mass, preferably air, cooling system
    - micron level alignment capability
  - **EM compliance :**
    - power cycling in high B field $\Rrightarrow$ F(Lorentz)
    - higher mode beam wakefield disturbance $\Rrightarrow$ pick-up noise ?
  - **Radiation load and SEE compliance at T_{room}**

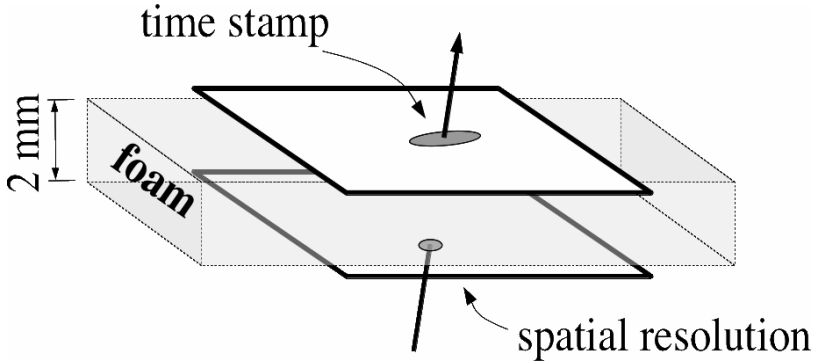
  $\Rrightarrow$ reduced material budget

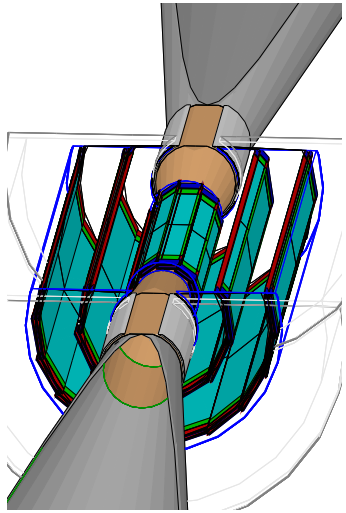




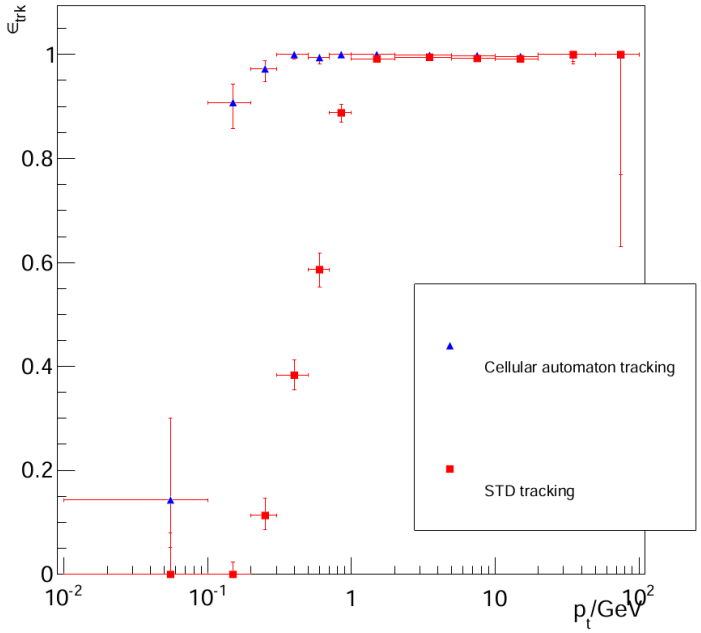
The RoleS of the ”Vertex” Detector

- DISPLACED VERTEX RECONSTRUCTION AND CHARACTERISATION :
  - reconstruction of collision point
  - reconstruction of D-meson and τ-lepton vertices
  - reconstruction of b-quark decays in (top-quark) jets
  - determination of displaced vertex electrical charge
  - etc.



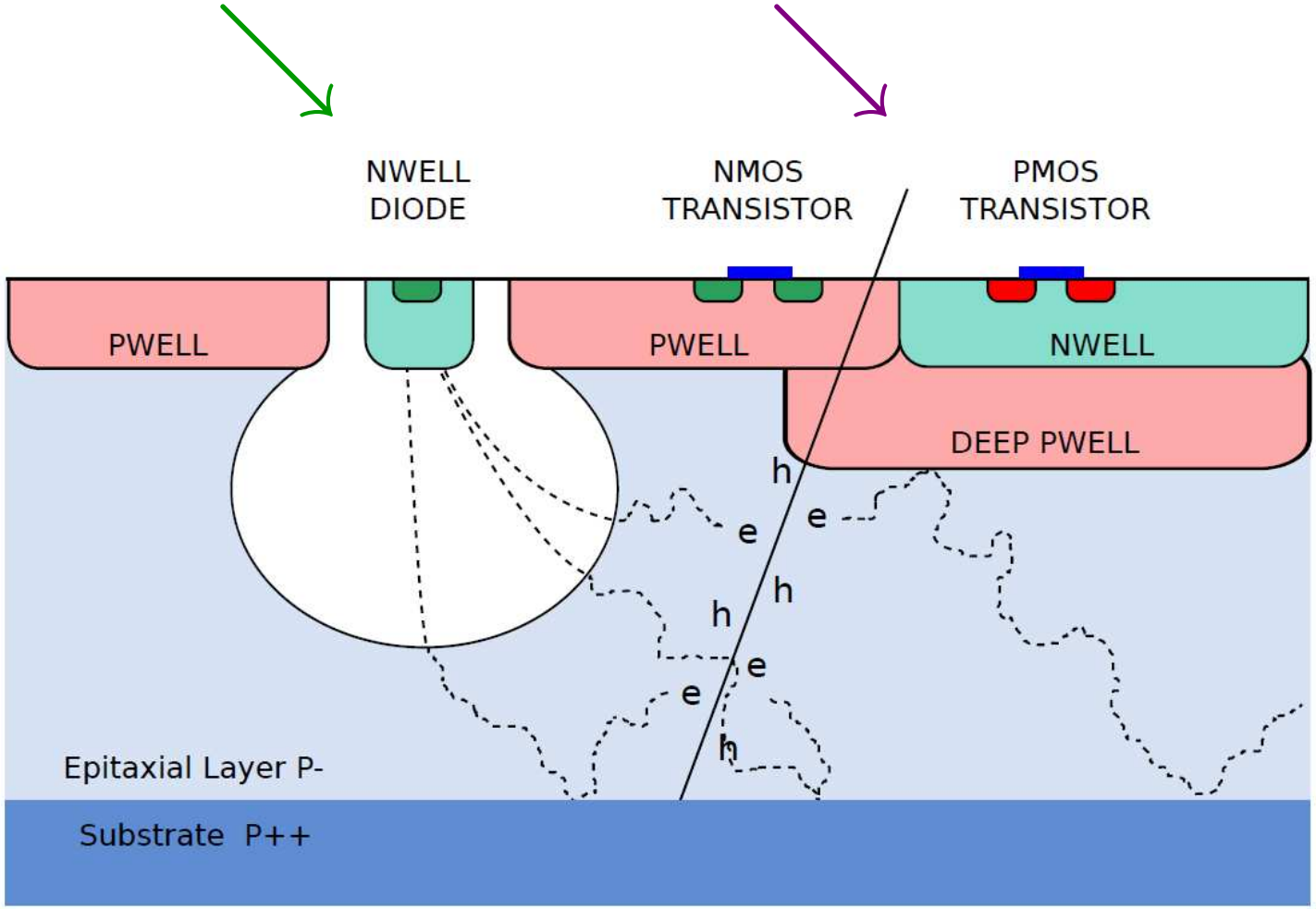


- ROLE IN THE TRACKING :
  - track seeding (depending on main tracker)
  - low P_t track reconstruction
  - track momentum determination (in particular low P_t)
  - fake tracks mitigation (E_{miss} determination)



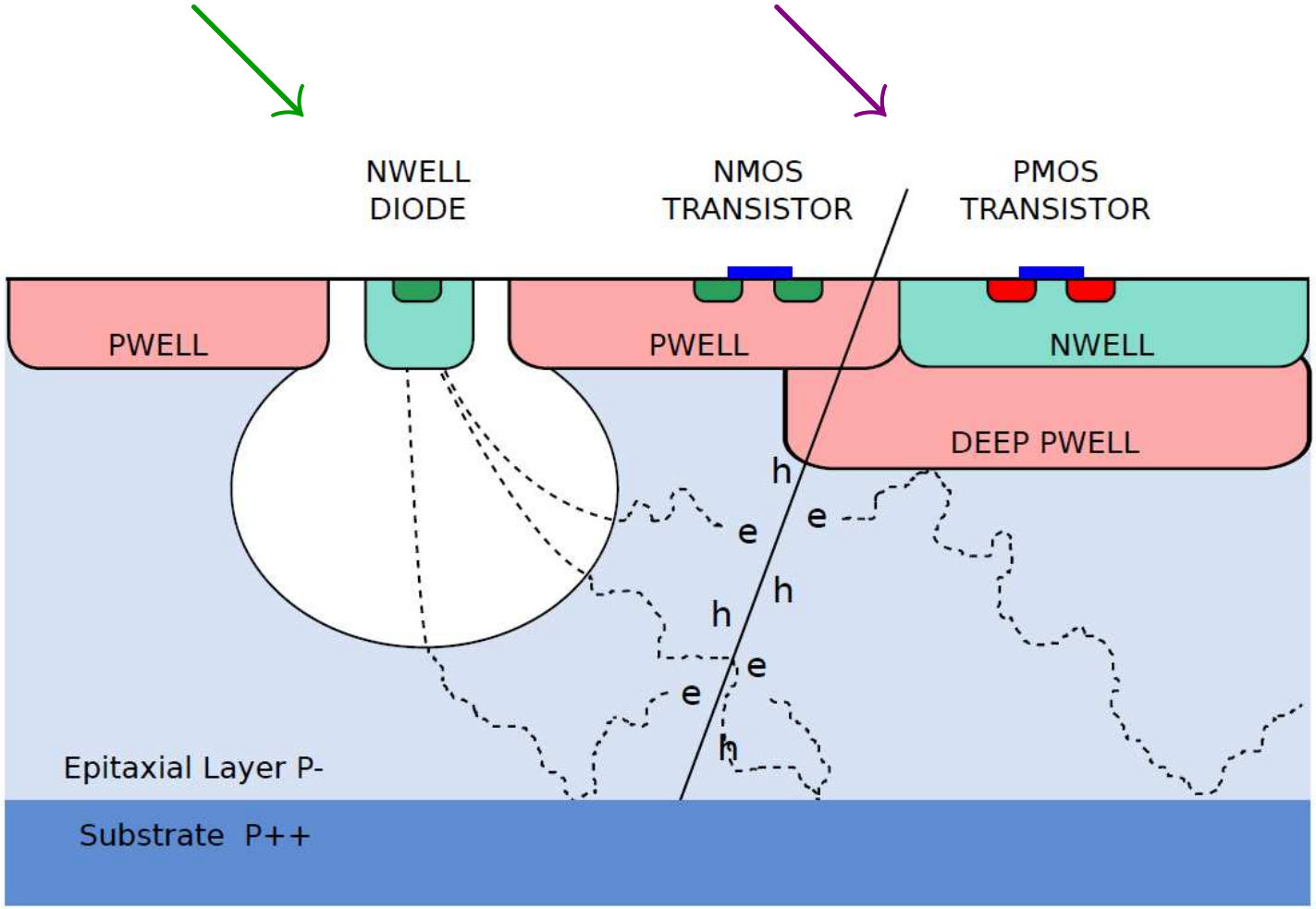
CMOS Pixel Sensors (CPS): Main Features

- **CMOS Pixel Sensors** ≡ **Detector** ⊕ **Front-End Electronics** in same die



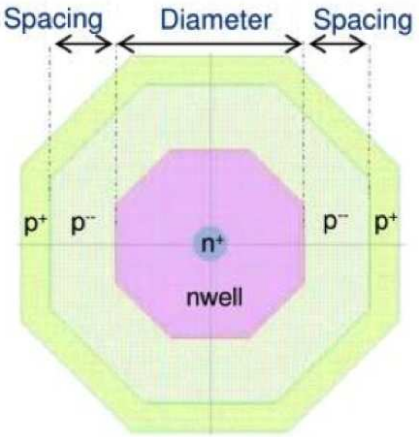
CMOS Pixel Sensors: Main Features

- R&D addresses **Sensing Element** $\oplus$ **Read-Out μcircuitry**

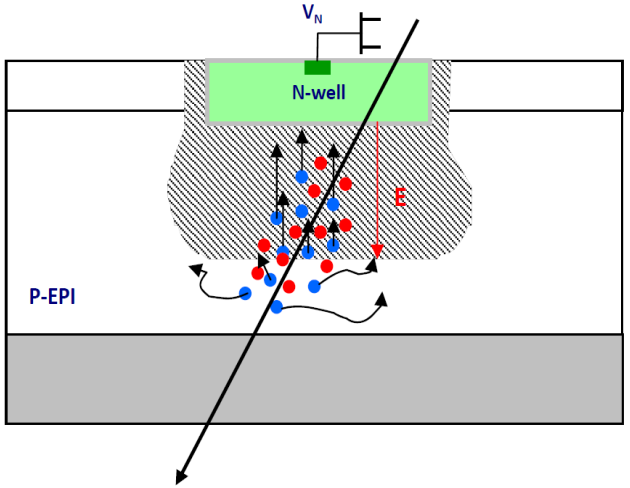


Sensing Node & VFEE Optimisation

- **General remarks on sensing diode :**
  - should be small because : $V_{signal} = Q_{coll}/C$; Noise $\sim$ C ; $G_{PA} \sim 1/C$
  - BUT should not be too small since $Q_{coll} \sim$ CCE (important against NI irradiation)



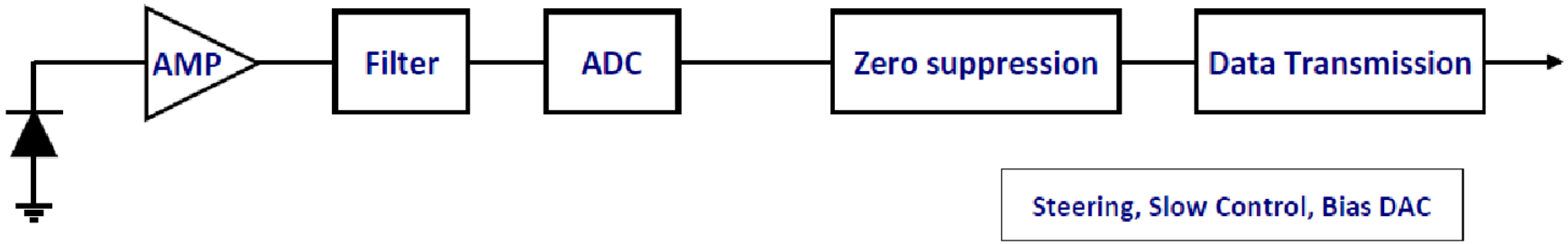
- **General remarks on pre-amplifier** connected to sensing diode :
  - should offer high enough gain to mitigate downstream noise contributions
  - should feature input transistor with minimal noise (incl. RTS)
  - should be very close to sensing diode (minimise line C)



- **General remarks on depletion voltage :**
  - apply highest possible voltage on sensing diode
    preserving charge sharing $\mapsto \sigma_{sp}$
  - alternative : backside/reverse biasing

$\Rightarrow$ **Multiparametric trade-off to be found,**
based on exploratory prototypes rather than on simulations

Main Components of the Signal Processing Chain



- **Typical components of read-out chain :**
  - **AMP :** In-pixel low noise pre-amplifier
  - **Filter :** In-pixel filter
  - **ADC :** Analog-to-Digital Conversion : 1-bit ≡ discriminator
    ↪ may be implemented at column or pixel level
  - **Zero suppression :** Only hit pixel information is retained and transfered
    ↪ implemented at sensor periphery (usual) or inside pixel array
  - **Data transmission :** O(Gbits/s) link implemented on sensor periphery

- **Read-Out alternatives :**
  - **Synchronous :** rolling shutter architecture
  - **Asynchronous :** data driven architecture

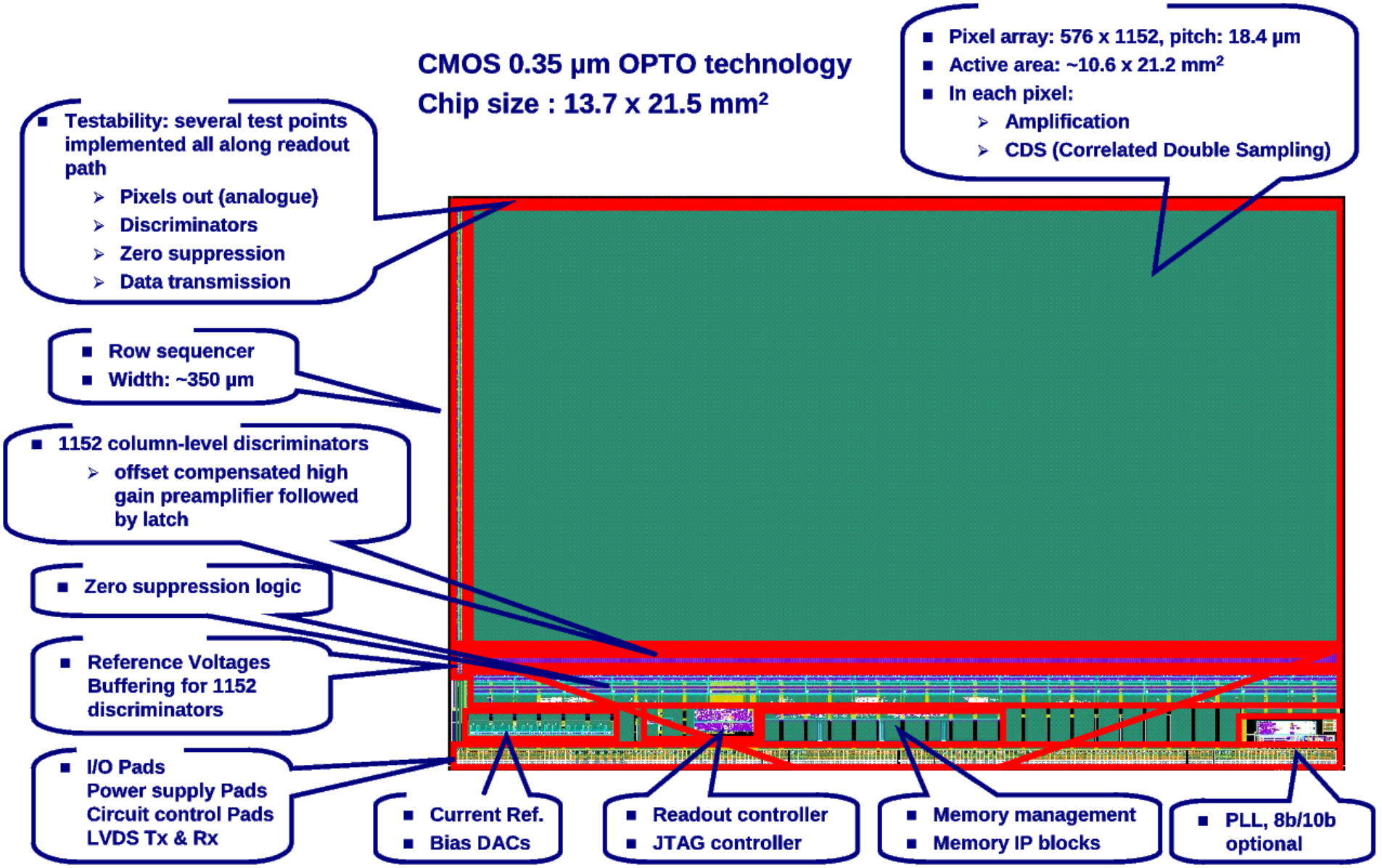
- **Rolling shutter : best approach for twin-well processes**

↪ trade-off between performance, design complexity, pixel dimensions, power, ...

↪ MIMOSA-26 (EUDET), MIMOSA-28 (STAR), ...

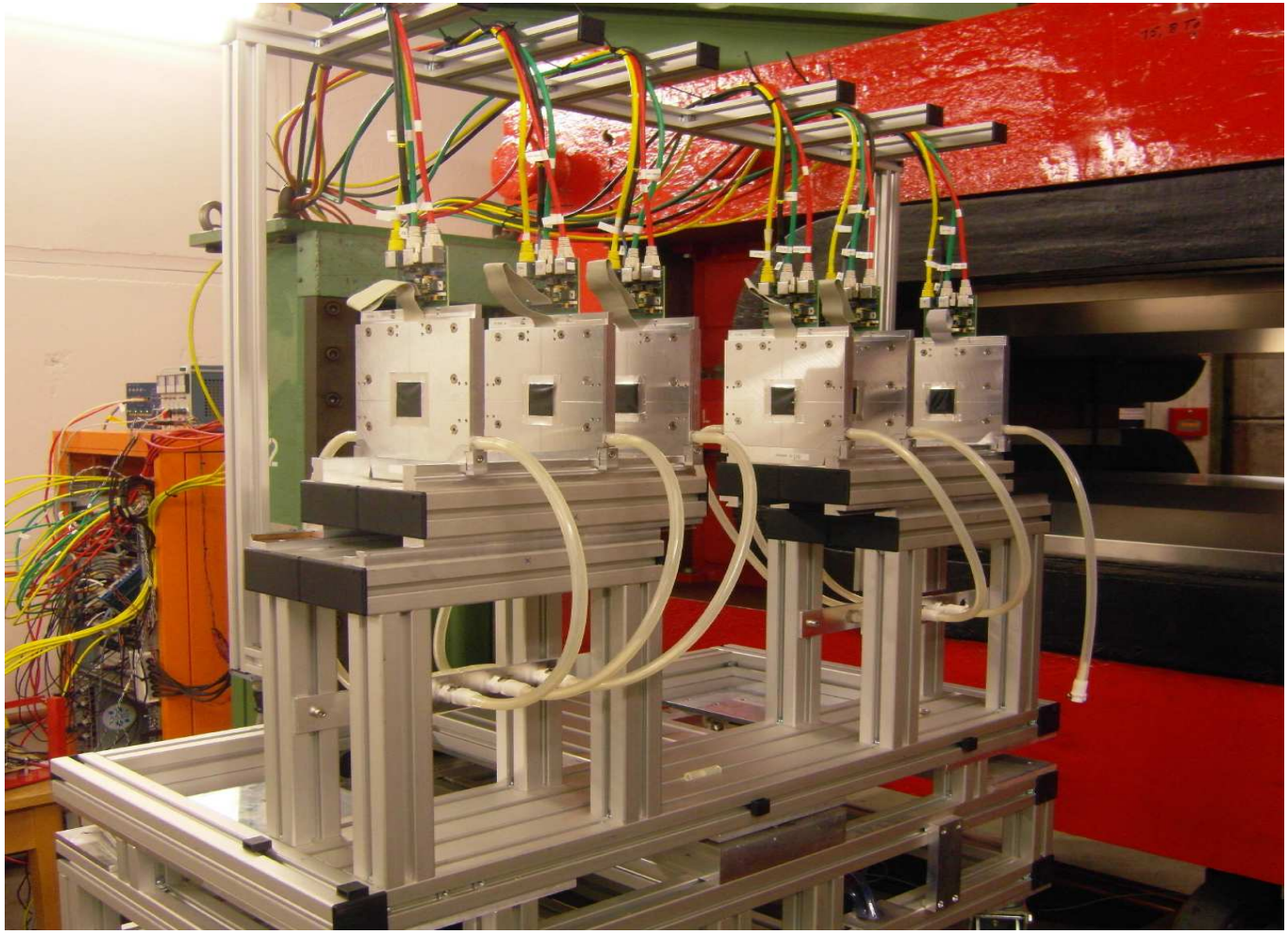
MIMOSA-26: Established Architecture

- Rolling shutter architecture applied to 1st generation of CPS applications



Widespread Application of MIMOSA-26

- EUDET Beam Telescope : adapted to sub-GeV electron beams

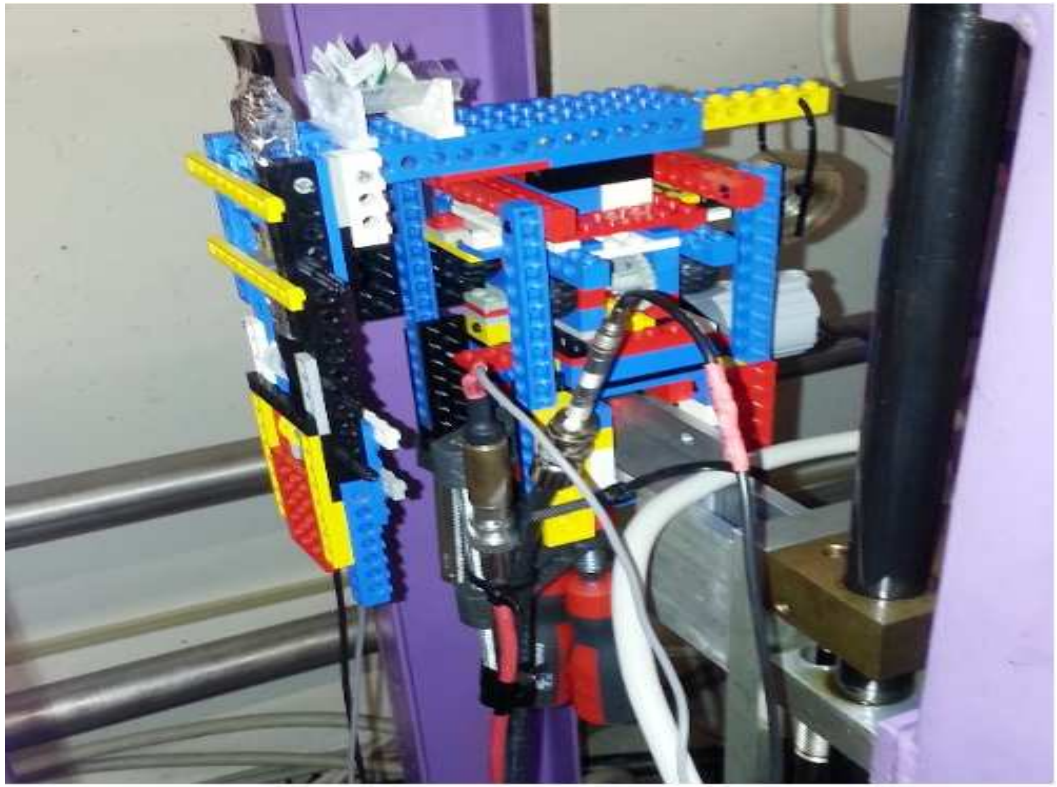


- about 10 copies or similar devices used at DESY, CERN, SLAC, TRIUMF, ...

Other Applications of MIMOSA-26

- **Ex: Vertex Detector of NA61/SHINE Heavy Ion Experiment at CERN**
  (http://ph-news.web.cern.ch/content/first-pb-beam-na61shine)

  - MIMOSA-26 sensors being exposed to radiation tolerance tests with $1.2 \cdot 10^{10}$ Pb ions/cm^2 on H2 beam at CERN

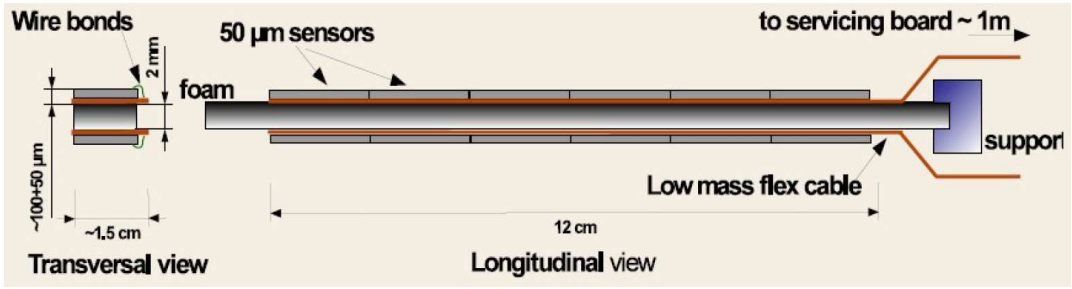


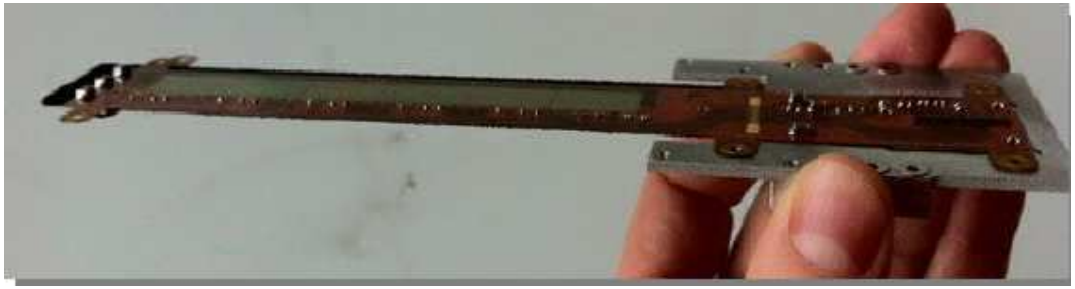
- Several other applications: FIRST/GSI, NA-63/CERN, CBM-MVD-demo./FAIR, hadrontherapy, X-Ray imager demo., etc.

PLUME Double-Sided Ladder Based on 12 MIMOSA-26

- ILC vertex detector triggered R&D on ultra-light double-sided ladder with $\lesssim$ 0.3% X0 material budget

- **PLUME ladder :**
  2x6 MIMOSA-26 (50 μm)





PLUME Double-Sided Ladder Based on 12 MIMOSA-26

- ILC vertex detector triggered R&D on ultra-light double-sided ladder with $\lesssim$ 0.3% X0 material budget

- **PLUME ladder : 2x6 MIMOSA-26 (50 μm)**

- Most recent application :

  BEAST-II at SuperKEKb with

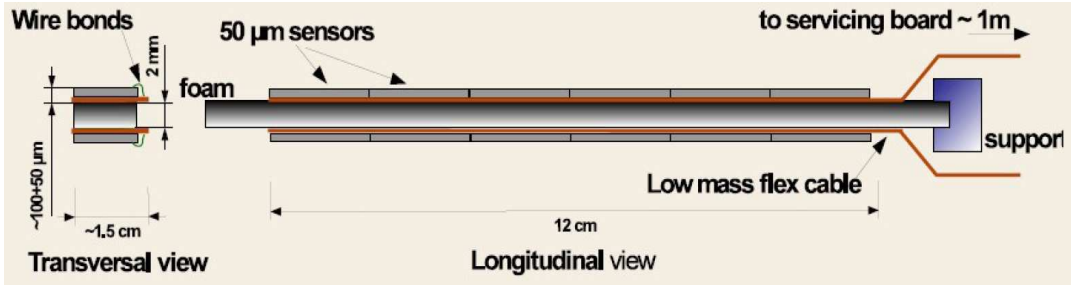
  2 PLUME ladders (0.4% X0) equipping

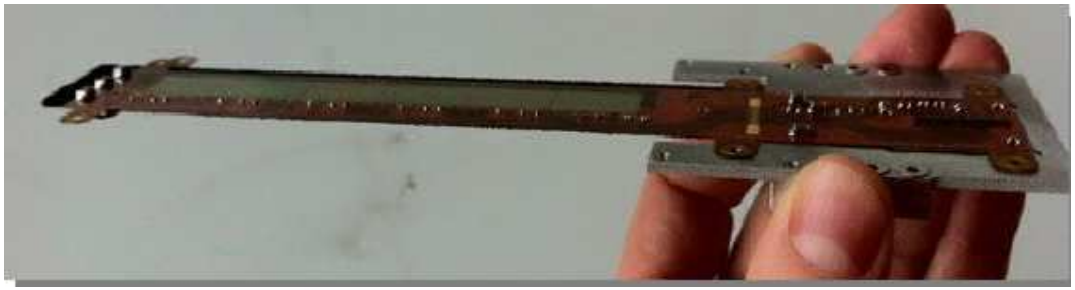
  IP environnement to characterise

  beam related background using

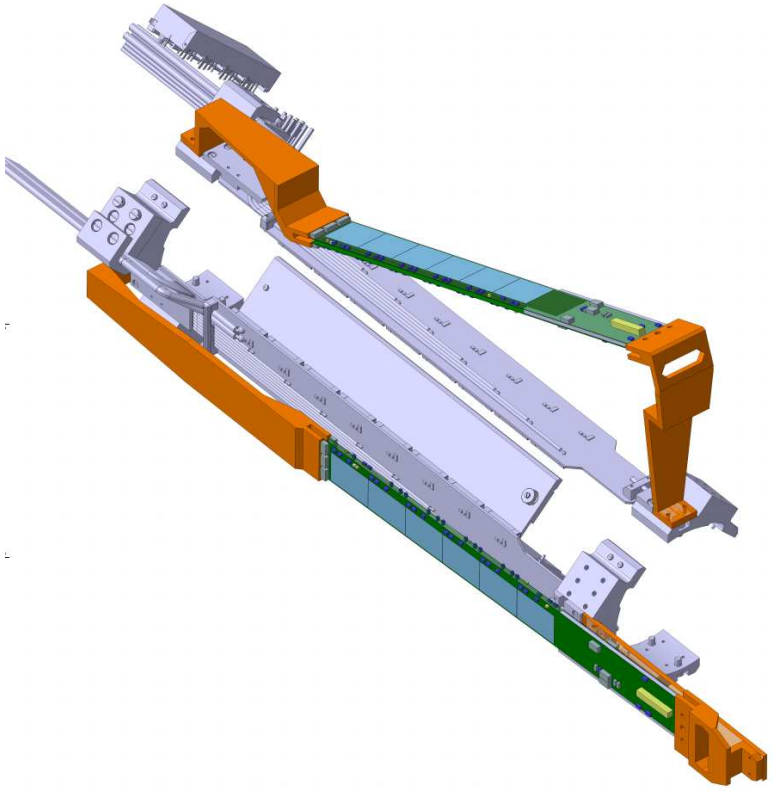
  mini-vectors $\Rightarrow$ rate & direction

- **Data taking starting in 2017**

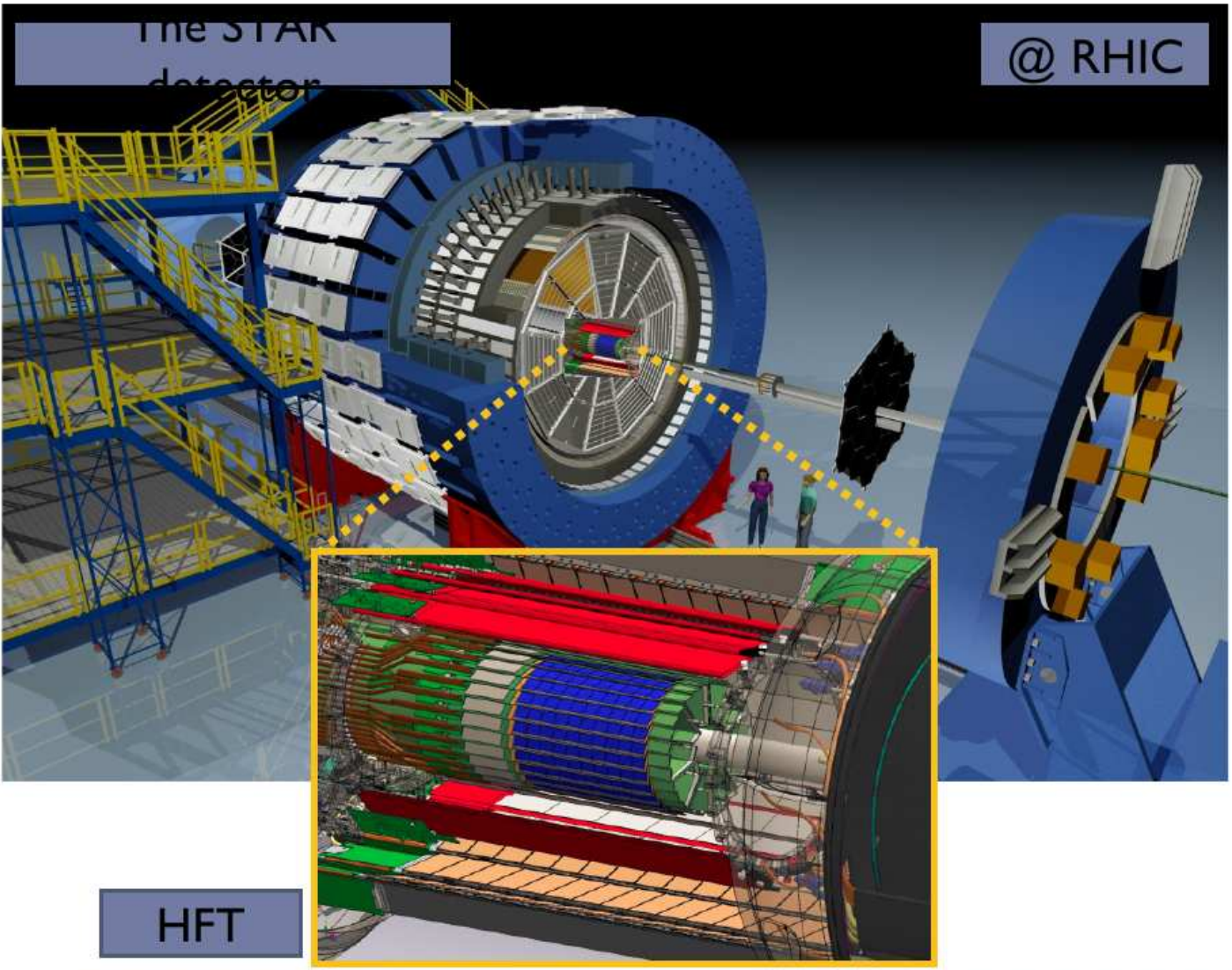


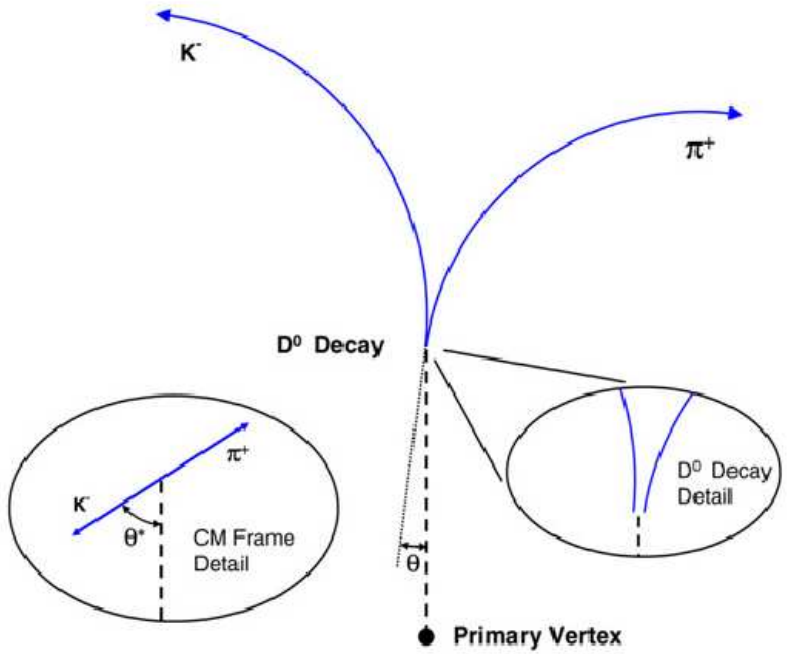


$\Rightarrow$



State-of-the-Art : STAR-PXL





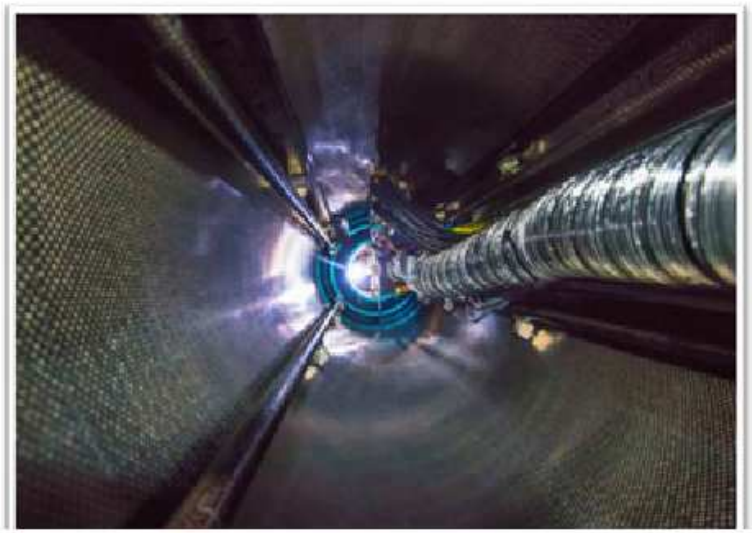
Method: Resolve displaced vertices (~120 μm)

200 GeV Au+Au collisions @ RHIC

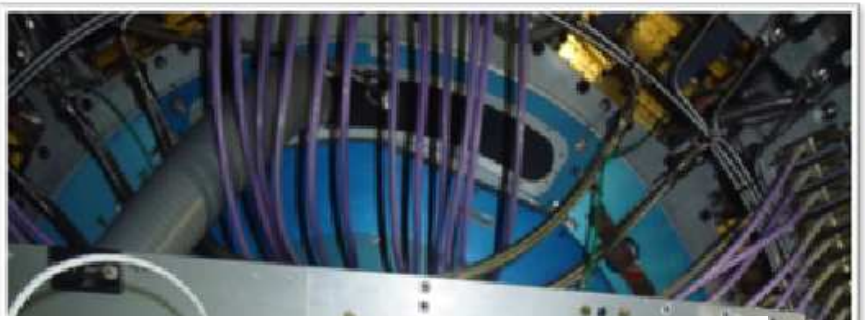
- $dN_{ch}/d\eta \sim 700$ in central events

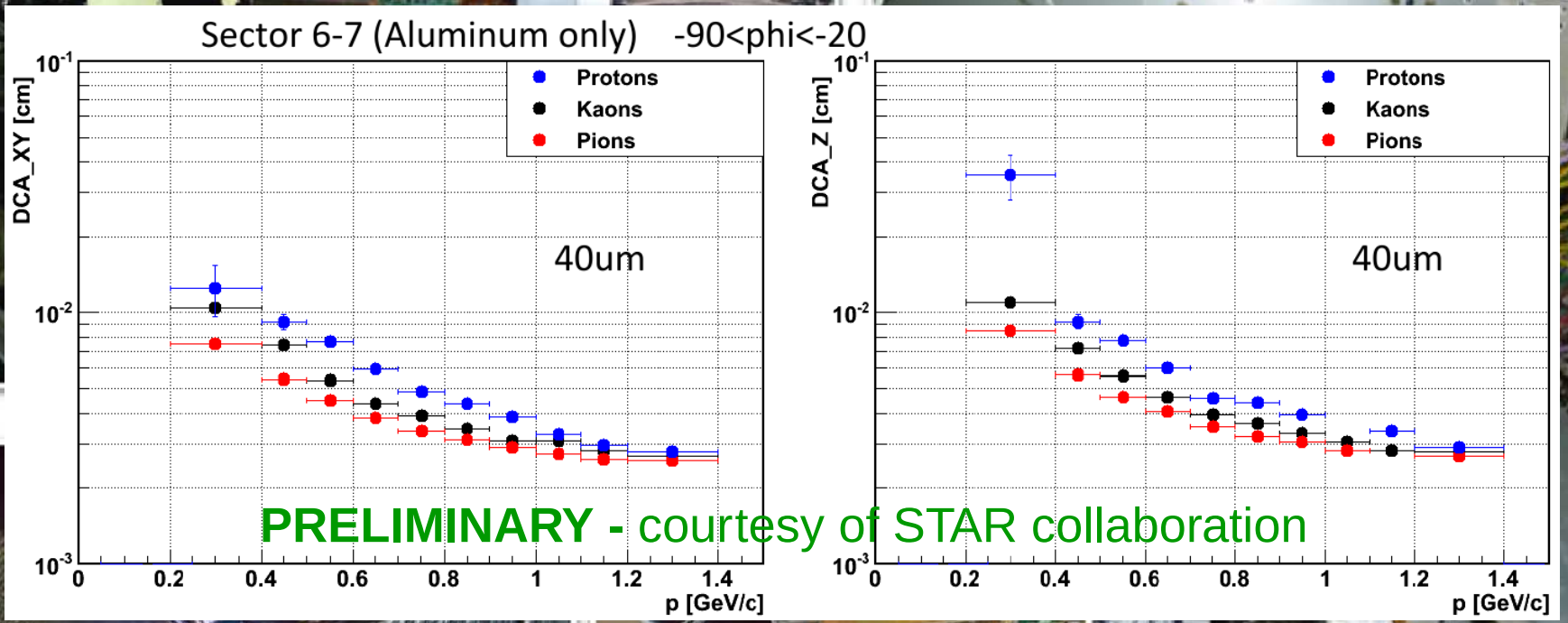
STAR

State-of-the-Art : STAR-PXL

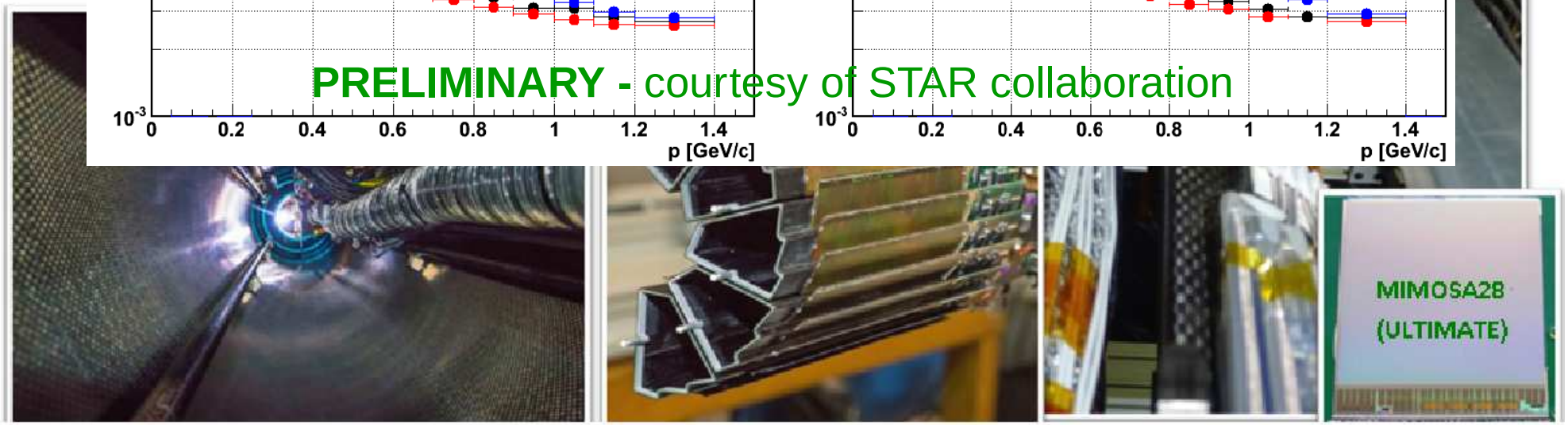


State-of-the-Art : STAR-PXL



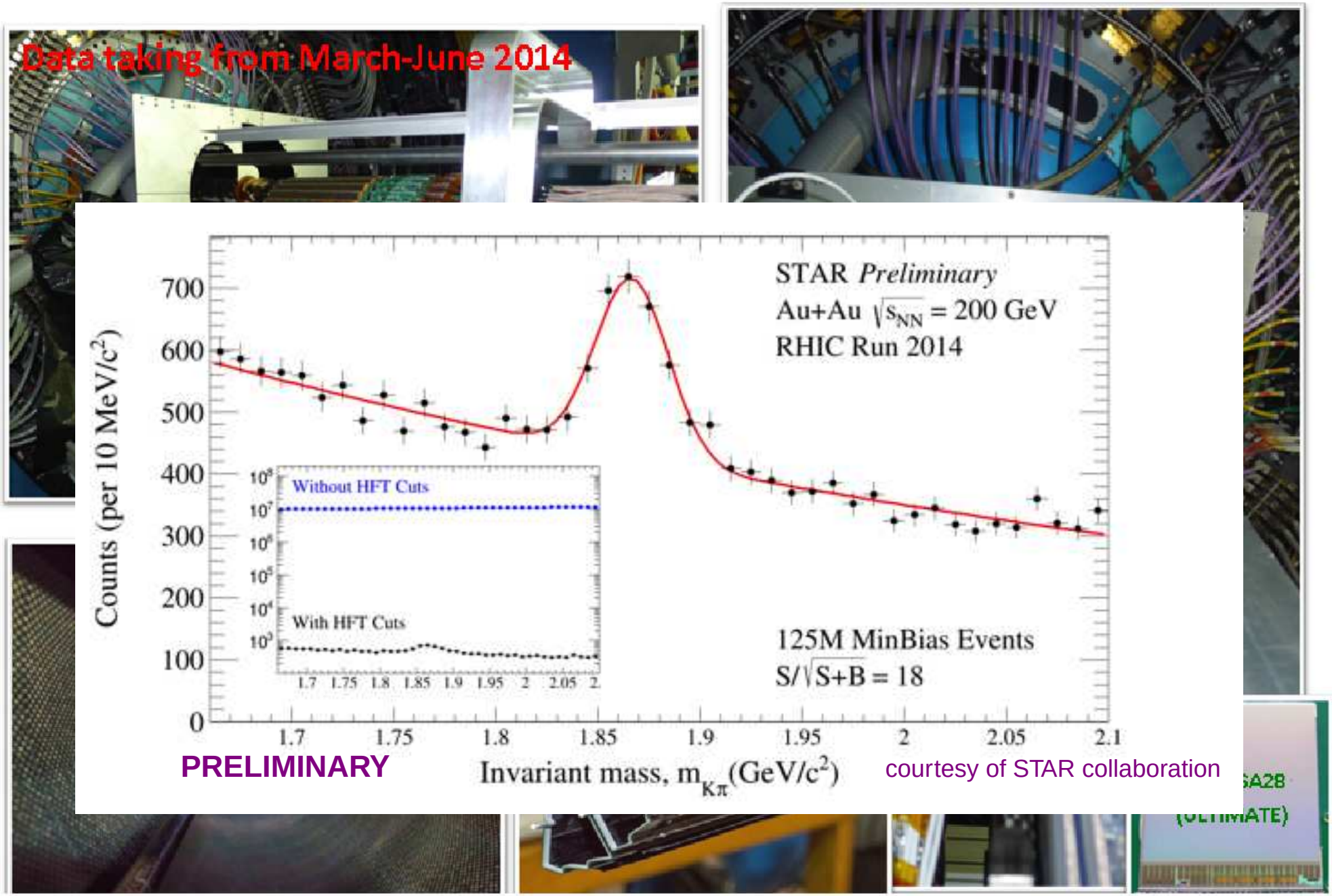


PRELIMINARY - courtesy of STAR collaboration



Validation of CPS for HEP (25/09/14 : DoE final approval, based on vertexing performance assessment)

State-of-the-Art : STAR-PXL

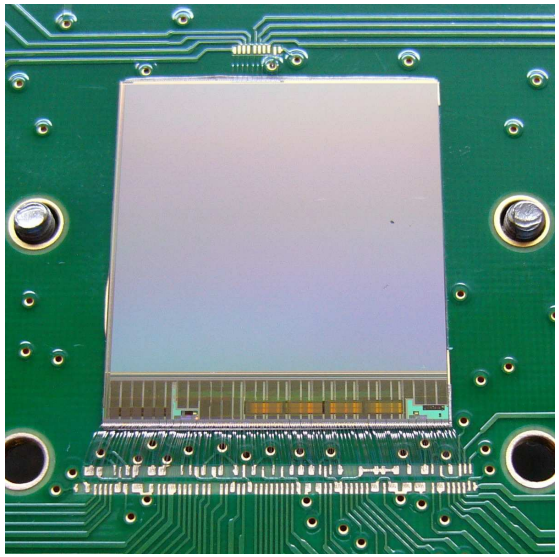


Validation of CPS for HEP (25/09/14 : DoE final approval, based on vertexing performance assessment)

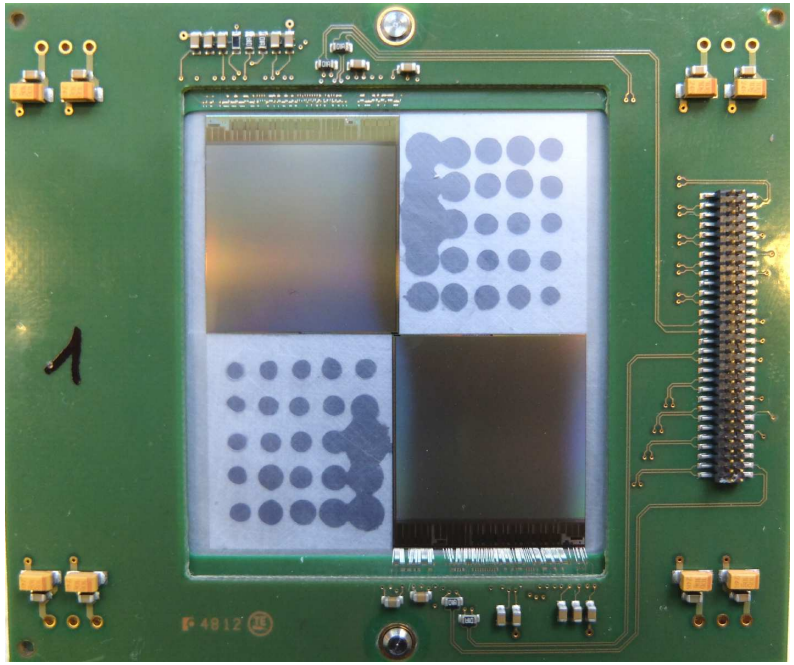
Applications of MIMOSA-28/ULTIMATE

- **Beam Telescope from hadrontherapy (ex: GSI)**

- **Frascati Beam Telescope (0.05 % X0/plane)**
  - adapted to 450 MeV electrons ⇒
  - becoming part of facility equipment



- **AIDA (EU-FP7)**
  - Single Arm Large Area Telescope (SALAT)
  - 4 MIMOSA-28 sensors per plane ⇒
  - $\ll$ 0.1% X0 per plane



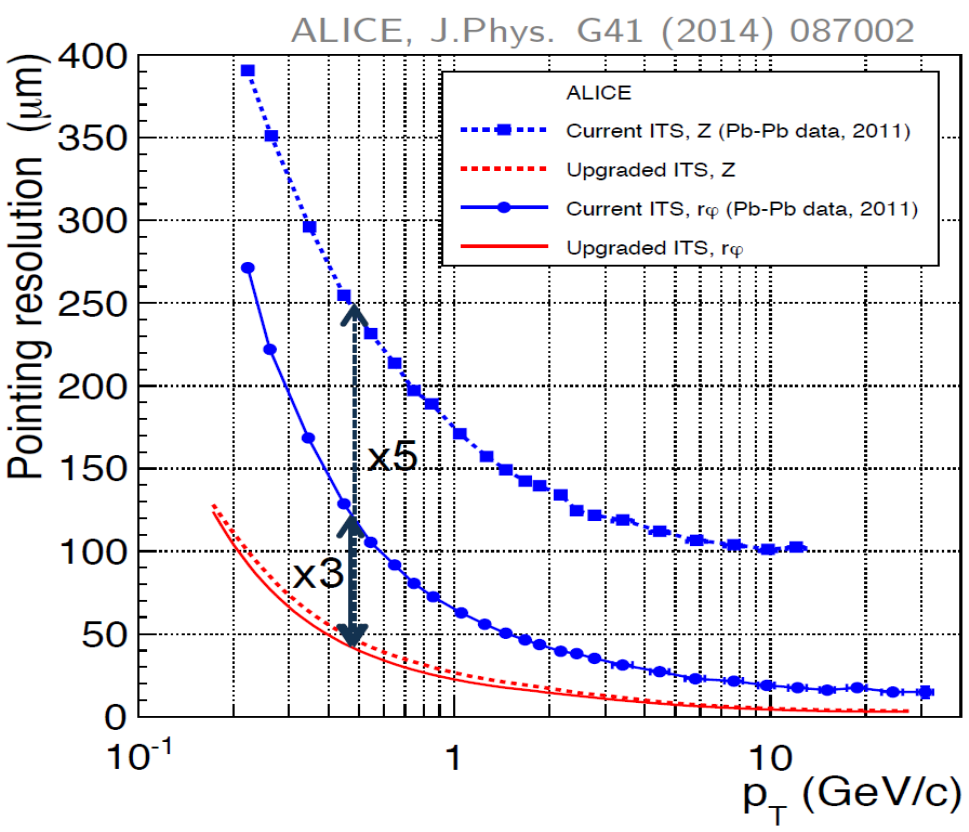
- **Prototype of an inner tracker**
  - reference requirements : BESIII upgrade
  - 3 layers (see LIU Quinyuan's talk)
  - 120 sensors thinned to 50 μm

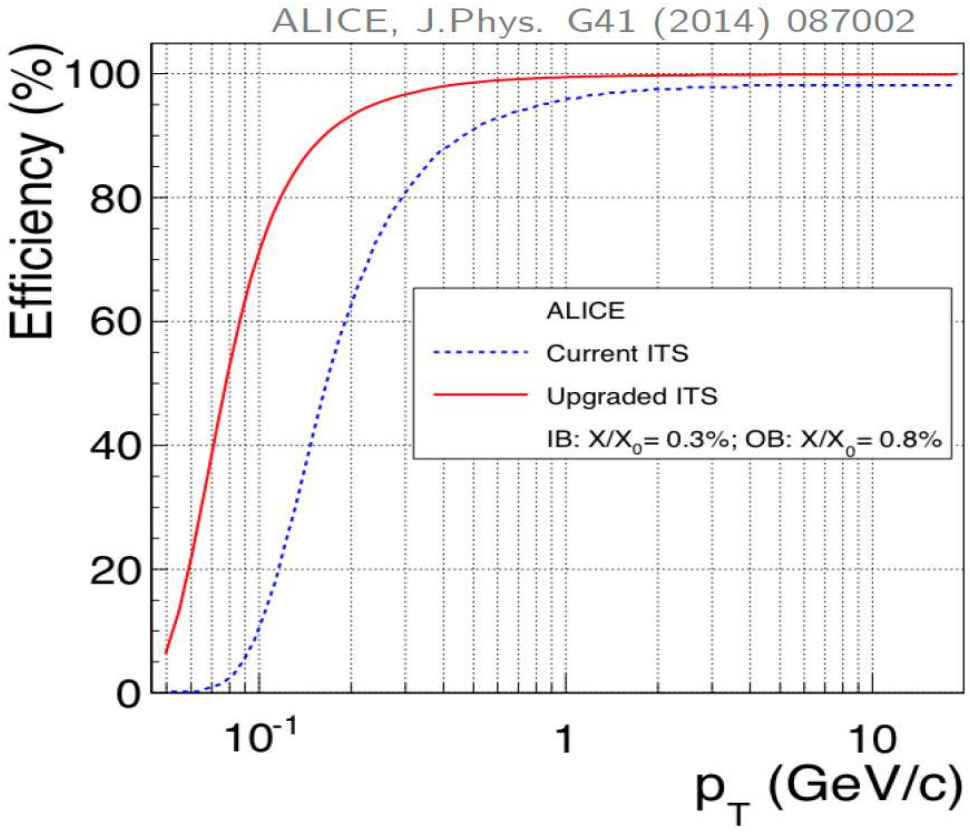
Next Step : Upgrade of ALICE-ITS

- **ALICE Inner Tracking System (ITS) foreseen to be replaced during LS2/LHC**

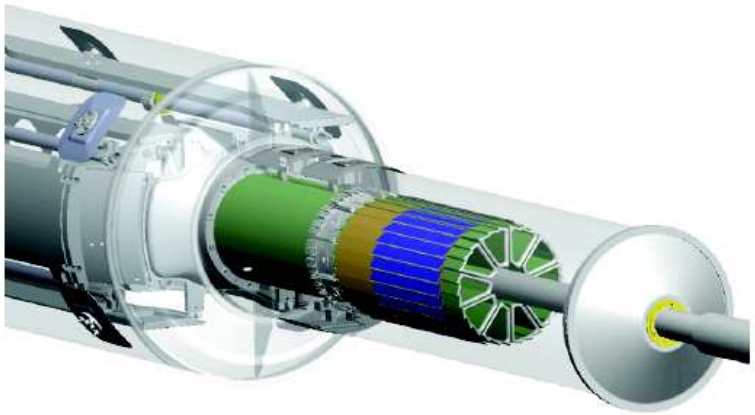
  ↪ higher luminosity (≡ collision rate), improved charm tagging (see talk of G. Martinez)

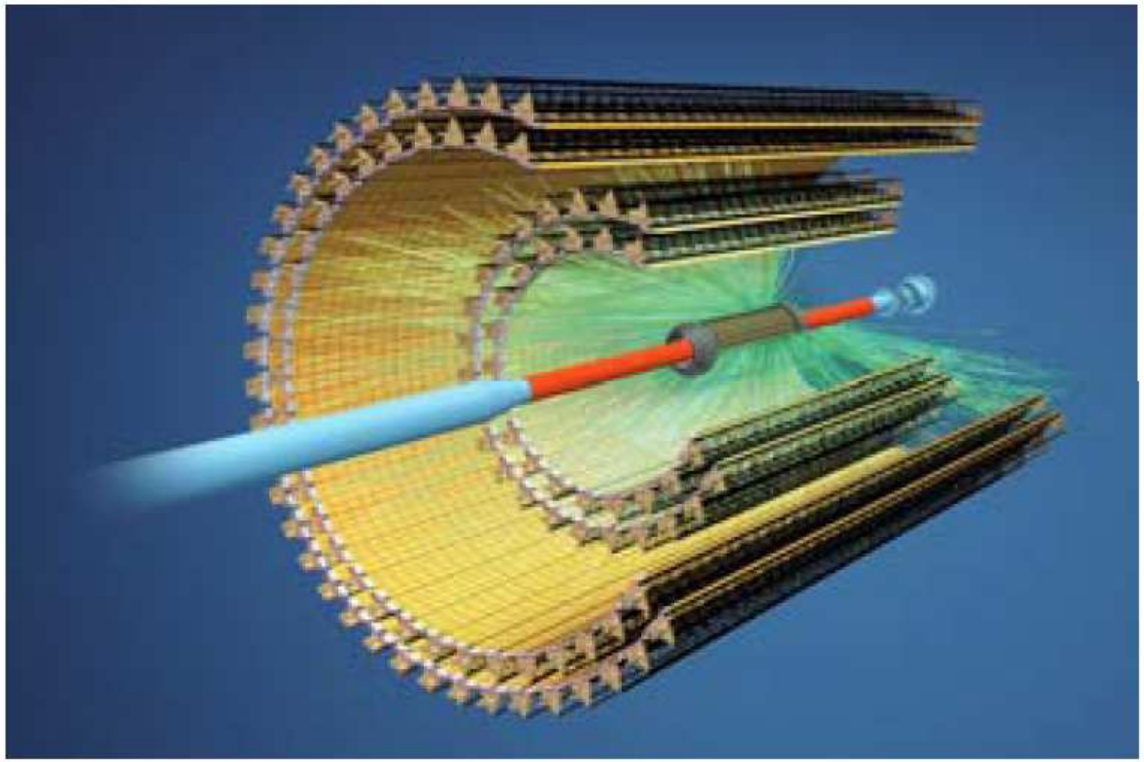
- **Expected improvement in pointing resolution and tracking efficiency**





From STAR/RHIC to ALICE/LHC



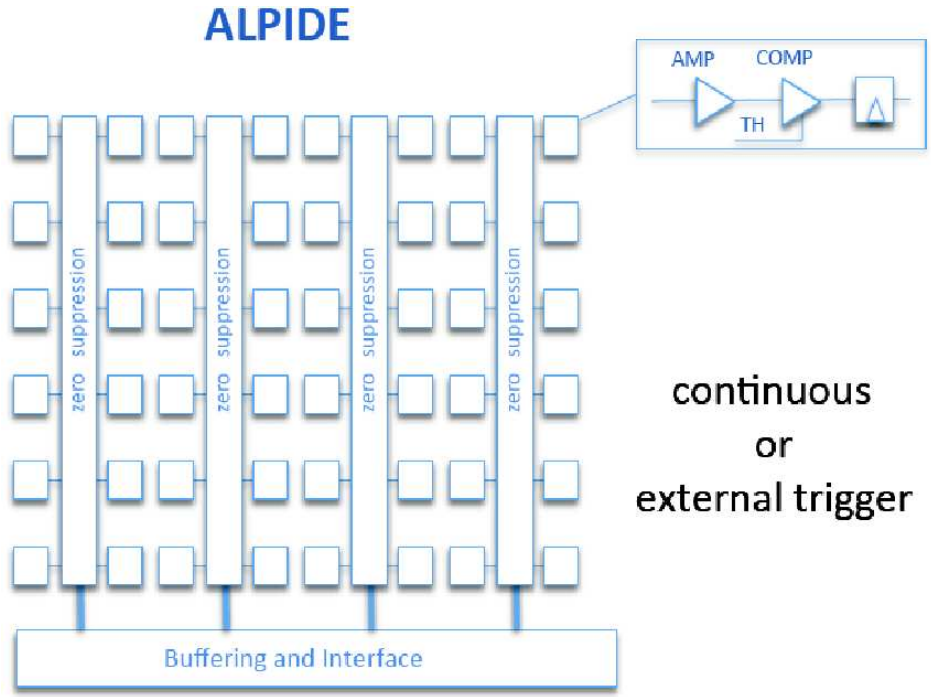


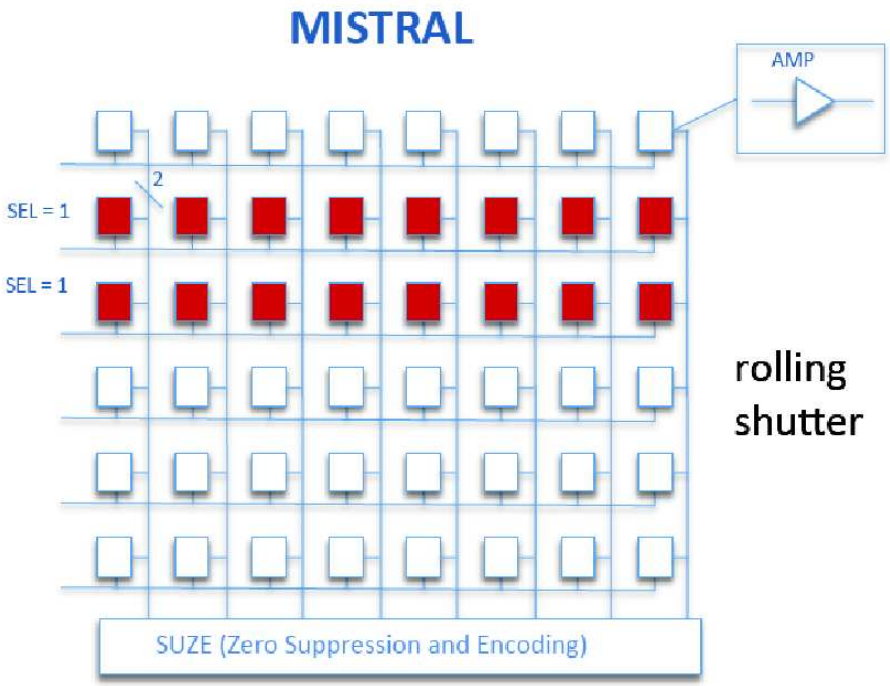
- CHALLENGES:
  - nearly 100 times larger sensitive area : 400 sensors (0.15 cm^2) $\longmapsto$ 25·10^3 sensors ($>$ 10 m^2)
  - $\sim$ 10 times faster read-out
  - somewhat higher radiation tolerance

$\Rrightarrow$ **investing a new CMOS fabrication process (imposed by requirements):**

AMS-0.35μm (twin-well) $\longmapsto$ Tower-0.18μm (quadruple-well)

ITS Pixel Sensor : Two Architectures





Pixel dimensions	**27μm x 29μm**
Event time resolution	**$< 10\mu s$**
Power consumption	**< 50mW/cm^2**
Insensitive area	**$\gtrsim$ 1mm x 30mm**
Nb(T) inside pixel	**~ 200**

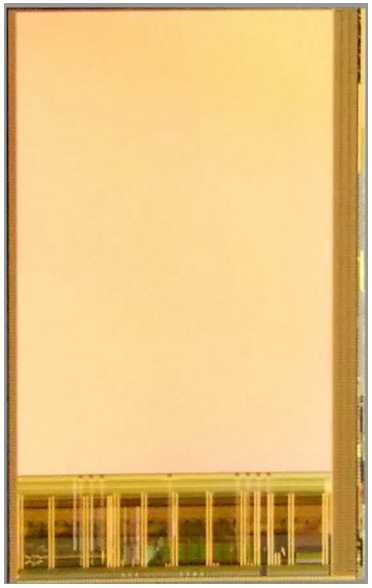
Pixel dimensions	**36μm x 65μm**
Event time resolution	**20μs**
Power consumption	**$\lesssim$ 90mW/cm^2**
Insensitive area	**1.5mm x 30mm**
Nb(T) inside pixel	**~ 15**

- **Both chips have identical dim. (15mm x 30 mm) as well as physical and electrical interfaces:**
  - ⁕ position of interface pads
  - ⁕ electrical signaling
  - ⁕ steering, read-out, ... protocoles

Main Features of the Final Prototypes

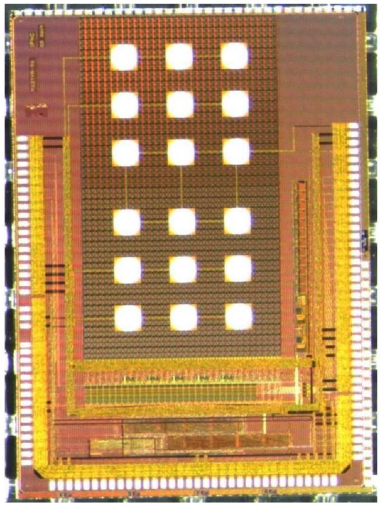
- **Full scale sensor building block :**
  - complete (fast) read-out chain $\simeq$ ULTIMATE
  - pixel area ($\sim$ 1 cm^2) $\simeq$ area of final building block
  - same nb of pixels (160,ooo) than complete final tracker chip
  - fabricated with 18 μm thick high-resistivity EPI
  - BUT : pixels are small (22 x 32.5 μm^2) and sparsification circuitry is oversized (power !)
  - **Tested at DESY (few GeV e$^-$) in June'15 and CERN-SPS (120 GeV "pions") in Oct. '15**

FSBB-M0bis



- **Large-pixel prototype without sparsification :**
  - 2 slightly different large pixels :
    - 36.0 μm x 62.5 μm
    - 39.0 μm x 50.8 μm
  - pads over pixels (3 ML used for in-pixel circuitry)
  - fabricated with 18 μm thick high-resistivity EPI
  - BUT : only $\lesssim$ 10 mm^2, 4,ooo pixels, no sparsification
  - **Tested in Frascati (450 MeV e$^-$) in March & May'15**

MIMOSA-22THRb



Detection Performances of the Final Prototypes

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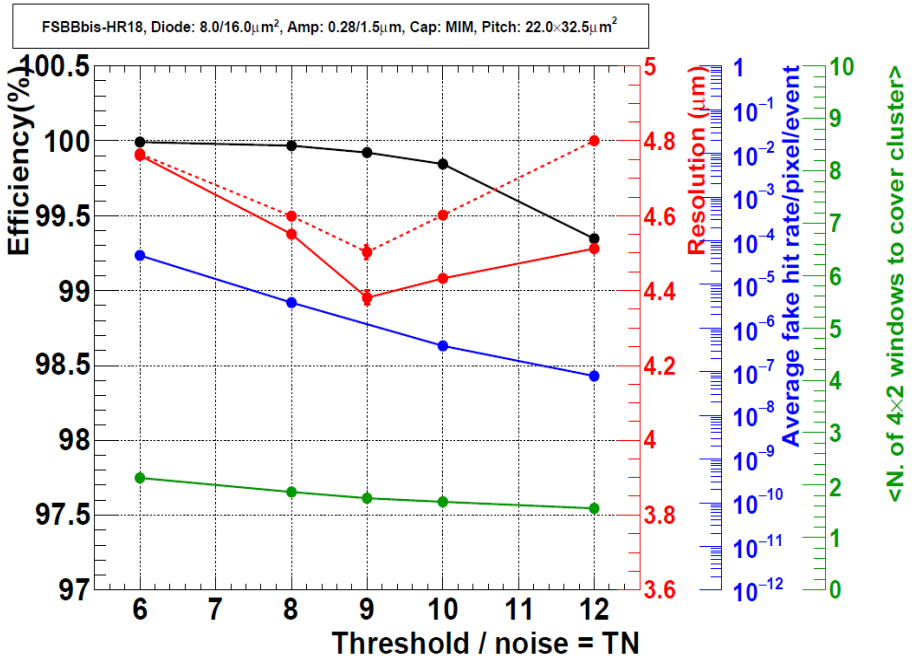

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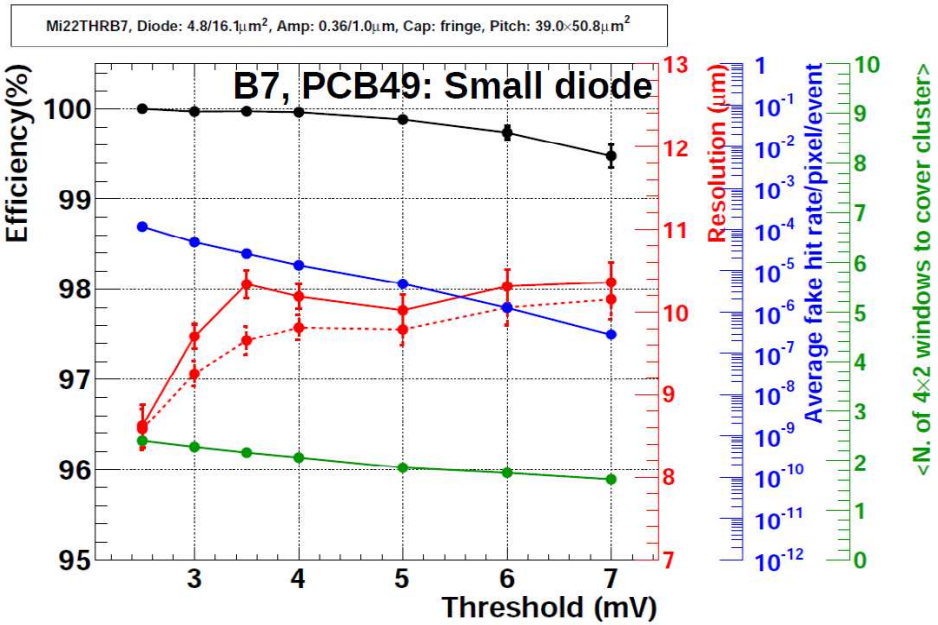
  - BUT : only $\lesssim$ 10 mm^2, 4,ooo pixels, no sparsification
  - **Tested in Frascati (450 MeV e$^-$) in March & May'15**



Vertex Detector at CEPC

- **Comparison between CEPC (240 GeV) and ILC (500 GeV) requirements**
  - Physics performance driven requirements equivalent for both machines
  - Running conditions driven requirements may be similar (design dependent, still under study)

    ↪ both machines induce beam related background in the detector

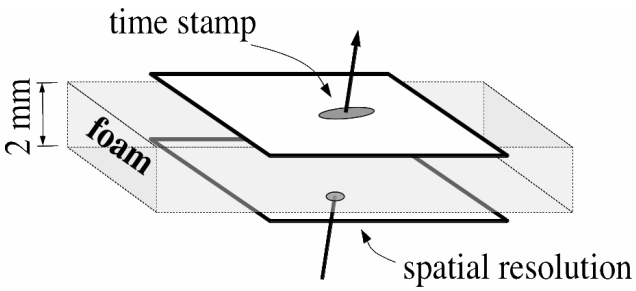
    dominating physics signal by several ordres of magnitude

- **Some typical requirements:**

Detector	σ_{sp}	t_{int}	**Dose** (30°C)	**Fluence** (30°C)
ILD-VXD/In	$< 3\ \mu m$	50/10 μs	$<$ 100 kRad	$\lesssim 10^{11}$ n$_{eq}$/cm^2
ILD-VXD/Out	$\lesssim 4\ \mu m$	100 μs	$<$ 10 kRad	$\lesssim 10^{10}$ n$_{eq}$/cm^2

- **Special attention: power $<$ 50 mW/cm^2 (power cycling required ?)**

Validation of CPS for ILD Vertex Detector



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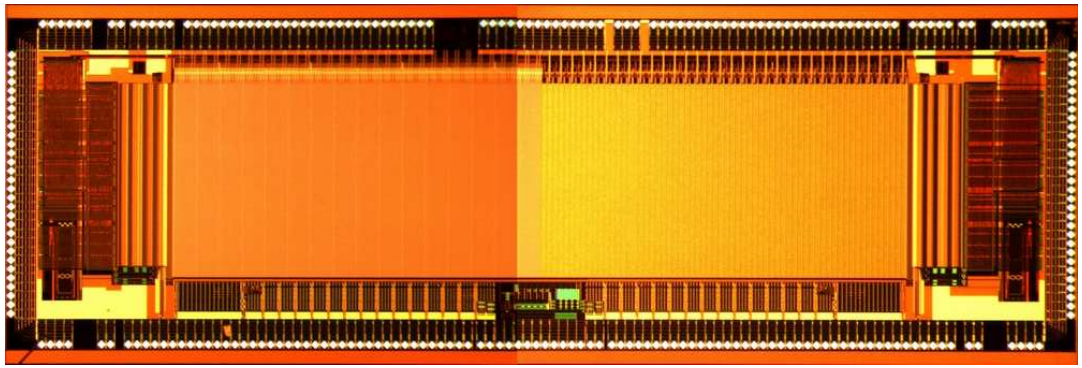
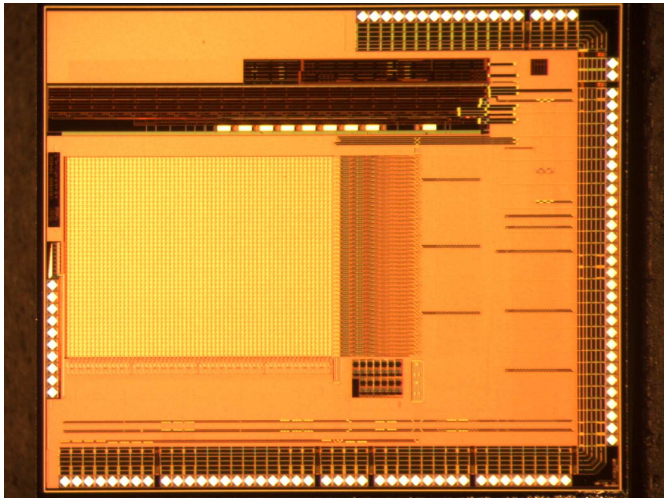
- **Medium-size proto. of each sensor fab. in AMS-0.35μm process (2012)**





- ILD-VXD/In: accurate / swift
- ILD-VXD/Out: power saving

$\Rightarrow$ **All measured performances comply with requirements**

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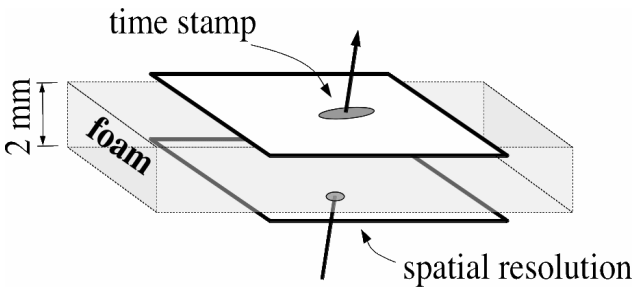

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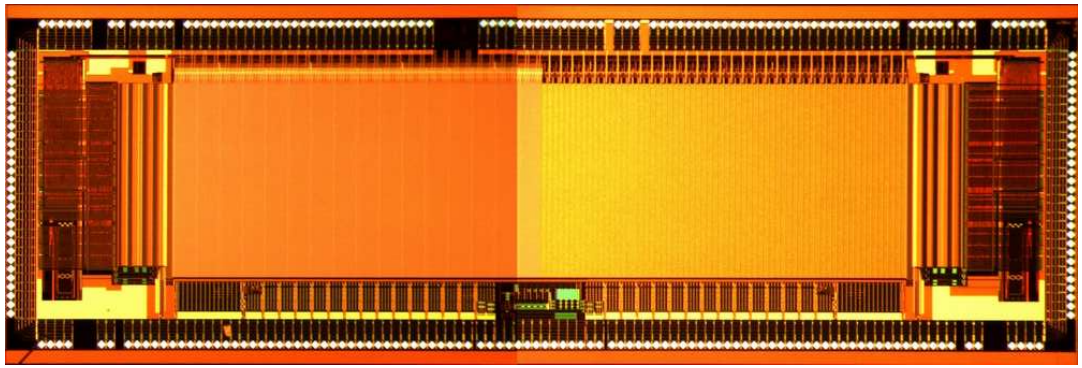

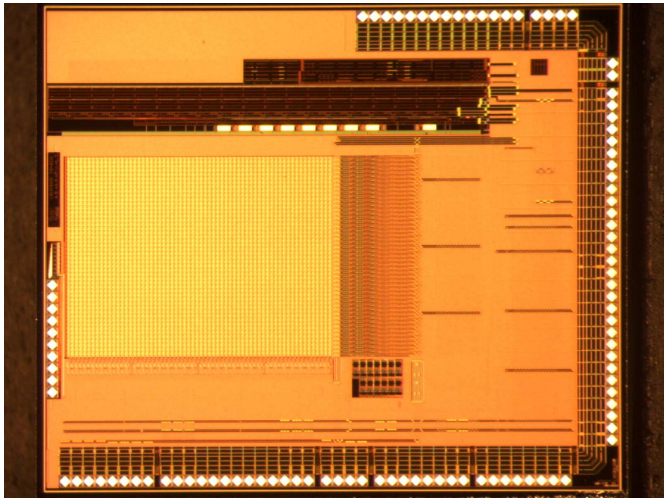

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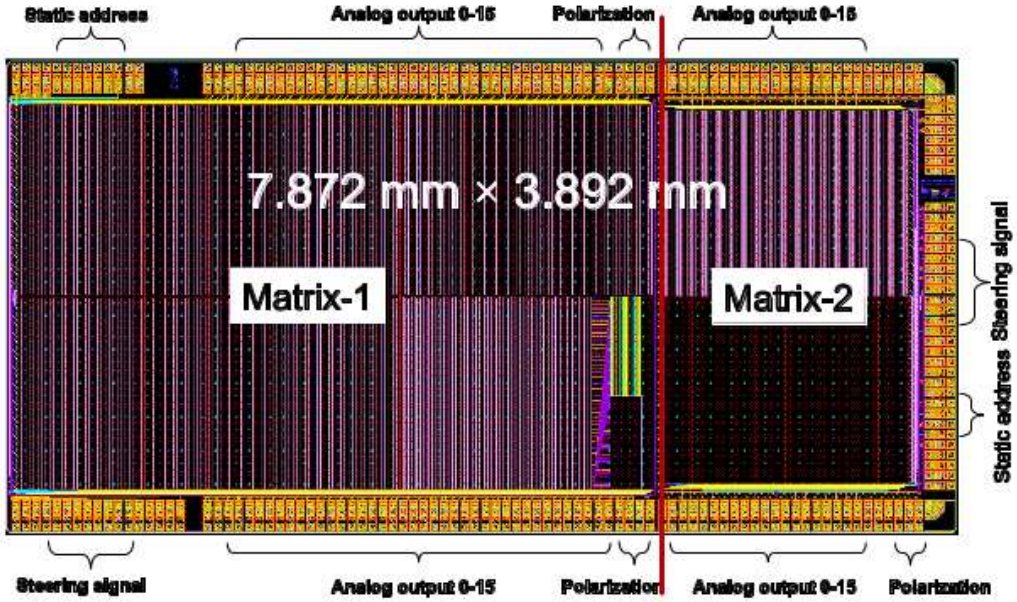
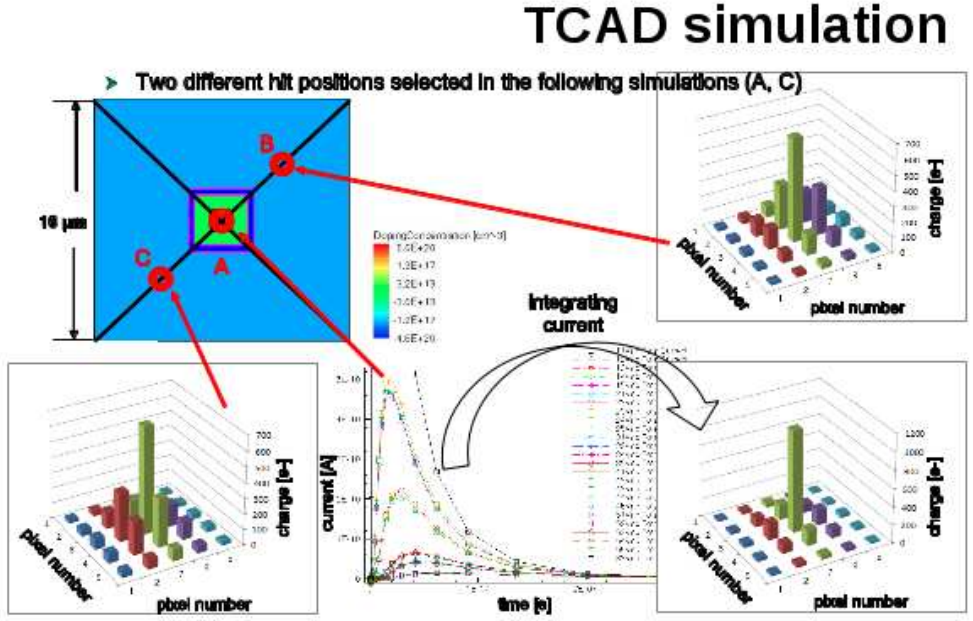
- **BUT requirements provide little safety margin (lumi, BG), no track seeding, ...**

CPS for CEPC

- CMOS PIXEL SENSORS RETAINED FOR R&D WITH INITIAL FUNDING FROM IHEP :
  - 1st joint MPW submission with IPHC in Novembre 2015 ⟼ expected back in April'16
  - Goal: understand charge collection performances vs diode geometry & epitaxial-layer properties





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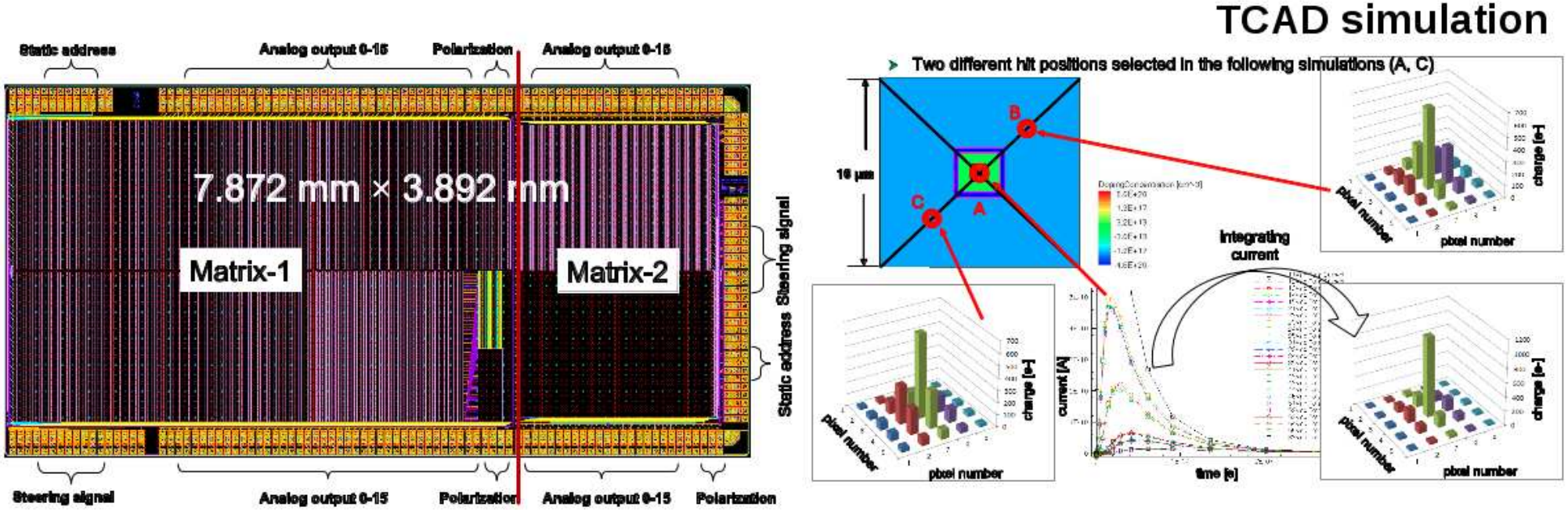
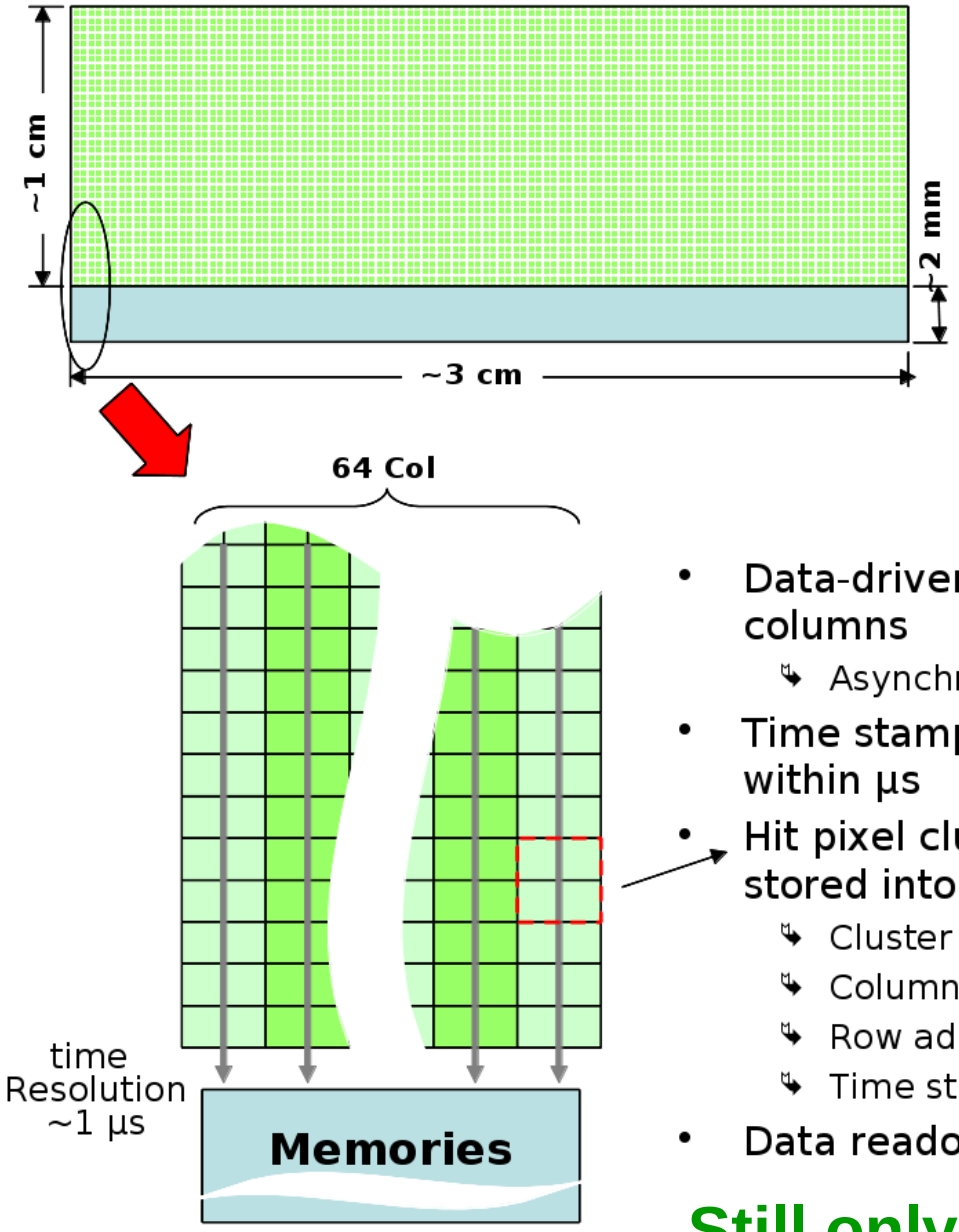


  - Funding request sent to MOST for next steps
  - **Collaboration of 4 groups from IHEP, Shandong Univ., Wuhan and IPHC**

- ALSO: EXPLORING THE TECHNOLOGY POTENTIAL FOR TRACKING SUB-SYSTEMS
  - large pixels $\longmapsto$ 10 μm resolution
  - $\ll$ 1% X_0 per layer

Noria Based CPS Architecture for ILC&CEPC Double&Single Bunch Id.



- Pixel dimensions ~20x20 µm²
  - σ_{sp} ~ 3 µm
- In-pixel amplification-shaping
  - integration time < 1 µs
- In-pixel digitisation
- Organised in N sub-matrices of 64 x 512 pixels

- Data-driven pixel readout in every pair of columns
  - Asynchroneous readout
- Time stamp at the bottom of pixel array within µs
- Hit pixel clusters of each column pair are stored into memories (possibly after cluster selection)
  - Cluster format 2x2 pixels
  - Column address
  - Row address
  - Time stamp (structure)
- Data readout in a few ms after end of train

Still only a concept, not yet a design

SUMMARY - CONCLUSION

- **CPS tend to comply with an increasing range of applications privileging highly granular & thin (low power) pixel devices :**

  $\Rightarrow$ STAR-PXL, CBM-MVD1, ILD-VXD(500), ..., ALICE-ITS, ILD-VXD(1000)

  (also attractive for large areas $\rightarrowtail$ cost, power)

  $\Rightarrow$ Architectures developed in AMS-0.35 μm CMOS process comply with present requirements of an ILC vertex detector (not including seed tracking)

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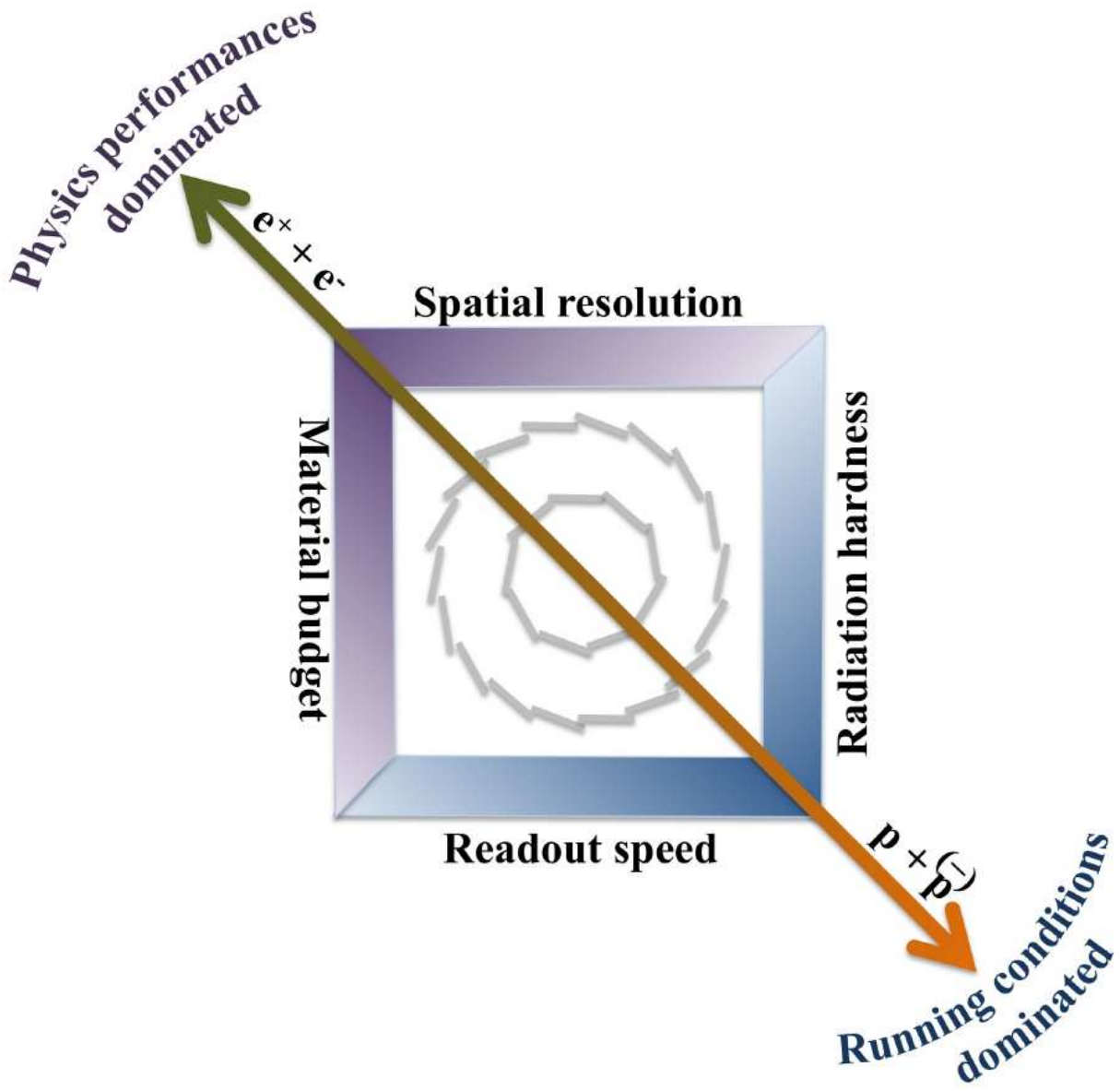
- Numerous spin-offs expected: imaging (single photon counting), cancer therapy (beam monitor, on-line imager), ..., large scale soldering inspection, ...

Motivation for High Precision CMOS Sensors



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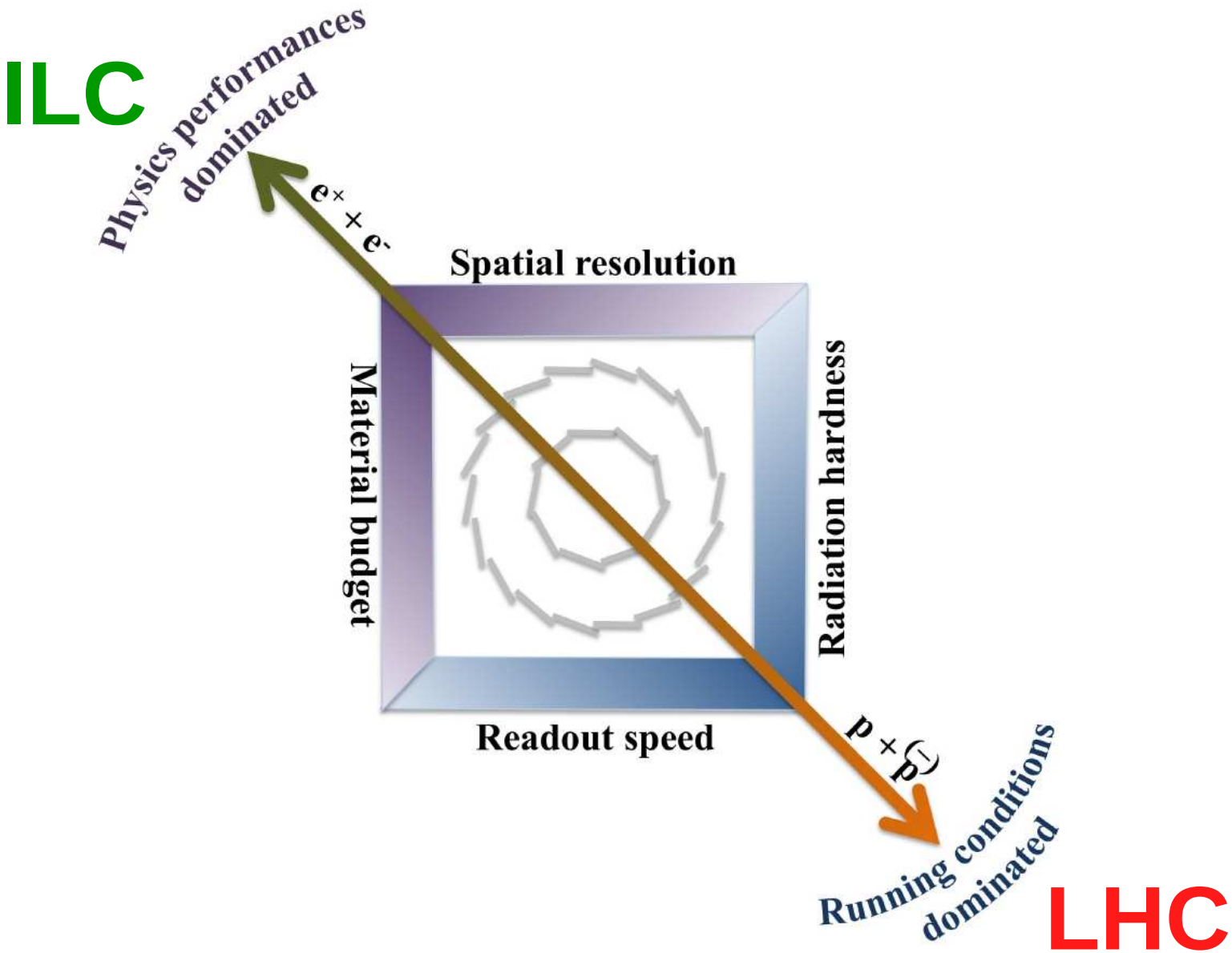

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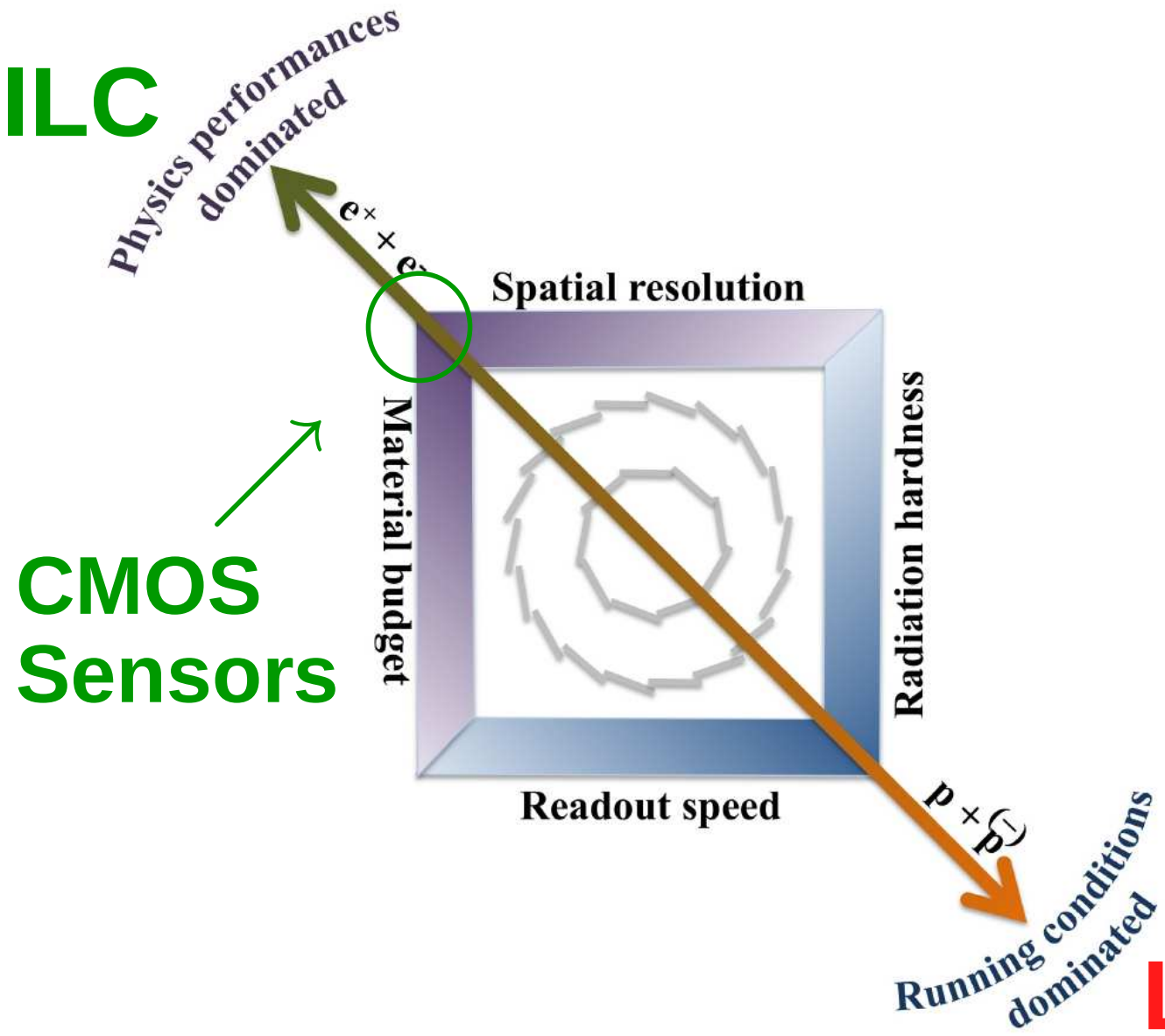

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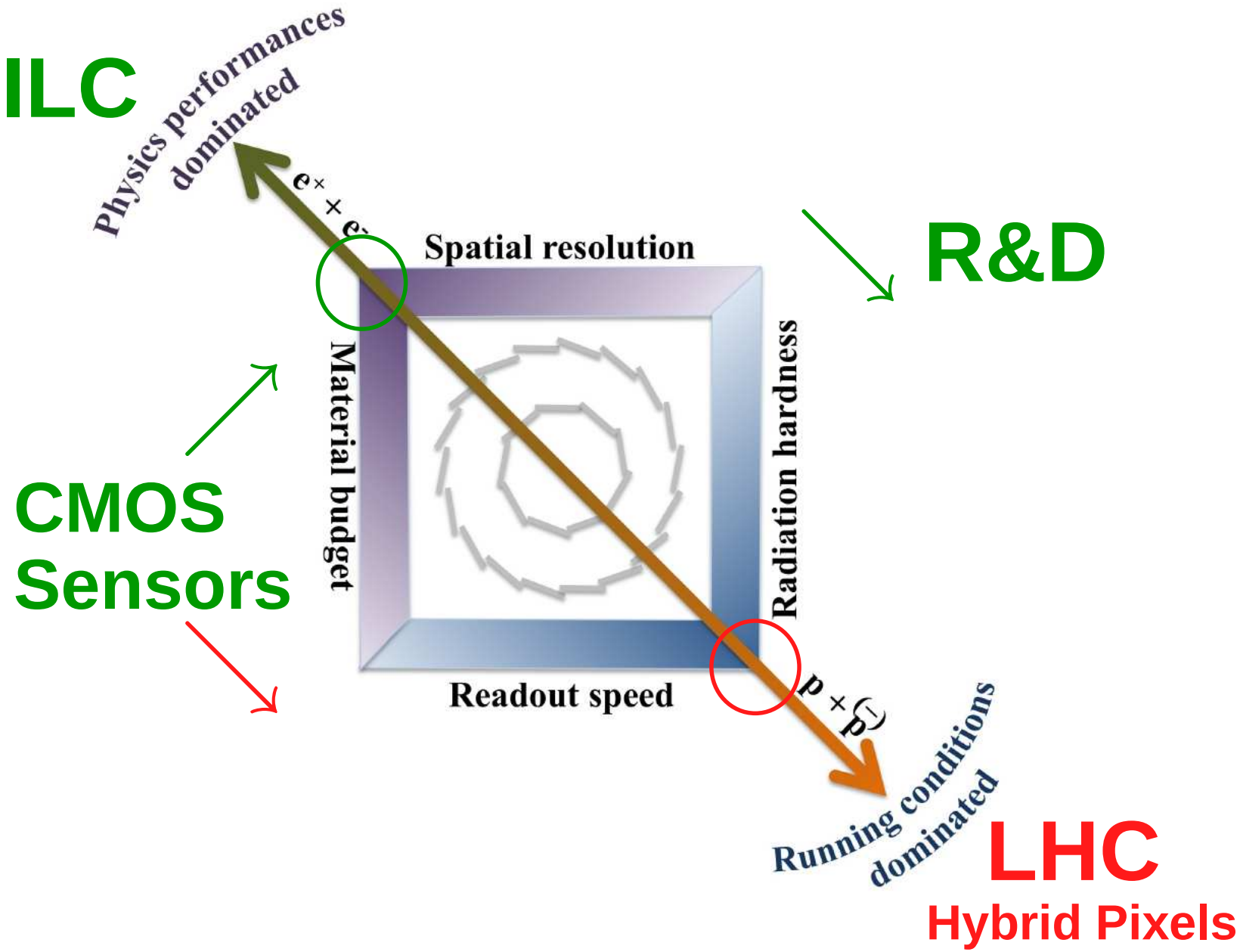


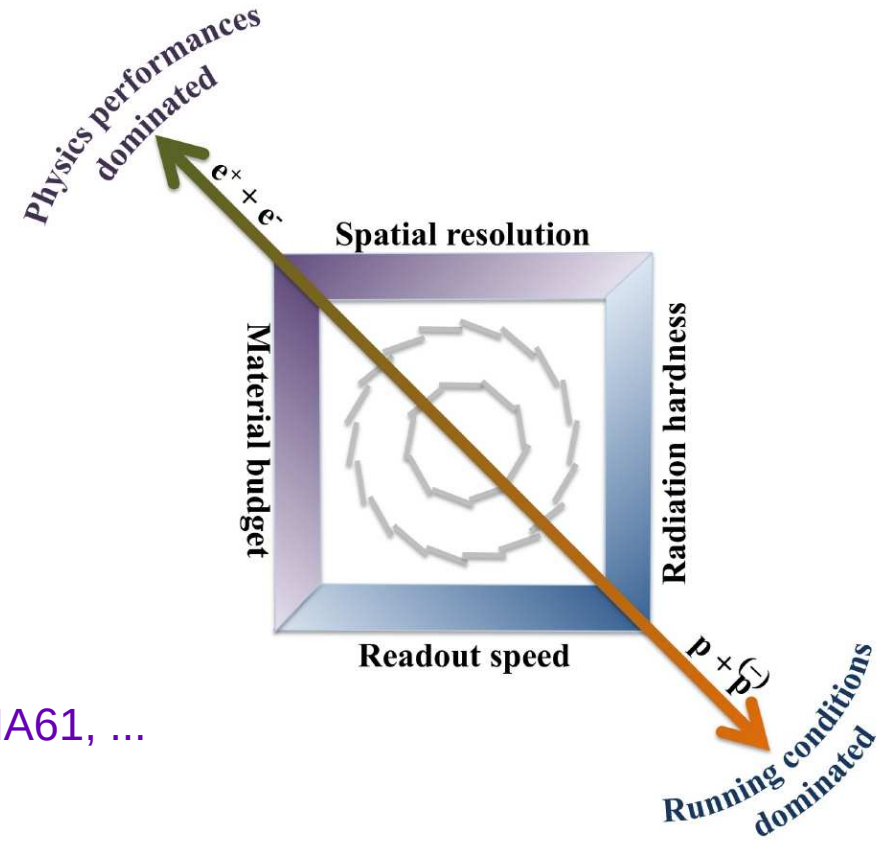
Motivation for Developing CMOS Sensors

Quadrature of the Vertex Detector

- **CPS development triggered by need of**
  very high granularity & low material budget

- **Applications exhibit much milder running conditions than pp/LHC**

  ⇒ **Relaxed speed & radiation tolerance specifications**

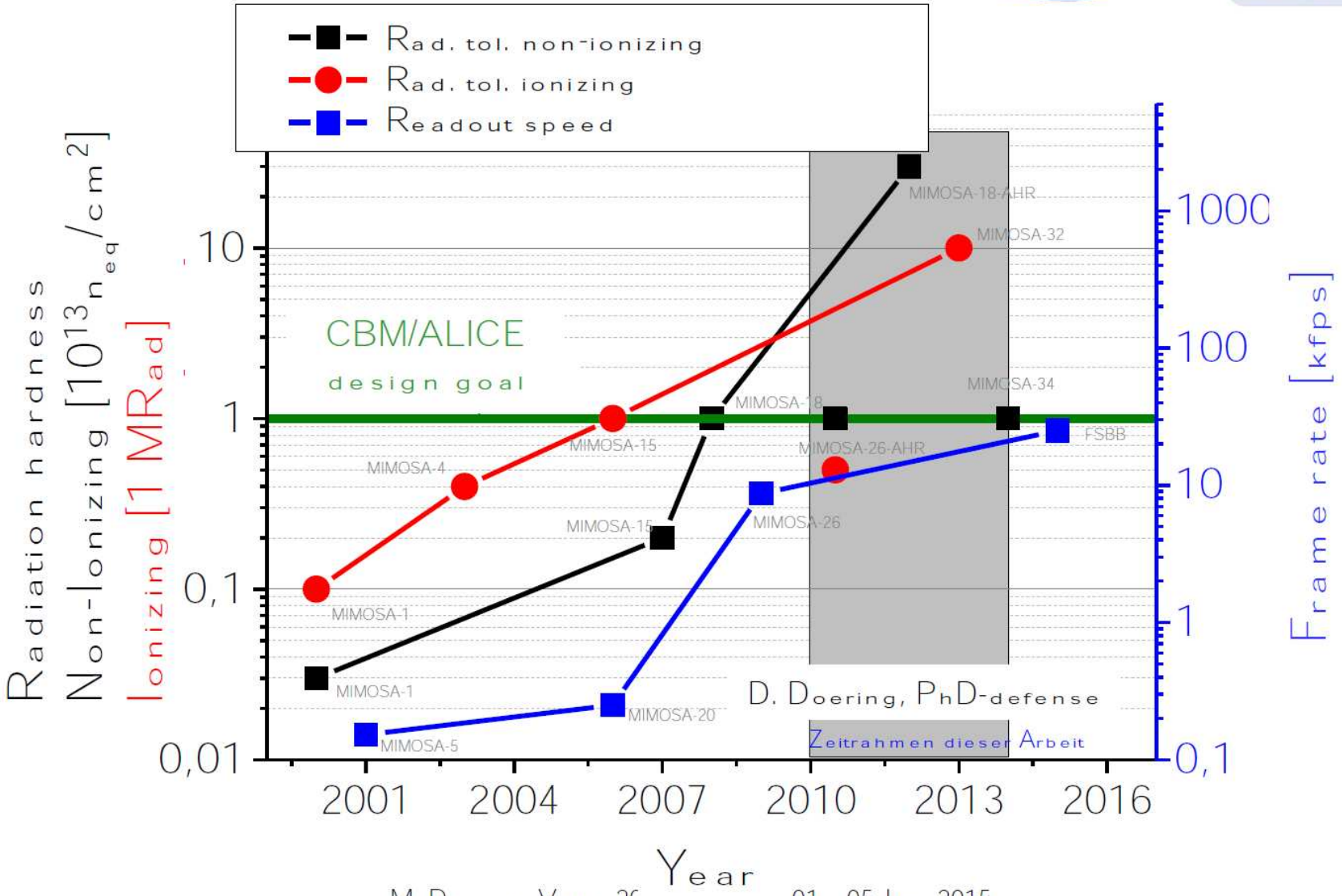


- **Increasing panel of existing, foreseen or potential application domains :**
  - **Heavy Ion Collisions :** STAR-PXL, ALICE-ITS, CBM-MVD, NA61, ...
  - **e^+e^- collisions :** ILC, BES-3, ...
  - **Non-collider experiments :** FIRST, NA63, Mu3e, PANDA, ...
  - **High precision beam telescopes** adapted to medium/low energy electron beams :
    ↪ few μm resolution achievable on DUT with EUDET-BT (DESY), **BTF-BT (Frascati)**, ...

Radiation Tolerance

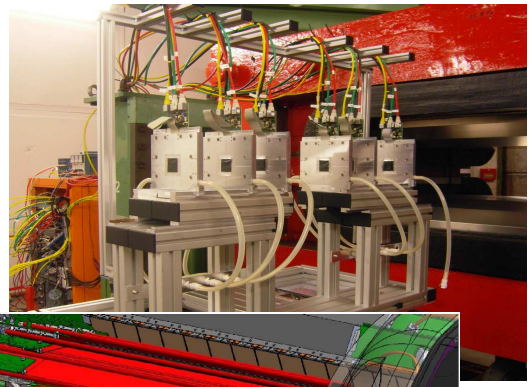
Material budget: 0.05% X_0

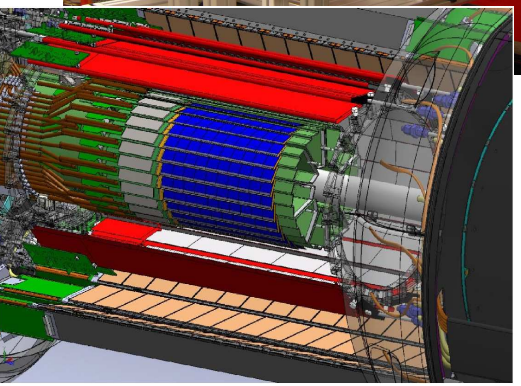
Spatial resolution: ~ 3-5 µm



Improving Speed and Radiation Tolerance

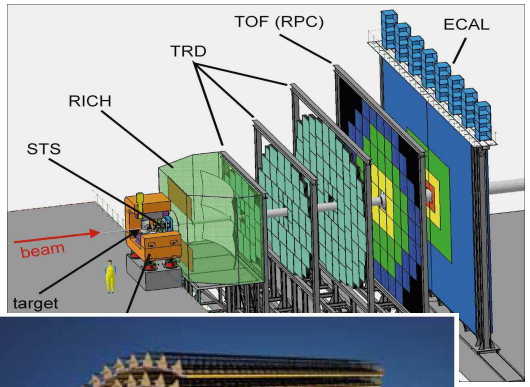
O(10^2) μs

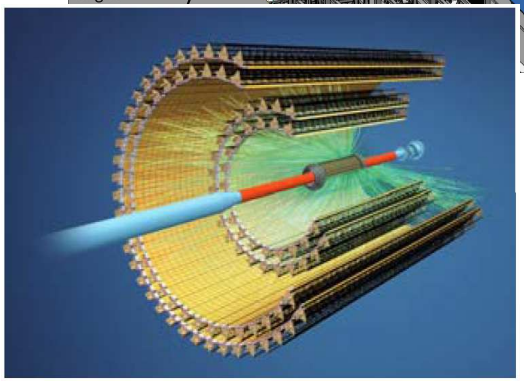




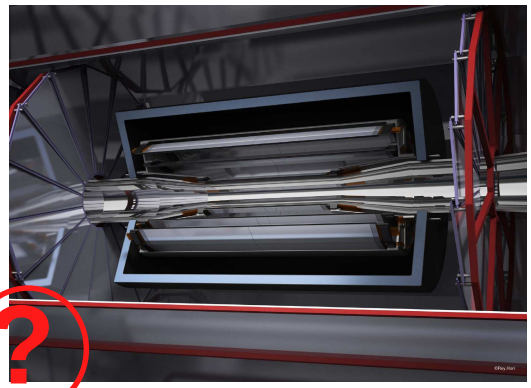
How to improve speed & radiation tolerance while preserving 3-5 μm precision & $< 0.1\%\ X_0$?

O(10) μs





O(1) μs



?

EUDET/STAR ⟶ **ALICE/CBM** ⟶ **?X?/ILC**

2010/14 ⟶ 2015/2019 ⟶ $\gtrsim$ 2020

Speed vs Pixel Dimensions

- **Pixel dimensions govern the spatial resolution at the expense of read-out speed**
  - $\Rightarrow$ **Trade-off to be found specific to each application**

Pixel pitch	$< 10\ \mu m$	$\gtrsim 15\ \mu m$	$> 20\ \mu m$	$\gtrsim 25\ \mu m$	$\lesssim 50\ \mu m$
Nb(T)	2–3	15	$\gtrsim$ 50	$\gtrsim$ 200	HV: few 10^2
σ_{sp} [μm]	$\lesssim$ 1x1	$<$ 3x3	$<$ 5x5	$\lesssim$ 5x5	$\gtrsim$ 10x10
Δt [μs]	10^3	$\lesssim$ 30/200	$\gtrsim$ 10-15	$<$ 10	10^{-2}
Pre-Amp+Filter	Out	In-Pix	In-Pix	In-Pix	In-Pix
Discrimination	Out	Out	In-Pix	In-Pix	In-Pix
Sparsification	Out	Out	Out	In-Pix	In-Pix
Ex.(chip)	Mimosa-18	ULTIMATE/MISTRAL	ASTRAL	ALPIDE	HV-CMOS
Depleted	No	No	No	Yes	YES
CMOS Process	AMS-0.35	AMS-0.35/Tower-0.18	Tower-0.18	Tower-0.18	AMS-0.35/0.18
Ex.(appli.)	Beam Tele.	STAR-PXL/ALICE-ITS	ALICE-ITS	ALICE-ITS	LHC ?

Sensor Development Organisation