Overview of Achieved & On-Going CPS Developments at IPHC

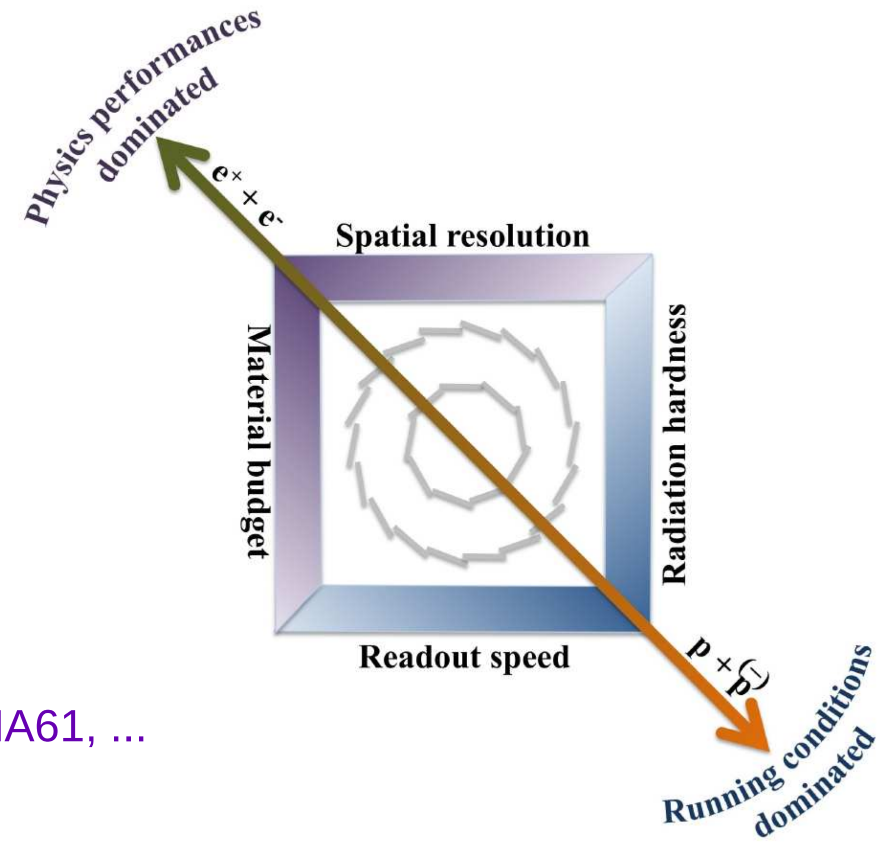
M.Winter / IPHC, 9 May 2017

Contents

- **Team profile : Composition & Expertise**
- **Overview of achievements**
- **Main on-going projects**
- **Long-term objectives**
- **Conclusion**

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**
  $\Rightarrow$ **Relaxed speed & radiation tolerance specifications**

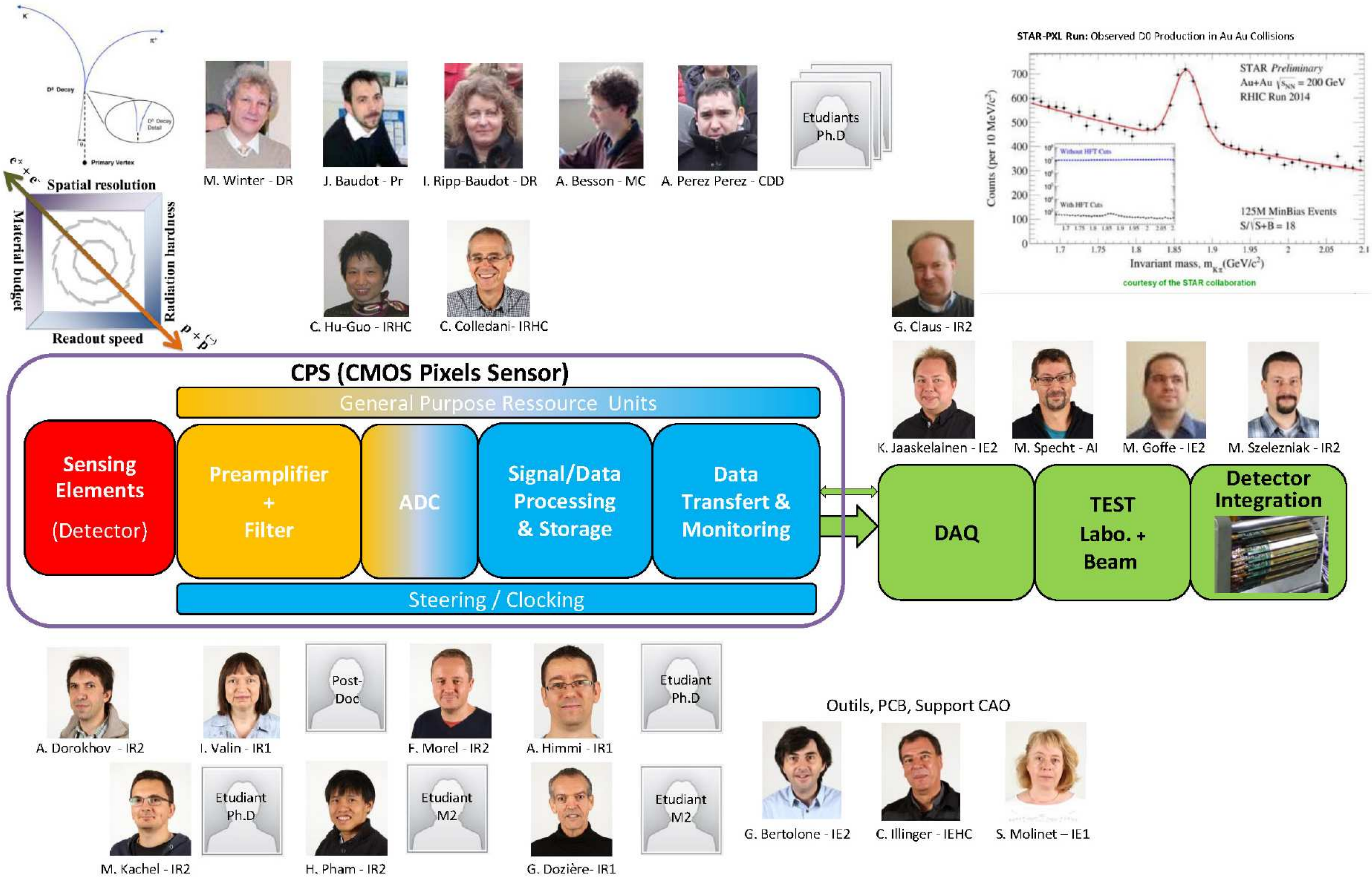
- **Increasing panel of existing, foreseen or potential application domains :**
  - **Heavy Ion Collisions :** STAR-PXL, ALICE-ITS, CBM-MVD, NA61, ...
  - **e^+e^- collisions :** ILC, BES-3, ...
  - **Non-collider experiments :** FIRST, NA63, Mu3e, PANDA, ...
  - **High precision beam telescopes** adapted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

PICSEL Team Profile

- **TEAM COMPOSITION:**
  - **Particle physicists:** 2 CNRS, 2 Univ., 1 post-doc, 2 PhD students
  - **Chip designers (6 PhD):** 10 engineers (9 CNRS, 1 Univ.), 1 post-doc ?, 3 PhD students
  - **Electronicians (1 PhD):** 6 engineers
  - **Support outside of PICSEL team:** micro-technics & mechanics workshops

- **SPECIFIC ASPECTS:**
  - **Activities are predominantly addressing instrumentation:**
    ↪ from R&D ab initio to demonstrators of detector concept
  - **Based on CHAIN of complementary expertises:**
    ↪ from scientific motivations to the realisation of the customised detection device
  - **Connected to network of partners using or testing our sensors**

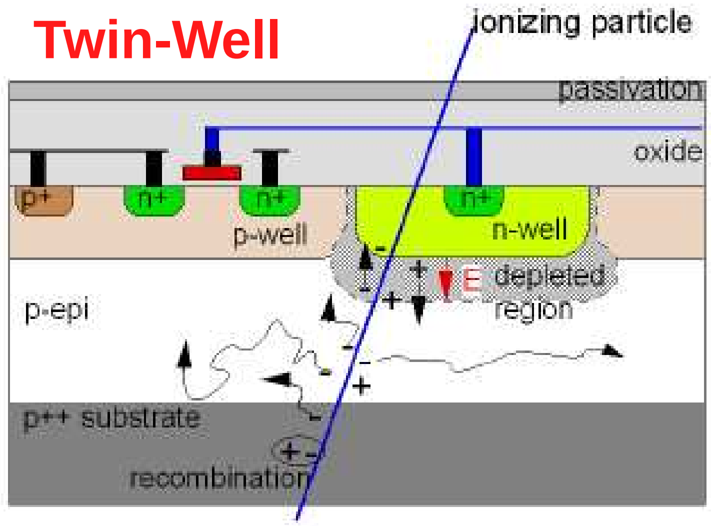
PICSEL ≡ Chain of Complementary Knowledges



CMOS Pixel Sensors: Main Features

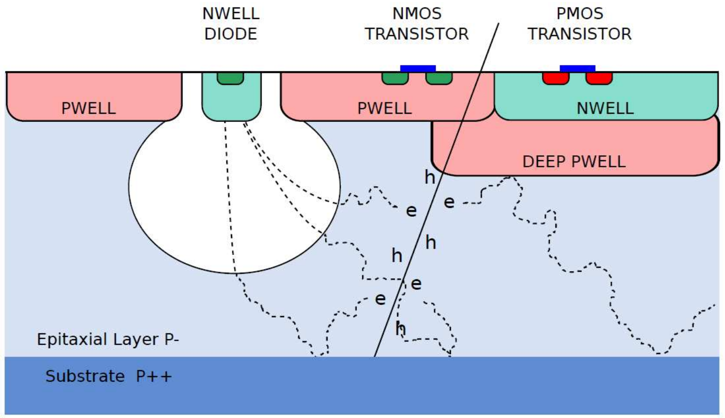
- **Prominent features of CMOS pixel sensors :**
  - high granularity $\Rrightarrow$ excellent (micronic) spatial resolution
  - signal generated in (very) thin (15-40 μm) epitaxial layer
    $\hookrightarrow$ resistivity may be $\gg$ 1 k$\Omega \cdot cm$
  - signal processing μ-circuits integrated on sensor substrate
    $\Rrightarrow$ impact on downstream electronics and syst. integration ($\Rrightarrow$ cost)

Twin-Well



- **CMOS pixel sensor technology has the highest potential :**

$\Rrightarrow$ R&D largely consists in trying to exploit potential at best with accessible industrial processes
  $\hookrightarrow$ manufacturing param. not optimised for particle detection: wafer/EPI characteristics, feature size, N(ML), ...



Quadruple-Well

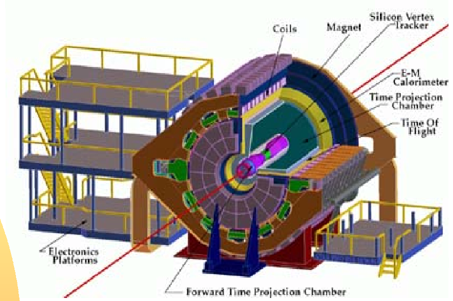
- **Read-out architectures :**
  - 1st generation : rolling shutter (synchronous) with analog pixel output (end-of-column discri.)
  - 2nd generation : rolling shutter (synchronous) with in-pixel discrimination
  - 3rd generation : data driven (asynchronous) with in-pixel discrimination
  - ...

CMOS Pixel Sensors (CPS): A Long Term R&D

- ***Ultimate objective: ILC, with staged performances***
  - *CPS applied to other experiments with intermediate requirements*

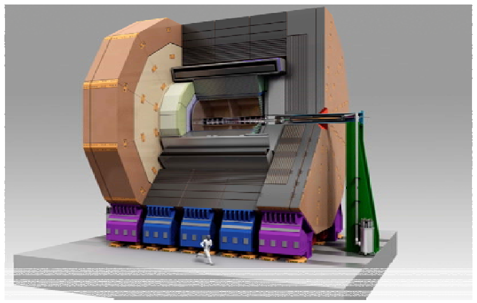
EUDET 2006/2010
Beam Telescope

STAR 2013
Solenoidal Tracker at RHIC

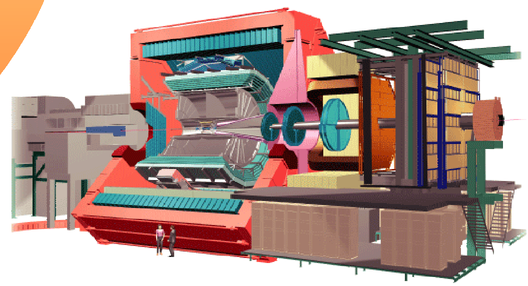


EUDET (R&D for ILC, EU project)
STAR (Heavy Ion physics)
CBM (Heavy Ion physics)
ILC (Particle physics)
HadronPhysics2 (generic R&D, EU project)
AIDA (generic R&D, EU project)
FIRST (Hadron therapy)
ALICE/LHC (Heavy Ion physics)
EIC (Hadron physics)
CLIC (Particle physics)
BESIII (Particle physics)
...

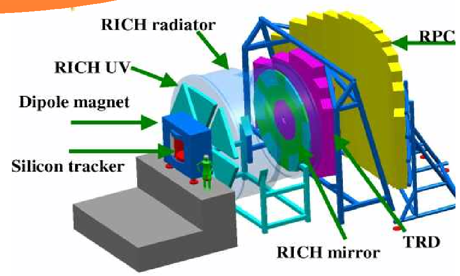
ILC >2020
International Linear Collider



ALICE 2018
A Large Ion Collider Experiment



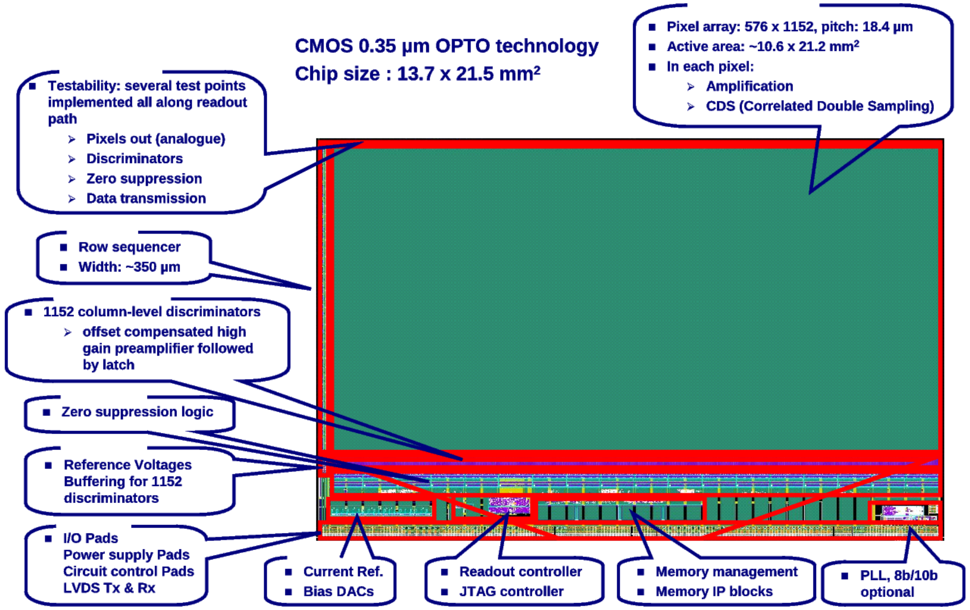
CBM >2018
Compressed Baryonic Matter

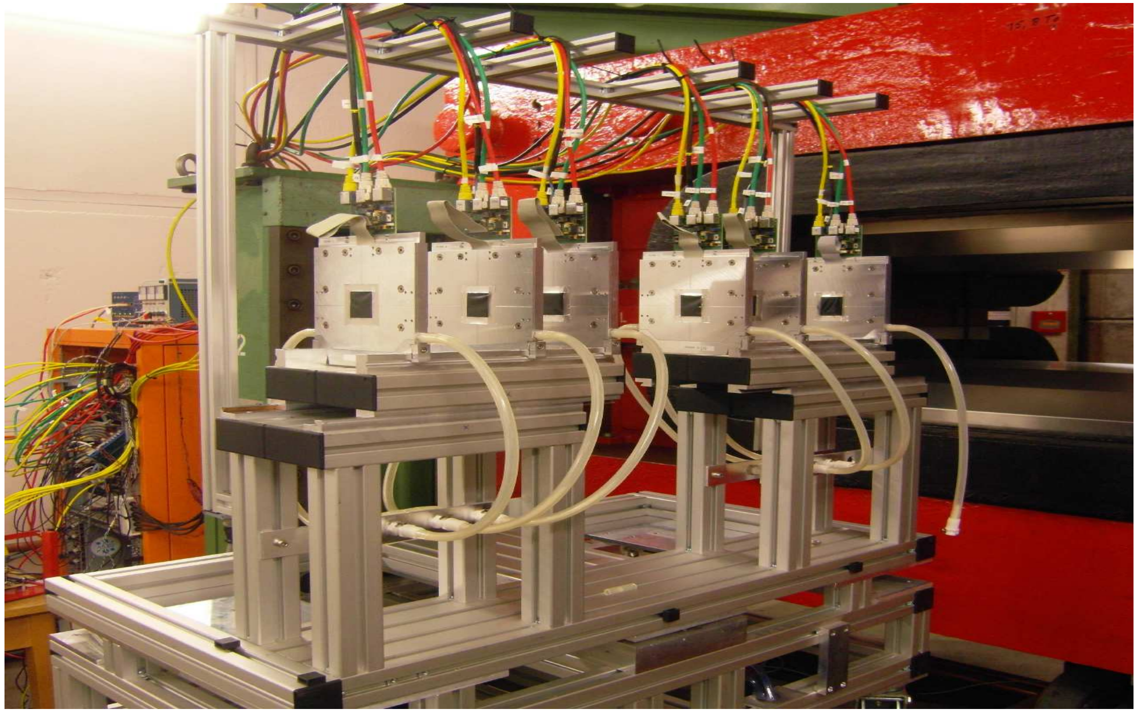


Achievement: MIMOSA-26 & Beam Telescopes (EUDET, ...)

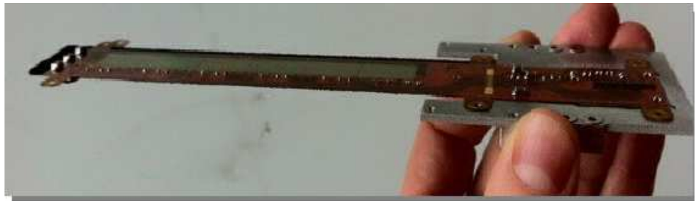
- MIMOSA-26: 1st CPS combining all signal processing functionalities

  $\sigma_{R\Phi,Z} \simeq$ 3.2 μm; thickness $\simeq$ 50 μm; 670,ooo pixels over 1x2 cm^2; $> 10^6$ part./cm^2/s





- EUDET beam telescope ($\sim$ 10 copies worldwide), suited to electron beams $<$ 1 GeV (e.g. LNF)
- MIMOSA-26 equips numerous devices: FIRST (GSI), NA-61 & NA-63 (SPS), beam telescopes (FE-I4), vertex detector demonstrators (CBM, ...), etc.
- 2x6 MIMOSA-26 equip PLUME double-sided ladder $\rightarrowtail$ BEAST-II

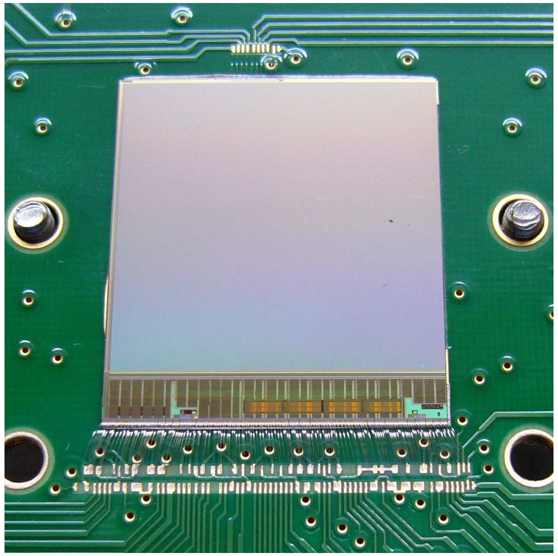


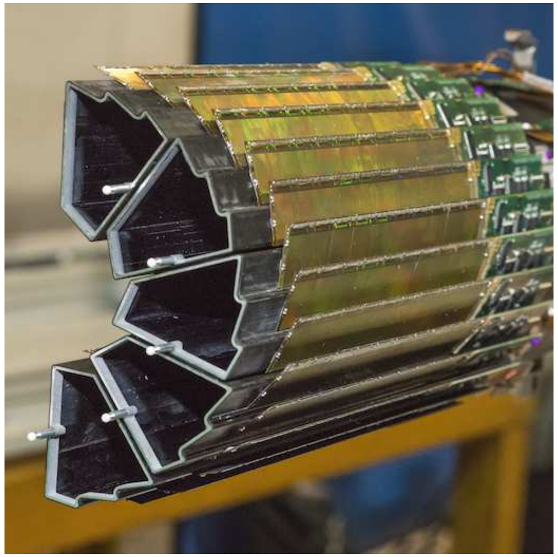
Achievement: MIMOSA-28 & STAR-PXL Detector (+ spin-offs)

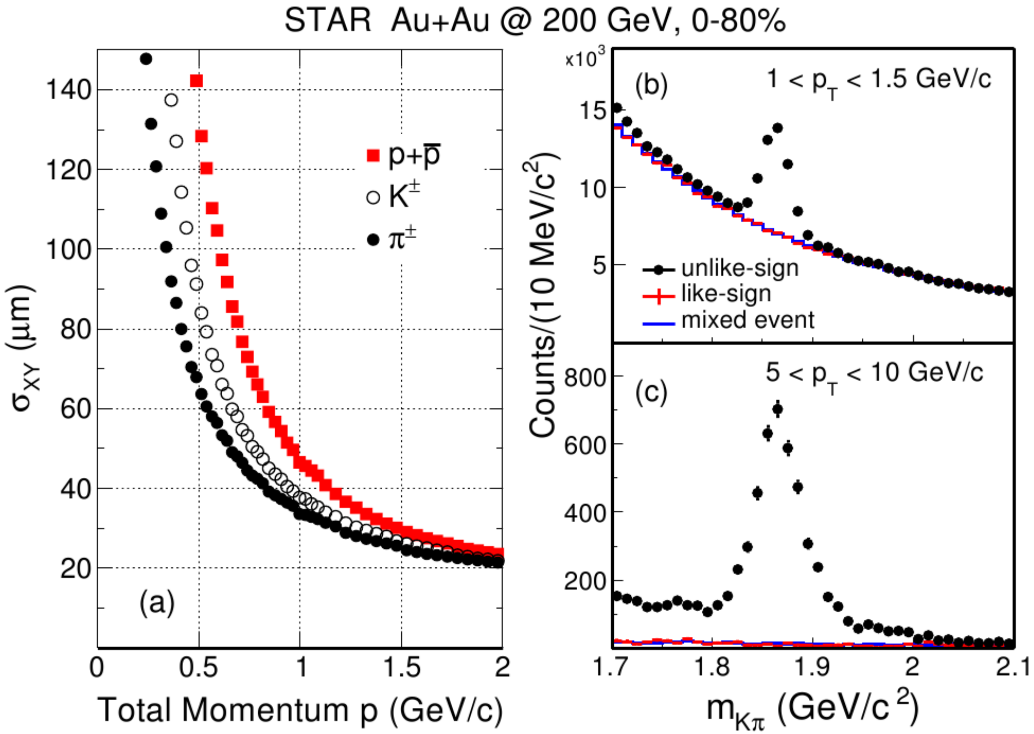
- **MIMOSA-28: 1st CPS equipping a subatomic phys. experiment (STAR at RHIC/BNL)**

  $\sigma_{R\Phi,Z} \simeq$ **3.7** μm; **thickness** $\simeq$ **50** μm; **970,ooo pixels over 2x2 cm^2;** $>$ **10^6 part./cm^2/s**

3 date taking campaigns (2014–16) $\Rightarrow$ state-of-the-art of the technology



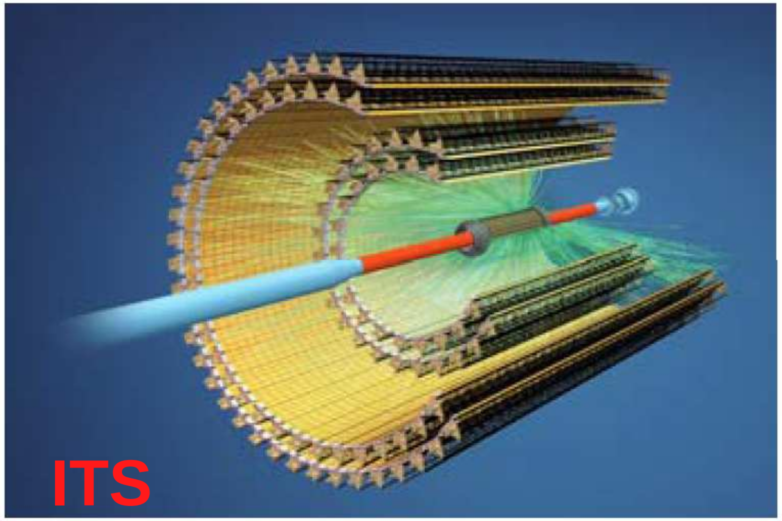


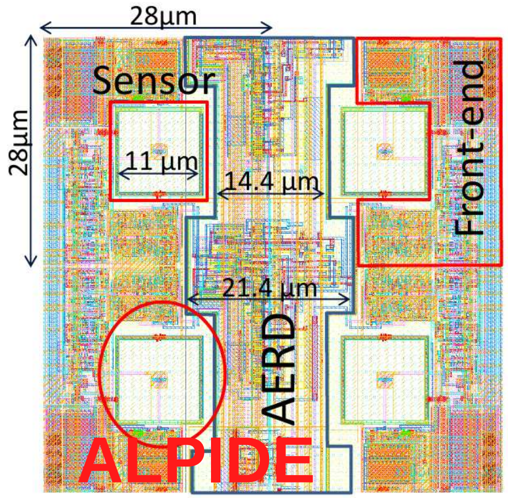


- MIMOSA-28 equips numerous devices, e.g.:
  - AIDA BT: 4 millions of pixels per plane (4x4 cm^2, $<$ 0.1% X_0)
  - BT part of LNF permanent infrastructure (450 MeV e^-)
  - telescope for hadrontherapy (GSI), etc.
  - demonstrator for inner tracker upgrade of BES-3 expt. at BEPC/IHEP

Achievement: 2 sensors for ALICE-ITS (LHC)

- **Objective: 1st pixellated inner tracker ($>$ 10 m^2 sensitive area, 25,ooo CPS)**
- **More demanding requirements than for STAR-PXL (MIMOSA-28)**
  - $\Rightarrow$ **evolution toward more advanced technology: TowerJazz 0.18μm**
- **2 approaches:**
  - MISTRAL: extension of MIMOSA-28 (STAR-PXL) – validated & robust
  - ALPIDE: extrapolation from hybrid pixels – higher perfo. but less robust & understood



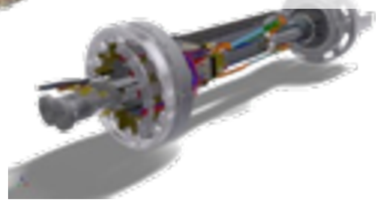


	σ_{sp}	t$_{r.o.}$	Dose	Fluency	T$_{op}$	Power	Active area
STAR-PXL	$< 4\ \mu m$	$< 200\ \mu s$	150 kRad	$3{\cdot}10^{12}$ n$_{eq}$/cm^2	30-35°C	160 mW/cm^2	0.15 m^2
ITS-in	$\lesssim 5\ \mu m$	$\lesssim$ **30 μs**	**2.7 MRad**	**1.7$\cdot$10^{13} n$_{eq}$/cm^2**	30°C	$<$ 300 mW/cm^2	0.17 m^2
ITS-out	$\lesssim 10\ \mu m$	$\lesssim$ **30 μs**	15 kRad	$4{\cdot}10^{11}$ n$_{eq}$/cm^2	30°C	$<$ **100 mW/cm^2**	$\sim$ **10 m^2**

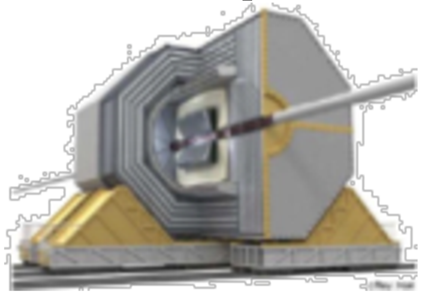
Towards the ILC via Spin-Off Appications

ALICE 2020
LHC/CERN

BEAST 2018
SuperKEKB-Japon



ILD ~2030
ILC-Japon



Tracking of charged particles

Subatomic Physics

Beam instrumentation

Hadrontherapy

Imaging

β-rays, low energy e-

X-rays

Dosimetry

Hybrid photo-detector

bio-inspired vision

en discussion

BELLE-II

Tests industrie non-destructifs

TRACKCAL

FOOT

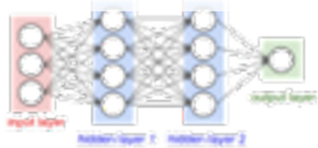
Channeling

ββ-0ν

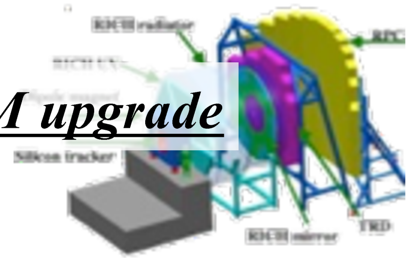
SOLEIL 2018

Sonde β

CIRENE



CBM upgrade

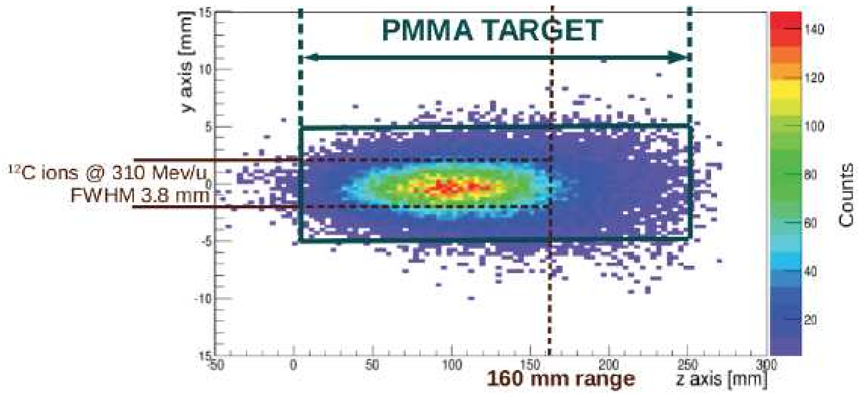


CBM >2020
FAIR/GSI-Germany

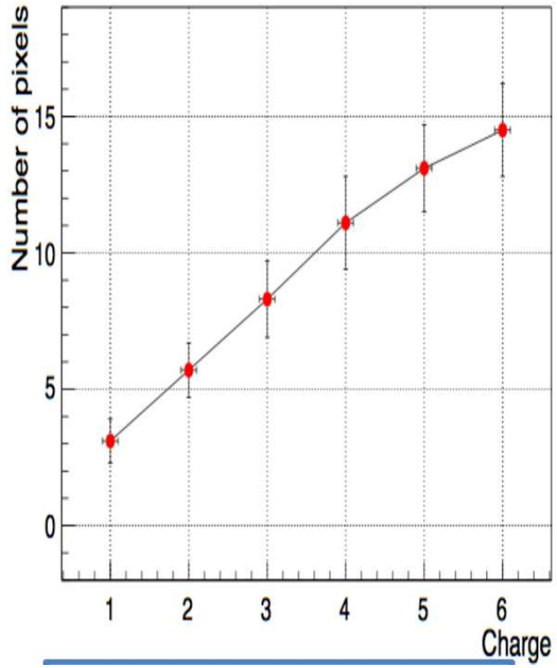
Achievement: Spin-Off Activities

- **Several sensors provided for hadrontherapy: imaging, dosimetry, etc.**

- **Reconstruction of Bragg peak**
  - National Cancer related research program: INCA
  - Telescope composed of MIMOSA-26 sensors (50μm thin)
  - Precise reconstruction of interaction point of ^{12}C ions in PMMA and indication of Bragg peak position

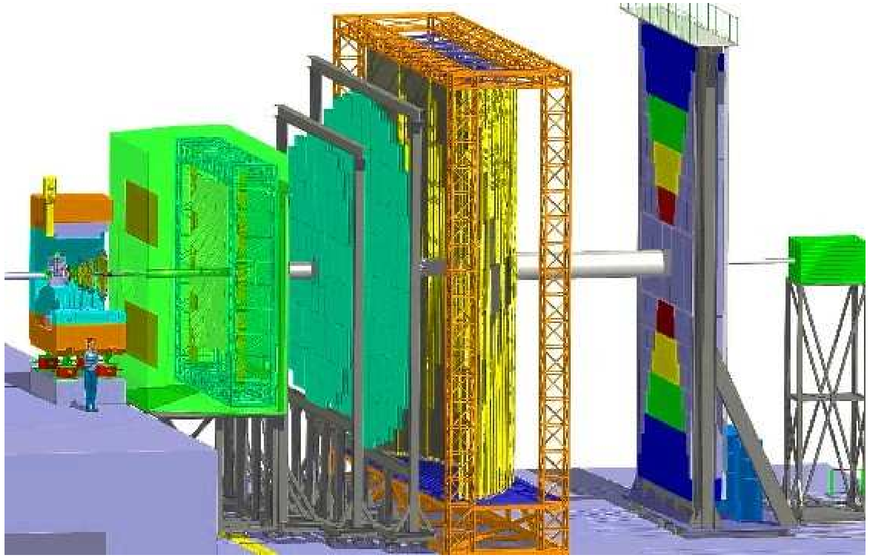


- **Identification of fragments from ^{12}C interaction**
  - Experience FIRST (GSI)
  - ^{12}C (80 MeV/N) beam on C_2H_4 target
  - Vertex detector using MIMOSA-26 sensors (50 μm thin)
  - Evidence for ability to derive electric charge of fragments from impact cluster size

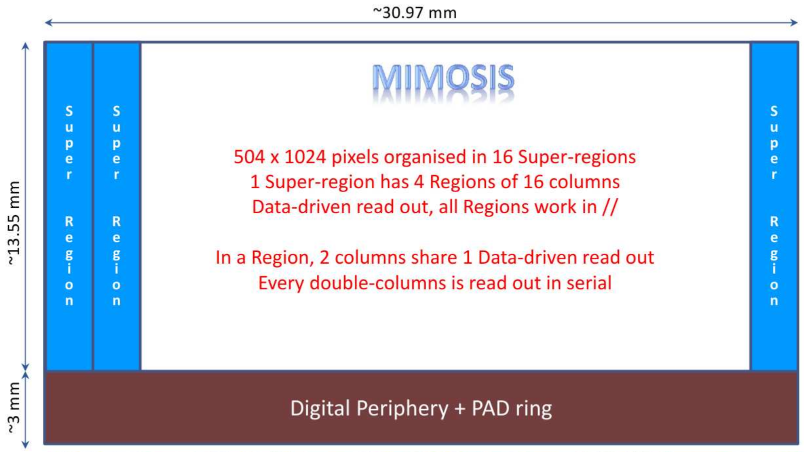


Present Main Project: CBM-MVD

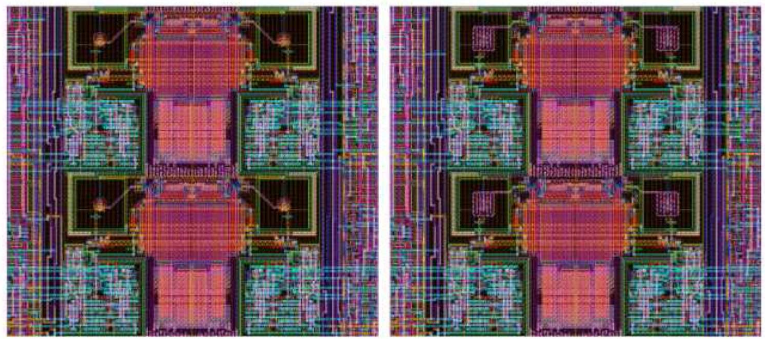
- **Objective: Sensor equipping Micro-Vertex Detector (MVD) of heavy-ion CBM expt at FAIR/GSI**
  - 4 double-sided stations equipped with 50 μm thin CPS, operated in vacuum at $T_{op} \sim -40^{\circ}C$
  - MIMOSIS sensor: asynchronous read-out architecture derived from ALPIDE sensor (ALICE-ITS)



- **Sensor target performances:**
  - Spatial & Time resolutions $\lesssim$ 5 μm & 5 μs
  - Radiation tolerance $\gtrsim$ 3 MRad $\oplus$ $3 \cdot 10^{13} n_{eq}/cm^2$
  - Power: 200-350 mW/cm^2 (depending on distance to target)
  - Hit/Data rate capability: $1.5\text{-}7 \cdot 10^5/mm^2/s \Rrightarrow$ 1.6 $Gbits/cm^2/s$



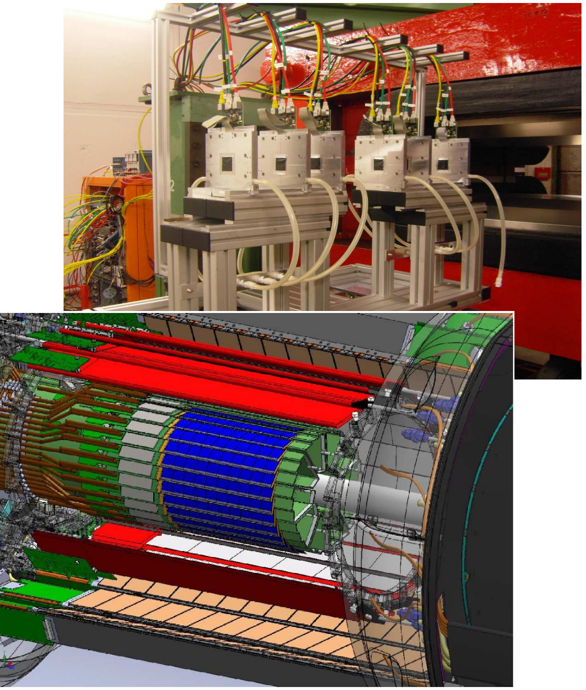
- **Development plan:**
  - MPW run in May 2017 $\rightarrowtail$
  - Engineering Runs in 2018, 2019 and 2020



DC coupling AC coupling

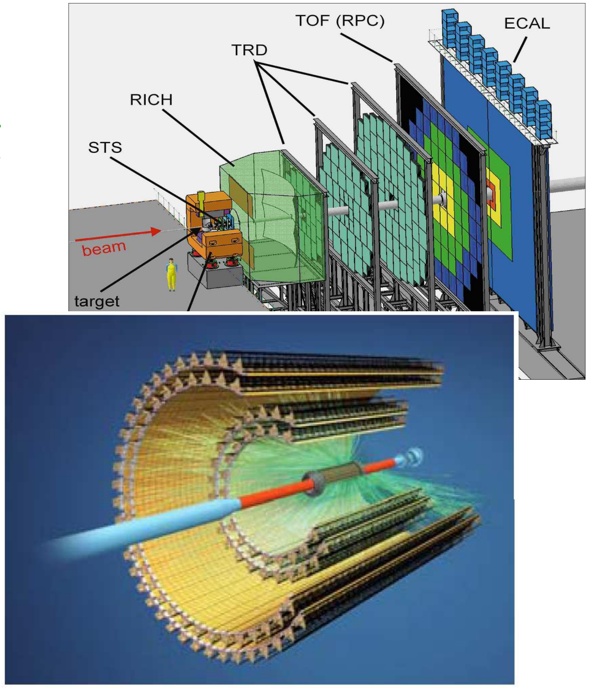
Improving Speed and Radiation Tolerance

O(10^2) μs

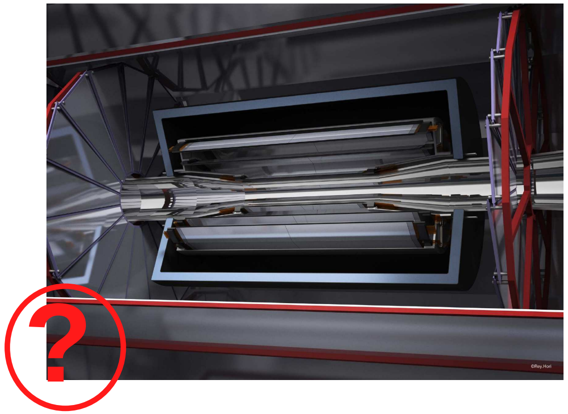


How to improve speed & radiation tolerance while preserving 3-5 μm precision & $< 0.1\%$ X_0 ?

O(10) μs

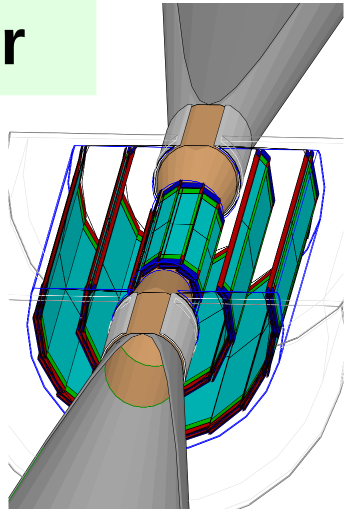


O(1) μs

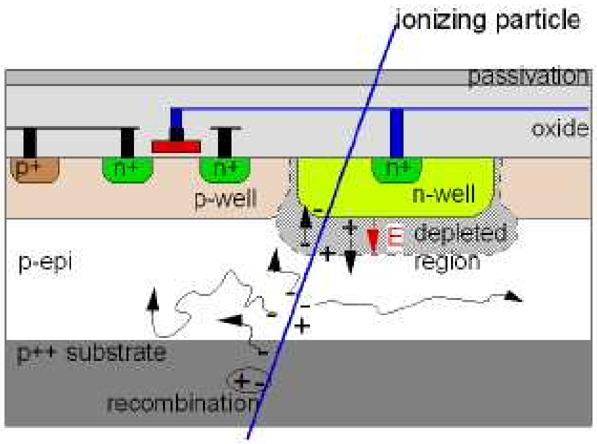


EUDET/STAR	$\rightarrowtail$	**ALICE/CBM**	$\rightarrowtail$	**?X?/ILC**
2010/14	$\rightarrowtail$	2015/2019	$\rightarrowtail$	$\gtrsim$ 2020

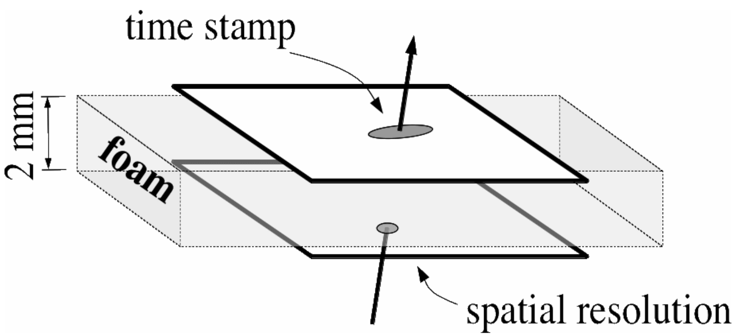
Main Long Term Project: ILC Vertex Detector



- **VERTEX DETECTOR CONCEPT :**
  - Cylindrical geometry based on 3 concentric 2-sided layers
  - Layers equipped with 3 different CMOS Pixel Sensors (CPS)



- **PIXEL SENSOR DEVELOPMENT:**
  - Exploit CPS potential & IPHC expertise
  - R&D performed in synergy with other applications
    $\hookrightarrow$ EUDET-BT, STAR, ALICE, CBM, ...
  - CPS $\equiv$ unique technology being simultaneously
    granular, thin, integrating full FEE, industrial & cheap
  - Address trade-off btw spatial resolution & read-out speed

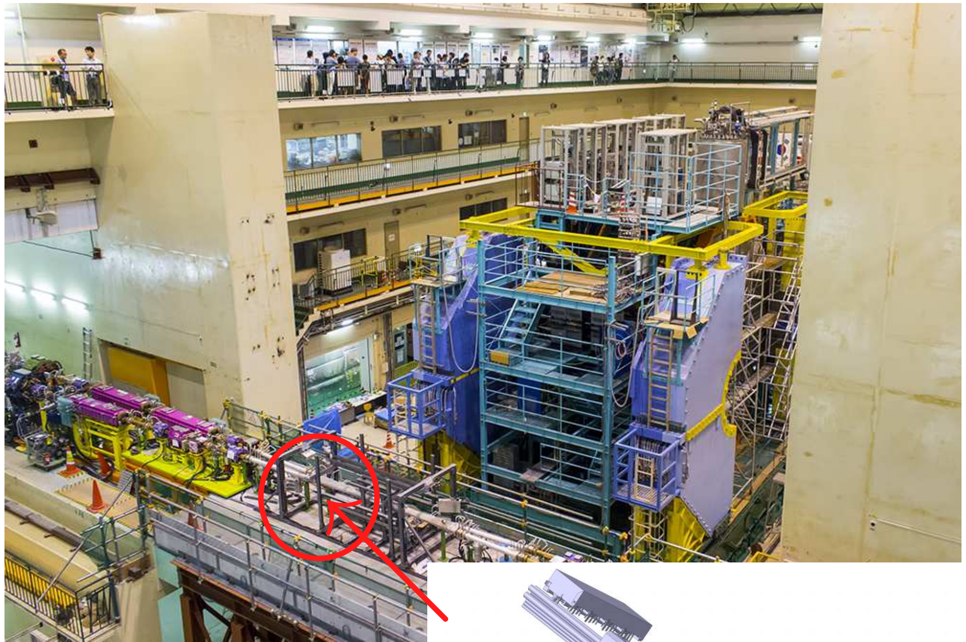


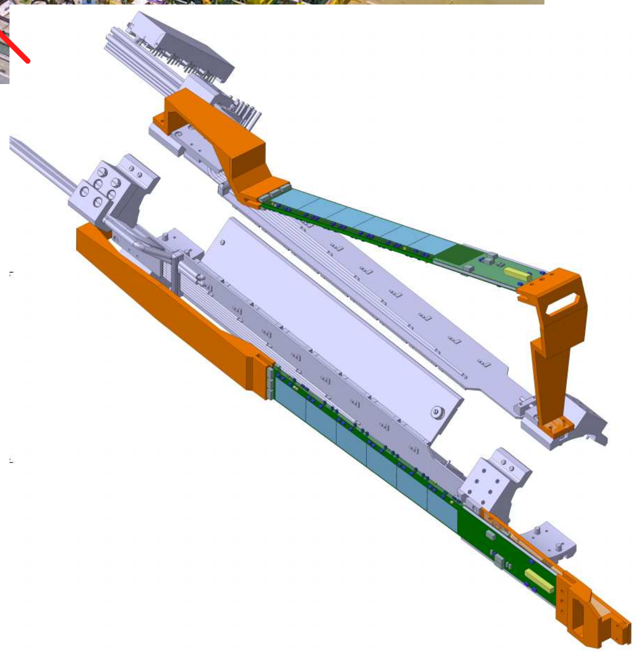
- **DOUBLE-SIDED LADDER DEVELOPMENT:**
  - Develop concept of 2-sided ladder using 50 μm thin CPS
  - Develop concept of mini-vectors providing
    high spatial resolution & time stamping
  - Address the issue of high precision alignment
    & power cycling in high magnetic field (ILC)

BEAST-II: Application of Ultra-Light Double-Sided Ladders

- **Double-sided ladders used for beam related background studies**
  - 2 PLUME ladders (2x6 MIMOSA-26 sensors) to be installed near the IP
  - Exploit pairs of impacts to reconstruct mini-vectors indicating directions (and origin) of traversing particles
  - Data taking in 2018

BEAST →





- **Feedback for ILC:**
  - Important opportunity to assess added-value of 2-sided ladders
  - Perspectives: fast sensors mounted on one (or two) ladder side(s) featuring reduced material budget

CONCLUSION

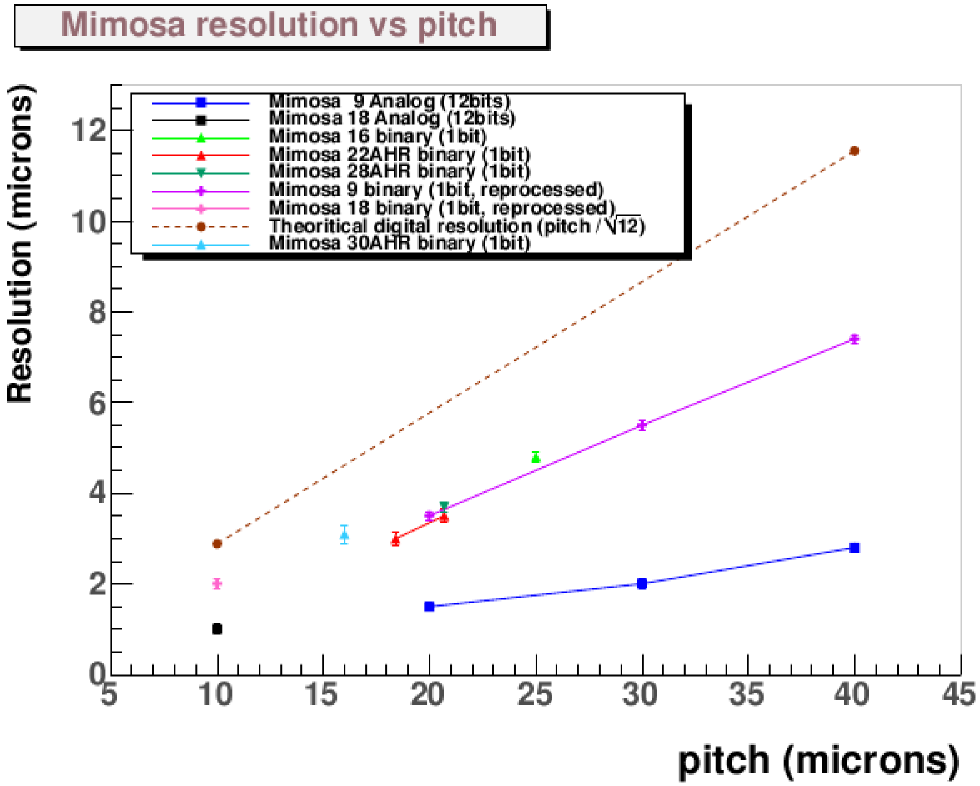
- **PICSEL team profile:**
  - experience in CPS development with physics results coroborating their added value
  - main activity oriented toward subatomic physics devices
    with constant interest for spin-offs (X-Ray & β detection)
  - CPS potential still not fully exploited $\Rrightarrow$ R&D carries on
  - CPS (& double-sided ladders) for an ILC vertex detector is the prominent long term goal
    (what if ILC does not converge ?)
  - CBM-MVD = important step in direction of ILC (CEPC may be one too): $\lesssim$ 5 μm / 5 μs

- **Framework of SoI-CMOS partnership:**
  - Applications: ILC vertexing & tracking devices, X-Ray detectors, others ?
  - Complementarity: sensor (read-out) design (translation ?), performance assessment/comparison,
    access to application domains ?
  - R&D main objective: (low power) fast read-out for small/precise pixels ?
  - Developments accompanied by simulations ?
  - Open to other partners ?
  - Connection to BELLE-II ?

Measured Spatial Resolution

- **Several parametres govern the spatial resolution :**
  - pixel pitch
  - epitaxial layer thickness and resistivity
  - sensing node geometry & electrical properties
  - signal encoding resolution

  $\Rrightarrow$ σ_{sp} fct of pitch $\oplus$ SNR $\oplus$ charge sharing $\oplus$ ADCu, ...



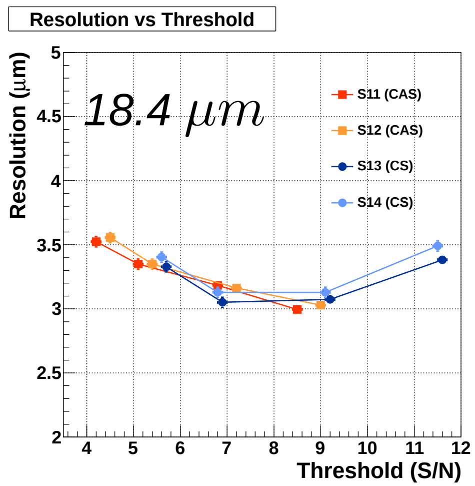
- **Impact of pixel pitch (analog output) :**

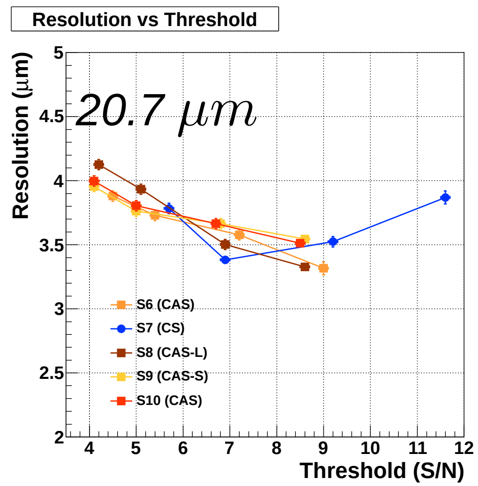
$\sigma_{\mathbf{sp}} \sim \mathbf{1}\ \boldsymbol{\mu}\mathbf{m}$ (10 μm pitch) $\rightarrowtail$ $\lesssim \mathbf{3}\ \boldsymbol{\mu}\mathbf{m}$ (40 μm pitch)

- **Impact of charge encoding resolution :**

$\triangleright$ ex. of 20 μm pitch $\Rrightarrow$ σ_{sp}^{digi} = pitch/$\sqrt{12} \sim$ 5.7 μm

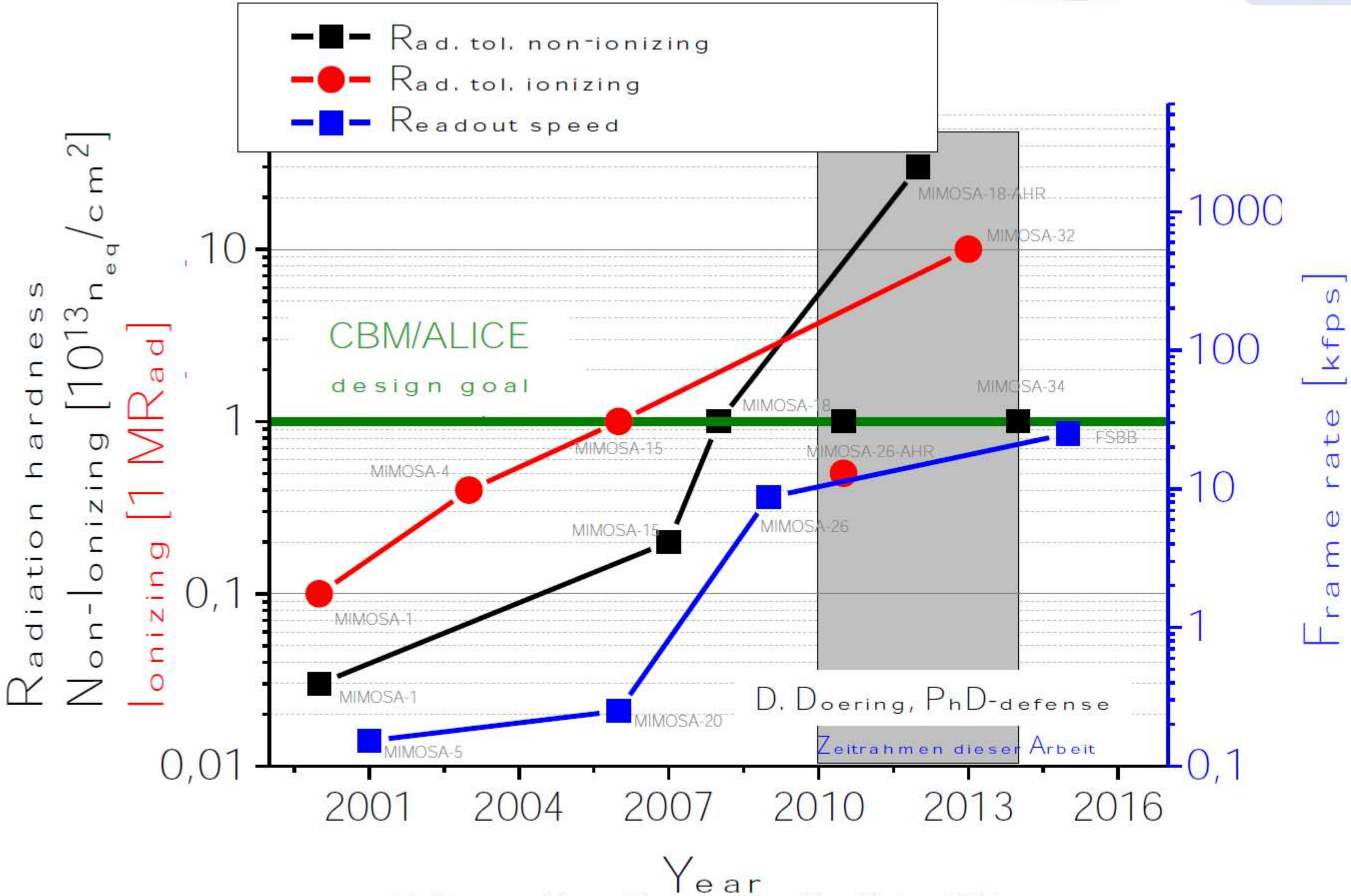
Nb of bits	12	3-4	1
Data	*measured*	*reprocessed*	*measured*
σ_{sp}	$\lesssim 1.5\mu m$	$\lesssim 2\mu m$	$\lesssim 3.5\mu m$





Radiation Tolerance

Material budget: 0.05% X_0
Spatial resolution: ~ 3-5 µm



Speed vs Pixel Dimensions

- **Pixel dimensions govern the spatial resolution at the expense of read-out speed**
  $\Rrightarrow$ **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 ?