From Novel Imaging Sensors to Advanced Tracking Devices

FROM DELPHI AT LEP TO MIMOSIS AT FAIR AND BEYOND

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Former PI of the PICSEL team of IPHC-Strasbourg

2024 ICFA INSTRUMENTATION AWARDS

CONTENT

Monolithic CMOS pixel sensors for charged particle detection:

The proof of principle: efficient detection of charged particles

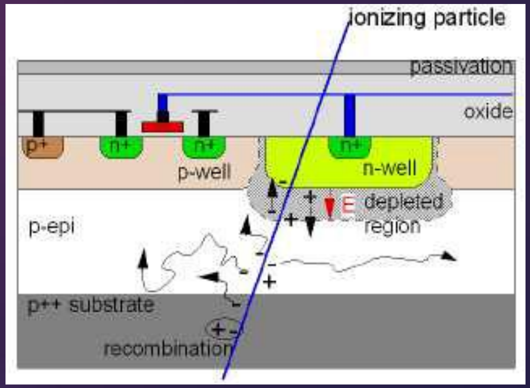
Establishing charged particle tracking

1st CMOS sensor based vertex detector in a collider experiment

Follow-ups: ALICE-ITS2 at CERN-LHC and CBM-MVD at FAIR/GSI

Kernel actors of > 20 years of CMOS sensors developpement

Conclusion - Outlook



ESTABLISHING A PROOF OF PRINCIPLE

SUCIMA
AMS-0.6

LEP/e+e- coll./HF tagging with HAPS:
Delphi: 200x200 μm²; > 1% X0, > 1 W/cm²

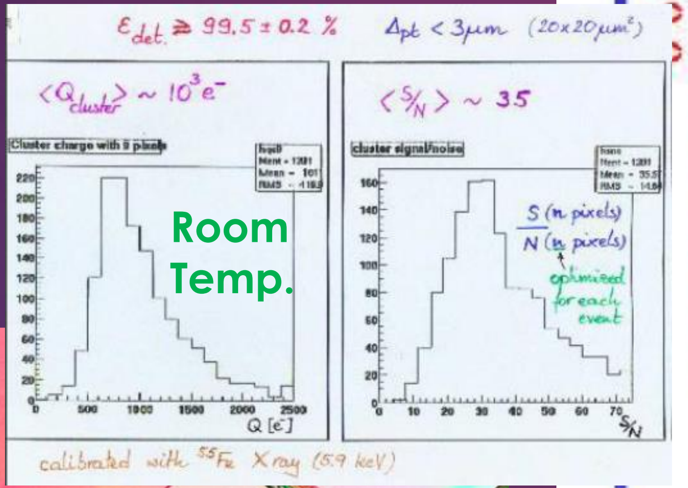
> join TESLA collider project on VD (F.Richard)
> contact LEPSI-Strasbourg: **Renato Turchetta**

March '99: 1st talk on MAPS for a VD at ECFA-LC workshop in Oxford

MIMOSA-1: fabricated in **2000** with AMS-0.6 μm commercial CMOS process

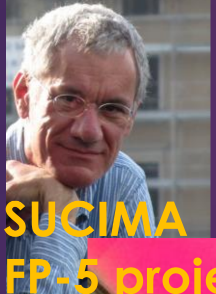
A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI technology, **NIM A458 (11 Feb. 2001), pp 677-689**

G. Deptuch
1st PhD



Room Temp.

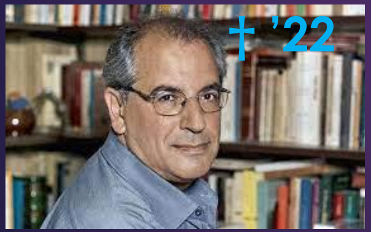
M. Caccia



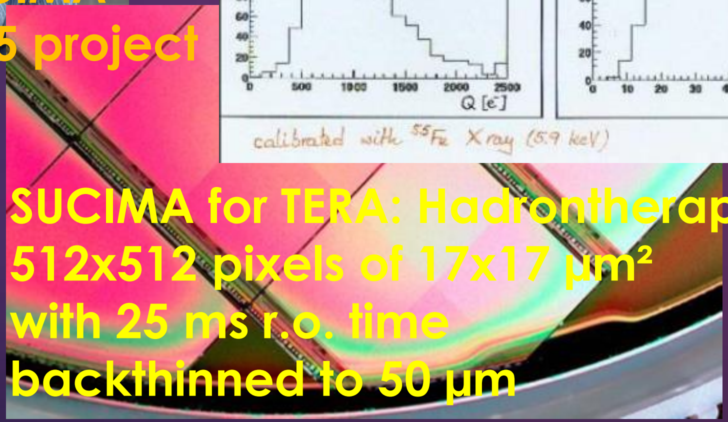
SUCIMA FP-5 project

MIMOSA-5 Fab. In 2003

S. Katsanevas † '22



MIMOSA-5 in HPD Photonis / Antares



SUCIMA for TERA: Hadrontherapy
512x512 pixels of 17x17 μm²
with 25 ms r.o. time
backthinned to 50 μm

W. Dulinski

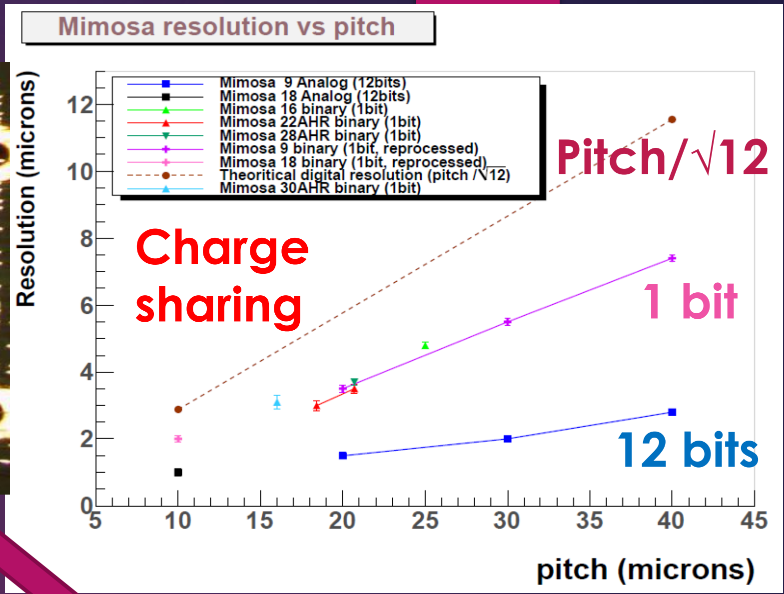
† '14

ESTABLISHING CHARGED PARTICLE TRACKING

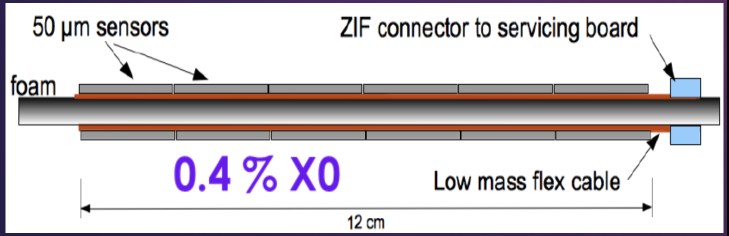
EUDET
AMS-0.35

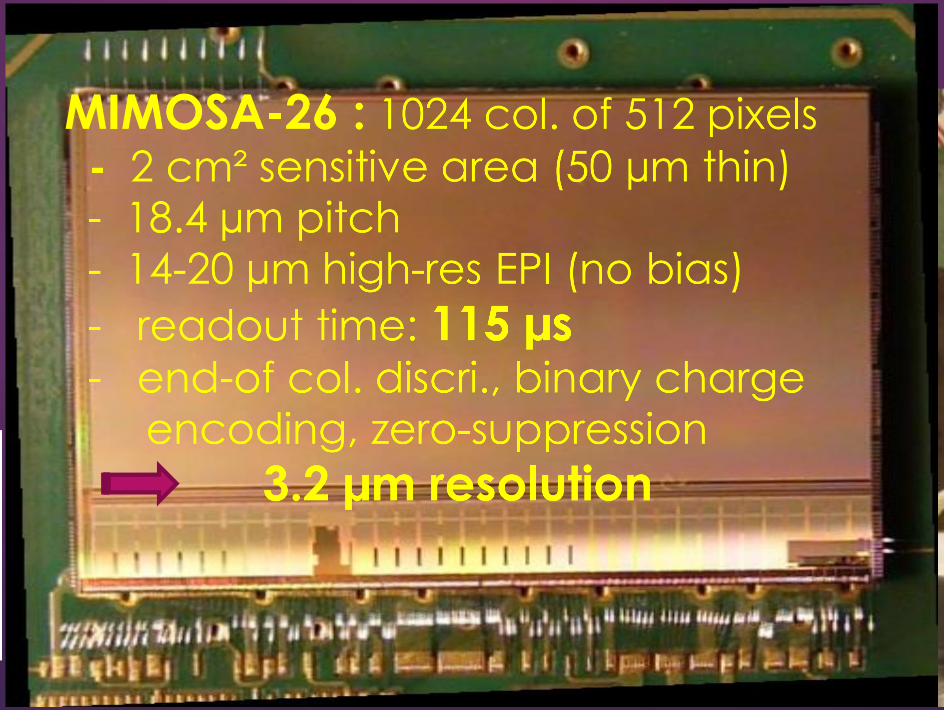
O(1) μm resolution exploiting charge sharing
➡ read-out time > 1 ms
But a Higgs-Factory Vx Det. requires < 10 μs

MIMOSA-8 proto. (TSMC-0.25): **2004/5**
end of col. discri. (Yavuz Degerli/Saclay)
→ **MIMOSA-16/22** proto. (AMS-0.35 OPTO)
→ **MIMOSA-26** final sensor (EUDET-FP6):
High resolution beam telescope



Numerous applications:
- > 10 BT (DESY, CERN, SLAC, ../)
- Fixed target expts (NA61, …)
- Hadrontherapy
- Industrial imager
- Research in biology
- PLUME 2-sided ladder

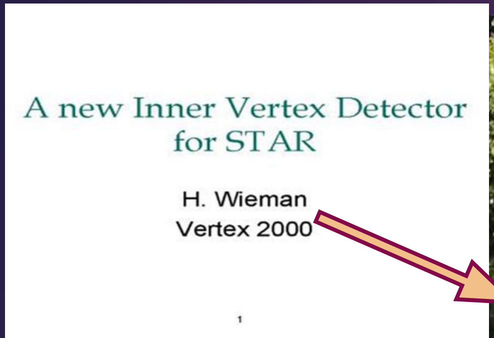




APPLICATION TO A VERTEX DETECTOR COMPOSING A COLLIDER EXPERIMENT

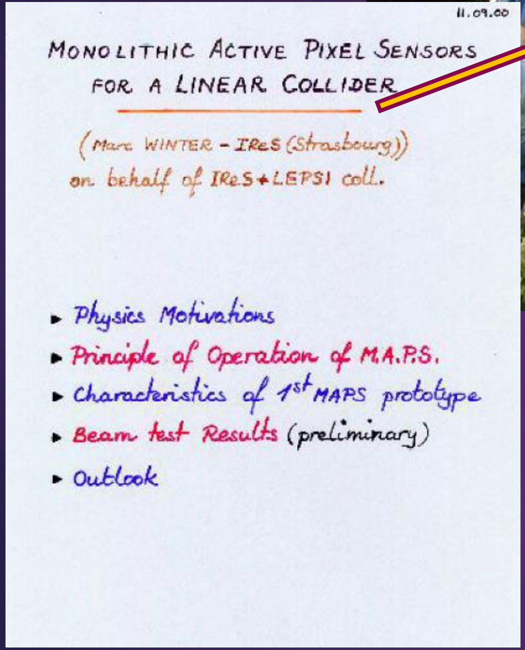
STAR

AMS-0.35


A new Inner Vertex Detector for STAR

H. Wieman
Vertex 2000

1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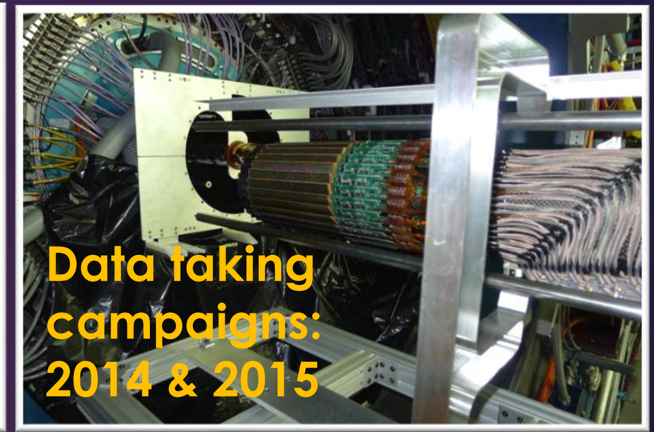
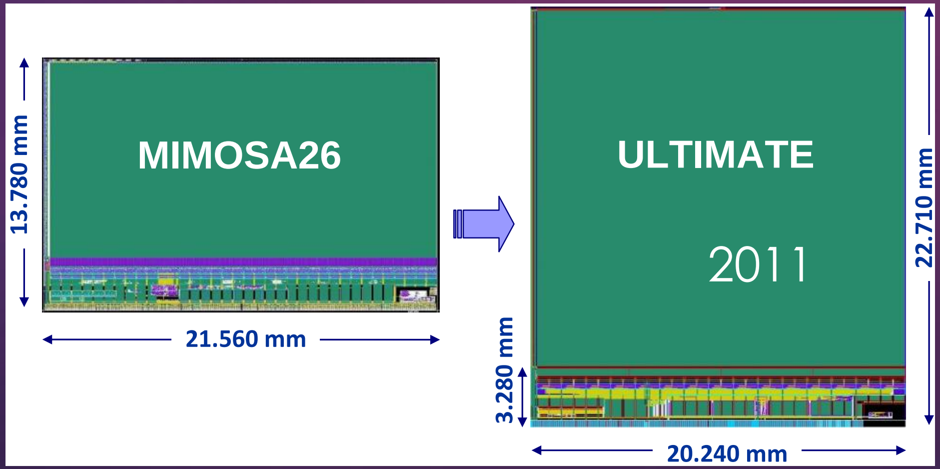
MONOLITHIC ACTIVE PIXEL SENSORS FOR A LINEAR COLLIDER

(Marc WINTER – IReS (Strasbourg))
on behalf of IReS+LEPSI coll.

- Physics Motivations
- Principle of Operation of M.A.P.S.
- Characteristics of 1st MAPS prototype
- Beam test Results (preliminary)
- Outlook



STAR-PXL: 2 layers (~ 0.4 % X0/layer),
400 ULTIMATE sensors (1600 cm²),
back-thinned to 50 µm
170 mW/cm2, air-cooled (10 m/s)



AMS-0.35 OPTO (twin-well process)

Customised EPI: 15 µm, **High Res.**

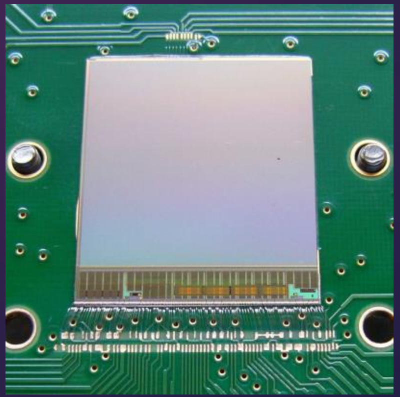
960 x 928 pixels (pitch = 20.7 µm)

Spatial resolution < 4 µm

Readout time: 185 µs

In-pixel Amp. & Corr. Dble Sampling

Deep Reactive Ion Etching (DRIE)



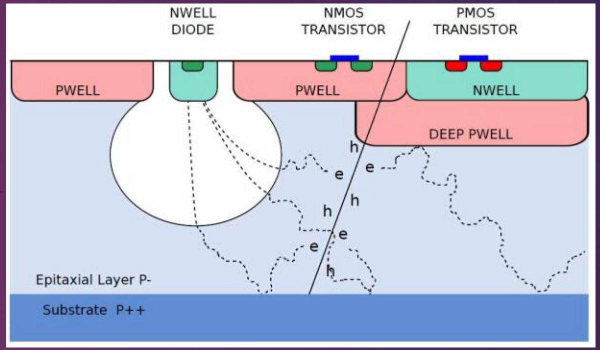
APPLICATION TO AN INNER TRACKER COMPOSING A COLLIDER EXPERIMENT

ALICE
TJsc-0.18

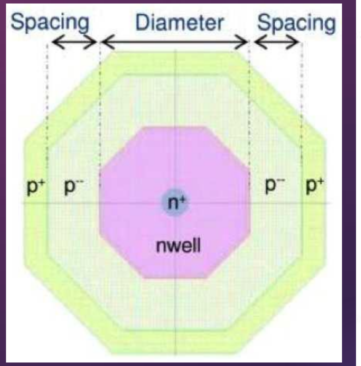
2010/11: proposal to consider CMOS pixel sensor fo the upgrade of the ALICE vertex detector, based on the same readout architecture (**rolling shutter**) as MIMOSA-26/-28, customised for the ALICE physics goal & more demanding running conditions

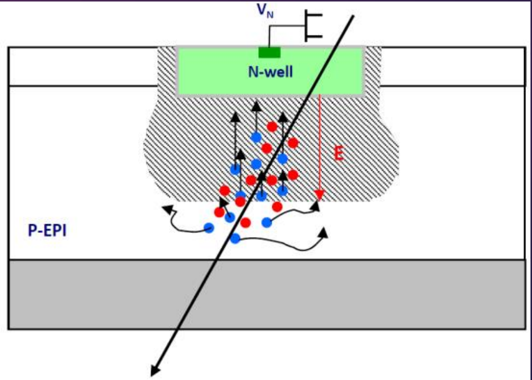
ALICE coll. approved the proposal in 2011/12,
promoted by Luciano Musa,
who extended the concept to the whole ITS (10 m²)

New CMOS process (INMAPS pionnered by **Renato T.** at RAL):
- Tower-Jazz 180 nm CIS process
- **quadruple well** technology → in-pixel P-MOS & N-MOS transistors
- EPI: Thickness = 18/25/30/40 µm, -- High-Res. ~ 1-8 kΩ.cm



PICSEL Team (IPHC-Strasbourg):
- extensive study of the techno. charge coll. & sensing characteristics
- find out an **optimal sensing system** (EPI, diode, etc.)
- design a sensor adapted to the ITS (MISTRAL/ASTRAL)
  → surpassed by ALPIDE, designed by **Walter S.** (et al.):
  featuring a superior readout architecture
  in-pixel discri., priority encoding, faster, low power

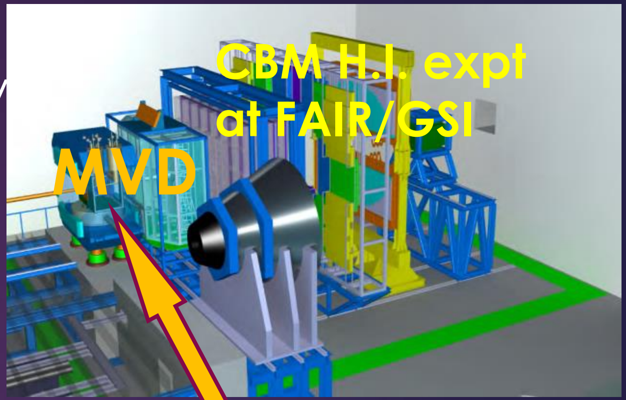




APPLICATION TO A VERTEX DETECTOR COMPOSING A FIXED TARGET EXPERIMENT

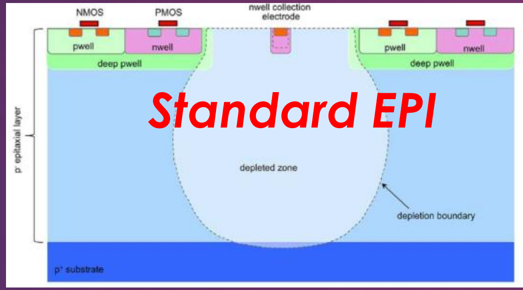
CBM
TJsc-0.18 modified

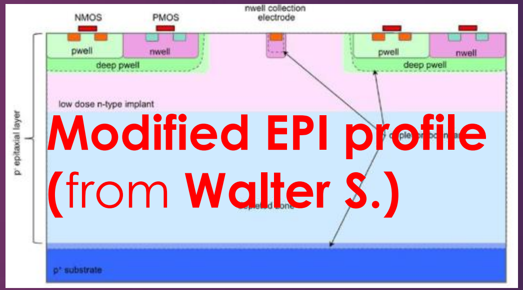
March 2003:1st seminar on CMOS pixel sensors at GSI (invited by H. Gutbrod)
CBM ≡ H.I. fixed target expt ➡ Micro-Vertex Detector faces very high hit density
➡ more demanding running conditions than ALICE-ITS2

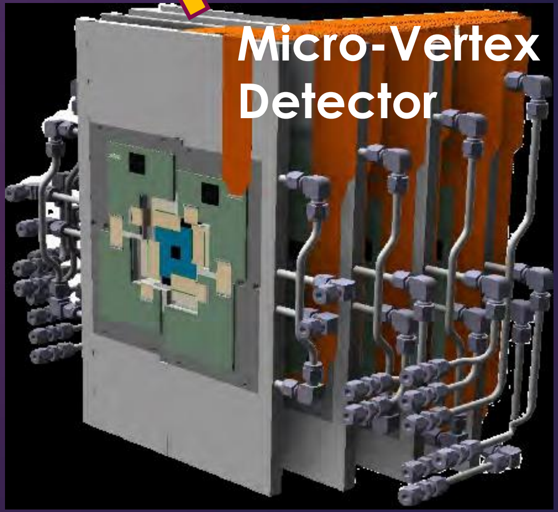


Stretched timeline allowed to benefit from evolution of CMOS industry (Tower-Jazz 180 nm) and progress on CMOS sensor design (ALPIDE, mod. EPI)

Priority encoder & pixel design derived from ALPIDE
EPI layer doping profile modified for improved rad. tol.







20 yrs of steady support and trust from GSI / Darmstadt & Univ. Goethe / Frankfurt, with highly appreciated collaborators

EXTENSICE STUDY OF KEY PARAMETRES RULING CHARGED PARTICLE DETECTION

PICSEL: **P**hysics with **I**ntegrated **C**mos **S**ensors and **EL**ectron machines

Support from IN2P3/CNRS Dir.:
→ PICSEL & CMOS sensor devt:
- ≈ 10 engineer positions created
- ≥ 6 post-docs, 2 phys. positions
- funding: foundry submissions, test equipment

& Support from IPHC-Strasbourg

Strasbourg **PICSEL** team (≤ 25 FTE):
3-5 physicists, O(10) ASIC designers,
4-5 electroniciens, ≤ 5 PhD students
> 20 PhDs on CMOS sensor R&D

Essential Partners *(incomplete)*:
- Irfu-CEA (Y.Degerli): end-of-col. discri. (MIMOSA-8)
- DESY/Univ.Hamburg (I.Gregor): EUDET Beam Tel., AIDA
- STAR coll. (Berkeley, BNL): STAR-PXL/HFT
- Univ. Frankfurt (J.Stroth), GSI: CBM-MVD, Hadron-Physics-2
- ALICE-ITS2/CERN (L.Musa): → ALPIDE (Walter S.)

Charge collection & signal sensing:
- EPI: thickness, resistivity doping profile
- junction: dimensions, insulation
- depletion: top vs back vs field amplitude
- impact of/on pixel dimensions
- ISE/TCAD simulations

In-pixel signal processing:
- pre-amp T: size & shape vs gain & RTS
- noise suppression: double-corr. sampling, …
- junction to preamp: DC vs AC

Read-out architecture:
- charge encoding: binary, ADC (4-5 bits, …)
- zero-suppression, elastic buffering, …)

Particle detection performance assessment:
- lab tests: noise, steering param. , threshold dispersion, …
- beam test: det. eff., cluster characteristics, spatial resol.
- radiation tolerance assessment: TID, NIEL, SEE, …

Determination of requirements:
- ILC vertex detector and inner tracke
- optimisation of conflicting design param.
- investigate charge coll. system variants

Comparaison of CMOS processes:
- impact of feature size, design rules, IP µcircuits
- planar vs triple-well vs quadruple-well
- nb of ML
- intrinsic radiation tolerance

CONCLUSION & OUTLOOK

My involvement in the birth and devt of CMOS pixel sensors for charged particle tracking stems from an **idea proposed by Renato** and benefited from **R&D realised/supervised by Walter**

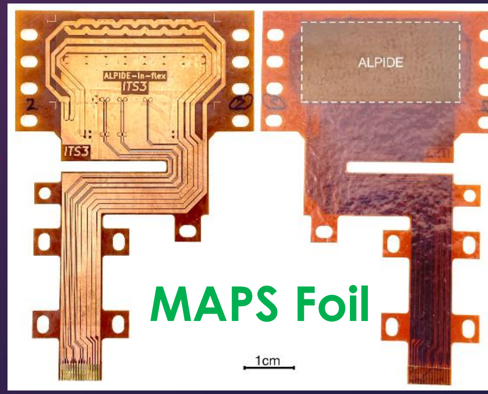
Monolithic CMOS Pixel Sensors for charged particle tracking are born 25 years ago. They have evolved in numerous aspects, relying on an industrial market which was not anticipated to preserve characteristics essential for charged particle detection

Toward a future (e+ e-) Higgs Factory:

- the challenge is still to concentrate in a single, thin, low power sensor the ambitionned spatial and time resolution
- on-going & emerging projects pave a promissing path:
  CBM-MVD (& STS upgrade), ALICE-ITS3 (& eIC expts), Belle-II ?, ALICE-3
- …..

Numerous pending questions:

- which CMOS technology: TPSCo 65 nm ?, XXX 28 nm ? … or TJsc 180 nm ?
- with/without stitching (e.g. what about sensors embedded in mylar foils ?)
- why restricting to processes featuring an EPI layer ?
- what about stacked sensors ?
- etc.



Thank You Very Much !