Vertex Detector R&D for CLIC

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on behalf of the CLICdp collaboration

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CLIC – a collider for the future

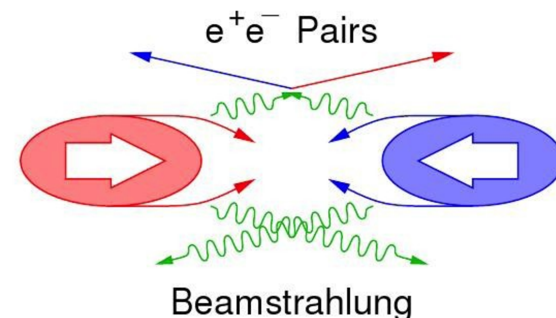
CLIC: concept for e^+e^- linear collider with $\sqrt{s}$ up to 3 TeV, aiming at performing precision measurements of Standard Model (Higgs, top) and seeking new physics beyond Standard Model

… its program is complementary to LHC

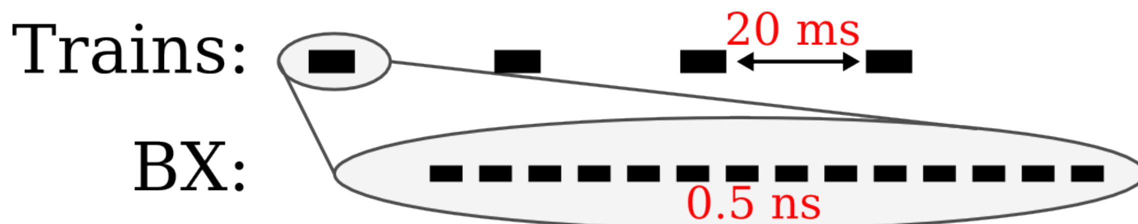
More details presented by Lucie, Sophie, Steinar

Challenging machine environment:

- Beam profile: **45 nm / 1 nm / 44 µm** (σx / σy / σz)
  → Beamstrahlung creates high particle rate
  '*beam induced backgrounds*'



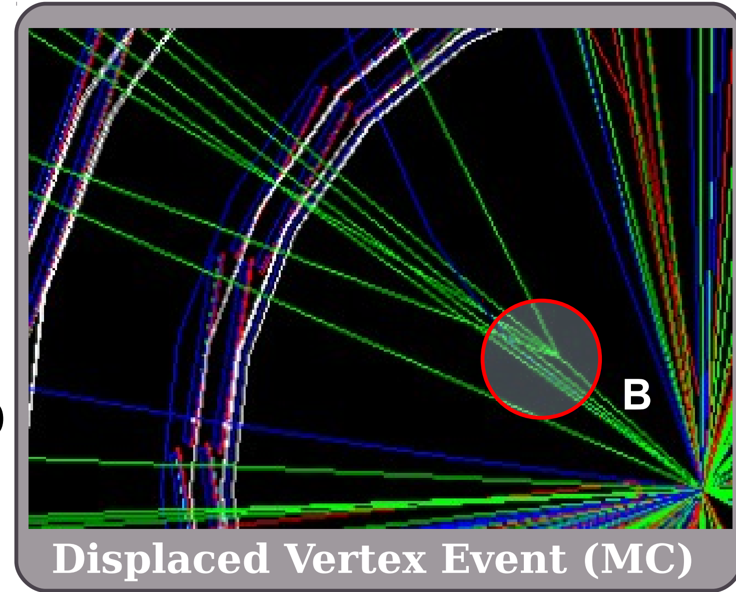
- Time beam structure:
  - Bunch crossing separation : **0.5 ns**
  - Bunches per train : 312 **(156 ns)**
  - Repetition rate : 50 Hz



Drives **timing requirements** for CLIC detectors

Vertex Detector Requirements

- Efficient tagging of heavy quarks
  (through precise determination of displaced vertices)
  - good single point resolution: **σ_{SP}~3 μm**
    → small pixels <**~25x25 μm²** (analog readout)
  - low material budget: **X ≲ 0.2% X_0 / layer**
    (corresponds to ~200 μm Si, including supports, cables, cooling)
    → very thin sensors and ASIC (**~50 + 50 μm**)
    → gas-flow cooling
    → low-power ASICs (**~50 mW/cm²**)
- 156 ns bunch trains
  → **trigger-less readout**
- 20 ms gaps between trains
  → **power pulsing**
- Beam-induced background
  → **time stamping ~10 ns**
- Moderate radiation exposure
  (NIEL < 10^{11} n_{eq}/cm²/y, TID < 200 Gy / year)



Displaced Vertex Event (MC)

Multi-layer barrel and endcap pixel detectors
(560 mm in length, Barrel radius from 30 mm to ~70 mm)

Detector R&D road map

Motivation: **Evaluate performances and yield of thin pixel sensor and demonstrate the feasibility of a good tracking efficiency with thin assemblies**

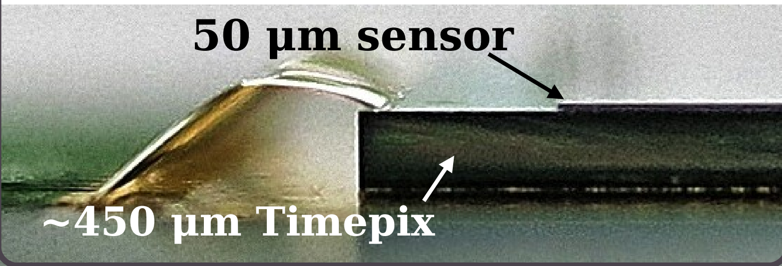
Ultimate goal: 50 µm thick sensors + 50 µm thick ASICs, 25µm pixel pitch

- **Timepix readout ASIC** (55x55µm^2 pixel pitch) was used for **feasibility tests** of ultra-thin sensors-assemblies (**50, 100, 200 µm** thick sensor on 450 µm and **100 µm** thick ASIC)
- **CLICpix** readout ASIC development (**25x25 µm^2** pixels). Assemblies with planar sensor in production (bump bonding challenging). Assemblies with **capacitively coupled HVCMOS active sensor** used to validate the chip.

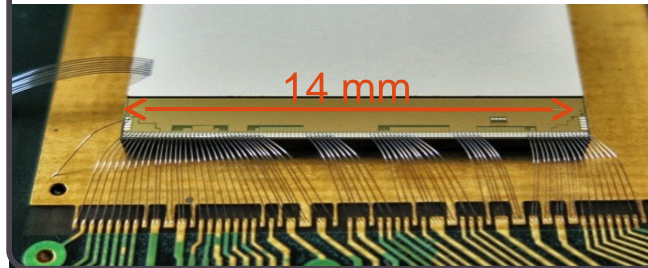
50 µm dummy wafer

Thin sensor assemblies: laboratory tests

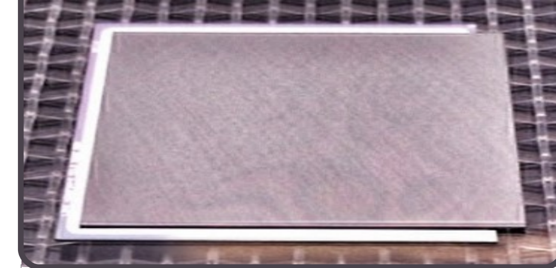
50 µm active-edge sensor (side view)



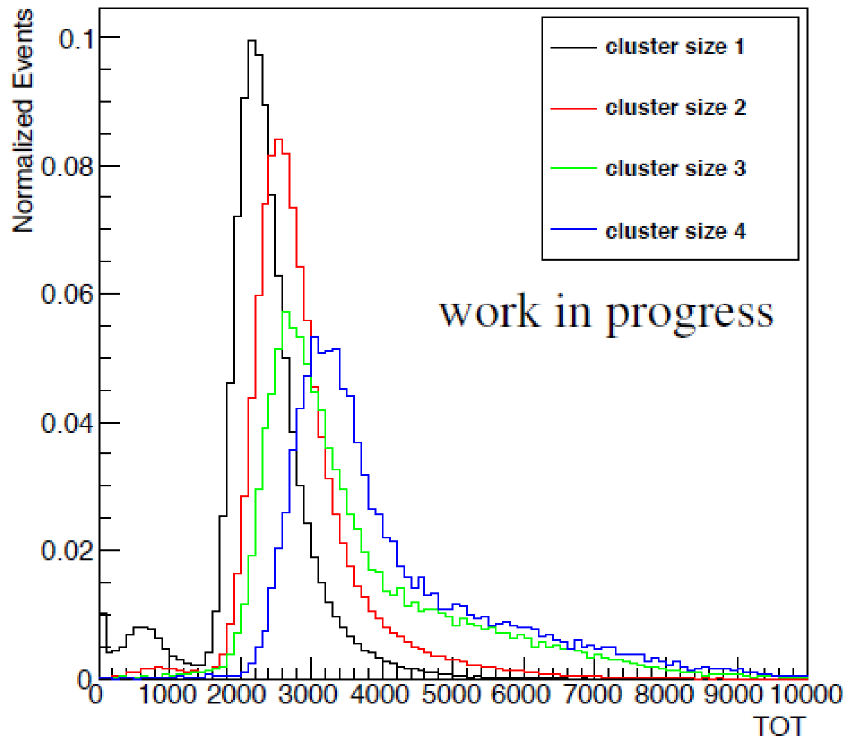
50 µm active-edge sensor (front view)



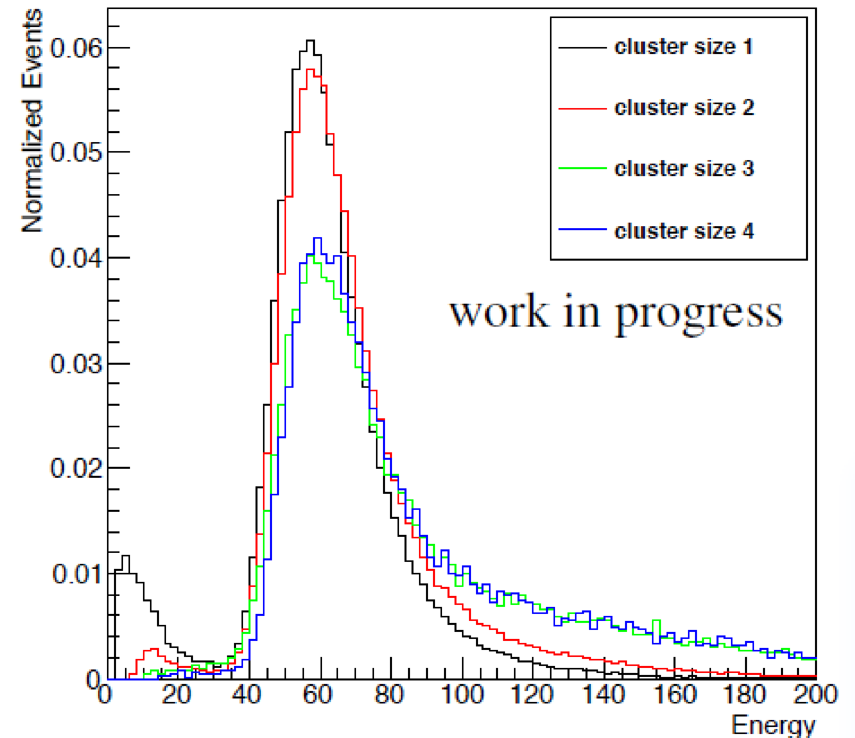
100 µm slim-edge sensor on 100 µm Timepix ASIC



Uncalibrated energy spectra



Calibrated energy spectra

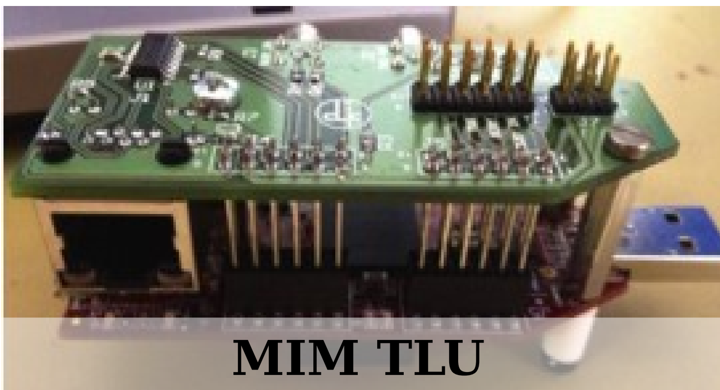


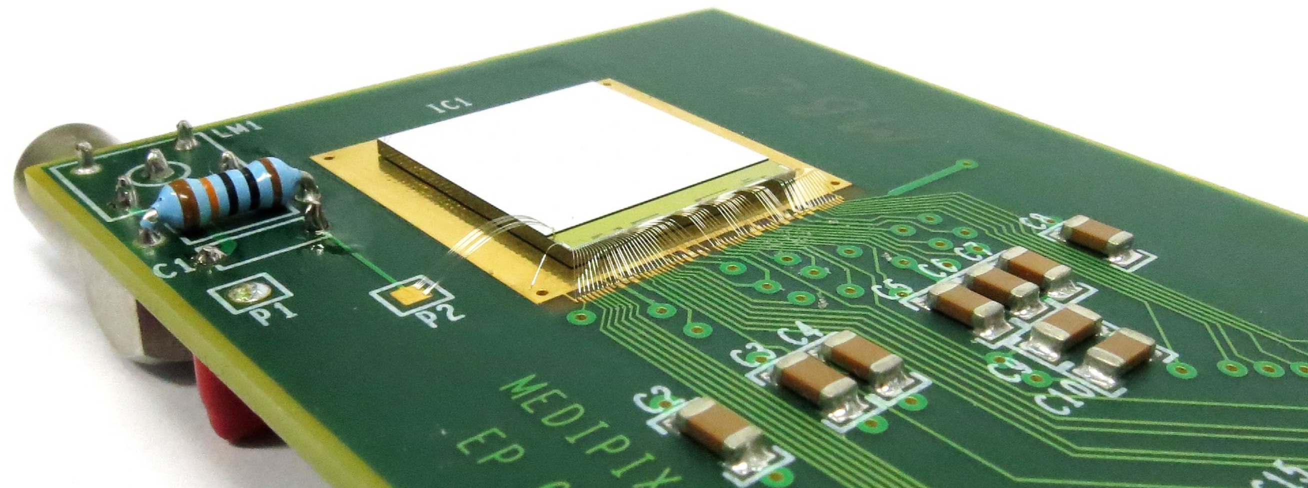
200 µm thick sensor | sensor calibration was performed in lab tests at CERN and LNLS synchrotron. | Spectra for MIPs

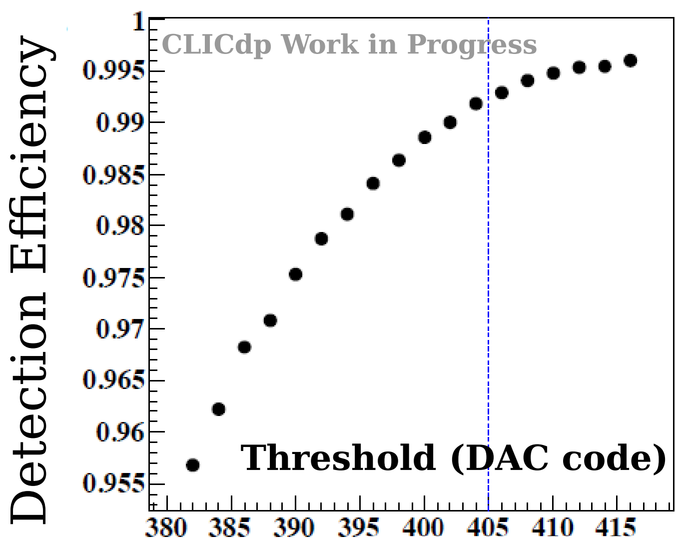
Thin sensor assemblies: testbeam setup

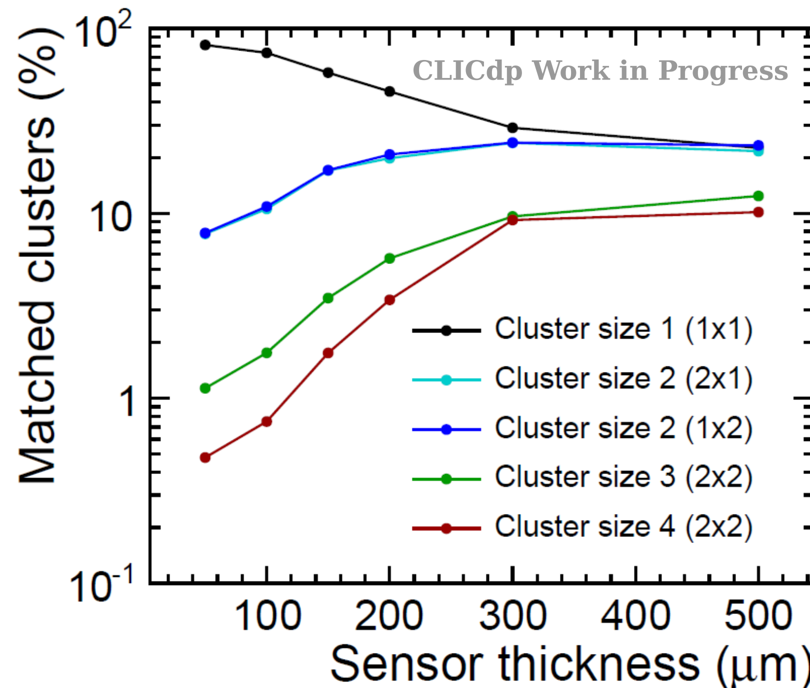
Test beams at DESY and CERN

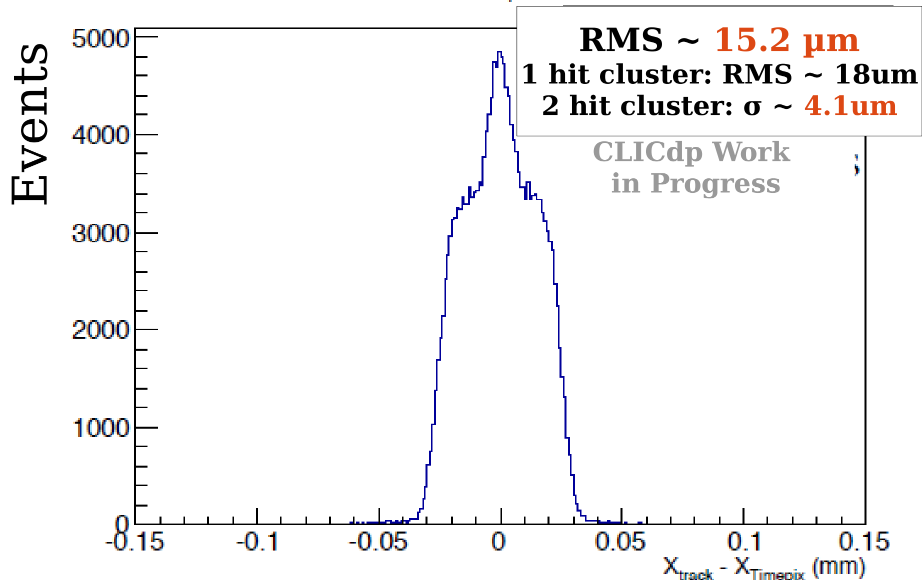
- **EUDET Telescope** based on MIMOSA detectors → resolution at DUT ~ 3 μm
- **Hardware and software integration** of Timepix detector (MIM TLU) with EUDAQ
- **Optimized** telescope **geometry**
- Assemblies on translational and rotational stages
- **Analysis software**









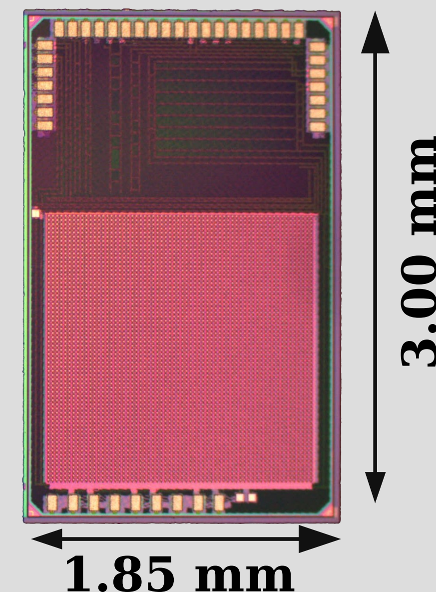


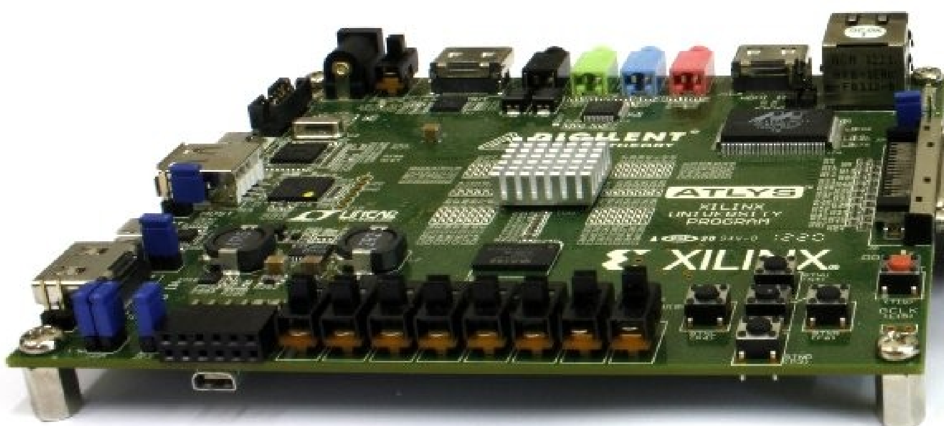
Using **charge sharing information** (for cluster size > 1) it is possible to **gain more than factor of 3 in single-point resolution**.

For **50 µm** thick sensor (and 55µm pixel size) this type of events represents only 20% of the data → **smaller pixel size is needed.**

CLICpix Chip and Readout system

- 65 nm CMOS hybrid r/o chip, targeted to CLIC vertex detectors
- based on Timepix/Medipix chip family,synergy with HL-LHC pixel r/o projects (RD53 collaboration on 65 nm r/o)
- demonstrator chip with 64 x 64 matrix
- 25 µm pixel pitch
- simultaneous time (4-bit TOA, 10ns) and energy (4-bit TOT) measurement per pixel
- selectable compression logic (pixel, cluster + column-based)
- power pulsing enabled (P_{avg} < 50 mW/cm^2)



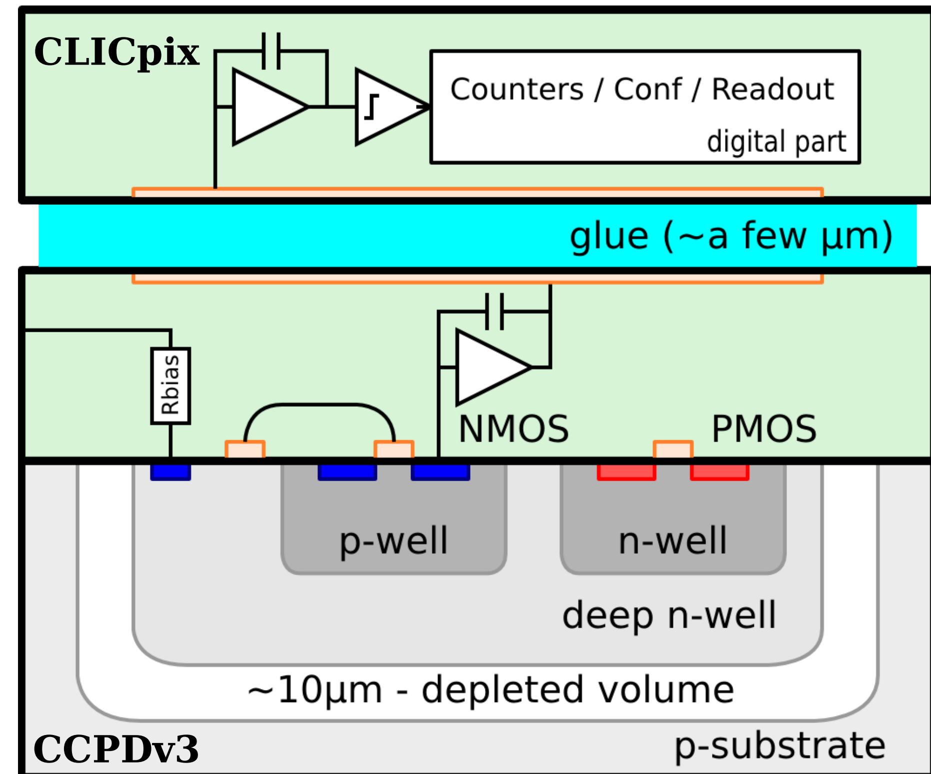


FPGA Board   Interface Board   Chip Board

Capacitively Coupled Pixel Detector

Conventional sensors require (costly and low pitch) bump-bonding in order to DC-couple the pixel implant with the amplifier input

- AC-coupling not previously used due to low coupling capacitance
- Can be overcome by amplification and shaping of the signal on the sensor side



Half way between conventional hybrid pixel detectors and fully-integrated CMOS circuits

Advantages:

- low material budget (sensor can be thinned, active area is in order of ~10µm)
- sub pixels position encoding possible → to a demonstrated
- industry standard deep n-well technology (large volume, cheap)
- cost savings (lack of bump-bonding) → to a demonstrated

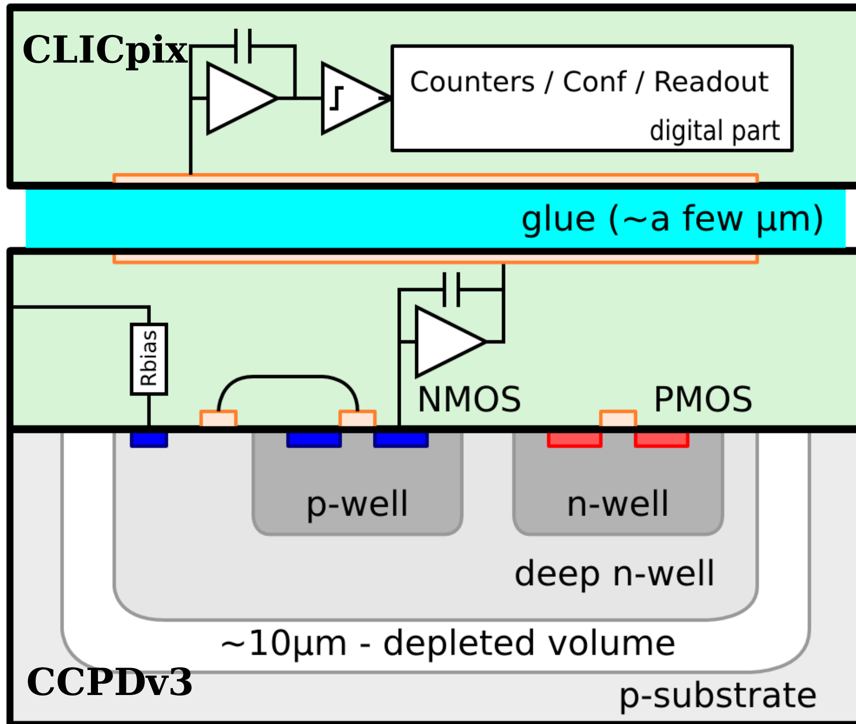
Disadvantages:

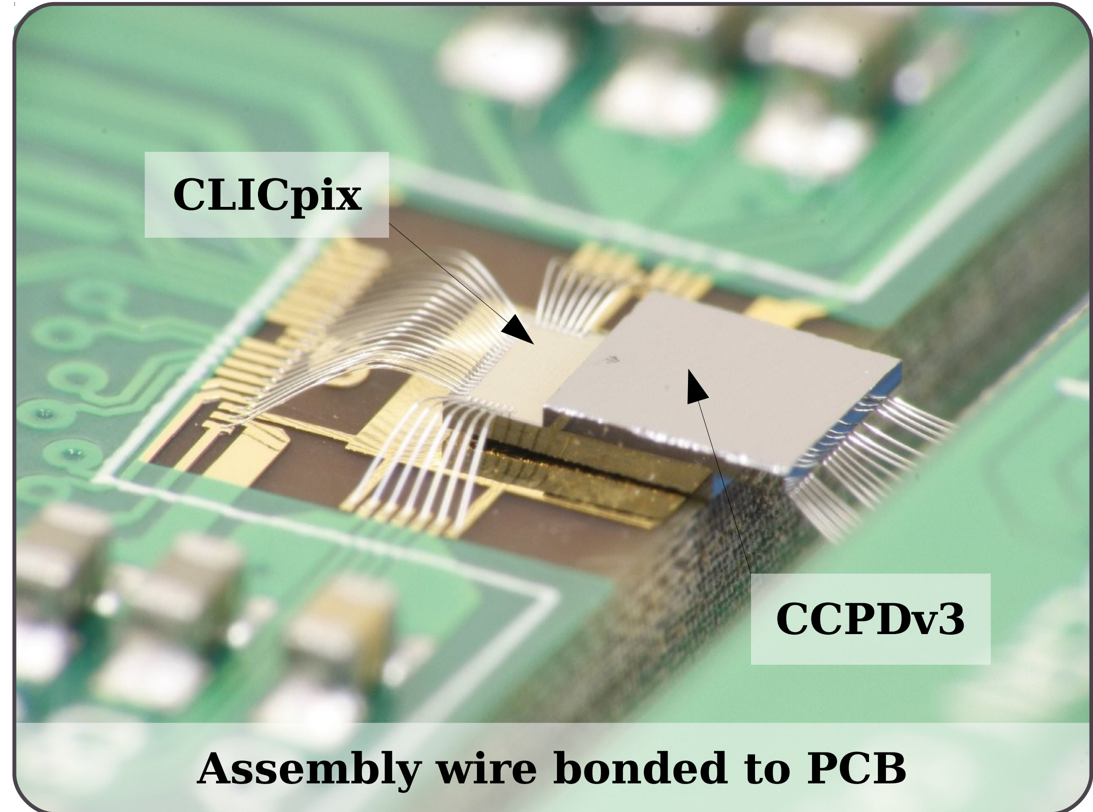
- sensor consumes power (may be significant)

Challenges:

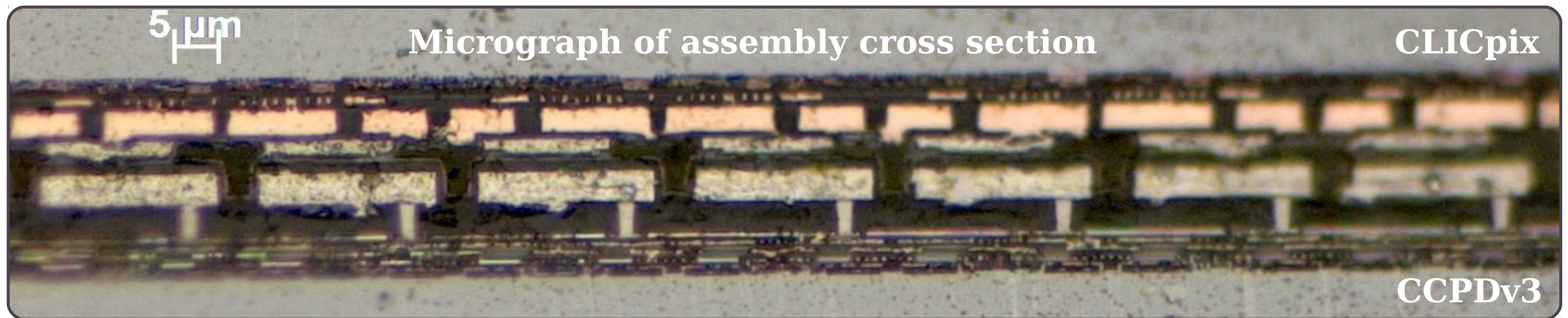
- precise gluing and alignment

CCPD Assemblies





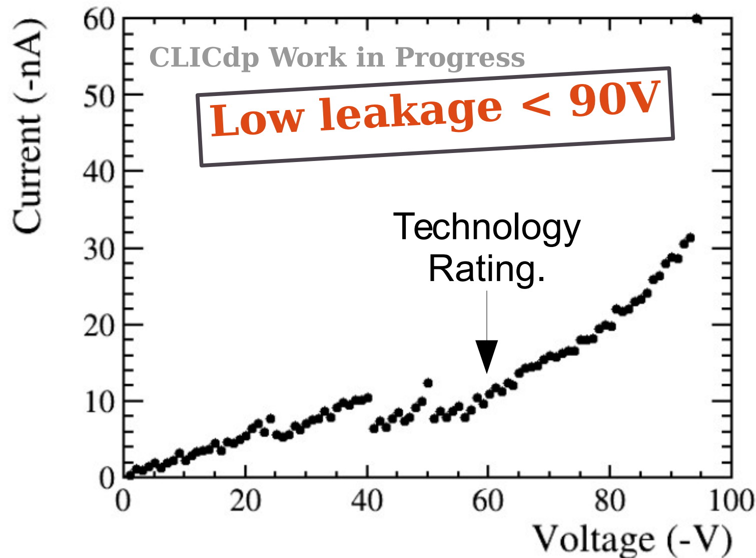
Assembly wire bonded to PCB

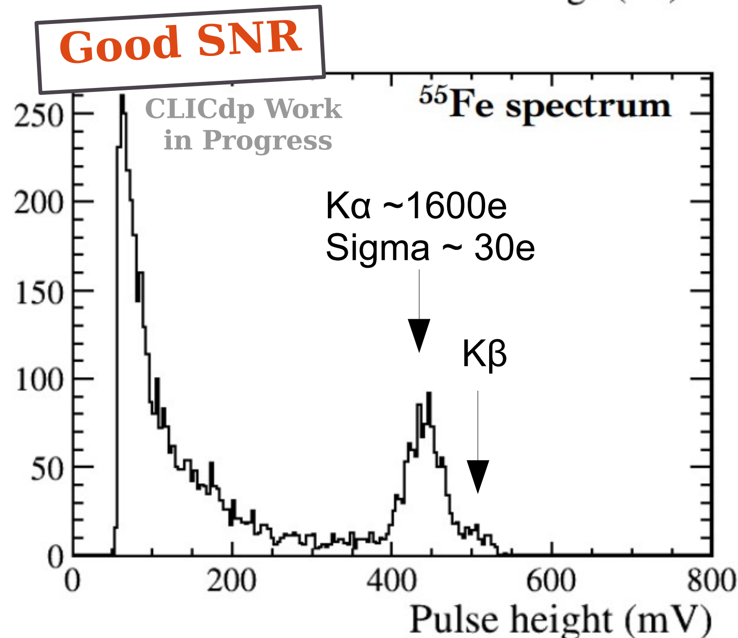


Micrograph of assembly cross section

CLICpix & CCPDv3 – Lab measurements

CCPDv3 only measurements



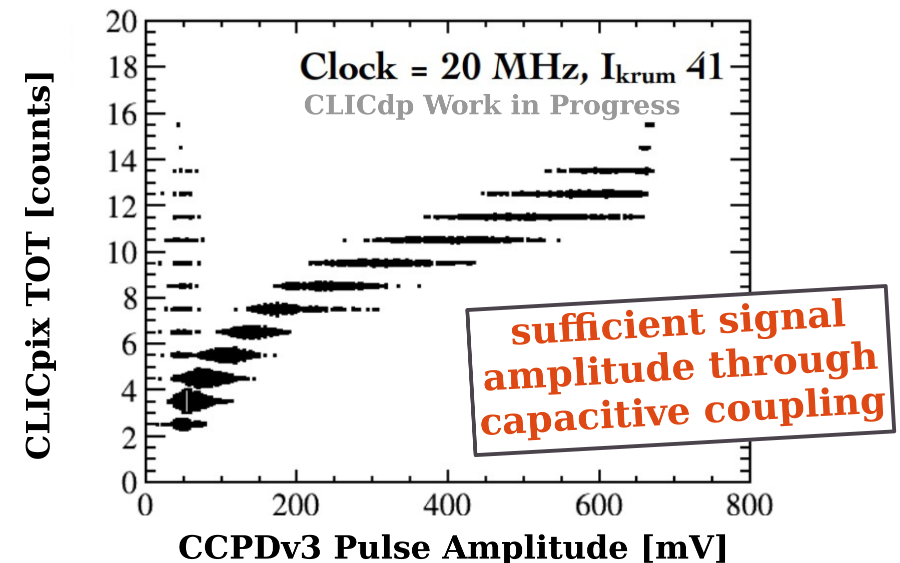


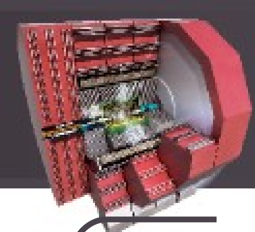
CLICpix performance

Chip has been fully characterized, nominal operating point:

- ENC: **55 [e-]** *(without sensor)*
- Threshold spread **128 / 22 [e-]** *(uncalibrated/ calibrated)*
- Power consumption: **7 [μW/pixel]** *(without power pulsing)*
- Gain: **44 [mV/ke]**
- Timing accuracy: **<10ns** (chip can be tuned to CCPD signals)

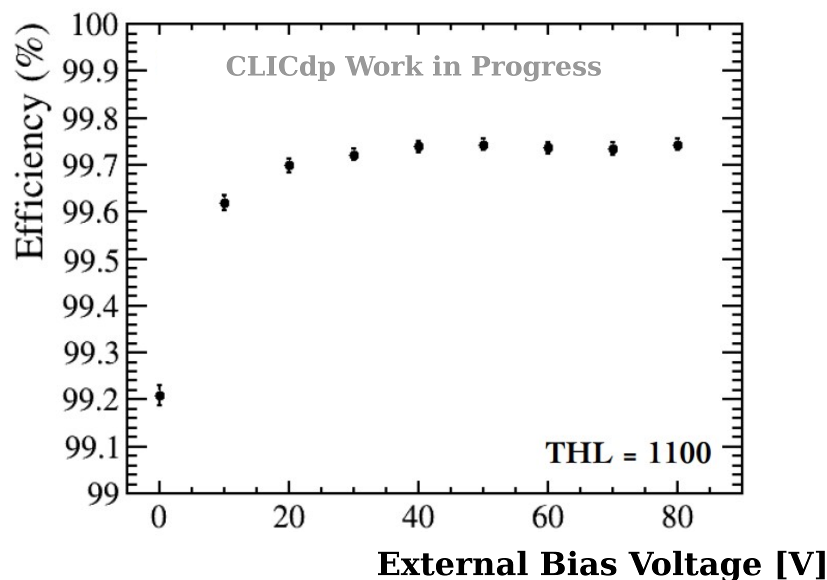
CLICpix + CCPD - coupling

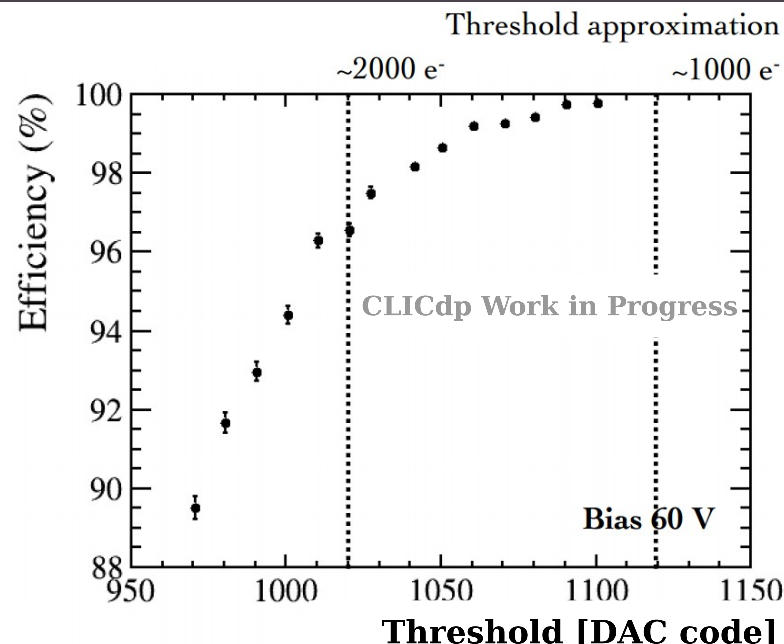




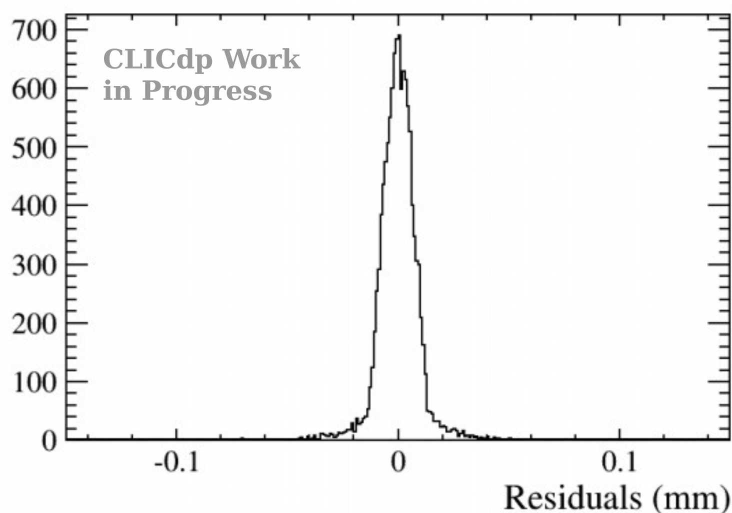
CLICpix & CCPDv3 – results

Detection efficiency





Residuals



Promising early results from CCPDv3 assemblies:

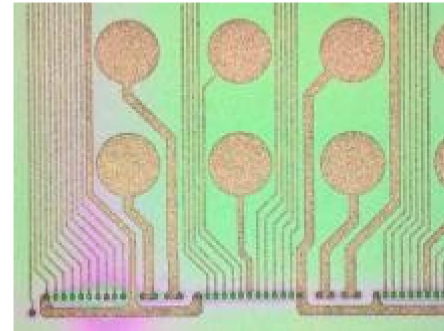
- **full matrix appears responsive**
- **high detection efficiency** (even without applied bias voltage)

More studies needed to make device manufacture robust (gluing and measurements of the coupling capacitance)

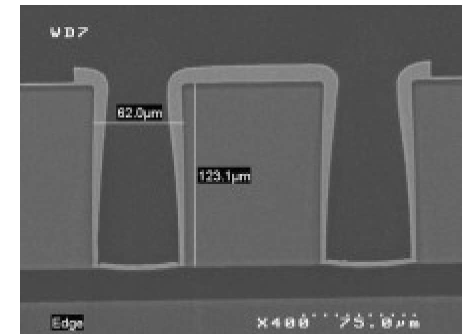
Through-Silicon Vias (TSV)

Through Silicon Via: vertical electrical connection passing through Si wafer

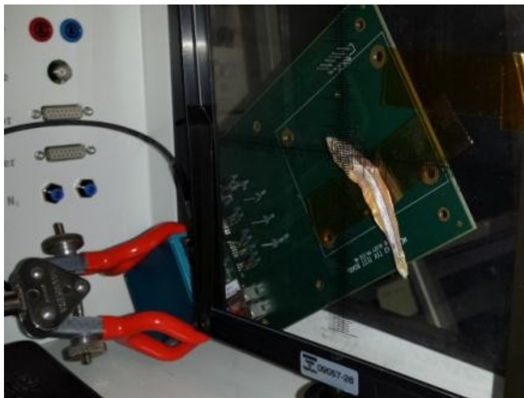
- eliminates need for wirebonds
- enables 4-side buttable chips
- increased reliability



Medipix3 redistribution layer



SEM cross section of TSVs



X-ray setup

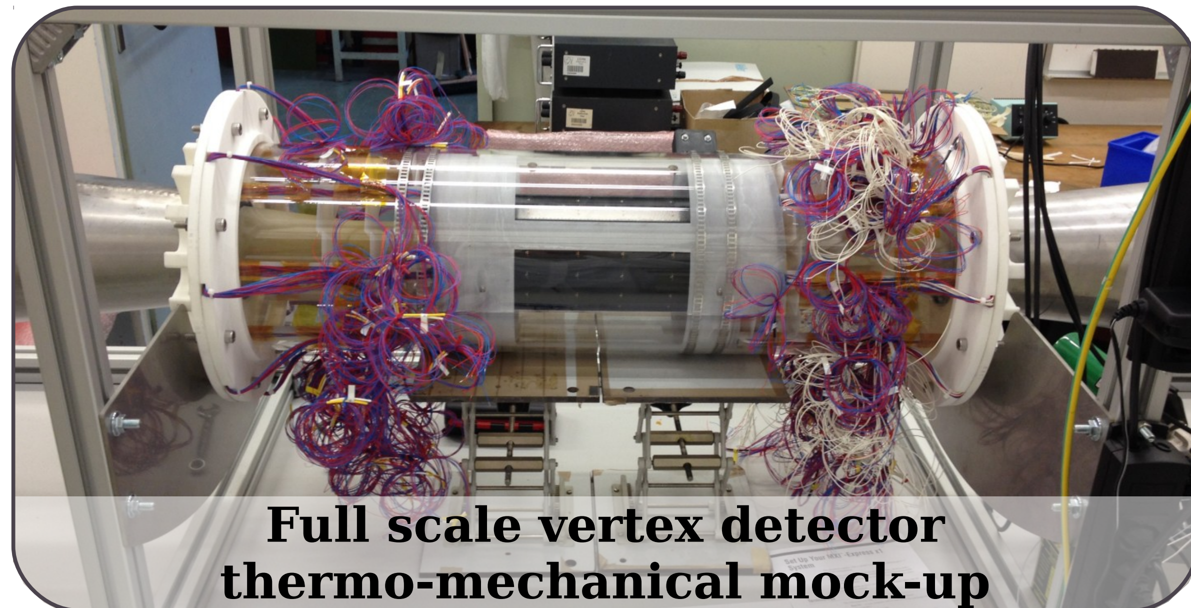
X-ray photograph

TSV project (ALICE, CLIC, ACEOLE, AIDA) with CEA-Leti

- 130 nm Medipix3 and Timepix3 wafers
- first phase: feasibility demonstrated
- second phase: good yield demonstrated
- on-going third phase:
  TSV with 50 µm thick wafers (CLIC goal!)

500 µm sensor on 120 µm ASIC bump bonded to PCB (side view)

- Evaluation of forced convection air cooling *(full scale prototype)*
- Measurement & characterization air-flow induced vibrations *(wind tunnel, laser sensor)*
- Development and characterization of low-mass ladder support *(~0.05% X_0)*



Ladder support structure prototypes

Summary & Outlook

- CLIC environment + physics requirements pose challenging demands on vertex-detector system *(a new kind of challenges compared to LHC)*
  - Less radiation damage but ...
  - Higher spatial resolution precision (~3 µm)
  - Finer time stamping (~10 ns)
  - Lower power (0.3 µW/channel, 50 mW/cm^2)
  - Lower material budget (0.2 % X_0)
- Ongoing active R&D on:
  - Thin sensors
  - Readout technologies
  - Interconnection technologies
  - Power-delivery and power pulsing *(not covered in this talk)*
  - Mechanics, cooling