UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

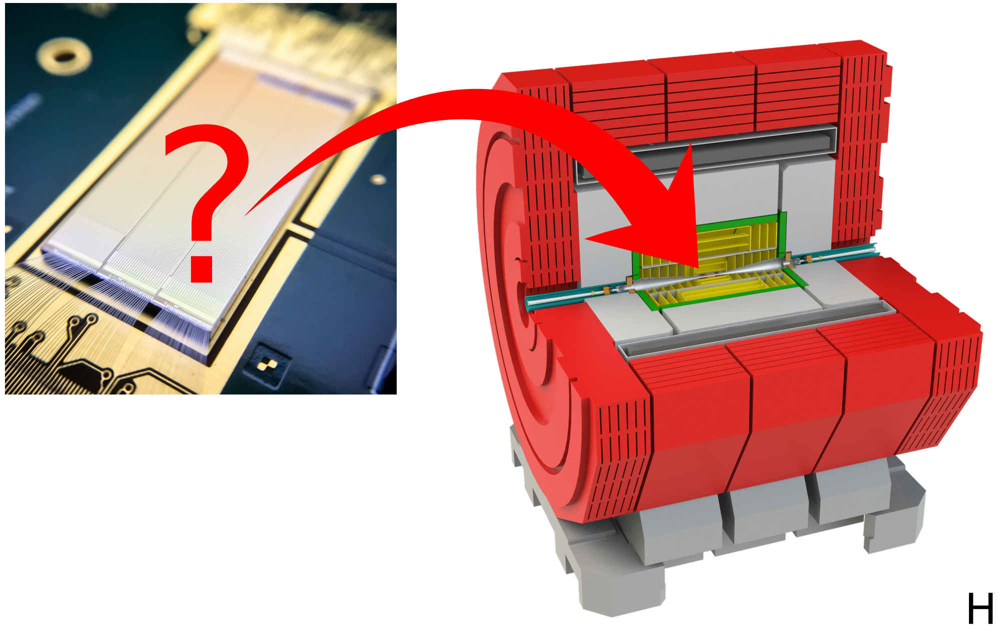
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

EP R&D

CERN

Silicon Pixel Detector R&D

for Future HEP Experiments



18th Wolfgang Gentner Day

CERN, October 28th, 2020

Jens Kröger

Heidelberg University & CERN

supervisors:

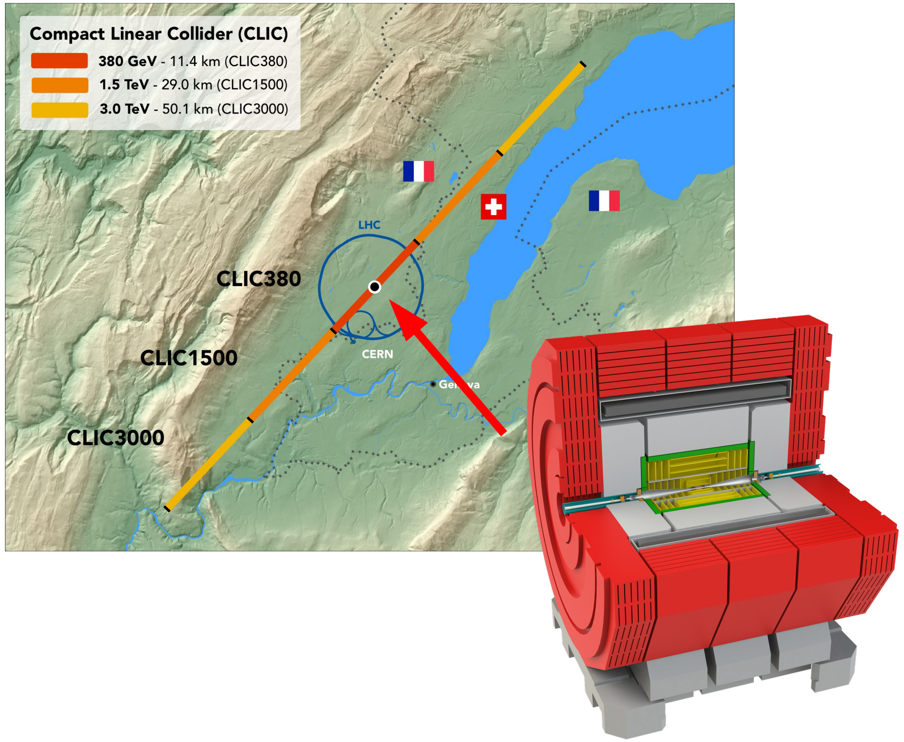
Prof. Dr. Andre Schöning (Uni Heidelberg)

Dr. Dominik Dannheim (CERN)

The Future of HEP

and then?

- **circular?**
- **linear?**



Compact Linear Collider

- $e^+ e^-$ with energies up to 3 TeV
- up to 50 km long
  → construction in 3 stages
- precision Higgs + top physics + BSM

We don’t know yet…but for all:

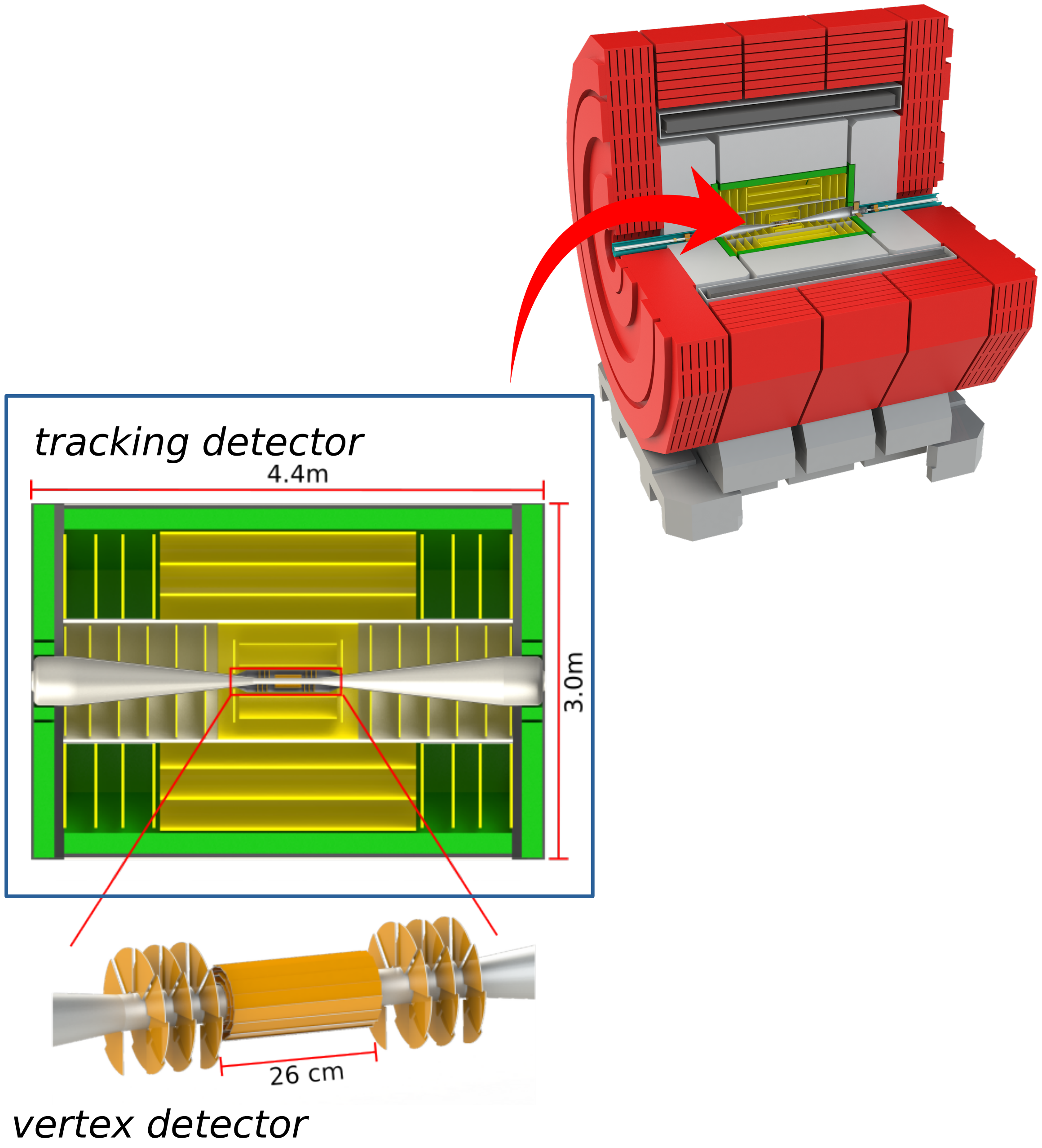
→ stringent detector requirements
→ extensive R&D needed

clic – detector requirements

- **triggerless readout**
  in 20 ms gaps between bunch trains
- timing resolution: ~ **5 ns**
- hit detection efficiency: **99.7-99.9%**
- low radiation exposure

Tracking Detector

- ~140 m² silicon
- spatial resolution: **~ 7 μm** (transversal)
- max. granularity: **1-10 mm** pixel size (long.)
- material budget: ~ **1-1.5 %** X_0/layer



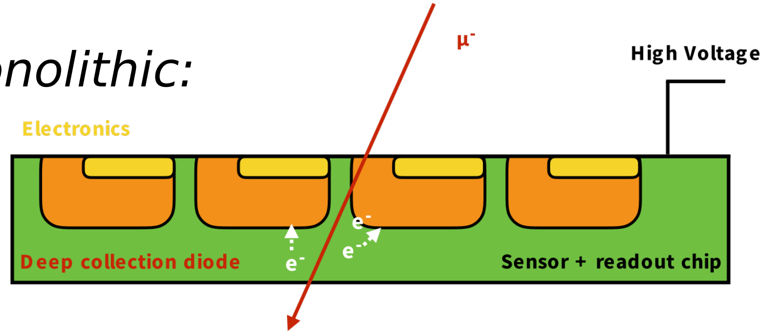
see also *CLICdp-Note-2017-002*

HV-MAPS – the technology

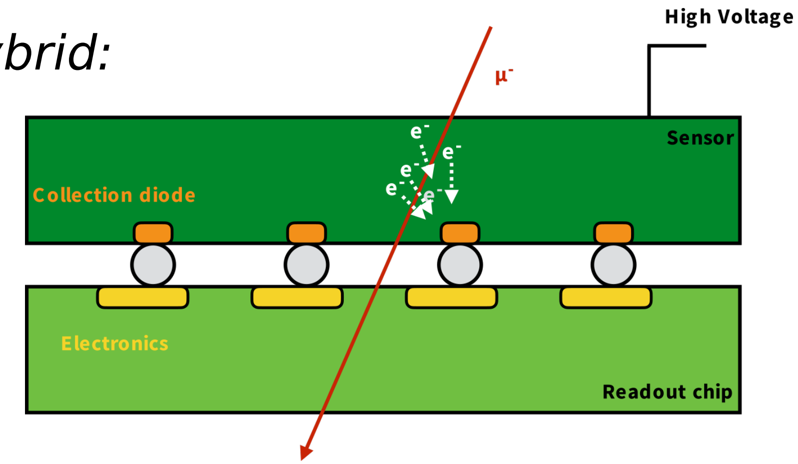
High **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors:

- **active**
  - in-pixel amplifier
- **monolithic**
  - signal generation + readout integrated in single chip (↔ hybrid sensor)
  - **low material budget**
- **high voltage**
  - O(100V) bias voltage
  - **fast** charge collection via drift (↔ diffusion)
  - large depleted volume → **large signal**

monolithic:



hybrid:



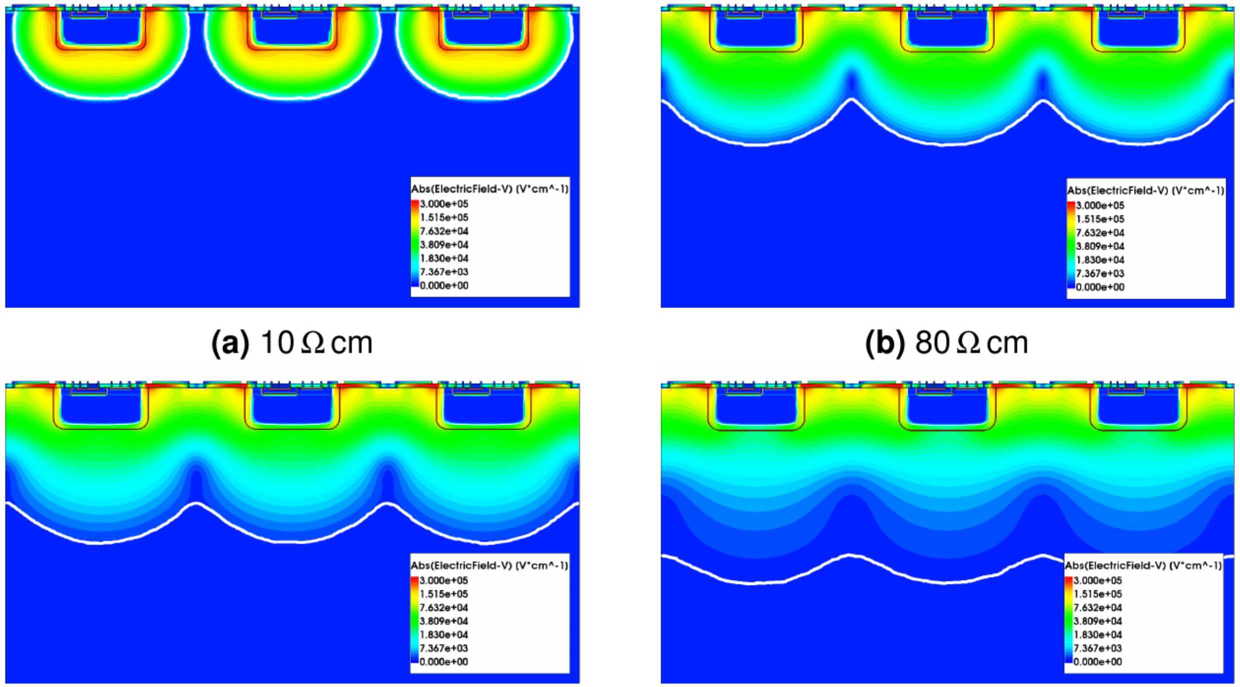
HV-MAPS with large collection electrodes

- intrinsic **radiation hardness**
- large depleted volume
  → **large signal**
- uniform electric field
  → **uniform response**
  (similar to planar sensor)

substrate resistivity ρ:

$$\text{Ohmic } R = \rho \cdot \frac{\text{length}}{\text{area}}$$

- higher resistivity → larger depleted volume for given high voltage

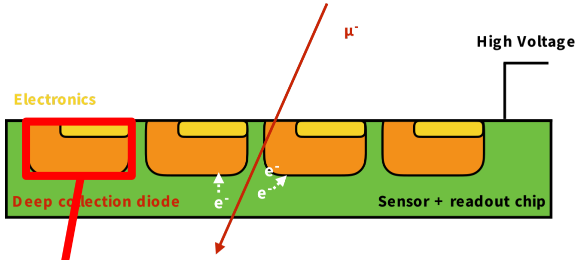


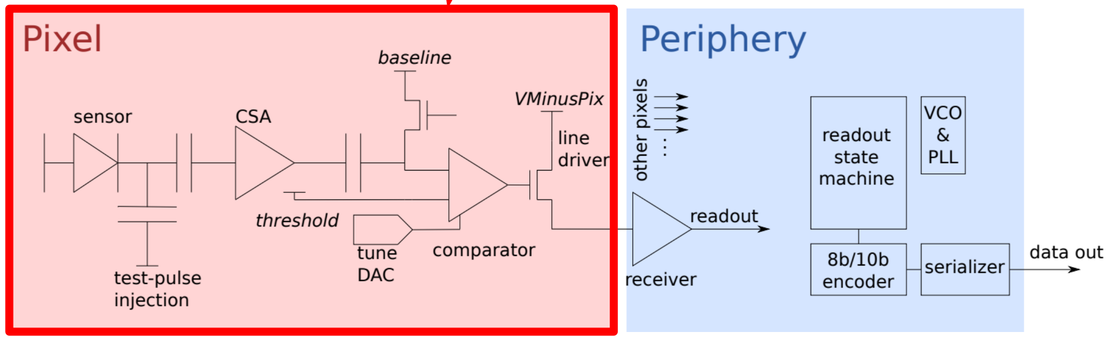
(a) 10 Ω cm **(b)** 80 Ω cm **(c)** 200 Ω cm **(d)** 1 kΩ cm

|Electric field| for ***different substrate resistivities*** *at same high voltage*

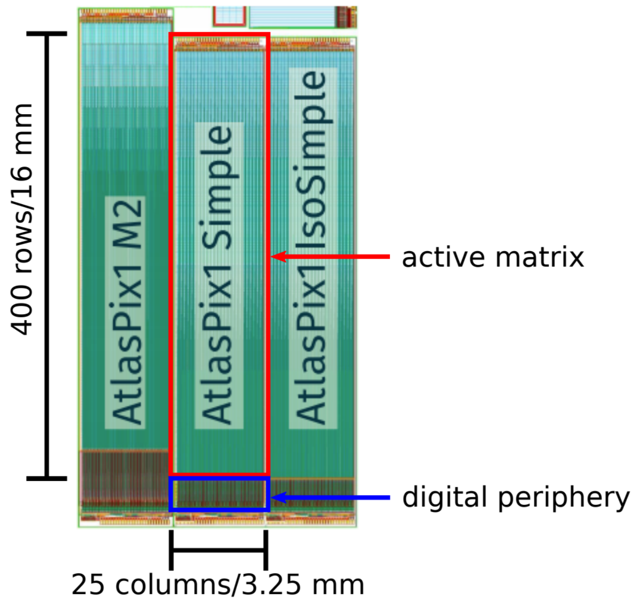
The ATLASpix – an HV-MAPS example

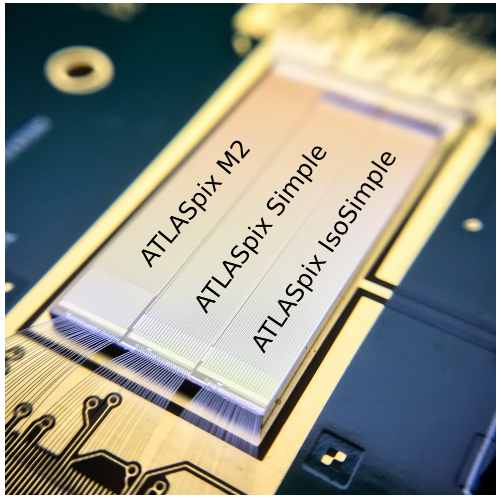
- designed for
  - **ATLAS ITk** upgrade
  - **CLIC** tracking detector





technology	180nm HV-CMOS
pixel matrix	25 columns x 400 rows
pixel size	130 x 40 µm²
readout scheme	self-triggered/continuous
readout mode	time + energy (in each pixel)
substrate resistivity	**20, 80, 200 Ωcm**

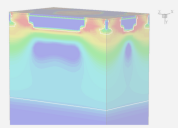




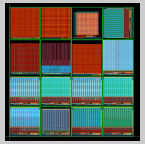
part of my thesis:
yes, no

The Life Cycle of Prototyping

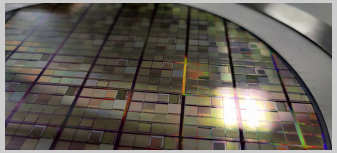
Early R&D
- TCAD simulations
- process optimization



Chip Design

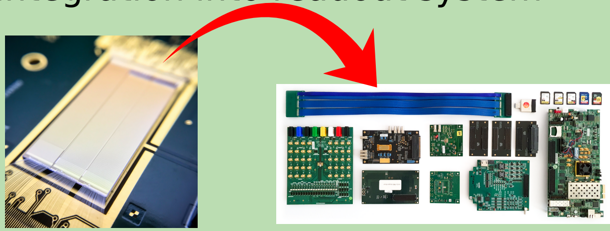


Manufacturing



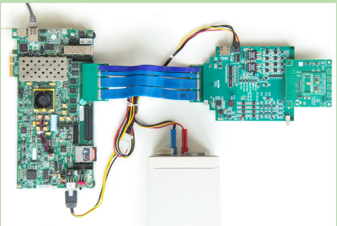
not covered today

Commissioning
- integration into readout system



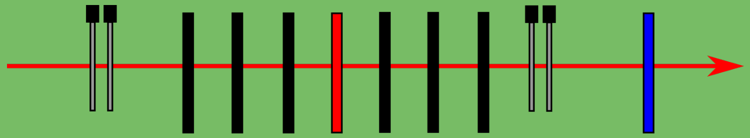
not covered today

Lab Characterization
- optimization of chip settings

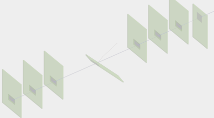


Focus of today

Test-beam Characterization
- hit detection efficiency
- spatial + time resolution

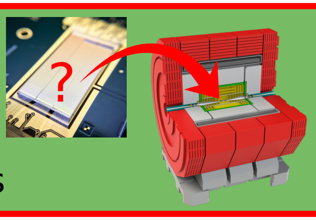


Complementary Simulations
- telescope performance
- ...



Focus of today

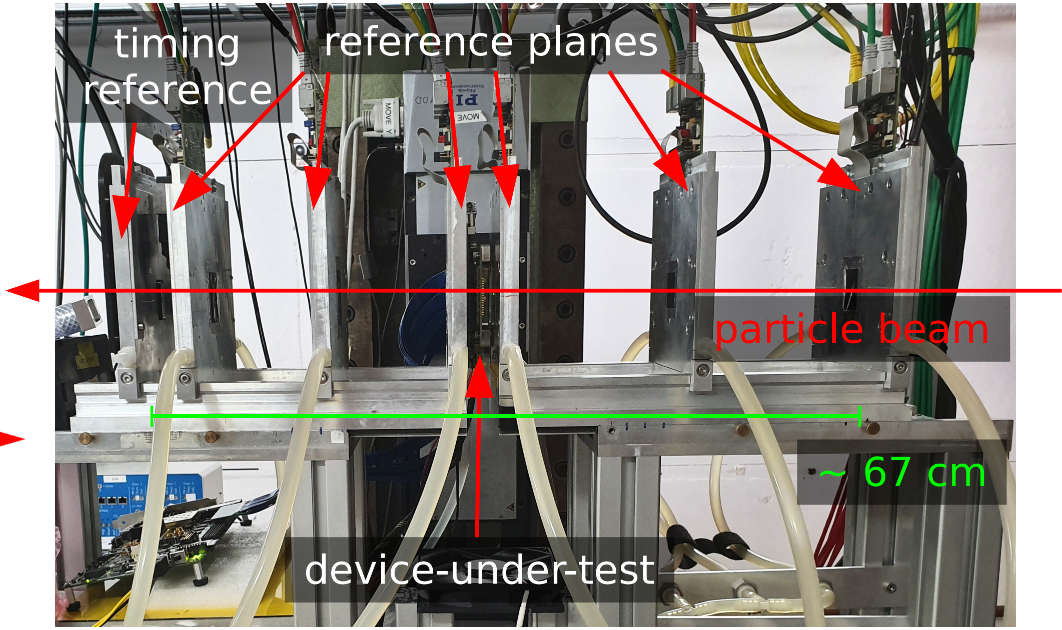
Evaluation
- compare to specifications
- feedback to chip designers

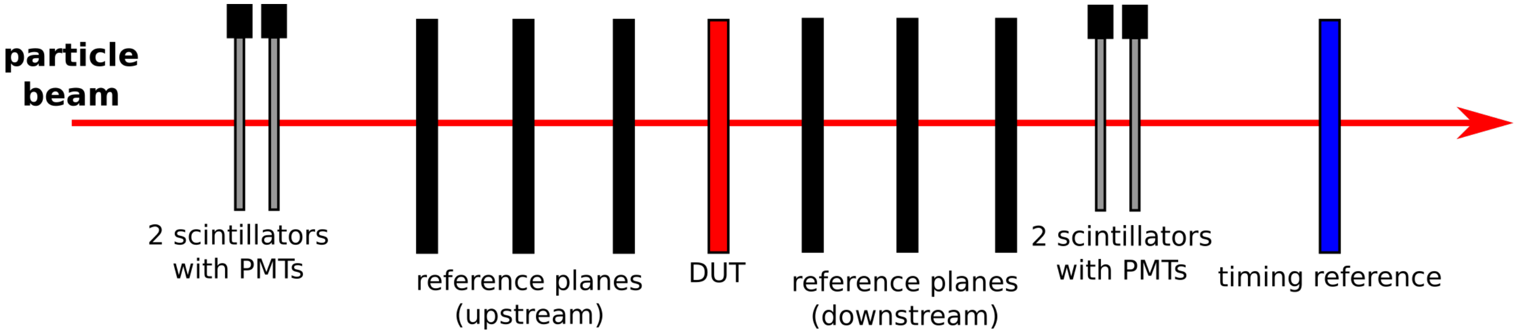


Test Beam Setup at DESY

DESY II test-beam facility
(Hamburg, Germany)

- reference detectors:
  - combine hits into **reference track** (incl. timestamp)
  - determine **precise intercept** with device-under-test (DUT)
- compare track with hits on DUT
  - spatial + time resolution
  - hit detection efficiency



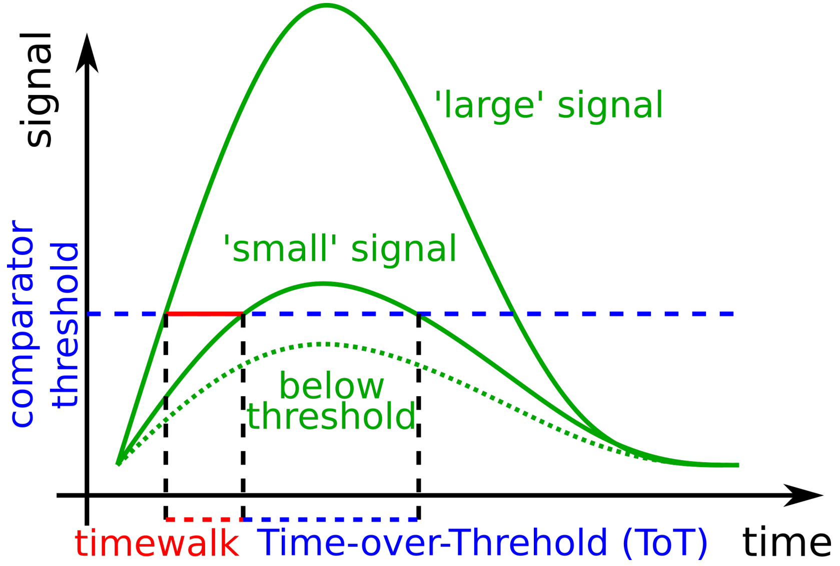


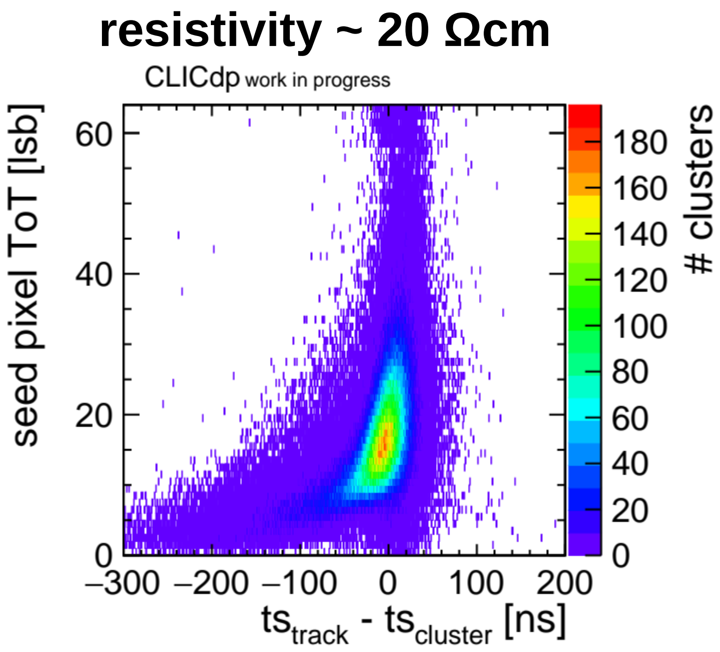
Some Example Results

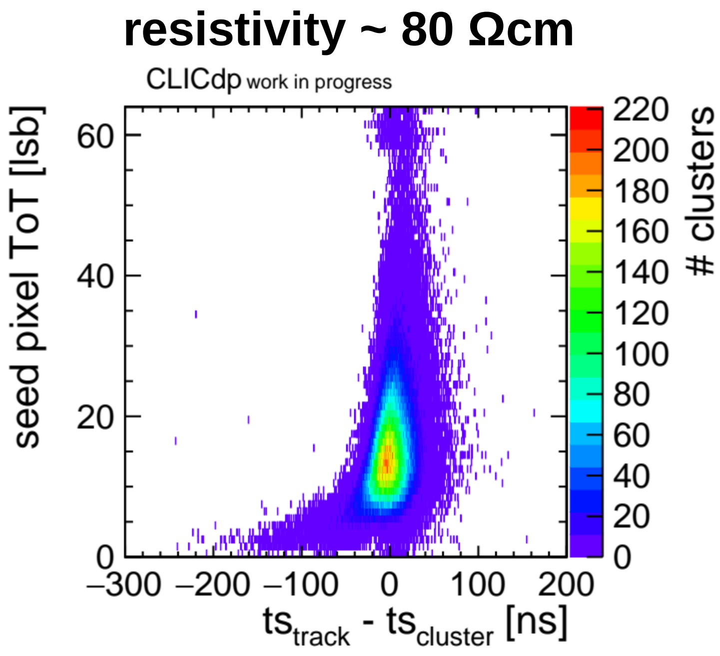
from ATLASpix test-beam measurements

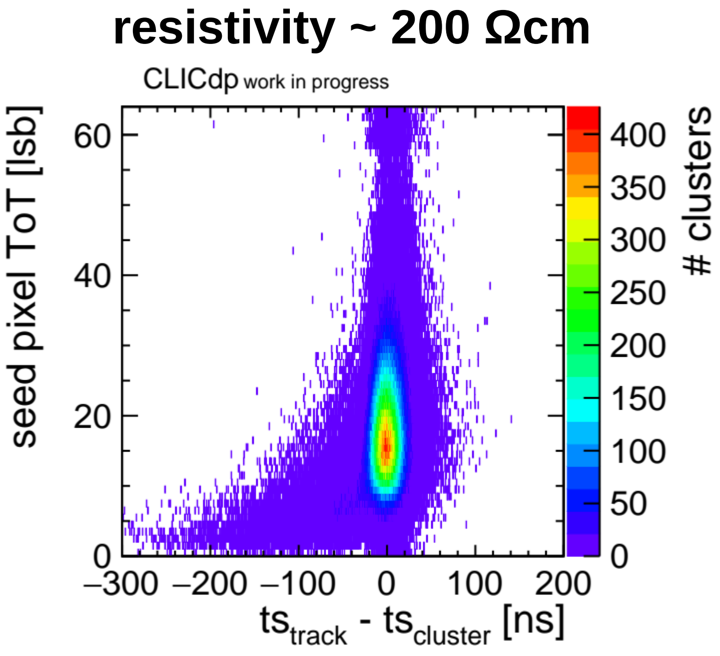
ATLASpix – timewalk

- comparing **different resistivities** at:
  - threshold ~ 1080 e⁻
  - high voltage = -50 V
- clear dependence on resistivity









ATLASpix – timing performance

- comparing **different resistivities** at:
  - threshold ~ 650 e^-
  - high voltage = -50 V

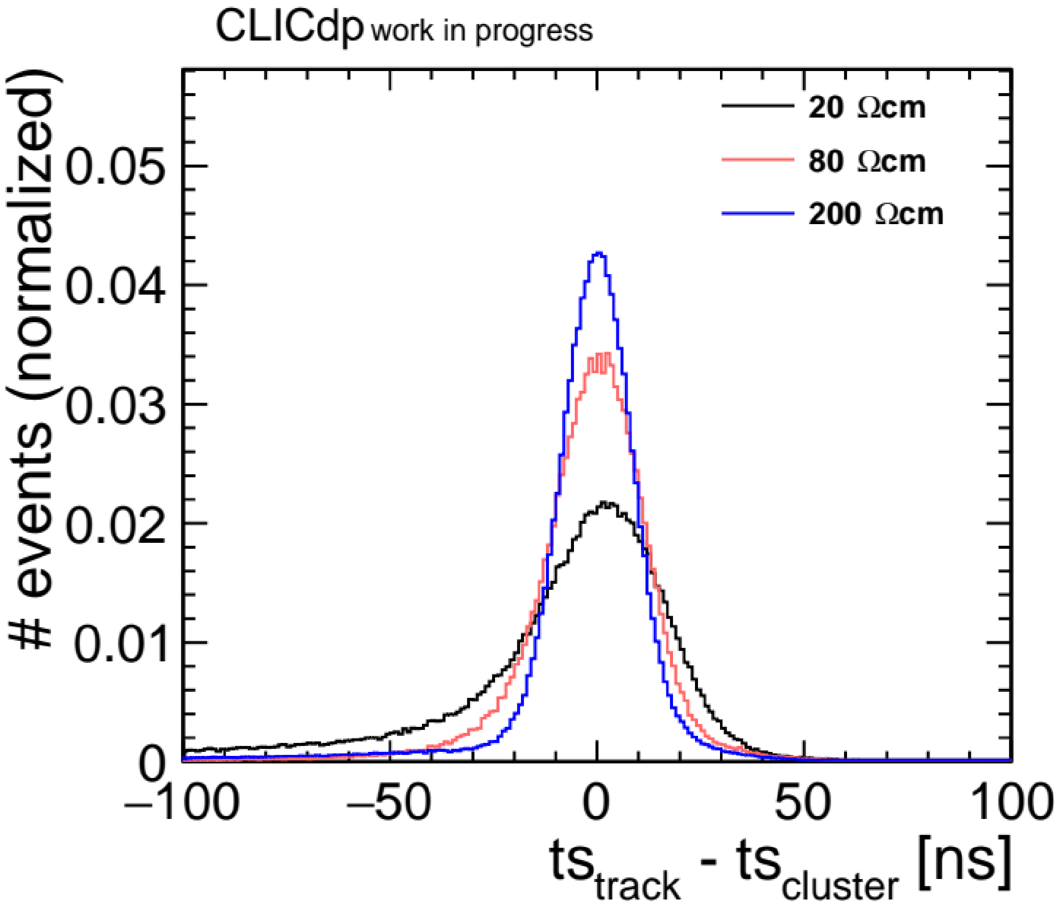
- clear dependence on resistivity:
  higher resistivity → larger depleted volume
  → higher signal/better S/N → larger field
  → faster charge collection/less timewalk

- after timewalk correction:

resistivity [Ωcm]	σ_{Gauss} [ns]
20	13.3
80	9.4
200	8.3

- **best result: σ_{Gauss} = 6.8 ns**
  (200 Ωcm, 100 µm, high voltage = -50V, threshold = 480 e^-)

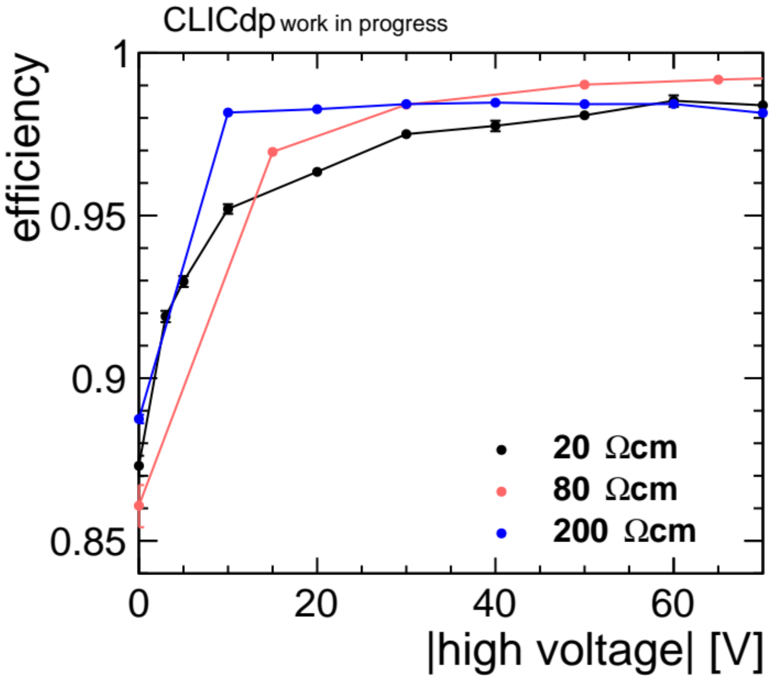
time residuals for different resistivities



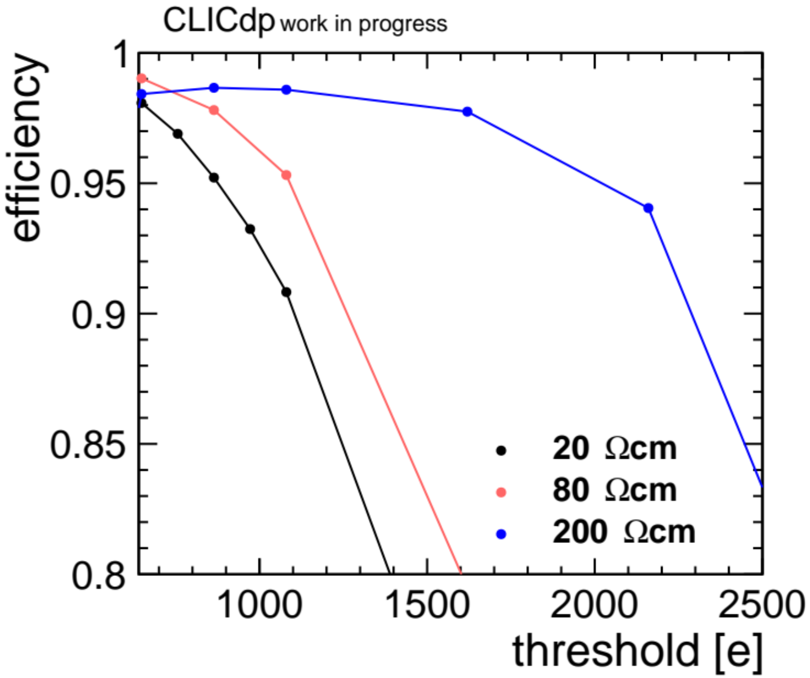
ATLASpix – hit detection efficiency

- comparing **different resistivities**
- efficiency peaks above ~ 99 %
- as expected: larger efficiency operating window at higher resistivities

threshold ~ 650 e⁻



high voltage = -50V

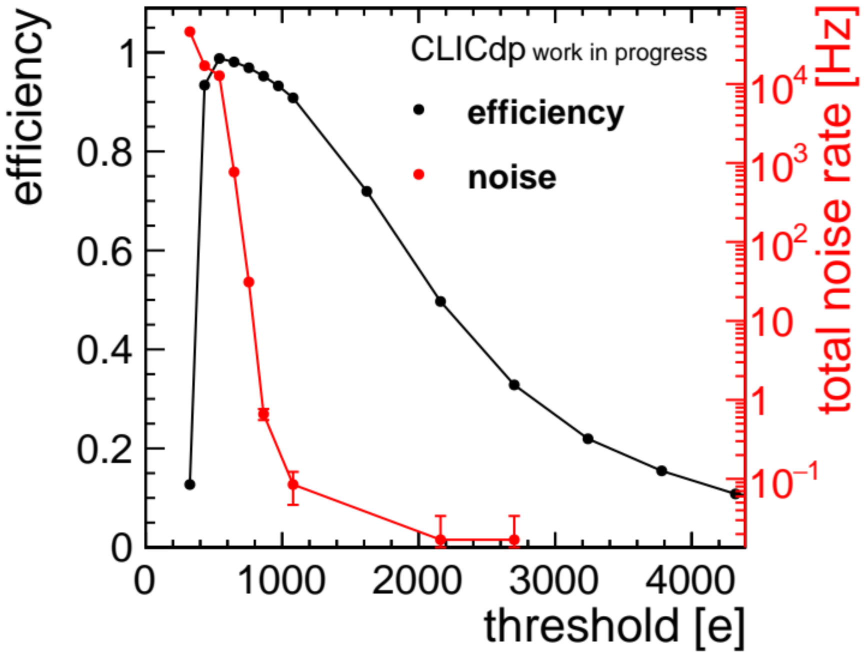


ATLASpix – efficiency & noise

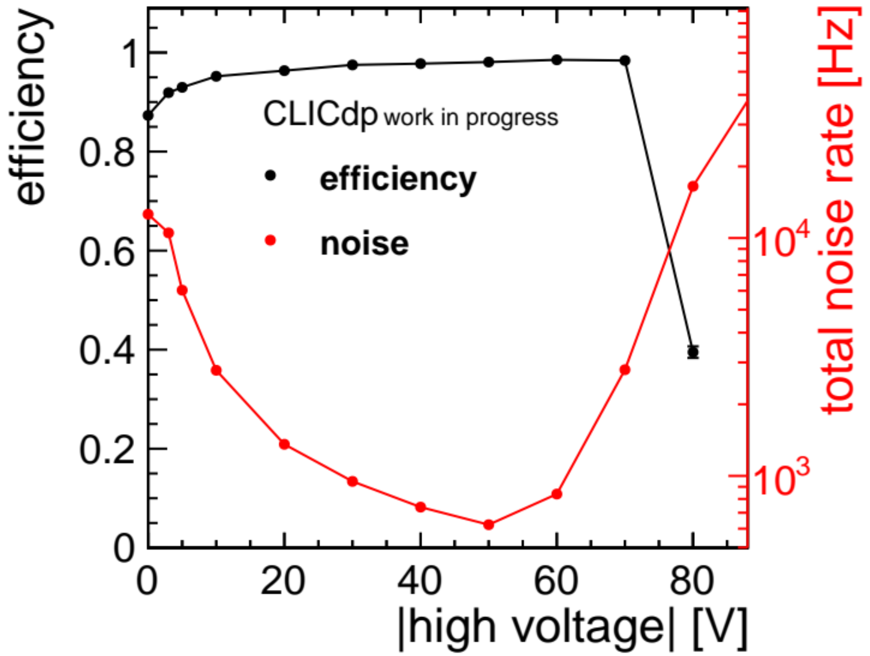
- here: sample with 20 Ωcm
- find balance
  efficiency ↔ noise rate

- large bias/low threshold:
  - **over-saturated readout**

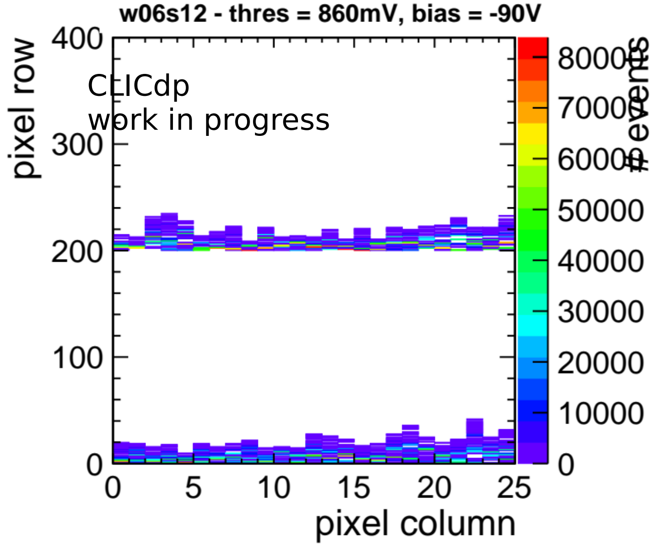
high voltage = -50V



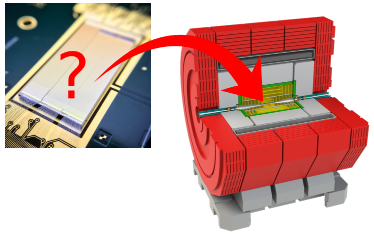
threshold = 860 mV ~ 650 e



noise hitmap



Comparison to the Requirements
of the CLIC Tracking Detector



Requirement	ATLASpix
• spatial resolution	
→ in y: < 7 µm (RMS)	~11.3 µm
→ in x: 1-10 mm (pixel size)	130 µm
• timing resolution ~5 ns	6.8 ns at ~480e$^-$ thres
• material budget < 200 µm	62-100 µm (50 µm possible)
• efficiency > 99.7-99.9%	> 99.7%

→ overall **very good performance**

→ interesting technology for HEP

→ new sensors

- with adapted pixel geometry + other improvements
- in collaboration with LHCb
  → *"MightyTracker"* (study for upgrade Ib and II)

	ATLASpix 40 x 130 µm²	new sensors: 25 x 165 µm²
longitudinal	130 µm << 1 mm	165 µm << 1 mm
transversal (binary resolution)	40 µm/√12 ~ 11.5 µm	25 µm/√12 ~ 7.2 µm (or better)

Summary & Outlook

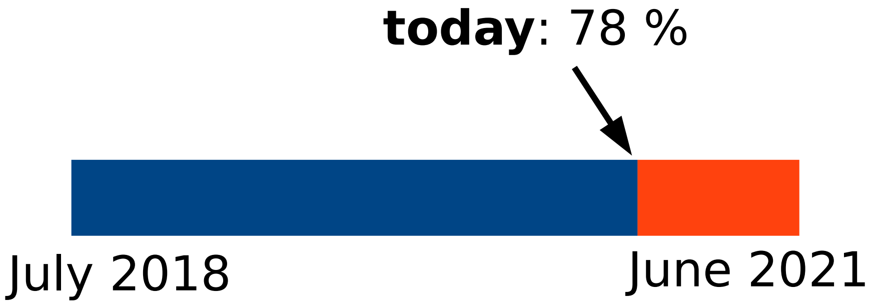
- future HEP experiments:
  - very **stringent detector requirements**
- monolithic pixel sensors:
  - **HV-MAPS = promising technology** for future HEP applications (and beyond)

Acknowledgment:
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

What's next?

- rotation analysis
- x-ray calibration
- compare with new sensor

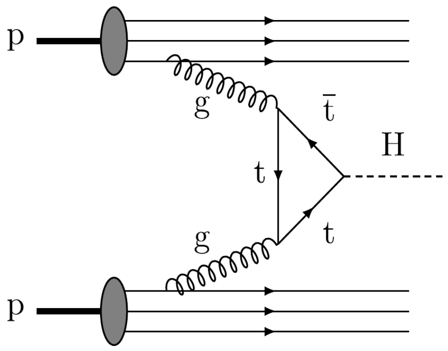
PhD progress:



Backup

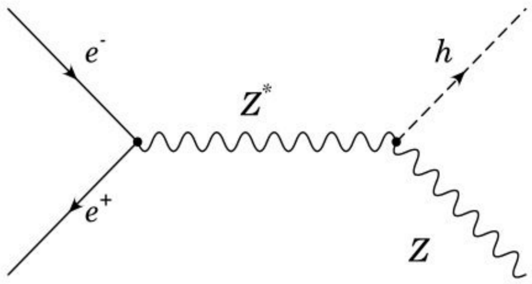
in case there are some questions...

Motivation for an e^+e^- collider



pp collisions

- protons = compound objects
  - event-by-event initial state unknown
    → limits achievable precision
- circular collider feasible
- high rates of QCD background
  - complex triggering schemes
  - high radiation levels

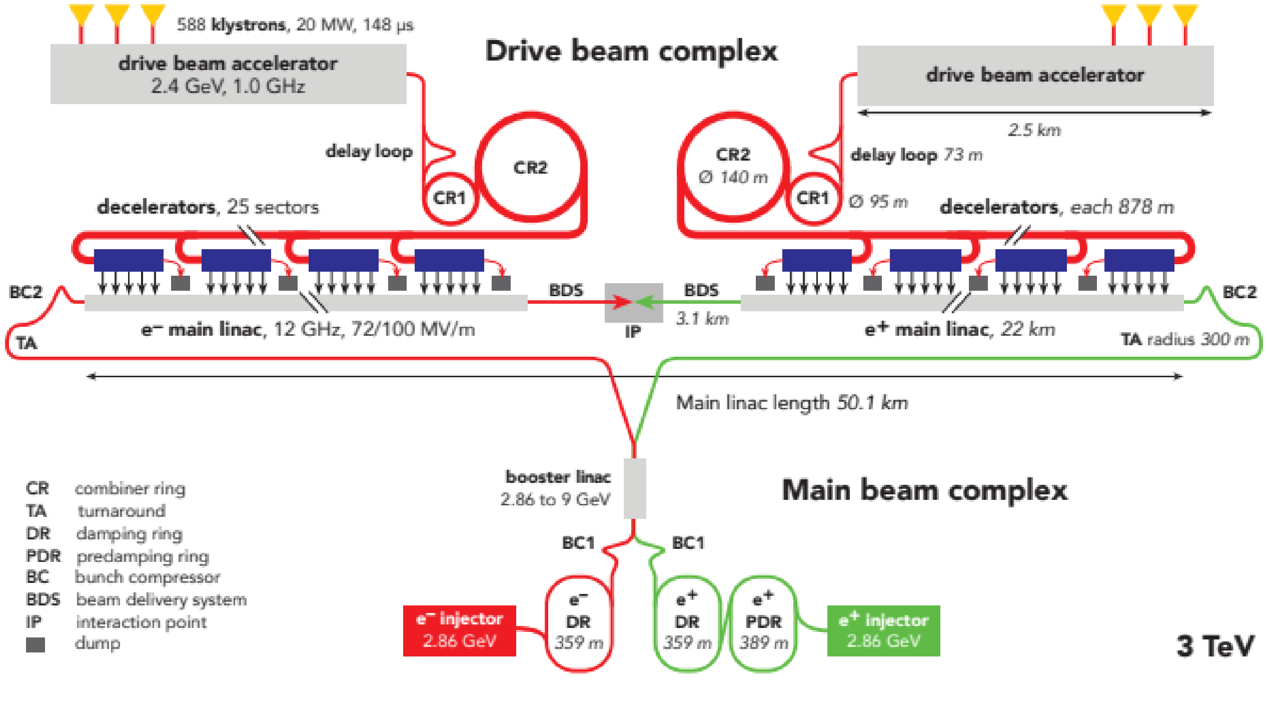


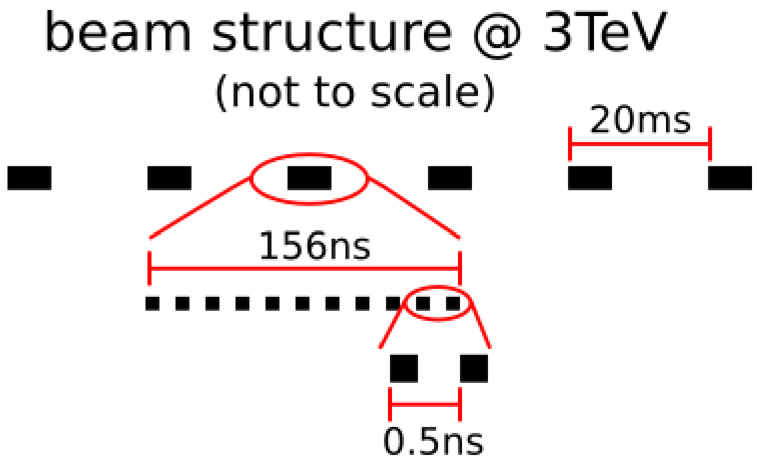
e^+e^- collisions

- electrons = elementary particle
  - well-defined initial state
    → allows high precision measurements
- linear collider required
  → synchrotron radiation
- cleaner experimental environment
  - triggerless readout
  - low radiation levels
- superior sensitivity to electroweak processes

CLIC – the accelerator

- accelerating structures + magnets
  - operated at room temperature
- two-beam acceleration scheme
  - drive beam: high current, low energy
  - main beam: low current, high energy
- bunch structure:
  - low duty-cycle:
    156ns/20ms ~ 0.00078%
  - allows triggerless readout
    + power-cycling between bunches

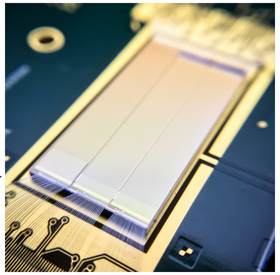


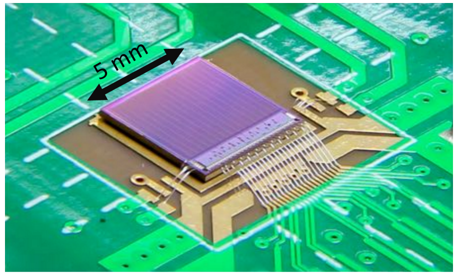


Broad Pixel Detector R&D for CLIC

Prototype Testing

- **monolithic CMOS**
  - ATLASpix_simple
    180nm HV CMOS process
    with a large collection electrode
  - CLICTD
    180nm CMOS imaging process
    with small collection electrode

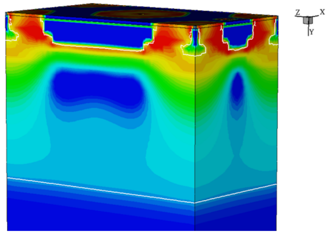


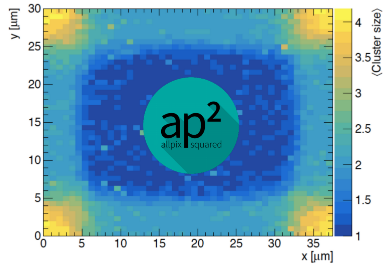


- **Silicon-on-Insulator**
- **hybrid CMOS**
  - CLICpix(2)
  - hybridisation methods:
    - bump bonding
    - anisotropic conductive films
    - capacitive coupling, ...

Simulations

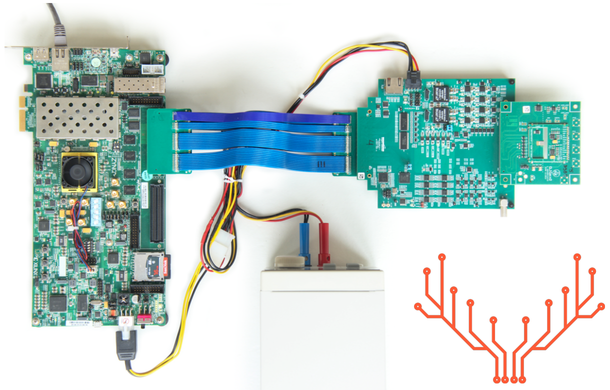
- 3D TCAD
- high statistics Monte-Carlo





Readout Systems

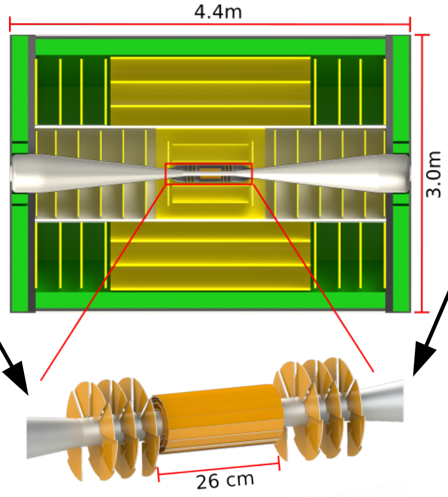
- Caribou DAQ System
  flexible & modular



Software

- Corryvreckan
  test-beam analysis
- Allpix Squared
  sensor simulation

Comparison of Pixel Sensor Technologies



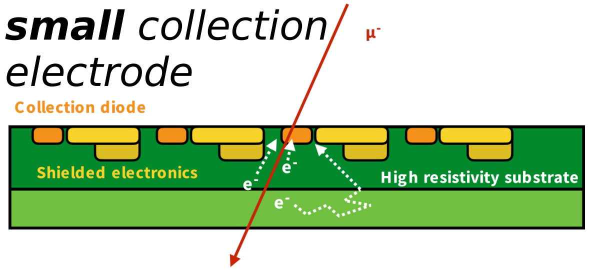
Monolithic → *tracker & vertex detector?*

- advantages
  - based on commercial processes (**reduced cost**/manufacturing complexity)
  - no bump bonding (expensive, difficult)
  - **low material budget** (can be thinned to 50 µm)
- challenges
  - circuitry ↔ sensor influence
  - complex sensor layouts/ limited information on processing details

Hybrid → *vertex detector?*

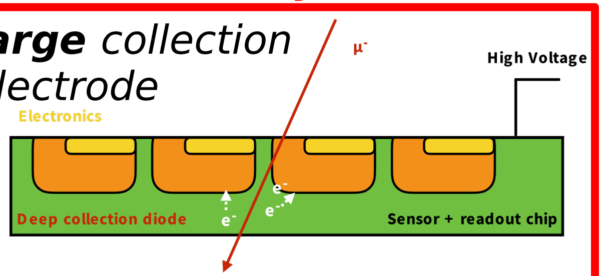
- advantages
  - separate optimisation: sensor / readout chip
- challenges
  - fine pitch interconnects (yield, cost)
  - material budget

***small** collection electrode*

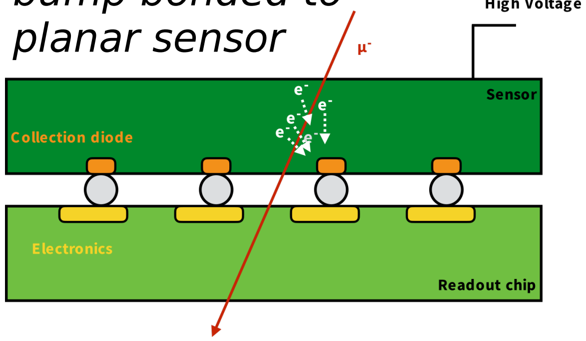


Focus of today

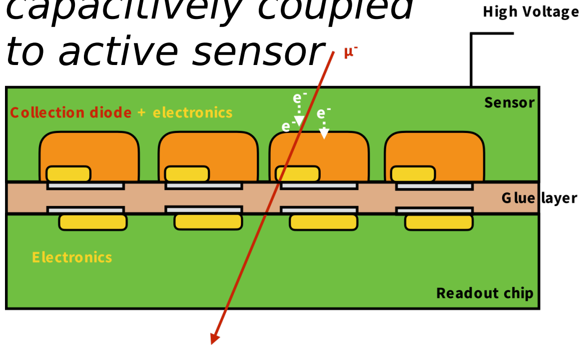
***large** collection electrode*



bump bonded to planar sensor



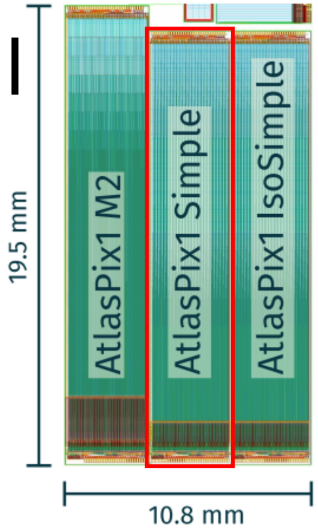
capacitively coupled to active sensor

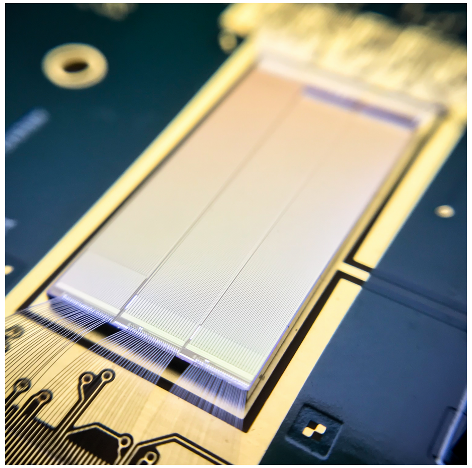


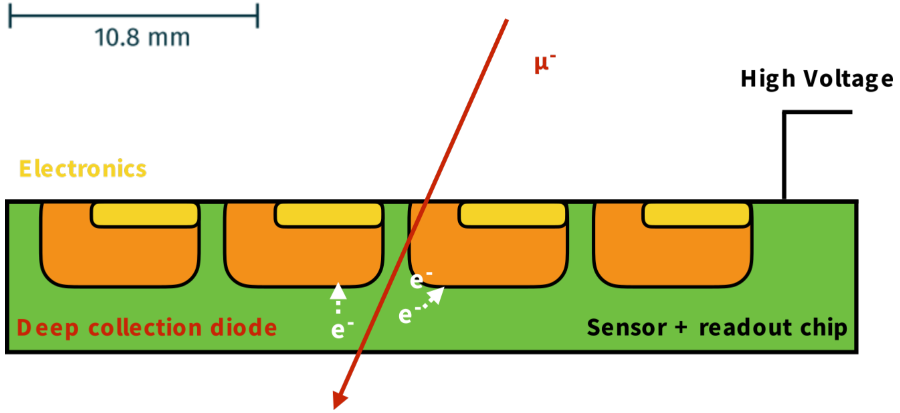
The ATLASpix – in more detail

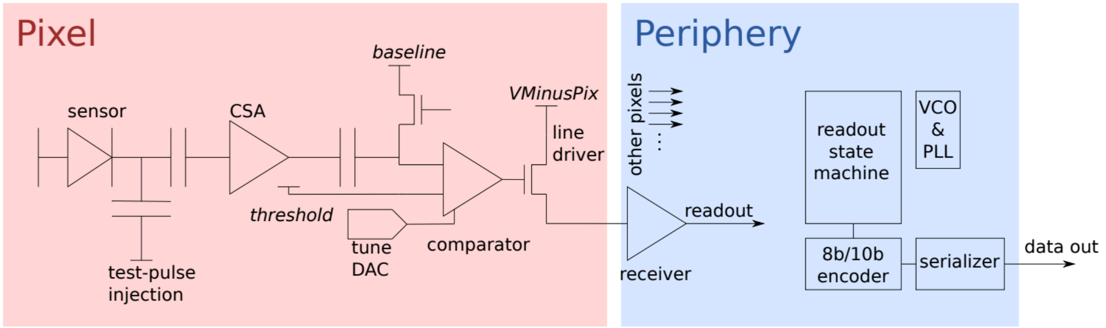
- **h**igh-**v**oltage **m**onolithic **a**ctive **p**ixel **s**ensor (HV-MAPS)
- designed for ATLAS ITk upgrade
  (submatrix *simple* also interesting for CLIC Tracker)
- large collection electrode

technology	AMS/TSI 180nm CMOS
readout scheme	triggerless column drain
pixel matrix	25 columns x 400 rows
pixel size	130 x 40 µm²
time-of-arrival (hit timestamp)	10 bit, 8ns binning
time-over-threshold (charge measurement)	6 bit
substrate resistivity	20, 80, 200 Ωcm
sensor thickness	62 – 100 µm









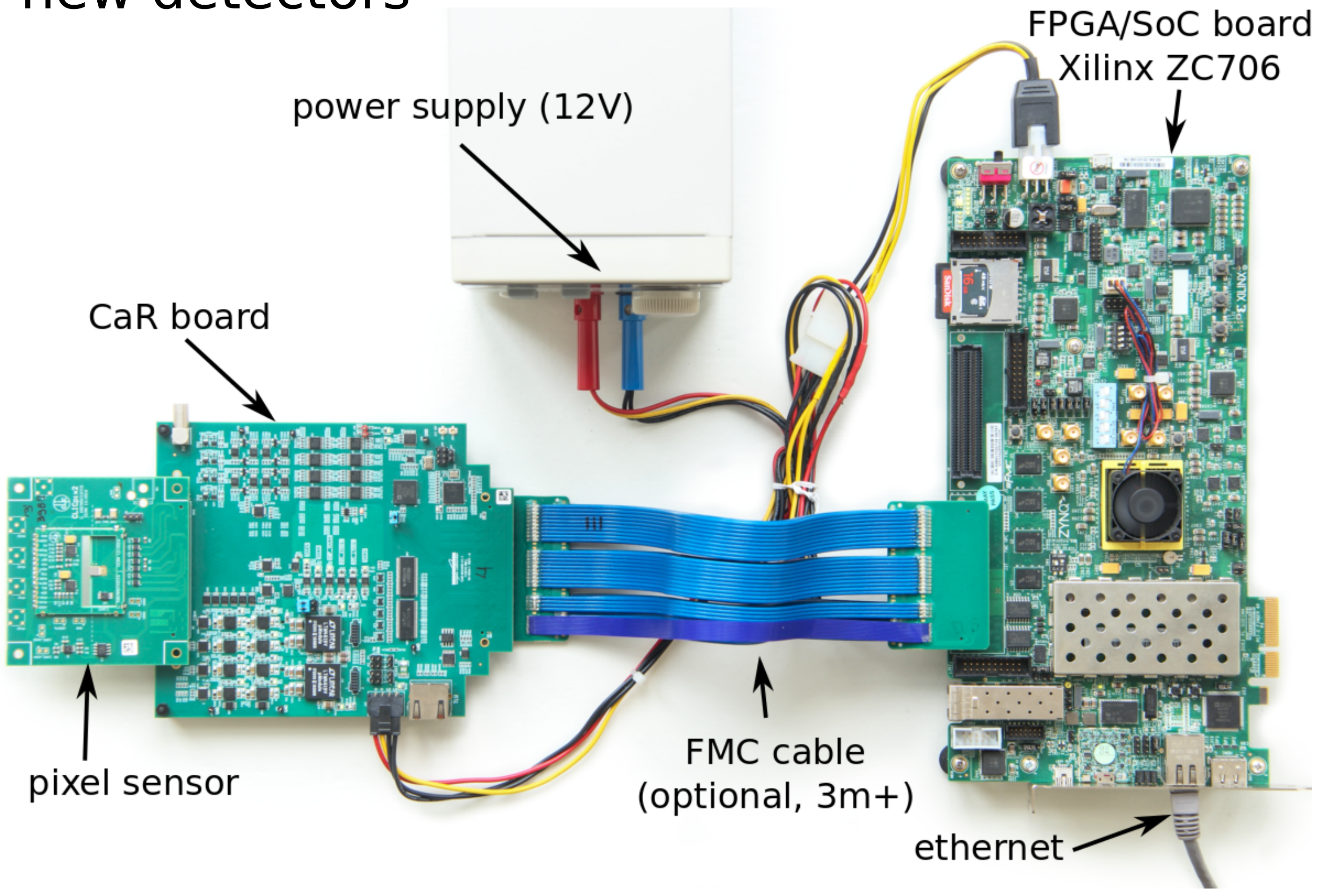
The ATLASpix – investigated samples

- w06s12:
  - resistivity ~ 20 Ωcm
  - thickness = 100 µm
- w10s30:
  - resistivity ~ 80 Ωcm
  - thickness = **62 µm**
- w23s11:
  - resistivity ~ 200 Ωcm
  - thickness = 100 µm

- w10s30 is thinner than the other 2 samples
  - no 80 Ωcm sample available with 100 µm
  - expect no effect on performance:
active depth/depletion depth < 50 µm

Caribou – the readout system

- versatile, open-source, linux-based
- fast & simple implementation of new detectors
  → “fast prototyping”
- **universal:**
  - FPGA board
  - Control & Readout (CaR) board
  - “most of the” firmware/software
- **chip-specific:**
  - chip board
  - “some” firmware/software blocks



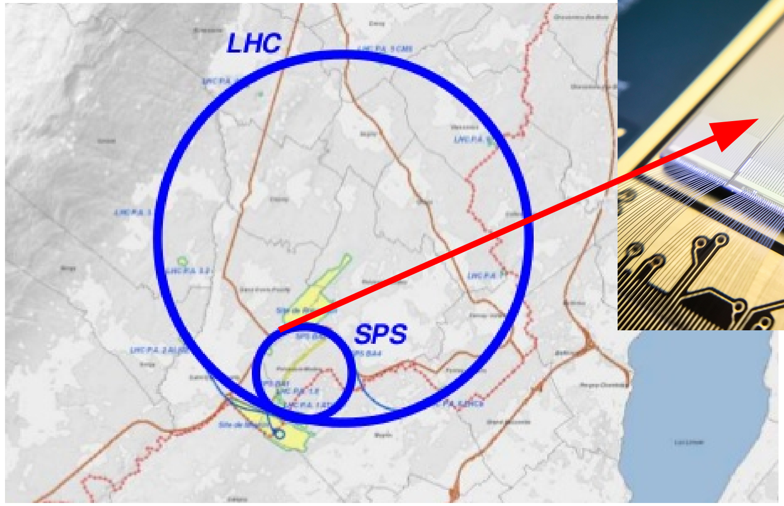
How to characterize a pixel sensor?

- need **ionizing particles**
- need **reference (position, time)** with higher precision than device-under-test

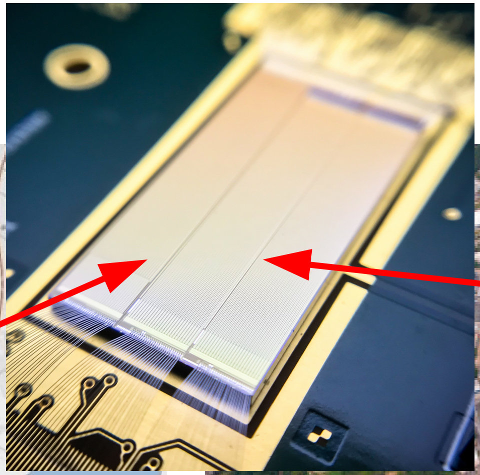
- **particle beams** from an accelerator
  - ➔ SPS @ CERN
  - ➔ DESY II @ DESY

- **beam telescope**
  for tracking

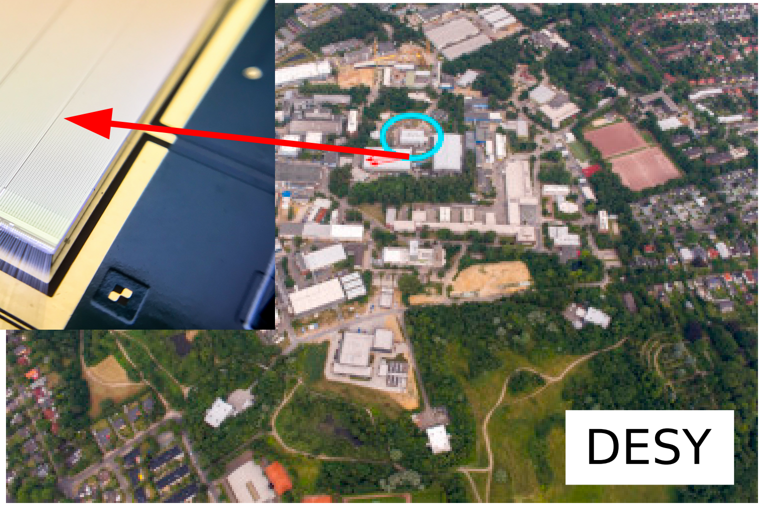
circumference ~ 7km



size ~ 3.25 x 10 mm²



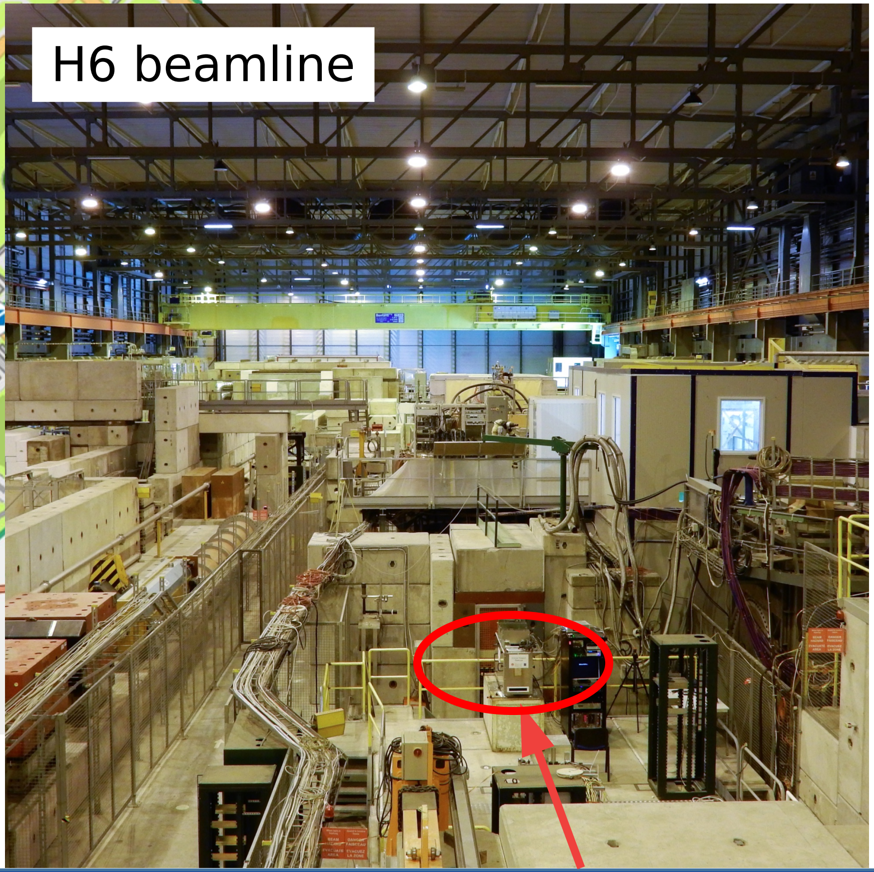
circumference ~ 300m

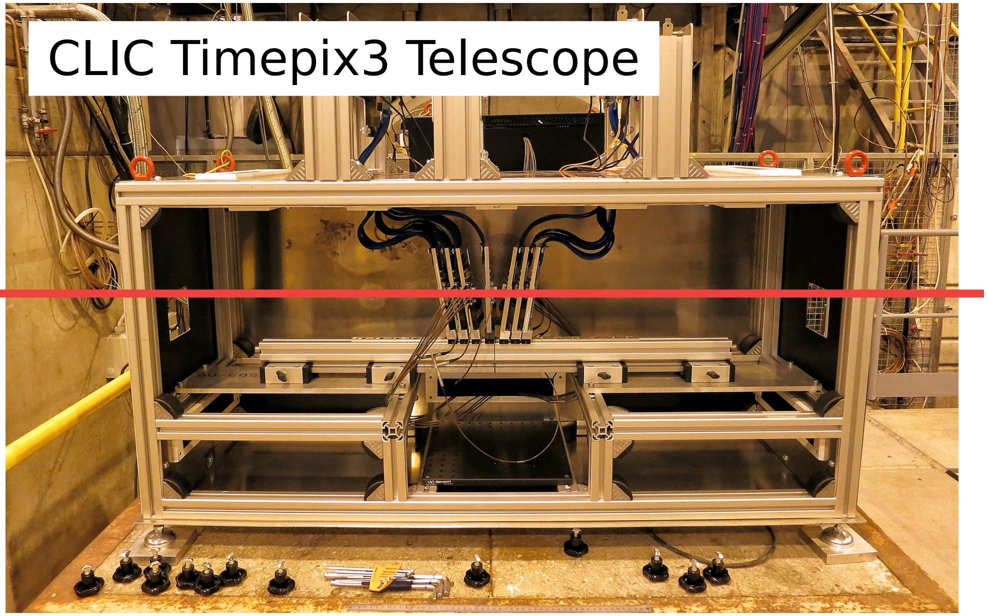


from https://www.slideshare.net/SparkSummit/the-next-cern-accelerator-logging-servicea-road-to-big-data-with-jakub-wozniak-cern

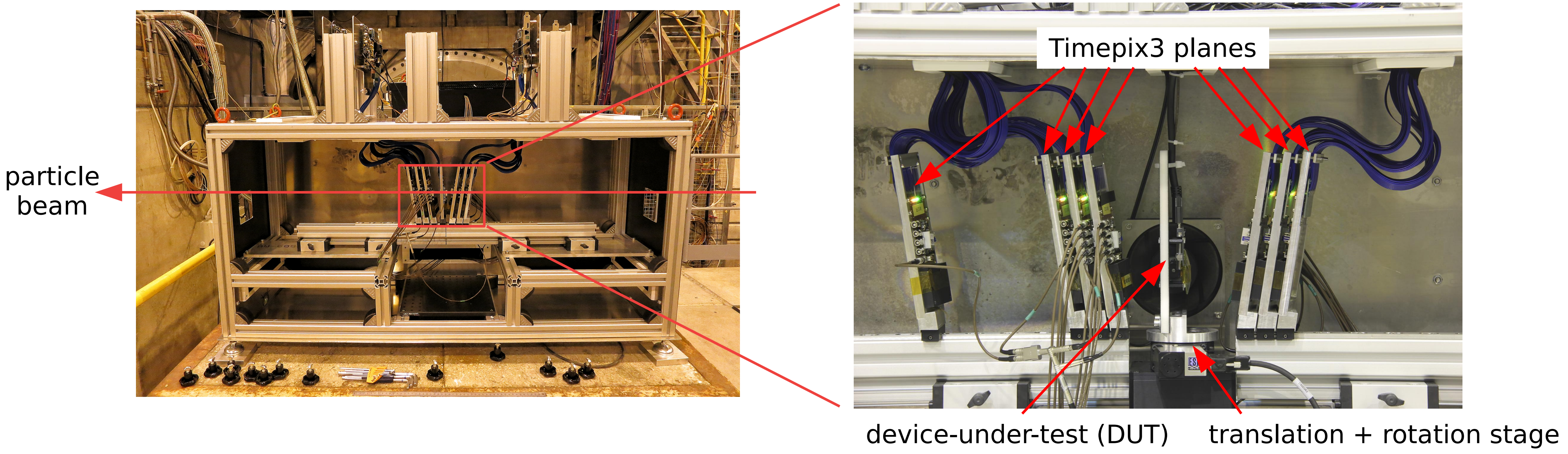
from https://doi.org/10.1016/j.nima.2018.11.133

SPS at CERN – a look into the North Area beam lines

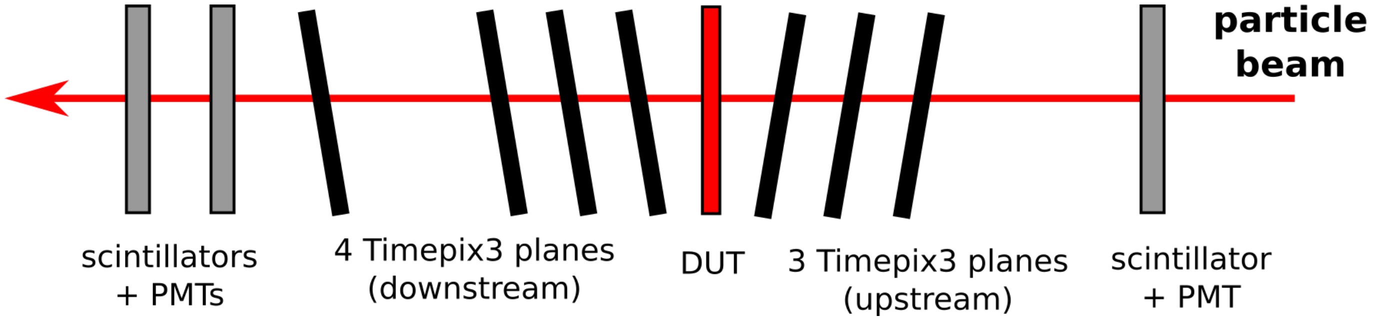




Beam Telescope – providing the reference tracks

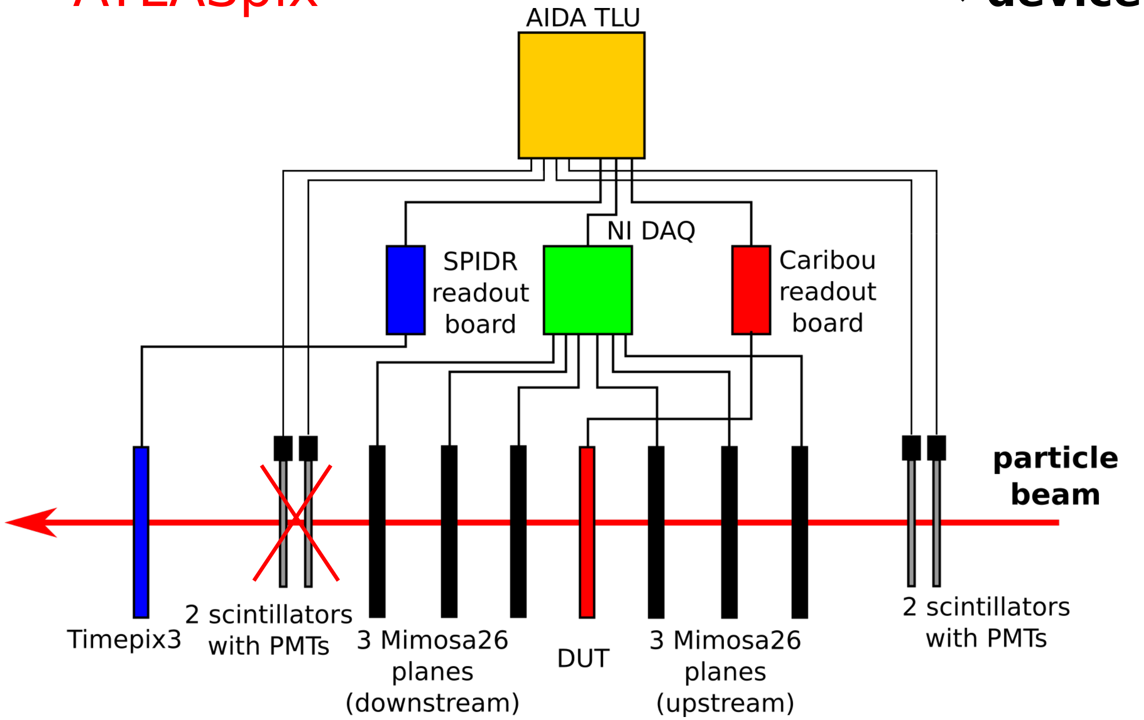


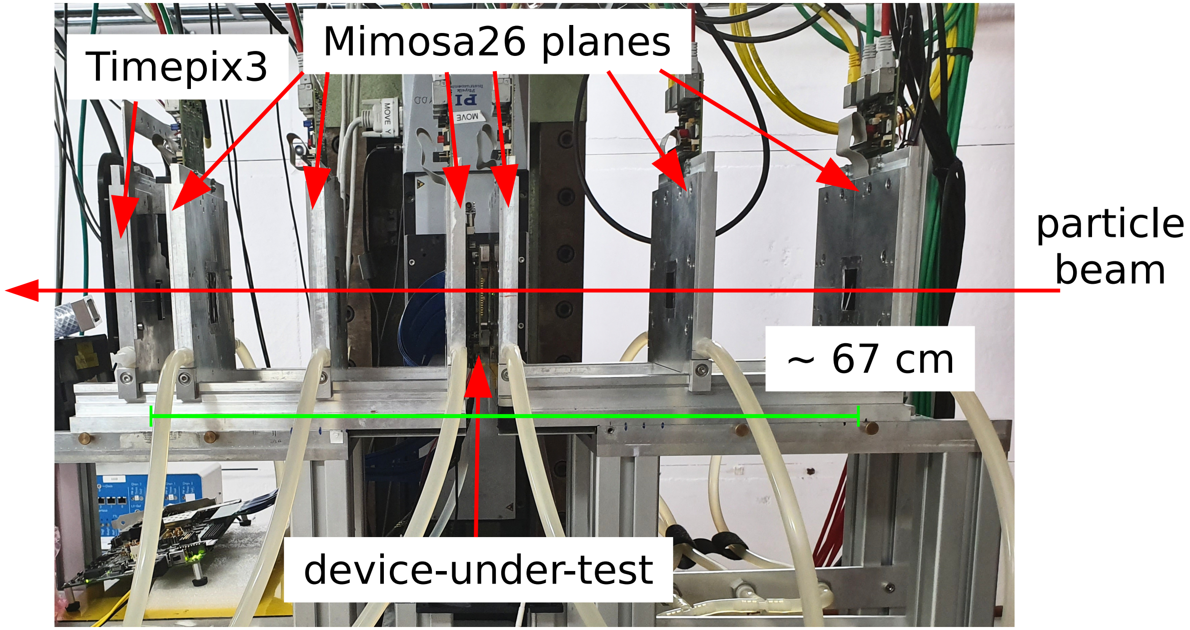
- typical beam condition at **SPS**:
  - pions with ~120 GeV
  - rate of ~1 MHz
    (1 spill of 4.8s/50s super-cycle)



Test Beam Setup at DESY

- AIDA Trigger Logic Unit (TLU) → provides **global clock** (time sync.) + **trigger**s Mimosa Readout
- 2-3 scintillators + PMTs → input to TLU
- 6 Mimosa26 planes → good **spatial resolution**, “no” timing (2x 115µs bins rolling shutter)
- Timepix3 → nanosecond **track timestamps**
- ATLASpix → **device-under-test** (DUT)

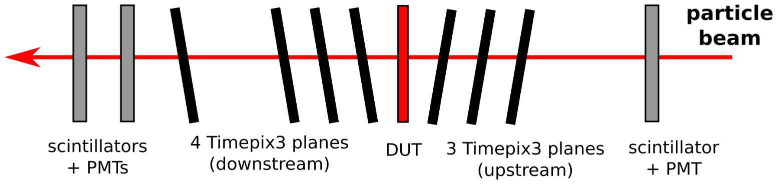


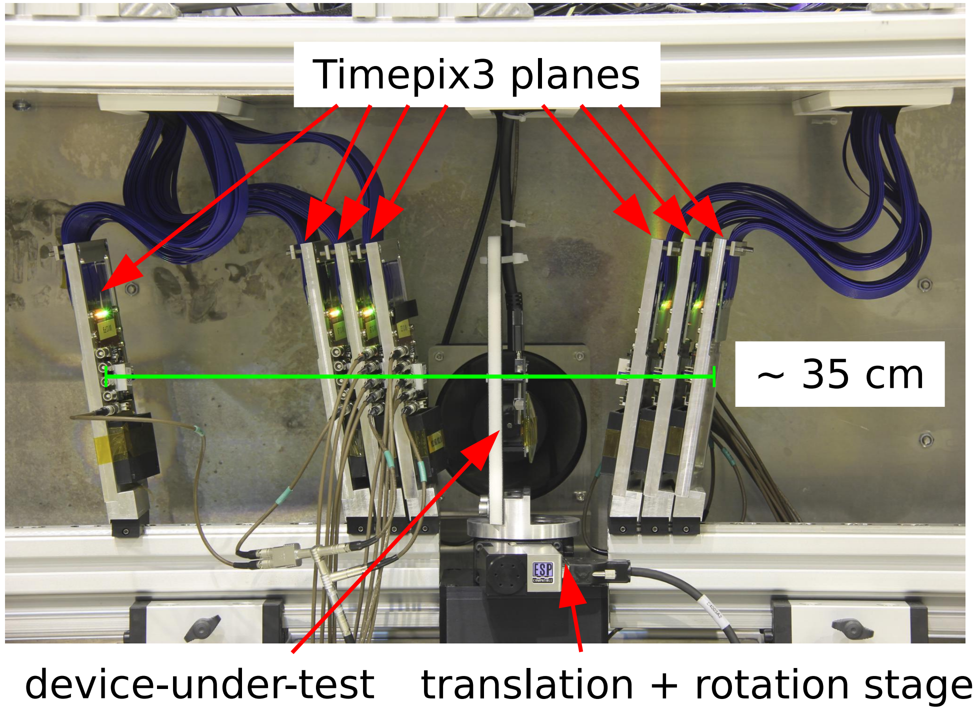


SPS vs. DESY II

SPS:

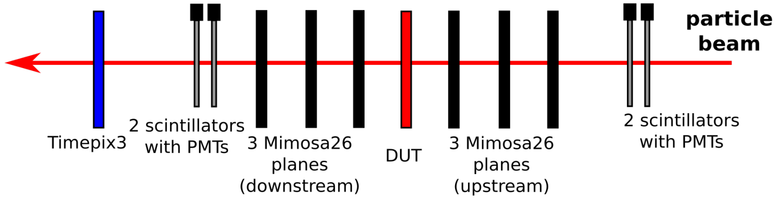
- typical beam condition:
  120 GeV pions @ few MHz
- telescope in operation
  2014-2018

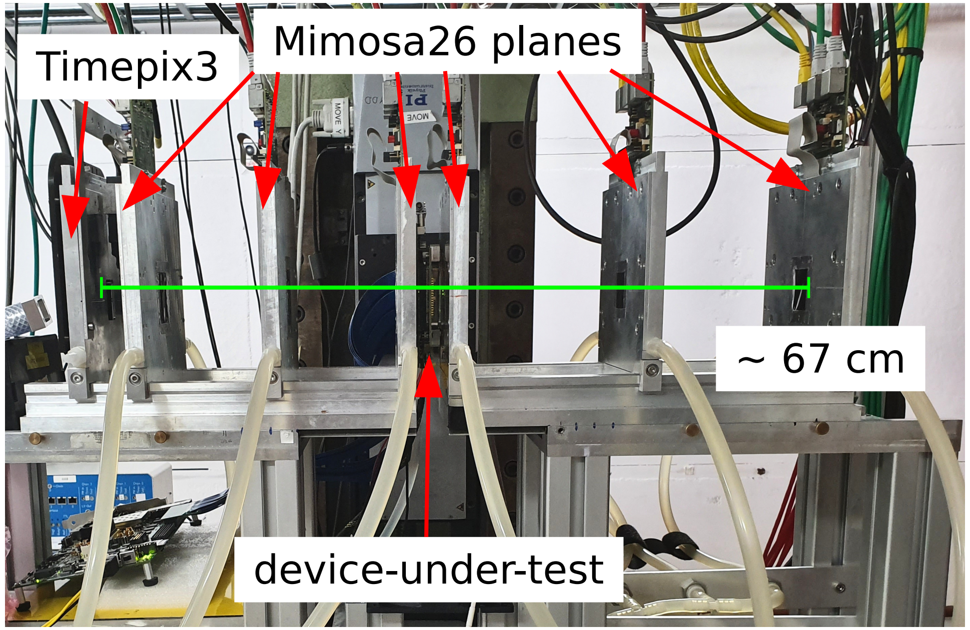




DESY:

- typical beam condition:
  5.4 GeV electrons @ few kHz
- use for CLICdp testbeam campaigns during
  LHC LS2 2019-2020





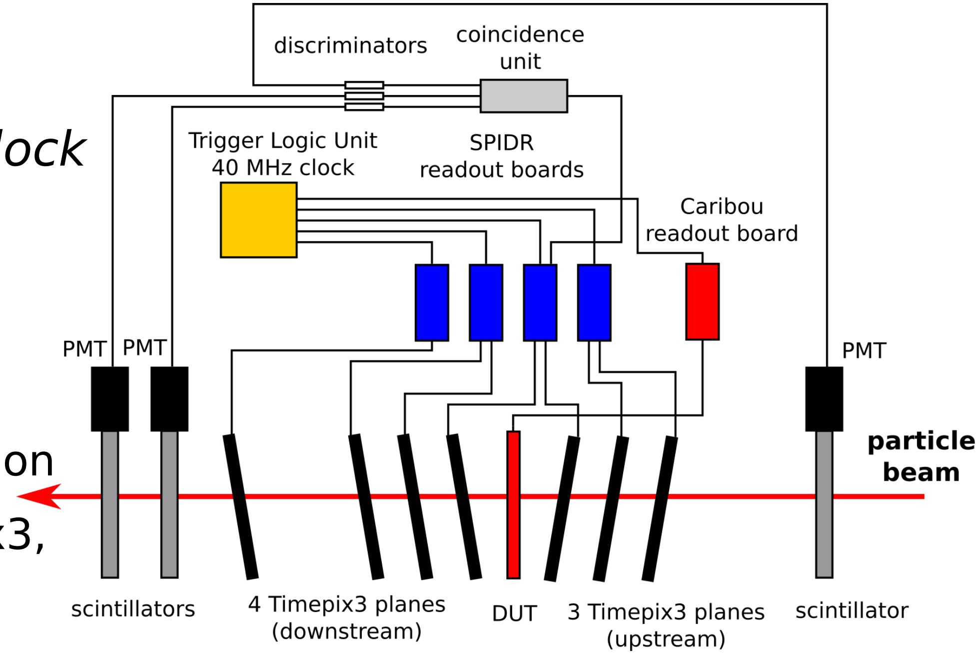
→ **much lower rate & energy**

SPS vs. DESY II – Readout

continuous readout, timestamps synchronous with global clock

SPS:

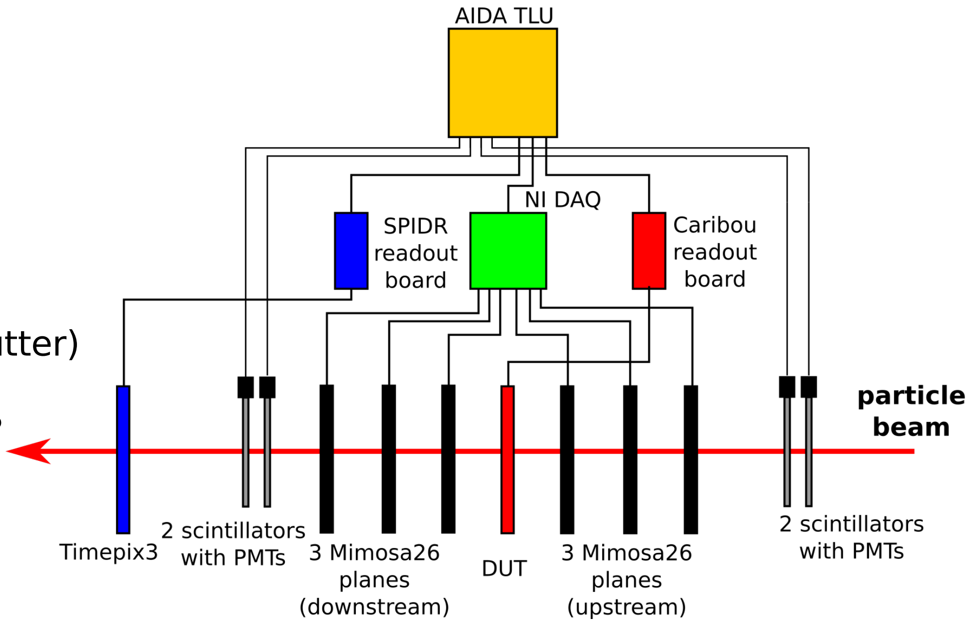
- Trigger Logic Unit (TLU) → provides global clock (time sync.)
- 3 scintillators + PMTs → trigger timestamps
- 7 Timepix3 planes → excellent spatial + timing resolution
- DUT → Investigator, Cracow SOI, Timepix3, CLICpix, CLICpix2, **ATLASpix**



DESY:

- AIDA TLU → provides global clock (time sync.)
  + triggers Mimosa Readout
- 4 scintillators + PMTs → input to TLU
- 6 Mimosa26 planes → good spatial res. (2x 115µs bins rolling shutter)
- Timepix3 → used to assign ns timestamp to tracks
- DUT → CLICpix2, **ATLASpix**, CLICTD

→ additional subsystem

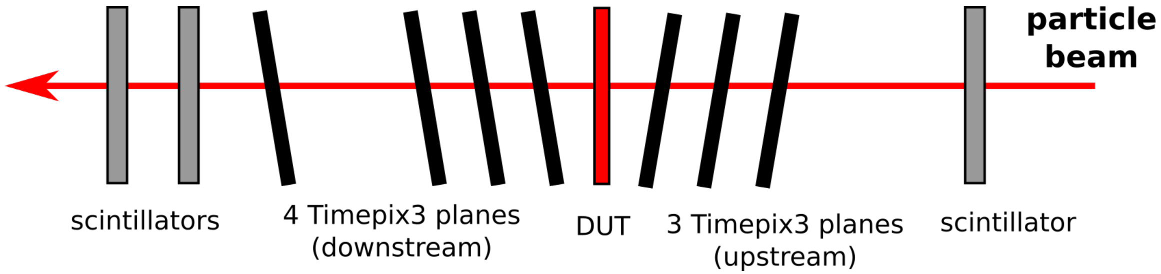


SPS vs. DESY II – Changes in the Analysis

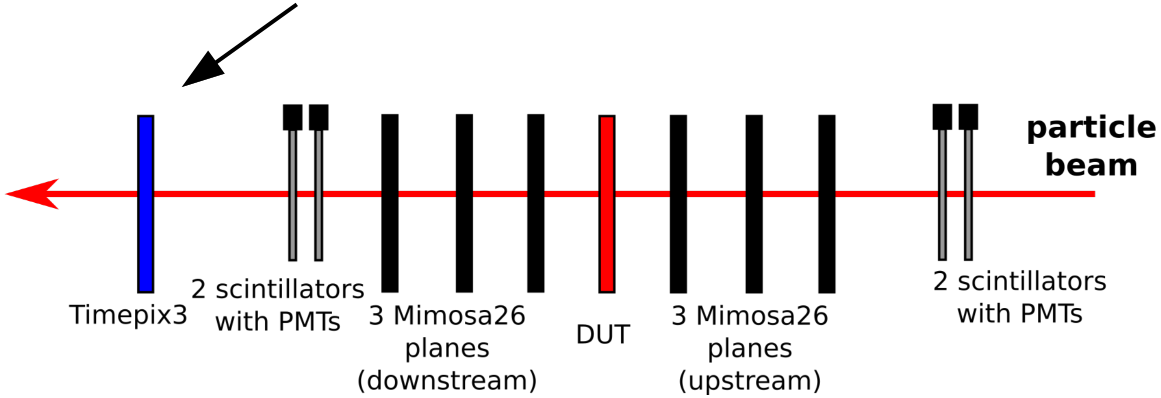
Tracking:

- **SPS**:
  - ➔ 7 Timepix3 hits with precise timestamp
  - ➔ track timestamp = average TPX3 timestamp
- **DESY**:
  - ➔ Mimosa26 hits (3x 115µs) with multiple trigger timestamps
  - ➔ require Timepix3 for unambiguous track time
  - ➔ track timestamp = TPX3 timestamp

SPS:
all sensors provide hit timestamps for tracking



DESY:
unambiguous track timestamp only with TPX3



Test-beam Analysis for Pixel Sensors

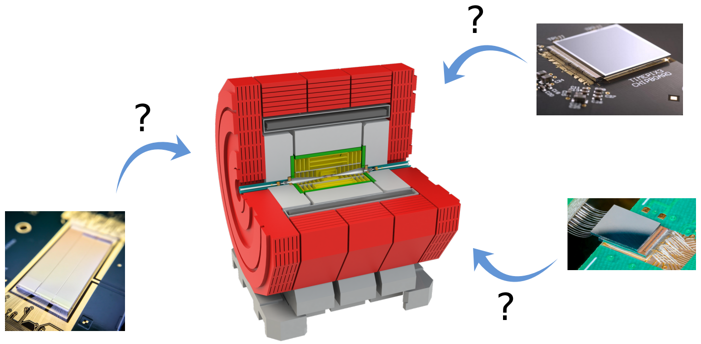
Challenge:

LHC upgrades + future HEP experiments:

- stringent detector requirements
- pushing limits of technology

→ R&D on vast range of pixel detector technologies

- different readout concepts
- highly specialized to each use case

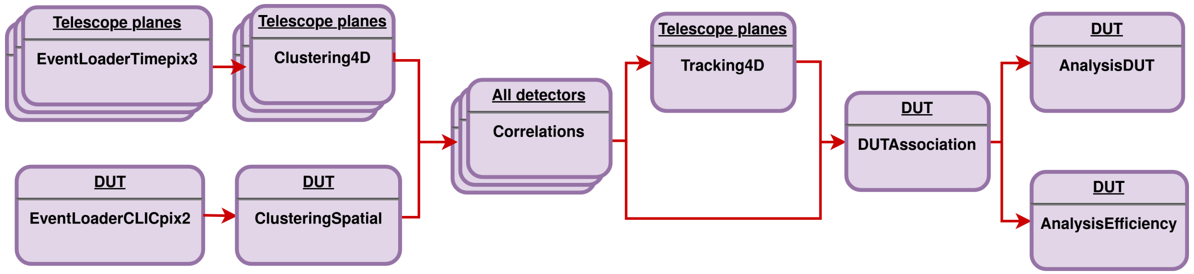


Our Motivation:

- maximize synergies
  - avoid numerous similar frameworks
  - ”one framework fits all”
- flexible reconstruction
  - combine detectors with different read-out schemes
  - different analysis objectives
- easy to use, understand, contribute

The Corryvreckan Framework

- modular structure
  - framework core
  - (user) modules for specific tasks



- highly flexible and configurable
  - TOML style = easy to read
  - support of physical units (e.g. 25um)

```
[Corryvreckan]
log_level = "WARNING"
detectors_file = "geometry.conf"
number_of_tracks = 900000

[EventLoaderEUDAQ2]
file_name = "data/run0000456.raw"
inclusive = false
buffer_depth = 1000
shift_triggers = -1
```

```
[W0013_D04]
number_of_pixels = 256, 256
orientation = 10.9deg, 17.2deg, -1.3deg
orientation_mode = "xyz"
pixel_pitch = 55um, 55um
position = 886.5um, 270um, 0
spatial_resolution = 4.8um,4.8um
time_resolution = 1.56ns
type = "Timepix3"
role = "reference"
```

- clean code & documentation
  - modern C++, code reviews, CI
  - comprehensive user manual (> 100 pages!)

Some Notable Features:

- 4D tracking (spatial + time cuts)
- various alignment methods (track χ^2, Millepede)
- General Broken Line (GBL) track reconstruction (multiple Coulomb scattering)
- EUDAQ integration https://github.com/eudaq/eudaq/
  - include **AIDA TLU** as auxiliary device
  - process data recorded with **EUDAQ2 DAQ**
- job submission tool (HTCondor etc.)
- read in simulated data from **Allpix Squared** https://cern.ch/allpix-squared

Combining Different Readout Schemes

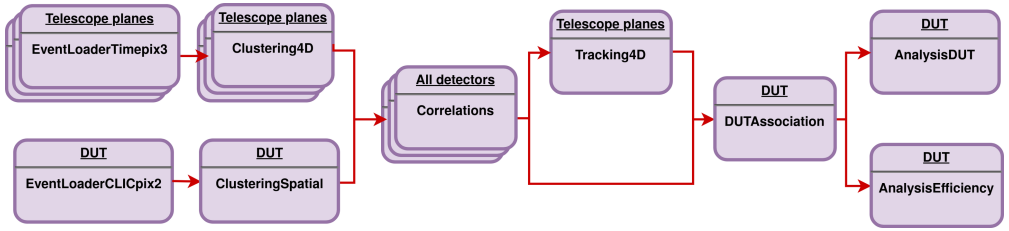
- event building:

  arrange data from different devices in **“time slices”** (events) for reconstruction/analysis

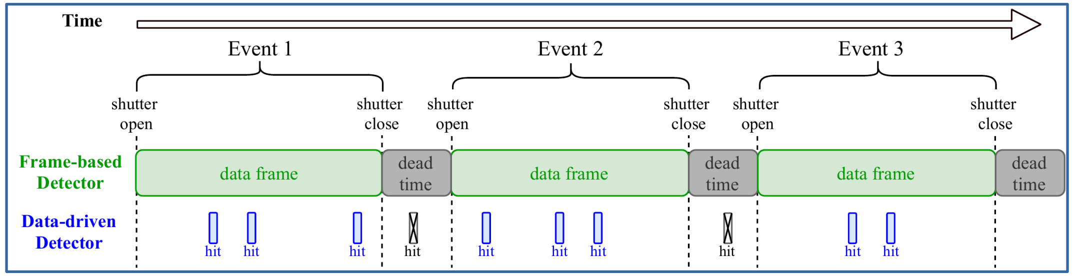
- flexible:

  combine devices with different readout schemes
  - frame-based,
  - data-driven,
  - triggered,
  - …

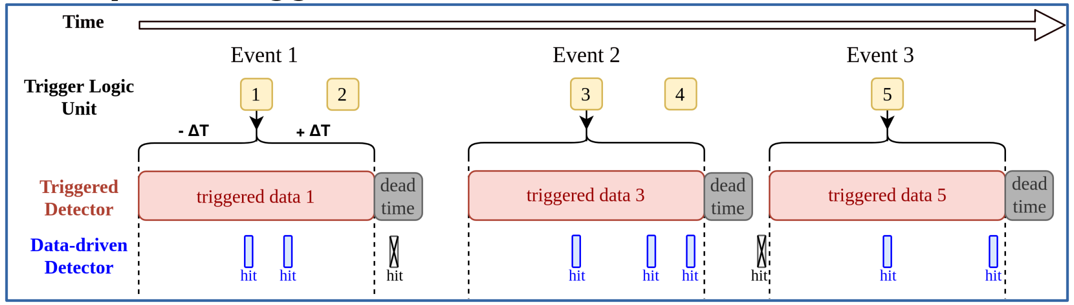
→ full analysis chain event-by-event



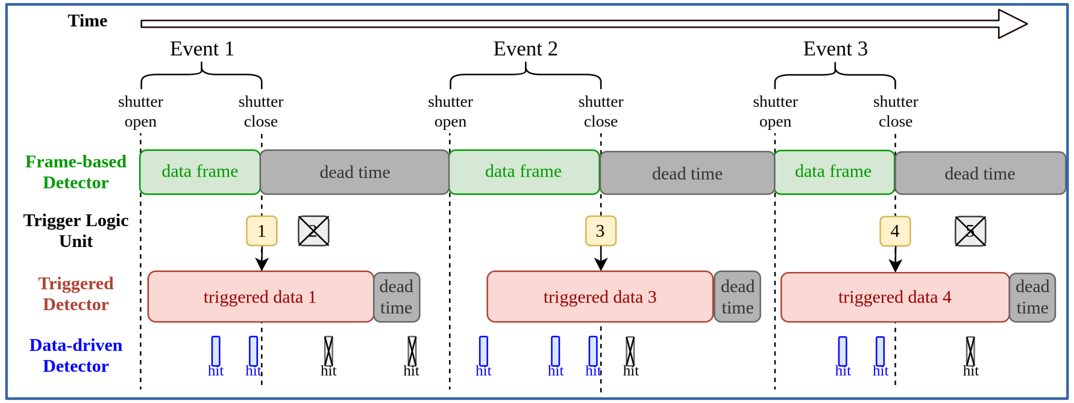
***Example 1:** frame-based + data-driven detectors*



***Example 2:** triggered + data-driven detectors*



***Example 3:** frame-based + triggered + data-driven detectors*



Corryvreckan in short

reconstruction and analysis tool
for pixel detector test beam data

- highly flexible/configurable
  - separate modules for each reconstruction/analysis step
  - many different event building options
- comprehensive documentation
  + beginner-friendly tutorials
- growing number of users
  + contributors

Learn more:

Visit our website:
https://cern.ch/corryvreckan

Browse through our manual:
→ Get the lastest version here

Try our tutorials:
→ Get Started (no prior experience required)
→ Advanced (more complex use cases)

Check out the repository:
https://gitlab.cern.ch/corryvreckan/corryvreckan

Discuss in the forum:
https://corryvreckan-forum.web.cern.ch/

Contact us:
corryvreckan.info@cern.ch
https://mattermost.web.cern.ch/corryvreckan

References & Repositories

- **The Compact Linear Collider (CLIC) - 2018 Summary Report**, CERN-2018-005
- **Detector Technologies for CLIC**, CERN-2019-001
- **ATLASpix**: doi:https://doi.org/10.1016/j.nima.2018. 06.060
- **CLICTD**: doi:https://doi.org/10.22323/1.343.0072
- **Cracow SOI**: doi:https://doi.org/10.1016/j.nima. 2018.06.017
- **Simulations**: doi: 10.1088/1748-0221/14/05/C05013, CLICdp-Pub-2019-008

- **Caribou**: https://gitlab.cern.ch/Caribou/
- **Corryvreckan**: https://gitlab.cern.ch/corryvreckan/corryvreckan
- **Allpix Squared**: https://gitlab.cern.ch/allpix-squared/