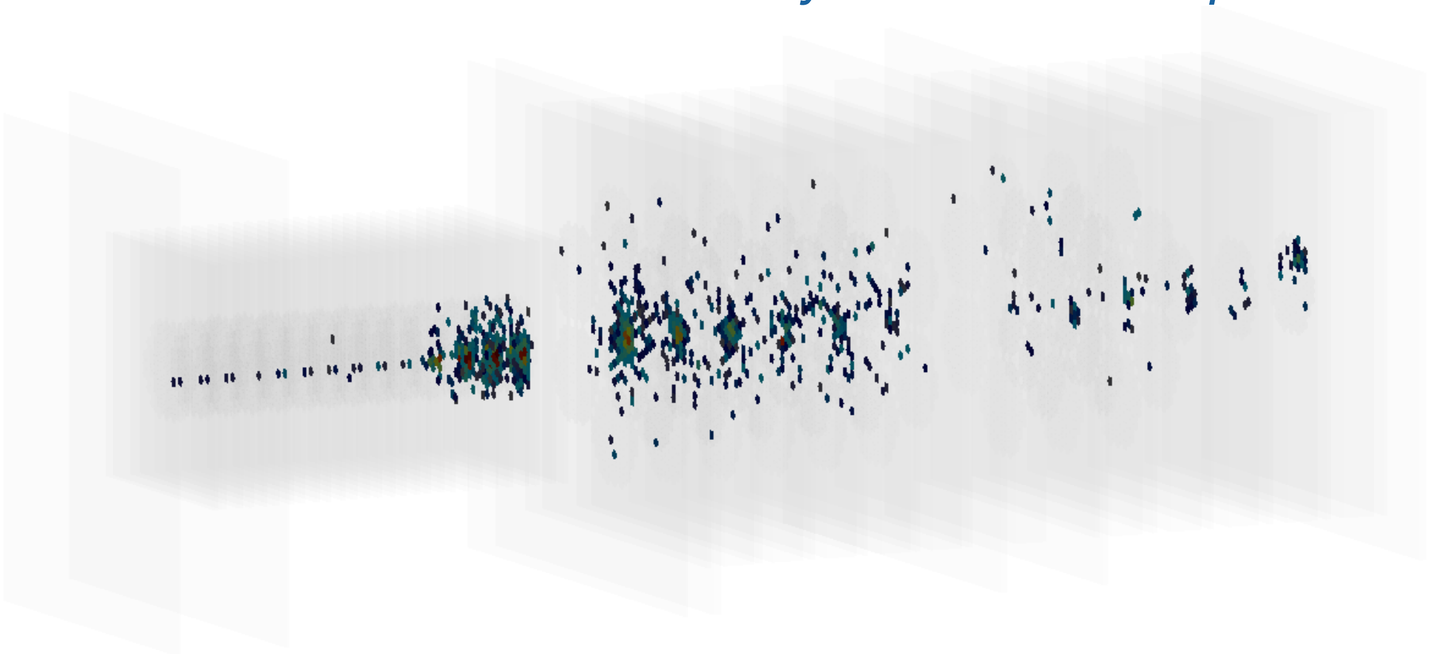
7th Beam Telescopes and Test Beams Workshop
17 January 2019

Beam tests for CMS High Granularity Calorimeter Prototypes at CERN and DESY 2018

Thorben Quast
for the CMS HGCal System Test Group



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

Bundesministerium für Bildung und Forschung

III. Physikalisches Institut

RWTH AACHEN UNIVERSITY

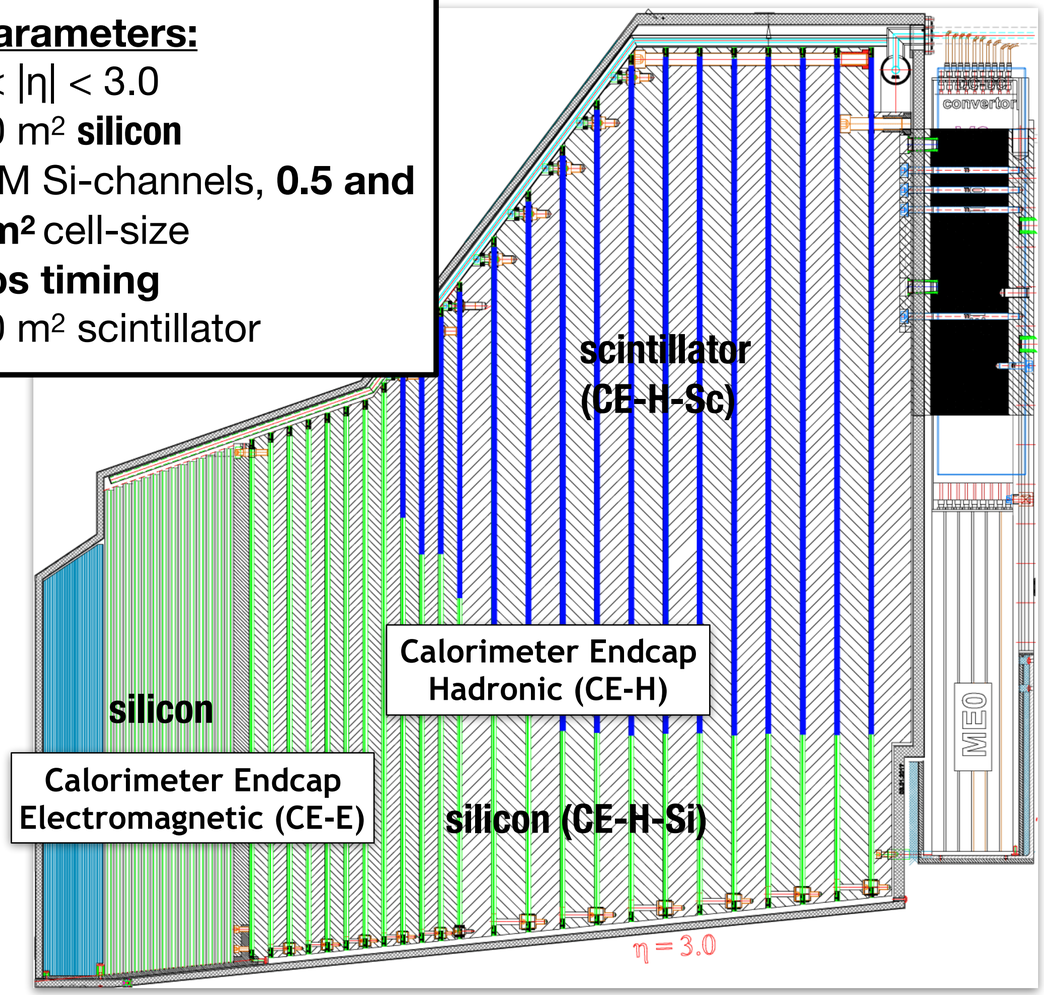
The CMS HGCal upgrade in a nutshell

➡ **Calorimetry for Upgrades: Frank Simon**

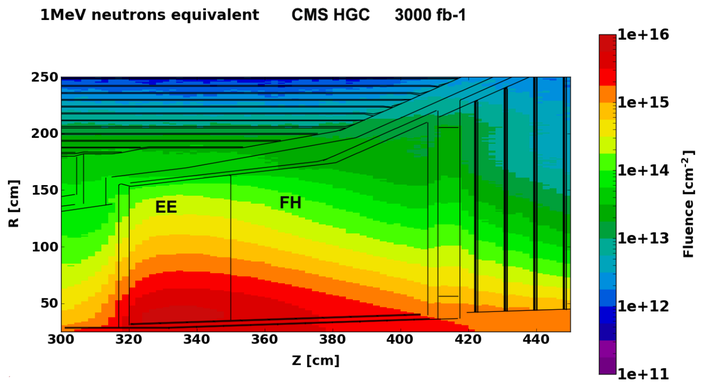
Replacement of CMS' complete endcap calorimeter during HL-LHC upgrade:

Key parameters:

- 1.5 < |η| < 3.0
- ~600 m² **silicon**
  - ~6 M Si-channels, **0.5 and 1cm²** cell-size
  - **50ps timing**
- ~500 m² scintillator

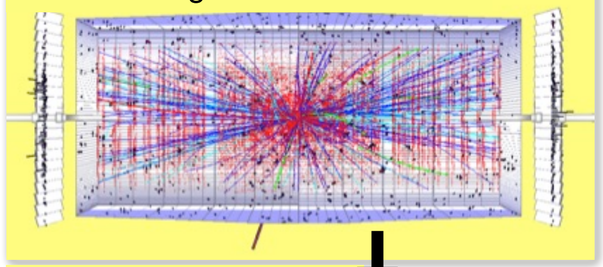


Radiation hardness

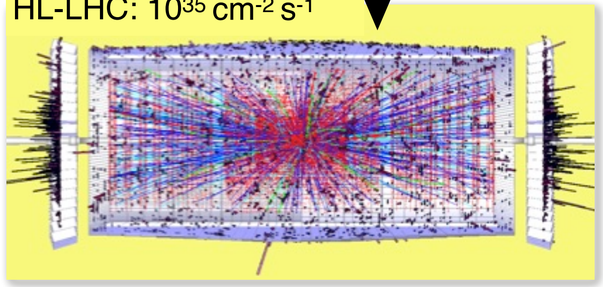


Increased pileup

Current design: 10^{34} cm^{-2} s^{-1}



HL-LHC: 10^{35} cm^{-2} s^{-1}

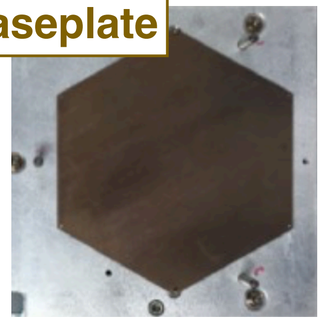


Shower sampling: HGCal prototype modules

HGCal beam test DAQ:
➡ Rajdeep M. Chatterjee

Modules assembled as glued stack of **baseplate**, **Kapton®**, **Si sensor** and **PCB**:

baseplate



- CuW
- Cu

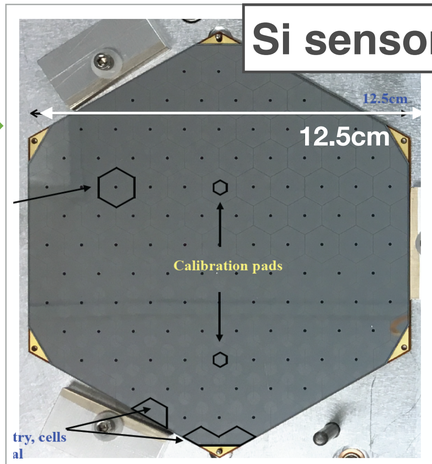
Kapton®

- Gold plated

+

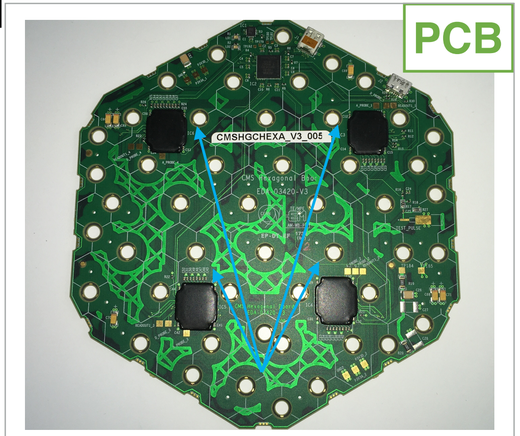
Active material

Si sensor



6” silicon sensors:
- n-type, 128 cells
- 1 cm² cell-size
- depletion: 200 & 300μm

PCB



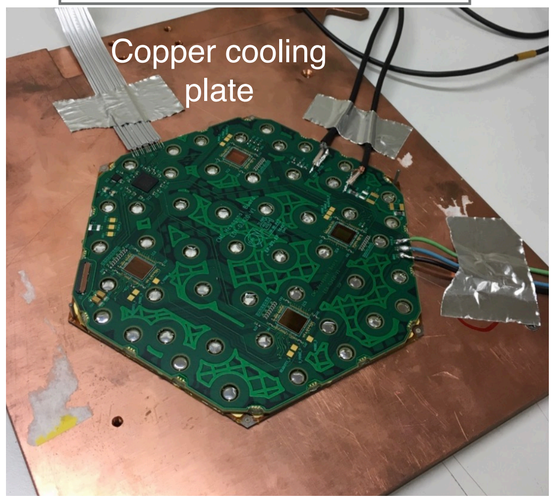
- **Skiroc2-CMS** ASIC, 64 ch., 4 chips/module
- Developed for CALICE (Skiroc2) & adjusted for HGCal requirements

gluing

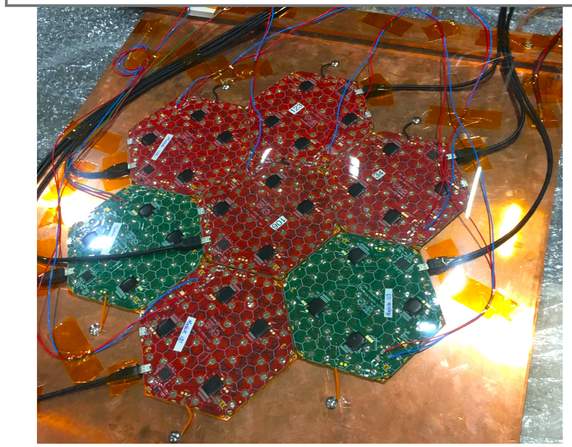
➡

wire bonding

1-module layer in CE-E



7-module “daisy” layer in CE-H-Si



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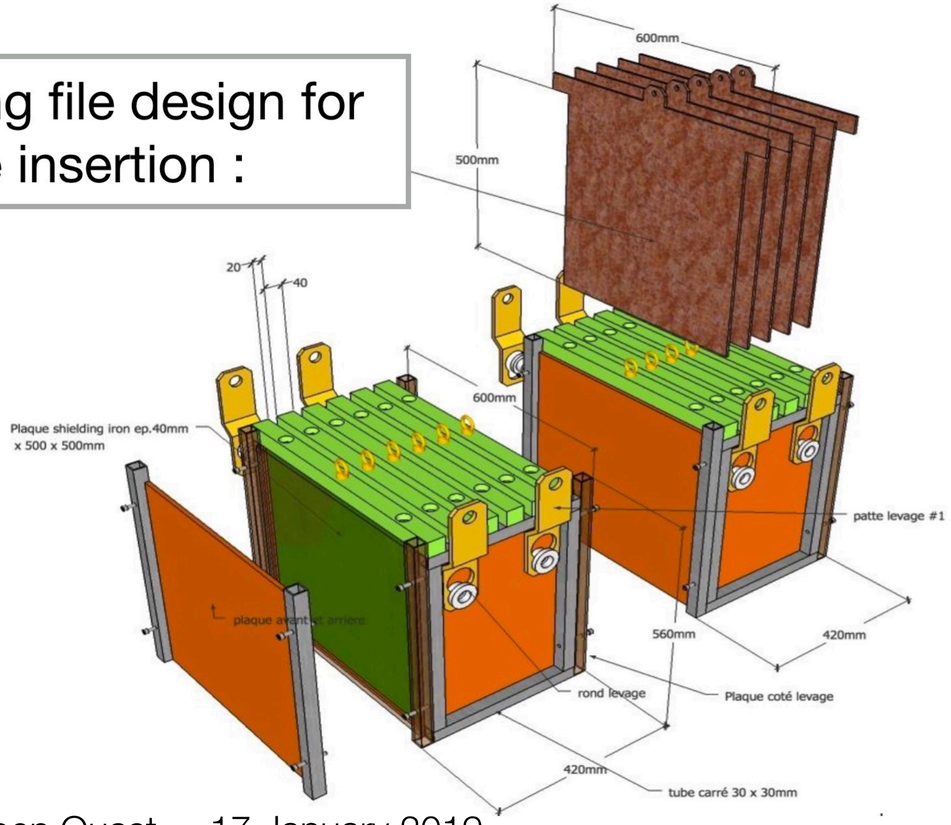
Making a shower: Absorbers & Mechanics

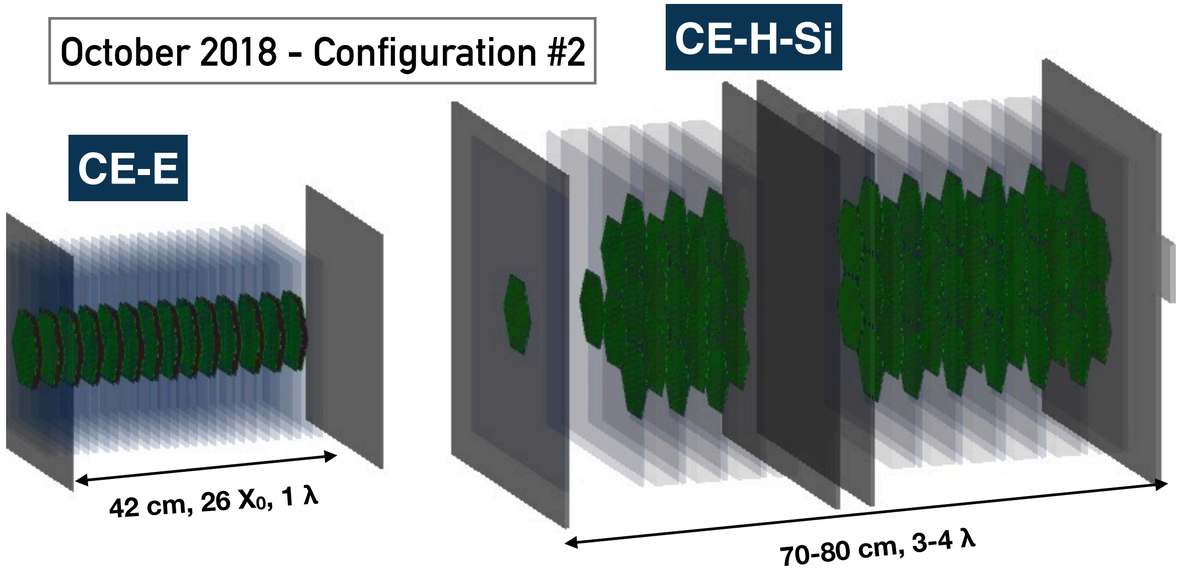
Passive material

- **CE-E:**
  - **material: Pb, W, Cu**
  - **thickness: 5-6 mm**
- **CE-H-Si:**
  - **material: Fe**
  - **thickness: 4 cm**
  - **weight: O(1000kg)**

Hanging file design for flexible insertion :

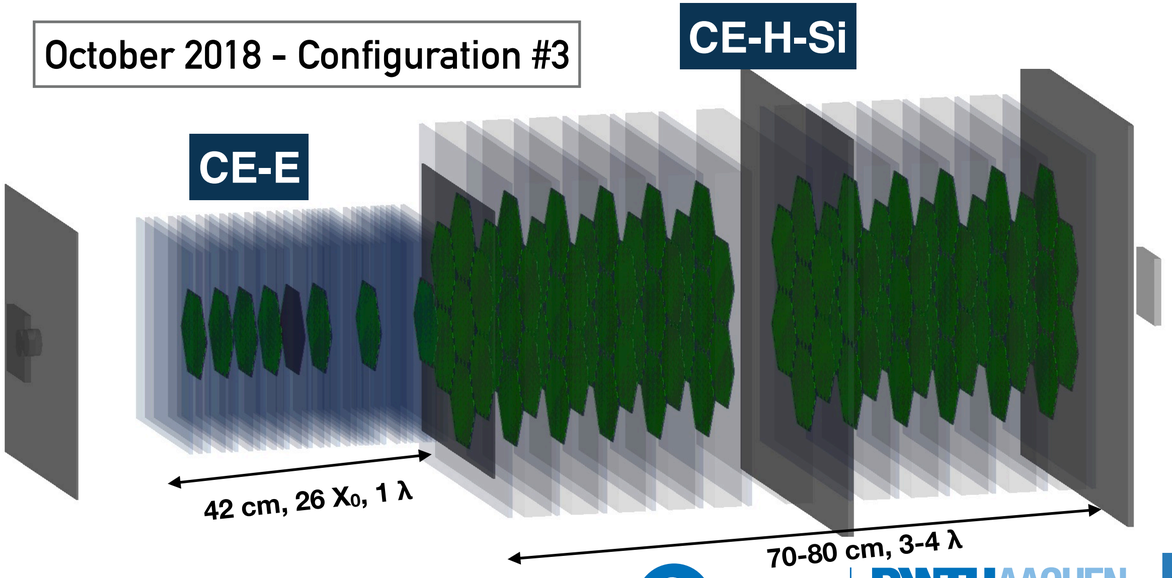


October 2018 - Configuration #2



few hours!

October 2018 - Configuration #3



Busy 2018: Three CMS HGCal test beams

Time

2016

➡ *N. Akchurin et al 2018 JINST 13 P10023*

2017

First tests with **Skiroc2-CMS** ASIC

Begin of "serious" beam tests with Skiroc2-CMS ASIC

March 2018

@ **DESY**

3 modules

June 2018

@ CERN's **SPS**

full CE-E: 28 modules

October 2018

@ CERN's **SPS**

full prototype: 94 modules

Prototype size

First HGCal beam test at DESY in March 2018

- **1.6-6 GeV positrons**

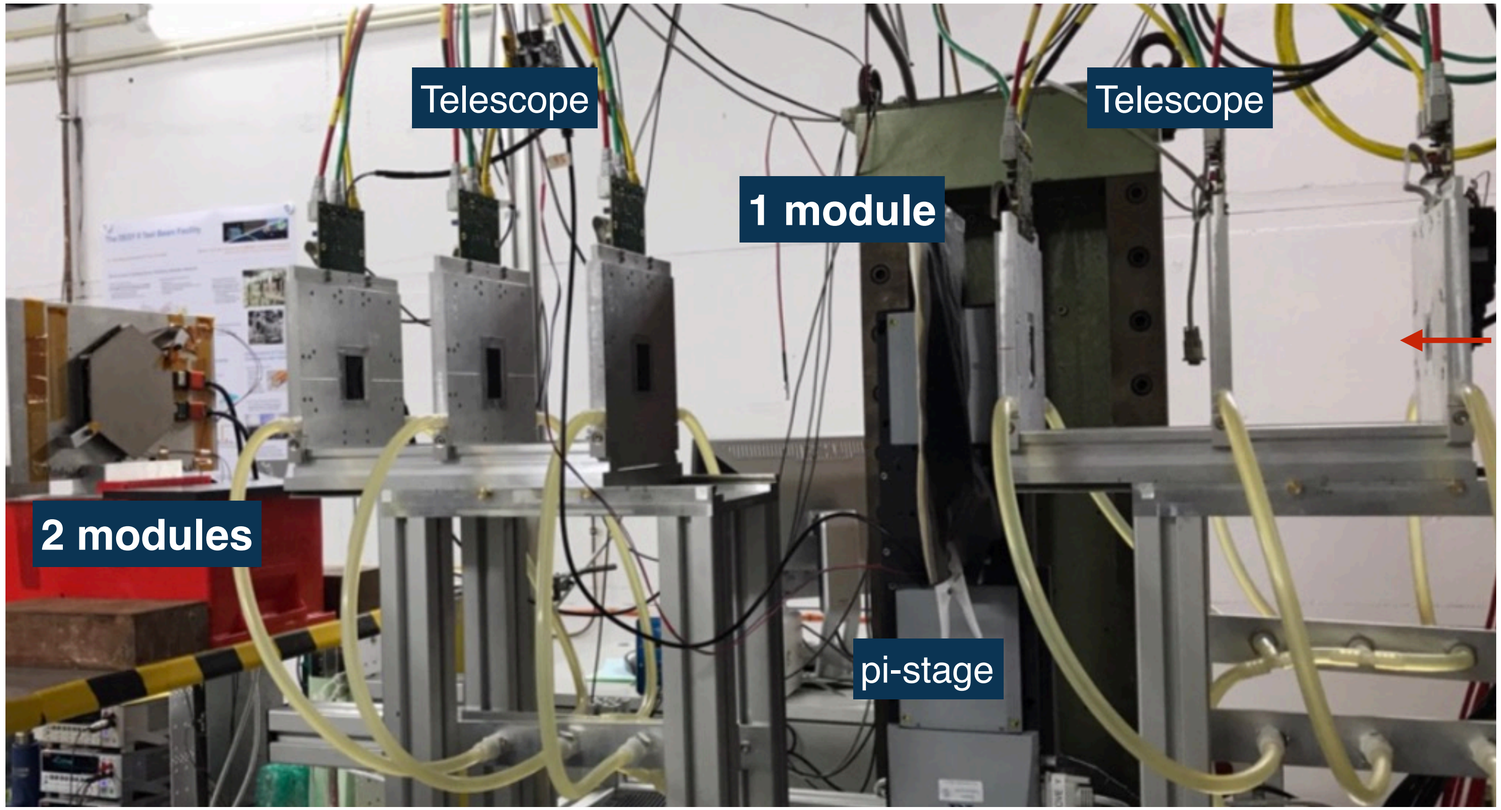
DESY II TB Facility:
➡ **Norbert Meyners**

- Only **1+2 HGCal modules**

- DATURA beam telescope for precise tracking with O(μm) resolution
  - 1 module: mounted on moving pi-stage
  - 2 modules: 2-layer "calorimeter" (W absorbers in front)

- Trigger: 2x scintillators
- Synchronisation: EUDET TLU

Trigger Logic Unit
➡ **David Cussans**



➡Positive experience:
First HGCal beam test at DESY

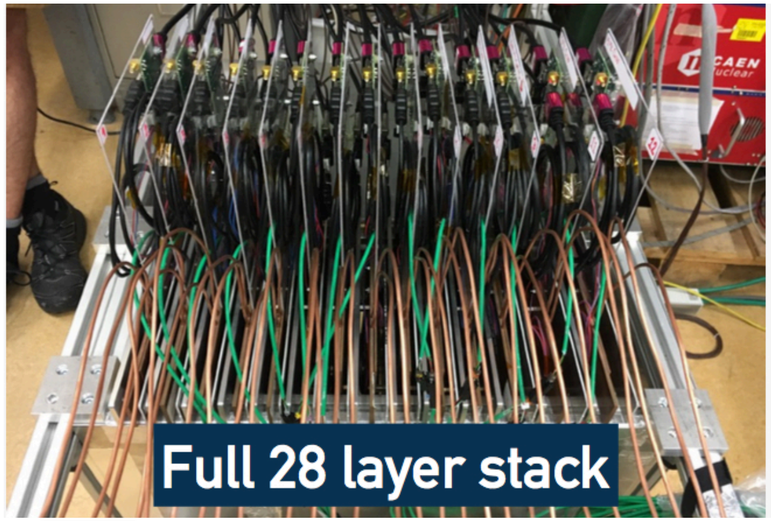
Second beam test at CERN's SPS in June 2018

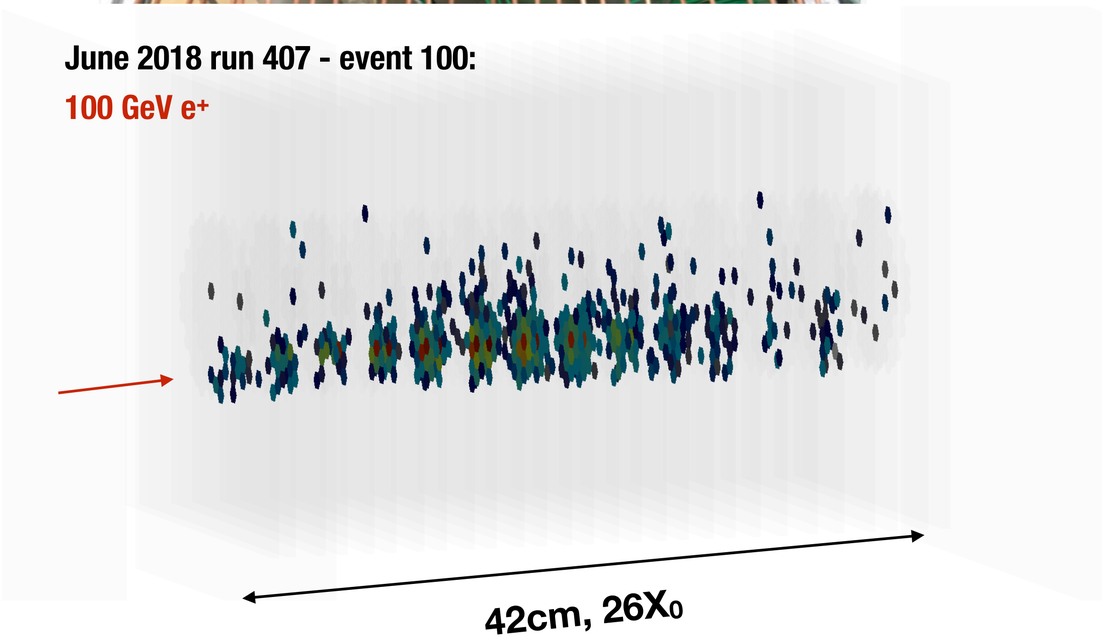
- **Double-sided cassettes** with two modules on CuW baseplate on Cu plate and integrated cooling

Second beam test at CERN's SPS in June 2018

- **Double-sided cassettes** with two modules on CuW baseplate on Cu plate and integrated cooling
- **Full 28-layer CE-E only setup**

- **e, μ up to 150 GeV**
- Trigger: 2x scintillators in front of CE-E



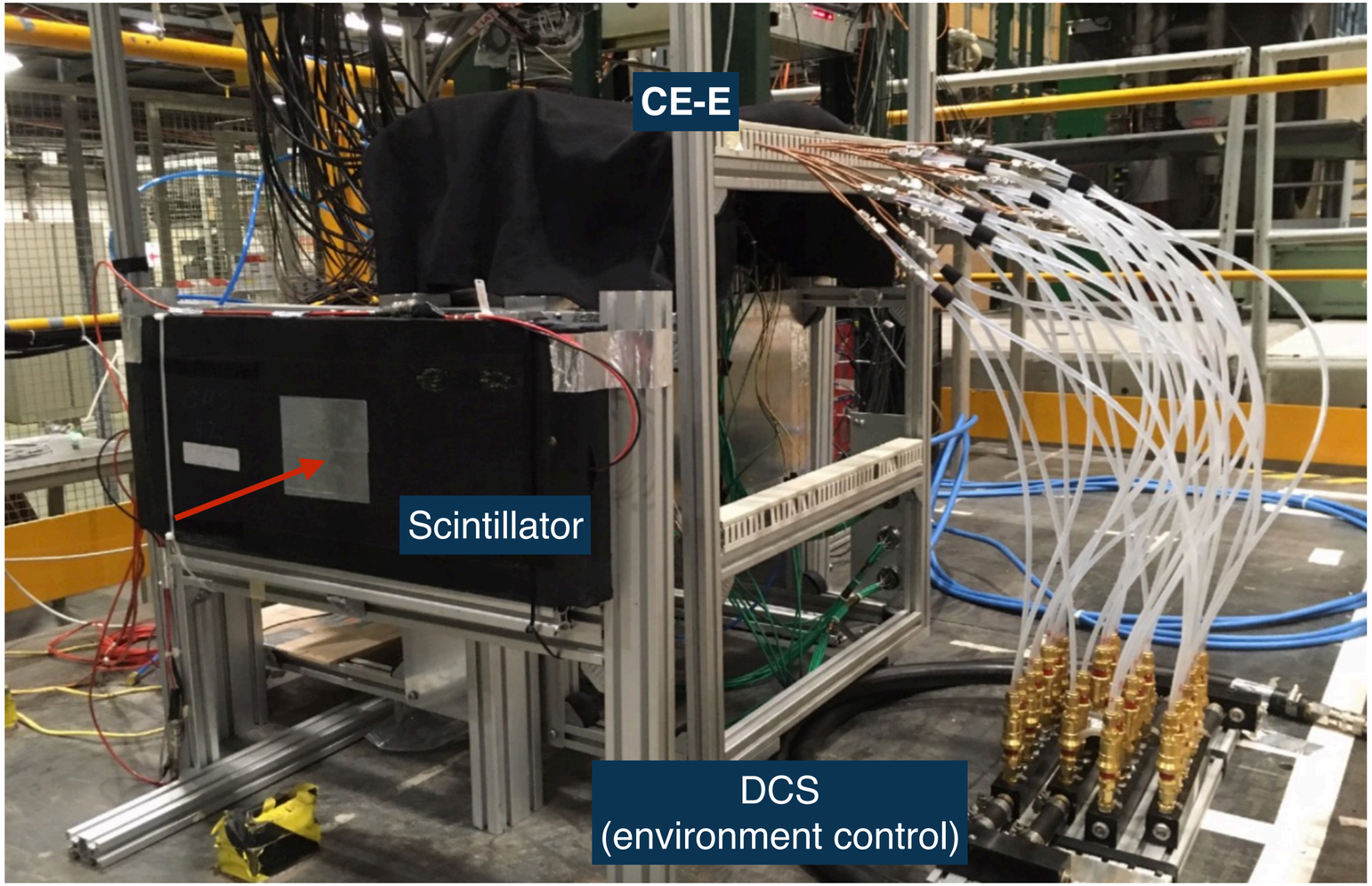


Second beam test at CERN's SPS in June 2018

- **Double-sided cassettes** with two modules on CuW baseplate on Cu plate and integrated cooling
- **Full 28-layer CE-E only setup**

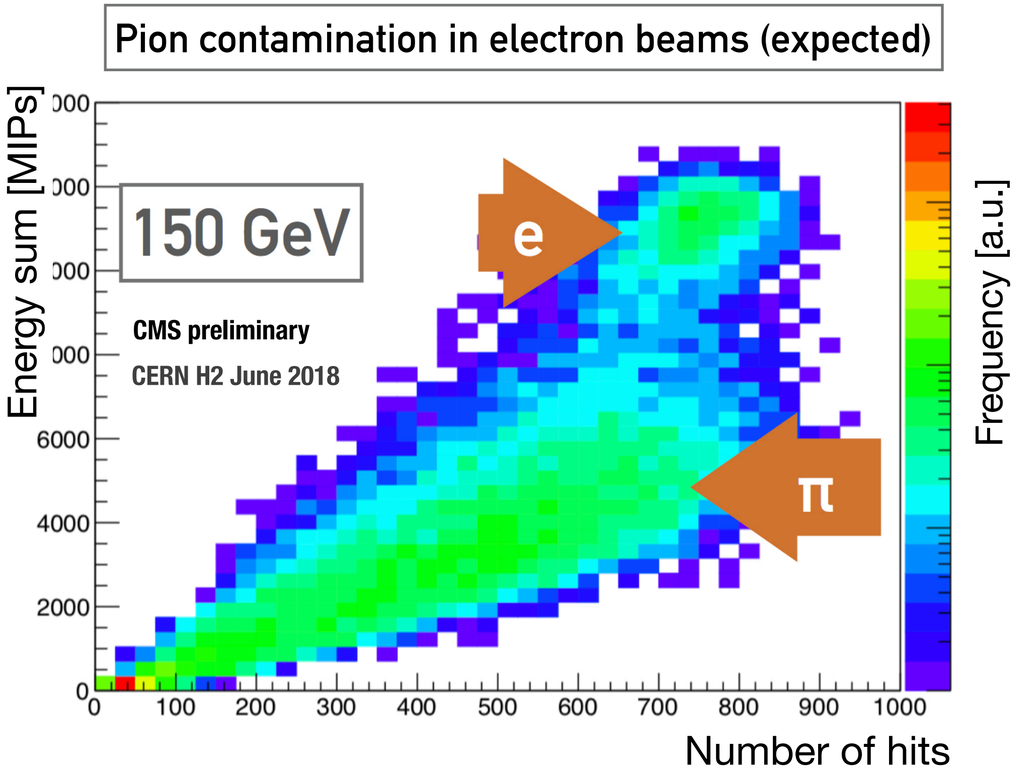
- **e, μ up to 150 GeV**
- Trigger: 2x scintillators in front of CE-E

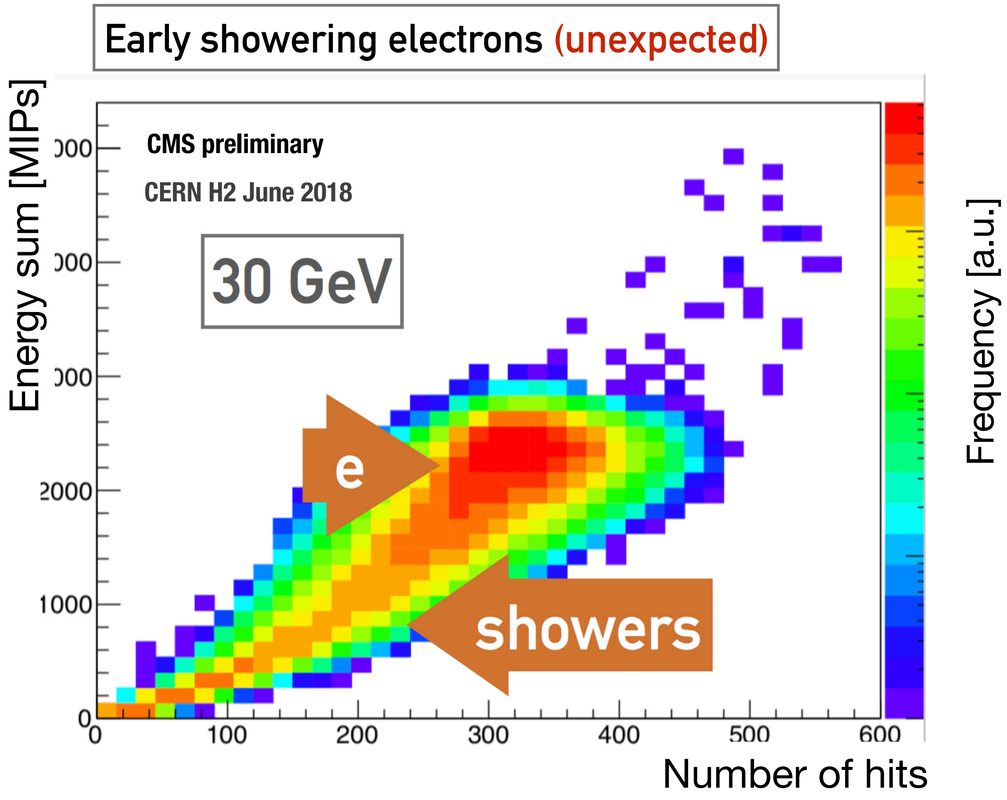
- Active temperature control by chiller
- Nitrogen flux to dry setup
- Temperature & humidity sensors
- HV/LV currents monitored
- Delay wire chambers



➡**System getting serious and mature**

Difficult electron beam conditions in June 2018





- Especially at higher energies:
  - 99% purity < 80 GeV;
    10% for 150 GeV

- Also seen by CALICE AHCAL before
- Requires cleaning of data
- Provides interesting data set for pattern recognition/clustering

Third beam test at CERN's SPS in October 2018

- **28-layer CE-E setup from June**

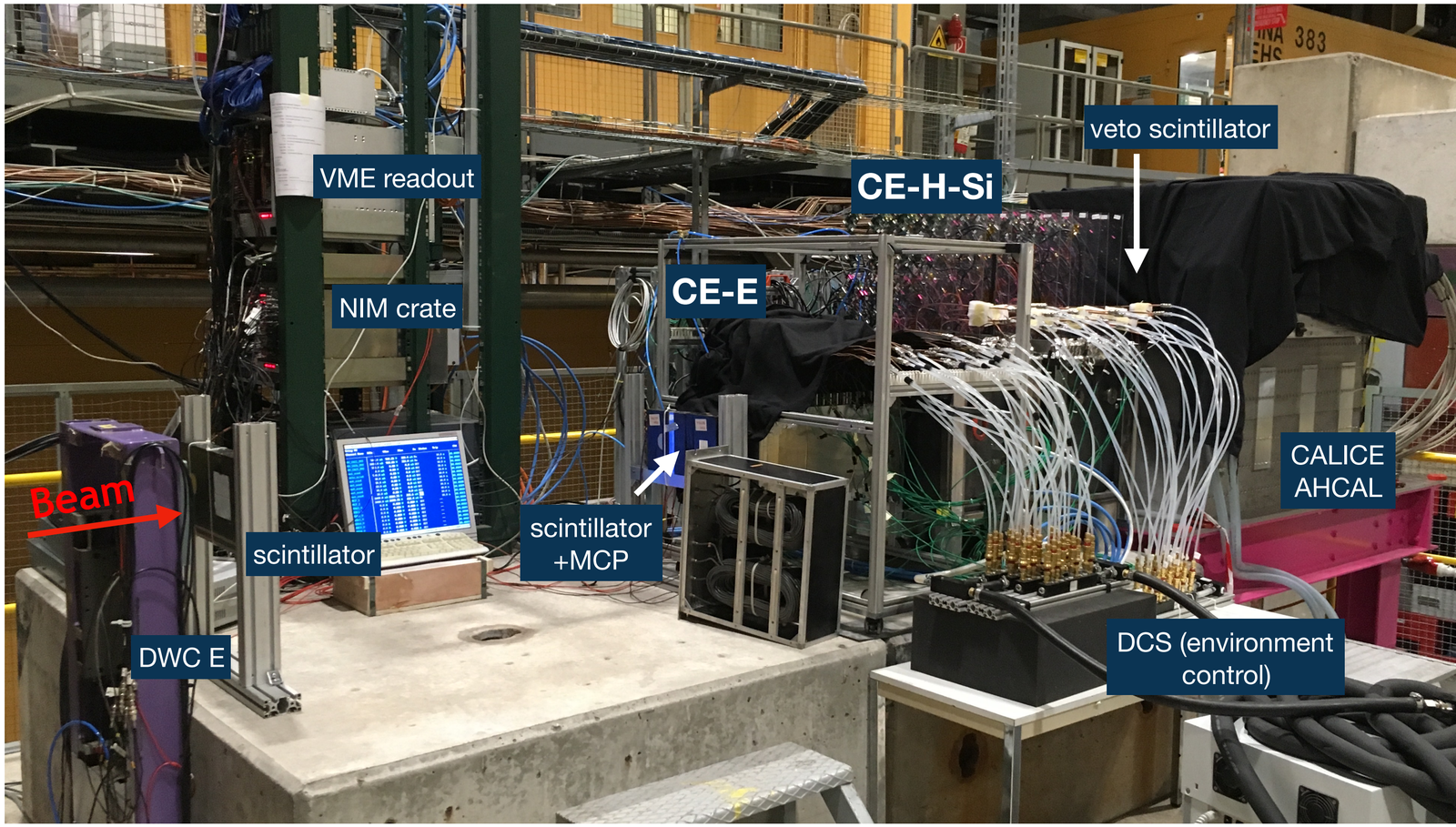
+12-layer CE-H-Si setup (94 modules)

- 3 configurations tested

- environmental control as in June
- Delay Wire chambers
- Threshold Cherenkov counters
- MCPs
- CALICE - AHCAL

AHCAL prototype tests
➡ Katja Krüger

- **e, μ, hadrons up to 300 GeV**
- Trigger: 2x scintillators in front of CE-E + 1x additional (veto) behind CE-H-Si

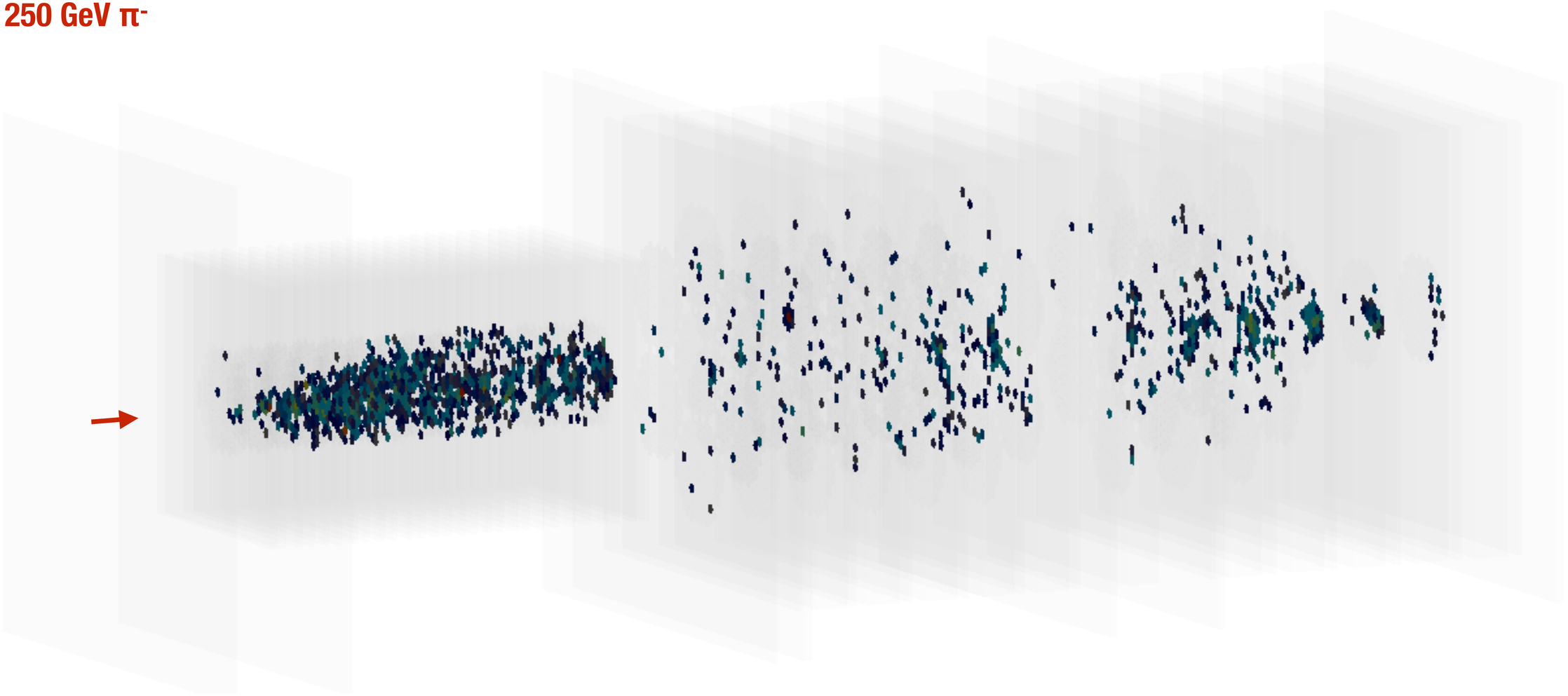


➡First large-scale test of O(100) HGCal modules

HGCal = Imaging calorimeter

October 2018 run 517 - event 1:

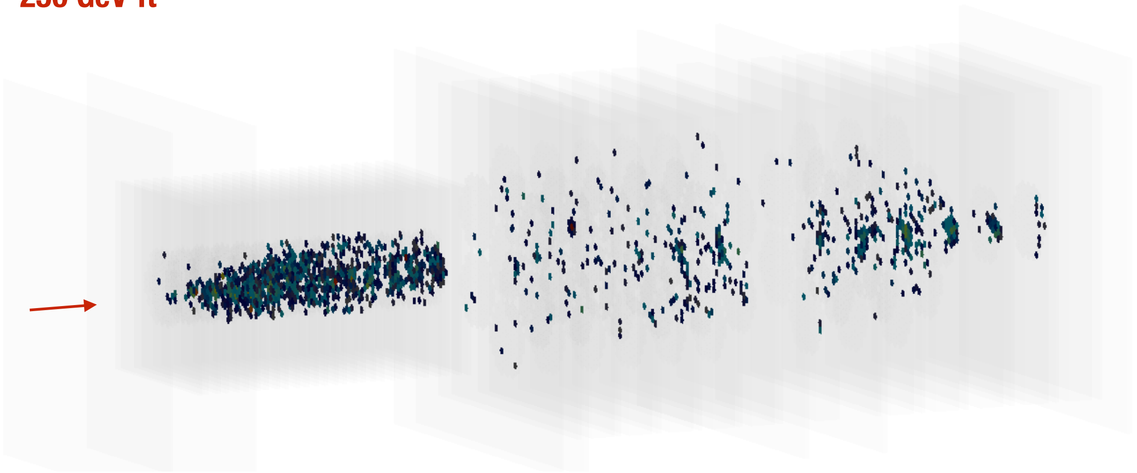
250 GeV π^-



Variety of hadron shower signatures

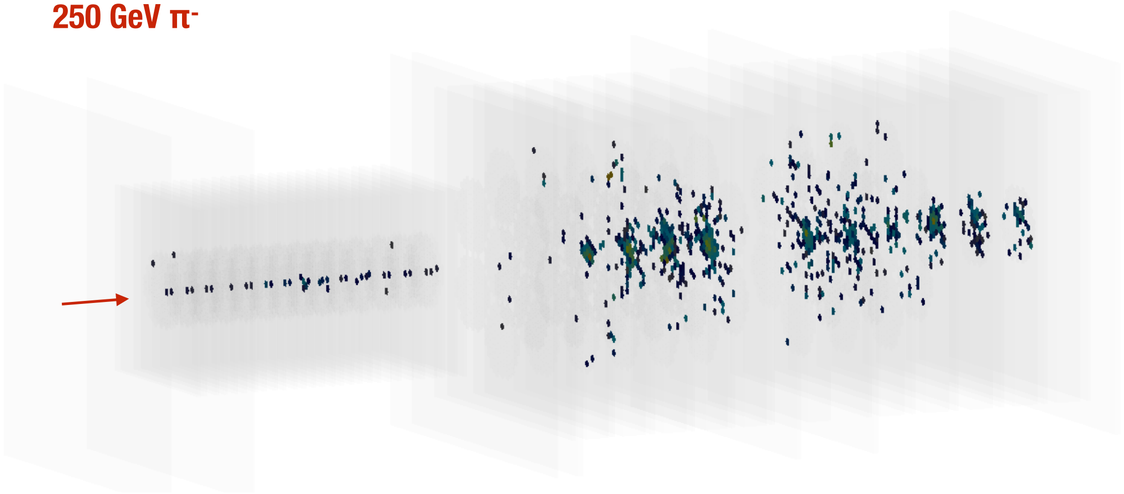
October 2018 run 517 - event 1:

250 GeV π^-



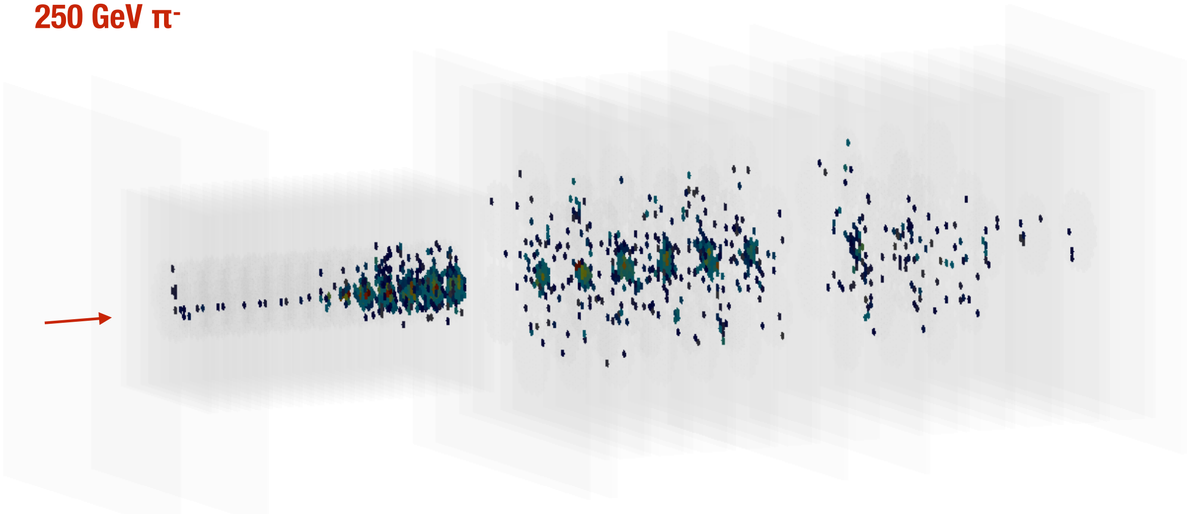
October 2018 run 517 - event 2:

250 GeV π^-



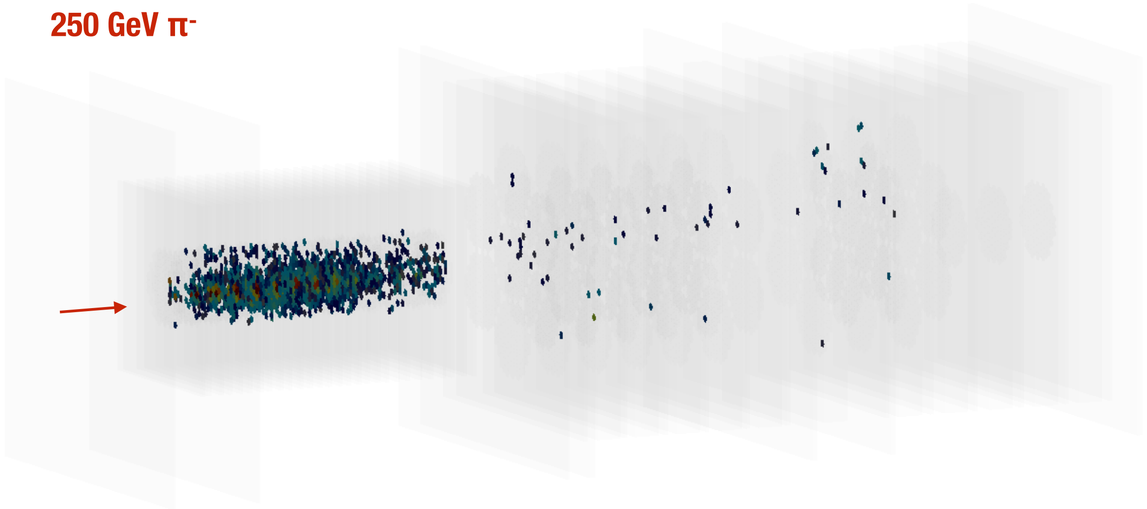
October 2018 run 517 - event 3:

250 GeV π^-

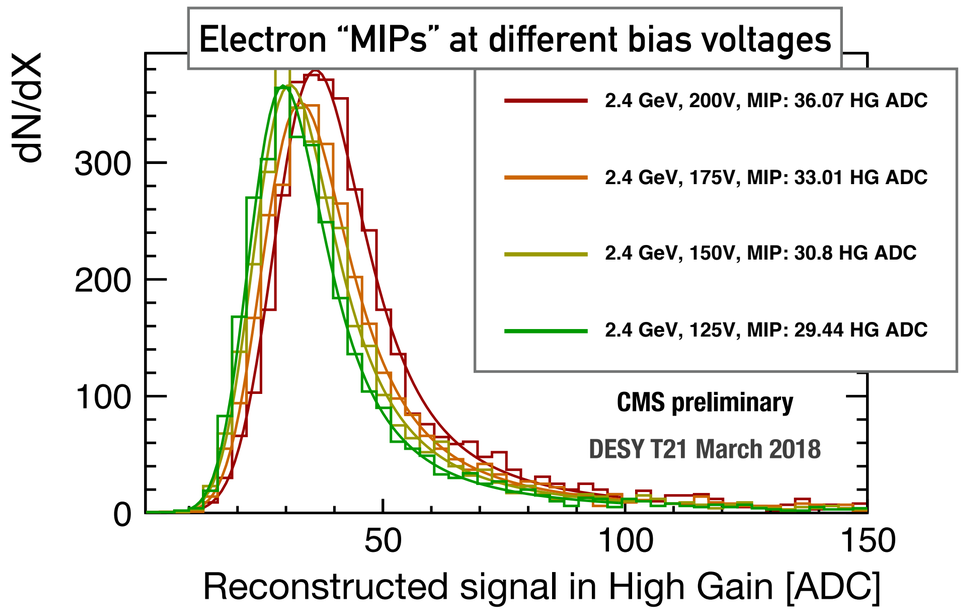


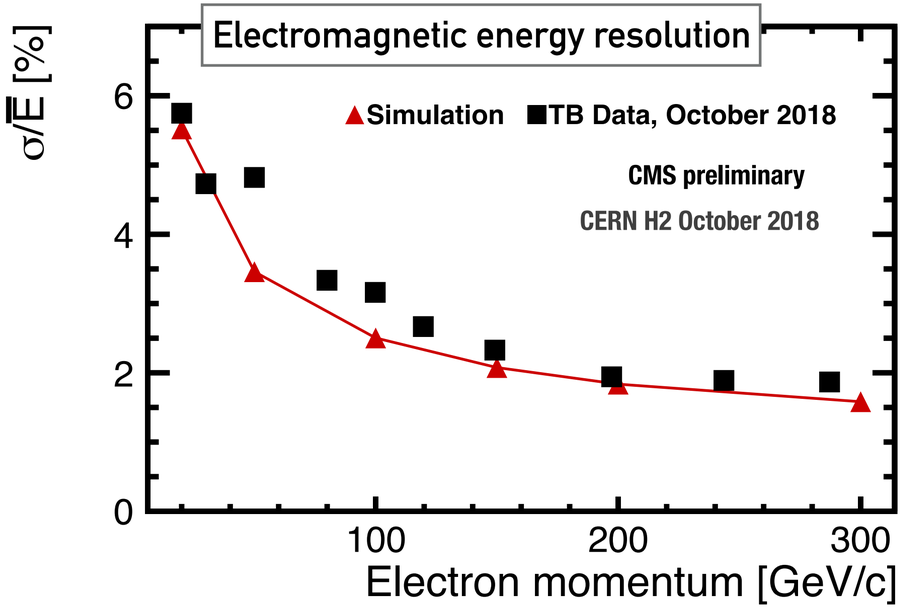
October 2018 run 517 - event 101:

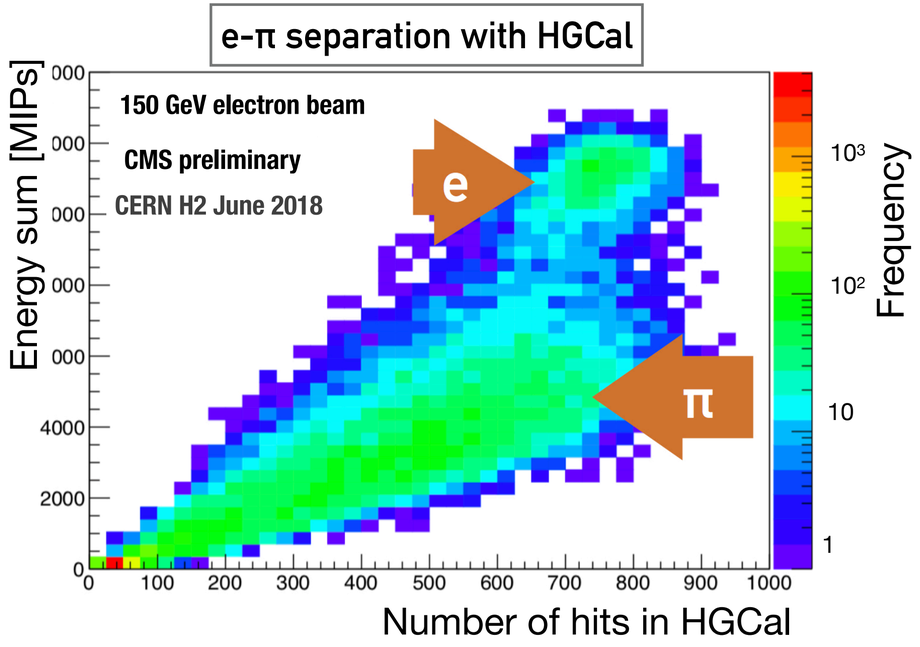
250 GeV π^-

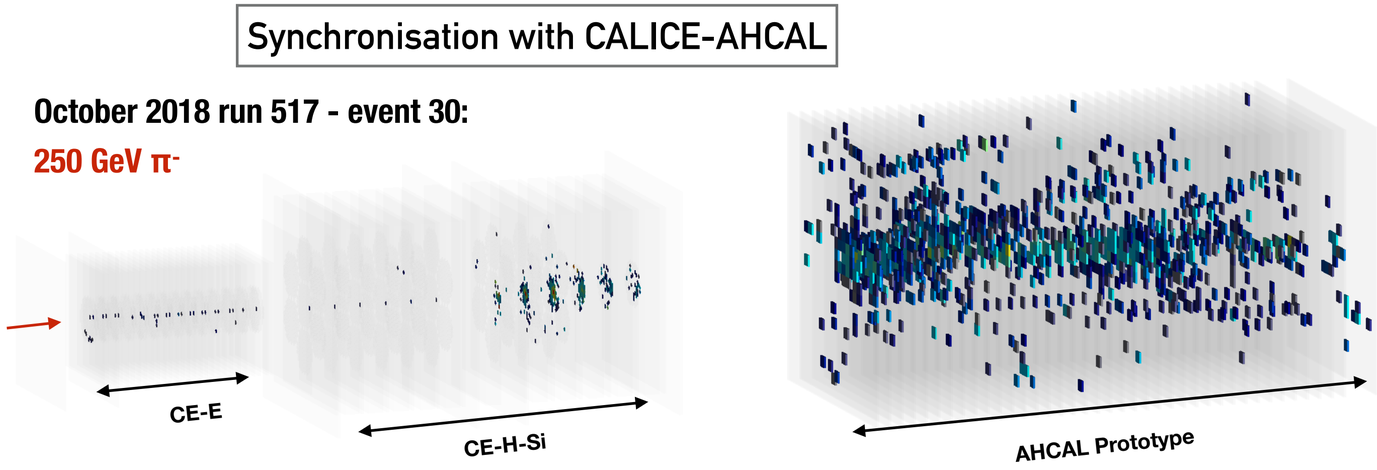


2019: Data analysis









Beam test motivation

- Main objectives for beam tests:
  - ✓ Technological **prototyping** of the detector modules
  - **First experience** with a **FE ASIC** with components of the ultimate (HGC)ROC **in beam conditions**: ADC, ToT, ToA
  - **Physics performance** of the CE-E and CE-H silicon / scintillator parts
  - Check **agreement** with **simulation**

Lesson learnt: Beam characterisation helpful

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➡Required / helpful:
Beam characterisation with independent detectors

Tracking | Hadron ID | t_0

Lesson learnt: Beam characterisation helpful

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  - ✓ Technological **prototyping** of the detector modules
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➡Required / helpful:
Beam characterisation with independent detectors

DATURA DWCs

XCET

MCP

Lesson learnt: Beam characterisation helpful

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  - ✓ Technological **prototyping** of the detector modules
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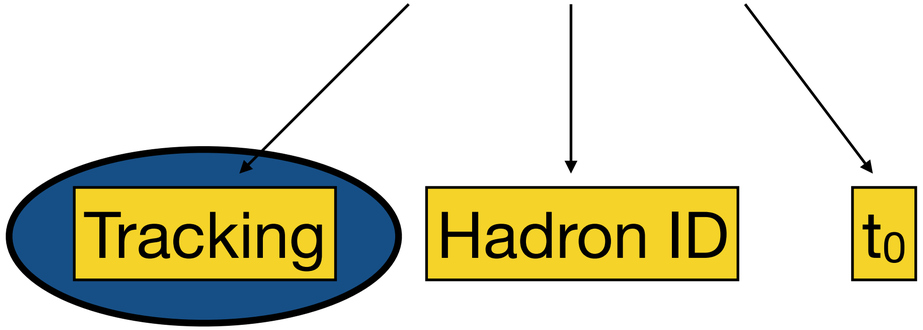
➡Required or at least helpful: Beam characterisation with independent detectors



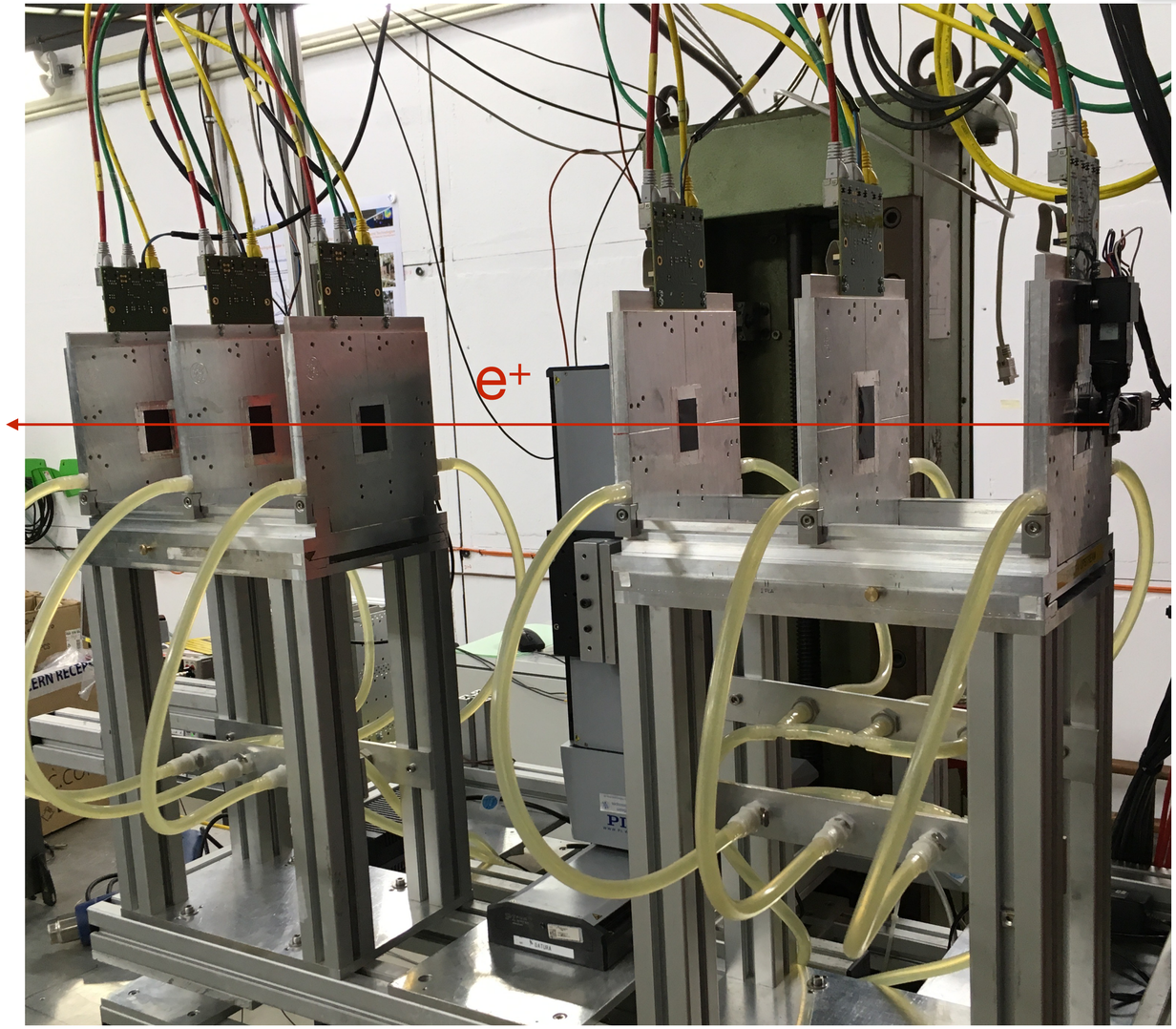
Rest of this talk

DATURA telescope @ DESY

Tracking

Tracking with DATURA Telescope @ DESY T21

EUDET-type beam telescopes
➡ Jan Dreyling-Eschweiler



MIMOSA26 chips

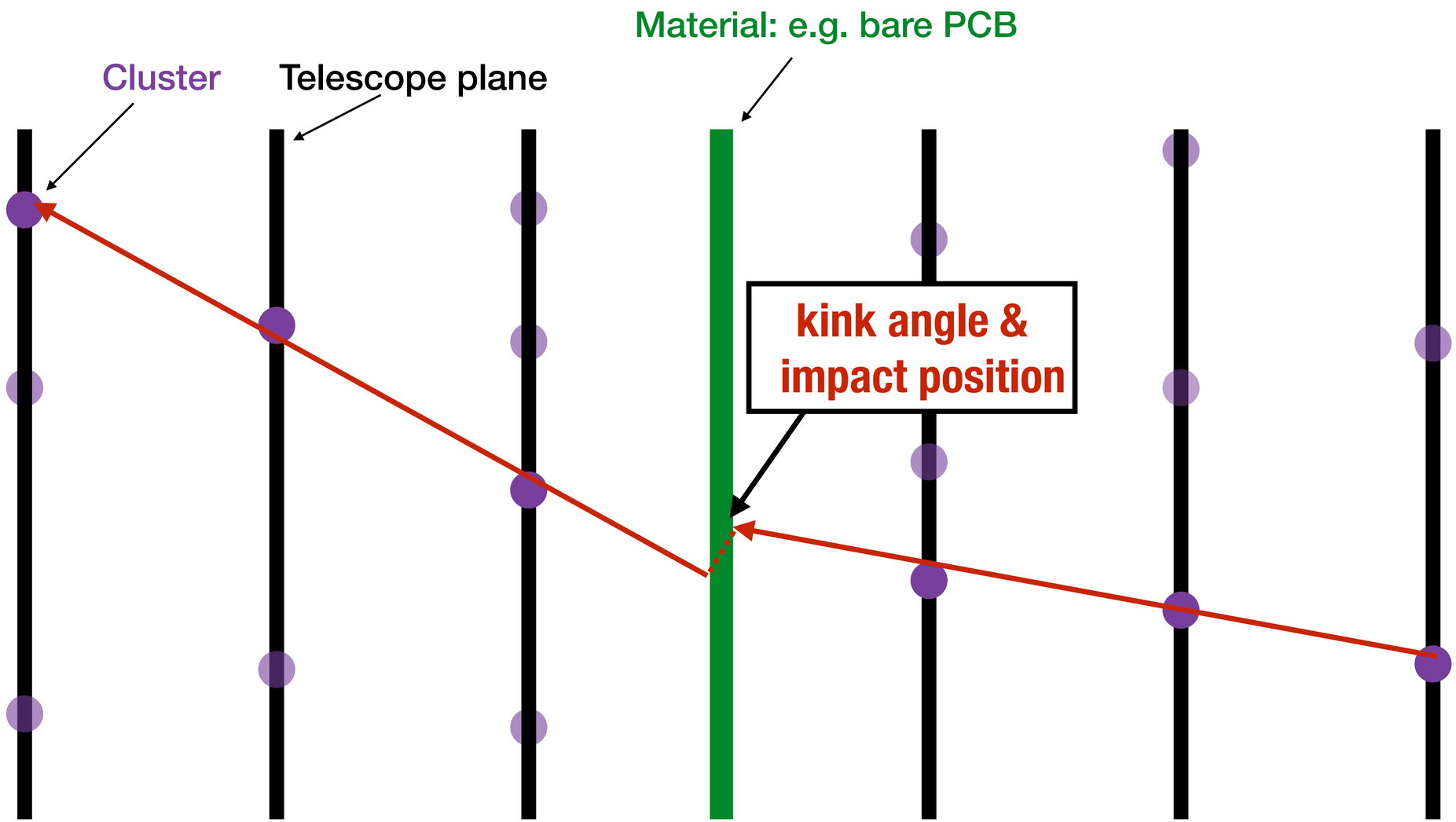
- 576 x 1152 pixels
- 10.6 x 21.2 mm²
- **18.4 µm pitch**
- 100 µs rolling shutter

✓ **EUDAQ1 readout provided**

Reconstruction:

Corryvreckan (v0.6)

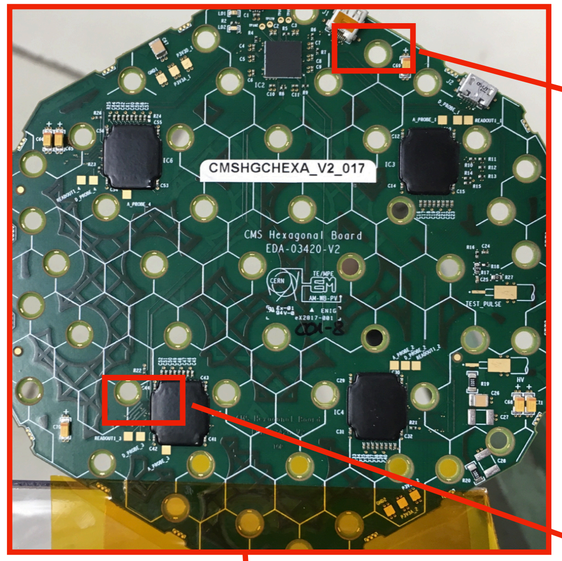
Corryvreckan
➡ Morag J. Williams


Material: e.g. bare PCB
Cluster
Telescope plane
kink angle &
impact position

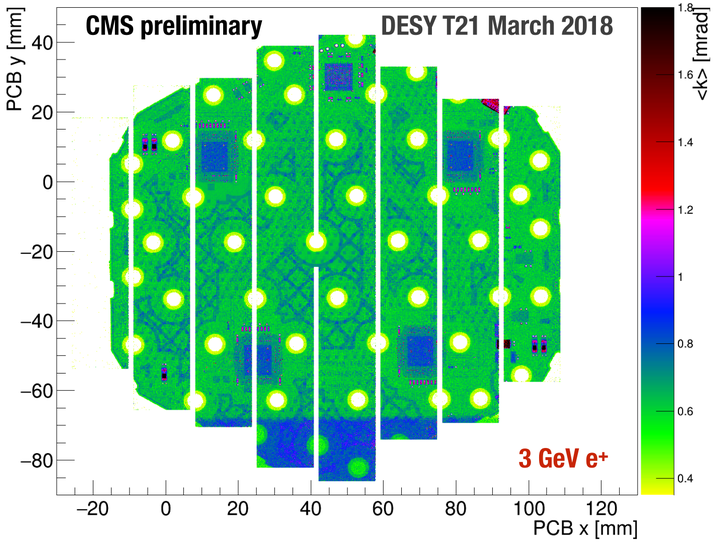
PCB tomography

Material Budget Imaging
➡ **Paul Schütze et al.**

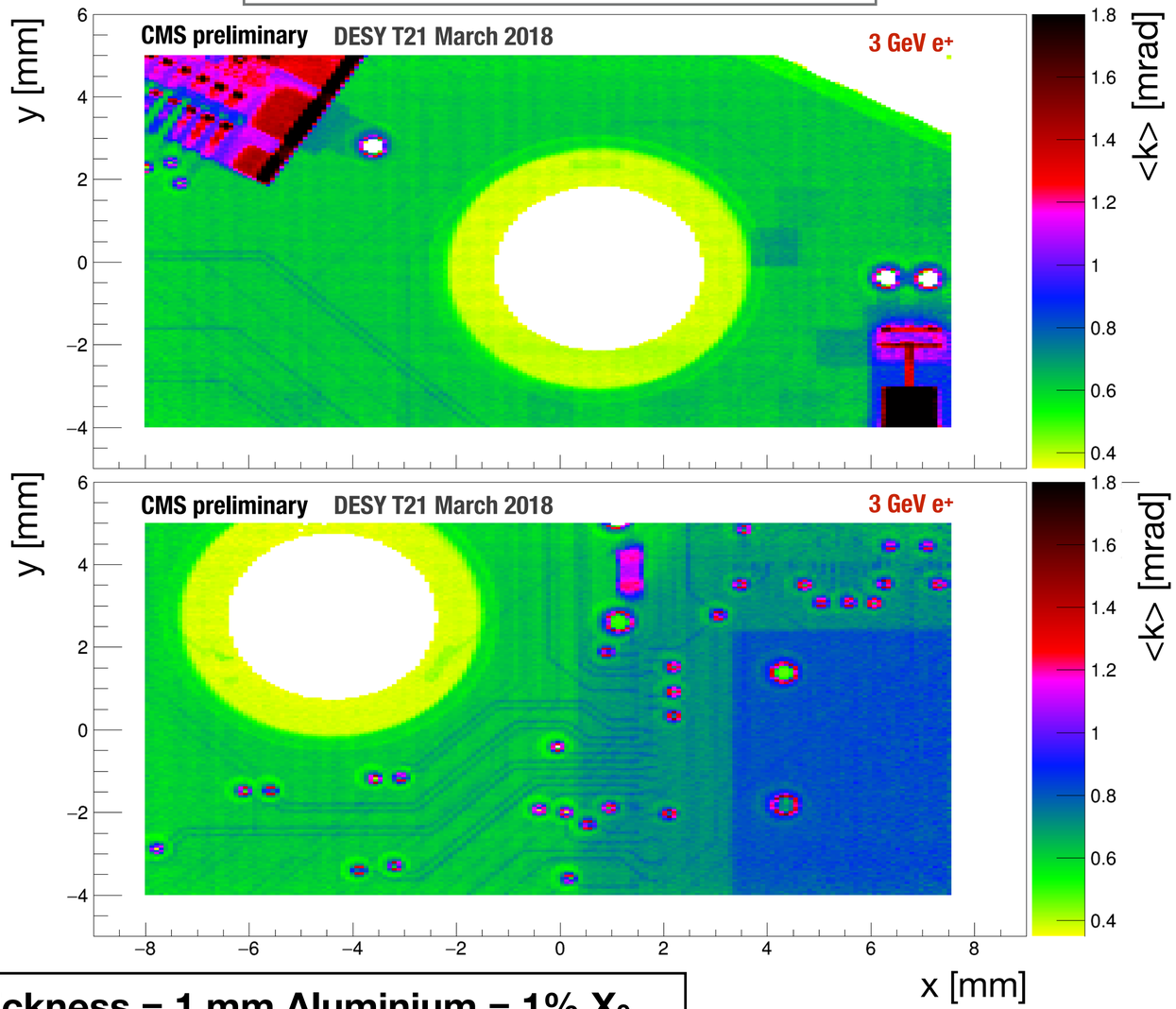
Tracking



Tomography of the full PCB



Tomography of selected areas on the PCB

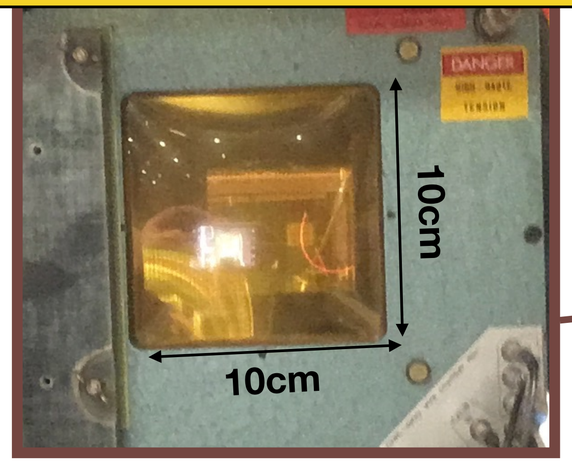


➡ **PCB thickness = 1 mm Aluminium = 1% X_0**
➡ **ASIC thickness = 3 mm Aluminium = 3% X_0**

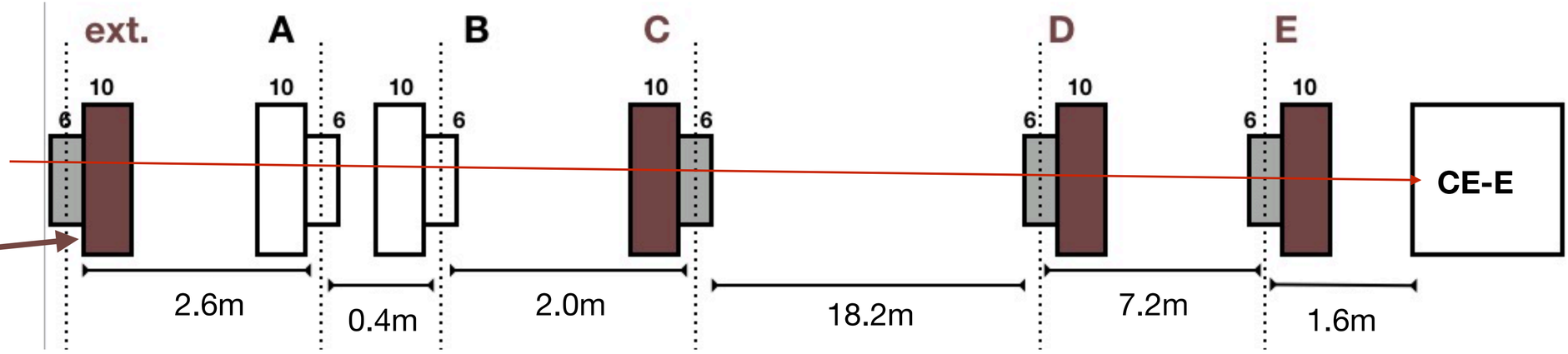
Delay Wire Chambers @ CERN

Tracking

Tracking with DWCs @ CERN



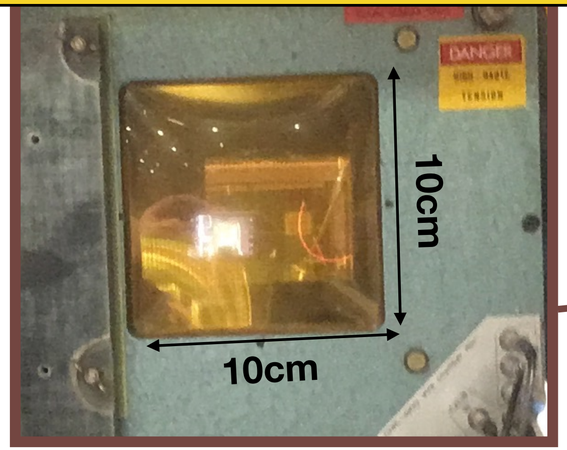
DWCs in CERN's North Area H2 for the October 2018 test



Sub-mm pointing resolution with these DWCs

Tracking

Tracking with DWCs @ CERN



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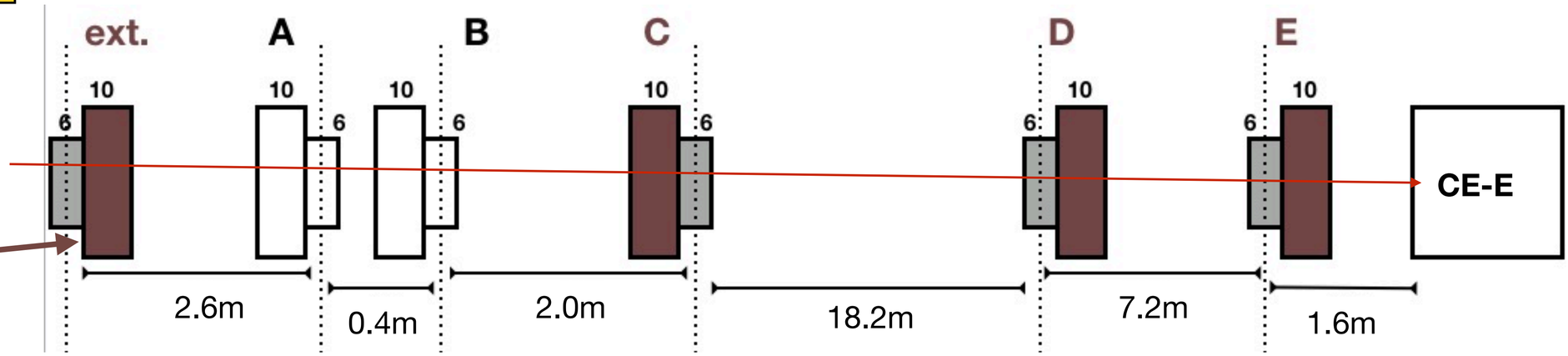
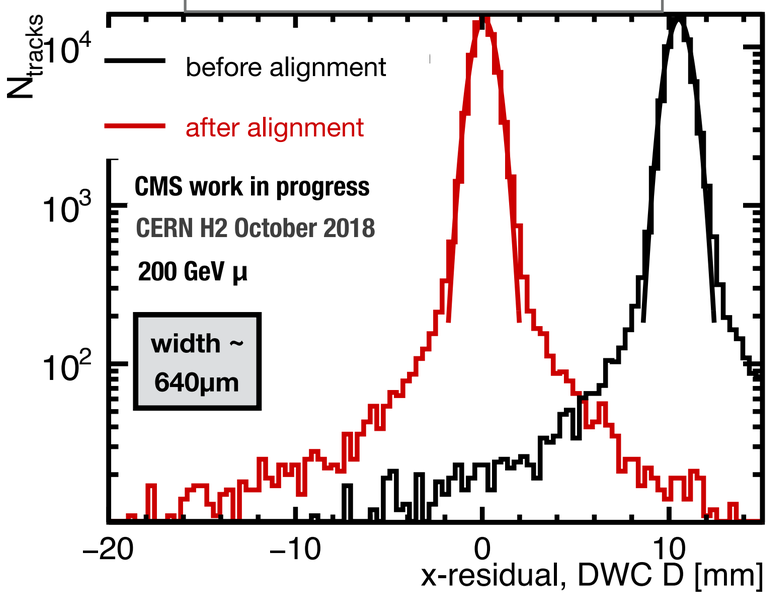
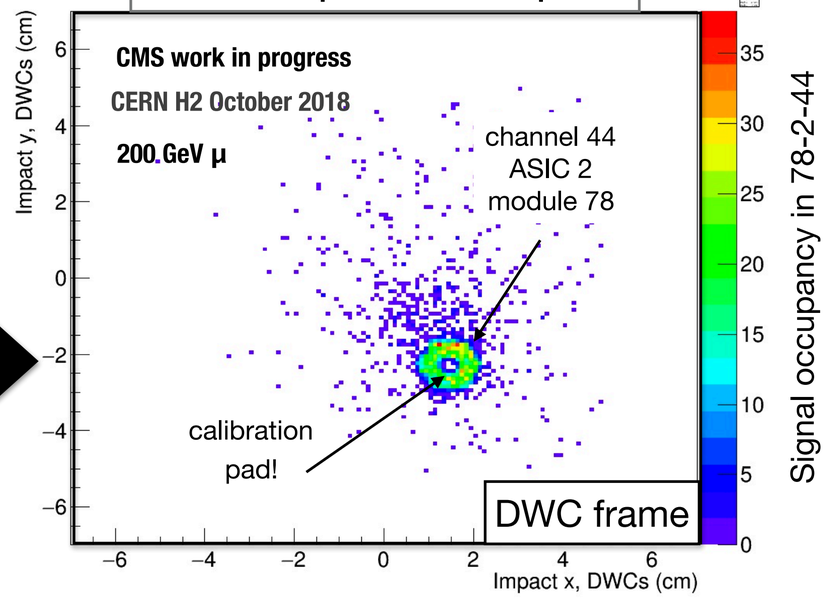


Unbiased residuals at DWC D



500μm pointing resolution

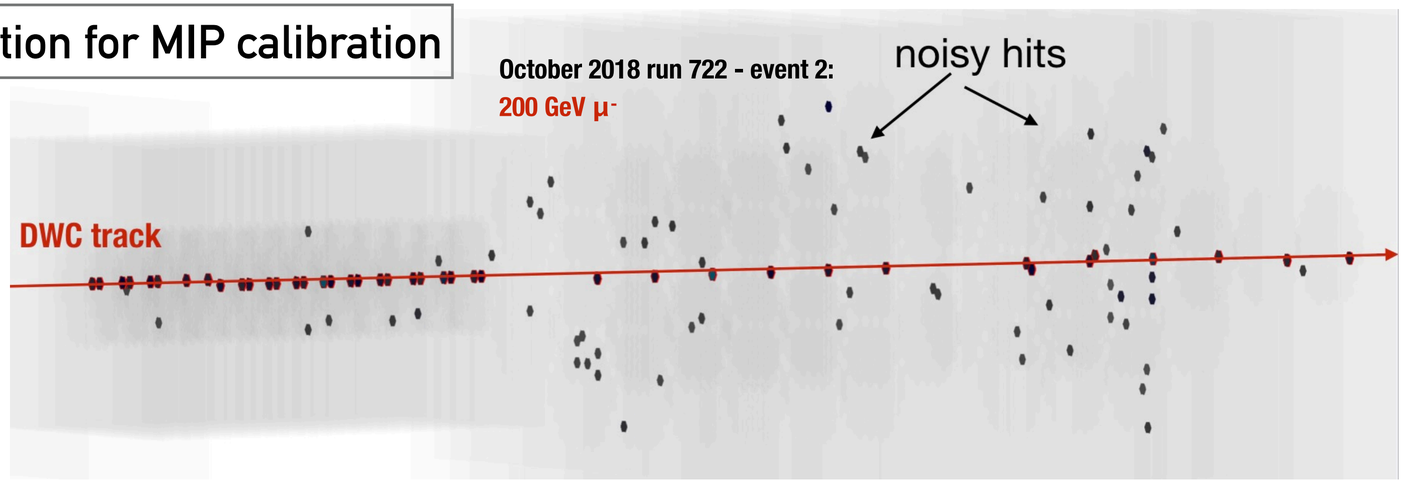
DWC Track points to DUT pixels



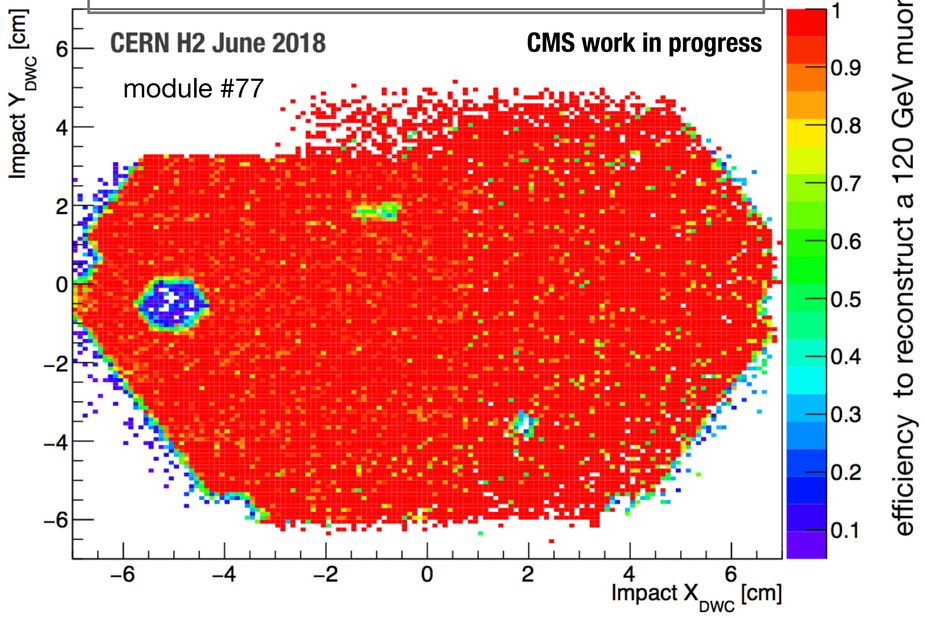
DWC-tracking helpful for our analyses

Tracking

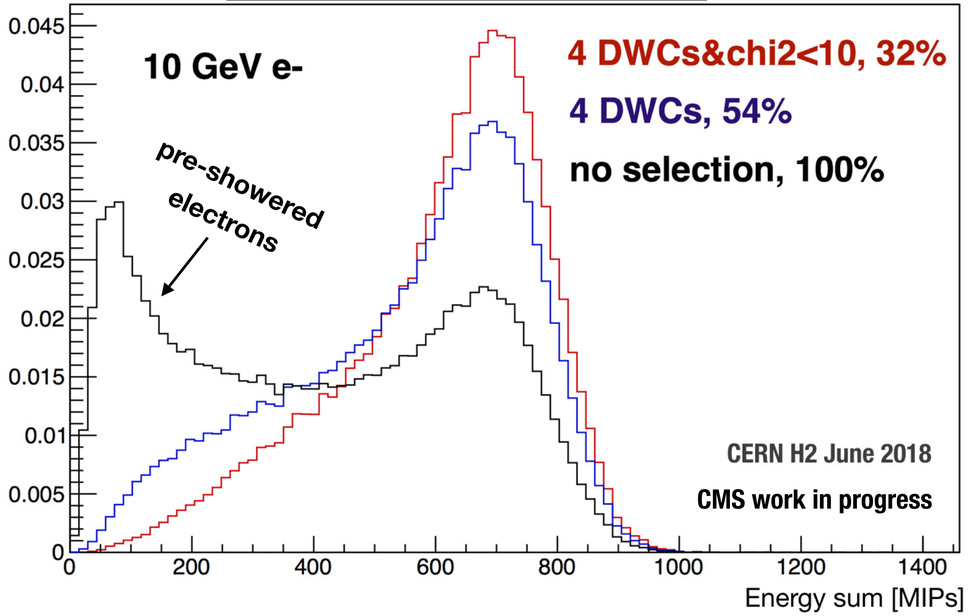
Hit selection for MIP calibration



Search for "holes" in the modules



Pre-showering filtering



Summary

<u>HGCal beam tests in 2018</u>

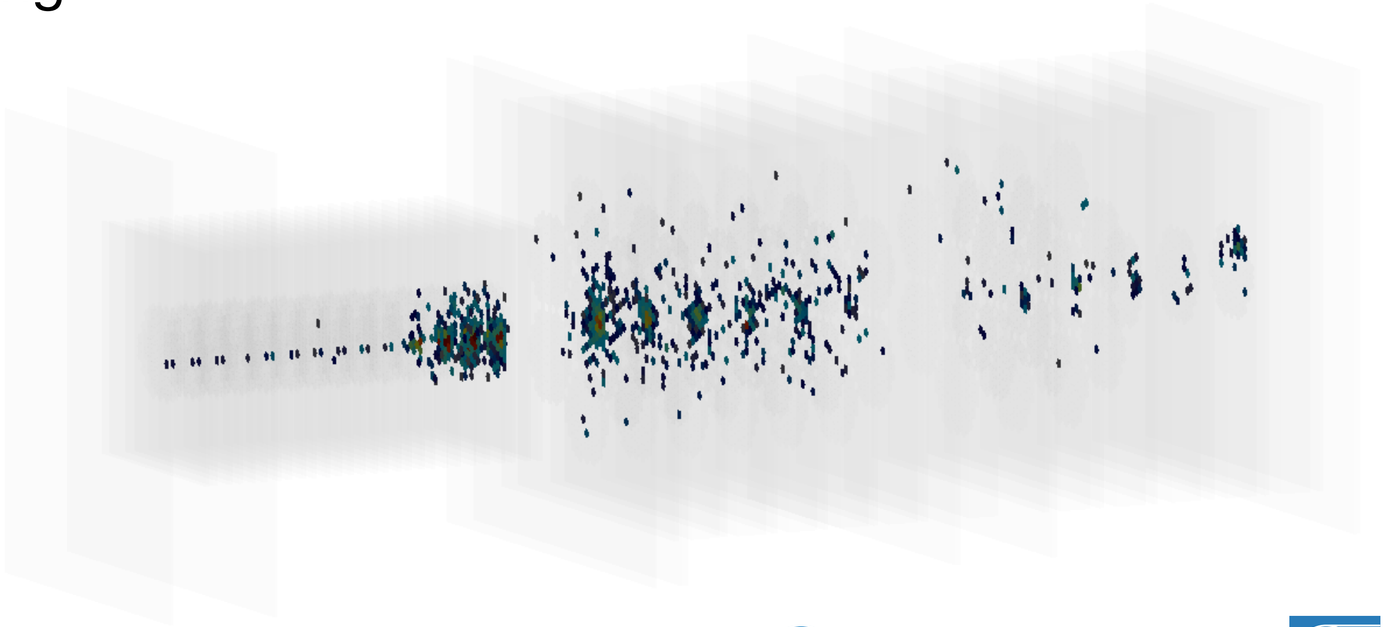
1. March, DESY: First HGCal beam test at DESY
2. June, CERN: Towards a mature system
3. October, CERN: First large-scale tests, O(100) modules

<u>Beam characterising detectors incorporated</u>

- ✓ DATURA telescope: precise tracking
- ✓ Delay wire chambers: tracking
- (✓) Cherenkov detectors: hadron ID
- (✓) MCP: O(10ps) t_0 reference

★Good data quality

➡Datasets to be analysed now…



Additional material

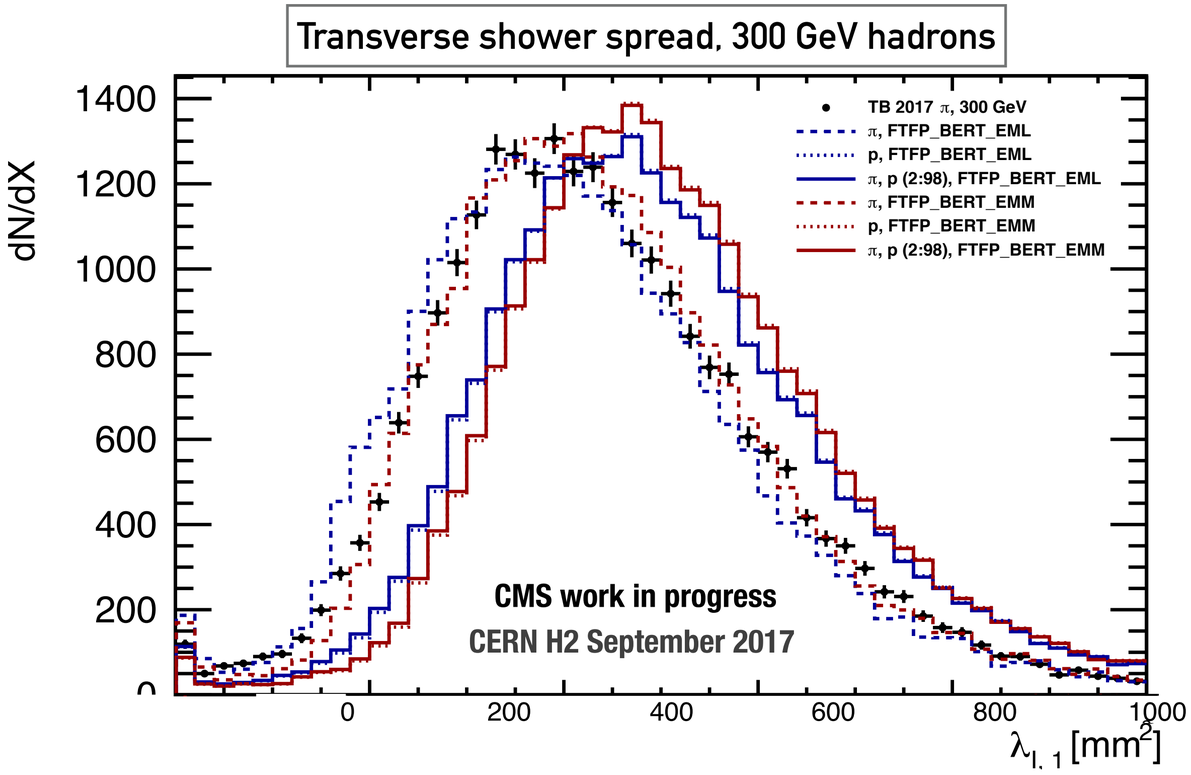
Independent hadron ID helpful

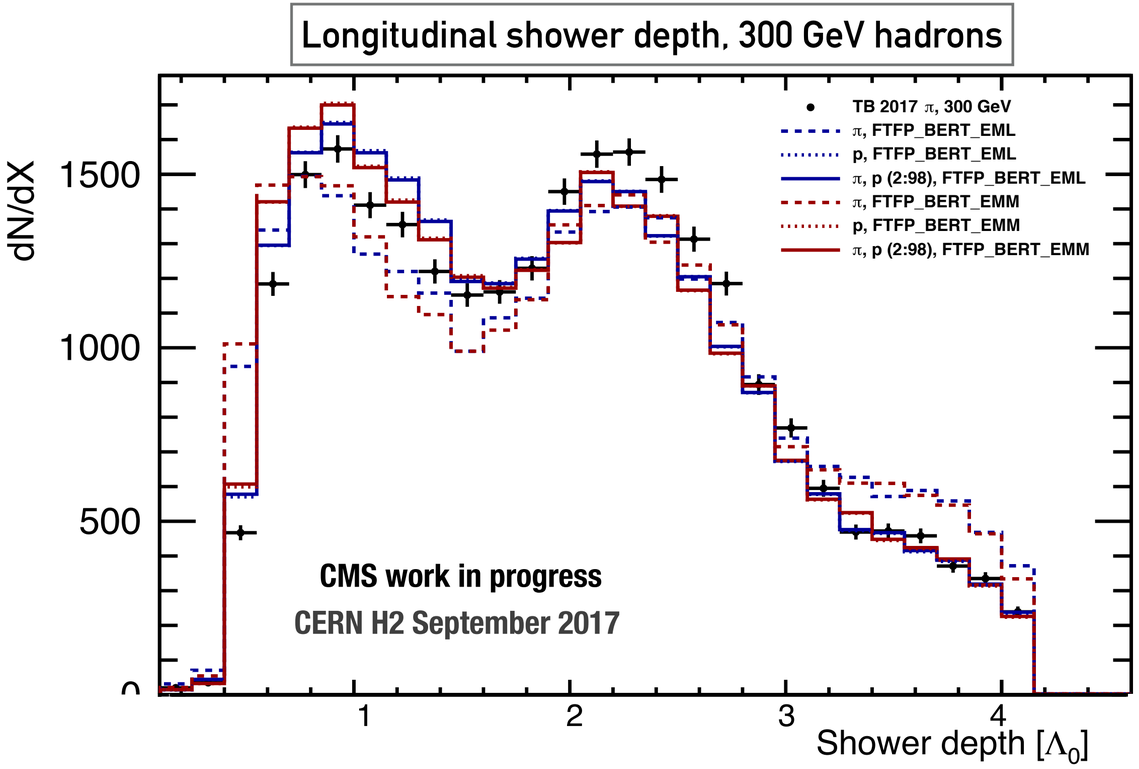
Hadron ID

Challenge:

Experimental condition: π-beam != 100% π

+ calorimeter response depends on hadron type





➡ 300 GeV beam = pions

➡ 300 GeV beam = protons

Cherenkov Counters @ CERN

Hadron ID

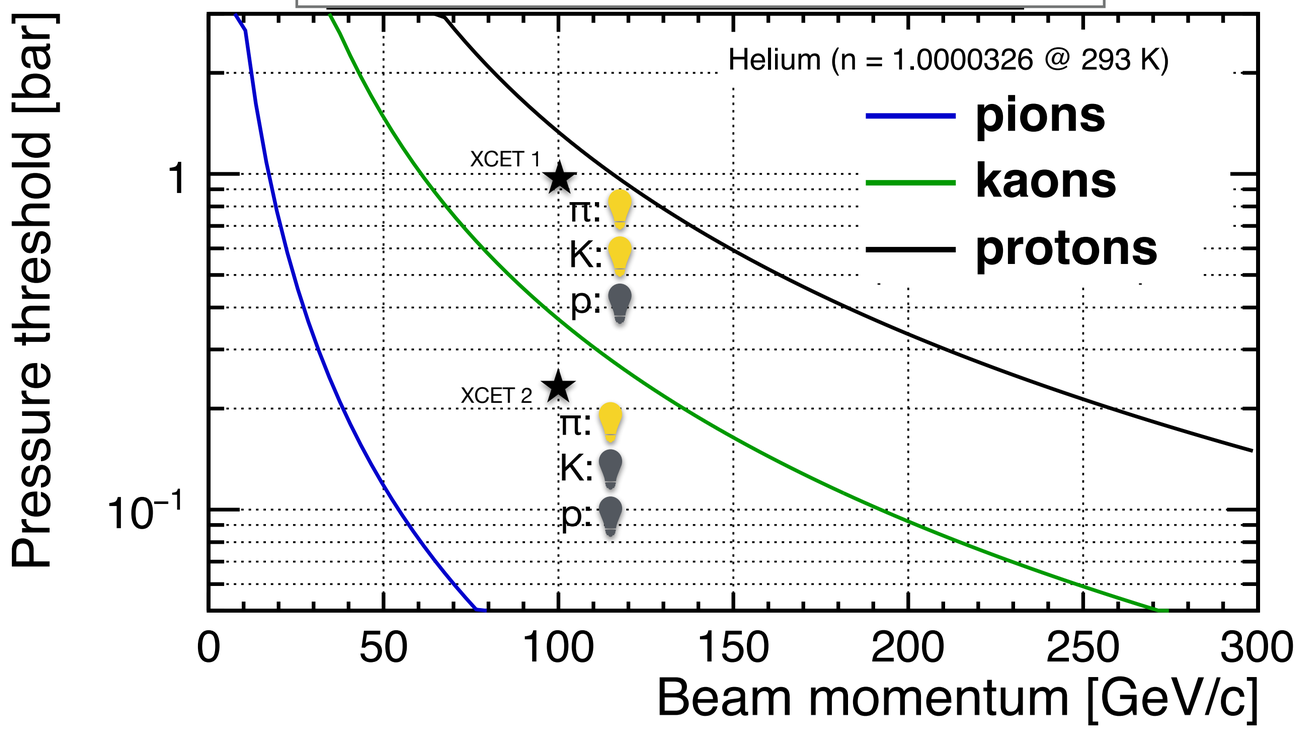
Challenge:

Experimental condition: π-beam != 100% π

+ calorimeter response depends on hadron type

➡ Hadron ID with 2 upstream XCETs

Theoretical turn-on pressure for different particles



North Area beam instrumentation
➡ Alexander Gerbershagen

- Good:
  ~0% fake-rate below threshold
- Not so good:
  Tubes only 2m long
  average #photo-electrons < 1

➡we saw low efficiency:

~2-10% @ ΔP=0.3 bar

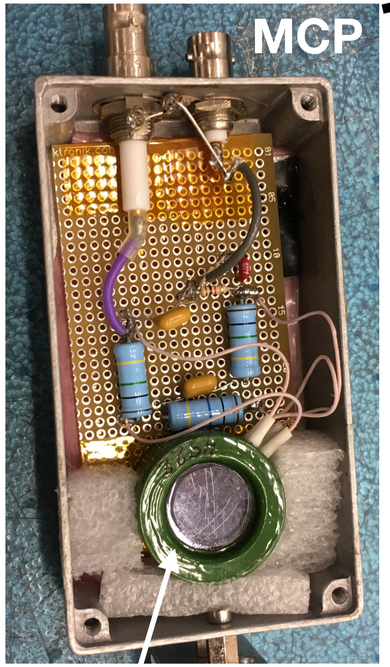
➡ Not yet clear if and how to be used for our analyses…

Use of MCPs for t_0 measurement

t_0

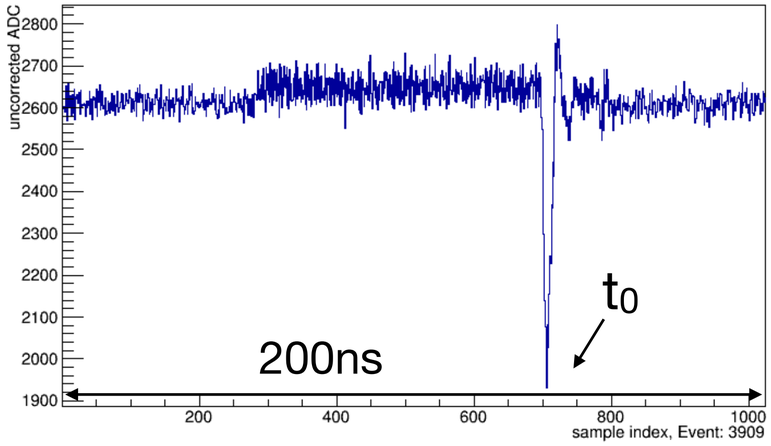
Skiroc2-CMS designed to provide timing resolution of 50ps

➡ 2 MCPs for O(10ps) t_0 measurement installed in front of CE-E



sensitive area (~1cm²)

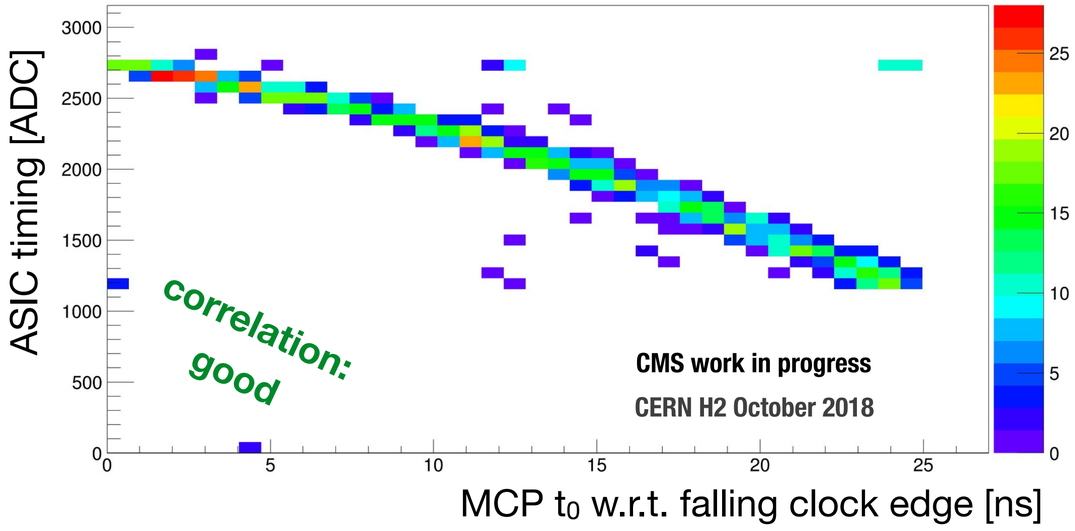
Digitised MCP Waveform



waveform analysis for many events

MCP-PMTs as t_0 detector
➡ Lukas Sohl

MCP-t_0 correlation to HGCal ASIC timing



➡Facilitated: Timing calibration

➡Possible: Unbiased measurement of timing resolution

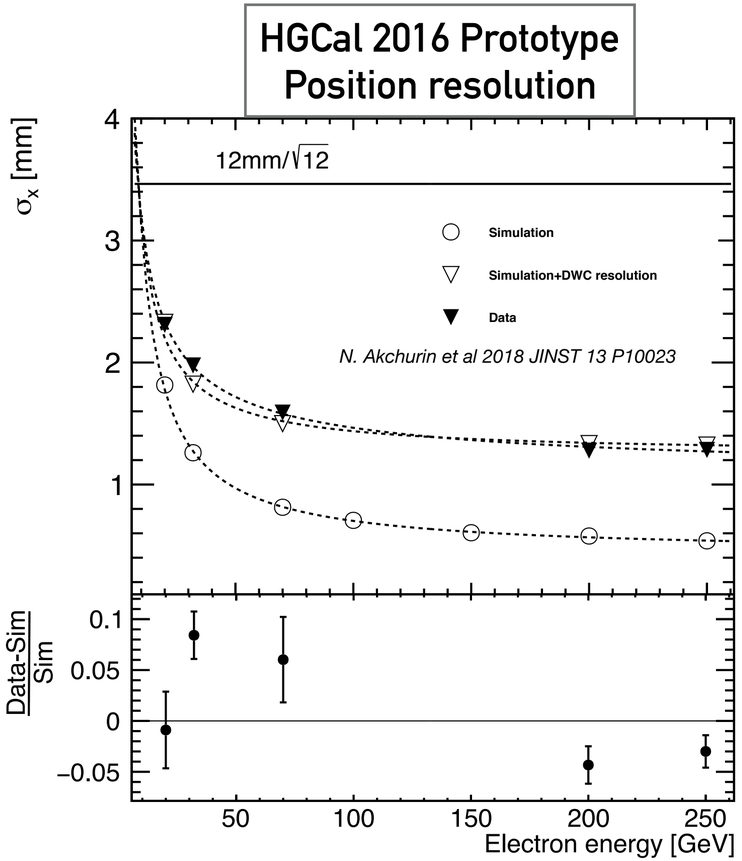
MCPs in timing resolution studies
➡ Simone Pigazzini

III. Physikalisches Institut RWTH AACHEN UNIVERSITY CERN

Backup

Beam test objectives

- Main objectives for beam tests:
  - Technological **prototyping** of the detector modules
  - **First experience** with a **FE ASIC** with components of the ultimate (HGC)ROC **in beam conditions**: ADC, ToT, ToA
  - **Physics performance** of the CE-E and CE-H silicon / scintillator parts
  - Check **agreement** with **simulation**



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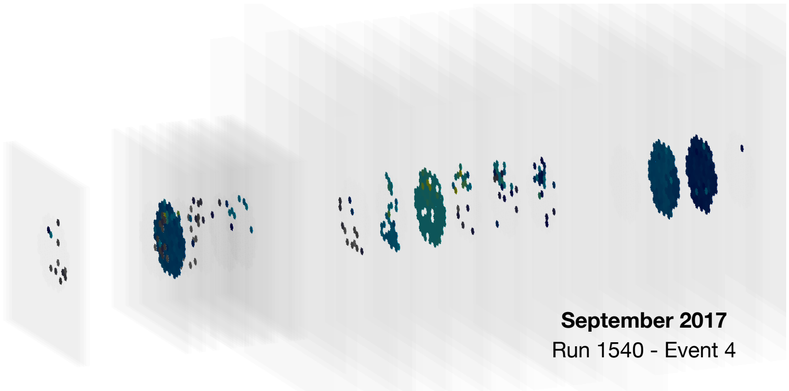
  - Check **agreement** with **simulation**
- *(what ever challenges we encounter!)*

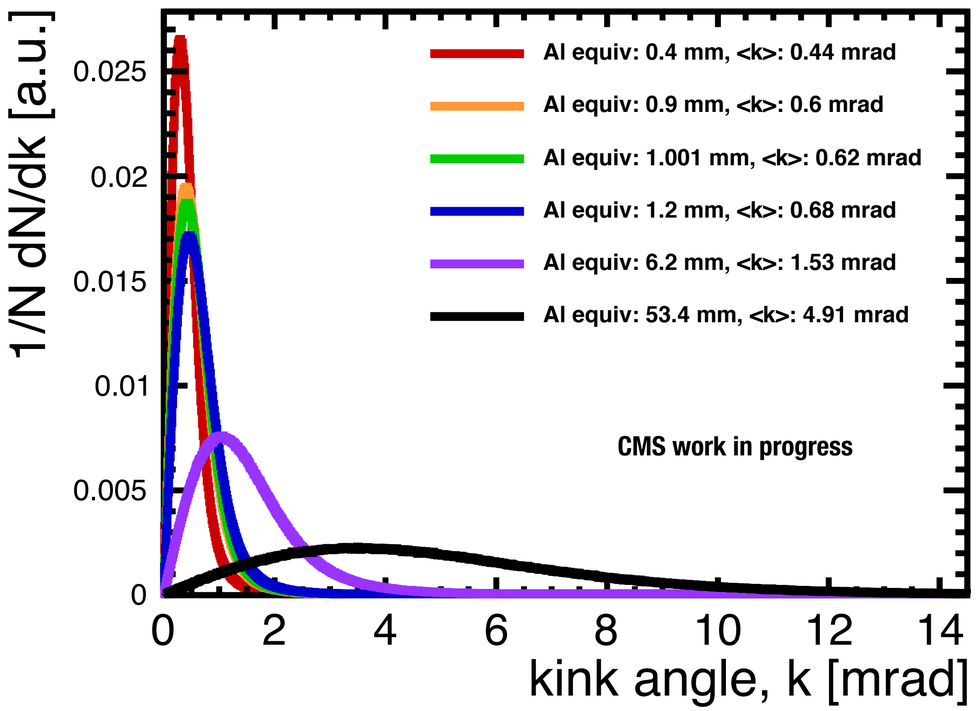
High noise level in 2017 prototypes

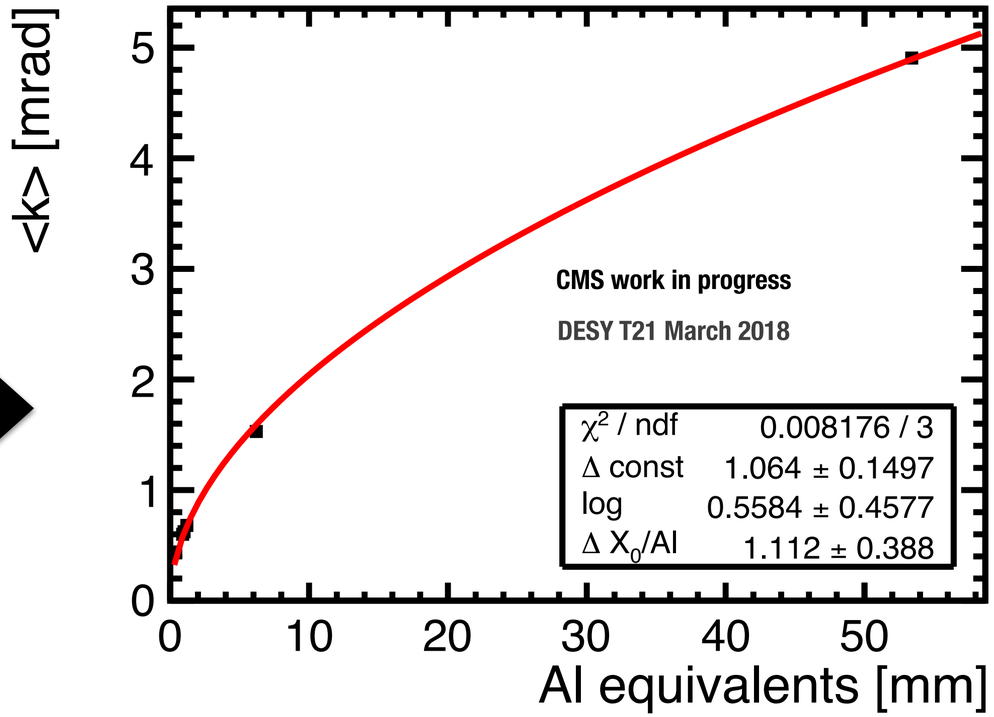


Tomography calibration

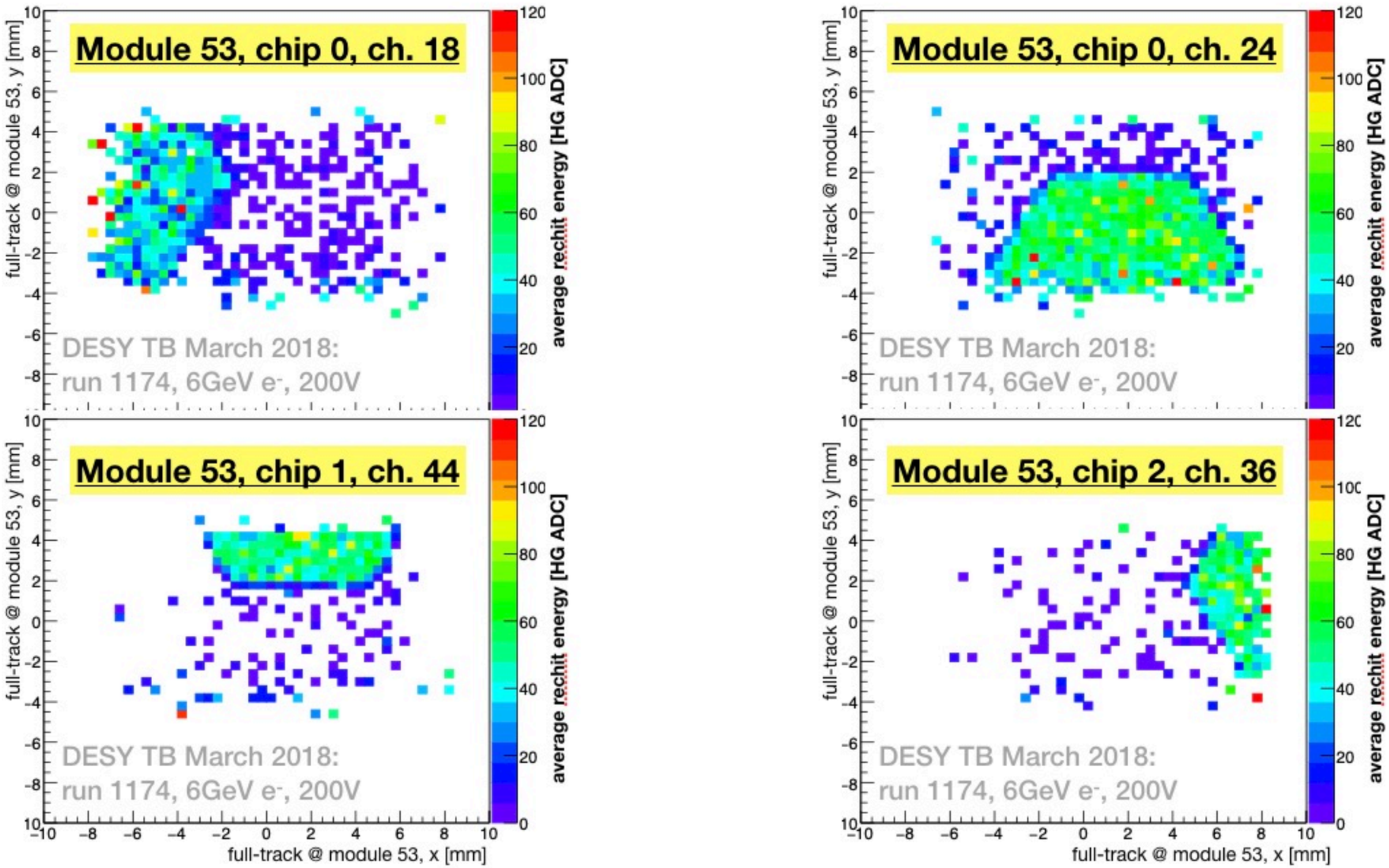
Reference:

- Aluminium plates of various thicknesses
- one tungsten plate (=53.4 mm Al)





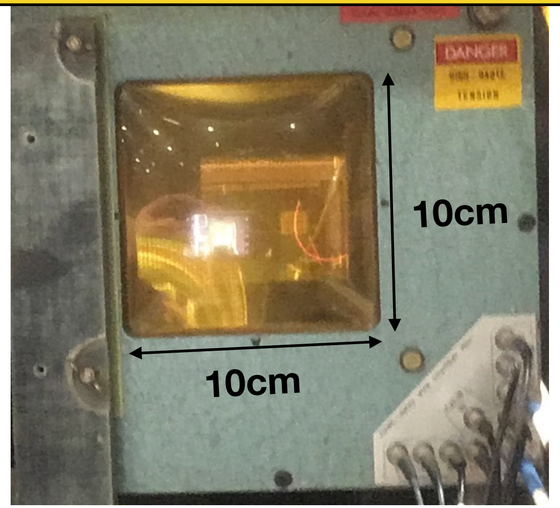
DATURA Telescope - HGCal correlation

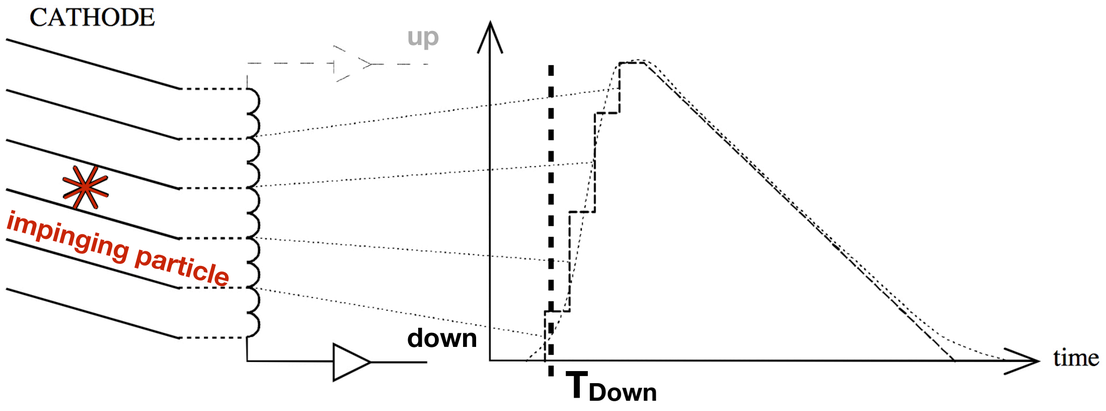


Delay wire chambers @ CERN's North Area

Tracking

Tracking with DWCs @ CERN

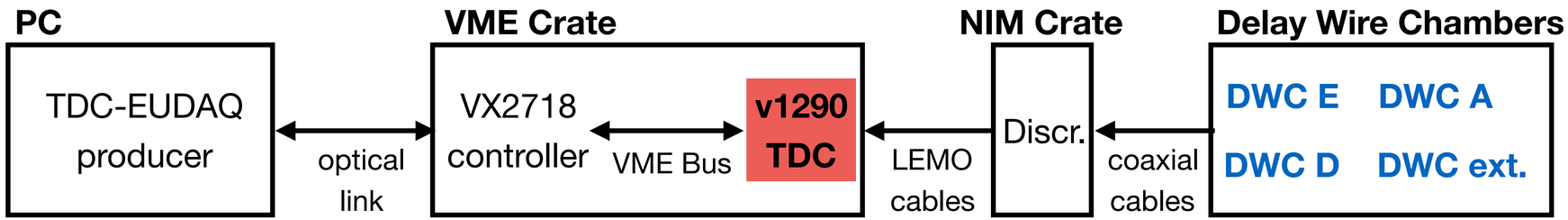




➡ Straight-forward position reconstruction:

Y-Position = $(T_{Down} - T_{Up}) \times slope_y + offset_y$
X-Position = $(T_{Left} - T_{Right}) \times slope_x + offset_x$

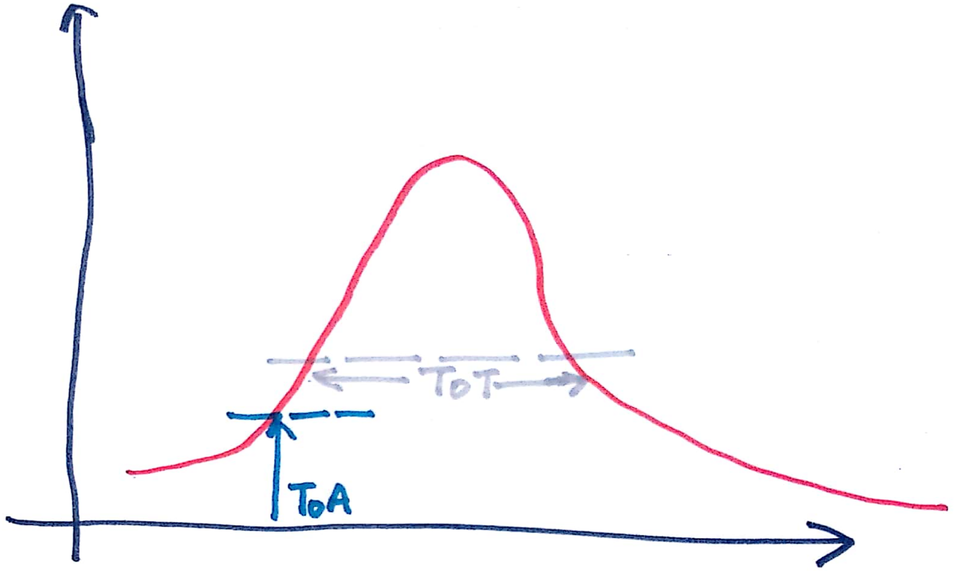
Readout via TDCs

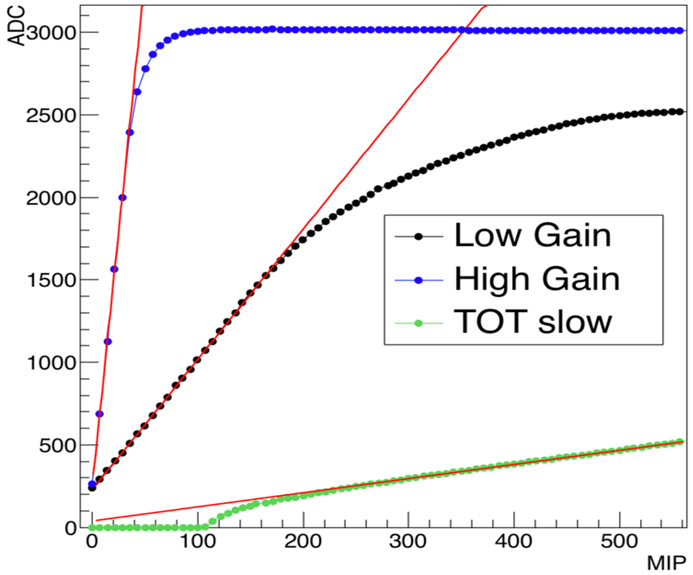


Skiroc2-CMS is the new readout chip in 2017

- Skiroc2-CMS is based on the CALICE Skiroc2.
- Shapes, amplifies and digitises signals from the silicon sensors.

- 64 channels.
- **13 SCA rolling analog memory** with 40MHz clock.
  - Overwrites every 13x25ns.
- Four quantities read out: Low- and High gain, **"Time over Threshold" (ToT)** and "Time of Arrival" (ToA).





- Larger pulses stay longer over some threshold.
  - ToT is a measure of the signal pulse amplitude.
  - ToT can be used for energy reconstruction when low gain is saturated (left plot).

left: Relation of HG-LG and LG-TOT with test pulses in the lab.

ASIC-Calibration: TOT & Time-of-Arrival (TOA)

Gain calibration

High Gain<—>Low Gain<—>TOT

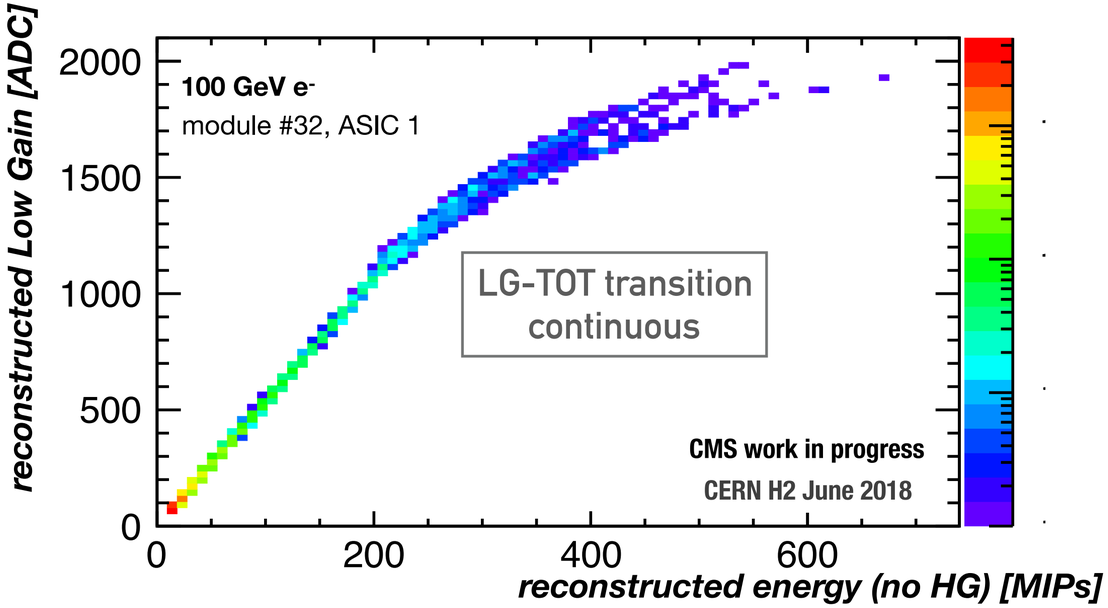
- May use LG directly (MIPs in LG)
- TOT Pedestal must be taken into account

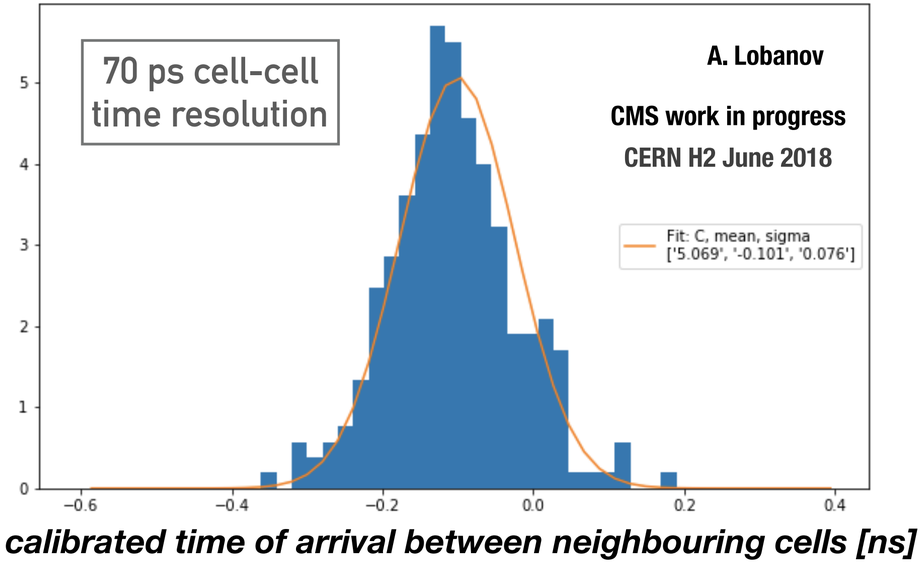
Time calibration

TOA [ADC]<—>time [ps]

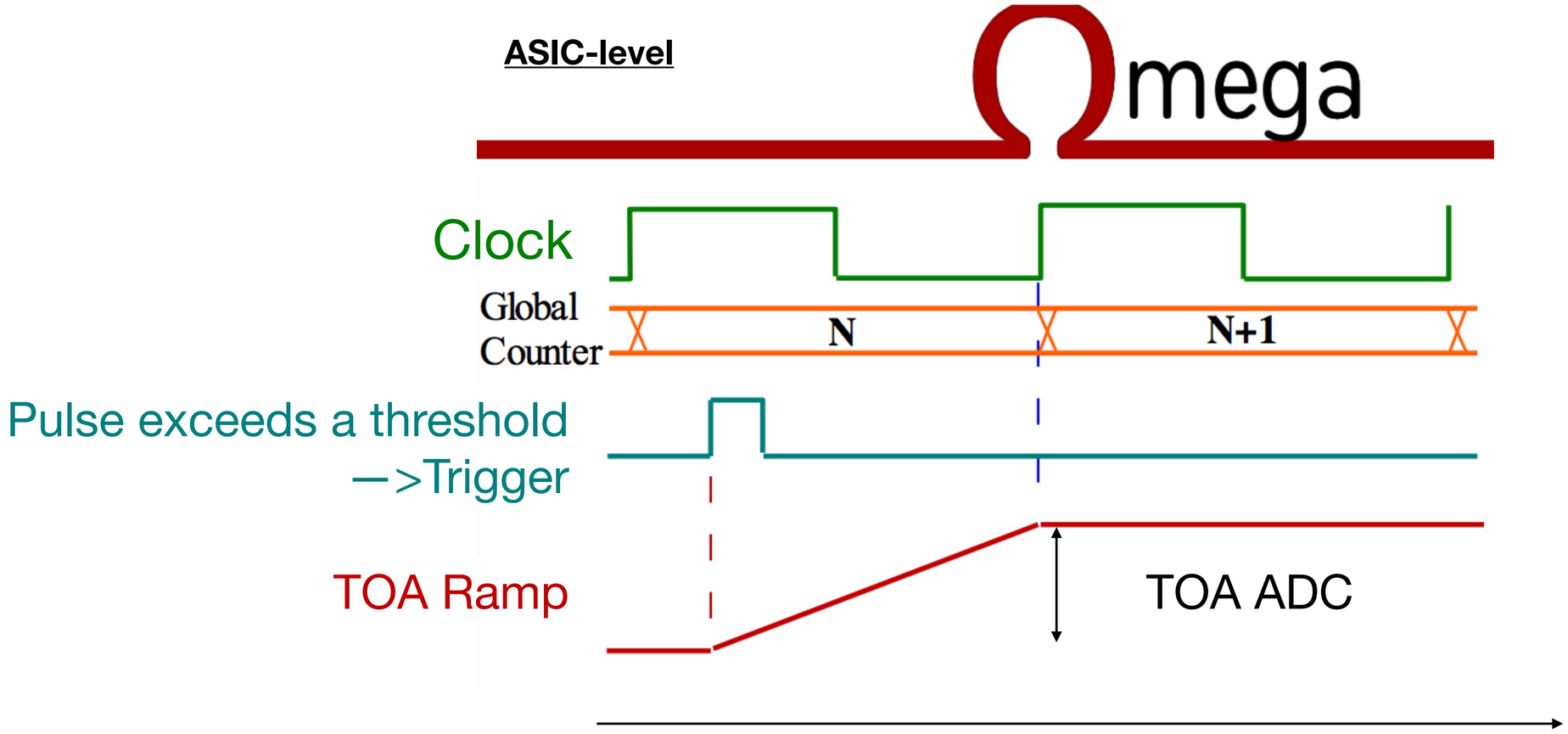
- Data driven approach (exploits: asynchronous beam wrt to clock)

➡promising first results!



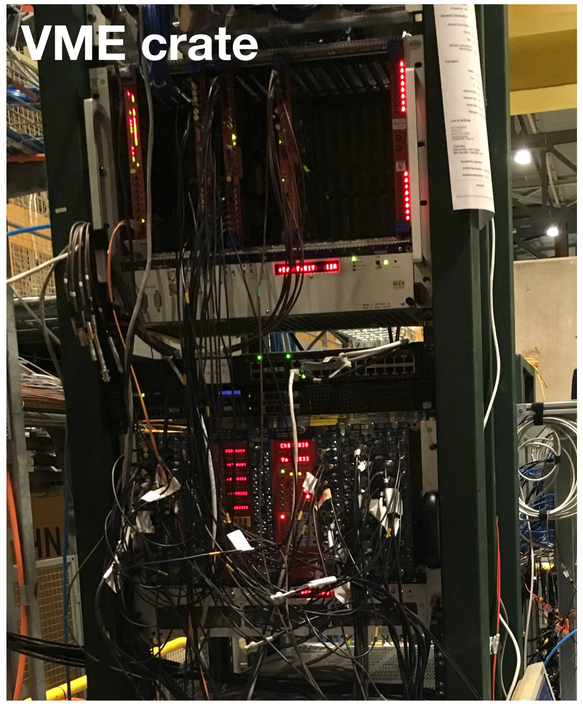


TOA measurement principle

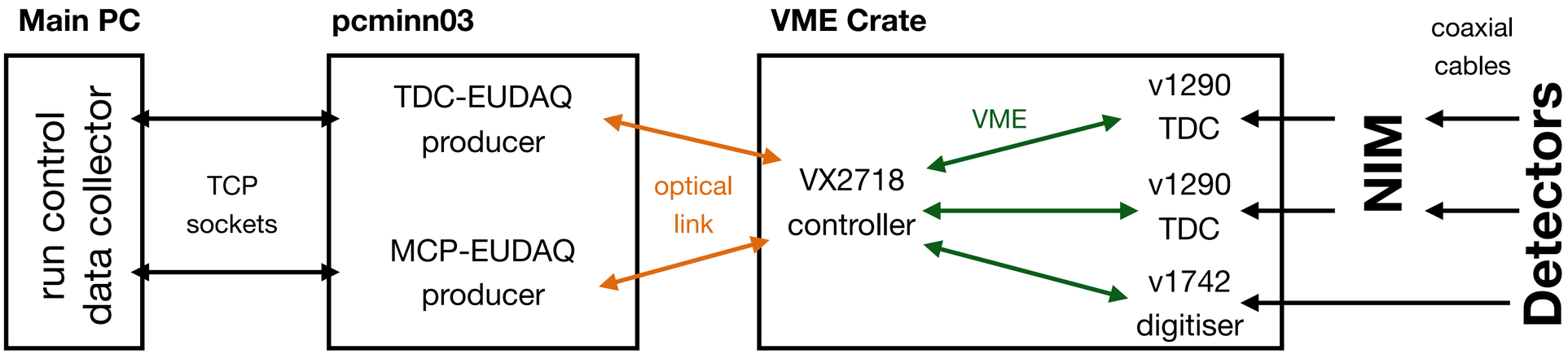


➡ early arrival: TOA high
➡ late arrival: TOA low

VME DAQ during the beam test



- **2x TDC**: CAEN v1290
  - 24 input channels = up to 6 DWCs
  - 2 input channels = 2 XCET
  - 2 input channels = veto & coincidence of scintillators
- **1x digitiser**: CAEN v1742
  - 1024 samples up to 5GHz
  - fast trigger with low latency (40ns)

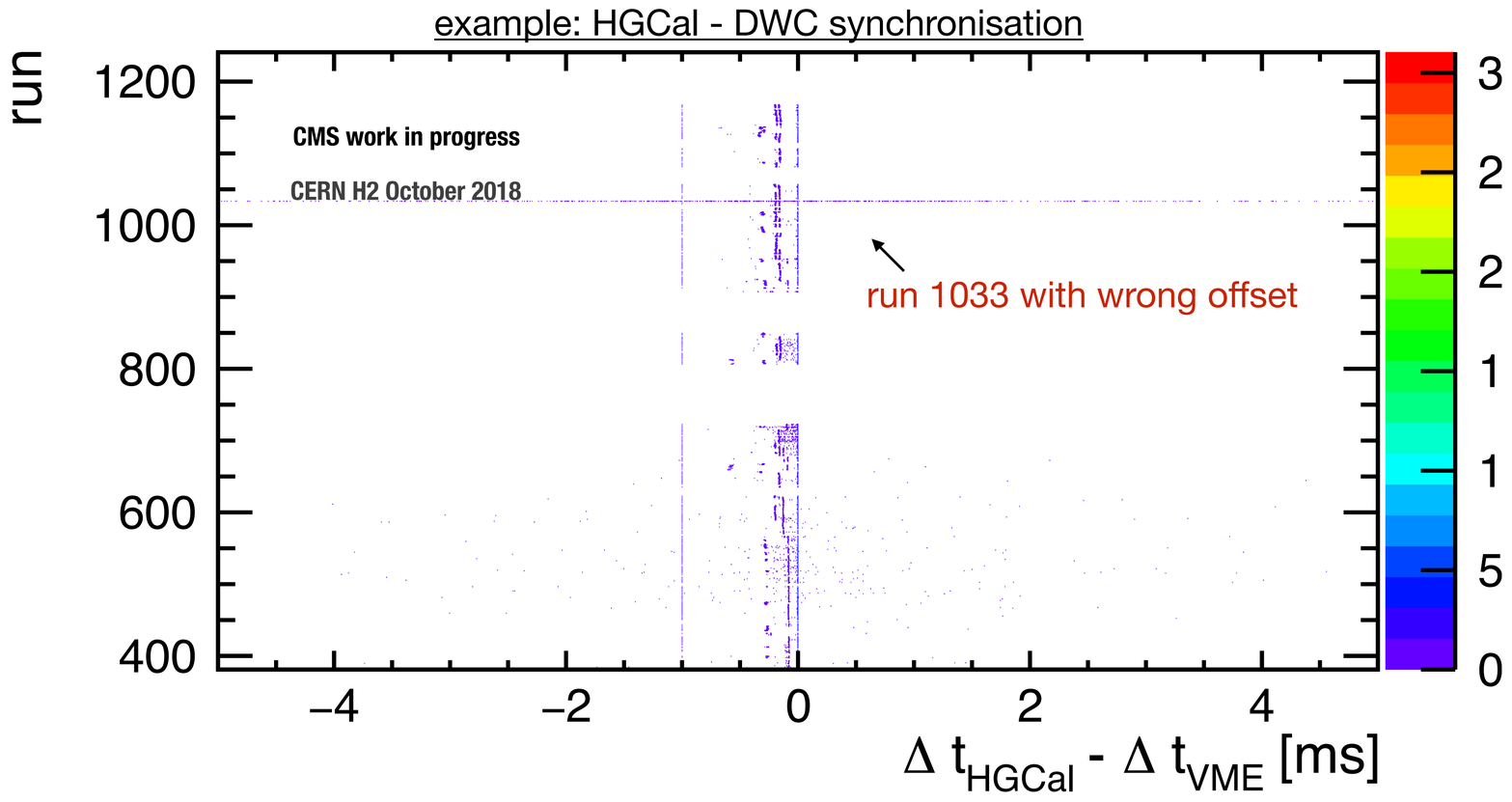


Event synchronisation

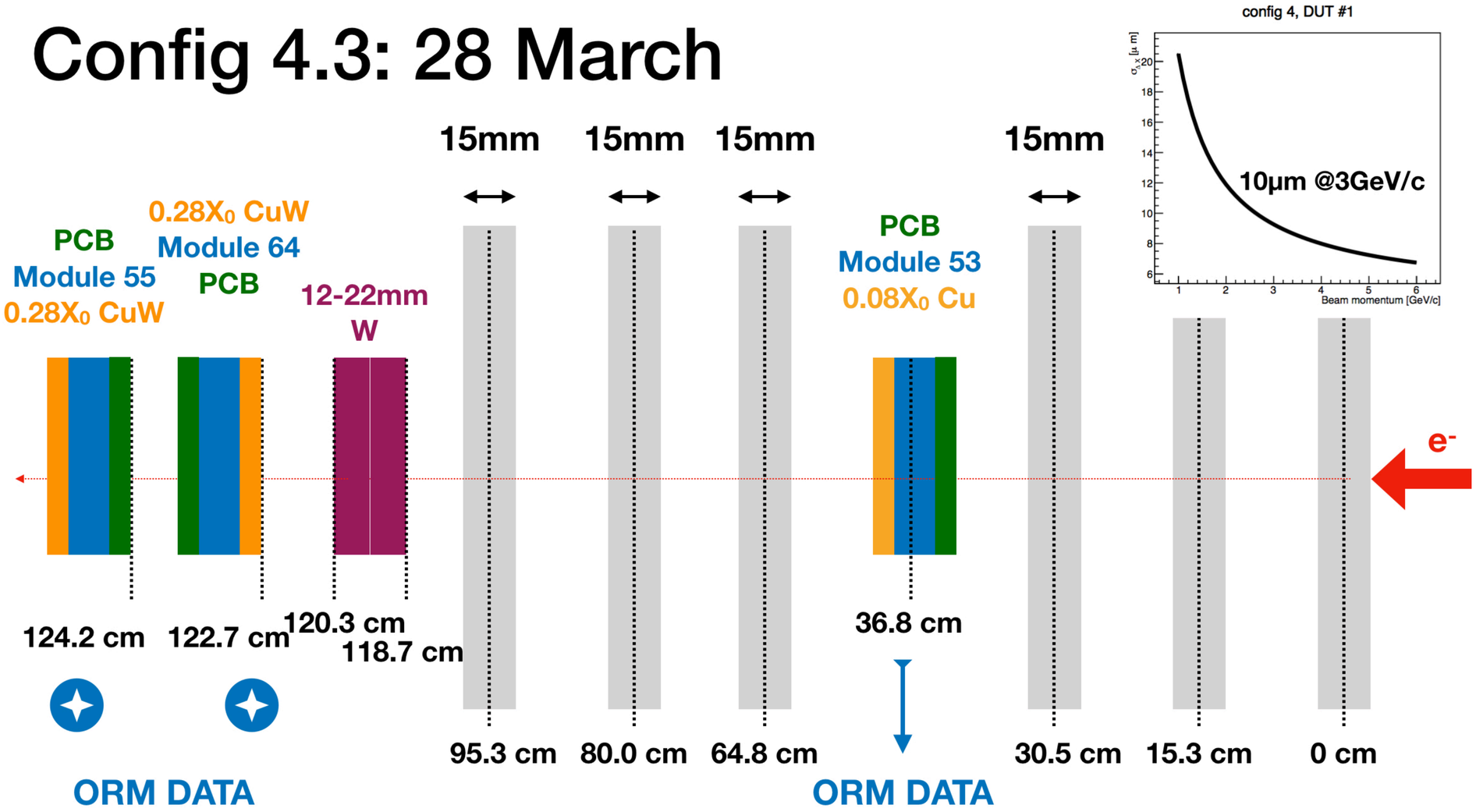
Δ t := time between two events

Data streams are synchronised —> $(\Delta t_1 - \Delta t_2) \sim 0$

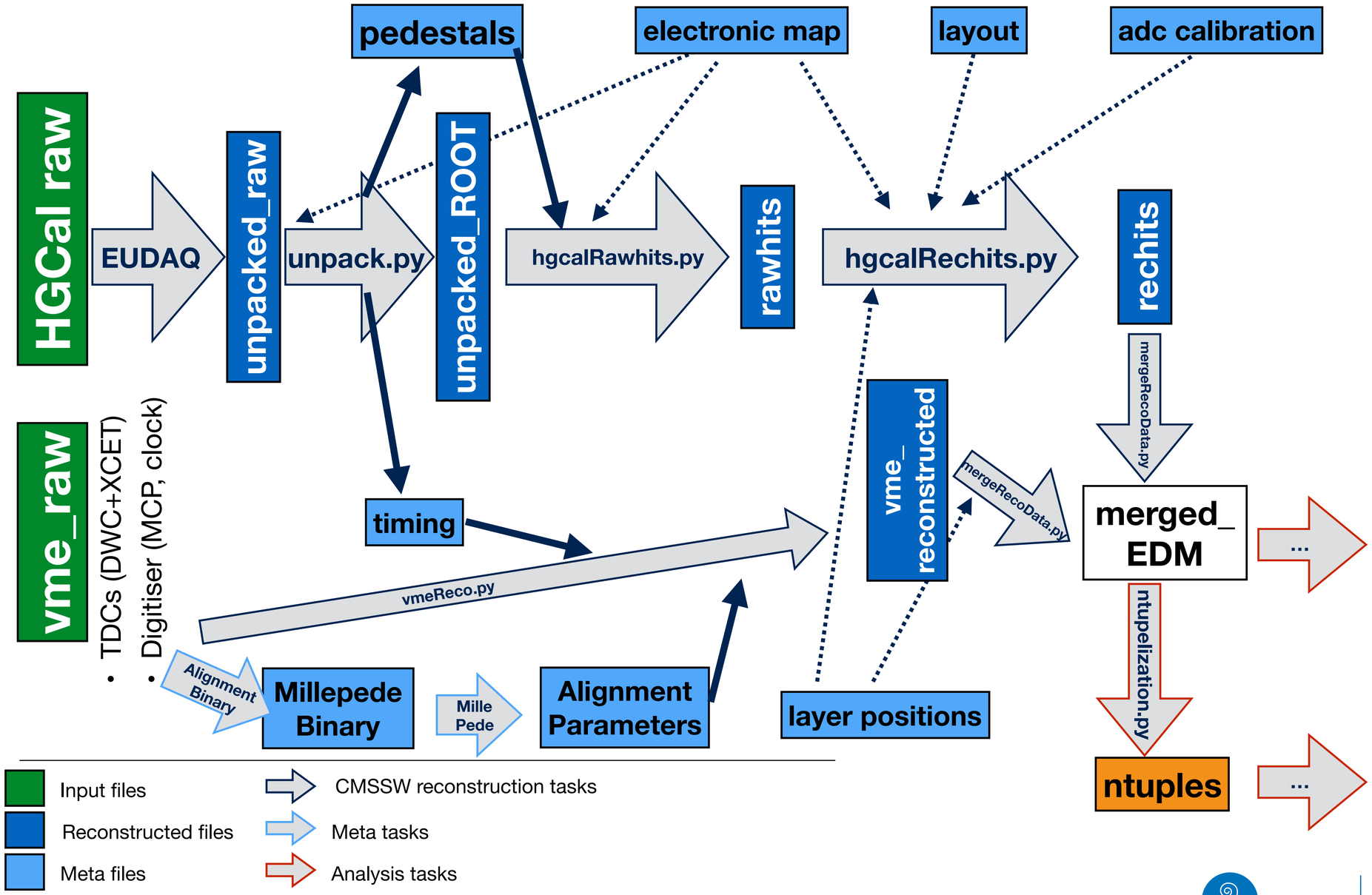
HGCal vs. DWC (etc.): offset at beginning of each run



“Calorimeter” configuration at DESY 2018



Data reconstruction workflow



Exemplary MIP Energy spectra