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High-D
R&D for highly segmented multidimensional detectors for future experiments

Erika Garutti & Heiko Lacker

On behalf of the High-D collaboration

RWTH Aachen, HU Berlin, TU Darmstadt, U Freiburg, U Giessen, U Göttingen, U Frankfurt a. M., U Hamburg, DESY, U Heidelberg, JGU Mainz, MPI für Physik München, TU München, U Bonn, FZ Jülich, GSI

The High-D consortium

First large scale coordinated effort on detector development in HEP and SMuK

Mandate:

- Research on new generation high-precision detectors with unprecedented spatial, temporal, and energetic resolution, for applications at future accelerator-based experiments at both the Energy Frontier as well as the Intensity Frontier

Members:

10 universities + 4 research centers in Germany

Program:

Fundamental research on 5D detectors with extreme granularity and on novel reconstruction techniques

The High-D research overview

Higher segmentation is achieved by:

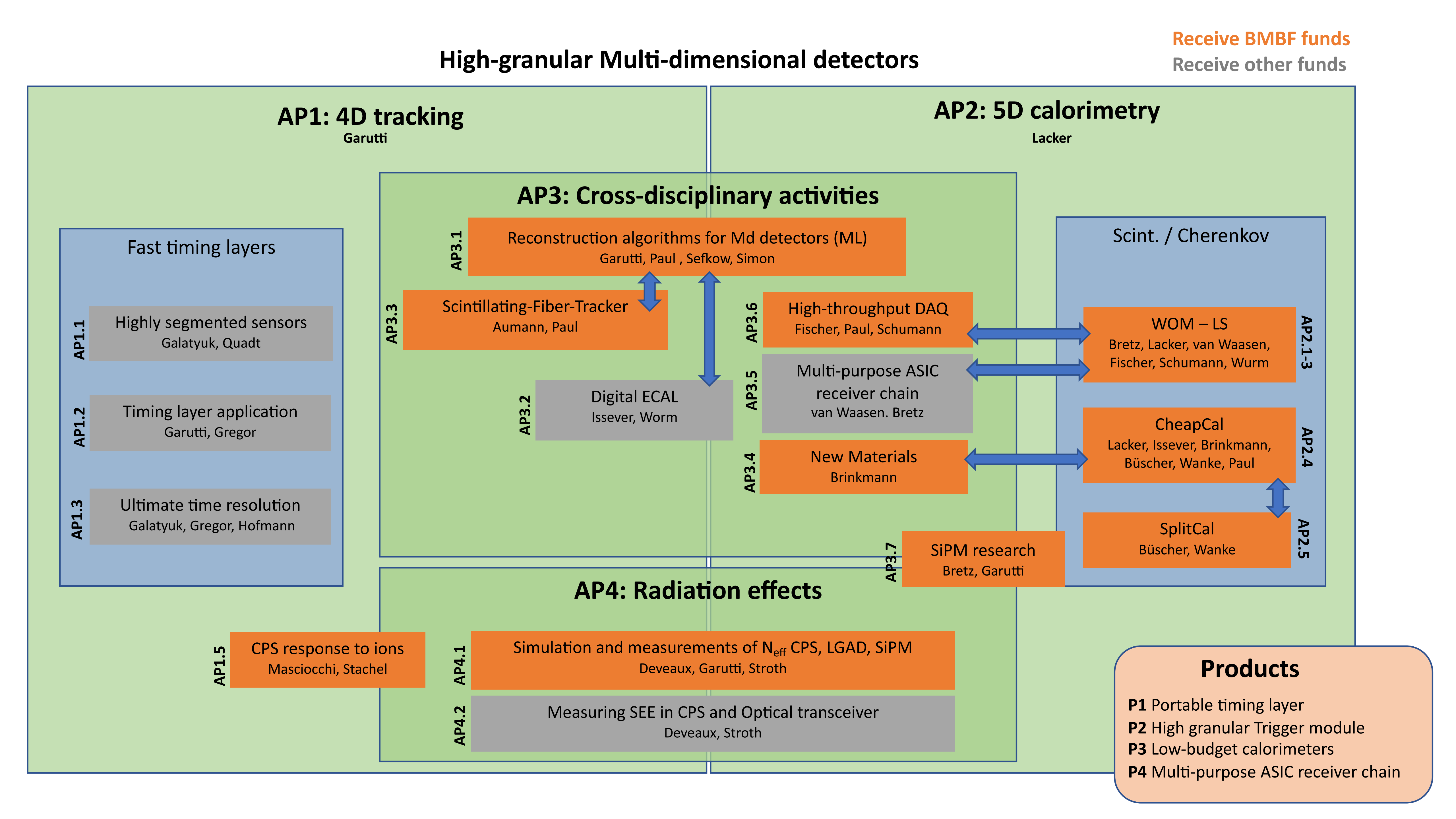
- novel microelectronic technologies
- novel semiconductor designs
- new segmentation concepts
- novel readout electronics

to ensure optimal reconstruction precision these must be accompanied by:

- novel algorithms that effectively utilize 5D information
- integration of all components of a detector system ("particle flow" approach)

Consortium divided in 4 interconnected work packages: ➔

- Two main pillars: **4D tracking** and **5D calorimetry**
- Two cross-linking packages



Receive BMBF funds
Receive other funds
High-granular Multi-dimensional detectors
AP1: 4D tracking
Garutti
AP2: 5D calorimetry
Lacker
AP3: Cross-disciplinary activities
Fast timing layers
AP1.1
Highly segmented sensors
Galatyuk, Quadt
AP1.2
Timing layer application
Garutti, Gregor
AP1.3
Ultimate time resolution
Galatyuk, Gregor, Hofmann
AP3.1
Reconstruction algorithms for Md detectors (ML)
Garutti, Paul , Sefkow, Simon
AP3.3
Scintillating-Fiber-Tracker
Aumann, Paul
AP3.2
Digital ECAL
Issever, Worm
AP3.6
High-throughput DAQ
Fischer, Paul, Schumann
AP3.5
Multi-purpose ASIC receiver chain
van Waasen. Bretz
AP3.4
New Materials
Brinkmann
Scint. / Cherenkov
WOM – LS
Bretz, Lacker, van Waasen, Fischer, Schumann, Wurm
AP2.1-3
CheapCal
Lacker, Issever, Brinkmann, Büscher, Wanke, Paul
AP2.4
SplitCal
Büscher, Wanke
AP2.5
AP3.7
SiPM research
Bretz, Garutti
AP4: Radiation effects
AP1.5
CPS response to ions
Masciocchi, Stachel
AP4.1
Simulation and measurements of Neff CPS, LGAD, SiPM
Deveaux, Garutti, Stroth
AP4.2
Measuring SEE in CPS and Optical transceiver
Deveaux, Stroth
Products
P1 Portable timing layer
P2 High granular Trigger module
P3 Low-budget calorimeters
P4 Multi-purpose ASIC receiver chain

4D tracking

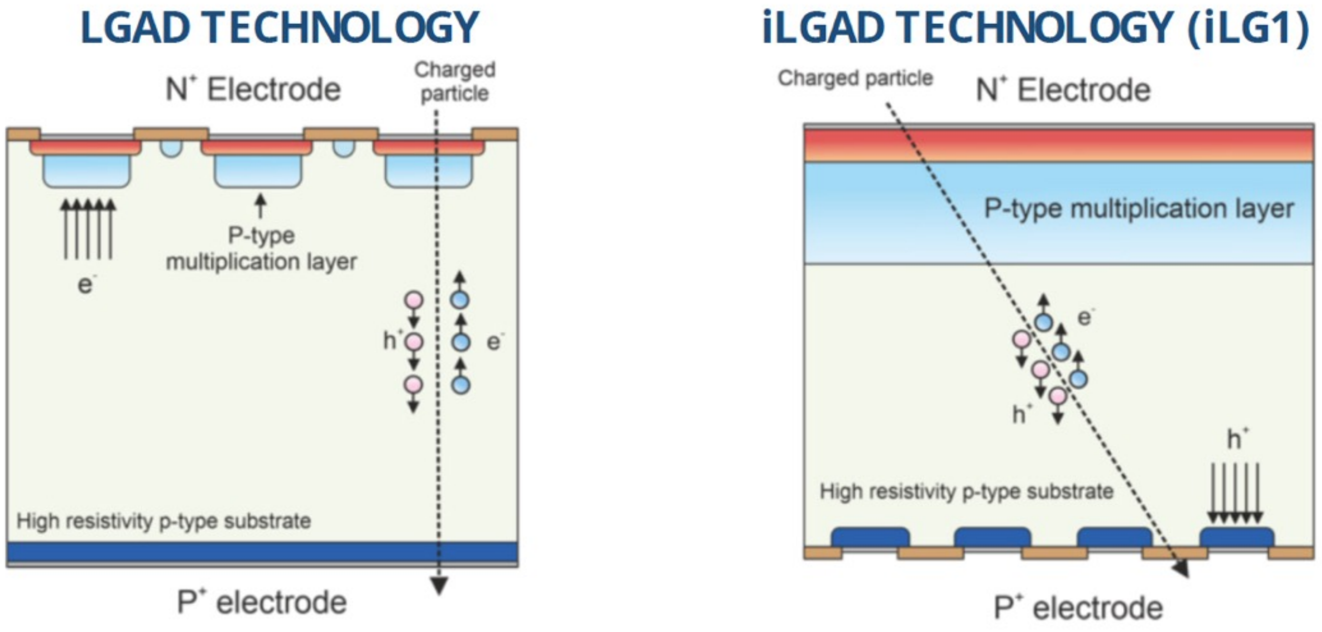
Highly segmented sensors

New Low Gain Avalanche Diodes (LGADs) technologies promise to significantly reduce the inter-pad gap needed for 4D tracking with high spatial and temporal resolution

Novel LGADs investigated:

- iLGAD
- trench LGAD
- AC-LGAD

Sensors are produced in collaboration with

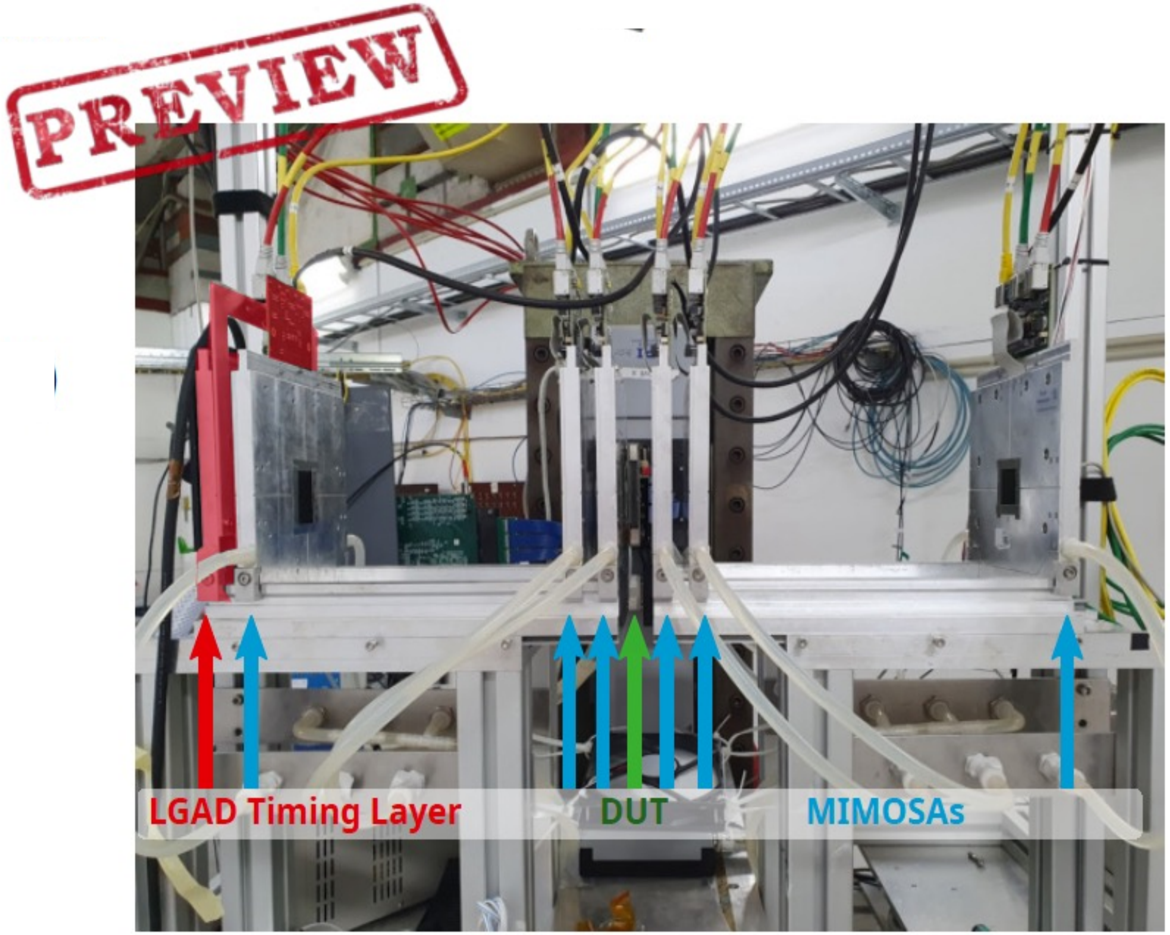


[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

4D tracking

Timing layer application

- LGAD to measure space and time coordinate of test beam tracks
- **Fast timing requires:**
  - 30-50 µm thickness
  - gain O(10)
  - improved S/N
- **Goal**: equip EUDET-like telescopes with a LGAD layer to satisfy the increasing users demand for fast timing measurements



4D tracking

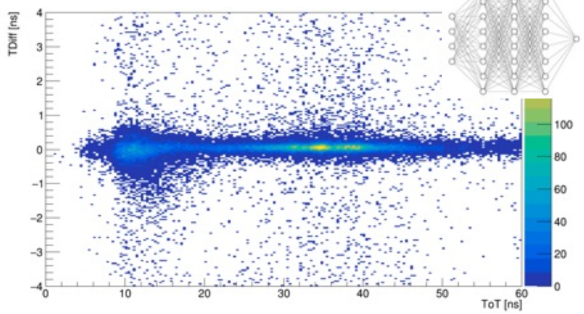
Ultimate time resolution

TECHNISCHE UNIVERSITÄT DARMSTADT

Development of fast readout electronics for a large area LGAD-based detector:

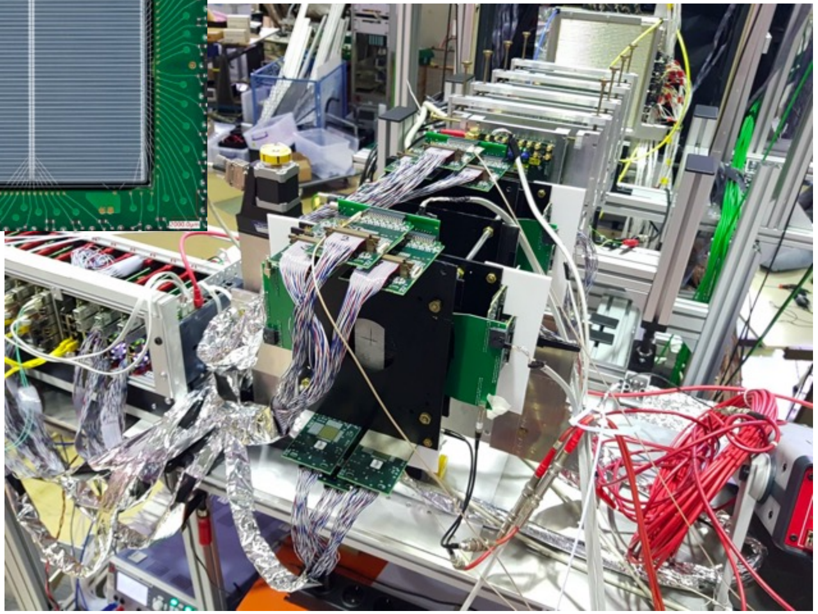
ExHiLo-ASIC

Extreme High-SensiOvity / Low-Pitch – radiaOon hard readout-ASIC for LGAD Sensors



- Concept for corrections on the basis of AI and in real time implemented either directly in an FPGA or at the event builder level

Vadym Kedych HK3.6



- Develop a second generation of the discreet FEE for larger sensors (2×2 cm^2) utilizing larger number of channels ~O(100) and rate capability (~10 MHz/strip)

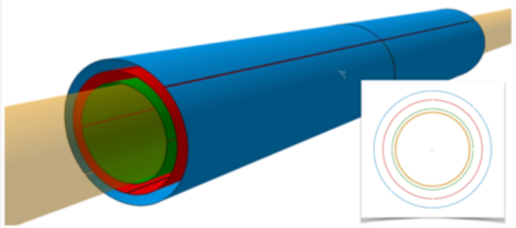
Wilhelm Krüger HK11.7

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS · UNIVERSITY OF LIVERPOOL · GOETHE UNIVERSITÄT FRANKFURT AM MAIN · FAIR Phase 0 Research Program · HADES · INFN TORINO · FBK CMM CENTER FOR MATERIALS AND MICROSYSTEMS FONDAZIONE BRUNO KESSLER

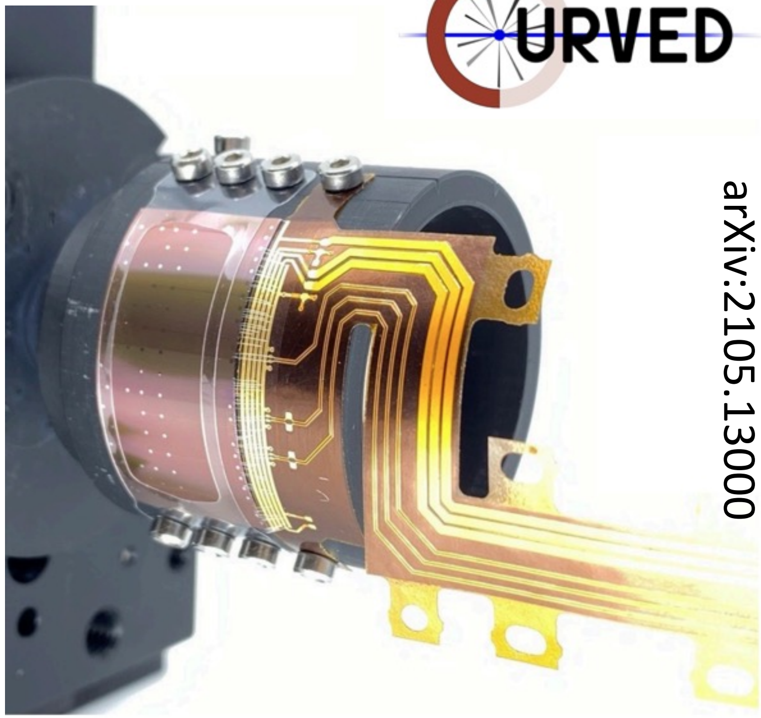
(4)D tracking & Radiation effects

CMOS pixel sensors for Ultra-light, high-Resolution VErtex Detectors

- Monolithic Active Pixel Sensors in 180 nm CMOS technology (ALPIDE chip) bent to cylindrical geometry
  → ultimate minimization of material budget
- Development of pixel sensors in *65 nm technology*
  → next frontier in point resolution
  with *stiching* on 30 mm wafers
  → large area



- Test of radiation hardness of 65nm tech. devices



arXiv:2105.13000

Pascal Becht
HK 18.2

(4)D tracking & Radiation effects

CMOS pixel sensor MIMOSIS-1

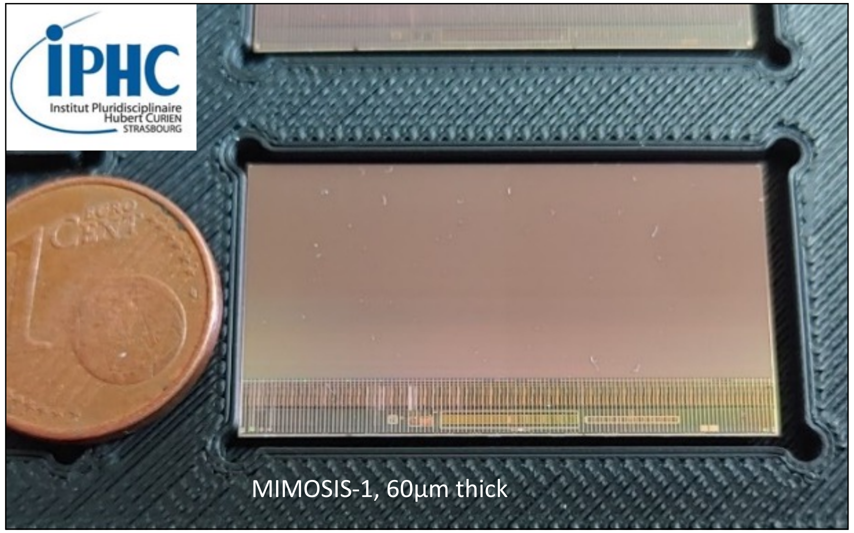
MIMOSIS (design IPHC, test GSI/GU):

Aim for

- $\Delta x \approx 5\mu\mathrm{m}, \Delta 5\mu\mathrm{s}, 0.05\%\ X_0$
- $< 100\mathrm{mW/cm^2}\ at\ 20\ \mathrm{MHz/cm^2}$
- $\geq 10^{14}\ \mathrm{n_{eq}/cm^2}$

Target application: CBM@FAIR

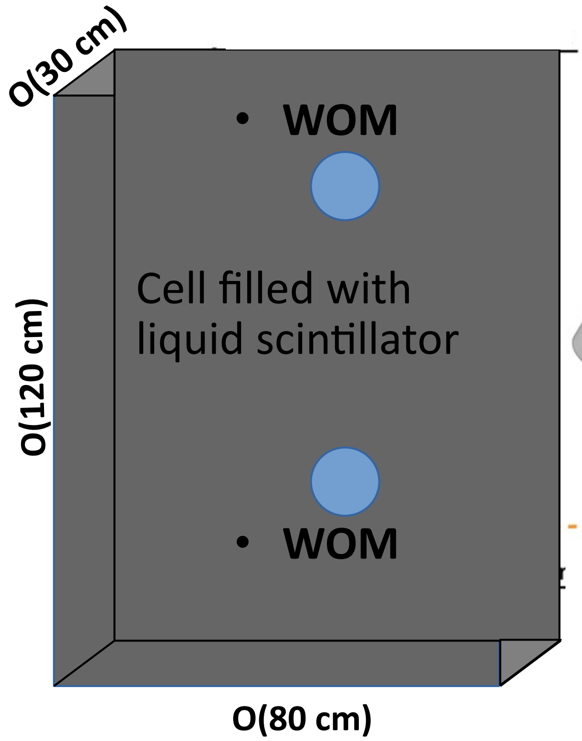
Open for other users/applications

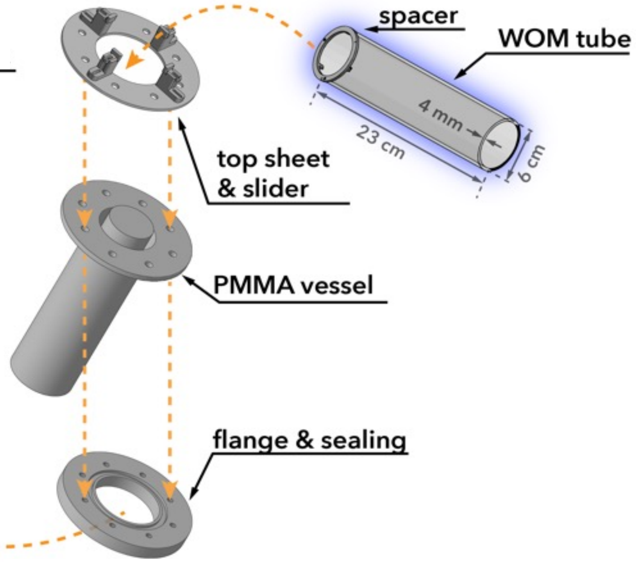


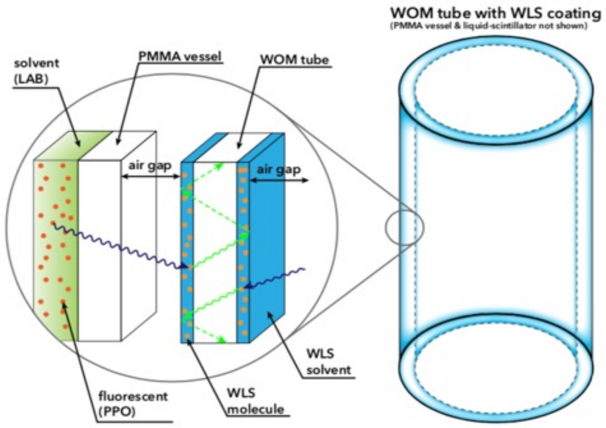
Michael Deveaux HK 28.1
Hassan Darwish HK 28.3
Benedict Arnoldi HK 28.4

5D Calorimetry

- WOM-based large area/volume
  Liquid-Scintillator (LS) detector principle

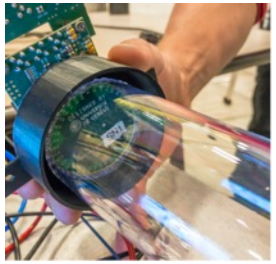






* WOM: Wavelength-Shifting Optical Module
(first proposed for IceCube ext.)

Optical coupling to 40-SiPM array



Scint. / Cherenkov

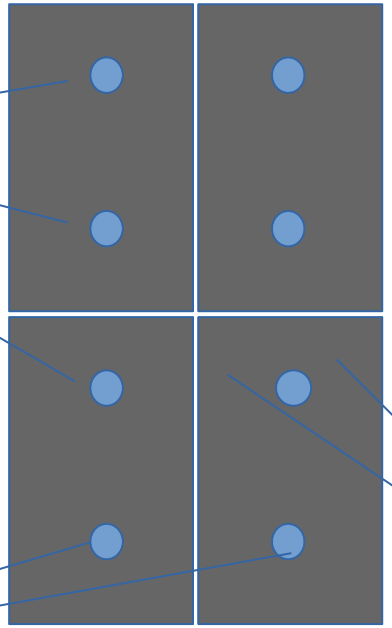
WOM – LS Bretz, Lacker, van Waasen, Fischer, Schumann, Wurm	AP2.1-3
CheapCal Lacker, Issever, Brinkmann, Büscher, Wanke, Paul	AP2.4
SplitCal Büscher, Wanke	AP2.5

5D Calorimetry

Lacker

- **Goal: First multiple-cell WOM-LS prototype**

Energy deposition,
ns time resolution,
spatial information
from
2 WOMs in one cell
or in adjacent cells



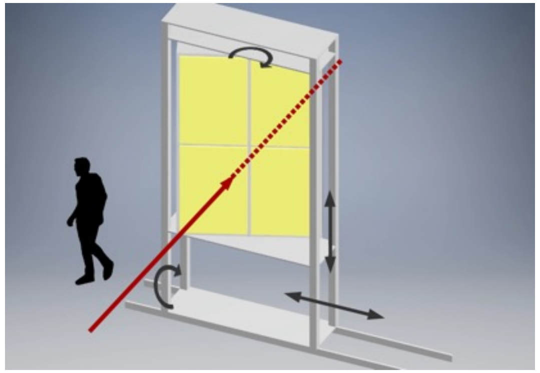
Particle incident angle
from
→ signal arrival times
→ light-yield share

btw adjacent cells

- e/γ vs μ/π separation:
- e.m. preshower in detector steel wall

AP3.6 — High-throughput DAQ
Fischer, Paul, Schumann

AP3.5 — Multi-purpose ASIC receiver chain
van Waasen. Bretz



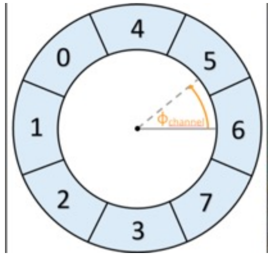
Scint. / Cherenkov

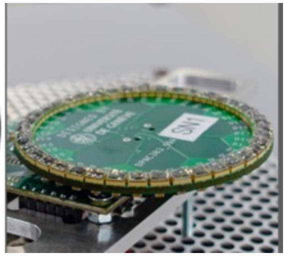
WOM – LS
Bretz, Lacker, van Waasen, Fischer, Schumann, Wurm — AP2.1-3

CheapCal
Lacker, Issever, Brinkmann, Büscher, Wanke, Paul — AP2.4

SplitCal
Büscher, Wanke — AP2.5

Resolving
Left-Right ambiguity
using light-yield distr.
over SiPM array





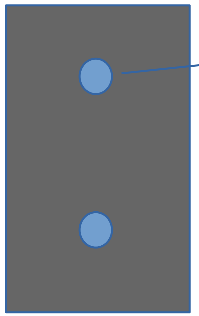
5D Calorimetry

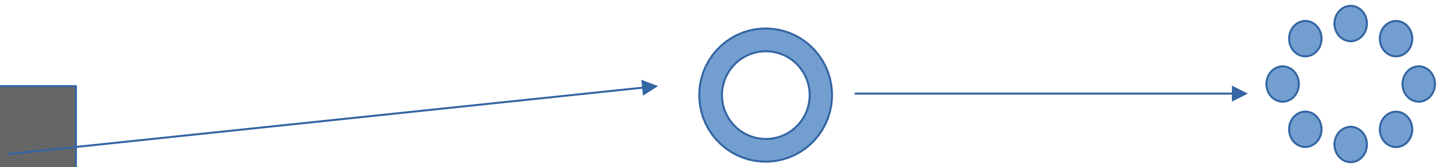
WOM segmentation to improve spatial info

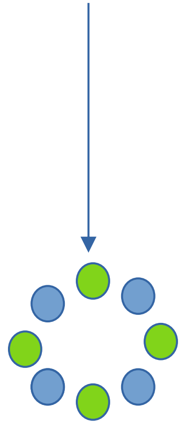
Resolving Left-Right ambiguity:
Secondary WOM light-yield distr. over SiPM array diluted wrt primary light direction

Replace large-diameter WOM tube

by several small-diameter WOM rods

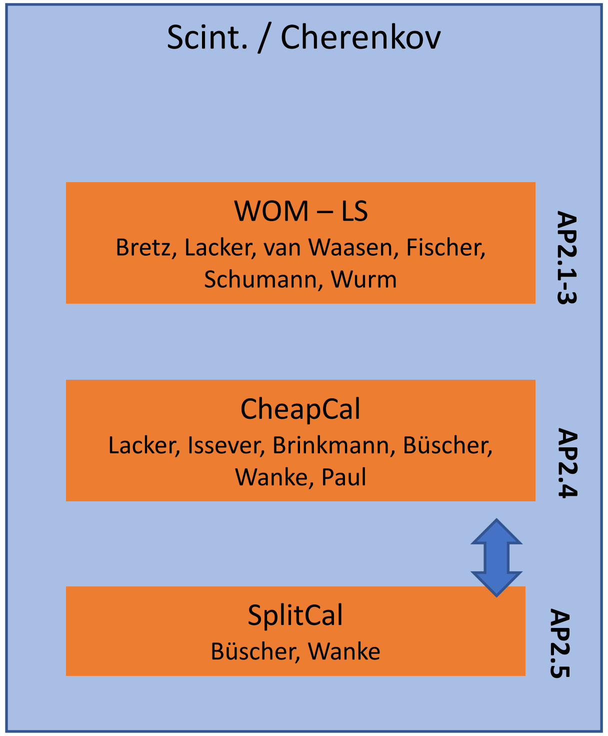






LS ν detectors look for ways to separate Cherenkov and scintillation light

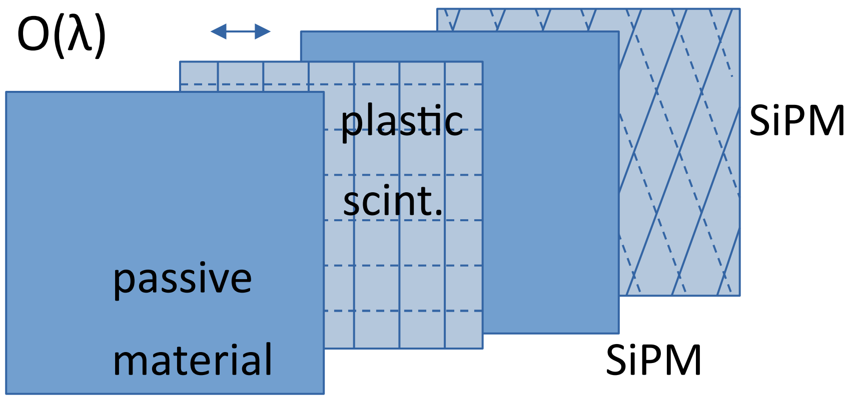
Will study new Ansatz here:
Wavelength separation using different WOM wavelength shifters

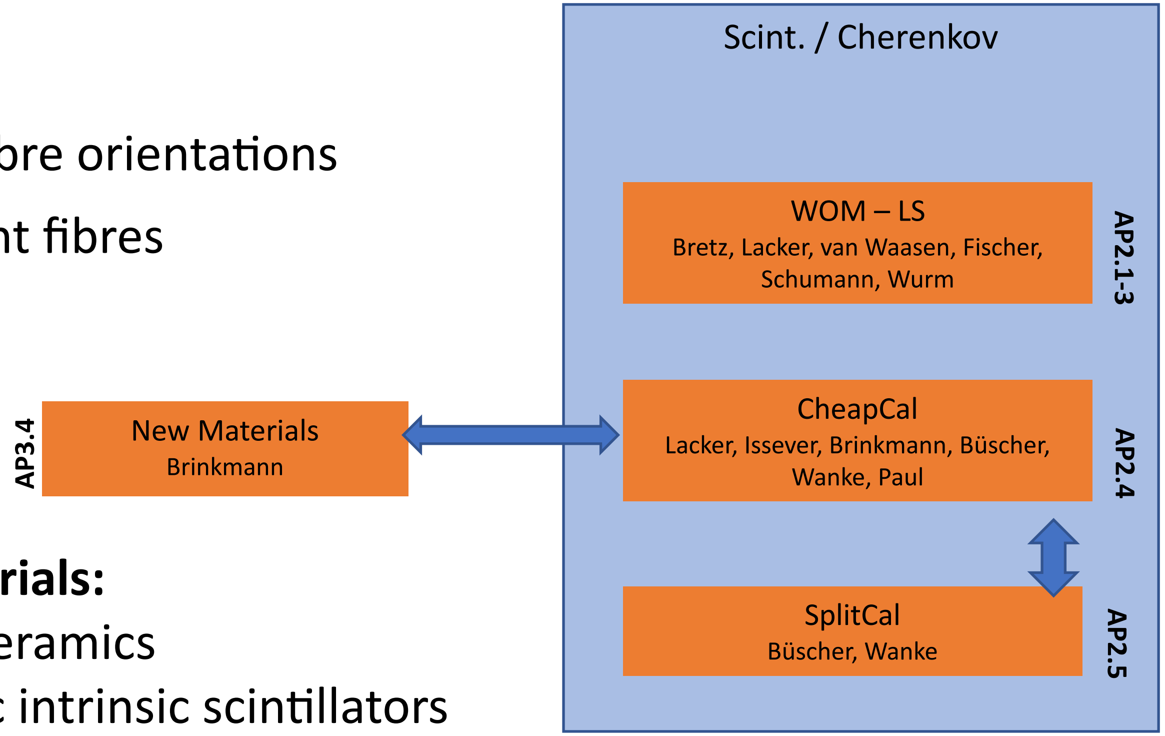


5D Calorimetry

“CheapCal”

- Large plates of extruded plastic scint. (λ = few cm)
- structured on front and back side with different WLS fibre orientations
- Spatial point/track: hit fibres & light-share btw. adjacent fibres in consecutive planes





New Materials:

- Glass ceramics
- Organic intrinsic scintillators

Goal: Prototypes for

- Low-budget calo/tracker/muon detector/hodoscope
- Possibly pointing capability (e.g. for SplitCal: ALP→ $\gamma\,\gamma$)

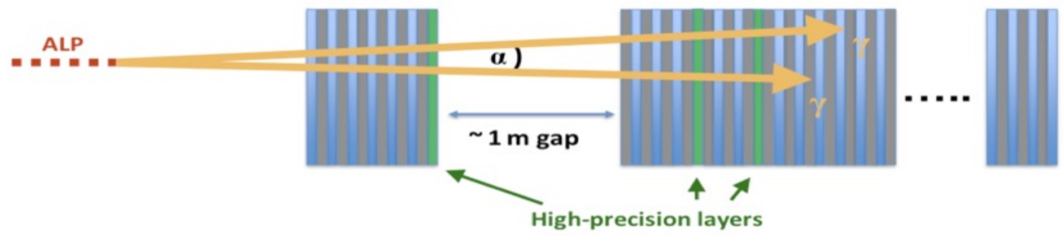
5D Calorimetry

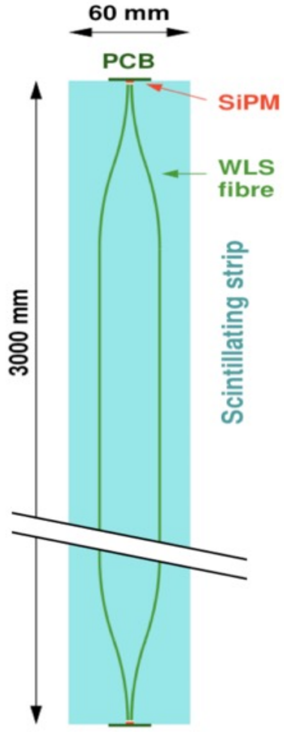
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- **“SplitCal”**

Large-scale low-budget calorimeters (ECAL & HCAL).

- Absorber-scintillator sandwich calorimeter.
- Long **scintillating strips** (2-3 m × 6 cm × 1 cm), light readout with **WLS fibres** and **SiPMs**.
- SiPM readout & digitization with ASICs (similar to Calice AHCAL).
- Possibly **high-precision layers** for measurement of shower directions ($X \rightarrow \gamma\gamma$ decays).





Scint. / Cherenkov

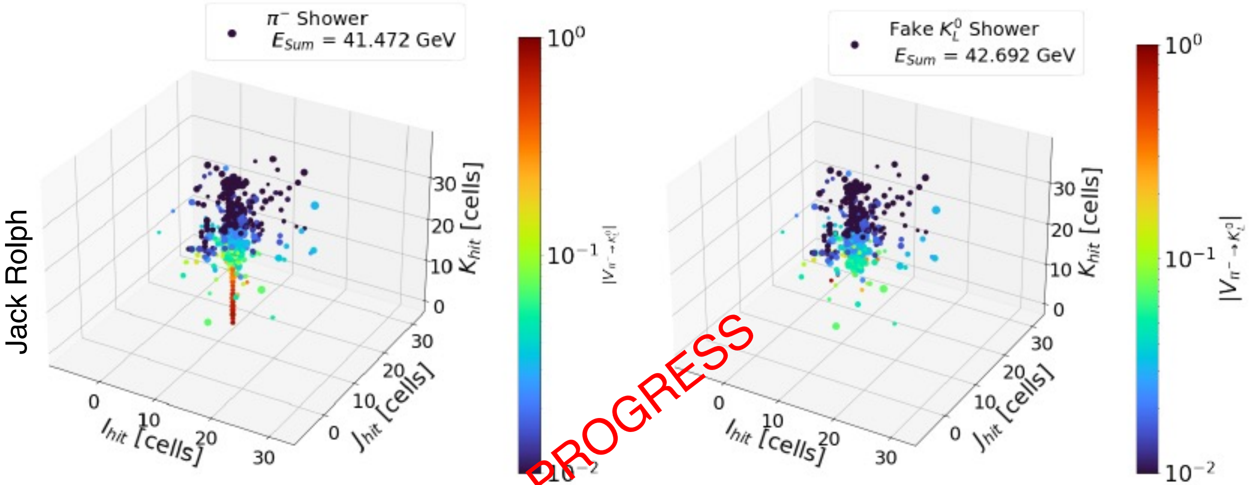
Project	Names	Work package
WOM – LS	Bretz, Lacker, van Waasen, Fischer, Schumann, Wurm	AP2.1-3
CheapCal	Lacker, Issever, Brinkmann, Büscher, Wanke, Paul	AP2.4
SplitCal	Büscher, Wanke	AP2.5

Cross-disciplinary activities

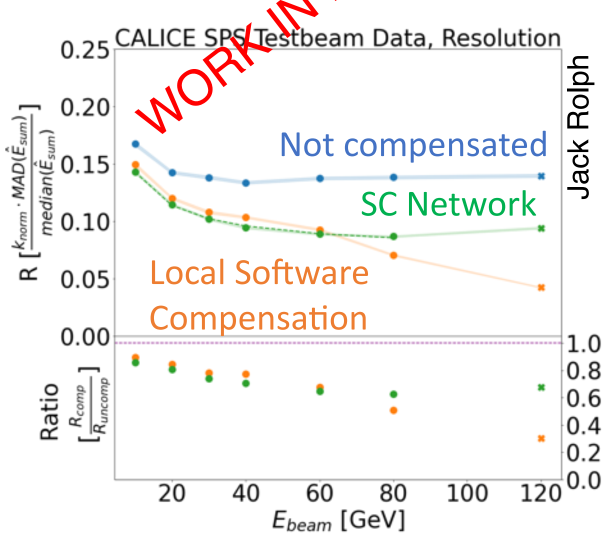
Machine learning based reconstruction algorithms

Some selected examples:

- Unsupervised Background Classification using Generative Adversarial Networks: Learn difference between charged pion and neutral kaon showers



- Use of energy density and timing in energy reconstruction extending software compensation to machine learning techniques



Cross-disciplinary activities

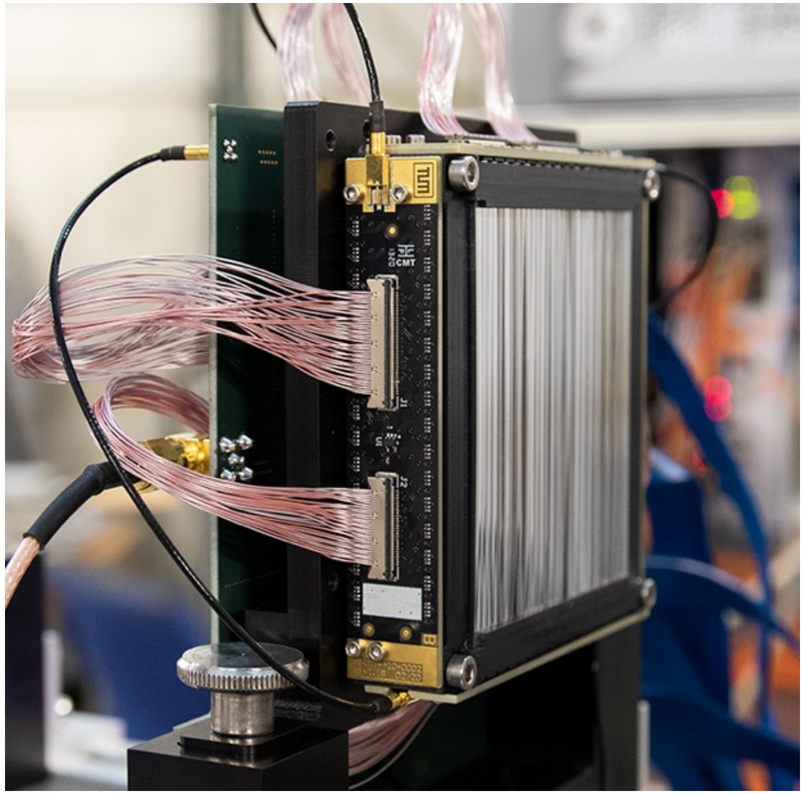
Scintillating-fiber tracker

Fast, scalable, and inexpensive '5D' tracking detectors:

- Position resolution down to <200 µm in 2/3 dimensions
- Time resolution << 1 ns
- Focus of research: energy (loss) resolution with fiber thicknesses of 200 µm and 500 µm
- Coincident readout with two SiPMs per channel to suppress dark counts and to lower energy threshold
- $\mathcal{O} \sim 10^3$ to 10^5 channels per detector with ultra-low mass budget

Use as

- Track information for multidimensional high-level trigger
- Tracking calorimeter with PID for ground and space applications



Tracking calorimeter with 2-mm fibers

→ Scalable high-throughput DAQ, SiPM radiation hardness, reconstruction algorithms

Cross-disciplinary activities

Multi-purpose signal receiver & scalable high-throughput DAQ developments

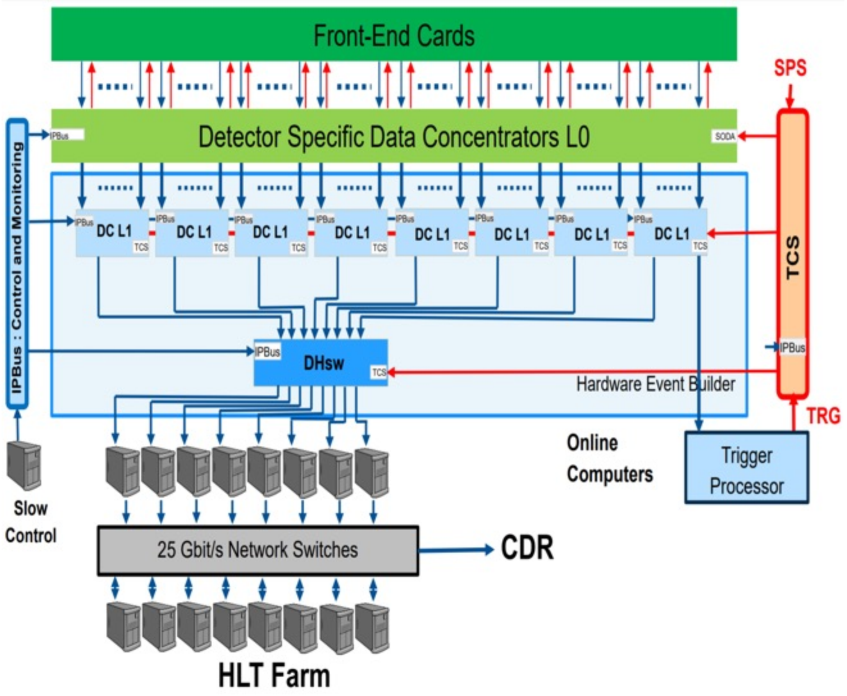
Detector Front-Ends
- digitization & feature extraction
- up to 650MB/s/data link

Data Concentrators
- data buffer, data multiplexing 15:1
- chronological data sorting
- merging data images

Custom Switch 8 x 8
- multiplexing and distribution

Spill Buffers
- data buffer & distribution
- PCIe Interface to DAQ PCs

High Level Trigger & Filter
- calibration
- filter



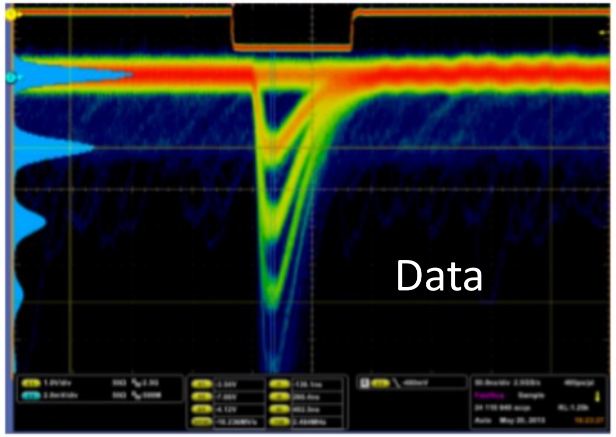
ASIC Development for Detector Front-Ends
- 500 MS/s sampling ADC
- programmable input impedance and gain
- daisy chained data concentrator
- smart feature extraction, triggerless operation
- high voltage for SiPM biasing

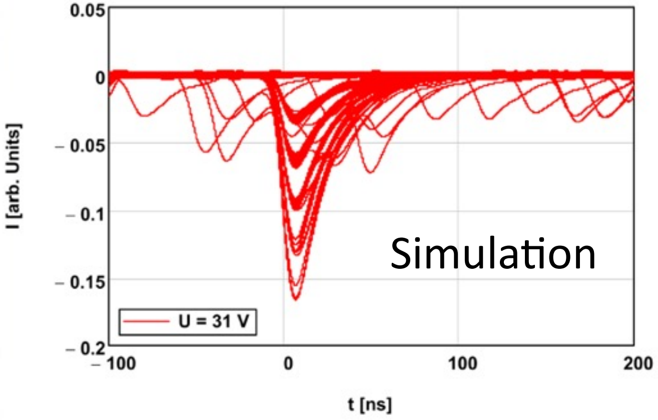
Cross-disciplinary activities

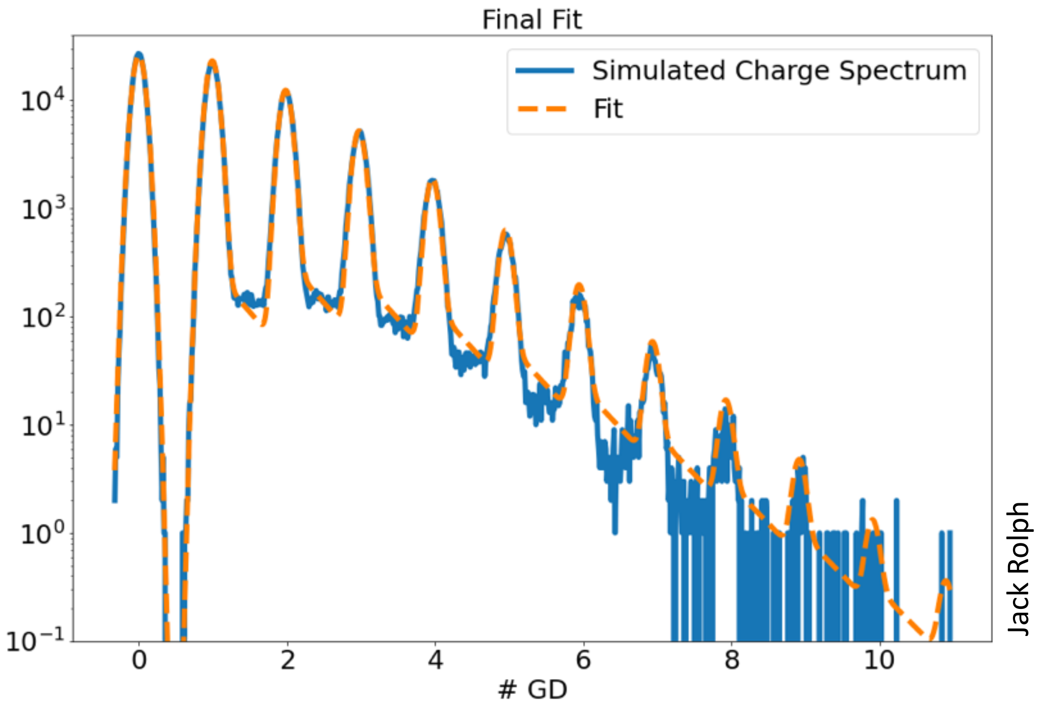
SiPM research

arXiv:2006.11150

- Characterization, modelling, simulation of SiPM





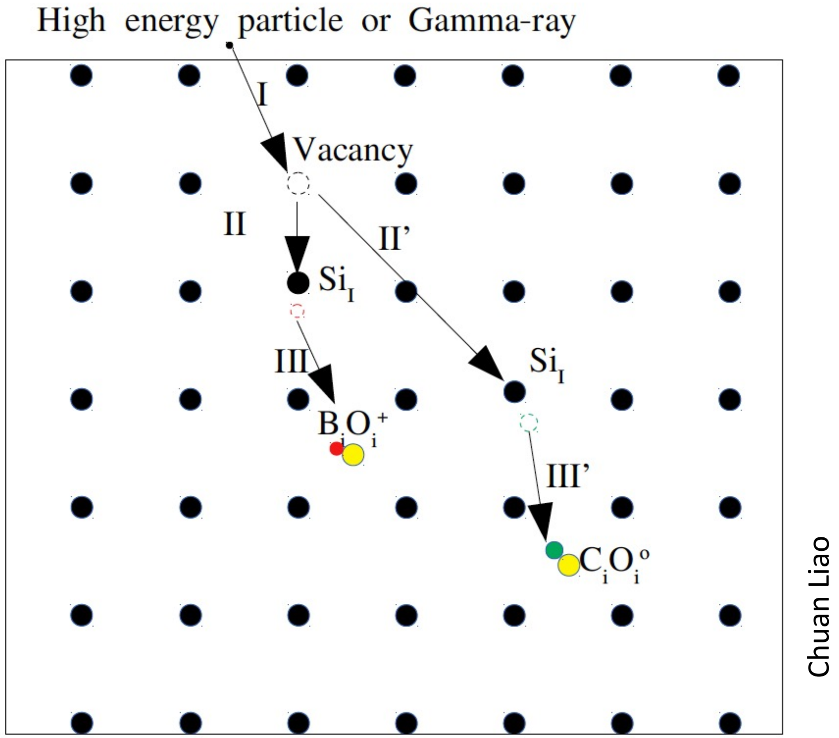


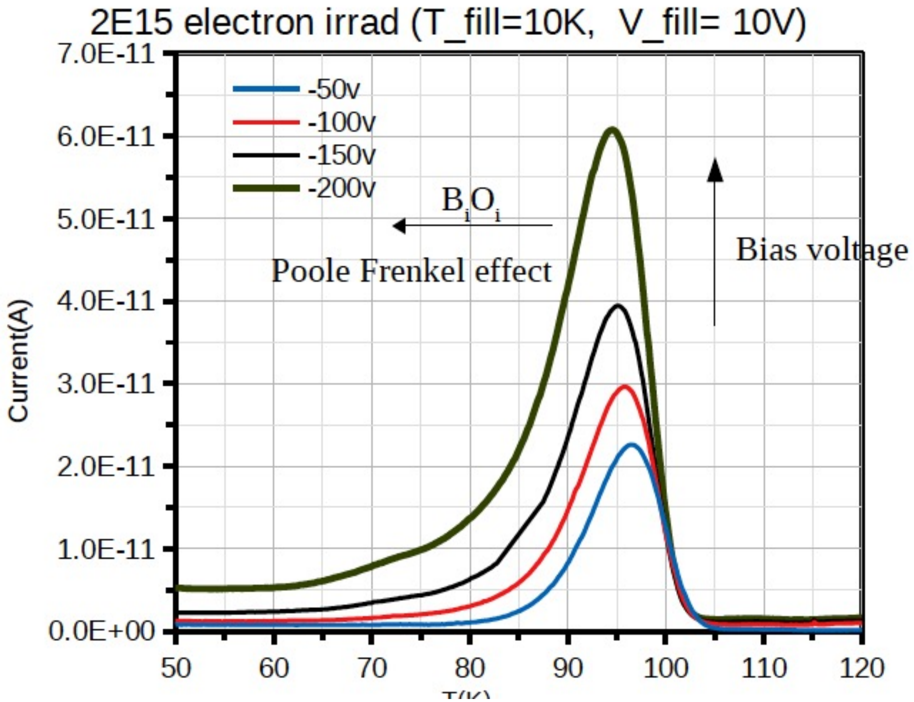
- Calibration of SiPM response function
- Increase SiPM dynamic range

- Investigation of radiation damage in SiPM

Radiation effects

Simulation and measurements of N_{eff} CPS, LGAD, SiPM





Boron removal is the main cause of gain loss in irradiated LGAD.

It also affects SiPM and CPS performance after irradiation

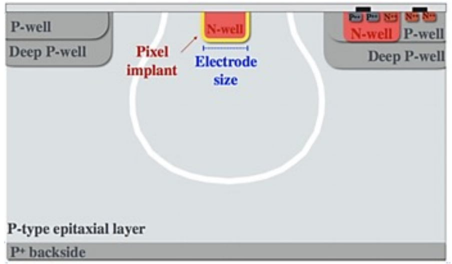
Radiation damage of p-type silicon is initially dominated by Boron removal: B^- turn to $BiOi^+$

Investigate introduction rate and annealing of $BiOi^+$ defect

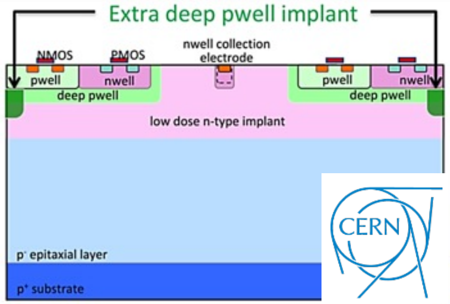
- Study of radiation damage caused by light, proton, neutron and heavy ions (no data exists so far)

Radiation effects

Studies on CPS and damage by heavy ions



Standard sensor



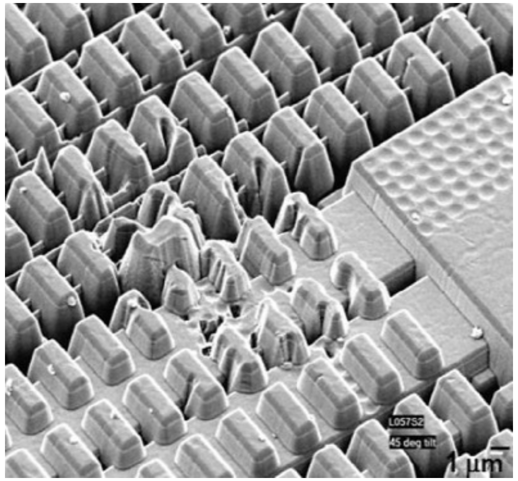
Improved sensor
Thanks to CERN (*)

Full depletion possible with modified sensing volume.
HV > 20V (top + back bias)
Will performance change due to acceptor removal (?)
⇒ Test & simulate in synergy with SiPM/LGAD (E. Garutti)
⇒ Consider radiation damage in sensor response simulation.

Heavy ions may cause:

Single event latch-up:
- Reversible short circuit
- May burn device if not power cycled

Bit-flips:
- May modify status registers



⇒ Test and establish hardening procedures.
⇒ Make procedures and GSI-HI beams available for interested partners.

Concluding remarks

High-D
is a consortium to coordinate the effort on detector development in HEP and SMuK

It covers cutting-edge research on highly-segmented detectors with unprecedented resolution in space, time and energy measurements

Not all projects received support by BMBF, but

all scientific activities remain part of the High-D research portfolio

Further scientific connections to enlarge the consortium are welcome

The High-D consortium and PIs

- Albert-Ludwigs-Universität Freiburg, Prof. Dr. Marc Schumann, apl Prof. Dr. H. Fischer
- Humboldt-Universität zu Berlin, Prof. Dr. Heiko Lacker, Prof. Dr. C. Issever
- Johannes Gutenberg-Universität Mainz, Prof. Dr. Michael Wurm, Prof. Dr. V. Büscher, Dr. R. Wanke
- Justus-Liebig-Universität Gießen, Prof. Dr. Kai-Thomas Brinkmann
- Technische Universität München (TUM), Prof. Dr. Stephan Paul
- Universität Hamburg, Prof. Dr. Erika Garutti
- Universität Heidelberg, Prof. Dr. Silvia Masciocchi, Prof. Dr. J. Stachel

Associate partners:

- TU Darmstadt, Prof. Dr. T. Galatyuk, Prof. Dr. T. Aumann
- Uni Goettingen, Prof. Dr. A. Quadt
- RWTH Aachen, Prof. Dr. T. Bretz
- GSI und Goethe Universitaet Frankfurt am Main, Prof. Dr. J. Stroth, Dr. M. Deveaux
- DESY Hamburg, Prof. Dr. I. Gregor, Prof. Dr. S. Worm, Dr. F. Sefkow
- MPI für Physik München, Dr. F. Simon
- FZ Jülich GmbH, Prof. Dr. S. van Waasen