April 10, 2024

DRD6
Subtask 1.1.3 - DECAL

Jim Brau, Oregon
Nigel Watson, Birmingham

on behalf of
MAPS ECal efforts
(DECAL and SLAC/Oregon)

"Performance of the electromagnetic pixel calorimeter prototype Epical-2", JINST 18 (2023) 01, P01038;
"The SiD Digital ECal Based on Monolithic Active Pixel Sensors", 10.3390/instruments6040051, Instruments, 6, 51 (2022);
TWEPP 2023 (https://indico.cern.ch/event/1255624/contributions/5443776/)

UNIVERSITY OF OREGON

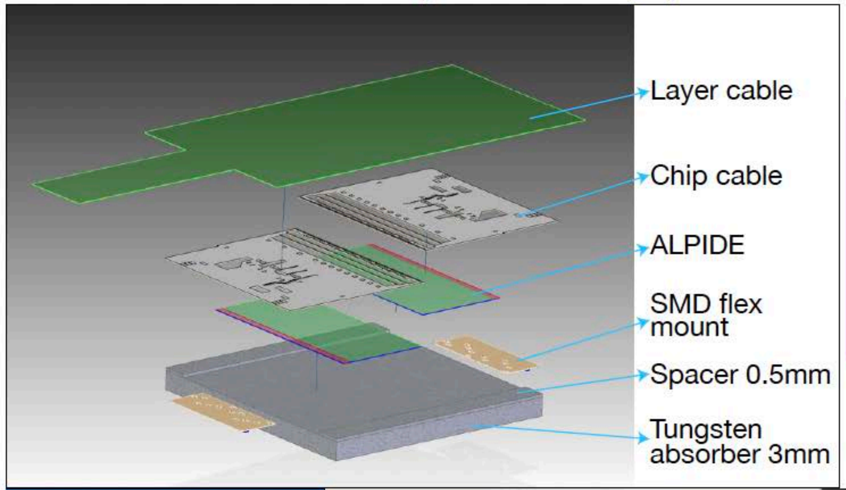
Research partially supported by the U.S. Department of Energy

Main R&D Topics

- Development of a CMOS MAPS-based DECAL sensor optimised for calorimetry.
    - This implies, in particular, the reduction of the power consumption from around 10mW / cm^2, as of today, by at least an order of magnitude.
- Sensor size and stitching technologies have to be developed in order to equip a surface of around 2000 m^2.
- The selected sensors and technology will have to be validated by beam-test prototypes.

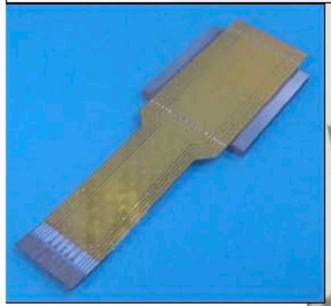
The Two Projects

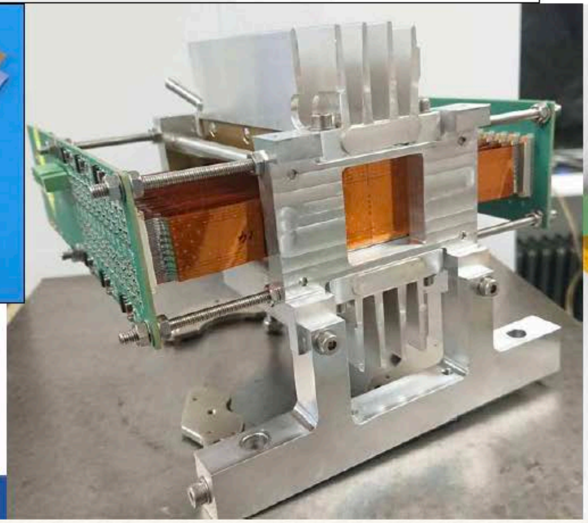
DECAL prototype reality: EPICAL-2

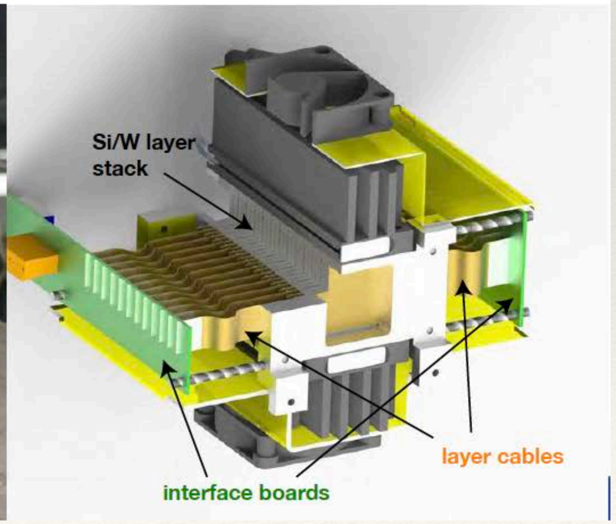


24 layers, each
- 3 mm W / 2 ALPIDE CMOS
- 3 x 3 cm² active
- 1M (29.24 x 26.88 μm²) pixels
- ultra-thin flex cables (LTU Kharkiv)
- compact design: expect $R_M \approx 11$ mm

Very successful DESY beam test [JINST 18 (2023) 01, P01038]







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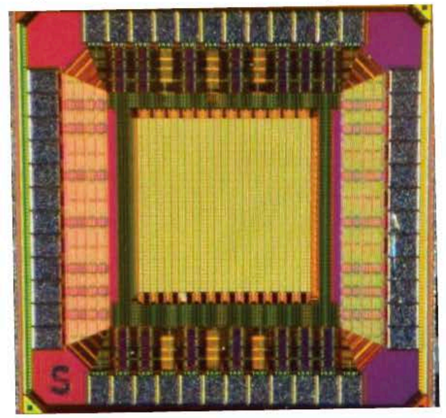
NAPA-p1 at SLAC

	Specification	Simulated NAPA-p1
Time resolution	1 ns-rms	0.4 ns-rms ✓
Spatial Resolution	7 μm	7 um ✓
Noise	< 30 e-rms	13 e-rms ✓
Minimum Threshold	200 e-	~ 80 e- ✓
Average Power density	< 20 mW/cm²	0.1 mW/cm² for 1% duty cucle ✓

The chip was received at SLAC in September 2023



Microscope photo of NAPA-p1

Acknowledgement: CERN WP 1.2 for the excellent cooperation: NAPA-p1 uses the pixel masked developed and optimized by CERN, and was fabricated in a shared run led by CERN

EPICAL-2 resulted from significant effort by many:

EPICAL-2 Team

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g Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
h European Organization for Nuclear Research (CERN), Geneva, Switzerland
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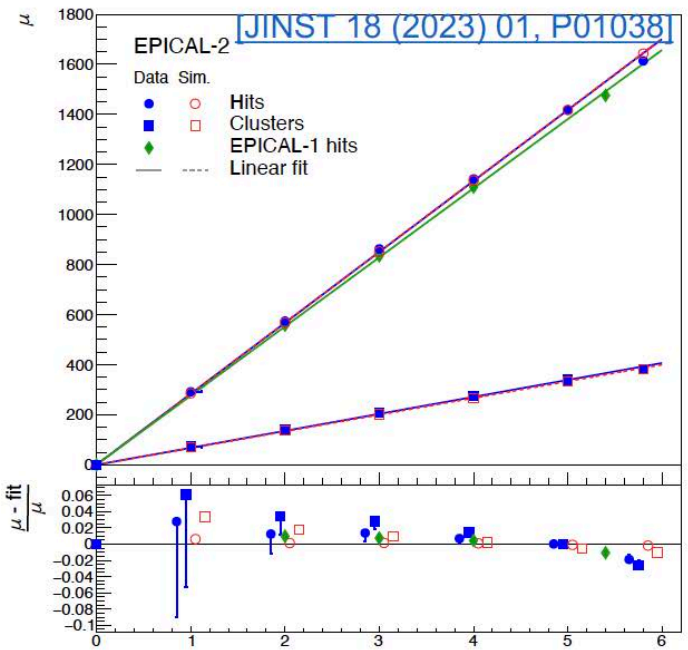
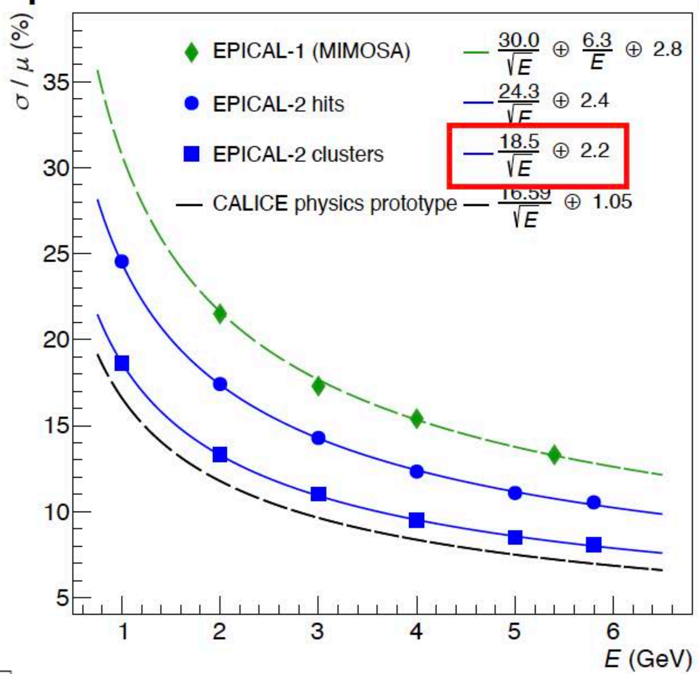
Energy resolution

Calorimetric performance





hits	a (%)	b (%)	c (%)
data	24.30 ± 0.03	2.41 ± 0.08	-
sim (E_{spread} = 0)	21.27 ± 0.06	2.30 ± 0.16	-
sim (E_{spread} = 158 MeV)	21.58 ± 0.25	1.8 ± 0.5	15.1 ± 0.4
clusters	a (%)	b (%)	c (%)
data	18.54 ± 0.02	2.17 ± 0.05	-
sim (E_{spread} = 0)	14.10 ± 0.04	2.52 ± 0.07	-
sim (E_{spread} = 158 MeV)	14.57 ± 0.21	1.96 ± 0.26	14.93 ± 0.23

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b \oplus \frac{c}{E/\mathrm{GeV}}$$

- Good standard performance
- Better resolution from clusters
- Uncertainties in beam energy spread

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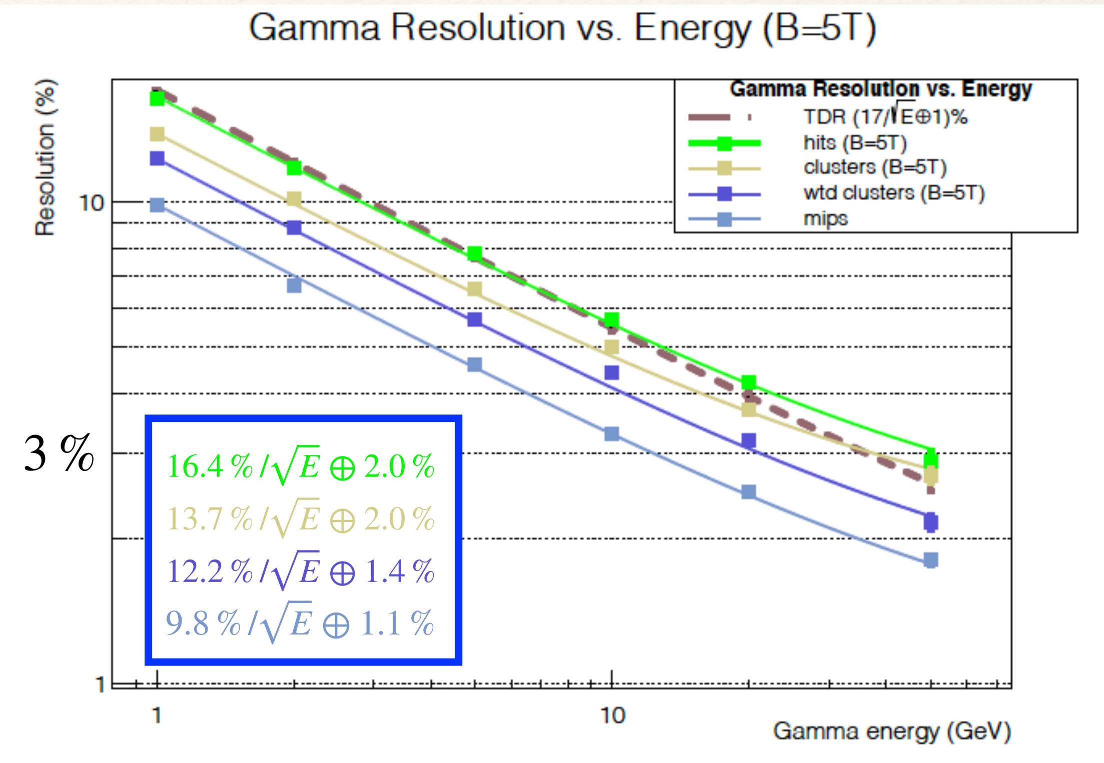
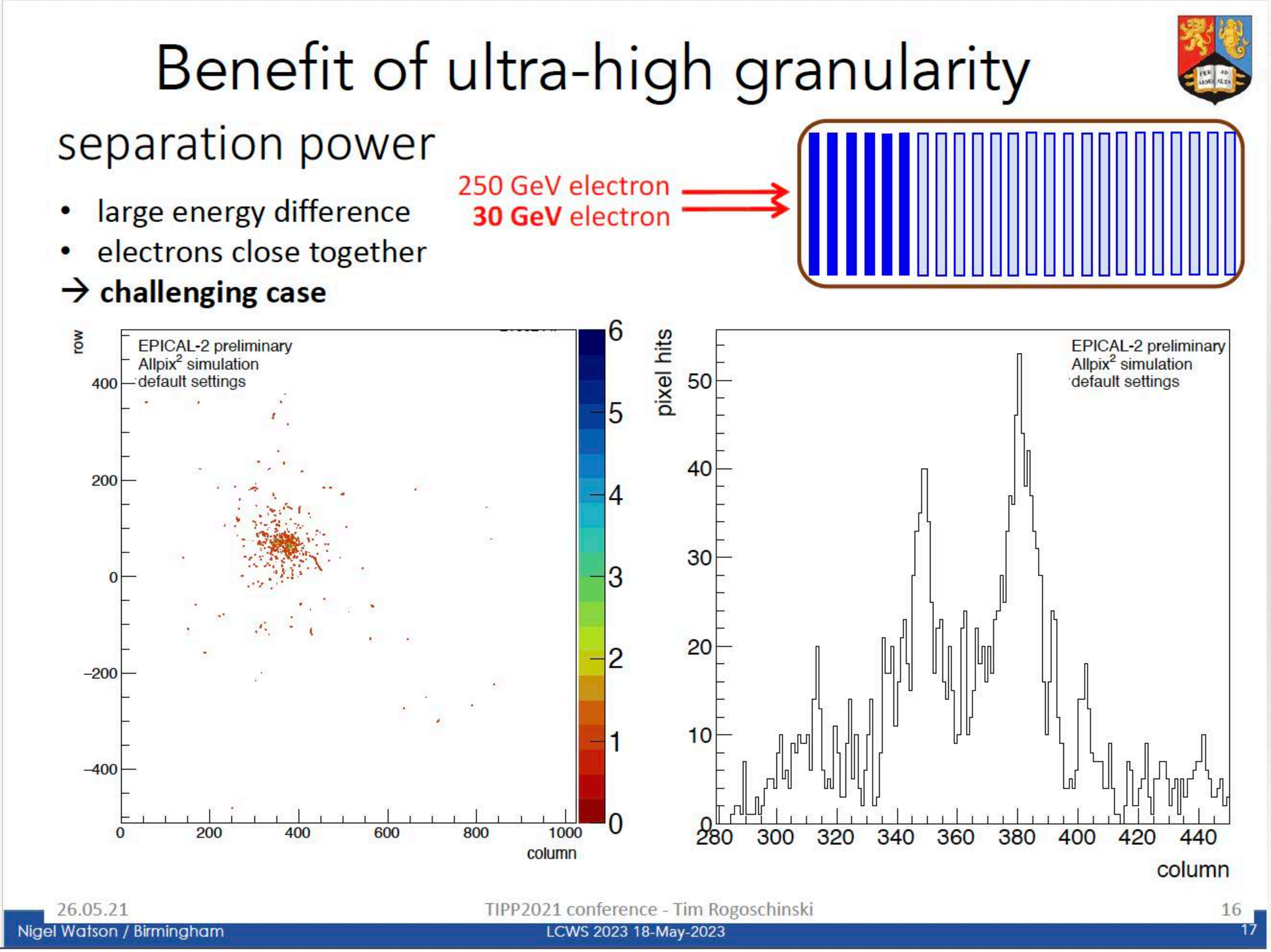
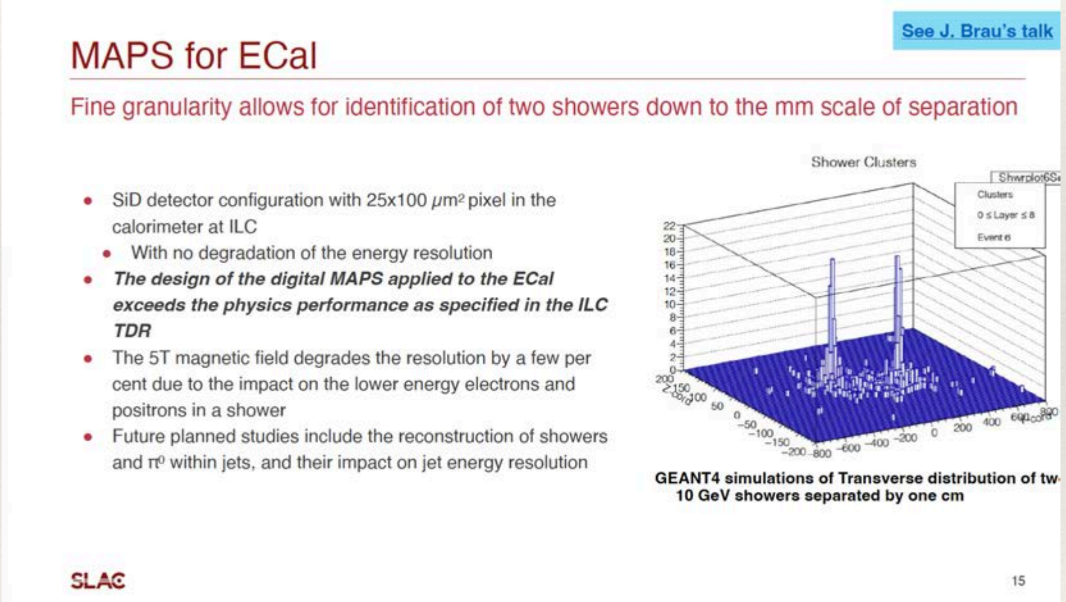


Cluster counting with weighting yields good resolution

Multi-shower separation





DRD6 Deliverables and Milestones

Milestone	Description	Due date
M1.3	Requirements for DECAL-specific sensor design established	2024
M1.4	Full evaluation of (ALPIDE-based) EPICAL-2 performance	2025
M1.5	Design for next-generation sensor with DECAL-specific optimisation (with machine-specific options)	2026

Deliverable	Description	Due date
D1.5.	New sensors produced and evaluated in EPICAL-3 prototype	>2026

US effort led by SLAC is a parallel development,
concentrated on the tracking application,
with calorimetry as an application. (See next slide)

Proposed US Effort - CPAD RDC9

arXiv:2306.13567

US MAPS ECal development will proceed in parallel with US Tracking Sensor Development Efforts (CPAD RDC3) and ECFA DRD3 to enable large scale production at competitive cost.

- **FY23-24:** Develop power and signal distribution schemes compatible for cal and tracking, in addition to evaluating first pixel results.
- **FY25:** Design PCBs with variations for the services balcony at the edge of sensors. Submission for sensors for large prototype active layers. Understand options for alternative foundries.
- **FY26:** Prototype attachment of sensors to PCB, probably with a conveyor oven so large production is feasible.
- **FY27:** Build prototype multilayer section with edge cooling and prepare/begin beam test.
- **FY28:** Complete beam tests with technical verification.
- **FY29-32:** Design, construct and test MAPS ECal modules based on final design of sensors and sampling layer configuration.

MAPS ECal Institutes: SLAC, University of Oregon

Future Directions for DECAL

- **Si-W DECAL can give excellent particle flow-based calorimetry**
  - Not intended for optimal single-particle performance
  - High potential esp. for future e^+e^-, but applicable more widely
  - **Ultra-high** granularity can benefit physics as well as cost (boosted decays)
- Affordable Si-W calorimeters, sensors ~ CHF/cm^2 (active areas > 10^7cm^2)
  - Potentially achievable with CMOS MAPS
- **Two** main strands to project
  - Sensor design optimised for DECAL requirements
  - Calorimetric performance for detectors/testbeams

Sensor design, two (so far) **independent** activities (SLAC/Oregon and UK/Germany)

- Potential for reconfigurable sensor technology: same for outer tracker/preshower/ECAL, e.g.
  - I.Kopsalis et al, NIM A1038 (2022) 166955
  - P.P.Allport et al, Sensors 2022, 22(18) 6848
- Power consumption needs R&D, estimates range ~20-100mW/cm^2
  - Dedicated sensor designs, or
  - Brute force mitigation by power pulsing – what gains (settling time)? – **but** collider-specific
- Requirements
  - Prototype demonstrating concept of digital ECAL, in same CMOS line as CERN et al, can deliver radiation hardness to > 10^{15}neq/cm^2
  - Collaborate to make best use of limited resources in the two activities

Calo performance
  - Calorimetric performance demonstrated, e.g. JINST 18 (2023) 01, P01038
  - Extending with recorded EPICAL-2 beam data up to 80 GeV / SPS (analysis in progress)
  - Extensive simulation (AllPix2) modelling
    - Benchmarked/validated using data
    - Extend validated model to study benefits for particle / shower separation

Subtask 1.1.3 - DECAL

UK/Germany sensor activity

- Main goals
  - Resolve identified faults with current DECAL sensor design
  - Reduce power consumption (power pulsing or better ideas)
- Other avenues under consideration
  - 3d stack + semi-digital approach
  - Multi-threshold per pixel
  - Increased configurability options
  - Move configurability from the chip to FPGA
  - Simulation
- Starting point for collaboration with SLAC/Oregon, review overlaps/agree on division of fundamental design goals

Subtask 1.1.3 - DECAL

DRD6 Subtask 1.1.3 Institutes

- Germany
  - DESY
  - Goethe Universit¨at Frankfurt
  - Humboldt U.
- Greece
  - NTUA
- Netherlands
  - Utrecht U.
- UK
  - Birmingham U.
  - Imperial Coll.
  - Rutherford
  - U. Sussex
- USA
  - SLAC
  - U Oregon

The path forward

- MAPS Digital ECal groups will aim to meet the milestones and deliverables as outlined in this presentation.
- Building on past work:

  1) "Performance of the electromagnetic pixel calorimeter prototype Epical-2", JINST 18 (2023) 01, P01038;
  2) "The SiD Digital ECal Based on Monolithic Active Pixel Sensors", 10.3390/instruments6040051, Instruments, 6, 51 (2022);
  3) TWEPP 2023 (https://indico.cern.ch/event/1255624/contributions/5443776/) to be published in TWEPP 2023 Proceedings.

- Thank you for your interest and attention!