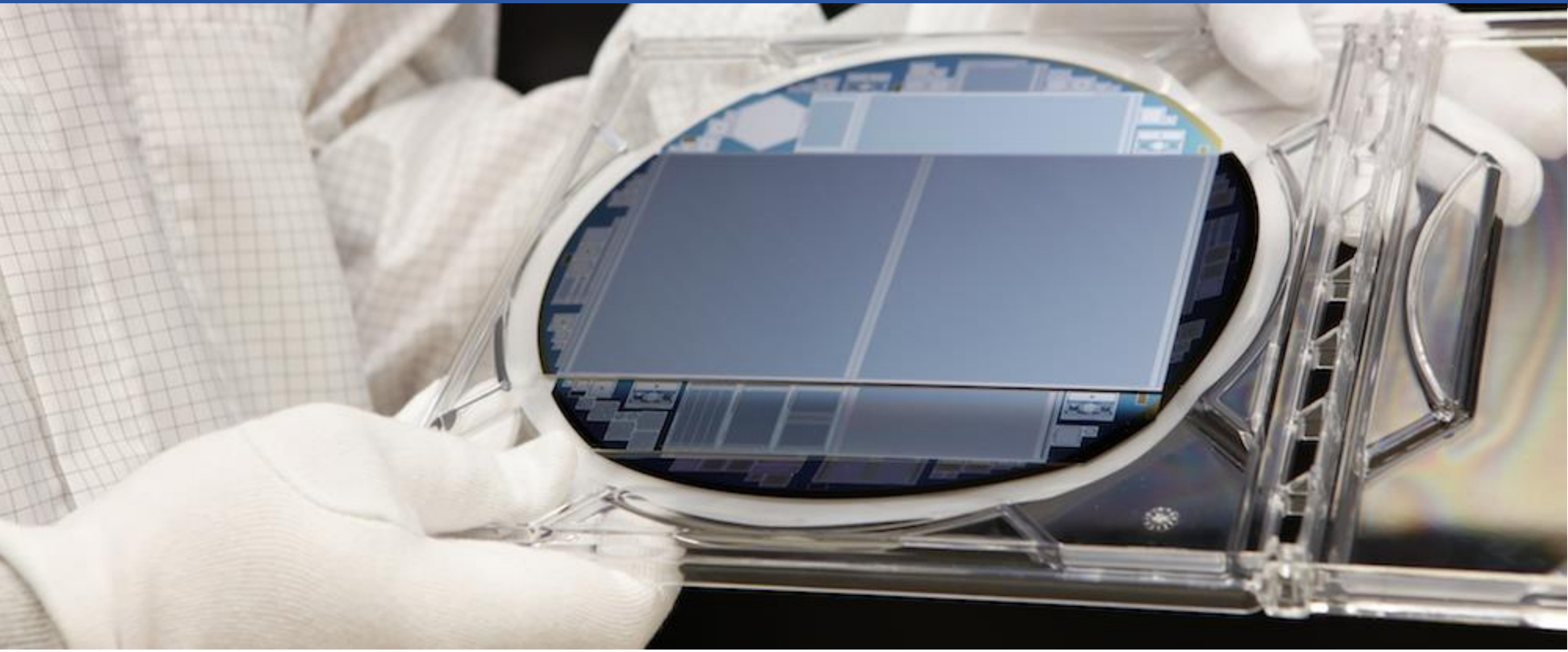


Hardware Activities at HEPHY

Thomas Bergauer

Austrian FCC Meeting

11 Oct 2021

Institute for High Energy Physics (HEPHY)

- Founded 1966 to take advantage of Austria's CERN membership (1959)
- Situated in Vienna, two locations
- Staff: ~80 people

Institut für Hochenergiephysik
Nikolsdoerfer Gasse 18

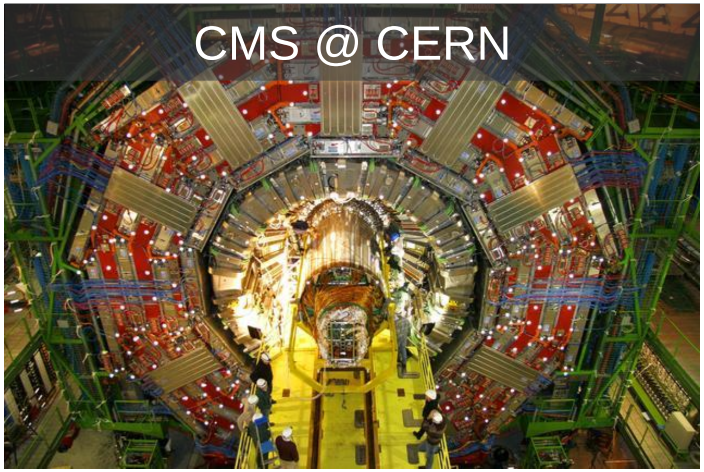
Belongs to

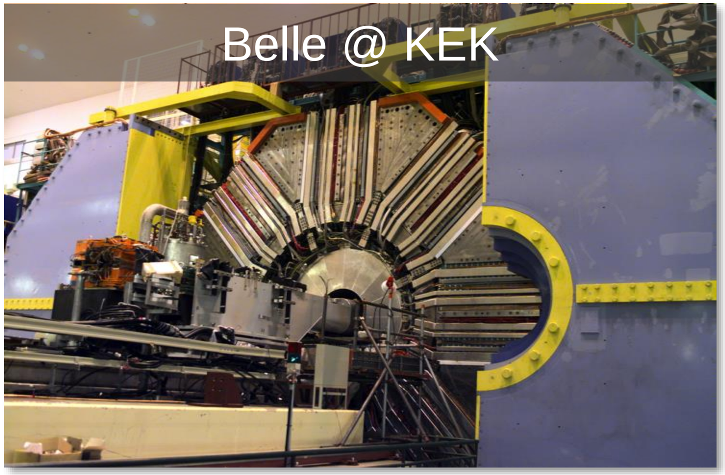
Austrian Academy of Sciences (ÖAW/OEAW)

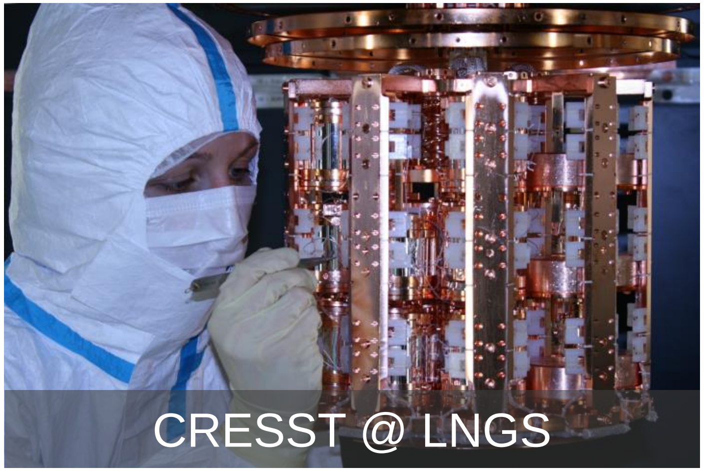
- Founded 1847 as "scientific club"
- Nowadays the largest non-university institution for basic research in Austria
- 28 Institutes with around 1450 staff
  - Humanities
  - Natural sciences

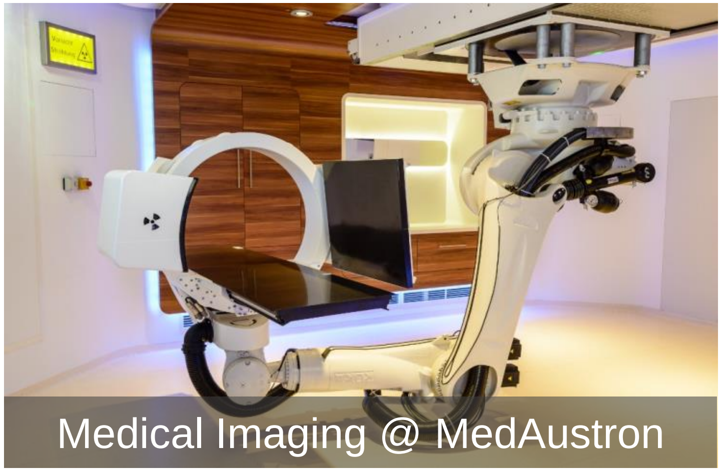
Österreichische Akademie der Wissenschaften
Hauptgebäude, Ignatz Seipel Platz

Frontiers in HEP @ HEPHY

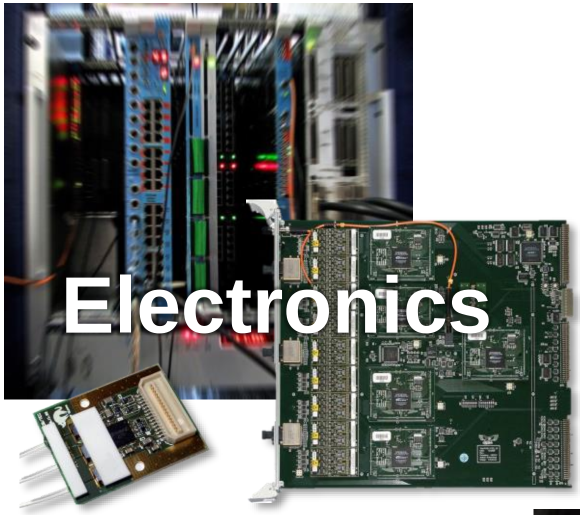

CMS @ CERN

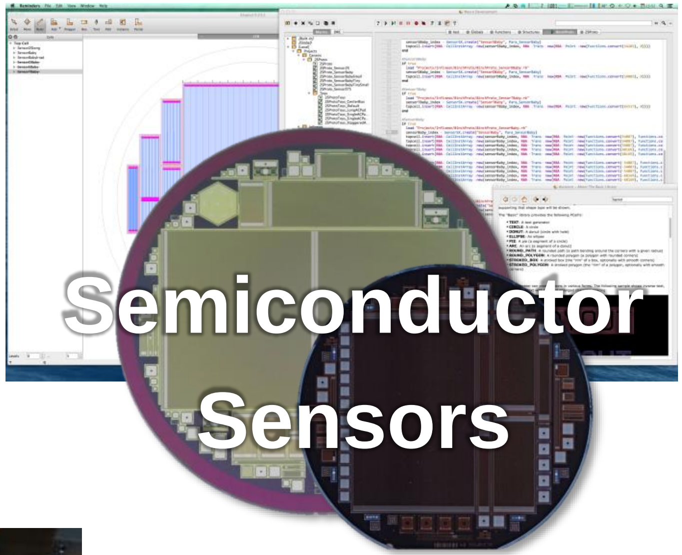

Belle @ KEK

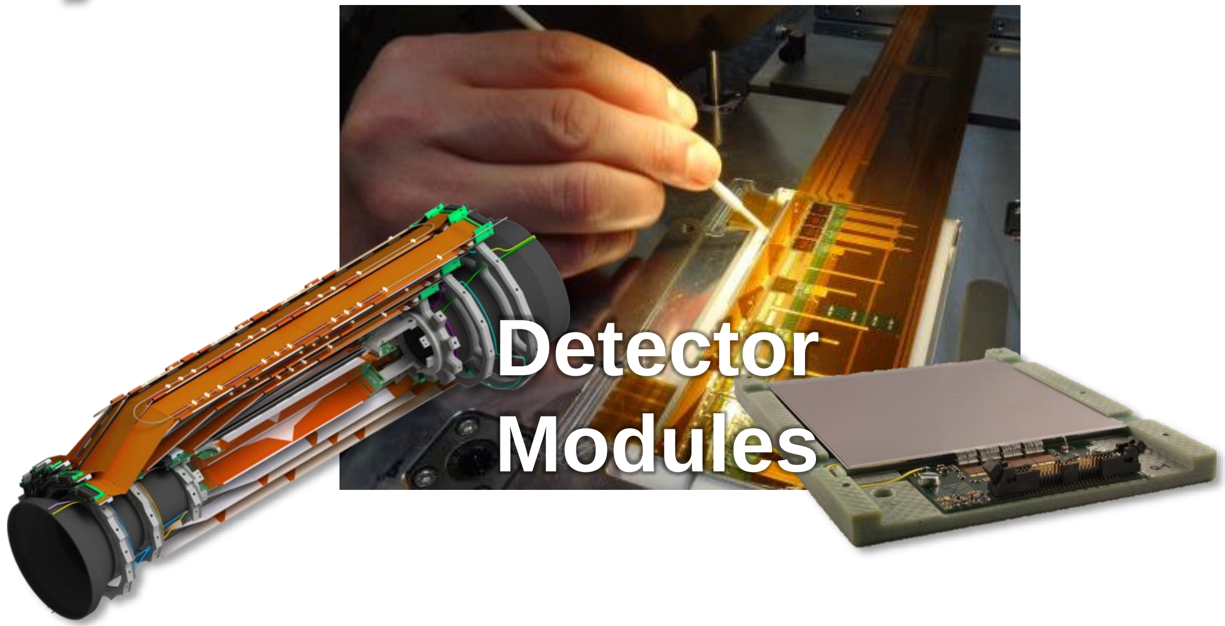

CRESST @ LNGS


Medical Imaging @ MedAustron

Experimental Expertise @ HEPHY



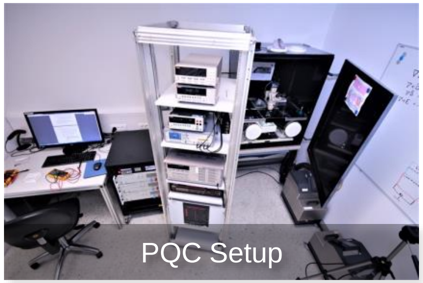


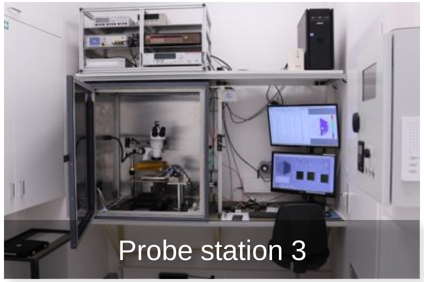


Infrastructure at HEPHY

We are operating high level equipment for sensor characterization and module construction

- Several probe stations for sensor tests (own developments)
- Semi-automatized module assembly (CMM, glue robot)
- Fully automatic thin-wire bonding machine
- Microscopes for optical measurements
- Radioactive sources and Lasers for signal stimulation (TCT)
- Software frameworks for sensor design and simulation (TCAD)
- Chip design Workflow (Cadence, Mentor, SOS,….)


PQC Setup

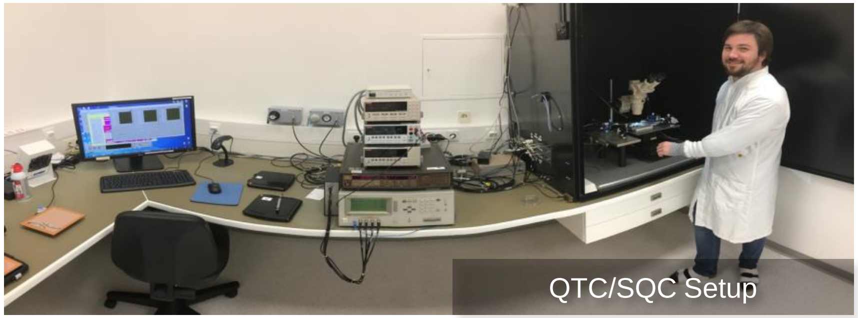

Probe station 3


Coordinate Measurements

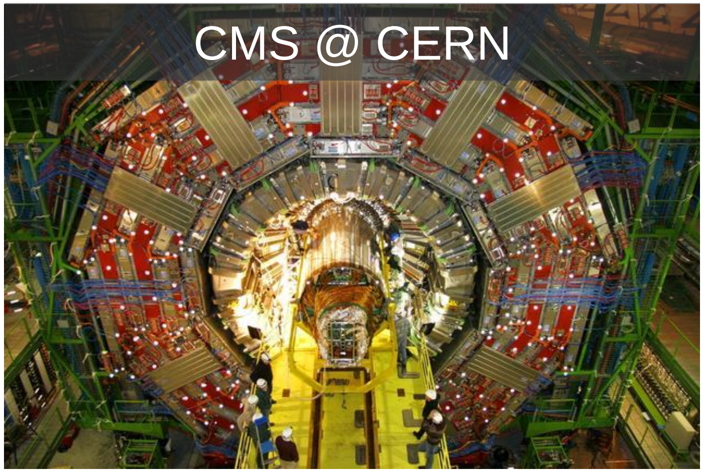

Thin-wire bonding machine

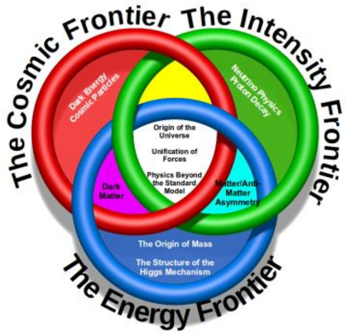

Laser Setup


Climatic Chamber


QTC/SQC Setup

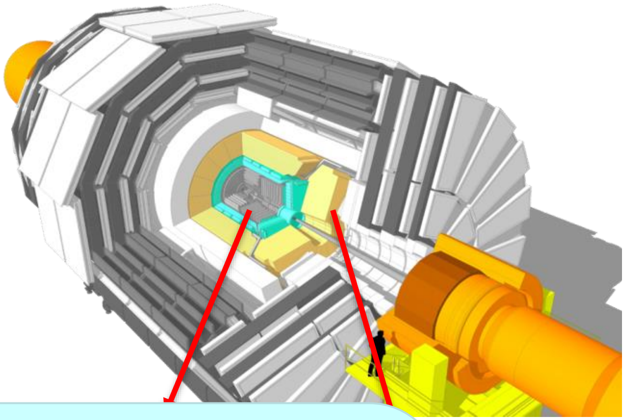

HGCCal Setup





The Energy Frontier

CMS Phase-II Upgrades



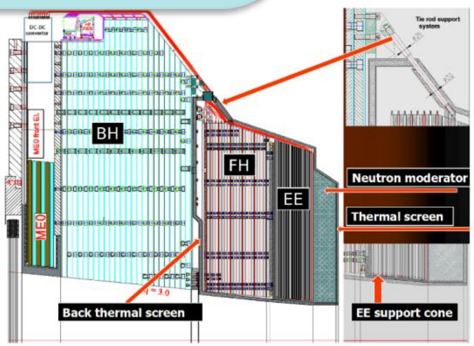
LHC Long Shutdown 3 (LS3) in 2025-2027

- Accelerator upgrade to High-Luminosity (HL)-LHC
- Upgrade of experiments necessary
  - Existing systems reach end of life (radiation damage)
  - Increase in luminosity at HL-LHC: 300 → 3000 fb^{-1} → More radiation hard material necessary
  - Increase in pile-ups → new techniques ne
    - "Track trigger" in Tracker
    - Timing layer as complete new subdetect

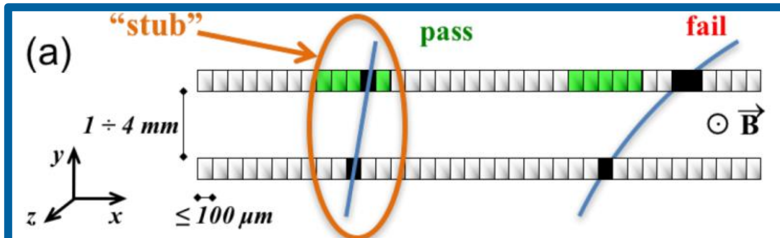
Big responsibility and commitments in both projects as institute members are convenors of working groups for sensor development in both subdetectors

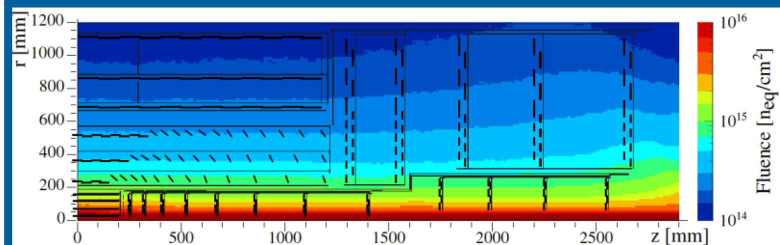
Phase-II Upgrade of CMS:

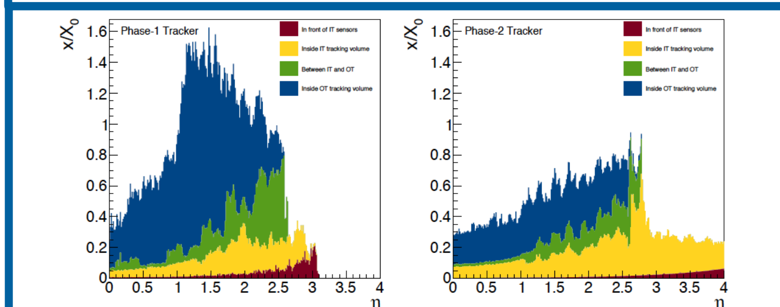
- **Complete exchange of Outer Tracker**
  → 200 m^2 Si Sensors needed
- **New Highly Granularity Calorimeter (HGCal)**
  → 600 m^2 Si Sensors (8 inch)
- New Timing Layer
  → Ultra-Fast detectors to enable "4D" tracking"

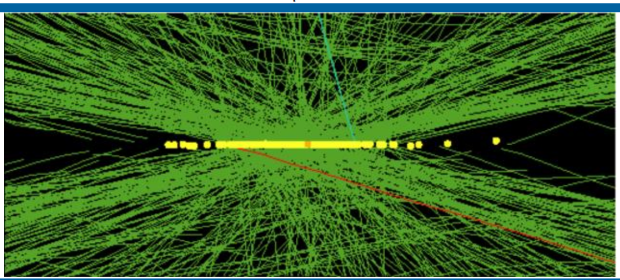


Completely replace Outer tracker for Phase II









- Maintain physics performance
  - Track trigger concept
- Increase radiation hardness
  - 2.3×10^{16} n_{eq}/cm^2 → Pixel
  - 1×10^{15} n_{eq}/cm^2 → Strips
- Reduce material budget
- Extend tracking acceptance
  - $|\eta| = 2.4$ → $|\eta| = 4$
- Increase granularity
  - Keep channel occupancy below 1 % at high pile-up

High Granularity Calorimeter

Calorimeter Endcap or **H**igh **G**ranularity **CAL**orimeter

- CALICE-inspired imaging calorimeter optimized for particle flow analysis
- Covers 1.5 < η < 3.0
- 215 tons per endcap, full system at -35° C

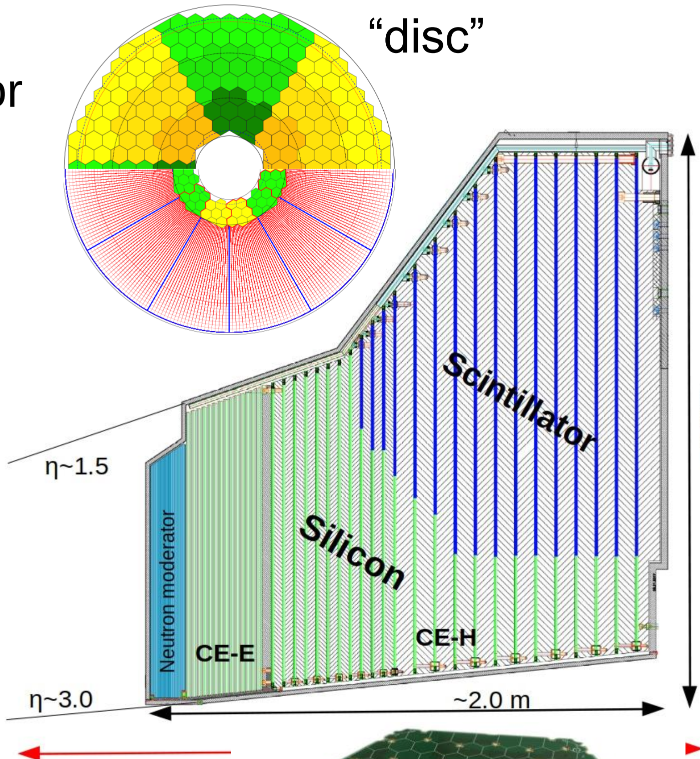
Silicon part:

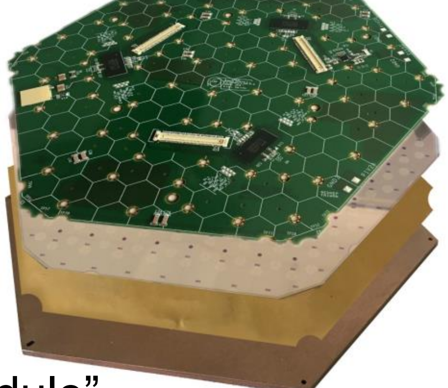
- ~620 m^2 of silicon sensors, 8" (200mm wafers)
- ~6M channels in
- ~30k modules, two cell sizes 0.5 and 1.1 cm^2

Scintillator part:

- ~400 m^2 of scintillator,
- ~240k tiles + SiPMs in ~4000 boards, two tile size 4–30 cm

- El.-mag. section CE-E: **Si**, Cu, CuW, Pb absorbers, 28 layers, $25X_0$ & ~1.3λ
- Hadronic section CE-H: **Si**+scintillator/SiPM, steel absorbers, 22 layers, ~ 8.5λ





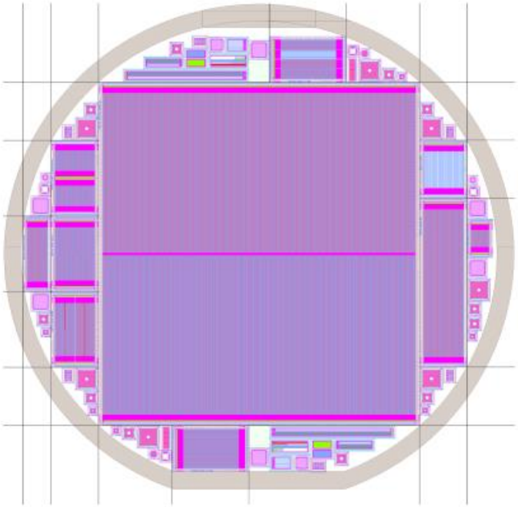
"Si module"

Sensor Design

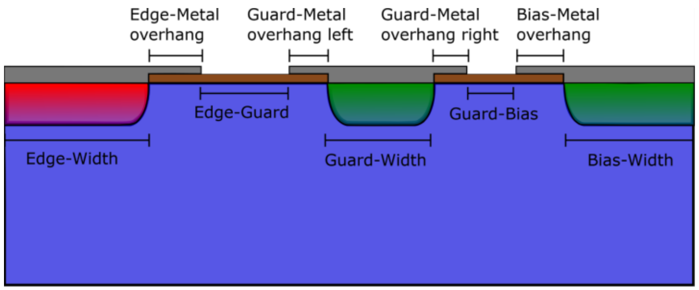
Wafer layouts for both strip sensors of Tracker and HGCal sensors is fully driven by us at HEPHY

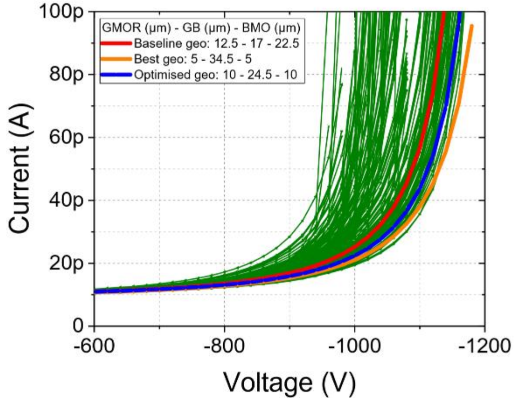
  – Main sensor, test structures

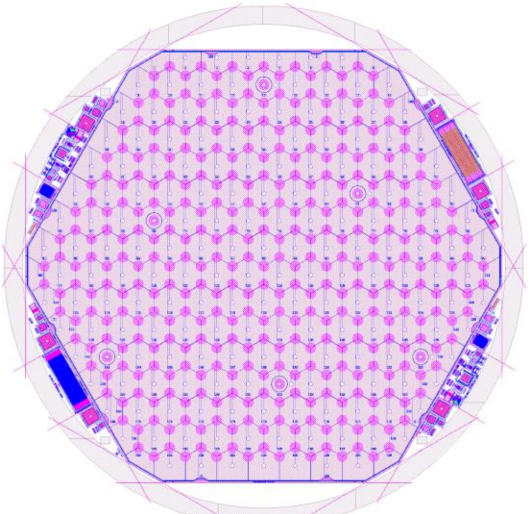
- Using self-developed framework based on open source tools
- Needs negotiations with vendors on details (e.g. design rules, dicing precision,..)
- Supported by TCAD simulations for optimizing different aspects
  – E.g. periphery simulation



2S Wafer layout







HGCal full wafer LD layout

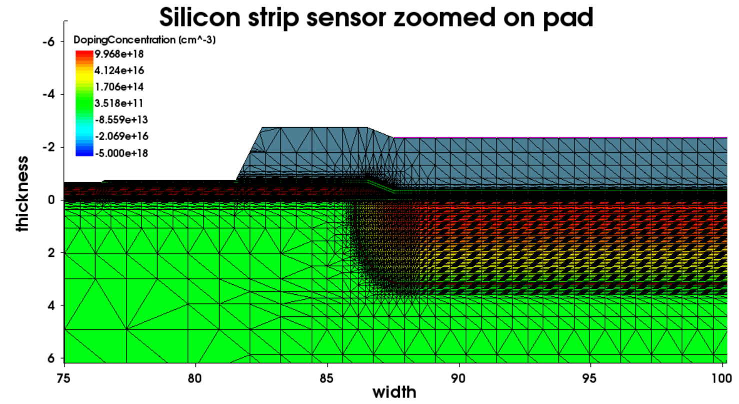
Sensor Simulation

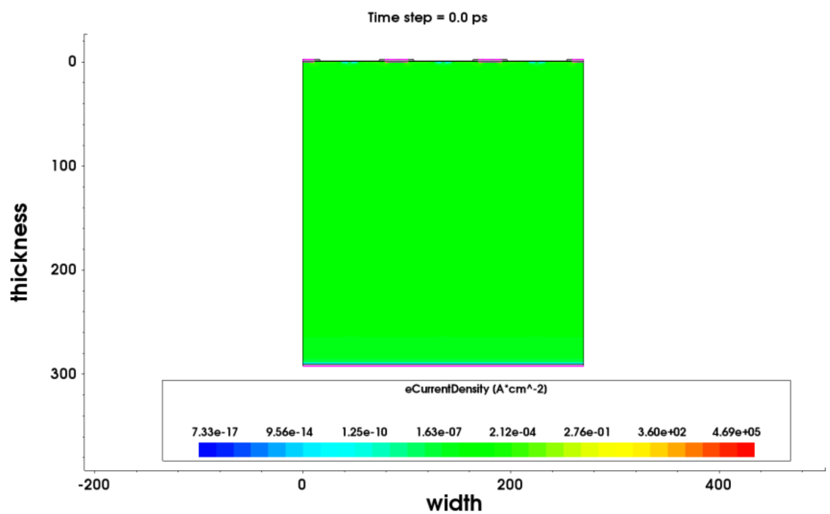
Goal: fully reproduce strip-sensor measurements

- Better understanding on Electric field, currents, breakdown behavior, interstrip characteristics,..

Performed tasks at HEPHY:

- Improved/tuned sensor mesh and design
- Improved physics models
- Includes “real” doping profiles as result of scanning resistance profiling (SRP)
- Added additional traps, revealed by DLTS (deep level transient spectroscopy) in unirradiated sensors
- Further improvements by determining the correct charge carrier lifetime through GCD measurements



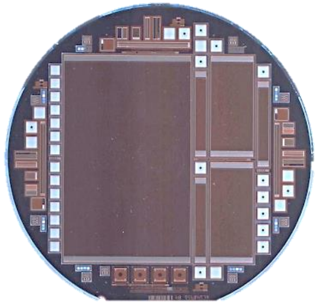


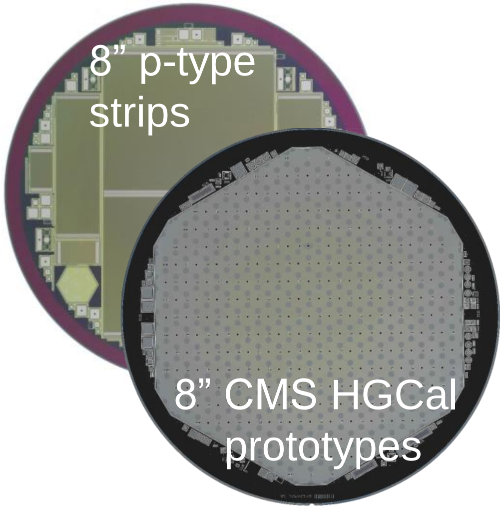
Sensor Production

We worked with Infineon to find a “second source” for large-area planar Si sensors

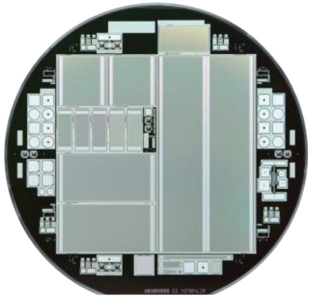
- 2009: Project started by private contacts as a bottom-up approach
- 2012-2014: production of 6” p-on-n sensors
  - Goal: **re-produce the current CMS tracker sensors**
  - **Production workflow:** design by HEPHY, production at IFX, characterization (lab, beam tests,…) by HEPHY (mostly done in the framework of Bachelor’s and Masters’ theses)
- **2015: First AC-coupled sensor on 8” wafer**
- 2015-2017: production of first Si strip sensors on 8-inch FZ p-type wafers
- 2016/17: production of pad sensors for HGCal and 6-inch p-type sensors for CMS Tracker
- 2018 program stopped due to economic reasons

6“ p-on-n Wafer:





6” CMS PS-S prototypes




Infineon CEO together with HEPHY and CERN representatives


Former CERN DG Heuer with Infineon manager and M. Dragicevic

Sensor Testing

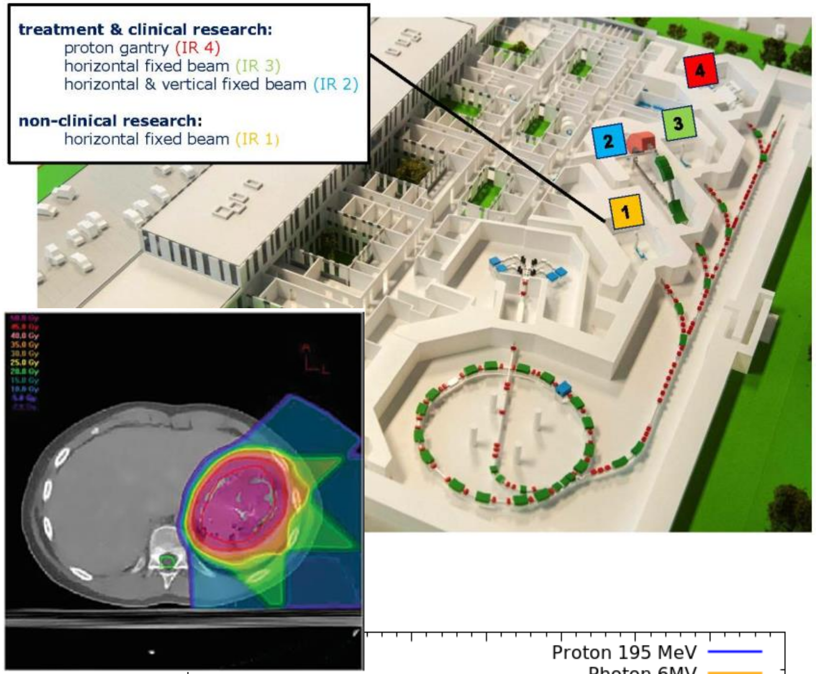
- Characterizing sensors with several custom probe stations in our clean rooms
  - ”custom” refers to develop both hardware and software to our own needs by help of our large electronics and mechanics groups
- Tracker and HGCal in different status at the moment:
  - “Series production” of Tracker sensors require quality control of tracker sensors using full sensors and process control on dedicated test structures (PQC)
  - R&D of HGCal sensors to qualify 8” process of HPK
    - Bulk irradiation tests (neutrons)
    - Gamma/X-Ray irradiations for Oxide studies
    - Full wafer characterization
    - Backside fragility

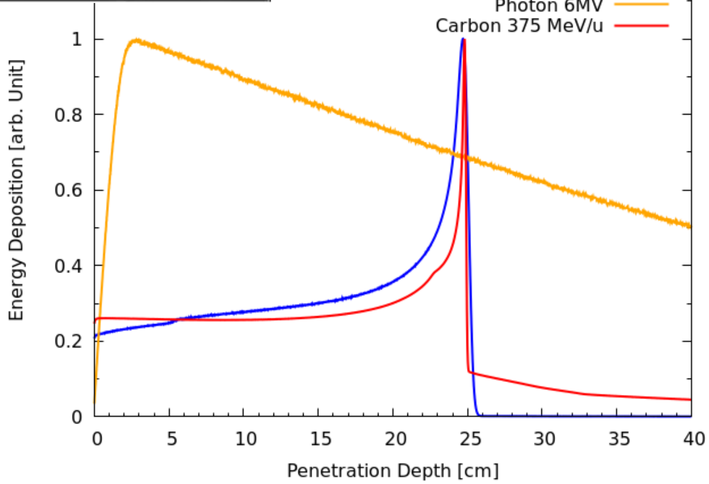
Medical Imaging at

MEDAUSTRON

MedAustron: Austrian hadron cancer therapy center

- Based on CERN PIMMS study
- Became operational end of 2016
- Patient treatment using proton and carbon beams utilizing Bragg peak
  - Protons: 60 MeV to 800 MeV, Clinical energies ≤ 250 MeV
  - Carbon ions: 120 MeV/u to 400 MeV/u
- Dedicated non-clinical irradiation room (IR1) for research
- We perform regular beam tests there and collaborating with a group of TU Wien to establish an **Ion-CT system**

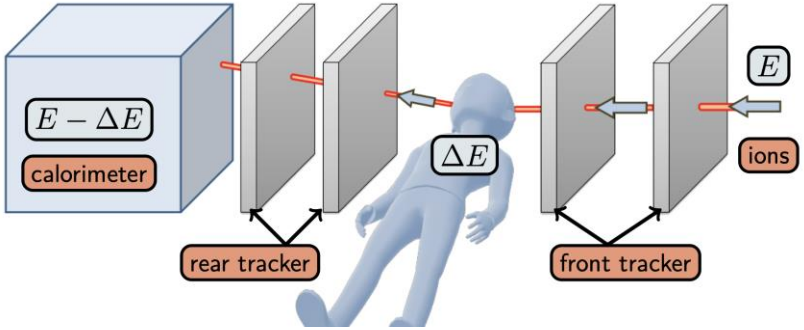


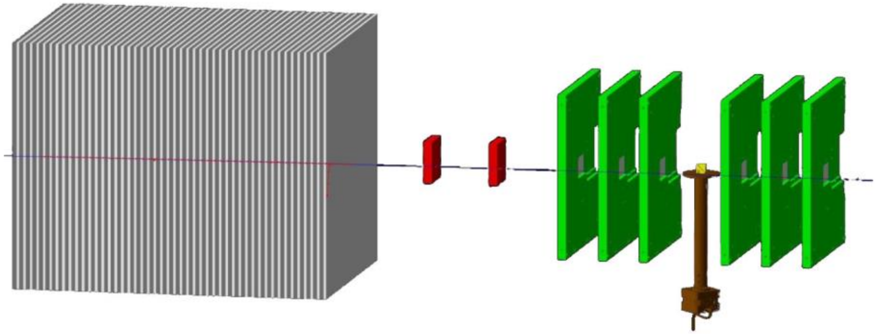


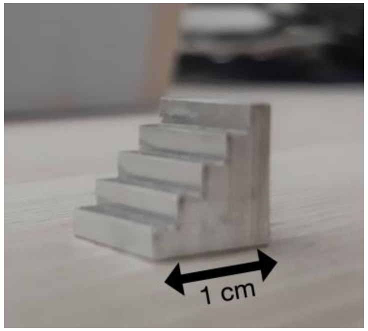
Ion Imaging

"Ion CT" by measuring stopping power in object per voxel needs

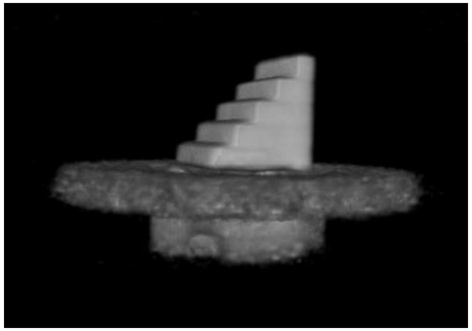
- Tracker (similar beam telescope)
  - Currently DSSDs
- Calorimeter to measure residual energy
  - Sandwich calo using scintillator planes and SiPM readout
- Image Reconstruction



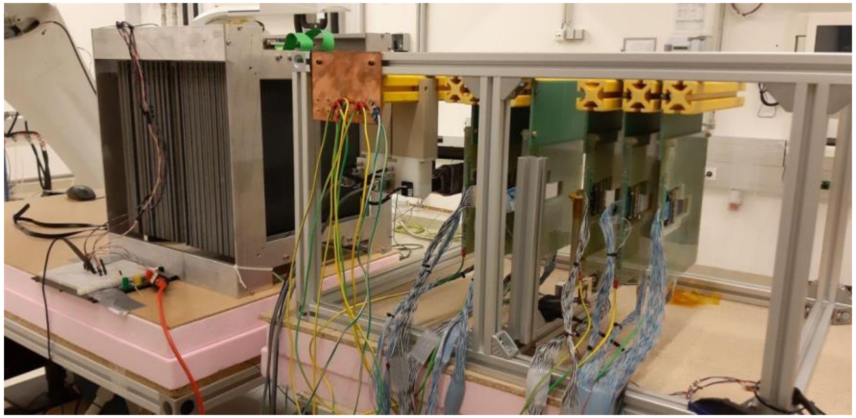




Phantom

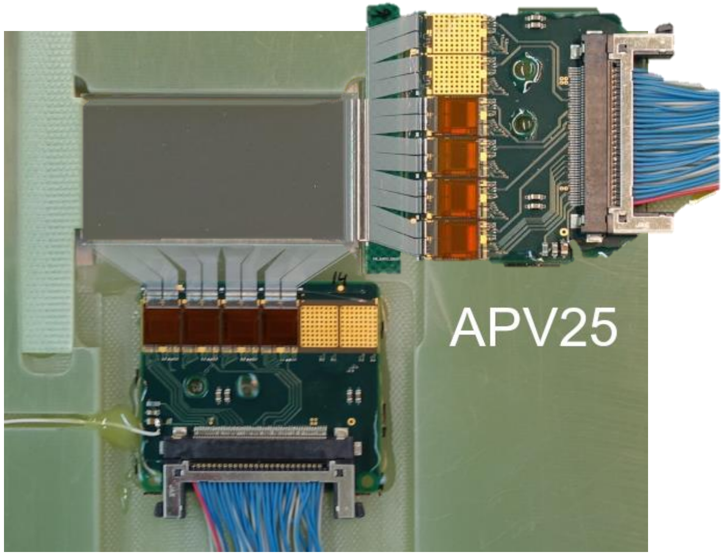


Reconstructed image

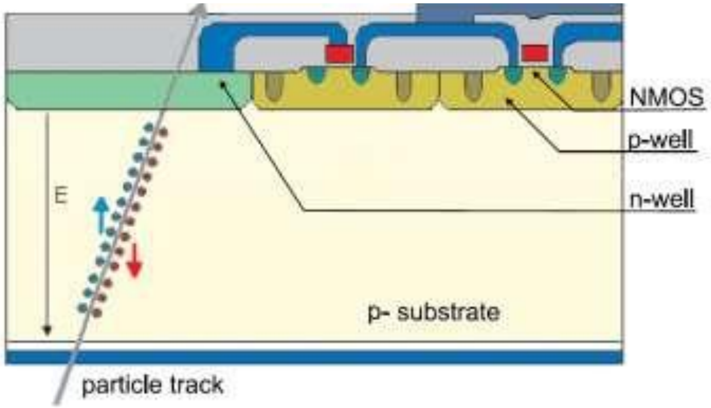


pCT Tracker Upgrade: Monolithic

- **D**epleted **Monolithic A**ctive **P**ixel **S**ensor combines both active sensing element and readout electronics into one device
  - Sensor development becomes chip development
  - Generally agreed that this technology will be the future of Si sensors in HEP
  - Deep wells fully shield CMOS electronics from active volume and allows full CMOS electronics



DMAPS (a.k.a. HV-CMOS)



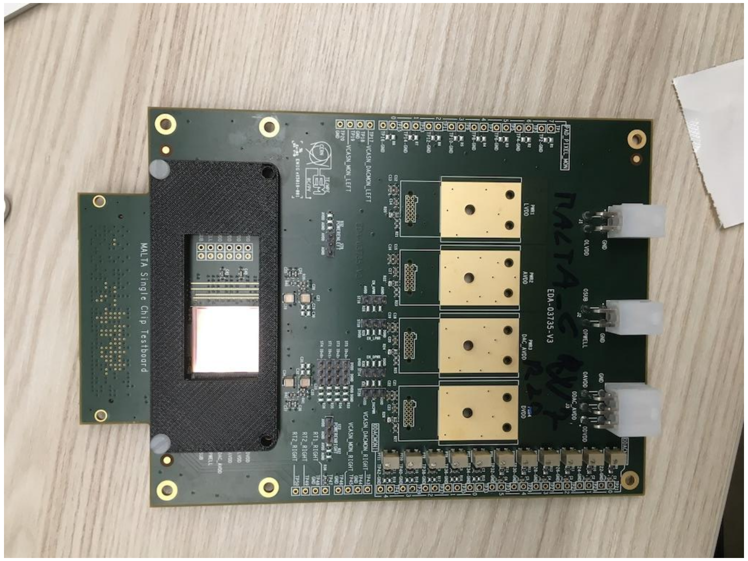
Ion Imaging Tracker Upgrade

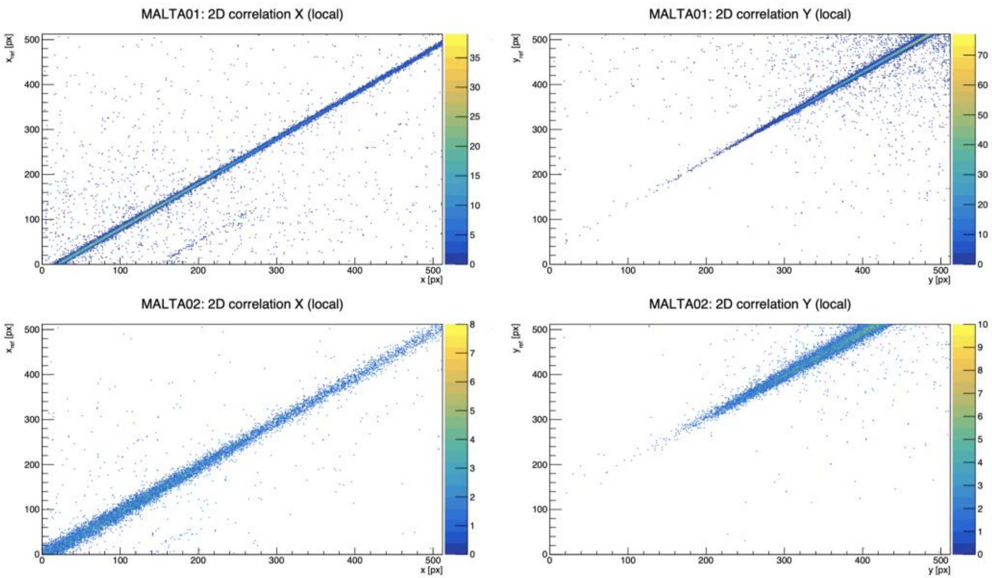
MALTA HV CMOS

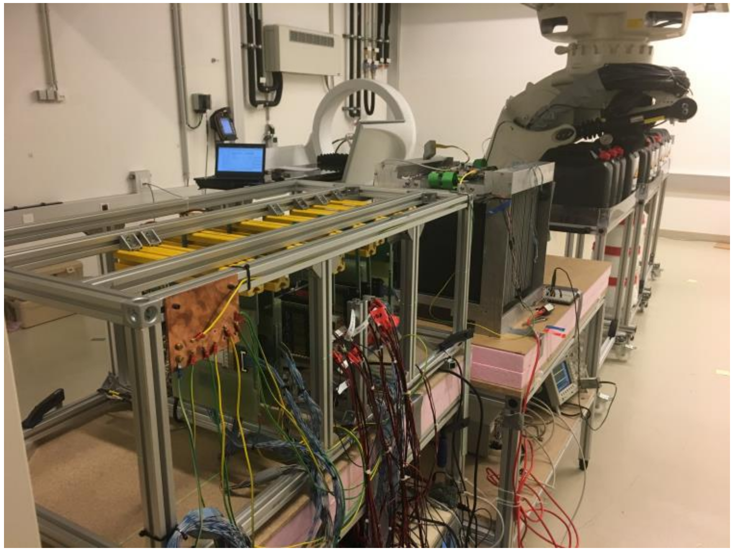
- TowerJazz 180nm
- 512 × 512 square pixels, pitch 36.4 µm -> 1.8^2 cm^2
- asynchronous readout

Tested in beam time at MedAustron in summer 2019:

- 4 sensor planes of MALTA-C with Epi substrate used as „proof of principle“ as high-rate replacement
- Due to small chip size no “phantom”
- Plot below shows hitmap of not fully centered beam

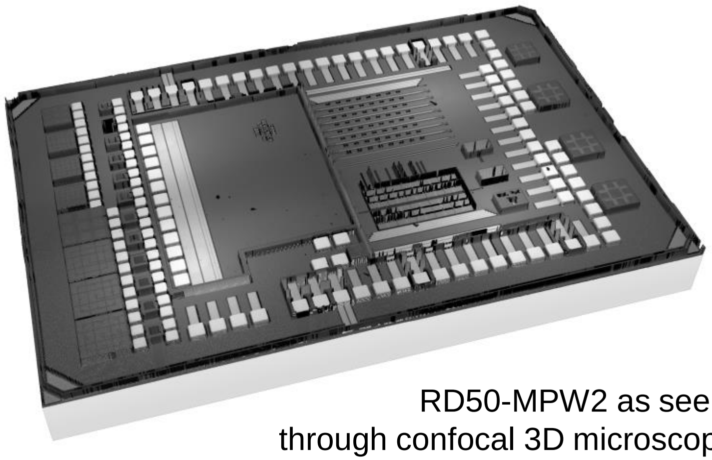






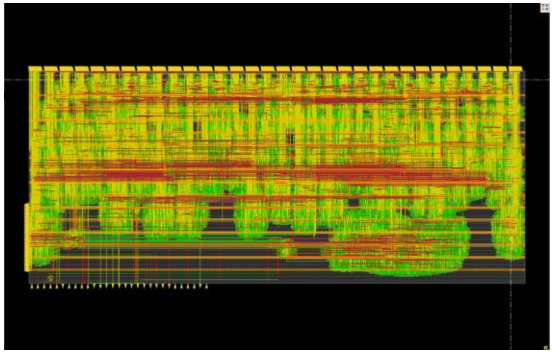
DMAPS/CMOS at HEPHY

- **Current Projects:**
  - RD50-MPW (2|3)
  - OBELIX (Belle-II Upgrade)
  - HiBPM Readout chip
- **Available foundries/processes**
  - Lfoundry 150nm (LF15A)
  - Towerjazz 180 nm CMOS Imaging Process (TS18IS)
  - STM BiCMOS Bipolar/CMOS combination
- **Setups/Readout systems**
  - Chip design Software infrastructure (Cadence, Mentor,… tools)
  - FPGA design (Xilinx, Altera) and test stands



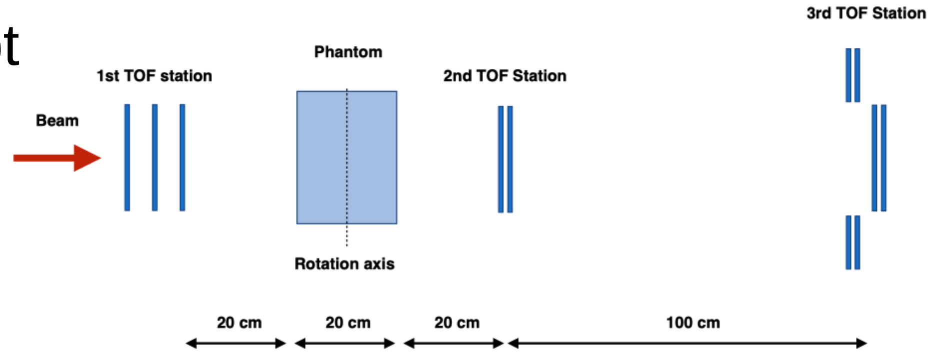
RD50-MPW2 as seen through confocal 3D microscope

Current periphery of RD50-MPW3

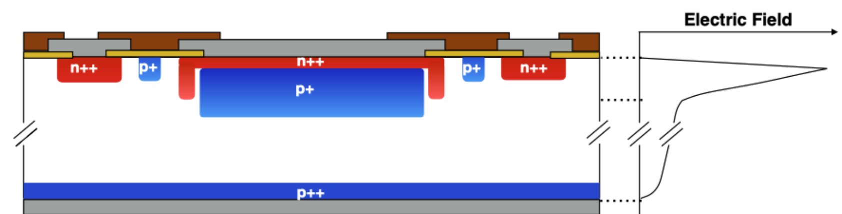


pCT calorimeter upgrade

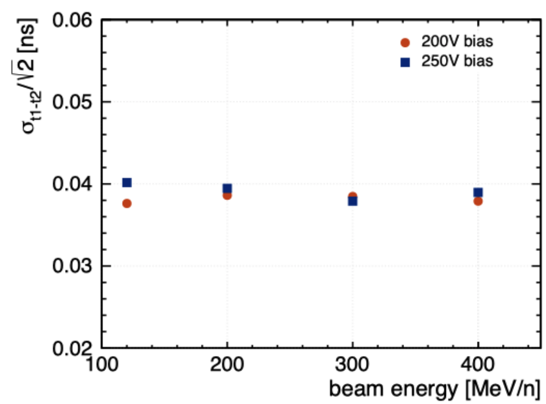
- Use Time-of-flight (ToF) concept to reconstruct residual energy
- Precision timing based on Low Gain Avalanche Detectors (LGAD) a.k.a. UFSD needed
  - LGAD have an additional deep implant layer to create locally a high electric field to initiate an avalanche
- First tests performed successfully at MedAustron reaching 40ps
  - System concept currently studied
  - Taking advantage of developments of MTD layer of CMS Upgrade (and FCC later)

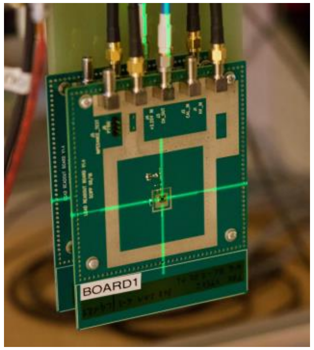


Sketch of full 4D tracking setup



LGAD single diode sketch with illustrative field





time resolution for carbons

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

Conclusion

ÖAW

- HEPHY is very active detector development and well prepared for future detectors at FCC

- Current projects:
  - CMS Phase-II Upgrades: Tracker and HGCal
  - Belle II:
    - Silicon Vertex Detector (installed 2019) with key contributions to electronics, mechanics, readout
    - Belle-II Upgrade (DMAPS-based currently starting)
  - Dark Matter
    - CRESST (with COSINUS, NUCLEUS)
    - DANAE: DEPFET Silicon sensor based
  - Medical application
    - Ion Imaging: Hardware setup and image reconstruction
    - Ideal test bed for new concepts (DMAPS, LGAD sensors,…)

- Rich expertise in all aspects of detector development
  - Sensor Design, Simulation, Implementation
  - Detector Module design, assembly
  - Electronics & FPGA design, hardware and firmware
  - Cleanroom laboratories with several test stands
  - Most recently: ASIC and DMAPS Sensor Design, Precision Timing

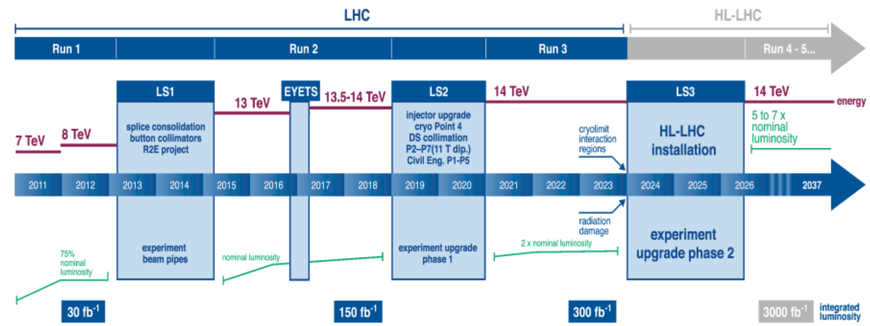
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

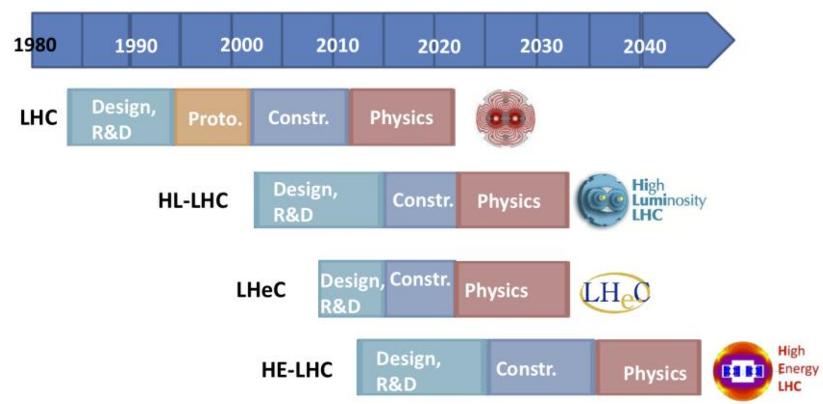
ÖAW

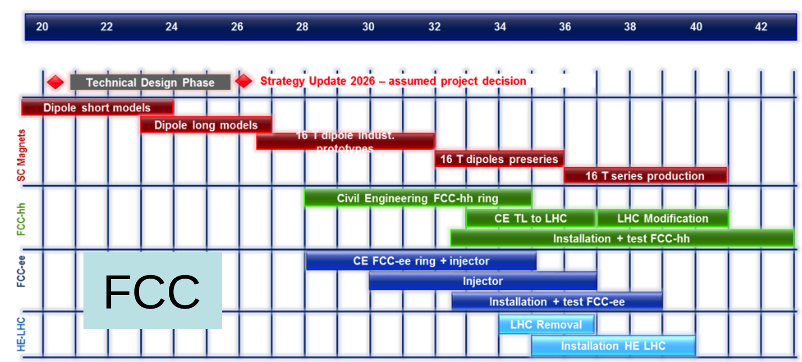
The End.

LHC Roadmap

- Most of our work is now for Phase-II Upgrades (LS3)
- What is the next European project after HL-LHC?
  - HE-LHC, FCC, CLIC, ILC,…
  - Development for detector technologies need to start well in advance
- European Strategy for Particle Physics Update 2020~2030
  - Scheduled for approval in 2020
    - Open Symposium May 2019 Granada (Spain)





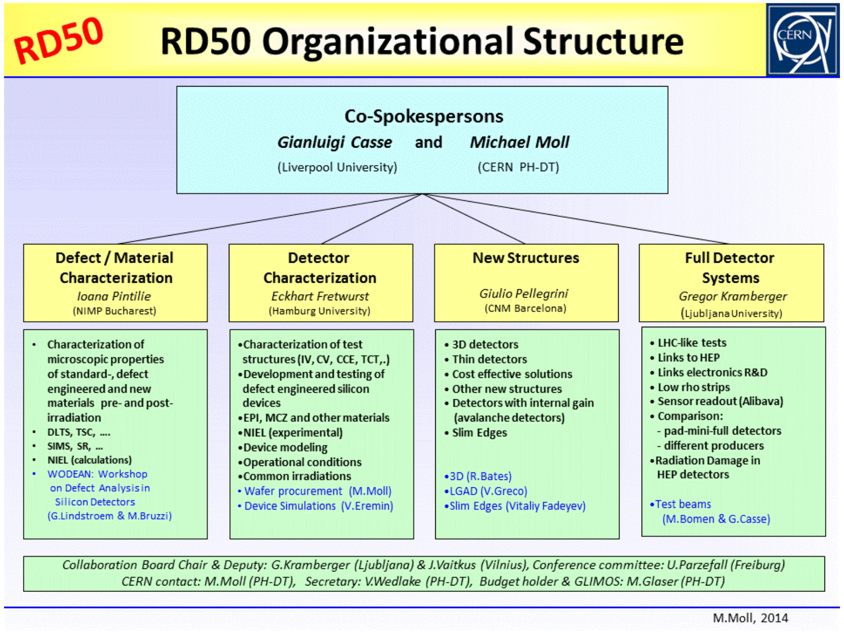


CERN RD50 collaboration

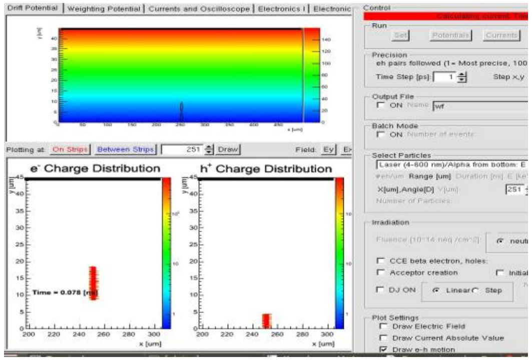
RD50 is a CERN R&D collaboration with currently 63 institutes (370 authors)

- Initially focused on radiation hardness of silicon
  - widened its scope, e.g. towards timing detectors (LGADs)
  - Recently started also HV-CMOS developments

- Covers now all Si development paths we see important for future HEP detectors
  - Thus we joined RD50 in Dec 2017



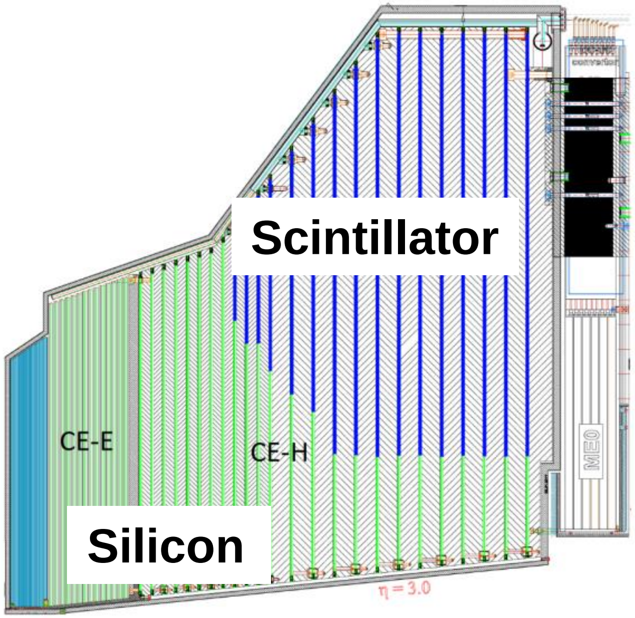
Weightfield2 (1st version created at HEPHY):

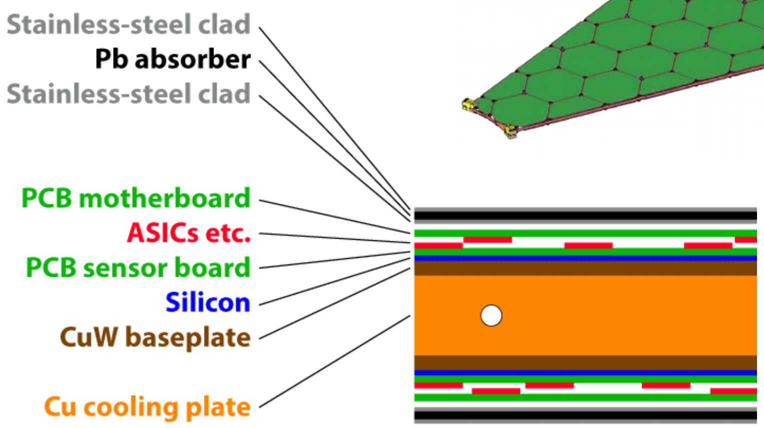


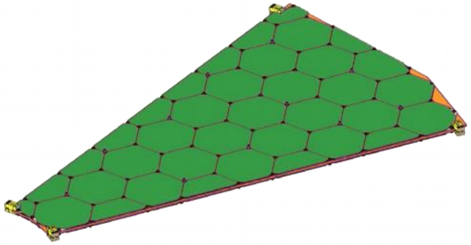
CMS High Granularity Calorimeter

CMS is planning to build a High Granularity Calorimeter for Phase-II at HL-LHC

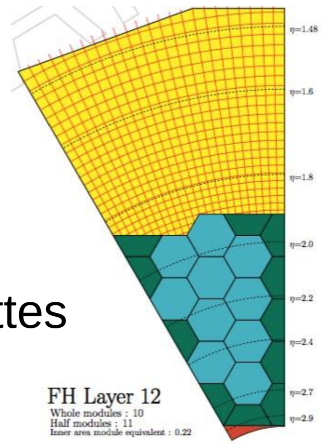
- Covering $1.5 < \eta < 3.0$
- Features unprecedented transverse and longitudinal segmentation
  - Silicon in high radiation areas
  - Scintillating tiles in the low-radiation region of CE-H (Mixed Silicon-Scintillator cassettes)

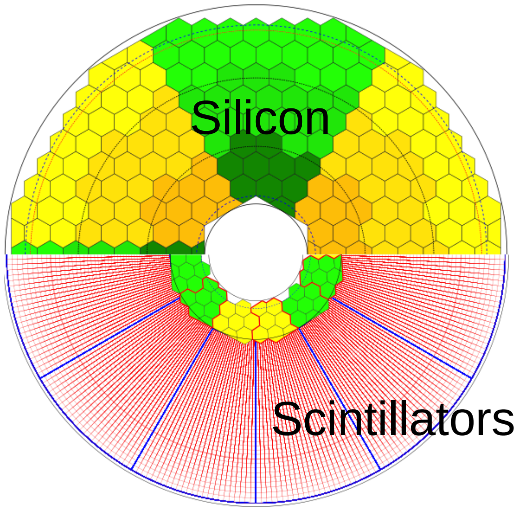






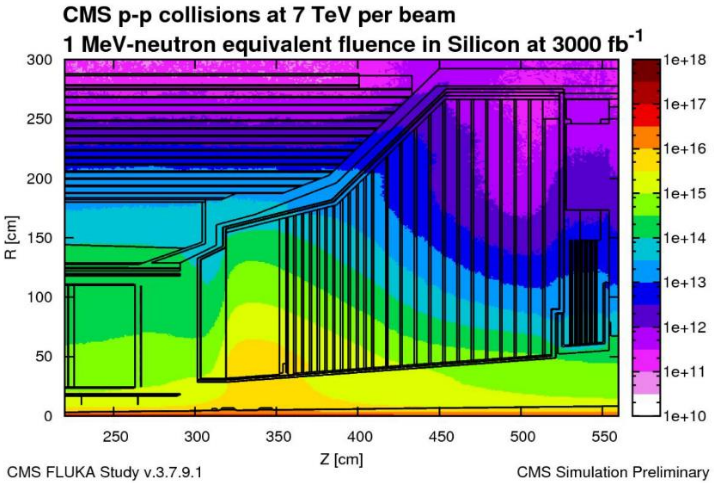
Cassettes

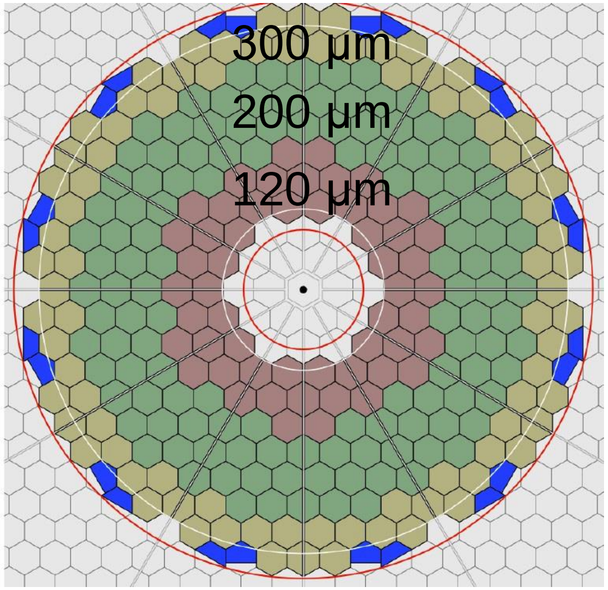




Radiation Hardness

- Fluence is n-dominated w.r.t. charged hadrons (90%/10%)
  - No validated irradiation model in TCAD up to fluence of 10^{16} n_{eq}
- Deployment of thinner sensors in the higher fluence regions of the calorimeter
  - improved charge collection
  - reduced leakage current
- Typical signals in calorimeter much higher than MIPs
  - MIP sensitivity needed for energy calibration (e.g. isolated muons)

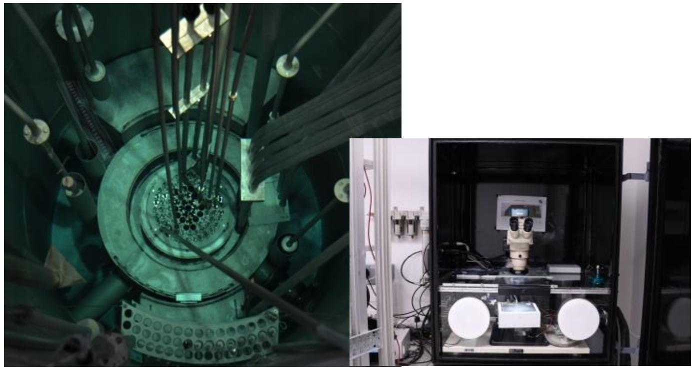


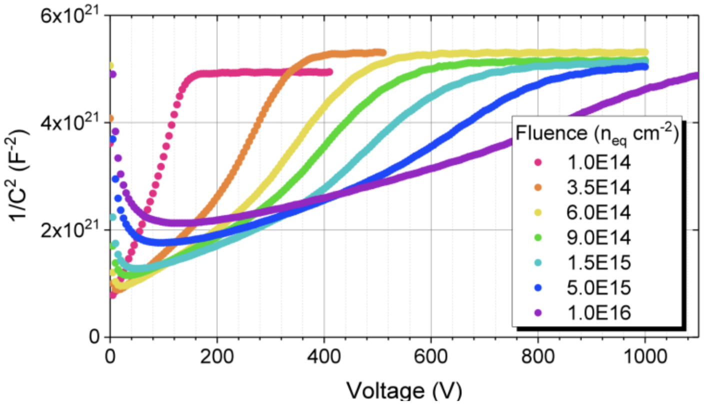


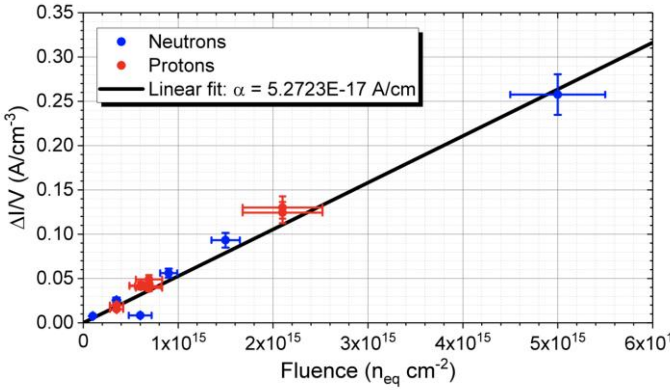
Sensor Irradiation

- Access to Triga Mark II nuclear reactor at TU Vienna
  - Similar to JSI Ljubljana, but only 2x10 cm wide samples possible (no larger irradiation channel
  - Distance to HEPHY 30 minutes by car or public transport

- Cold Chuck available at HEPHY for characterization of irradiated sensors
  - Self-made Peltier-based system
  - 6”, to be upgraded to 8” for HGCal
  - Used for irradiation studies of Infineon sensors
  - Study to understand E_{eff} as current has to be scaled to +20˚

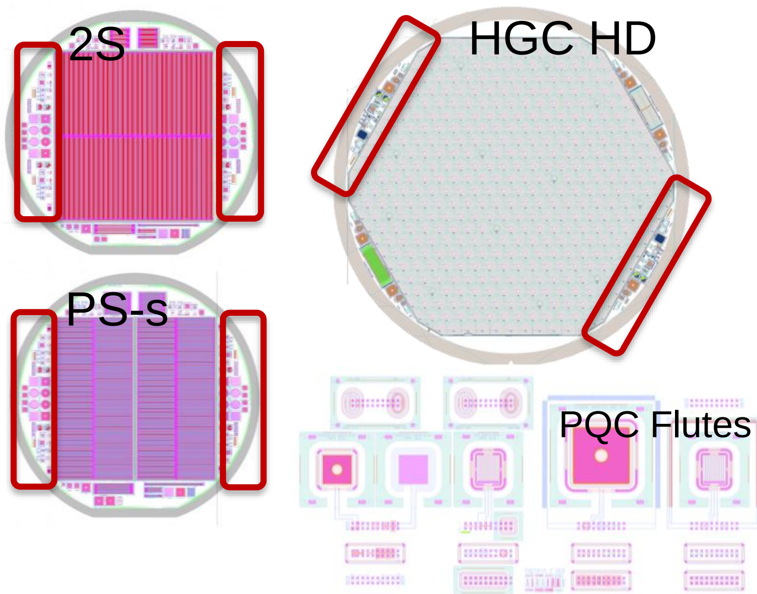


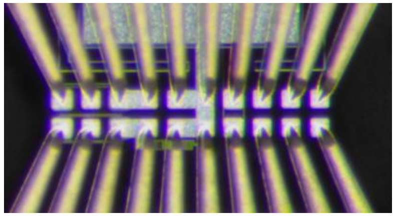


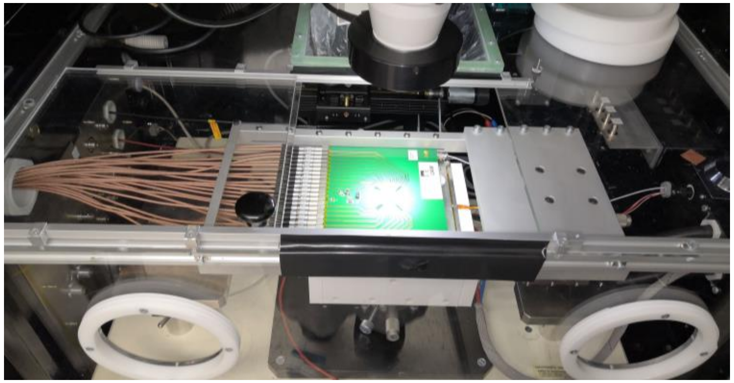


PQC: Tracker & HGCal

- **PQC** - **P**rocess **Q**uality **C**ontrol: Use test structures to asses the quality (stability) of the production process
  - 6” AC coupled (Tracker 2S and PS-s)
  - 6” DC coupled (Tracker PS-p)
  - 8” DC coupled (HGCal)
- Same set of test structures on all wafers
- Use standardised pattern of 20 connection pads: flute
  - Connect using standardised probe cards
  - Use switching to access all structures on one flute
  - Automatic movement to next flute



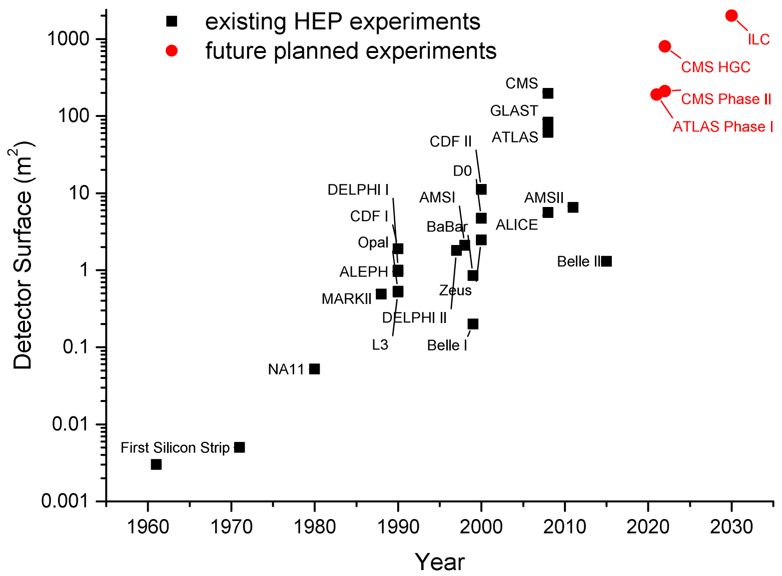




DD with Industry

Silicon is a key detector technology for future HEP experiments

- All LHC experiment upgrades will use Silicon detectors
- But Silicon detectors are a major cost driver

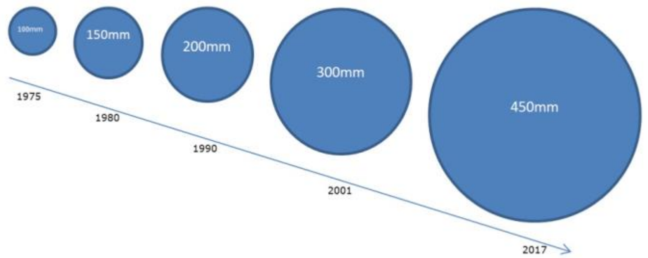


Silicon detector areas used in HEP

- From a few cm² at NA11 up to 200 m² (CMS)
- Tracker Upgrades of CMS and ATLAS (~200 m² each)
- Significant increase for CMS Highly Granular Calorimeter (HGCal) by ~ 600 m²

Wafer Sizes used for HEP detectors

- NA11 started with 2-3 inches (1980)
- Today 6 inch (150 mm) is standard (used by LHC Experiments)
  → Introduced in the industry in the 80ies



Producers

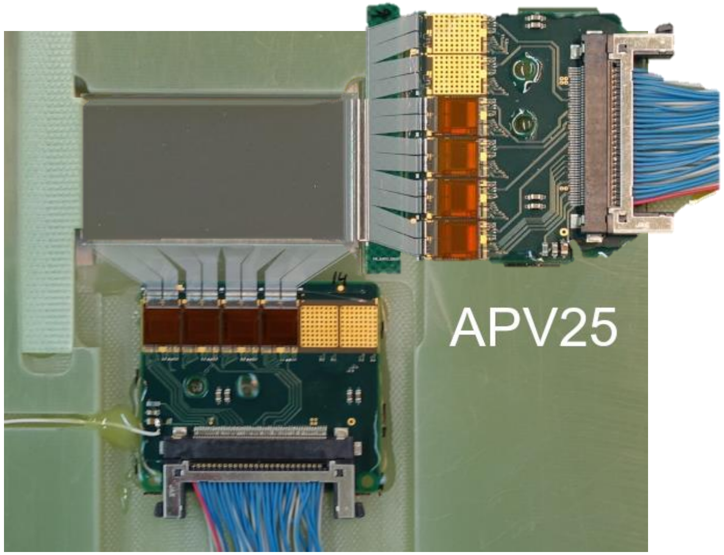
- Only one high-quality high-volume producer available during LHC construction

HAMAMATSU
PHOTON IS OUR BUSINESS

Ion Imaging Tracker

Currently using Double-sided strip sensors and FADC readout very similar to Belle-II SVD

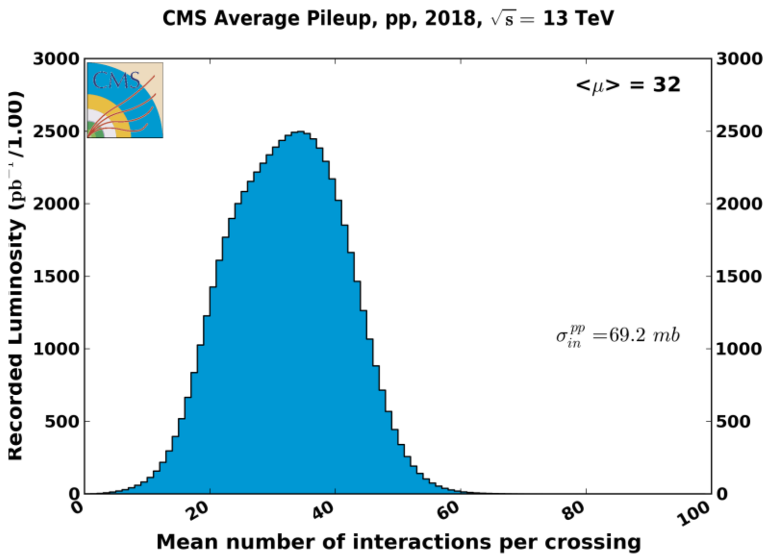
- Sensors:
  - Size: (2.56 × 5.12) cm^2
  - Thickness: 300 µm
  - Pitch 50 / 100 µm (Strips: 512)
- DAQ:
  - Readout chain APV → FADC → VME
  - Max. event rate: 500Hz
    → 90 minutes to record one image with 1E6 tracks
    → 11 days for full iCT 3D reconstruction (many images under different angles)
  - Planned short-term upgrade: Gbit Ethernet instead of VME readout to increase speed (will also implemented into SVD for speeding up local runs)

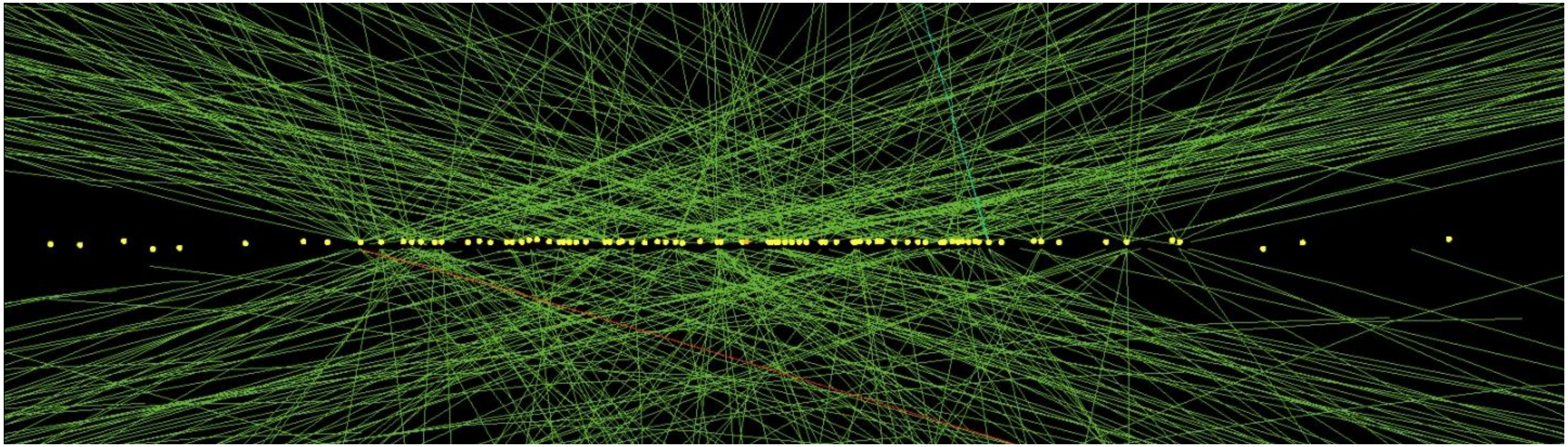


- Particle rates for clinical use (10^9 particles/s) are too high for both
  - detectors (ghost, pile-up) and
  - readout (trigger rate max 100kHz)

Tracking in 4D

- CMS currently sees 32 pp collisions per event (pile-up) in average
- CMS will suffer from a pile-up of ~200 collisions per event at HL-LHC
  - Too many ambiguities for vertexing and track reconstruction



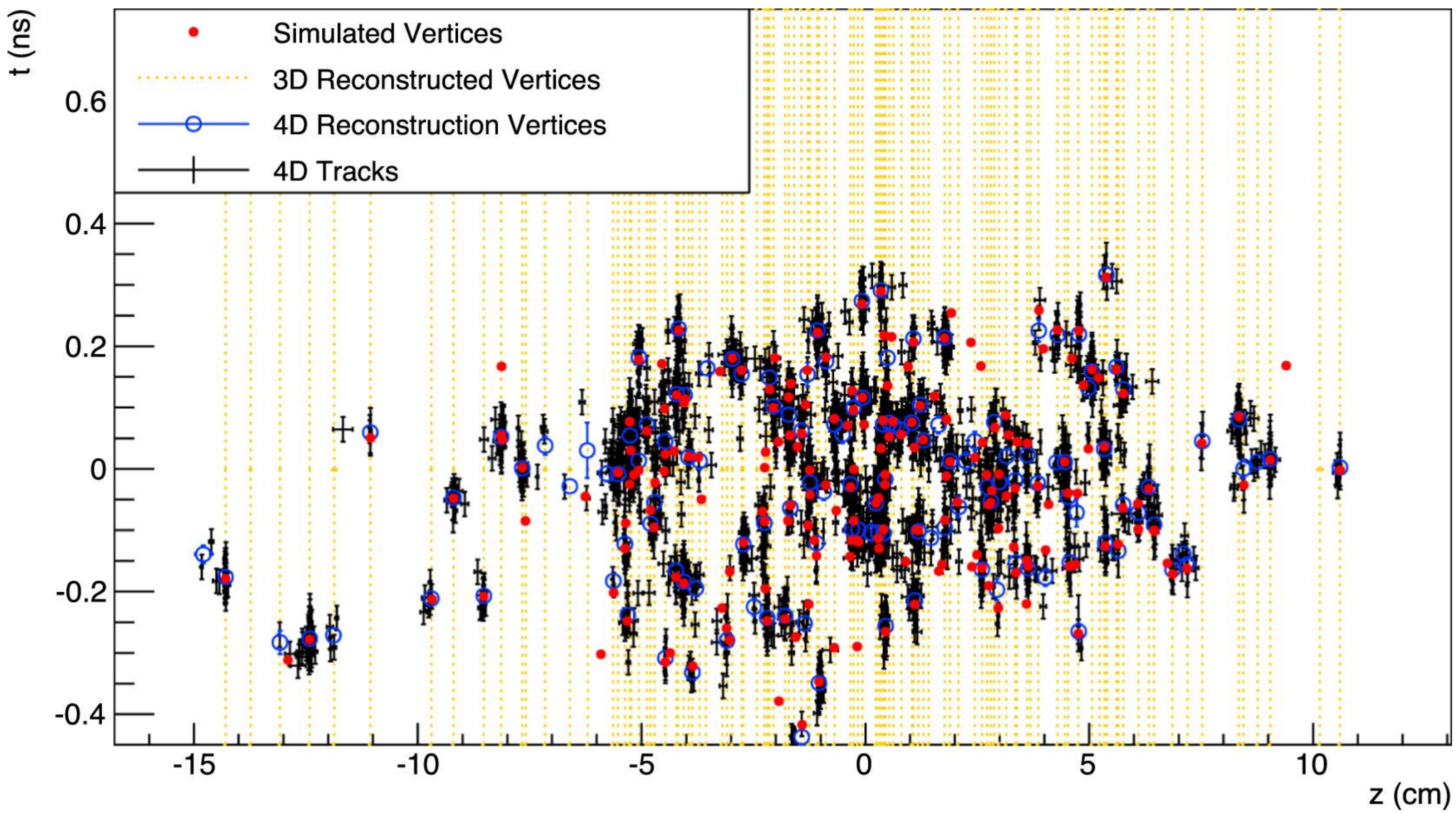


Real event with pile-up of 78 in CMS

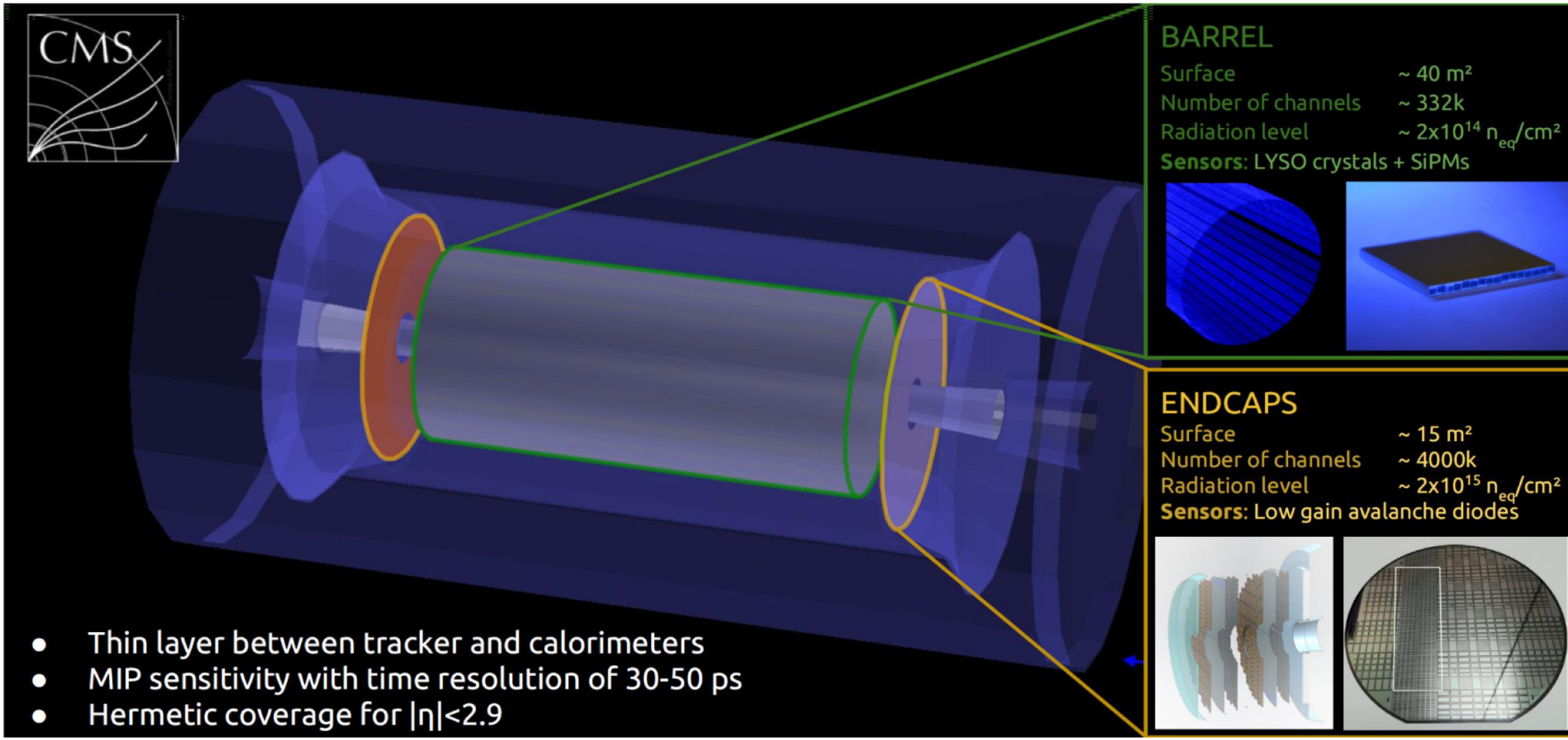
Tracking in 4D

- „Tracking in 4D“ allows to reduce pile-up of HL-LHC area to current levels

Simulation of pile-up of 200 and 30ps timing resolution of MTD:

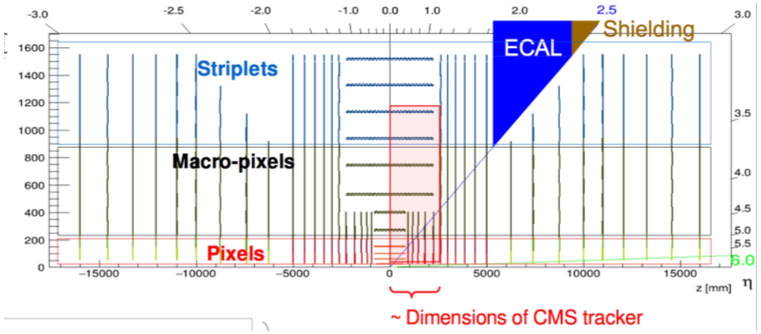


Tracking in 4D

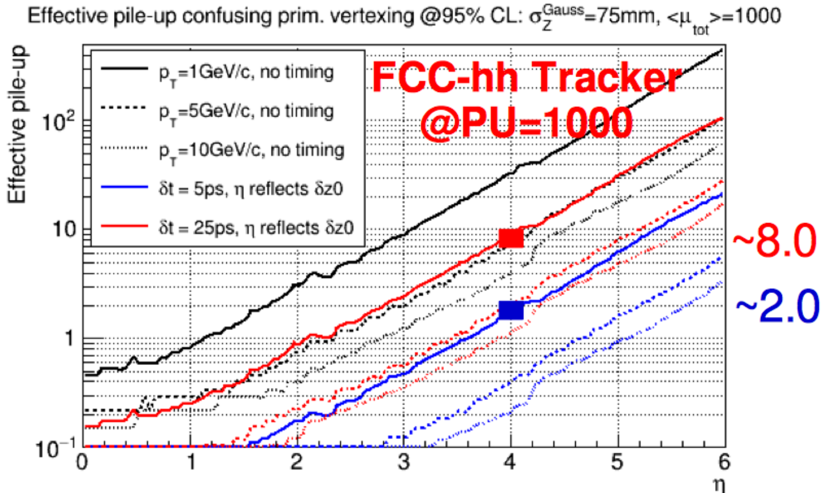


Future Circular Collider

- Circular collider with 80-100 km circumference
  - Different flavors: FCC-ee, FCC-eh, FCC-hh
- Detector concepts: scaled versions of ATLAS and CMS
  - Forward detectors up to η<6
  - Tremendous particle fluence of ~6×10^{17} n_{eq} cm^{-2} & TID ~0.4GGy → **ultra-high radiation tolerant detectors**
  - Pile up of 1000 mitigated by timing → **ultra-fast detectors**



Z.Drásal, Vertex 2017 Asturias Spain



Z.Drásal, Vertex 2017 Asturias Spain

DMAPS (HV/HR-CMOS)

Depleted Monolithic Active Pixel Sensors became available due to availability of:

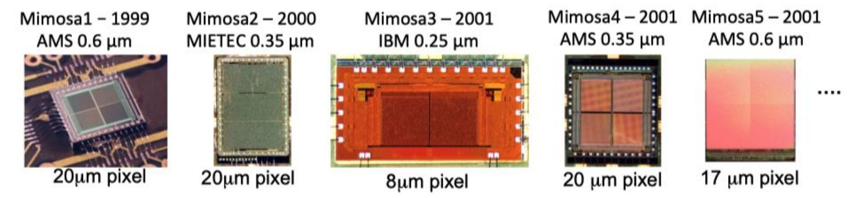
- HV processes in CMOS foundries
- high resistivity bulk material
- At a couple of foundries

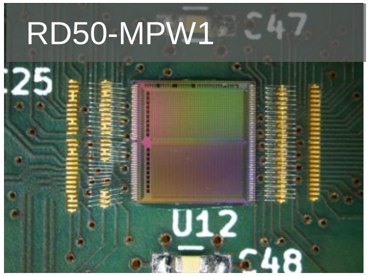
Examples:

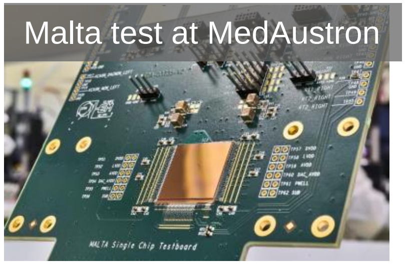
- **MAPS:** Mimosa Series
  - Quite old, charge collection due diffusion only
  - Different foundries and processes
- **DMAPS:** *ALPIDE, MALTA* and *Monopix*
  - TowerJazz Imaging process, 6 metal layers, small (180 nm) feature size, deep p-well
  - Process modified to optimize charge collection
  - RD50 Lfoundry and others

Still R&D issues to solve. E.g.:

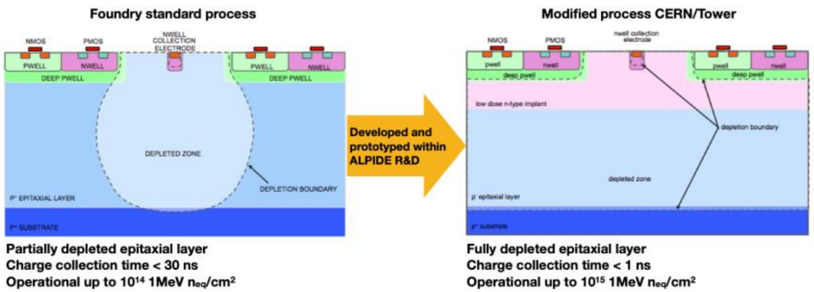
- Backplane metallization, biasing
- Radiation hardness
- Large sensors (stitching)
- Thin, flexible silicon







Modified Towerjazz process:



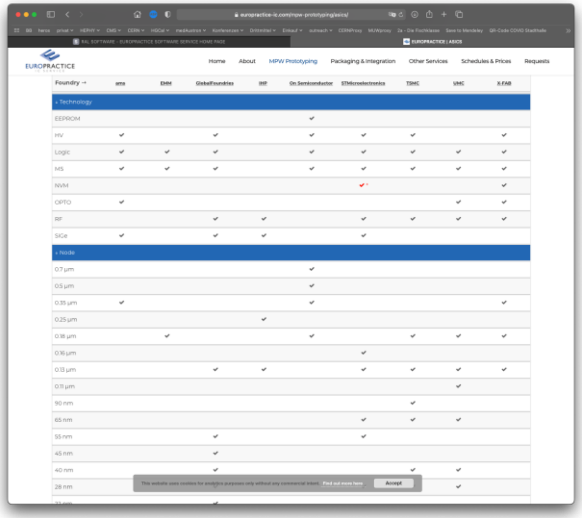
Access to Foundries and Tools

Demand of detectors/chips for HEP still vanishingly small compared to big industry

- Access through and help by proxies (Europratice, CERN,..) mandatory

Europractice IC initiative:

- Software services
  - Provides all necessary software tools for ASIC / FPGA development, chip simulation, verification, versioning (Cadence,…)
  - http://www.europractice.stfc.ac.uk/
- Foundry access
  - Multi-project wafer runs organized by Europractice: cost-effective way for prototyping
  - https://europractice-ic.com/



Different other foundry/process options:

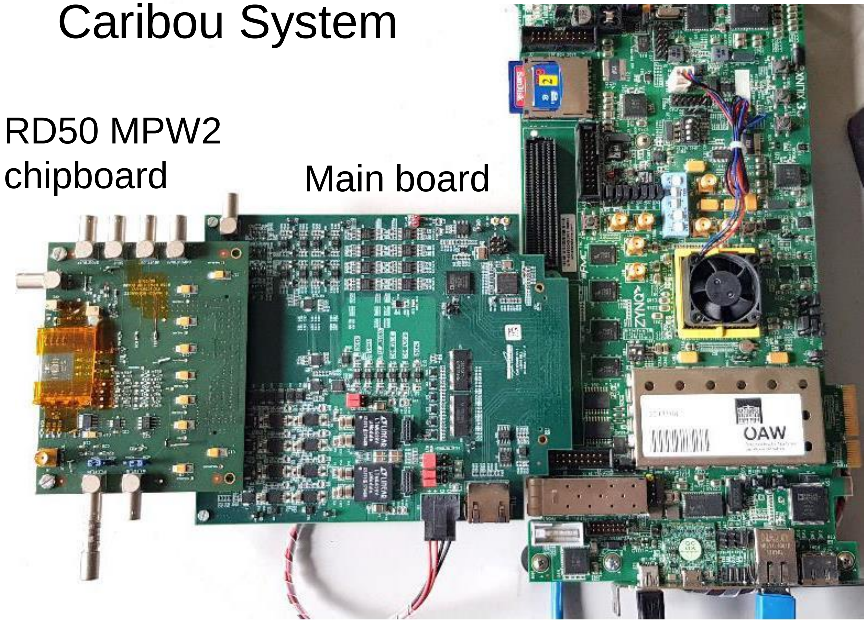
- TSMC 65nm via CERN frame contract
- STM, ONSemi, AMS,.. via CMP https://mycmp.fr/

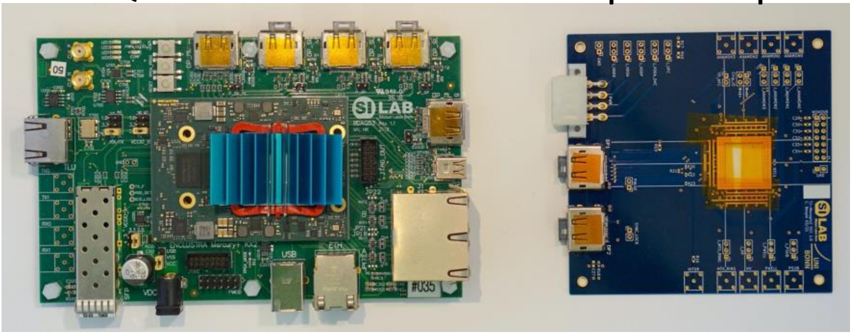
Hardware for Prototype tests

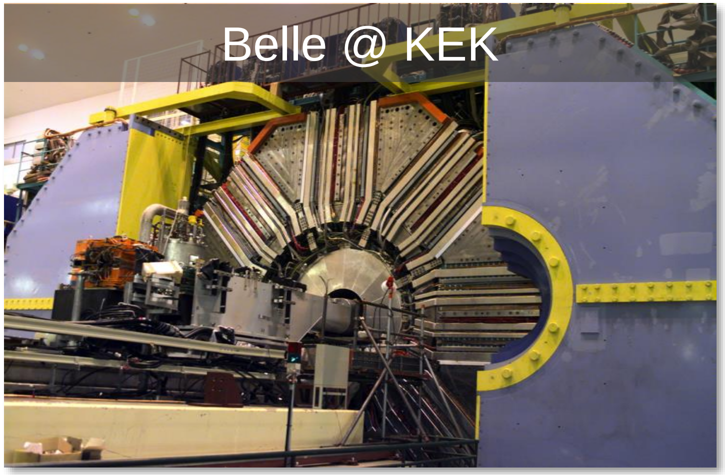
Typical setup consists of:

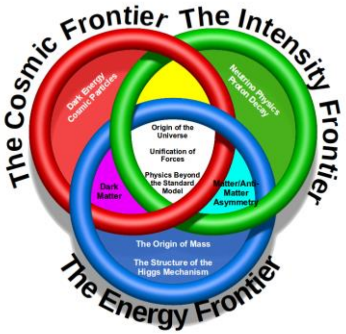
- FPGA Evaluation board
  - Xilinx, Trenz, Enclustra
- ASIC-specific chip board
- Custom FPGA firmware written in VHDL/Verilog
- SoC-Mini Linux distribution
- Typically an ethernet connection to PC

- Setup used for
  - R&D, debugging
  - lab measurements
  - beam tests at testbeam facilities, e.g. CERN, MedAustron





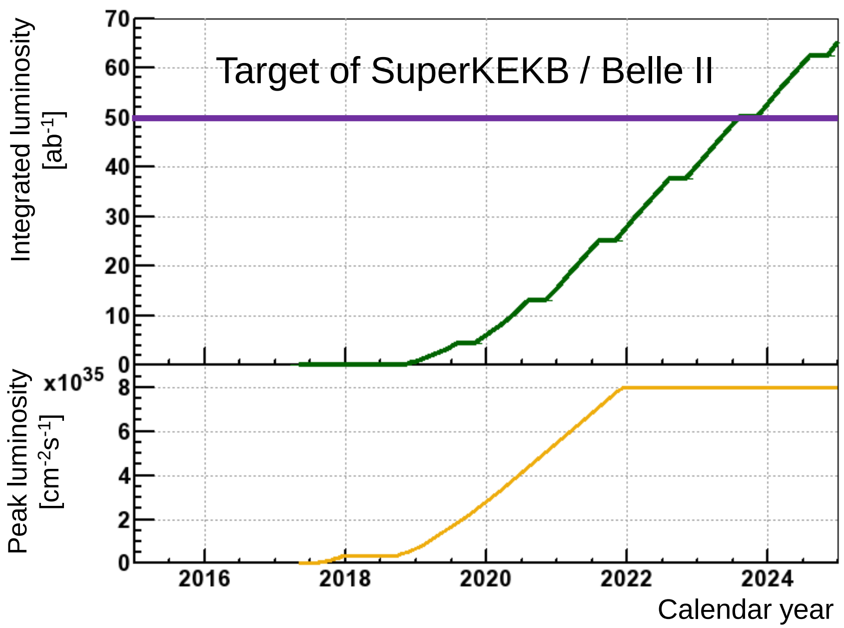


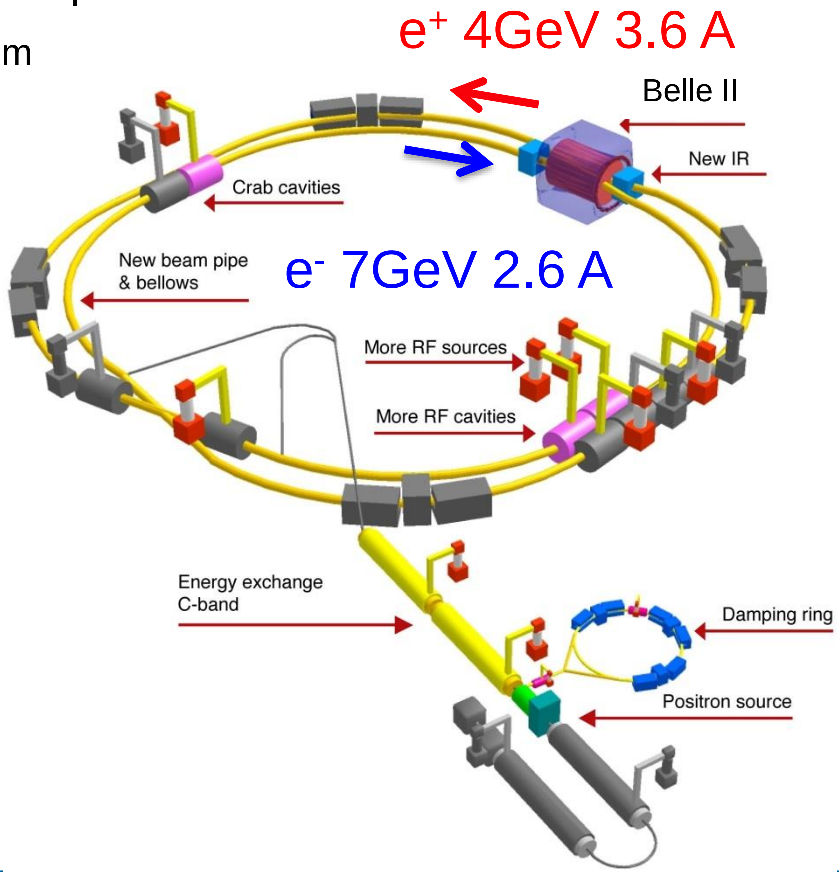


The Intensity Frontier

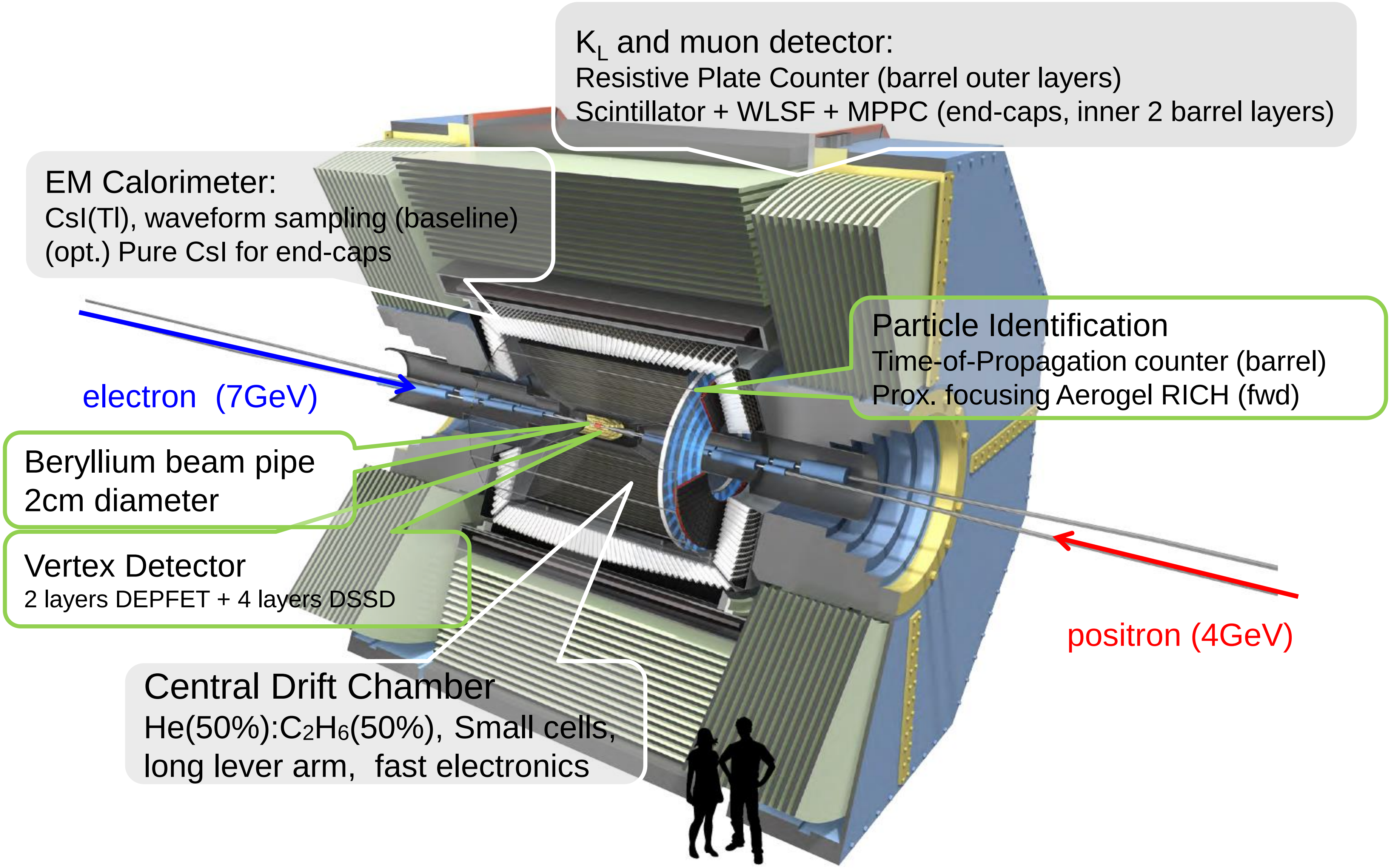
SuperKEKB / Belle II

- SuperKEKB: e^-/e^+ collider at KEK, Tsukuba, Japan → B factory
- 40-fold increase in peak luminosity to 8×10^{35} cm^{-2}s^{-1} → 1×10^{10} BB / year
- 50-fold increase in integrated luminosity until 2023 w.r.t. Belle
- Refurbishment of accelerator and detector required
  - Nano-beams with cross-sections of ~10 µm x 60 nm
  - 10 mm radius beam pipe at interaction region

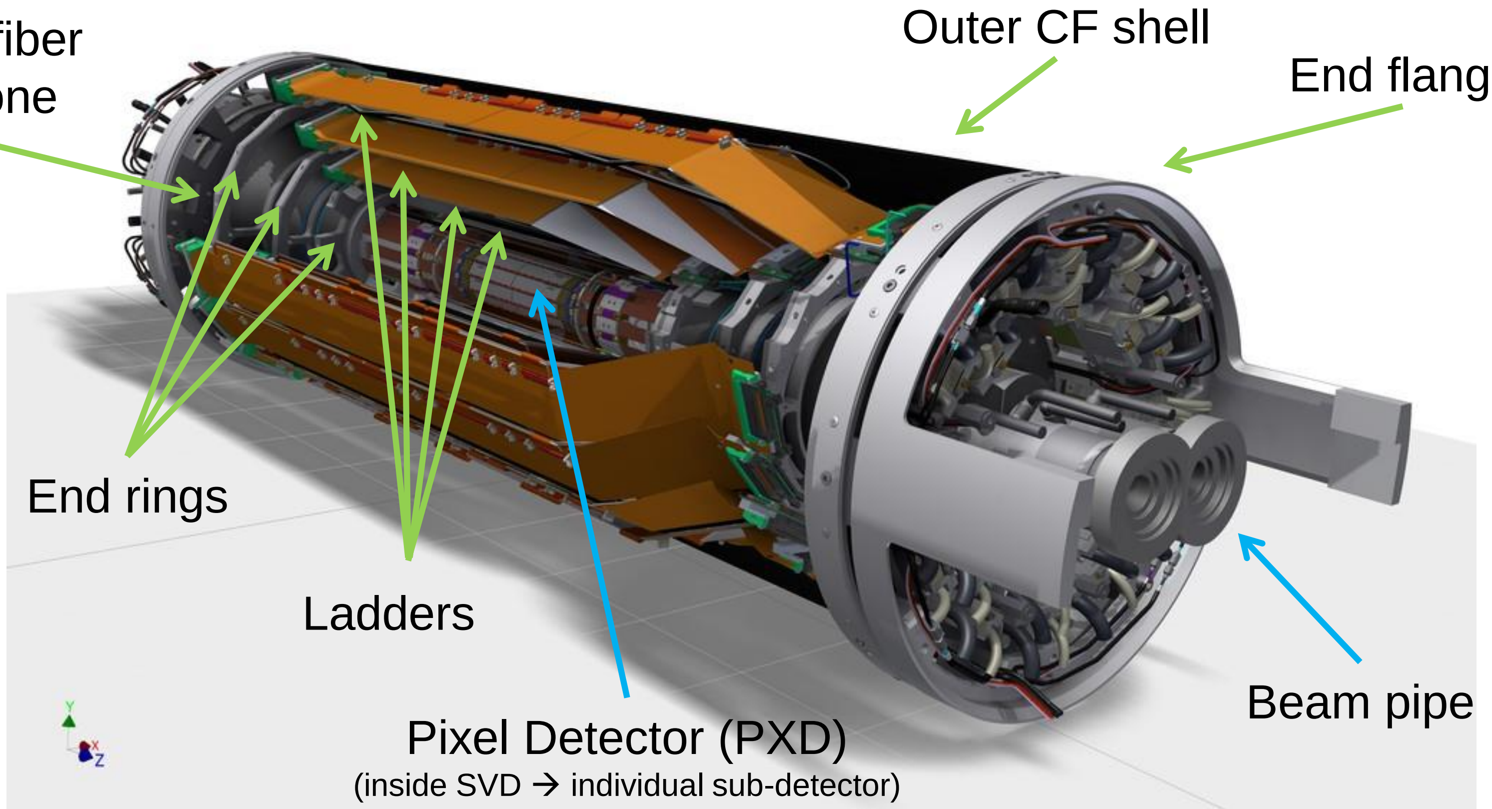




Belle II Experiment @ KEK

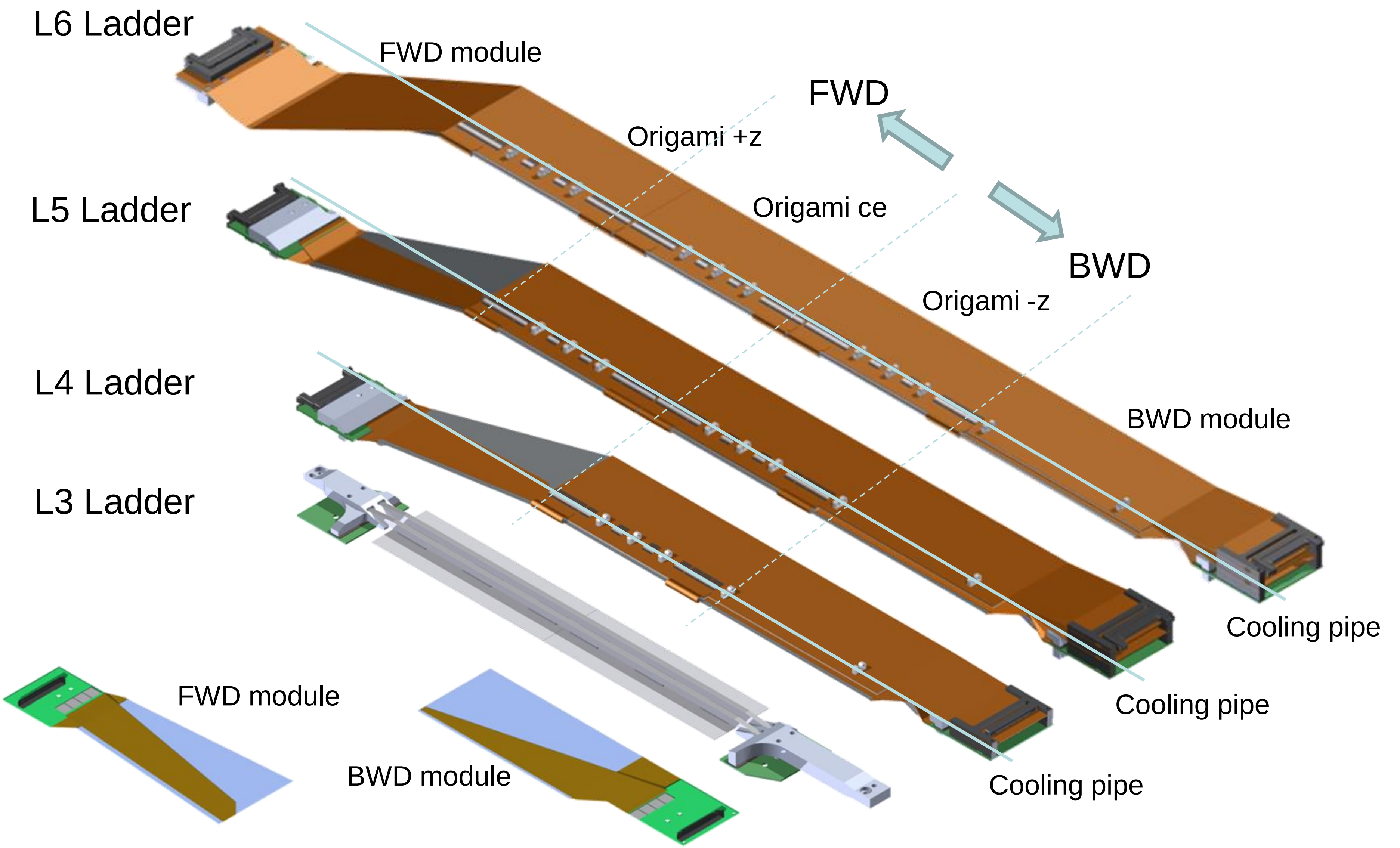


Belle II Silicon Vertex Detector



- Four layers of double sided silicon strip detectors (made from 6” wafers)
- Radii of SVD layers: 38 / 80 / 115 / 140 mm
- 2,3,4 or 5 sensors per ladder
- Belle II Vertex Detector (VXD) = SVD + PXD

SVD Ladder Design



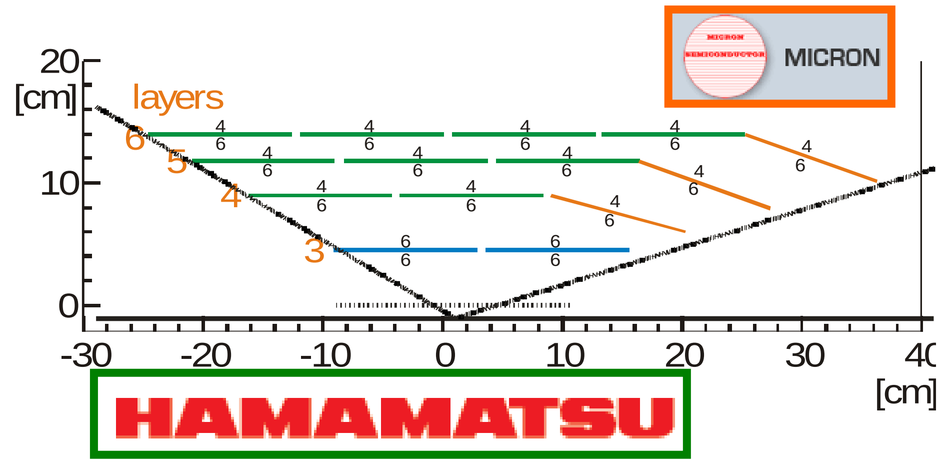
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

Double-sided strip sensors

ÖAW

Sensor Properties:

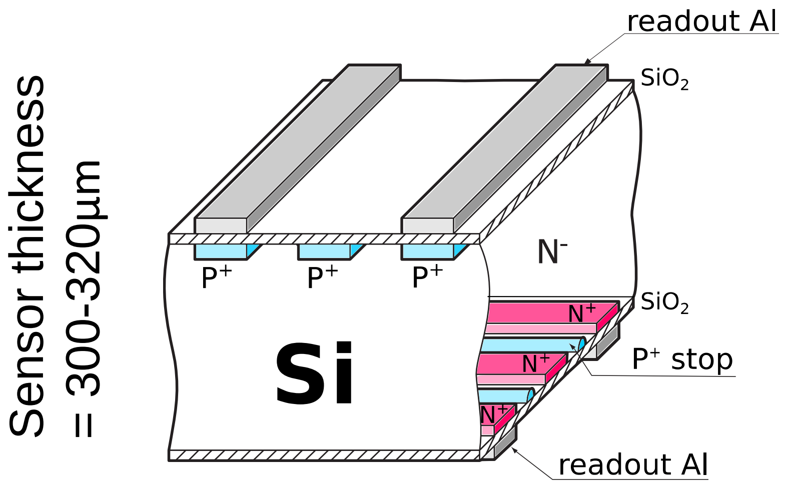
- Double-sided with perpendicular strips
- AC-coupled readout with poly-silicon resistor
- N-bulk, 300/320 micron thickness
- Three layouts only:
  - Rectangular small for layer 3 (HPK)
  - Rectangular large for layers 4-6 (HPK)
  - Trapezoidal for forward layers 4-6 (Micron)

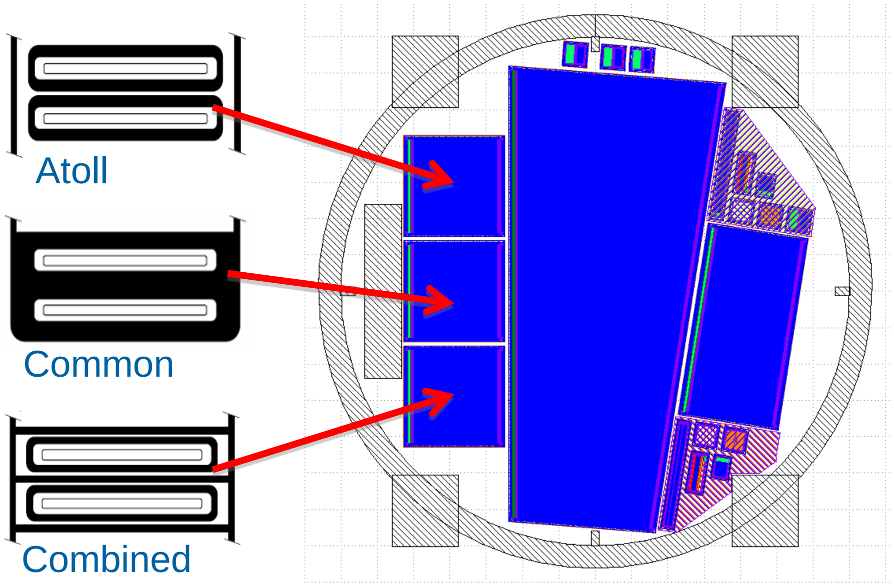


	Readout strips(p/Rϕ)	Readout strips(n/z)	Readout pitch (p/Rϕ)	Readout pitch(n/z)	Sensors # (+ spares)	Active area (mm²)
Large	768	512	75 µm	240 µm	120+18	122.90x57.72 =7029.88
Trapezoidal	768	512	50-75 µm	240 µm	38+6	122.76x(57.59+38.42)/2 =5893.09
Small	768	768	50 µm	160 µm	14+4	122.90x38.55 =4737.80

Sensors for Forward Region

- Trapezoidal sensor for forward region
- Designed completely in-house
  - Production at Micron Inc.
  - Testing again in-house
- Double sided with orthogonal strips
  - Special isolation measure necessary on ohmic side (p-stop)
  - Different p-stop layouts on test sensors
  - Testbeam and irradiation study to determine best structure

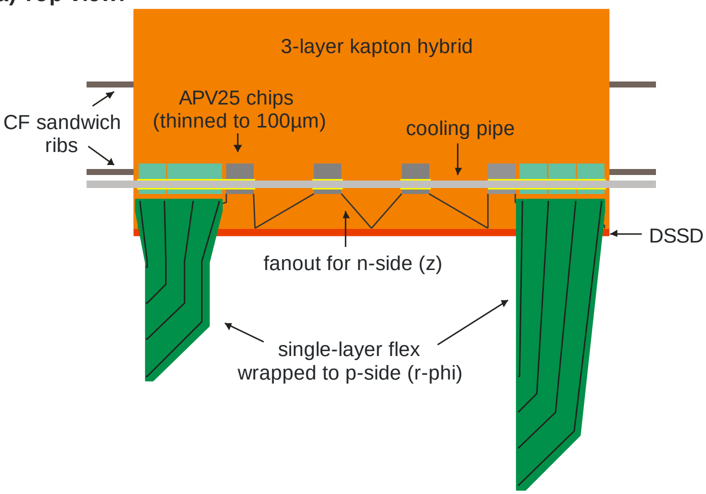


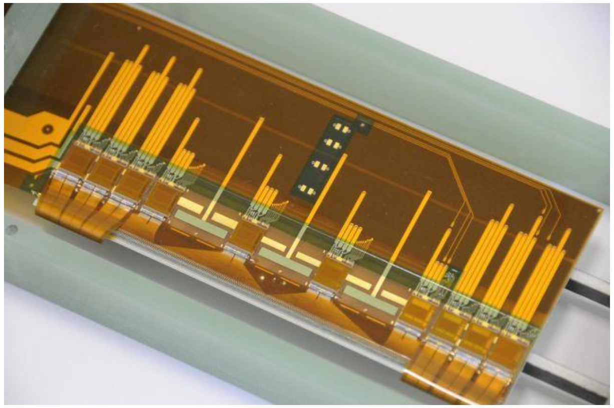


Detector Module Assembly

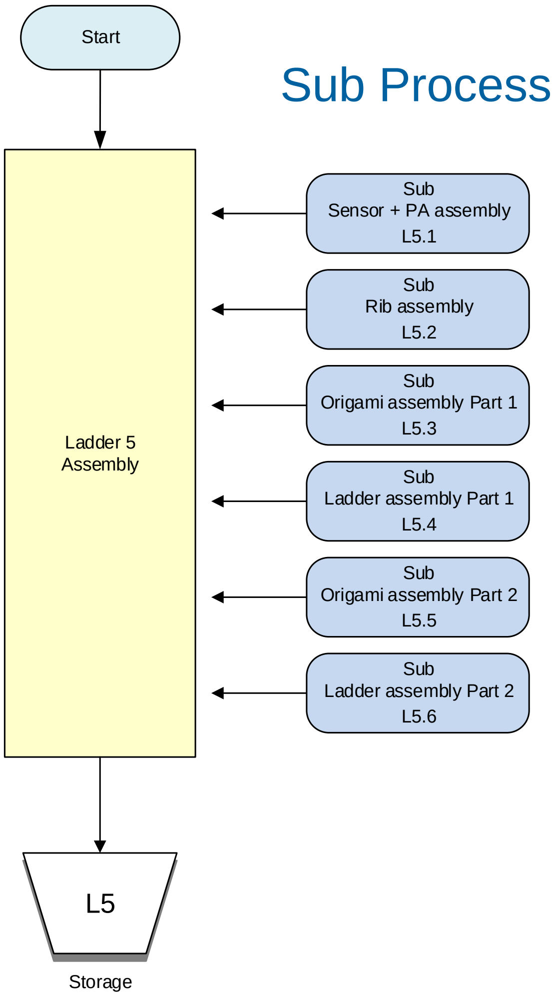
- **Design and construction** of the Belle II Silicon Vertex Detector
  - "Origami Module": Highly integrated and lightweight module
    - Carbon-fibre reinforced ribs
    - 6" DSSD, Kapton flex PCB
    - CO_2 cooling
    - Material budget 0.55 X_0 (averaged)
  - Design developed at HEPHY starting in 2008
  - Ladder assembly in-house finished 2017

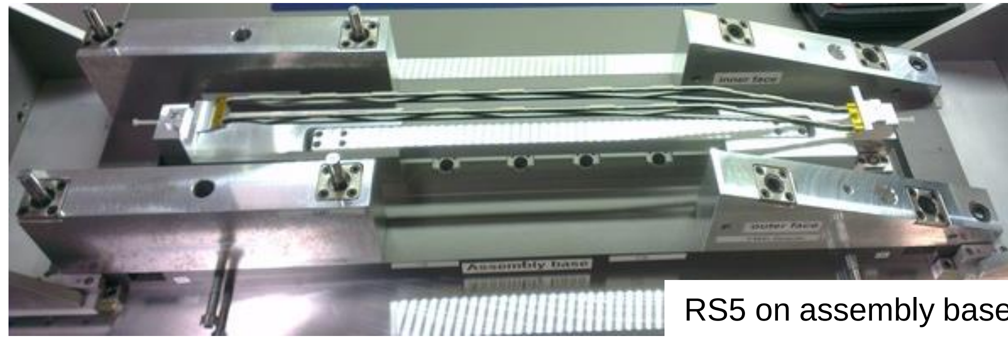
a) Top view:

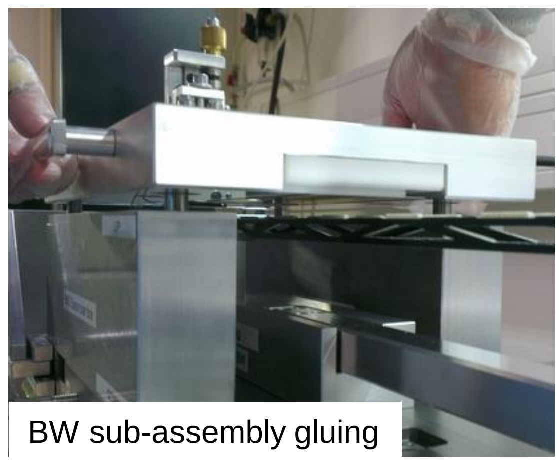




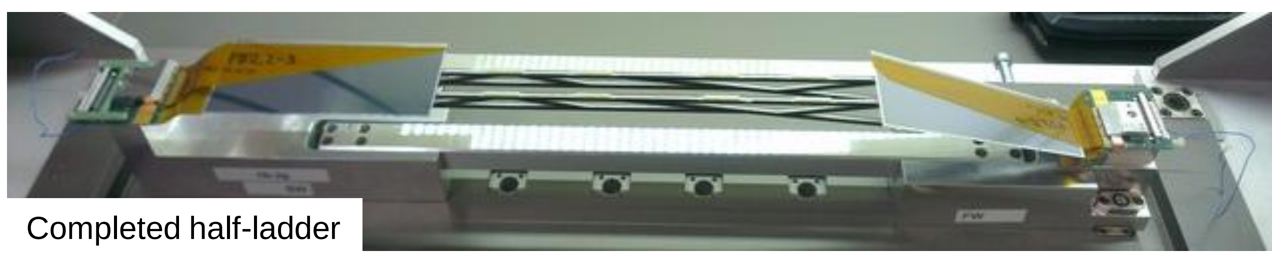
2015: Assembly process at HEPHY Clean room:




RS5 on assembly base

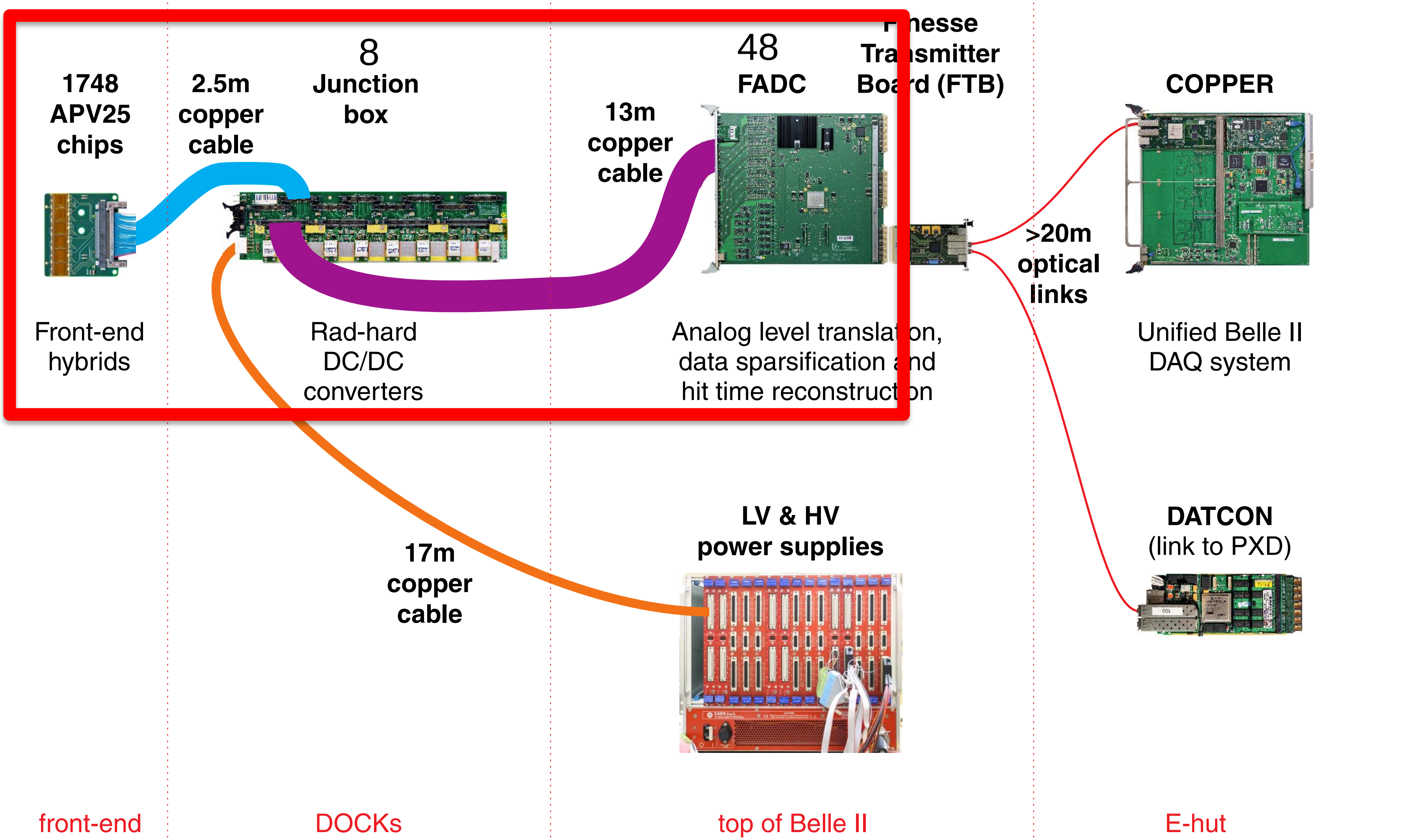

BW sub-assembly gluing


FW sub-assembly gluing


Completed half-ladder

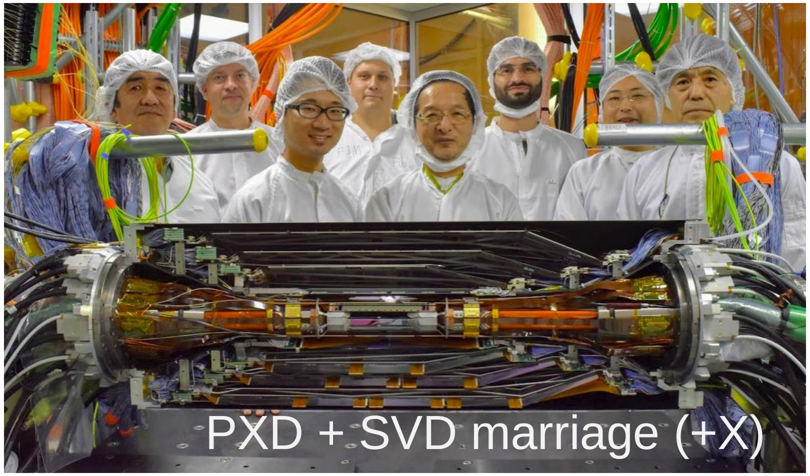
Belle II SVD Electronics

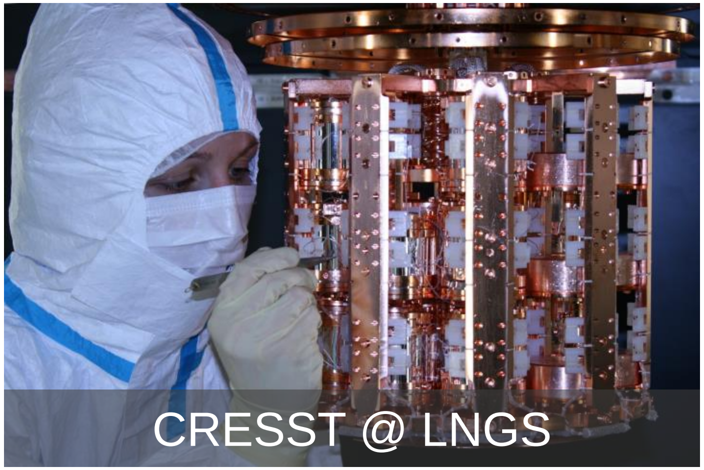
Belle II Electronics Chain:

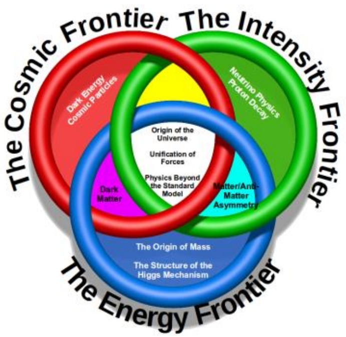


Belle II SVD – Activities and Status

- October 2018
  – Marriage of PXD+SVD = VXD
  – Commissioning of VXD
  – Outer cabling from dock boxes to FADC crates
- November 2018
  – Installation of VXD
  – Inner cabling between detector and dock boxes
- December 2018
  – Completion of cabling and services
  – Commissioning of installed Vertex Detector (VXD)





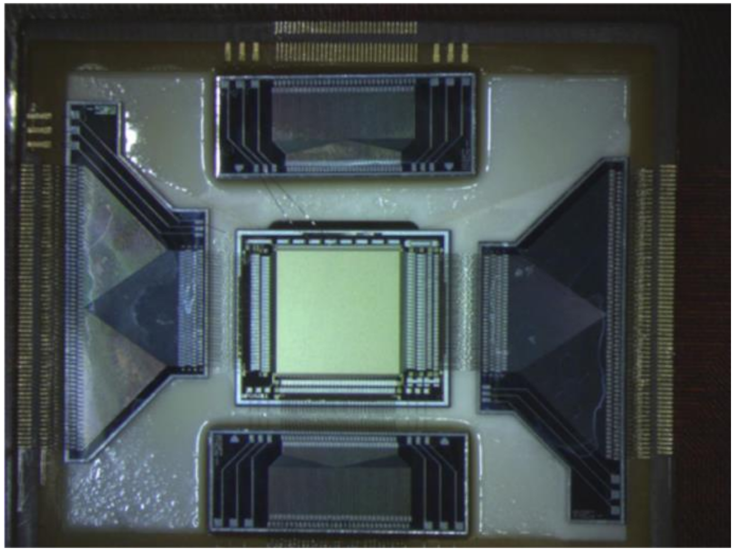


The Cosmic Frontier

Rare Event Searches

Working group on “Rare Event Searches” is synergetically working on these projects:

- DANAE: Search for very low-mass dark matter particles interacting with electrons
- CRESST III: Search for low-mass dark matter particles interacting with atomic nuclei
- COSINUS: Clarify the long-standing dark matter claim from DAMA
- NUCLEUS: Precisely measure coherent, elastic neutrino nucleus scattering (CEvNS)

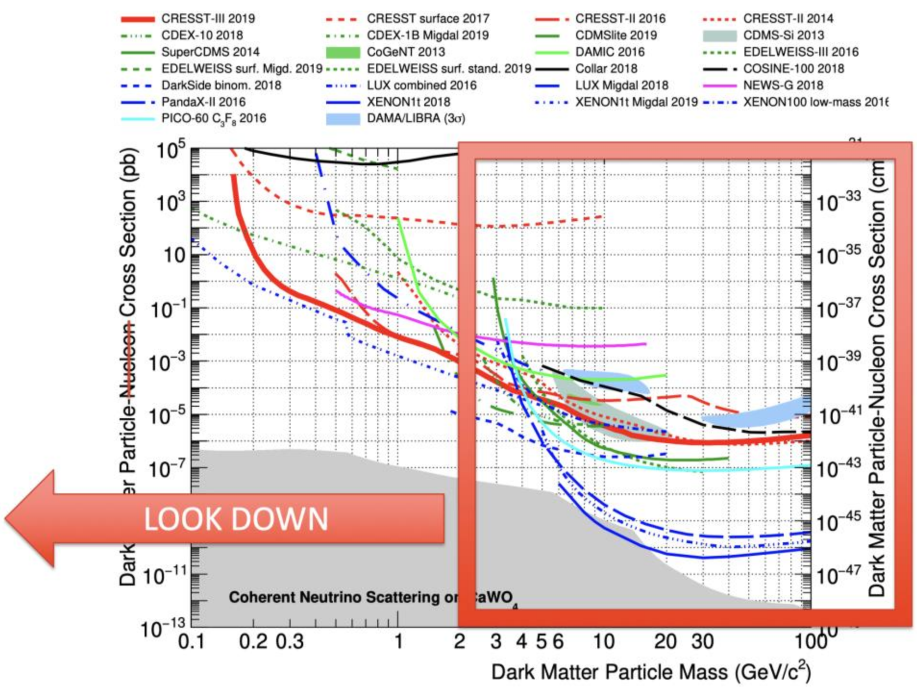


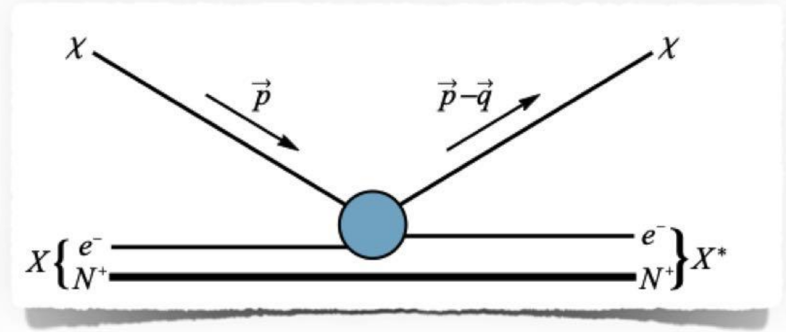
Synergy, more than a buzzword:

Experiment	Aim	Technology	Signal	Physics Case
DANAE	Search for very low-mass dark matter particles interacting with electrons	Silicon (DEPFET)	Electron recoil	Dark Matter
CRESST III	Search for low-mass dark matter particles interacting with atomic nuclei	Cryogenic	Nuclear recoil	
COSINUS	Clarify the long-standing dark matter claim from DAMA			
NUCLEUS	Precisely measure coherent, elastic neutrino nucleus scattering (CEvNS)			CEvNS

DANAE – Dark Matter Detection

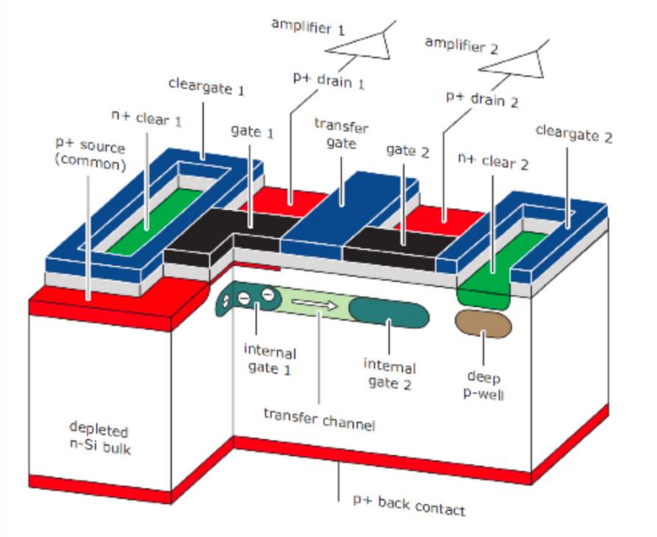
- Nothing found in classic WIMP windows
  - Also no candidate by SUSY
- dark matter detection using ionization signal from **Dark Matter-electron** scattering
  - inelastic nature of scattering and increased energy transfer possible due to lightness of electron

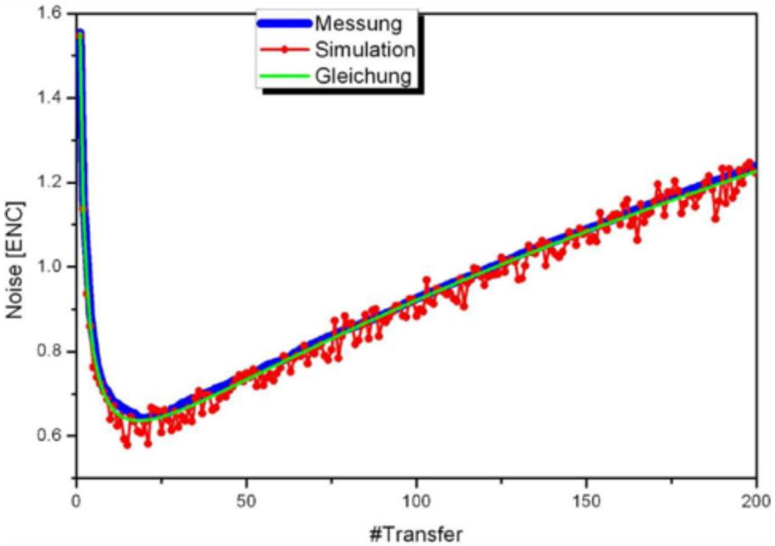




DANAE – Key Principle

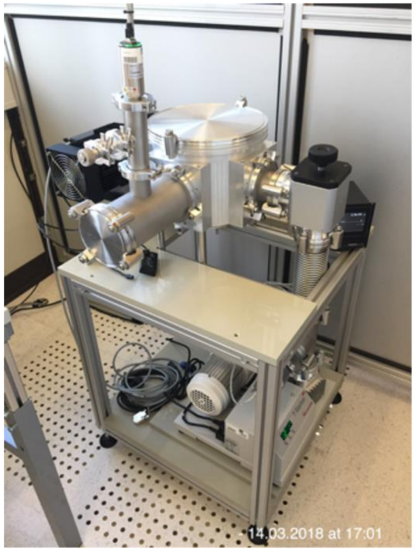
- DEPFET: DEPleted Field Effect Transistor
  - Charges are collected at internal gate → modulation of current in FET
  - Well-established concept (e.g. BELLE-II)
- RNDR-DEPFET
  - Modified to host two internal gates
  - Charge transfer between gates 1 & 2 with n transfers
  - Noise scales with 1/sqrt(n)
  - Minimum noise levels defined by leakage current

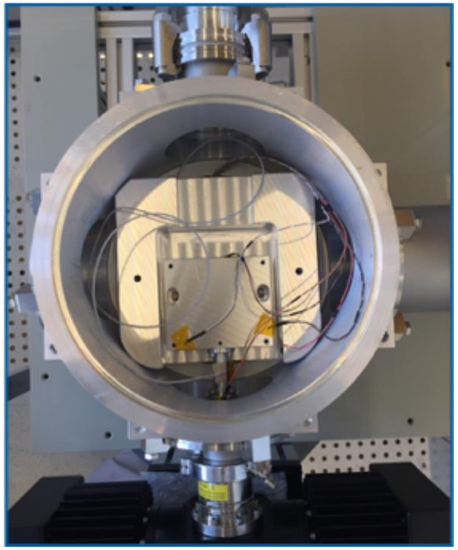


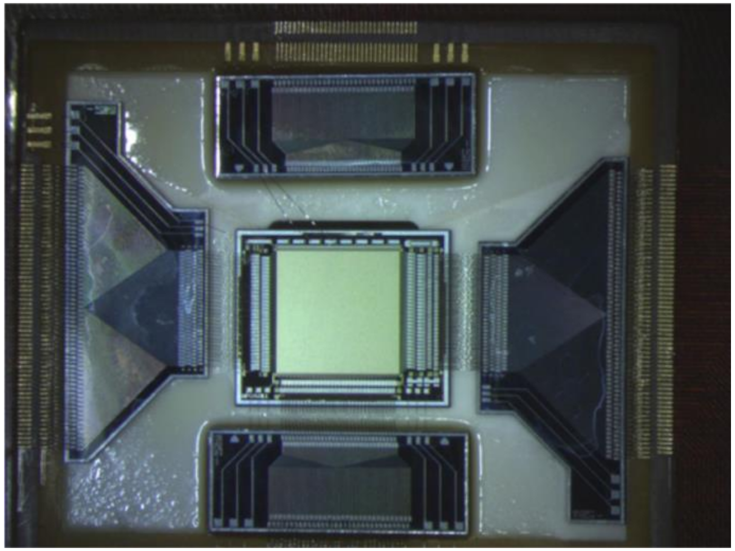


DANAE Implementation

- DANAE Test setup available at HLL Munich
  - Stirling cooler & vacuum chamber
  - To be transferred to Vienna
- DEPFET Sensor prototype detector matrix
  - 64x64 pixels á 75x75x450µm
  - Sensitive volume: 24mg

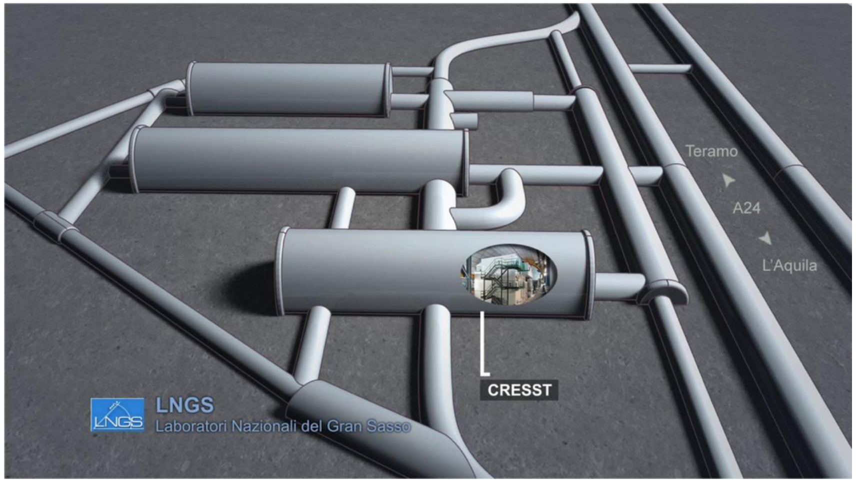






CRESST at LNGS Gran Sasso

- **C**ryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers
  - Direct detection of dark matter particles via their scattering off target nuclei



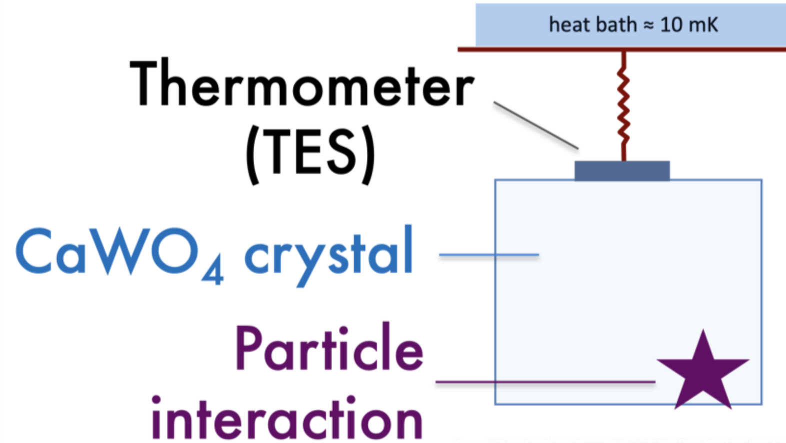
- **Scintillating $CaWO_4$** crystals as target operated as
  - Cryogenic calorimeter
  - Cryogenic light detector to detect scintillation light

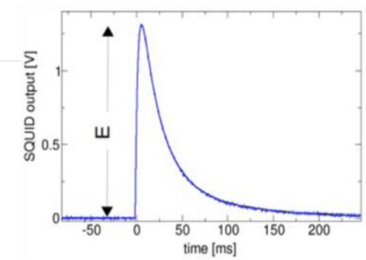
THE CRESST COLLABORATION

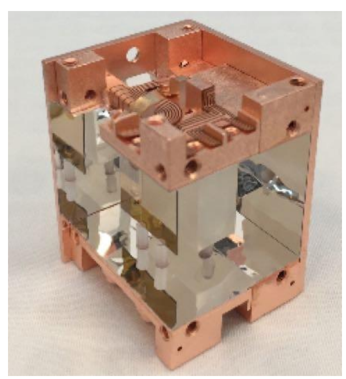
~50 scientists

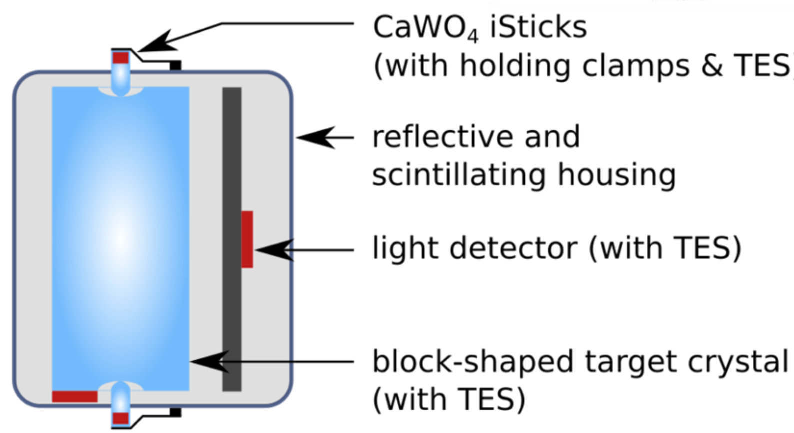
CRESST Detectors

- Cryogenic Detector with Phonons (>90%)
  - Transition Edge Sensor (SQUID-type)
  - Ultimate energy resolution is determined by how well you can measure T against thermodynamic fluctuations
- Scintillation light (few %)
  - Particle type dependent









CRRESST-III Timeline

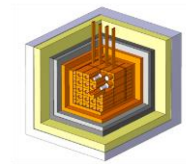
CRESST-III

- Run 1: 07/2016 – 02/2018
  - 30eV threshold reached
  - Leading sensitivity over one order of magnitude: 160MeV/c^2 – 1.8GeV/c^2
- Run 2: 12/2018 – 10/2019
  - Upgraded detector modules with dedicated hardware changes to understand unexplained rise
- Run 3: >01/2020
  - 2nd round with additional modifications

COSINUS

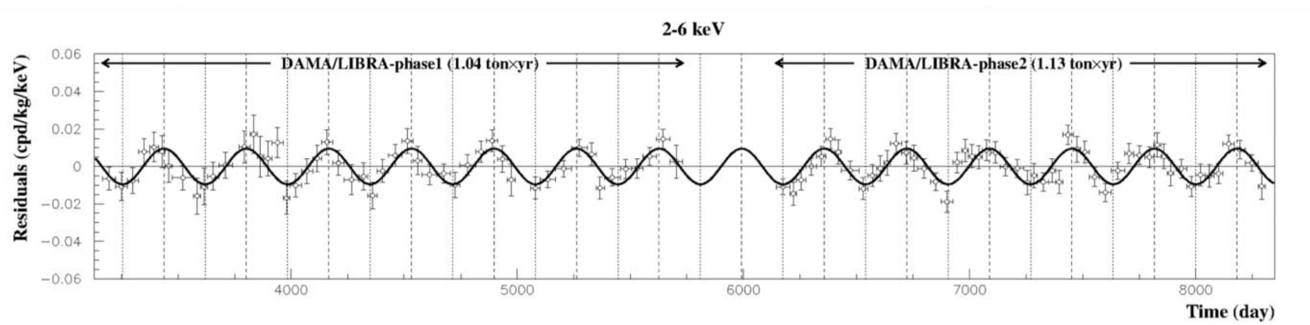
- COSINUS: Testing the DAMA signal with cryogenic NaI detectors
  - Re-use technology of CRESST
  - First data taking planned 2022
- DAMA/LIBRA claimed DM signal with statistical significance of 11.9σ

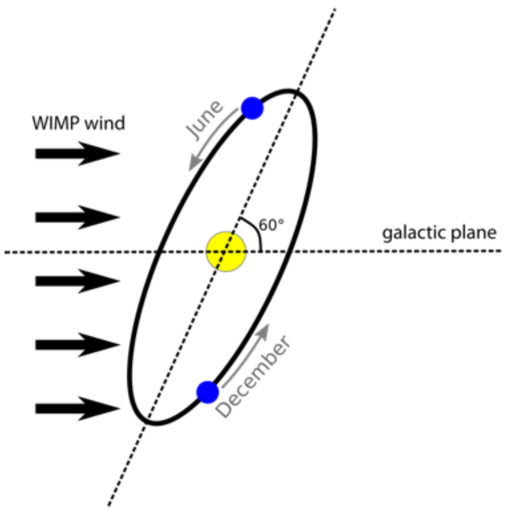
DAMA/LIBRA



Material	250kg of NaI (Tl)
Signal(s)	Light (PMTs)
Location	LNGS
β/γ-discrimination	no
Taking data	since 1996
Threshold	1keVee

Florian Reindl





Nucleus

- Study neutrino-induced nuclei recoil
  - Using reactor neutrinos at high flux
  - Challenges: recoil energies below 100eV → ultra-low thresholds required
- Nucleus collaboration: 5 institutes with ~40 members
- Scientific Goals:
  - Measurement of weak mixing angle
  - Approach neutrino floor