Detectors - the eyes of research

"Better Eyes" make the Difference

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

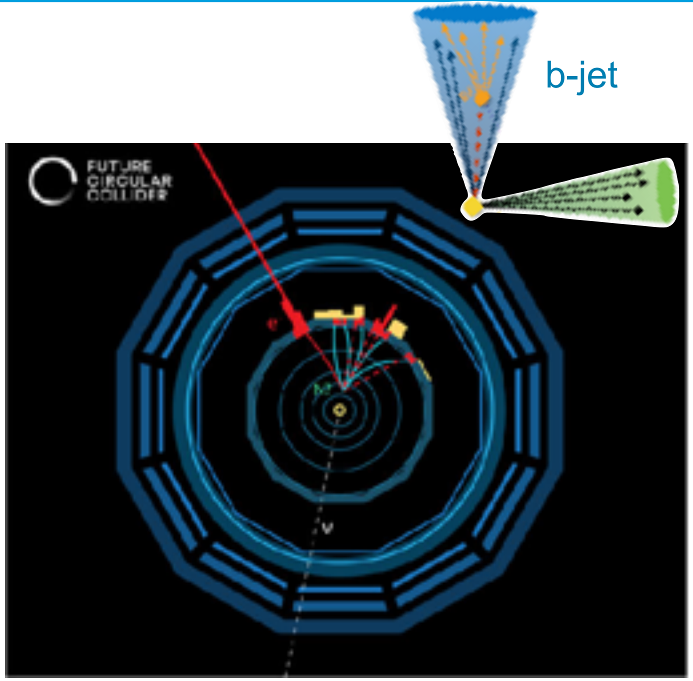
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

Prof. Dr. Erika Garutti
Universität Hamburg
13.06.2025

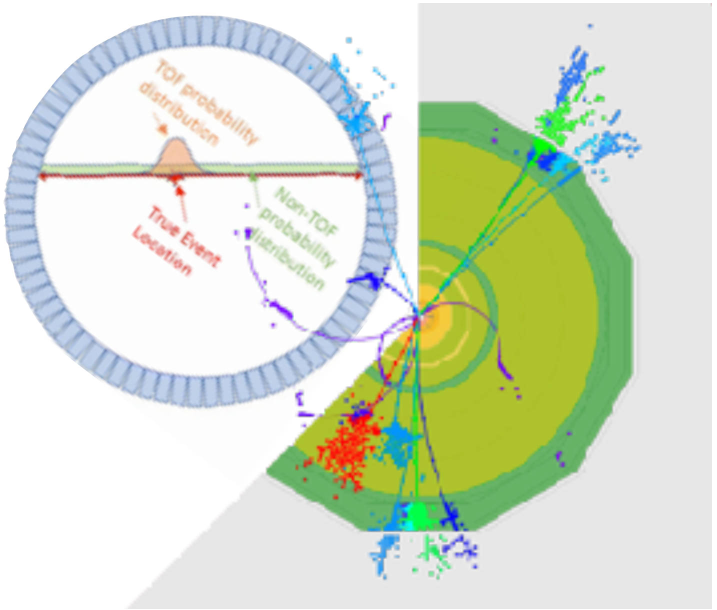
Technology Innovation Drives Discovery Potential

Micro



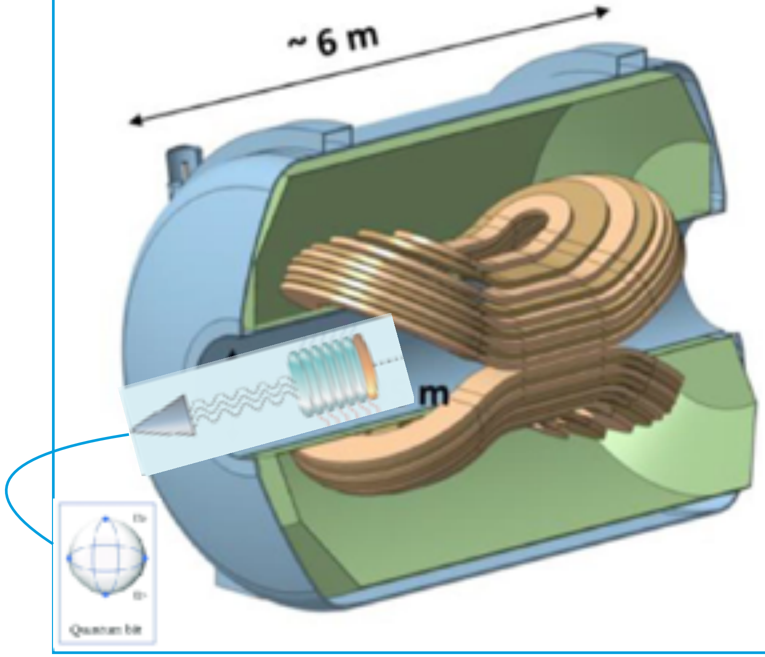
1 µm project

Pico



10 ps challenge

Quantum



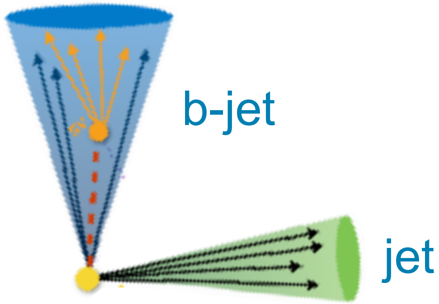
single photon detection frontier

Disclaimer: only covering my group activities, further covered at UHH gaseous detectors (K. Nikolopoulos), ML on FPGA for trigger (G. Kasieczka)

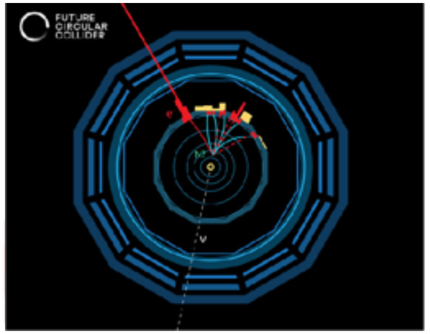
Micro

Micro - Spatial Resolution

High precision vertex reconstruction required for flavour tagging

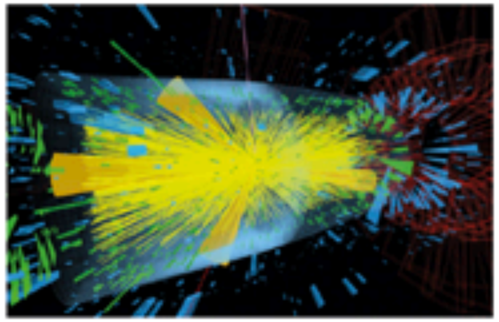


e+e- colliders, non-collider



dominated by
physics performance

hadron colliders



dominated by
running conditions

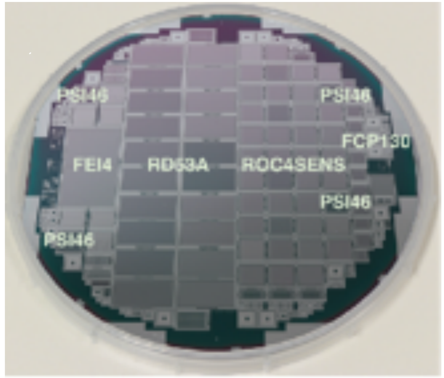
	Lepton Colliders	**(HL-) LHC (ATLAS/CMS)**
Material budget	< 1% X_0	10% X_0 * 2% for ALICE
Single-point resolution	≤ 3 μm	~ 15μm
Time resolution	~ ps – ns	25ns
Granularity	≤ 25 μm x 25 μm	50μm x 50μm
Radiation tolerance	< 10^{11} n_{eq} / cm^2	**O(10^{16} n_{eq} / cm^2)**
Max. hit rate	20 MHz / cm^2	2-4 GHz / cm^2 *)

Performance optimisation (Material budget, Single-point resolution, Time resolution, Granularity)

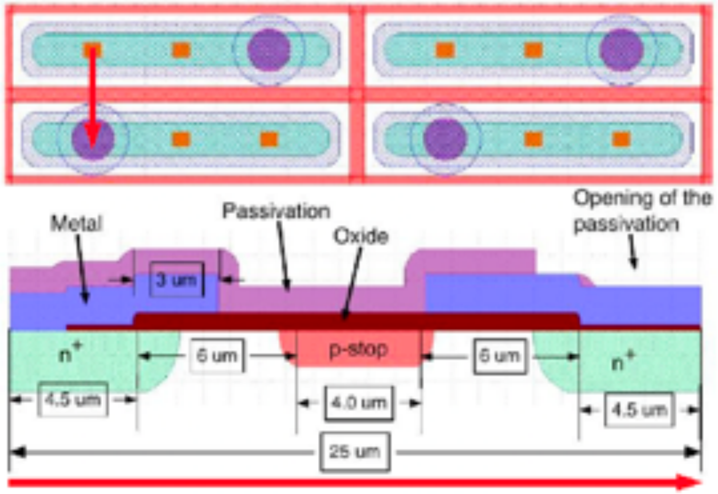
Survival optimisation (Radiation tolerance, Max. hit rate)

*) max. output rate for LHCb

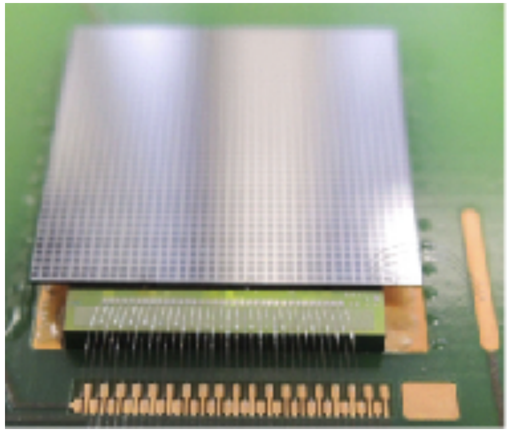
CMS Phase-II Pixel Detector



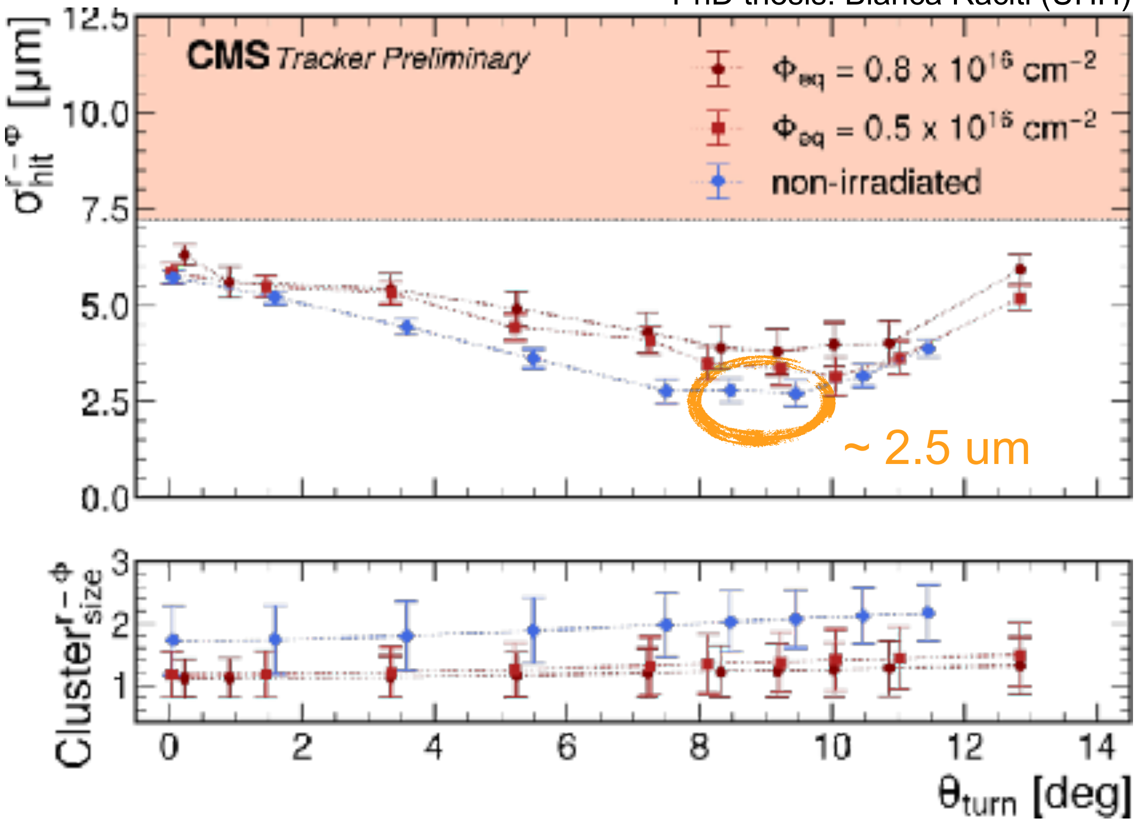
Top view 100x25 μm^2 default design



Cut image along red arrow



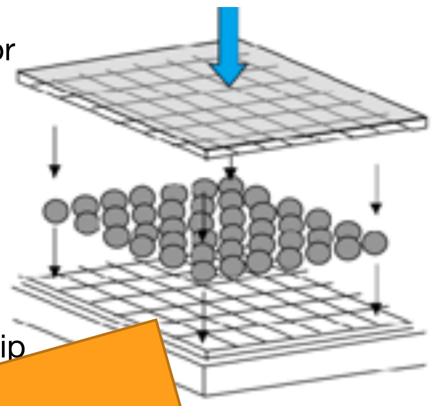
PhD thesis: Bianca Raciti (UHH)



UHH committed to produce 500 pixel modules for CMS pixel phase-II upgrade till 2027

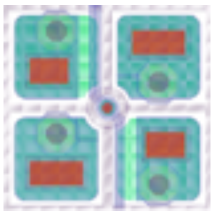
Lead by Georg Steinbrück, and the CMS team

Next: limits on small pixel size

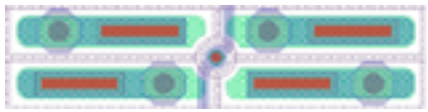


- Pixel size in hybrids is limited by **technology node** and **bonding techniques**
- 17 µm pixels successfully tested

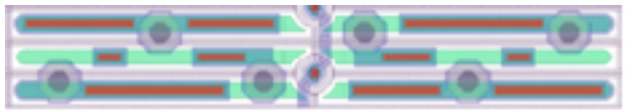
50 µm



"ATLAS" phase II pixel size

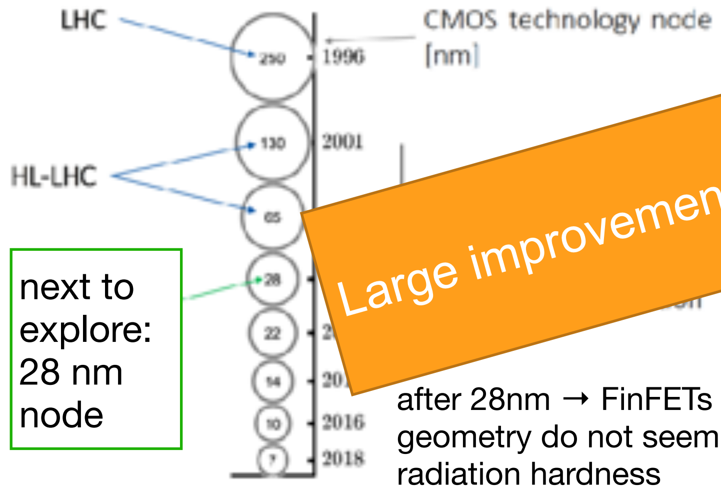


CMS phase II



Small pixels

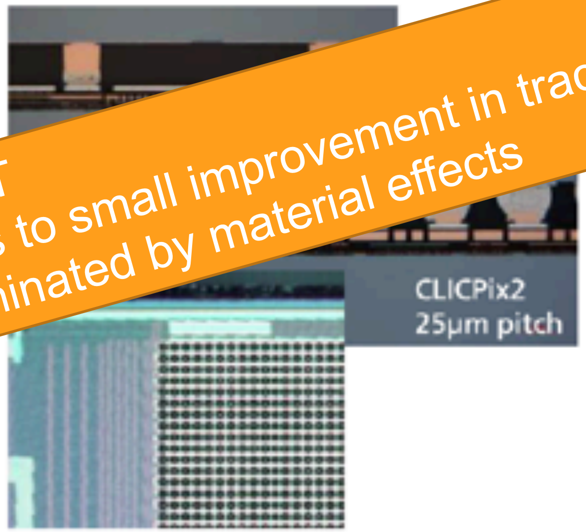
CMOS technology for readout chips



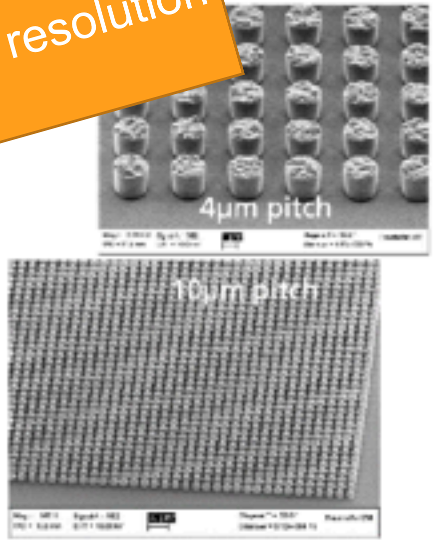
next to explore: 28 nm node

after 28nm → FinFETs have a completely different geometry do not seem so promising in terms of radiation hardness

BUT
Large improvement in hit resolution translates to small improvement in tracking resolution
Tracking resolution is dominated by material effects



µ-bumping:
Pitch 50…20µm
Bump size: 25…12µm
Material: Solder bumps, pillar bumps



Sub-10µ-pitch:
Pitch 10…2 µm
Bump size: 6…1µm
Material: pillar bumps, metal pins

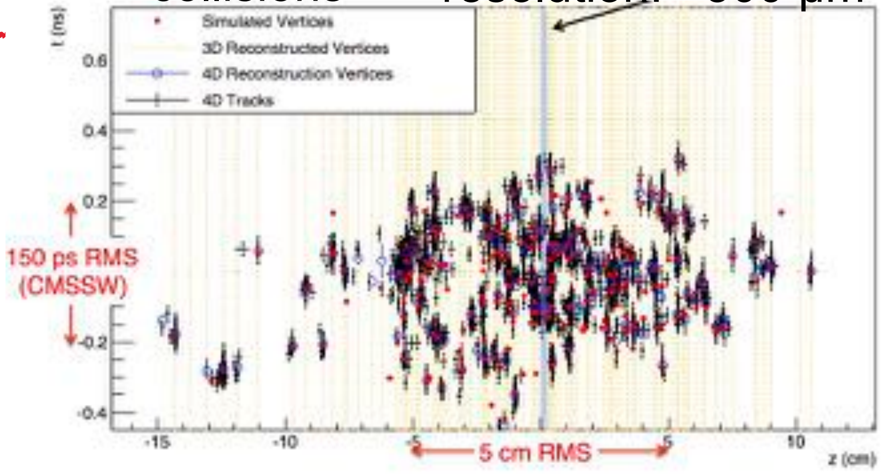
Pico

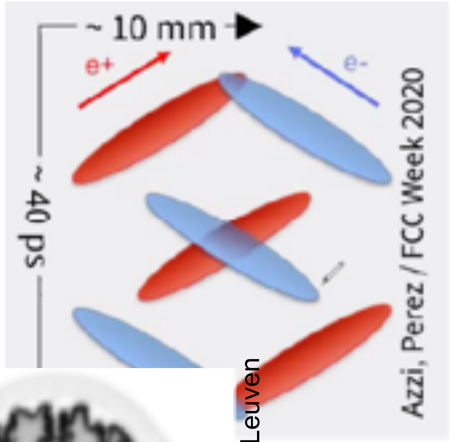
Pico - Time Resolution

- **Hadron collider:**
  - timing layers for pile-up mitigation $\sigma_t \sim 30$ ps
  - long-lived particle searches
- **Lepton collider / non-collider:**
  - PID, e.g. for heavy flavour, CP violation, heavy-ion physics
  - Chromatization: $\sqrt{s}$ depends on bunch position **$\sigma_t \sim 6$ ps**
- **Medical / societal applications:**
  - reconstruction-less PET **$\sigma_t \sim 10$ ps**
  - proton range monitoring in hadron therapy
- **LIDAR: laser imaging detection and ranging** $\sigma_t \sim 50$ ps

200 pileup collisions

longitudinal vtx resolution: ~300 µm





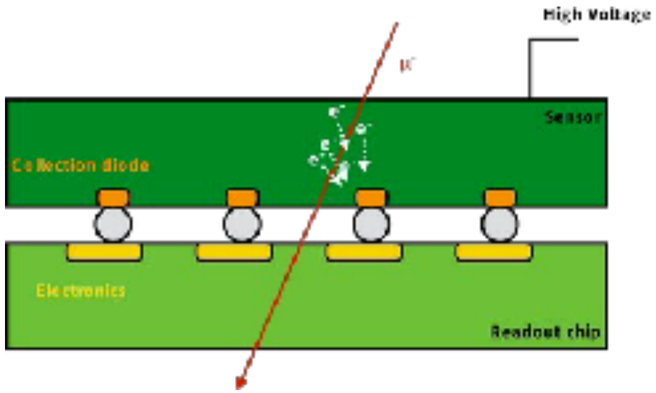
Johan Nuyts, University of Leuven

TOF back-projection with 10 ps CTR

Pico - Two Avenues

Charged Particle Detection

- Hybrid silicon detector

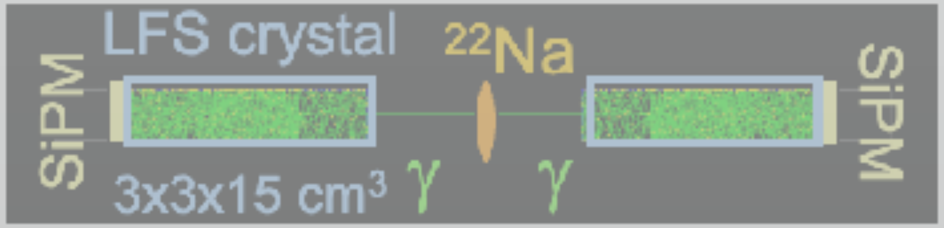


LGAD project within:

- DRD3
- Si-D Consortium

Photon Detection

- Silicon Photomultiplier coupled to an scintillators or Cherenkov emitter



SiPM project within:

- DRD6
- High-D-Calo Consortium

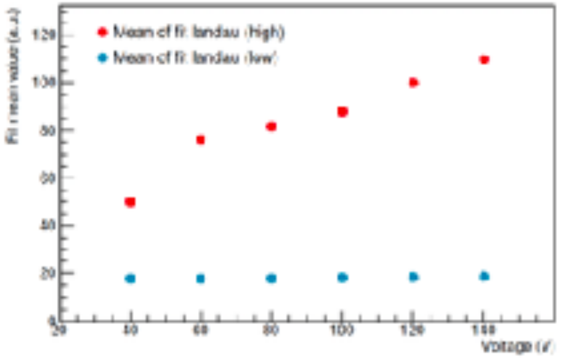
LGAD timing layer

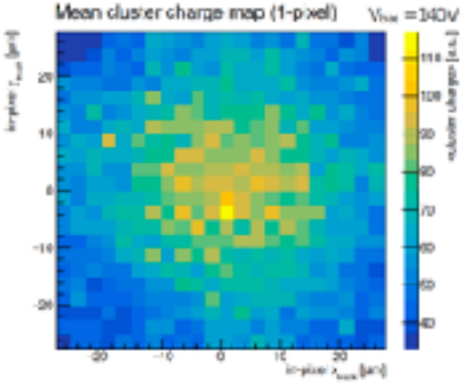
Technology choice: Low Gain Avalanche Diodes

- Short term: read out with Timepix3
- Long term: Timepix4?

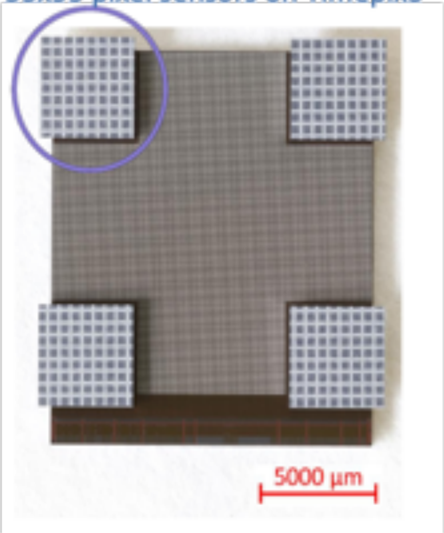
First prototypes: Trench-Isolated LGADs (FBK)

- small 2x2 pixel samples for characterisation in the lab
  → measurements with IR laser
- 55 µm pitch pixel samples bonded to Timepix3
  → first test in the DESYII test-beam





55x55 pixel sensors on Timepix3



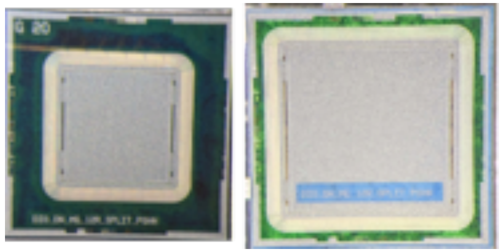
2x2 pixel samples in the lab

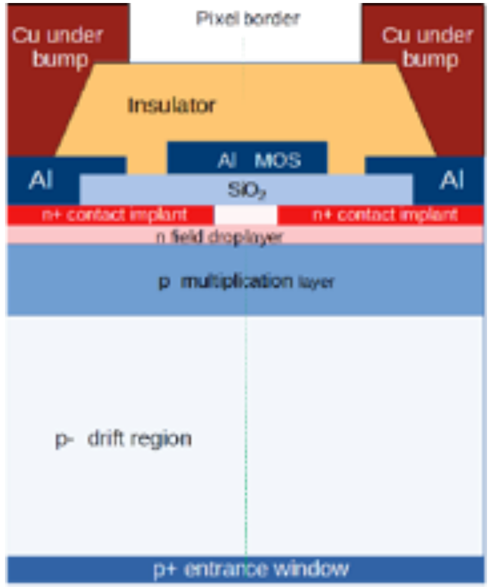
Lead by Annika Vauth and Joern Schwandt, and the LGAD team

Novel LGAD Design

UHH + DESY program
Supported by Si-D (BMBF)

- Increase sensitivity - 100% fill-factor
- Continuous multiplication layer to avoid gain degradation in the pixel gap region
- Field drop layer (n-doped) to prevent break down at n+ pixel edges





MARTHA
Monolithic Array of Reach THrough Avalanche photo diodes
R. H. Richter et al. (HLL / MPI)

- **UHH**: design and characterisation of a MARTHA for particle physics application
- Collaboration on MARTHA for photon science (H. Graafsma)

Long term quest:
Can a 10 ps silicon detector reach
1 µm space resolution ?

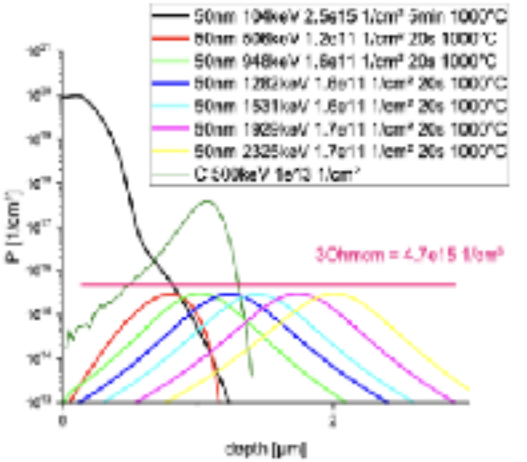
Joern Schwandt, Constanze Wais

Radiation hardness

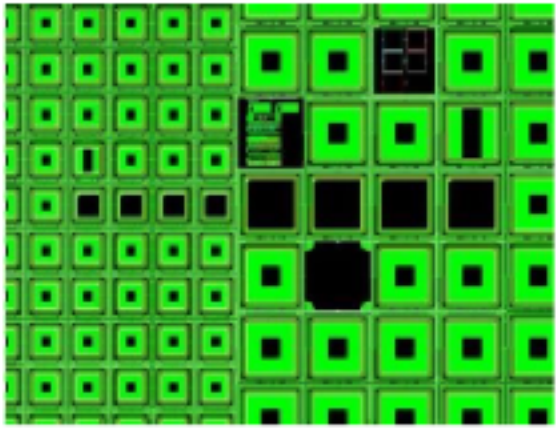
- RD50 project “Defect engineered diodes mimicking the gain layer in LGADs”

- 18 differently defect engineered wafers with respect to B, O and C impurities as well as with P in compensated n++-p+ diodess

P and C implantations in compensated n^{++}-p^{-} diodes with 50 nm of oxide



layout design including samples for Hall measurements and diodes with fully transparent electrodes.



Expected results

- Reveal the microscopic radiation induced effects above 10^{15} n_{eq}/cm^2 and identify the reasons for losing the gain in LGADs.
- Reveal the role of O, C and P impurities in low resistivity B doped Si and of defects impacting on the gain layers in LGADs
- Detection and characterization of new defects induced by irradiation above 10^{15} n_{eq}/cm^2 (e.g. 2nd order defects)
- provide real inputs for modelling the radiation damage above 10^{16} n_{eq}/cm^2, allowing the development of accurate parametrization models validated on the entire range of fluences, from low to extreme;

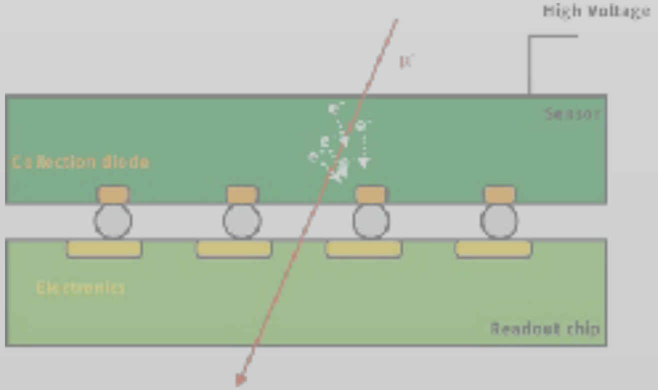
- First samples expected in Feb. 2025 (project will continue within DRD3)

Joern Schwandt

Pico - Two Avenues

Charged Particle Detection

- Hybrid silicon detector



LGAD project within:

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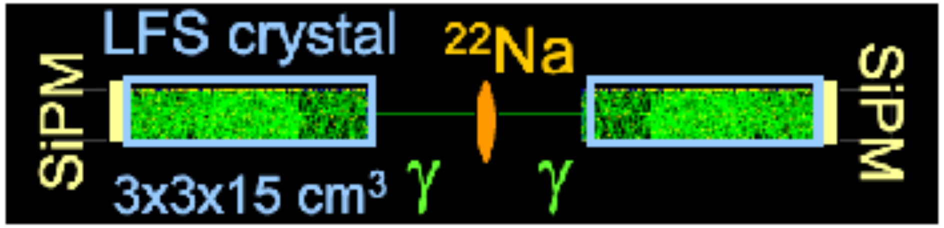
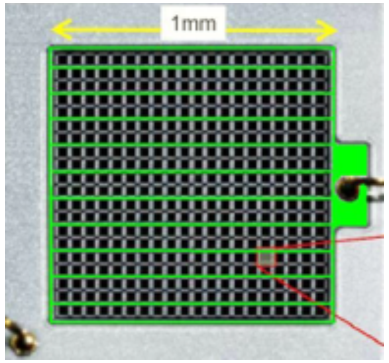


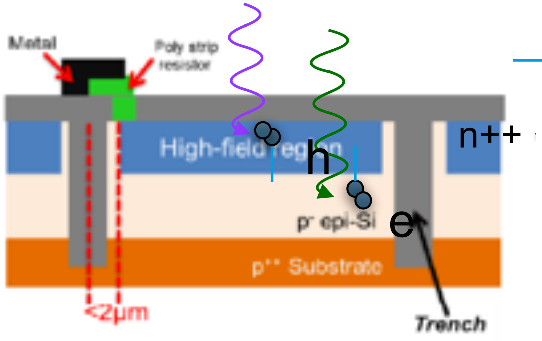
SiPM project within:

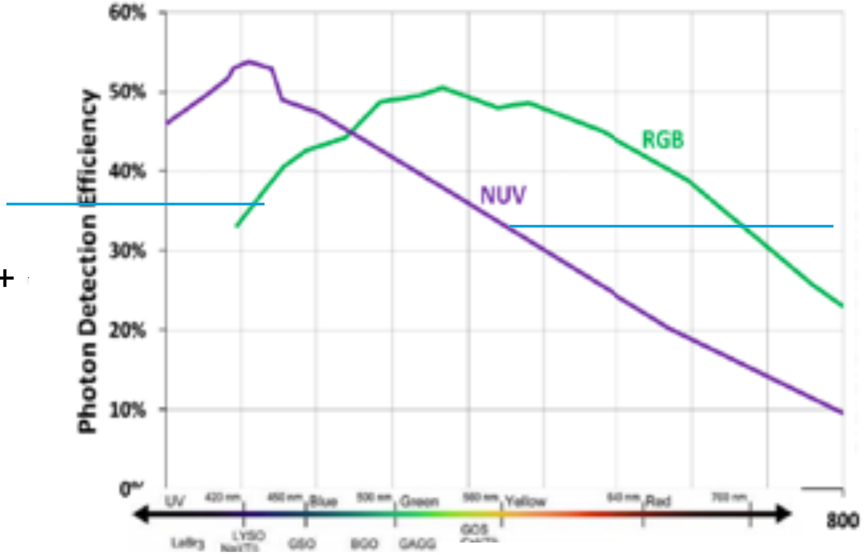
- DRD6
- High-D-Calo Consortium

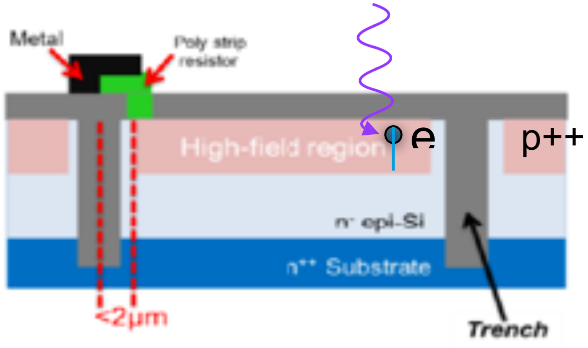
Silicon-Photomultipliers

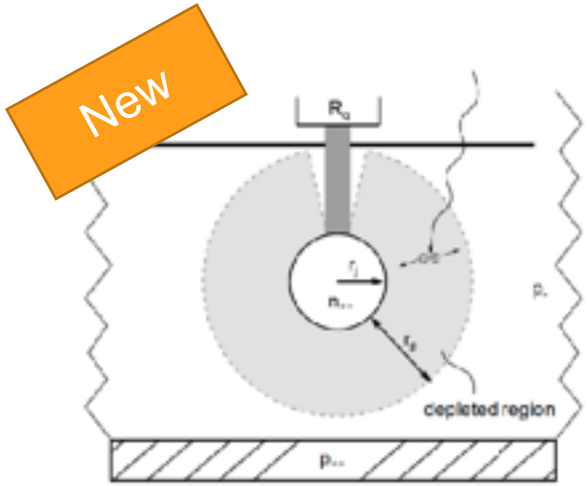
SiPM



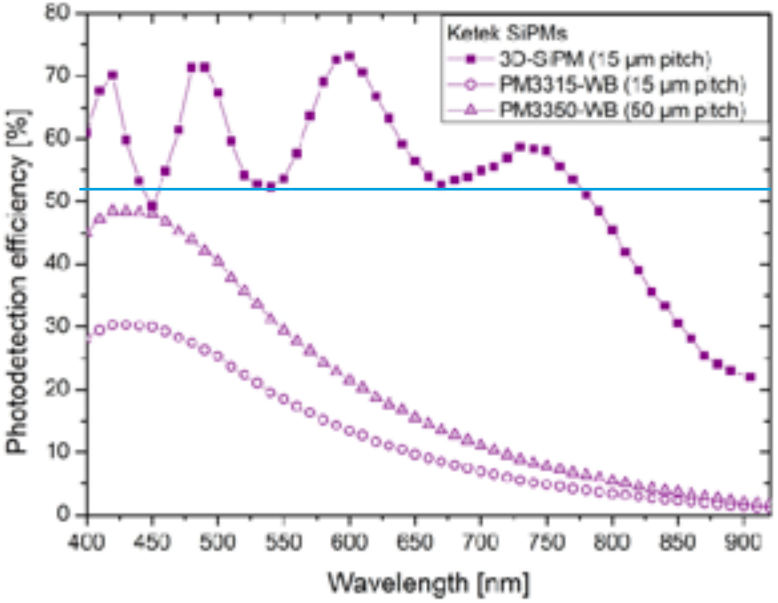


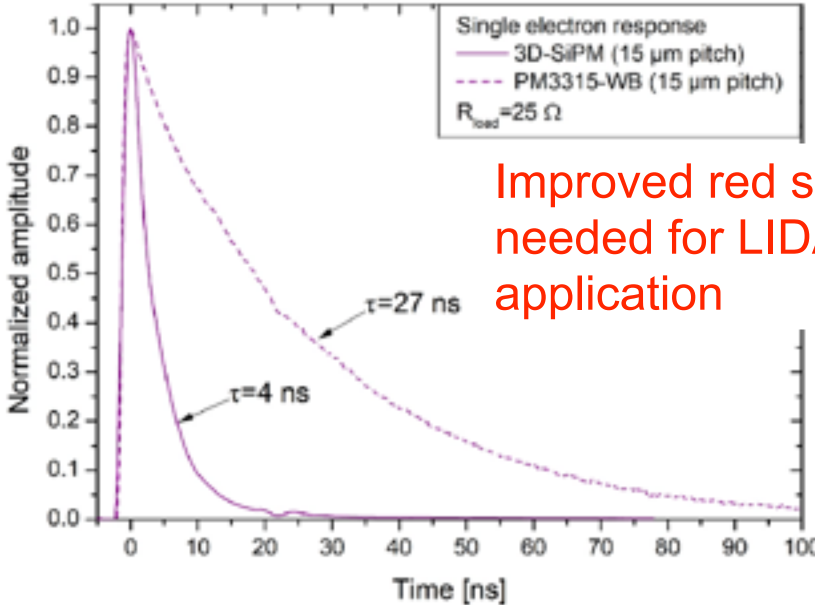






PhD thesis E. Engelmann (KETEK)
arXiv:2010.10183





Improved red sensitivity needed for LIDAR application

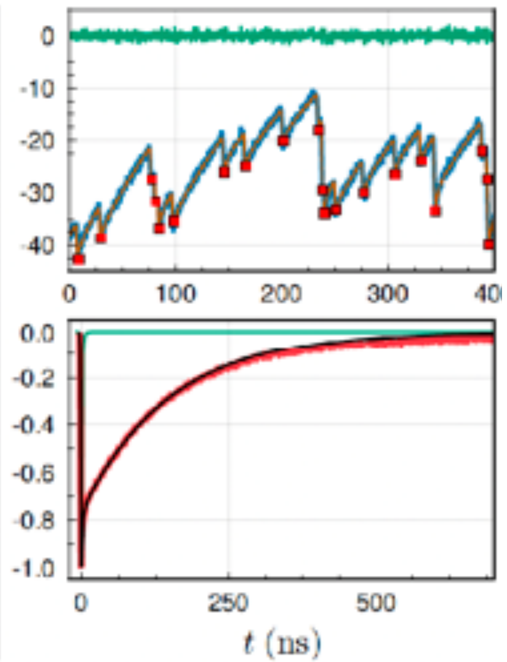
[Radiation hardness of a wide spectral range SiPM with quasi-spherical junction](#)
Römer, Garutti et al, Nucl.Instrum.Meth.A 1047 (2023) 167792

Silicon-Photomultipliers

Supported by High-D-Calo (BMBF)

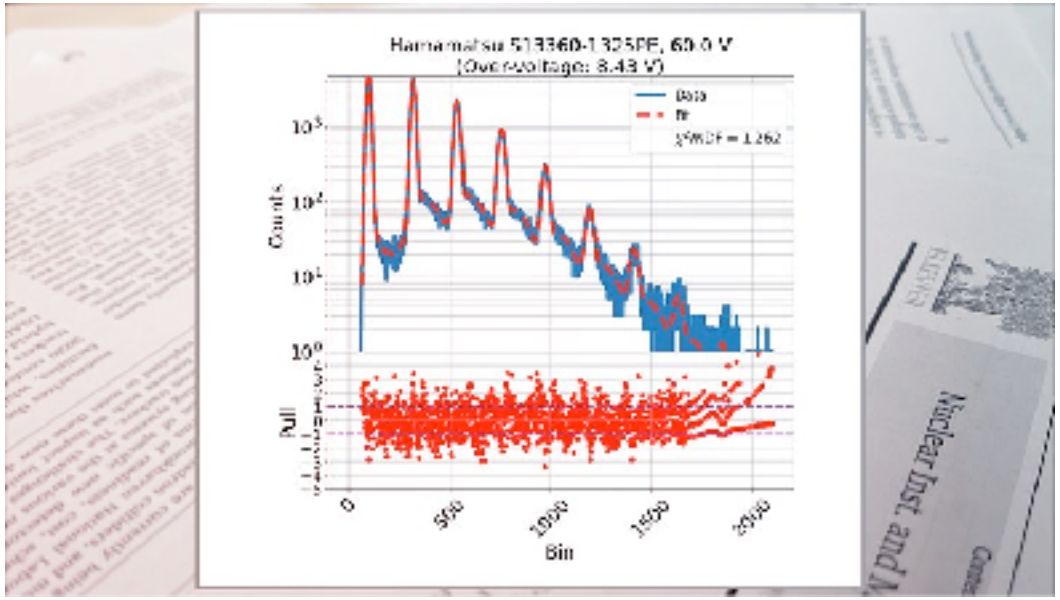
Analysis and modelling tools for fundamental characterisation and optimisation

Model SiPM waveform for operations with very high dark rate



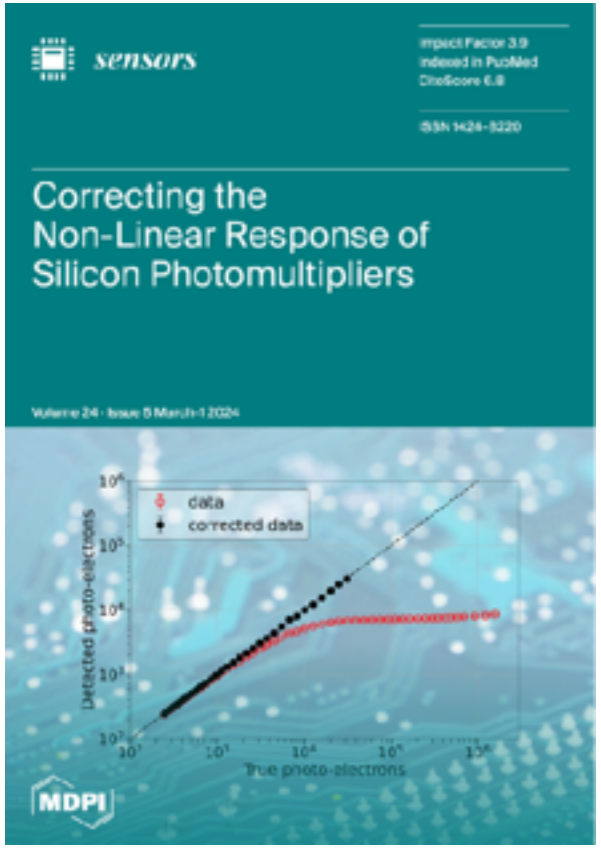
[SiPM signal processing via multiple linear regression](#)
W. Schmailzl, C.Piemonte, E. Garutti, W. Hansch

Model SiPM response to low and high light intensity
→ extract fundamental parameters
→ investigate effect of radiation damage



Charge

[PeakOTron: A Python Module for Fitting Charge Spectra of Silicon Photomultipliers](#)
J. Rolph, E. Garutti, R. Klanner, T. Quadfasel, J. Schwandt
PeakOTron: 10.5281/zenodo.10014537
LightSimtastic: 10.5281/zenodo.10019688



[Correcting the non-Linear Response of Silicon Photomultipliers](#)
L. Brinkmann, E. Garutti, S. Martens, J. Schwandt

Silicon-Photomultipliers: response model

01. Single cell signal

Real data, electric circuit simulation, physical models

02. SiPM key parameters

N_{cells}, PDE, T, G, DCR, OCT, AP, V_{ov}, etc.

03. Light source

Source type, photons arrival time and spatial distributions

→ SUM (SiPM Unified Model) →

SiPM response

- The "Geiger Array" (GA).
  For every event and Geiger discharge:
  - Time of arrival.
  - Signal amplitude.
  - Cell ID.
  - Type (light, DCR, OCT, AP).
- Transient for every event (from GA).

01.
Non-linear response and saturation

Perform systematic studies on the non-linear response correction as:

- T and V dependence.
- Fluence dependence.
- Variation across SiPMs.
- Etc.

02.
SiPM response with scintillation light

Obtain a non-linear response correction combining SiPM precise lab calibration and light emission spectrum from scintillator using SUM (validated).

03.
SUM model and framework

Develop the framework in Julia and make it ready also for further system optimisation studies.

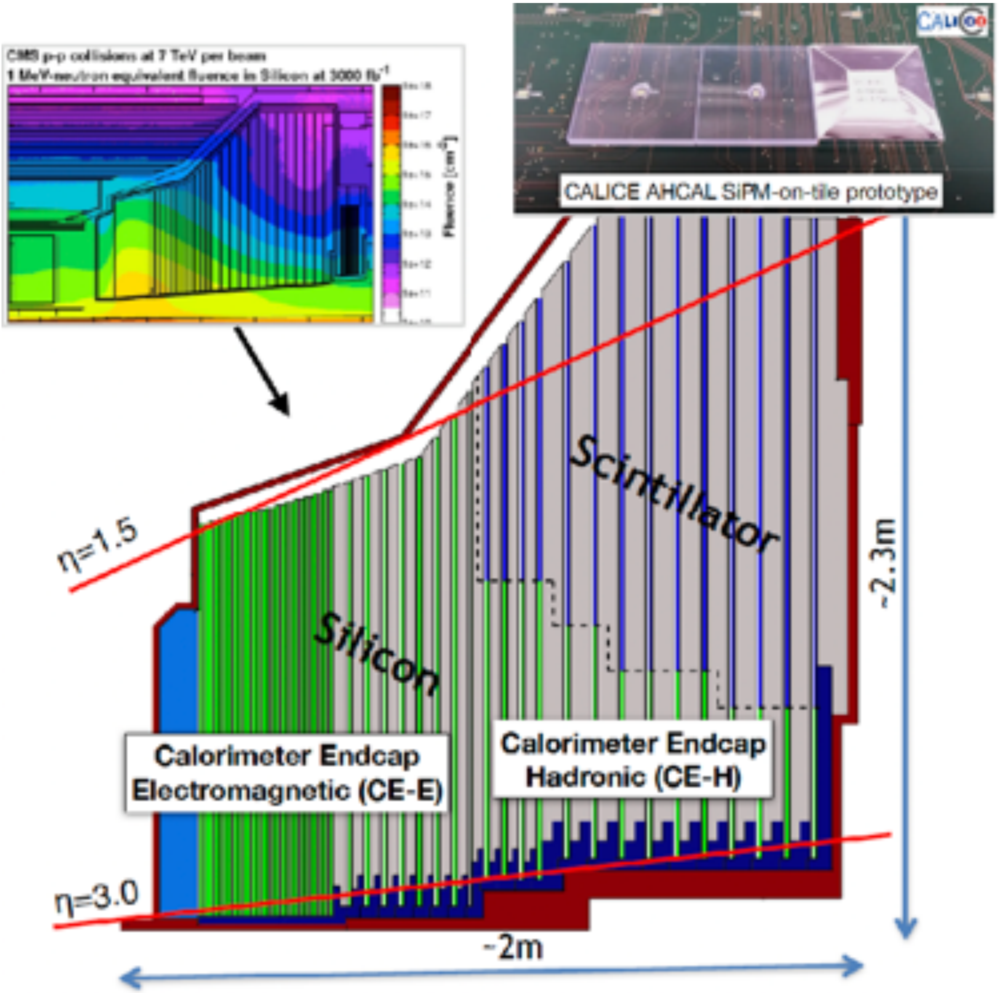
connect to DESY development: ap²

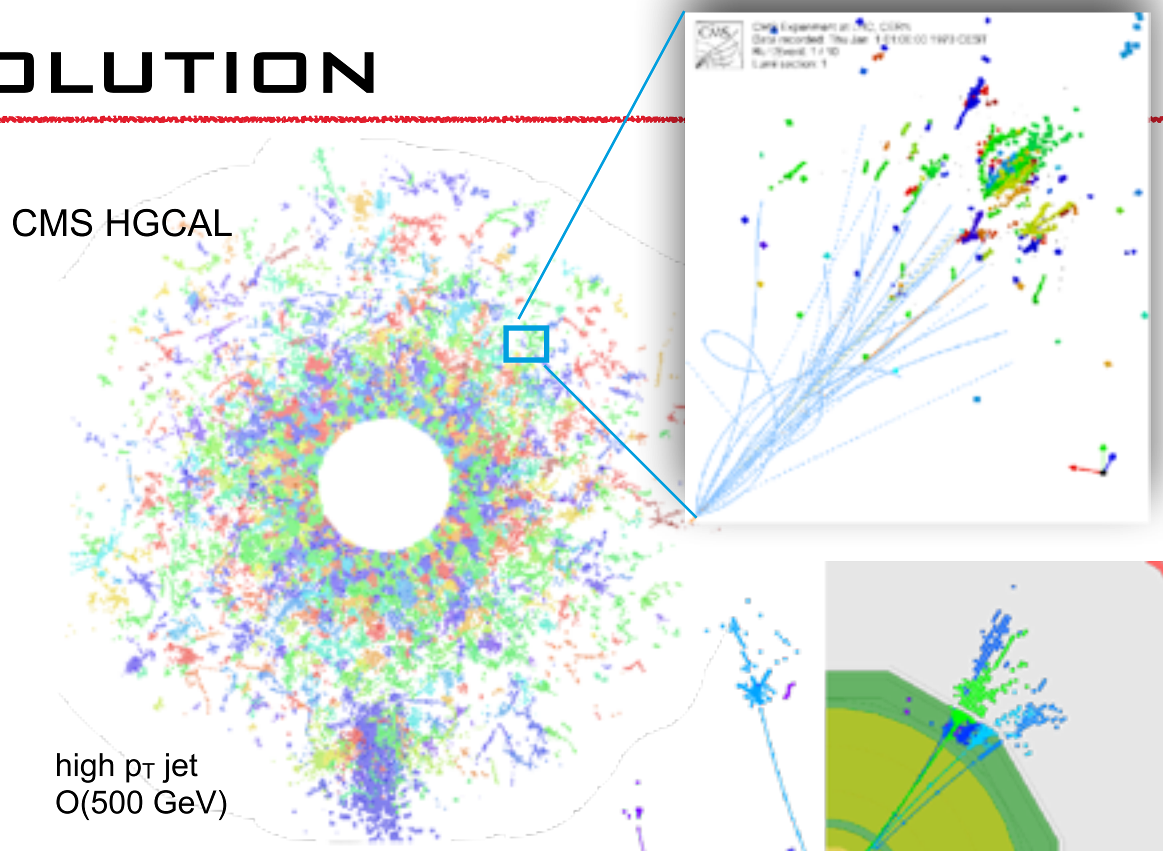
SUM SiPM Unified Model

Lead by Massimiliano Antonello, and the SiPM team

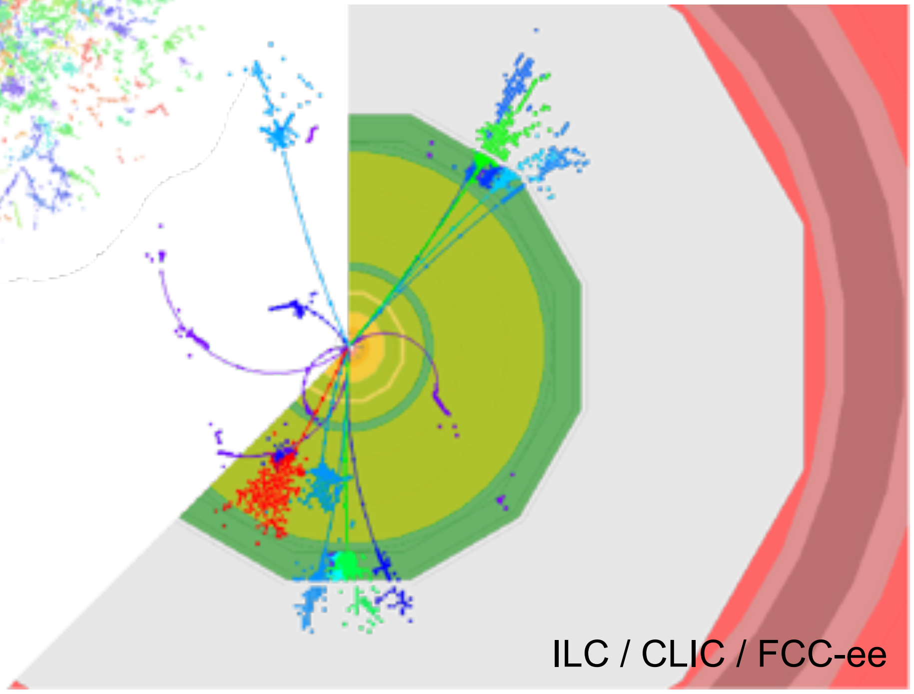
Spatial + Time Resolution

= 5D Calorimetry





Precision jet energy reconstruction with Particle Flow



Particle Flow - Does Time Matter ?

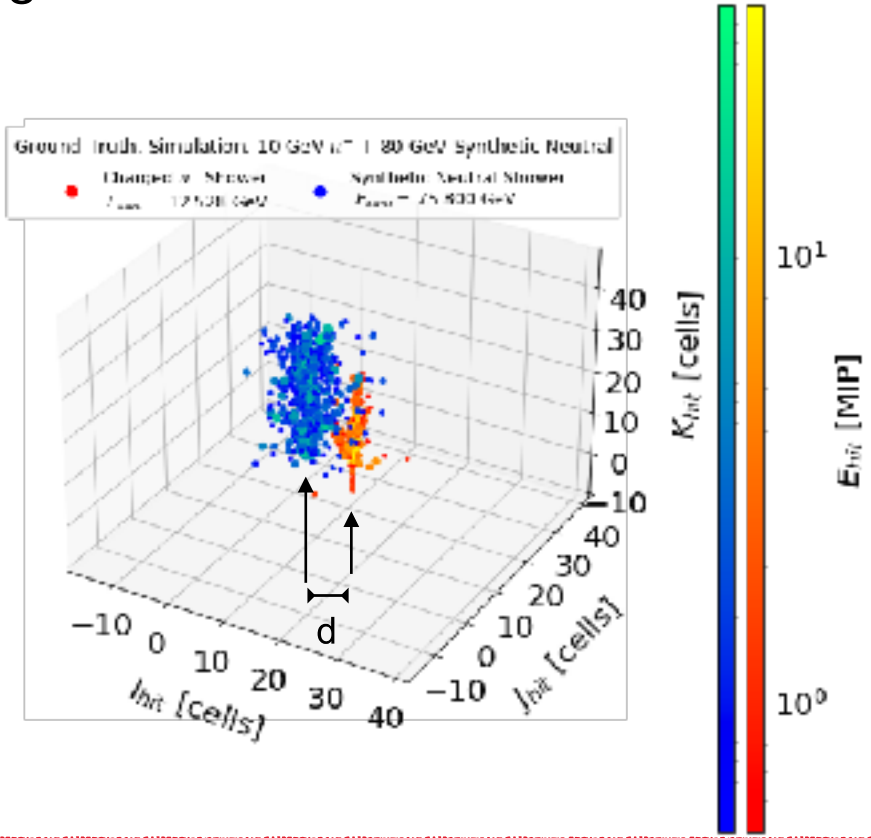
Quantify the impact of single hit time resolution on:

1) shower separation
2) energy compensation

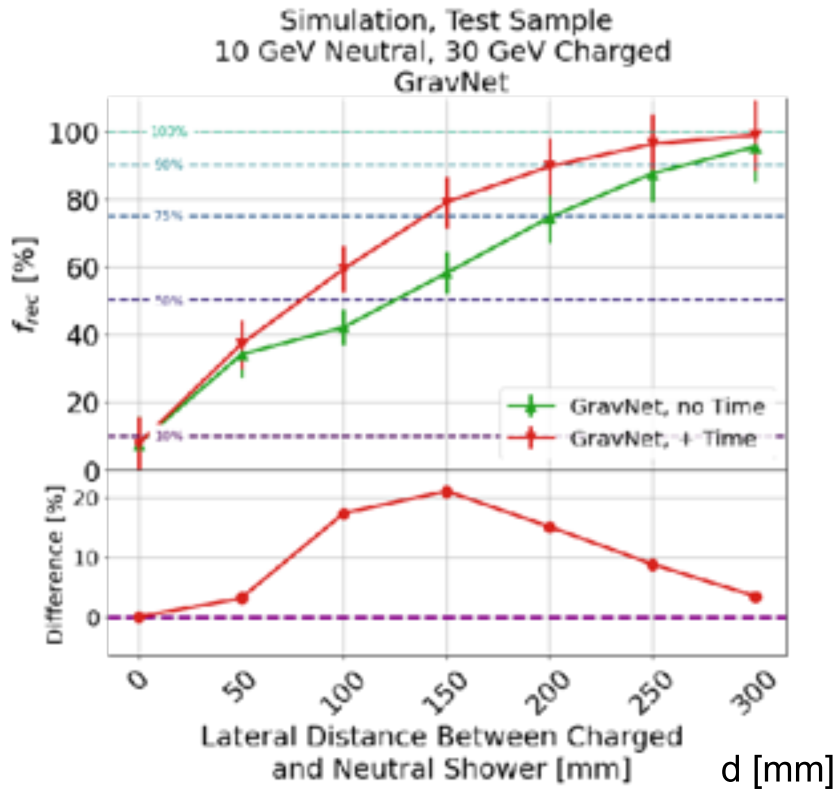
using 5D ML algorithms

[Shower Separation in Five Dimensions for Highly Granular Calorimeters using Machine Learning](), CALICE, *in revision*

[Software Compensation for Highly Granular Calorimeters using Machine Learning](), CALICE, *JINST* 19 (2024) P04037



Fraction of neutral hadrons reconstructed with energy within one sigma from truth



PhD thesis J. Rolph (UHH)

Next - Does Time Matter ?

UHH & DESY program
Supported by QU-II

- **Improve**
  - Reach 10 ps time resolution on a system
- **Quantify**
  - Quantify the improvement of time in jet energy resolution and PID
  - Employ ML to best exploit time in particle flow
- **Optimise**
  - Accordingly optimise future collider detector systems

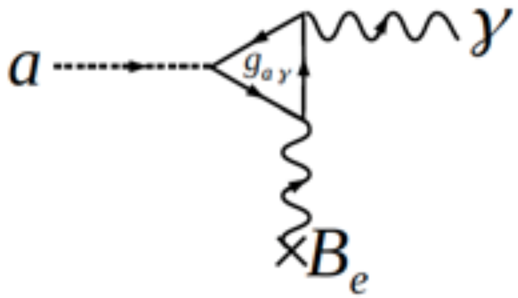
Considering alternatives for a medium time scale application project before the future collider —
best together with DESY

Quantum

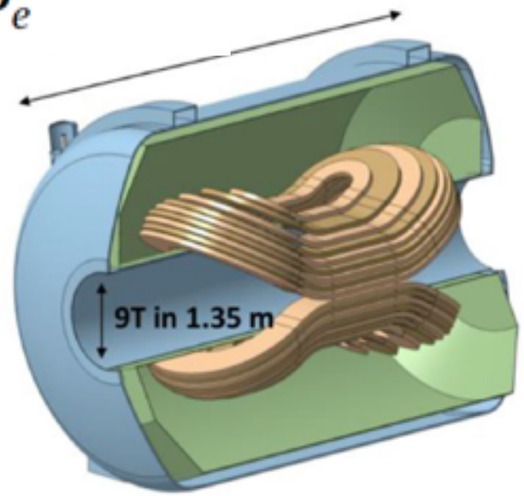
Quantum: Single Microwave Photon Detection

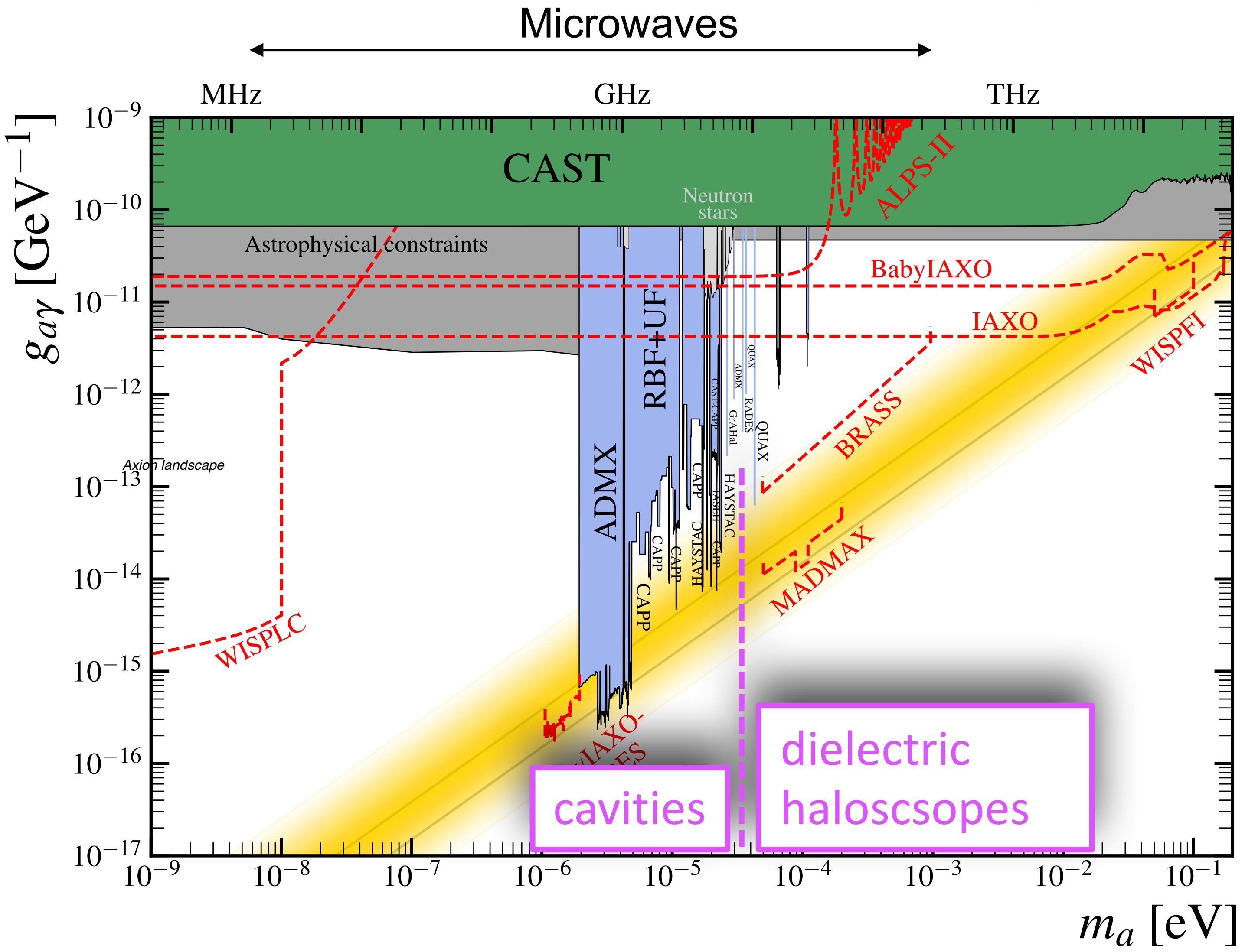
Motivation:

Axions Dark Matter Searches in microwave range

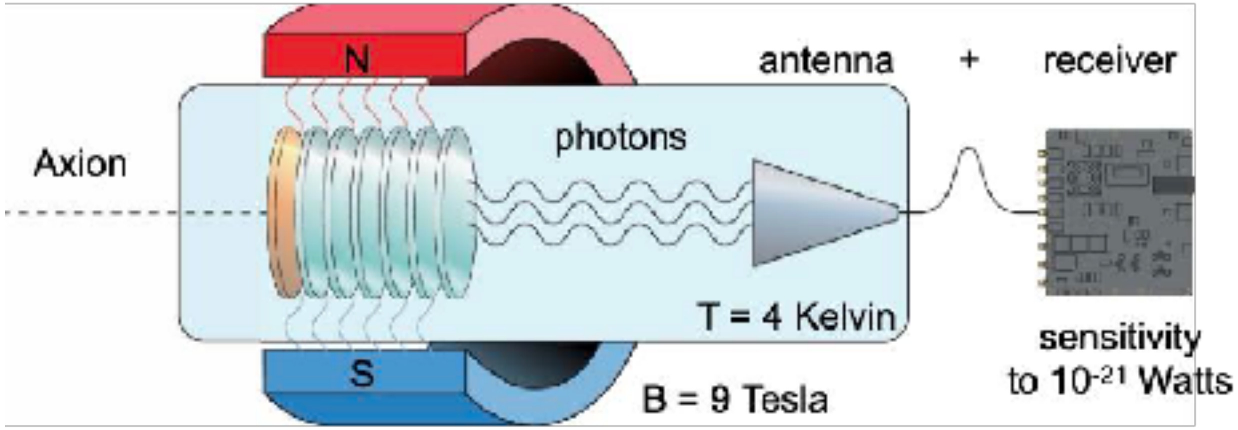


“Axion search is all about the magnet”
Y. Semertzidis





MAgnetized Disc and Mirror Axion eXperiment



- Tunable in frequency coverage:
  ~10-100 GHz (40-400 μeV axion mass)
- Boost emitted power through:
  - coherent emission from multiple interfaces
  - constructive interference effects

Lead by Christoph Krieger, and the MADMAX team

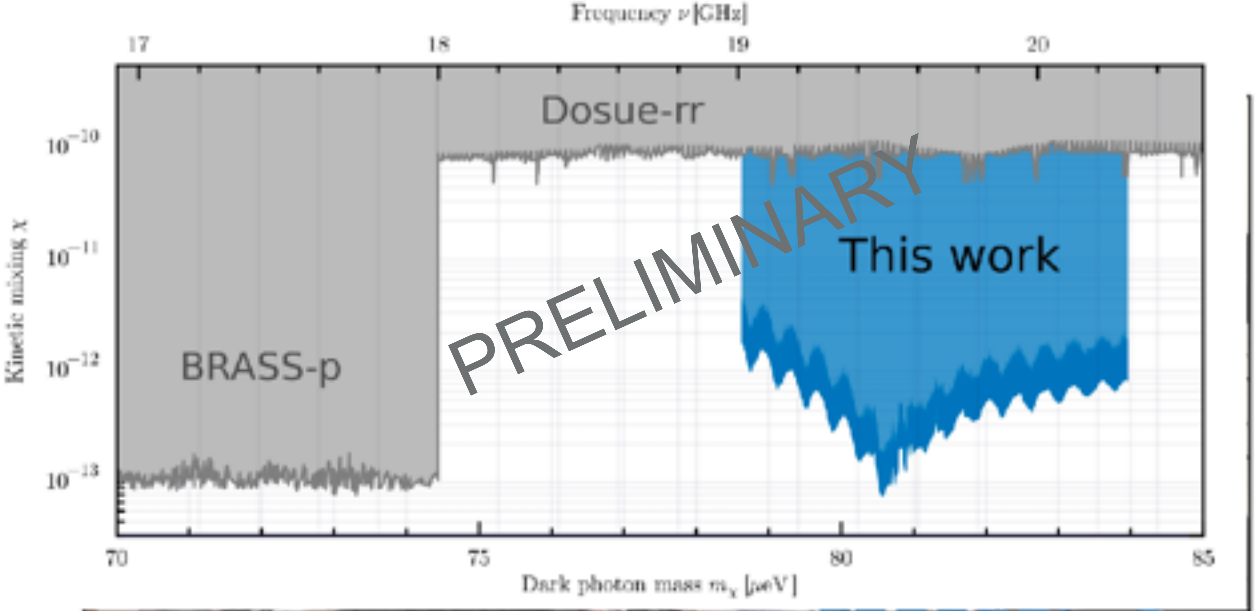
$$g_{a\gamma} = 2.04(3) \times 10^{-14}\ \mathrm{GeV}^{-1} \sqrt{\frac{\mathrm{SNR}}{5}} \sqrt{\frac{400^2}{\beta^2}} \sqrt{\frac{1\mathrm{m}^2}{\mathrm{A}}} \sqrt{\frac{\mathrm{T_{sys}}}{8\mathrm{K}}} \frac{10\ \mathrm{T}}{\mathrm{B_e}} \sqrt{\frac{0.8}{\eta}} \left(\frac{1.3\ \mathrm{days}}{\Delta t}\right)^{1/4} \sqrt{\frac{300\ \mathrm{MeV}^2}{\rho_0}} \left(\frac{\mathrm{m_a}}{100\ \mu\mathrm{eV}}\right)^{5/4}$$

reach the QCD band

System Temperature limited by receiver chain

Currently used: Heterodyne receiver chain with FPGA-based online FFT

$$\chi = 1.43 \times 10^{-13} \left(\frac{400}{\beta^2}\right)^{1/2} \left(\frac{707\ \mathrm{cm}^2}{A}\right)^{1/2} \left(\frac{T_{sys}}{290\ \mathrm{K}}\right)^{1/2} \left(\frac{11.7\,\mathrm{d}}{\Delta t}\right)^{1/4} \left(\frac{SNR}{5}\right)^{1/2} \left(\frac{m_\chi}{80\ \mu\mathrm{eV}}\right)^{1/4},$$



Sensitivity

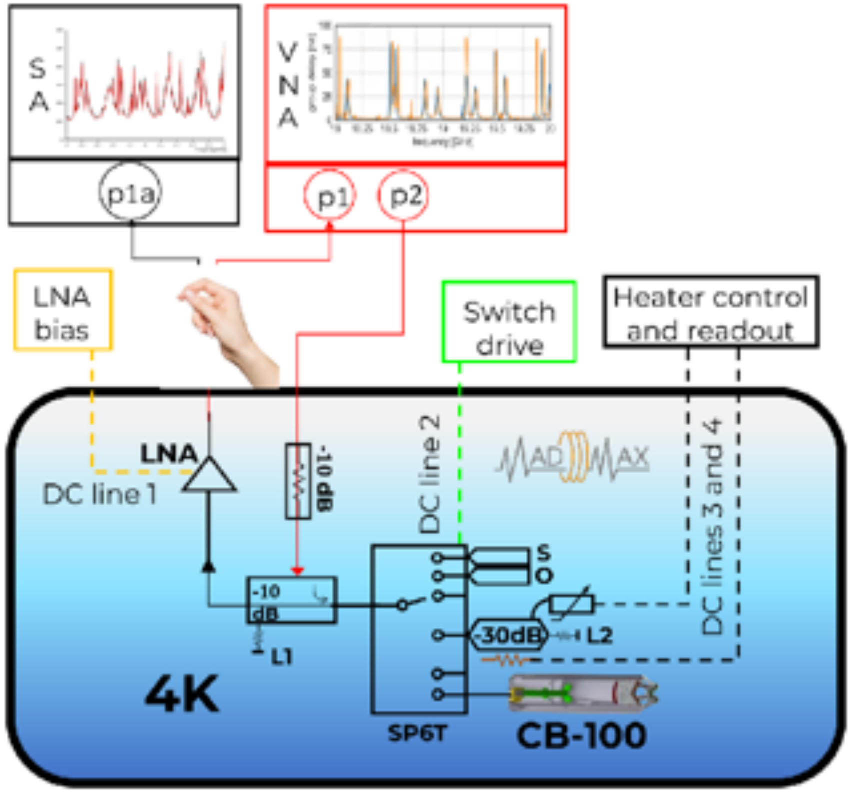
UHH & DESY program
Supported by QU-II

$$g_{a\gamma} = 2.04(3)\times 10^{-14}\,\mathrm{GeV}^{-1}\sqrt{\frac{\mathrm{SNR}}{5}}\sqrt{\frac{400^2}{\beta^2}}\sqrt{\frac{1\mathrm{m}^2}{A}}\sqrt{\frac{T_{sys}}{8\mathrm{K}}}\frac{10\ \mathrm{T}}{B_e}\sqrt{\frac{0.8}{\eta}}\left(\frac{1.3\ \mathrm{days}}{\Delta t}\right)^{1/4}\sqrt{\frac{300\ \mathrm{MeV}^2}{\rho_0}}\left(\frac{m_a}{100\ \mu\mathrm{eV}}\right)^{5/4}$$

reach the QCD band

Dagmar Kreikemeyer Lorenzo, Juan Maldonado, et. al

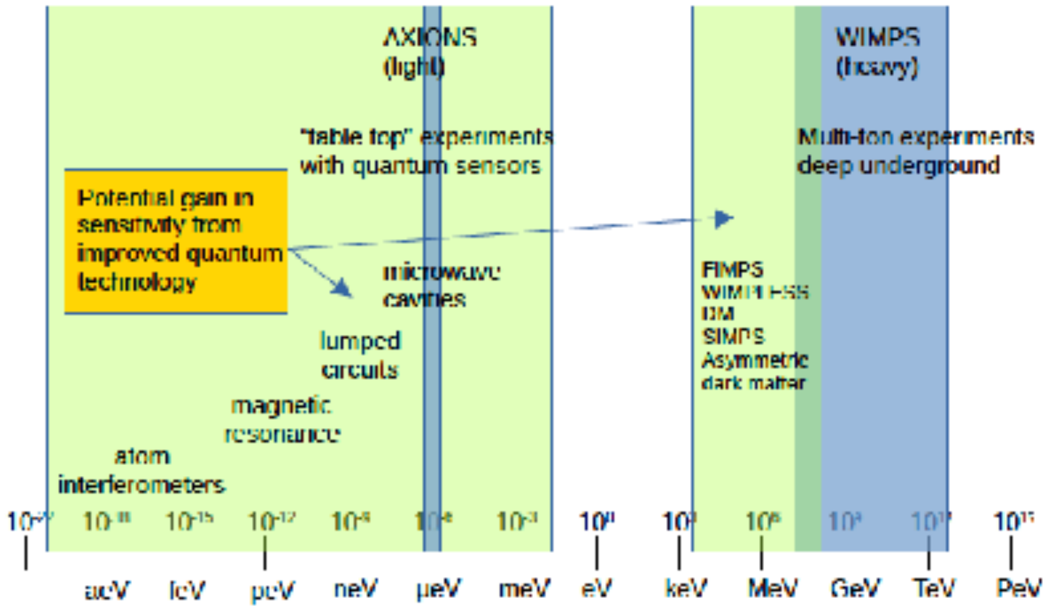
Low Noise Amplifier or HEMT (high-electron-mobility transistor): Field Effective Transistor with heterojuction



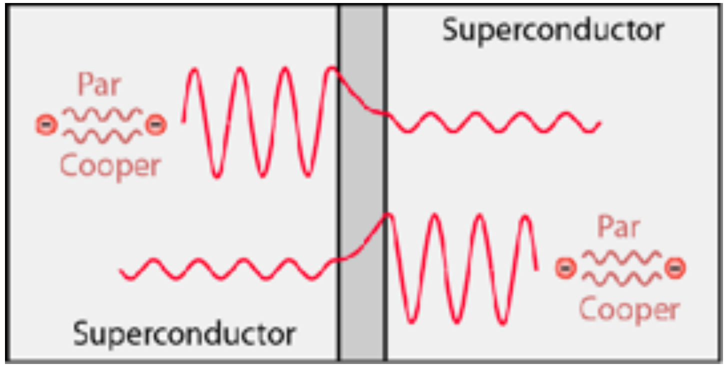
MPP

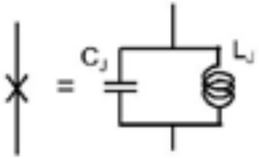
Next - Quantum-limited Amplifier

Photon counting via Q bits to beat the quantum noise limit and greatly improve sensitivity



Josephson Junction (JJ)

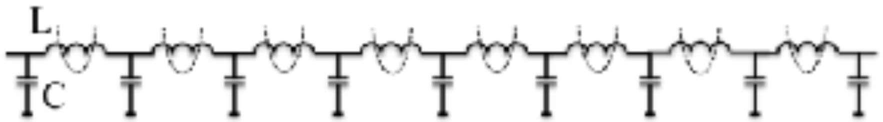


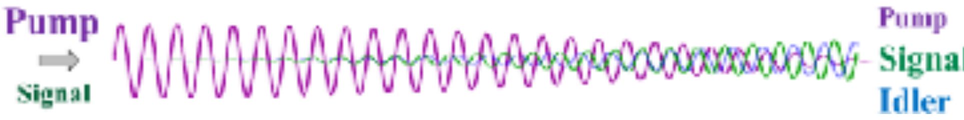


JJ symbol and electrical model

Discovered by Brian Josephson in 1962. Application in SQUIDs, superconducting qubits, and amplifiers.

Josephson TWPA



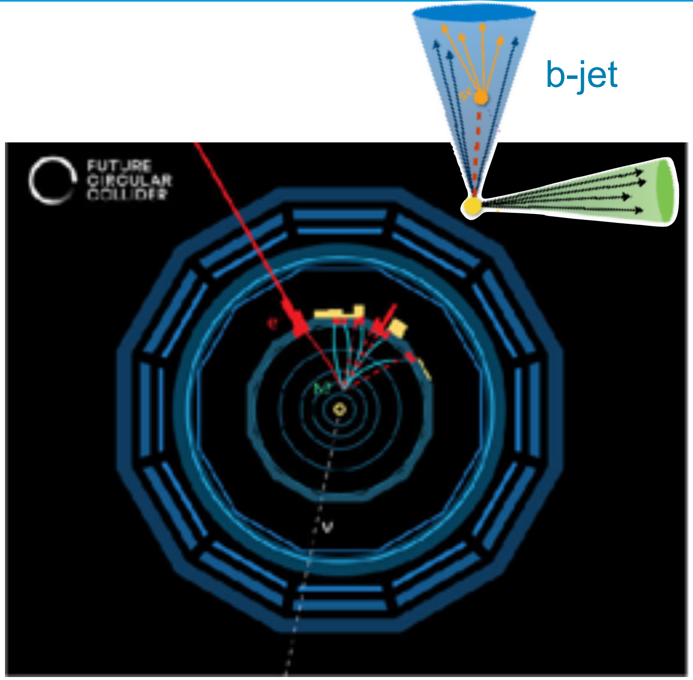


Juan Salum

Based on a non-linear transmission line of Josephson junctions

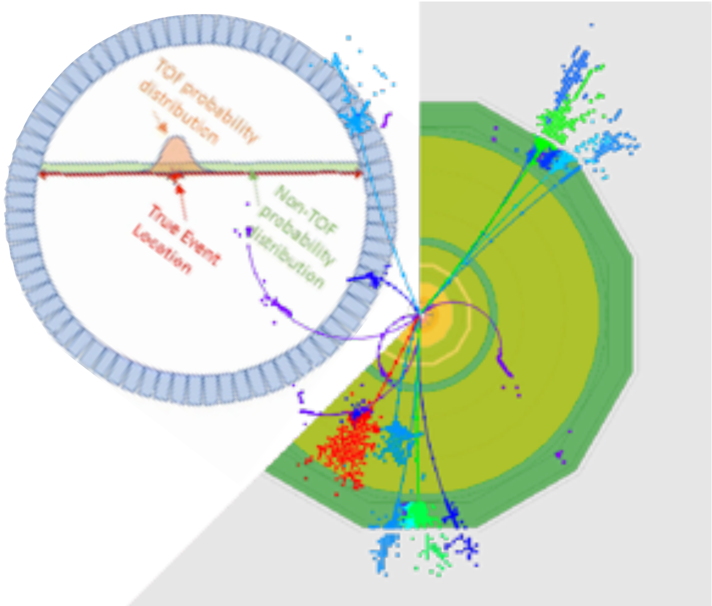
Technology Innovation Drives Discovery Potential

Micro



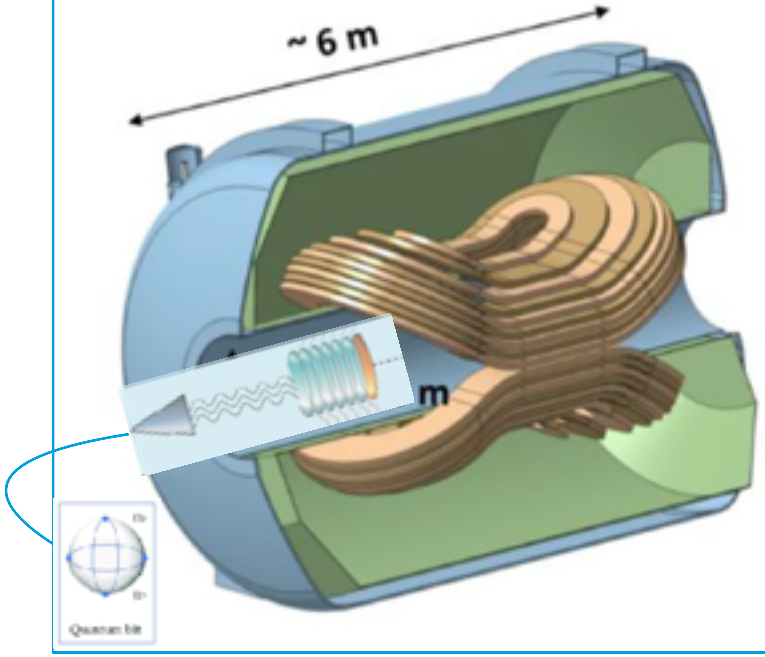
1 μm project

Pico



10 ps challenge

Quantum



single photon detection frontier