University of Hawaiʻi at Mānoa

Semiconductor detector R&D for for future experiments in particle physics

Tracking, timing and particle identification

Jennifer Ott

ottjenni@hawaii.edu

Siegen, January 8, 2026

College of Engineering
University of Hawaiʻi at Mānoa

Introduction

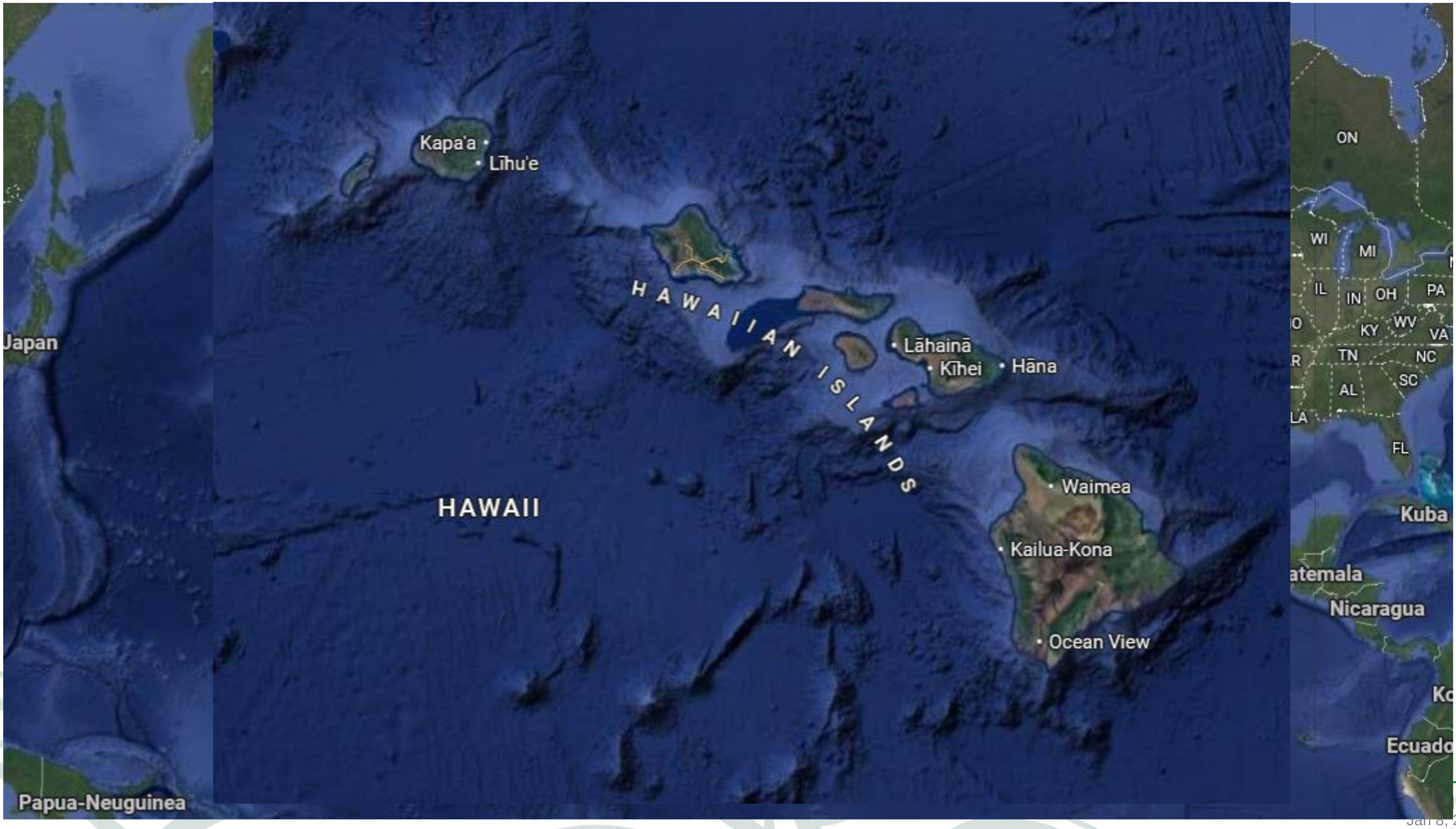
Jennifer Ott

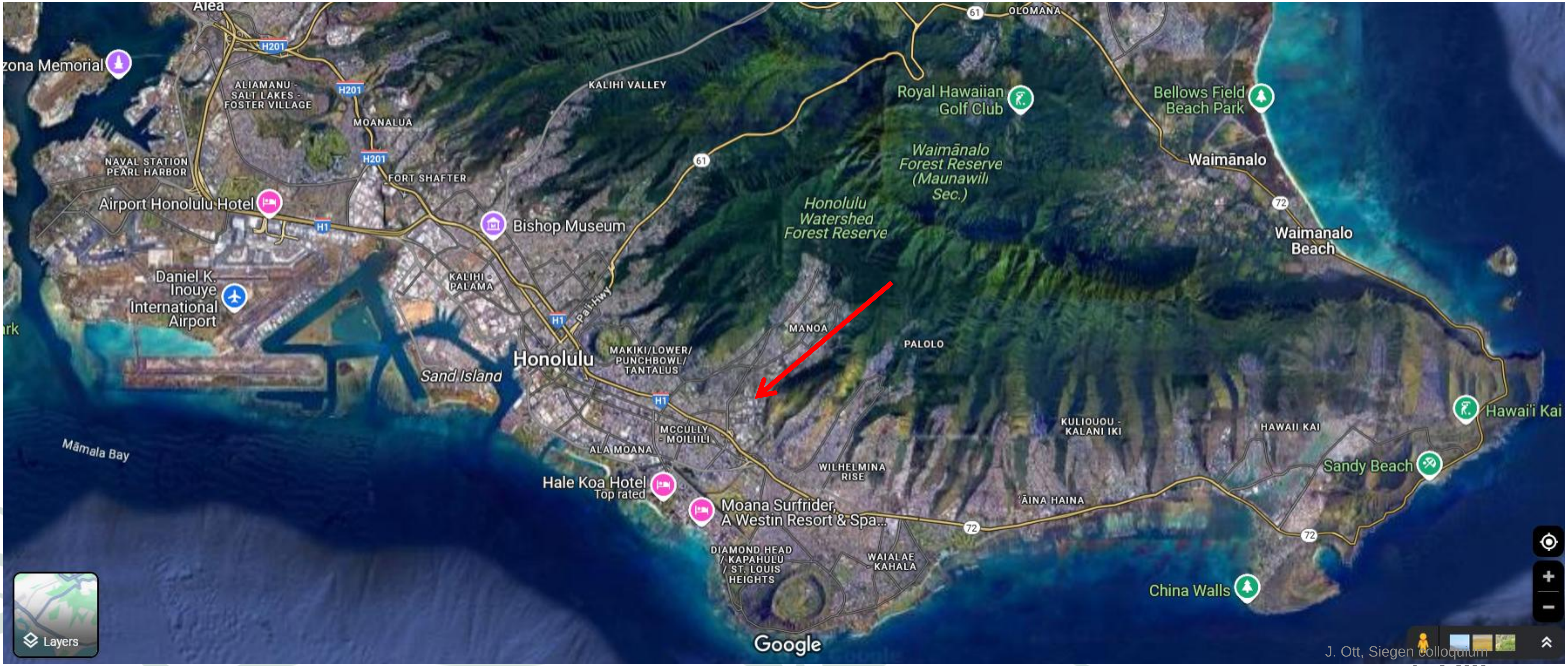
B.Sc., University of Helsinki, chemistry (2014)
M.Sc. University of Helsinki, radiochemistry (2015)

D. Sc. (Tech.) Helsinki Institute of Physics & Aalto University (spring 2021)

Postdoctoral researcher, UC Santa Cruz (2021-2024)

Assistant professor in Electrical & Computer Engineering, cooperating graduate faculty in Physics & Astronomy, University of Hawaiʻi at Mānoa (2025 -)


Kapa'a
Līhu'e
HAWAIIAN ISLANDS
Lāhainā
Kīhei
Hāna
Waimea
Kailua-Kona
Ocean View
HAWAII
Japan
Papua-Neuguinea
ON
WI
MI
IL
IN
OH
PA
KY
WV
VA
TN
NC
AL
SC
FL
Kuba
Nicaragua
Ecuado


Aiea
zona Memorial
H201
ALIAMANU - SALT LAKES - FOSTER VILLAGE
MOANALUA
KALIHI VALLEY
NAVAL STATION PEARL HARBOR
FORT SHAFTER
61
OLOMANA
Royal Hawaiian Golf Club
Bellows Field Beach Park
Waimānalo
Waimānalo Forest Reserve (Maunawili Sec.)
Honolulu Watershed Forest Reserve
Airport Honolulu Hotel
H1
Bishop Museum
72
Waimanalo Beach
Daniel K. Inouye International Airport
KALIHI - PALAMA
Pali Hwy
MANOA
PALOLO
Honolulu
MAKIKI/LOWER/ PUNCHBOWL/ TANTALUS
Sand Island
Mamala Bay
MCCULLY - MOILIILI
ALA MOANA
KULIOUOU - KALANI IKI
HAWAII KAI
Hawai'i Kai
WILHELMINA RISE
Sandy Beach
Hale Koa Hotel
Top rated
Moana Surfrider, A Westin Resort & Spa...
'AINA HAINA
DIAMOND HEAD / KAPAHULU / ST. LOUIS HEIGHTS
WAIALAE - KAHALA
China Walls
Layers
Google


Honolulu
Waikīkī

Background: UH

The University of Hawai‘i system encompasses several public university and community college campuses on the Hawaiian islands

- Flagship campus in the **Mānoa** valley: the only R-1 ranked university in the state of Hawai‘i
  - Among the most diverse student populations in the US; Minority-Serving Institution
  - Passed 20,000 enrolled students for the first time in AY24/25!

Background: UH

UH is situated on the traditional and ancestral homelands of the Native Hawaiians - kānaka ʻōiwi

Some Hawaiian words you may know, or encounter:

Aloha

Mahalo: *thank you*
Kōkua: *collaborate, support*
Makai: *towards the ocean*
Mauka: *inland-facing*

HEP detector R&D

Motivation: high-energy physics experiments

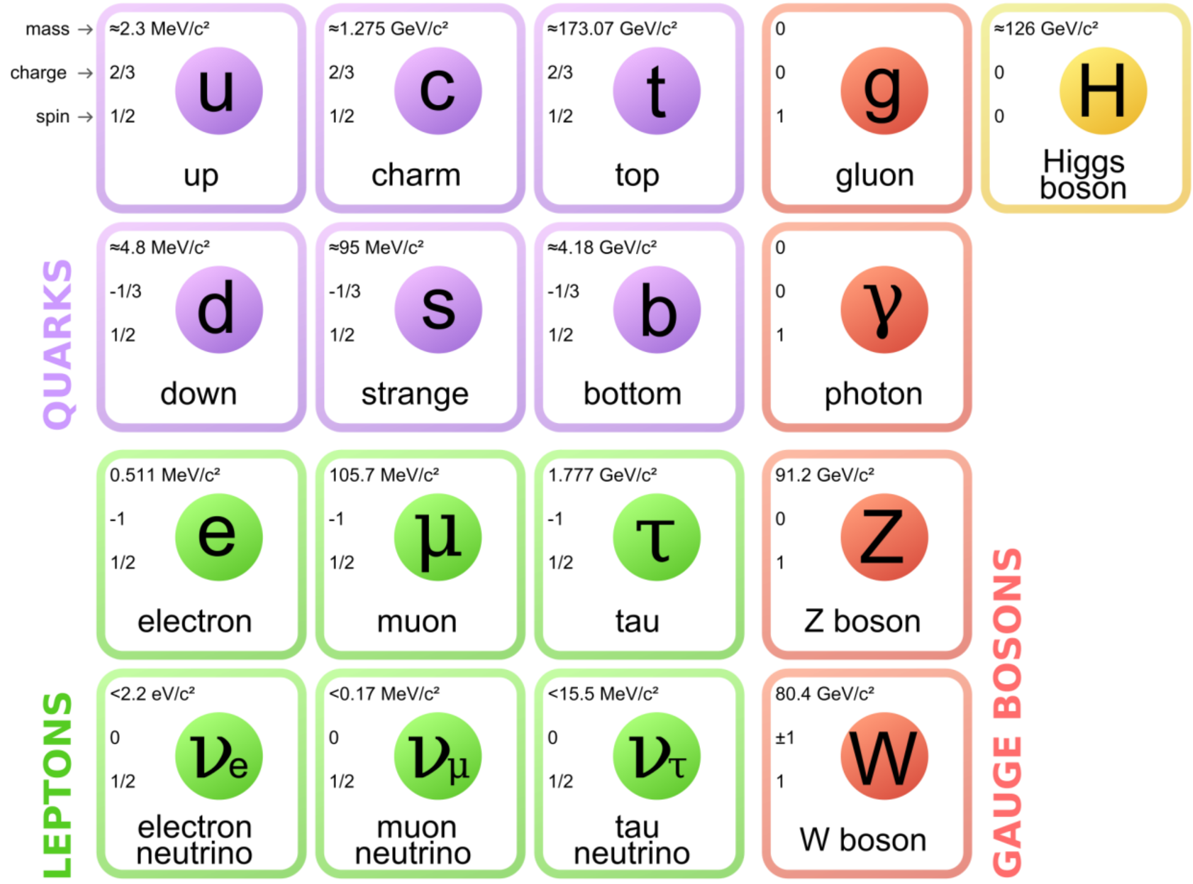
The Standard Model of particle physics

- Describes properties and interactions of fundamental particles
- **Experimental discovery of the Higgs boson at the Large Hadron Collider in 2012 confirmed one of the most significant missing pieces!**

Unsolved questions:

- *Gravity (quantum mechanics & gravity)?*
- *Matter-antimatter imbalance?*
- *Dark matter, dark energy?*

Extremely small particles at very high energies



Astroparticle physics?

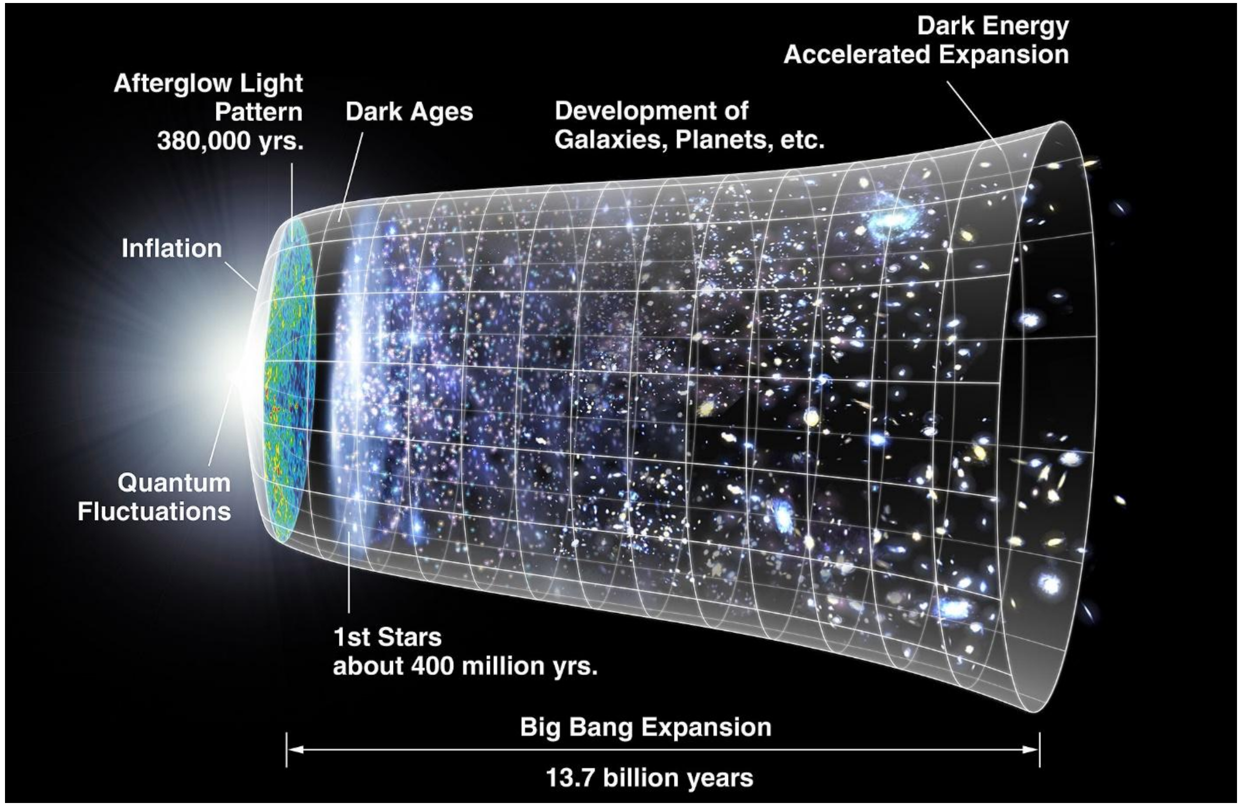
Extraterrestrial sources produce high-energy species!

- Cosmic particles: protons, muons
- Gamma rays

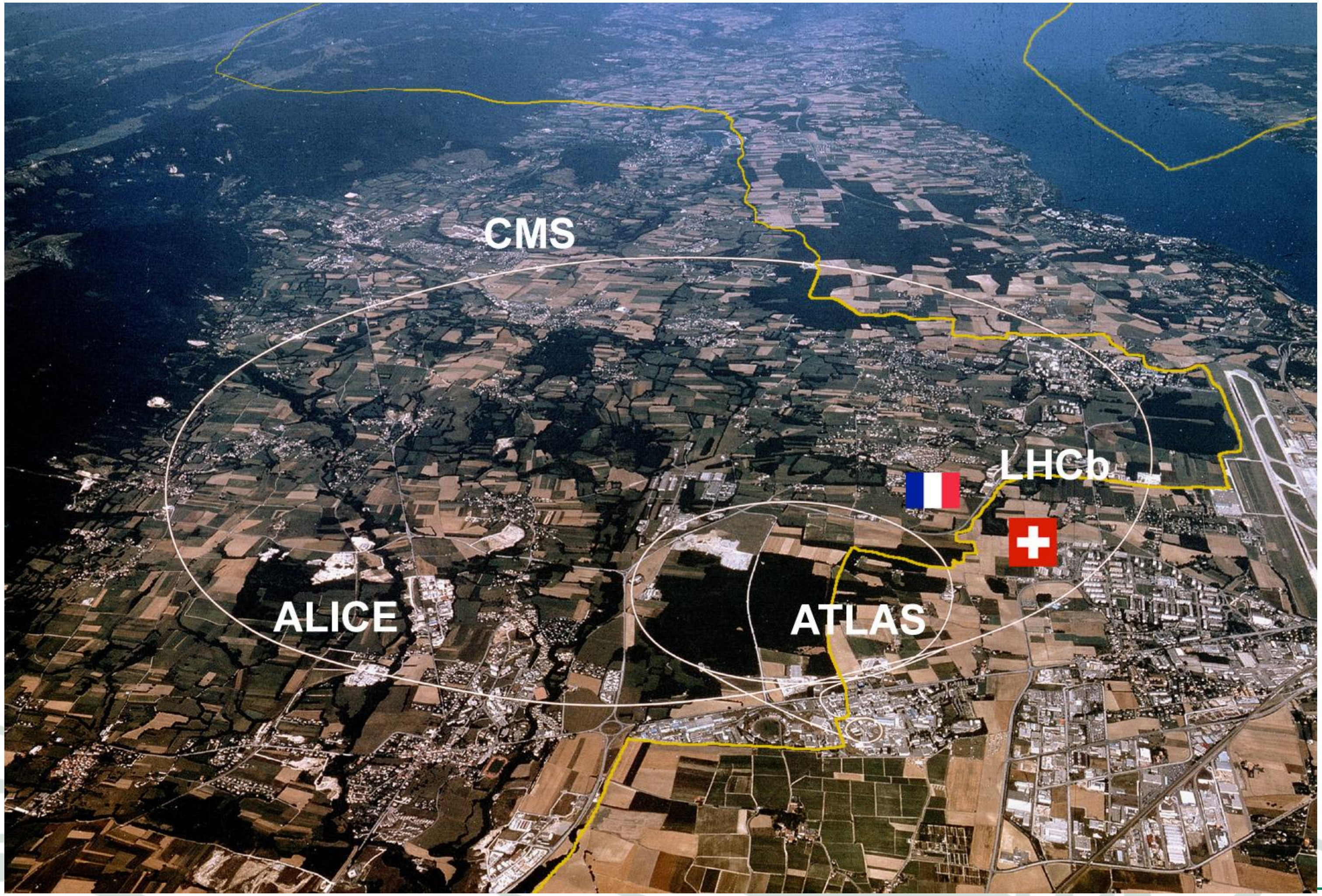
Provide information about processes in stars, galaxies, active galactic nuclei and objects with extreme mass (black holes, neutron stars)

- Formation of the universe
- Dark sectors
- Matter in extreme conditions

For studying fundamental properties and interactions, e.g. of the standard model: too little statistics, impossible to build precision detectors in a specific location



The Large Hadron Collider



Circumference: 27 km

Primarily proton-proton (p-p) collisions: center-of-mass energy 13 TeV

Luminosity: 2×10^{34} $cm^{-2}s^{-1}$

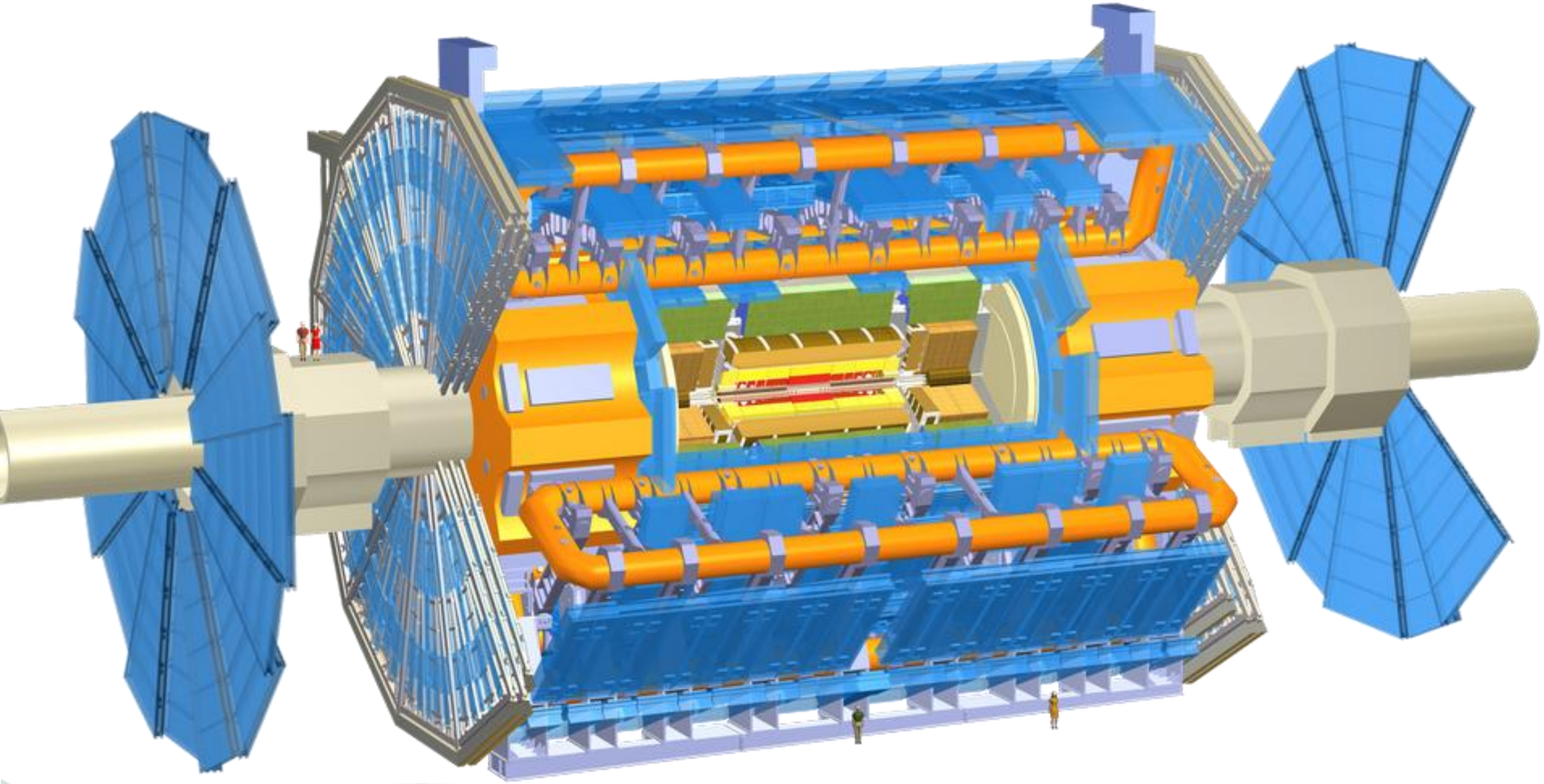
Collision frequency: 40 MHz = **25 ns**

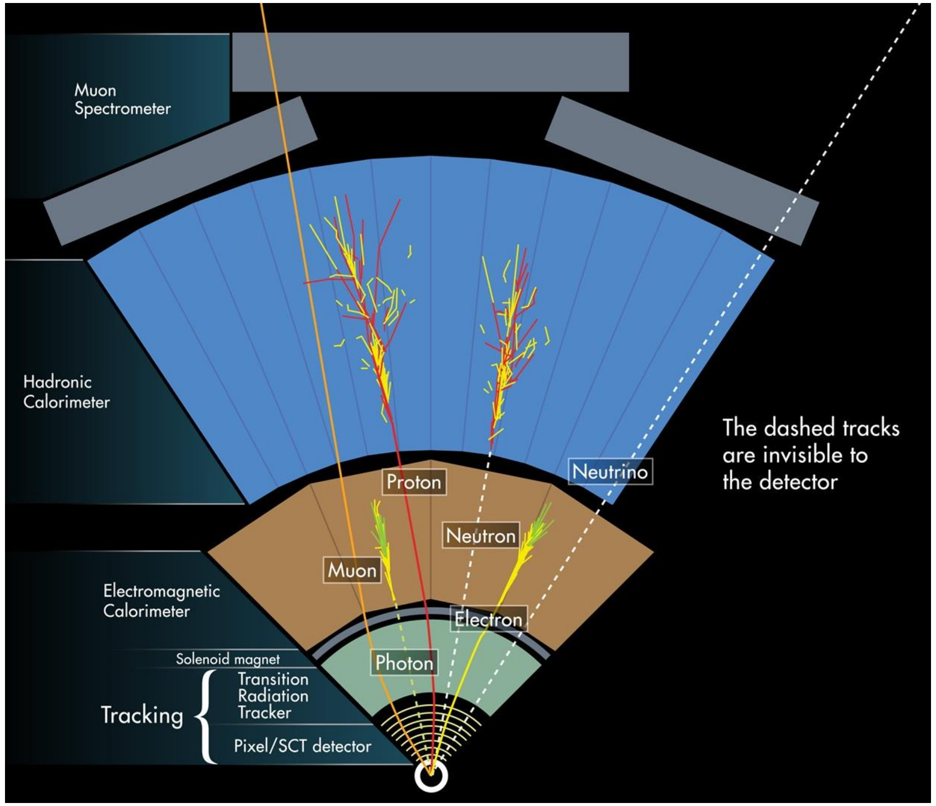
Experimental particle physics

Energies are very high compared to a normal laboratory scale

- High energies require large amounts of absorber material → large detectors
- Some particle species interact so little that they cannot feasibly be stopped (or do not interact at all)

Example: the ATLAS detector





Multiple layers of specialized detector technology: tracking, calorimetry, spectrometers

Experimental particle physics

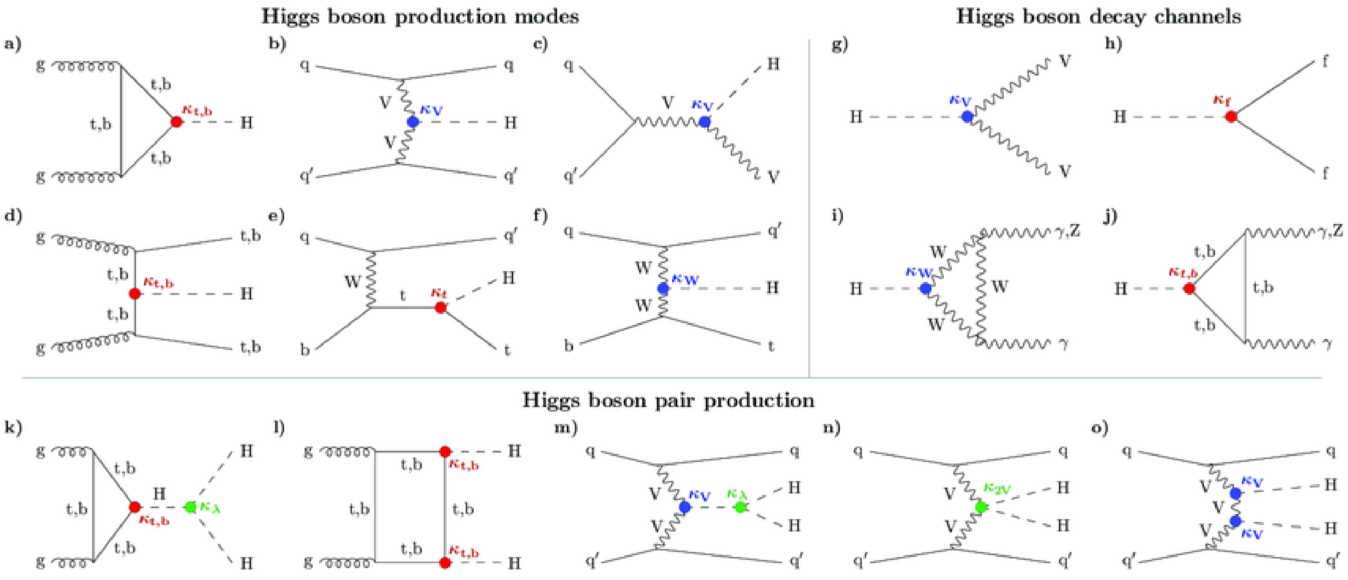
Energies are very high compared to a normal laboratory scale

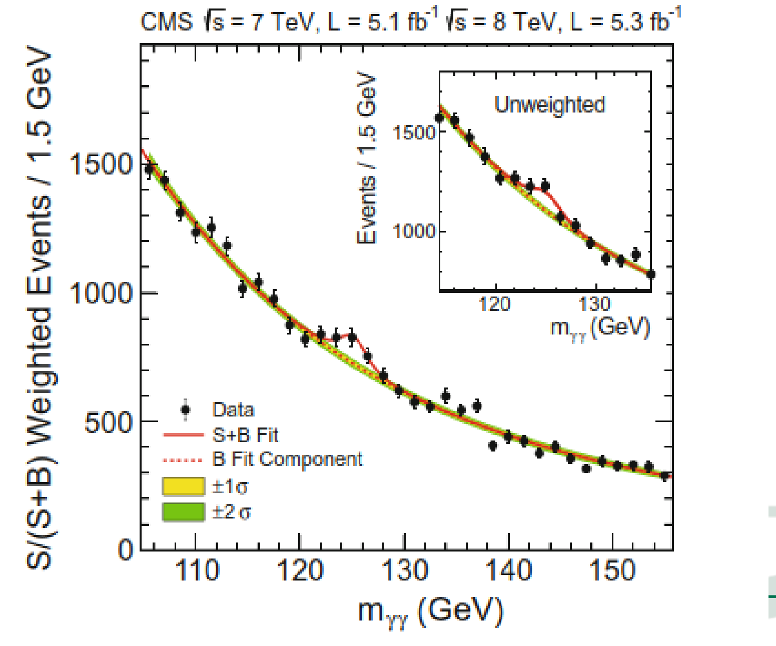
- ➢ High energies require large amounts of absorber material → large detectors
- ➢ Some particle species interact so little that they cannot feasibly be stopped (or do not interact at all)

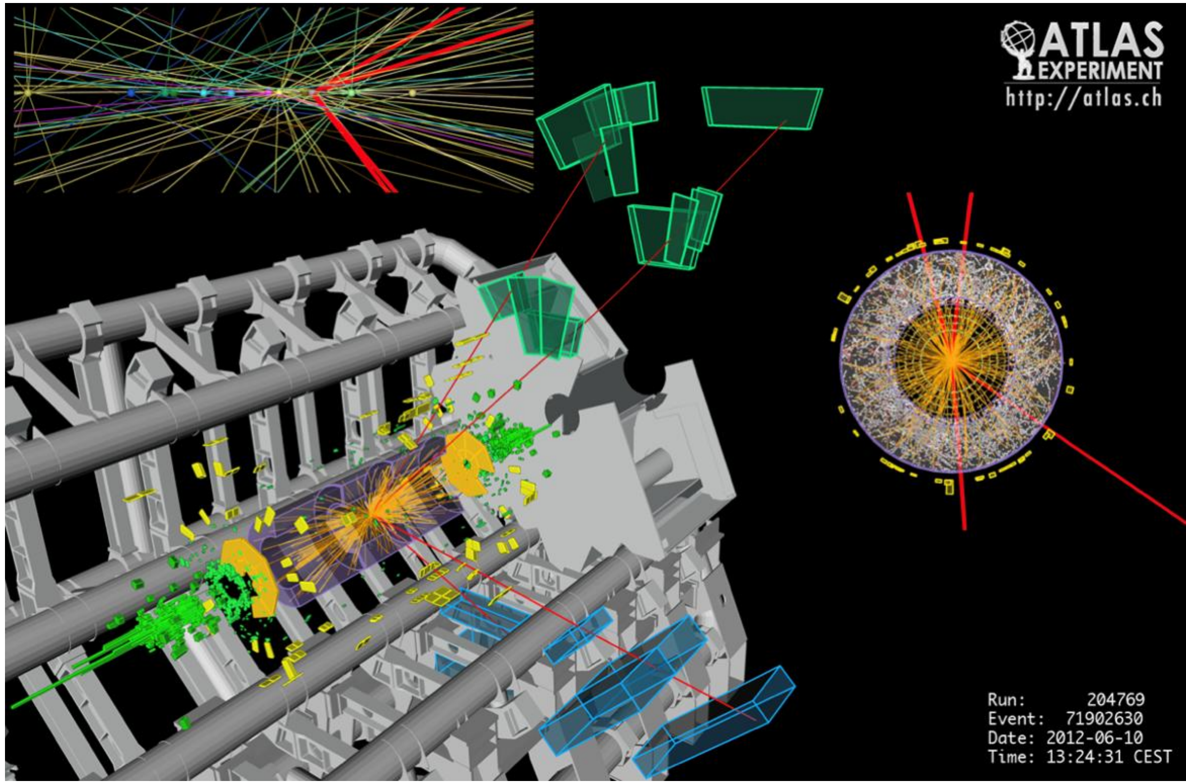
Identification of unstable fundamental particles produced in the collisions relies on precision measurements of their decay products:

- **Energy**
- **Momentum**
- Particle ID

Conservational laws!


Higgs boson production modes
Higgs boson decay channels
Higgs boson pair production
a) b) c) d) e) f) g) h) i) j) k) l) m) n) o)
g
q
q'
t,b
V
W
H
f
γ,Z
γ
$\kappa_{t,b}$
κ_V
κ_t
κ_W
κ_f
κ_λ
κ_{2V}


CMS $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
S/(S+B) Weighted Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)
Unweighted
Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2 σ


ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

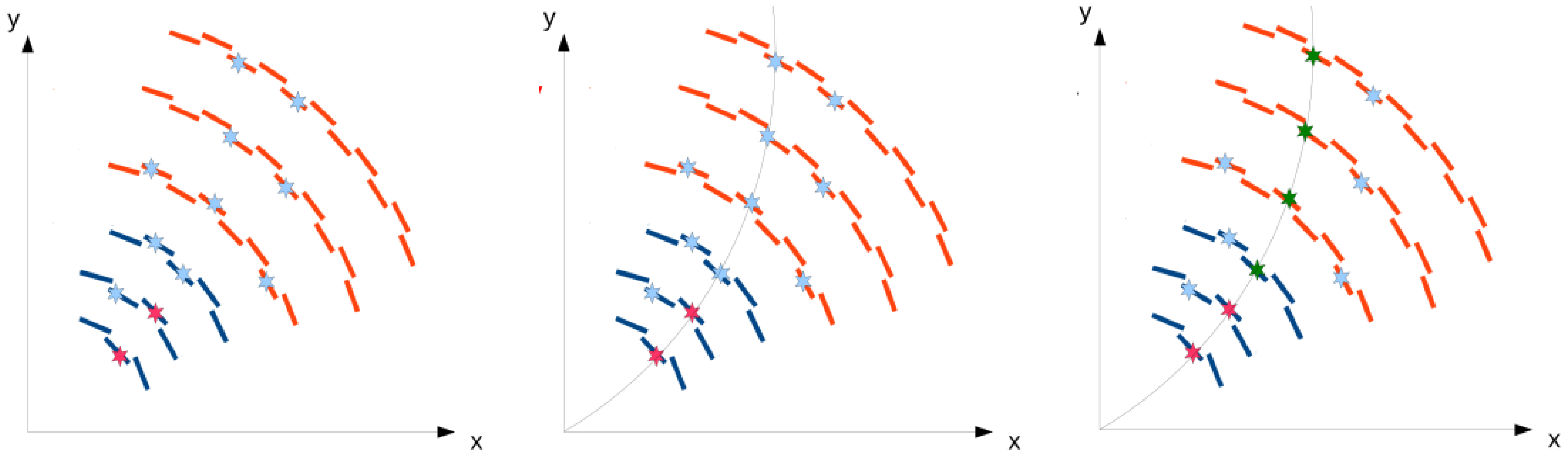
Tracking detectors

Objective: determine the ‘path’ of a particle → calculate its momentum

In a magnetic field, charged particles are deflected:

$$\boldsymbol{F_L} = \frac{d\boldsymbol{p}}{dt} = q\boldsymbol{v} \times \boldsymbol{B}$$

$$p_T = \frac{0.3Bl^2}{8s}$$



Tracking detectors

Objective: determine the ‘path’ of a particle → calculate its momentum

In a magnetic field, charged particles are deflected:

$$\boldsymbol{F_L} = \frac{d\boldsymbol{p}}{dt} = q\boldsymbol{v} \times \boldsymbol{B}$$

$$p_T = \frac{0.3Bl^2}{8s}$$

Requirements:

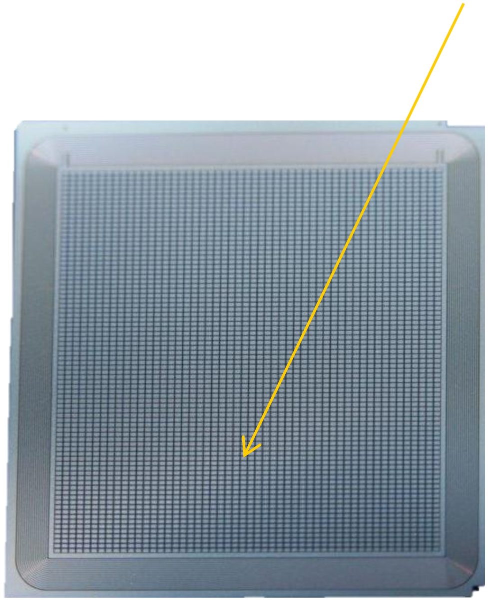
- Multiple layers
- Thin sensors
- Light material
- Capable of detecting small signal
- High spatial resolution = fine segmentation

Avoid scattering of particles

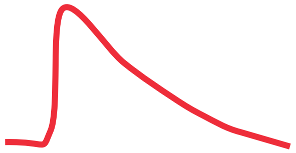
“Solid-state detectors”

Direct interaction = detection of primary particle or photon, conversion to electric charge in a solid material

- ~~**Polymers (bubble chambers etc)**~~ *Structural change instead of charge*
- ~~**Metals**~~ *Conductive*
- ~~**Gas detectors**~~ *Electron-ion pairs, but not solid*
- ~~**Scintillators + photodetectors**~~ *Semiconductor detector is detecting secondary light*



➢ **Semiconducting material: most commonly, but not exclusively, silicon**

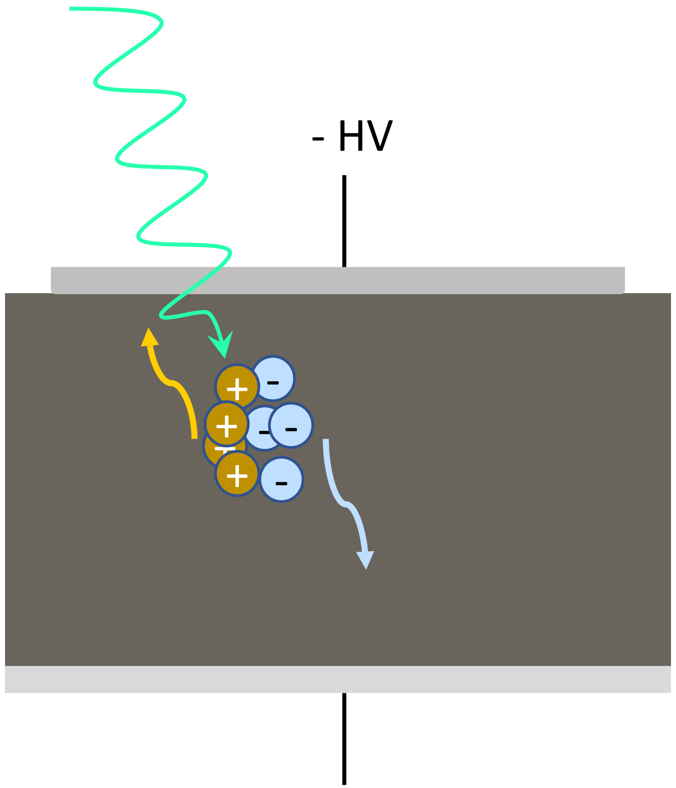


Semiconductor sensors

Similar underlying operation principle as solar cell (more distantly related...) or a silicon photodiode

- Incident photon or particle generates electron-hole pairs
  - Depending on the band gap and work function of the semiconductor: e.g. 1.12 eV for Silicon

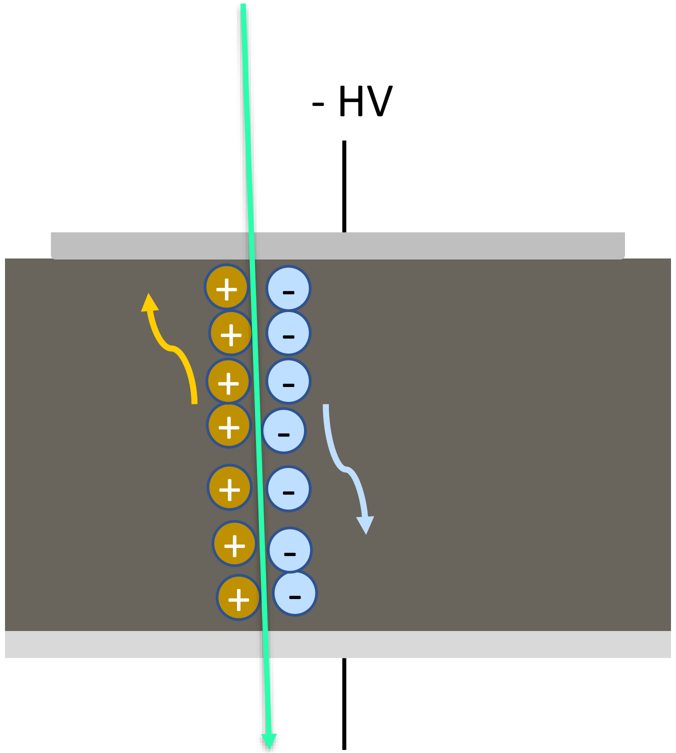
- In an externally applied electric field, i.e. bias voltage, these charges are separated and drift to opposite electrodes
  - ➢ **Signal is a current transient**



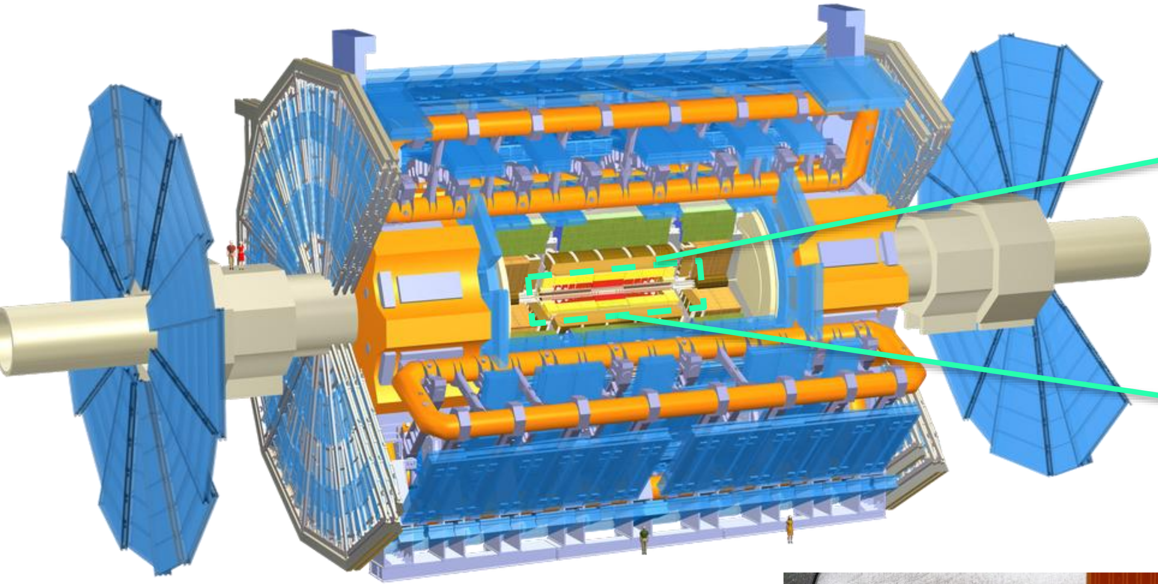
Semiconductor sensors

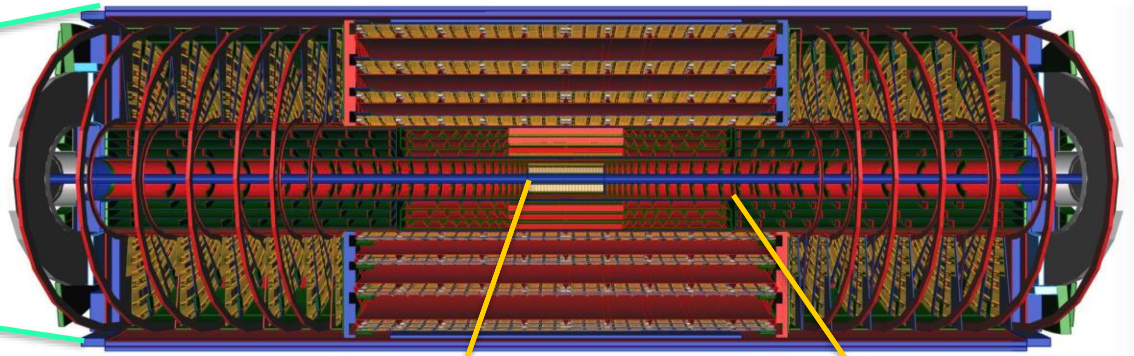
In most collider physics experiments, energies are above the scale of GeV, or at least many tens-hundreds of MeV

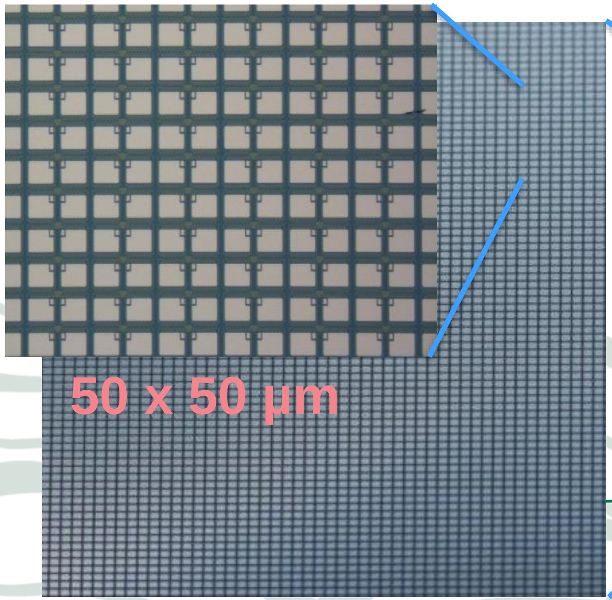
- **Photons do not give a signal in the tracking detector**
  - … As they are electrically neutral (and massless), the purpose of the tracking detector is lost in any case
- **Neutral particles do not interact electromagnetically, do not ionize the material**
- **Semiconductor sensor layers will not absorb, stop the particles!**
  - Instead of a single interaction, charge is generated along the trajectory of the particle in the sensor

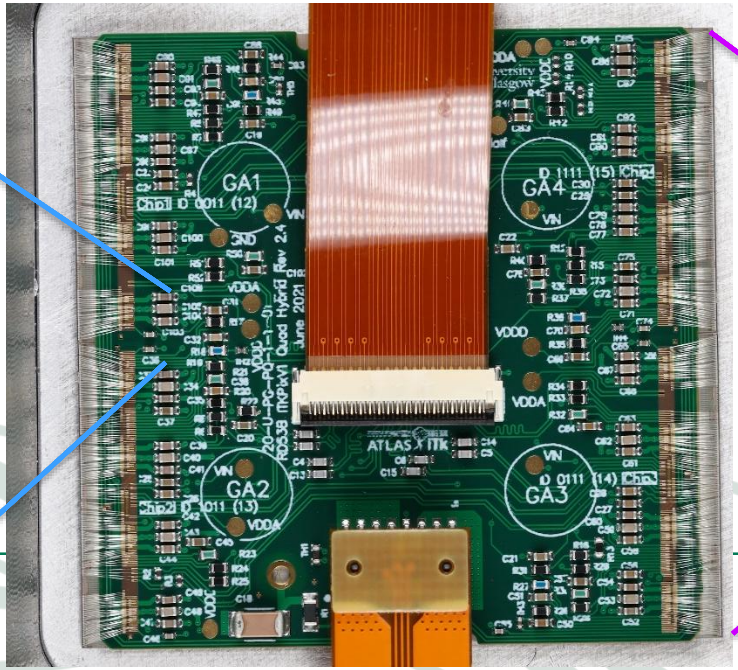


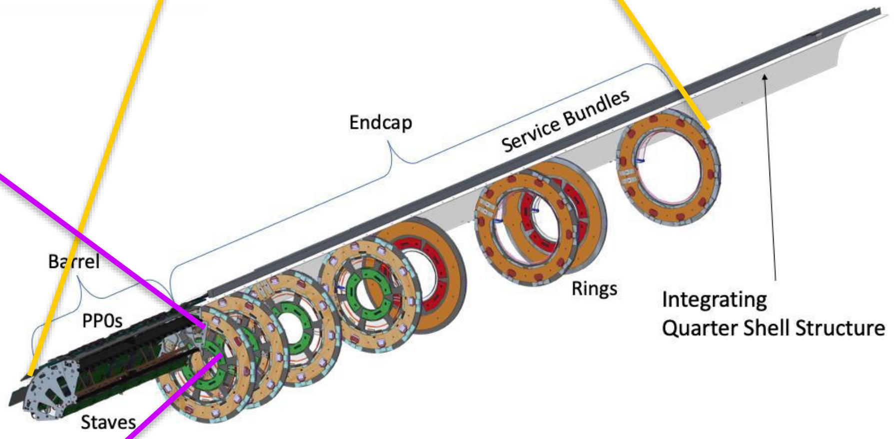
ATLAS Inner Tracker pixels





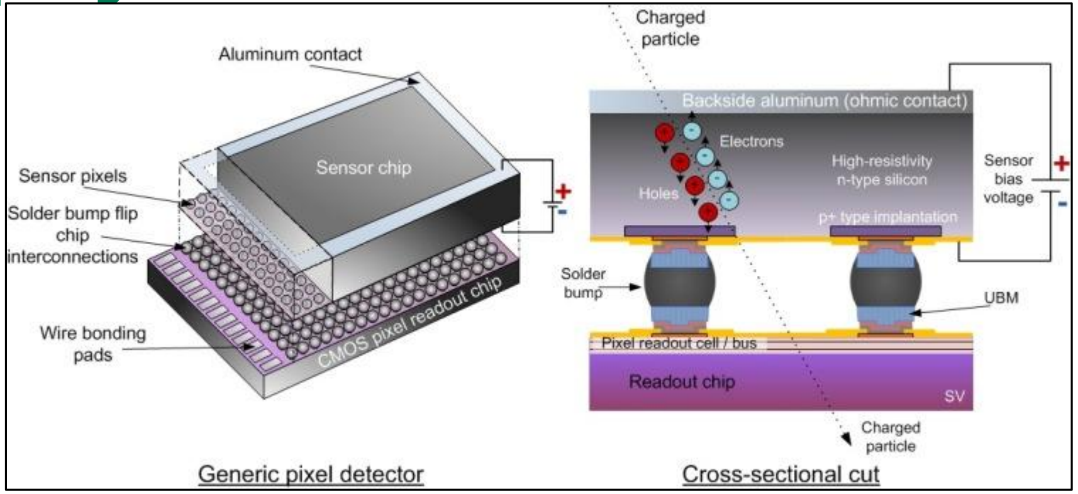






Pixel detectors in high-energy physics

- Research & development of sensors
- Research & development of readout electronics
  - Spatial resolution: decreasing pixel size
  - Radiation hardness
  - Scaling: size and surface area, power consumption



http://x-ray.camera/technology/flip-chip-bonding/

- Building tracking detectors for new collider experiments: sensor and front-end design, integration, services, cooling, quality control, ...

- **Integration of active sensor and readout circuitry: bump-bonding is reaching the limits of technical feasibility**
- **Other materials than silicon?**

Example: the RD53 readout ASICs

New detectors are installed for the high-luminosity stage of the LHC, which is scheduled to start in 2029

Pixel detectors:

- Radiation hardness
- Larger ASIC: ~ 2x2 cm
- Low occupancy, < 1%
- Smaller pixel size: 25 x 100 or 50 x 50 µm

ATLAS and CMS Experiments collaborated in developing a framework for the pixel readout chip through the 'RD53' collaboration

- 65 nm CMOS process at TSMC
- RD53A: divided into three regions with different front-end (linear, differential, synchronous)

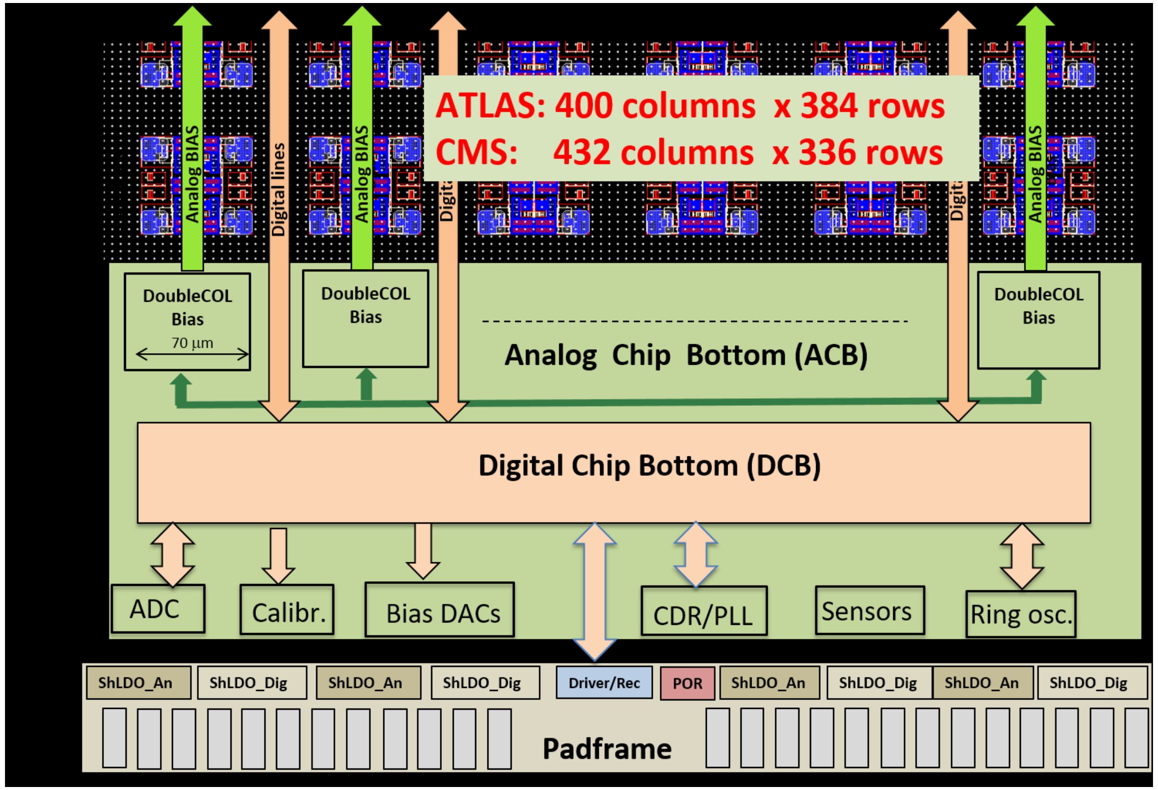
RD53C – ITkpix v2

RD53B: diverging into ITkpix (differential FE, for ATLAS) and CROC (linear FE, for CMS)

- Full chip size: 400 x 384 pixels in the case of ITkpix
- Two tapeouts to finalize design and correct flaws, including critical ones in the ToT block

RD53C: ITkpix v2 – final chip

- Full ToT functionality
- Self-triggering

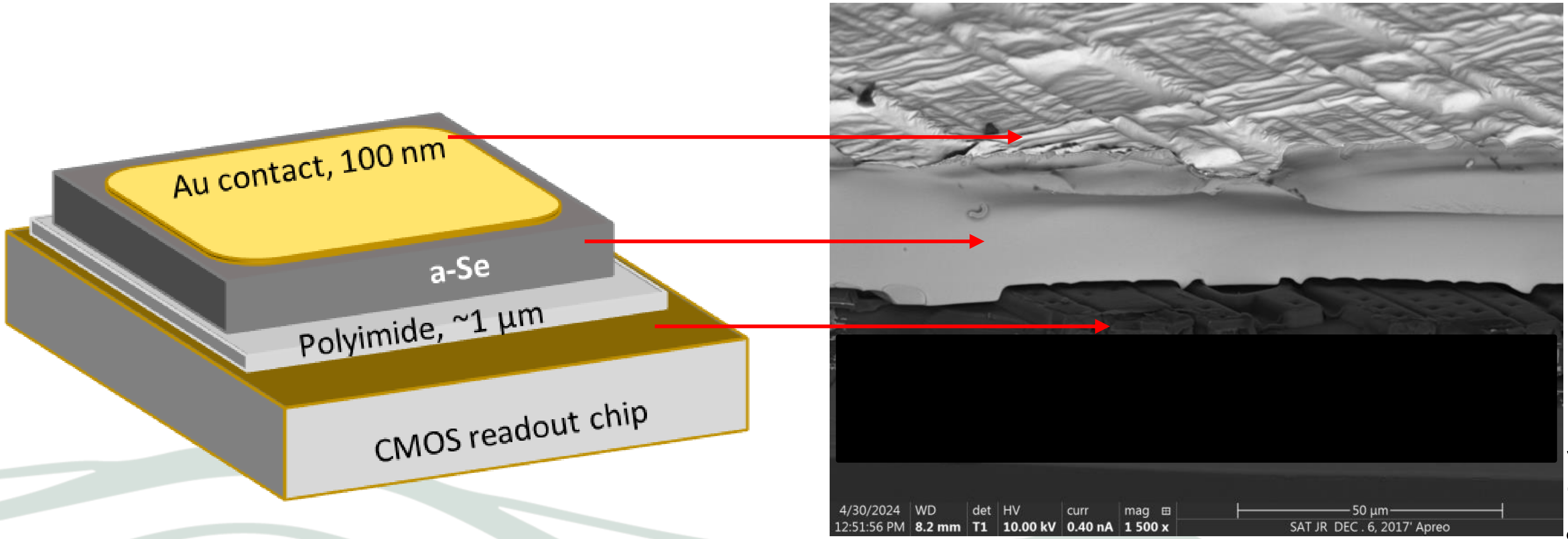


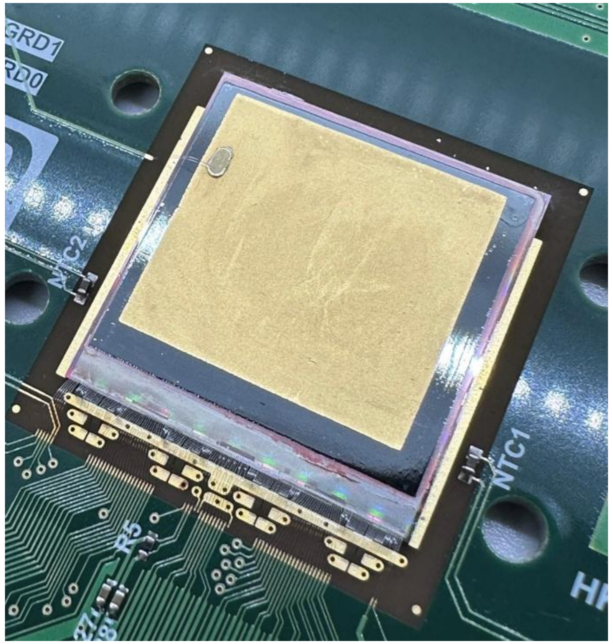
M. Garcia-Sciveres et al (2024), RD53C manual, CERN-RD53-PUB-24-001

Research example: thin film detectors

Active sensor material is deposited directly onto the fully fabricated ASIC

- Here: amorphous Selenium
- No solder bumps or flip-chip assembly
- No separate sensor processing



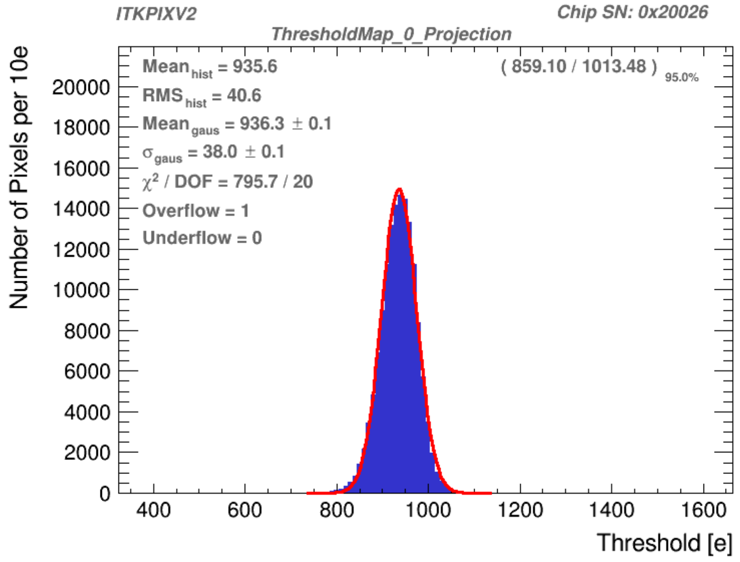


SEM cross-section of an a-Se / CMOS sensor, here with 25 µm a-Se

Research example: thin film detectors

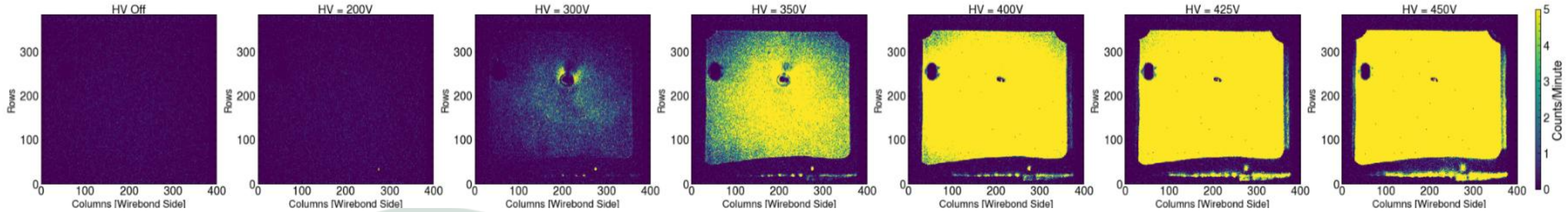
Active sensor material is deposited directly onto the fully fabricated ASIC

- Here: amorphous Selenium
- No solder bumps or flip-chip assembly
- No separate sensor processing

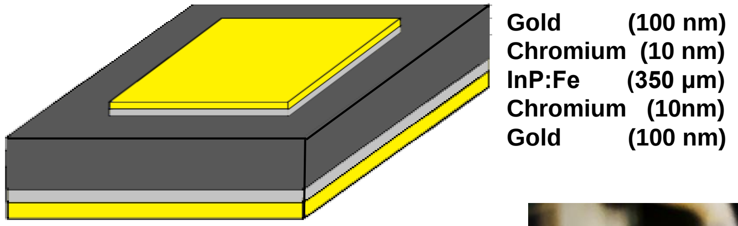


Selenium is used in flat panels for x-ray detection: applications to medical imaging

➢ **Interdisciplinary / cross-cutting research!**

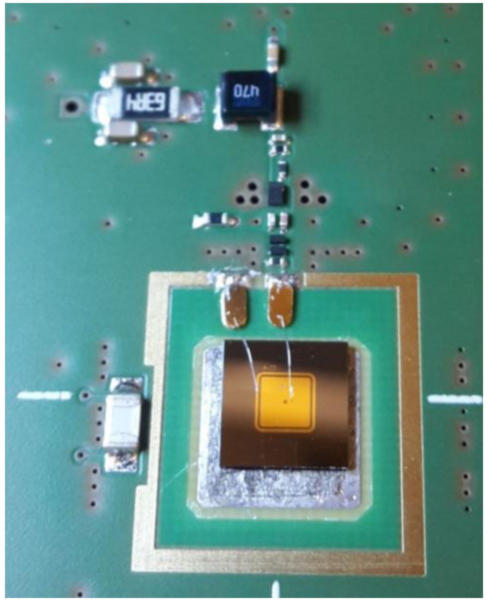


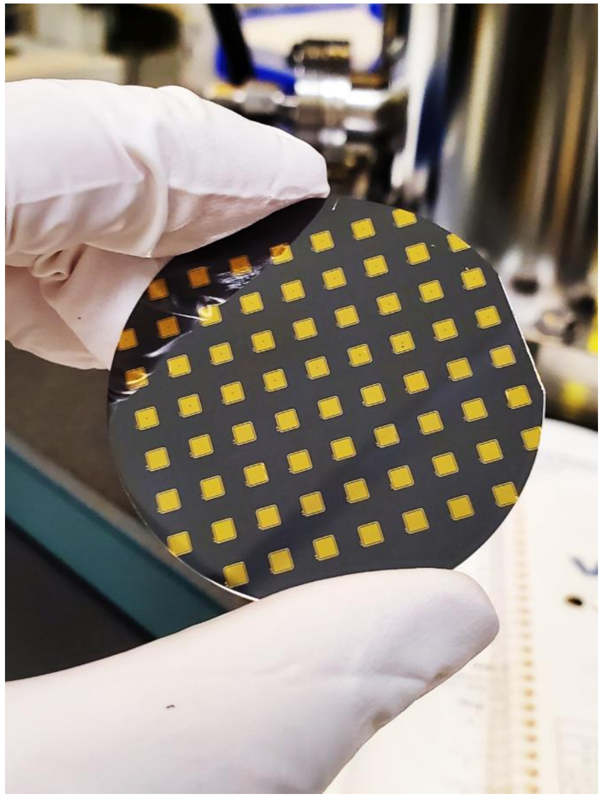
Research example: InP

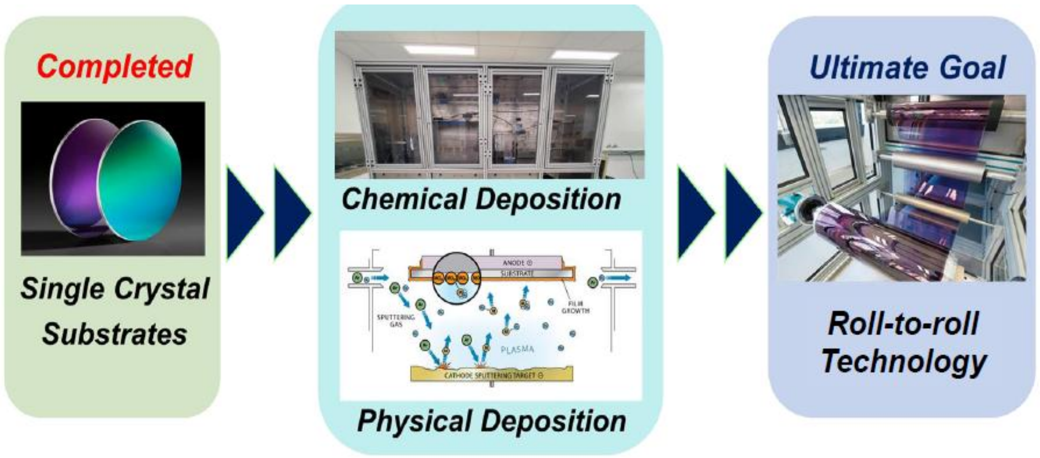


Indium phosphide: compound semiconductor with very high electron mobility

- Reference samples fabricated on crystalline substrates; goal is large-area deposition as thin films
- Studies on timing resolution and radiation hardness



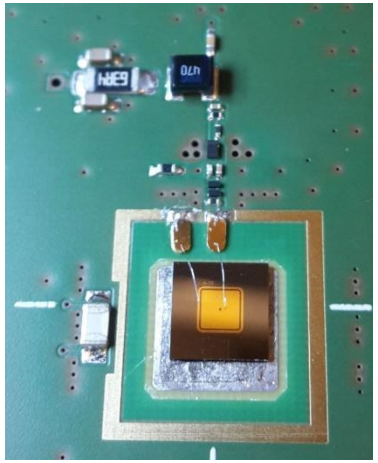




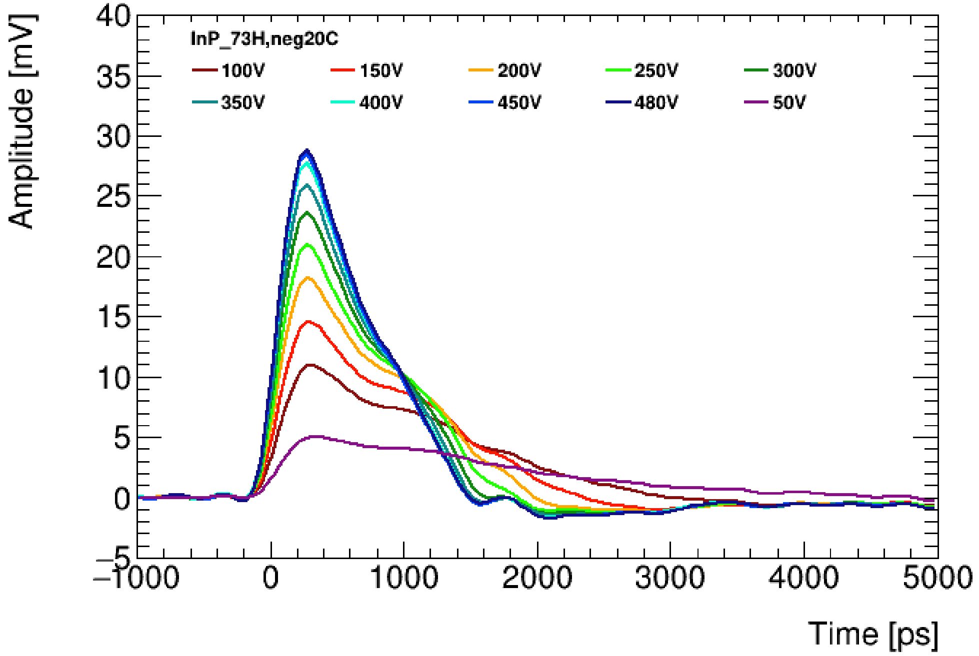
Research example: InP

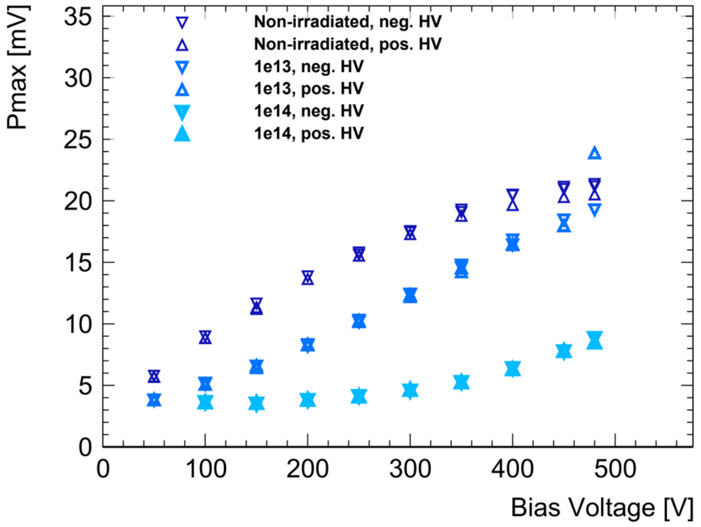
Indium phosphide: compound semiconductor with very high electron mobility

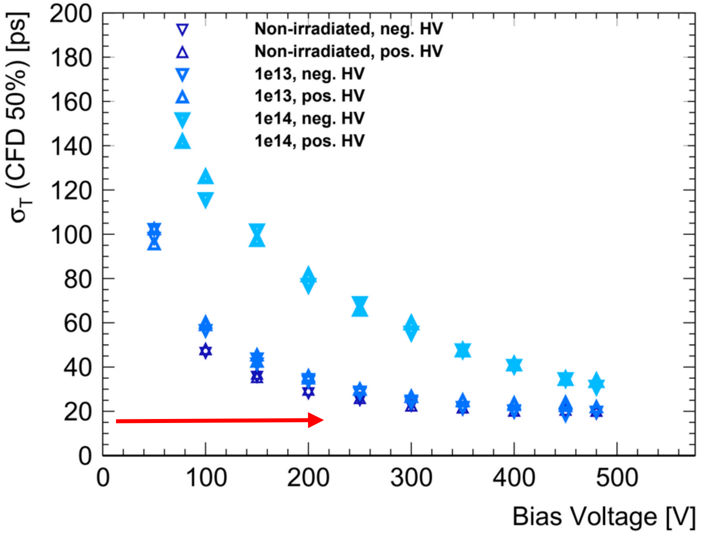
- Reference samples fabricated on crystalline substrates; goal is large-area deposition as thin films
- Studies on timing resolution and radiation hardness



< 1-2 ns signal collection







Retaining excellent timing resolution

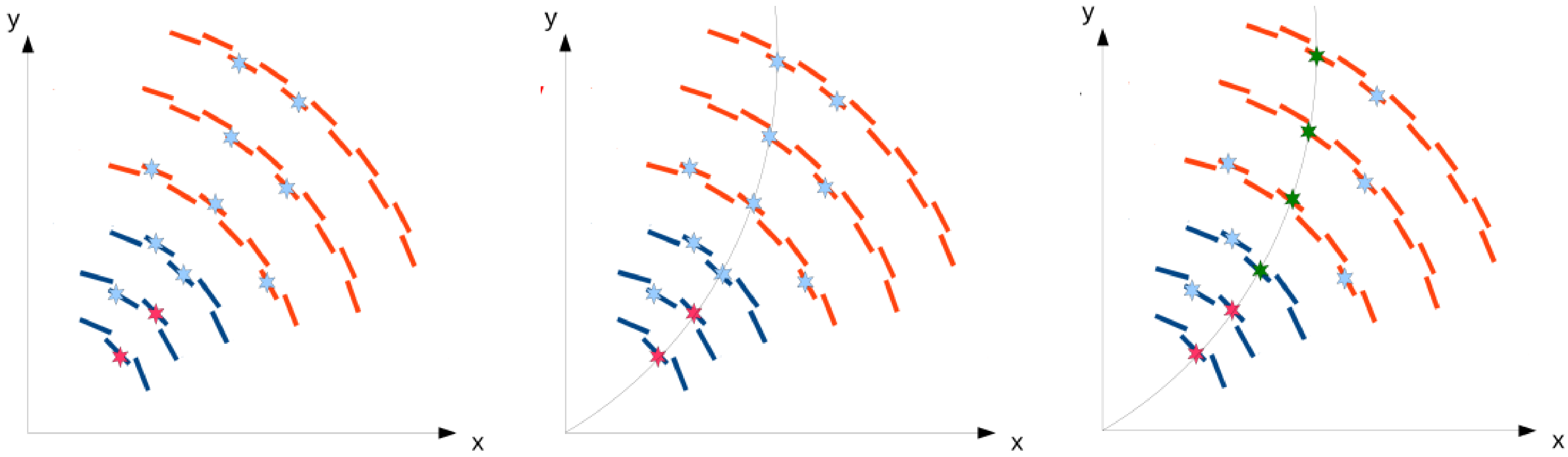
Tracking detectors ...

Objective: determine the 'path' of a particle → calculate its momentum

In a magnetic field, charged particles are deflected:

$$\boldsymbol{F_L} = \frac{d\boldsymbol{p}}{dt} = q\boldsymbol{v} \times \boldsymbol{B}$$

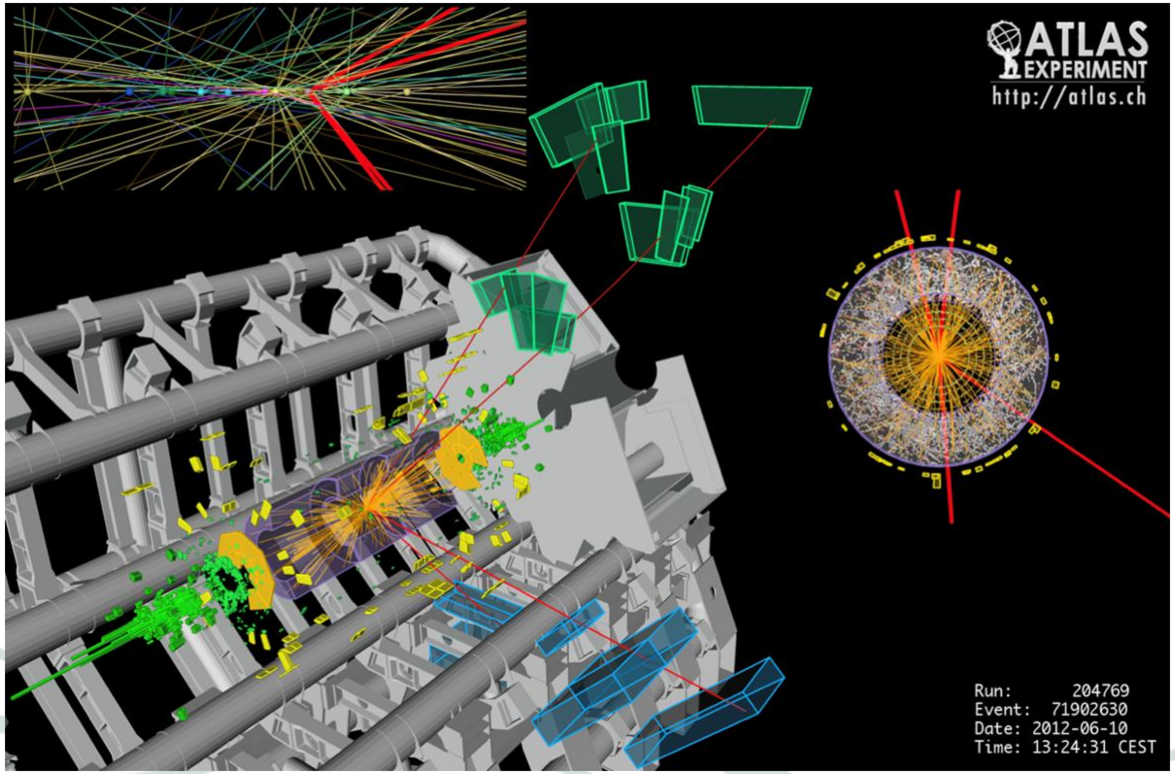
$$p_T = \frac{0.3Bl^2}{8s}$$

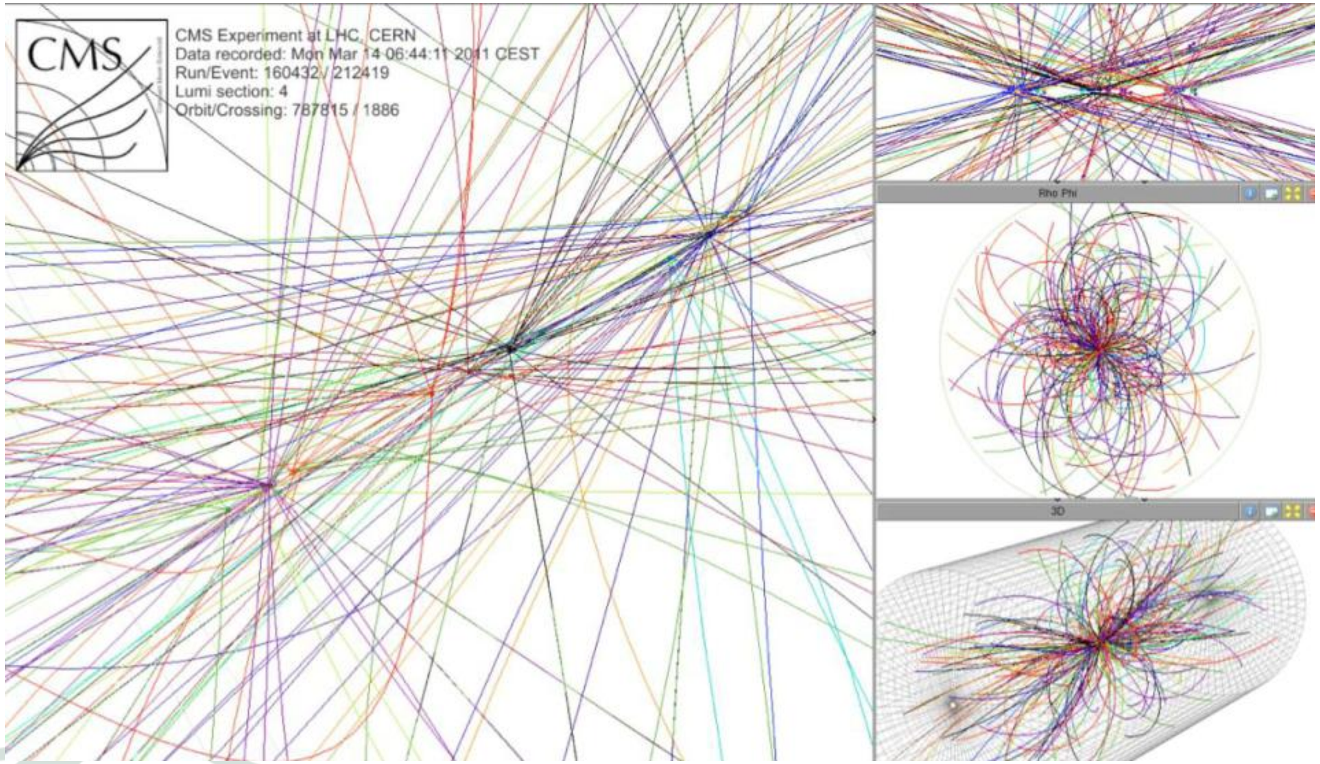


Particle tracking and vertexing

Several collisions per bunch crossing:

→vertexing: point / associate a track to the original interaction point

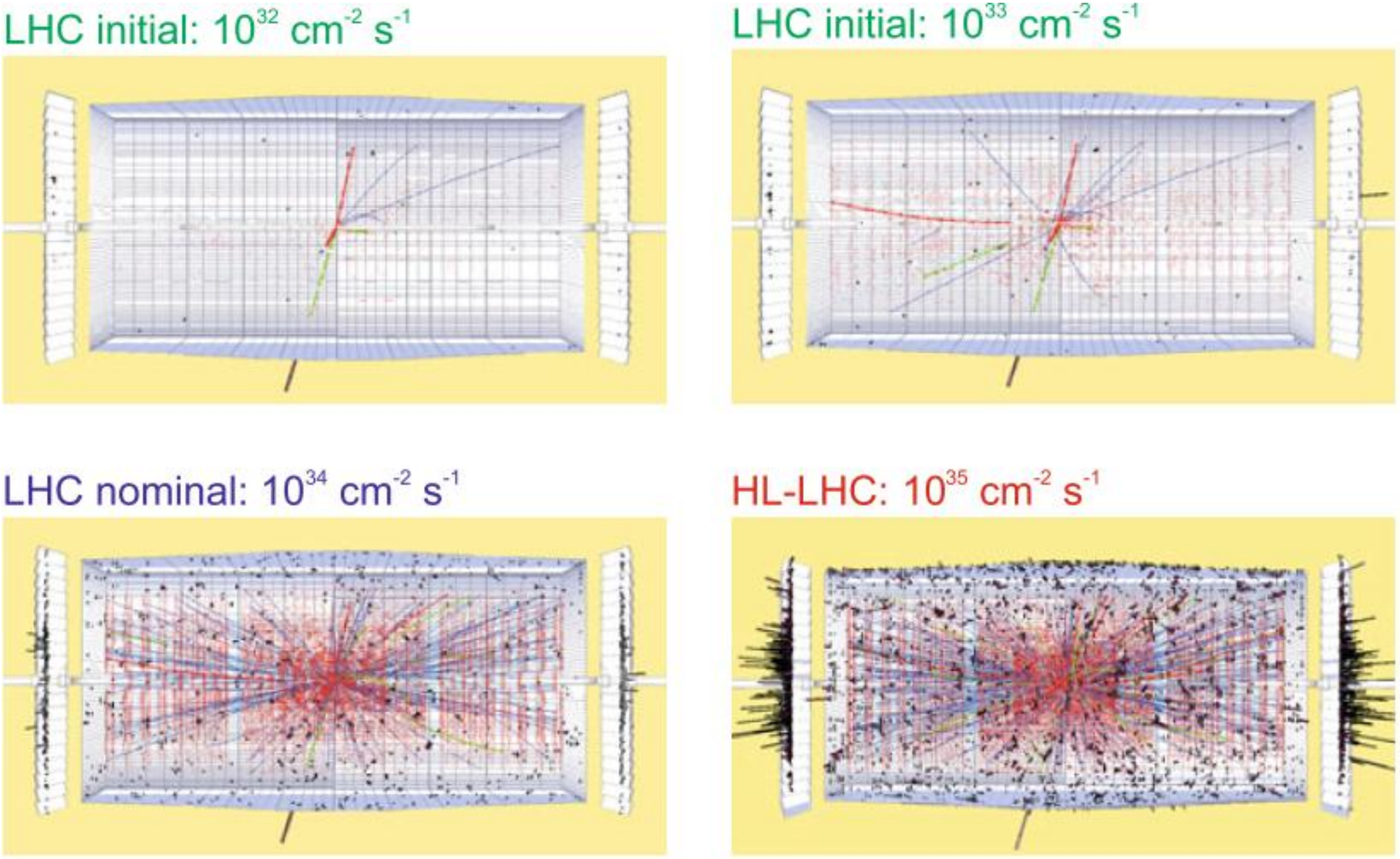




Precision timing

At the HL-LHC, the number of interactions per bunch crossing, i.e. *pile-up* increases from ~50 to ~200

- ***Timing resolution of 30-60 ps is needed to associated tracks to primary vertex (and improves many analyses performances)***



Timing detectors at the HL-LHC

Largest targeted efforts in fast sensor development: Phase-2 upgrades of ATLAS and CMS experiments at the LHC for the HL-LHC

- Bunch crossing frequency: 40 MHz = 25 ns
- p-p collision center-of-mass energy up to 14 TeV
- Schedule: HL-LHC planned to (re)start in 2030 -> timing detector production and installation after 2028

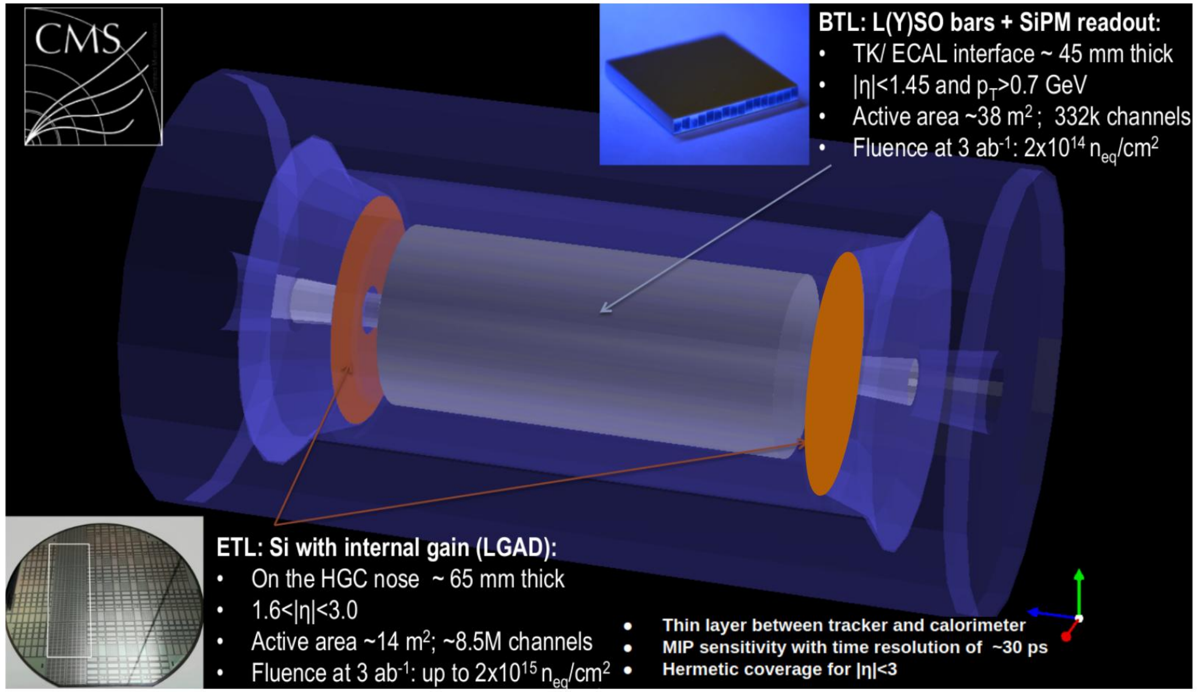
- Main objective: pileup mitigation, retaining it at the level of the current LHC (~30)
- Radiation hardness in a proton-proton collision environment: $2x10^{14}$ - $2x10^{15}$ n/cm^2
- Timing layers are new detector systems; located between Si tracker and EM calorimeters

Precision timing

CMS and ATLAS experiments will install dedicated MIP timing detector layers in the Phase-2 upgrades, between tracking systems and calorimeters

CMS
- Barrel and endcap region with different technologies: barrel scintillators + SiPM, endcap with fast silicon detectors – **LGAD**s

ATLAS
- Timing detectors only in the endcap region, with **LGAD**s



CMS MTD Technical Design report

CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

Precision timing

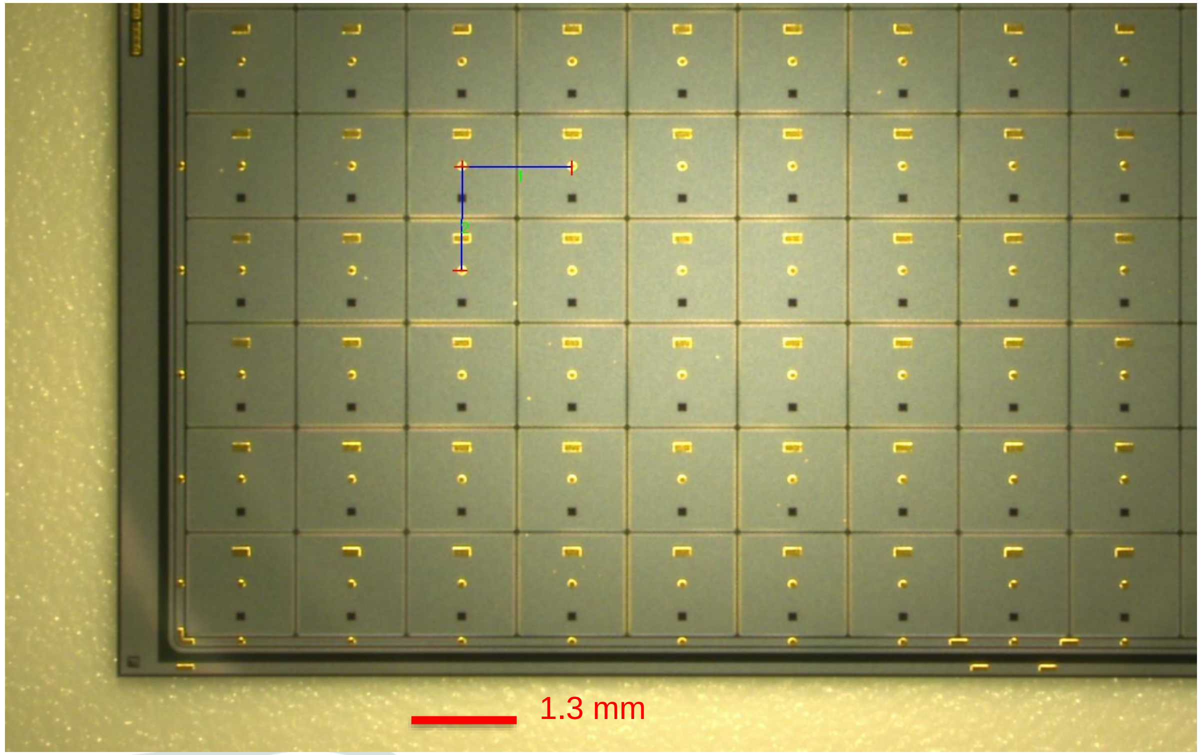
CMS and ATLAS experiments will install dedicated MIP timing detector layers in the Phase-2 upgrades, between tracking systems and calorimeters

CMS

- Barrel and endcap region with different technologies: barrel scintillators + SiPM, endcap with fast silicon detectors – **LGAD**s

ATLAS

- Timing detectors only in the endcap region, with **LGAD**s

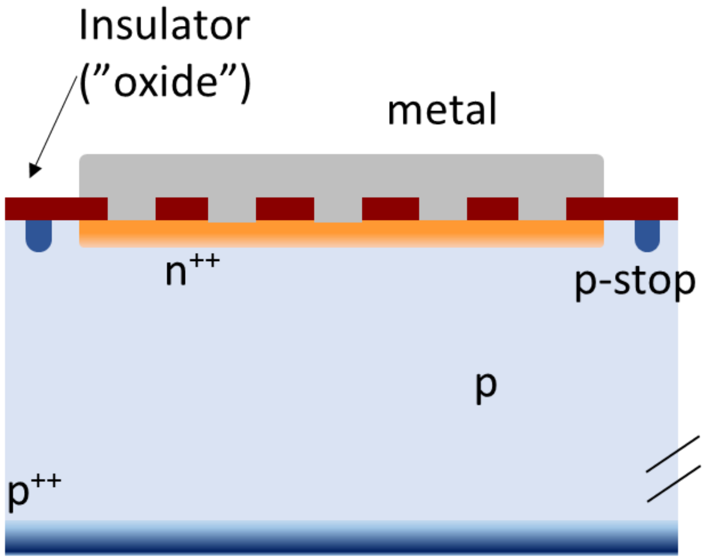


15x15 pad prototype LGAD sensor for HGTD

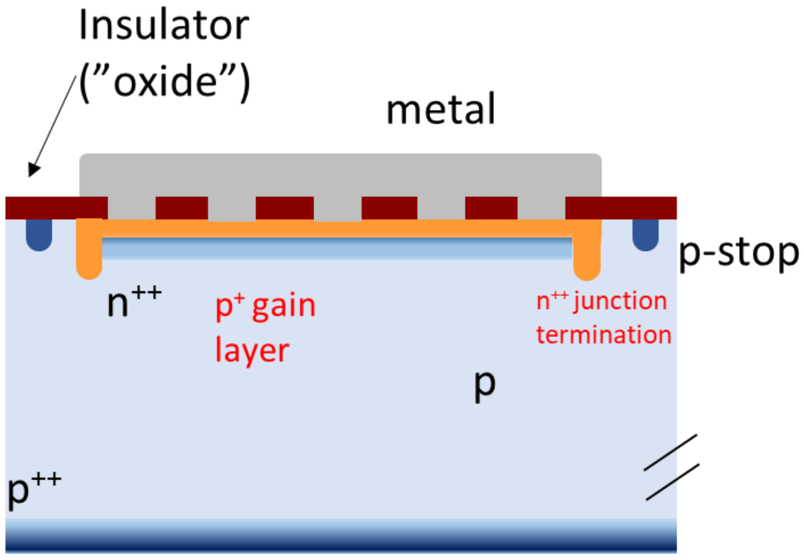
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

Low-gain avalanche diodes

Multiplication layer implanted with higher doping concentration – localized high electric field leads to impact ionization of secondary charge carriers



n-in-p normal diode

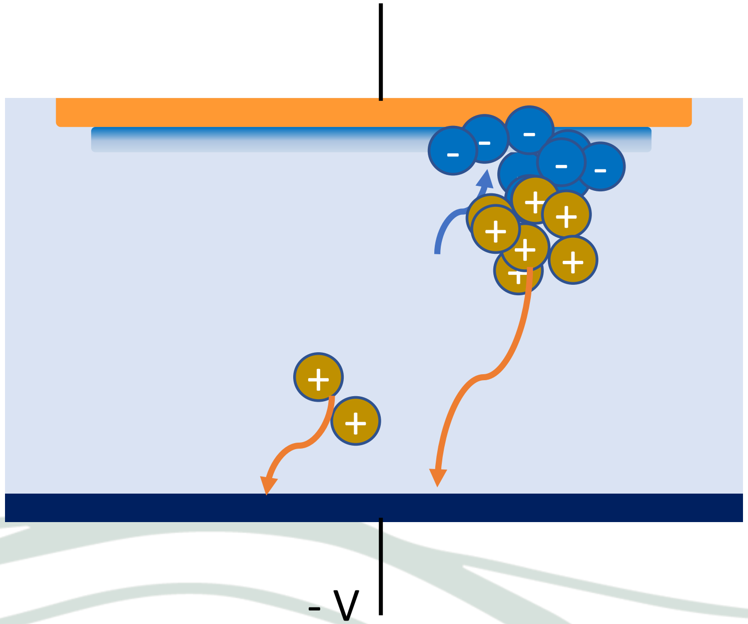


n-in-p LGAD

e.g. H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101

Low-gain avalanche diodes

- **Gain layer with moderate doping concentration (lower than n^{++} or p^{++} contacts) results in localized, higher electric field**
- **Electrons reach enough kinetic energy to ionize other atoms in the Si lattice – multiplication, 'avalanche'**



1. Electrons drift to the segmented electrode and pass by the gain layer
2. Holes drift to backplane
3. Electrons generate new e-h pairs at the gain layer
4. New electrons only drift a few µm to the front electrode: are typically obscured by rise time of the electronics
5. **New holes drift through the bulk to the backplane**

Low-gain avalanche diodes

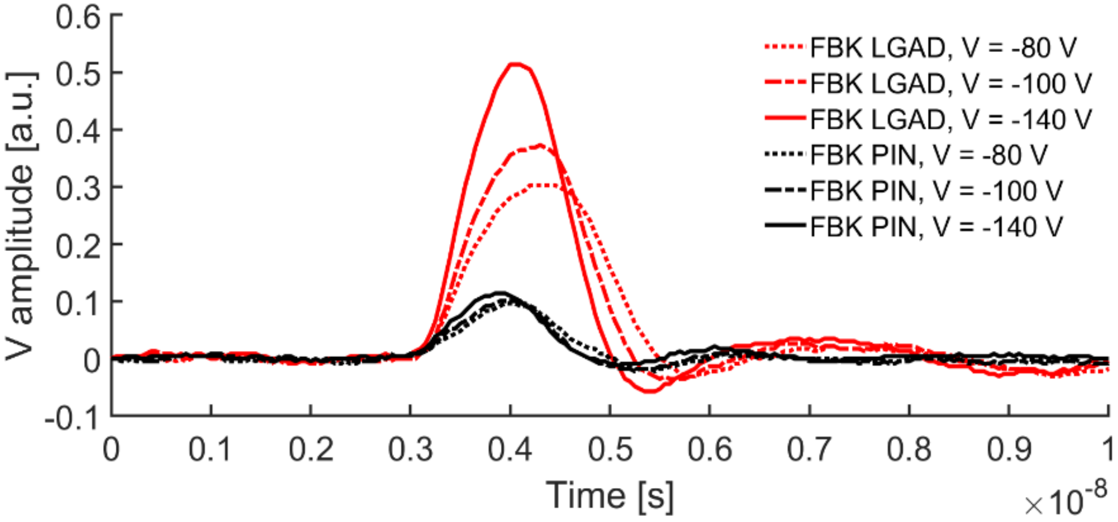
Thin sensors, typical active thickness 50 µm – shorter drift time, higher electric field, less Landau fluctuations!

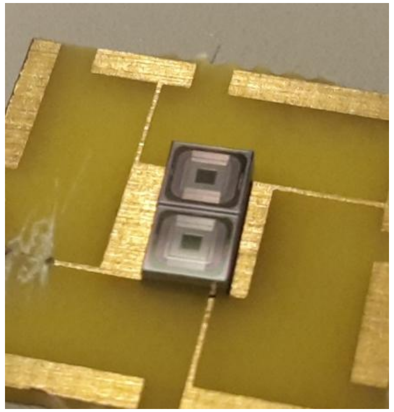
- Mechanical support wafer 150-400 µm!

Low to moderate gain (5-50) provided by p⁺ multiplication layer

Timing resolution down to ca. 20 ps

Good radiation hardness up to 10^{15} n_{eq}/cm^2





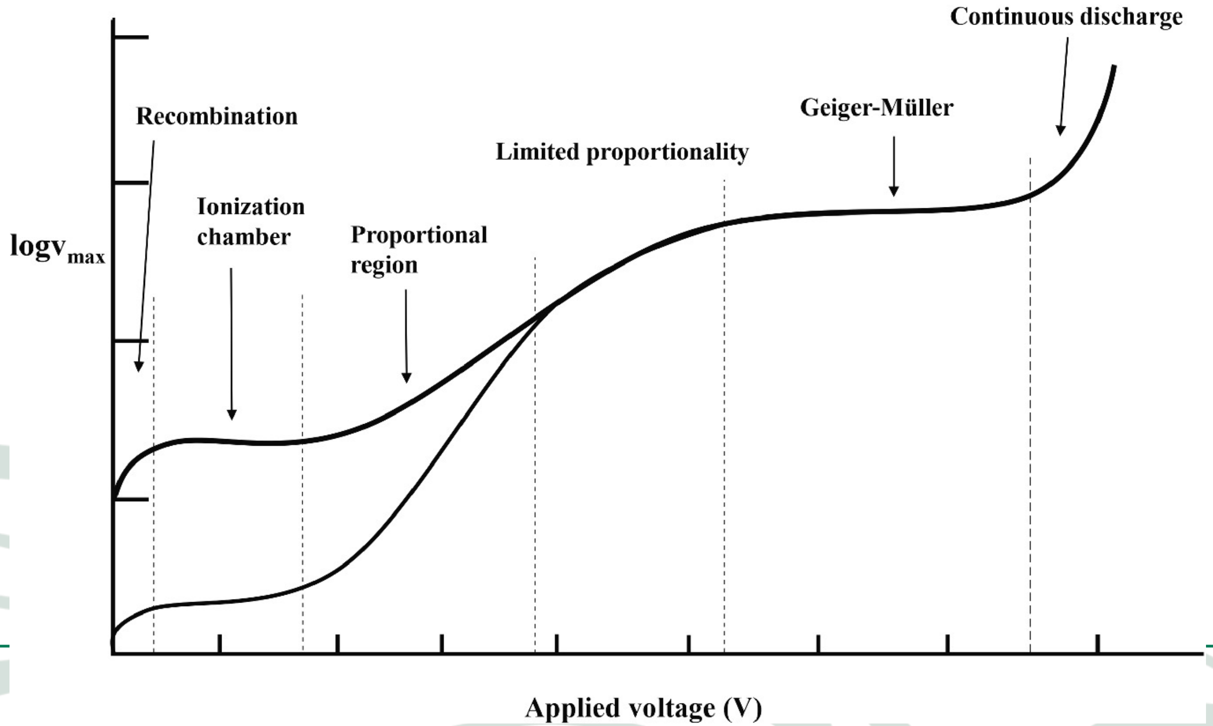
Gain determination with LGAD-diode pairs in laser TCT

H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

Low-gain avalanche diodes

Multiplication layer implanted with higher doping concentration – localized high electric field leads to impact ionization of secondary charge carriers

Difference to SiPM: only primary electrons are multiplied



Low-gain avalanche diodes

Multiplication layer implanted with higher doping concentration – localized high electric field leads to impact ionization of secondary charge carriers

Difference to SiPM: only primary electrons are multiplied

- Sensor is in proportional mode, not in Geiger mode reaching saturation for each photoelectron
  - Low to moderate gain of ca. 5 – 50
  - Spatial resolution is determined by electrode segmentation, like a standard planar Si sensor

- Slower onset of gain, increase with bias voltage
  - Operation voltage and breakdown depends on desired gain, gain layer and sensor edge architecture: 150 – 450 V

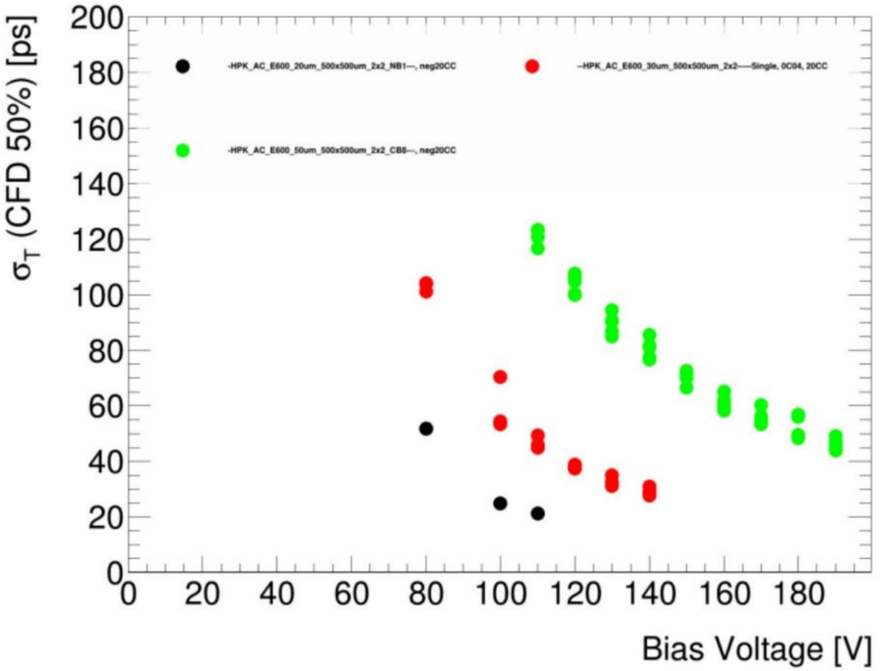
- *Directly detecting charged particles, not photons: no optimization of surface to reduce light reflection, external quantum efficiency not considered*

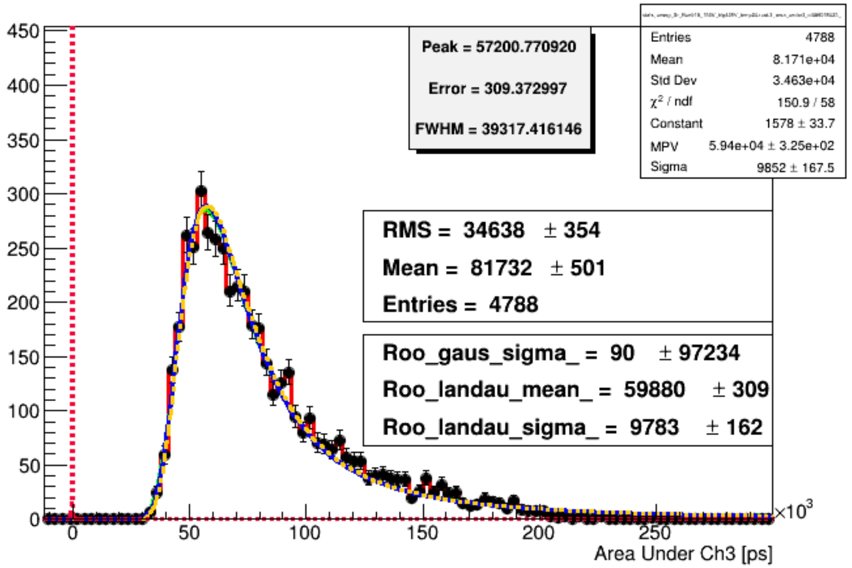
Timing resolution

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time\ walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$

Timing resolution consists of several contributions

- Landau fluctuations of charge deposition: reduce by thinner sensor
- Time walk
- Jitter (sensor & electronics)
- TDC



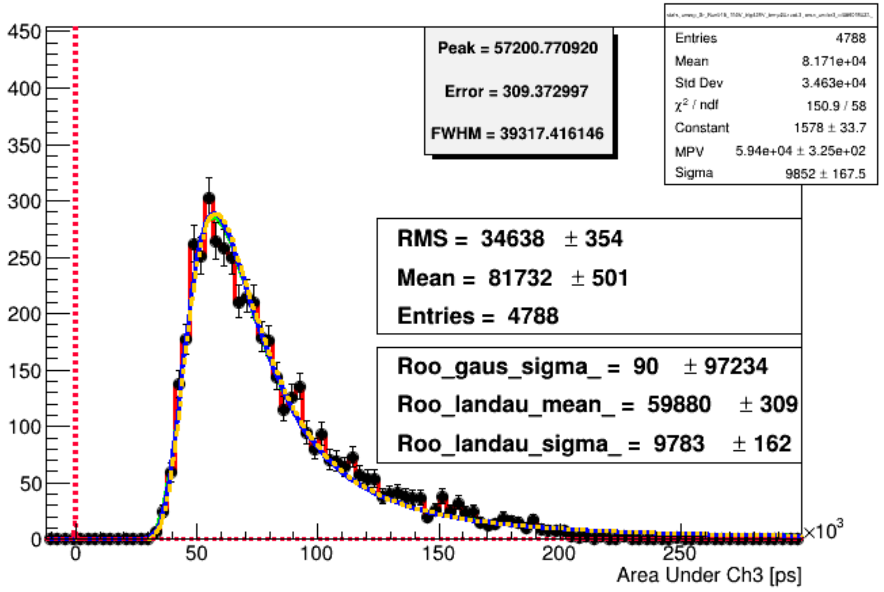


Timing resolution

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time\ walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$

Timing resolution consists of several contributions

- Time walk: can be corrected for
- Jitter (sensor & electronics)
- TDC
- **Landau fluctuations of charge deposition: lowered by reducing the amount of material traversed, i.e. using thin sensors**
  - ‘Standard’ LGAD active thickness 50 µm
  - Also results in shorter drift time and higher electric field at the same absolute voltage



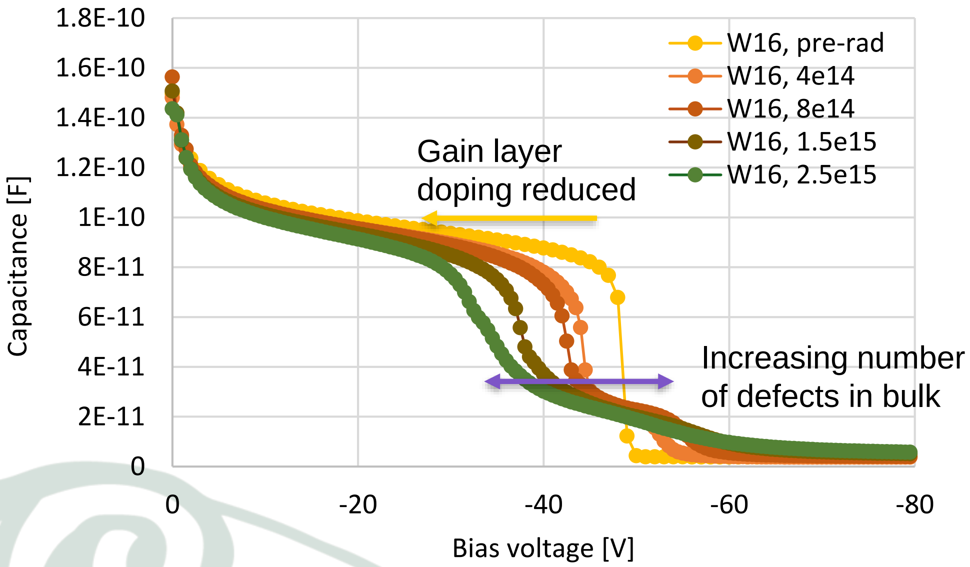
For handling reasons in fabrication – bonding or epitaxial growth of active Si on a low-resistivity mechanical support wafer, 150-400 µm!

Radiation damage in LGADs

LGADs (regardless of what structural variant) suffer from degradation of the gain due to deactivation of acceptors

Can be addressed to some extent by gain layer and defect engineering:

- Different dopant: e.g. Ga instead of B
  - Not successful
- **Carbon co-doping**
  - **Successful at reducing gain layer deactivation**
- Partially activated boron
  - More recent; very mixed results for different vendors



Fast timing at other colliders

Motivation: nuclear physics experiments

Nucleon and nuclei structure, mass and spin; QCD at extreme densities; ‘imaging’ of nuclei

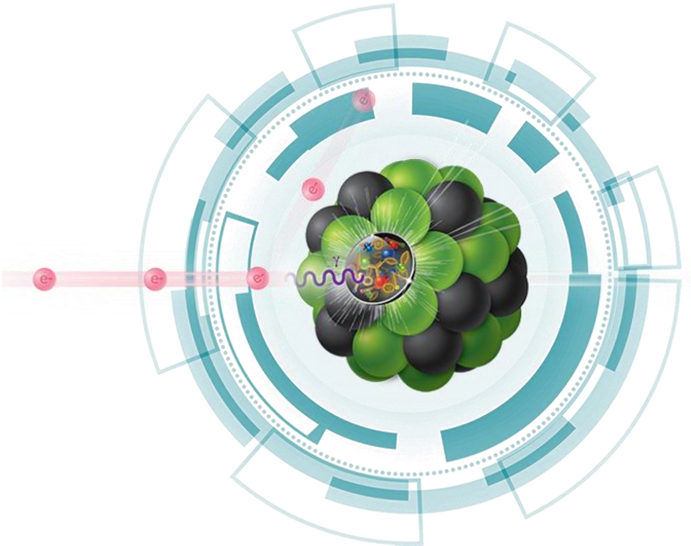
Electron-Ion Collider: joint project by Brookhaven and Jefferson National Laboratories

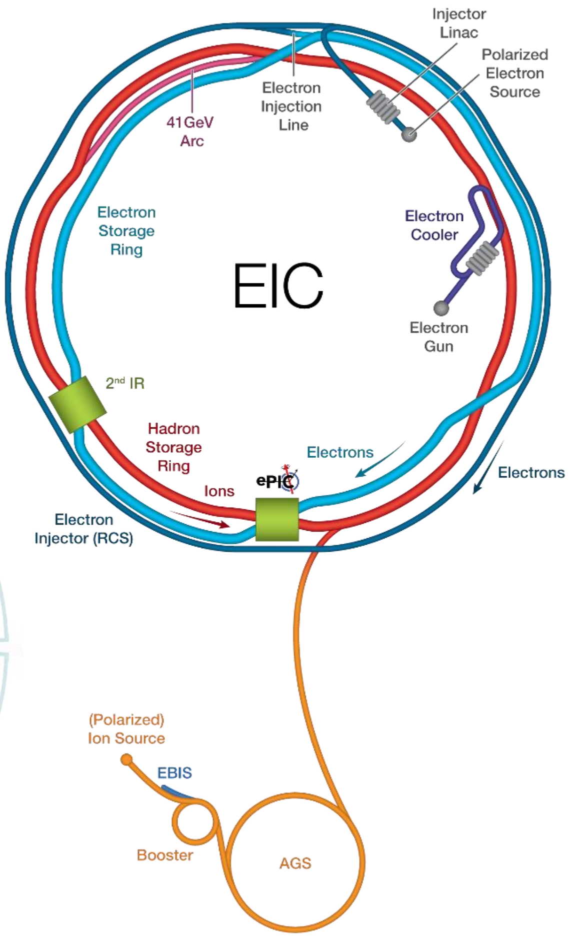
Operations scheduled to begin 2032-2034

Center-of-mass energy: 20 –140 GeV

- electrons: 2.5 –18 GeV
- protons: 40 –275 GeV (ions: Z/A * E_p)

Luminosity: 2×10^{34} $cm^{-2}s^{-1}$

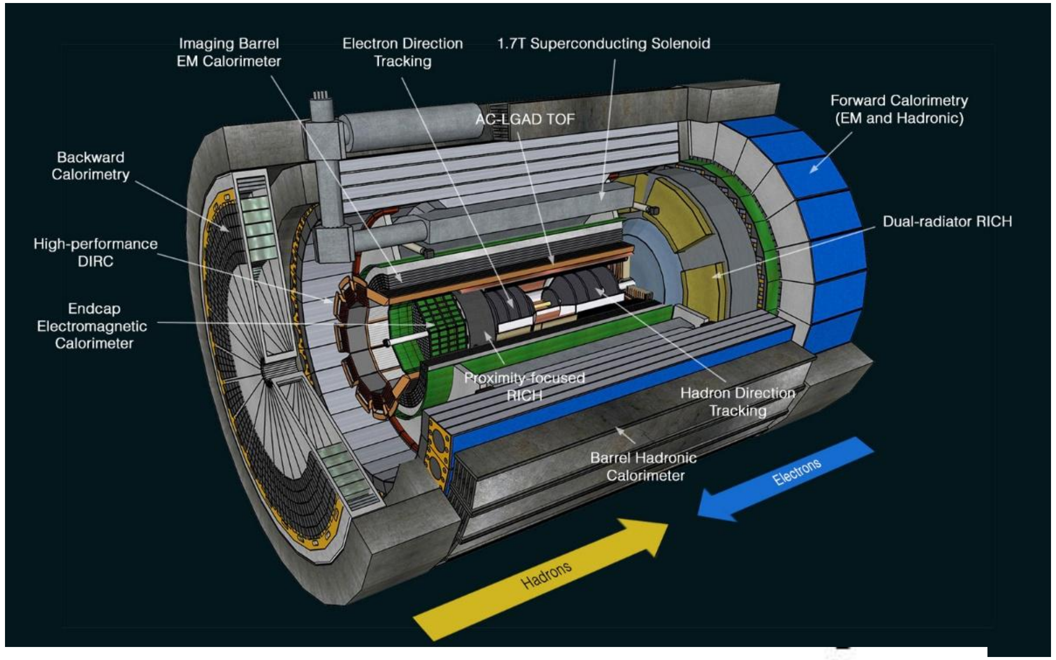




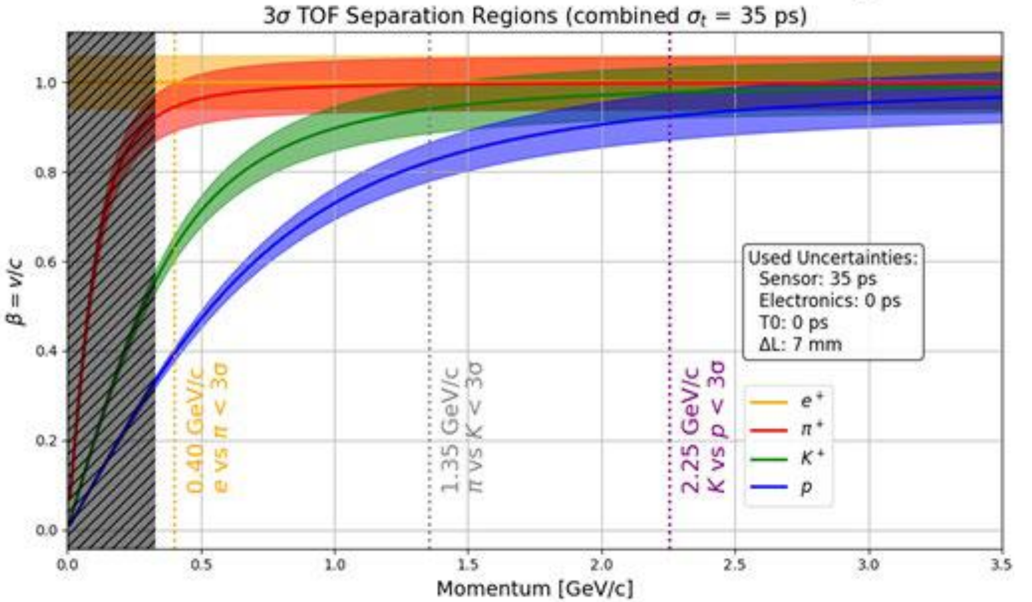
Particle ID

Several detectors for particle ID in inner or outer barrel layers, hadronic endcap, electron endcap

- Momentum and rapidity range cannot be covered by a single technology
- Leveraging variants of Cherenkov detectors



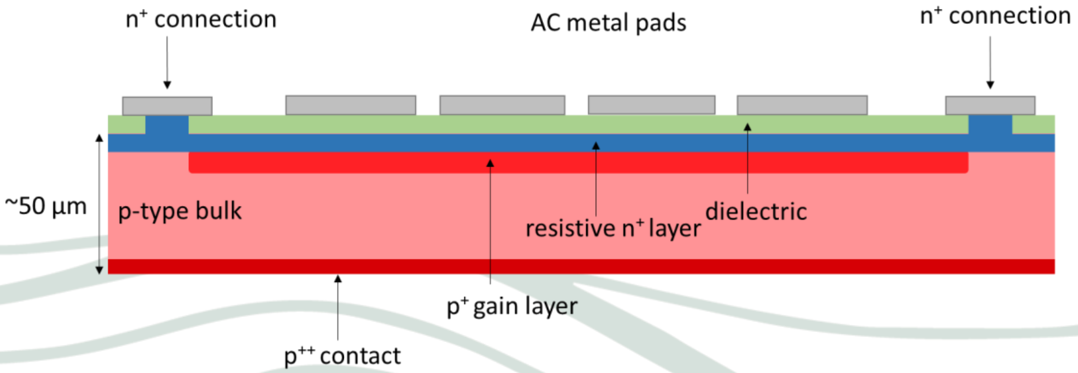
- ➢ **Time-of-flight particle ID layer: silicon AC-LGADs**
- ➢ **T_0 timestamp(?)**
- ➢ **Additional layer in tracking**

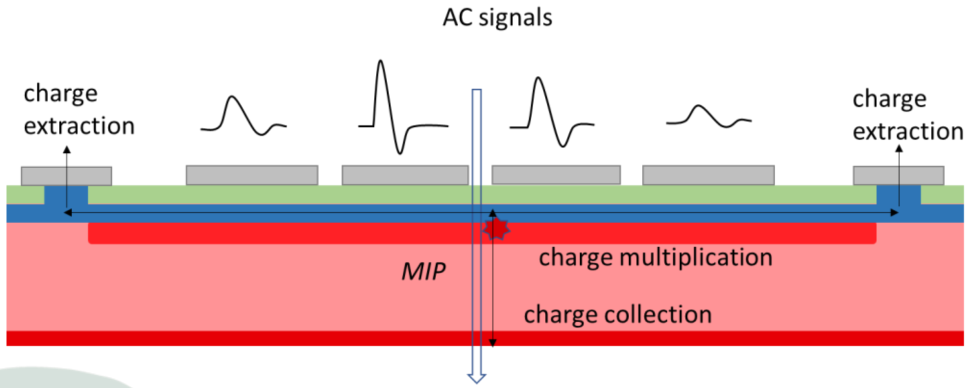


- AC-LGADs replaced by picosecond photodetectors in electron (backward) endcap
- Excellent performance in distinction of charged particle species at low momenta < 3 GeV

AC-LGADs

- **Also referred to as 'Resistive Silicon Detectors' (RSD): more resistive front side n^+ implant than in standard Si sensors**
- **Continuous dielectric, n^+ implant, and gain layer; patterned metal readout electrodes**
  - *No junction termination extension or p-stop between electrodes: fill factor ~100*
  - *Mirroring of charge at the n^+ layer on the metal pads: AC-coupling*
  - *Strong sharing of charge between metal pads*
  - ***Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels***





AC-LGADs in ePIC

AC-LGAD barrel and forward-endcap Time-of-Flight PID

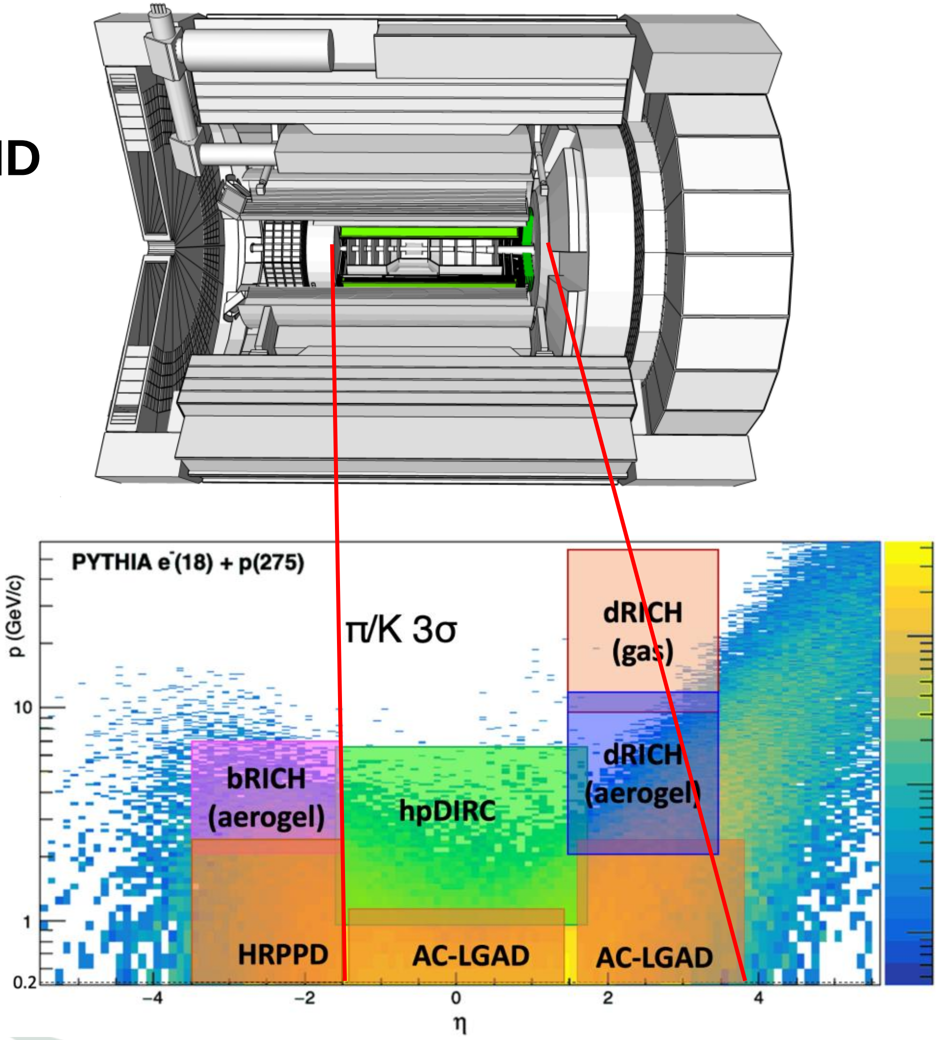
- **Combination of precise temporal and spatial resolution:**

25 ps and 30 µm / hit

- Low material budget

Current sensor design baseline:

- Barrel: **strips, 500 µm pitch and 1 cm length**
- Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**



Particle ID systems in ePIC

AC-LGADs in ePIC

AC-LGAD barrel and forward-endcap Time-of-Flight PID

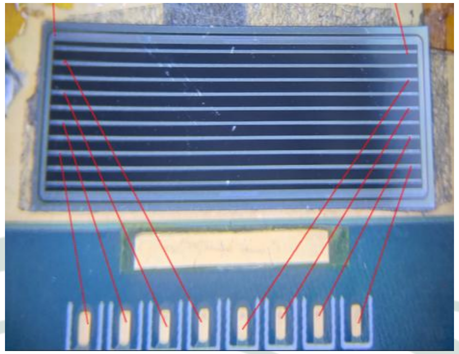
- **Combination of precise temporal and spatial resolution:**

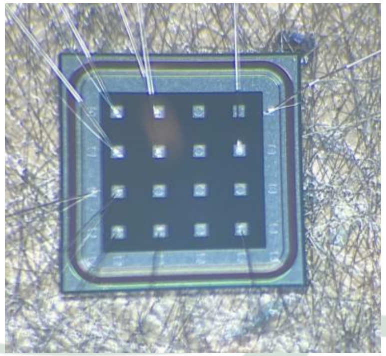
25 ps and 30 µm / hit

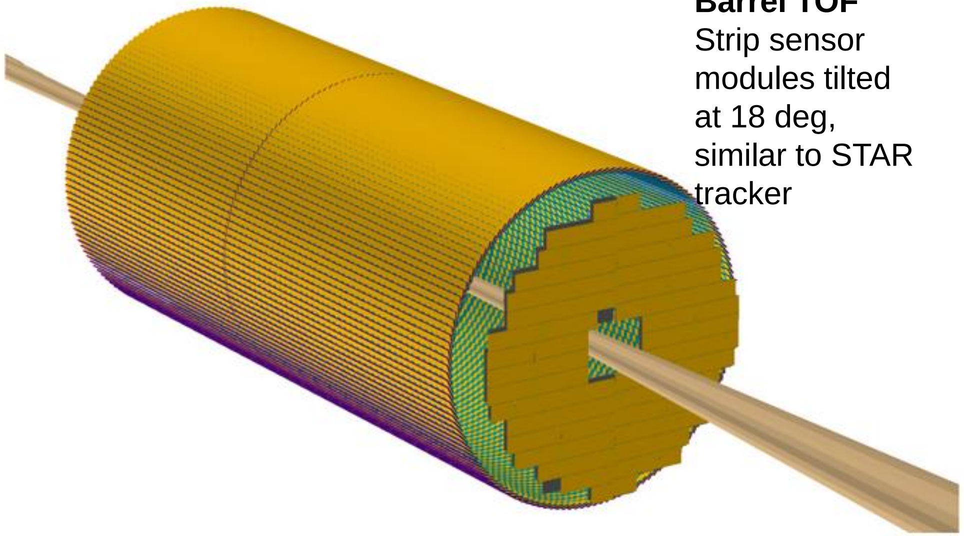
- Low material budget

Current sensor design baseline:

- Barrel: **strips, 500 µm pitch and 1 cm length**
- Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**







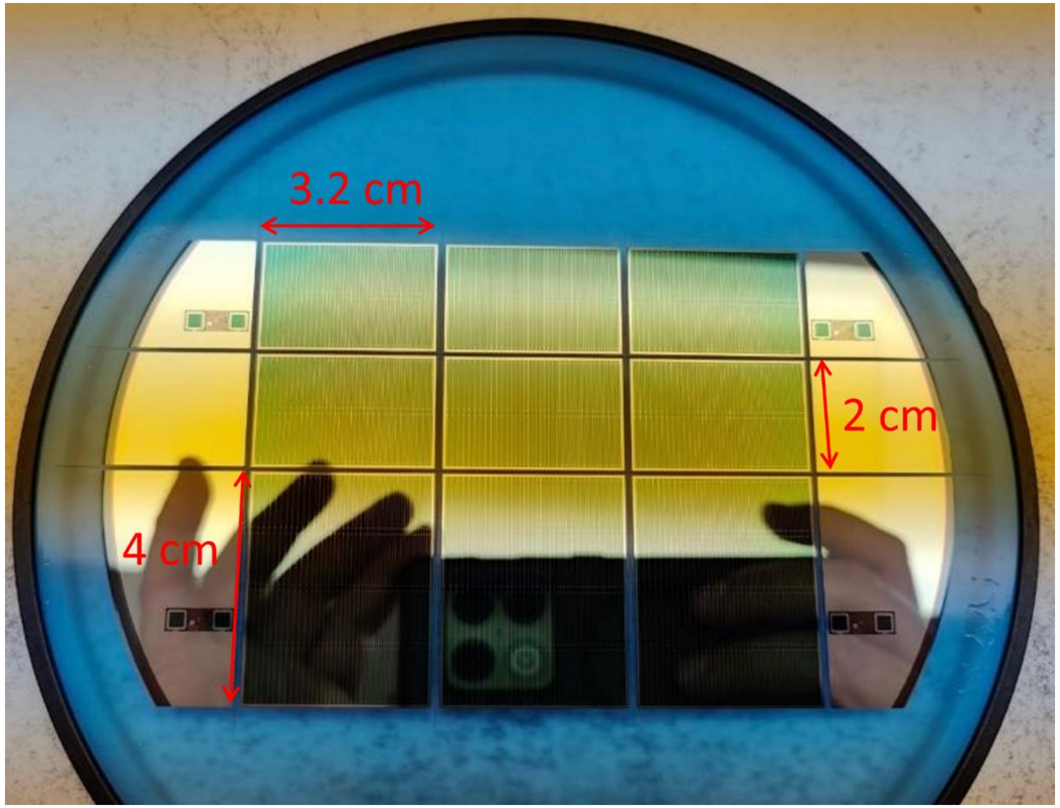
Barrel TOF
Strip sensor modules tilted at 18 deg, similar to STAR tracker

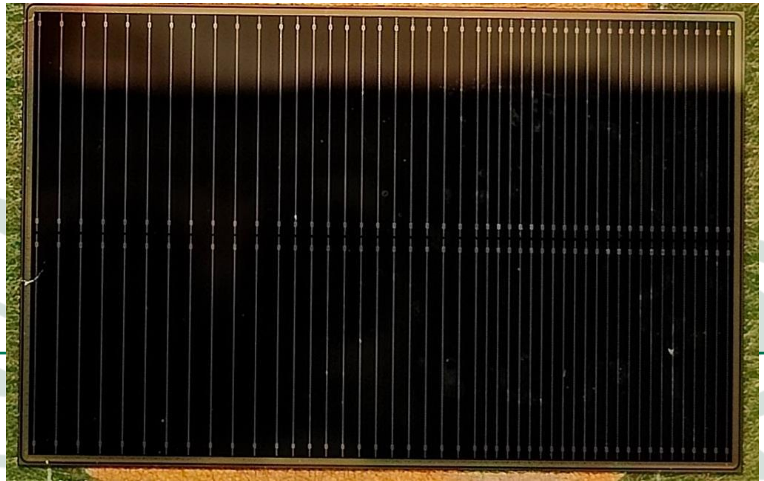
Forward TOF
Similar to CMS ETL

Barrel-TOF current sensor status

Barrel-TOF, strips:

- Large-area strips received
- 1 cm strip length, two ‘sets’ of strips on sensor die
  - Can be bonded from either edge
  - Could be ‘stitched’ together with a wirebond
- Variation of strip pitch
- 30 and 50 µm active thickness





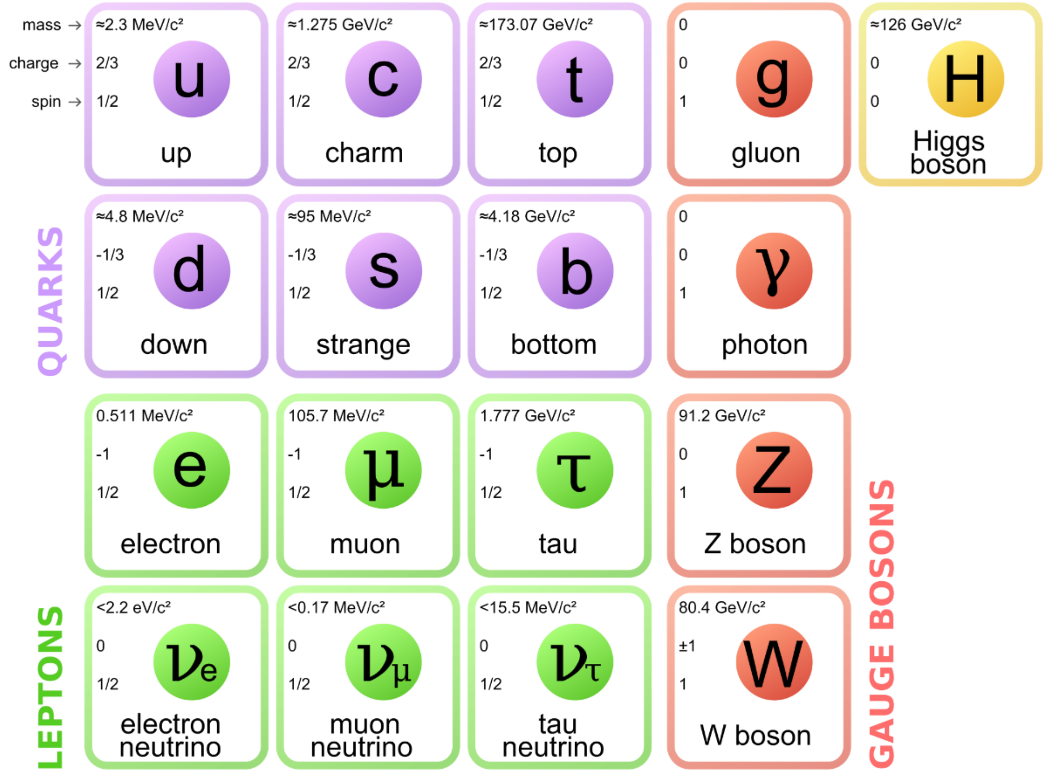
Flavor physics

Precision measurements at ‘lower’ energies

- **on the scale of 10s of GeV**

Lepton flavour, LF universality / universality violation: is coupling independent of lepton generation?

Decays of B mesons: production right above mass threshold – lower interference from unrelated background processes



4D (5D) tracking: PIONEER experiment

Precision measurement of lepton flavour universality through the charged pion decay branching ratio:

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

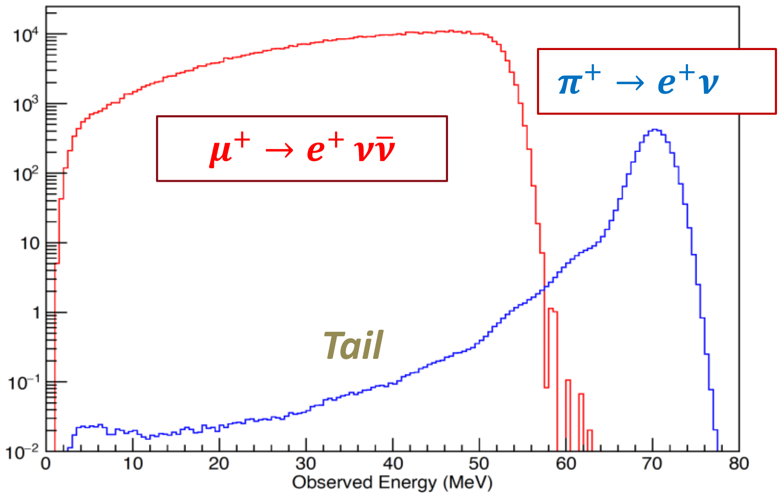
$\pi^+ \to e^+\nu(\gamma)$ $\quad \mathbf{1.23 \times 10^{-4}}$

E_e = 69.8 MeV

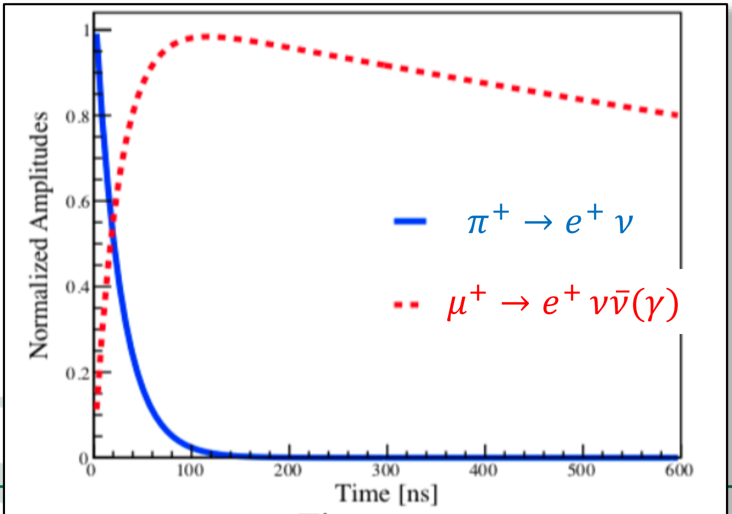
$\pi^+ \to \mu^+\nu(\gamma)$ $\quad \mathbf{99.99\%}$

$\mu^+ \to e^+\nu\bar{\nu}(\gamma)$ $\quad \mathbf{100\ \%}$

E_e = 0.5-52.8 MeV



e⁺ energy deposition in calorimeter

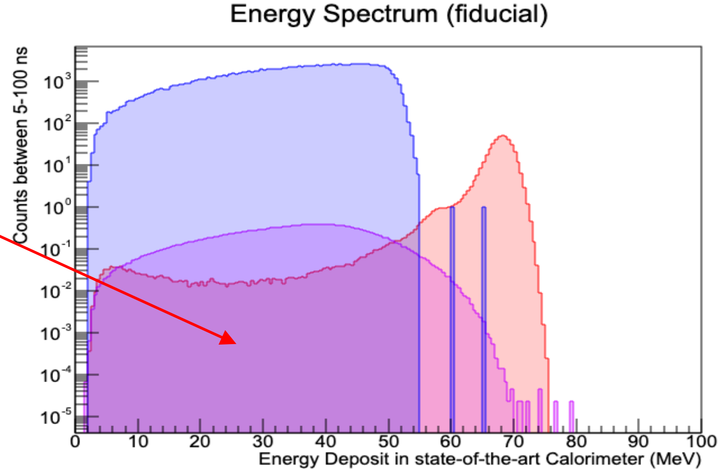


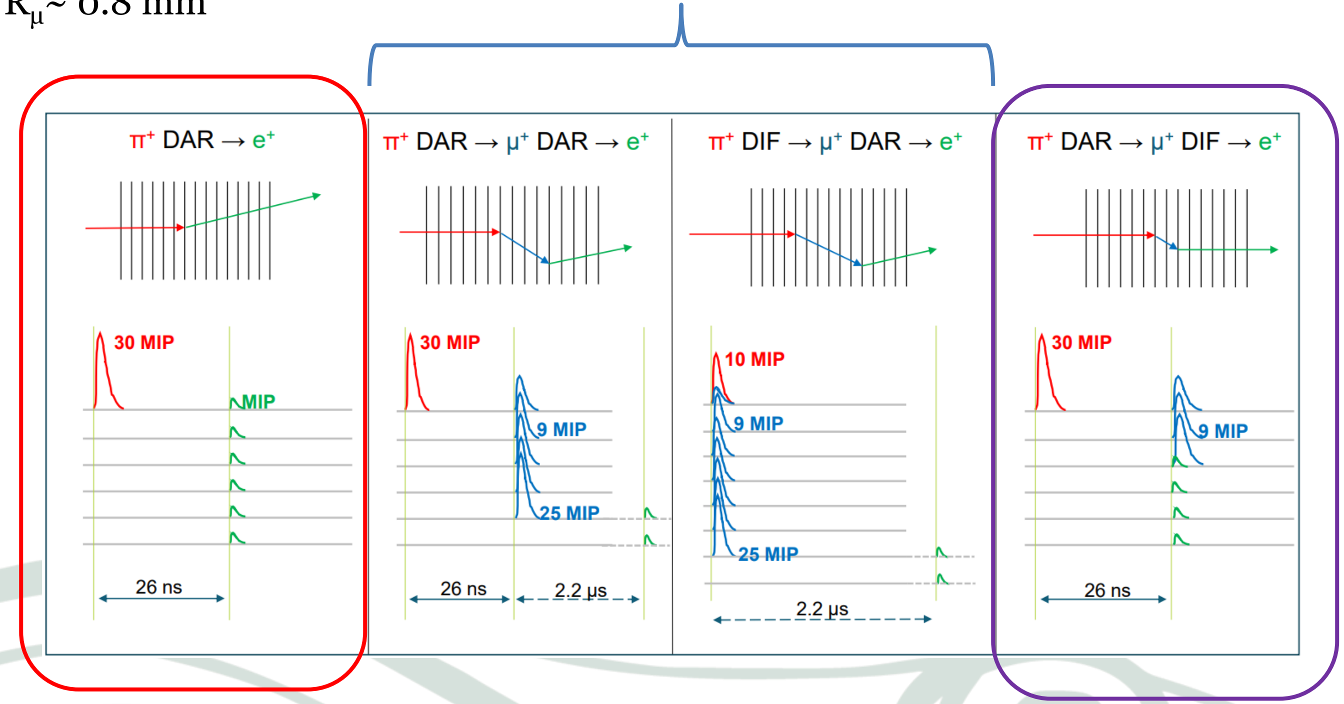
Time spectrum

PIONEER: separating muons and positrons

It will be crucial to separate the low-energy tail of $\pi \to e$ events from $\pi \to \mu \to e$ decays **in-flight** **and** **at-rest**

$R_\pi \sim 4$ mm, $R_\mu \sim 0.8$ mm





The Active Target detector

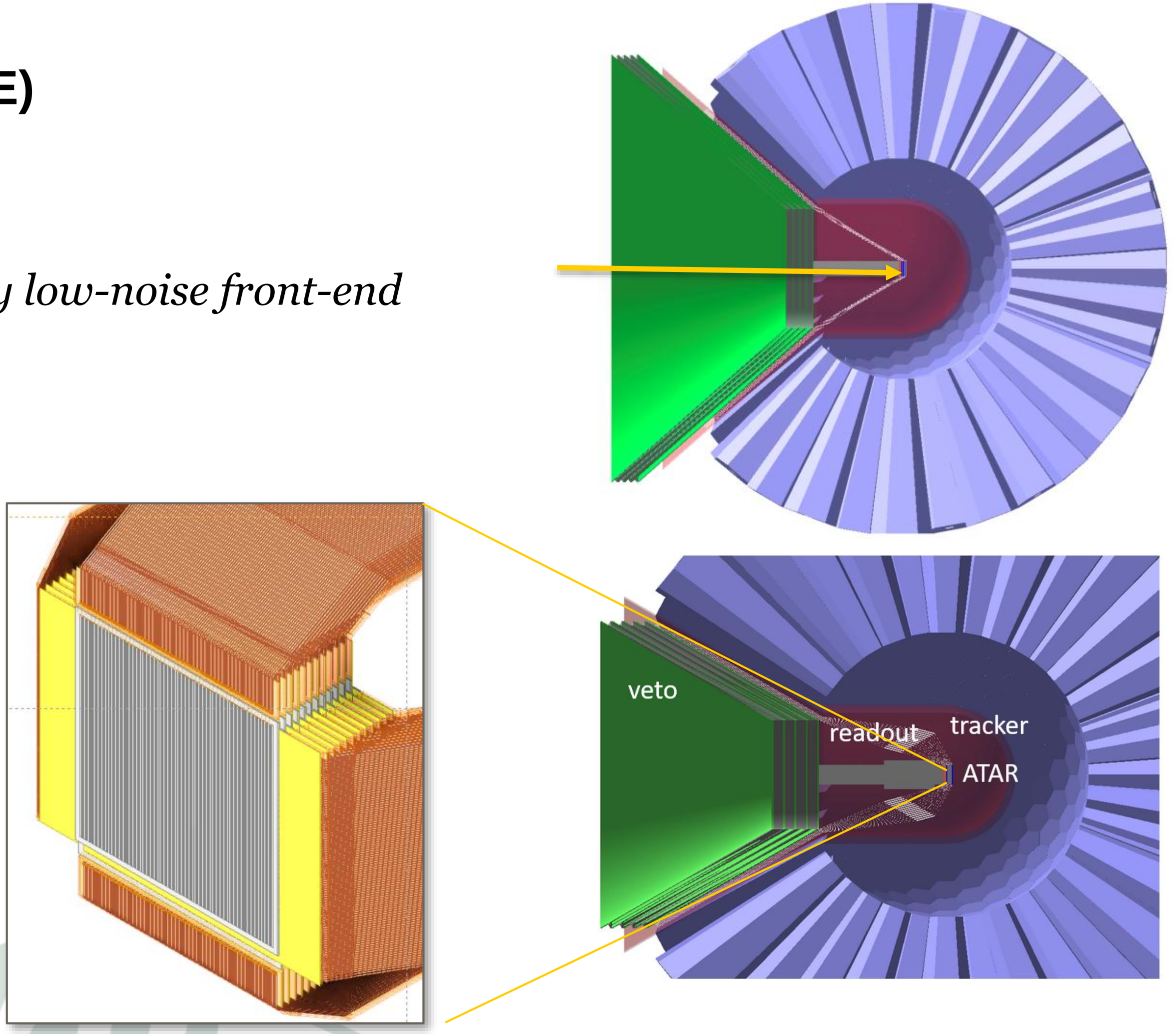
5-D tracker can provide rich information (x, y, z, t, E)

Baseline Technology: low-gain avalanche diodes

- *No-gain option has been / is being explored: requires very low-noise front-end*
- AC-LGADs
- TI-LGADs

Dimensions:

- 20 x 20 x 5.76 mm
- 48 sensor layers
- **120 µm thickness**, 200 µm strips

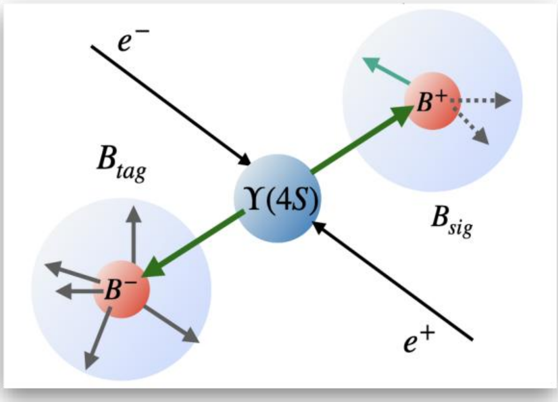


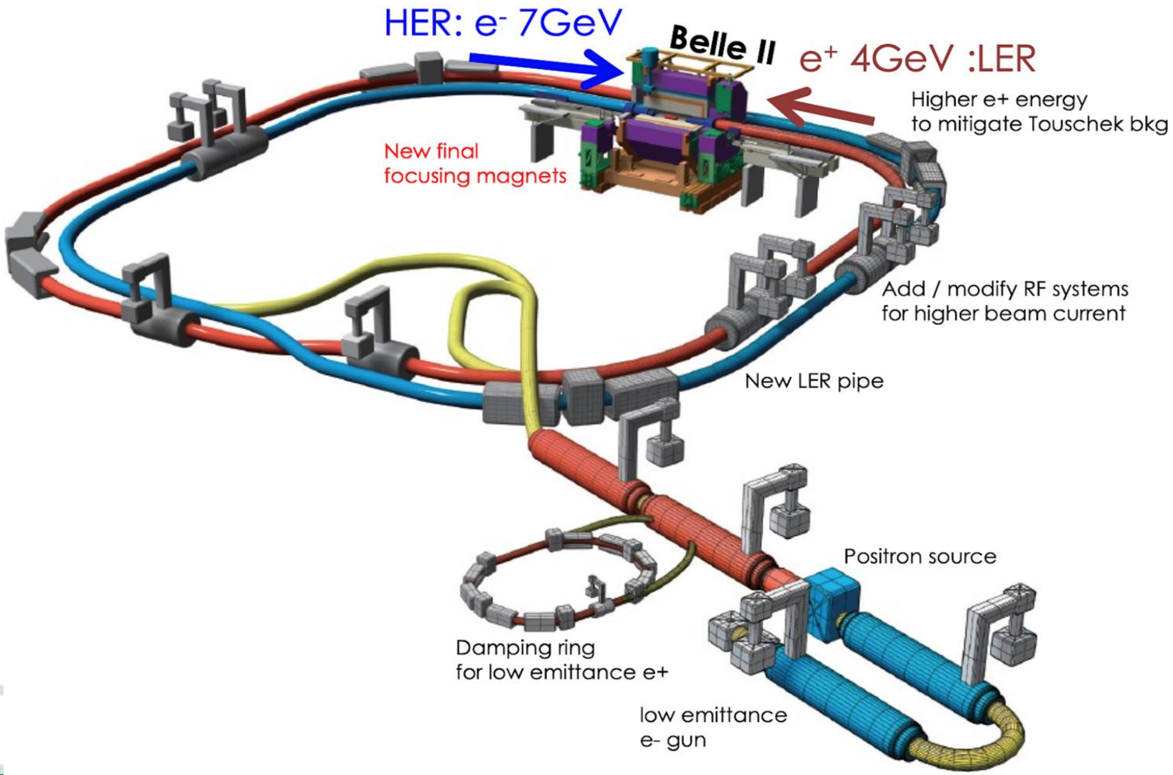
t: Δt ~ 200 ps, pulse pair 2 ns
E: ~ 100 dynamic range, $\sigma_E < 10\ \%$
stack: fully active, “no: dead material

Belle II

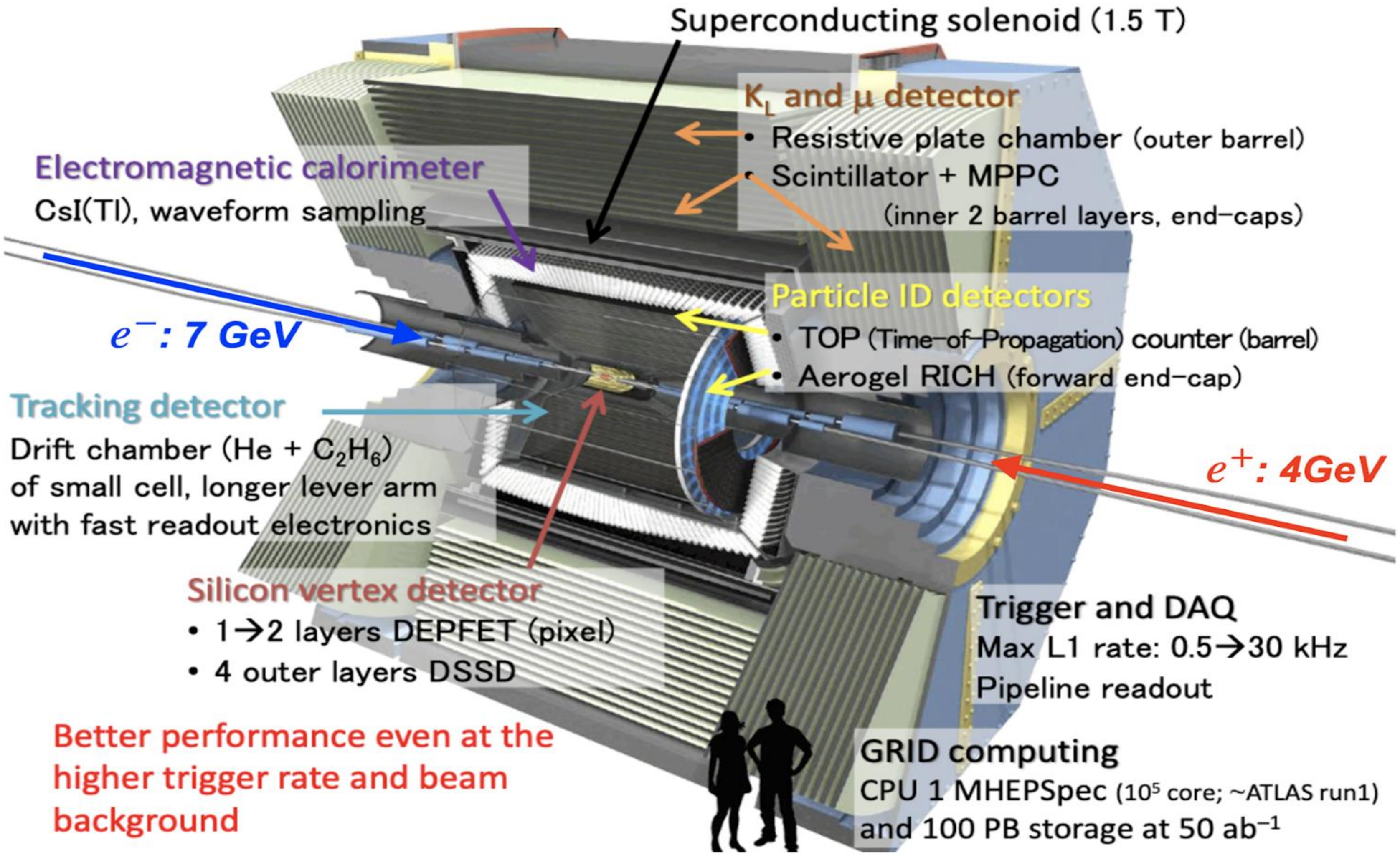
SuperKEKB:

- **Asymmetric e+(4GeV) e- (7GeV) collider in Tsukuba, Japan**
- **Operating around the Υ(4S) resonance ($\sqrt{s}$ = 10.58 GeV)**





Belle II



Includes gaseous tracking detector system: central drift chamber

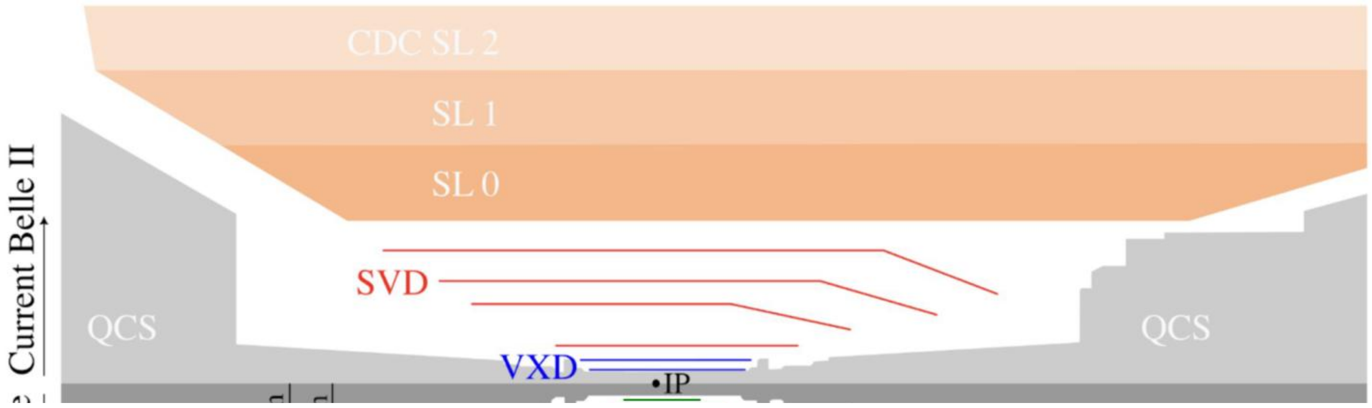
- ***Ageing challenges!***

Implementing a TOF layer?

Addition of an AC-LGAD –based TOF layer??

To consider:

- Radius of TOF layer?
- 1 layer with timing, or more? (>2 unlikely, due to material budget)
- Spatial resolution? Utilization in tracking as well?

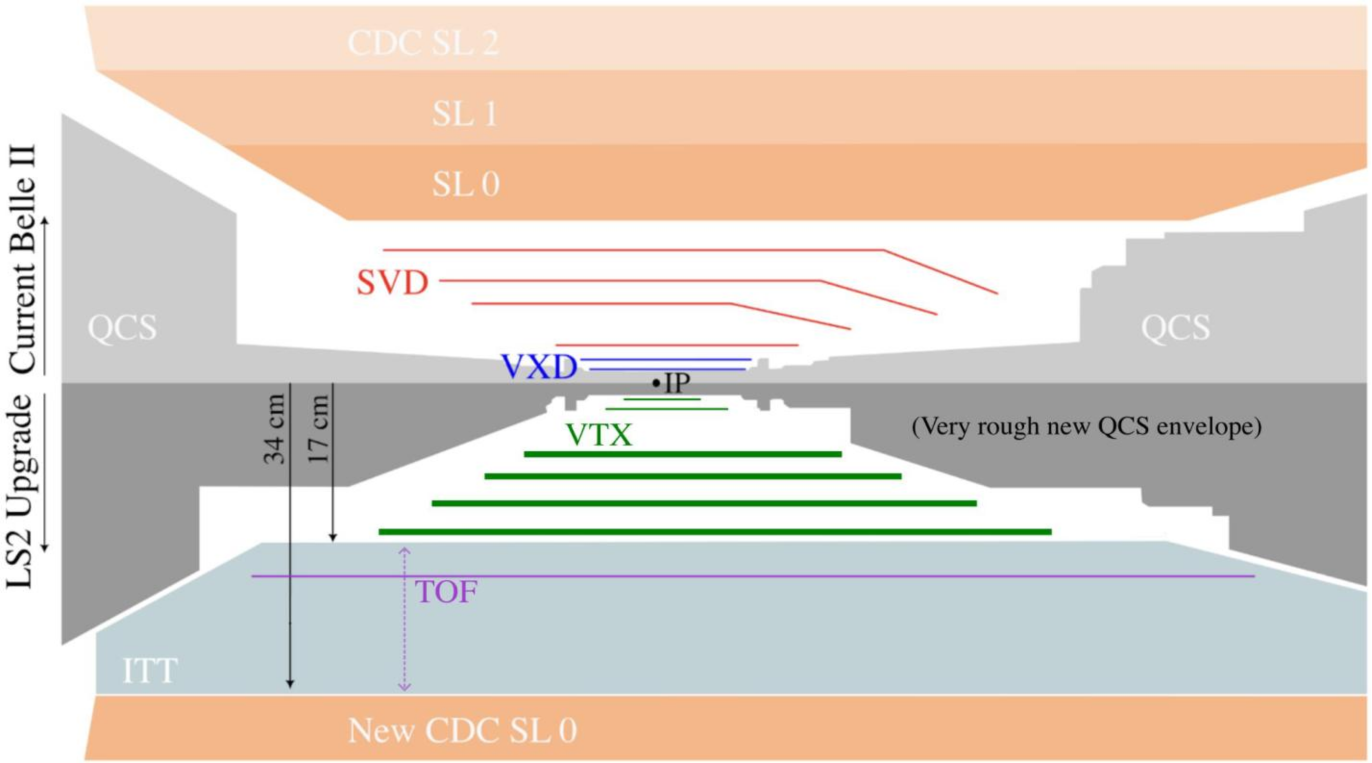


Implementing a TOF layer?

Addition of an AC-LGAD –based TOF layer??

Target not only recovery of CDC particle ID capabilities, but aim to generate additional value:

- ***TOF would give low-p_T PID capabilities totally new to B-factories***



- ***Approximate doubling of efficiency for channels with low-momentum muons, for example leptonic tau decays (R(D*), $K \to \tau\tau$, etc)***

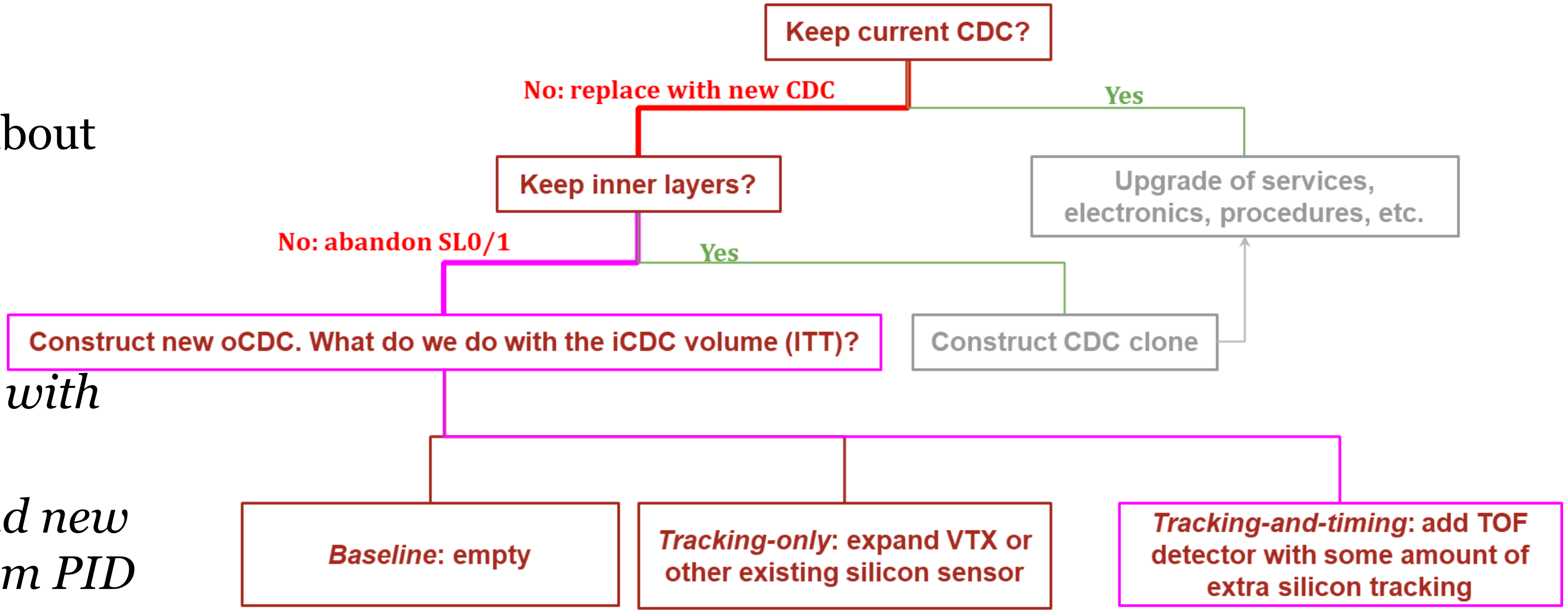
Belle II upgrade

Upgrade of the Inner region:

- IR: New QCS - ongoing discussions about different upgrade options

- PXD + SVD → 5-layer VTX
  - CDC: gas aging issue → *what to do with this volume?*
  - *If left empty: Gap between VTX and new CDC layer degrades low-momentum PID*

➢ ***Can it be recovered by a fast timing layer through time-of-flight particle ID?***



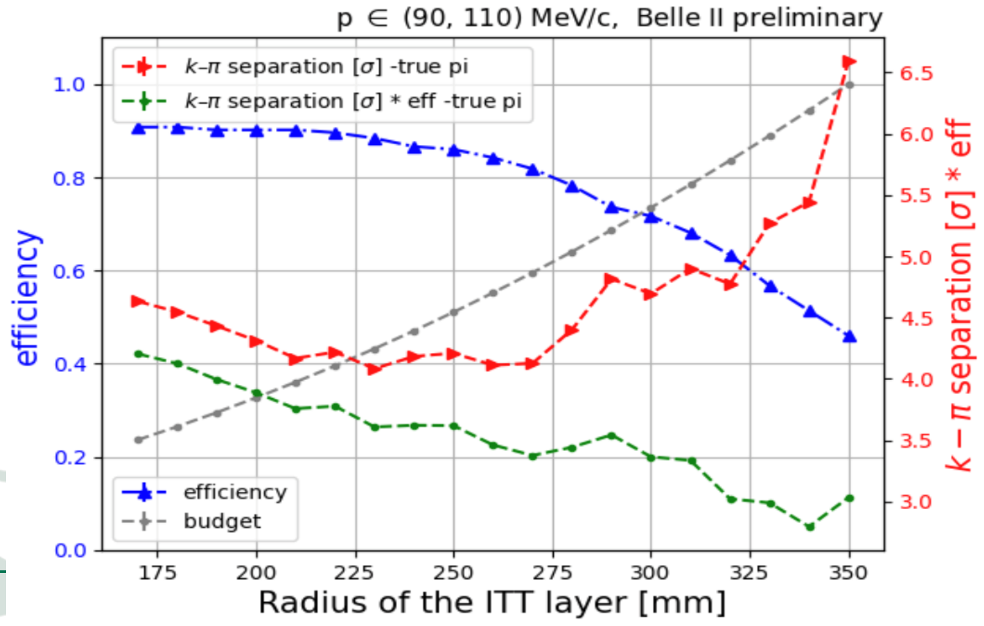
This is the 'working scenario' as of now

Initial simulations and detector requirements

Initial work: Geant4 simulations to quantify impact on PID, exercise placement at different radii, set constraints on X/X_0

- *Simple cylindrical volume with some specified radius, thickness and timing resolution – sensor technology, mechanical design etc not defined*

Example: $k - \pi$ separation

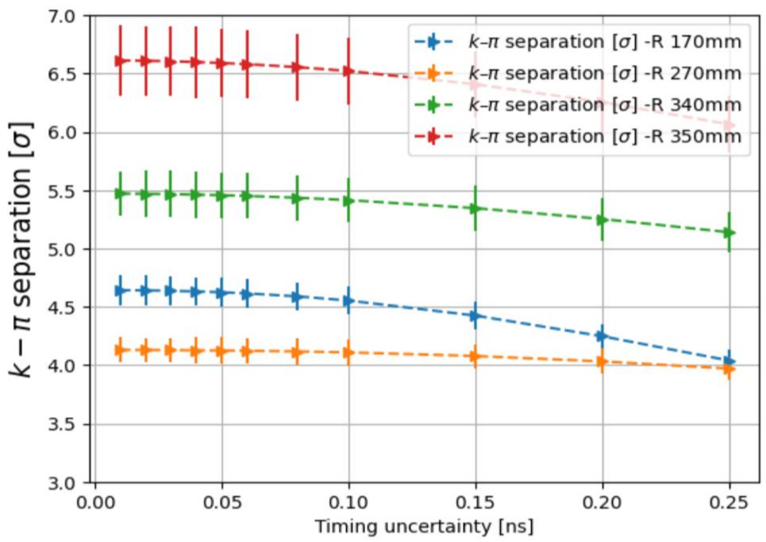


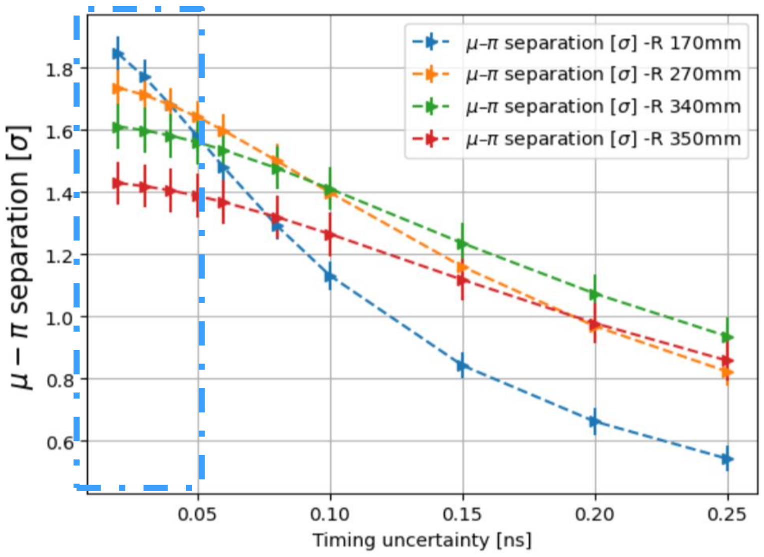
Initial simulations and detector requirements

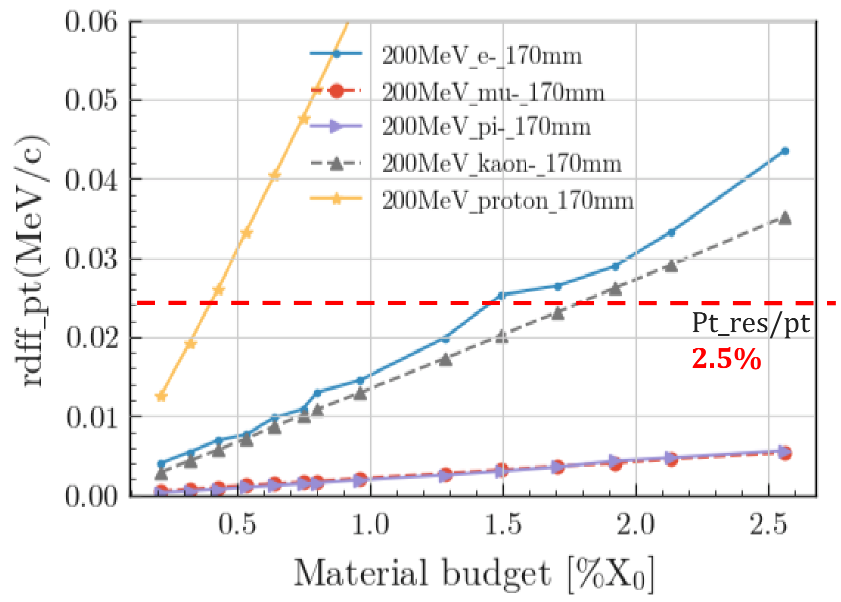
k – π (ref.) and μ – π (novel impact physics) separation

- **Timing resolution: 50 ps**
- **Material budget, low p_T tracks 100-200 MeV/c: 1.5 % X/X_0**

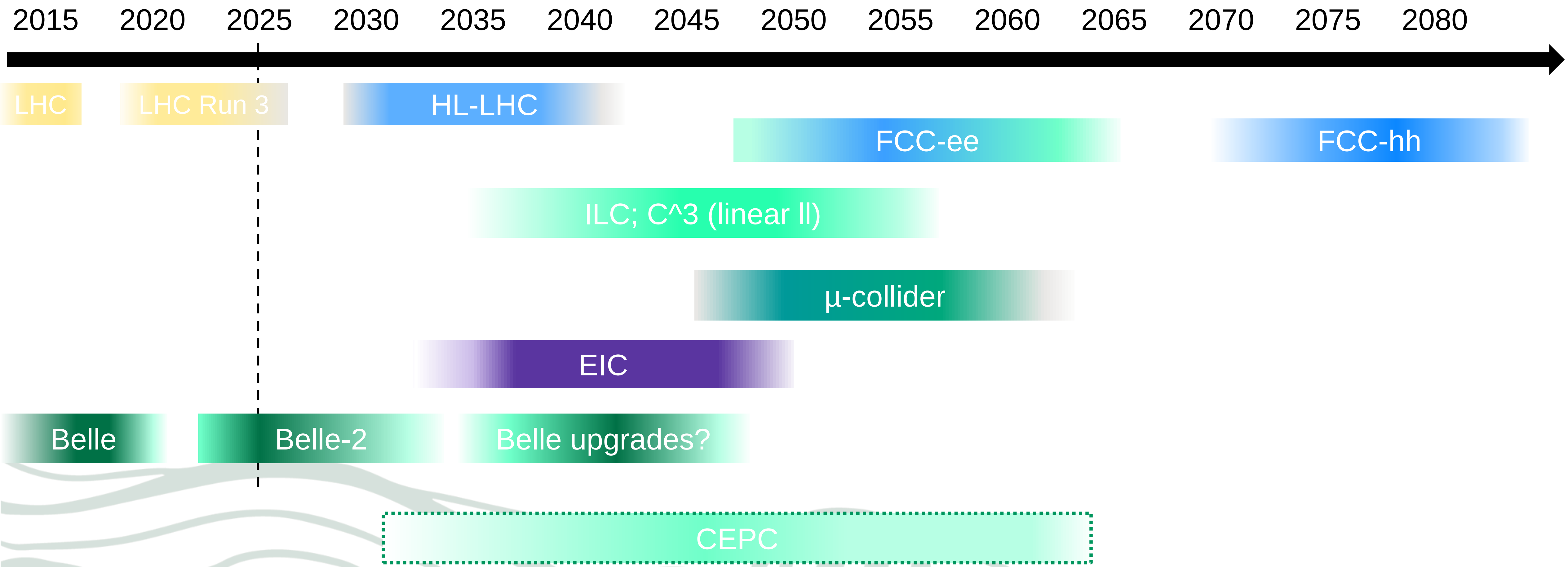
Impact on tracking resolution equivalent to current tracker – VTX material







Landscape of colliders



Monolithic CMOS detectors

Active CMOS / MAPS

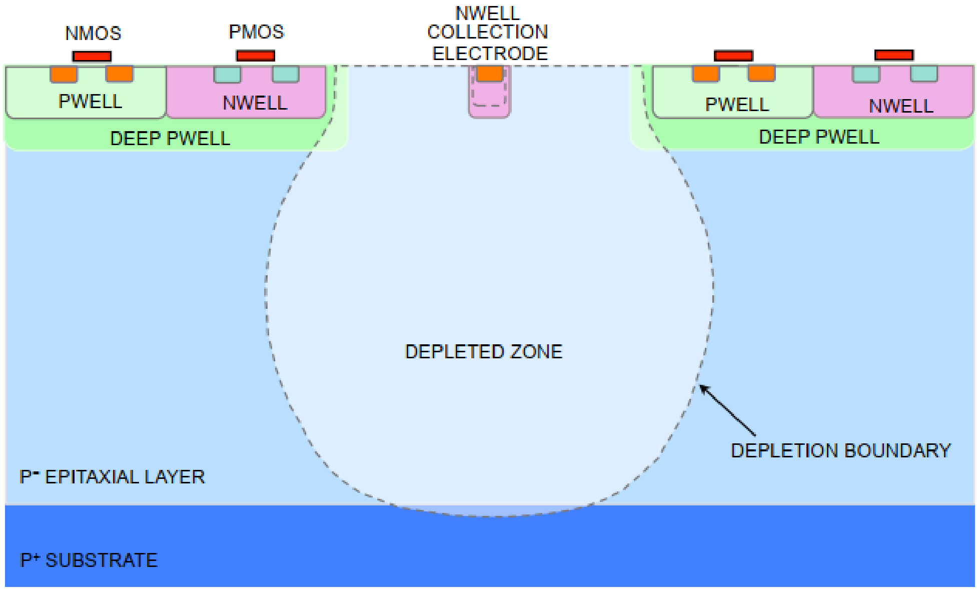
- Small pixels, better spatial resolution, do not require elaborate interconnection
- Commercial large vendor processes
- **Showstopper for p-p colliders so far: radiation levels**

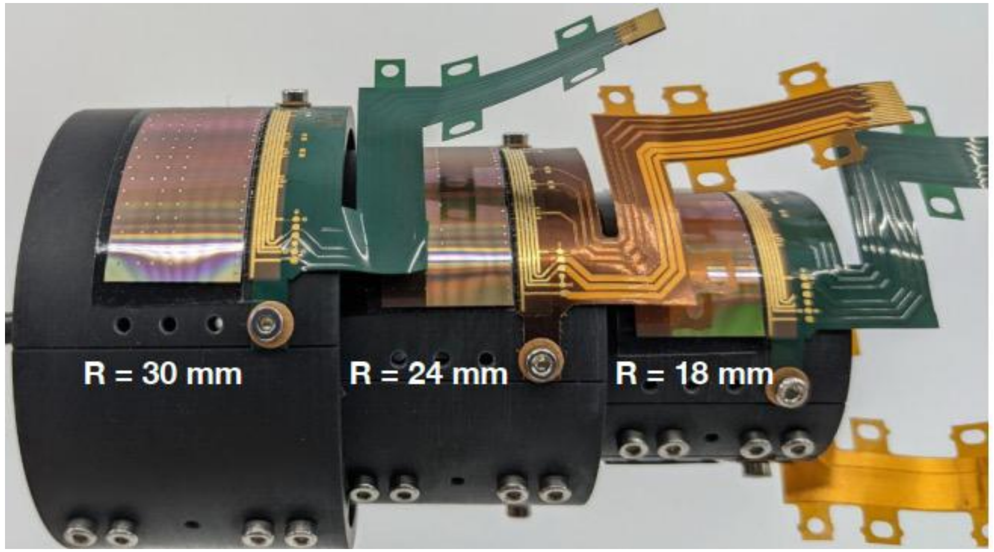
“Massless” detectors

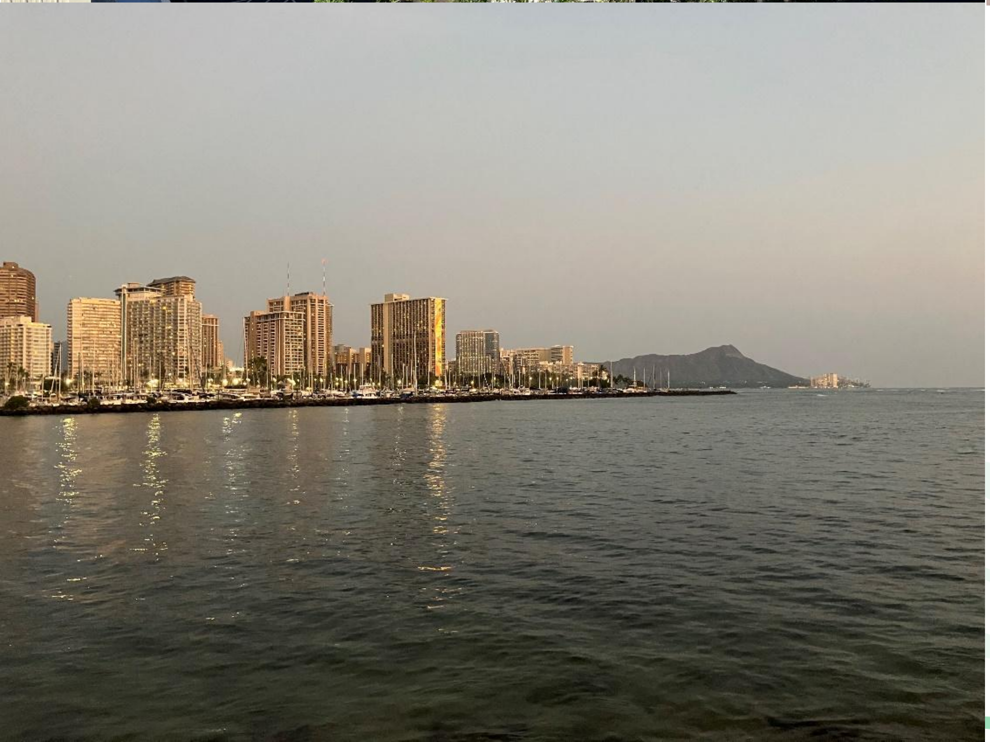
Thin stitched detectors: ALICE ITS-3 for the HL-LHC upgrade

➢ **Baseline for inner tracker and vertex detector at most future colliders: EIC, FCC-ee, etc**

Eventually MAPS with gain layer?







Thank you!

Mahalo!