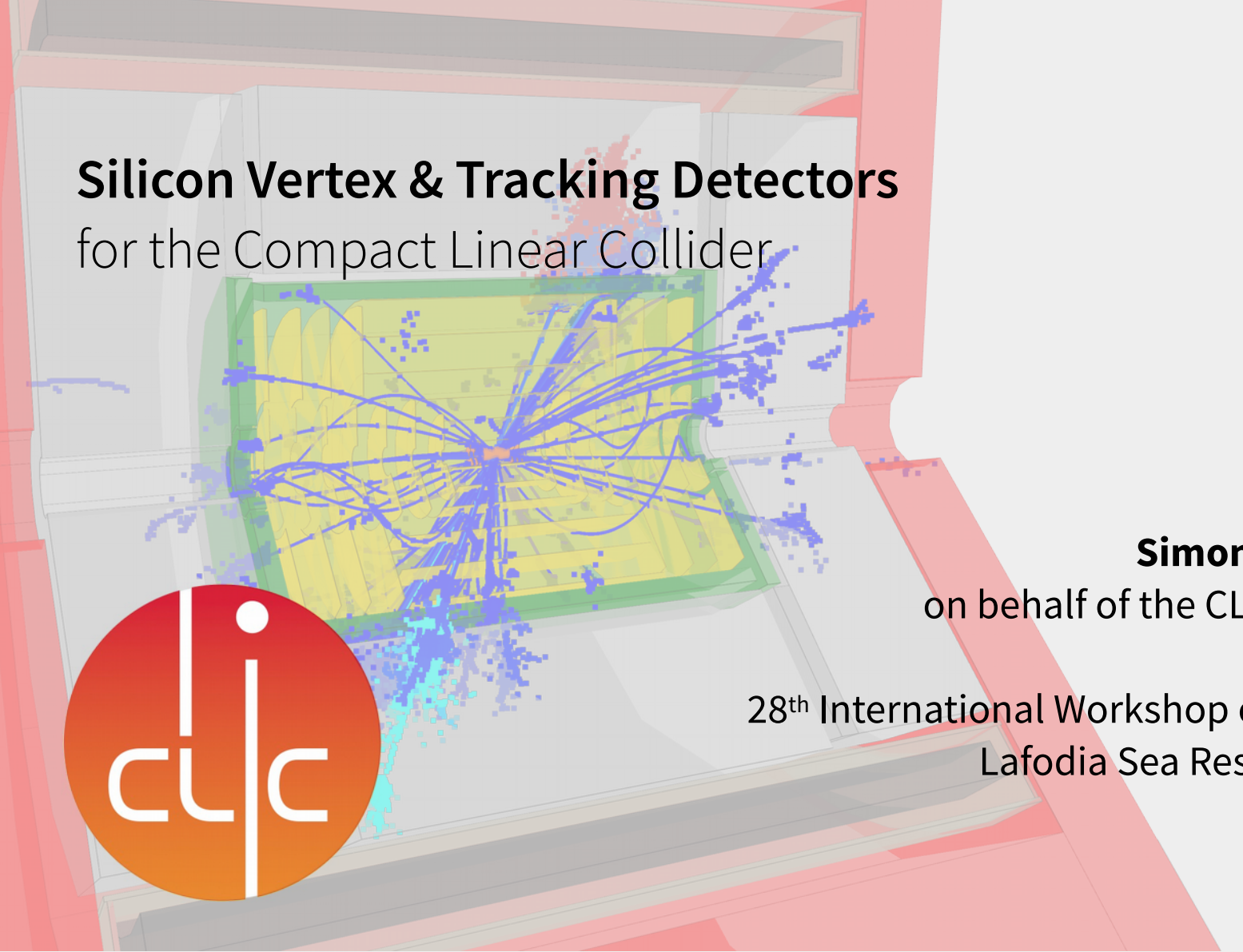
http://clicdp.cern.ch

Silicon Vertex & Tracking Detectors
for the Compact Linear Collider

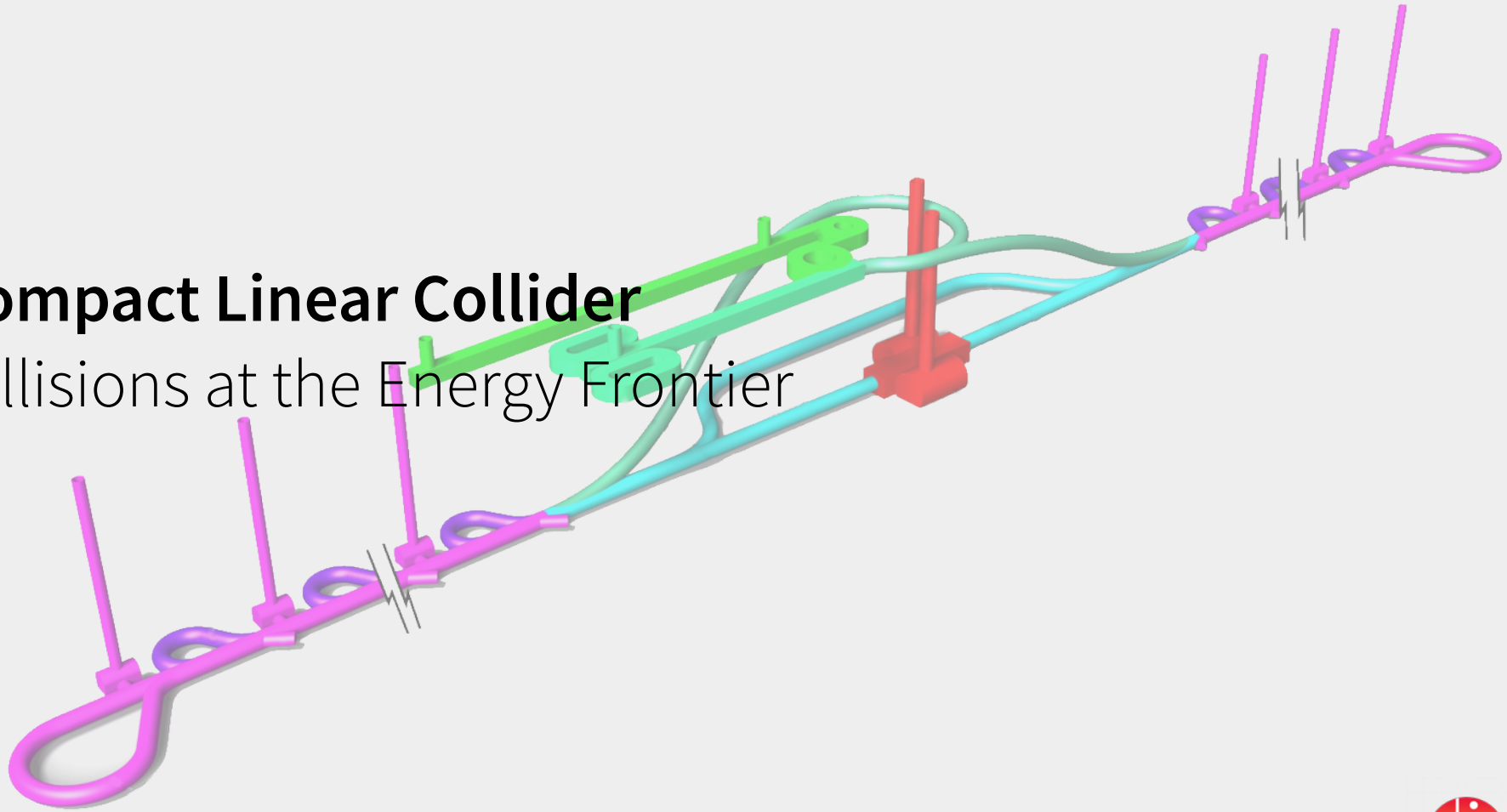


Simon Spannagel, CERN
on behalf of the CLICdp Collaboration

28th International Workshop on Vertex Detectors
Lafodia Sea Resort, Lopud, Croatia
17 October 2019

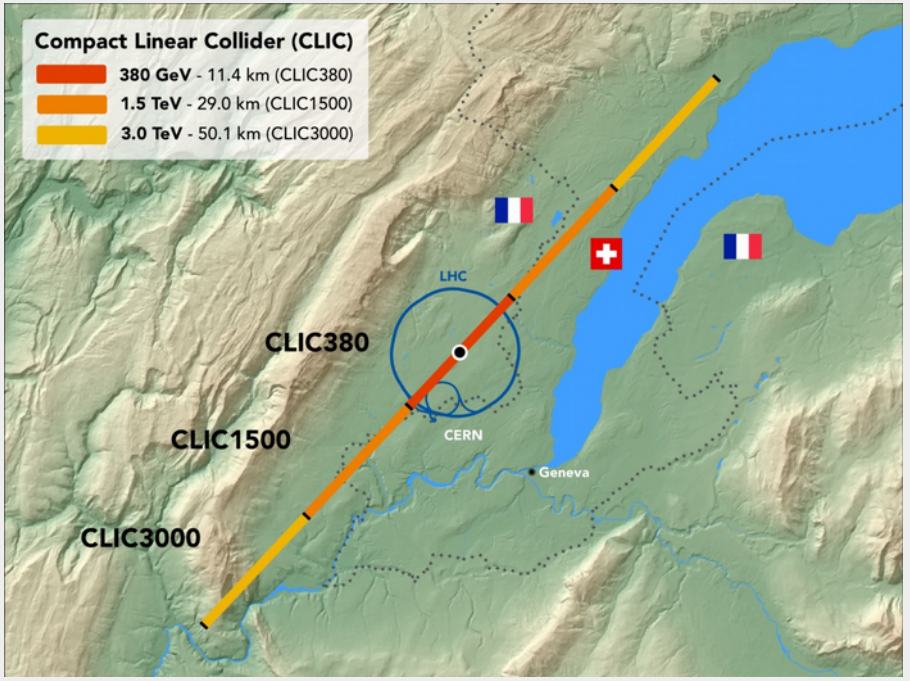
The Compact Linear Collider

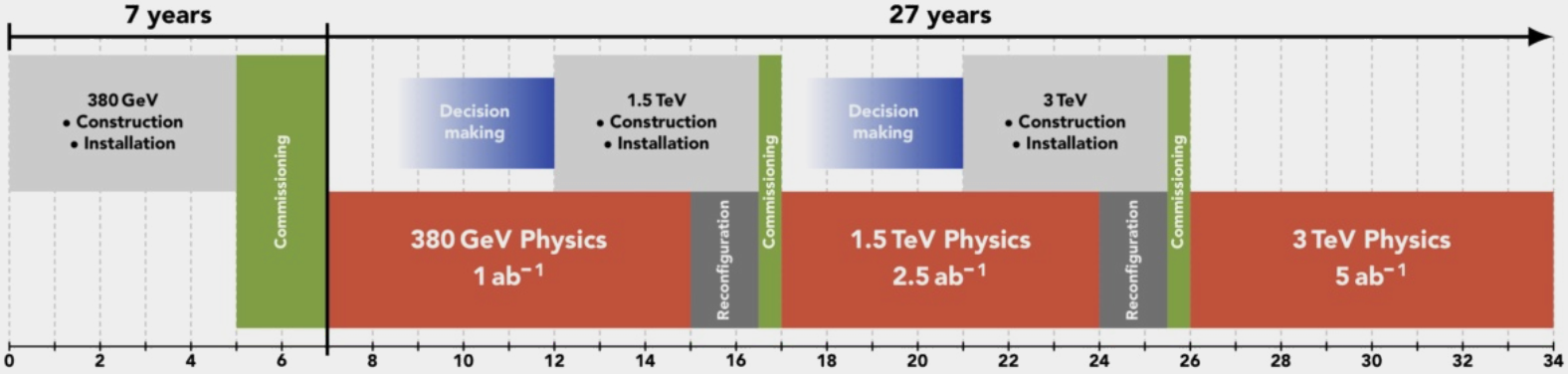
e^+e^- Collisions at the Energy Frontier



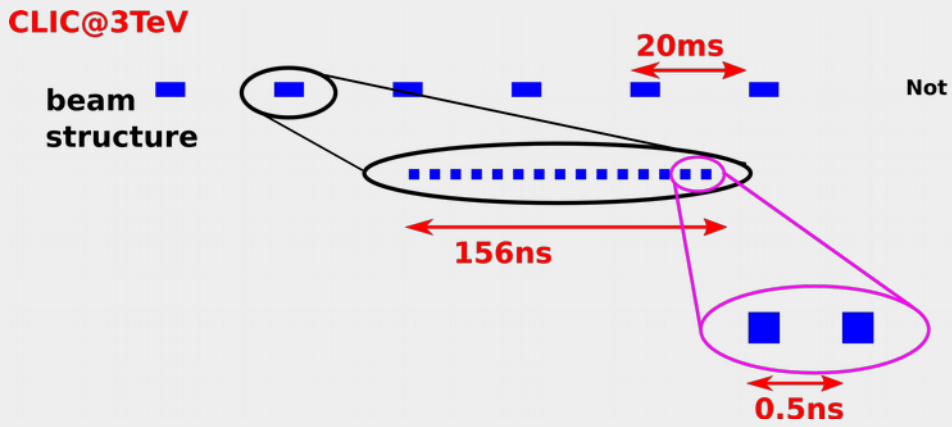
The Compact Linear Collider

- Proposed e+e- linear collider at CERN for the era beyond HL-LHC (~2035)
- Staging of the machine in 3 steps
- Novel and unique two-beam acceleration
  - High-current low-energy drive beam to accelerate high-energy main beam
  - High accelerating gradient of 100 MV/m



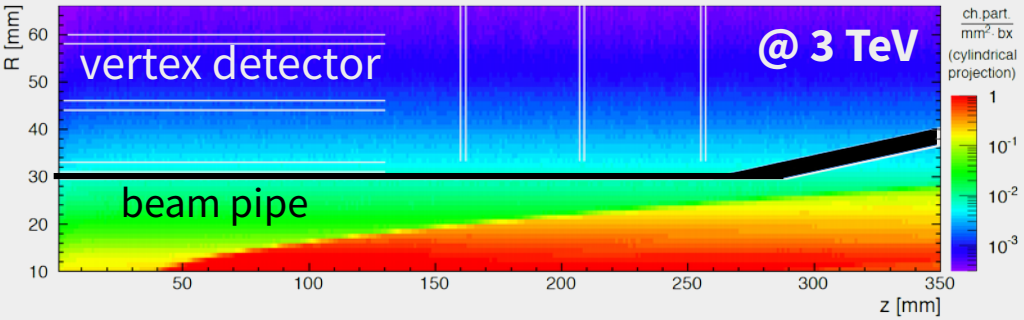


Experimental Conditions

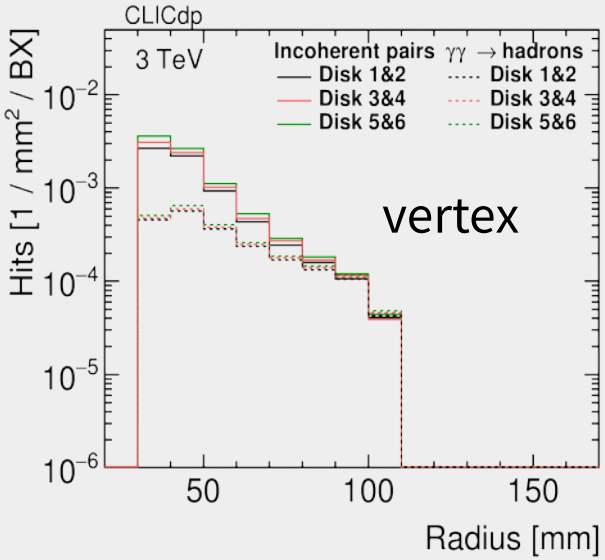


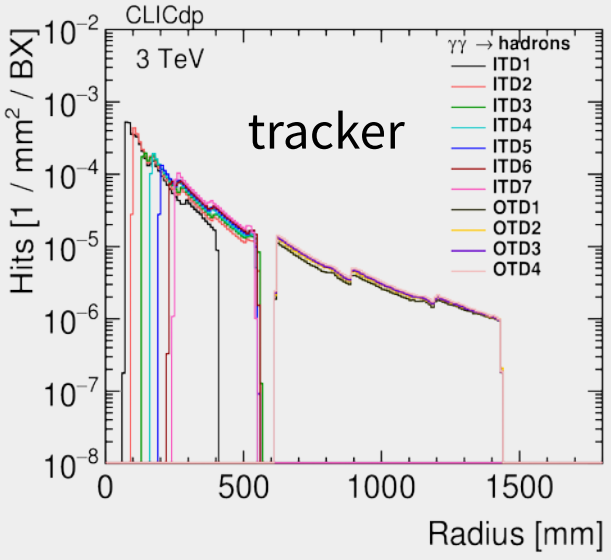
- CLIC operates in bunch trains, repetition rate of 50 Hz
  - Low duty cycle
  - Possibility for power pulsing:
    switch detector components off between trains to reduce heat dissipation
- 312 bunches within train (at 3 TeV), separated by 0.5 ns
- Bunch separation & cross-section of background events drive timing requirements for detector
  - 1 ns time resolution for calorimeters
  - **5 ns single-hit resolution for vertex/tracking detectors**

Occupancies & Granularity

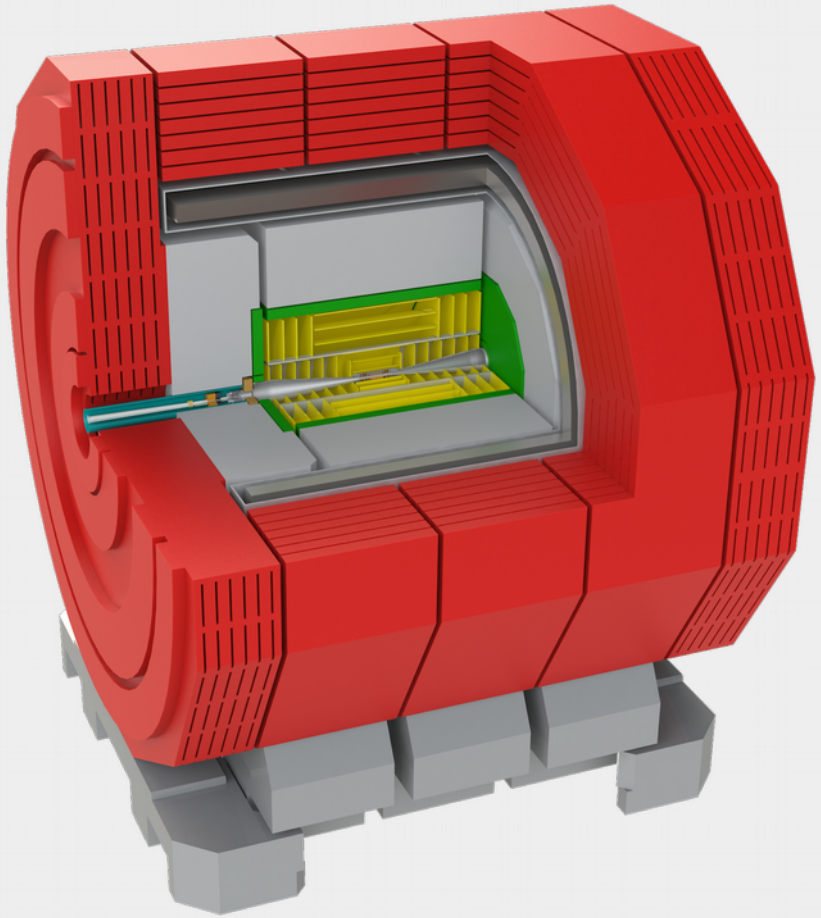


- Charged particles produced by beam-induced background
- Detector layout and granularity dependent on particle flux
- Goal: keep **occupancies below 3%** per bunch train including safety factors
- Occupancy limits:
  - Vertex: pitch **25 µm x 25 µm**
  - Tracker: **50 µm** in rϕ and **1mm – 10mm** in z
- Timing resolution ~ **5 ns**





Vertex & Tracking Detectors
for the CLIC detector concept



Requirements – Comparison

	Compact Linear Collider	(HL-) LHC (ATLAS/CMS)
Material Budget (barrel)	• **1 – 2% X_0** (vertex) **8 – 15% X_0** (tracker)	• 10 – 15% X_0 (vertex) 30 – 40% X_0 (tracker)
Single-point Resolution	• **3 µm – 7 µm**	• 5 µm – 30 µm
Time Resolution	• **5 ns**	• 25 ns (1 BC)
Tracking Acceptance	• $\|\eta\| \approx 2.7$	• $\|\eta\| \approx 4$ (currently: 2.5)
Min. Granularity	• **≤ 25 µm x 100 µm**	• 50 µm x 50 µm
Active Area	• ~1 m^2 / ~140 m^2	• ~5 – 10 m^2 / ~200 m^2
Radiation Tolerance (p.a.)	• **< 10^{11} n_{eq} / cm2** (vertex)	• O(10^{16} n_{eq} / cm^2) (vertex)

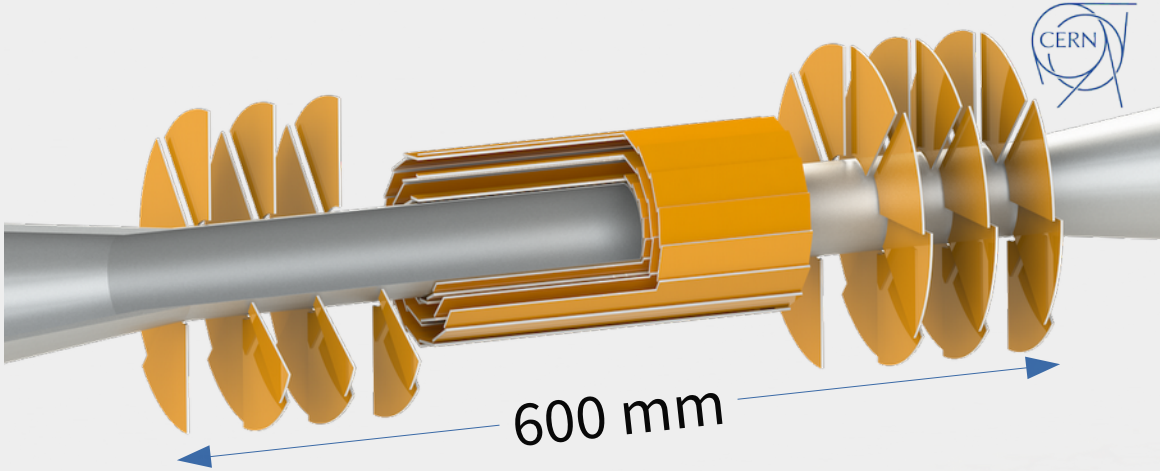
Vertex Detector

Design driven by flavor tagging

- Minimal scattering
- High-resolution

Requirements

- **Low mass**
  0.2% X_0 per layer
- **Low power consumption**
  < 50 mW/cm^{-2} for air-flow cooling
- **High single-point resolution**
  σ_{SP} ~ 3 µm
- **Precise time stamping** ~ 5 ns



Current design:

- Hybrid pixel detectors in double layers
- 50+50 µm sensor+ASIC, 25 µm pitch
- Surface area of ~ 0.84 m^2
- Three barrel double-layers,
  2x three spiral double-disks

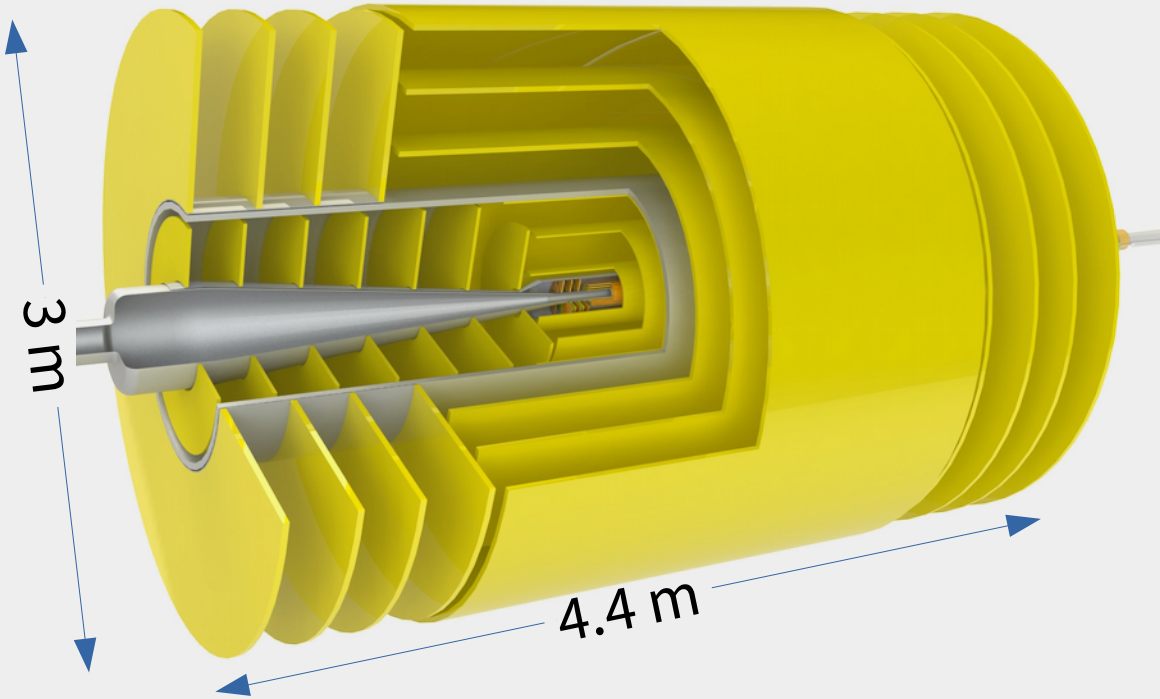
Tracking Detector

Design driven by
efficiency & momentum resolution

- Many layers, large lever arm

Requirements

- **Low mass, high rigidity**
  1 – 2% X_0 per layer
- **Good single-point resolution**
  σ_{SP} ~ 7 µm (transverse plane)
- **High granularity**
  few % occupancy from backgrounds
- **Precise time stamping** ~ 5 ns

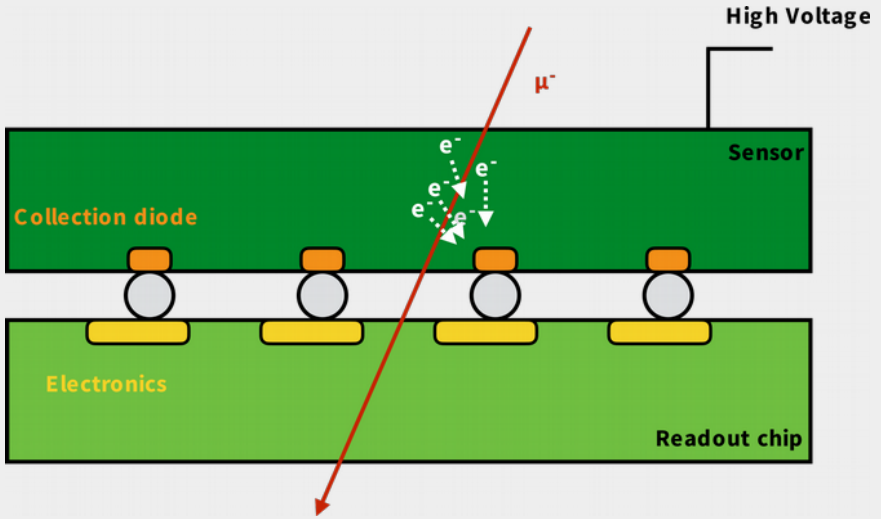


Current design:

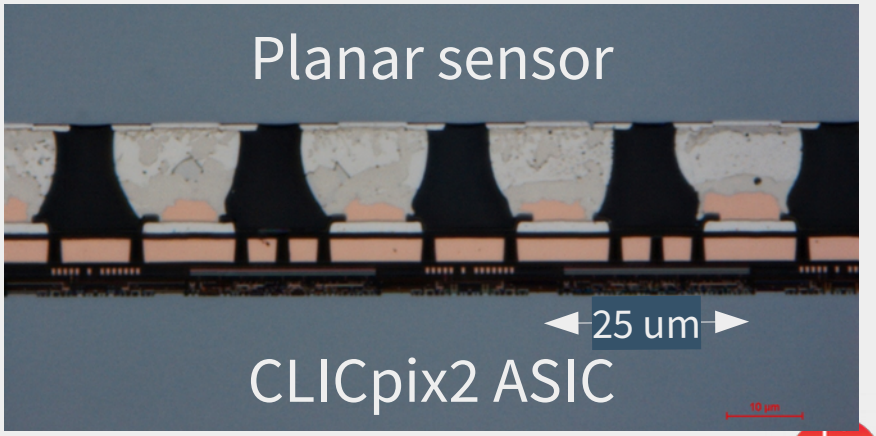
- Monolithic detector with (elongated) pixels
- Max. 200 µm sensor, including electronics
- Surface area of approx. 140 m^2
- Leakless water cooling

Silicon Technologies
for CLIC vertex & tracking detectors

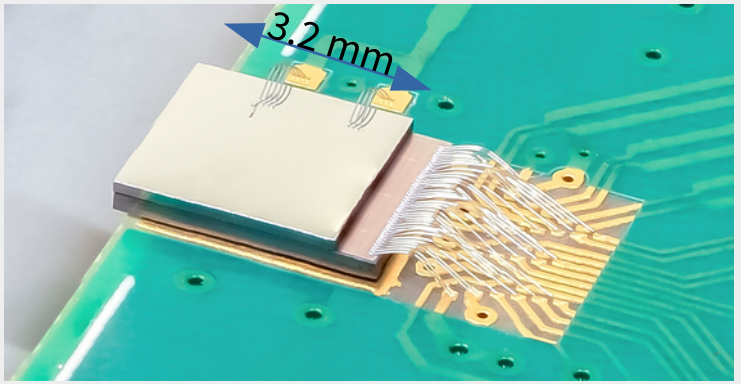
Hybrid Pixel Detectors



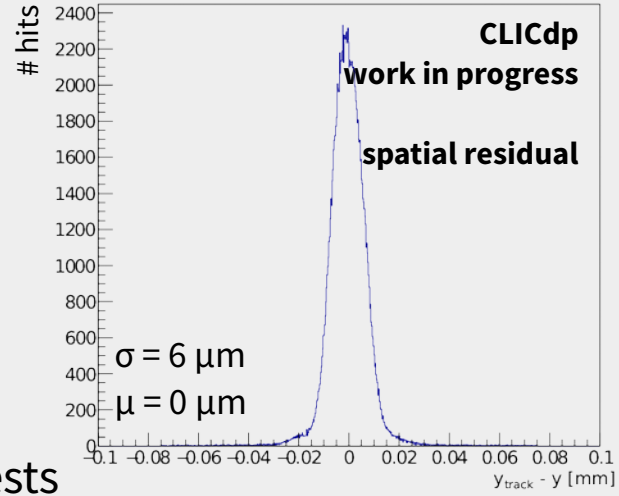
- Silicon pixel detector from two separately processed wafers:
  - Sensor (high-resistivity silicon with pn-junction)
  - CMOS readout chip with small feature size
  - Solder bumps as interconnect
- Allows extensive functionality on-pixel using mixed-mode CMOS circuits
- Small pixel cell sizes achievable, 25µm – 250µm
- Bump bonding
  - Cost-driving factor on detector production
  - Limiting factor for the pixel pitch
  - Limiting factor for device thickness: stability

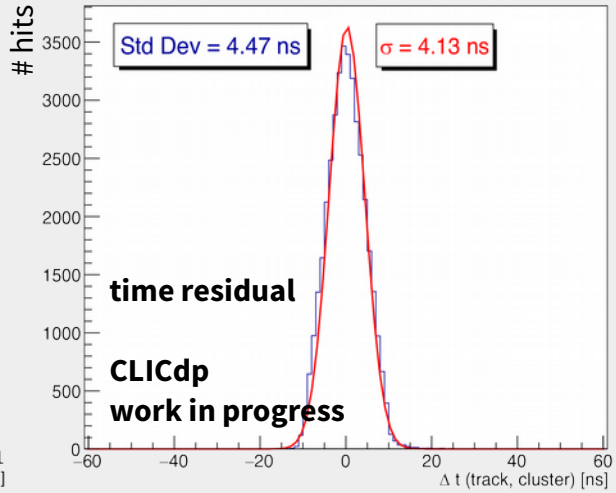


The CLICpix2 Prototype



- Readout ASIC to meet CLIC vertex requirements
- Derivative of Timepix/Medipix chip family
  - 128 x 128 pixels (3.2 x 3.2 mm^2 active area)
  - **65nm CMOS**, 25µm x 25µm pitch
  - Per-pixel 5-bit ToT and 8-bit ToA
- Shutter-based acquisition,
  Power pulsing of the pixel matrix
- Challenge: single-chip bonding of sensors with 25µm pitch

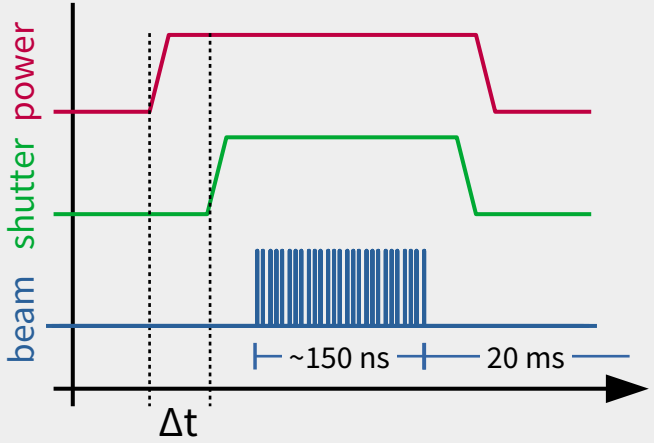


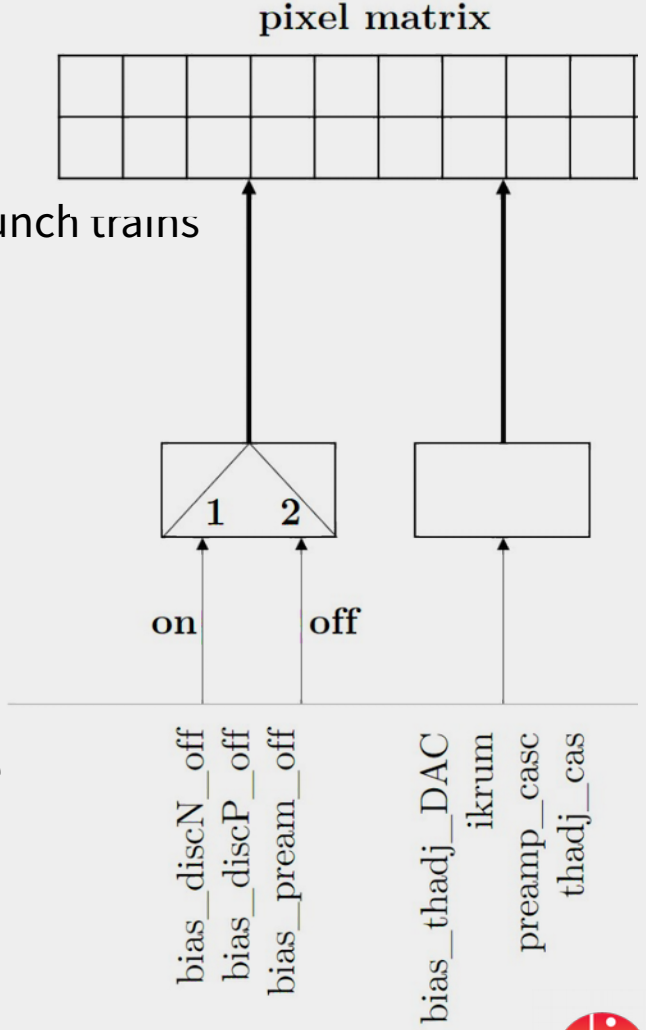


- Promising results from first beam tests
  Spatial resolution σ_{SP} **~5 µm** (130 µm sensor thickness), characterization ongoing
- However, with thin sensors (50 µm) target resolution of 3 µm not achievable at 25 µm pitch

Power Pulsing

- LC have very low duty cycle, for CLIC < 0.01 ‰
- Idea: save power by switching to lower-power idle state between bunch trains

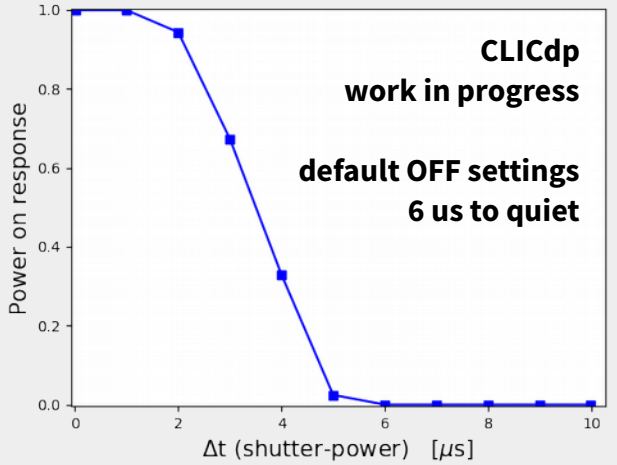


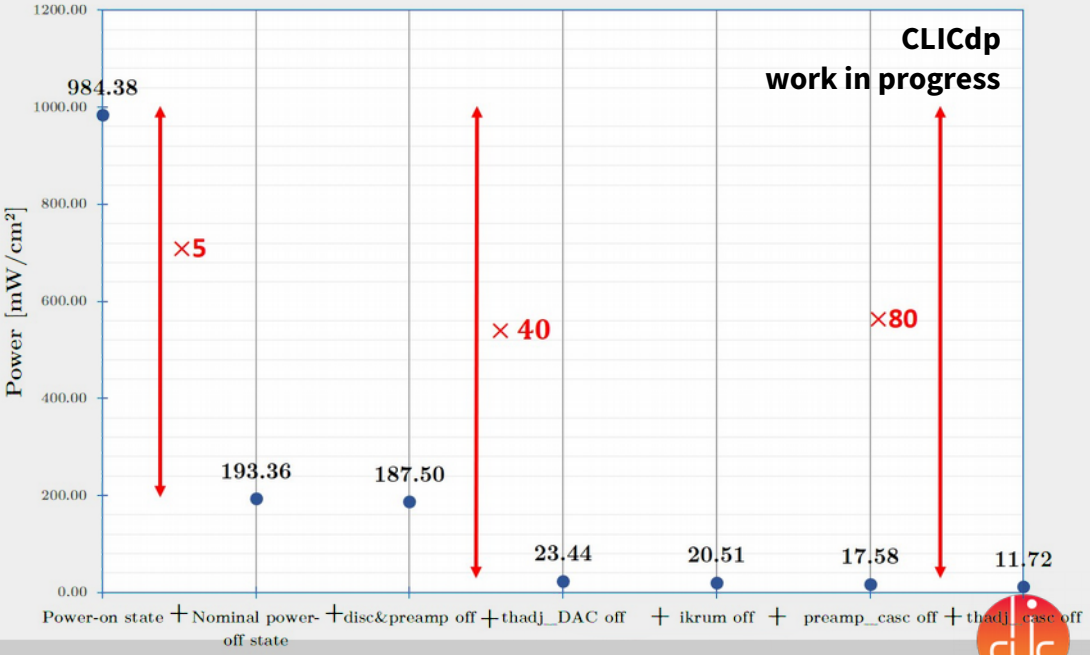


- Analog power pulsing:
  Multiplex DACs of preamp, discriminator between ON and OFF state
- Digital power pulsing:
  E.g. by gating clock to pixel matrix
- Power pulsing implemented: Timepix3, CLICpix, CLICpix2, CLICTD

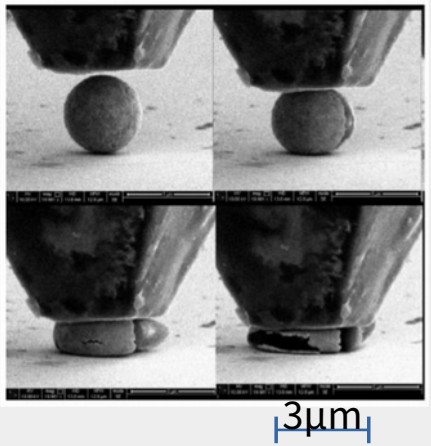
Analog Power Pulsing of CLICpix2

- Expect “power-on response” from pixel front-end
  - Requires certain time until chip is quiet, depending on how low OFF state of DACs is
  - Dominated by power consumption in idle state
- CLICpix2 analog power pulsing:
  - preamp & discriminator
  - Reduction: x5
    980 mW/cm² → 190 mW/cm²
- Reduce further: include more DACS threshold adjustment, feedback current:
  - For CLIC duty cycle: x80 (12 mW/cm²)

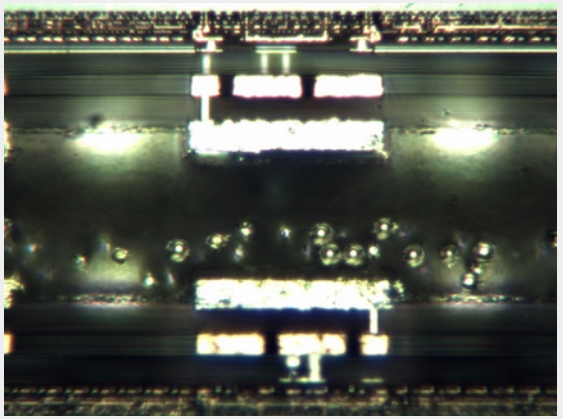


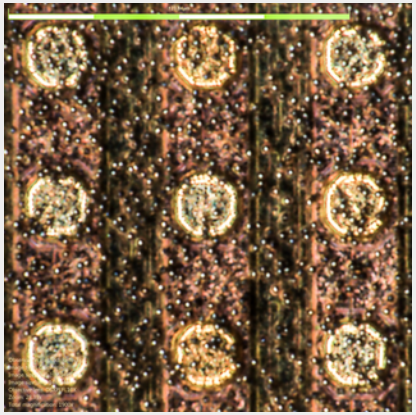


Hybridization with Anisotropic Conductive Film

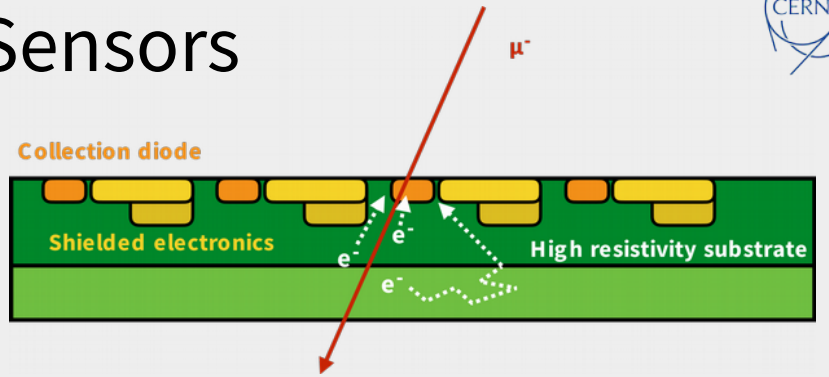


- Alternative to traditional solder-bump bonding
- Adhesive film filled with conductive micro-particles (~3 µm diam.)
  - Stochastically distributed in film with ~18 µm thickness
  - Form bond pad with mask-less ENIG process
  - Some spheres end up under bond pads, get deformed, establish contact
- Widely used in display industry in one dimension, challenge: 2D distribution
- Requires careful optimization of
  - Film thickness, # spheres/area, force…
- Currently early R&D phase
  - Glass samples for visual inspection
  - Timepix-to-Timepix for cross-sections



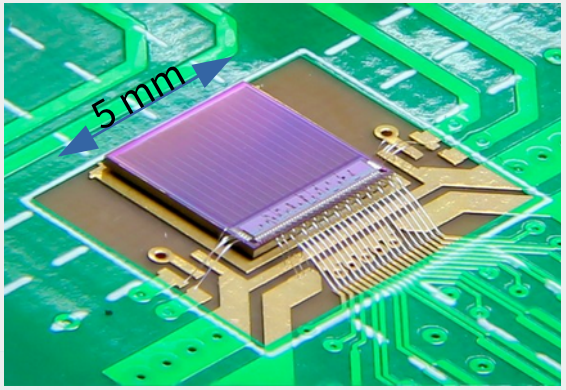


Monolithic High-Resistivity CMOS Sensors

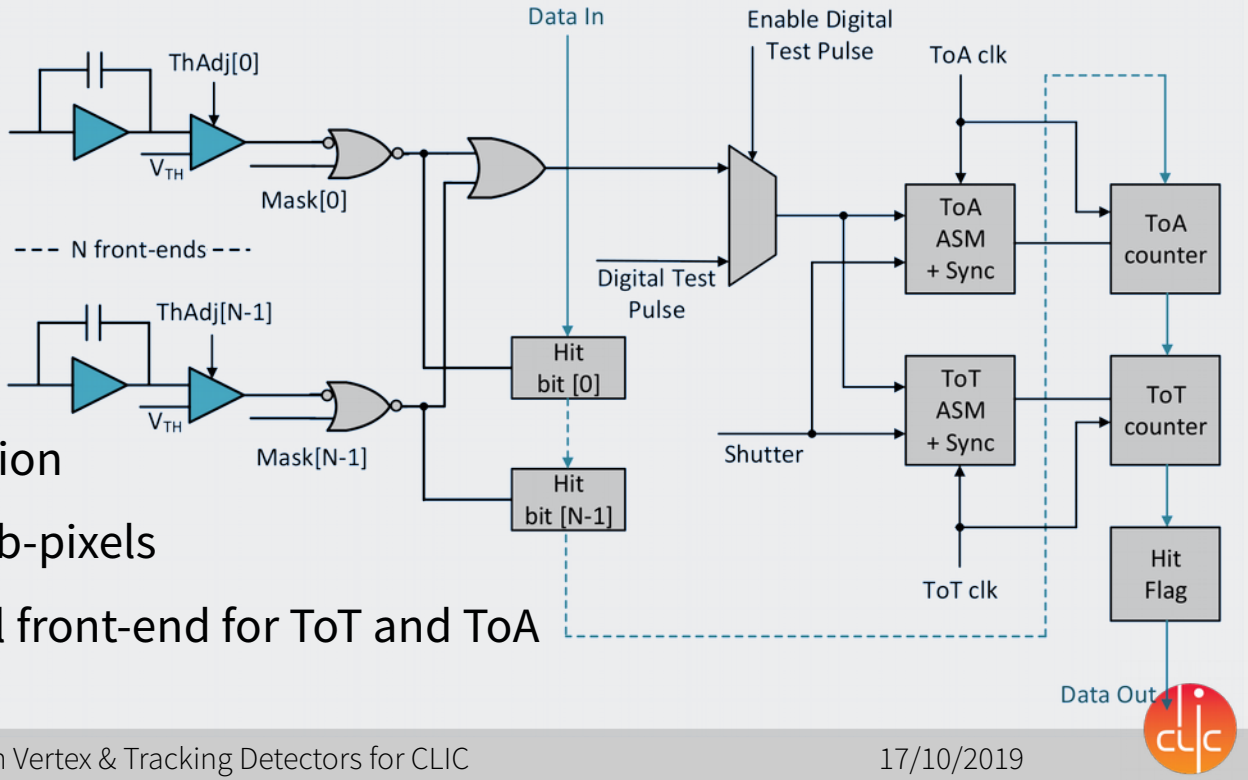


- Small collection electrode design
- Electronics outside charge-collection well
  - Small collection diode reduces input capacitance → low noise, low power consumption
  - Form depleted region by using high-resistivity substrate
- Limited to lower bias voltage compared to HV-CMOS processes
  Challenge: effect of p-wells on charge collection / electric field
- Process modifications allow full lateral depletion
  - Add deep N-layer
  - Higher backside bias possible due to isolation of electronics by depleted region

CLICTD – HR-CMOS Sensor for CLIC Tracker

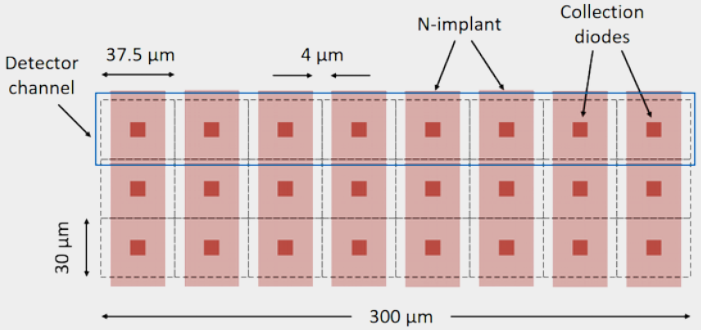


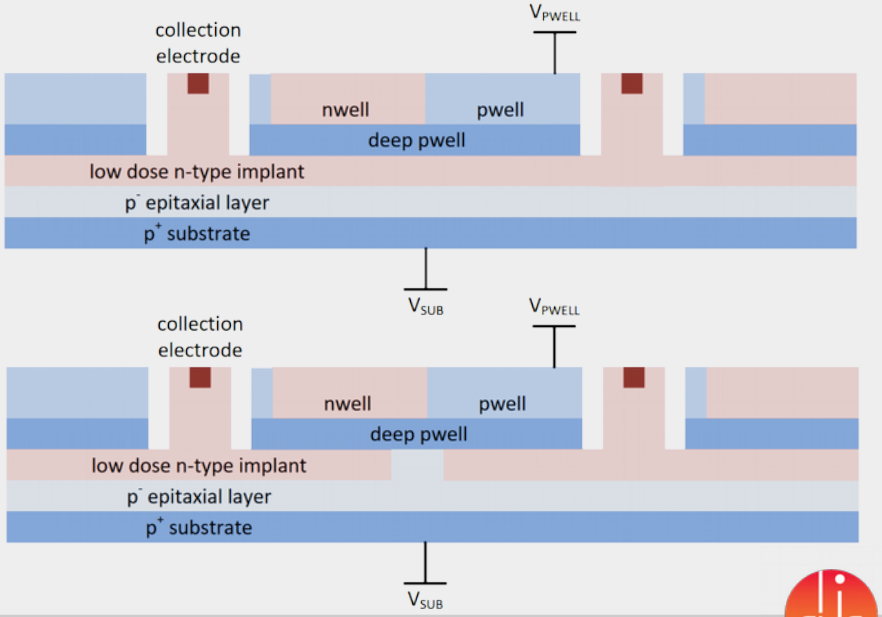
- Fully-integrated sensor for CLIC Tracking Detector
- Pixel matrix of 16 × 128 cells
  - Sensitive area 4.8 × 3.84 mm^2
  - Pixel pitch of 300 µm x 30 µm
  - 8-bit ToA and 5-bit ToT
- Analog domain: 8 sub-pixels
  - Enable prompt charge collection
  - Provide hit-bit patterns for sub-pixels
  - Combined global ***OR*** in digital front-end for ToT and ToA



CLICTD Production Process

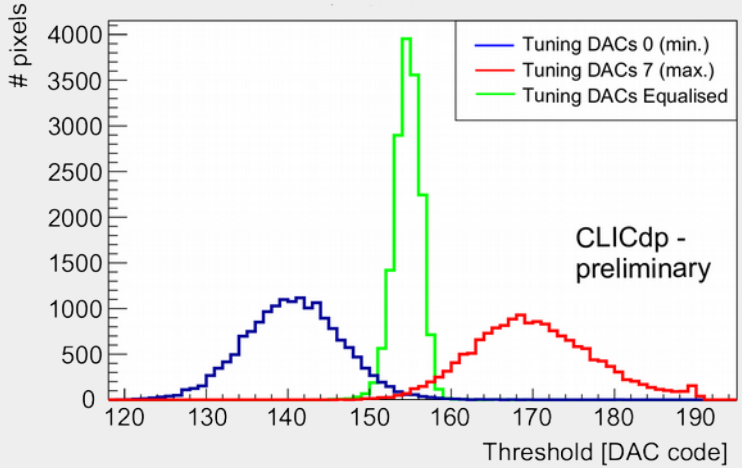
- TowerJazz 180nm CMOS imaging process
  - Small N-well collection electrode on P-type high resistivity epi layer (30µm)
  - Deep P-well shields electronics from collection electrode
  - Full lateral depletion via deep N-type blanket (“process modification”)
- Process split for second design:
  N-layer with gaps along one dimension
  - Reduce collection time & in-channel sharing



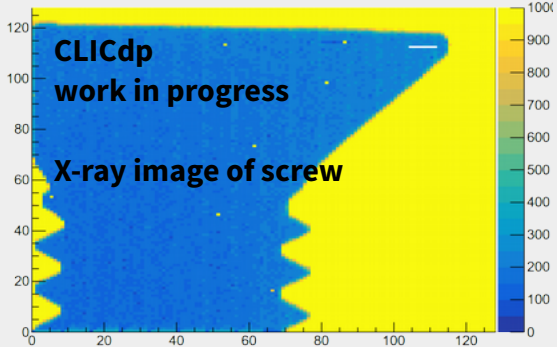


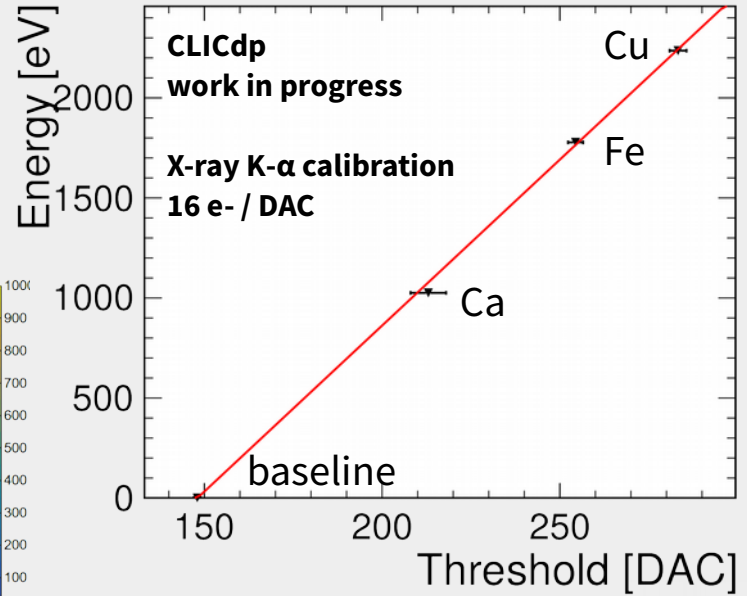
CLICTD – First Lab Measurements

- Initial tests went well (expected from UVM sim.)
  - Current and voltage DACs operate as expected
  - Slow control, periphery & matrix functional
- Observed strong influence from operation parameters on chip performance / calibration



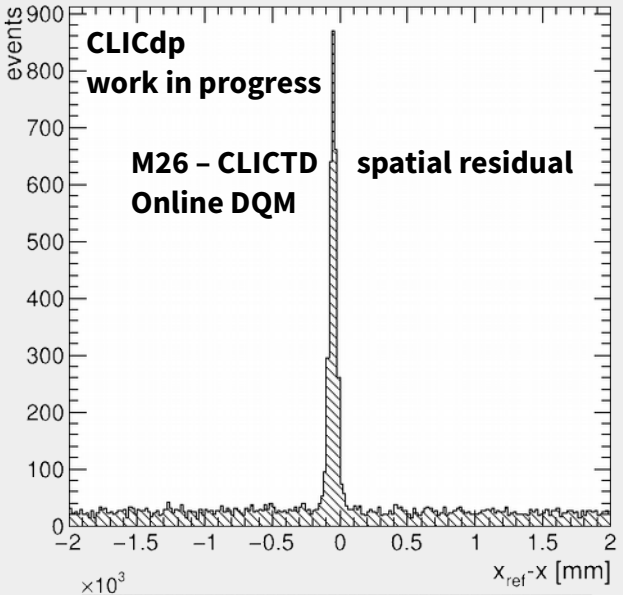
- Energy calibration with X-ray K-α
- Pixel noise RMS: 13 e-
  Threshold dispersion: 25 e-
- Further studies underway

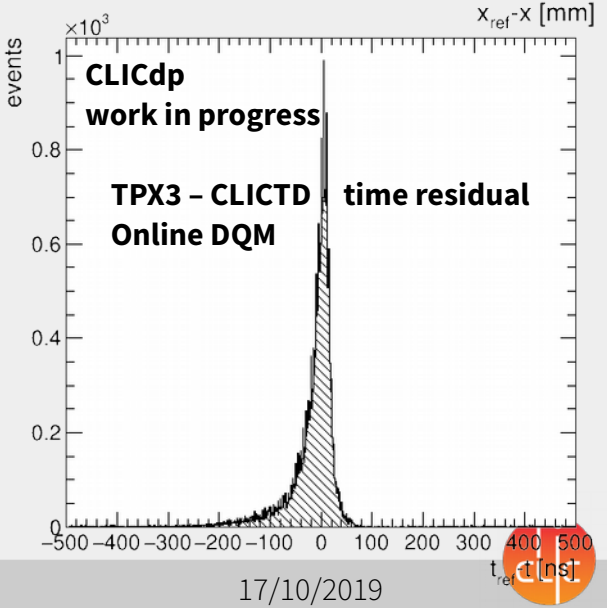




CLICTD – First Testbeam Results

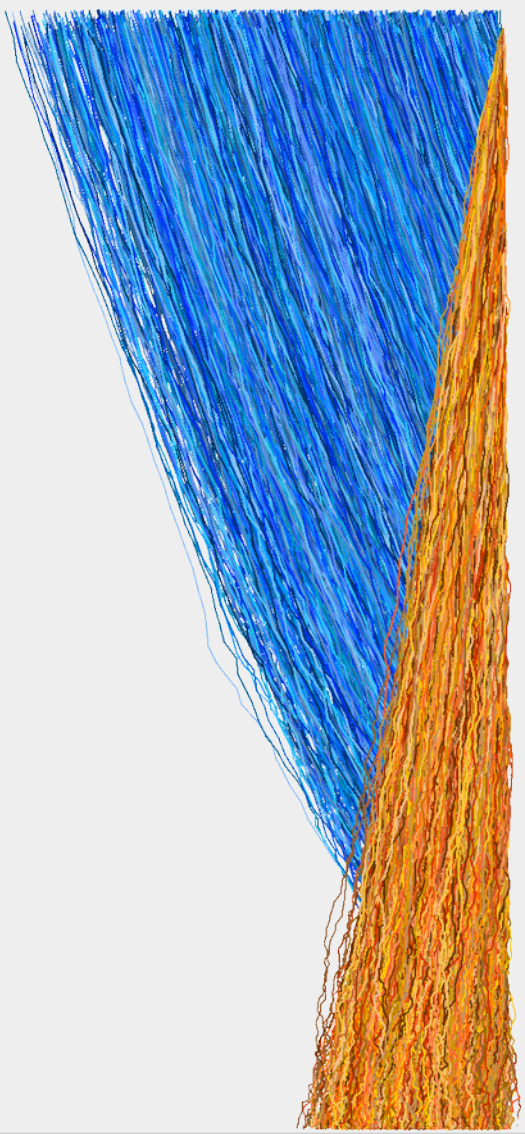
- Just finished first test beam campaign at DESY
  - Very successful – correlations (space and time) on **day 1**
  - Currently analyzing data
- Timing measurement is a bit tricky:
  - TOA measured with respect to shutter-close time
  - For free -running acquisition:
    max. shutter length 2.5 µs before saturating TOA counter
- Trick with DAQ: use scintillator triggers for shutter control
  - Open shutter, wait for particle
  - Close shutter fixed time after receiving trigger signal in DAQ
- Drastically increase data taking efficiency





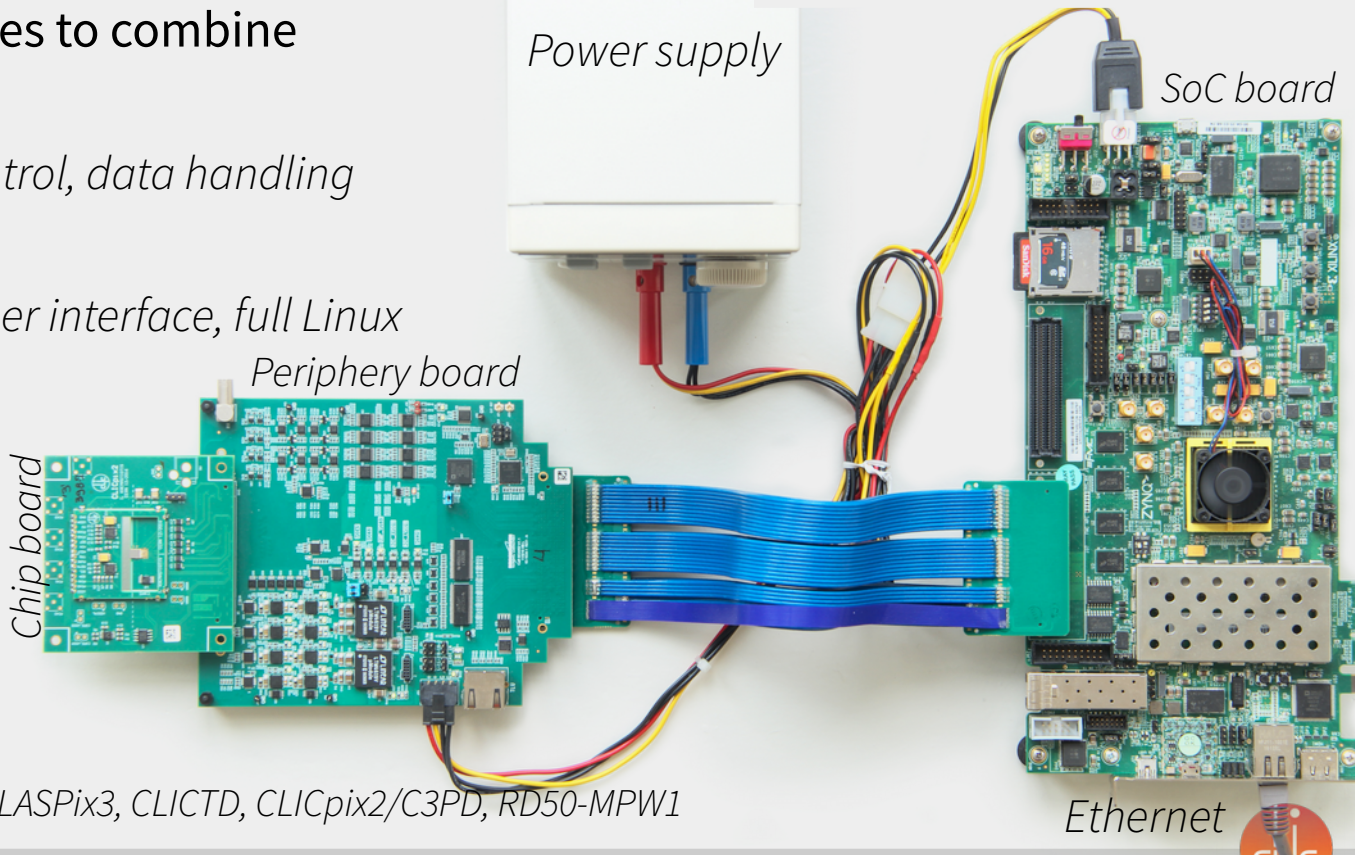
Tools for Silicon Detector R&D

for the community



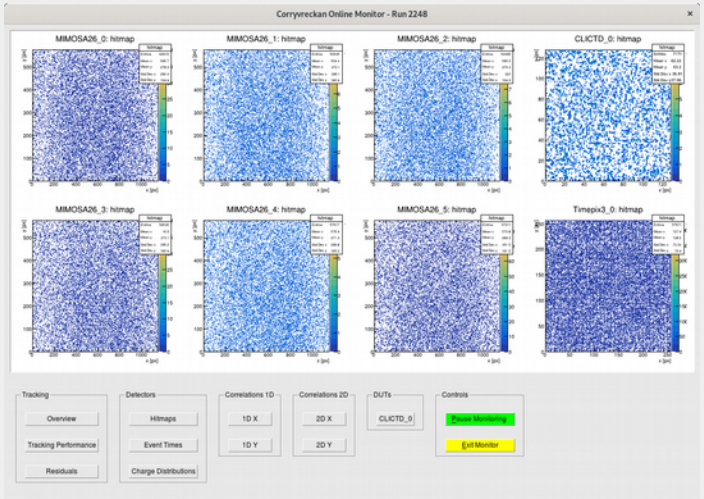
Pixel Detector Data Acquisition with **Caribou**

- Flexible DAQ system, minimal effort to support new prototypes
- Using System-on-Chip devices to combine
  - Programmable logic (PL)
    FPGA fabric for detector control, data handling
  - Processing system (PS)
    CPU for data acquisition, user interface, full Linux
- Custom-designed board:
  voltage regulators, ADCs,
  LVDS converters,
  pulse generators,
  clock generator, TLU interface
- Already used with:
  H35Demo/FEI4, ATLASPix, ATLASPix2, ATLASPix3, CLICTD, CLICpix2/C3PD, RD50-MPW1



Testbeam Data Reconstruction with **Corryvreckan**

- R&D with many prototypes – and different readout schemes
  - Data-driven (Tpx3), rolling shutter/triggered (M26), frame-based (CLICTD)
- Requires **flexible reconstruction framework** for offline event building
  - Modular approach, similar to EUTelescope but: **own event processor algorithm, file format, …**
  - No external dependencies apart from ROOT
  - **4D pattern recognition**, Millepede algorithm integration
- Very fast – used to reconstruct data during acquisition
  - "Online" monitoring with full tracking
- Implementation of General Broken Lines tracking underway
- Currently finalizing documentation & version 1.0, expecting release still this year

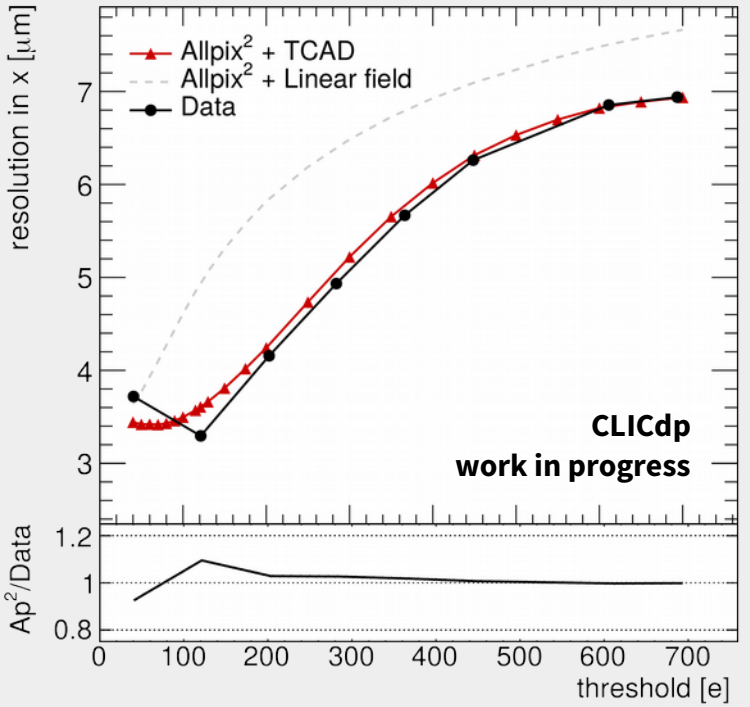


https://gitlab.cern.ch/corryvreckan/corryvreckan

Silicon Detector Monte Carlo Simulation with **Allpix²**

- Gauging performance requires simulation including full detection chain, **stochastic effects, fluctuations, secondaries, digitization**
- Decided to develop new framework
  - … to test different simulation models
  - … to easily implement new detectors
  - … that provides **interface to TCAD**
  - … that is well documented & maintainable
- **Core** & independent **physics simulation modules**
- Example: performance of CMOS detectors
  - here: ALICE Investigator chip position resolution,
  - comparison: data, APSQ+TCAD, APSQ+linear field

https://cern.ch/allpix-squared/



In a nutshell…

Summary & Outlook

- **CLIC: Proposed linear e+e- collider**, staged construction
- Linear collider environment poses challenges to silicon detectors
  - **… excellent spatial and temporal resolution, minimum material**
  - … ambitious detector design concept
- Comprehensive R&D program for CLIC silicon detectors
  - Many technologies and concepts under investigation
  - **Dedicated prototypes developed** in different technologies (monolithic, hybrid)
  - Most initial requirements shown to be achievable, integration necessary
    3 µm spatial resolution still to be reached
- **Developed tools for detector R&D** widely used in community
  - Simulation, data acquisition, reconstruction
- Many ongoing developments, testbeam campaigns, new prototypes planned

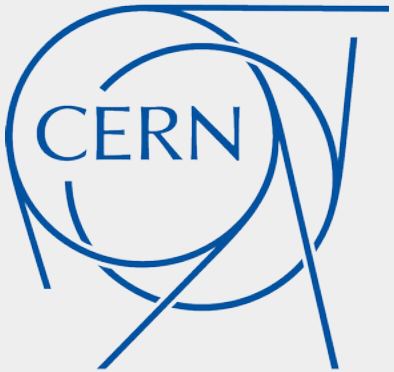
Resources

Compact Linear Collider Portal
http://clic.cern/

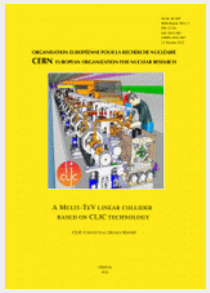
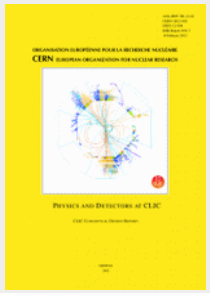
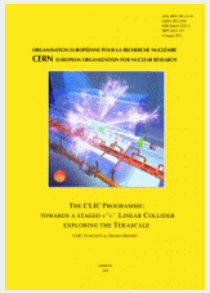
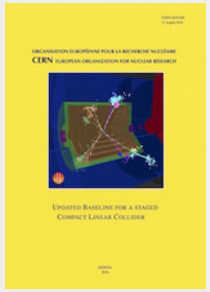
CLIC input to the European Strategy for Particle Physics Update 2018-2020
http://clic.cern/european-strategy

CLIC CDR & 2018 Summary Documents

CLICdp Publications on CERN Document Server
https://cds.cern.ch/collection/CLIC Detector and Physics Study


CERN

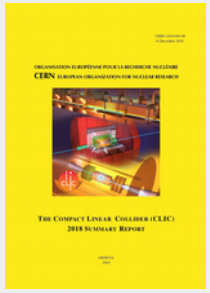
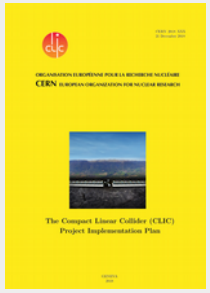
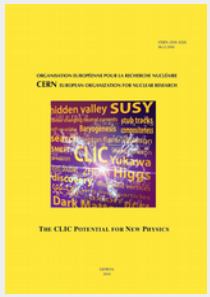
Summary Documents

2012 CLIC Conceptional Design Report

- A Multi-TeV Linear Collider Based on CLIC Technology
- Towards a staged e+e− linear collider exploring the terascale
- Physics and Detectors at CLIC

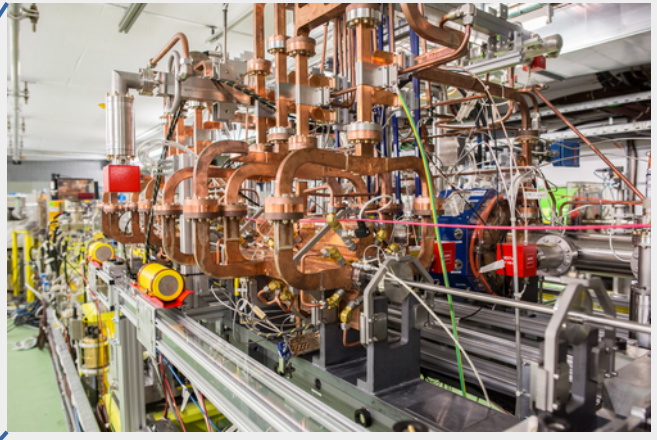
2016 Updated Baseline for a staged Compact Linear Collider

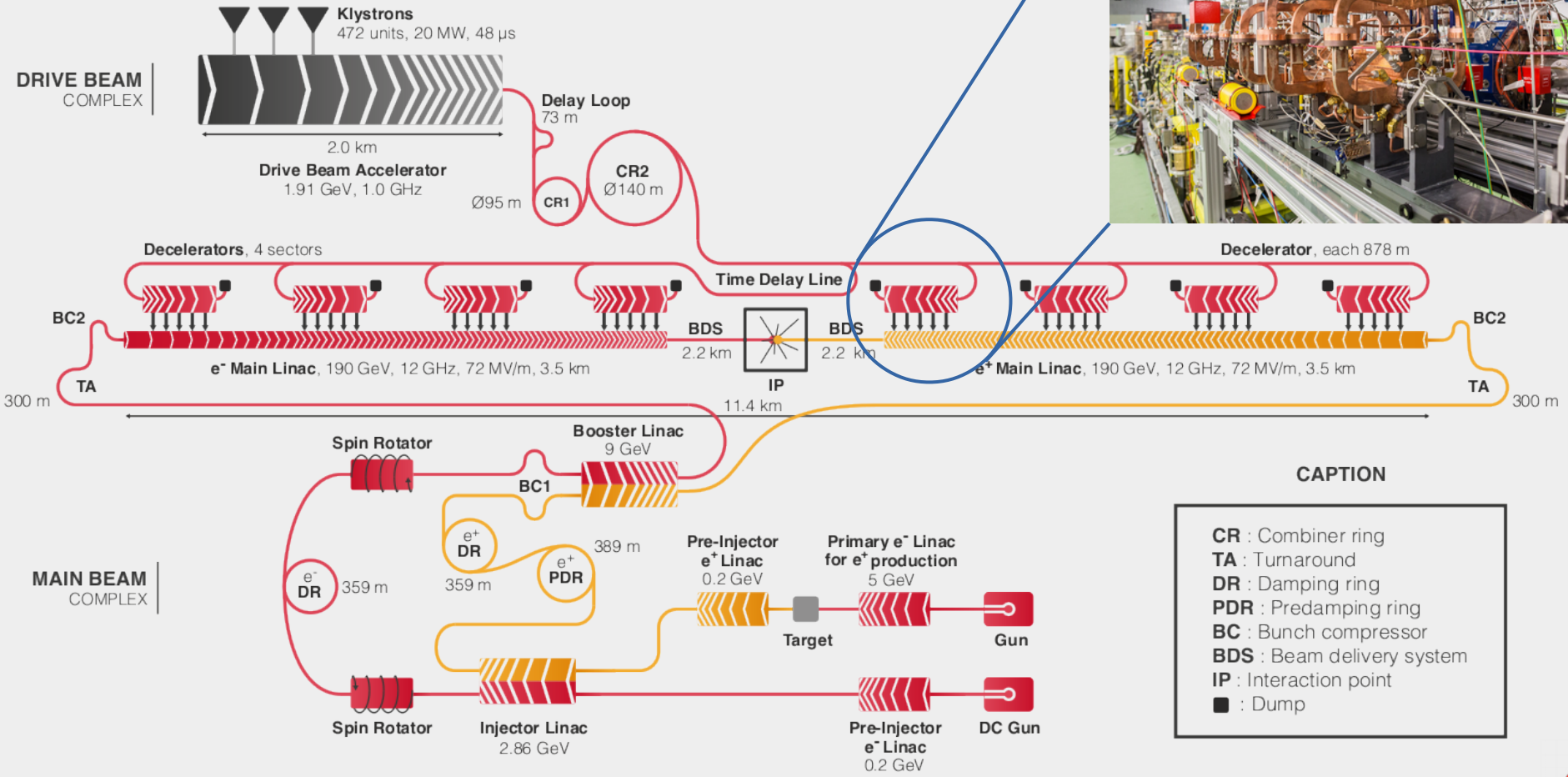




2018 Documents for the European Strategy Update

- CLIC 2018 Summary Report
- CLIC Project Implementation Plan
- The CLIC Potential for New Physics
- Detector technologies for CLIC

CLIC Accelerator Complex @ 380 GeV



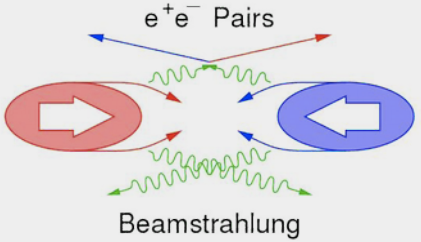


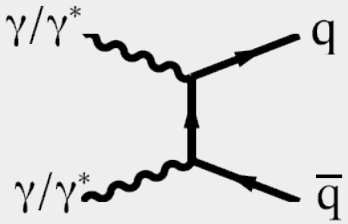
CAPTION

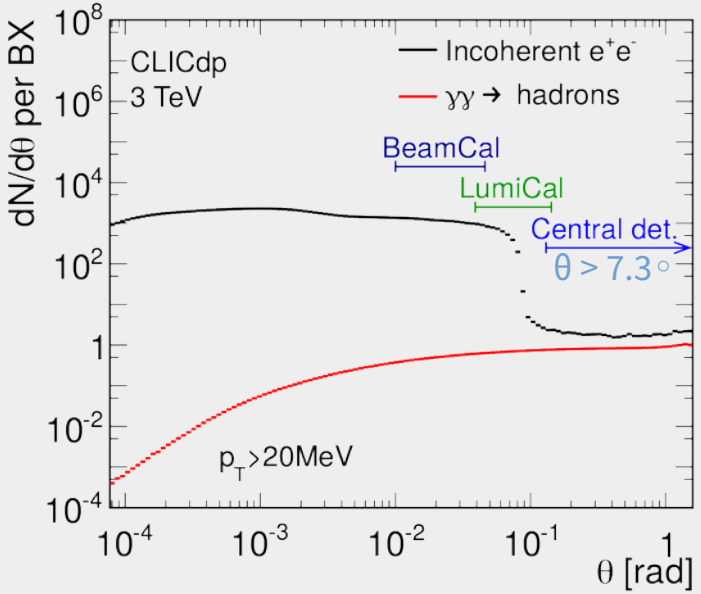
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Beam-induced Backgrounds

- High luminosity achieved by extremely small beam
  - Bunch size at 3 TeV CLIC: **40 nm** (x) x **1 nm** (y) x **44 µm** (z)
  - Resulting high e-field leads to beam-beam interactions
- Generates background particles, reduces √s





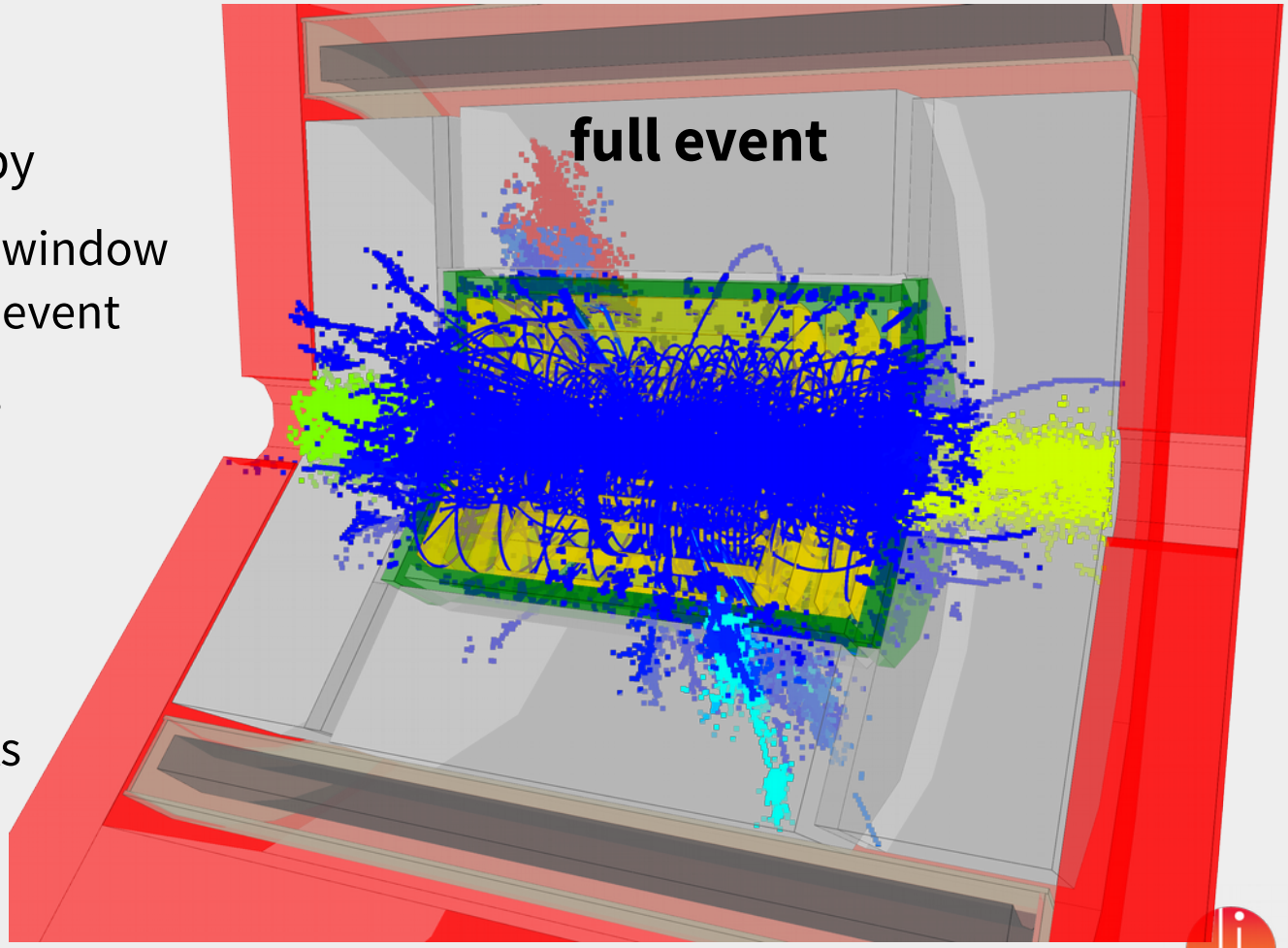


Main backgrounds in detector acceptance:

- **Incoherent e + e – pairs**
  - 19k particles / bunch train at 3 TeV
  - High occupancies, stringent requirements on granularity
- **γγ → hadrons**
  - 17k particles / bunch train at 3 TeV
  - Impact on detector granularity, layout, physics

Background suppression @ **3 TeV**

- **Fully-hadronic $t\bar{t}$ event**
- Background suppression by
  - Defining reconstruction window 10 ns before, 30 ns after event
  - Building physics objects
- Suppression via
  - Timing requirements
  - Particle type and p_T
  - Retaining high-p_T objects
- Cuts adapted per region



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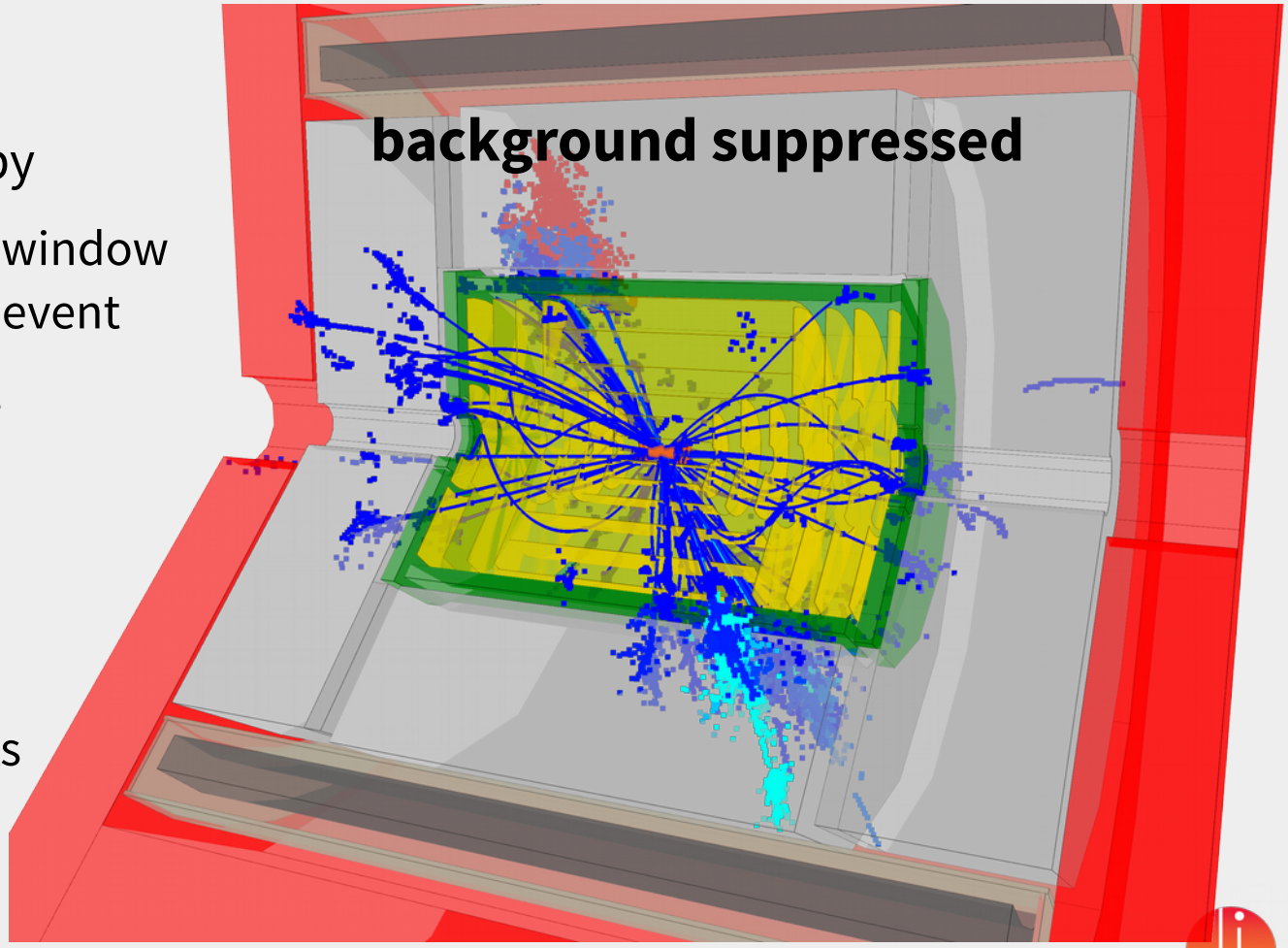

Cost Estimate for the CLIC Detector

- Based on detector work breakdown structure, aimed at 30% uncertainty
- Main cost driver: silicon sensors for electromagnetic calorimeter
  - Example: 25% cost reduction of silicon per unit of surface → overall detector cost reduction by > 10%

System	Cost fraction	Cost[MCHF]
Vertex		13
Silicon Tracker		43
Electromagnetic Calorimeter		180
Hadronic Calorimeter		39
Muon System		16
Coil and Yoke		95
Other		11
	0 10% 20% 30% 40% 50%	
Total		397