The CLIC detector

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on behalf of the CLICdp collaboration

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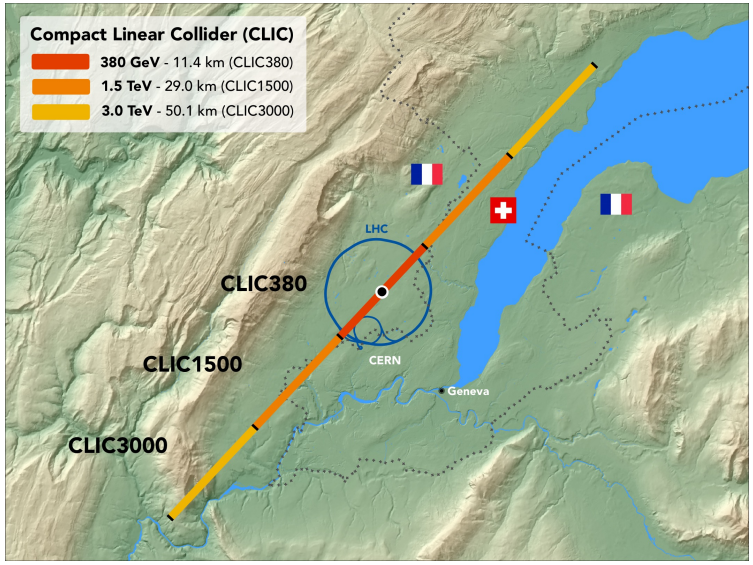
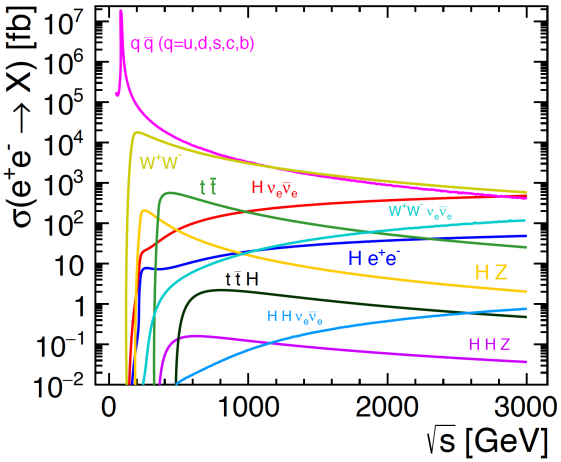
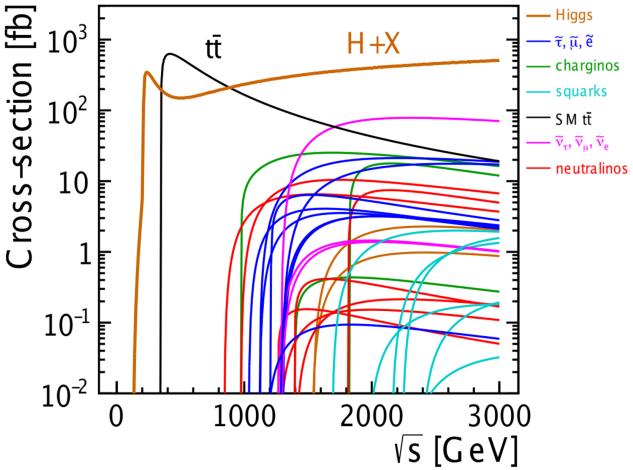
CLIC: Compact Linear Collider

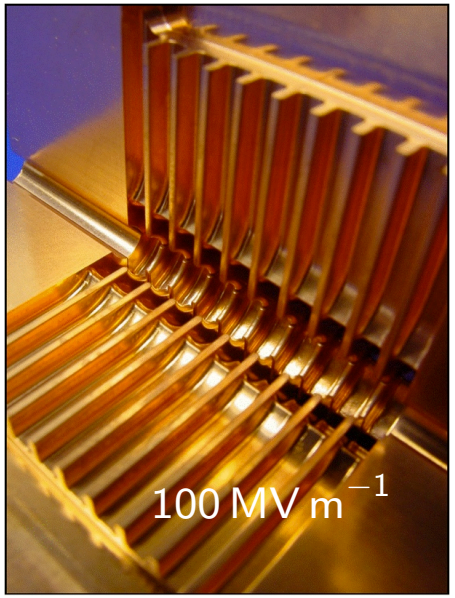
- High-luminosity linear e^+e^- collider at the energy frontier
- Energy from few hundred GeV up to 3 TeV
- Two-beam acceleration scheme
- High acceleration gradient of 100 MV/m

- Physics goals:
  - Precision measurements of SM processes: Higgs boson, top quark
  - Precision measurements of new physics potentially discovered at LHC or CLIC
  - Indirect and direct searches for new physics: unique sensitivity to particles with electroweak charge







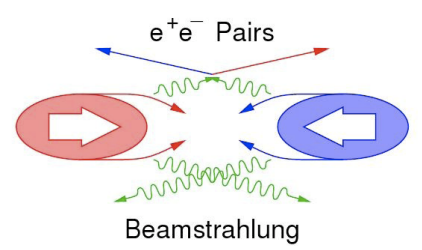


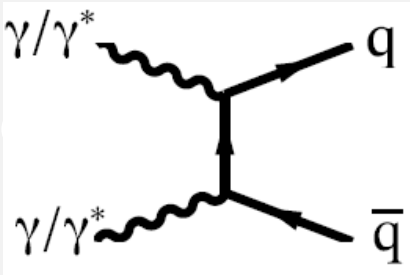
Input for CLIC detector design

Beam-induced backgrounds

Achieve high luminosities by using extremely small beam sizes

- Bunch size @ 3 TeV: $\sigma_{x;y} = \{40\,\text{nm}; 1\,\text{nm}\}$
- Very high E-fields $\rightarrow$ beam-beam interac.

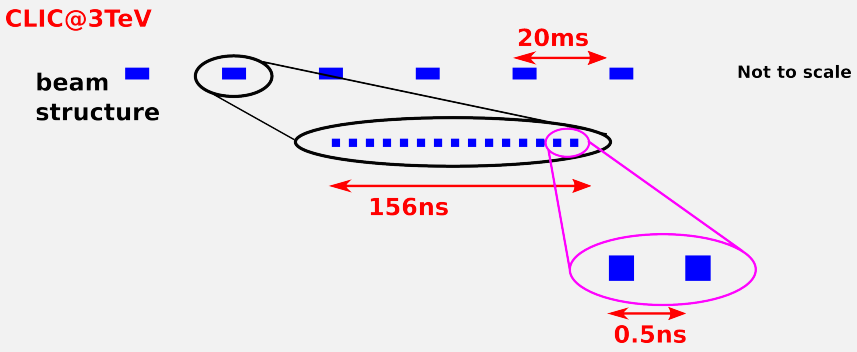




Main backgrounds ($p_T > 20\,\text{MeV}, \theta > 7.3^\circ$):

- **Incoherent e^+e^- pairs** and $\gamma\gamma \rightarrow$ hadrons
  - $\sim$ 34k particles/bunch train at 3 TeV
  - $\rightarrow$ Impact on detector granularity, design and physics measurements

Beam structure

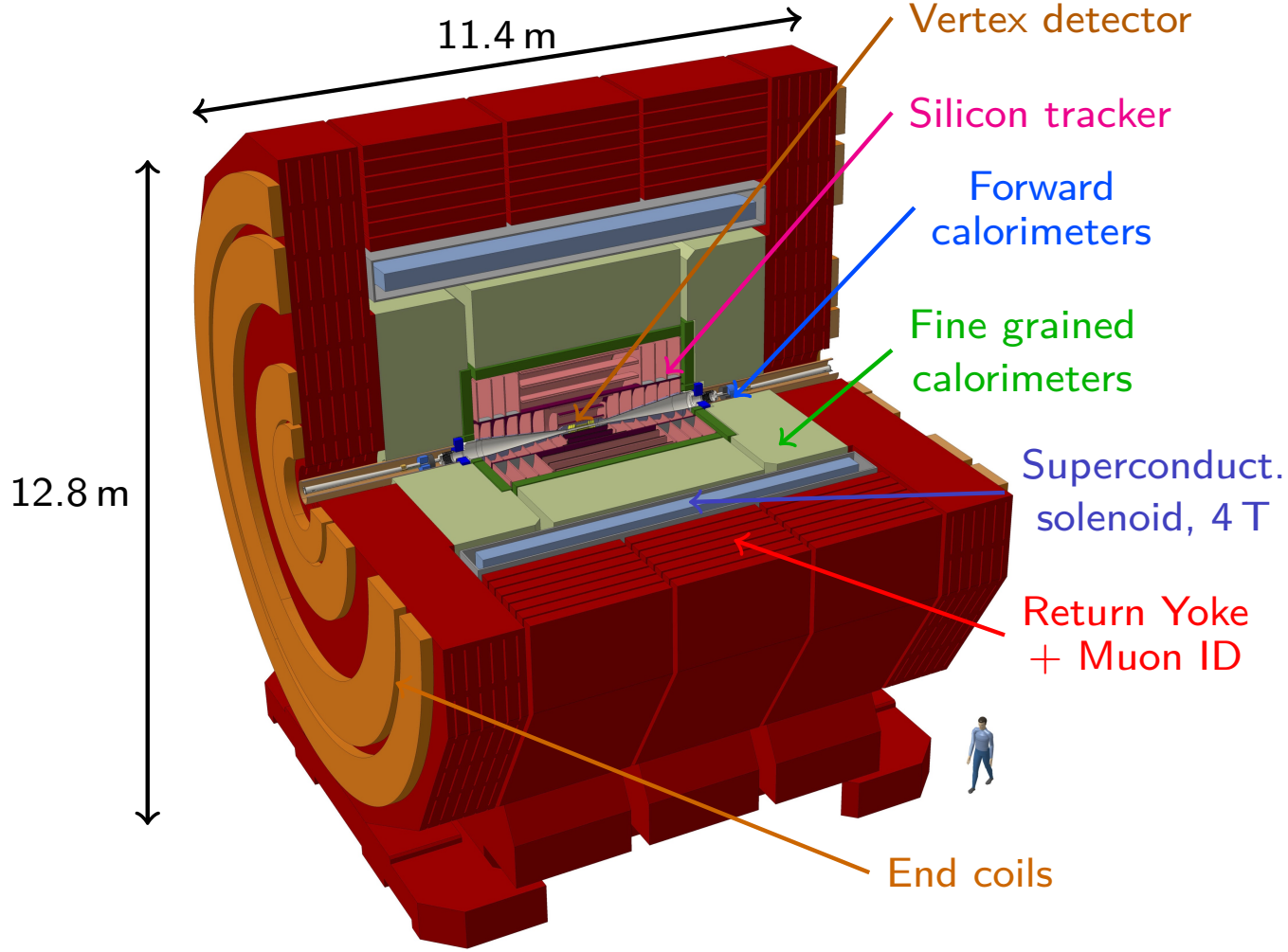


Property	
$\sqrt{s}$	3.0 TeV
Train repetition rate	50 Hz
Bunches / train	312
Train duration	156 ns
Bunch separation	0.5 ns
Duty cycle	0.00078%

1) Bunch separation and occupancies from beam-induced backgrounds define timing requirements of sub-detector
   - $\sim$ 5 ns hit time-stamping in tracking
   - 1 ns accuracy for calorimeter hits
2) Low duty cycle
   - Power pulsing of detectors

CLIC detector optimised for 3 TeV

- Large silicon tracker R=1.5 m
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ_I)
- B-field of 4 T
- Last focussing magnet QD0 outside detector: increased HCAL forward acceptance



Vertex and tracking detector requirements

Vertex-detector

- Flavour tagging

→ Single point resolution: $\sigma < 3\,\mu\text{m}$

→ Small pixels $\lesssim 25 \times 25\,\mu\text{m}^2$, analog readout → $\sim$ 1.3 billion channels

→ $\lessapprox 0.2\,\%X_0$ / layer

→ Power pulsing

→ Low power dissipation ASIC + air cooling →$\leq 50\,\text{mW/cm}^2$

Tracker

- Momentum resolution

→ 7 µm single-point resolution → (30-50 µm pitch in $R\phi$)

→ $\lessapprox 1-2\%X_0$ / layer

→ Light-weight support structure and services

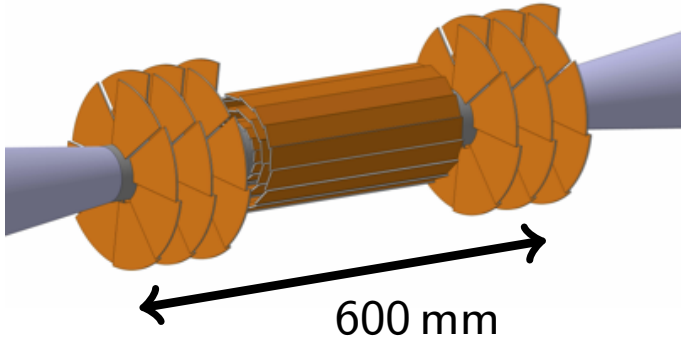
Vertex and Tracker

- Time stamping $\sim$ 5 ns

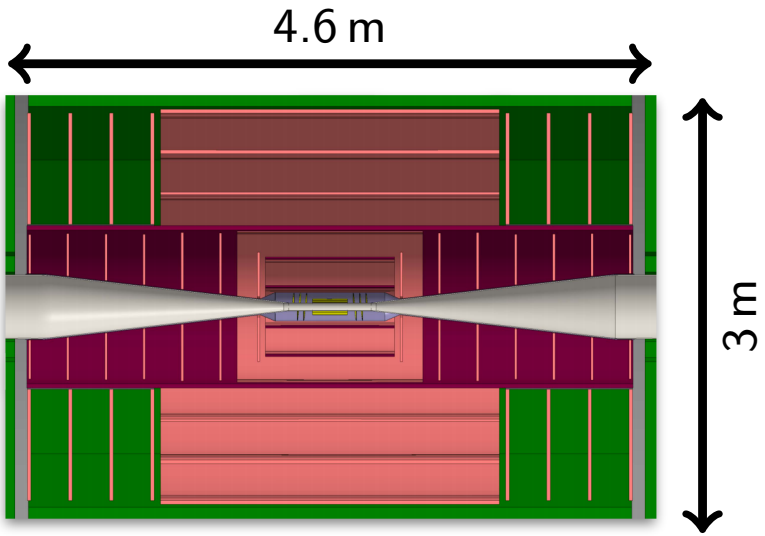
→ Depleted sensors (high resist./voltage)

- Few % occupancy from beam-induced bkg.
- Low radiation exposure (10^4 below LHC)

CLIC vertex detector: 0.84 m^2



CLIC all-silicon tracker: 137 m^2

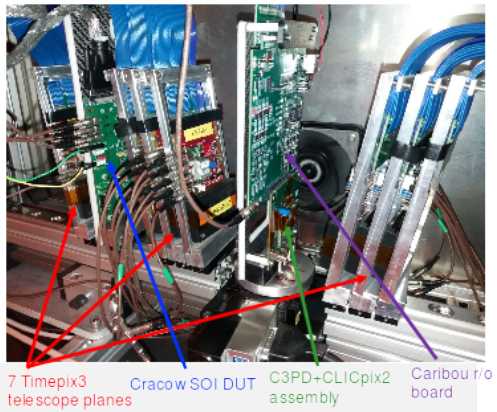


CLIC silicon pixel R&D activies

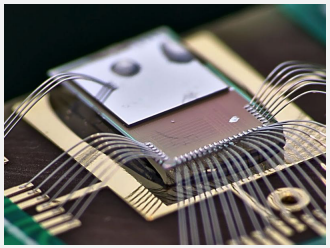
Sensor and readout technologies

Sensor and readout technology	Considered at CLIC for
Bump-bonded hybrid planar sensors	Vertex detector
Capacitively coupled HV-CMOS	Vertex detector
Monolithic HV-CMOS sensor	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensors	Vertex detector, Tracker

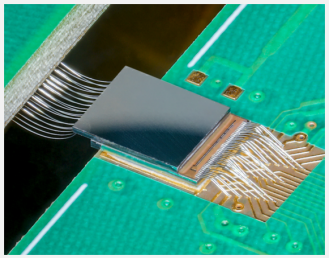
Beam tests with Timepix3 telescope



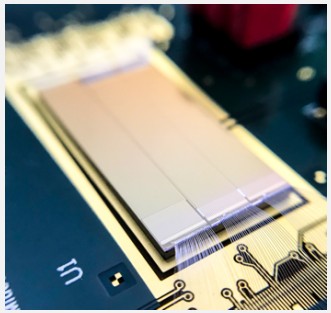
CLICpix bump bonded to 50 µm planar sensor



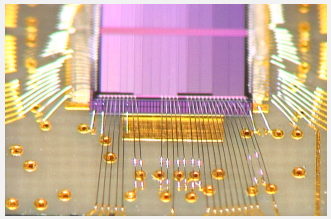
CLICpix2+C3PD glue assembly



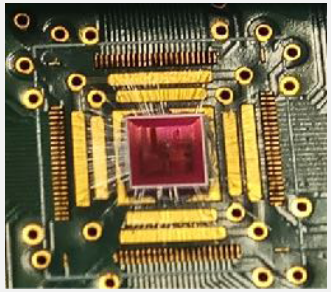
ATLASPix HV-CMOS



ALICE Investigator HR-CMOS

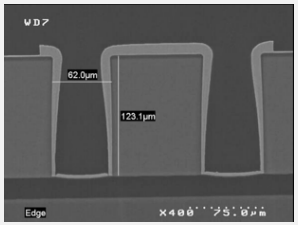


SOI

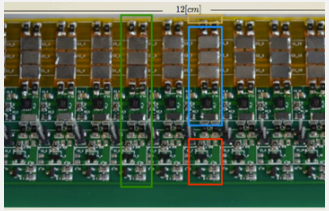


Detector integration studies

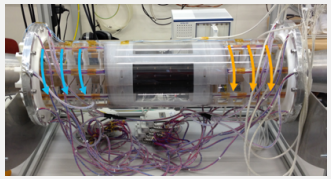
Interconnection tech.



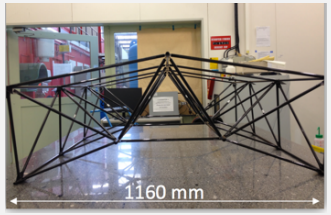
Powering concepts for power pulsing



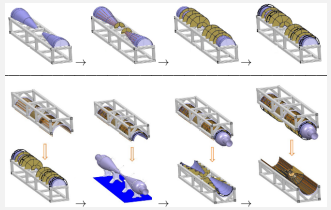
Cooling concepts



Light-weight supports

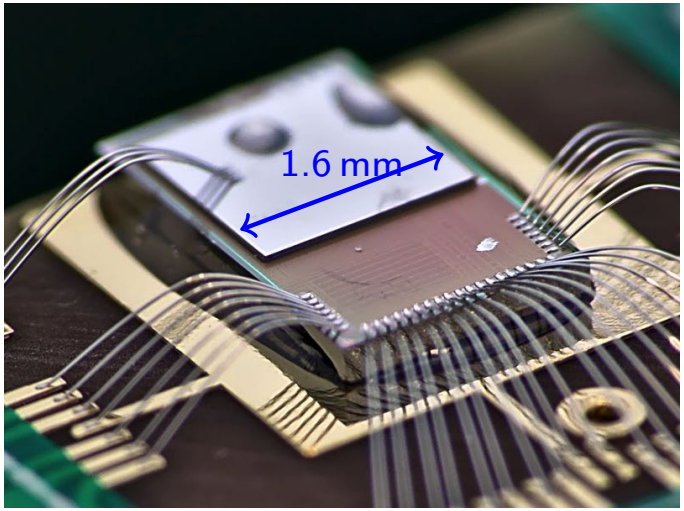


Detector assembly

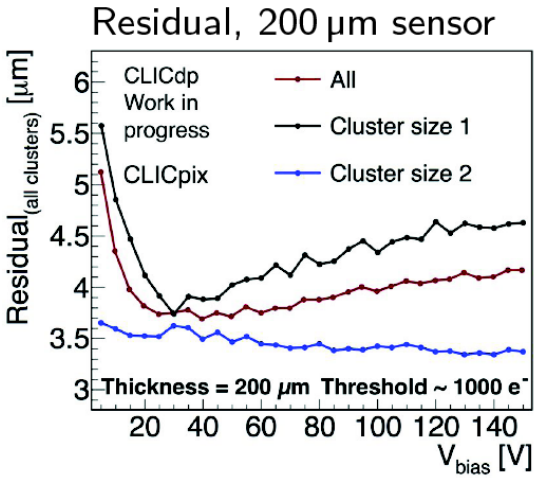


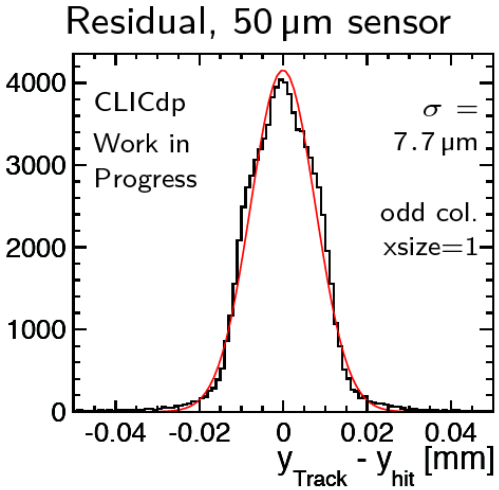
Hybrid: planar-sensor assemblies

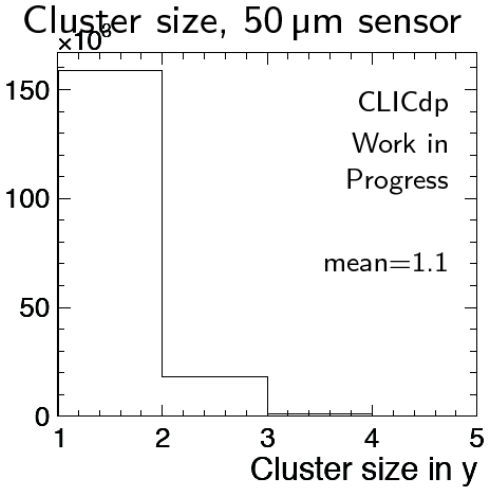
CLICpix with 50 µm planar sensor



- 65 nm demonstrator CLICpix r/o ASIC
  - 64 × 64 pixel matrix
  - 25 µm pixel pitch
- Indium bump-bonding
- Assemblies with 50 – 200 µm thick sensors
- Residuals at 3.5 µm for 200 µm sensors, ∼ 8 µm for 50 µm sensors
- More charge sharing in thicker sensors → better resolution
- Alternative for thin sensors: Increase charge sharing by dedicated implants in sensor

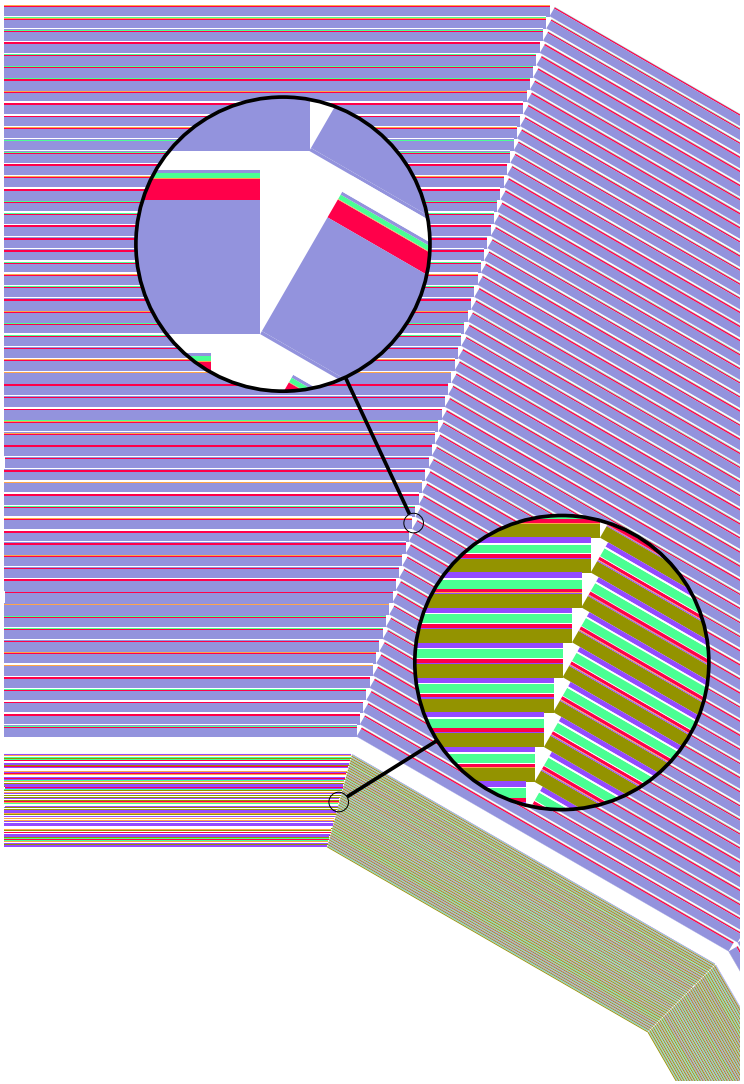






Particle flow calorimeters

- Jet energy resolution of $\sigma_E/E \approx 5 - 3.5\% \rightarrow$ Highly granular calorimeters

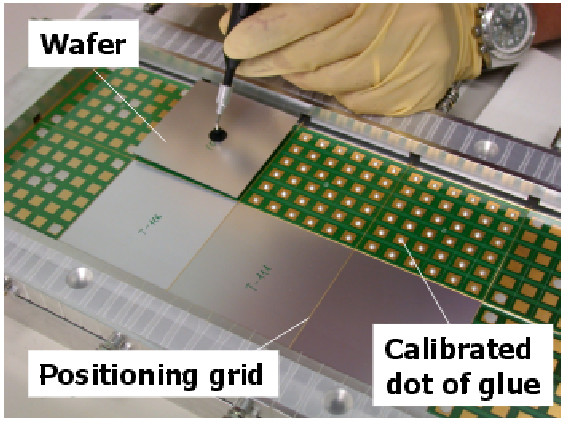


- Si-W-ECAL
  - 2 mm thick tungsten plates interleaved with 500 µm thick silicon sensors
  - 40 layers: 22 X_0 or 1 λ_I
  - $5 \times 5\,\mathrm{mm}^2$ silicon cell size
  - $\rightarrow$ $\sim 2500\,\mathrm{m}^2$ silicon
  - $\rightarrow$ $\sim$ 100 million channels
- Scint-Fe-HCAL
  - 19 mm thick steel plates interleaved with 3 mm thick plastic scintillator + SiPMs
  - 60 layers: 7.5 λ_I
  - $30 \times 30\,\mathrm{mm}^2$ scintillator cell size
  - $\rightarrow$ $\sim 9000\,\mathrm{m}^2$ scintillator
  - $\rightarrow$ $\sim$ 10 million channels / SiPMs
- Compact design of all components
- Calibration of channels
- Time stamping < 1 ns

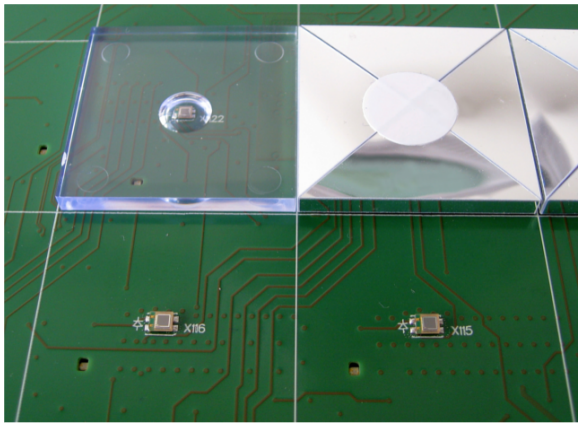
Calorimetry: technologies for active layers

- Hardware R&D by CALICE and FCAL collaborations
  - Build prototypes of highly granular calorimeters, compact design
  - Use different absorbers and different active layer technologies
  - Validate Geant4 simulations
  - Optimise detector geometry in simulations for optimal physics performance
- Synergy with ILC (ILD/SiD) and CMS HGCal

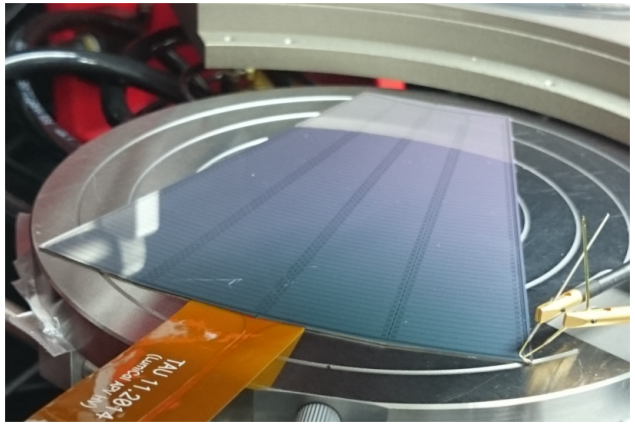
CALICE silicon PIN diodes
$1 \times 1\,\mathrm{cm}^2$ in 6×6 matrices



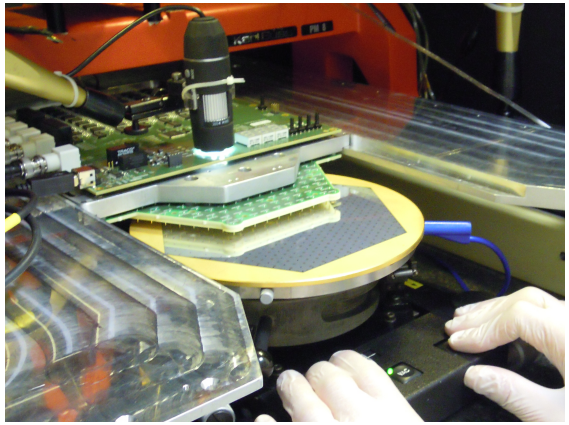
CALICE scint. tiles + SiPMs
$3 \times 3\,\mathrm{cm}^2$



LumiCal silicon sensor petal
1.8 mm wide strips, diff. lengths



CMS HGCal silicon diodes
$\sim 1\,\mathrm{cm}^2$ cells on 8-inch wafer



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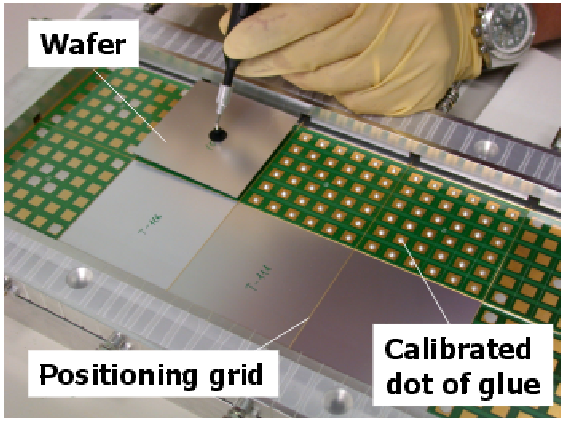

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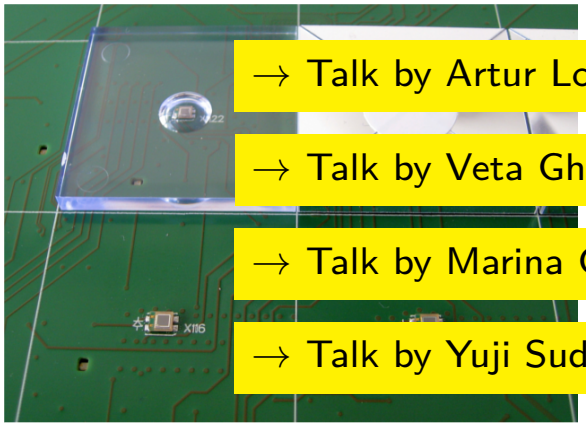

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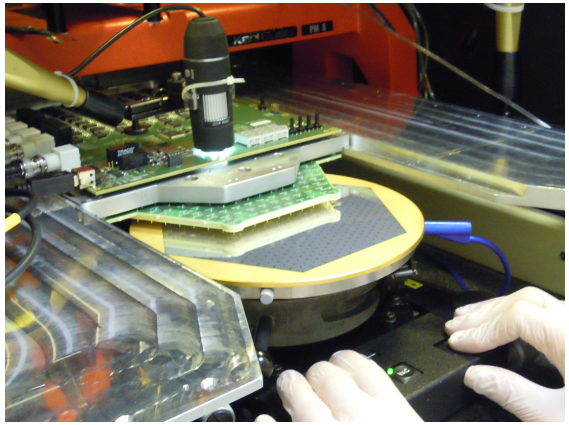


→ Talk by Artur Lobanov on CMS HGCal (Thu.)

→ Talk by Veta Ghenescu on LumiCal (Fri.)

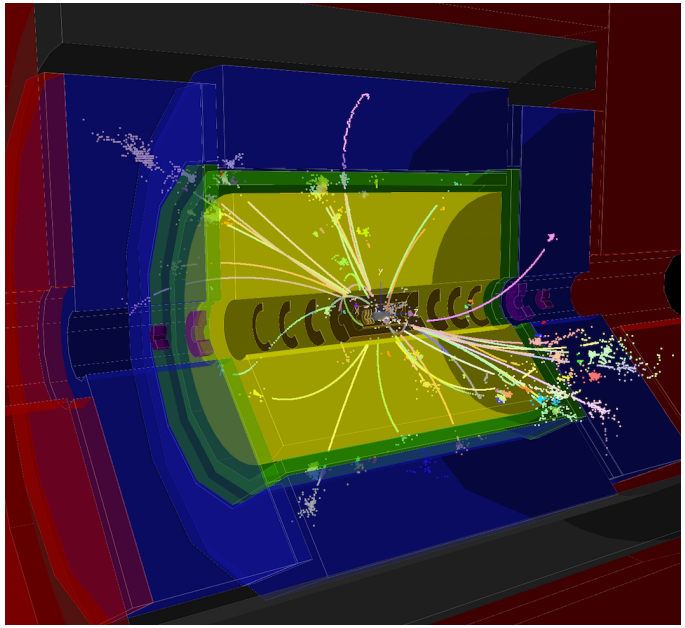
→ Talk by Marina Chadeeva on CALICE (Sat.)

→ Talk by Yuji Sudo on CALICE (Sat.)

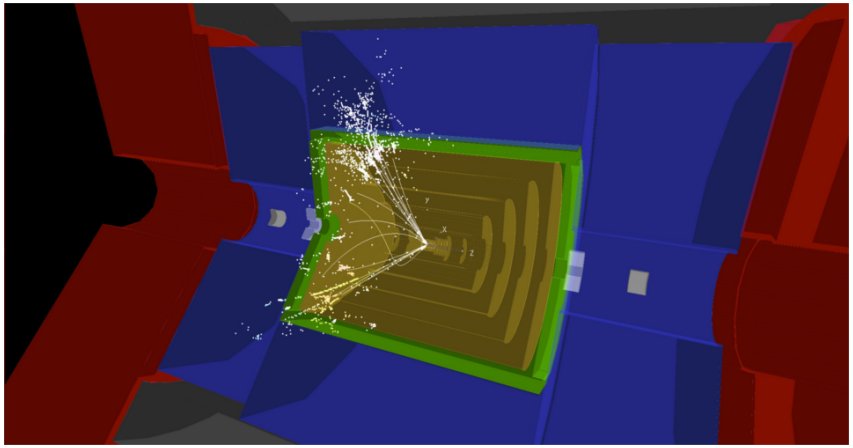
Full detector simulations at CLIC

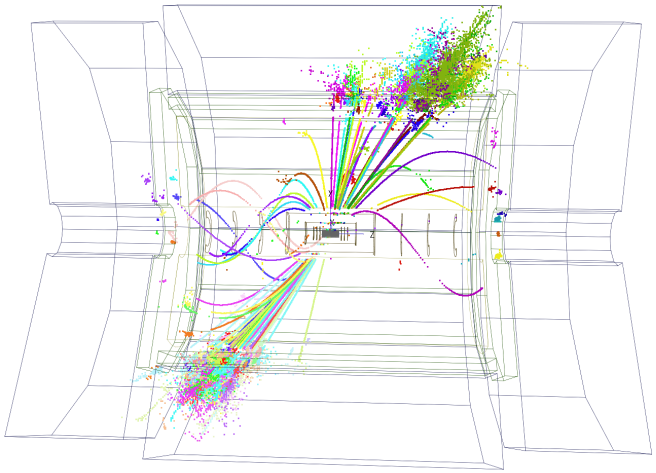
- Active software development for CLIC and LC community, e.g.
  - `DD4hep` → Generic detector description, Geant4 simulation
  - `Marlin` → Reconstruction
  - `iLCDirac` → Grid production
- Full Geant4 detector simulation including overlay of beam induced backgrounds
- Full reconstruction chain including reconstruction of tracks and clusters → particle flow objects → jets → flavour tagging

$e^+e^- \to t\bar{t}$ @ 380 GeV



$e^+e^- \to H\nu_e\bar{\nu}_e \to b\bar{b}\nu_e\bar{\nu}_e$ @ 1.4 TeV

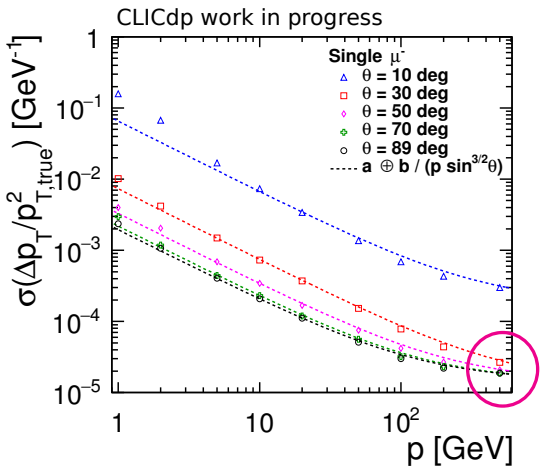




$e^+e^- \to t\bar{t}$ @ 3 TeV

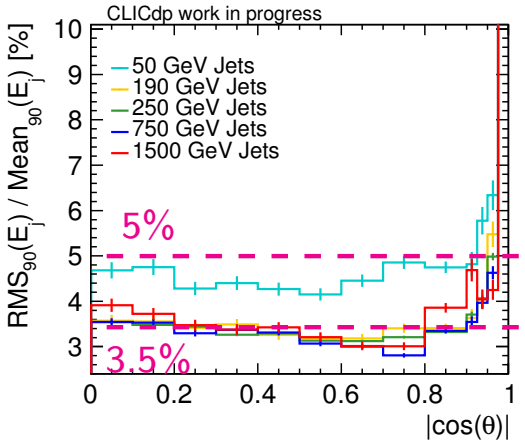
CLIC detector performance: examples

Momentum resolution



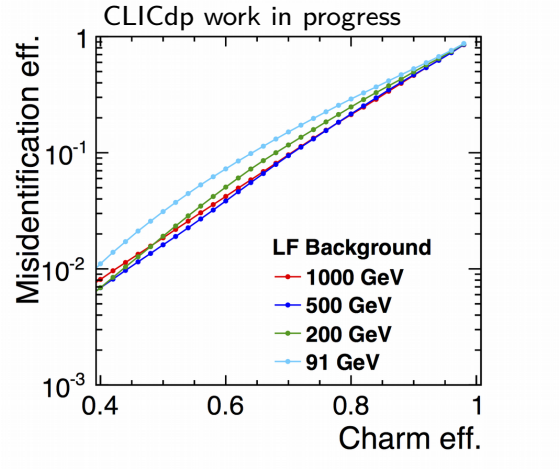
- Track reconstruction using conformal tracking
- Transverse momentum resolution of 2×10^{-5} GeV^{-1} achieved for high-energy tracks in the barrel

Jet energy resolution



- Jet energy resolution using particle flow analysis and software compensation
- Requires detailed calibration and tuning for all detector regions

Flavour tagging: charm



- Vertex finder reconstructs primary and secondary vertices
- Jet reconstruction using jet clustering algorithm

→ Feed information into multi-variate analysis → flavour of each jet

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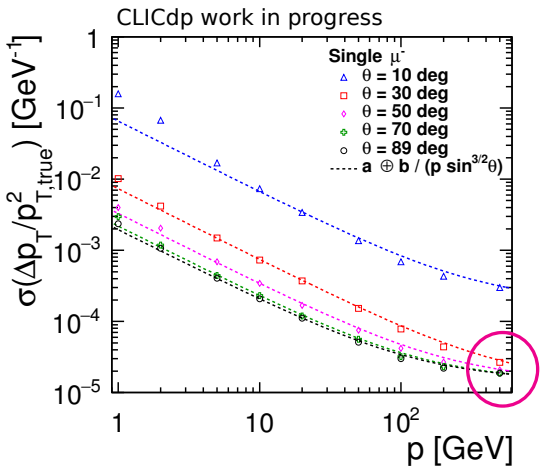

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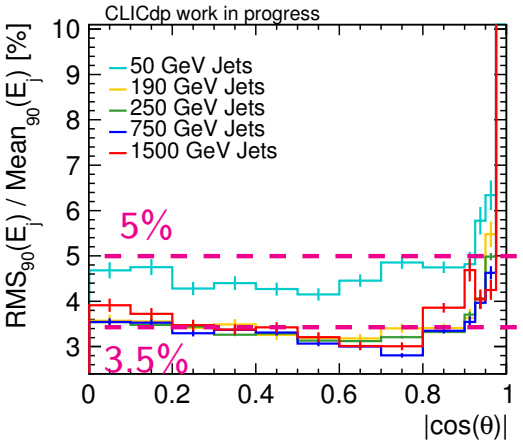

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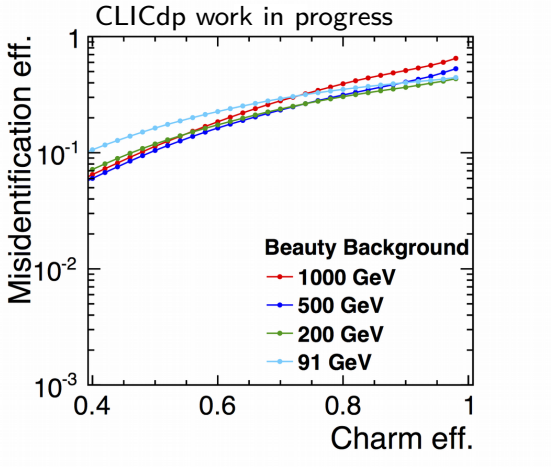

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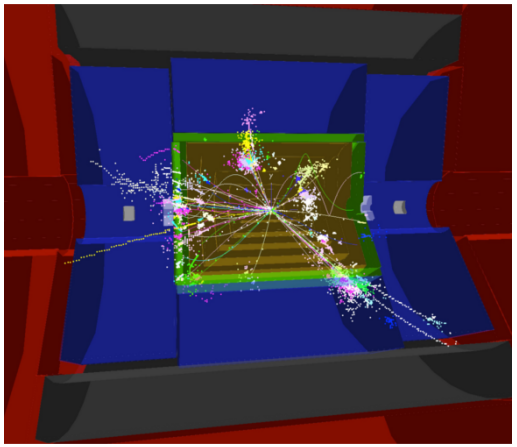
Summary



- CLIC detector concept is mature
  - Well-established detector technology development programme
    - Proof-of-concepts of most-challenging detector concepts
    - Study engineering challenges with realistic constraints
  - Performant reconstruction software
  - Optimized detector model from full detector simulation
  - Synergies with other future collider proposals and LHC experiment upgrades

- CLIC accelerator is ready to be built

→ Talk by Daniel Schulte: CLIC (Sat.)

- Valuable and guaranteed physics programme
  - Excellent Standard Model coverage
  - High-precision measurements of Higgs and top quark
  - Sensitivity to wide range of BSM phenomena through indirect and direct searches

→ Talk by Ulrike Schnoor: top quark (Fri.)

→ Talk by Filip Żarnecki: top quark (Sat.)

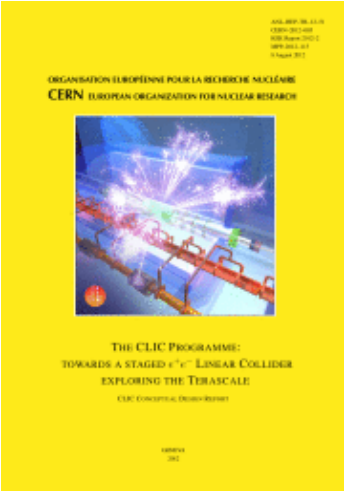
→ Talk by Matthias Weber: Higgs (Sat.)

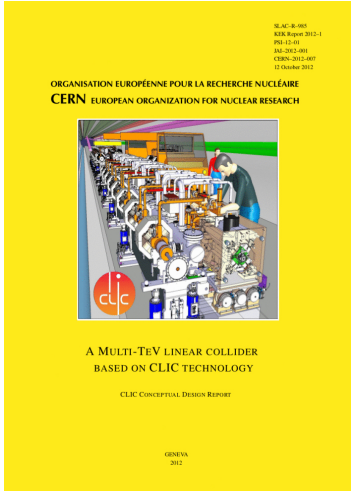
→ Talk by Roberto Franceschini: BSM (Sat.)

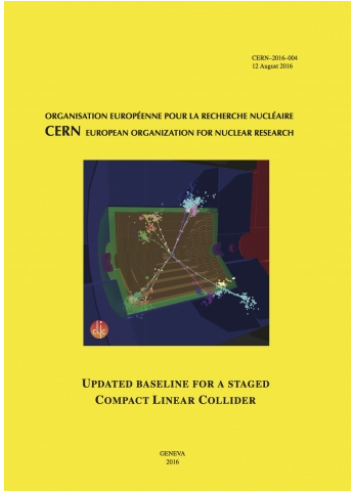
CERN

Backup

References







- CDR ▸ 10.5170/CERN-2012-007 / ▸ 10.5170/CERN-2012-003 / ▸ 10.5170/CERN-2012-005
- Staging baseline document ▸ DOI: 10.5170/CERN-2016-004
- CLIC detector description ▸ CLICdp-Note-2017-001
- CLIC detector performance
- CLIC website ▸ http://clic.cern
- More details in
  - CLIC luminosity spectrum ▸ Eur. Phys. J. C 74, 2833 (2014)
  - Vertex detector geometry ▸ CLICdp-Note-2014-002
  - Mechanical integration of vertex and tracking detectors ▸ CLICdp-Note-2015-002
  - Power pulsing for vertex detector ▸ CLICdp-Note-2015-004
  - CLIC tracker readout ▸ CLICdp-Note-2017-002

CLIC time line

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

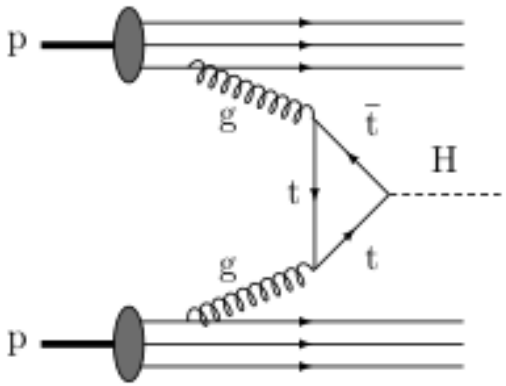
Ready for construction; start of excavations

2035 First Beams

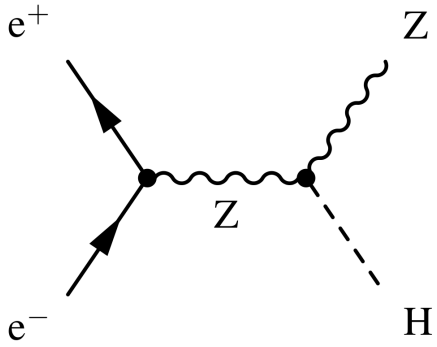
Getting ready for data taking by the time the LHC programme reaches completion

Hadron vs. lepton colliders

pp collision:
$gg \to H$



e^+e^- collisions:
ZH

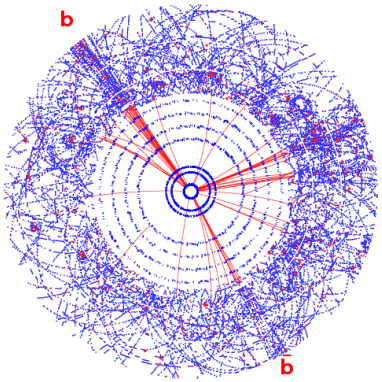


1) Proton is compound object
   - Initial state unknown
   - Limits achievable precision
2) High rates of QCD backgrounds
   - Complex triggers
   - High levels of radiation
3) Very high-energy circular colliders feasible

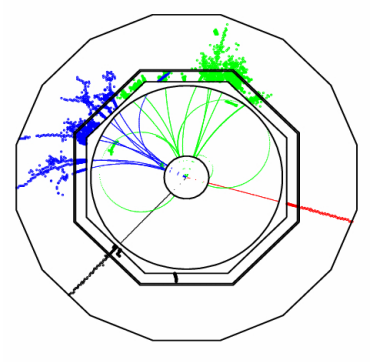
1) $e^\pm$ are point-like
   - Initial state well-defined (energy, opt.: polarisation)
   - High-precision measurements
2) Clean experimental environment
   - Less/no need for triggers
   - Lower radiation levels
3) Very high energies require linear colliders

Hadron vs. lepton colliders

pp collision:
$gg \to H \to b\bar{b}$



e^+e^- collisions:
$ZH \to \mu^+\mu^- b\bar{b}$



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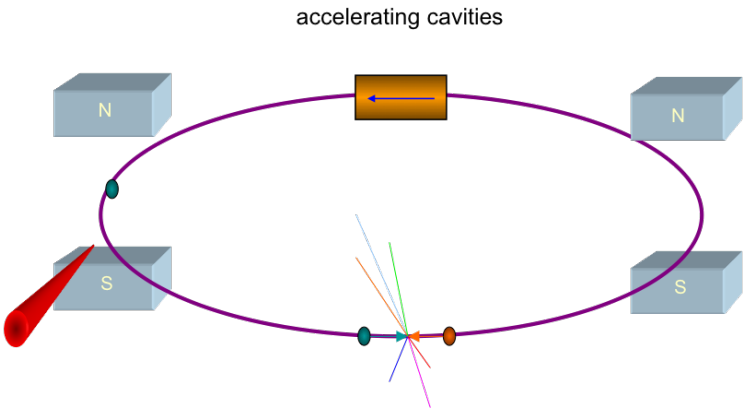
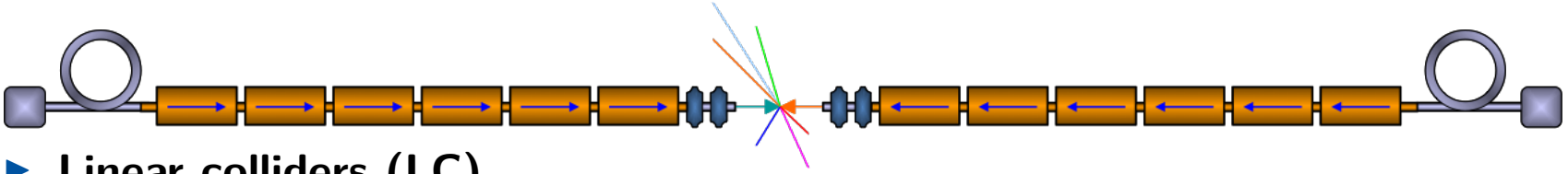
Circular vs. linear e^+e^- colliders

- **Circular colliders (CC)**
  - Can accelerate beam in many turns
  - Can collide beam many times
  - Possibility of several interaction regions
  - Limited energy due to synchrotron radiation
    - $\text{Mass}_{\text{proton}}/\text{Mass}_{\text{electron}} \approx 2000$
    - Synchrotron radiation$\sim \text{Energy}^4/(\text{Mass}^4 \cdot \text{Radius})$
    - E.g. 2.75 GeV/turn lost at LEP for $E = 105$ GeV
  - Shield detector against synchrotron radiation



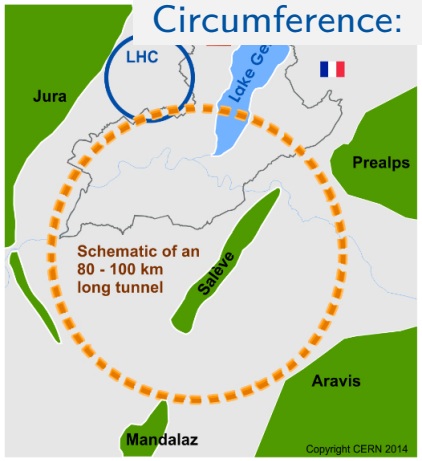


- **Linear colliders (LC)**
  - Very little synchrotron radiation in a linac
  - Can reach high energies
  - Have to achieve energy in a single pass
    $\rightarrow$ High acceleration gradients needed
  - One interaction region
  - Have to achieve luminosity in single pass
    $\rightarrow$ Small beam size and high beam power
    $\rightarrow$ Beamstrahlung, energy spread

Landscape of high-energy e^+e^- colliders

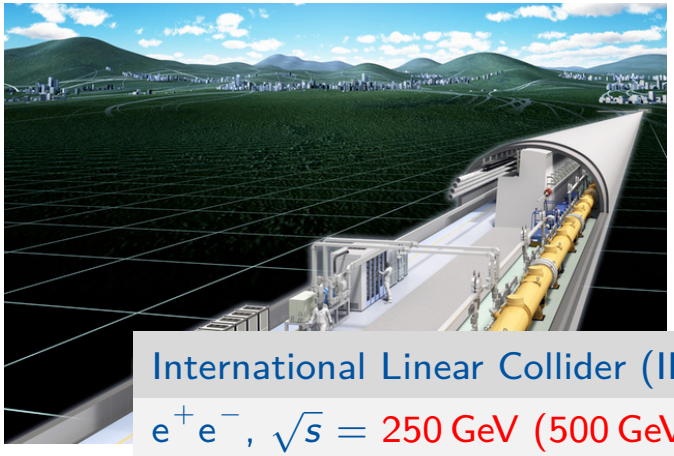
Future Circular Collider (FCC-ee)

e^+e^-, $\sqrt{s} = 90$–365 GeV;
Circumference: 97.75 km



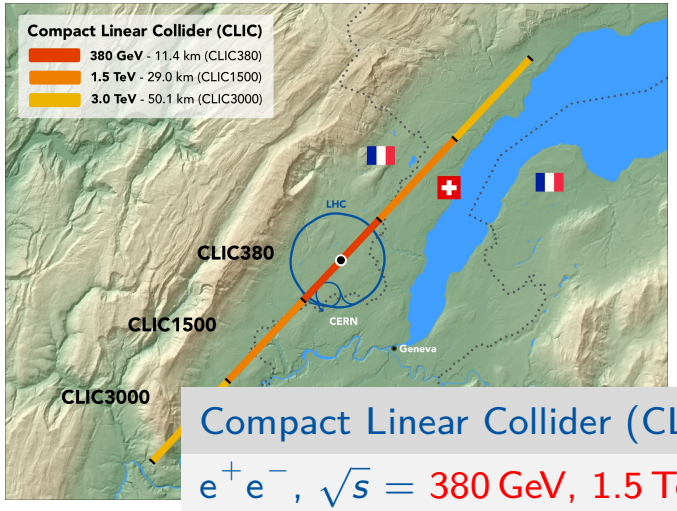
Circular Electron Positron Collider (CEPC)

e^+e^-, $\sqrt{s} = 90$–240 GeV
Circumference: ~ 100 km



International Linear Collider (ILC)

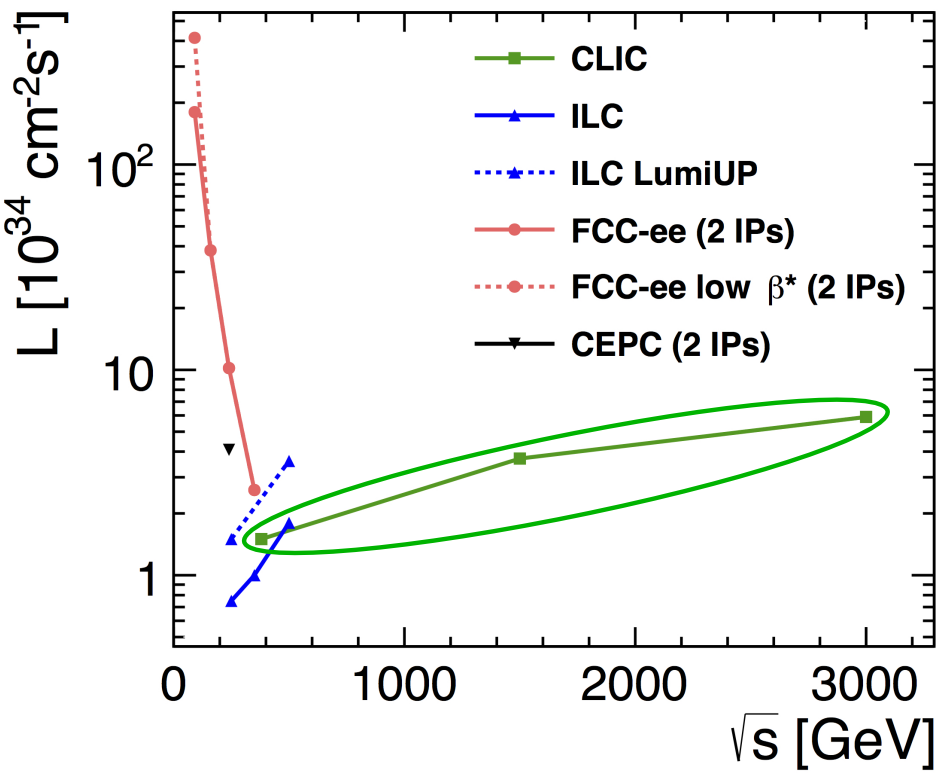
e^+e^-, $\sqrt{s} = 250$ GeV (500 GeV)
Length: 17 km (31 km)



Compact Linear Collider (CLIC)

e^+e^-, $\sqrt{s} = 380$ GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

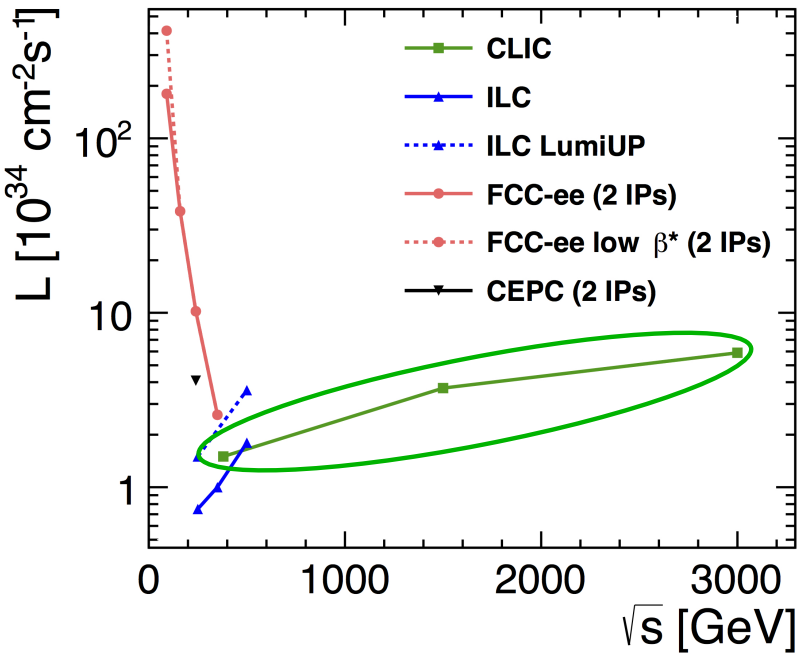
e^+e^- energy reach

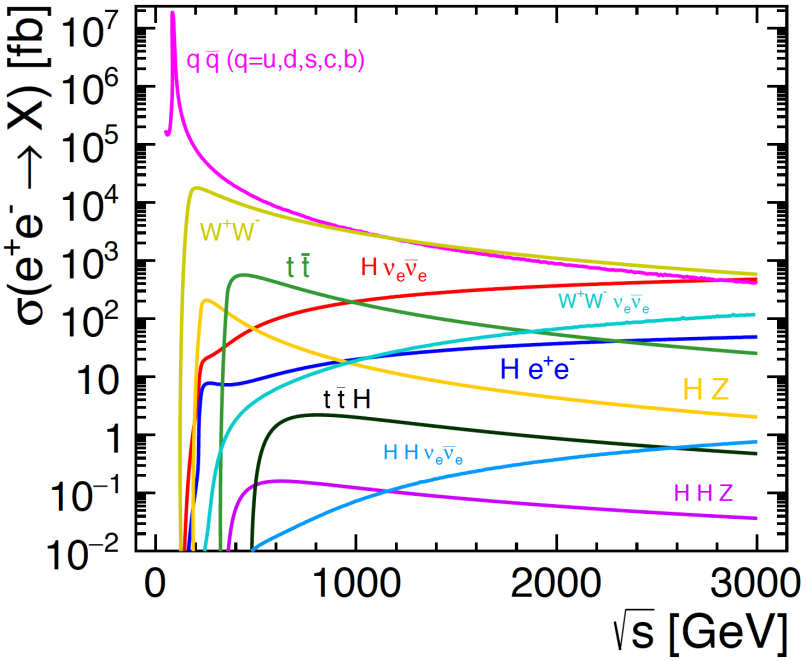


- Circular e^+e^- colliders: **FCC-ee, CEPC**
  - Huge luminosity at lower energies
  - Luminosity decreases with energy
- Linear e^+e^- colliders: **CLIC, ILC**
  - Can reach much higher energies
  - Luminosity rises with energy
  - Beam polarisation at all energies

- Comparison: Peak luminosity at LEP2 (209 GeV) was $\sim 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Disclaimer: figure for illustrative purposes only; it may not have the latest performance numbers

e^+e^- energy reach → physics programmes

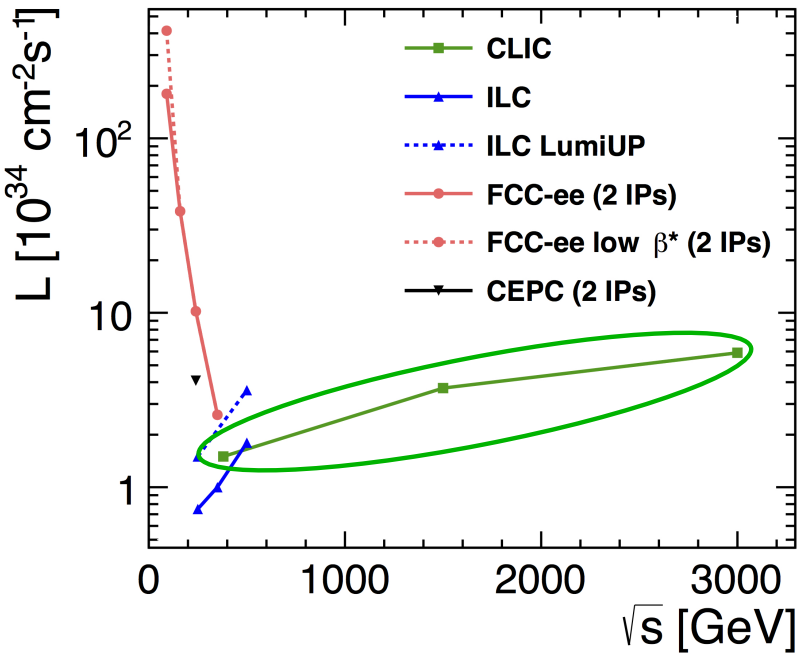


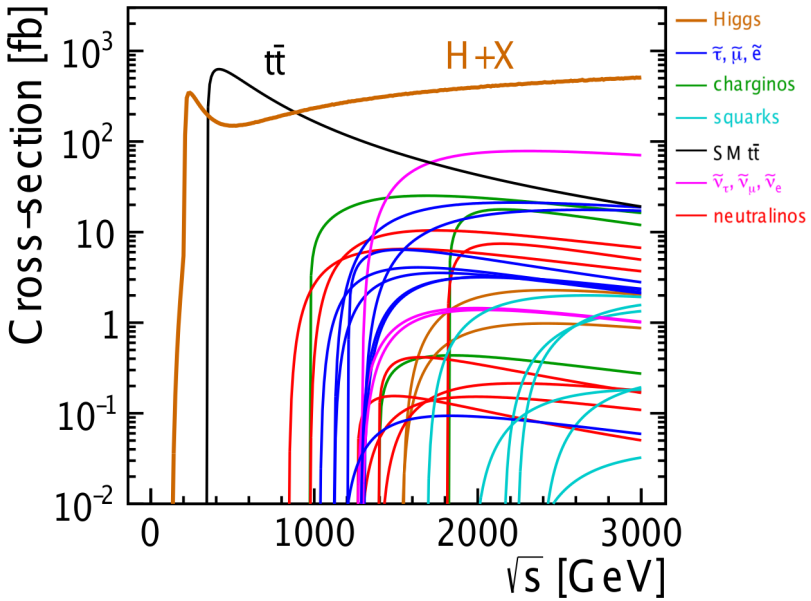


- Physics programmes focus on precision measurements and searches

  → FCC-ee: Z, W, Higgs, top, indirect BSM searches
  → CEPC: Z, W, Higgs, indirect BSM searches
  → ILC: Higgs, top, indirect and direct BSM searches
  → CLIC: Higgs, top, indirect and direct BSM searches with **highest mass reach** for available e^+e^- collider proposals

e^+e^- energy reach → physics programmes





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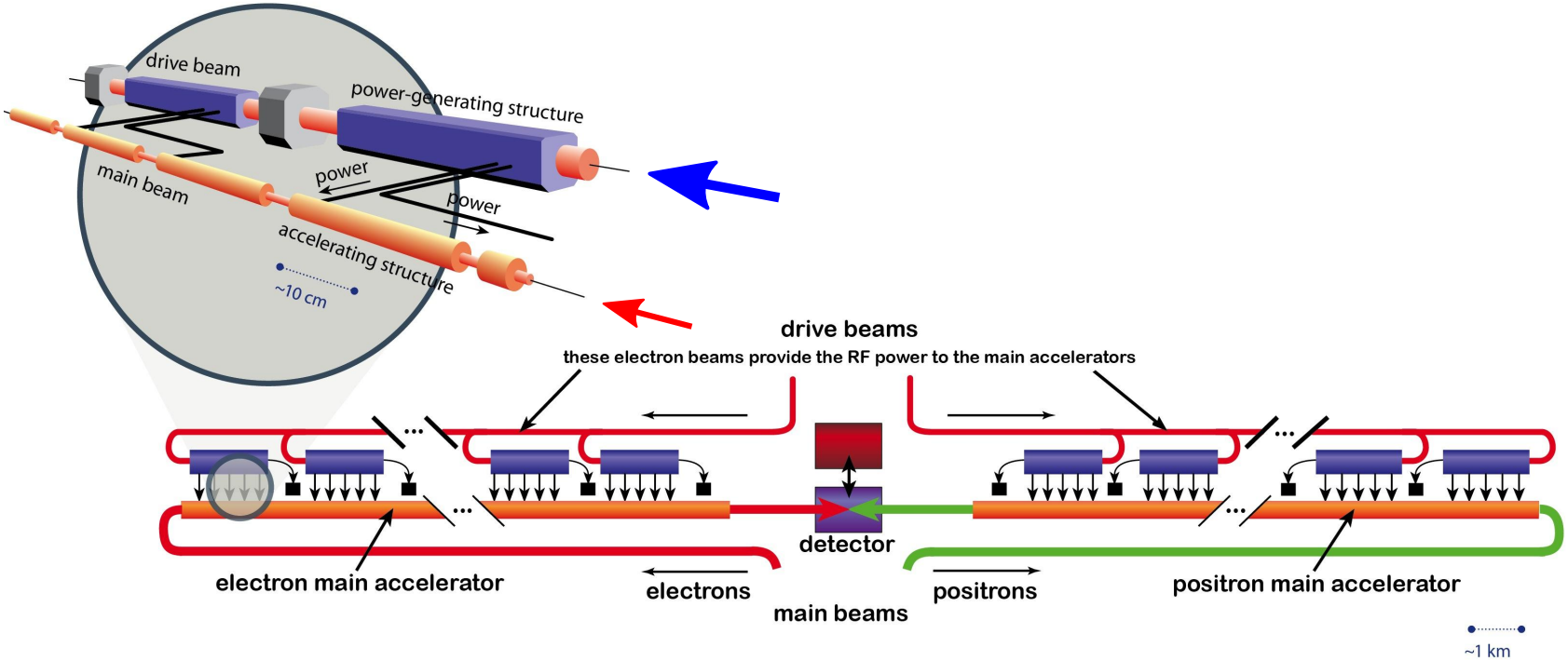
Two-beam acceleration scheme

- **Drive beam supplies RF power**
  - 12 GHz bunch structure
  - High current 100 A
  - Low energy 2.4 GeV –240 MeV
- **Main beam for physics**
  - Lower current 1.2 A
  - High energy 9 GeV – 1.5 TeV



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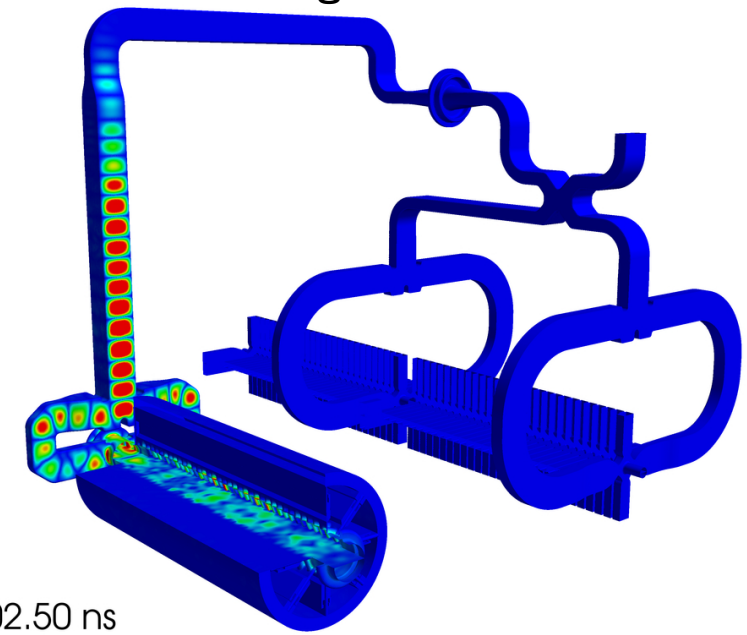
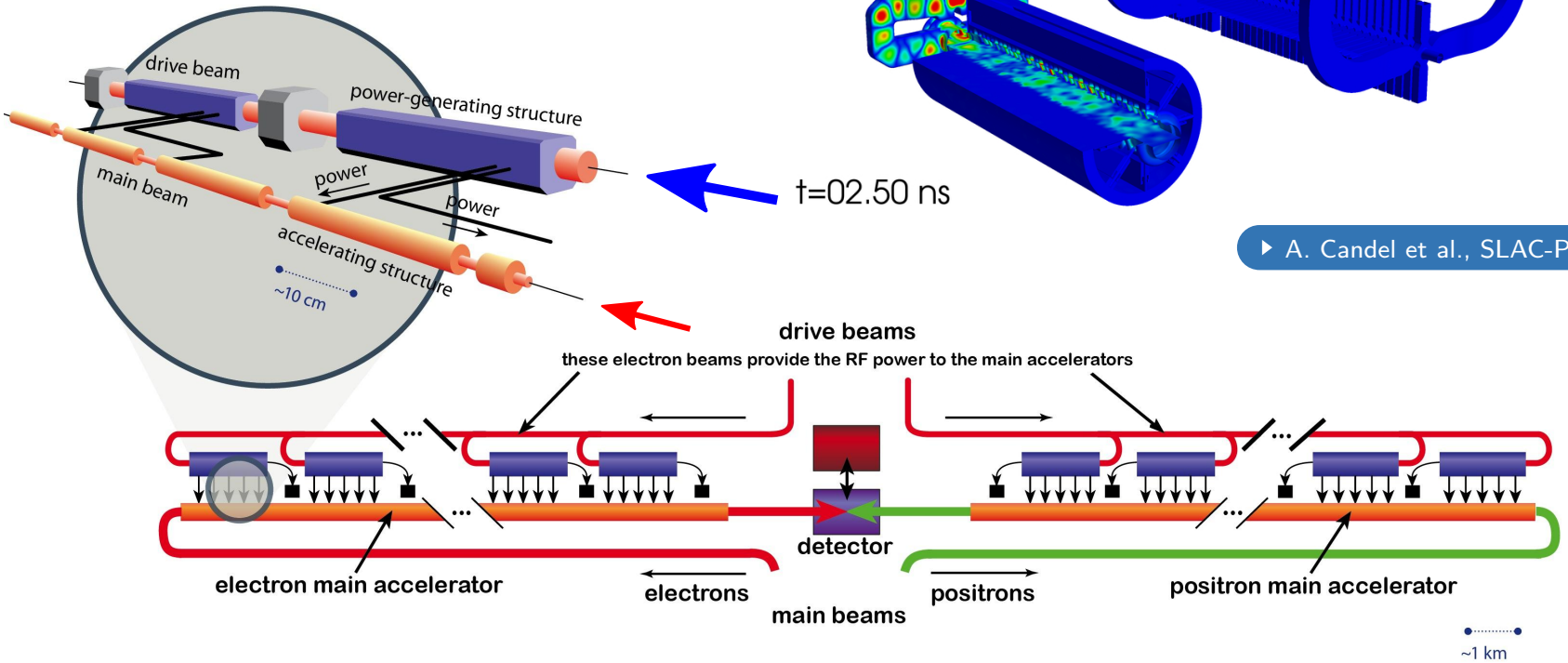
Electromagnetic field simulation



A. Candel et al., SLAC-PUB-14439



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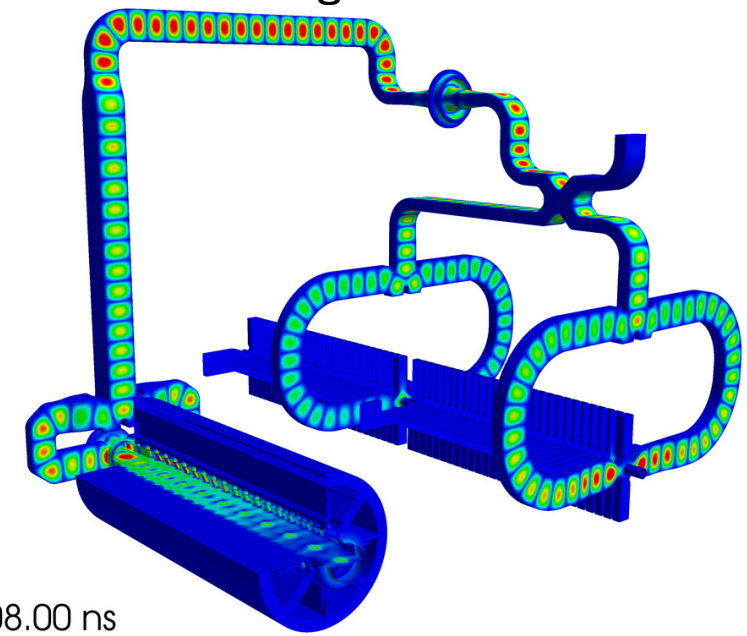

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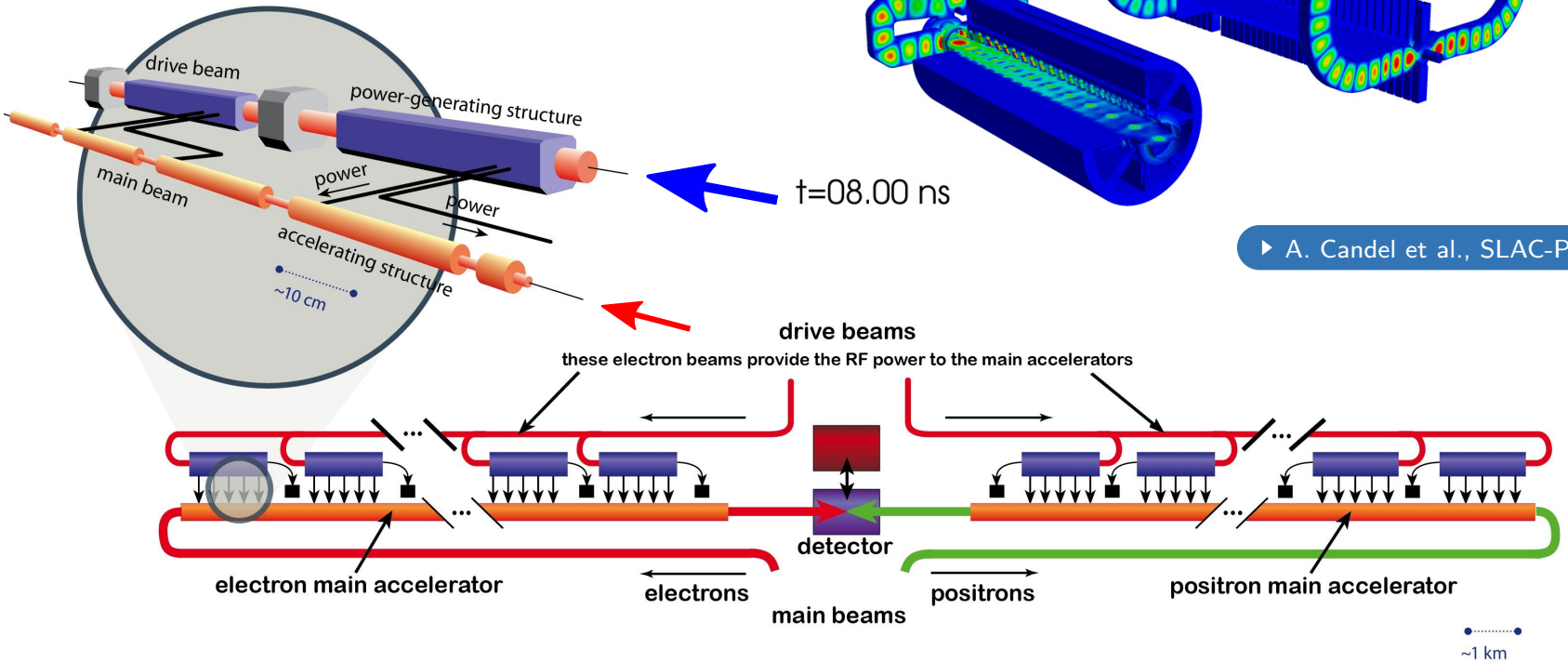

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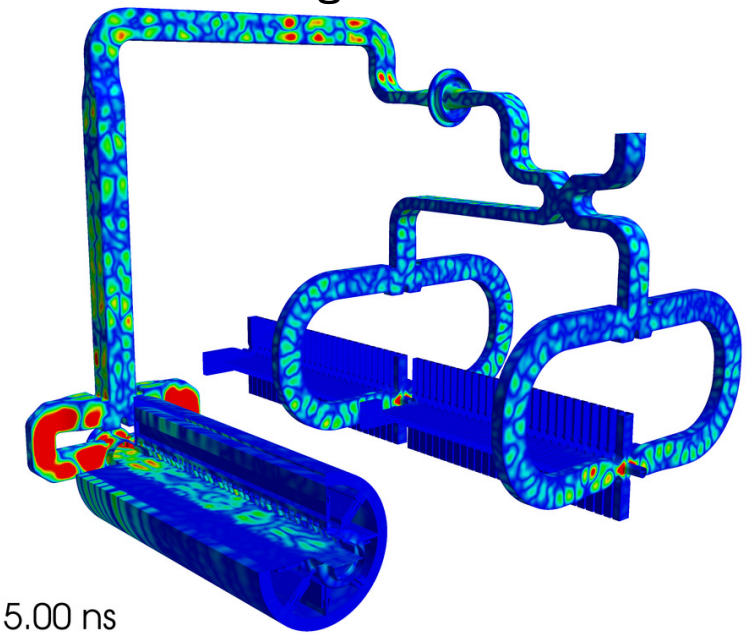

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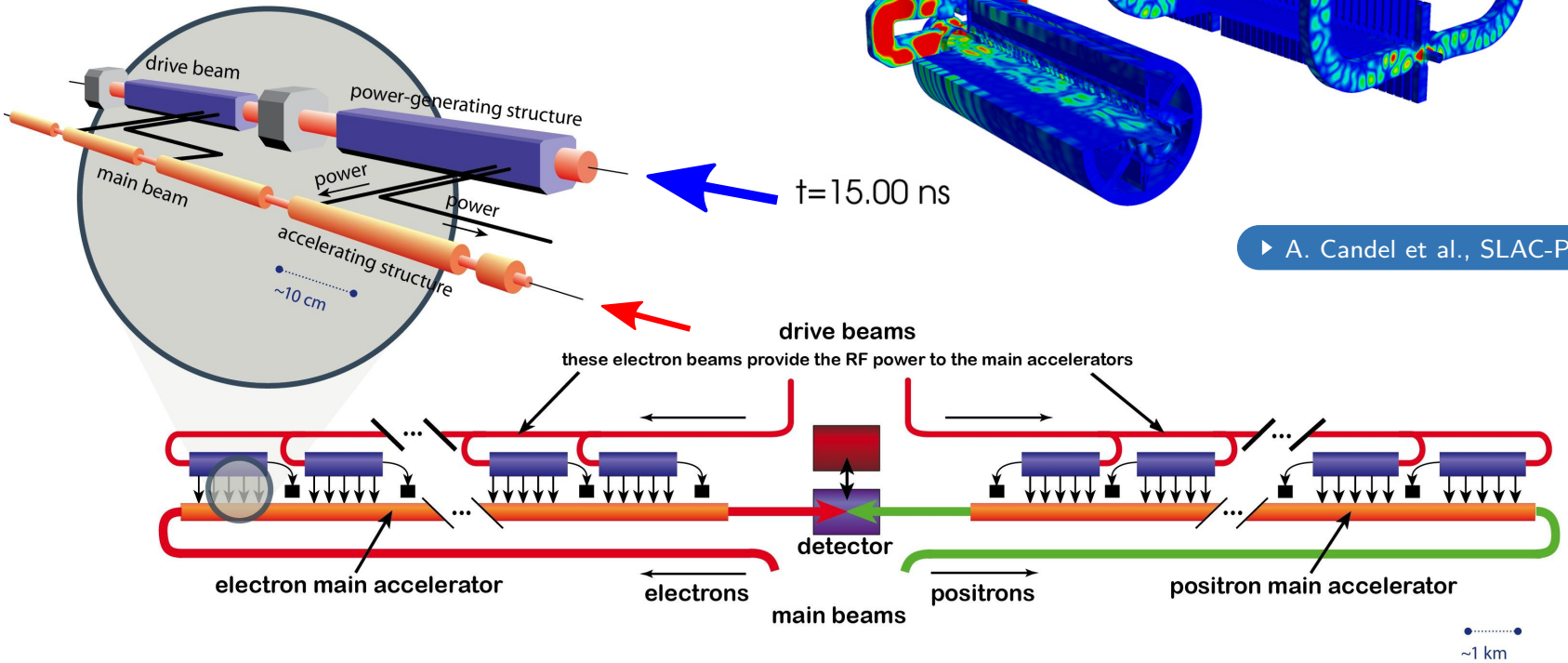
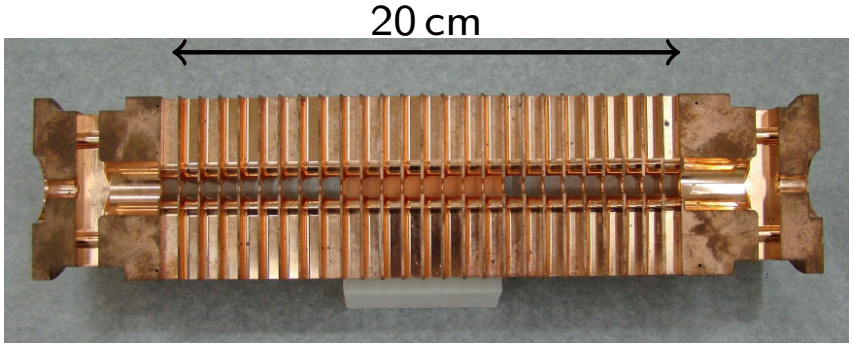
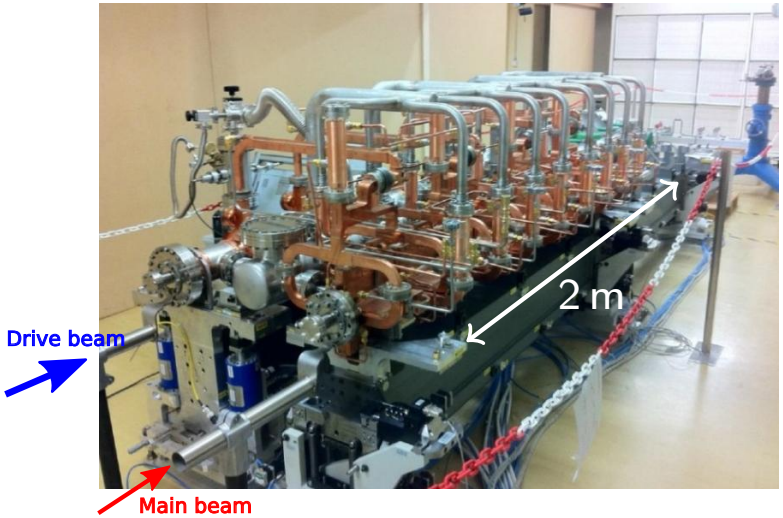


CLIC accelerator modules

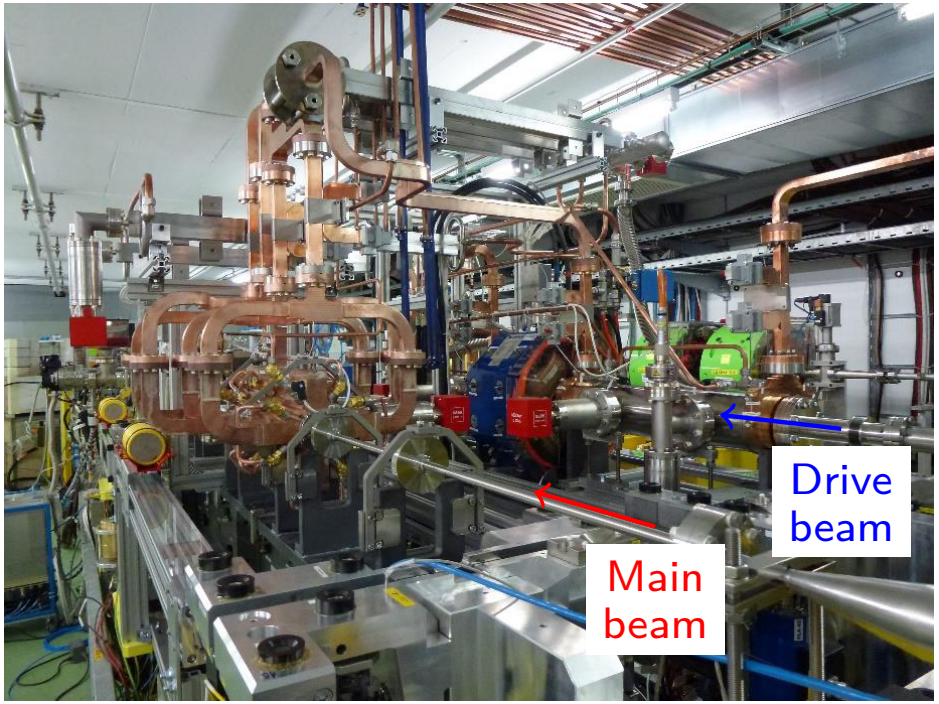
CLIC accelerating structure



CLIC two-beam module



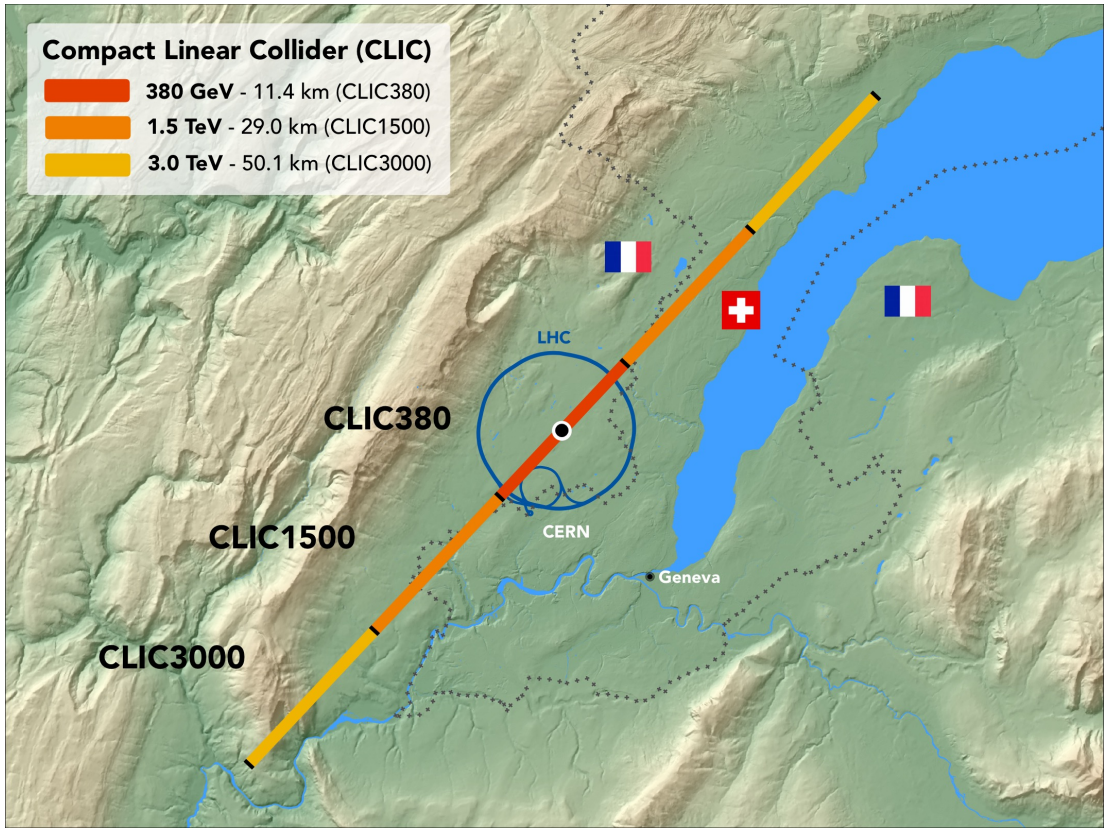
CLIC two-beam test stand



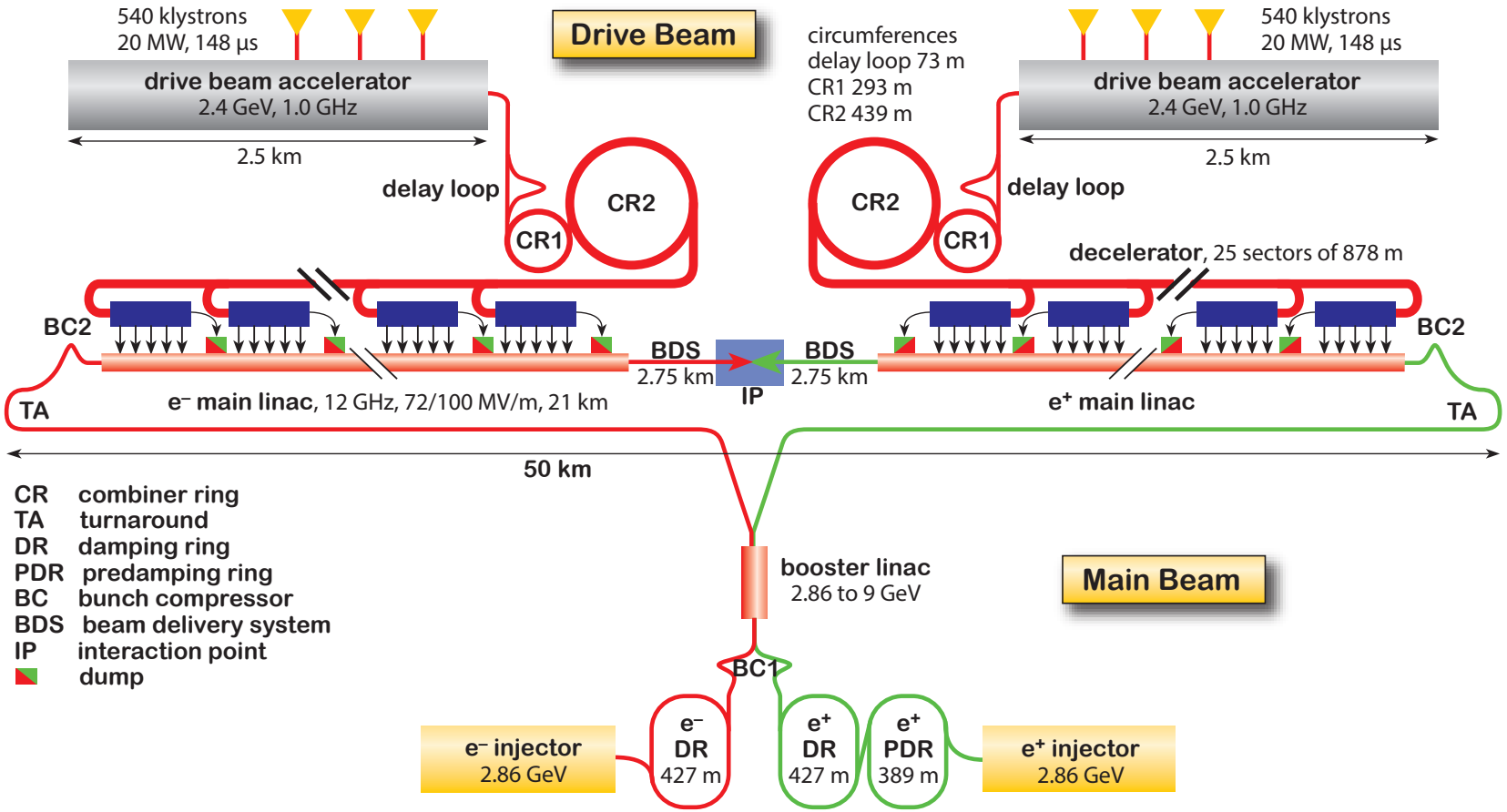
- Gradients of > 100 MV/m routinely achieved in two-beam test stand
- 20,000 modules needed for 3 TeV accelerator of 50 km length

Staged implementation

- Want to reach high luminosities ($\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Achievable for $\sqrt{s}$ from 350/380 GeV to 3 TeV in staged construction
- Three stages with 11 km – 50 km length
- Constructing next stage while taking data with current stage

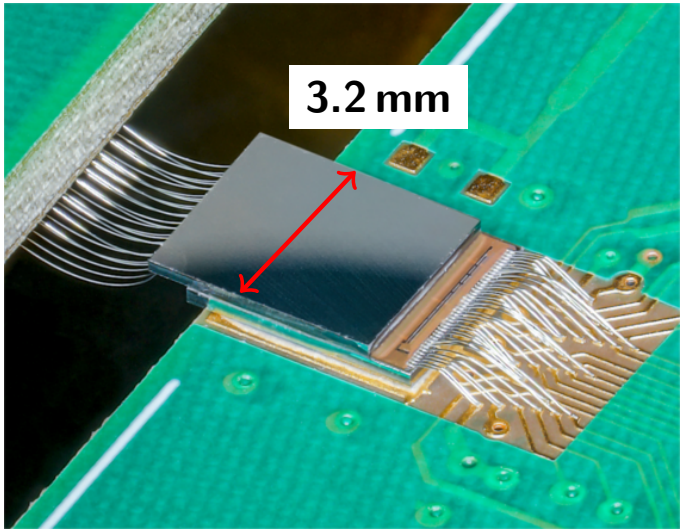


CLIC layout at 3 TeV



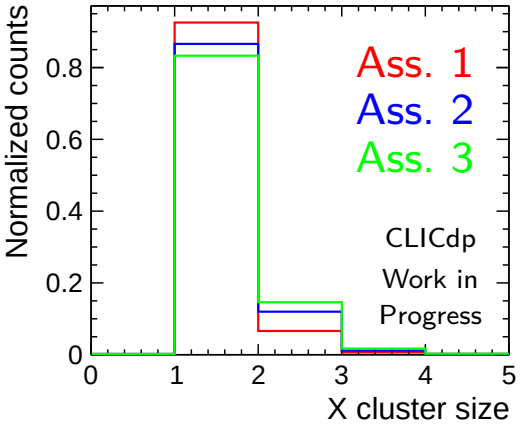
Hybrid: capactively coupled assemblies

CLICpix2 + C3PD glue assembly

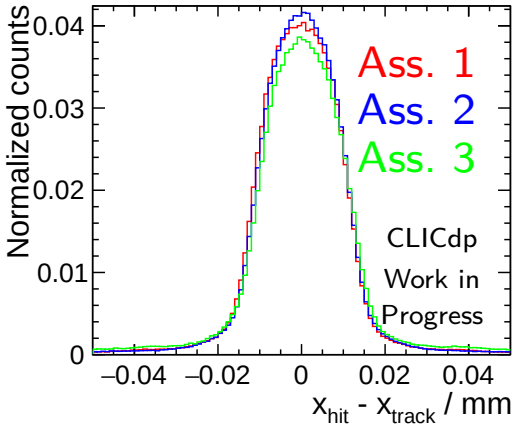


- 65 nm CLICpix2 r/o ASIC
  - Increased matrix with 128×128 pixels
  - 25 µm pixel pitch
- Glue assemblies with active HV-CMOS sensors with resistivities 20, 80 and 200 Ωcm
- Higher resistivity → larger depletion volume → larger and faster signal
- Beam tests with 20 Ωcm assemblies: spatial resolution of 8.5 – 9 µm
- Expect improved performance for high-resistivity substrates

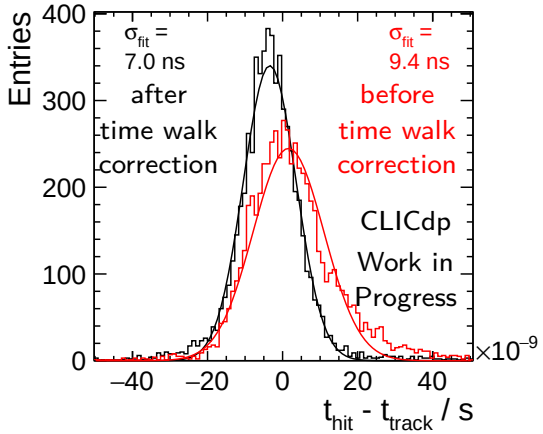
Cluster size



Position resolution



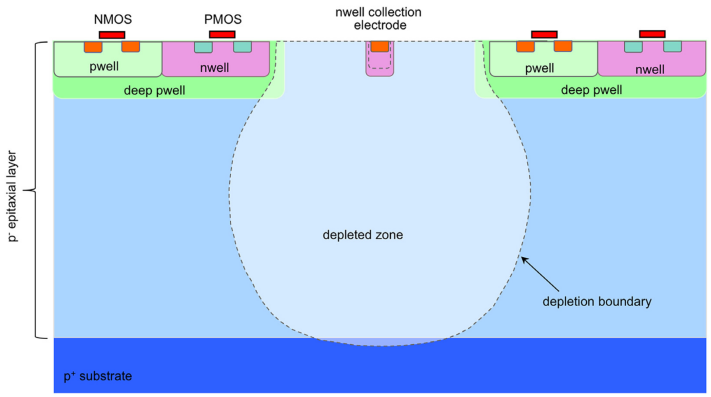
Hit time residuals



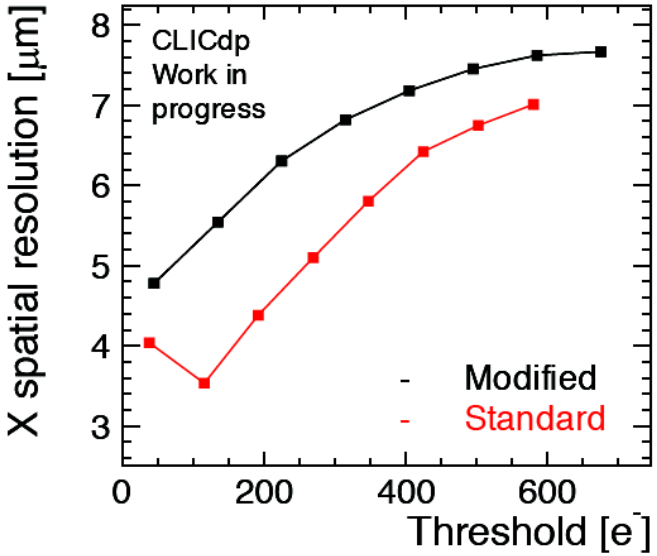
Monolithic: high-resistivity CMOS

- Monolithic Active Pixel Sensor (MAPS) based on fully integrated CMOS technology
- 180 nm HR-CMOS process
  - High-Resistivity epitaxial layer ($15 - 40\,\mu m$, $1 - 8k\,\Omega cm$)
  - CMOS circuitry shielded by deep P-well
  - Standard and modified process (additional low-dose N-implant for full lateral depletion $\rightarrow$ improved radiation hardness)
- ALICE Investigator analog test chip
  - 134 mini-matrices with 8 x 8 pixels with various pixel sizes ($20 \times 20\,\mu m$ to $50 \times 50\,\mu m$) and collection electrode geometries
  - Beam tests using chips with $25\,\mu m$ epitaxial layer and resistivity of $8k\,\Omega cm$
  - Spatial resolution down to $3.5\,\mu m$ for $28\,\mu m$ pixel pitch
  - Standard process: more charge sharing $\rightarrow$ better resolution

Standard process



Resolution for matrix with $28\,\mu m$ pitch



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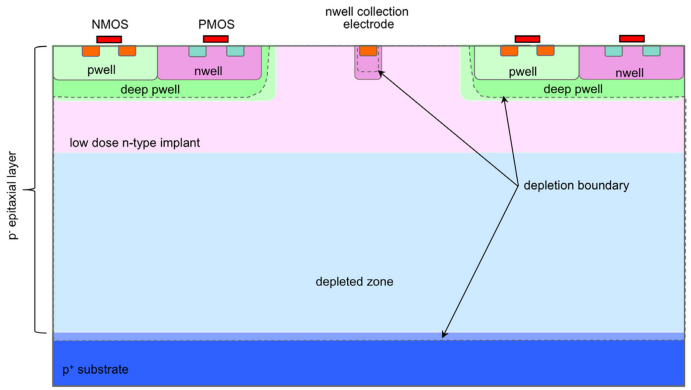
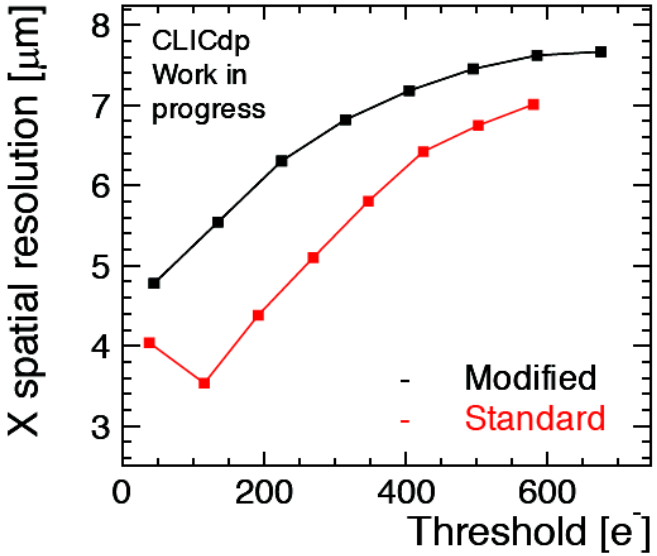
Modified process



Resolution for matrix with $28\,\mu m$ pitch



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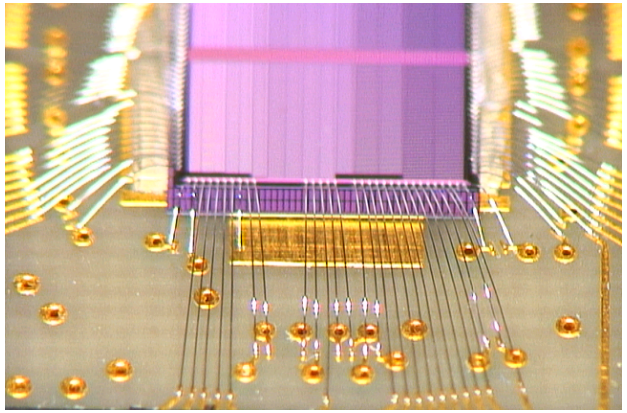
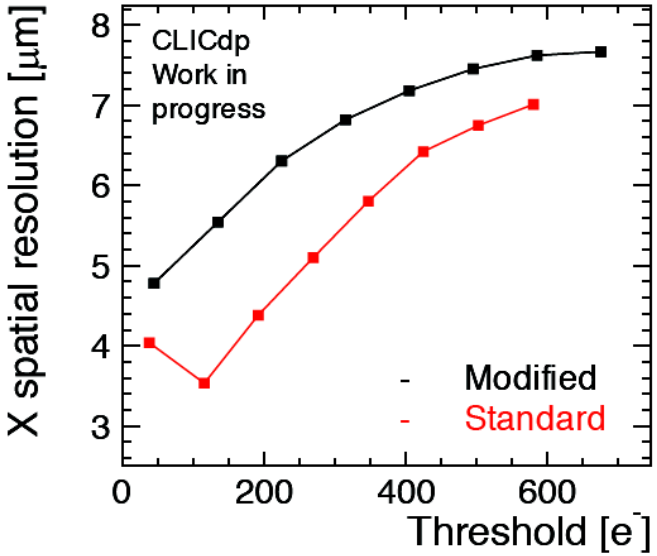
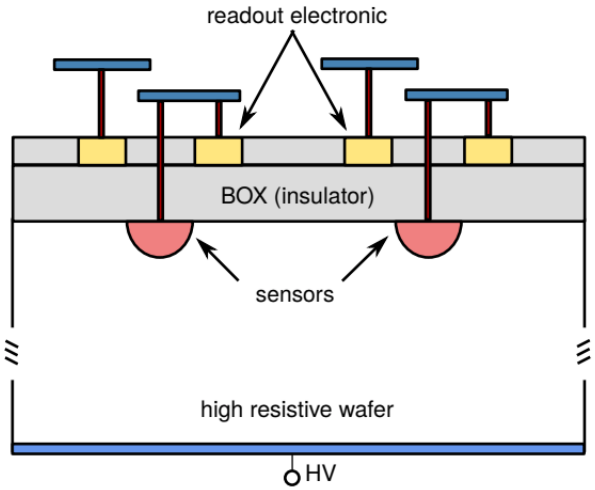
ALICE investigator



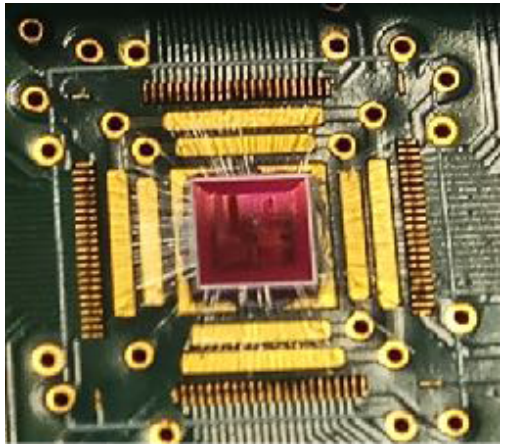
Resolution for matrix with $28\,\mu m$ pitch



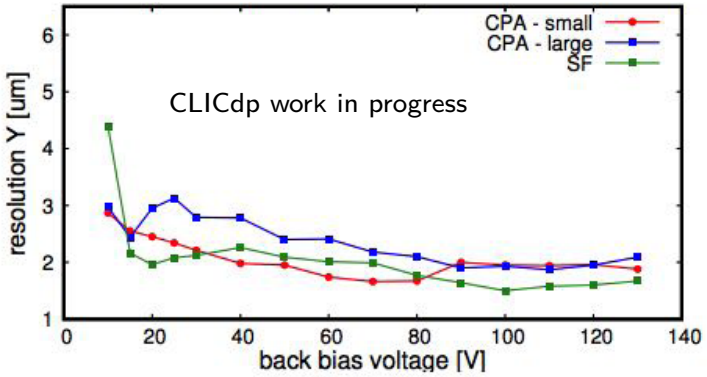
Monolithic: Silicon on Insulator



Cracow SOI test chip



Resolution in y-direction



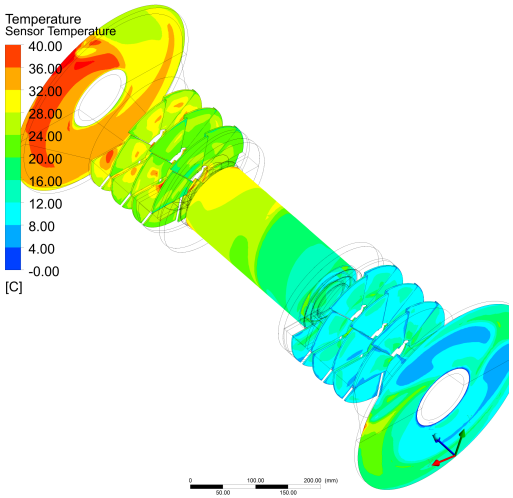
- Monolithic pixel detectors in SOI (Silicon on Insulator)
  - Thin SOI CMOS (200 nm feature size) and thick sensor bulk
  - High-resistive fully depleted sensor $\rightarrow$ Large S/N and high speed
  - Pixel pitch down to 30 µm
  - Target thickness of 100 µm for CLIC
- Test results for 500 µm thickness, $30 \times 30\,\mu m^2$ pitch, rolling-shutter r/o: $> 99\%$ efficiency, $\sigma_{SP} \lesssim 2\,\mu m$
- Outlook: Production of vertex test chip CLIPS (CLIC Pixel SOI) with 20 µm pitch and 75-500 µm thickness (summer 2018)

Vertex detector: air cooling

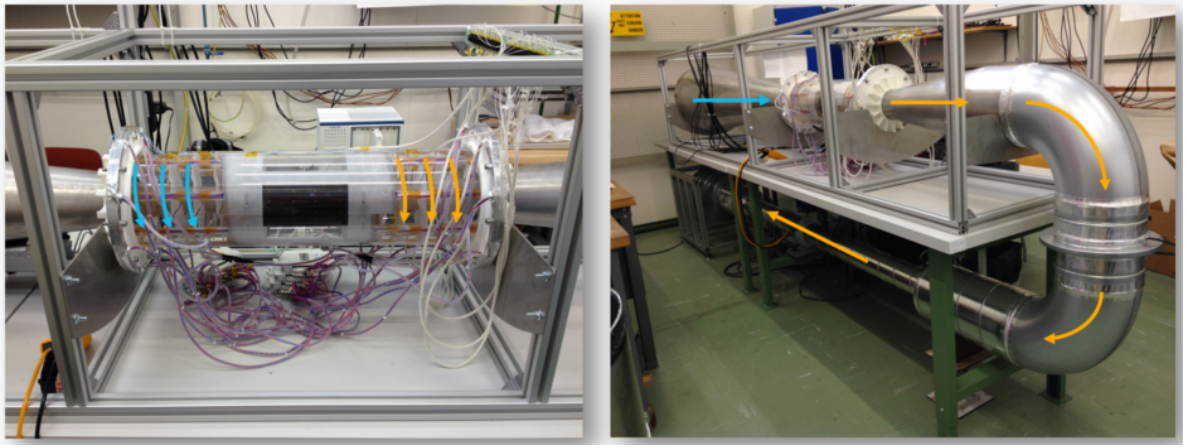
- Vertex-detector heat load of $\leq 50\,\mathrm{mW/cm^2}$
- Extractable using air flow $\rightarrow$ low material budget

- Spiral vertex disks allow air flow through detector
  - Simulation studies of air velocity, temperature, study of potential vibrations
  - Experimental verification with 1:1 thermo-mechanical mockup

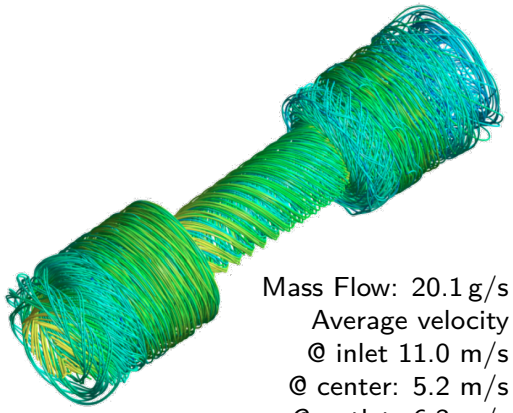
Simulation results:
Temperature



1:1 scale thermo-mechanical mockup of vertex detector



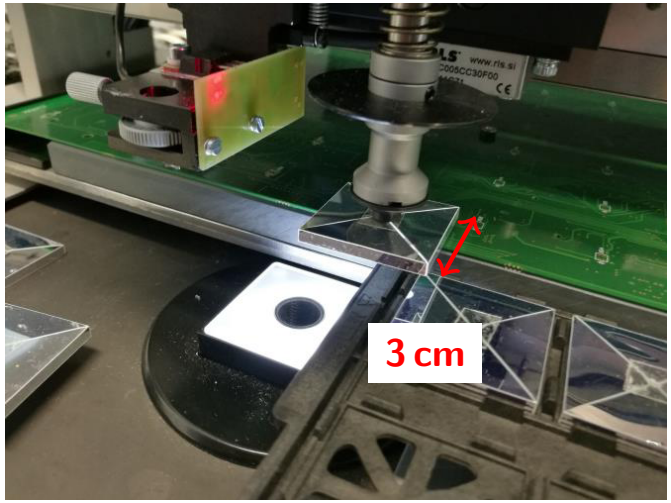
Air velocity



Mass Flow: 20.1 g/s
Average velocity
@ inlet 11.0 m/s
@ center: 5.2 m/s
@ outlet: 6.3 m/s

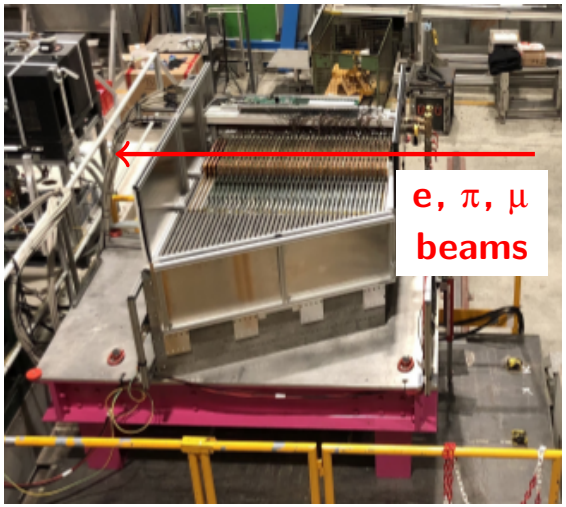
CALICE technology prototypes

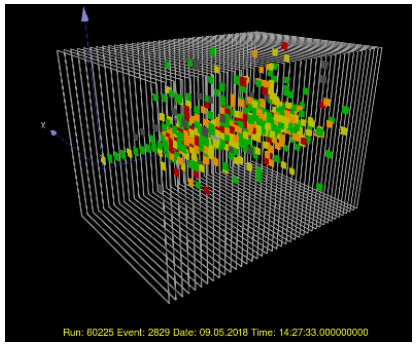
Tile-board assembly: $3 \times 3\,\mathrm{cm}^2$ tiles



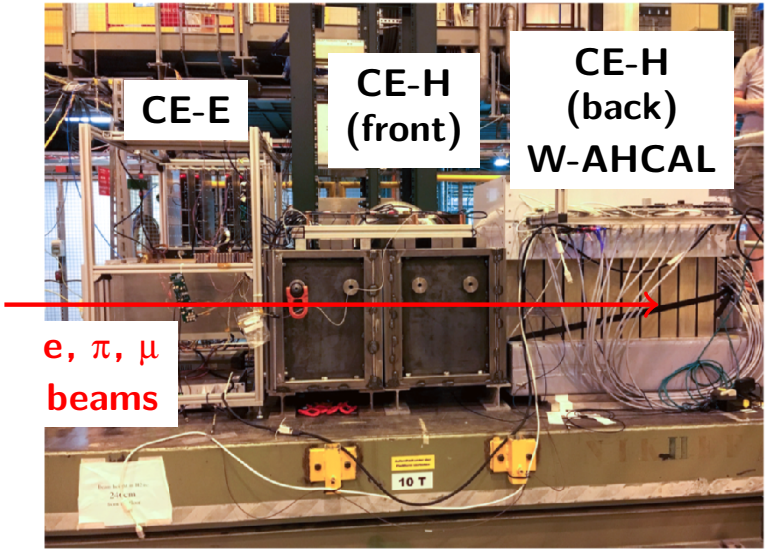
- Beam tests with AHCAL technology prototype in 2018
  - 38 layers, 21 888 tiles and SiPMs
  - Automated production, quality assurance
  - LED calibration, active temperature compensation
- Smaller AHCAL stacks also used as backing HCAL in combined CMS HGCal + AHCAL beam tests

CALICE AHCAL: 38 full layers of 24×24 tiles



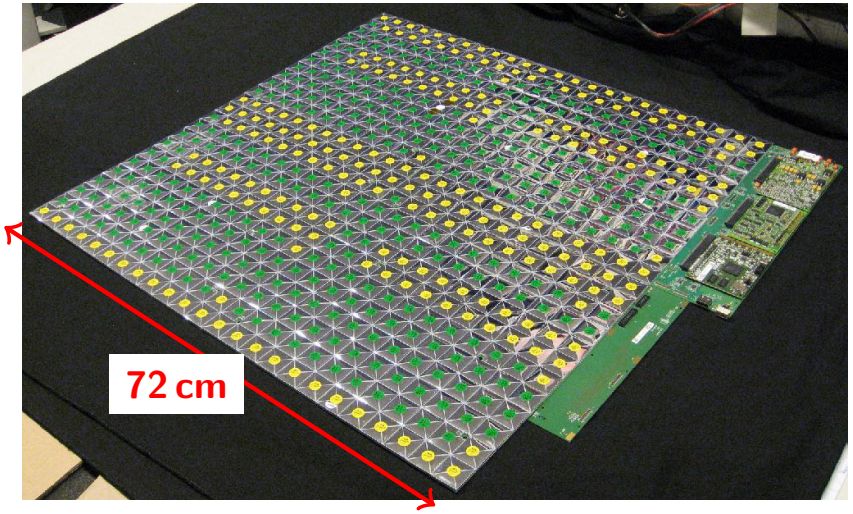


CMS HGCal + AHCAL beam tests



CALICE technology prototypes

Layer with 24 × 24 tiles of 3 × 3 cm^2 size



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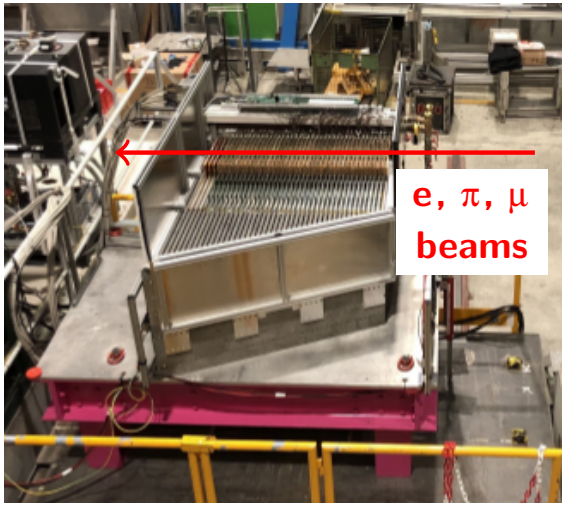
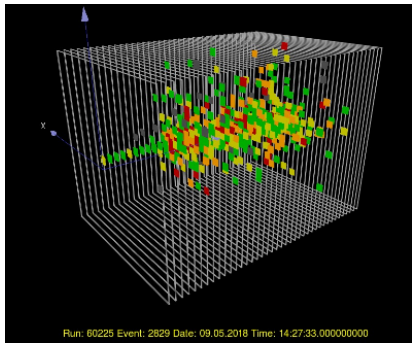
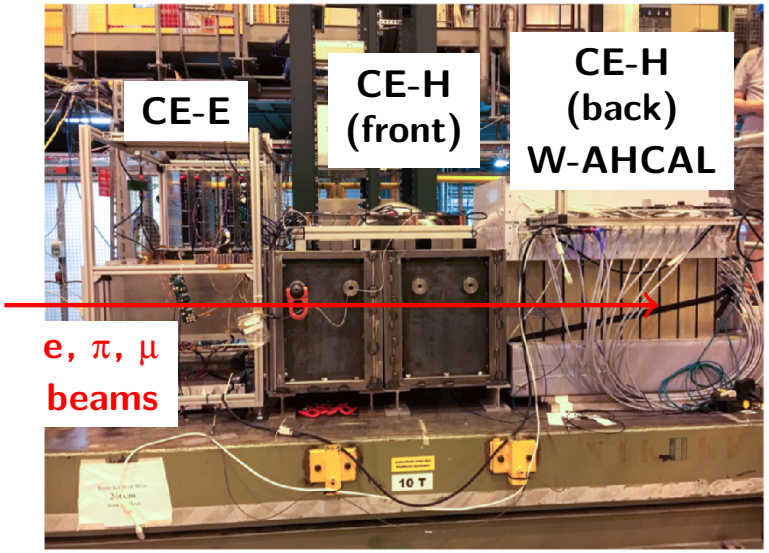




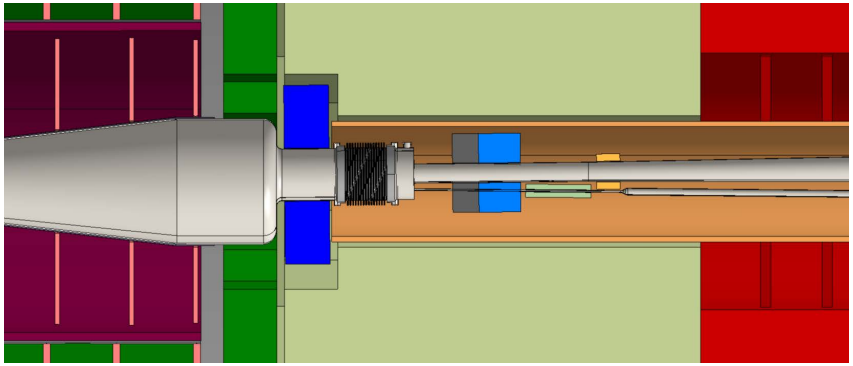
CMS HGCal + AHCAL beam tests



Forward CALorimetry: FCAL

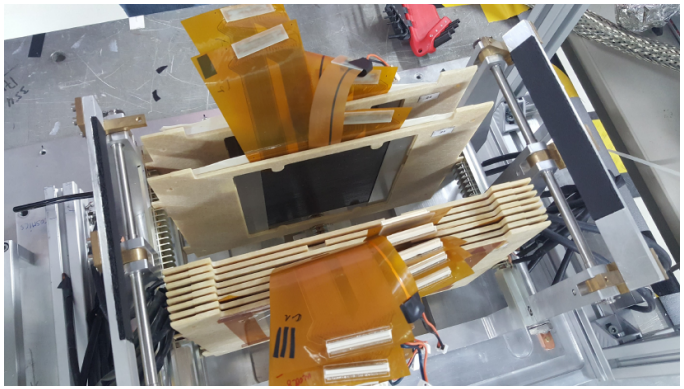
- Very forward e.m. calorimeters
- e and γ acceptance to small angles
  - LumiCal for luminosity measurement ($< \pm 1\%$ accuracy)
  - BeamCal for very forward electron tagging
  - BeamCal: GaAs, LumiCal: silicon
- Very compact design (sensors, read-out, absorber)
  $\rightarrow$ small Molière radius
- Test beams at DESY with first submilimiter LumiCal detector module (640 µm)

LumiCal $R_{out} = 34\,\mathrm{cm}$, **BeamCal** $R_{out} = 15\,\mathrm{cm}$

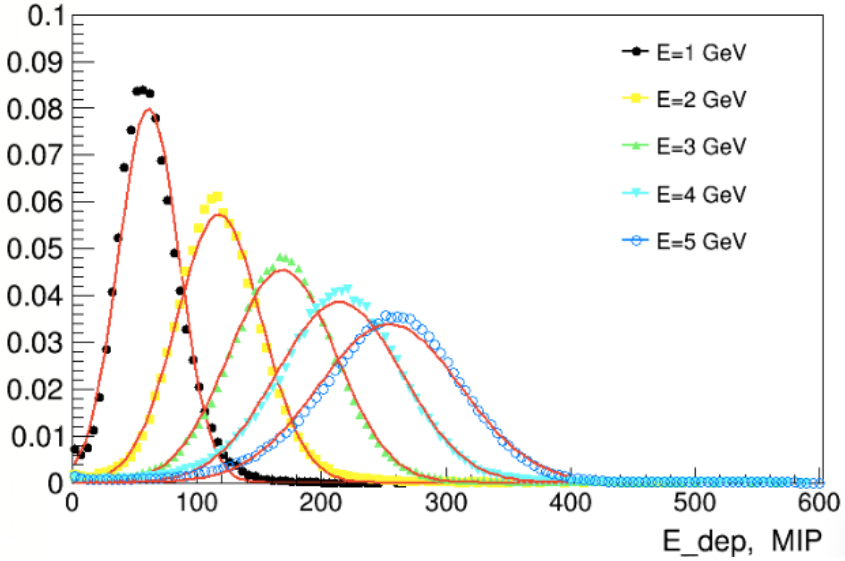


Tracker **ECAL** **HCAL** **Muon system**

Stack used in test beam



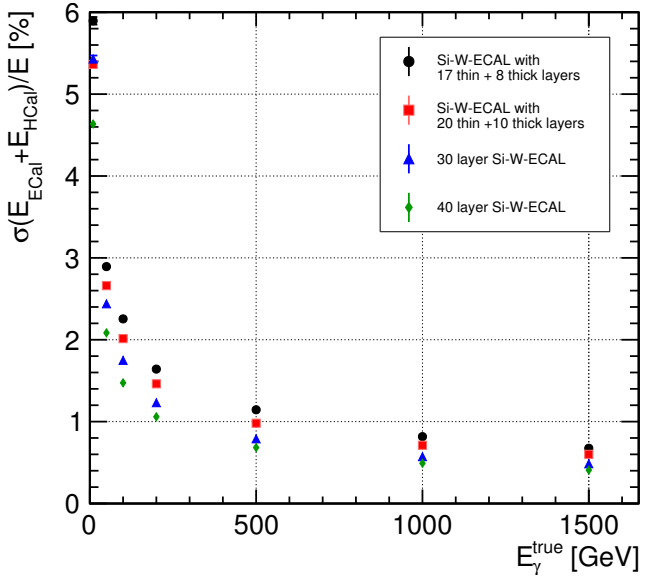
LumiCal Energy Response



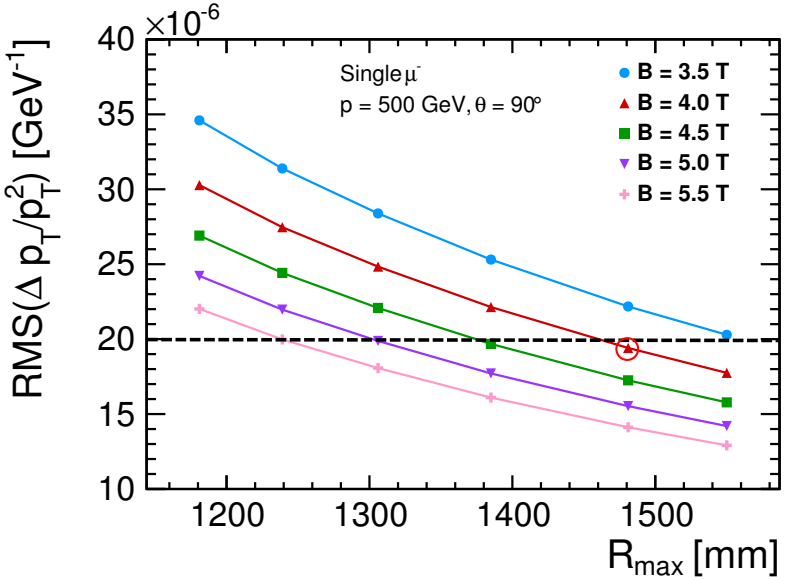
CLIC detector optimisation

- Optimisation of CLIC detector model in full detector simulations
  - Ensure that detector performance meets requirements
  - Validate full software chain

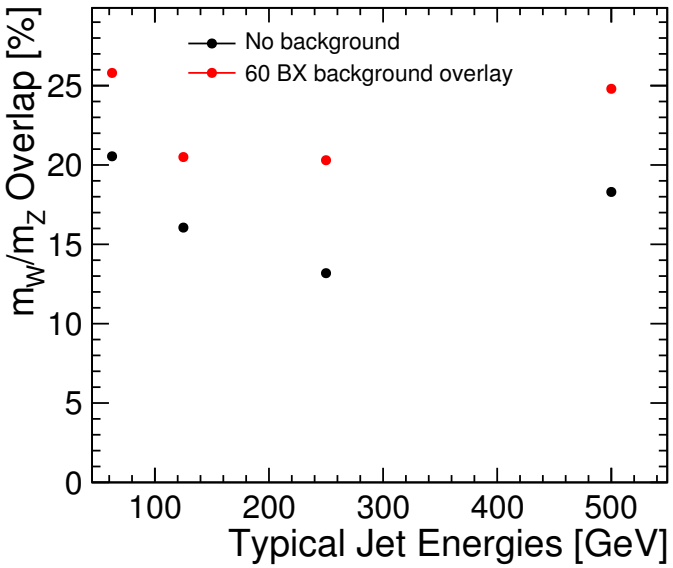
ECAL configuration ↔ Photon energy reco.



Tracker radius and B-Field ↔ momentum resolution



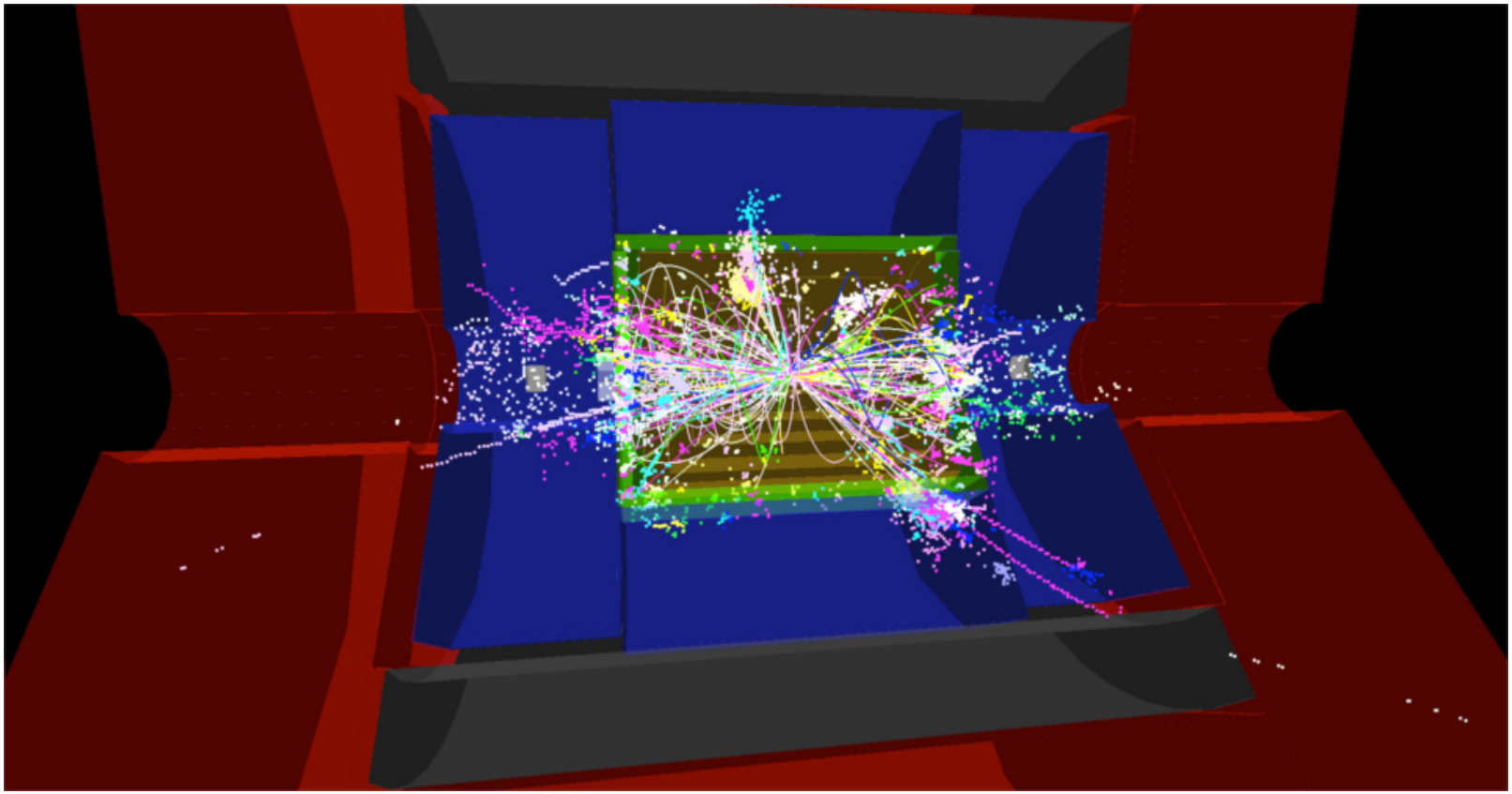
Background overlay ↔ W and Z separation



Reduce out-of-time background

- Use combined p_T and timing cuts to reduce out-of-time background
  - Cuts optimised for detector regions
  - Cluster timing by combining hit timing information
    $\rightarrow$ tighter cuts possible on cluster timing
- Example: $e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\,W\bar{b}\,H \rightarrow q\bar{q}b\,\tau\nu\bar{b}\,b\bar{b}$ at 1.4 TeV

Before p_T and timing cuts



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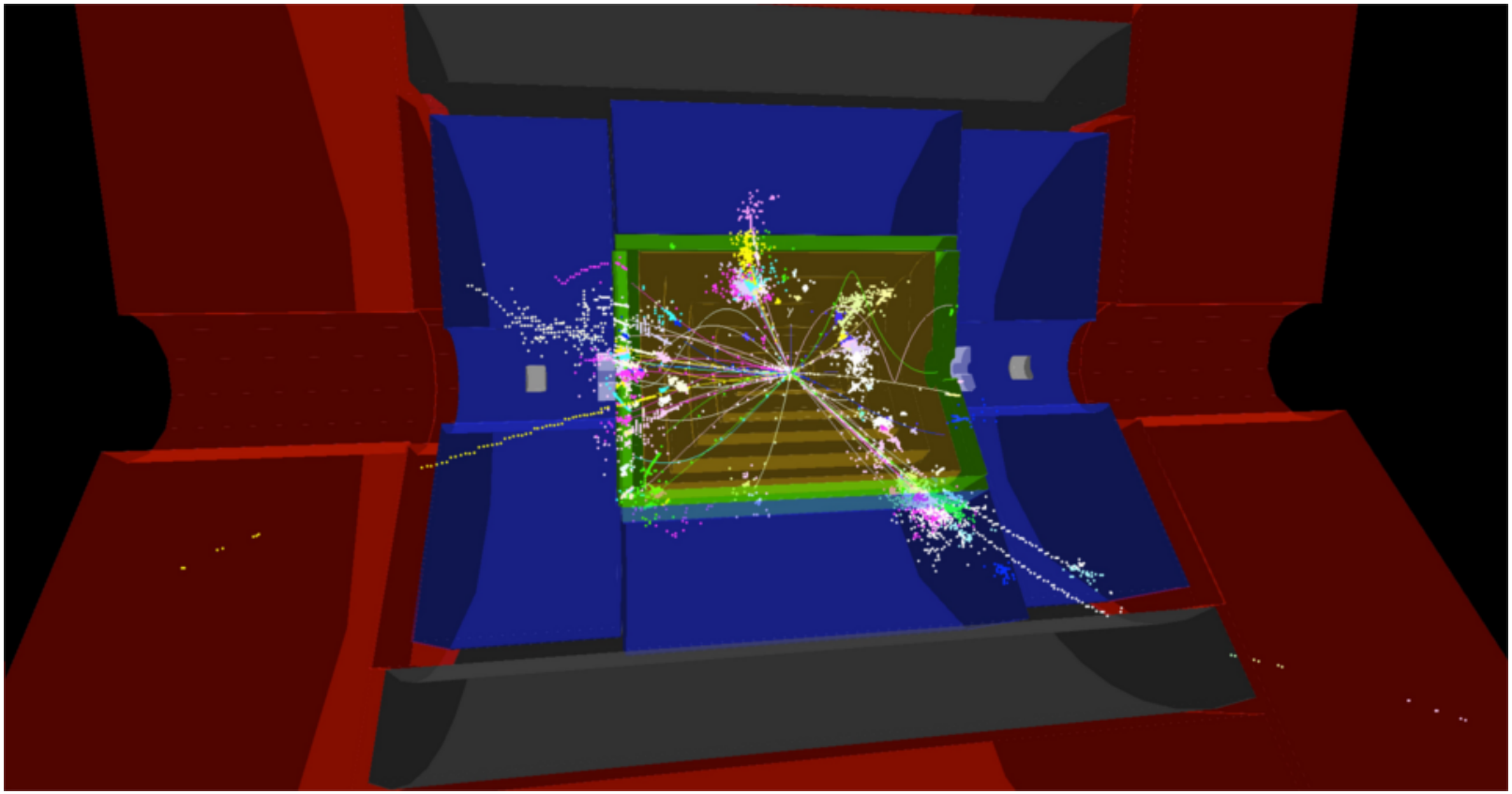
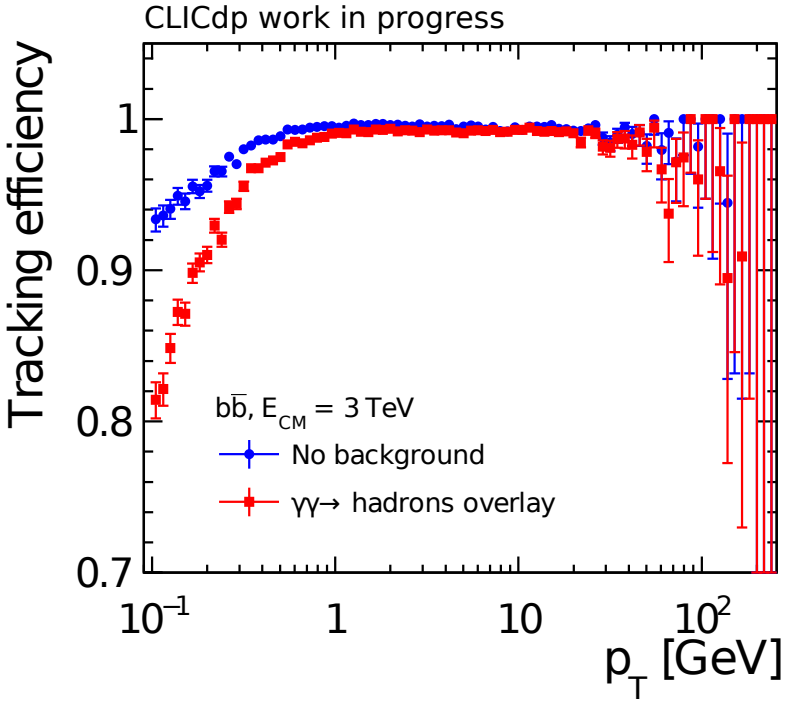
After p_T and timing cuts



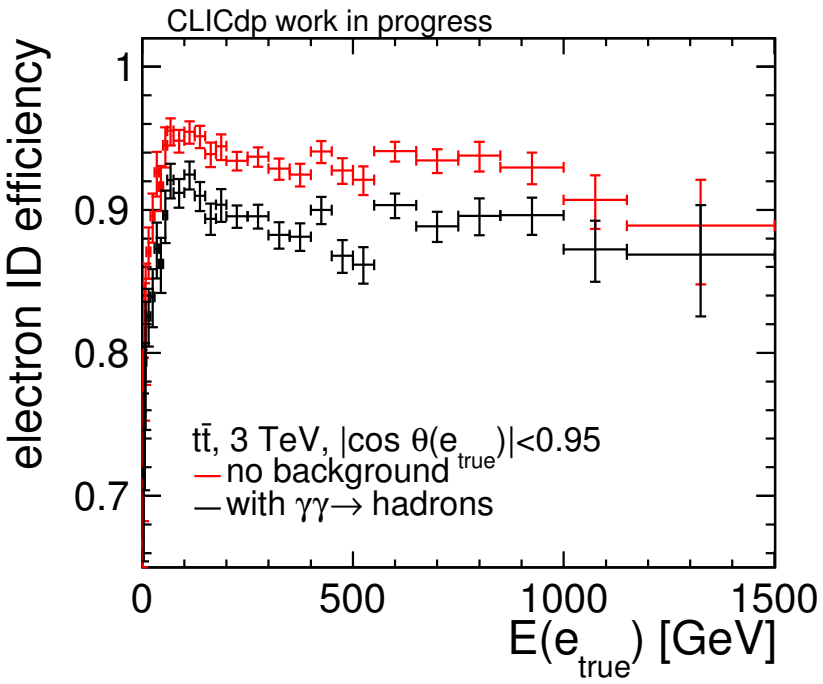
CLIC detector performance: examples

Tracking efficiency



- For tracks down to 600 MeV: Detector and tracking algorithm perform with 100% efficiency, effect of background overlay is small

Electron ID efficiency



- Electrons above 20 GeV identified with in 90–95%
- Background causes efficiency loss by 5%