Latest results from the Compact Linear Collider (CLIC)

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on behalf of the CLICdp Collaboration

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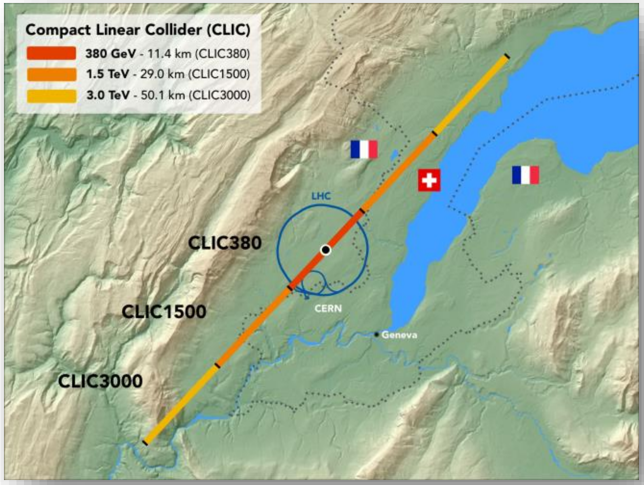
The CLICdp Collaboration

CLIC detector and physics study (CLICdp)

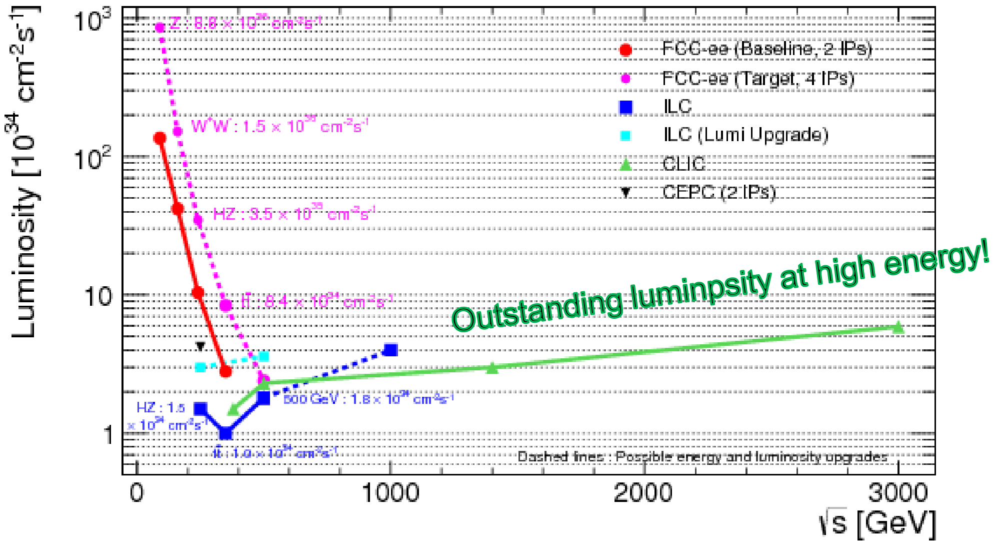
- Physics studies
- Detector technology R&D
- 158 members from 30 institutes in 18 countries
- Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020 project

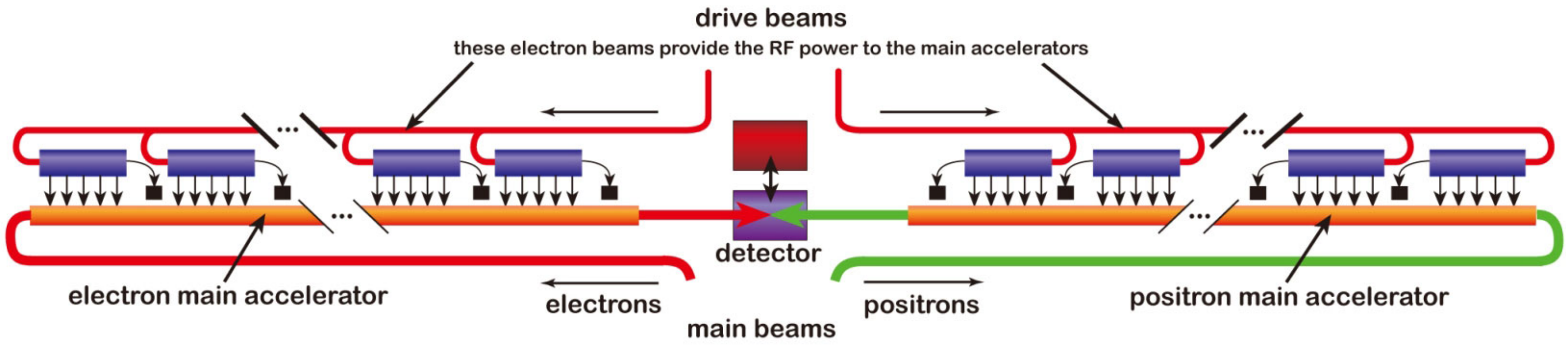


Detector and physics: clicdp.cern.ch
Accelerator: clic-study.web.cern.ch

The CLIC accelerator concept

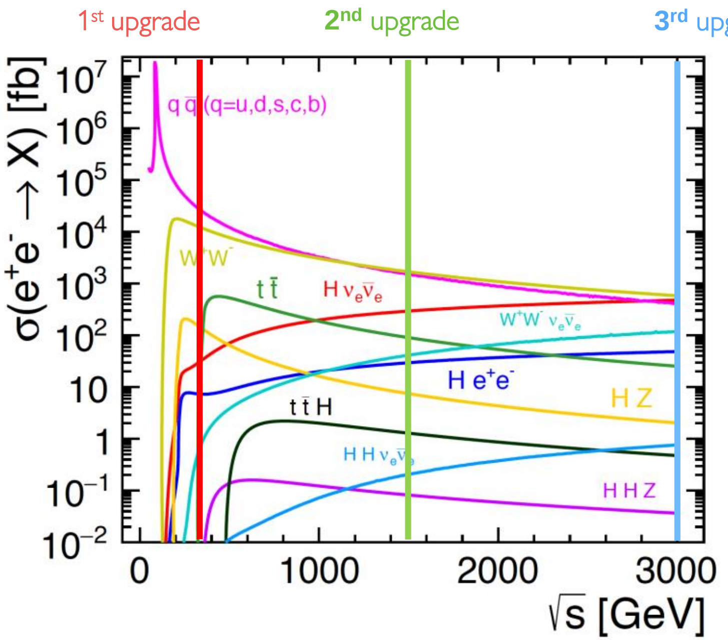
- Two-beam acceleration scheme (drive/main beams)
  - High accelerating gradient of 100 MV/m
  - About 150’000 room temperature RF cavities
  - Allows a 3 TeV collider to be built in only 50 km (compact)
- Electron beam polarization at all energies
- Energy staging from 380 to 3000 GeV

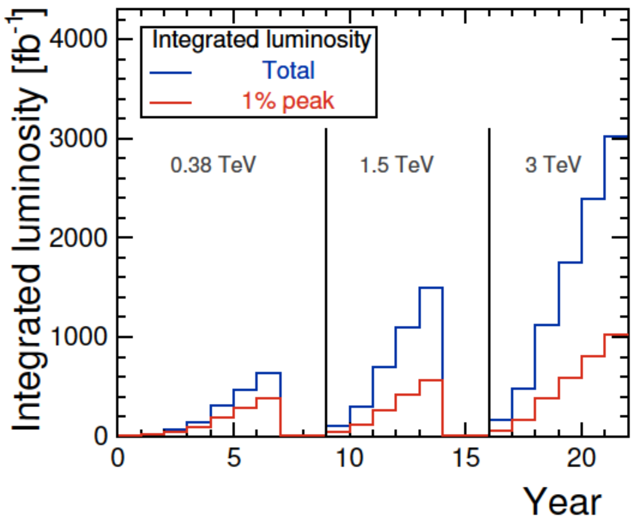




Conceptual Design Report: http://clic-study.web.cern.ch/content/conceptual-design-report

A Staged Physics Program





1) $\sqrt{s}$ = 380 GeV (500 + 100 fb^{-1})
- Higgs/Top precision physics
- Top mass threshold scan (350 GeV)

2) $\sqrt{s}$ = 1.5 TeV (1.5 ab^{-1})
- Target: Precision SUSY, BSM reach
- Higgs/Top precision physics
- Rare Higgs decays
- Top Yukawa coupling

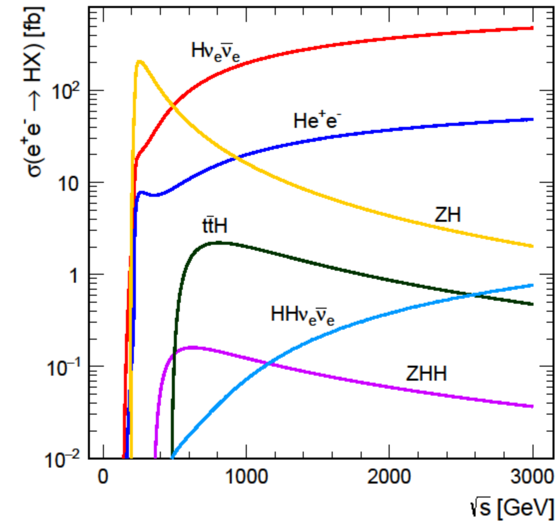
3) $\sqrt{s}$ = 3 TeV (3.0 ab^{-1})
- Target: Precision SUSY, BSM reach
- Higgs self-coupling
- Rare Higgs decays

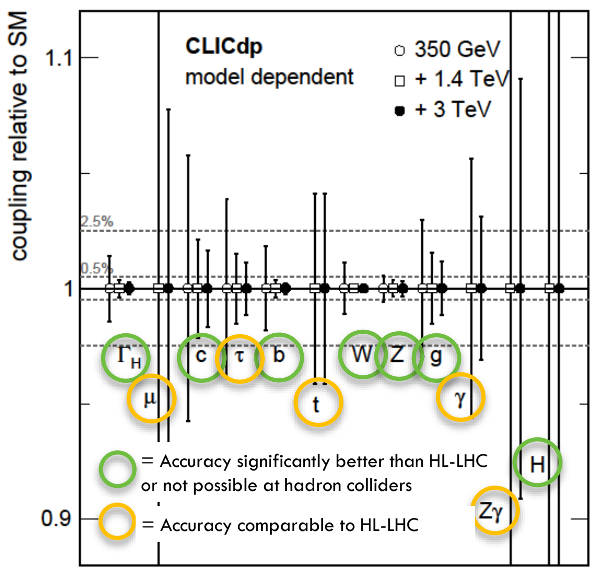
Staging can be adapted to possible LHC discoveries
CLIC staging baseline document: CERN-2016-004

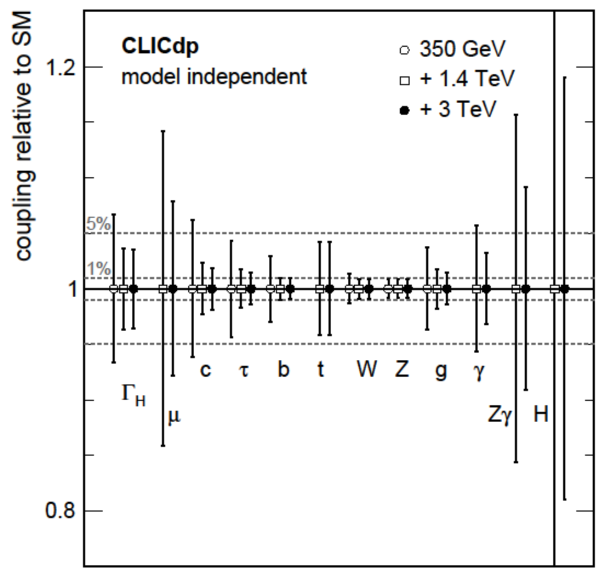
Significantly higher precision than HL-LHC for many observables
More information: arXiv:1608.07538

Higgs Physics at CLIC

- CLIC covers several Higgs production processes
- Highlights:
  - Higgsstrahlung $e^+e^- \to ZH$- **model independent measurement of Higgs properties** using the Z-recoil mass (unique to lepton colliders)
  - **Vector-boson fusion** (dominates at high energies)
  - Extraction of **top Yukawa coupling** ($e^+e^- \to t\bar{t}H$)
  - Double Higgs production: simultaneous extraction of **model-independent tri-linear self-coupling** (Δλ CLIC: ~10% from differential distributions) and **quartic coupling** (gHHWW: ~3%)
  - Higgs couplings and width can be determined with a **percent-level statistical uncertainty**



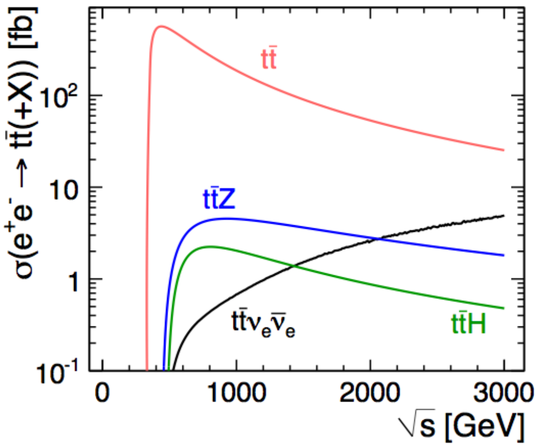


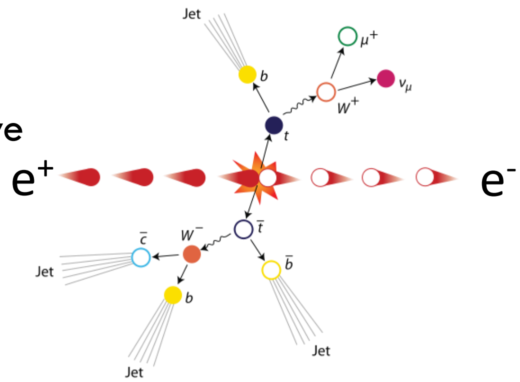


Comprehensive report on our Higgs studies in Eur. Phys. J. C 77 (2017) 475

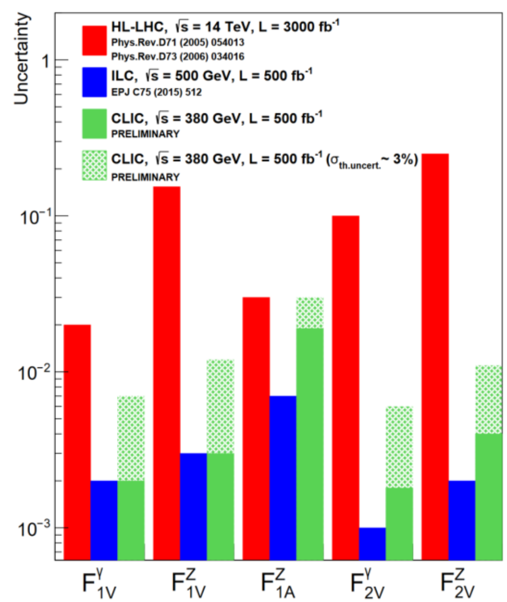
Top Physics at CLIC

- Several tens of thousands of top quark pairs are produced at CLIC
- Top quarks have not been studied in e^+e^- collisions yet
- The top quark is of particular interest:
  - Couples strongly to the Higgs field
  - Relation to SM gauge bosons
  - Connection to BSM scenarios
- CLICdp is preparing a comprehensive top physics report





- Highlights
  - **Complete $t\bar{t}$ study at all three stages:** 380 GeV (resolved), 1.5 TeV (semi-boosted), 3 TeV (boosted)
  - **Threshold scan:** 1S-mass with precision O(10) MeV
  - **FCNC top decays:** competitive limits on rare decays such as $t \longrightarrow cH$ and $t \longrightarrow c\gamma$
  - **Top couplings** at high precision
  - **Combined EFT* interpretation,** dim-6 operators (TeV operation provides better sensitivity to contact-interaction operators)

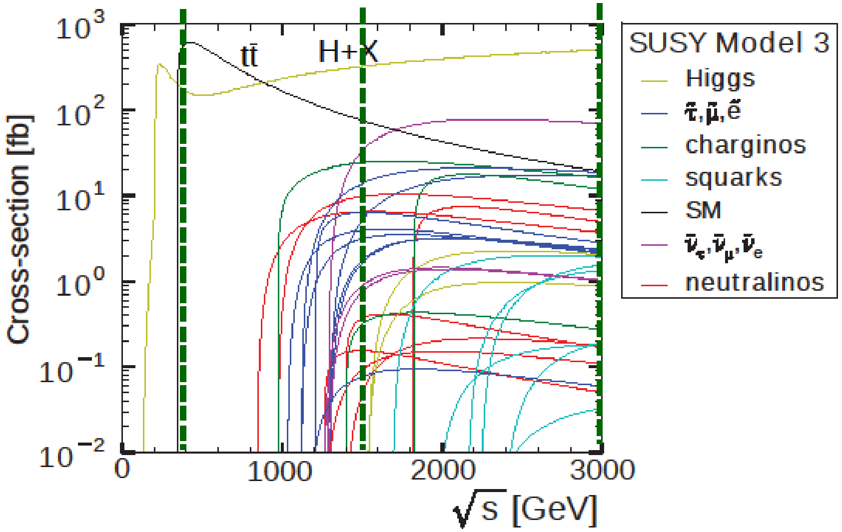


*Effective Field Theory and CLIC, see [JHEP05(2017)096]

BSM Physics at CLIC

- Indirect searches: through precision observables
  - discovery beyond the center-of-mass energy
- Direct Production: of new particles
  - Up to the kinematic limit ($\sqrt{s}/2$ for pair production)
  - Precision measurements - measure the mass and production cross-sections to percent-level
  - Complements the HL-LHC program to measure heavy SUSY partners

- Highlights:
  - Lepton colliders offer superior sensitivity to EW state
  - Expected sensitivities ~15-20 times better than limits set by LEP
  - 3 TeV energy stage yields factor 10 more precision compared to 1.5 TeV → benefit of multi-TeV operation
  - Vector boson scattering for tests of EW symmetry breaking CLICdp-Conf-2017-018
  - Di-photon production (3 TeV) for deviations from QED CLICdp-Conf-2017-018

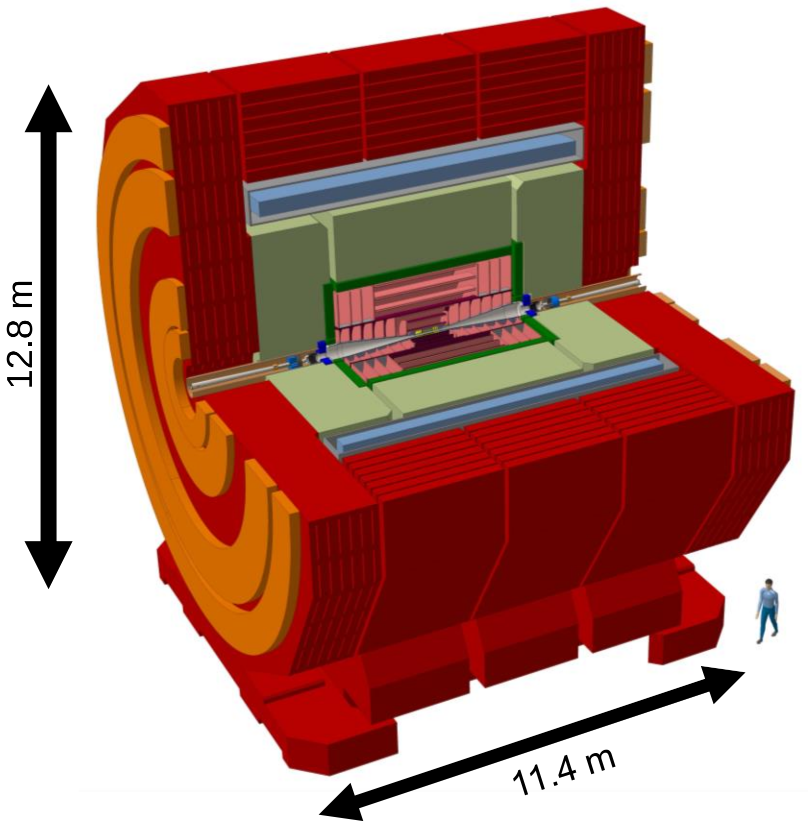


New particle/scenario	CLIC3000 reach
Anomalous gauge couplings*	$-0.001 < \alpha_4 < 0.0011$ $-0.00070 < \alpha_5 < 0.00074$
Extra dimensions $M_S/\lambda^{1/4}$ (95% CL)	~16 TeV
Contact interactions (Λ') (95% CL)	~21 TeV
Chargino, neutralinos	≲1.5 TeV
Sleptons	≲1.5 TeV
Z' (SM couplings)	~20 TeV
Triple gauge coupling (95% CL)	λ_γ: 0.0001
Higgs composite scale	~70 TeV

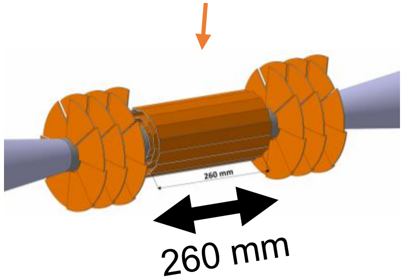
Example models (CLIC 3 TeV, up to 2 ab^{-1})

CLIC detector model ‘CLICdet’

- **Iron return yoke** instrumented with muon detectors, for muon identification
- 4 T superconducting **solenoid magnet** (R_{in} = 3.4 m, L = 8.3 m)
- Fine grained **calorimetry system** (ECAL and HCAL) using particle flow approach
  - Strong contribution to the CALICE and FCAL calorimeter R&D collaborations



- Low-mass all-silicon **tracking system** with separate tracker and **vertex detector**



- Enclosed in forward region: LumiCal (luminosity monitoring), BeamCal (extended coverage)

More details: “CLICdet: The post-CDR CLIC detector model”, CLICdp-Note-2017-001

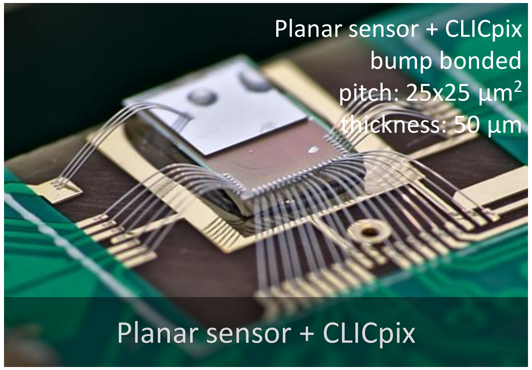
Silicon R&D

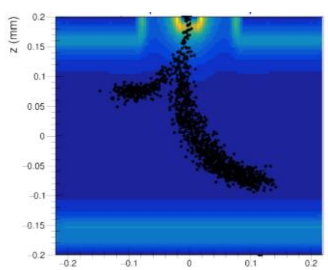
Pixel technology

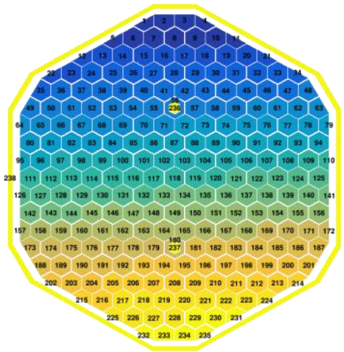
- Research areas: sensors, readout, powering, mechanical integration and cooling
- Beam tests: of both hybrid (readout ASICs down to 65 nm) and monolithic assemblies
- Challenging: position-resolution target of ~3 µm for the vertex detector
- Software development:
  - CaRIBOu – detector readout system
  - Allpix^2 - generic pixel detector simulation

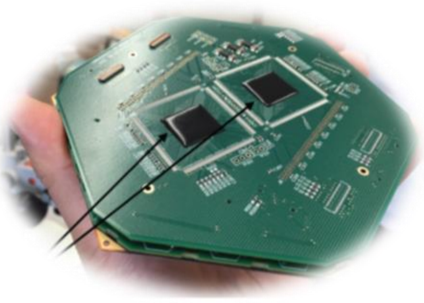
Silicon calorimeter: synergy with CMS

- CMS High Granularity Calorimeter (HGCAL) (installation in 2024) shares a lot of technology with CLICdet
- Key parameters:
  - 600 m^2 of silicon (hexagonal sensors)
  - Power at end of life ~60 kW per endcap
  - CO_2-cooled operation at -30°C
- Synergy in sensor design, electrical tests, beam tests





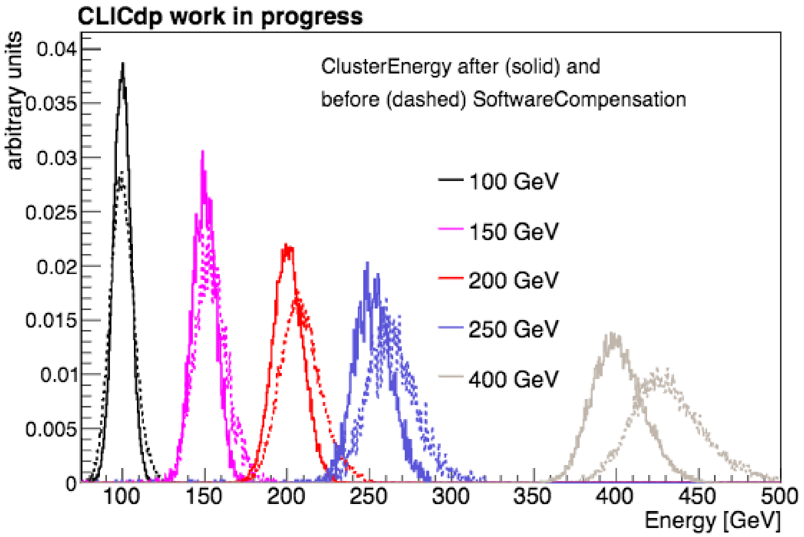




Reconstruction and Simulation

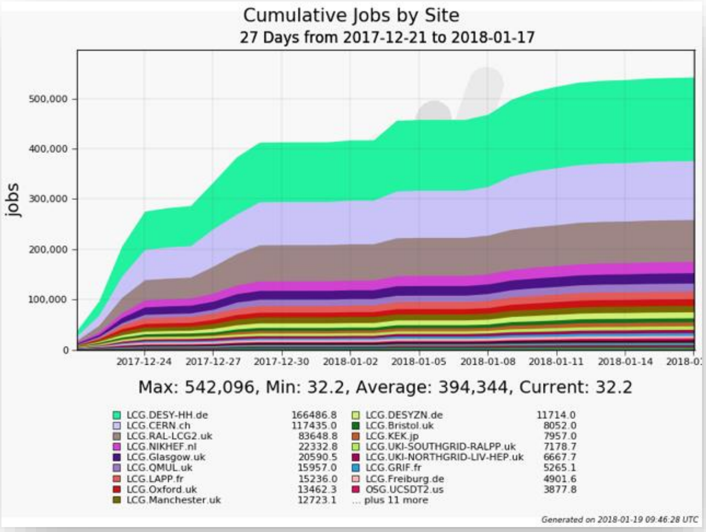
Validation of CLICdet

- Flavor tagging
- Tracking – muon momentum resolution of <2x10-5 GeV^{-1}
- Particle Flow Algorithm (PFA) – jet energy resolution of < 3.5-5%



Computing

- iLCSoft for simulation and reconstruction, DD4hep-based detector description
- Physics simulation and reconstruction is performed on the grid (iLCDirac for submissions)



Time plan

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

Summary and conclusions

- CLIC: **a future multi-TeV** e^+e^- collider at CERN
  - **Powerful** tool to address the open questions in particle physics
  - **Optimized** for a broad precision physics program
  - **Affordable** first stage at 380 GeV, **upgradable** to 3 TeV
  - Well-established and **flexible** physics program (potential LHC/ HL-LHC discoveries)
- Feasibility demonstrated through extensive simulation and prototyping, accelerator and detector R&D
  - Optimization studies of the CLICdet detector model finalized
  - Broad and active R&D on the vertex and tracking detectors with focus of finding technologies that simultaneously fulfil all the CLIC requirements
  - Contributing to the CALICE and FCAL calorimeter R&D collaborations on fine-grained prototypes of SiW ECALs, Scintillator-W HCAL, and forward calorimeters
  - Collaboration with CMS to construct the silicon calorimeter HGCAL
- The CLICdp Collaboration is currently preparing a series of reports and summary documents for the European Strategy Update

Thank you for your attention!