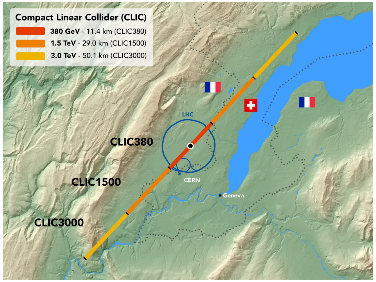
CLICdp status and plans

Dominik Arominski
(Warsaw University of Technology/CERN)
on behalf of the CLICdp collaboration

Asian Linear Collider Workshop
2018-06-01

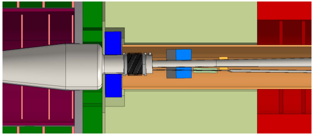
CLICdp collaboration

- CLIC detector and physics study (CLICdp) collaboration consists of
  - 30 member institutes from 18 countries
  - 158 participants
- New working group: Physics Potential involving the theoretical physics community
- Ongoing effort to prepare a series of documents for the European Strategy for Particle Physics
- More about CLIC accelerator and staging scenario in CLIC overview talk by Philip Burrows
- More about CLIC plans for the next stage in CLIC preparation phase programme 2020-2025 talk by Steinar Stapnes
- More info: clicdp.cern.ch

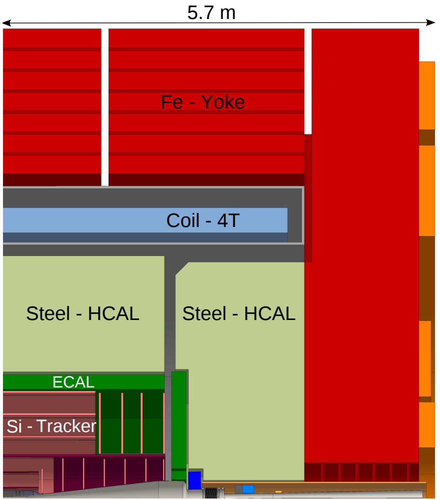


CLICdet model

- Low-material tracking system with vertex detector and tracker
- High granularity calorimetry system (ECal and HCal) necessary for Particle Flow Algorithm
- Forward calorimeters for luminosity measurement and monitoring: LumiCal and BeamCal



- 4 T superconducting solenoid magnet
- Return yoke with muon identification system
- Last quadrupole of final doublet outside detector ($L^* = 6$ m)
- More details in 'CLICdet: The post-CDR CLIC detector model'
- Detector performance thoroughly discussed in upcoming CLIC Detector Performance Note

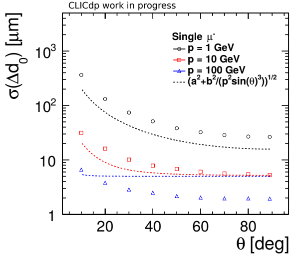


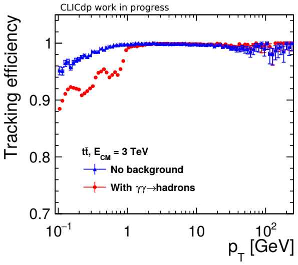
CLIC detector requirements

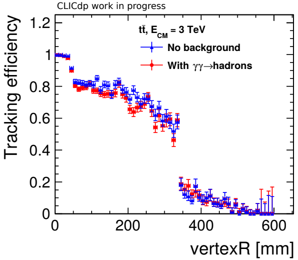
- Vertex detector requirements:
  - Driven by flavour tagging with precise determination of displaced vertices
  - Single-point resolution ~ 3 µm
  - Low material budget $\leq 0.2\%$ X_0 per layer
  - Low power ASICs and air cooling ($\leq$50 mW/cm^2)
- Tracker requirements:
  - Driven by momentum resolution: $\sigma_{p_T}/p_T^2 \sim 2 \cdot 10^{-5}$ GeV^{-1}
  - Single-point resolution: ~ 7 µm (elongated pixels / small strips)
  - Material budget 1-2% X_0 per layer: low-mass supports and services
- Both:
  - 20 ms between bunch trains - trigger-less readout and pulsed powering
  - Time stamping with ~ 5 ns resolution - depleted sensors (high resistivity / high voltage)
- Calorimeter detector requirements:
  - Driven by PFA requirements: high granularity for good jet energy resolution
  - $\sigma_E/E \sim 3.5\%$ in the range 100 GeV - 1 TeV
  - ns-level timing of calorimeter clusters

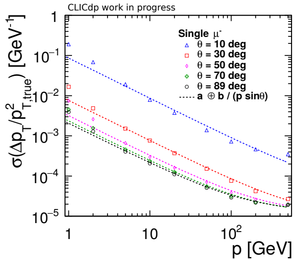
Tracking validation - conformal tracking

- Conformal tracking used in validation study, more on the technique in CLIC Week 2018 talk of Emilia Leogrande
- Good tracking performance even in complex events with background overlay or displaced production vertices
- Tracking validation study achieved momentum resolution down to $2 \cdot 10^{-5}$ GeV^{-5} and impact parameter resolution below 5 μm with single high energy muons – performance goals



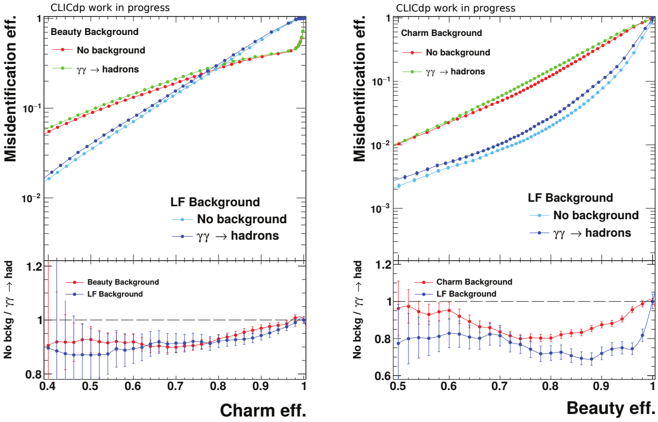






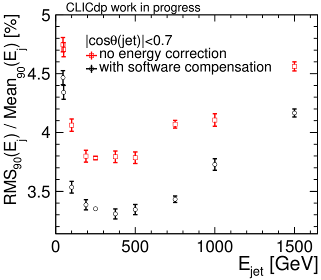
Flavour tagging performance

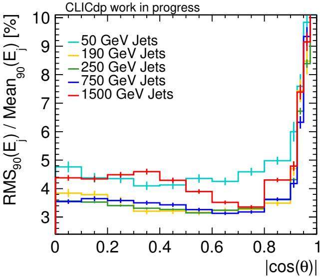
- Many important CLIC benchmark processes have multiple flavour jets
- The b-tagging performance is typically degraded by about 20-30% when $\gamma\gamma \rightarrow$ hadrons background is introduced, while the c-tagging performance is less impacted by background overlay, at the level of about 15%
- Benefits from improvements in conformal tracking and particle flow reconstruction – better performance expected in the future
- More info in CLIC Week 2018 presentation of Ignacio Garcia Garcia



Jet energy resolution

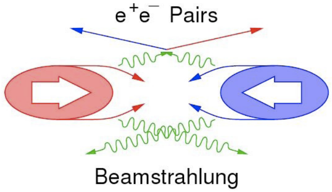
- Jet performance was studied in dijet events using decays of a Z-like particle into light quarks (u, d, s) at different energies
- Applying software compensation improves the σ_E for jets by about 10%
- Modification in PFA to address long standing issues of inefficiency of charged particle ID in calorimeter transition region (only minor effect of gap remaining)
- Jet energy resolution is within $3.5 - 4.5\%$ up to the endcaps ($|cos(\theta)| < 0.925$) – performance goal

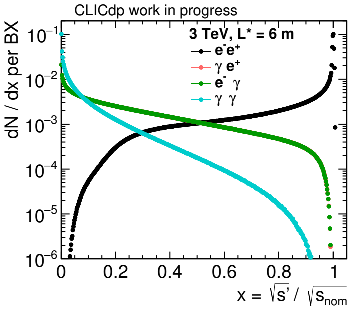




Beam-induced backgrounds introduction

- Synchrotron radiation is created along the Beam Delivery System, and especially in the strong focusing magnets of the Final Focus System
- Beamstrahlung photons, a type of synchrotron radiation caused by charged particles' interactions with the electromagnetic field of the incoming beam, are produced in large quantities and with high energies in the interaction region
- Beamstrahlung emission is the main cause of the lower energy tail in $\mathrm{e^-e^+}$ luminosity spectrum
- Beamstrahlung interactions with $\mathrm{e^-}$, $\mathrm{e^+}$ or other photons lead to production of unwanted particles: incoherent pairs, hadrons, coherent pairs and trident cascades (for $\sqrt{s} > 1$ TeV)



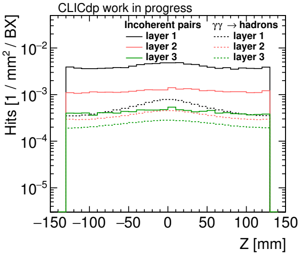


CLIC logo / CERN logo

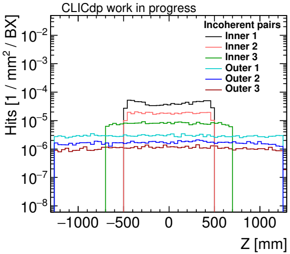
Beam-induced backgrounds

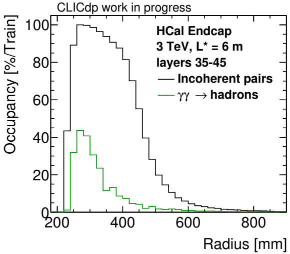
- Hit densities and occupancies in the tracking detectors and ECal and HCal calorimeters coming from incoherent pairs and $\gamma\gamma \rightarrow$ hadrons events have been estimated at two energy stages: 380 GeV and 3 TeV
- Occupancies in tracking detector are on acceptable levels below 3% read-out per train "(cf. Requirements for the CLIC tracker readout)"
- Occupancy in HCal at small radii can be minimized using varying energy integration time, granularity, or use of an absorber
- More info in Thursday's talk: Beam induced backgrounds and occupancies in CLICdet

Vertex barrel 3 TeV



Tracker barrel 3 TeV





Readout for a detector at CLIC

The data rates and occupancies in CLICdet have recently been updated for the new detector model for the 3 TeV energy stage, assuming worst case without zero suppression in the calorimeters:

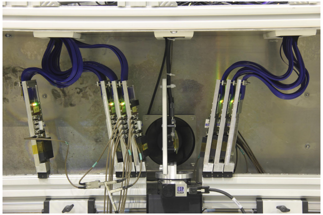
Detector	Event size [MByte]	Repetition rate [Hz]	Data volume [GByte/s]
CLICdet (strip tracker)	4000	50 (train)	200
CLICdet (pixel tracker)	6000	50 (train)	300
ATLAS/CMS (pp)	~ 1	100 000 (L1)	100

- The largest data flow coming from Electromagnetic Calorimeter
- Large event sizes at CLIC of 4-6 GByte per bunch train are compensated by low train frequency (50 Hz) not above 300 GByte/s
- With optical data link bandwidth of 10 Gbit/s, CLICdet read-out is achievable with 160 – 240 links

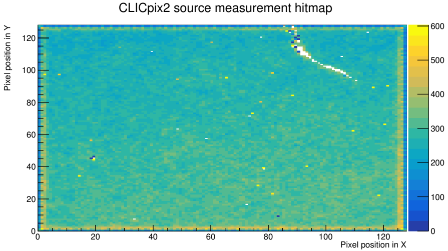
Silicon tracking detector technology R&D

- Ongoing test-beam studies on CLICpix2 bump-bonded planar sensors from Advacam & FBK
- CLIC Tracker Detector (CLICTD) monolithic HR-CMOS chip under development; more info in CLICTD manual
- Enhanced lateral drift sensors (ELAD) test samples being currently produced; foreseen beam tests in DESY
- CLIPS - SOI chip for Linear Collider requirements submitted for fabrication; recently also considered for vertex detector; more info SOI test-beam results
- CLICdp test beam activities prepared to move to DESY during Long Shutdown 2 at CERN; tests in the PS in the preparation for different experimental conditions

telescope with Timepix3



FBK assembly hitmap



Simulation and reconstruction software R&D

- Allpix^2 - generic pixel detector simulation framework
  - Combines tools: Geant4 + TCAD fields + Front-end simulation
  - Simulates full setup with high-statistics samples taking into account the stochastic nature of studied processes
  - See more at dedicated webpage
- Contributing to iLCSoft Simulation and Reconstruction software: iLCsoft repository, see more in Andre Sailer's Tuesday iLCCDirac: Status and Plans talk
- Finalized a CLICdet Delphes card
  - Modular system including detector components and their performances
  - Added Linear Collider jet algorithm and observables based on FastJet plugins
  - More info in TWiki page, implementation and validation in Ulrike Schnoor's DPG Wuerzburg presentation

CLIC physics potential

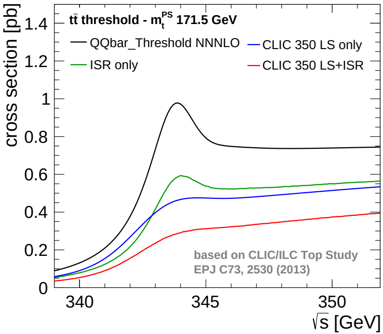
- New CLIC physics potential working group aims to involve theorist community to study the possible reach of the physics programme at CLIC, more info: Physics at CLIC kick-off
- Energy staging offers complementary physics programme:
  - 100+500 fb^{-1} at 350 & 380 GeV with precision SM Higgs and top physics
    - top mass precision at 50 MeV level
    - Higgs model-independent mass precision at $\sim$ 100 MeV level
    - Higgs invisible decays constrained down to 0.6%
  - 1.5+3.0 ab^{-1} at 1.5 & 3 TeV with more luminosity and reach to new phenomena:
    - Higgs couplings down to 0.1% precision, access to rare decays
    - Double Higgs; Higgs self-coupling
    - Top Yukawa coupling with 3.4% precision
    - Possible double Higgs self- and quadratic couplings extraction using template fits with precision of $\sim$ 10%
    - Enhanced senstivity to new physics
- More info about Higgs physics at CLIC in: Eur. Phys. J. C 77, 475 (2017)
- Top physics paper under collaboration review

Top physics at CLIC - mass measurement

- CLIC 100 fb^{-1} run at the $t\,\bar{t}$ production threshold is ideal for a comprehensive exploration of EWSB sector
- Mass measurement with 50 MeV precision including statistical and systematic uncertainties
- The machine parameters can be tuned (at a cost in instantaneous luminosity) to minimize the impact of the luminosity spectrum on the threshold shape

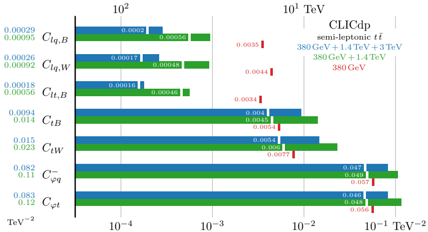
There are alternatives to determine top mass other than threshold scan, both with mass measurement precision $\sim$ 100 MeV:

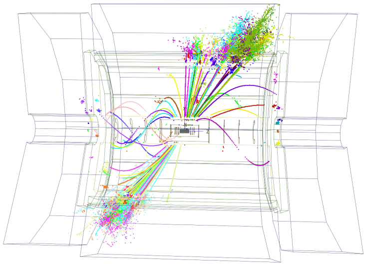
- LHC style 'direct reconstruction': understand MC mass post-hoc
- Radiative events: 'return-to-threshold': access to the running of the mass



Top physics at CLIC - couplings

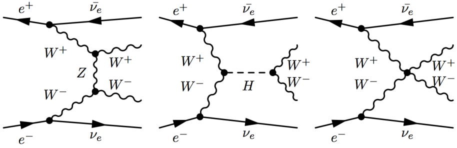
- Above the c.m. energy region where threshold effects are relevant top electroweak couplings and rare decays can be measured
- FCNC top-quark decays are strongly suppressed in the SM – any signal can be a signature of new physics
- Sensitivity to contact interaction operators rises steeply with energy – CLIC benefits from higher energy stages
- Top Yukawa coupling measurement with possible precision of 3.8% with 1.5 ab^{-1} at 1.4 TeV
- Ongoing effort on boosted top reconstruction at 3 TeV



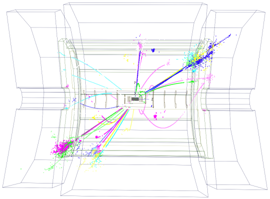


Beyond SM physics searches

- Direct observation of new particles coupling to $\gamma^*/Z/W$ bosons allows for precision measurement of new particle masses and couplings to percent-level
- Physics programme complementary to HL-LHC, e.g. possible measurements of heavy SUSY partners
- Vector boson scattering (VBS) gives insight into the mechanism of electroweak symmetry breaking
  - Example processes investigated for high-energy operation: $e^-e^+ \to W^+W^-\nu\nu$ and $e^-e^+ \to ZZ\nu\nu$
  - Fully hadronic events can be used: $W^+W^-/ZZ\nu\nu \to qqqq\nu\nu$



$e^-e^+ \to qqqq\nu\nu$ at 1.4 TeV



Summary

- A high-performing detector has been designed and optimized for CLIC
- Hardware and software techniques are employed with excellent results to mitigate the effect of 3 TeV background on detector and physics performances
- Stringent requirements for CLIC vertex and tracking detectors have inspired broad and integrated technology R&D program, with various sensor and readout choices under study
- Calorimetry for CLIC is very well developed and understood - based on technical developments by CALICE and CMS HGCal upgrade project
- Guaranteed physics programme at 380 GeV with focus on Higgs and top quark; at higher energy stages access to rare Higgs processess (e.g. self-coupling), possible direct and indirect discoveries
- Ongoing effort to prepare a series of documents for the European Strategy for Particle Physics, including an overview of CLIC top physics, extended BSM studies and CLICdp detector R&D report forseen for completion by the end of the year

clic.cern

Additional material

CLICdet calorimetry

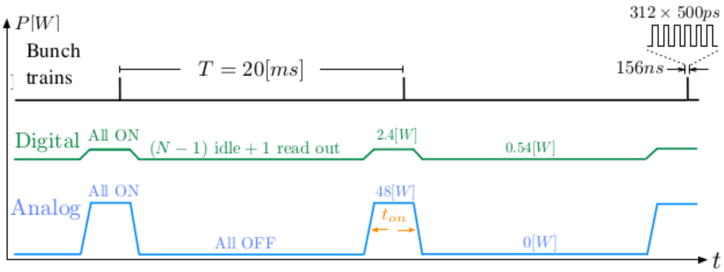
Key parameters:

- ECal
  - Depth: 40 layers, 22 X0 ($\sim 1\lambda_I$)
  - Absorber: W, 1.9 mm / layer
  - Active elements: Si
  - Granularity: 5x5 mm^2
- HCal
  - Depth: 60 layers, 7.5λ_I
  - Absorber: Stainless steel, 20 mm / layer
  - Active elements: Scintillator tiles / SiPMs
  - Granularity: 30x30 mm^2

- Silicon activities profit from CALICE and CMS HGCAL project - CLICdp directly involved in sensor testing & test beam activities
- Auto triggering: Enables triggerless operation of the calorimeter
- No active cooling in detector volume for maximum compactness
- Power-pulsing allowed by bunch train structure of CLIC - allows a duty cycle of $< 1\%$ for front-end electronics
- W absorber in HCal instead of Fe studied; presence of delayed neutrons require longer integration time which increases sensitivity to backgrounds

Powering and power pulsing at CLIC

- Small duty cycle of CLIC machine: 0.00078% at 3 TeV allows to turn off electronics between the bunch trains
- Power pulsing is optimized for low-material budget in the inner barrel detectors, reduces the average power consumption
- Local energy storage and voltage regulation
- Small continuous current through low-mass Al cables, stable voltages for r/o ASICs
- Measurements on vertex ladders prototypes show total power dissipation < 50 mW/cm^2, compatible with air-cooling



CLIC detector: data rates at 3 TeV

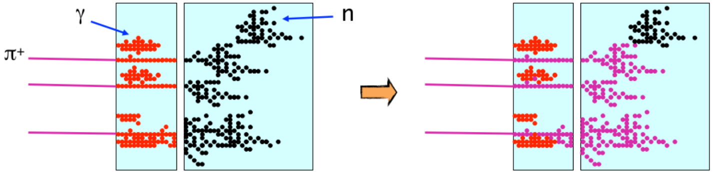
Strip tracker geometry

Number without safety factors, *Worst case without zero suppres

	time sampling period [ns]	hit time stamping resolution [ns]	cell size [mm^2]	number of channels [10^6]	average to maximum train occupancy [%]	number of bits per cell (hit, not hit) [bit]	data volume* [MByte]
VTX barrel	10	$\sim$ 5	0.025 × 0.025	780	0.5 - 3	13,1	110
VTX disks	10	$\sim$ 5	0.025 × 0.025	560	0.005 - 3	13,1	75
Inner Tracker Barrel 1	10	$\sim$ 5	0.05 × 1	16	0.4 - 1.6	22,1	2
Inner Tracker Barrel 2	10	$\sim$ 5	0.05 × 1	44	0.1 - 0.6	22,1	6
Inner Tracker Barrel 3	10	$\sim$ 5	0.05 × 5	21	0.3 - 1.7	22,1	3
Outer Tracker Barrel 1	10	$\sim$ 5	0.05 × 10	29	0.4 - 1.3	22,1	4
Outer Tracker Barrel 2	10	$\sim$ 5	0.05 × 10	41	0.2 - 0.8	22,1	5
Outer Tracker Barrel 3	10	$\sim$ 5	0.05 × 10	52	0.1 - 0.6	22,1	7
Inner Tracker Disk 1	10	$\sim$ 5	0.025 × 0.025	2000	0.00006 - 0.008	13,1	267
Inner Tracker Disk 2	10	$\sim$ 5	0.05 × 1	46	0.003 - 0.2	22,1	6
Inner Tracker Disk 3	10	$\sim$ 5	0.05 × 1	44	0.003 - 0.17	22,1	6
Inner Tracker Disk 4	10	$\sim$ 5	0.05 × 1	42	0.003 - 0.15	22,1	5
Inner Tracker Disk 5	10	$\sim$ 5	0.05 × 1	40	0.002 - 0.14	22,1	5
Inner Tracker Disk 6	10	$\sim$ 5	0.05 × 1	38	0.002 - 0.05	22,1	5
Inner Tracker Disk 7	10	$\sim$ 5	0.05 × 1	36	0.002 - 0.03	22,1	5
Outer Tracker Disk 1	10	$\sim$ 5	0.05 × 10	27.8	0.002 - 0.1	22,1	4
Outer Tracker Disk 2	10	$\sim$ 5	0.05 × 10	27.8	0.002 - 0.1	22,1	4
Outer Tracker Disk 3	10	$\sim$ 5	0.05 × 10	27.8	0.002 - 0.1	22,1	4
Outer Tracker Disk 4	10	$\sim$ 5	0.05 × 10	27.8	0.002 - 0.1	22,1	4
ECAL barrel	25	1	5 × 5	72	$<$ 5	16 · 15	2160
ECAL endcap	25	1	5 × 5	29	0.8 - 40	16 · 15	870
HCAL barrel	25	1	30 × 30	4.8	$<$ 5	16 · 15	144
HCAL endcap	25	1	30 × 30	4.5	37 - 4800	16 · 15	135
HCAL rings	25	1	30 × 30	0.4	$<$ 5	16 · 15	12
LumiCal	10	5	4 × 13–44	0.245	415 - 21810	32 · 36	35
BeamCal	10	5	8 × 8	0.093	12730 - 31200	32 · 36	13

Particle Flow Algorithm validation

- Pandora PFA - hardware + software
- High-granularity calorimeters needed to define energy deposit from different particle types
- Knowing the jet composition, profit from the detectors with best resolution:
  - 60 % charged particle - tracking detector
  - 30 % photons - ECal
  - 10 % neutral hadrons - HCal

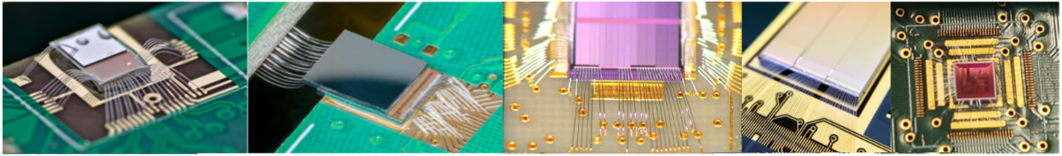


$E_{JET} = E_{ECAL} + E_{HCAL}$ $\quad$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- Modification in PFA to address long standing issues of inefficiency of charged particle ID in calorimeter transition region (only minor effect of gap remaining)
- Adopted software compensation with CLIC specific weights; achieved jet energy resolution between 3.1-4.5%

CLIC silicon tracker technology R&D - vertex

- Challenging requirements lead to extensive R&D programme involving beam tests and collaboration with ATLAS, ALICE, LHCb, RD53, AIDA2020
- Comprehensive studies performed using Timepix/Timepix3 and CLICpix/CLICpix2 read-out ASICs
- **Hybrid planar** pixel sensors bump-bonded to r/o ASICs; prototypes with $\sim 100\%$ efficiency, few ns timing, $\sigma_{SP} \sim 7$ µm
- σ_{SP} can be reduced by increased charge sharing in ELAD – Enhanced LAteral Drift sensors
- Capacitively coupled **HV-CMOS** – CCPDv3 and C3PD with $90 - 100\%$ efficiency, few ns timing, $\sigma_{SP} \sim 6$ µm
- Thin glue layer replaces costly small-pitch bump bonds; ongoing optimization of the gluing process



CLIC silicon tracker technology R&D - tracker

- Monolithic **HV-CMOS** – ATLASPIX prototypes with 99.5% efficiency, $\sigma_t \sim 16 - 20$ ns, $\sigma_{SP} \sim 13$ µm
- Almost no charge sharing; timing limited by read-out system; future developments focused on improving digital design, adapting pixel layout to CLIC requirements (30 µm)
- Integrated CMOS sensors on High-Resistivity substrate (**HR-CMOS**) – tests with INVESTIGATOR analog prototype chip; for 28x28 μm^2 pitch: 99.3% efficiency, $\sigma_t < 5$ ns, $\sigma_{SP} \sim 4$ µm
- Future developments: thinning to 100 µm,
- Monolithic **SOI** - Sensor and electronics integrated on single wafer with high resistivity substrate, separated by insulation oxide layer and buried p wells; considered for both vertex & tracker
- Cracow SOI test chip with various geometries and parameters; $> 90\%$ efficiency, $\sigma_{SP} \sim 4.5$ µm for $>= 30x30$ μm^2 pitch, 500 µm thickness, rolling-shutter r/o
- Future works: development of read-out