http://clicdp.cern.ch

The CLIC detector and physics study

An Overview

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on behalf of the CLICdp Collaboration

CLIC Workshop

CERN, 21 – 25 January 2019

The *CLIC detector and physics study* Collaboration

Collaboration with

- 30 institutes
- 159 members

formed to carry out

- physics studies
- detector technology R&D

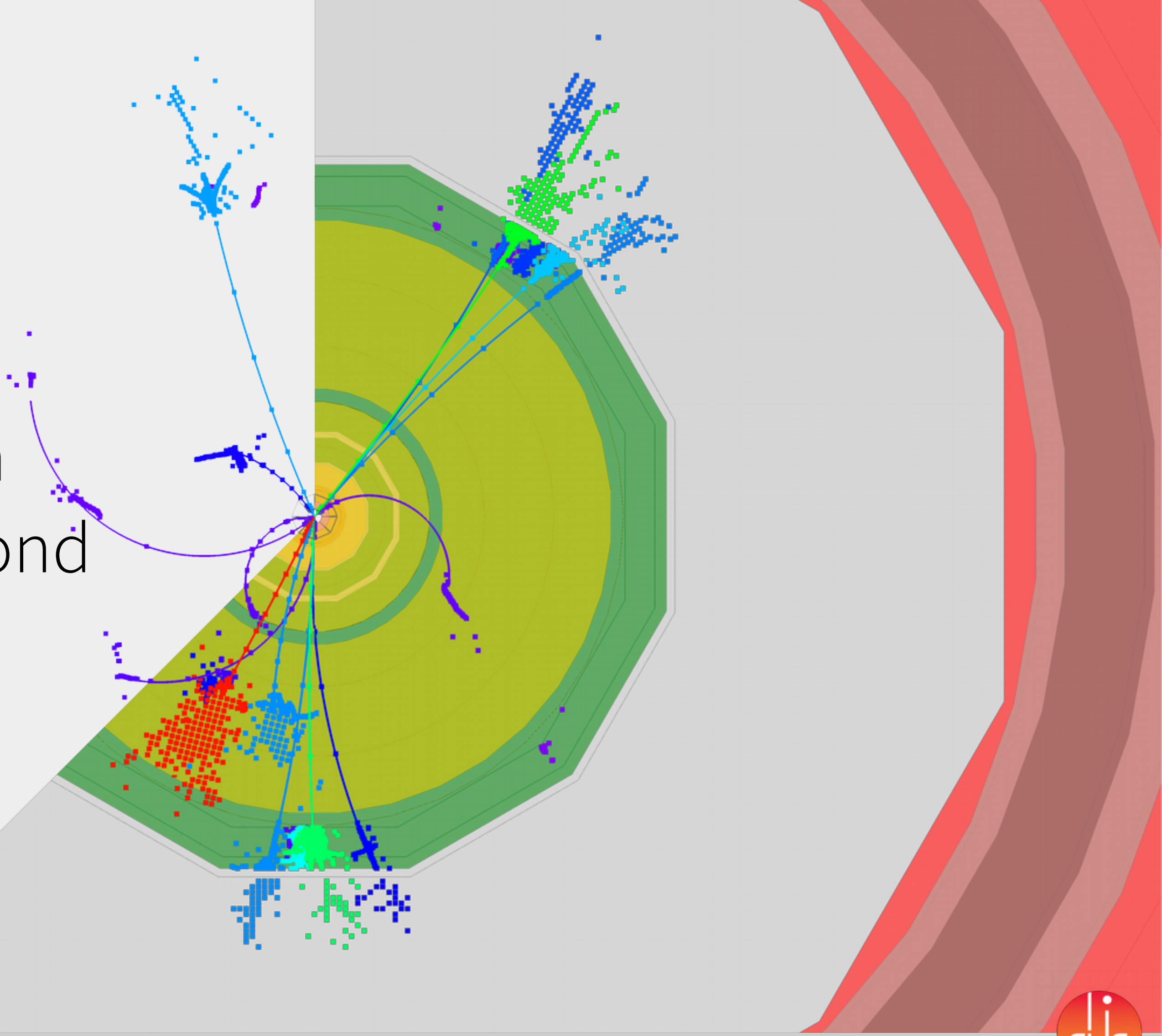
Close collaboration with other R&D / LC projects such as CALICE, FCAL as well as AIDA-2020 and CMS

Outline

- CLIC Physics Program
- Experimental Conditions
- The CLIC detector concept CLICdet
- Detector Technologies & Prototypes
- Performance Studies & Validation
- Cost Estimate
- Summary Documents

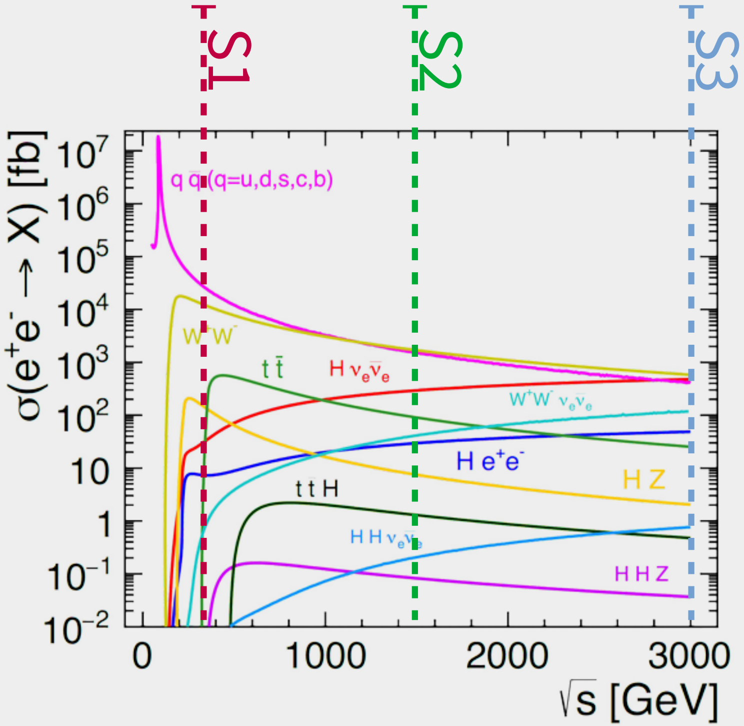
CLIC Physics Program

Standard Model & beyond



CLIC Physics Program – in 3 Stages

- Dedicated CLICdp Physics session in this workshop (Wed. & Thur.)



Stage 1: $\sqrt{s}$ = 380 GeV (1.0 ab^{-1})

- Higgs/top precision physics
- Top mass threshold scan

Stage 2: $\sqrt{s}$ = 1.5 TeV (2.5 ab^{-1})

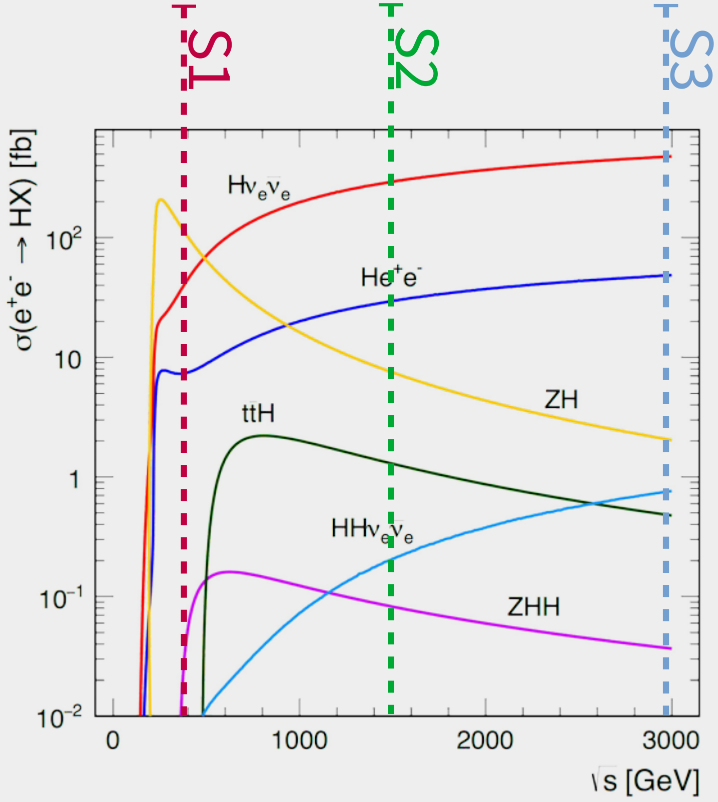
- Focus: BSM searches
- Higgs/top precision physics

Stage 3: $\sqrt{s}$ = 3 TeV (5.0 ab^{-1})

- Focus: BSM searches
- Higgs/top precision physics

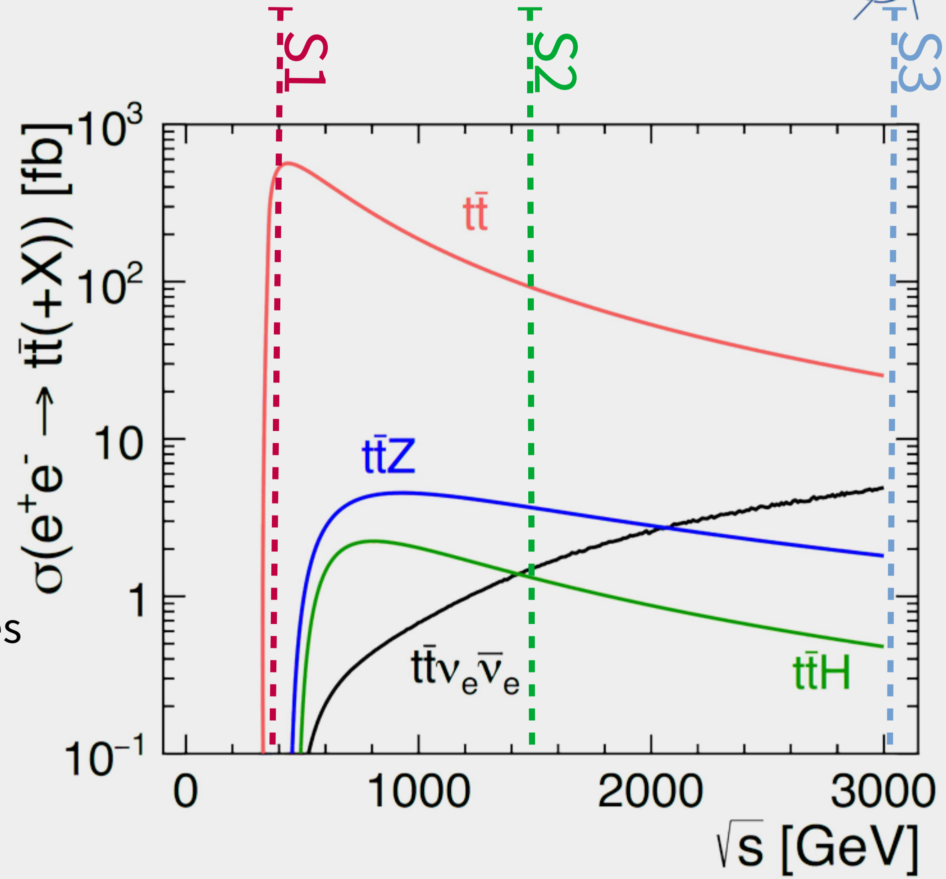
Higgs Physics

- Initial stage: study of Higgs boson production in
  - Higgsstrahlung ($e^+e^- \rightarrow ZH$)
  - WW-fusion ($e^+e^- \rightarrow H\ \nu_e\nu_e$)
  - Precise measurements of cross sections, decay width Γ_H, couplings (model-independent)
- High-energy stages:
  - High-statistics WW-fusion samples constrain Higgs couplings
  - Studies of rarer processes ($e^+e^- \rightarrow ttH$, $e^+e^- \rightarrow HH\ \nu_e\nu_e$) to measure top Yukawa coupling, Higgs boson self-coupling
- Talk on Higgs boson self-coupling by U. Schnoor
- **Detailed paper published:**
  "Higgs physics at the CLIC electron-positron linear collider"



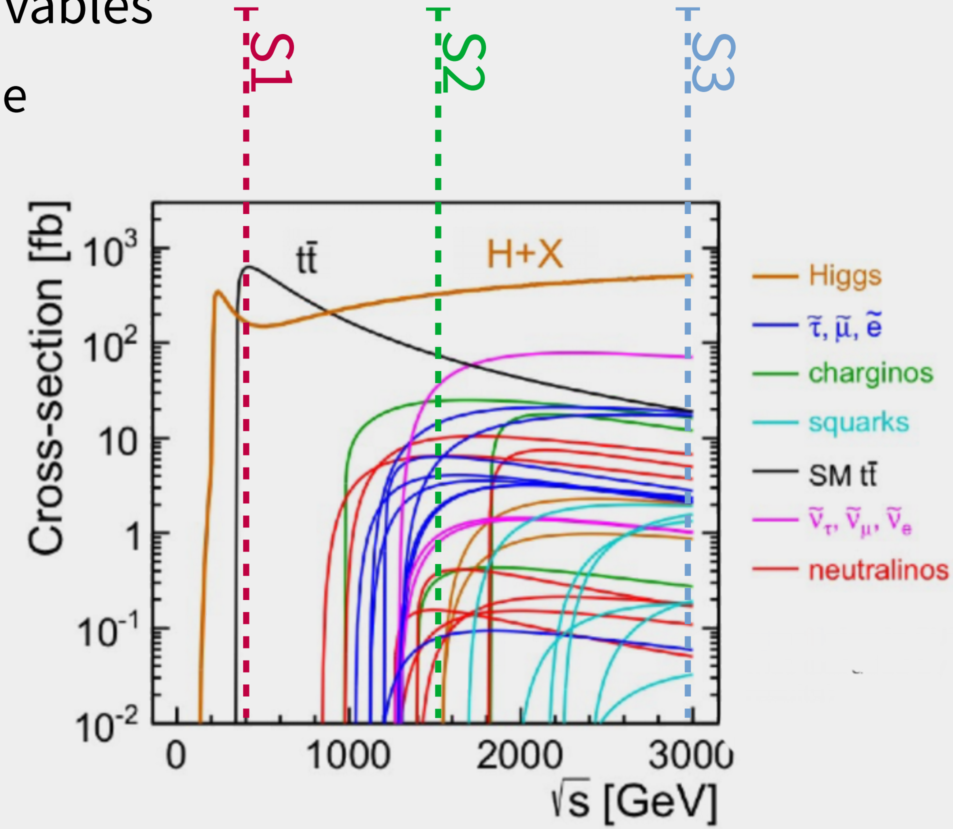
Top-Quark Physics

- Initial stage: focus on
  - top-quark pair production
  - search for rare FCNC top-quark decays
  - tt pair production threshold scan at 350 GeV
    - Precise measurement of top-quark mass in well-defined theoretical framework
- Higher-energy stages:
  - top-quark pairs in association with other particles
  - ttH production, top Yukawa coupling
  - Vector boson fusion (VBF) production
- **Detailed paper in journal review:** “Top-Quark Physics at the CLIC Electron-Positron Linear Collider”

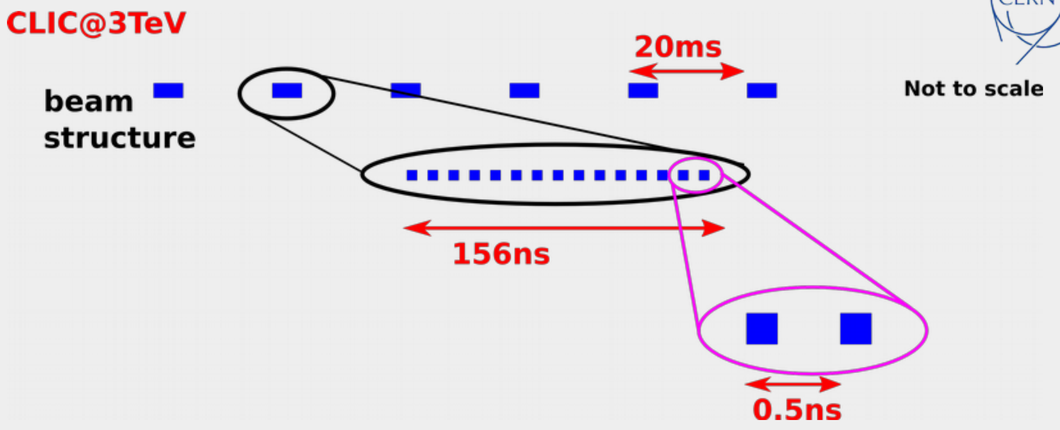


Beyond-Standard-Model Physics

- **Indirect searches** through precision observables
  - Allow discovery of new physics beyond the center-of-mass energy of the collider
- **Direct production** of new particles
  - Possible up to the kinematic limit
  - Precision measurements
  - Complements the HL-LHC program
- **Comprehensive report published:**
  "The CLIC Potential for New Physics"



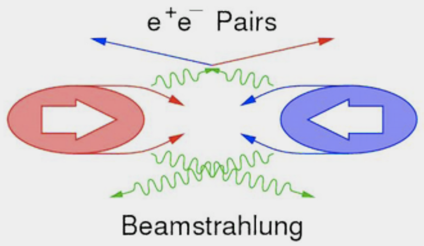
Experimental Conditions

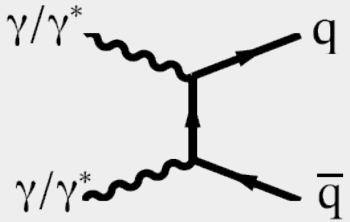


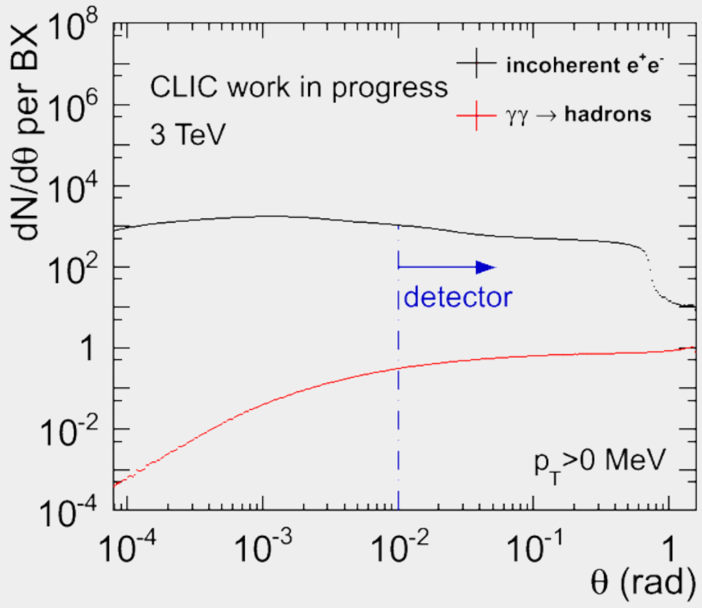
- CLIC operates in bunch trains, repetition rate of 50 Hz
  - Low duty cycle
  - Possibility for power cycling: switch detector components off between trains to reduce heat dissipation
- 312 bunches within train (at 3 TeV), separated by 0.5 ns
- Bunch separation drives timing requirements for detector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

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







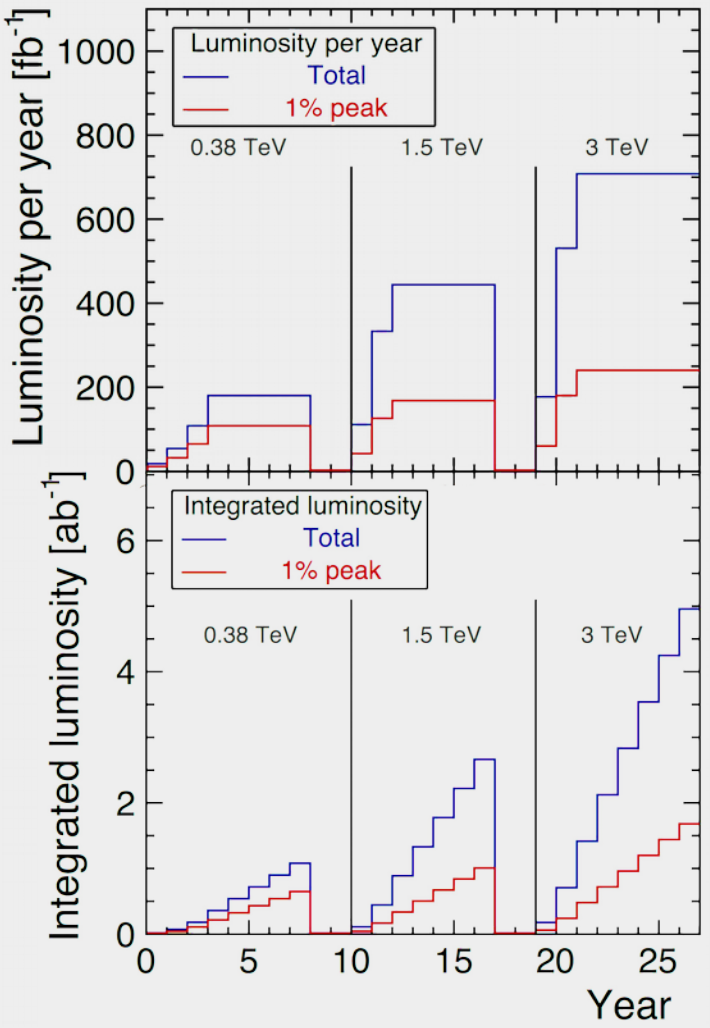
Main backgrounds in detector acceptance (p_T > 20 MeV, θ > 7.3 ◦)

- **Incoherent e + e − pairs**
  - 19k particles / bunch train at 3 TeV
  - High occupancies, stringent requirements on detector granularity
- **γγ → hadrons**
  - 17k particles / bunch train at 3 TeV
  - Main background in calorimeters and trackers → Impact on detector granularity, design and physics measurements

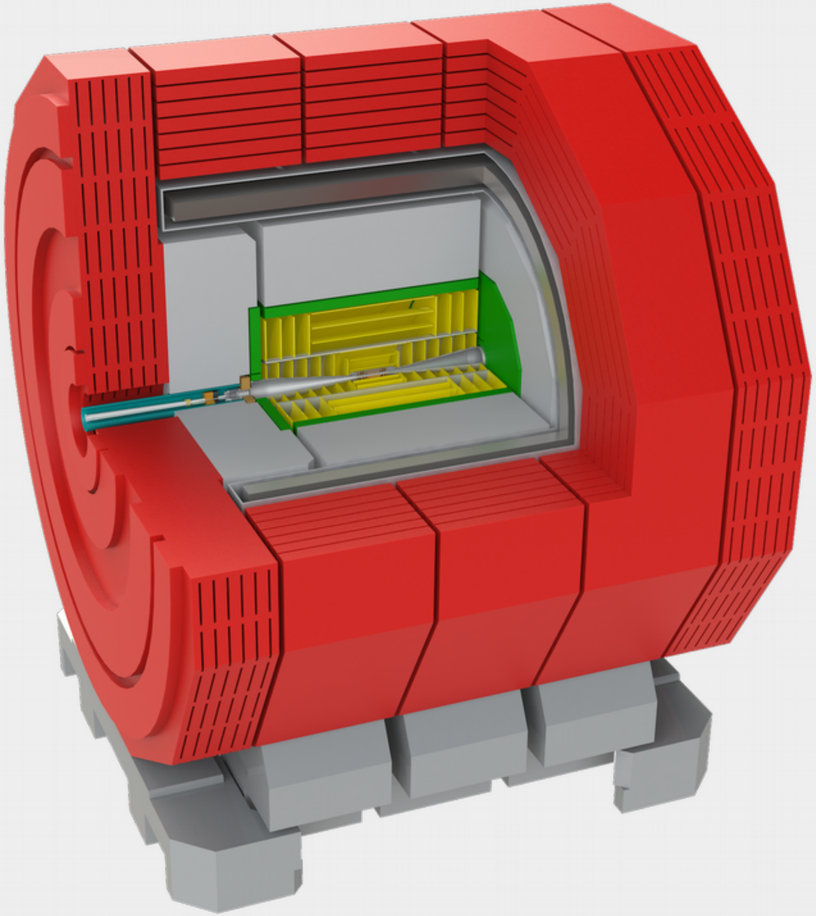
Integrated Luminosity

- Updated projections for luminosity
  - Harmonized with other future collider projects
  - Based on 185 days of physics operation
  - Luminosity ramp-up at beginning of each stage

- Total integrated luminosities:
  - Stage 1, 380 GeV: 1.0 ab^{-1}
    (including tt threshold scan around 350 GeV)
  - Stage 2, 1.5 TeV: 2.5 ab^{-1}
  - Stage 3, 3 TeV: 5.0 ab^{-1}

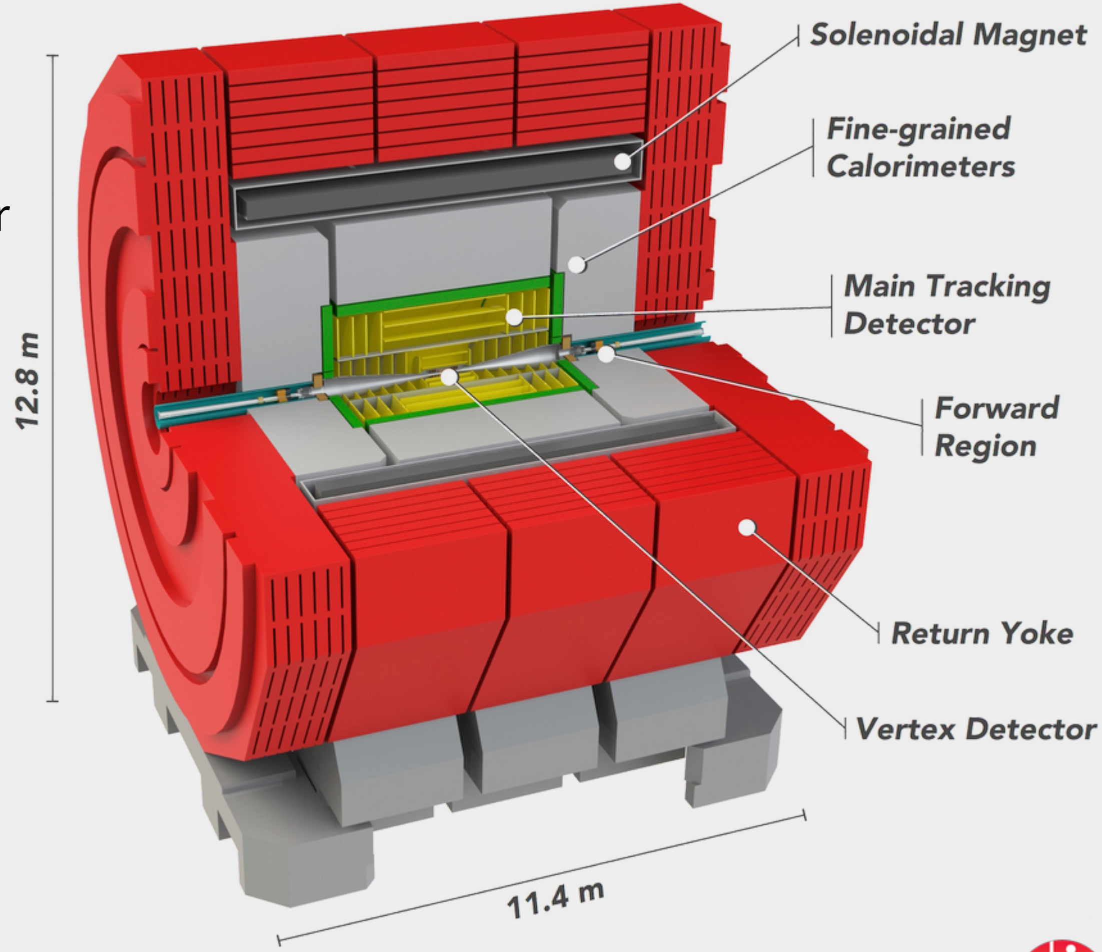


CLICdet
the CLIC detector Concept



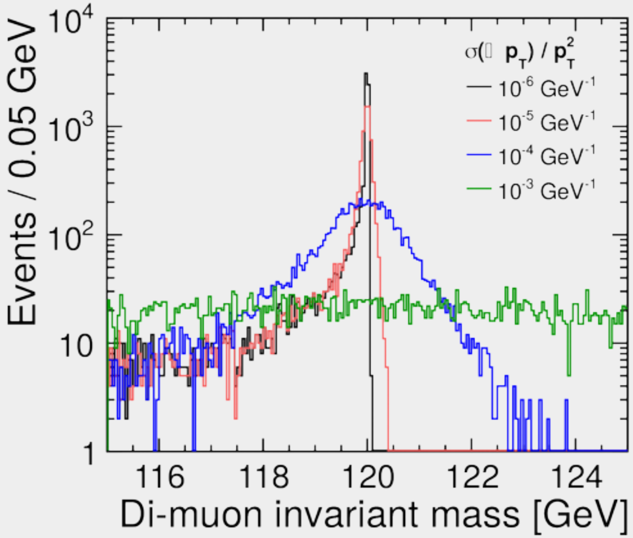
CLICdet – the CLIC detector Concept

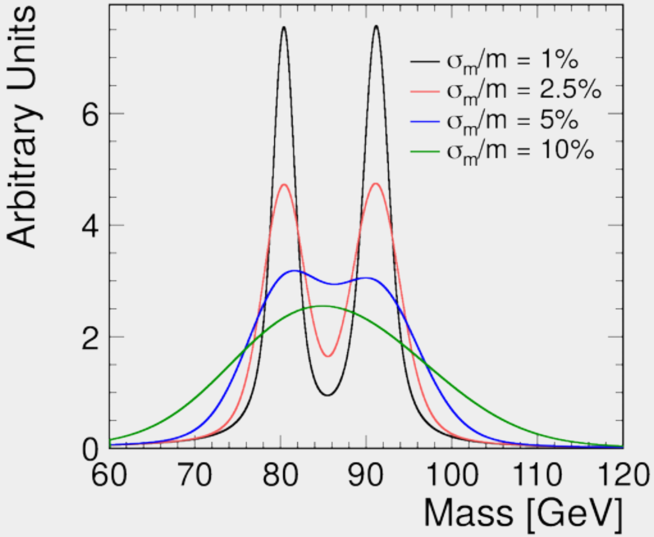
- Originally inspired by ILC detector concepts SiD and ILD
- Large all-silicon vertex/tracking detector R = 1.5m
- High-granularity calorimeters:
  - ECAL: 22 X_0
    40 layers Si sensors, W plates
  - HCAL: 7.5 λ_I
    60 layers plastic scintillator/SiPM, steel
- 4T superconducting solenoid
- **Optimized for Particle Flow Algorithm**



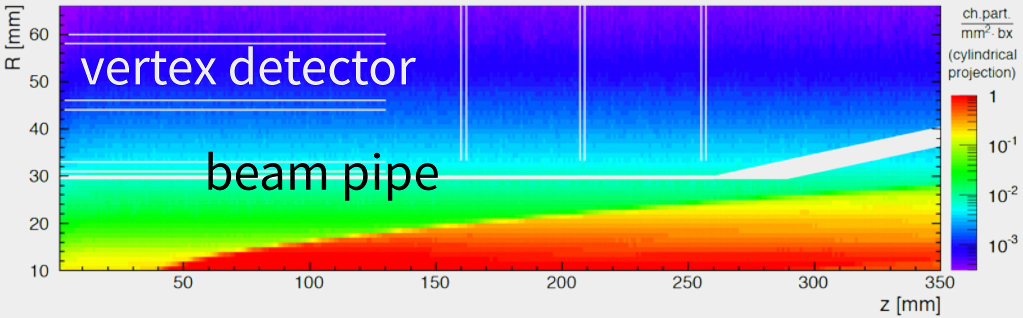
Detector requirements

- Momentum resolution
  - Higgs recoil mass, Higgs coupling to muons
  - $\sigma_{p_T}/p_T \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - $\sigma_{r\phi} \sim a \oplus b\ /\ (p[\mathrm{GeV}]\ \sin^{3/2}\theta)\,\mu\mathrm{m}$ with a = 5 µm, b = 15 µm
- Jet energy resolution
  - Separation of W/Z/H di-jets
  - $\sigma_E/E \sim 5\%$ - 3.5% for jets at 50 GeV – 1000 GeV
- Angular coverage
  - Very forward electron and photon tagging
  - Down to $\theta = 10$ mrad ($\eta = 5.3$)

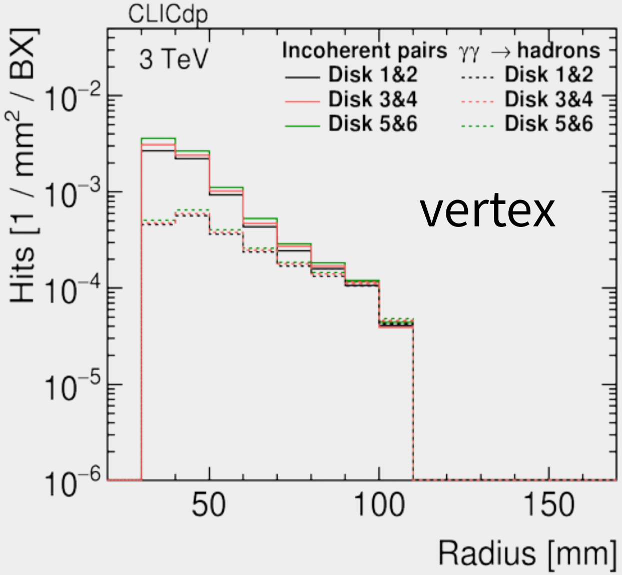


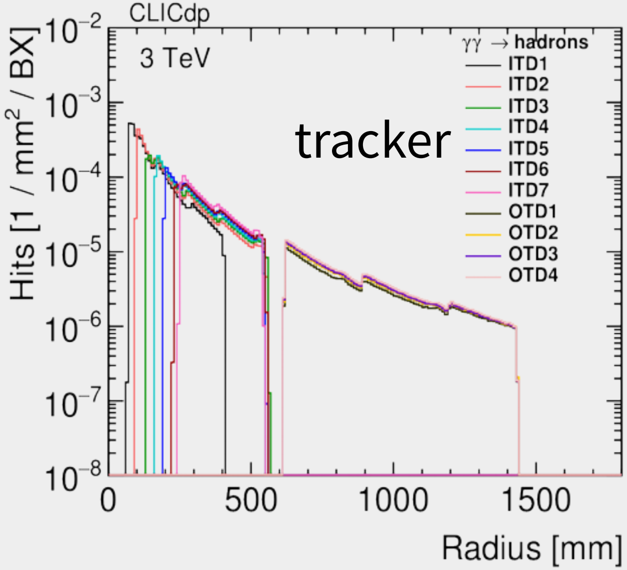


Occupancies



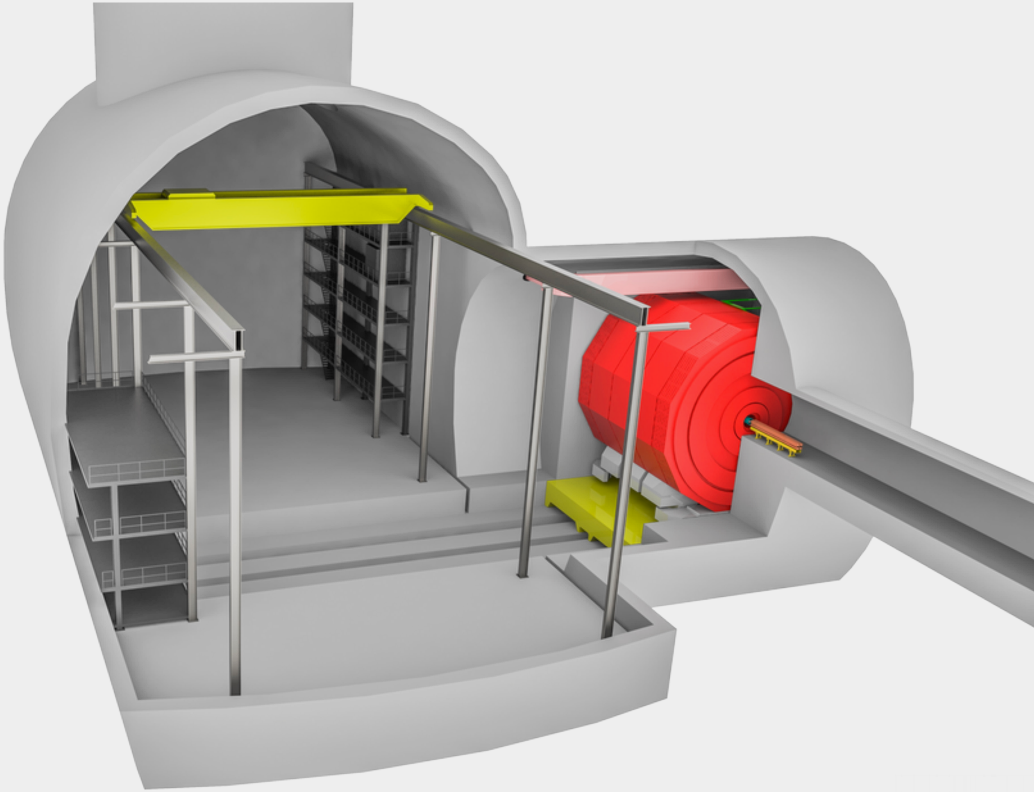
- Charged particles produced by beam-induced background
- Choice of detector granularity dependent on particle flux and geometry
- Goal: keep **occupancies below 3%** per bunch train including safety factors
  - Vertex: quadratic pixels, pitch **25 µm x 25 µm**
  - Tracker: strips / pixels with **50 µm** in rϕ and **1mm – 10mm** in z





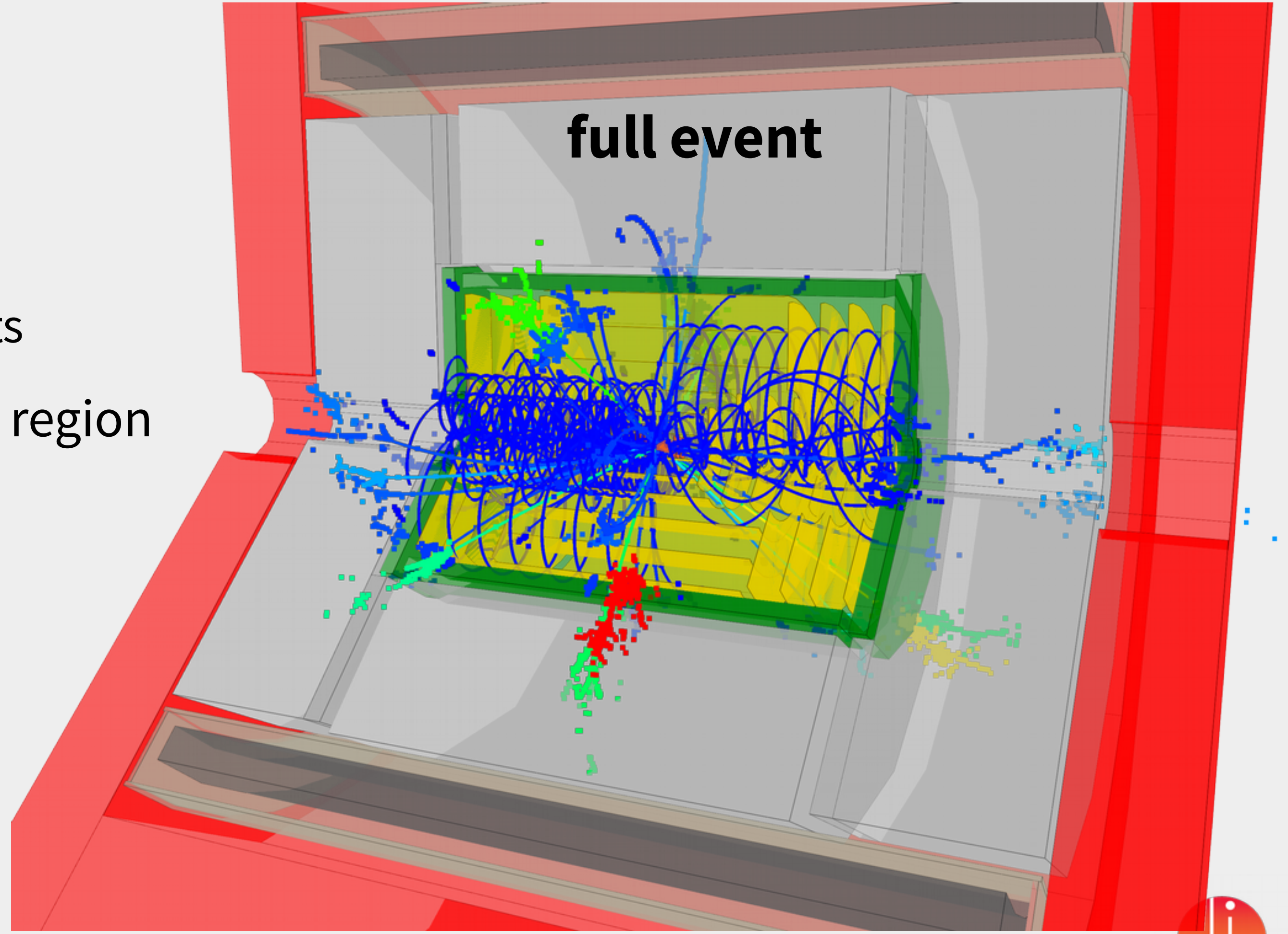
Same Detector for 380 GeV and 3 TeV?

- Different beam conditions would allow to consider different detectors
- Solenoid, yoke, calorimeters (tracker?) unchanged for practical reasons
- Possible differences:
  - Replacement of BeamCal necessary
  - Reduced beamstrahlung @ 380 GeV
    - Allows smaller beam pipe
    - Could move innermost vertex layer closer to interaction point
- Currently focusing on **single detector**, with a layout **optimized for 3 TeV**



Background rejection @ **380 GeV**

- Rejection based on:
  - Timing requirements
  - Particle type and p_T
  - Retaining high-p_T objects
- Cuts adapted per detector region



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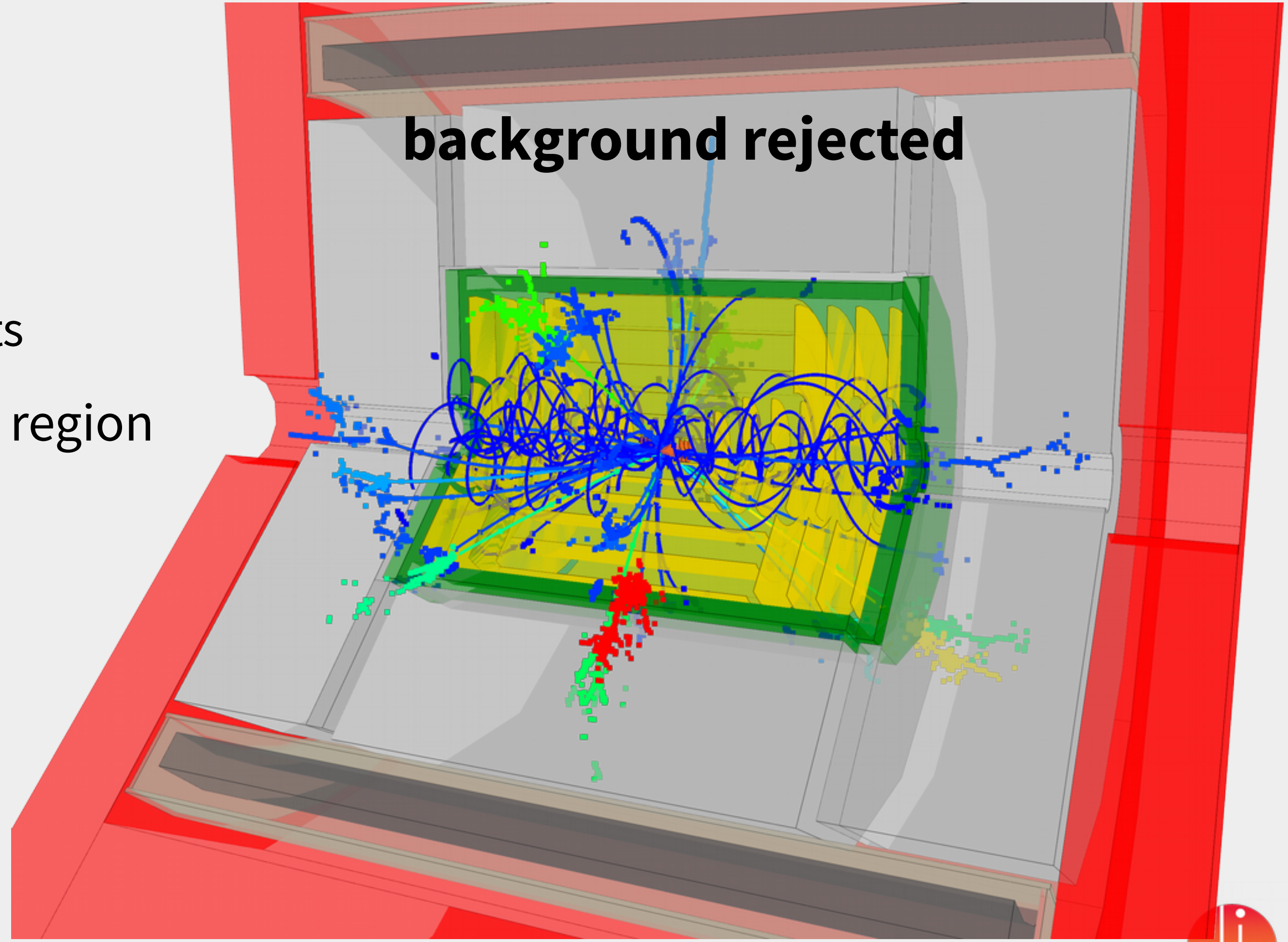

Background rejection @ **3 TeV**

- Rejection based on:
  - Timing requirements
  - Particle type and p_T
  - Retaining high-p_T objects
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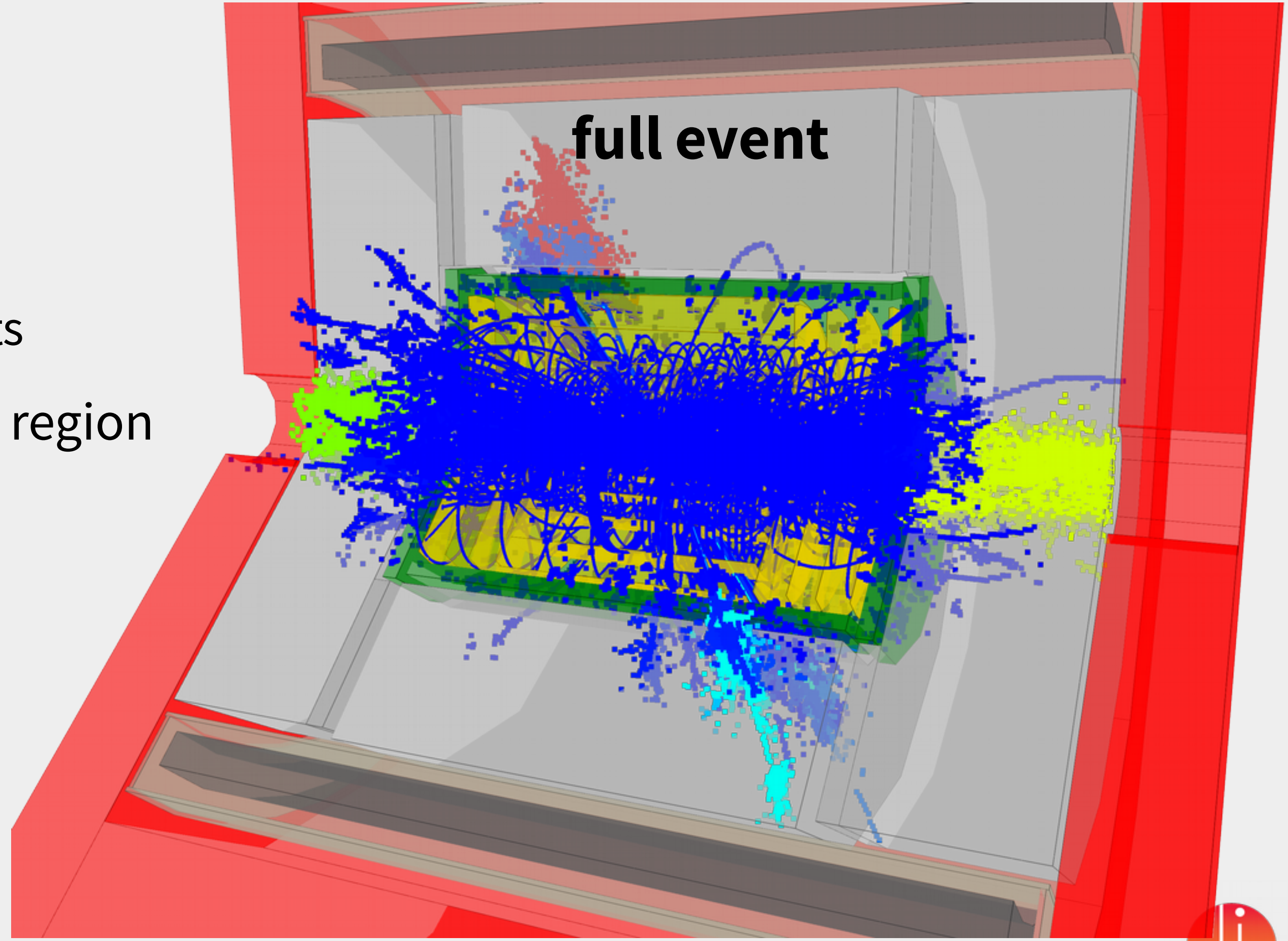

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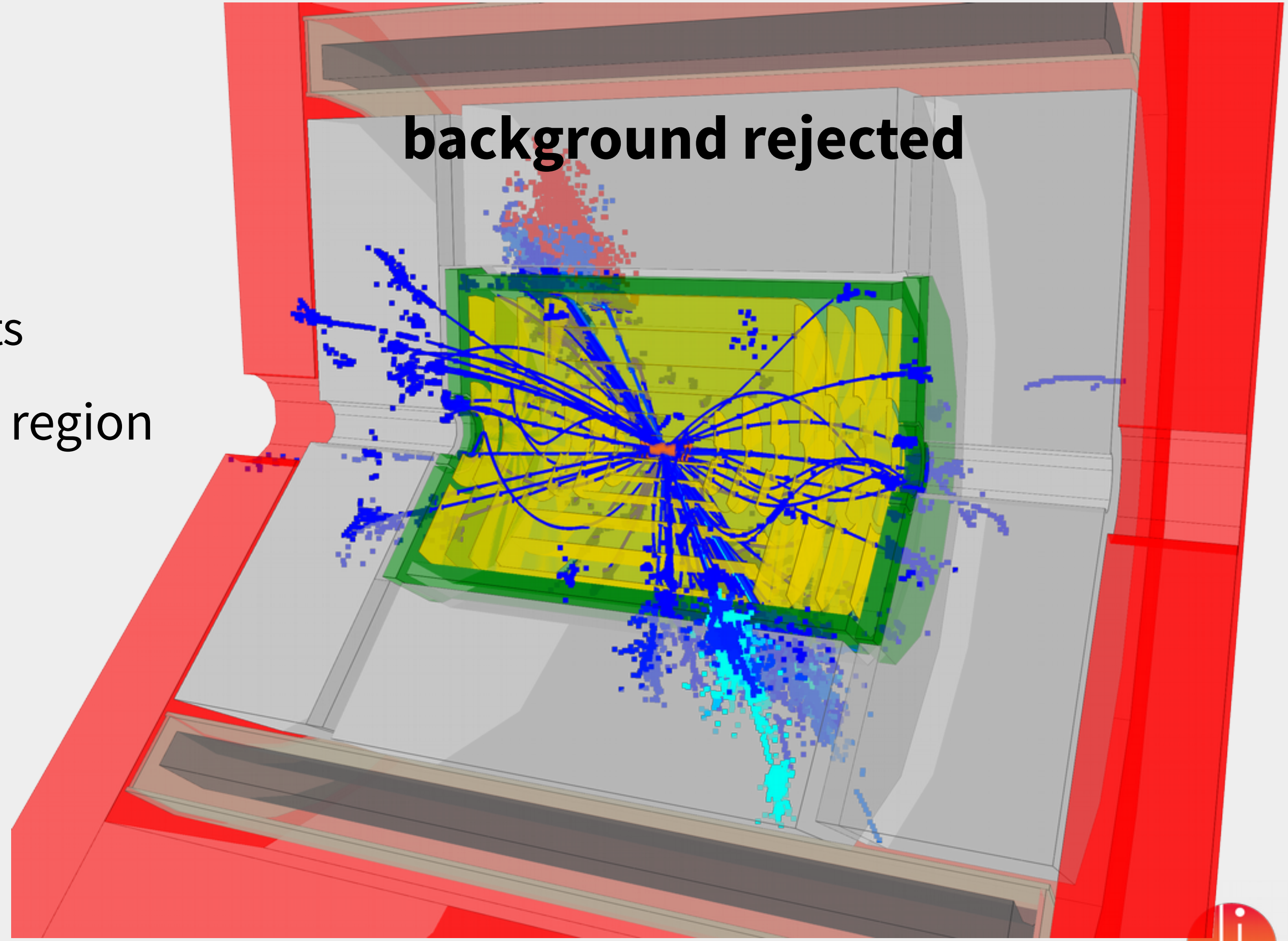
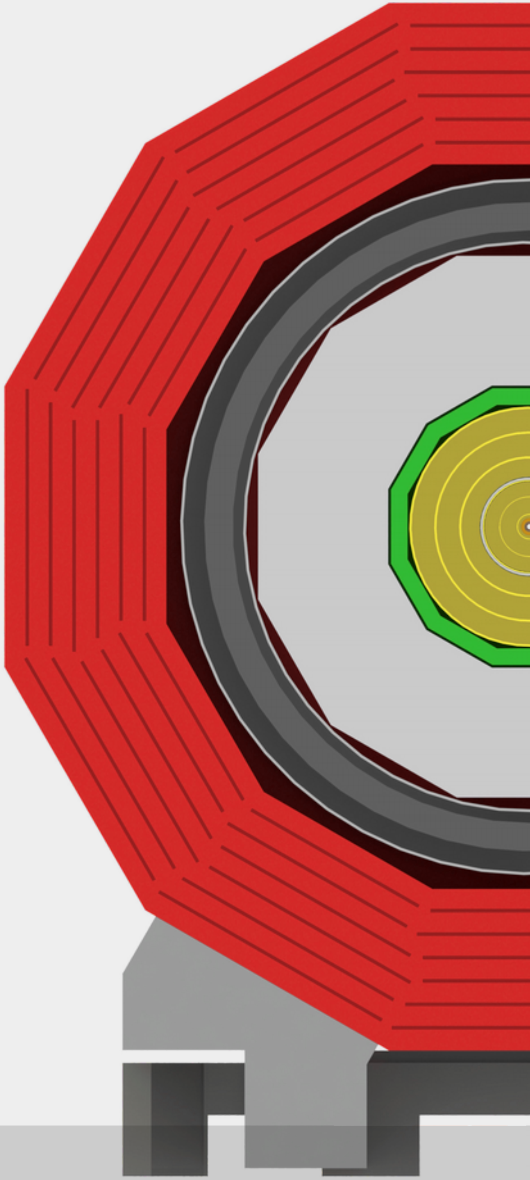
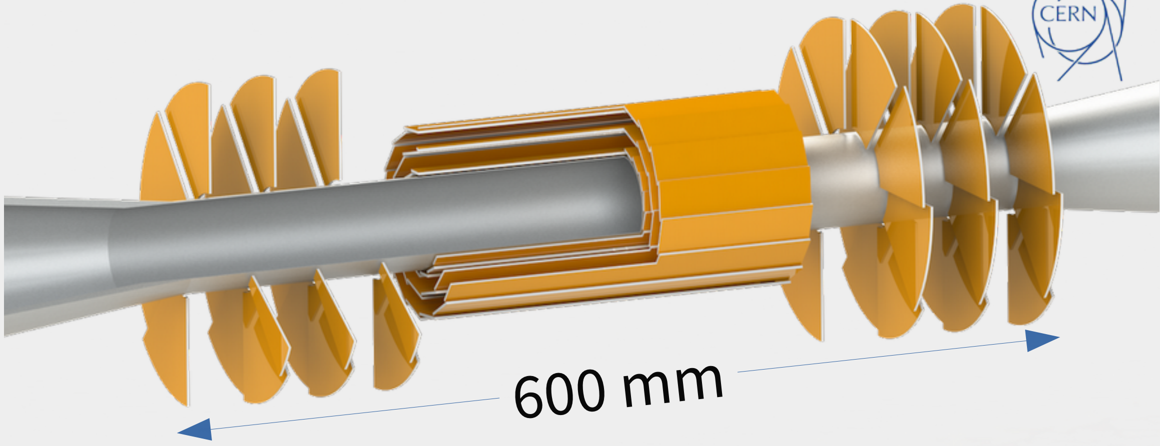


Detector Technologies
and Prototype Evaluation



Vertex Detector



Design driven by flavor tagging

- Minimal scattering
- High-resolution

Requirements

- **Low mass**
  0.2% X_0 per double 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 baseline design

- Hybrid pixel detectors, 25 µm pitch
- Double layers, 50+50 µm sensor+ASIC
- Surface area of ~ 0.84 m^2
- Three barrel layers
- Three spiral end disks per side

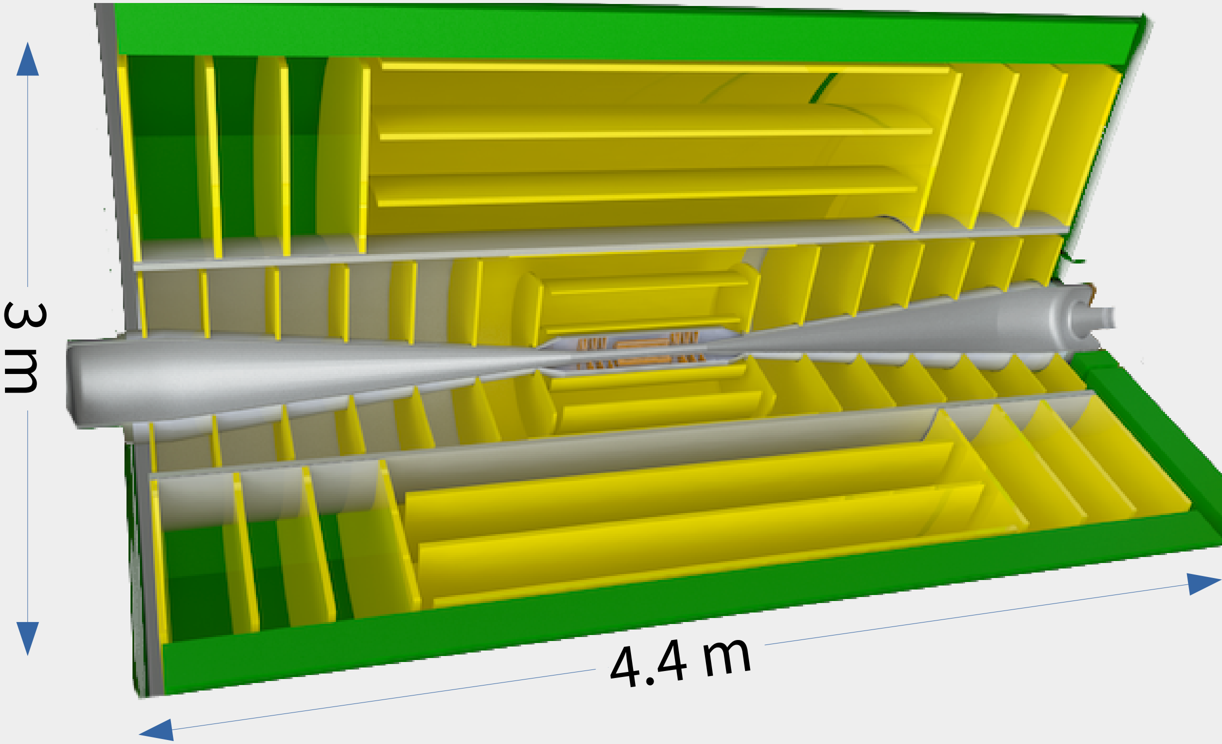
Tracking Detector

Design optimized for good momentum resolution

- Many layers
- Large lever arm

Requirements

- **Low mass, high rigidity**
  1 – 2% X_0 per layer
- **Good single-point resolution**
  $\sigma_{SP} \sim 7\ \mu m$
- **High granularity**
  few % occupancy from backgrounds



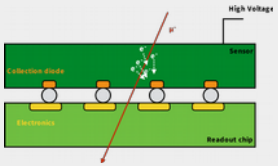
Current baseline design

- Strip or monolithic pixel detectors
- 200 µm sensor, including electronics
- Surface area of approx. 140 m^2

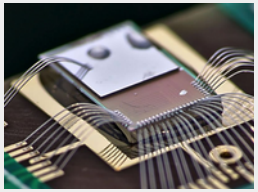
Silicon Technologies

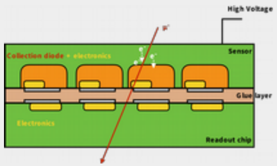
- Many different silicon detector technologies under investigation
  - Collaboration with other experiments (ALICE: HR-CMOS, ATLAS: HV-CMOS)
  - Some technologies dedicated to vertex, some considered for vertex & tracker

hybrid detectors

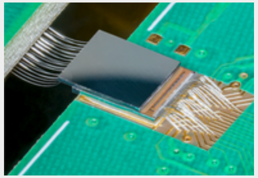


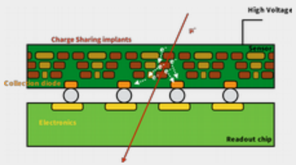
Hybrid



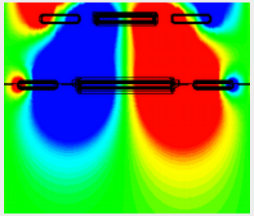


Capacitive

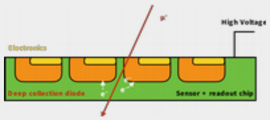




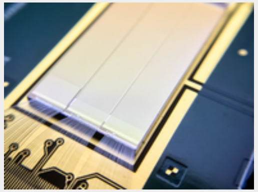
ELAD

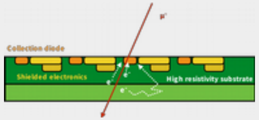


monolithic detectors

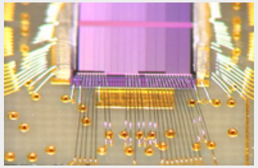


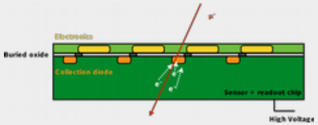
HV-CMOS



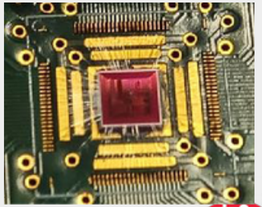


HR-CMOS

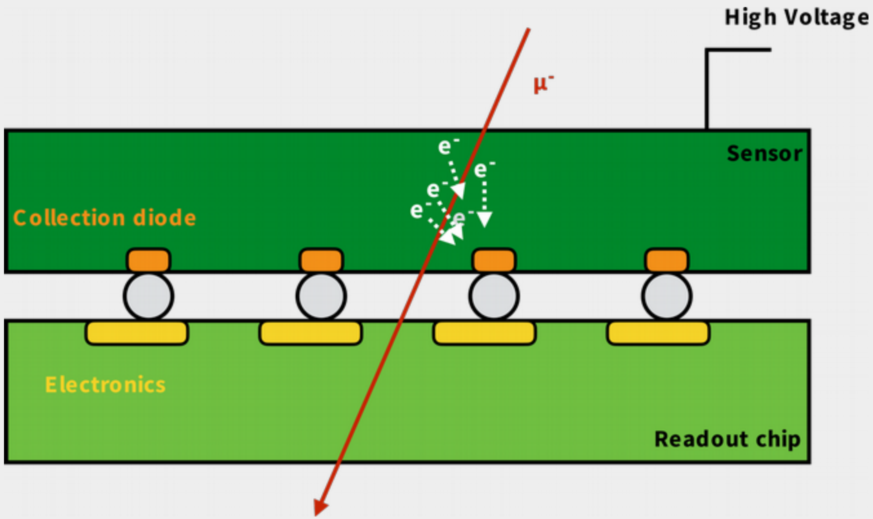




SOI



Hybrid Silicon Detectors



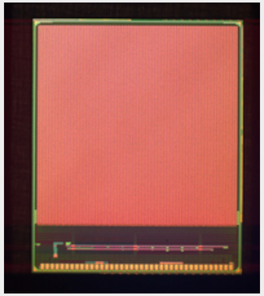
- Traditional design of HEP silicon pixel detectors: independent sensor/readout
  - Sensor contains pn-junction
  - Readout chip implements front-end
- Small pixel cell sizes achievable, down to 25 μm
- Different possibilities for interconnects: solder bumps, glue, ACF

Established mixed-mode CMOS
Complex circuits possible
Small technology nodes available

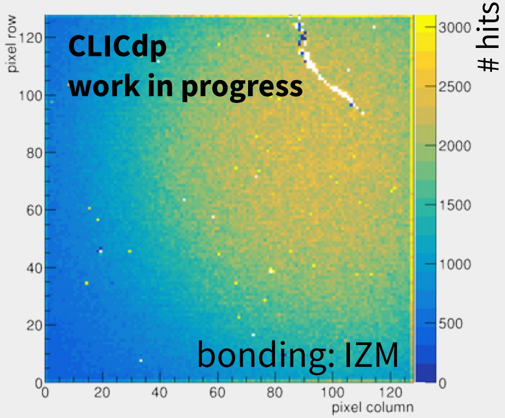
Relatively high material budget
Interconnects: cost-driver,
limits pixel pitch & thickness (stability)

Hybrid Prototypes

CLICpix2 + planar sensor



- Baseline: 50 µm thin planar silicon sensors
- Challenge: single-chip bump bonding at 25 µm pitch
- First successes with IZM, 130 µm thick sensor

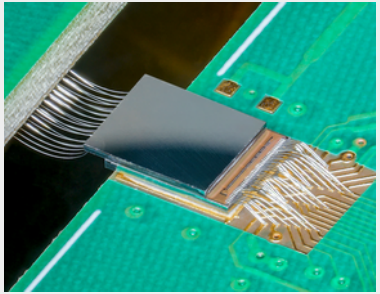


Good bonding yield
First assemblies tested in beam

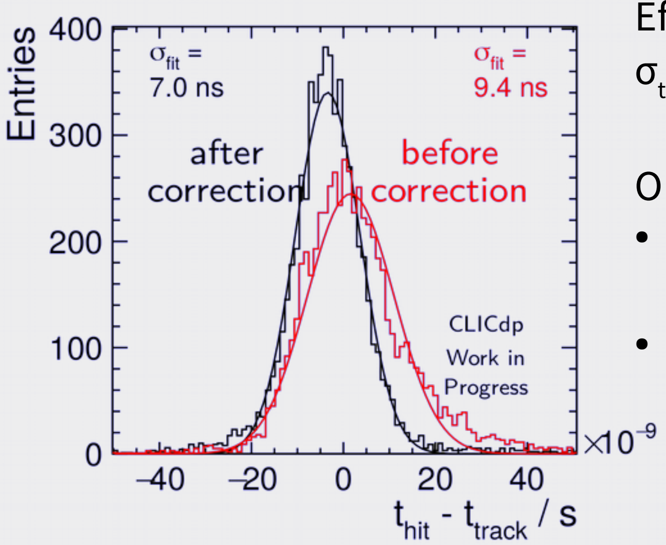
Ongoing:
- Sensor calibration
- Analysis of data
- Production of thin assemblies

CLICpix2 + C3PD

- Capacitively coupled
- Sensor fabricated in 180 nm HV-CMOS process



- Finite-element simulation of capacitive coupling

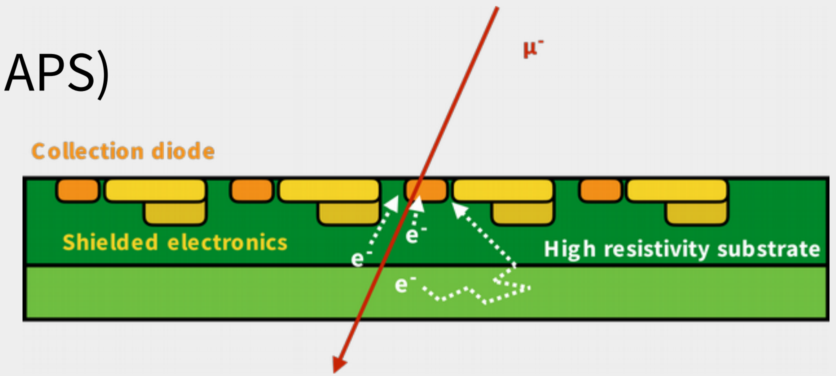


Efficiency > 90%
σ_t ~7 ns, σ_{SP} ~8 µm

Ongoing:
- optimization of gluing process
- Evaluation of high-resistivity wafers

Monolithic Silicon Detectors

- Depleted Monolithic Active Pixel Sensors (DMAPS)
  - Electronics and sensor on same wafer
  - Fully integrated: amplification & readout
- Shield electronics via additional implants
  - Deep collection diode surrounding electronics (large depletion, higher noise)
  - Separate shielding & collection diode (limits bias & depletion region)

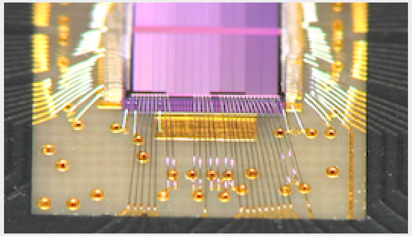


Lower mass than hybrids
No bump-bonding
Cheaper manufacturing

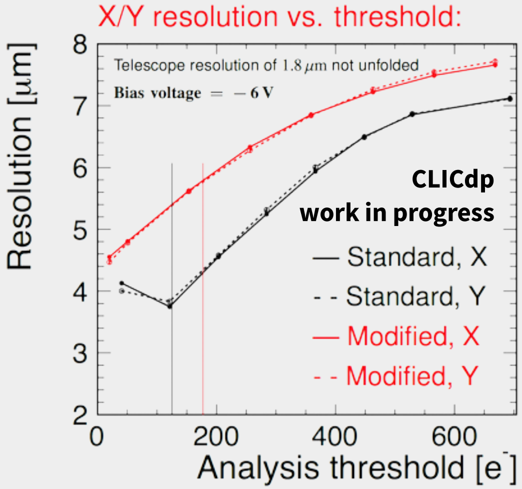
Smaller depletion volume & signal
Intricate sensor design
Limited in-pixel functionality

Monolithic Prototypes

ALICE Investigator



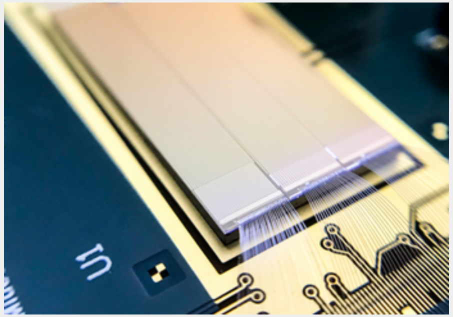
- Analog test chip for technology evaluation
- 180 nm HR-CMOS process
- Different pixel pitches & geometries



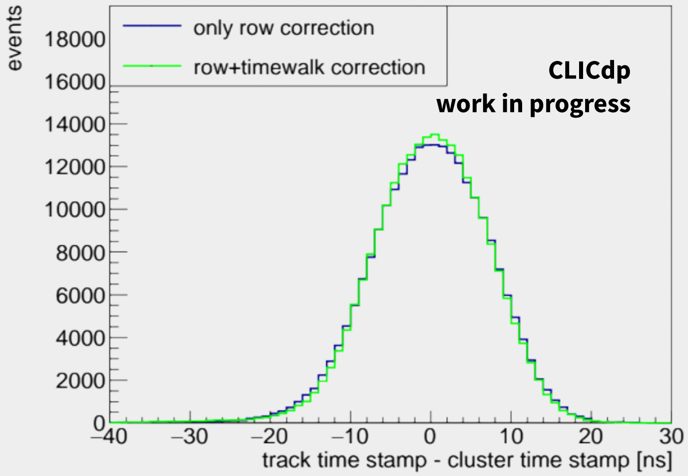
28 x 28μm^2 pitch: 99.3% efficiency, $\sigma_t < 5$ns, σ_{SP} ~4µm

CLIC-specific prototype **CLICTD** to be submitted

ATLASpix_Simple



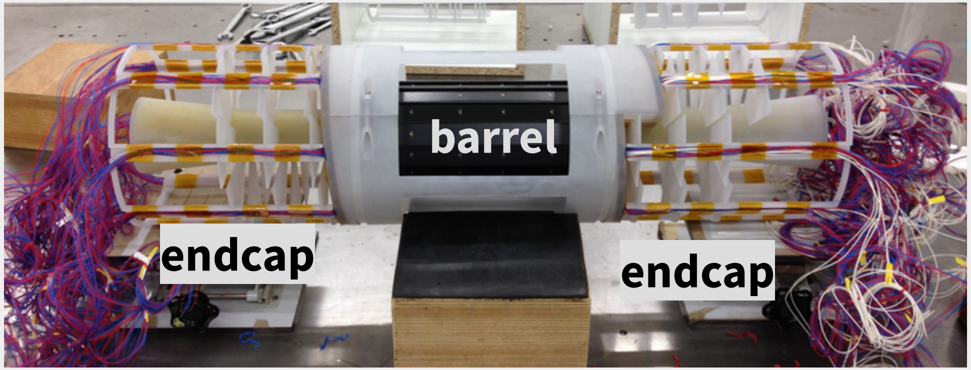
- Commercial 180nm HV-CMOS process
- Designed for ATLAS ITK Upgrade
- Timing performance investigated in test beams



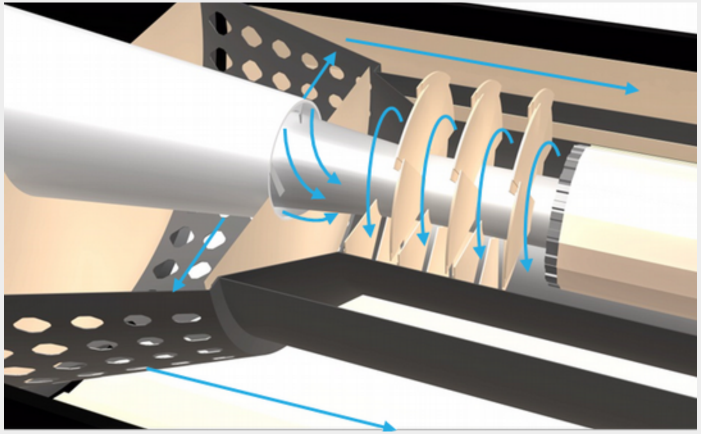
RMS = 6.9 ns at threshold = 490e

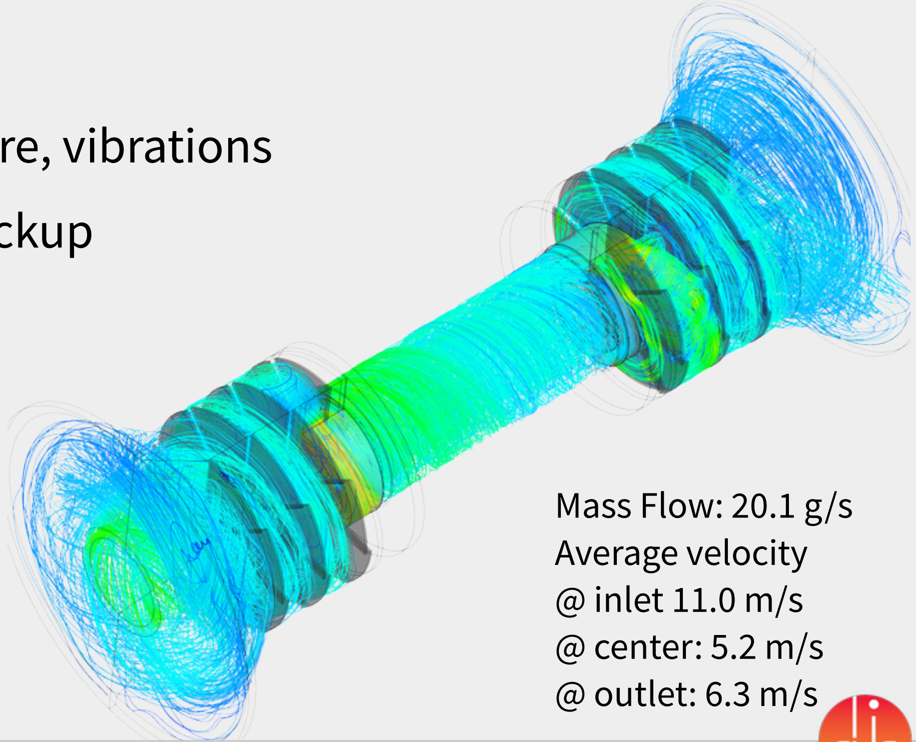
CLIC-specific prototype is being designed

Vertex Detector Air Cooling



- Vertex detector cooled with forced air flow for minimum material
- Spiral vertex disks allow air flow through detector
  - Simulation studies of air velocity, temperature, vibrations
  - Verification with 1:1 thermo-mechanical mockup

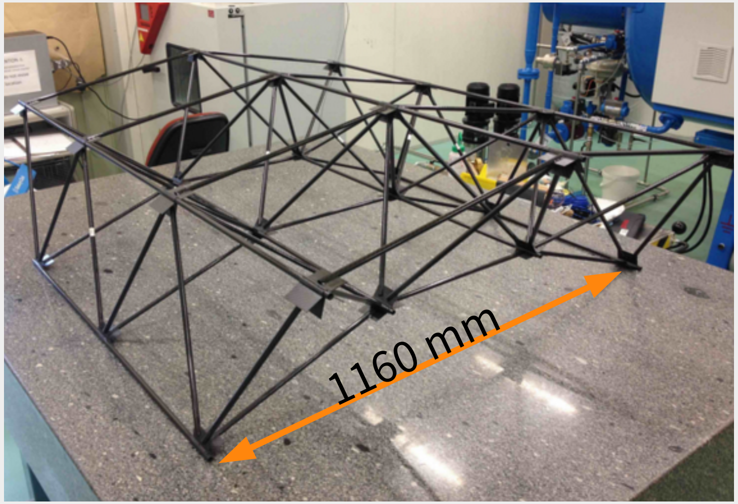


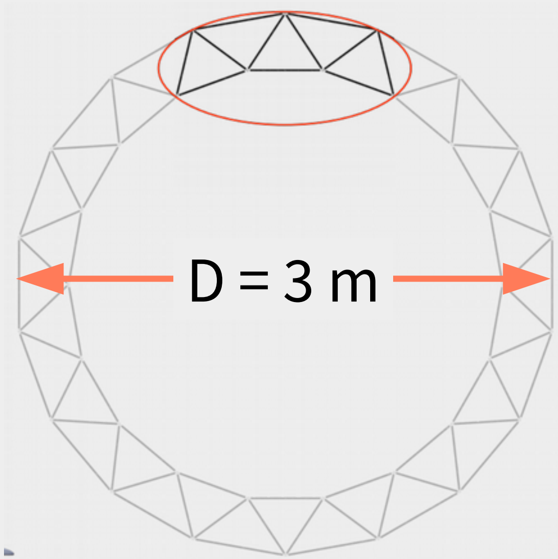


Mass Flow: 20.1 g/s
Average velocity
@ inlet 11.0 m/s
@ center: 5.2 m/s
@ outlet: 6.3 m/s

Lightweight Support for the Tracking Detector

- Proof-of-concept for light tracking detector mechanics
  - Confirm stability and material budget assumptions
  - Off-the-shelf carbon fiber tubes
  - Custom nodes developed and fabricated

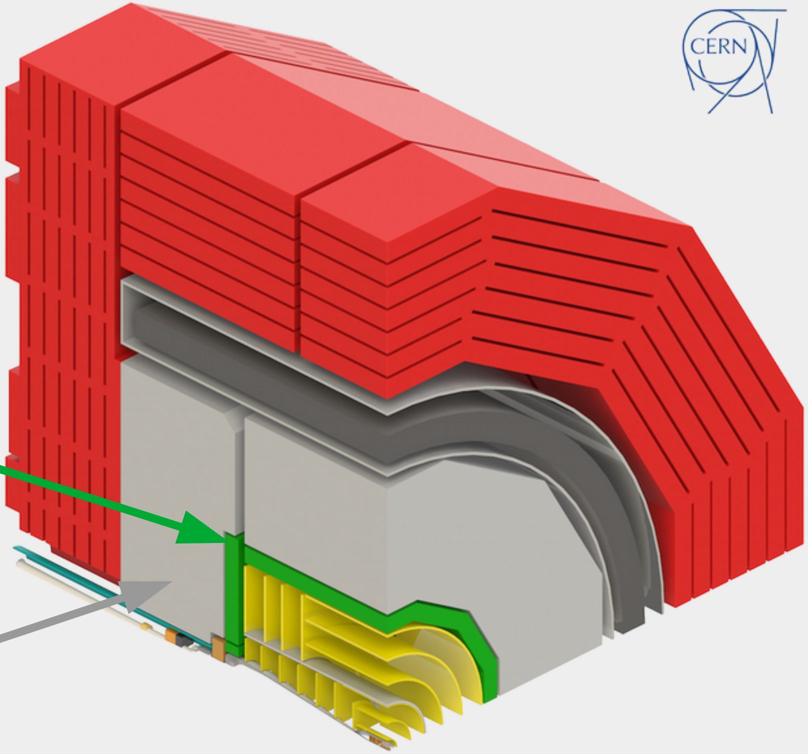




- Synergies with ALICE ITS upgrade's outer stave
- Stiffness achieved with low mass structure
- Total weight 926 g
  (70% tubes, 26% nodes, 4% glue)

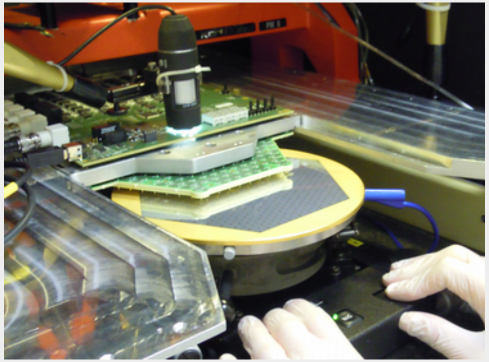
Calorimeters

- Jet energy resolution of $\sigma_E/E \sim 5 - 3.5\%$
  - Highly granular calorimeters required
- **Electromagnetic Calorimeter: Si-W**
  - 2 mm tungsten plates, 500 µm silicon sensors
  - 40 layers 22 X_0 or 1 λ_I, 5 × 5 mm² cell size
  - ~2500 m² silicon, 100 million channels
- **Hadronic Calorimeter: Scint-Fe**
  - 19 mm thick steel plates, interleaved with 3 mm thick plastic scintillator + SiPMs
  - 60 layers: 7.5 λ_I, 30 × 30 mm² scintillator cell size
  - ~ 9000 m² scintillator, 10 million channels / SiPMs



ECAL: CMS HGCal Prototype

- High-granularity calorimeter for CMS calorimeter endcap upgrade for HL-LHC
- Participating in R&D effort, test beams, module assembly
  - Silicon sensor, cell sizes 1 cm^2,
    CALICE-developed readout chip SKIROC2
  - Different absorbers for ECAL and HCAL parts (Cu, CuW vs. Fe)



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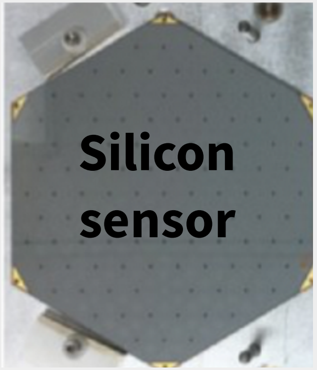

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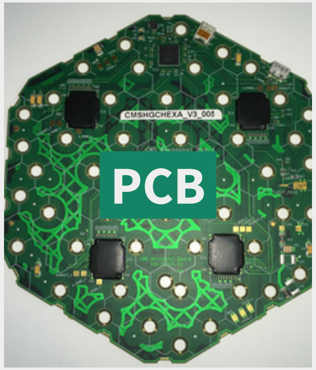

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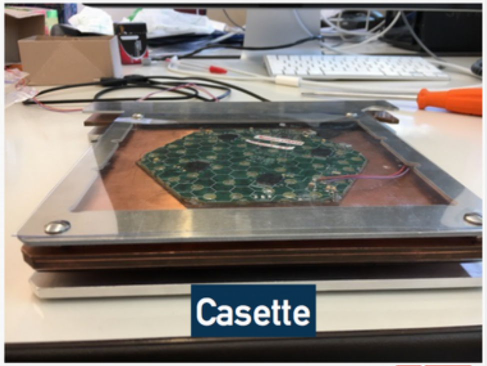
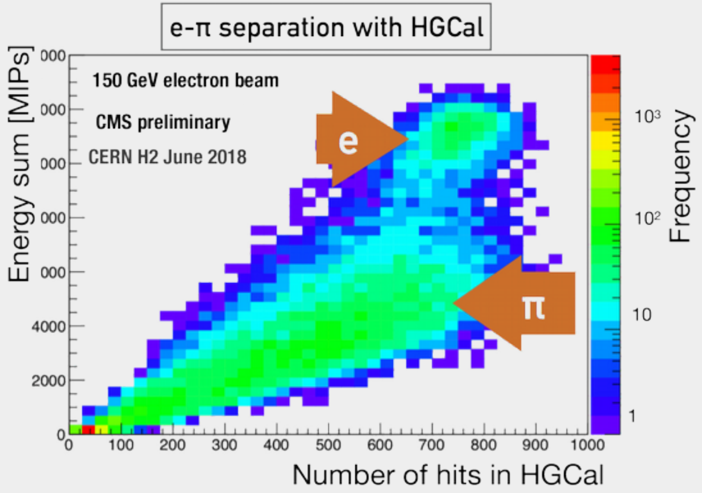
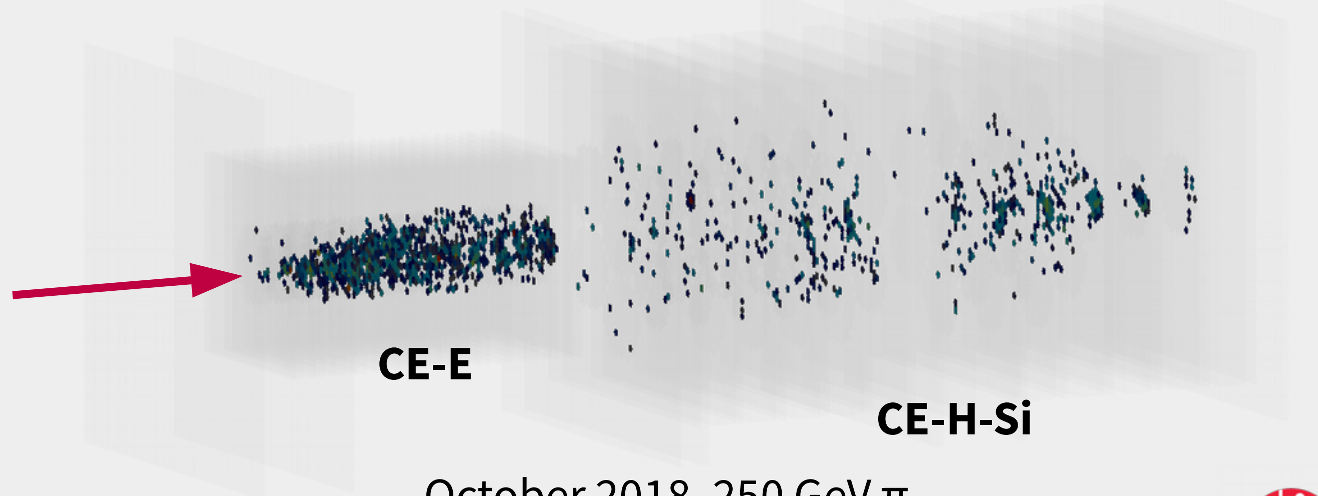


CMS HGCal Test Beam Results

- Enormous test beam efforts in 2018, including:
  - PCB tomography @ DESY
  - CE-E prototype @ SPS H2
  - Full CE-E + CE-H-Si prototype @ SPS H2
- Main objectives:
  - Technological prototyping of modules
  - First experience with FE ASIC
  - Evaluation of physics performance
  - Comparison with simulation

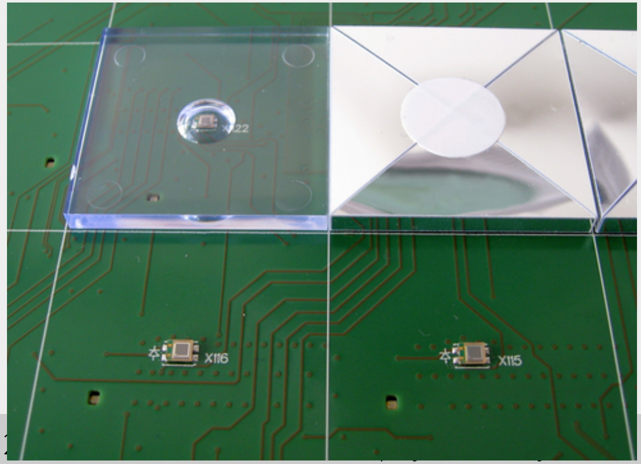




October 2018, 250 GeV π -

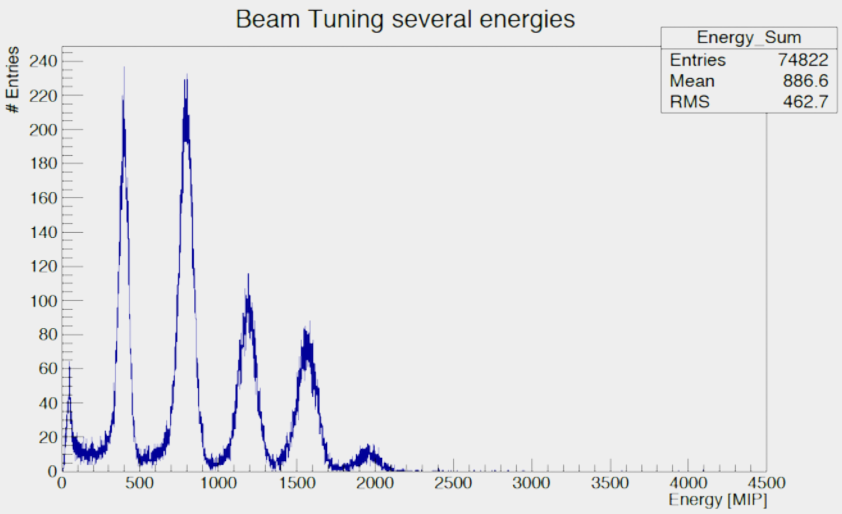
HCAL: CALICE AHCAL Prototype

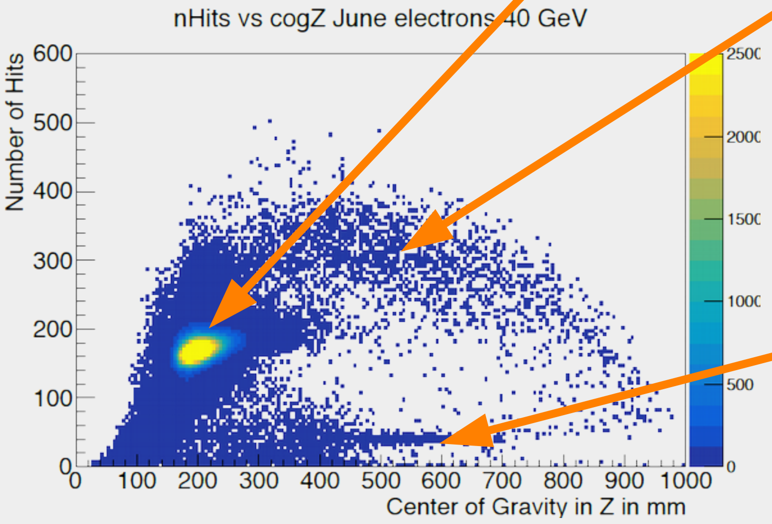
- Highly granular scintillator SiPM-on-tile HCAL
  - 3 x 3 cm^2 scintillator tiles, fully integrated design
  - 38 active layers of 72 x 72 cm^2 in steel absorber
  - Automatic temperature compensation for SiPMs
- Design optimized for mass production:
  - Automatic SMD SiPM soldering
  - Injection-molded polystyrene tiles
  - Automated wrapping in reflector foil

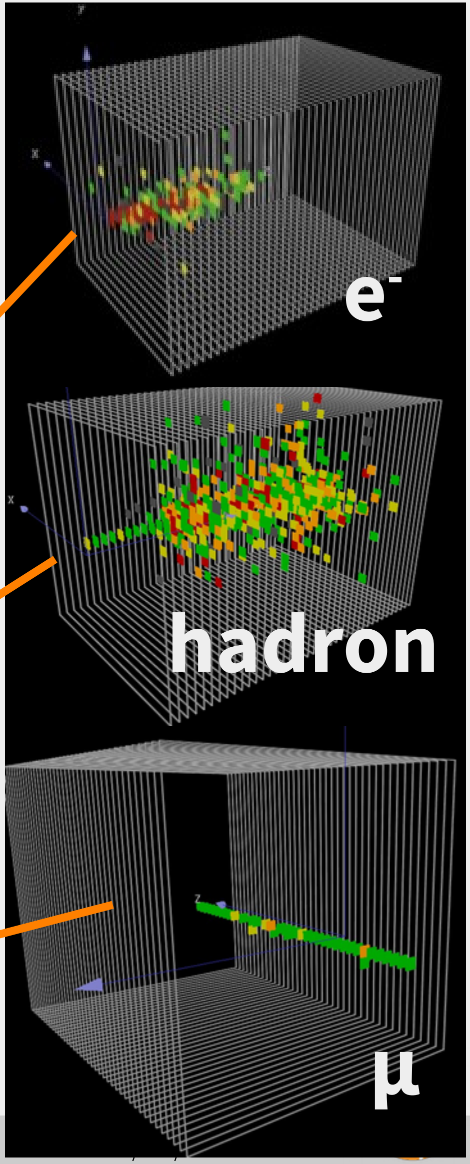


AHCAL Prototype Test Beam Results

- Many test beam campaigns in 2018 at SPS H2 beam line
  - Calibration with muons, energy scans for e-, π
- Prototype can resolve spatial and temporal development of hadronic showers in detail

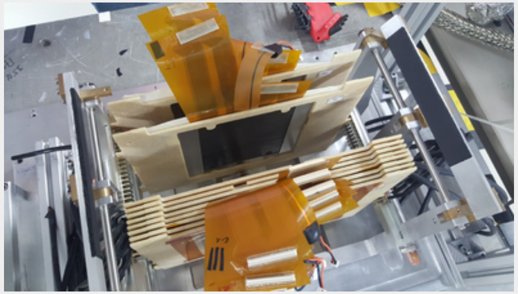


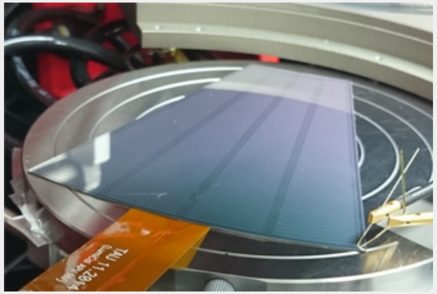


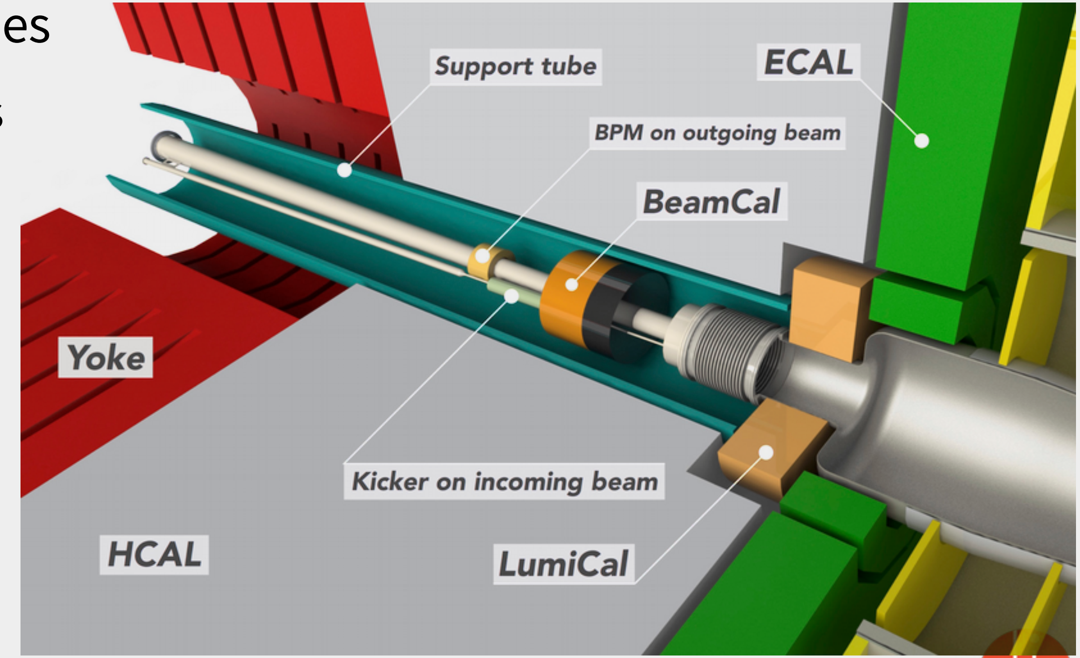


Forward Instrumentation: BeamCal & LumiCal

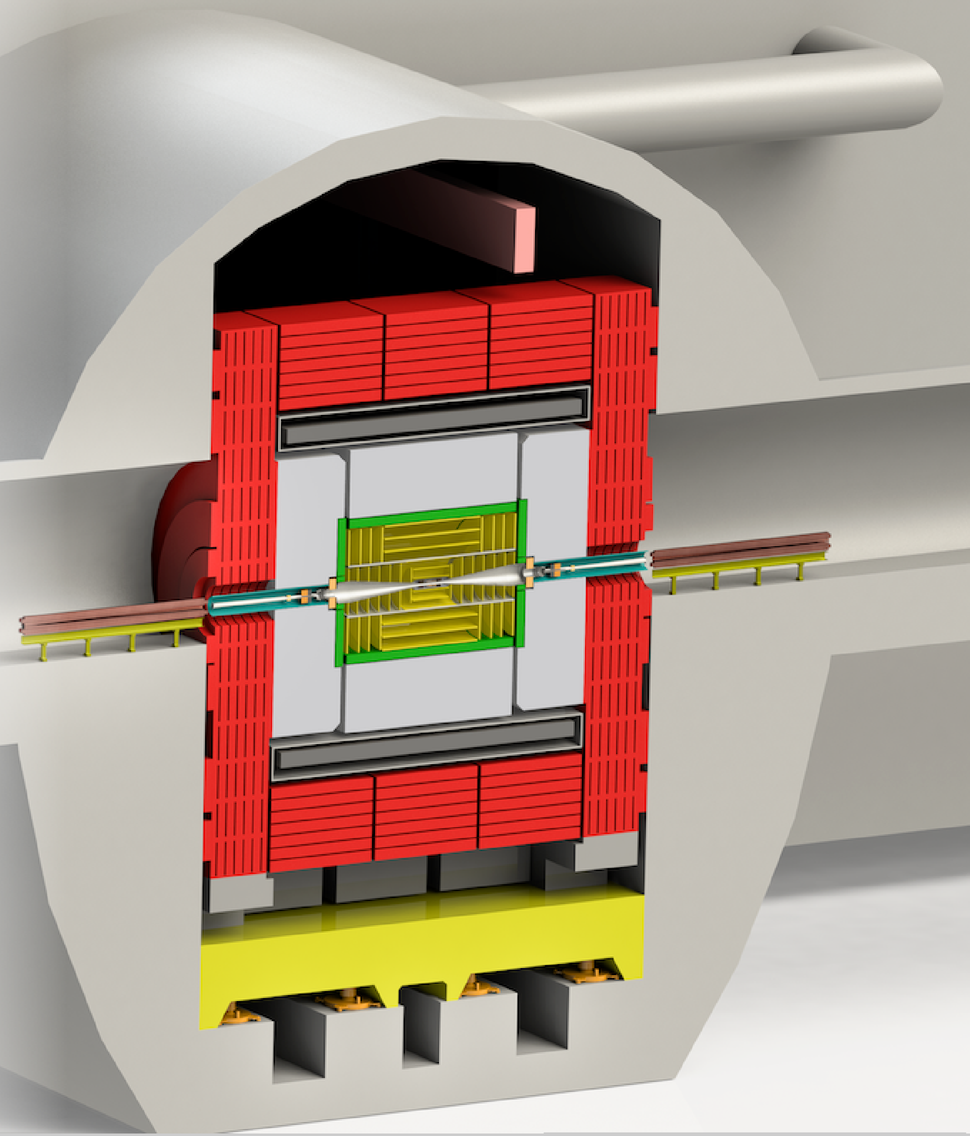
- Very forward electromagnetic calorimeters
  - **LumiCal** for luminosity measurement via Bhabha scattering (few per mille accuracy)
  - **BeamCal** for very forward electron tagging (for beam tuning)
- e and γ acceptance down to small angles
  - Compact design, small Molière radius
- Current baseline:
  - BeamCal: GaAs, LumiCal: silicon







Performance Studies
and Detector Design Validation



Performance Studies & Validation

- Continuous improvements of simulation & reconstruction software
  - **DD4HEP** for geometry description, others are on the move: LHCb, CMS…
  - **DELPHES** card available in their official repository
    - Three cards for the different CLIC stages

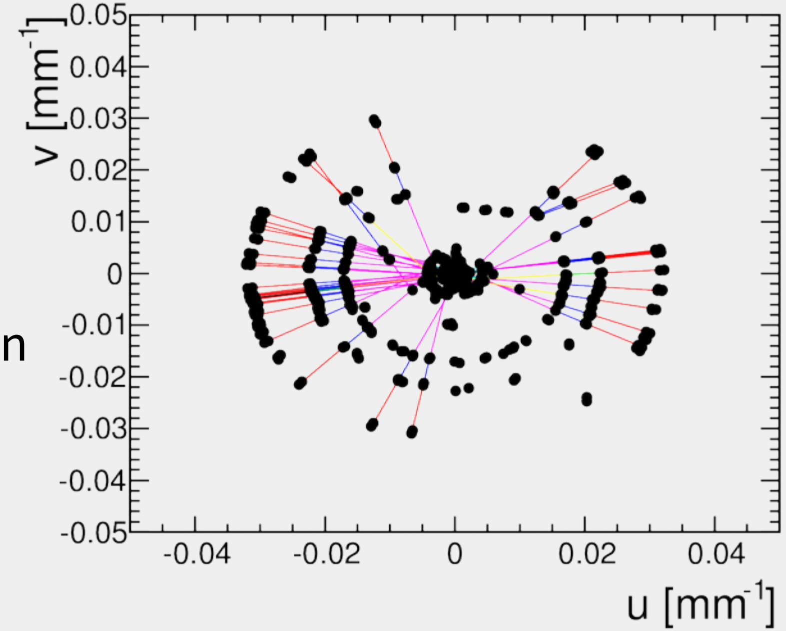
- Main Talk on performance studies by M. Weber:
  "Detector Performance at CLIC"
- Document with comprehensive performance studies published:
  "A detector for CLIC: main parameters and performance"

Tracking

- Tracking based on conformal transformation:

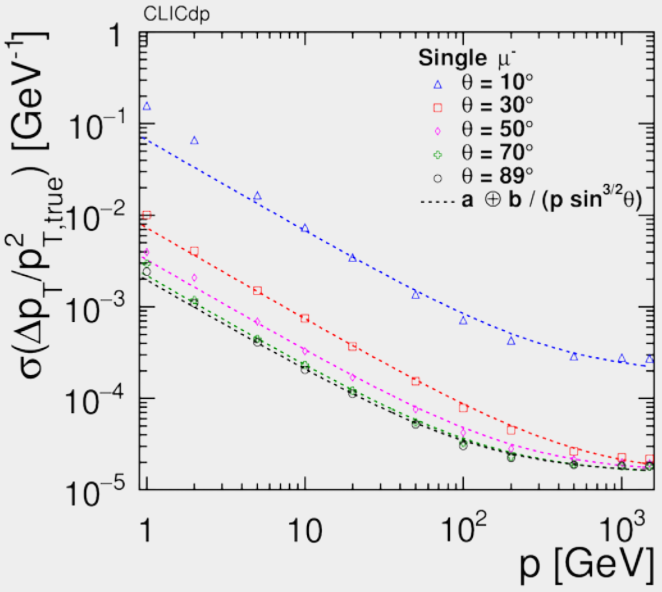
  "maps circles passing through the origin onto straight lines"

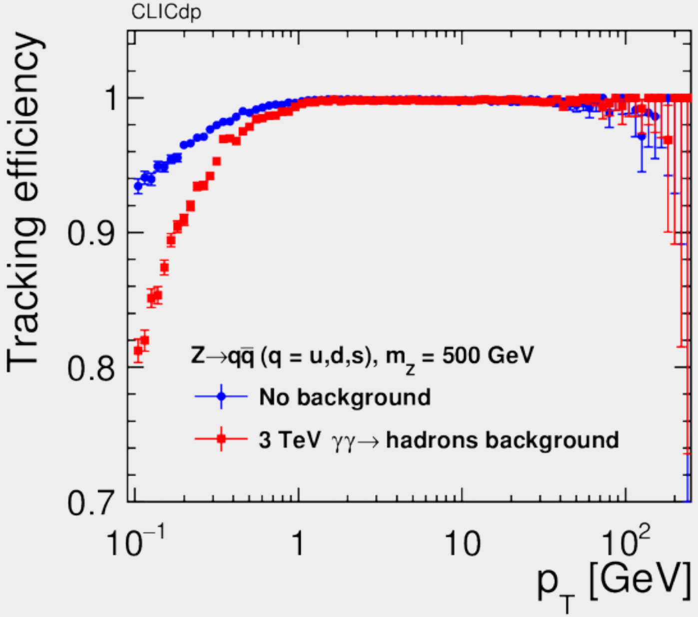
  - Pattern recognition: straight line search with cellular automaton (robust against noise…)
  - Additional fit in z-s (along helix) for 3rd coord.
- Displaced tracks do not go through origin
  - Apply second-order corrections to transformation
  - Adapt search parameters and order
- Kalman-filter based fit of reconstructed tracks

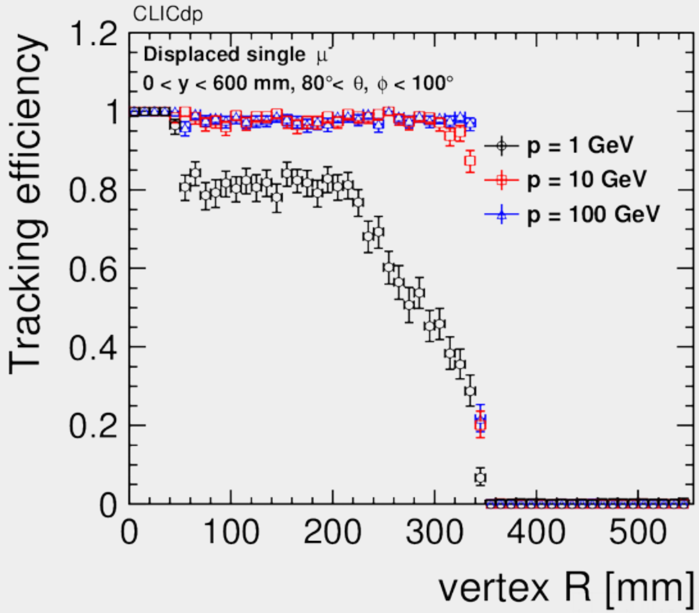


CLICdet Tracking Performance

- Achieved momentum resolution 2 x 10^{-5} GeV^{-1} for high energy muons in the barrel
- Tracking efficiency very high, negligible impact of background particles > 1 GeV
- High efficiency for displaced tracks within acceptance (min. 5 tracker hits required)



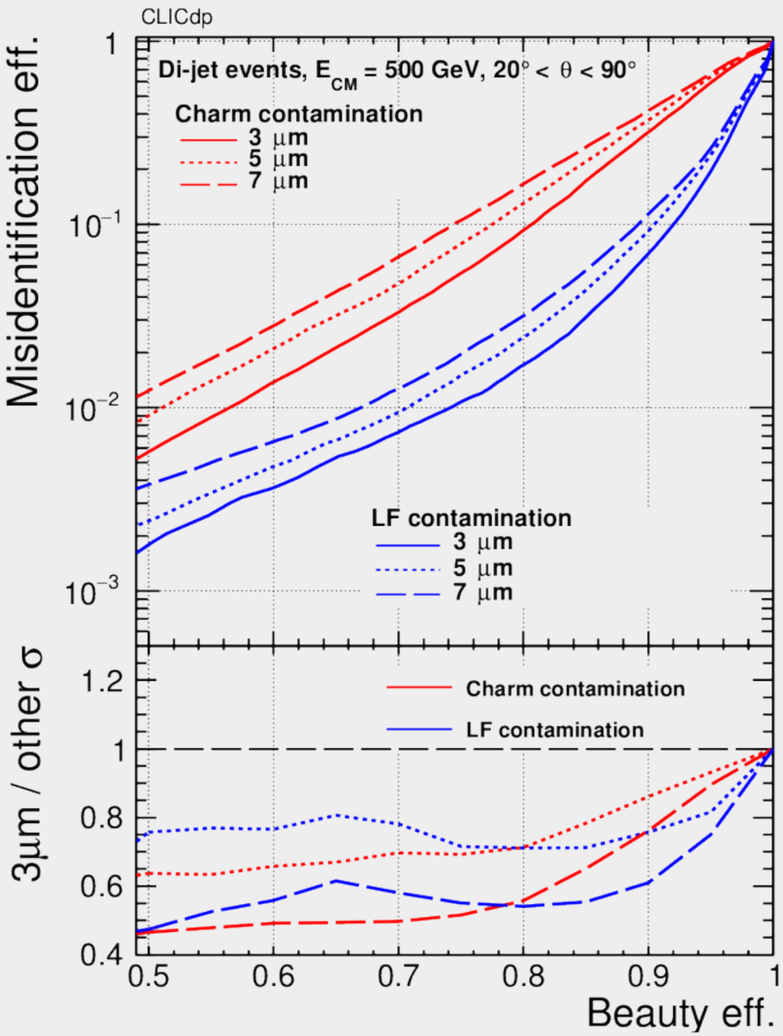




Flavor Tagging Performance

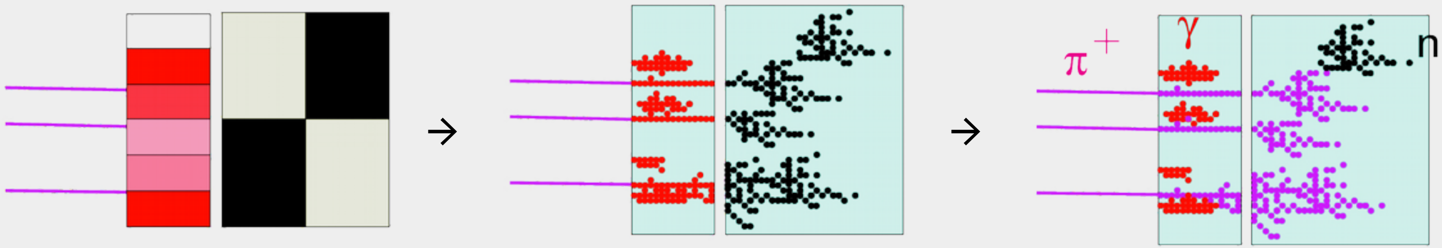
- Several studies on flavor tagging efficiencies performed, to be found in performance note

- Performance for different vertex detector single-point resolutions
  - Using di-jet samples, E_{CM} = 500 GeV
  - Varying vertex detector resolution: 3 µm (nominal) → 5 µm → 7 µm
  - Flavor tagging efficiency deteriorates as expected

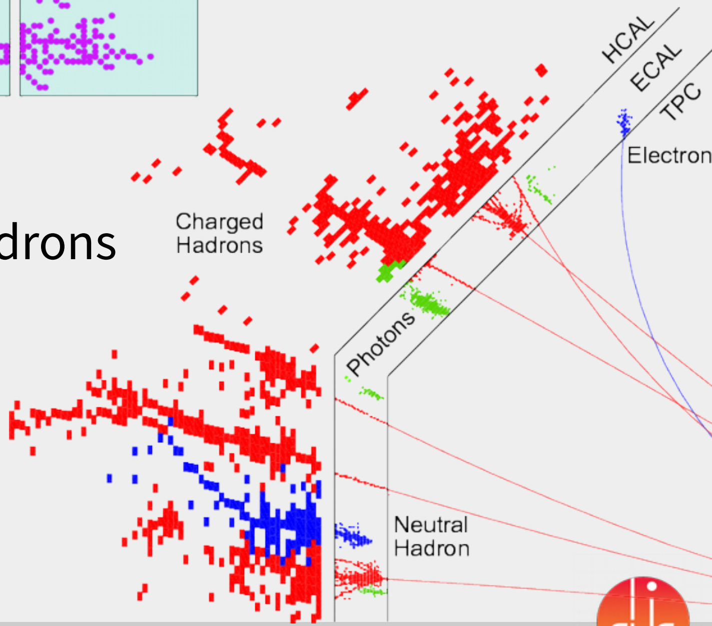


Jet Reconstruction & Particle Flow Algorithm

- Calorimeter clusters reconstructed via particle flow by **PandoraPFA**
  - Uses reconstructed tracks and muon hits to match calorimeter hits

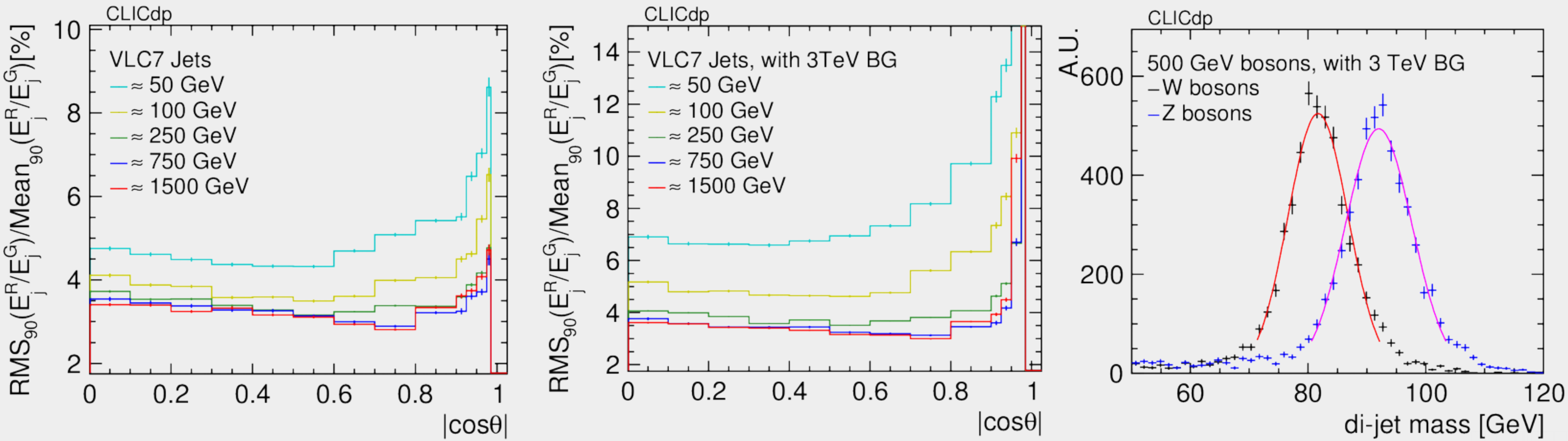


  - Requires highly granular calorimeter detectors
  - Software compensation: improve energy meas. of hadrons
- Jets formed using Valencia algorithm with R = 0.7
- Dedicated note:
  "Jet performance at CLIC" (CLICdp-Note-2018-004)



Jet Energy & Missing E_T Resolution

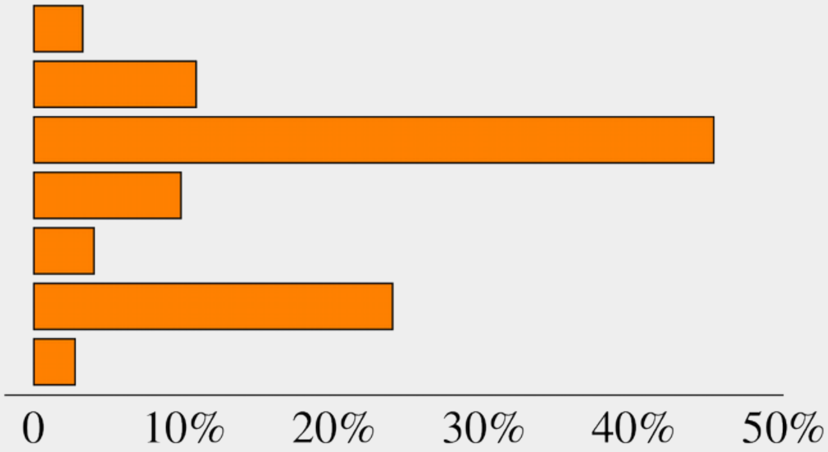
- Jet energy resolution from $Z/\gamma^* \rightarrow qq$, reconstructed and MC truth particle jets
  - Impact from 3 TeV backgrounds especially for low-energy jets, resolution 6-8%
- Di-jet mass: 2σ separation with VLC7 jets, including 3 TeV backgrounds



Cost Estimate for the CLIC Detector

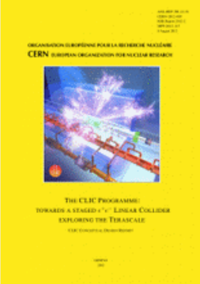
- Based on detailed detector work breakdown structure
- Main cost driver: silicon sensors for electromagnetic calorimeter
- Example: 25% cost reduction of silicon per unit of surface → overall detector cost reduction by > 10%

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
Total		397



Summary Documents

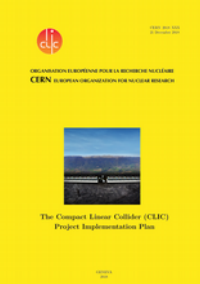




2012 CLIC Conceptional Design Report

- 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

CLIC Potential
for New Physics

Detector technologies
for CLIC

2018 Documents for the European Strategy Update

- CLIC 2018 Summary Report
- CLIC Project Implementation Plan [draft]
- The CLIC Potential for New Physics
- Detector technologies for CLIC [in review]

Summary & Outlook

- CLIC offers opportunity for broad precision physics program
- Detector model CLICdet optimized and validated
- Broad and active R&D on vertex and tracking detectors
  - Focus on technologies to simultaneously fulfill all CLIC requirements
- Contributions to CALICE and FCAL calorimeter R&D collaborations
  - High-granularity ECAL and HCAL prototypes constructed and tested
- The CLICdp Collaboration has prepared comprehensive documentation on physics program, detector design and R&D activities
- Summaries have been submitted to the European Strategy Update for Particle Physics

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

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

CERN

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