http://clicdp.cern.ch

# The CLIC detector and physics study
## An Overview

**Simon Spannagel, CERN**
on behalf of the CLICdp Collaboration

CLIC Workshop
CERN, 21 – 25 January 2019

# The *CLIC detector and physics* Collaboration

Collaboration with

- 30 institutes
- 159 members

formed to carry out

- physics studies
- detector technology R&D

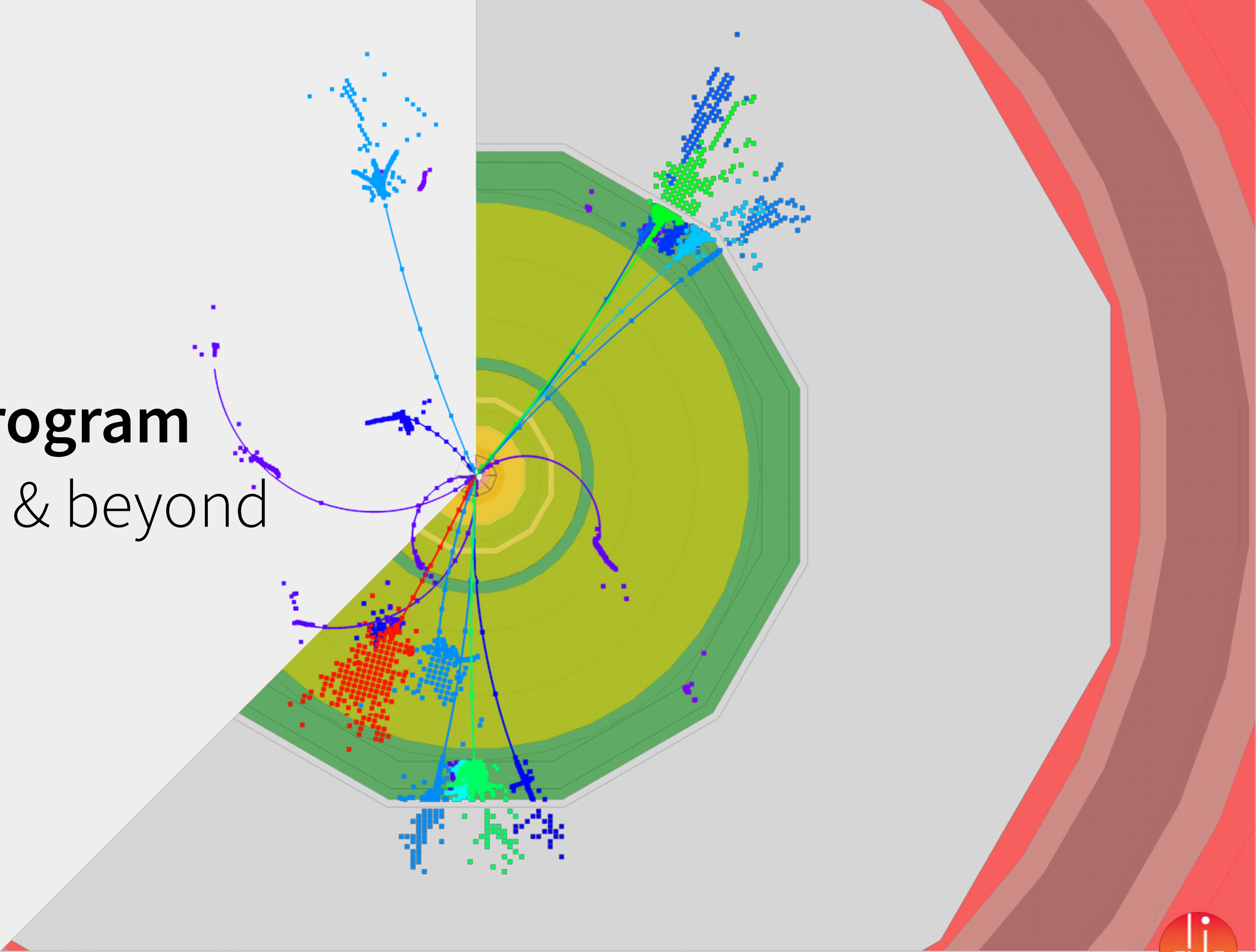
**Close collaboration** with other R&D / LC projects such as CALICE, FCAL
as well as AIDA-2020 and LHC experiments


# Outline

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

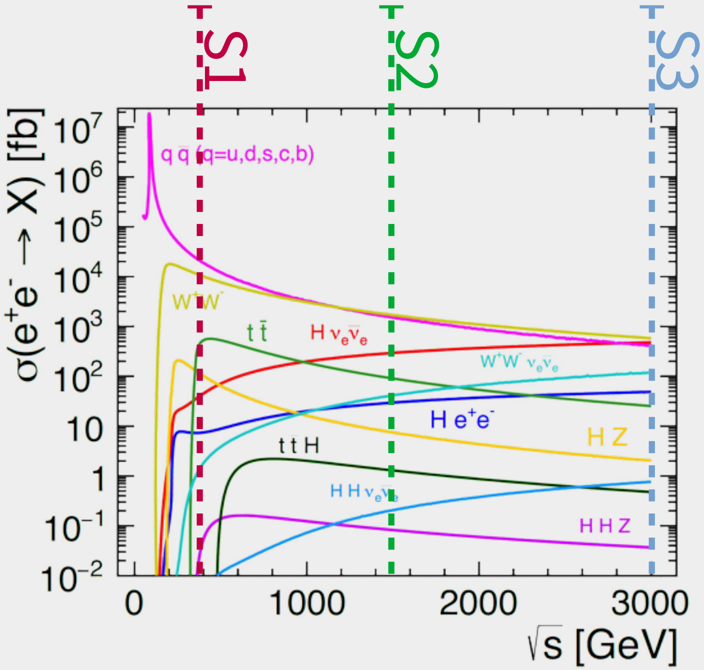
# CLIC Physics Program

Standard Model & beyond



# CLIC Physics Program – in 3 Stages

- Dedicated CLICdp Physics session in this workshop (Wed. & Thur.)
- Talk by F. Riva in this session:
  "Precision Physics and motivations for a high energy LC"




**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 $ab^{-1}$)**

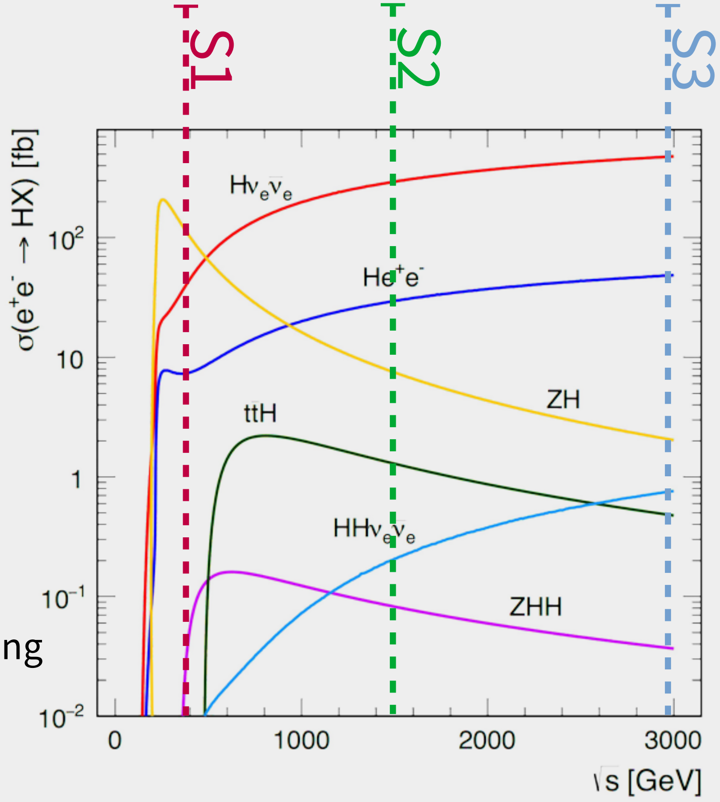
- Focus: BSM searches
- Higgs/top precision physics

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

- Focus: BSM searches
- Higgs/top precision physics

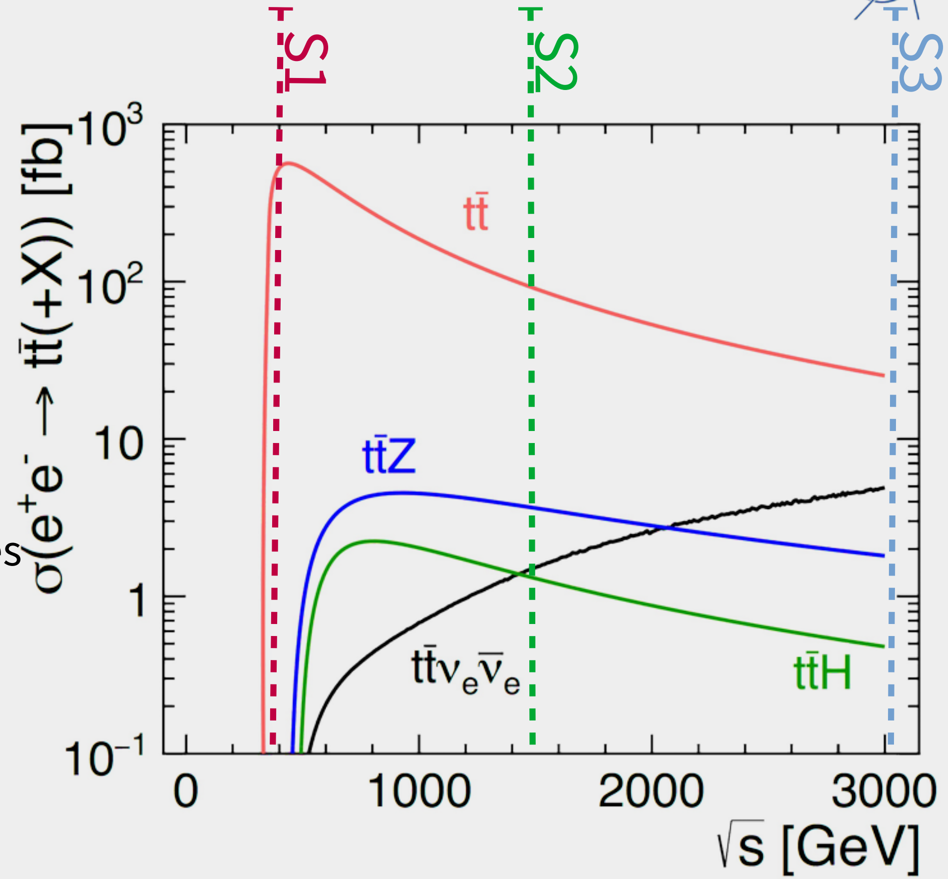
# Higgs Physics

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



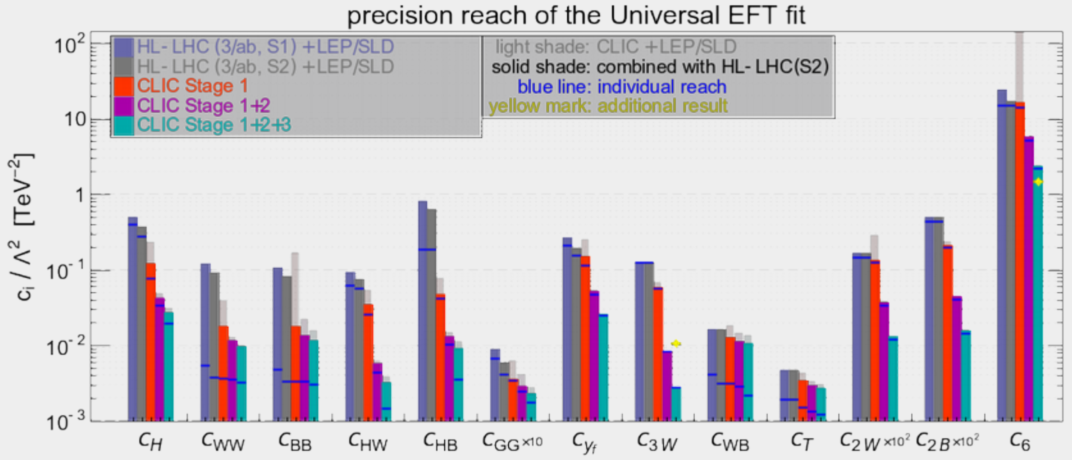
# Top-Quark Physics

- Initial stage: focus on
  - top-quark pair production
  - 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
  - Combine measurements in global fits
- **Detailed paper in journal review:** "Top-Quark Physics at the CLIC Electron-Positron Linear Collider"



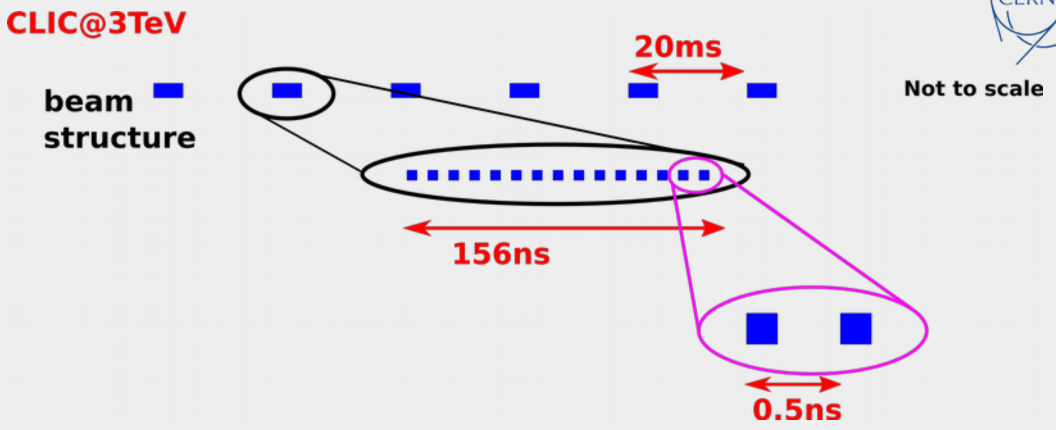
# Beyond-Standard-Model Physics

- **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
- EFT fits combining measurements, talk by F. Riva




- **Comprehensive report published:** "The CLIC Potential for New Physics"

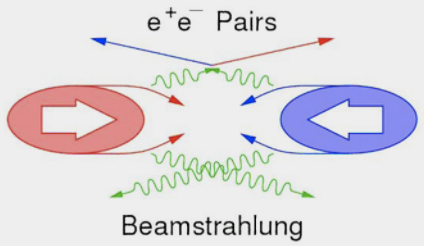
# Experimental Conditions

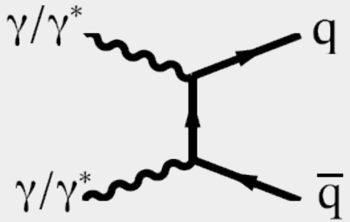


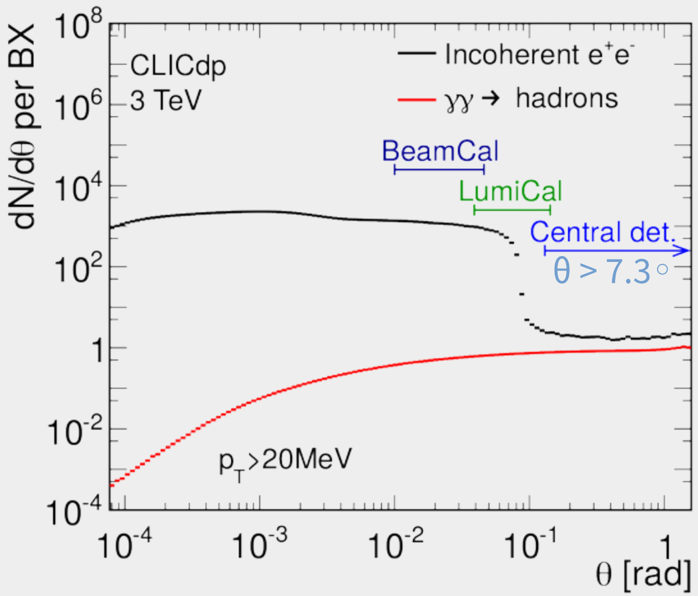

- CLIC operates in bunch trains, repetition rate of 50 Hz
  - Low duty cycle
  - Possibility for power pulsing:
    switch detector components off between trains to reduce heat dissipation
- 312 bunches within train (at 3 TeV), separated by 0.5 ns
- Bunch separation & cross-section of background events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

# Beam-induced Backgrounds

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



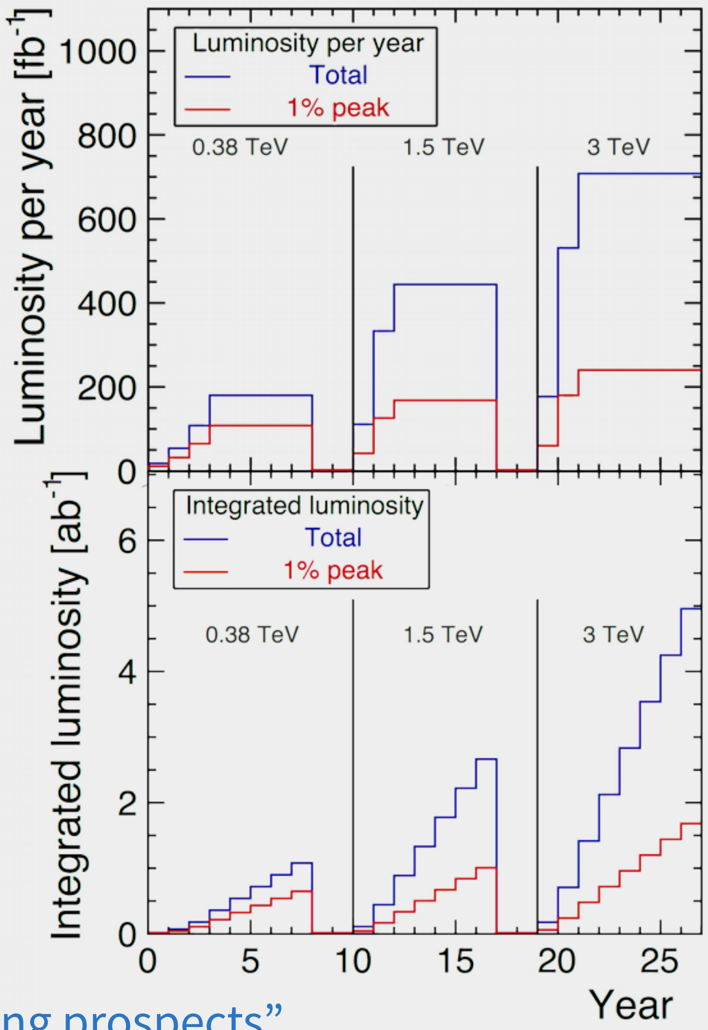




Main backgrounds in detector acceptance:

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

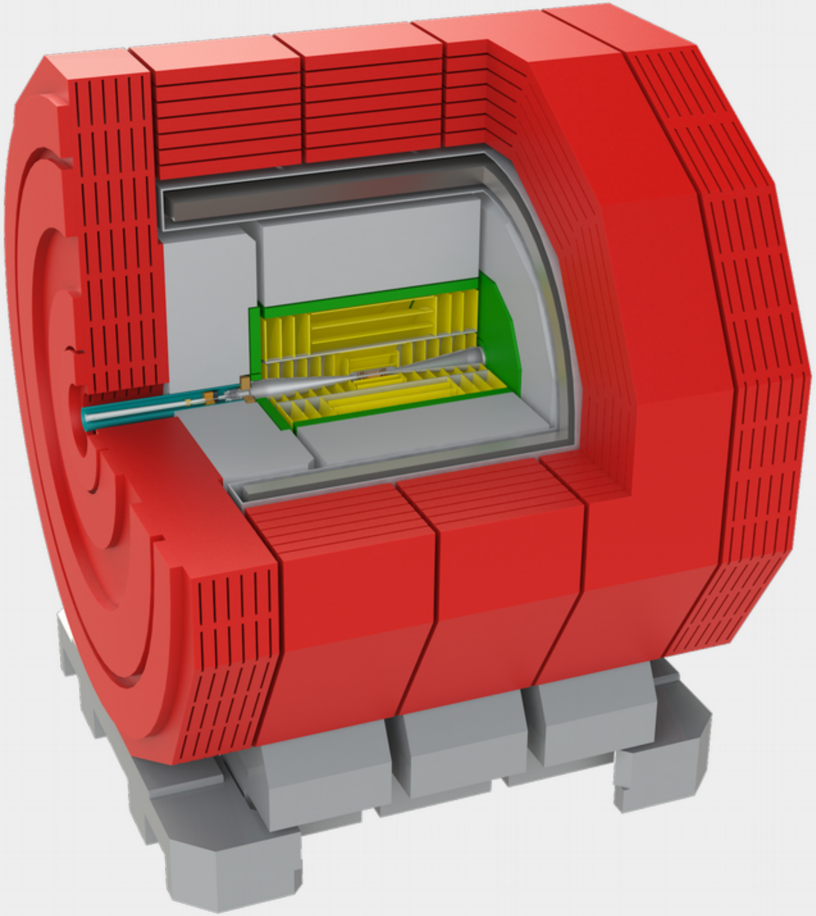
# Integrated Luminosity

- Updated projections for luminosity
  - Harmonized with other future collider projects
  - Based on 185 days of physics operation per year
  - Luminosity ramp-up at beginning of each stage
- ±80% longitudinal polarization for the electron beam
- 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 $ab^{-1}$
- Document published:
  "Updated CLIC luminosity staging baseline and Higgs coupling prospects"



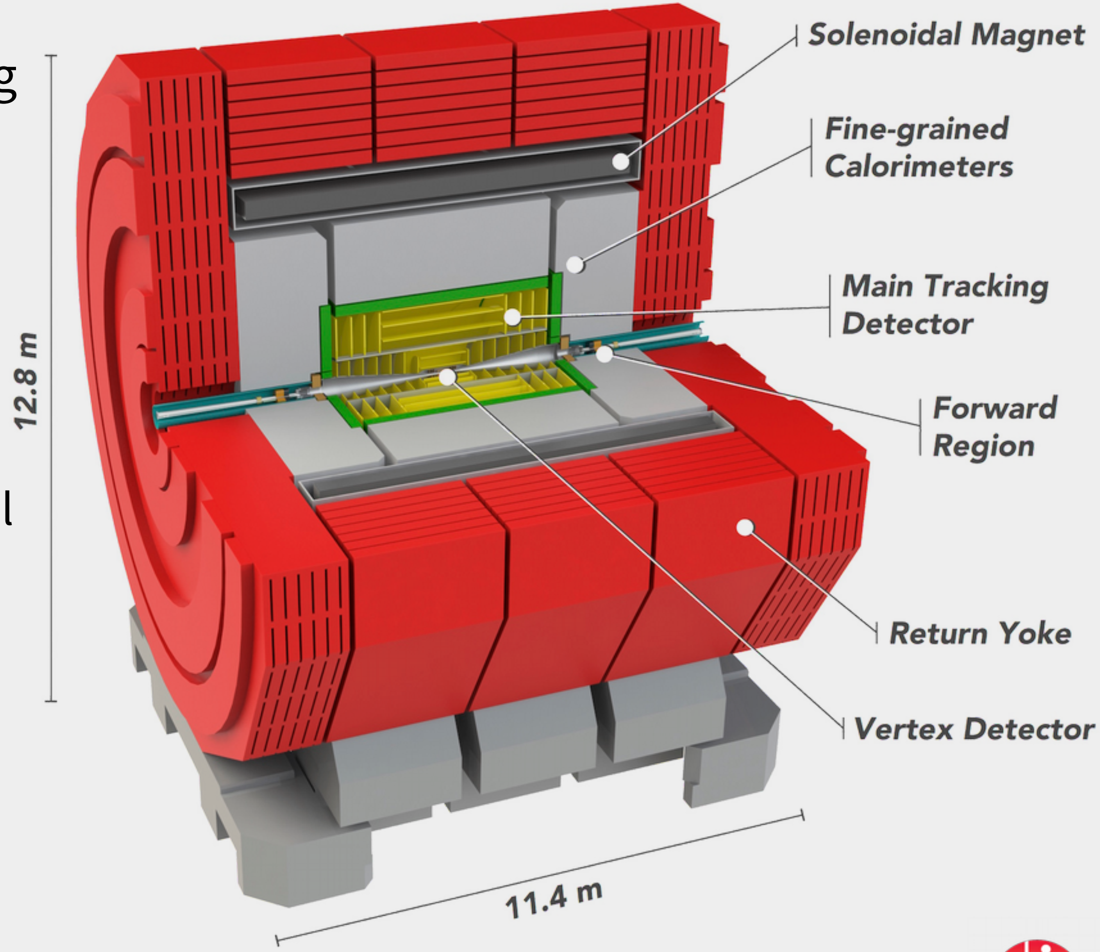
# CLICdet

the CLIC detector Concept



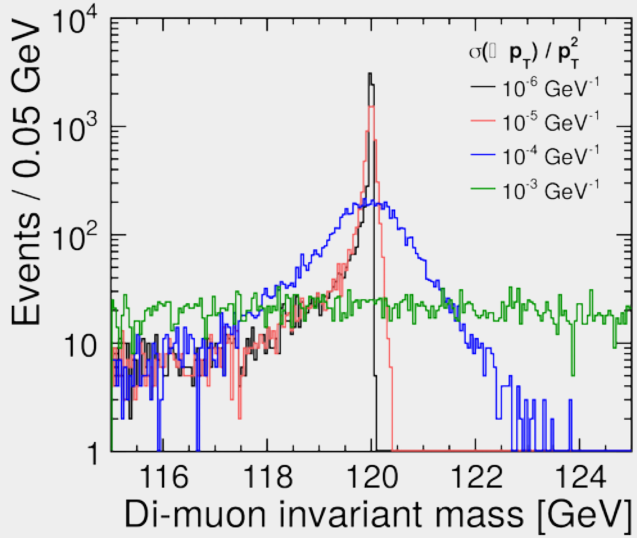
# *CLICdet* – the CLIC detector Concept

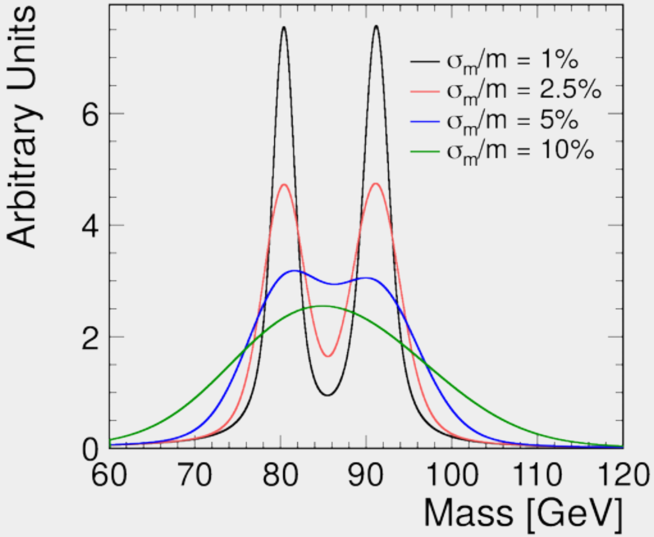
- Low-mass all-silicon vertex and tracking detectors, R = 1.5 m
- High-granularity calorimeters:
  - ECAL: 22 $X_0$ + 1 $\lambda_I$
    40 layers Si sensors, W plates
  - HCAL: 7.5 $\lambda_I$
    60 layers plastic scintillator/SiPM, steel
- 4T superconducting solenoid
- Return yoke,
  Muon detectors interleaved
- **Optimized for Particle Flow Analysis**



# Detector requirements

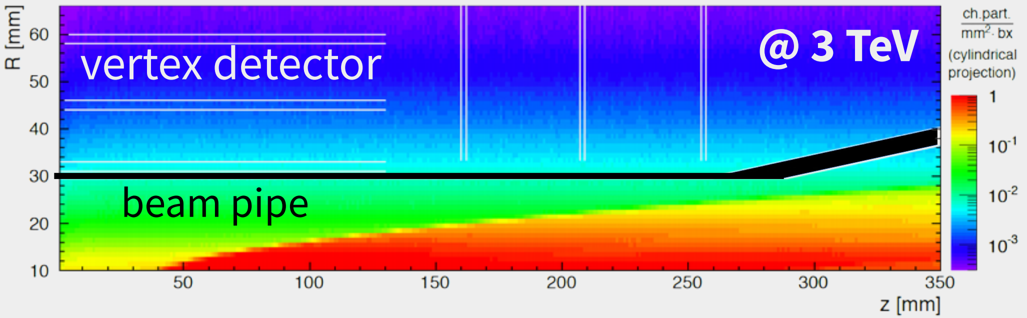
- Momentum resolution
  - Higgs recoil mass, Higgs coupling to muons
  - $\sigma_{p_T}/p_T \sim 2 \times 10^{-5}$ **GeV**$^{-1}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - $\sigma_{r\phi} \sim a \oplus b\,/\,(p[\text{GeV}]\,\sin^{3/2}\theta)$ **µm** with a = 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 θ = 10 mrad (η = 5.3)

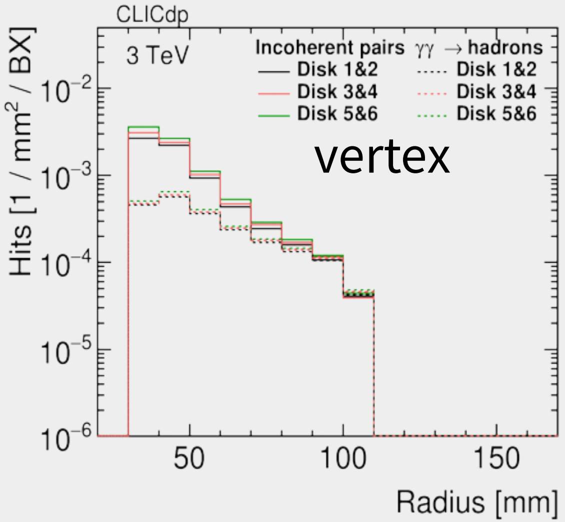


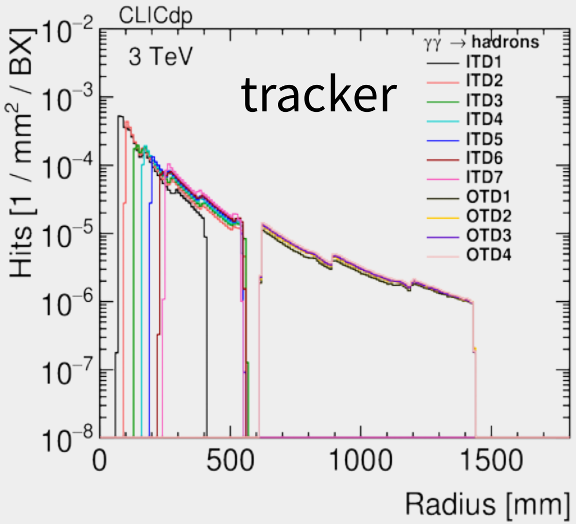



# Occupancies

- Charged particles produced by beam-induced background
- Detector layout and granularity dependent on particle flux
  - Talk by D. Arominski: "Updates on beam-induced backgrounds"
- Goal: keep **occupancies below 3%** per bunch train including safety factors
- Occupancy limits:
  - Vertex: pitch **25 µm x 25 µm**
  - Tracker: **50 µm** in rϕ and **1mm – 10mm** in z

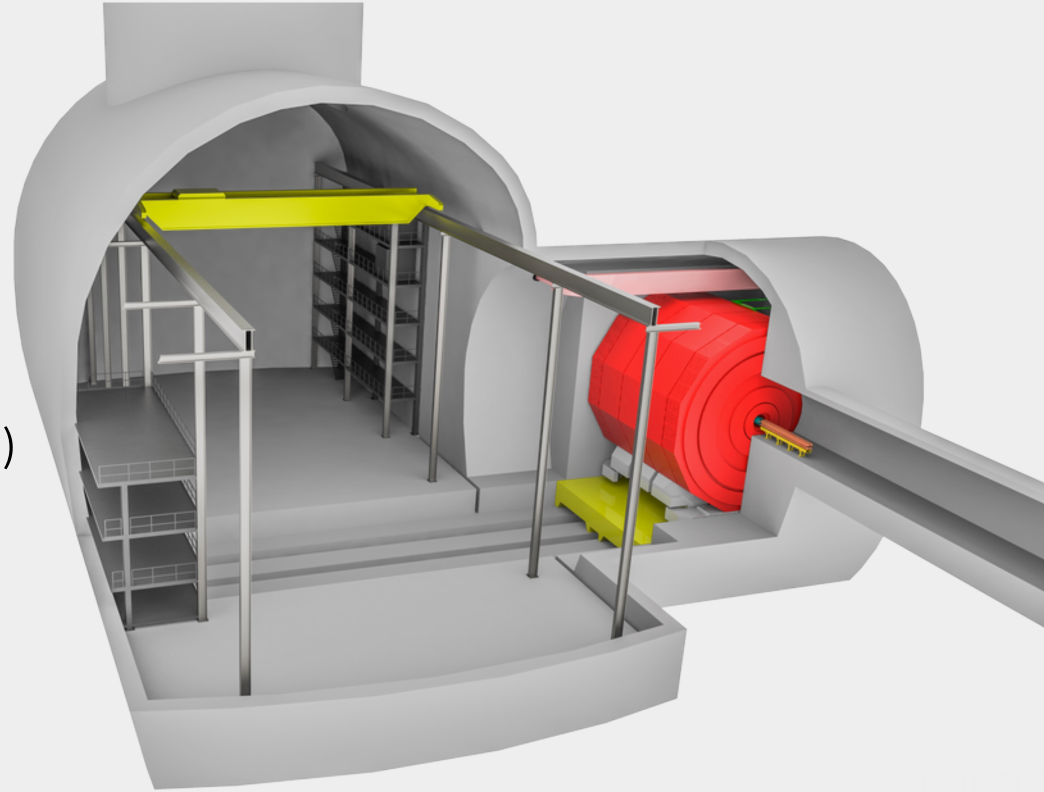


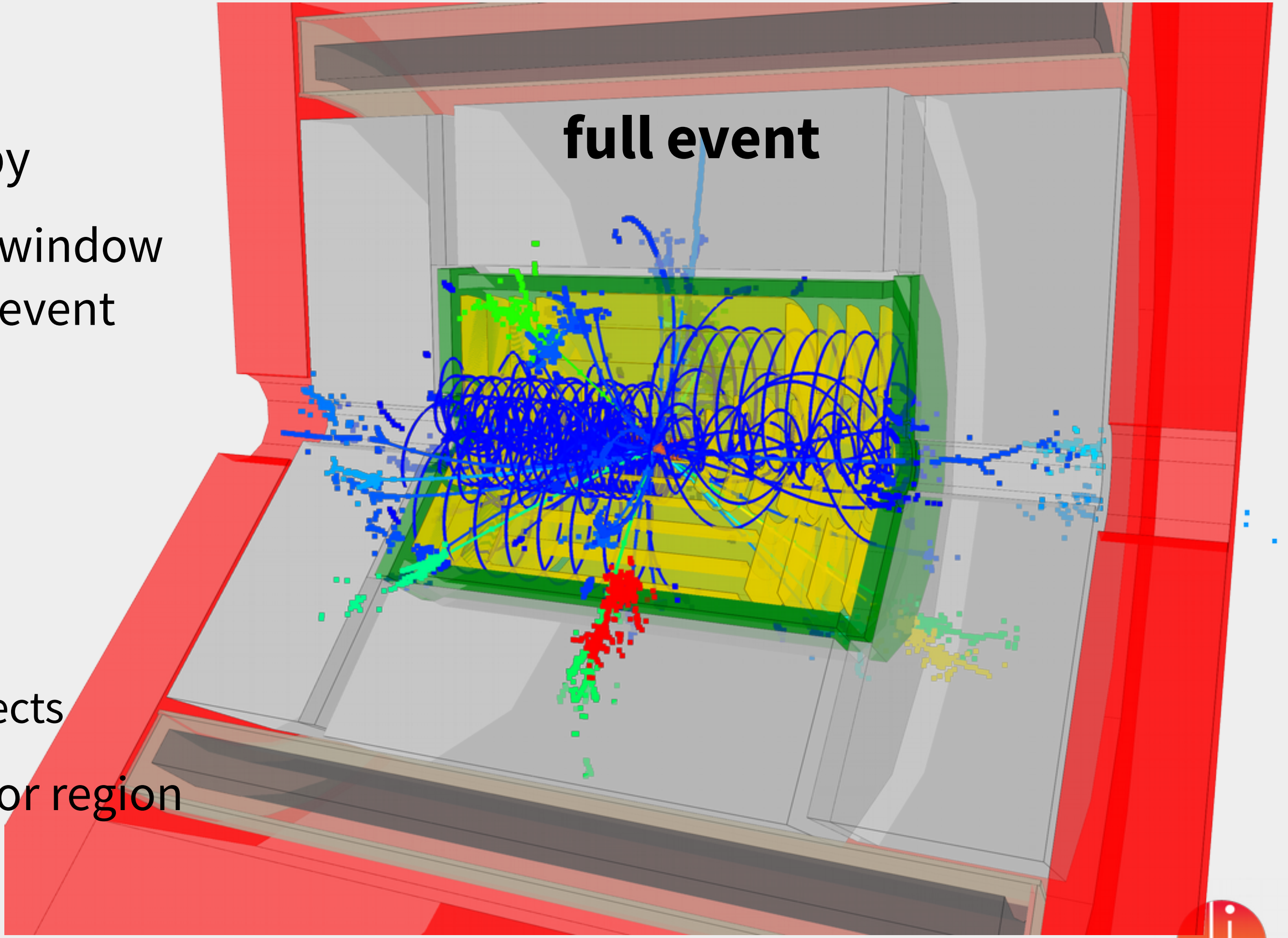
# Same Detector for 380 GeV and 3 TeV?

- 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 (Δr ~ 3 mm)
    - Move innermost vertex layer closer to interaction point
- Currently focusing on **single detector**, with a layout **optimized for 3 TeV**



# Background suppression @ **380 GeV**

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



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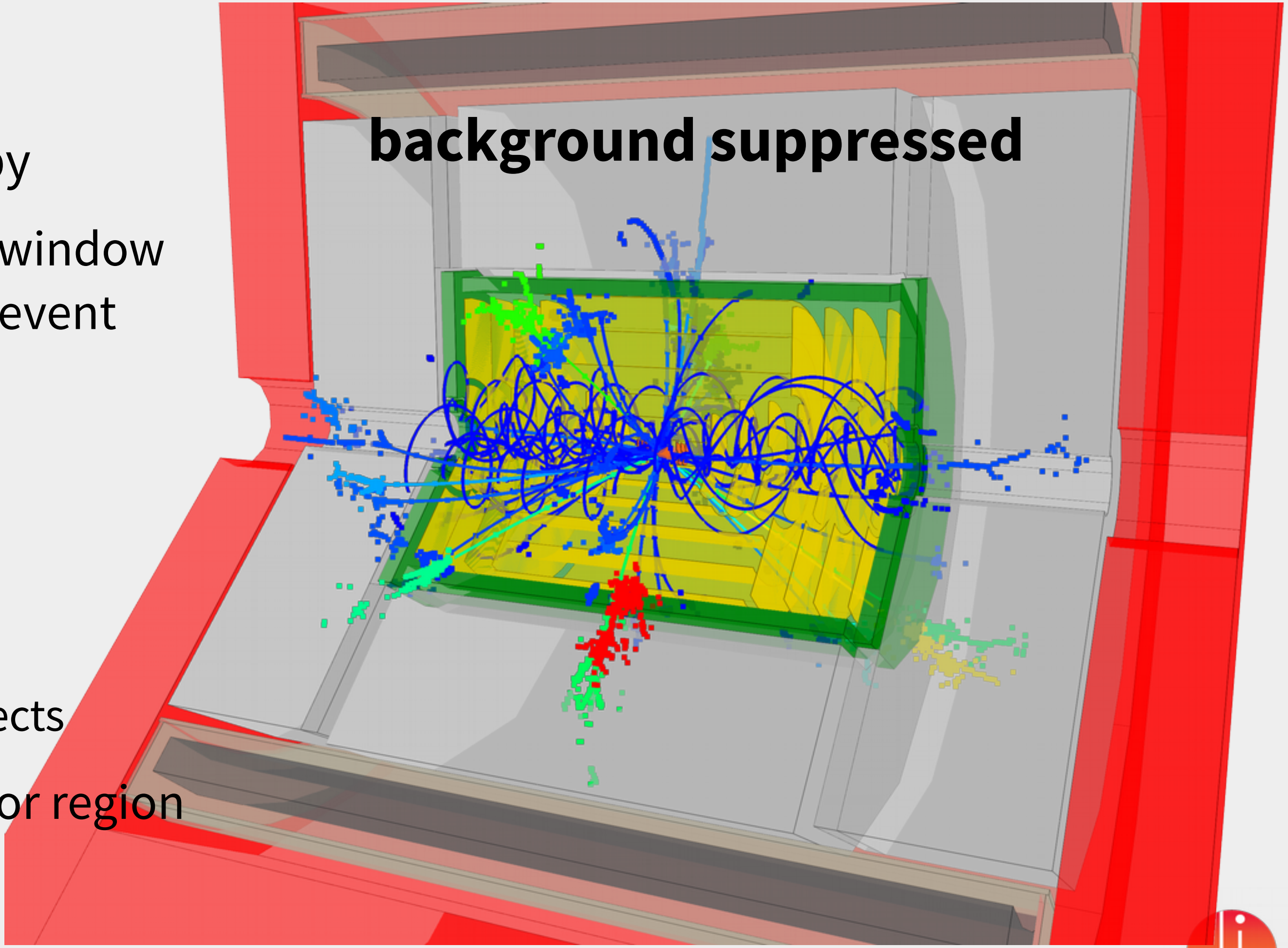

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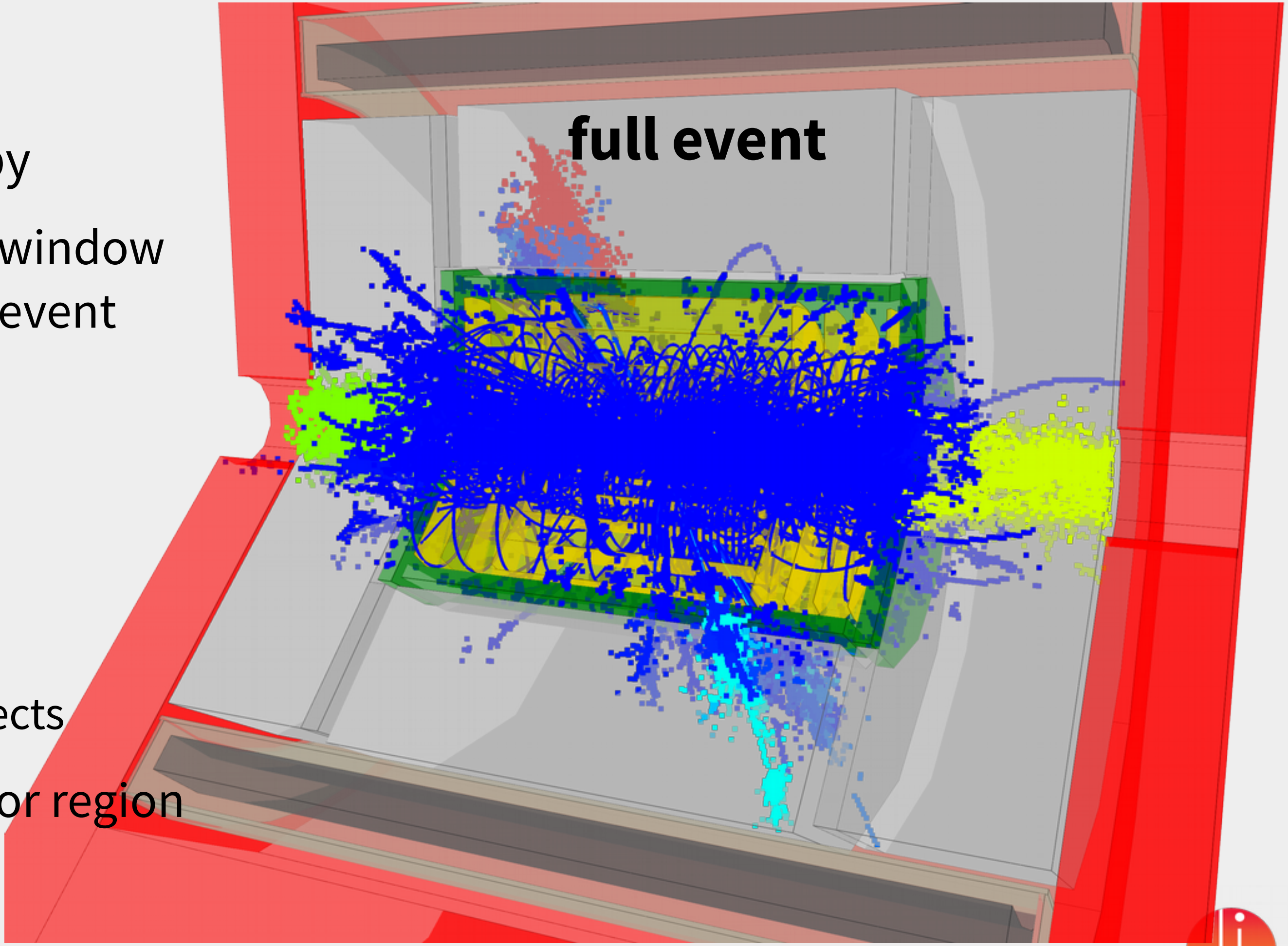

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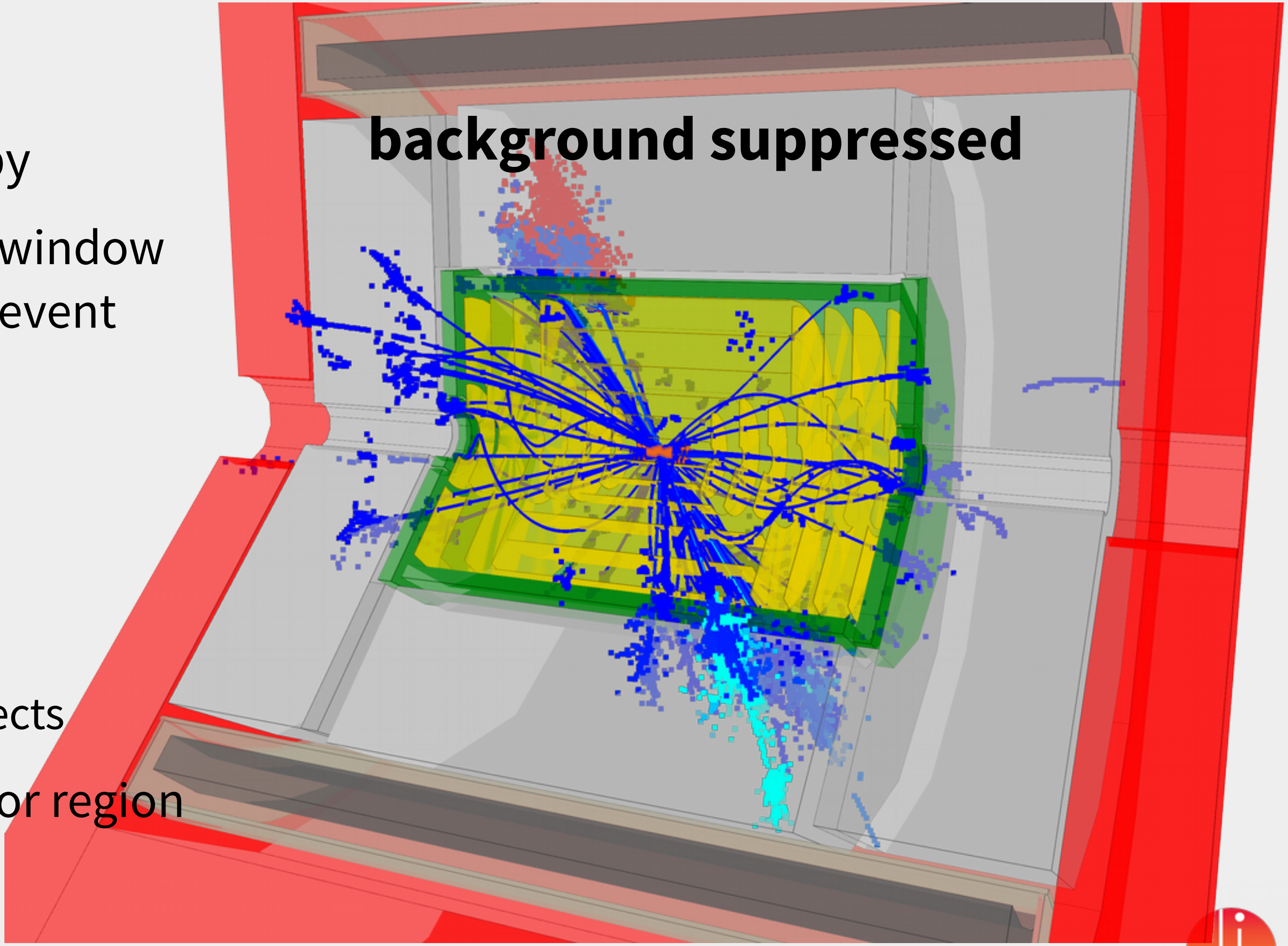
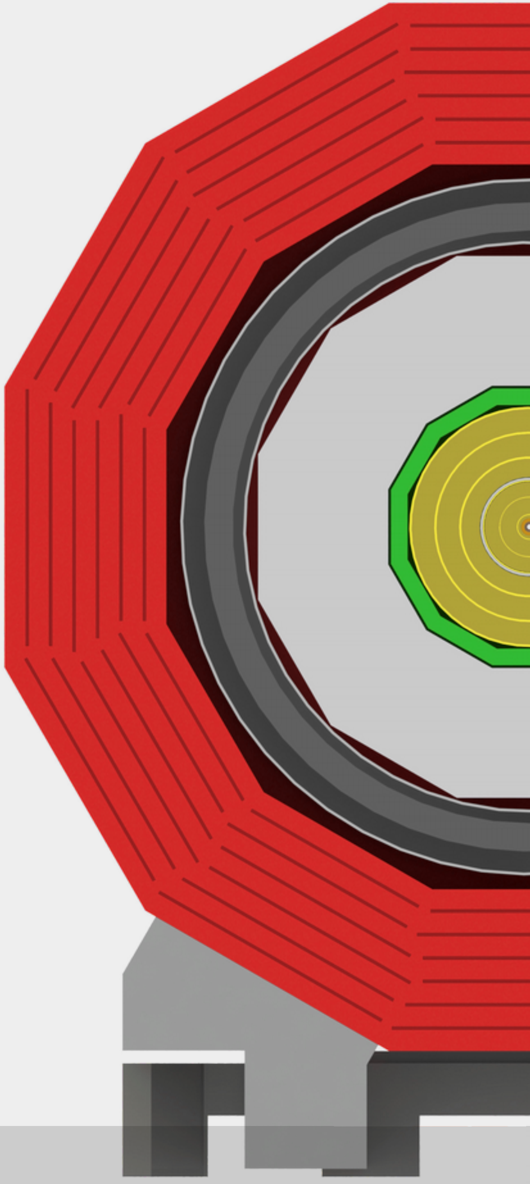


# **Detector Technologies**
and Prototype Evaluation



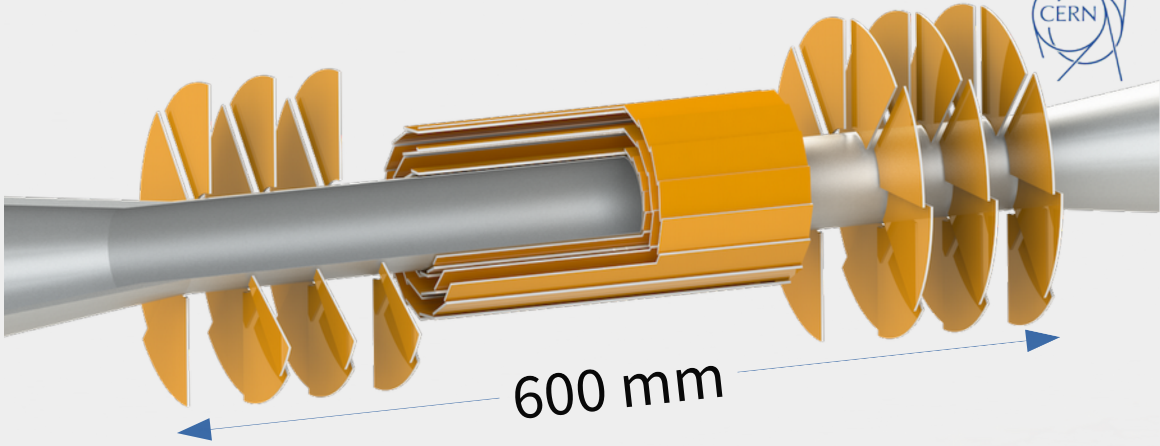
# Vertex Detector

Design driven by flavor tagging

- Minimal scattering
- High-resolution

Requirements

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




Current design:

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

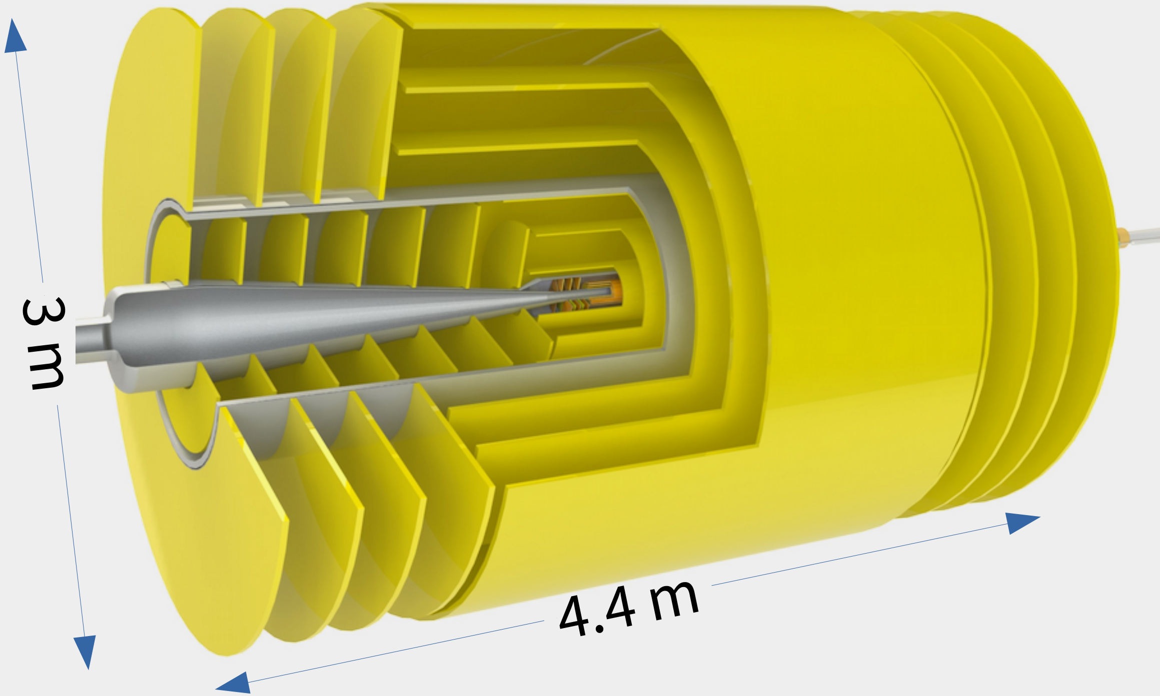
# Tracking Detector

Design optimized for good efficiency & momentum resolution

- Many layers
- Large lever arm

Requirements

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



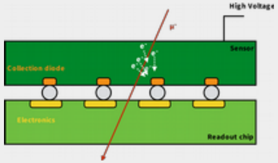

Current design:

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

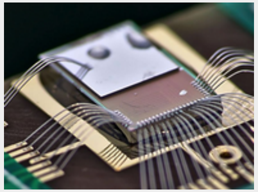
# Silicon Technologies

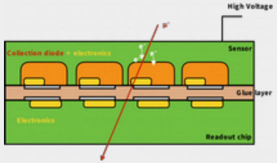
- Looking at selected silicon detector technologies under investigation
- Collaboration with other experiments (ALICE: HR-CMOS, ATLAS: HV-CMOS)

## hybrid detectors

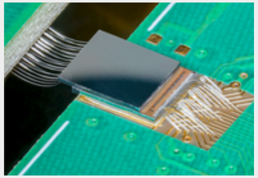


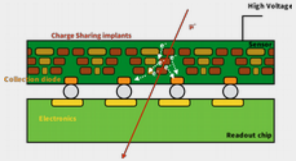
Hybrid



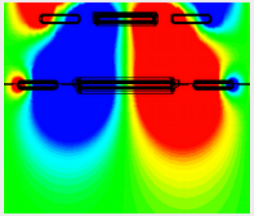


Capacitive

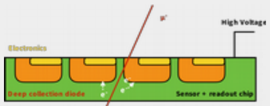




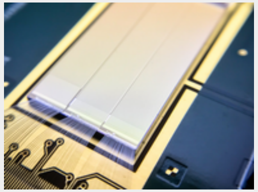
ELAD

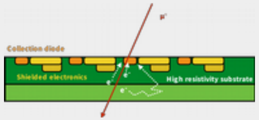


## monolithic detectors

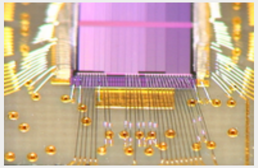


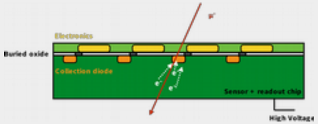
HV-CMOS



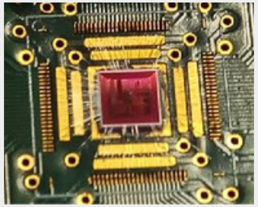


HR-CMOS

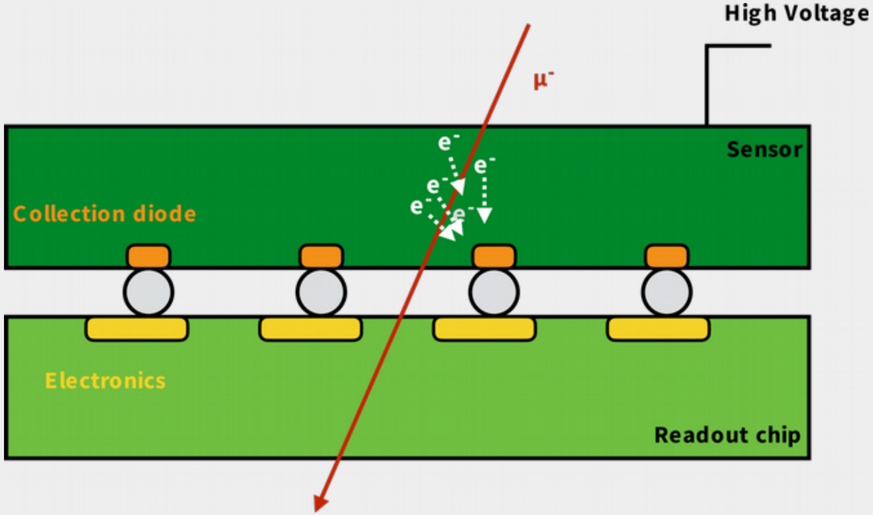




SOI



# Hybrid Silicon Detectors




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

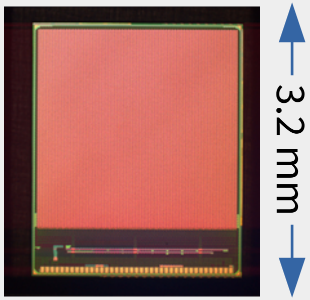
Established mixed-mode CMOS
Complex circuits possible
Small technology nodes available

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

# Hybrid Prototypes

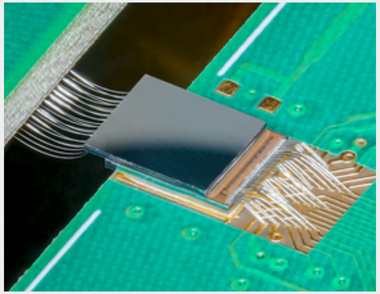
**CLICpix2 + planar sensor**

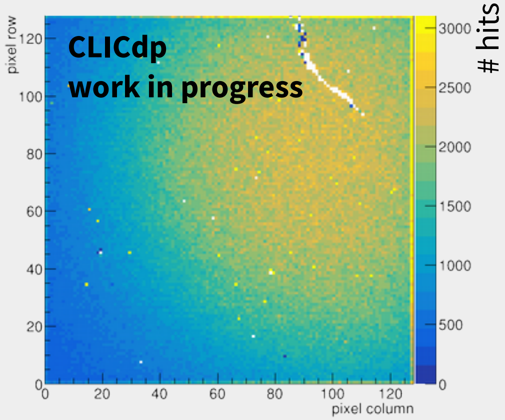
- Goal: 50 µm thin planar silicon sensors
- Challenge: single-chip bump bonding at 25 µm pitch
- First successes, 130 µm thick sensor




**CLICpix2 + C3PD**

- Capacitively coupled
- Active sensor fabricated in 180 nm HV-CMOS process
- Finite-element simulation of capacitive coupling

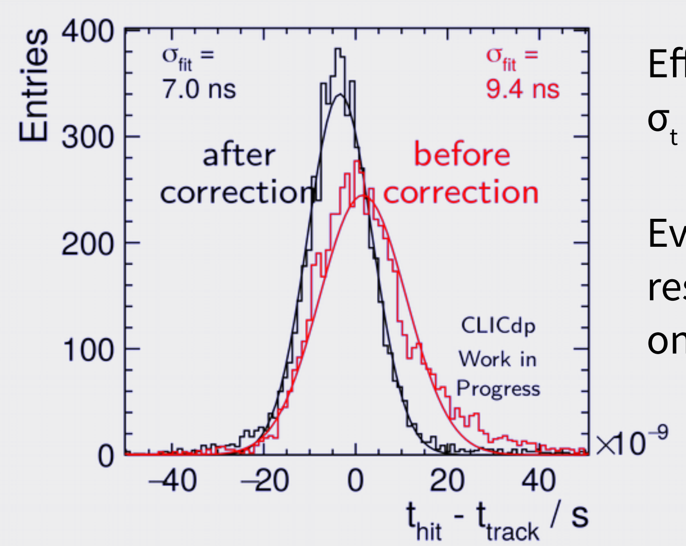





Good bonding yield

First assemblies tested in beam

Calibration ongoing



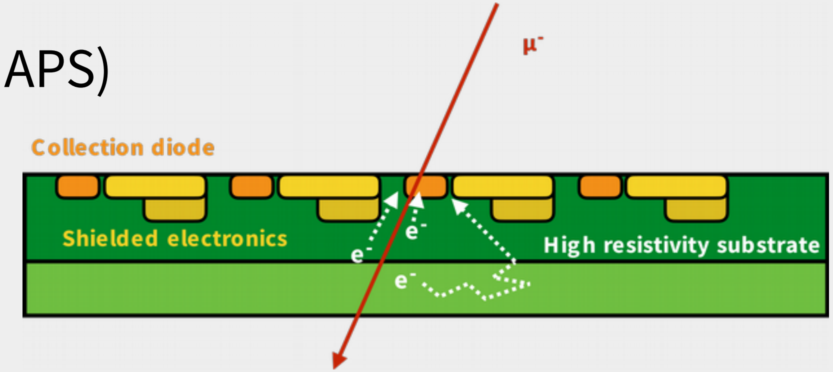

Efficiency > 90%

$\sigma_t$ ~7 ns, $\sigma_{SP}$ ~8 µm

Evaluation of high-resistivity wafers ongoing

# 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
  - Separate shielding & collection diode

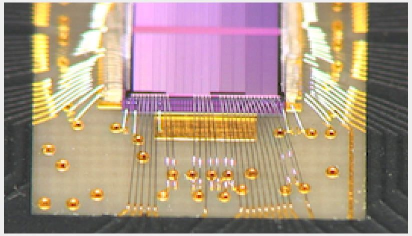



Lower mass than hybrids
No bump-bonding
Cheaper manufacturing

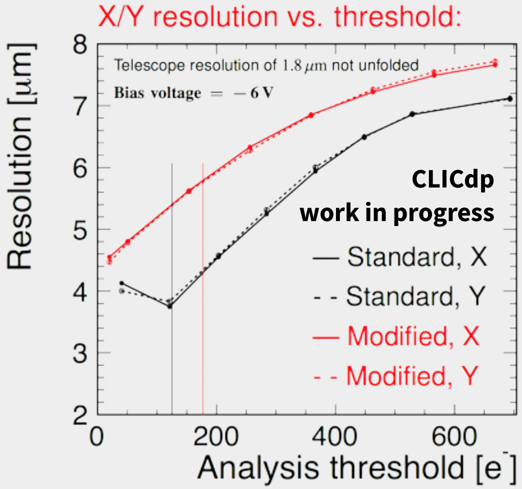
Smaller depletion volume & signal
Intricate sensor design
Limited in-pixel functionality

# Monolithic Prototypes

## ALICE Investigator



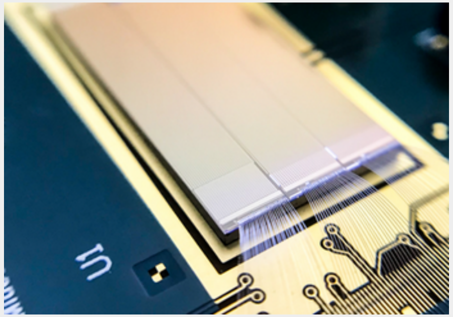
- Analog test chip for technology evaluation
- 180 nm HR-CMOS process
- Different pixel pitches & geometries



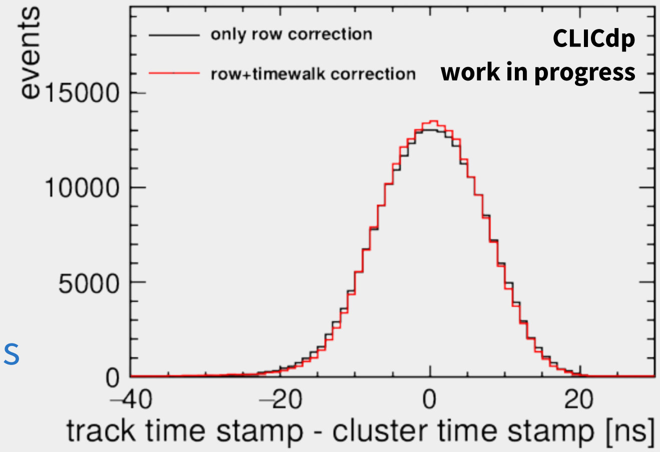

28 x 28μm$^2$ pitch:
99.3% efficiency,
$\sigma_t$ < 5ns, $\sigma_{SP}$ ~4μm

CLIC-specific prototype **CLICTD**
→ Talk by I. Kremastiotis

## ATLASpix_Simple



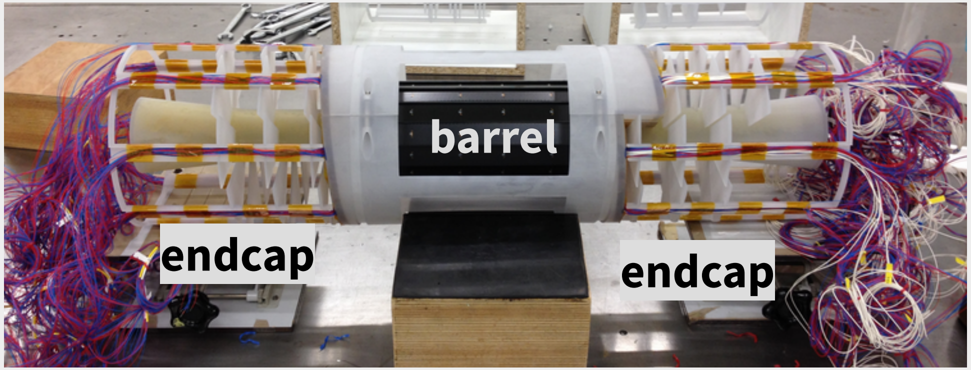
- Commercial 180nm HV-CMOS process
- Designed for ATLAS ITK Upgrade
- Timing performance investigated in test beams



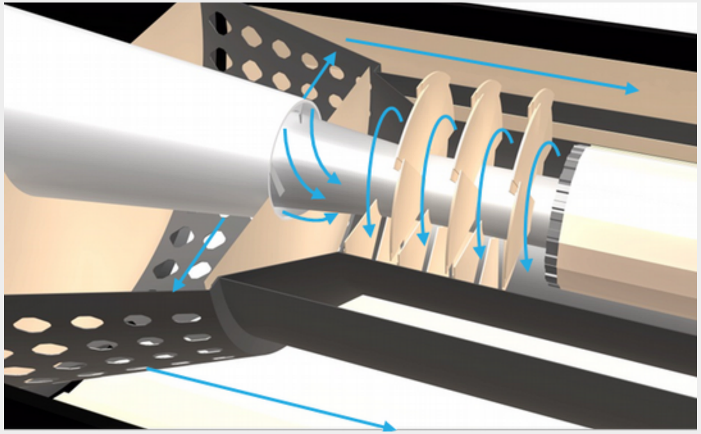

RMS = 6.9 ns at threshold = 490e

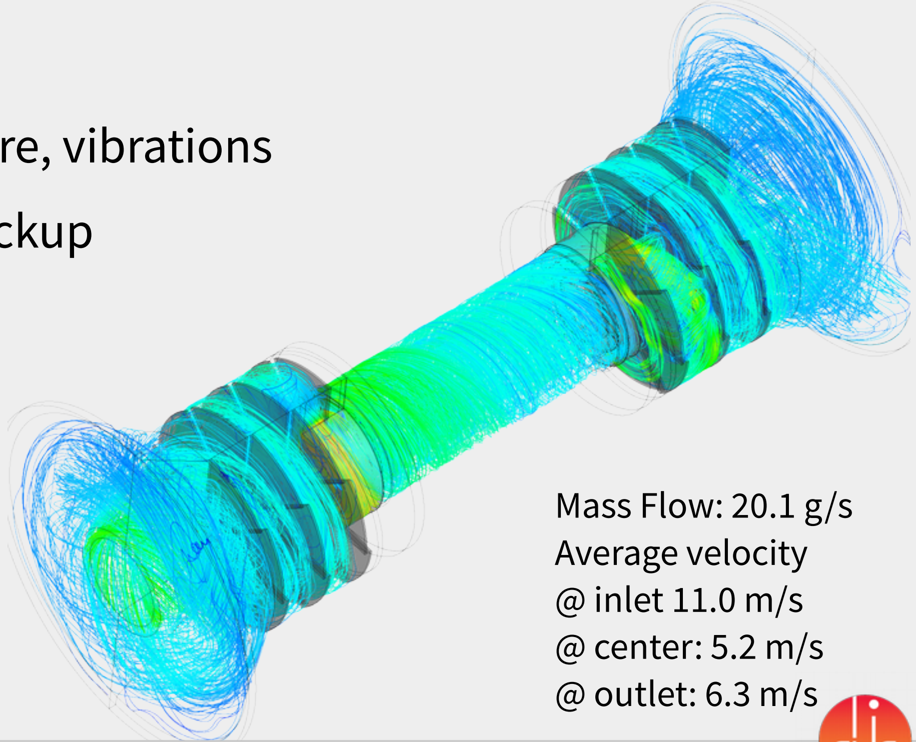
CLIC-specific prototype in design
→ Talk by J. Kroeger

# 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

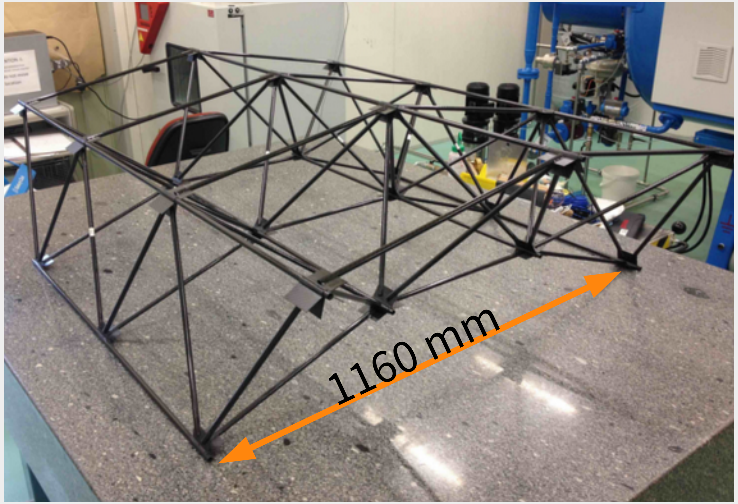


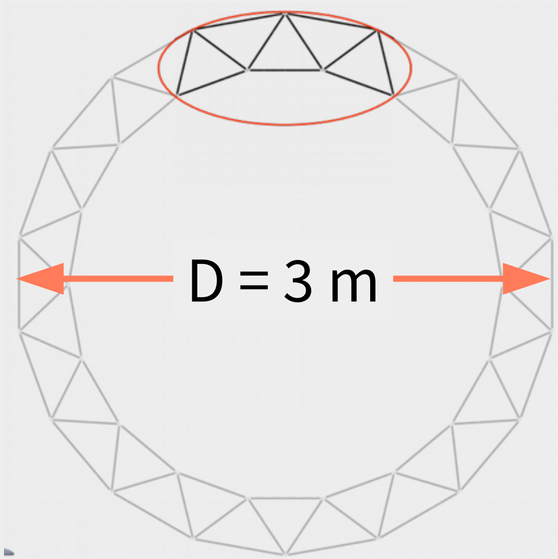


Mass Flow: 20.1 g/s
Average velocity
@ inlet 11.0 m/s
@ center: 5.2 m/s
@ outlet: 6.3 m/s

# 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

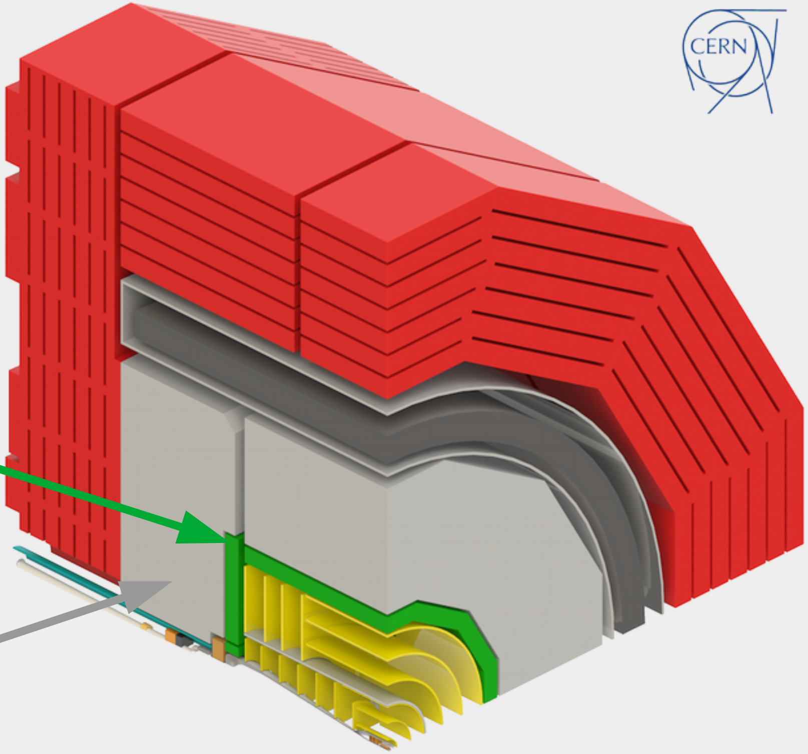



- Synergies with ALICE ITS upgrade's outer stave
- Stiffness achieved with low mass structure
- Total weight of the prototype: 926 g

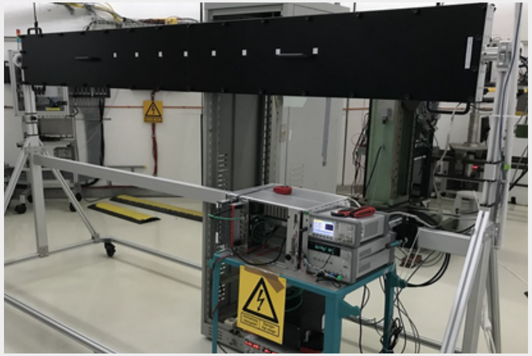
# Calorimeters

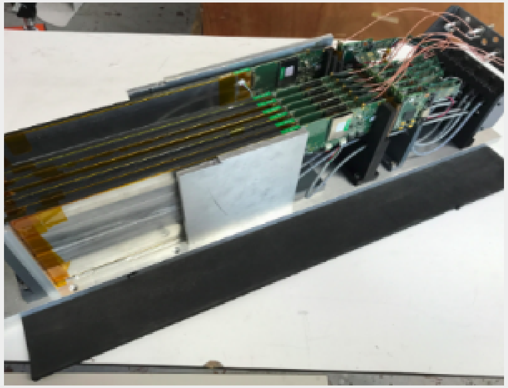
- Jet energy resolution of $\sigma_E/E \sim 5 - 3.5\%$
  - Highly granular calorimeters required
- **Electromagnetic Calorimeter: Si-W**
  - 2 mm tungsten plates, 500 µm silicon sensors
  - 40 layers 22 $X_0$ or 1 $\lambda_I$, 5 × 5 mm² cell size
  - ~2500 m² silicon, 100 million channels
- **Hadronic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

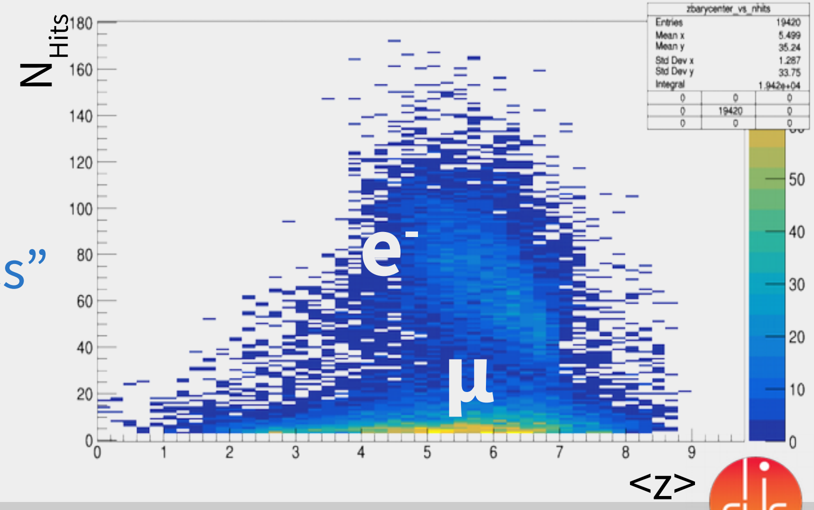


# ECAL: CALICE SiECAL Prototype

- Highly granular calorimeter, optimized for particle flow
  - Si sensors, W absorbers
  - Many years of experience: ASICs, sensor studies, physics prototypes
- Recently developments:
  - Test beams at SPS H2
  - First functional “long slab” built
- Talk by V. Boudry
  “Toward practical feasibility of a SiW-ECAL for LCs”
- Synergies with CMS HGCal project

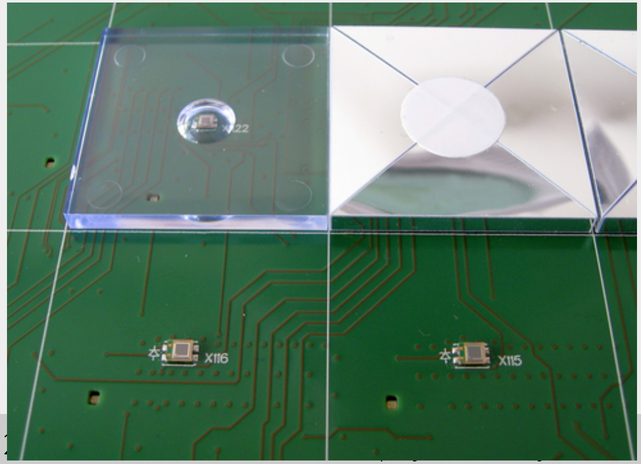






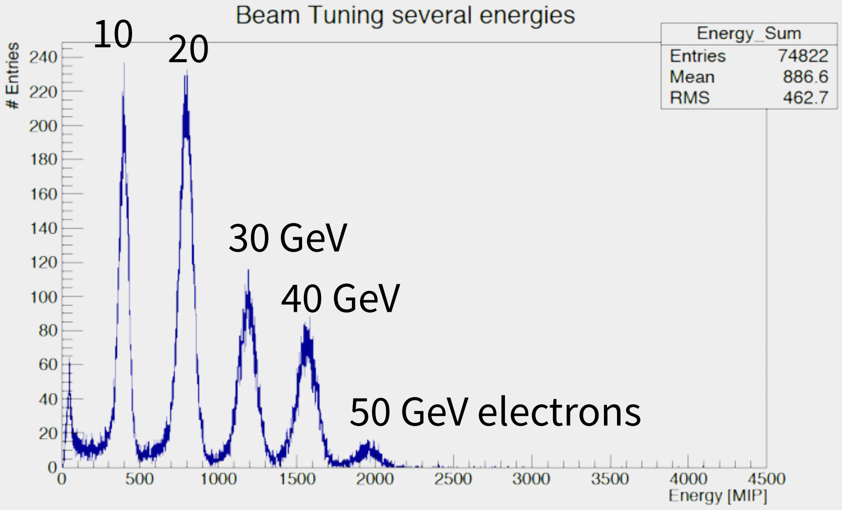
# HCAL: CALICE AHCAL Prototype

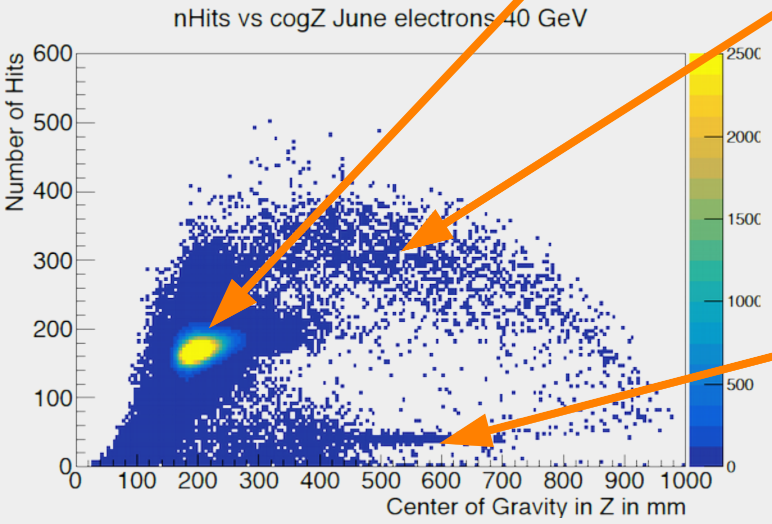
- Highly granular scintillator SiPM-on-tile HCAL
  - 3 x 3 $cm^2$ scintillator tiles, fully integrated design
  - 38 active layers of 72 x 72 $cm^2$ in steel absorber
  - Automatic temperature compensation for SiPMs
- Design optimized for mass production:
  - Automatic SMD SiPM soldering
  - Injection-molded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

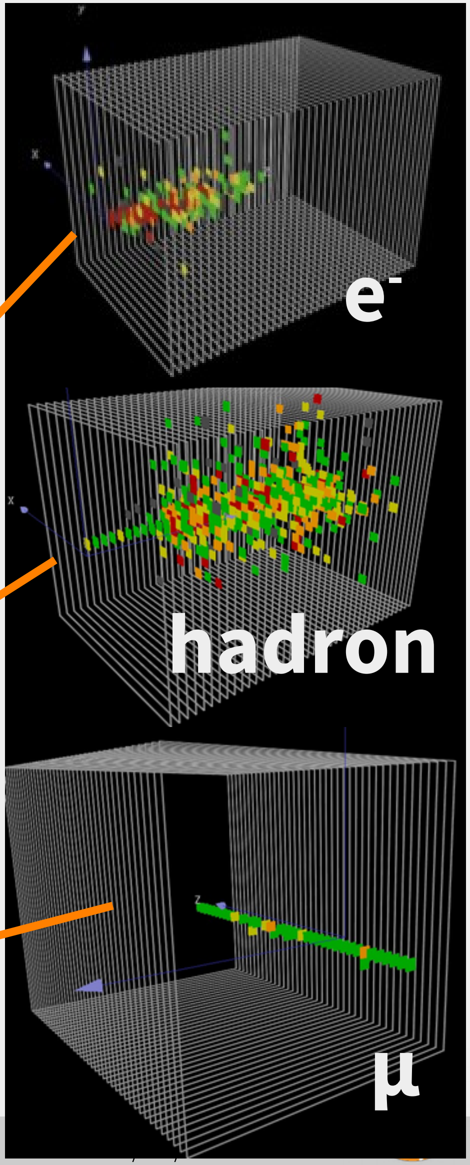


# AHCAL Prototype Test Beam Results

- 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



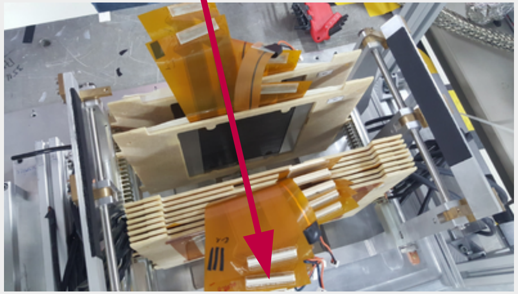



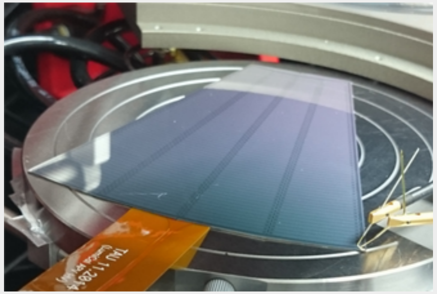



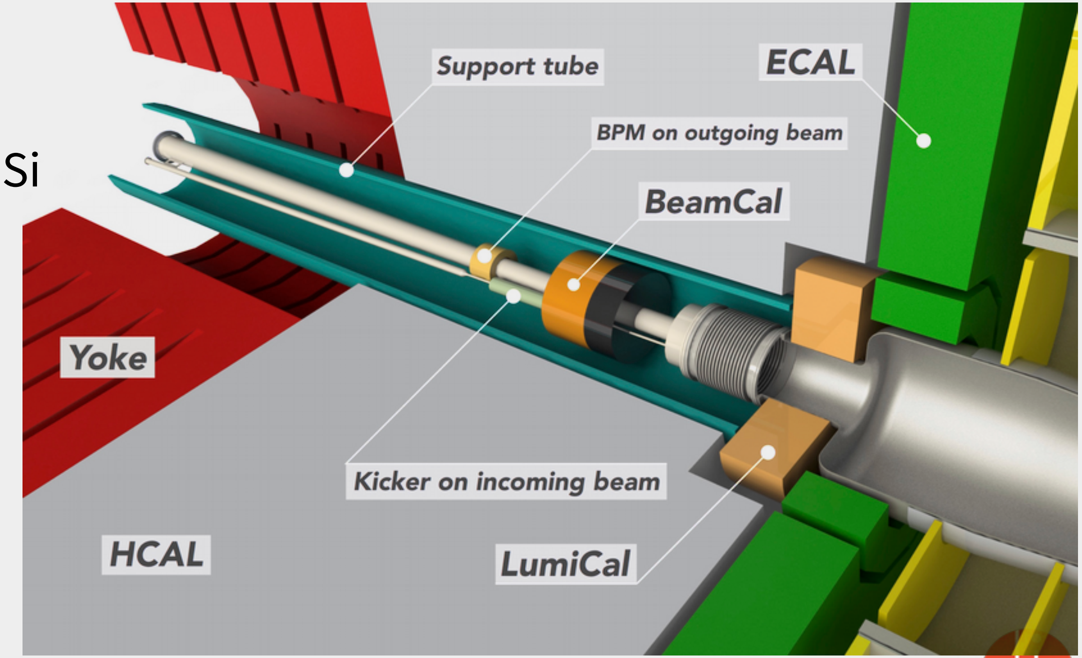
# Forward Instrumentation: BeamCal & LumiCal

- Very forward electromagnetic sampling 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 design: BeamCal: GaAs, LumiCal: Si
- Talk by M. Idzik on LumiCal tests & ASIC

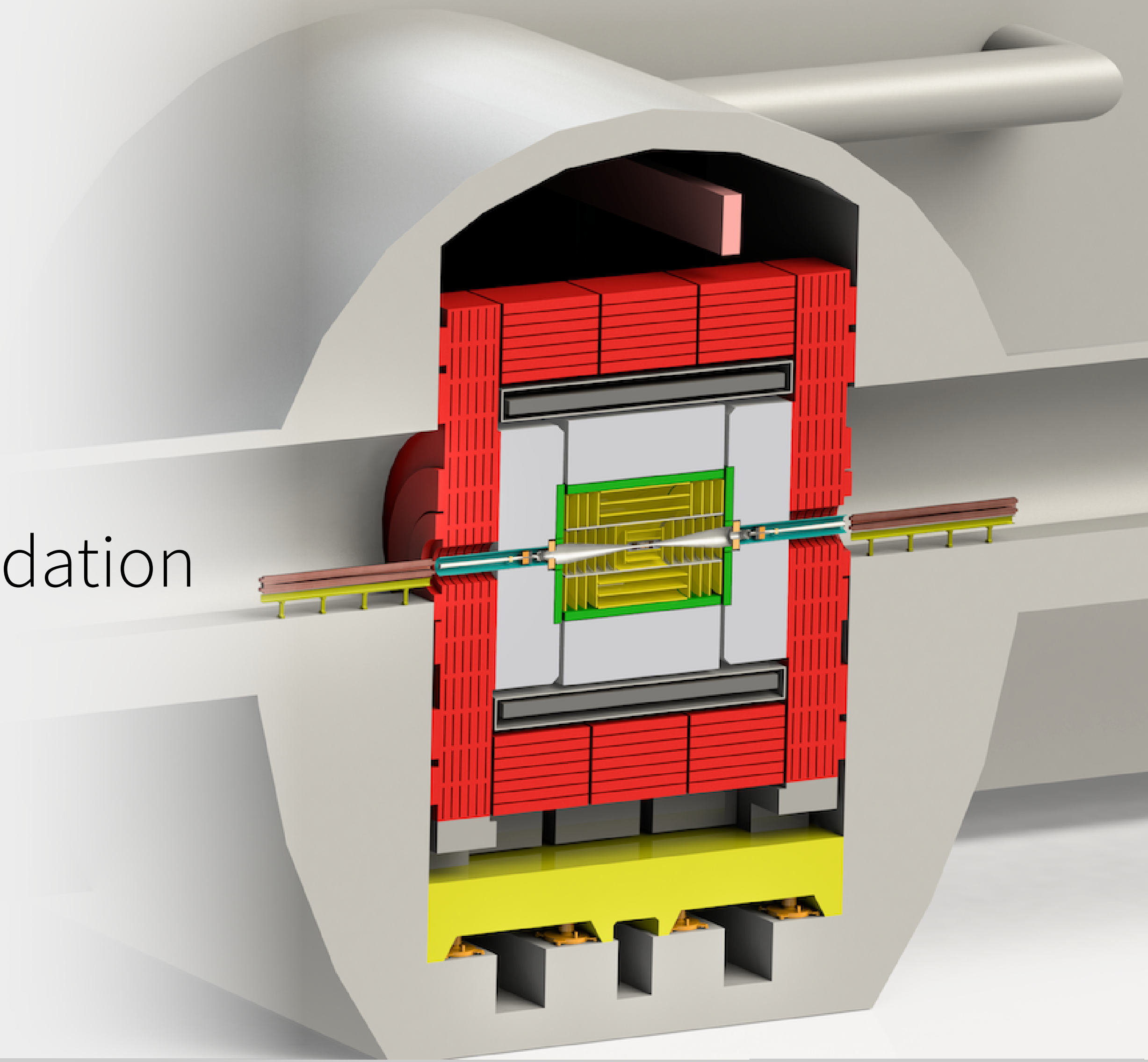
$e^-$ DESY Testbeam







# **Performance Studies**
# and Detector Design Validation



# Performance Studies & Validation

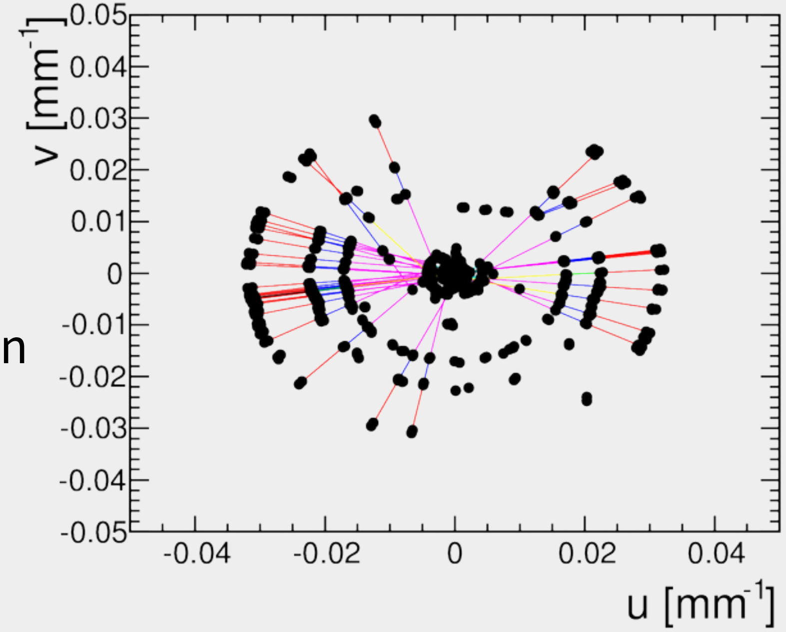
- Full simulation and reconstruction studies performed with **iLCSoft framework**, developed by the Linear Collider Community
- Continuous improvements of simulation & reconstruction software
  - **DD4HEP** for geometry description, others are on the move: LHCb, CMS…
- **DELPHES** card available for fast simulation in their official repository
  - Three cards for the different CLIC stages
- 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: $u = \frac{x}{x^2 + y^2} \quad v = \frac{y}{x^2 + y^2}$

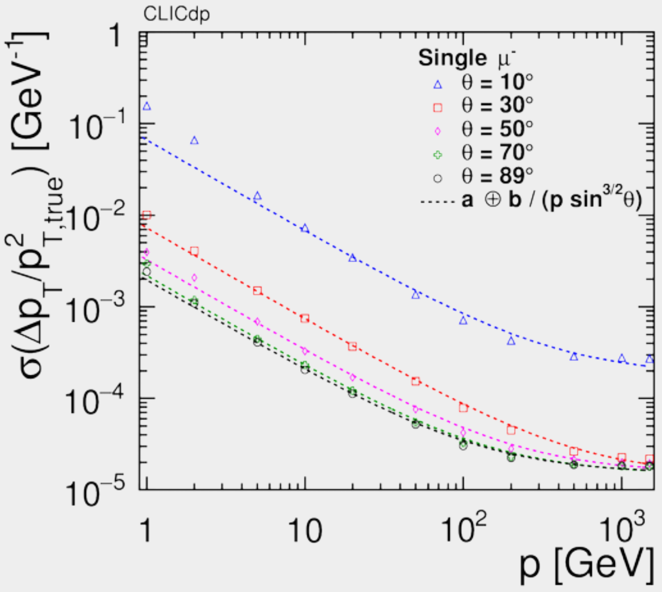
"maps circles passing through the origin onto straight lines"

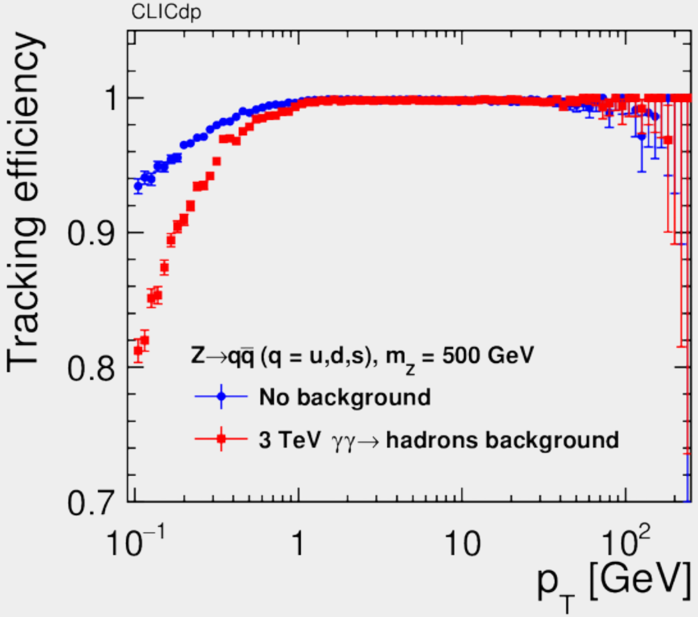
  - Pattern recognition: straight line search with cellular automaton (robust: noise, missing hits)
  - Fit in z-s (along helix) reduces combinatorics
- Displaced tracks do not go through origin
  - Apply second-order corrections to transformation
  - Adapt search parameters and order
- Kalman-filter based fit of reconstructed tracks

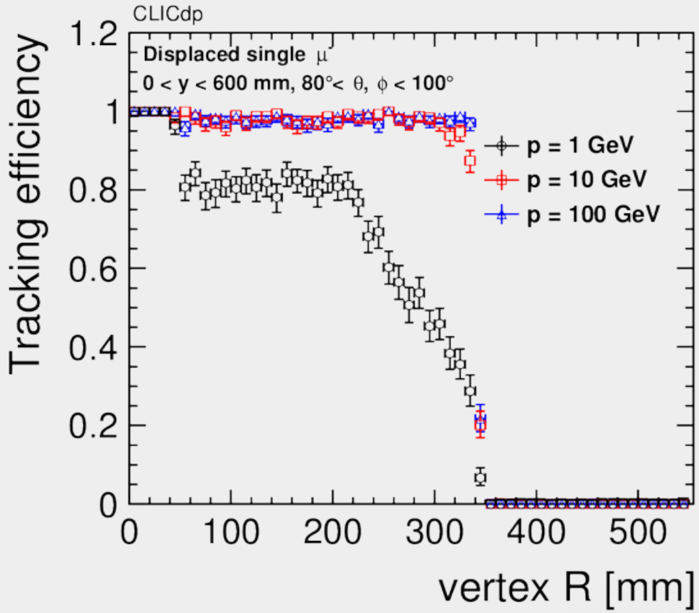


# CLICdet Tracking Performance

- 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)

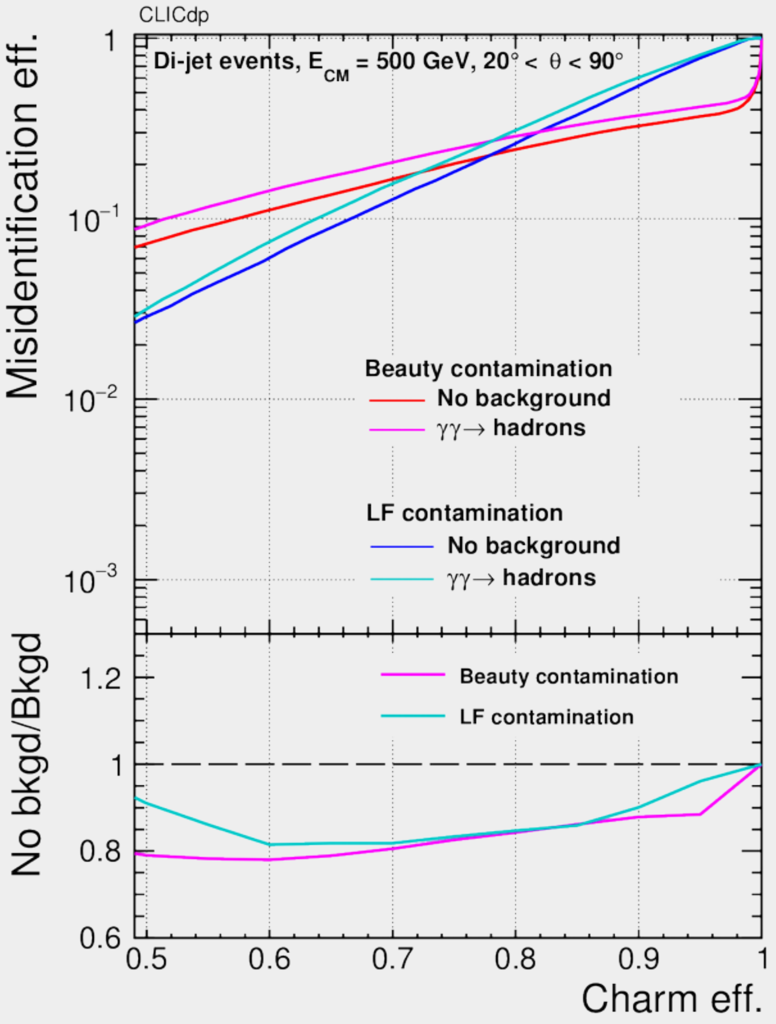


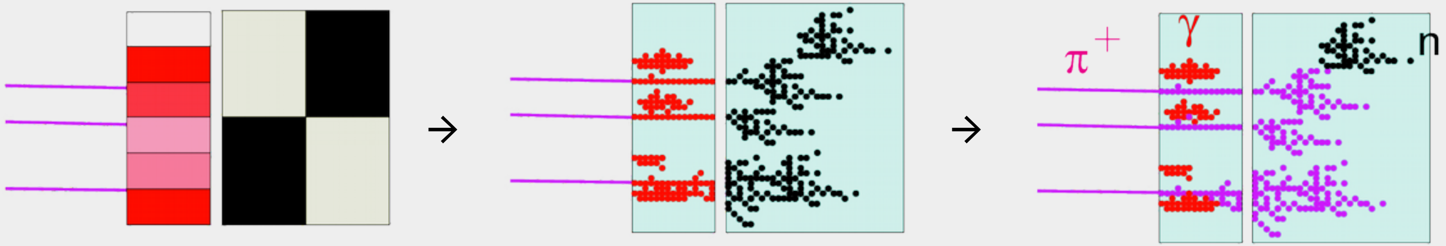
# Flavor Tagging Performance

- Several studies on flavor tagging efficiencies performed, to be found in performance note
  - LCFIPlus package is used for flavor tagging
- Charm tagging performance
  - Using di-jet samples, $E_{CM}$ = 500 GeV
  - With and without background (3 TeV, 30 BX)
  - At 80% charm identification efficiency, beauty/light-flavor misidentification is
    - 25% without backgrounds
    - 30% with 3 TeV background overlay

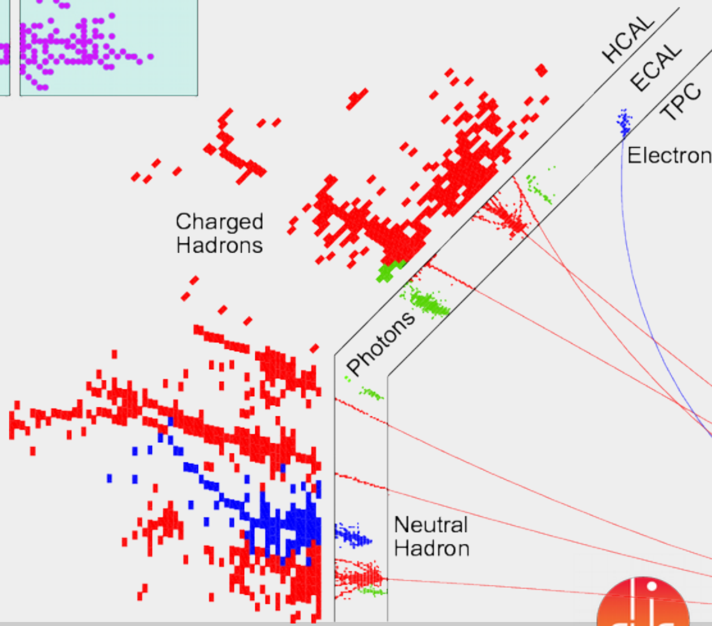


# Jet Reconstruction & Particle Flow Algorithm

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

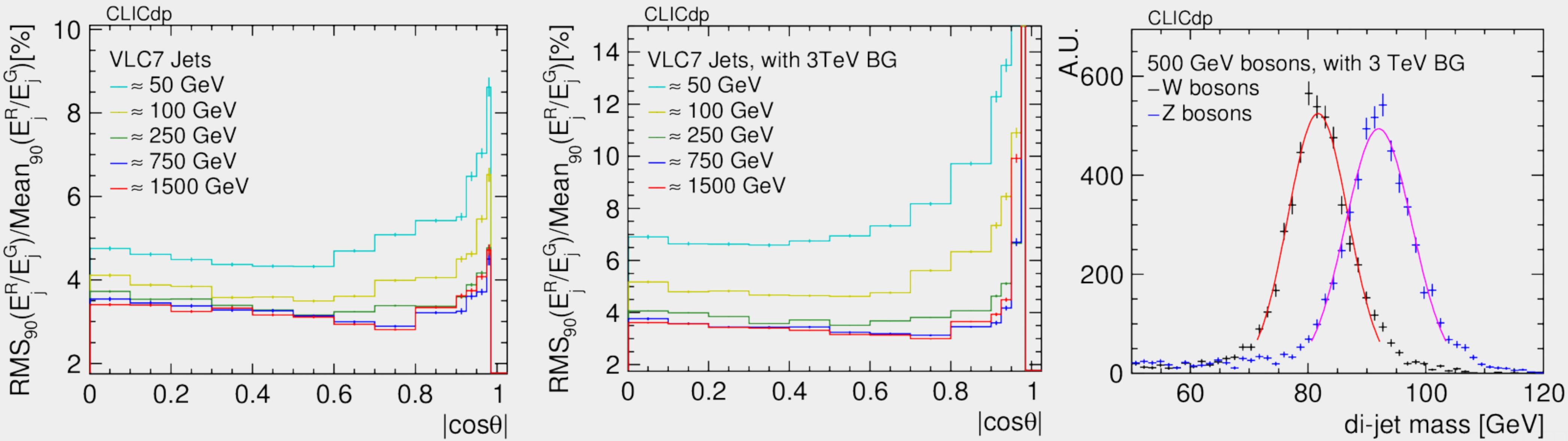



  - Requires highly granular calorimeter detectors
  - Talk on Software compensation by F. Simon
- Jets formed using VLC algorithm with R = 0.7
- Dedicated note:
  "Jet performance at CLIC" (CLICdp-Note-2018-004)



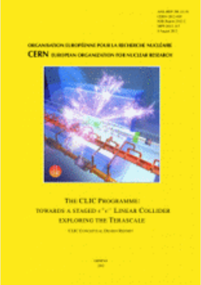
# Jet Energy & Missing $E_T$ Resolution

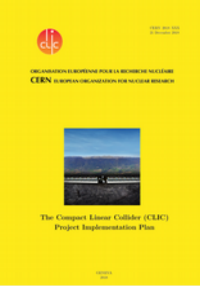
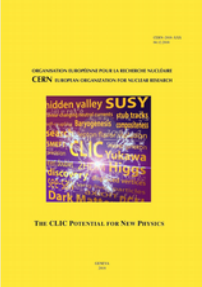
- Jet energy resolution from $Z/\gamma^* \rightarrow qq$, compare reconstructed and MC truth jets
  - Impact from 3 TeV backgrounds especially for low-energy jets, resolution 6-8%
- W/Z mass: 2σ separation with VLC7 jets, including 3 TeV backgrounds



# Summary Documents





Detector technologies for CLIC

2012 CLIC Conceptional Design Report

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

2016 Updated Baseline for a staged Compact Linear Collider

2018 Documents for the European Strategy Update

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

# Summary

- CLIC offers opportunity for broad precision physics program
- Detector model CLICdet optimized and validated in full simulation
- 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

# The CLICdp Collaboration

**CLICdp Institute Board**

**CLICdp Executive Team**

| | |
|---|---|
| Spokesperson | **Aidan Robson** |
| Tech. Coord. | Lucie Linssen |
| Other members | Philipp Roloff, Frank Simon |

**Publication Committee**
- **Nigel Watson**
- Aharon Levy
- Ulrike Schnoor
- Simon Spannagel

**Speakers Committee**
- **Naomi Van Der Kolk**
- Eva Sicking
- Emilia Leogrande

**WG Physics Potential**
- Philipp Roloff
- Filip Zarnecki

**WG Physics Analysis**
- Jorge de Blas
- James Wells
- Andrea Wulzer

**WG Vertex and Tracking Detector Technology**
- Dominik Dannheim
- Mathieu Benoit

**WG Detector Optimisation and Validation**
- Konrad Elsener
- Frank Simon

CLICdp Working Groups (WG)

# Cost Estimate for the CLIC Detector

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

| System | Cost fraction | Cost[MCHF] |
|---|---|---|
| Vertex | | 13 |
| Silicon Tracker | | 43 |
| Electromagnetic Calorimeter | | 180 |
| Hadronic Calorimeter | | 39 |
| Muon System | | 16 |
| Coil and Yoke | | 95 |
| Other | | 11 |
| Total | | 397 |