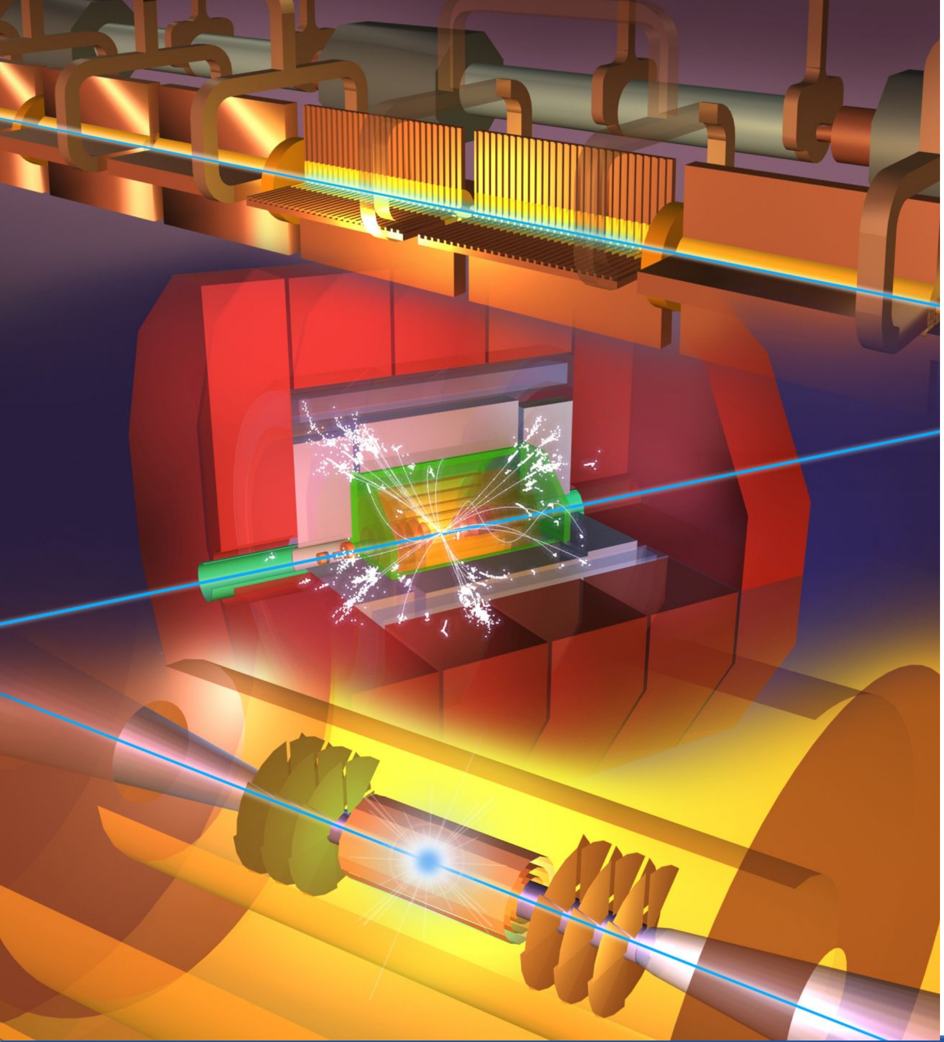
"My own visions of CLIC", artwork by Natasha de Heney, 2010

CLIC

Erica Brondolin, on behalf of CLIC & CLICdp collaborations

Chicago workshop on the Circular Electron Positron Collider

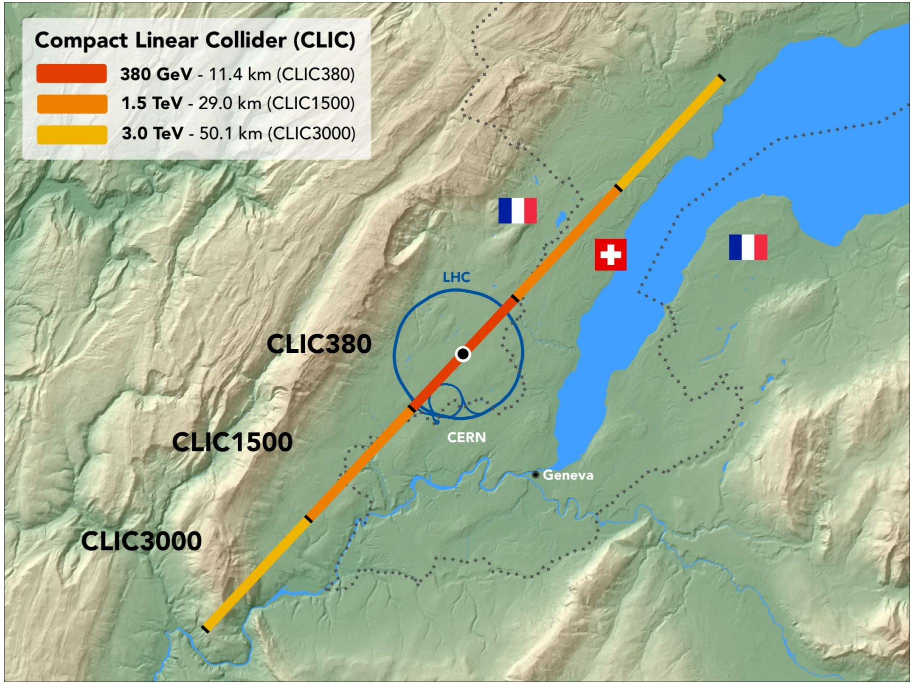
16th September 2019



Outline

- Introduction
- The Physics Potential
- The Accelerator
- The Detector
- Summary

The CLIC project



- **CLIC = Compact Linear Collider**
- High-energy linear e^+e^- collider
- Centre-of-mass energy from 380 GeV up to 3 TeV
- CLIC would be implemented in three energy stages (7-8 years each)

- Physics goals:
  - Precision measurement of Higgs boson and top quark
  - Precision measurement of new physics (discovered at LHC, CLIC, ...)
  - Search for physics Beyond Standard Model (BSM)

Possibility to adapt the stages to new LHC discovery!

Collaborations

CLIC accelerator collaboration
~70 institutes from ~30 countries

CLIC accelerator studies:

- CLIC accelerator design and development
- Construction and operation of CTF3

CLIC detector and physics (CLICdp)
~30 institutes from 18 countries

Focus of CLIC-specific studies on:

- Physics prospects and simulation studies
- Detector optimization + R&D for CLIC

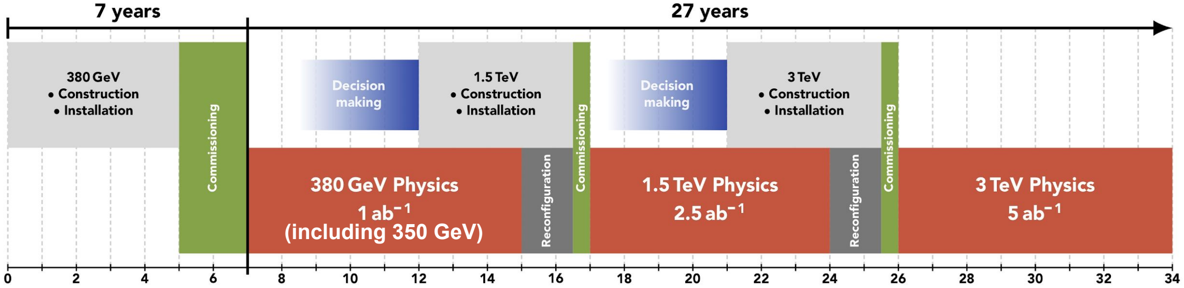
http://clic.cern

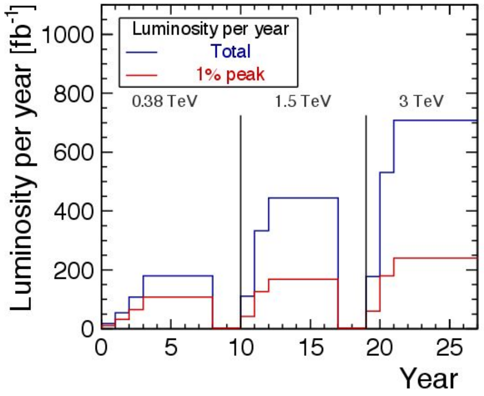
CLICdp Participating Institutes

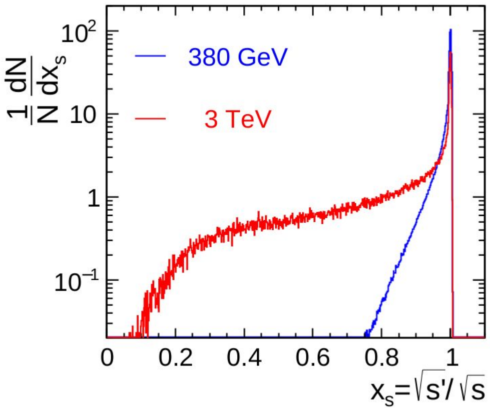
CLIC
Physics Potential

CLIC staging

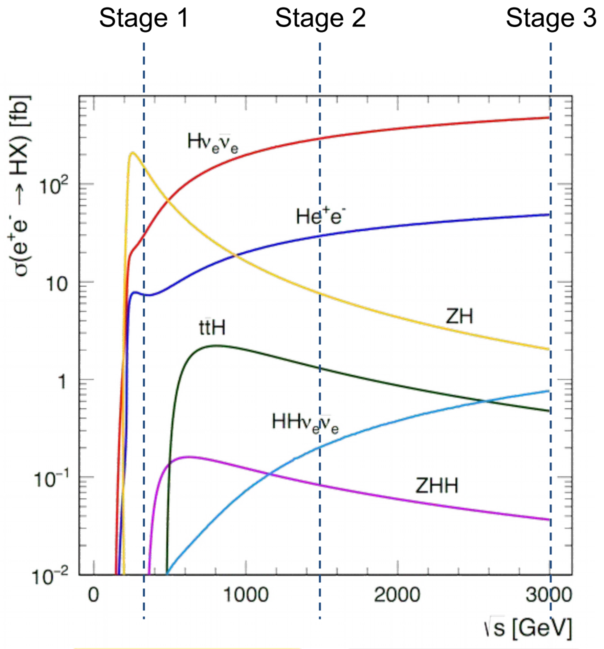
- Physics programme extends over 25–30 years
- Electron polarisation :
  - ±80% longitudinal polarization for the electron beam
  - Enhances Higgs production at high-energy stages
  - Provides additional observables sensitive to BSM physics
  - Helps to characterise new particles in case of discovery
- Luminosity spectrum
  - Effect is dependent on √s
  - Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
  - Most of the analyses use the entire lumi spectrum
- Baseline scenario:



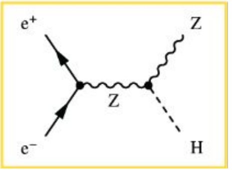


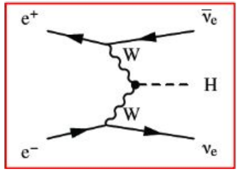


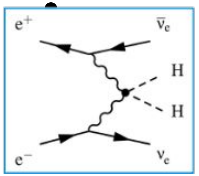
Higgs Physics

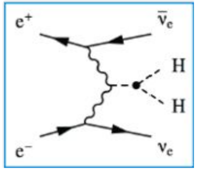


- **Higgsstrahlung: $e^+e^- \rightarrow ZH$**
  - **$\sigma \sim 1/s$**, dominant up to ~ 450 GeV
  - Higgs identification from recoil
- **WW fusion: $e^+e^- \rightarrow H\nu_e\nu_e$**
  - **$\sigma \sim \log(s)$**, dominant above ~ 450 GeV
  - Large statistics at high energy -> rarer decays
- **$e^+e^- \rightarrow HH\nu_e\nu_e$**
  - Allow simultaneous extraction of triple Higgs coupling and HHWW quadratic coupling
  - Benefits from high-energy operation



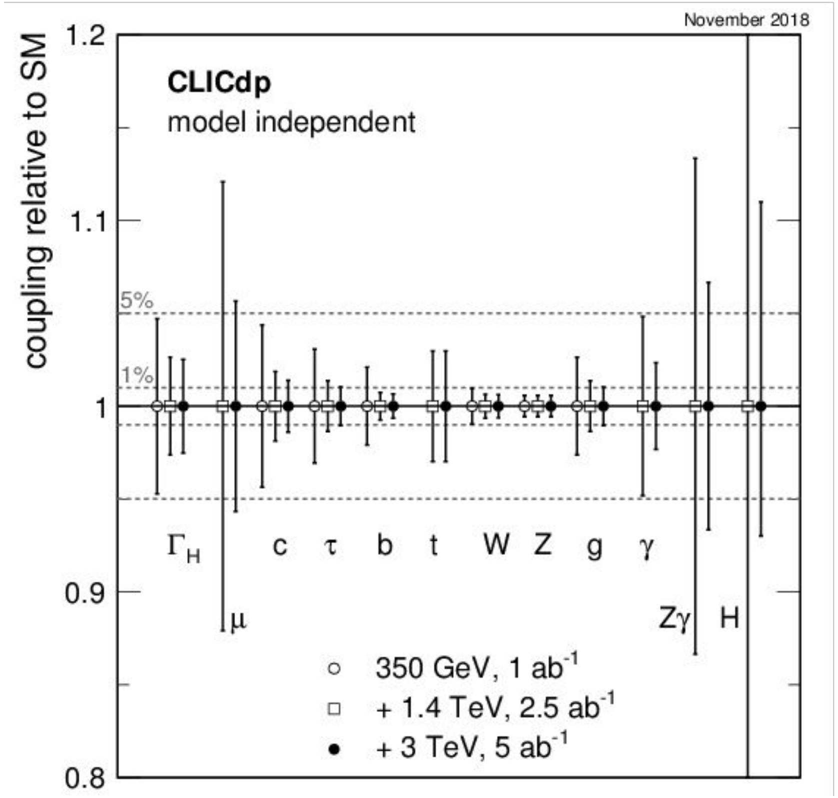






All Higgs studies summarised in [Eur. Phys. J. C 77 (2017) 475]

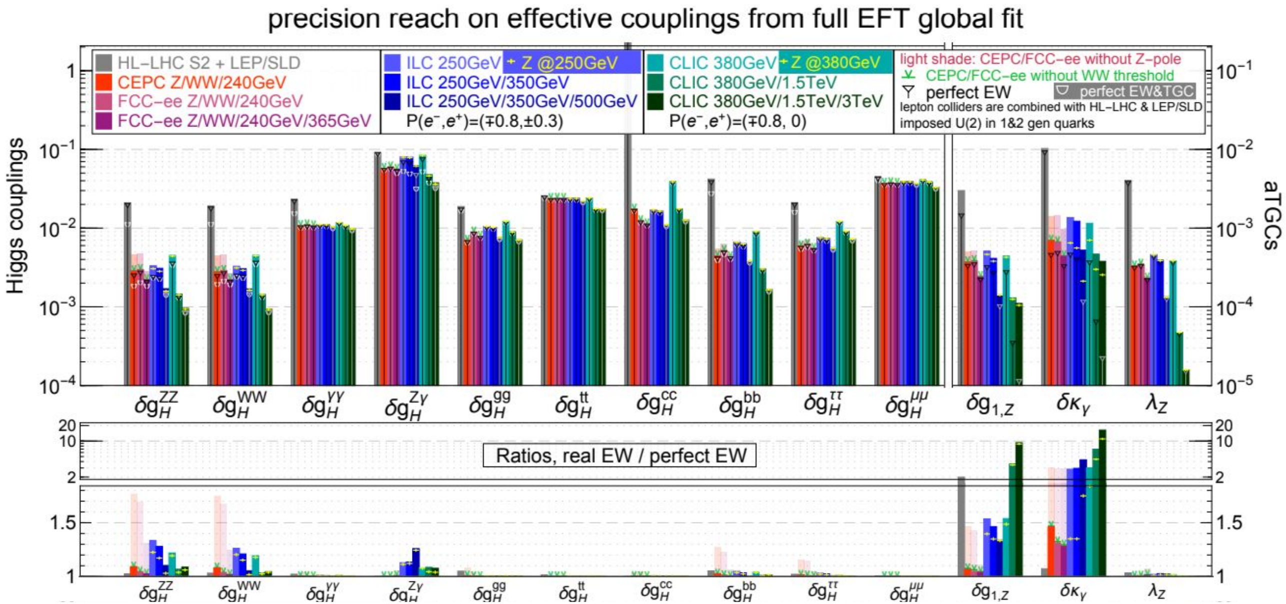
Higgs coupling sensitivity



- **Fully model-independent analysis**:
  - Free parameters Γ_H and ten Higgs couplings
  - No assumption on invisible Higgs decays
- High precision measurements @ CLIC:
  - Precision ≲**1% for most couplings**
  - The Higgs width is extracted with **4.7 – 2.5%** precision

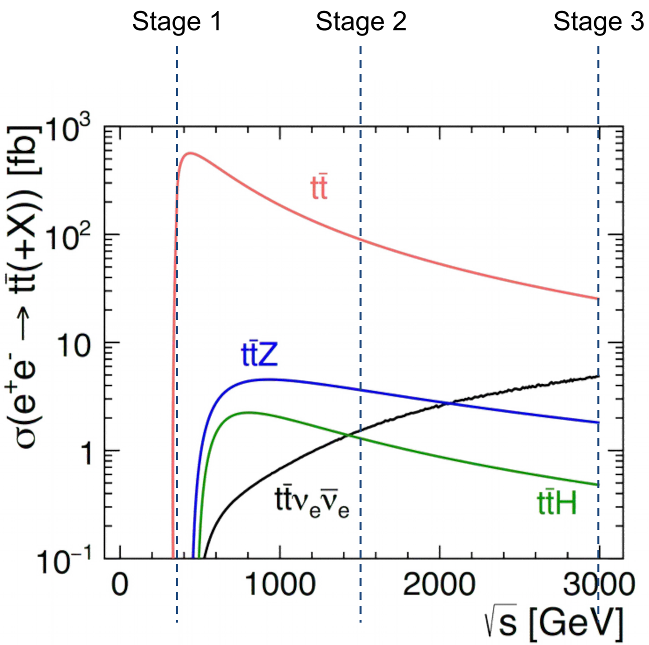
arXiv:1812.01644

Higgs coupling sensitivity

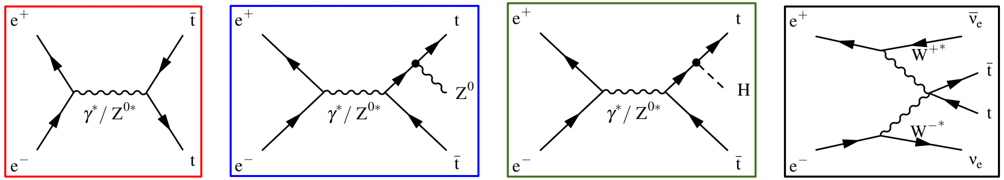


- Many Higgs couplings can be measured significantly better CLIC compared to HL-LHC
- Some couplings are very challenging at hadron colliders
  - Example: H → cc

Top Physics



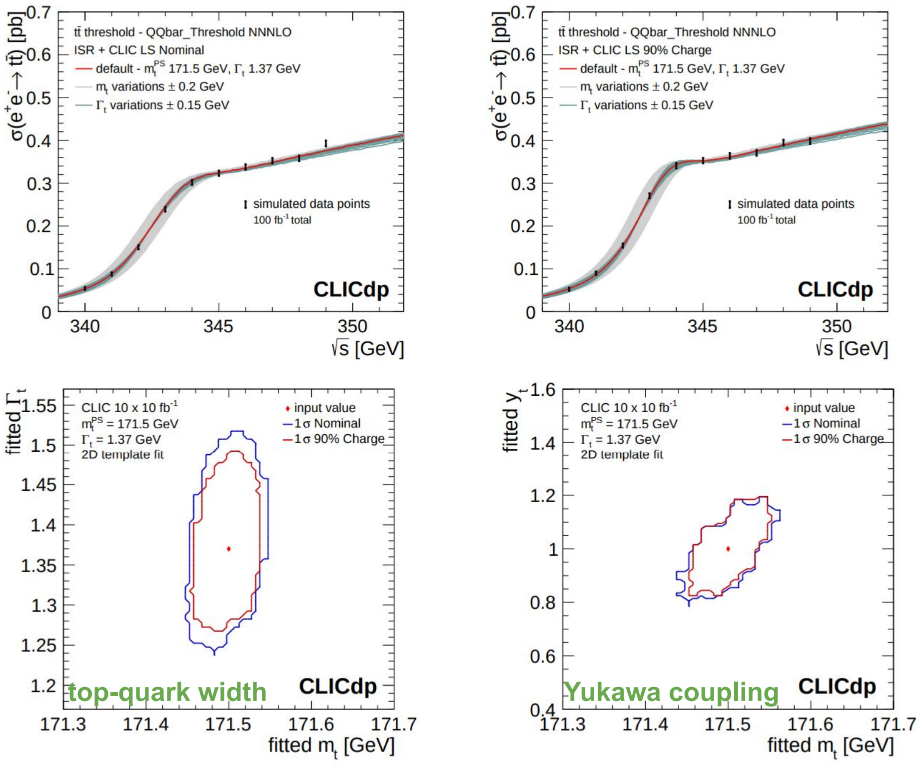
- $e^+e^- \rightarrow tt$
  - Production threshold at $\sqrt{s} \sim 2m_{top}$
  - Large event sample at 380 GeV
  - Threshold scan around 350 GeV
- $e^+e^- \rightarrow ttH$
  - Maximum near 800 GeV
- $e^+e^- \rightarrow tt\nu_e\nu_e$ (Vector Boson Fusion):
  - Benefits from highest energies
  - Potential high-energy probe of the Top Yukawa coupling



All Top studies summarised in [arXiv:1807.02441](https://arxiv.org/abs/1807.02441)

Top Threshold Scan

- Energy scan: 10 points with 10 fb^{-1} from 340 GeV to 349 GeV
- $\sigma_{e+e- \to tt}$ around threshold is sensitive to well-defined 1s top-quark mass, width and other model parameters
- Statistical uncertainty: ≈ 20 MeV
- Expected uncertainty on the top-mass σ_{mtop} ≈ 50 MeV (dominated by theory NNLO scale uncertainties)
- Precision at the HL-LHC limited to several hundred MeV

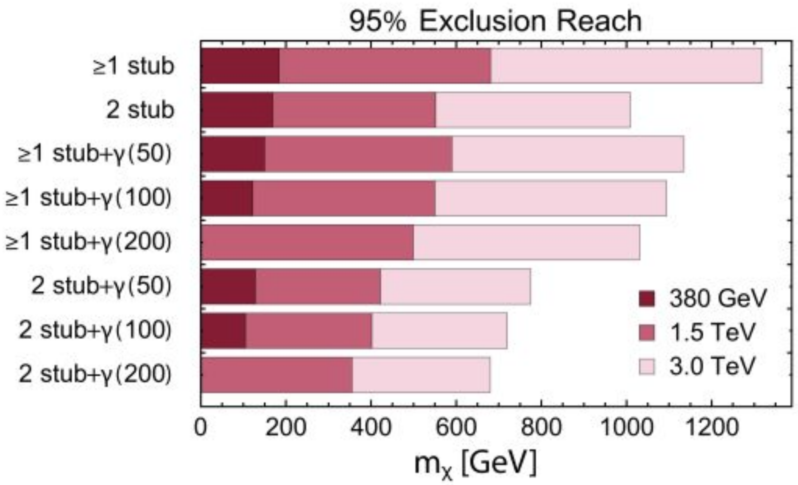


New physics searches

- CLIC operating at high energy provides significant discovery potential for BSM physics
- **Direct searches** of new particles:
  - Direct searches can find particles up to kinematic limit of 1.5 TeV
  - Possible observation of the new phenomena thanks to the low background (no QCD)
  - Precision measurements of new particle properties

Example: $e^+e^- \rightarrow \chi^+\chi^-$ (+γ)

Small mass difference: $\chi^\pm \rightarrow \chi^0\pi^\pm$
Long-lifetime: $\chi^\pm$ leaves a short, disappearing ("stub") track in the detector



CLIC has potential to discover the thermal Higgsino at 1.1 TeV

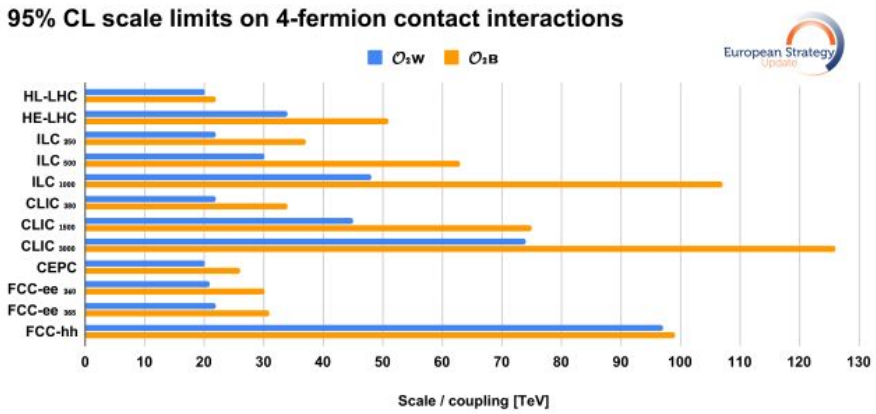
New physics searches

- CLIC operating at high energy provides significant discovery potential for BSM physics
- **Indirect searches** of new physics:
  - Precision measurements of sensitive observables reveal a signs of new physics, comparing to the SM expectations
  - Standard Model Effective Field Theory: contributions from new physics expressed by dimension-6 operators
  - <u>The reach is higher</u> – several tens of TeV

Example

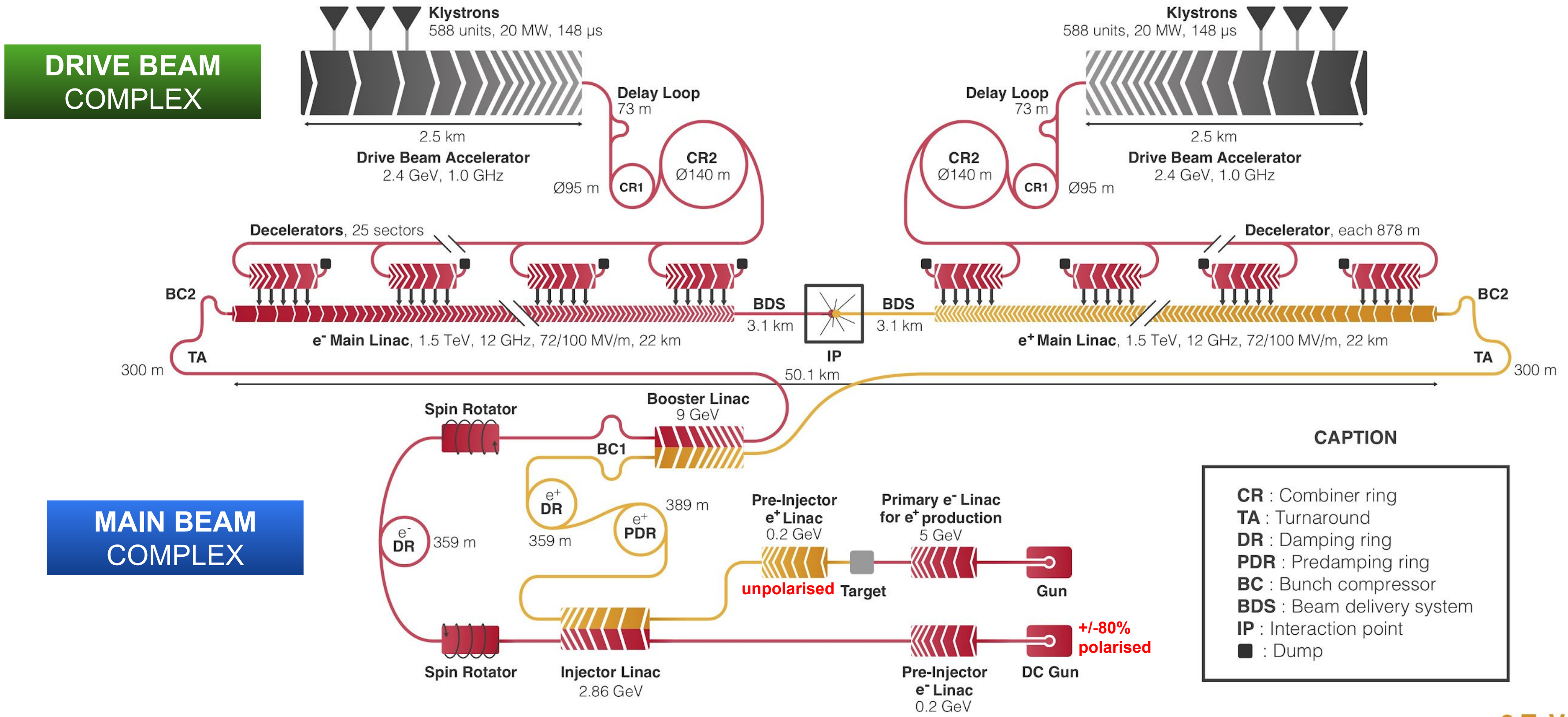
Projected limits from di-fermion final states

CLIC sensitivity increases significantly with √s



CLIC accelerator

CLIC accelerator layout @ 3 TeV

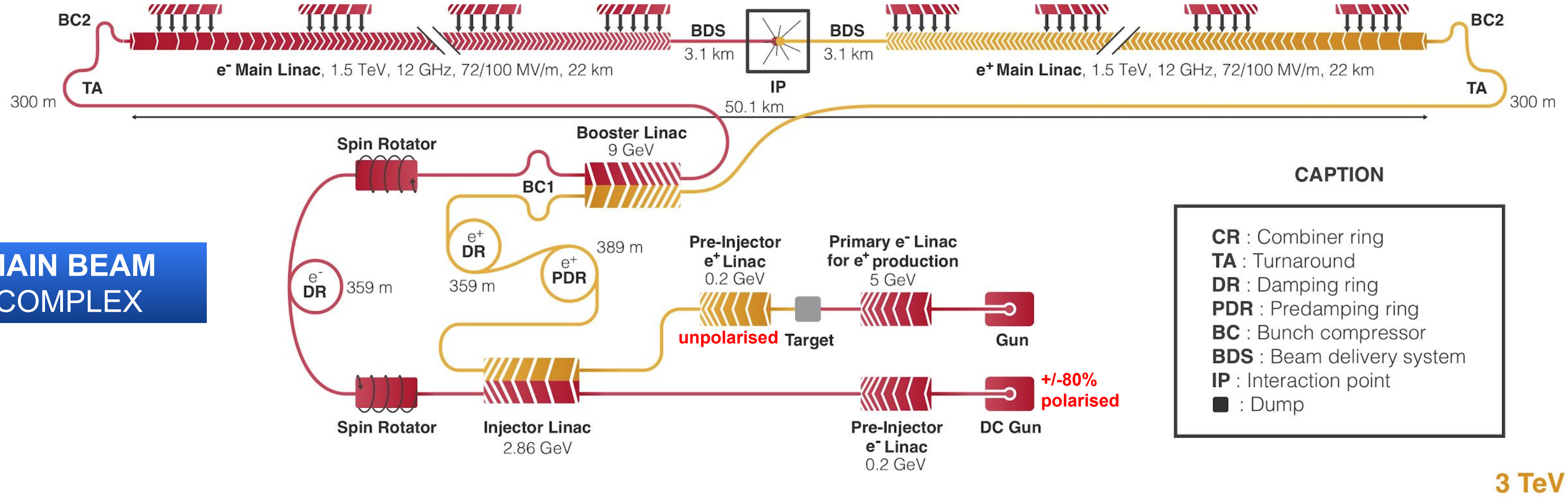


CAPTION

- **CR** : Combiner ring
- **TA** : Turnaround
- **DR** : Damping ring
- **PDR** : Predamping ring
- **BC** : Bunch compressor
- **BDS** : Beam delivery system
- **IP** : Interaction point
- ■ : Dump

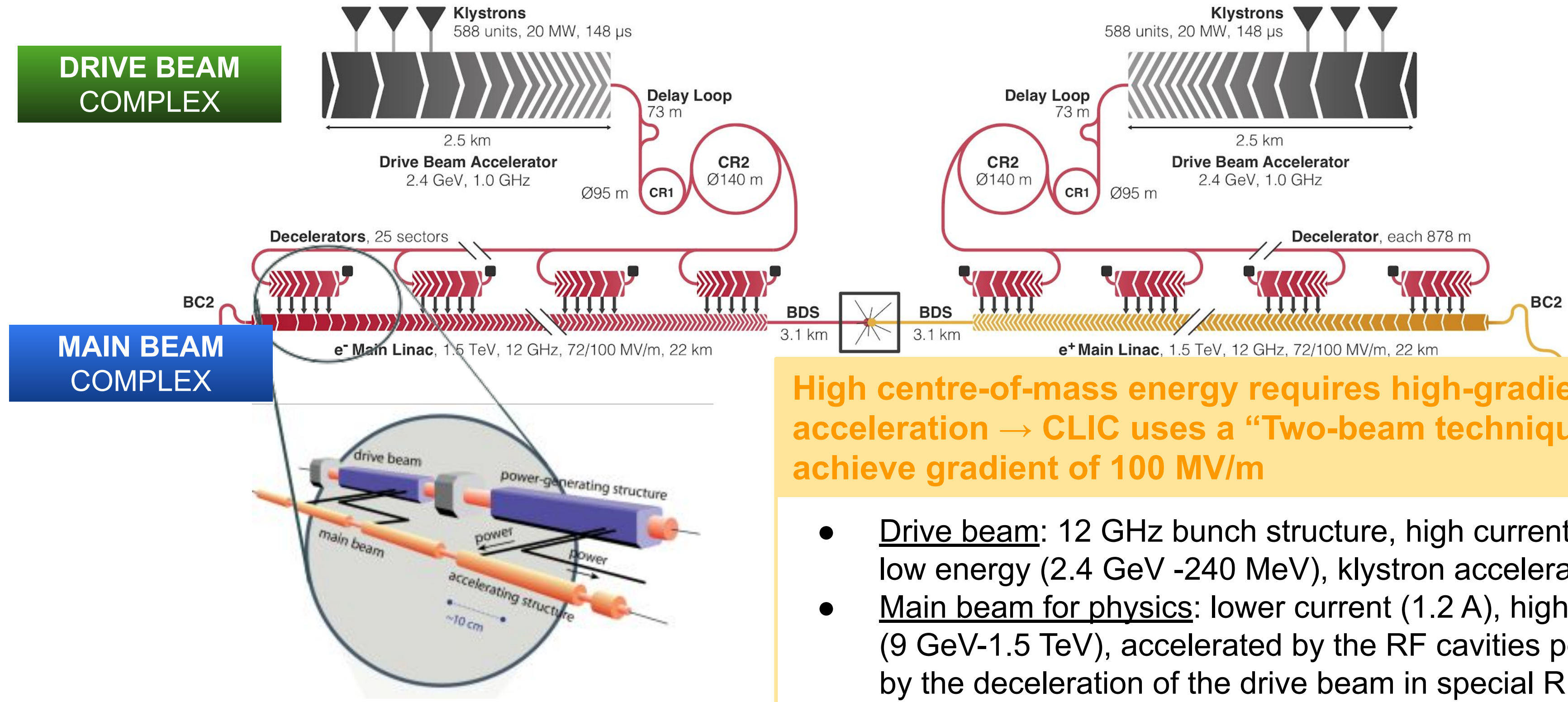
3 TeV

CLIC accelerator layout @ 3 TeV



MAIN BEAM COMPLEX

CLIC accelerator layout @ 3 TeV

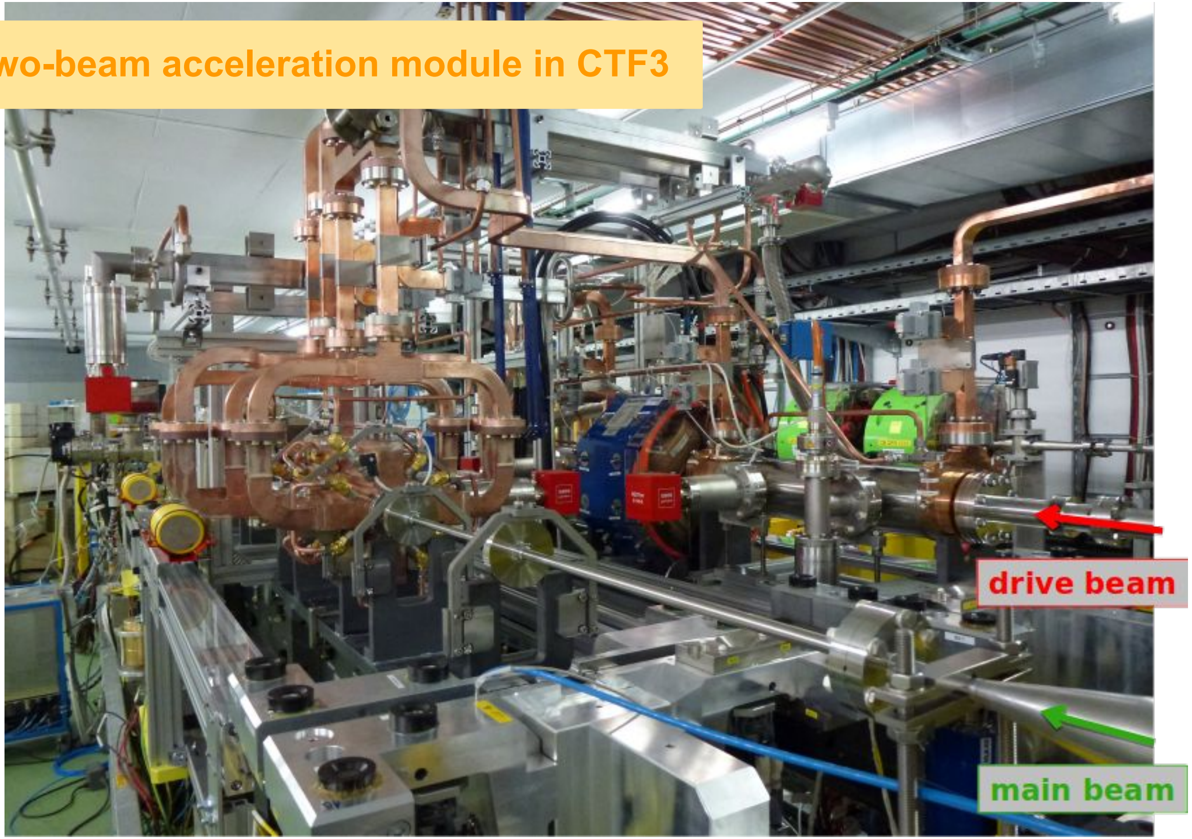


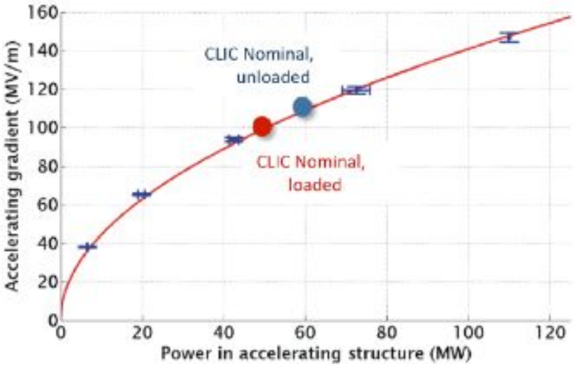
High centre-of-mass energy requires high-gradient acceleration → CLIC uses a "Two-beam technique" to achieve gradient of 100 MV/m

- Drive beam: 12 GHz bunch structure, high current (100 A), low energy (2.4 GeV -240 MeV), klystron acceleration
- Main beam for physics: lower current (1.2 A), high energy (9 GeV-1.5 TeV), accelerated by the RF cavities powered by the deceleration of the drive beam in special RF structures (PETS)

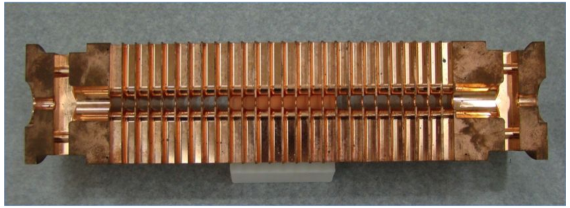
“Two-beam” setup

Two-beam acceleration module in CTF3

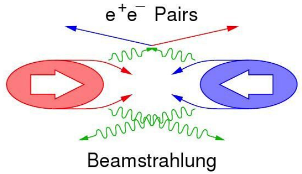


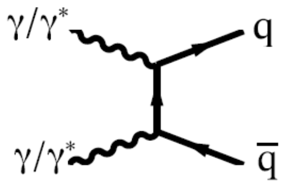


PETS

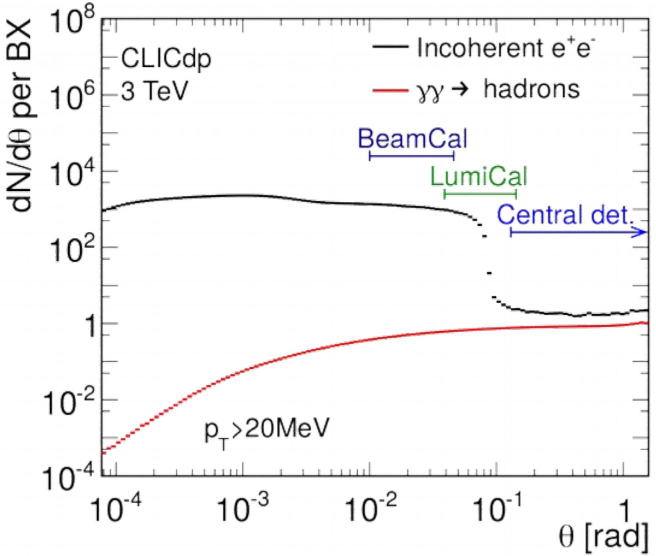


Experimental Conditions



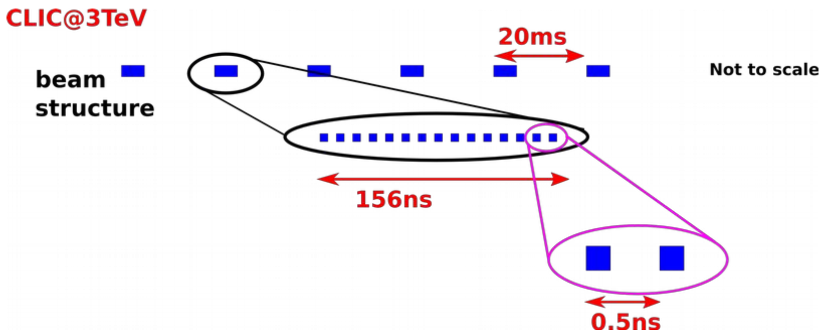


- High luminosities achieved by using extremely small beam sizes
  → CLIC bunch size (@3 TeV): **40 nm** (x) **x 1 nm** (y) **x 44 μm** (z)
  → very high EM-fields→ beam-beam interactions
- Main backgrounds:
  - **Incoherent e^+e^- pairs**
    - High occupancy
    - Mostly in the forward region
    - Impact on detector granularity and design
  - **γγ → hadrons**
    - High energy deposits
    - Impact on detector granularity, design and physics measurement
- Detector acceptance starts at 10 mrad



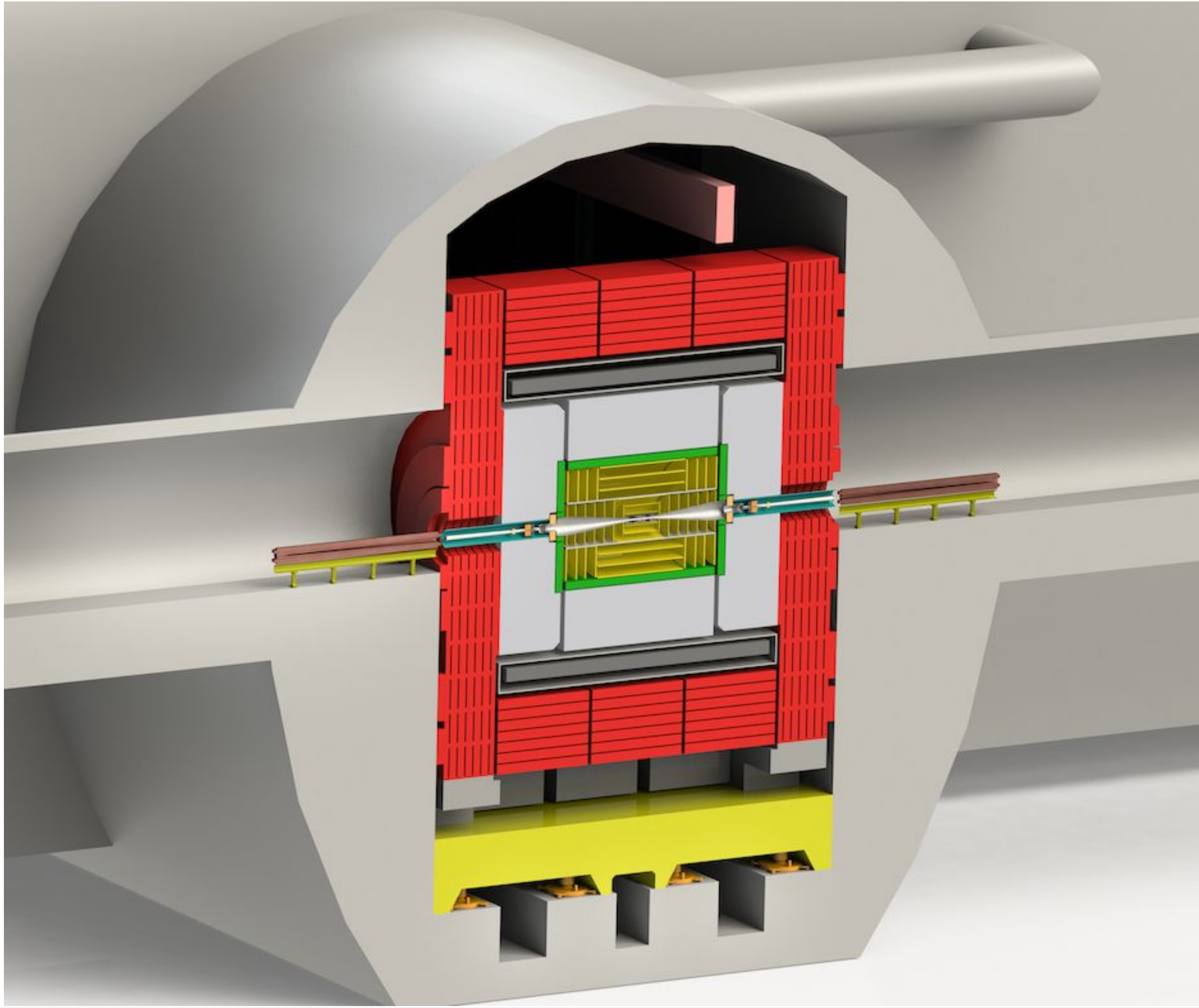
Experimental Conditions

- 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 separated by 0.5 ns (@ 3 TeV)



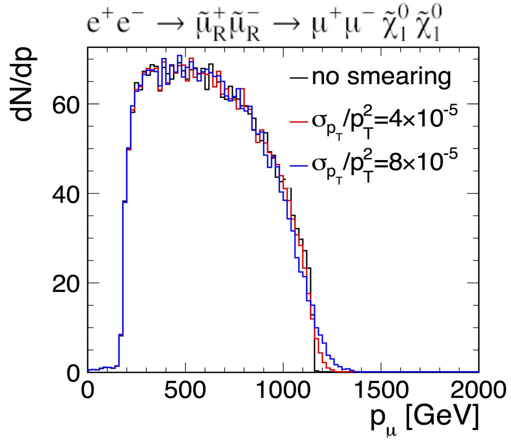
- Trigger-less readout foreseen
- Time structure of the beam & background suppression drive timing requirements for detector
  - 5 ns hit time-stamping in tracking
  - 1 ns hit time resolution for calorimeters

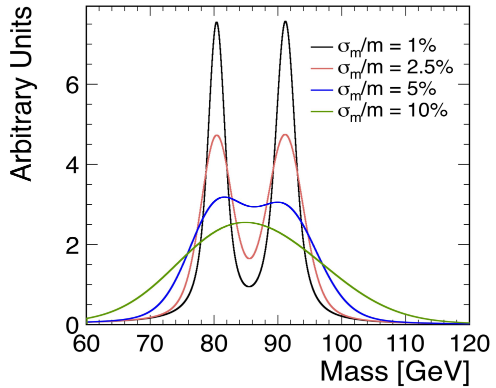
CLIC detector



Detector requirements

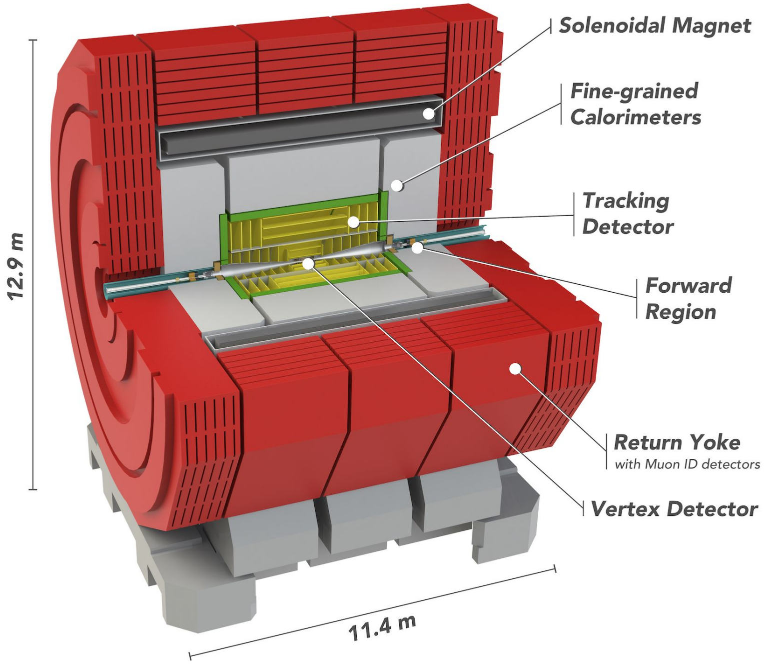
- Momentum resolution
  - e.g. Higgs coupling to muons, leptons from BSM
  - **$\sigma_{p_T}/p_T \sim 2 \times 10^{-5}$ GeV $^{-1}$** above 100 GeV
- Jet energy resolution
  - e.g. separation of W/Z/H di-jets
  - **$\sigma_E/E \sim 5\% - 3.5\%$** for jets at 50 GeV – 1000 GeV
- Impact parameter resolution
  - e.g. b/c-tagging, Higgs couplings
  - **$\sigma_{r\varphi} \sim a \oplus b / (p[\text{GeV}] \sin^{3/2}\theta)$ µm**
    with a = 5 µm, b = 15 µm
- Lepton identification efficiency **> 95 %**
- Angular coverage
  - Very forward electron and photon tagging
  - Down to **θ = 10 mrad** (η = 5.3)





The CLIC detector model

Designed for Particle Flow Analysis and optimised for CLIC environment!

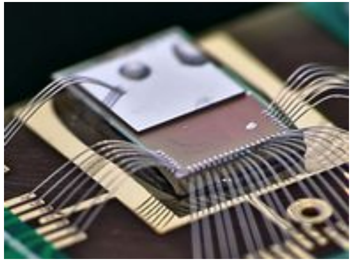


- Superconducting solenoid with 4T magnetic field
- Vertex detector
  - 3 double layers with 25 × 25 μm2 pixels
  - Extremely accurate (σ < 3 μm) and light (< 0.2 % X0 per layer)
- Silicon Tracker
  - Composed of large pixels/strips
  - Outer R ~ 1.5 m
  - 5 ns hit time-stamping in tracking
- Fine grained calorimeters
  - Si-W ECAL
    - 40 layers → 22 X_0 and 1 λ_I
    - 5 × 5 mm^2 Si cell size (~ 2500 m^2)
    - 1 ns accuracy for calo hits
  - Scint-Fe HCAL
    - 60 layers → 7.5 λ_I
    - 30 × 30 mm^2 scintillator cell size (~ 9000 m^2) +SiPM
    - 1 ns accuracy for calo hits
- Forward calorimeters
  - very forward electron tagging and luminosity measurements
- Return yoke & muon chambers
  - Mainly for muon ID

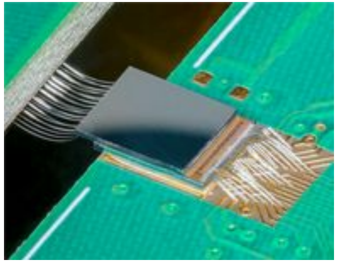
Detector Technology R&D

Vertex & Tracker

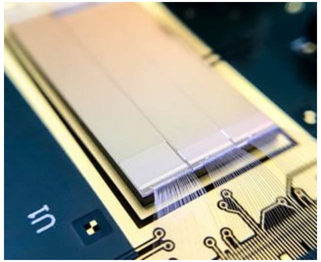
Hybrid detectors
CLICpix + 50 um sensor



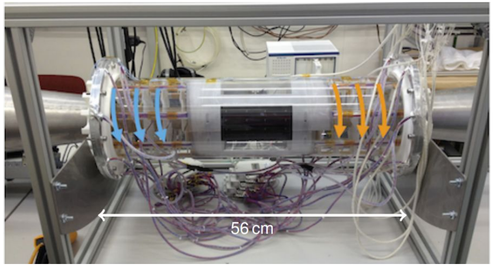
Hybrid detectors
CLICpix2 + C3PD



Monolithic detectors
AtlasPix_Simple

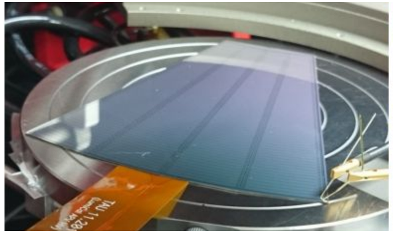


Detector integration
Cooling system

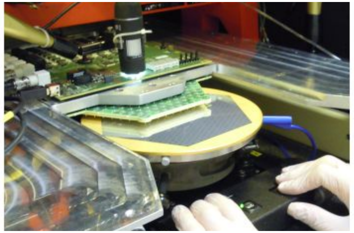


Calorimeters

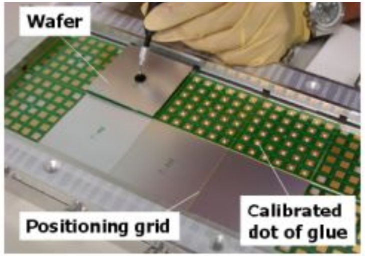
FCAL LumiCal silicon sensors
1.8 mm wide strips



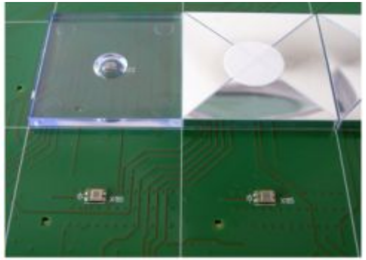
CMS HGcal silicon sensors
~1 cm^2 cells on 8-inch wafer



CALICE silicon PIN diodes
1x1 cm^2 in 6x6 matrices



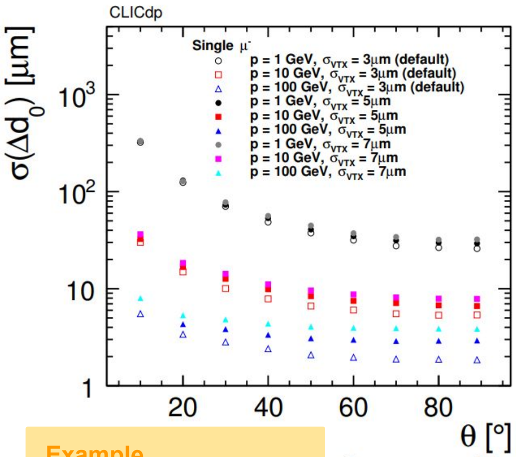
CALICE scint. tiles + SiPMs
3x3 cm^2 cells



Simulation and optimization

- Full Geant4 detector simulation including overlay of beam-induced backgrounds
- Full reconstruction chain:
  - reconstruction of tracks and clusters
  - particle flow objects
  - jets
  - flavor tagging
- Optimization of 3 TeV CLIC detector model in full detector simulations
  - → Ensure that detector performance meets requirements
- Software tools widely used

DIRAC THE INTERWARE iLCSoft iLCDIRAC DD4hep

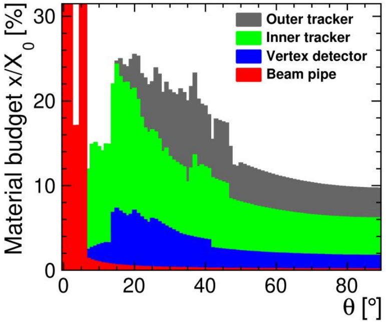


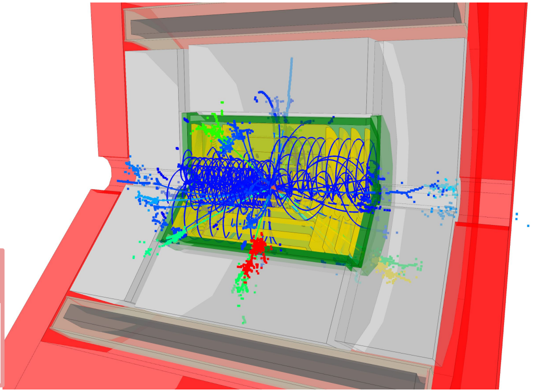
Example

Vertex detector single point resolution ↔ track impact parameter resolution

Example

Material budget in full simulation





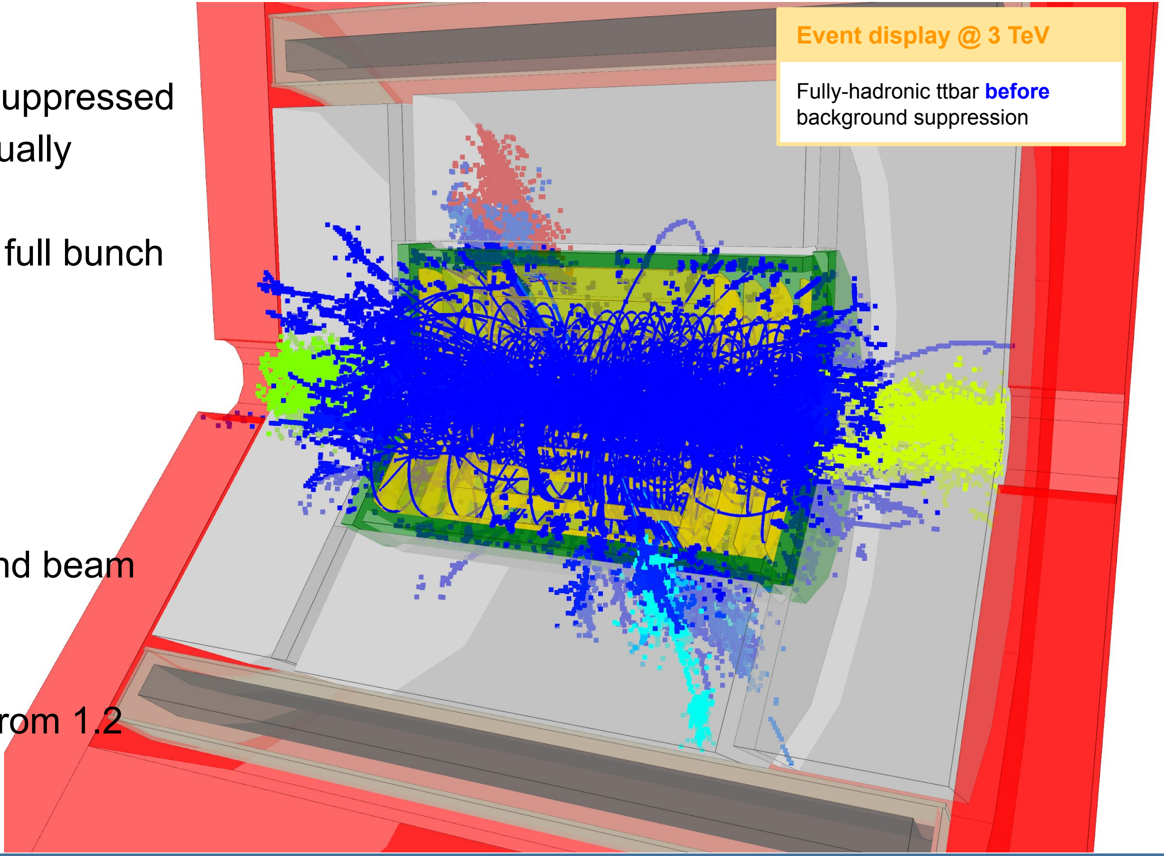
Example @ 380 GeV

Fully-hadronic ttbar event + $\gamma\gamma \rightarrow$ hadrons

Beam-induced background rejection

- γγ → hadrons background can be suppressed by **p_T vs. time** selections on individually reconstructed particles
- Identify time of physics event in the full bunch train
- Suppression via
  - Cluster time
  - Particle type
  - p_T
- Cuts adapted per detector region and beam energy

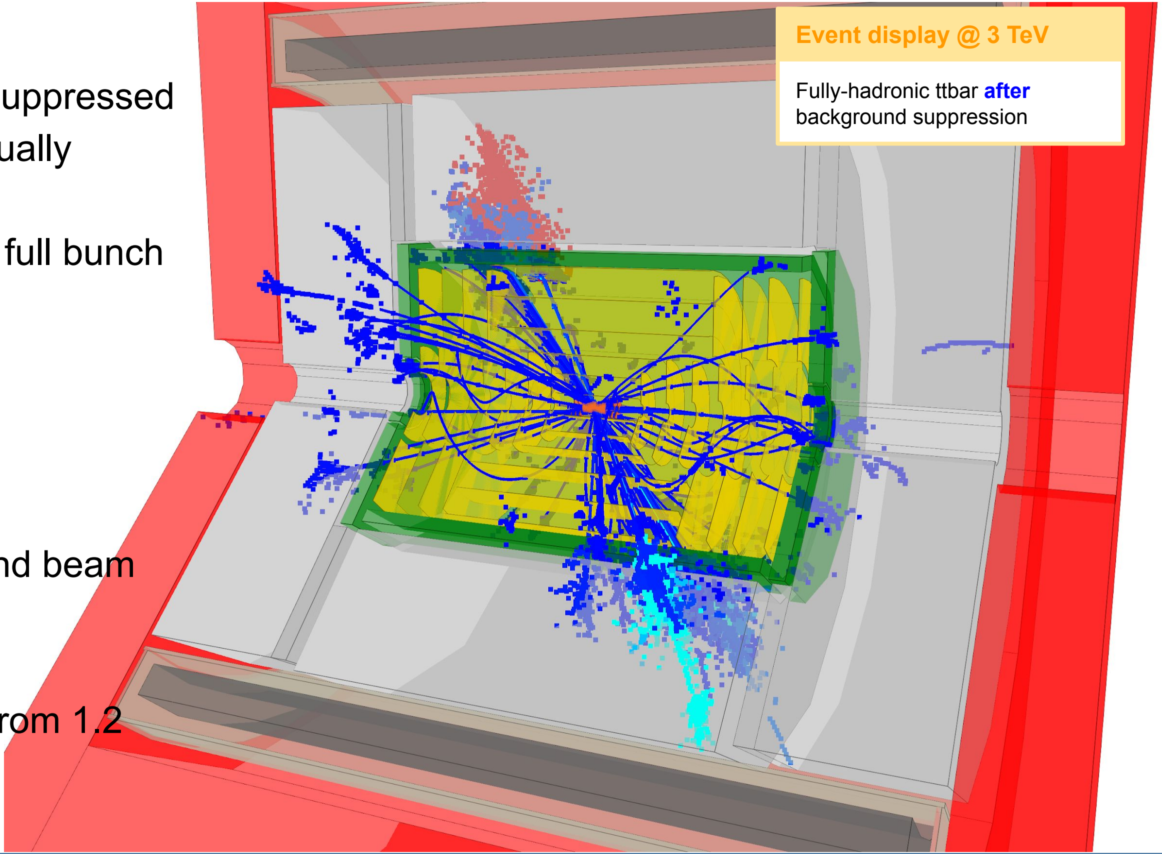
- Selection cuts reduce background from 1.2 TeV to 100 GeV @ 3 TeV!



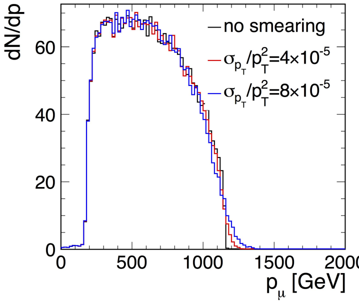
Beam-induced background rejection

- $\gamma\gamma \rightarrow$ hadrons background can be suppressed by **p_T vs. time** selections on individually reconstructed particles
- Identify time of physics event in the full bunch train
- Suppression via
  - Timing requirements
  - Particle type
  - Retaining high-p T objects
- Cuts adapted per detector region and beam energy

- Selection cuts reduce background from 1.2 TeV to 100 GeV @ 3 TeV!



Detector requirements & performance



- **Momentum resolution**
  - e.g. Higgs coupling to muons, leptons from BSM
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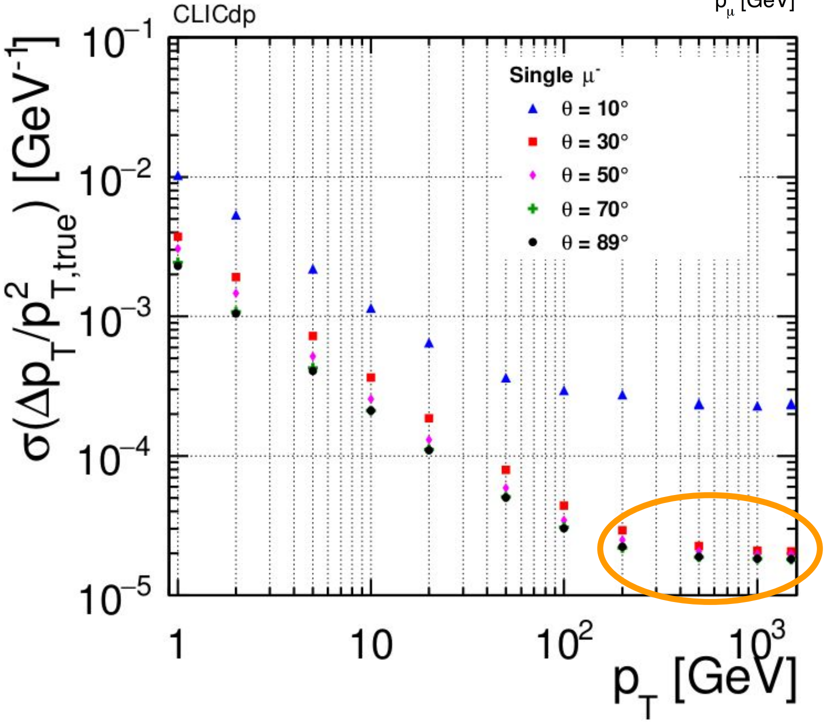
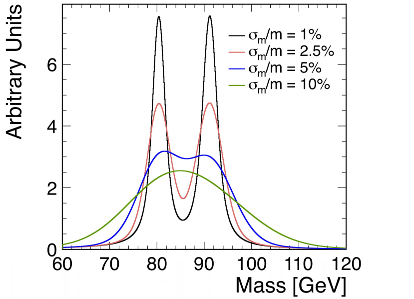


Detector requirements & performance



- Momentum resolution
  - e.g. Higgs coupling to muons, leptons from BSM
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- **Jet energy resolution**
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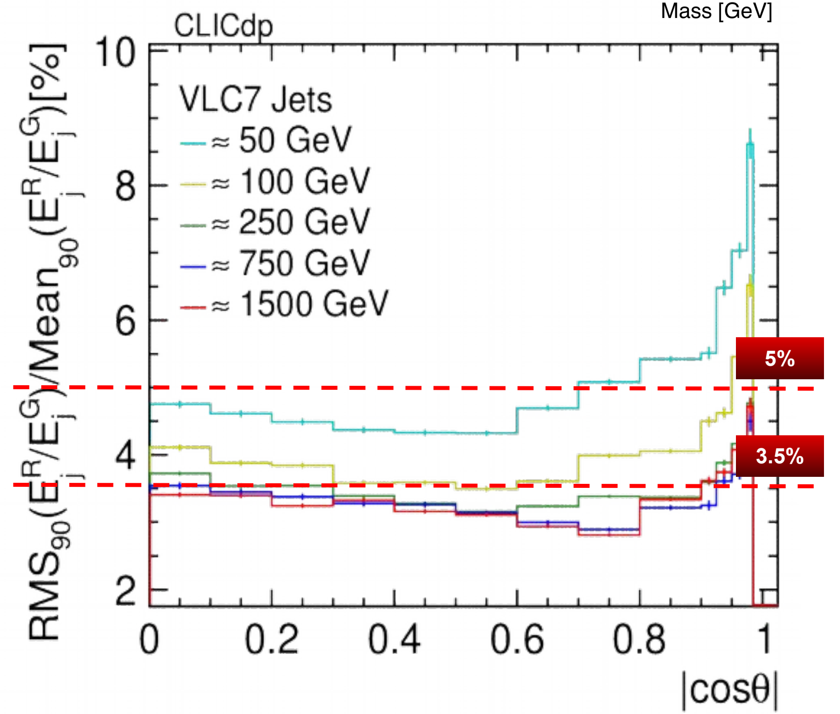
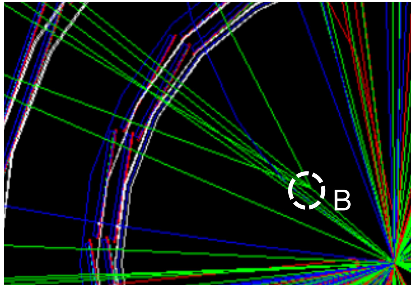
  - Down to **θ = 10 mrad** (η = 5.3)



Detector requirements & performance



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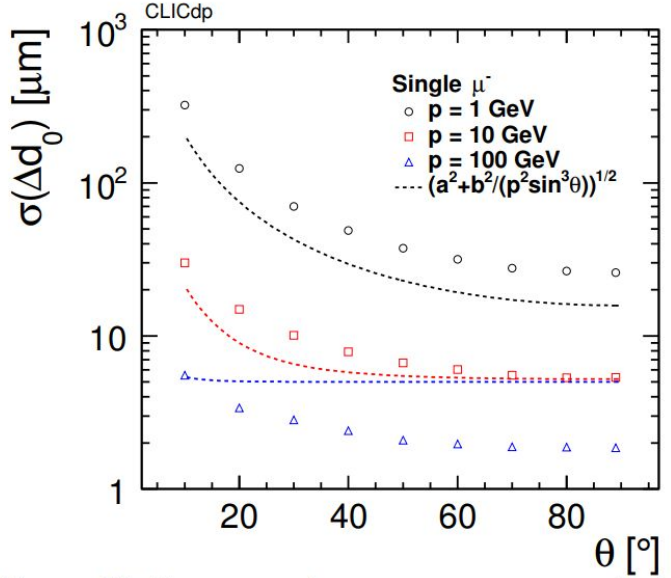

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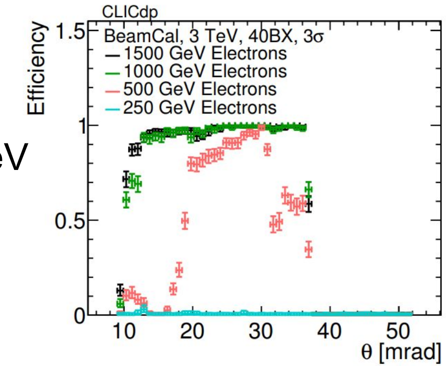
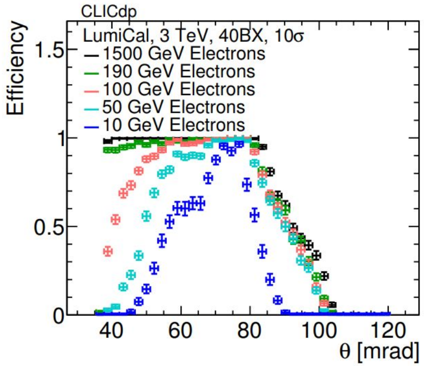
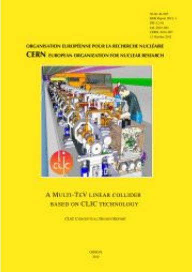
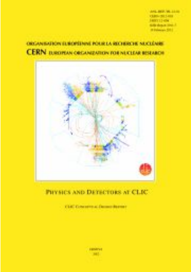


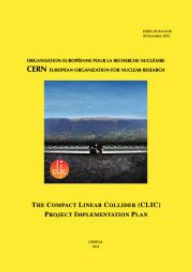


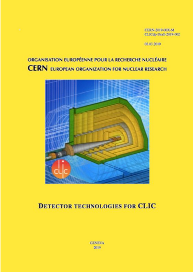
CLICdet parameters and performance: arXiv:1812.07337

Summary Documents







- **2012** CLIC Conceptual 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

+ Many supporting notes and papers

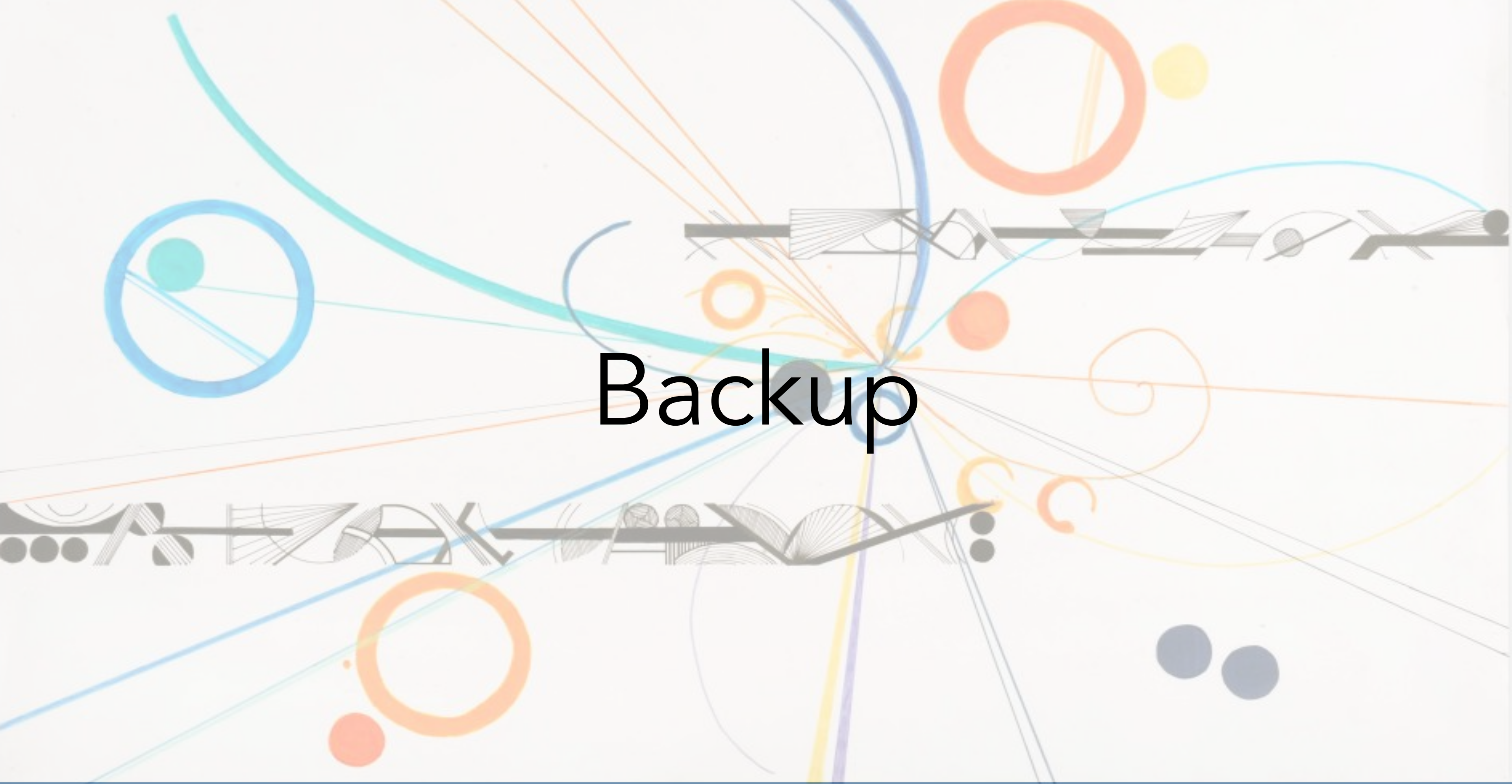
- Two formal ESU submissions:
  - http://clic.cern/european-strategy

Summary & conclusions

- CLIC is a **mature international project** with possible start from 2035
- CLIC offers opportunity for **broad precision physics program**
  - 380 GeV Optimised for high precision measurements of Higgs boson and top quark
  - 1.5, 3 TeV Best sensitivity for BSM searches, rare Higgs processes and decays
- CLIC environment and physics goals lead to challenging **requirements**
- Detector model CLICdet **optimized and validated** in full simulation
- **Broad and active R&D** on vertex and tracking detectors

  + synergies with CALICE and FCAL collaborations for R&D on calorimeters
- 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

“My own visions of CLIC”, artwork by Natasha de Heney, 2010



Backup

Beam-induced background rejection

- $\gamma\gamma \rightarrow$ hadrons background can be suppressed by $\mathbf{p_T}$ **vs. time** selections on individually reconstructed particles
- Identify time of physics event in the full bunch train
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  - Particle type
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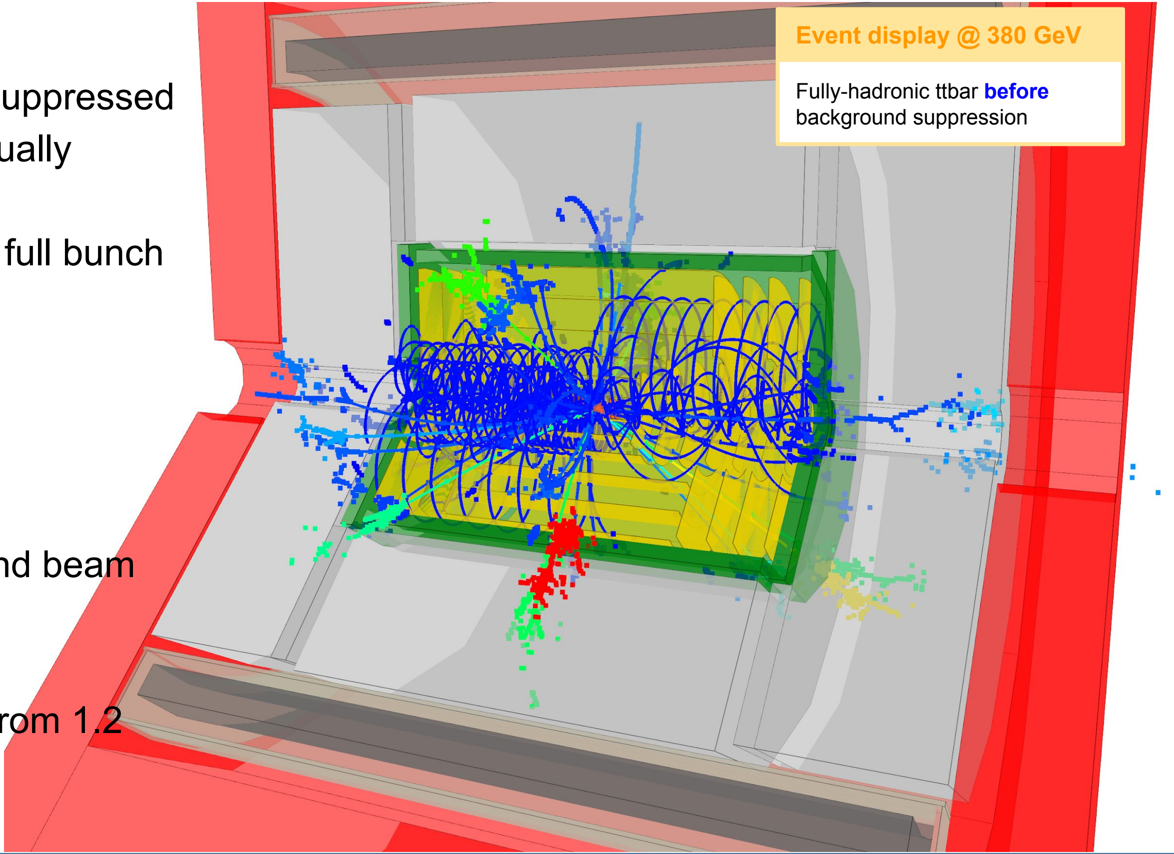
- Cuts adapted per detector region and beam energy
- Selection cuts reduce background from 1.2 TeV to 100 GeV @ 3 TeV!



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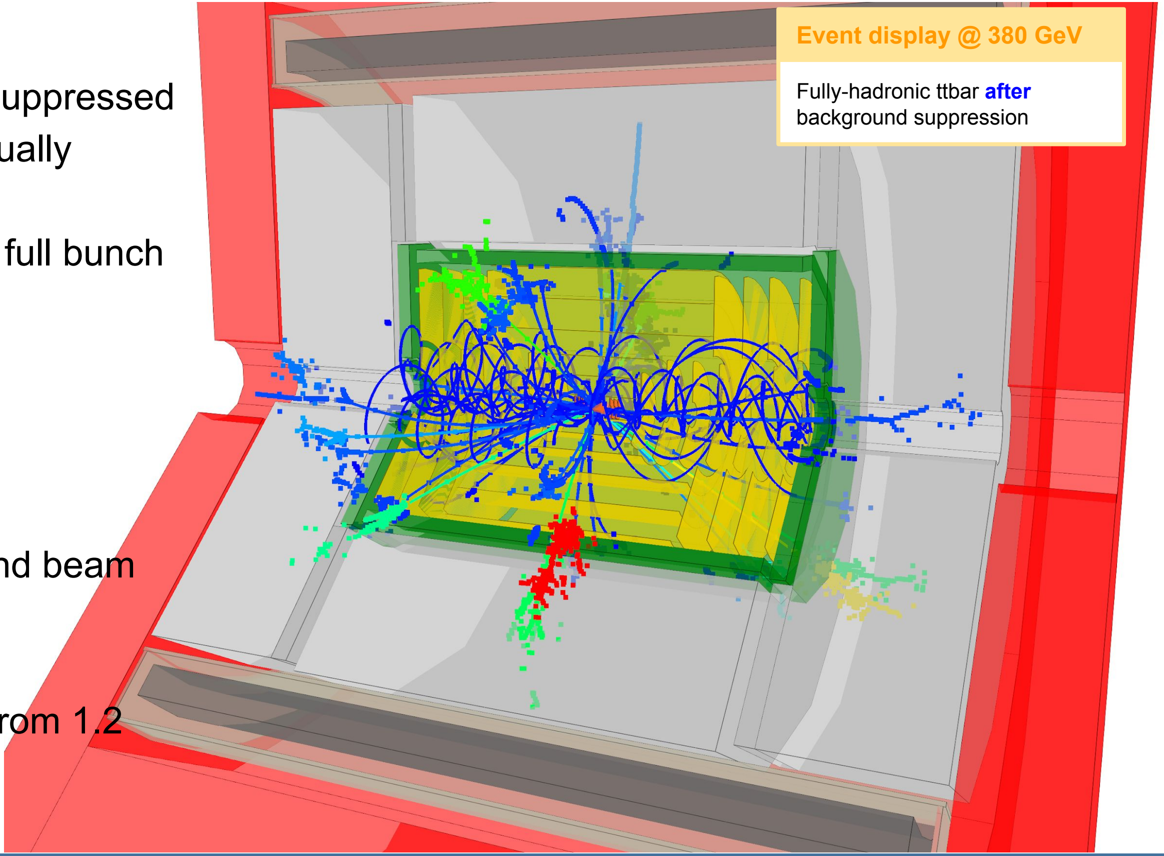

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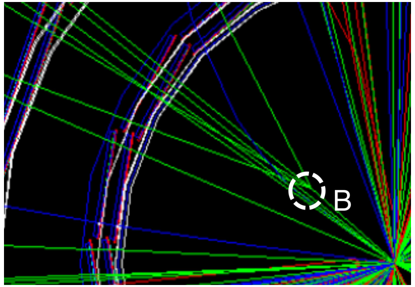

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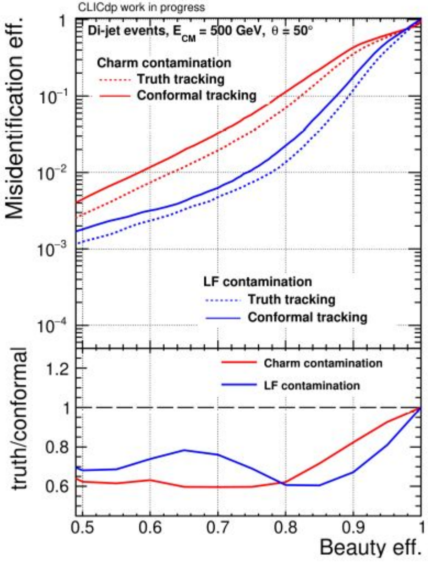
b-tagging



c-tagging