

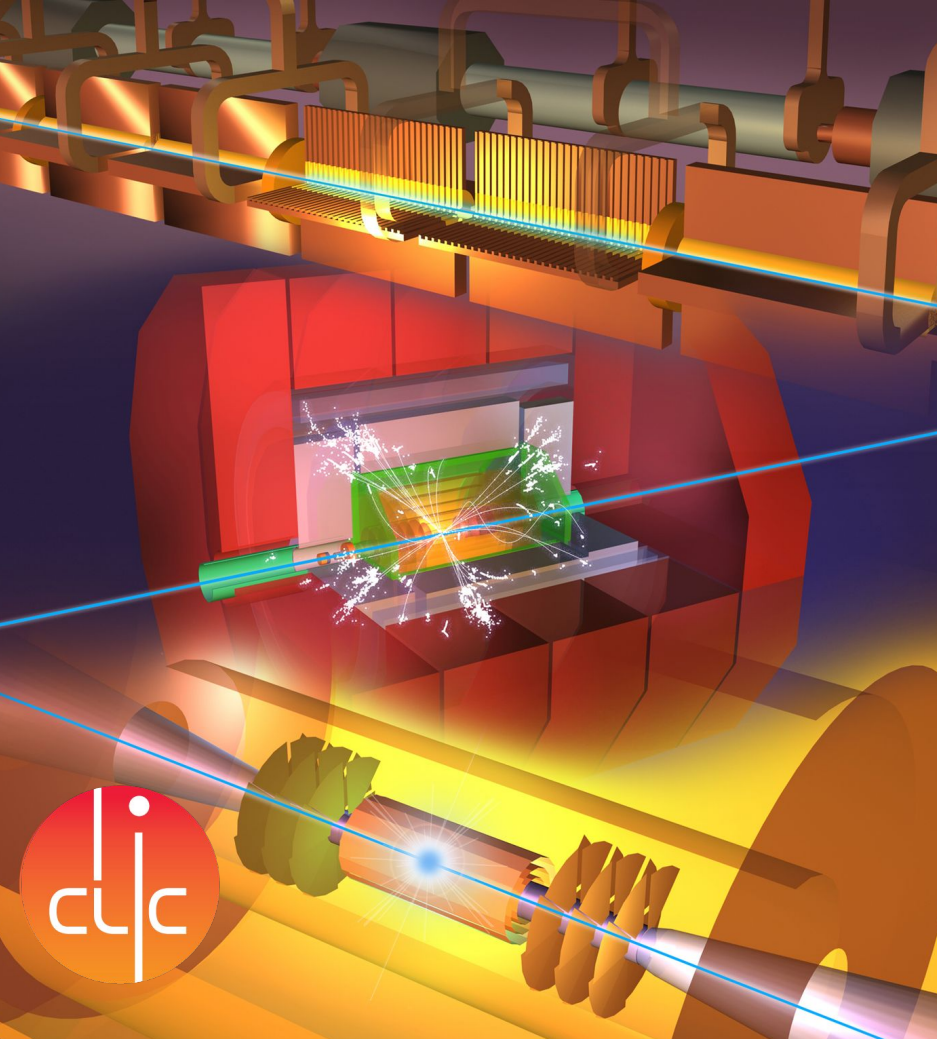


CLIC

Erica Brondolin, on behalf of CLIC & CLICdp collaborations

Chicago workshop on the Circular Electron Positron Collider

16th September 2019

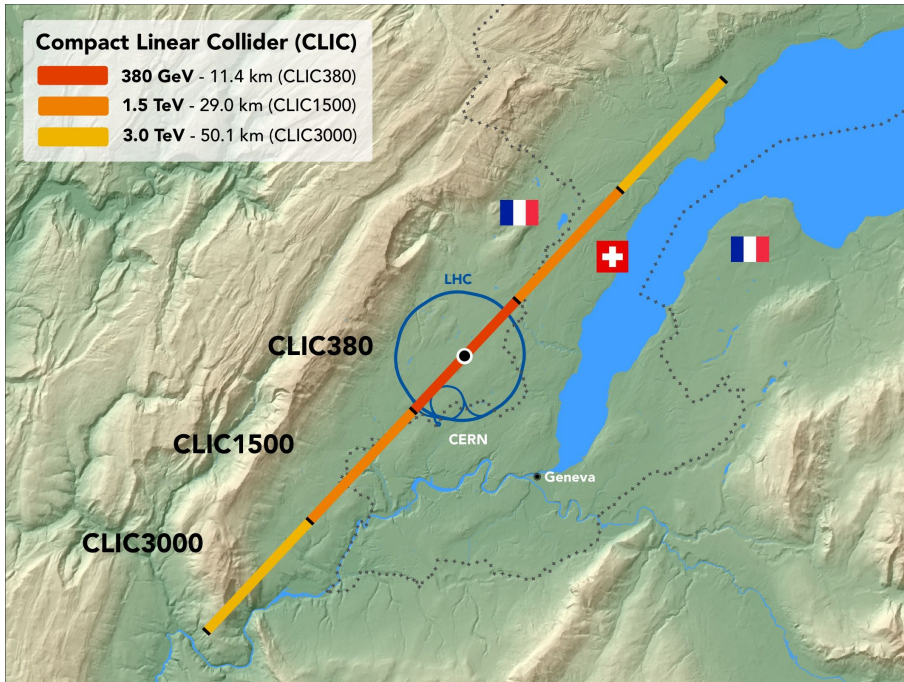


Outline



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





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

CLIC accelerator studies:

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

Focus of CLIC-specific studies on:

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



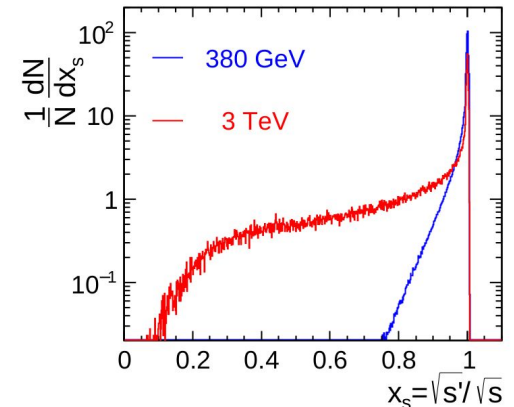
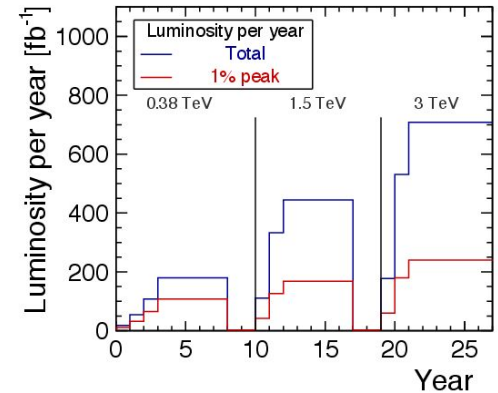
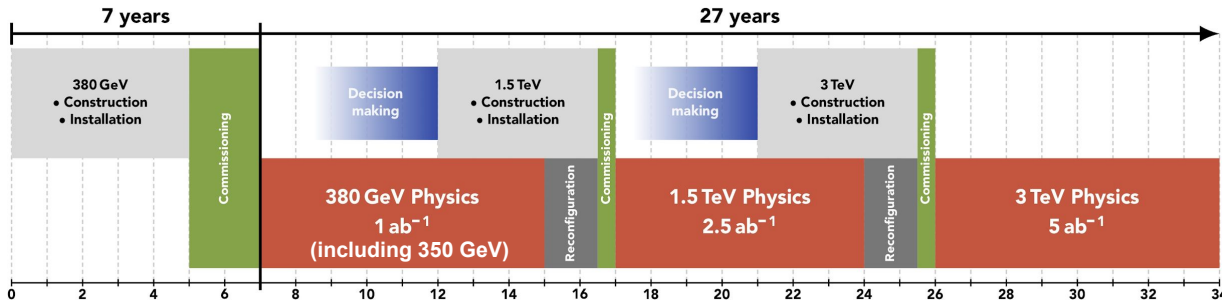


CLIC Physics Potential

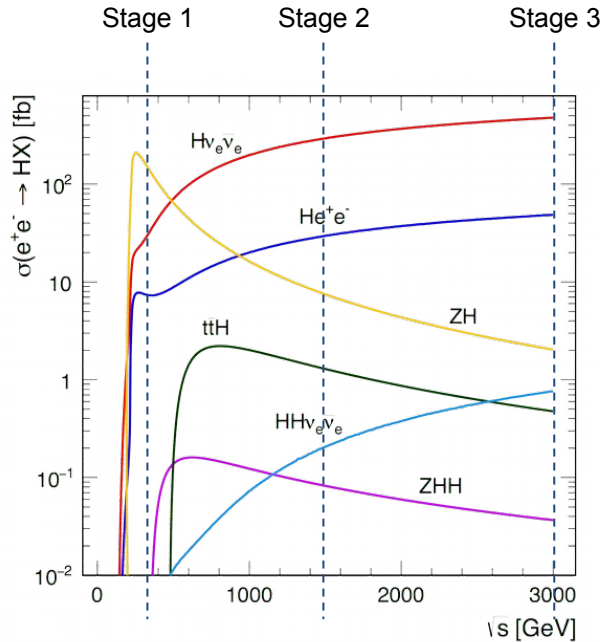
Physics Potential
CLIC



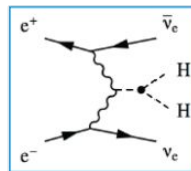
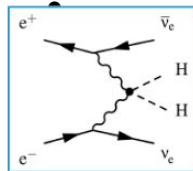
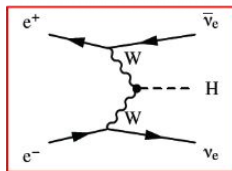
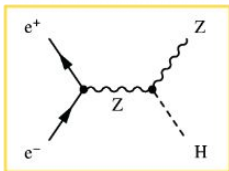
- Physics programme extends over 25–30 years
- Electron polarisation :
 - $\pm 80\%$ longitudinal polarization for the electron beam
 - Enhances Higgs production at high-energy stages
 - Provides additional observables sensitive to BSM physics
 - Helps to characterise new particles in case of discovery
- Luminosity spectrum
 - Due to beamstrahlung, important energy losses right at the interaction point
 - Effect is dependent on \sqrt{s}
 - Collision energy is reduced by the amount lost in beamstrahlung before collision
- Baseline scenario:



Higgs Physics

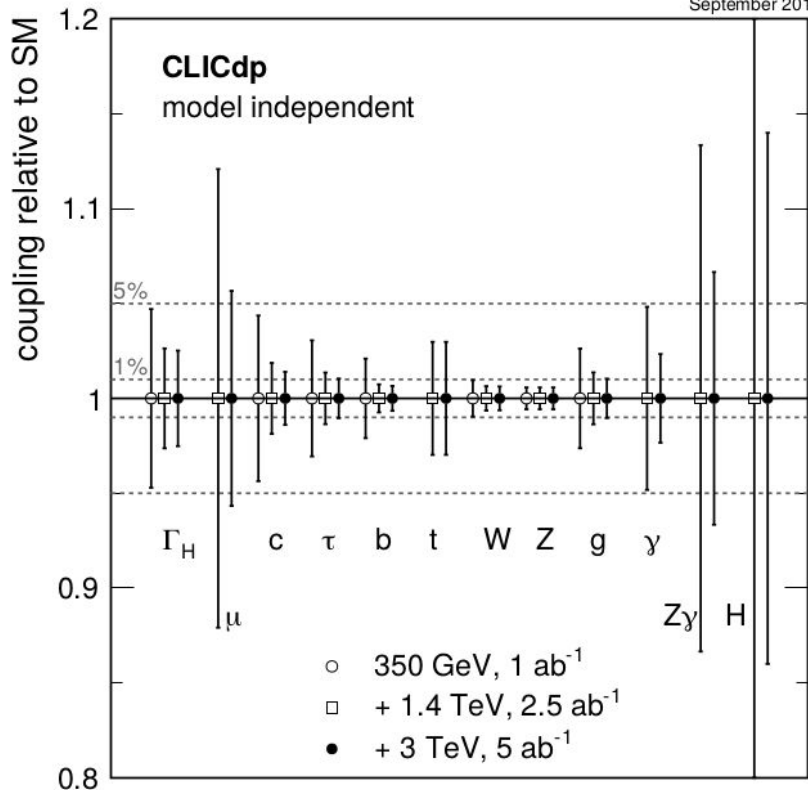


- **Higgsstrahlung: $e^+e^- \rightarrow ZH$**
 - $\sigma \sim 1/s$, dominant up to ~ 450 GeV
 - Higgs identification from recoil
- **WW fusion: $e^+e^- \rightarrow H\nu_e\nu_e$**
 - $\sigma \sim \log(s)$, dominant above ~ 450 GeV
 - Large statistics at high energy \rightarrow rarer decays
- **$e^+e^- \rightarrow HH\nu_e\nu_e$**
 - 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](https://arxiv.org/abs/1705.02524)

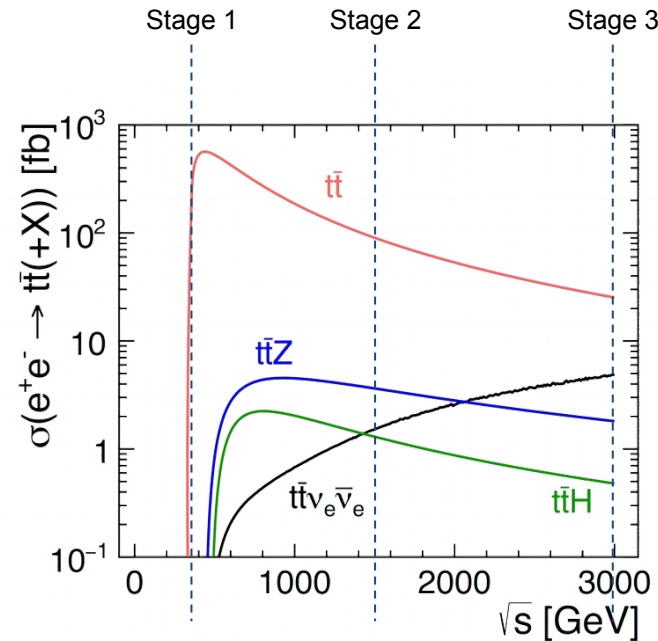
September 2018



- **Fully model-independent analysis:**
 - Free parameters Γ_H and ten Higgs couplings
 - No assumption on invisible Higgs decays
- High precision measurements @ **CLIC**:
 - Couplings with **sub-1% level** (at 1% for rare decays)
 - The Higgs width is extracted with **4.7 – 2.5%** precision
- Many Higgs couplings can be measured **significantly better CLIC** compared to HL-LHC
- Some couplings are very challenging at hadron colliders
 - **Example: $H \rightarrow cc$**

[arXiv:1907.04311](https://arxiv.org/abs/1907.04311)

Top Physics



- $e^+e^- \rightarrow tt$

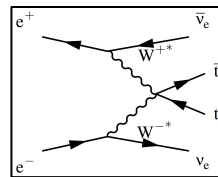
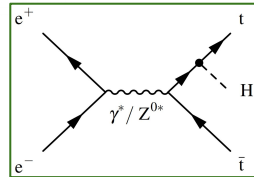
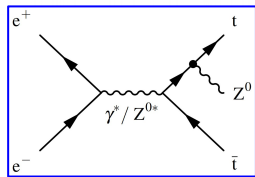
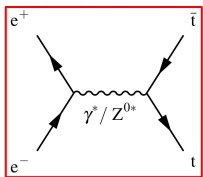
- Production threshold at $\sqrt{s} \sim 2m_{\text{top}}$
- Large event sample at 380 GeV
- Threshold scan around 350 GeV

- $e^+e^- \rightarrow ttH$

- Maximum near 800 GeV

- $e^+e^- \rightarrow ttv_e v_e$ (Vector Boson Fusion):

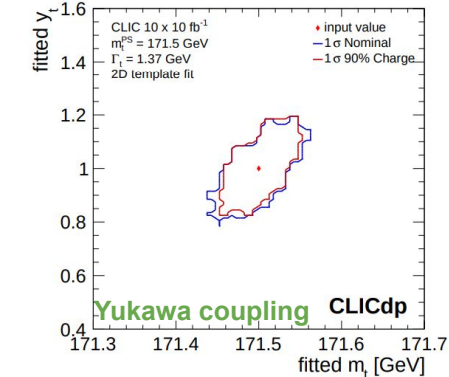
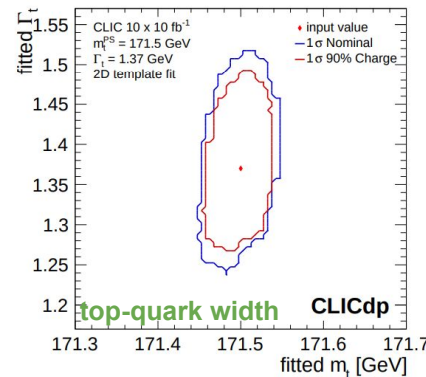
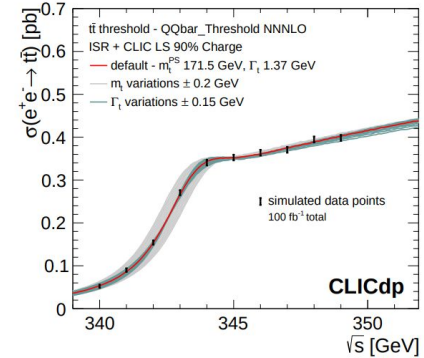
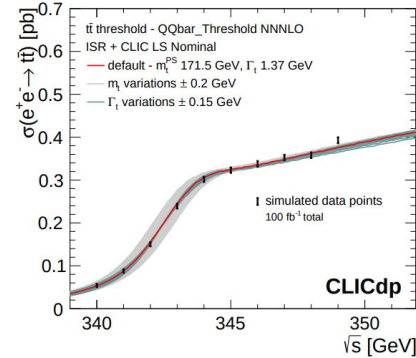
- Benefits from highest energies
- Potential high-energy probe of the Top Yukawa coupling



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
- $\sigma_{e^+e^- \rightarrow t\bar{t}}$ around threshold is sensitive to well-defined 1s top-quark mass, width and other model parameters
- Statistical uncertainty: $\approx 20 \text{ MeV}$
- Expected uncertainty on the top-mass $\sigma_{m_{\text{top}}} \approx 50 \text{ MeV}$ (dominated by theory NNNLO scale uncertainties)
- Precision at the HL-LHC limited to several hundred MeV

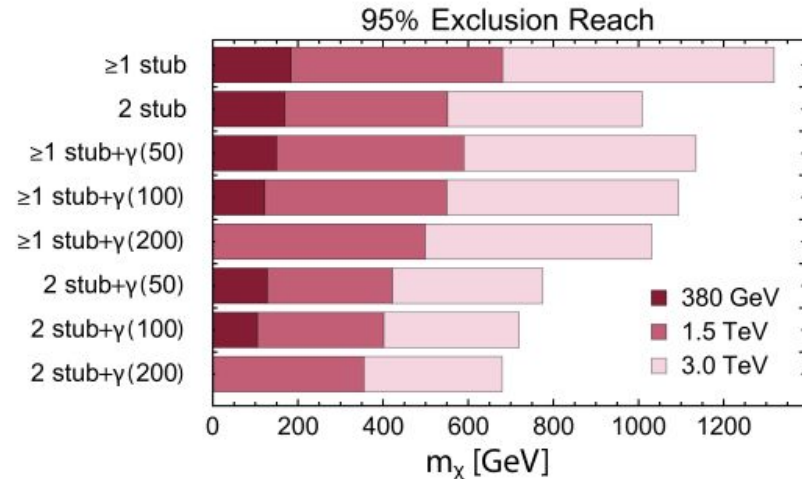


- CLIC operating at high energy provides significant discovery potential for BSM physics
- **Direct searches** of new particles:
 - Direct searches can find particles up to kinematic limit of 1.5 TeV
 - Possible observation of the new phenomena thanks to the low background (no QCD)
 - Precision measurements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

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

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

CLIC have potential to discover the thermal Higgsino at 1.1 TeV



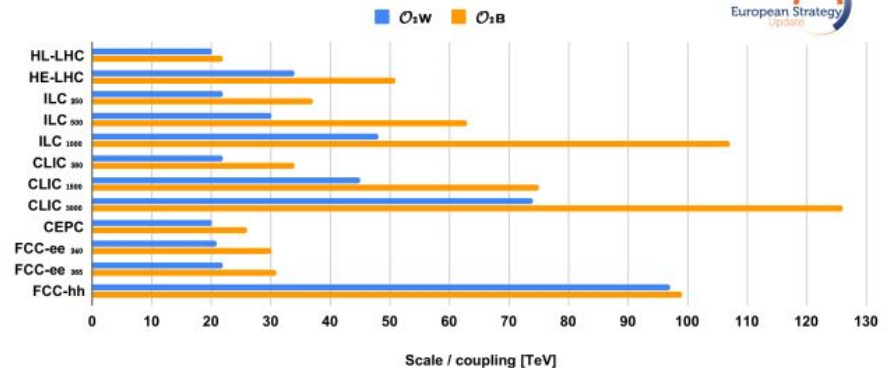
- CLIC operating at high energy provides significant discovery potential for BSM physics
- **Indirect searches** of new physics:
 - Precision measurements of sensitive observables reveal a signs of new physics, comparing to the SM expectations
 - Standard Model Effective Field Theory: contributions from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

Example

Projected limits from di-fermion final states

CLIC sensitivity increases significantly with \sqrt{s}

95% CL scale limits on 4-fermion contact interactions





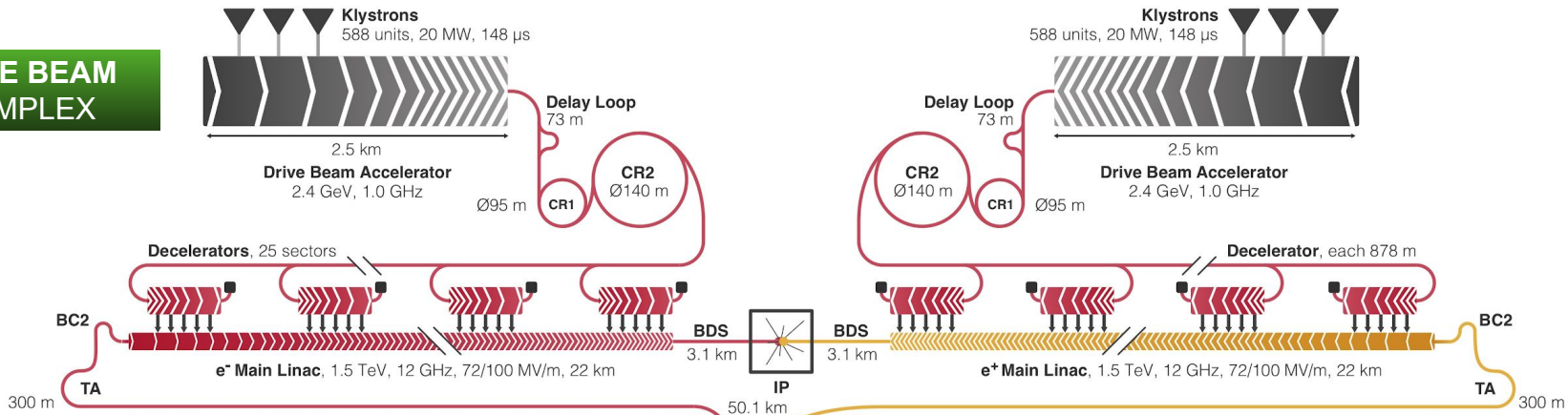
CLIC accelerator

CLIC accelerator

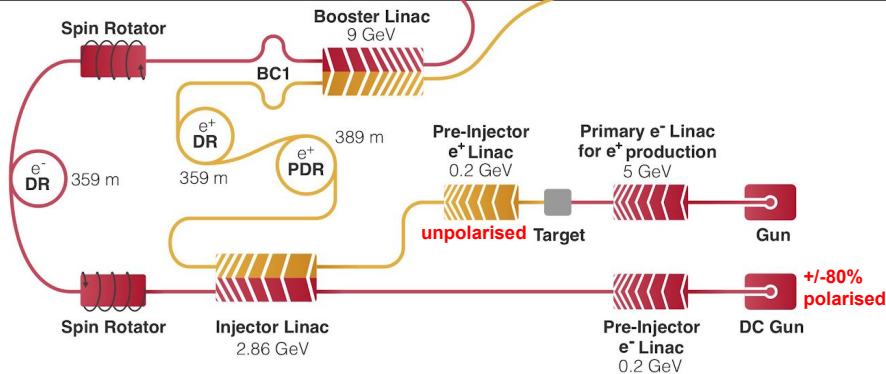


CLIC accelerator layout @ 3 TeV

DRIVE BEAM COMPLEX



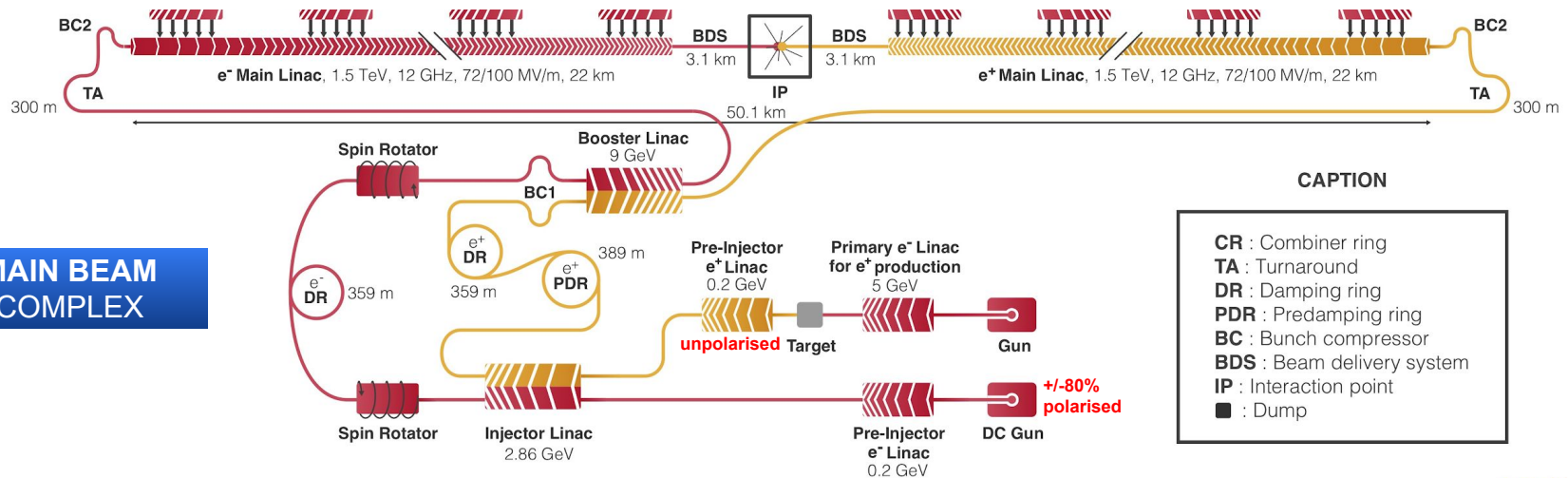
MAIN BEAM COMPLEX



CAPTION

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

3 TeV



MAIN BEAM COMPLEX

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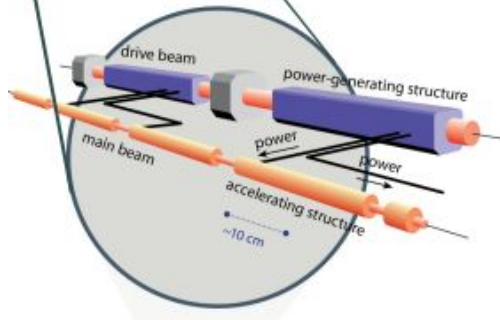
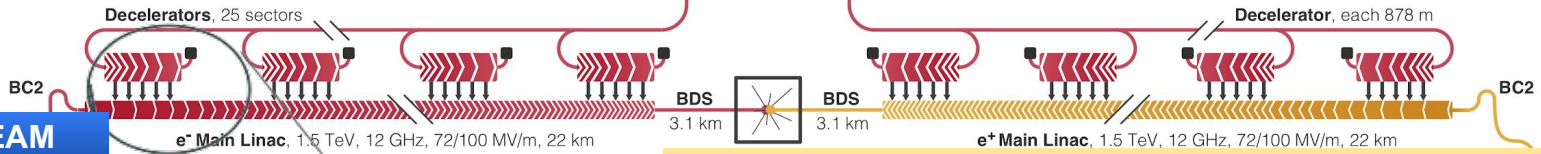
3 TeV

CLIC accelerator layout @ 3 TeV

DRIVE BEAM COMPLEX



MAIN BEAM COMPLEX

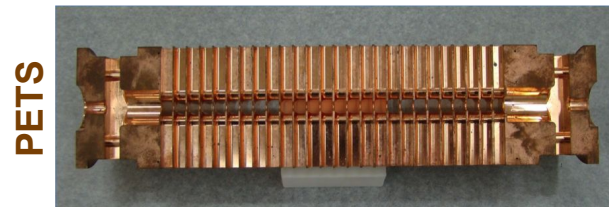
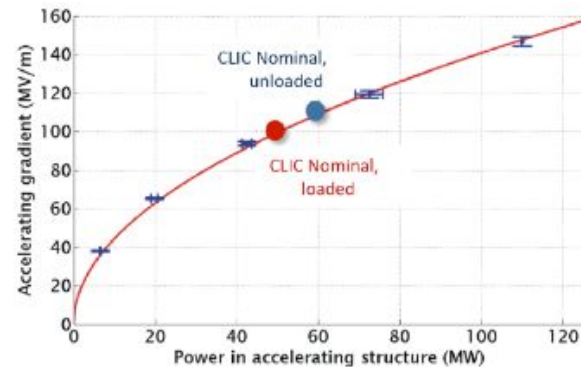
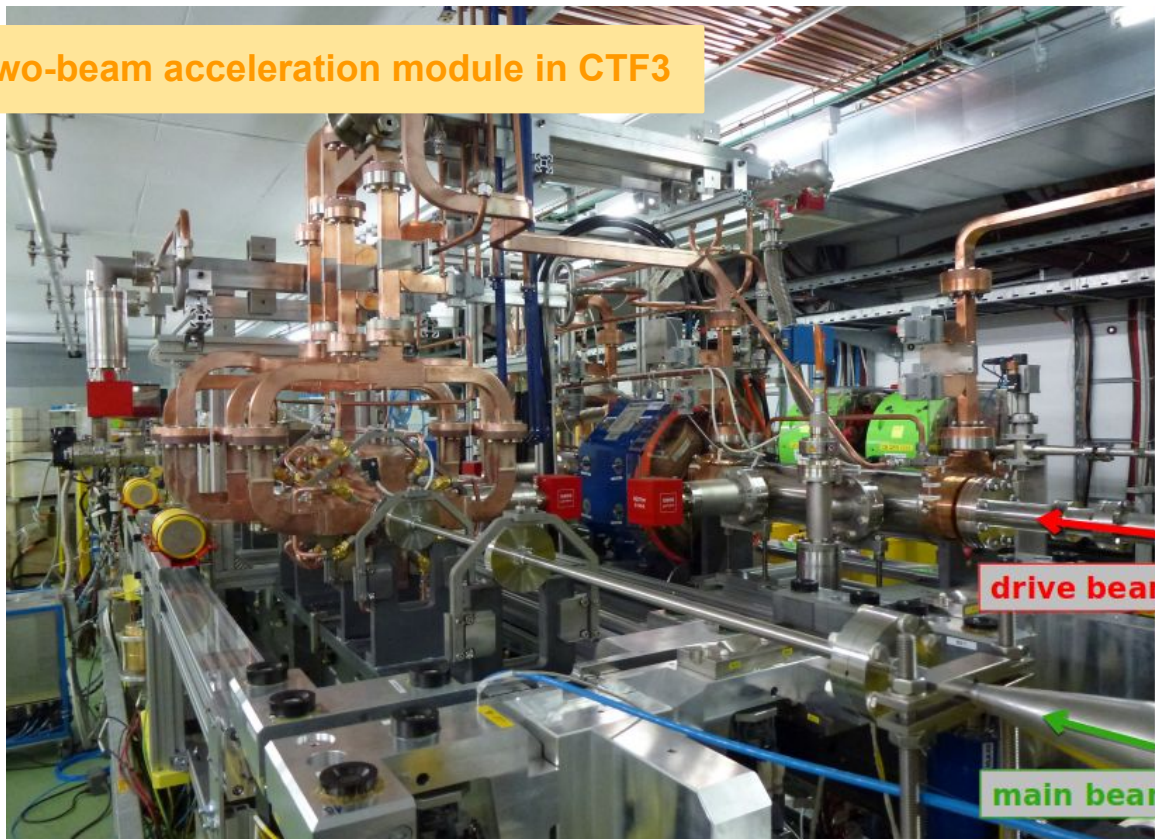


High centre-of-mass energy requires high-gradient acceleration → CLIC uses a “Two-beam technique” to achieve gradient of 100 MV/m

- 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)

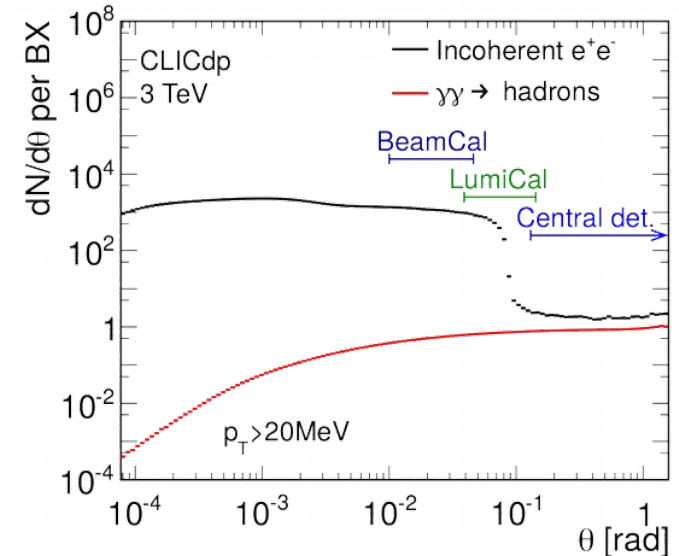
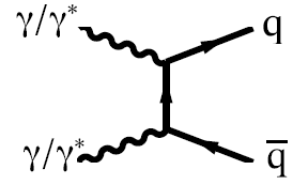
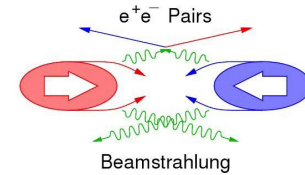
“Two-beam” setup

Two-beam acceleration module in CTF3

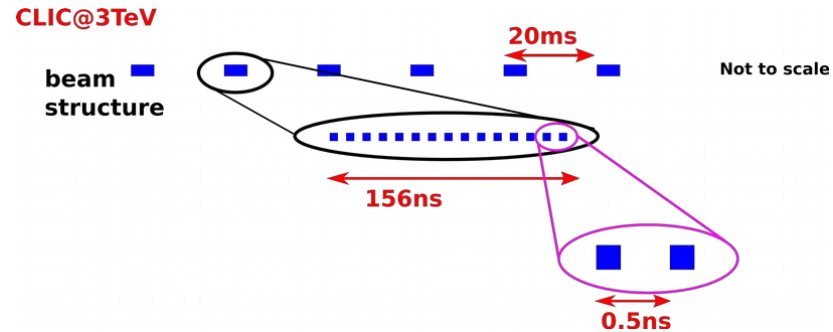


Experimental Conditions

- 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
 - **$\gamma\gamma \rightarrow$ hadrons**
 - High energy deposits
 - Impact on detector granularity, design and physics measurement
- Detector acceptance starts at 10 mrad

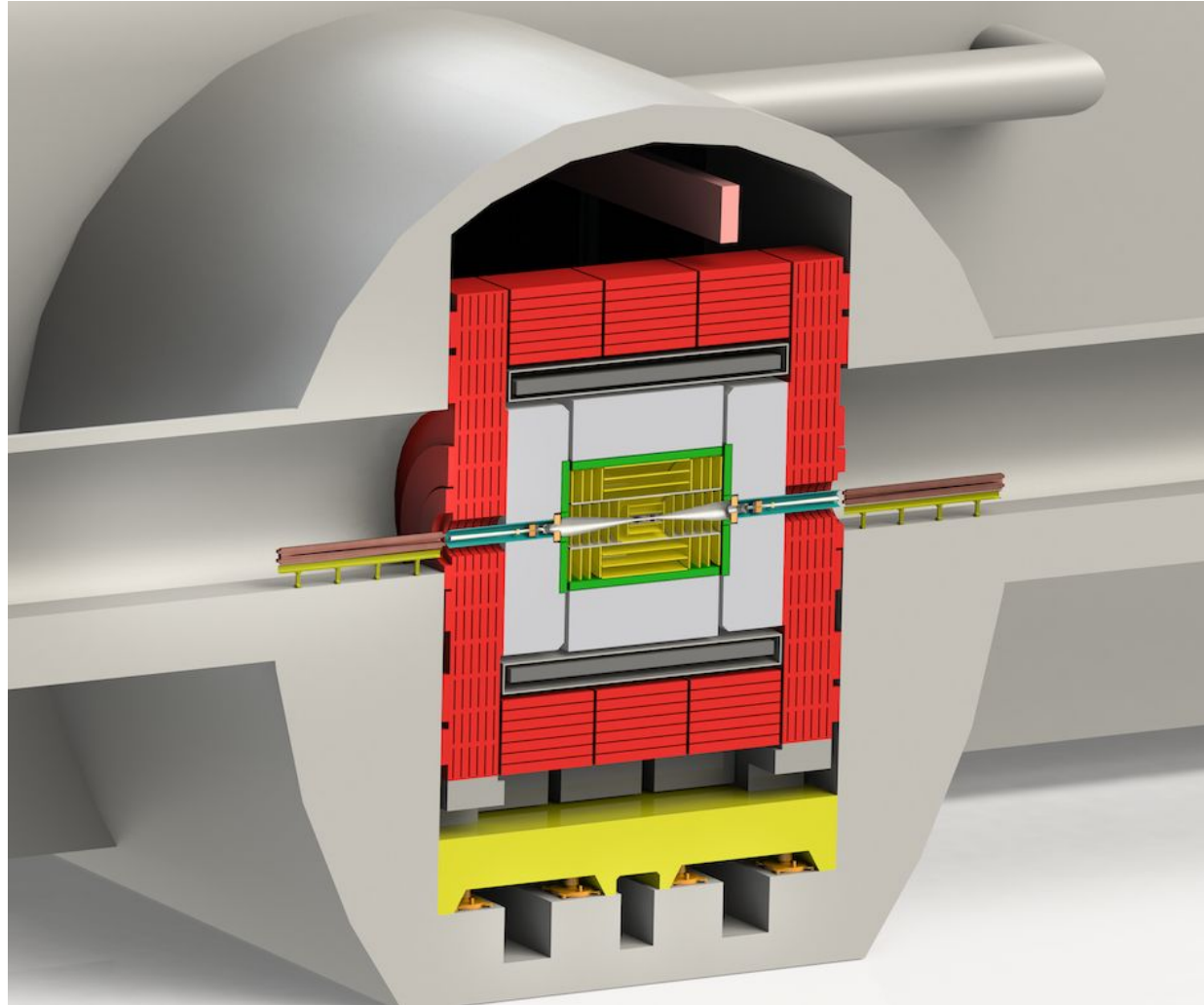


- CLIC operates in bunch trains, repetition rate of 50 Hz
 - Low duty cycle
 - Possibility for power pulsing: switch detector components off between trains to reduce heat dissipation
- 312 bunches within train separated by 0.5 ns (@ 3 TeV)
- Trigger-less readout foreseen
- Time structure of the beam & background suppression drive timing requirements for detector
 - 10 ns hit time-stamping in tracking
 - 1 ns time resolution for calorimeters

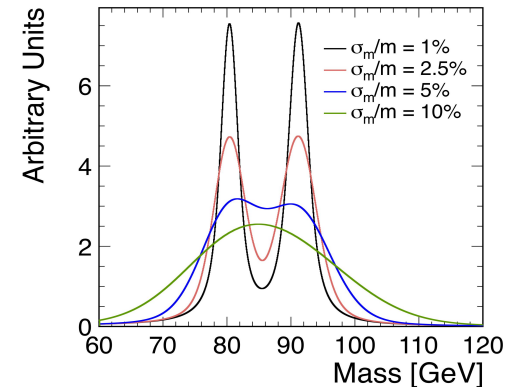
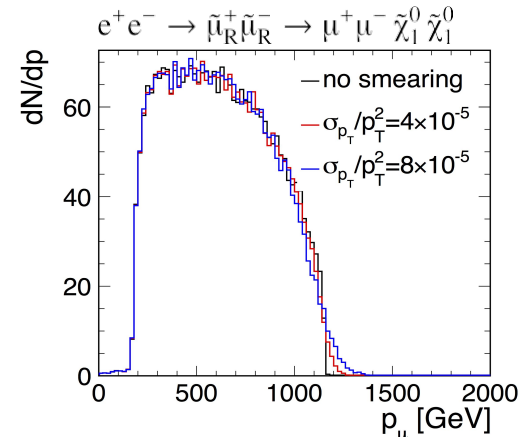


CLIC detector

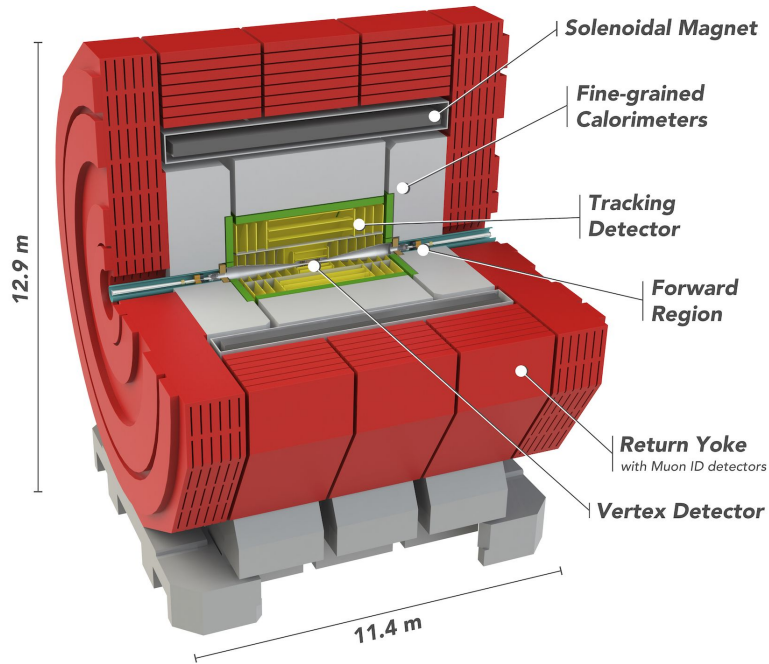
CLIC detector



- Momentum resolution
 - e.g. Higgs coupling to muons, leptons from BSM
 - $\sigma_{p_T}/p_T \sim 2 \times 10^{-5} \text{ GeV}^{-1}$ 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
 - $\sigma_{r\phi} \sim a \oplus b / (p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m}$
with $a = 5 \mu\text{m}$, $b = 15 \mu\text{m}$
- Lepton identification efficiency **> 95 %**
- Angular coverage
 - Very forward electron and photon tagging
 - Down to $\theta = 10 \text{ mrad}$ ($\eta = 5.3$)



Designed for Particle Flow Analysis
and optimised for CLIC environment!

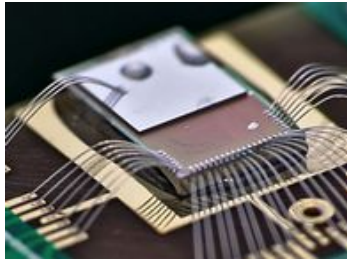


- Superconducting solenoid with 4T magnetic field
- Vertex detector
 - 3 double layers with $25 \times 25 \mu\text{m}^2$ pixels
 - Extremely accurate ($\sigma < 3 \mu\text{m}$) and light ($< 0.2 \% X_0$ per layer)
- Silicon Tracker
 - Composed of large pixels/strips
 - Outer R $\sim 1.5 \text{ m}$
 - 10 ns hit time-stamping in tracking
- Fine grained calorimeters

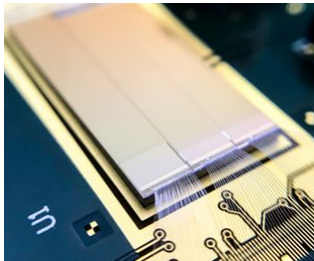
<ul style="list-style-type: none"> ○ Si-W ECAL <ul style="list-style-type: none"> ■ 40 layers $\rightarrow 22 X_0$ and $1 \lambda_1$ ■ $5 \times 5 \text{ mm}^2$ Si cell size ($\sim 2500 \text{ m}^2$) ■ 1 ns accuracy for calo hits 	<ul style="list-style-type: none"> ○ Scint-Fe HCAL <ul style="list-style-type: none"> ■ 60 layers $\rightarrow 7.5 \lambda_1$ ■ $30 \times 30 \text{ mm}^2$ scintillator cell size ($\sim 9000 \text{ m}^2$) ■ 1 ns accuracy for calo hits
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- Forward calorimeters
 - very forward electron tagging and luminosity measurements
- Return yoke & muon chambers
 - Mainly for muon ID

Vertex & Tracker

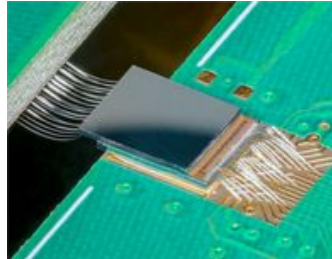
Hybrid detectors
CLICpix + 50 um sensor



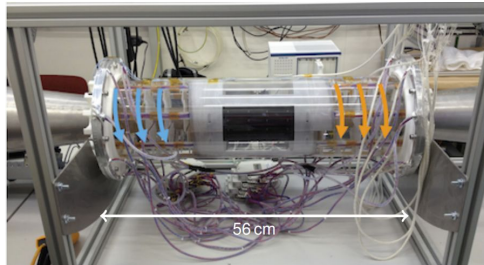
Monolithic detectors
AtlasPix_Simple



Hybrid detectors
CLICpix2 + C3PD

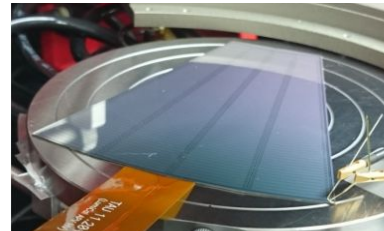


Detector integration
Cooling system

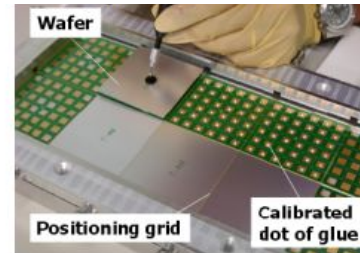


Calorimeters

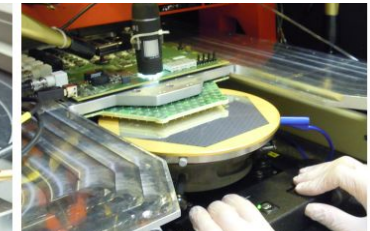
FCAL LumiCal silicon sensors
1.8 mm wide strips



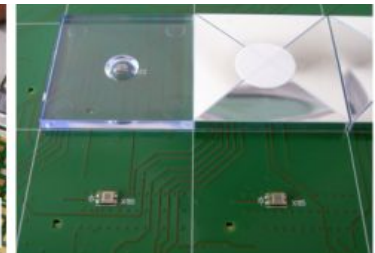
CALICE silicon PIN diodes
1x1 cm² in 6x6 matrices



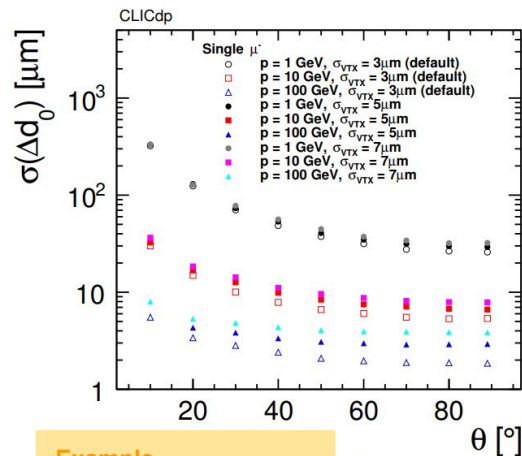
CMS HGcal silicon sensors
~1 cm² cells on 8-inch wafer



CALICE scint. tiles + SiPMs
3x3 cm² cells

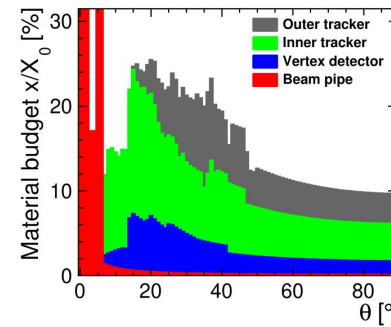


- Full Geant4 detector simulation including overlay of beam-induced backgrounds
- Full reconstruction chain:
 - reconstruction of tracks and clusters
 - particle flow objects
 - jets
 - flavor tagging
- Optimization of 3 TeV CLIC detector model in full detector simulations
 - → Ensure that detector performance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



Example

Material budget in full simulation

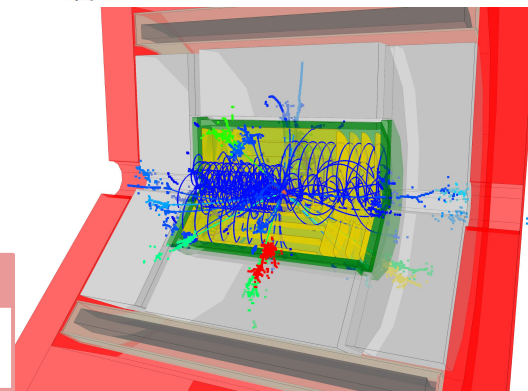


Example

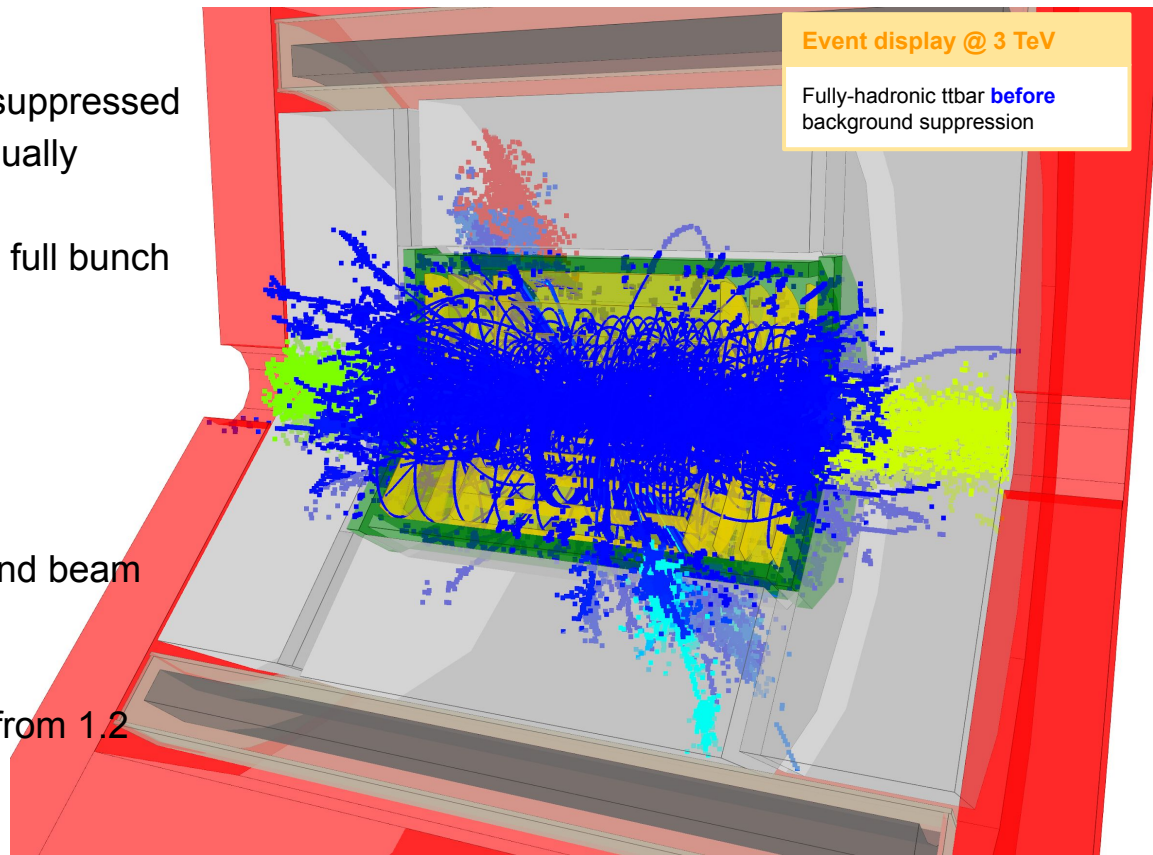
Vertex detector single point resolution \leftrightarrow track impact parameter resolution

Example @ 380 GeV

Fully-hadronic $t\bar{t}b\bar{b}$ event
+ $\gamma\gamma \rightarrow \text{hadrons}$

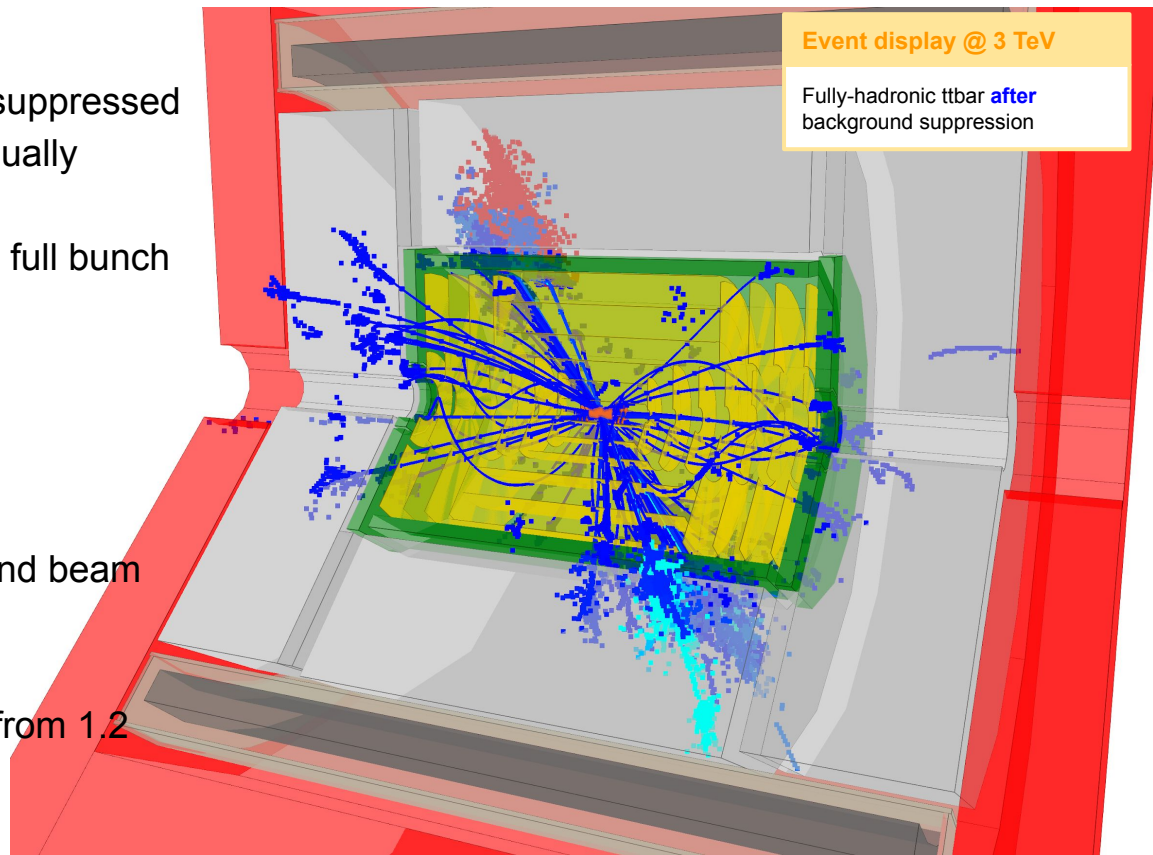


- $\gamma\gamma \rightarrow$ hadrons background can be suppressed by p_T vs. time selections on individually reconstructed particles
- Identify time of physics event in the full bunch train
- Suppression via
 - Cluster time
 - Particle type
 - p_T
- Cuts adapted per detector region and beam energy
-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



Beam-induced background rejection

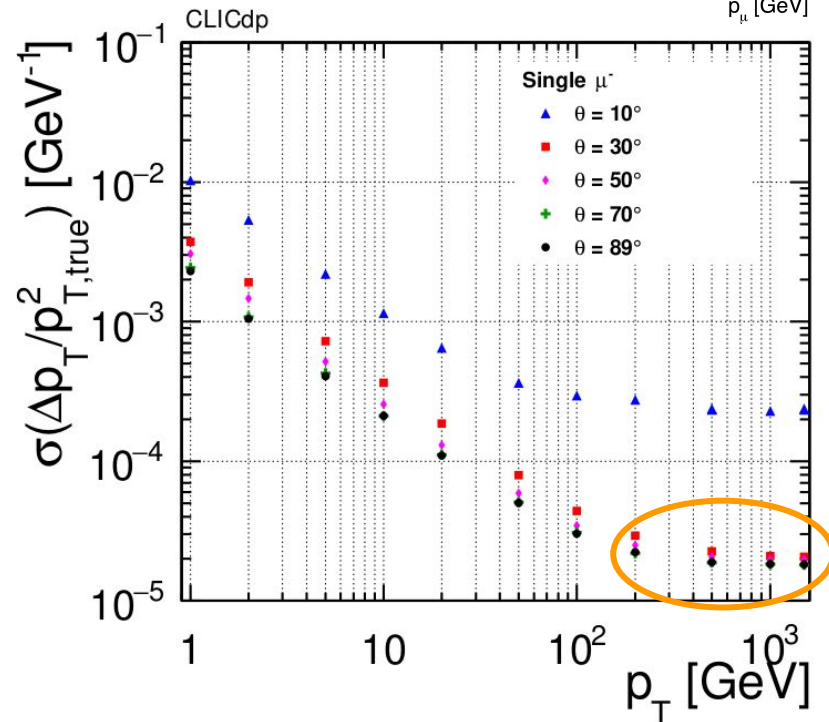
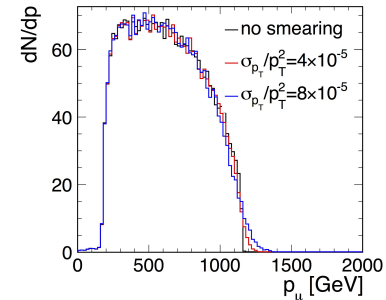
- $\gamma\gamma \rightarrow$ hadrons background can be suppressed by p_T vs. **time** selections on individually reconstructed particles
- Identify time of physics event in the full bunch train
- Suppression via
 - Timing requirements
 - Particle type
 - Retaining high- p_T objects
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Detector requirements & performance

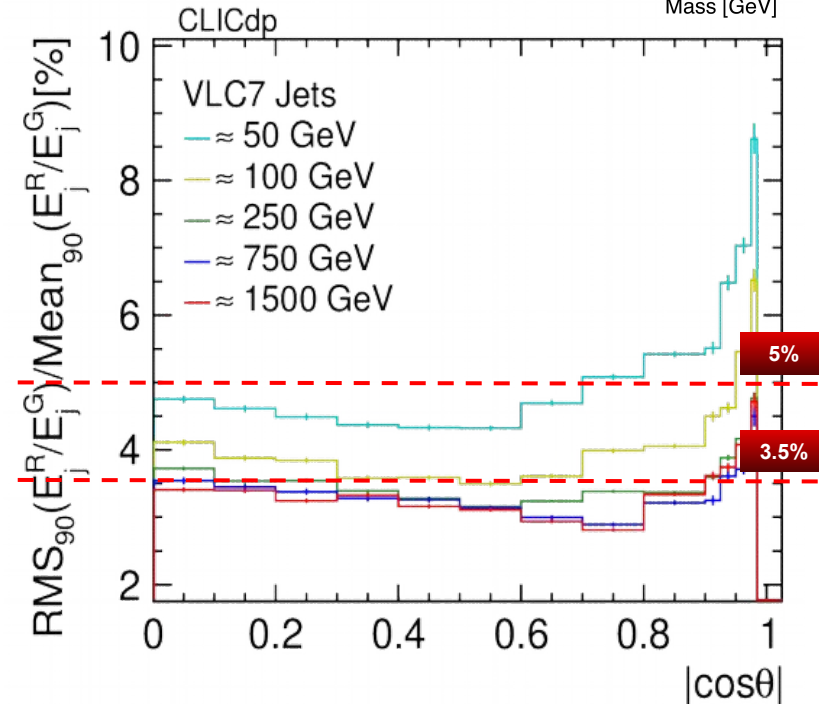
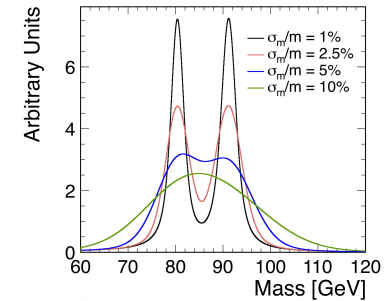
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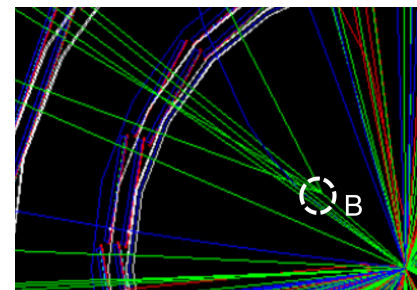


Detector requirements & performance

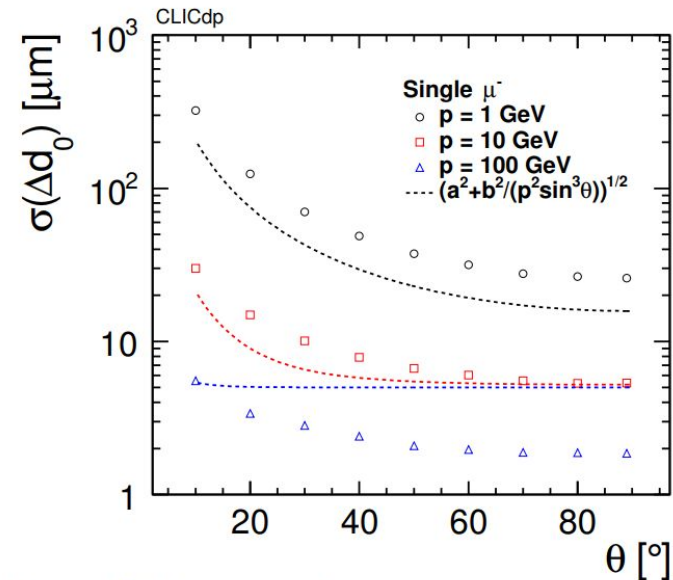
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- **Jet energy resolution**
 - e.g. separation of W/Z/H di-jets
 - $\sigma_E/E \sim 5\% - 3.5\%$ for jets at 50 GeV – 1000 GeV
- Impact parameter resolution
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with $a = 5 \mu\text{m}$, $b = 15 \mu\text{m}$
- Lepton identification efficiency $> 95\%$
- Angular coverage
 - Very forward electron and photon tagging
 - Down to $\theta = 10 \text{ mrad}$ ($\eta = 5.3$)



Detector requirements & performance

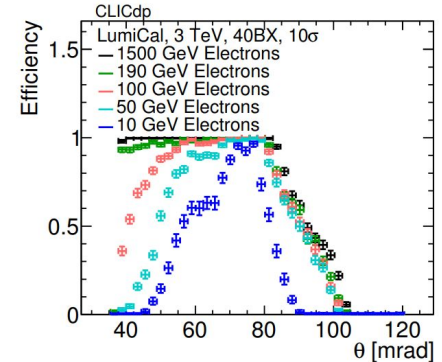
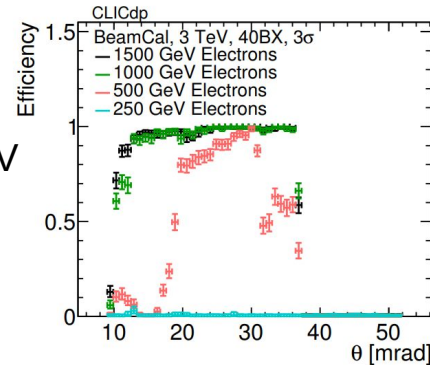


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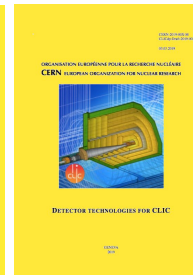
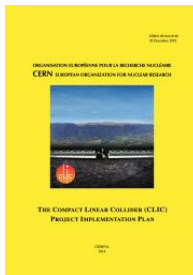
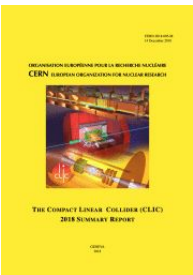
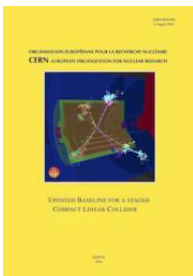
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CLICdet parameters and performance: [arXiv:1812.07337](https://arxiv.org/abs/1812.07337)

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

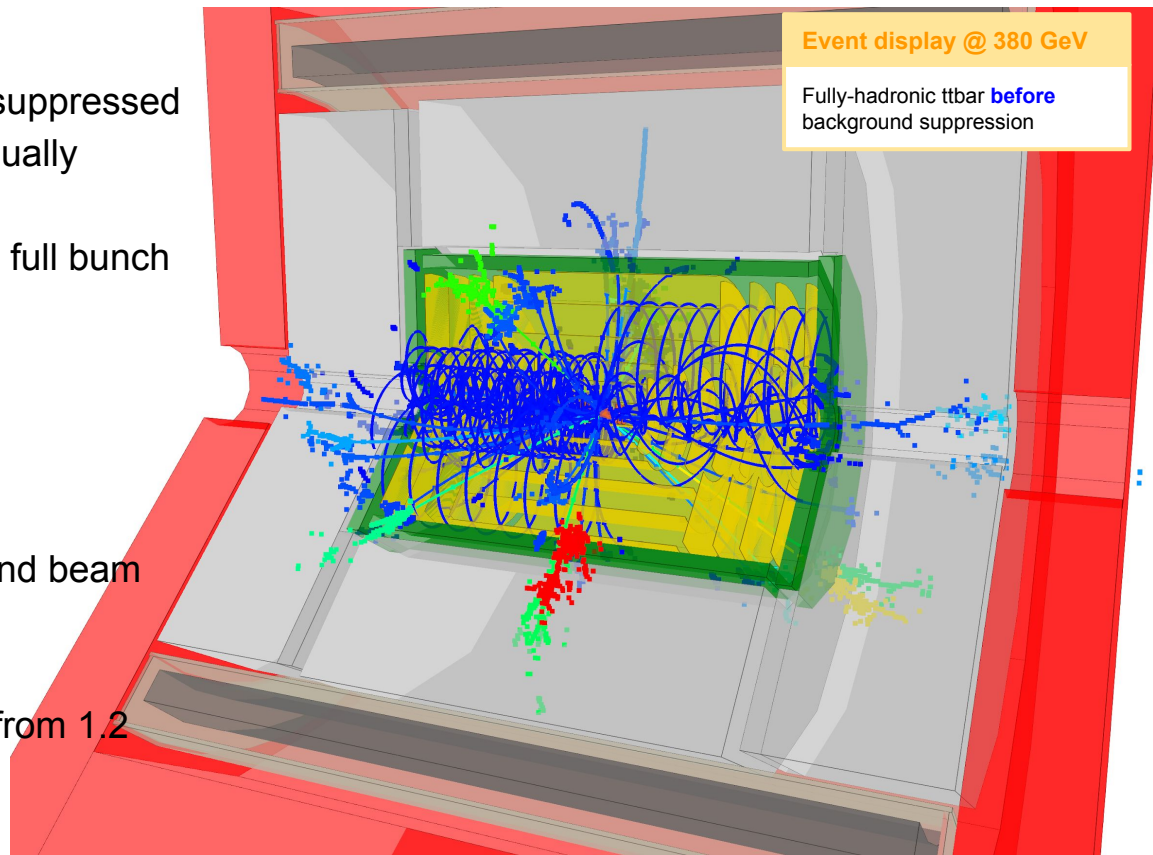


Backup

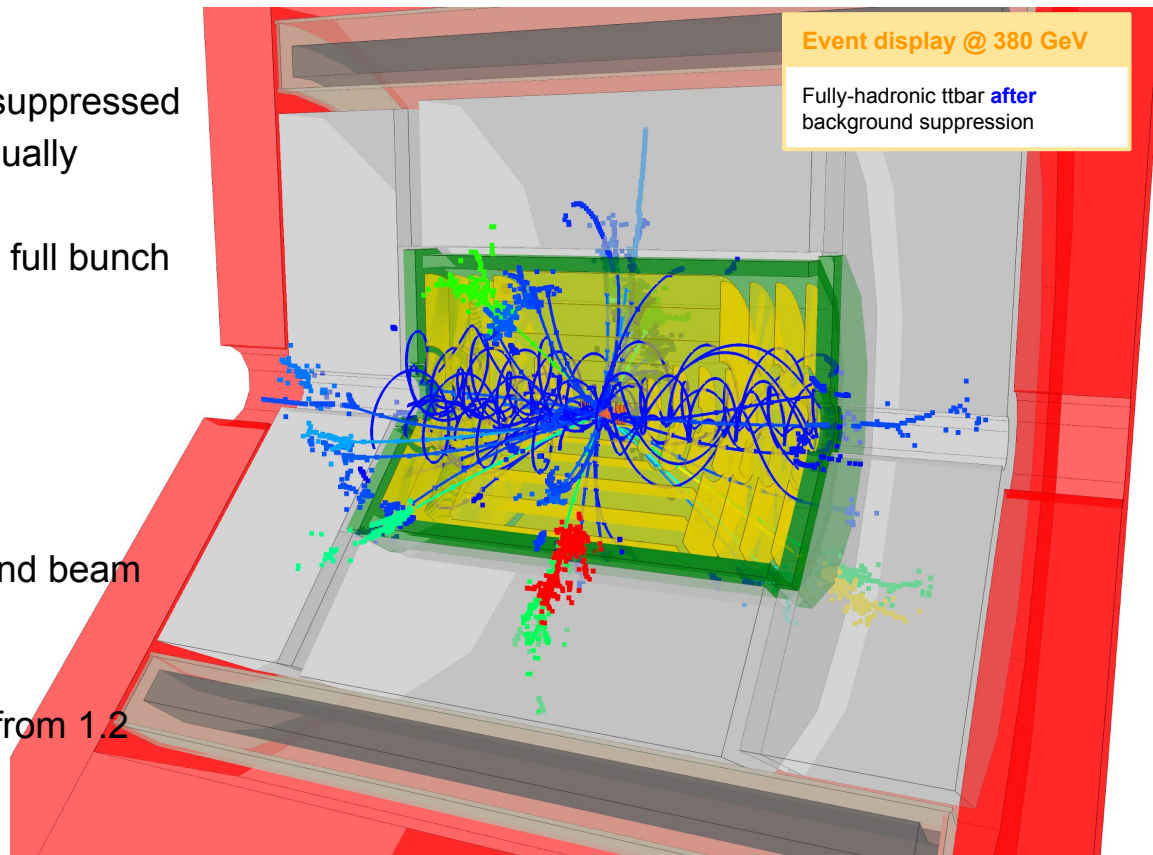
The artwork is a complex abstract composition. It features a central point from which numerous lines radiate outwards. The lines are primarily in shades of blue, orange, and yellow, with some grey and purple lines. There are several large, thick circles in orange and blue, some of which are hollow. Smaller solid circles in various colors (orange, yellow, blue, grey) are scattered throughout. Two horizontal bands of intricate, grey, geometric patterns run across the middle of the composition. The overall style is reminiscent of mid-century modern abstract art, with a focus on clean lines and vibrant colors. The word "Backup" is centered in a large, black, sans-serif font.

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!

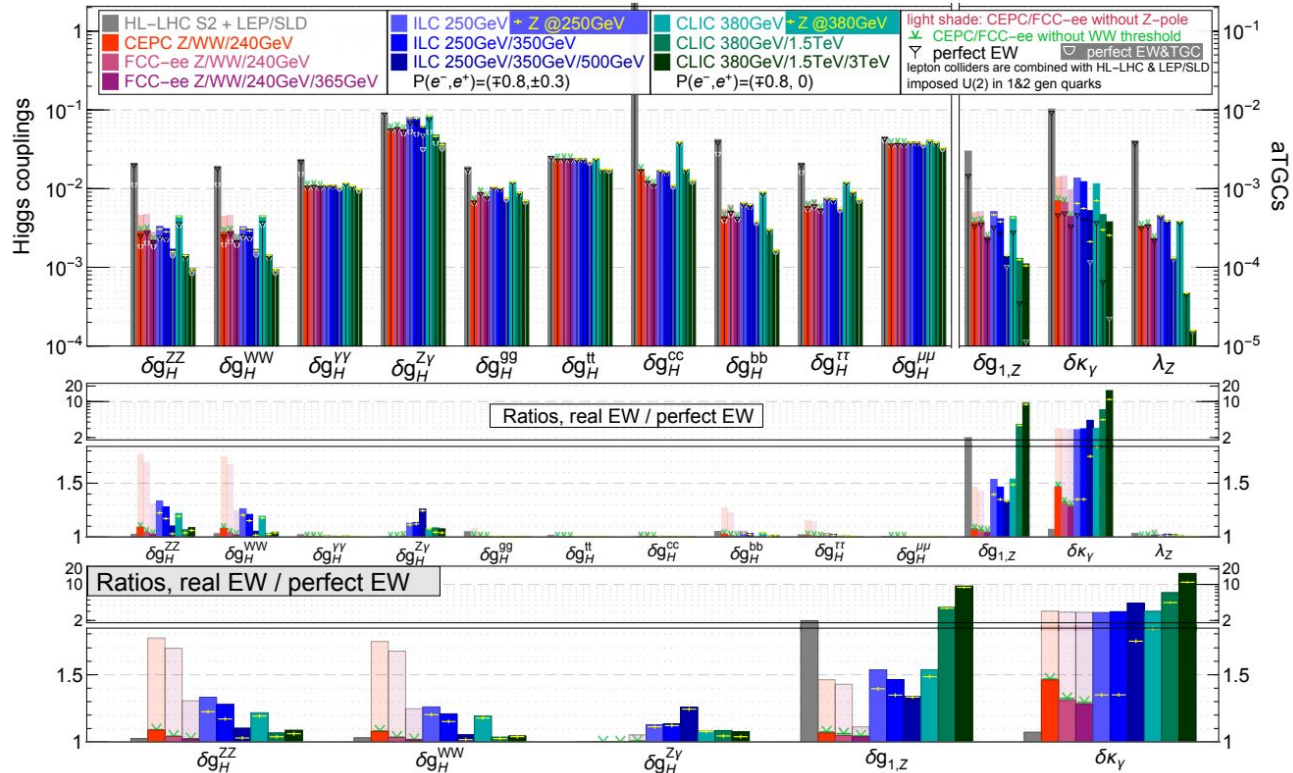


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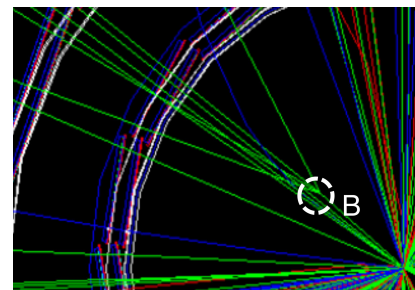
Higgs coupling sensitivity

precision reach on effective couplings from full EFT global fit





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