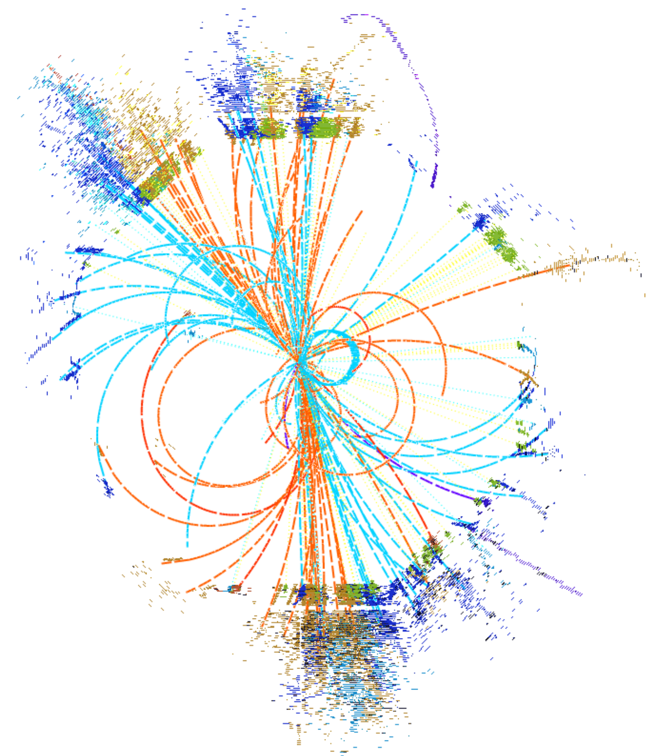
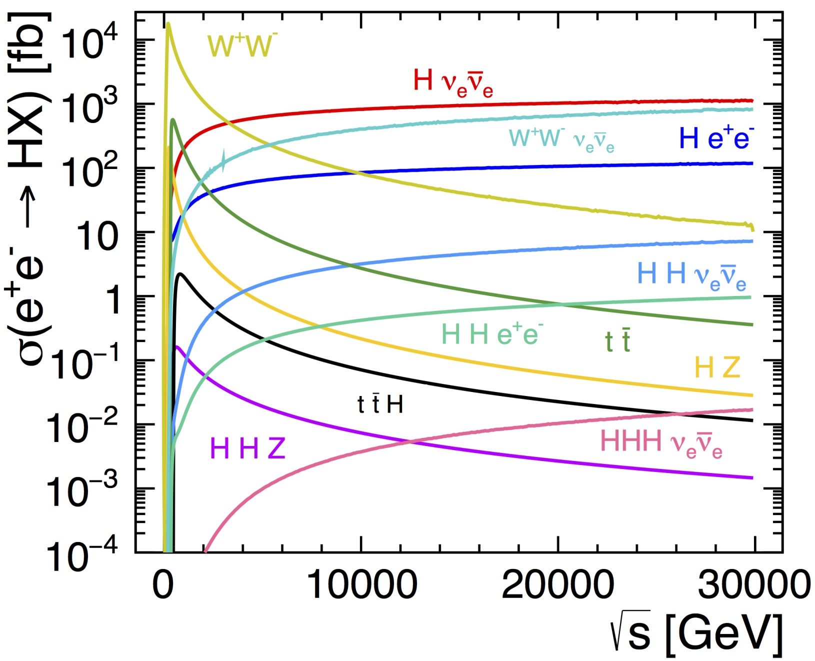
Physics simulations for high-energy lepton colliders

Philipp Roloff (CERN)



Muon Collider
Preparatory Meeting



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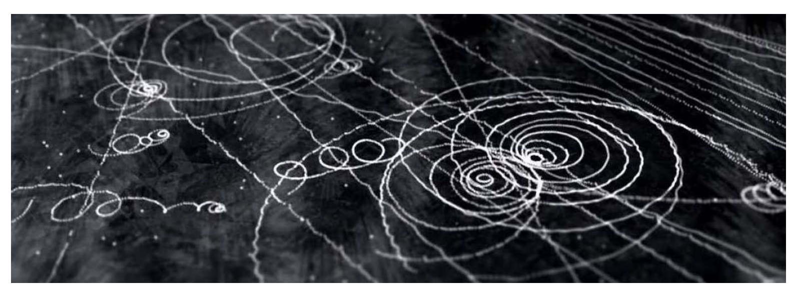
10/04/2019

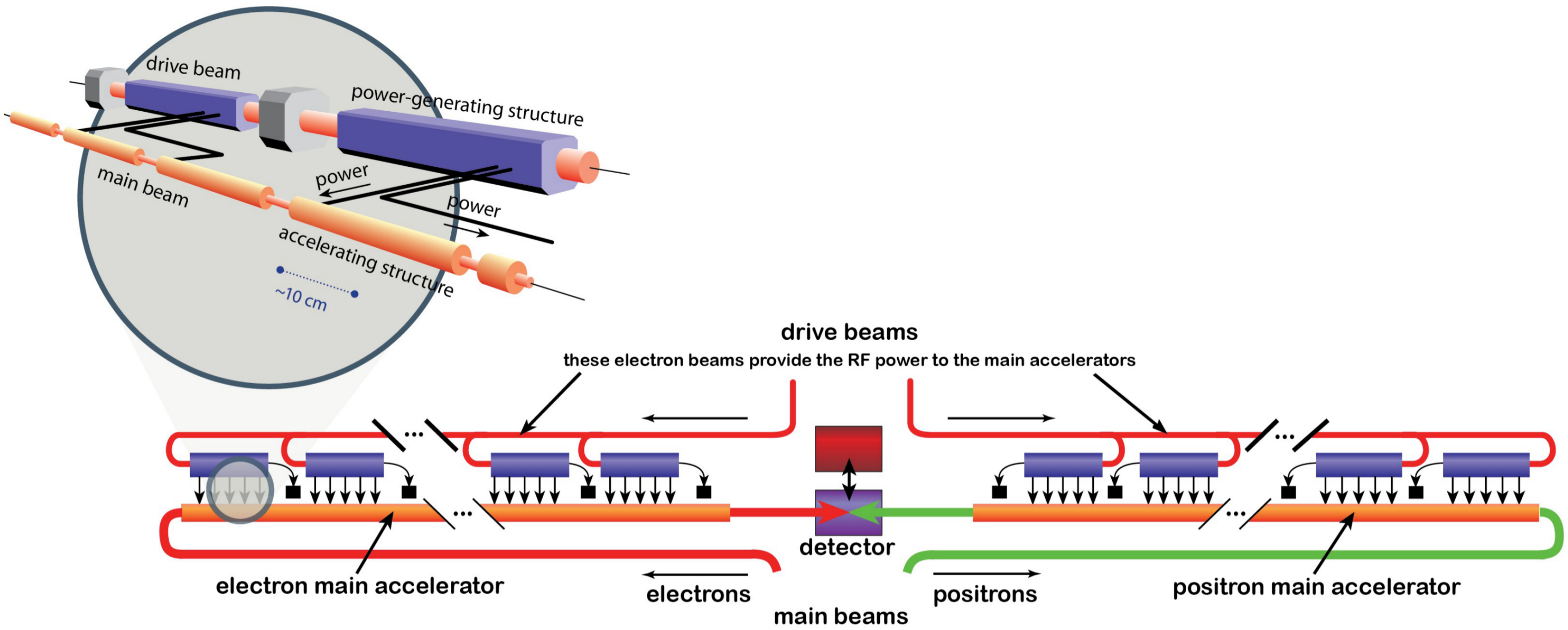


Introduction

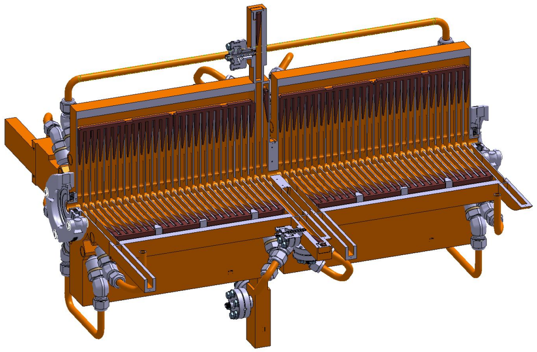
Detailed studies of detector optimisation and physics potential available for CLIC

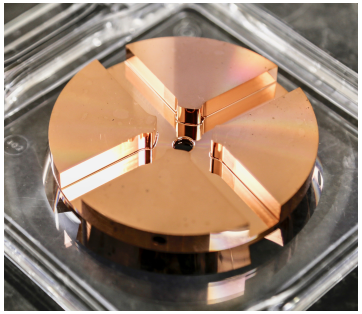
- **Introduction:** CLIC, energy staging, experimental conditions, detector concept
- **Software chain and detector performance**
- **Example physics benchmark studies**

The Compact Linear Collider (CLIC)



Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
- Length: 50 km (for 3 TeV)
- $P(e^-) = \pm 80\%$
- Upgrades could benefit form novel approaches (dielectric structures, PWFA, ...)



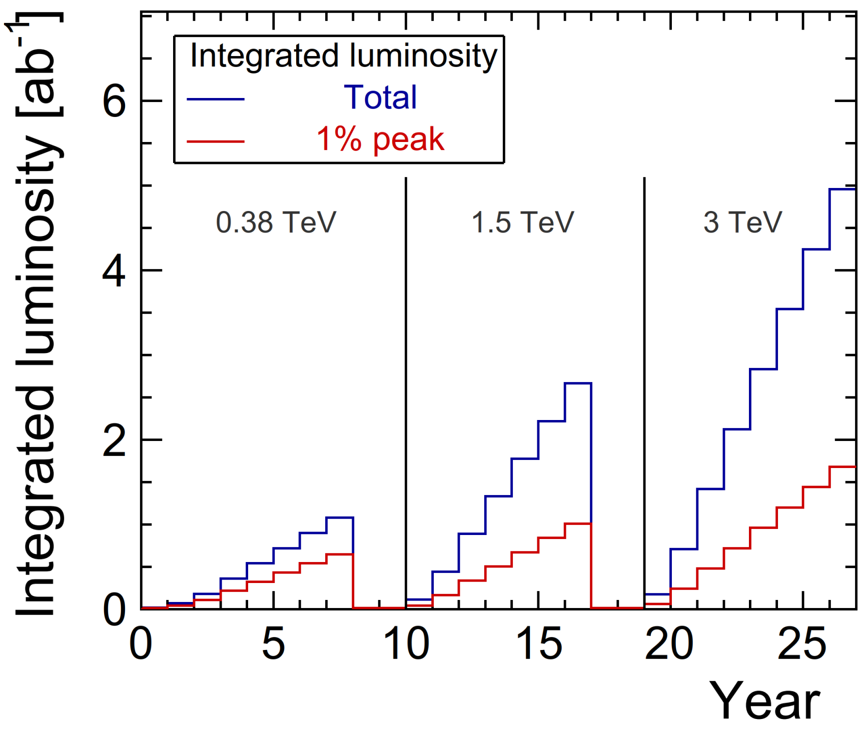


CLIC staged implementation

CLIC would be implemented
in several energy stages

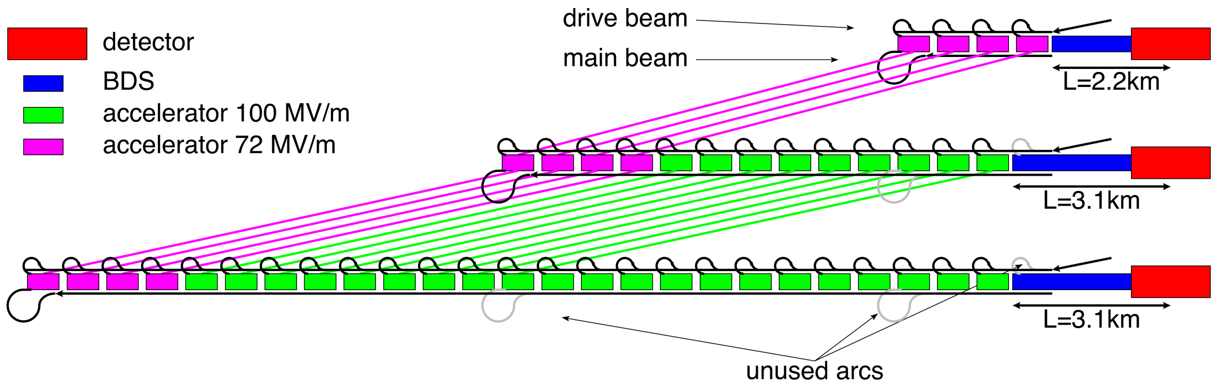
Current baseline scenario:

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = -80\%$ $\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = +80\%$ $\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0



- The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)

- 1 year = 1.2×10^7 seconds (based on CERN experience)



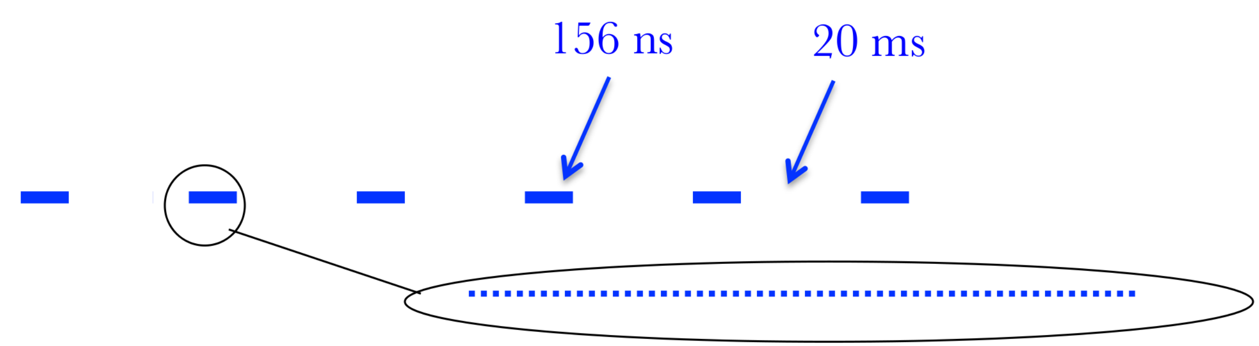
CERN-2018-005-M
arXiv:1812.01644

CLIC experimental conditions

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
L above 99% of $\sqrt{s}$ ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Repetition frequency (Hz)	**50**	**50**	**50**
Bunch separation (ns)	**0.5**	**0.5**	**0.5**
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	**149/2.9**	**~60/1.5**	**~40/1**
Beam size at IP σ_z (μm)	**70**	**44**	**44**

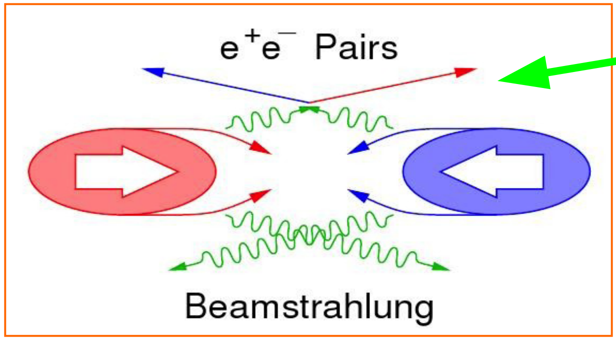
Drives timing requirements for CLIC detector

Very small beam

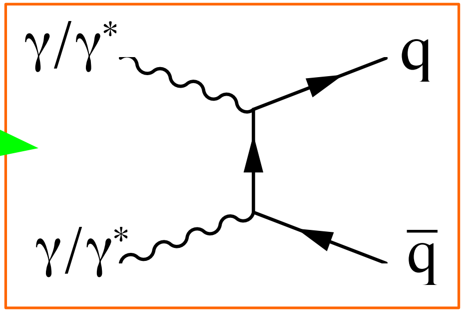


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam-induced backgrounds

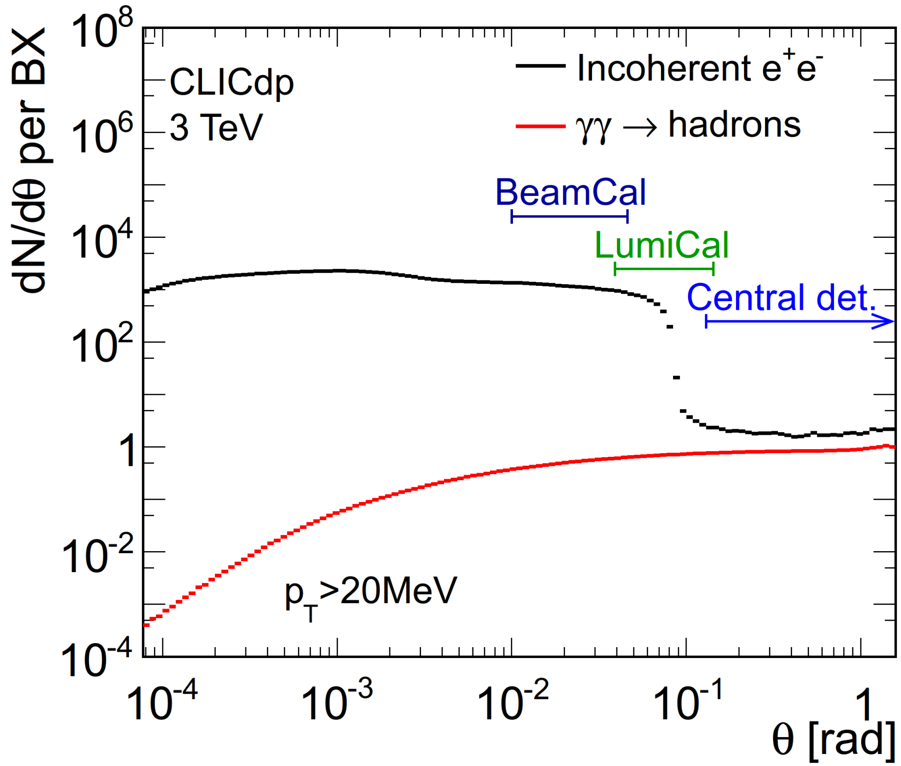


- e^+e^- pairs
- γγ → hadrons



e^+e^- pairs:
High occupancies
→ Detector design issue
(small cell sizes)

γγ → hadrons
Main background
in calorimeters and trackers
→ Impact on physics
(needs suppression in the data)



Detector requirements

- **Momentum resolution**
(e.g. Higgs recoil mass, $H \rightarrow \mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\, GeV^{-1}$$

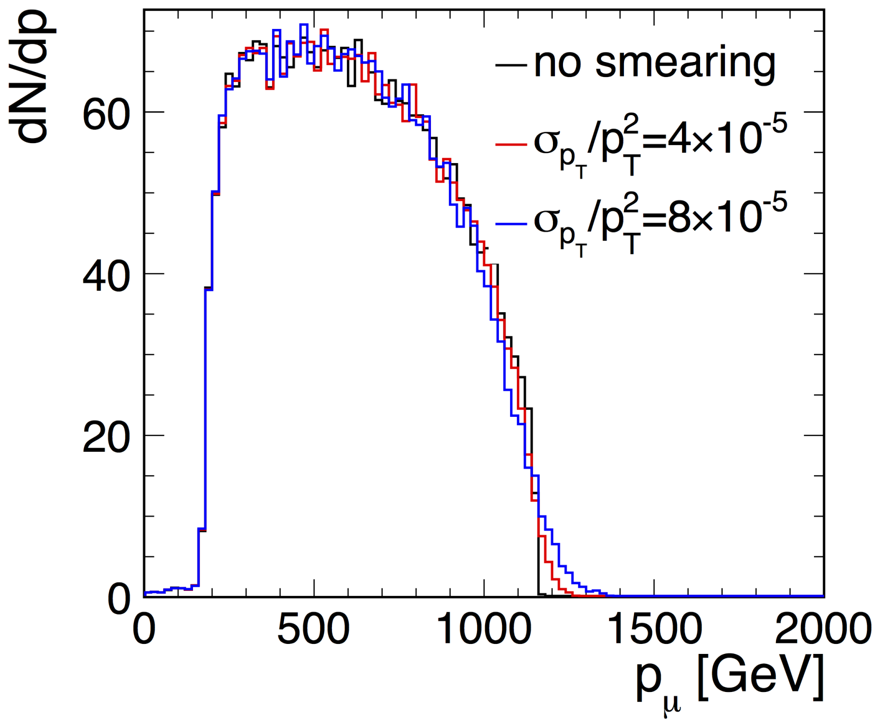
- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5\,\%\ for\ E > 100\, GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 15\,\mu m$$

- **Lepton identification, very forward electron tagging**



$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

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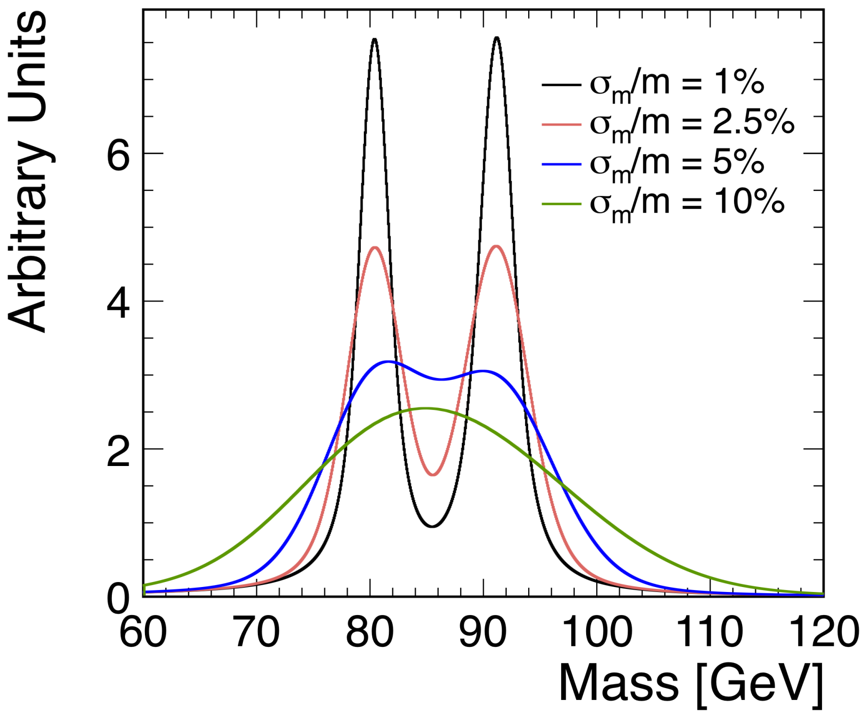

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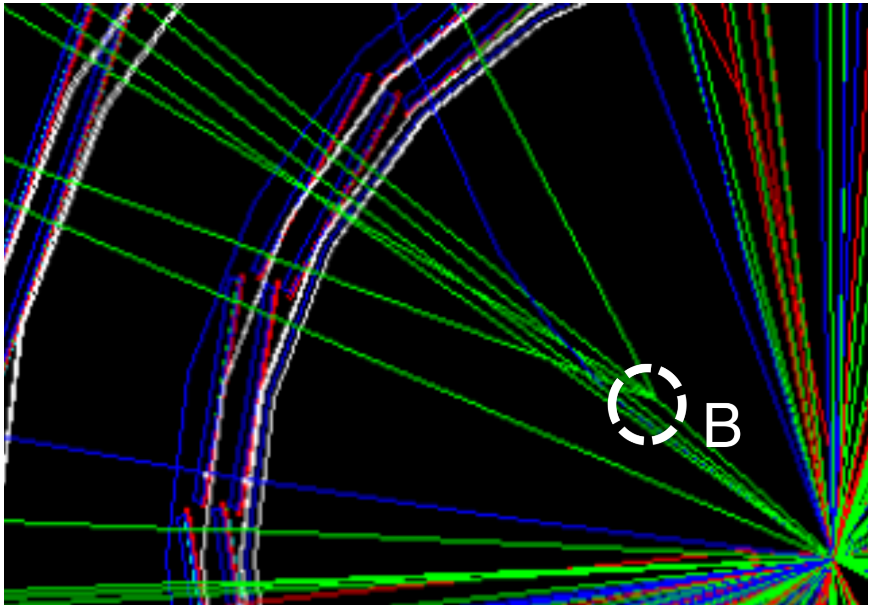
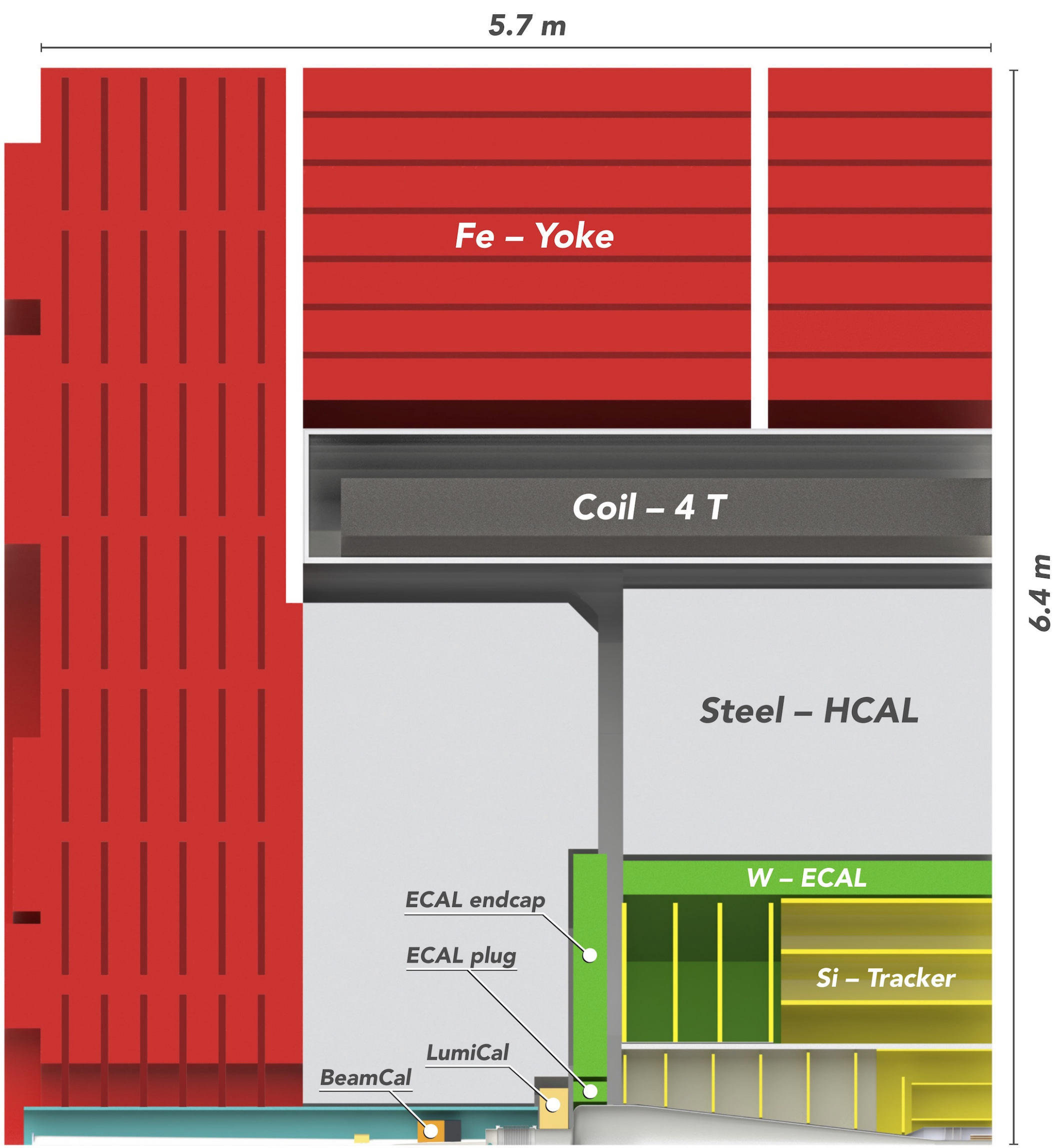
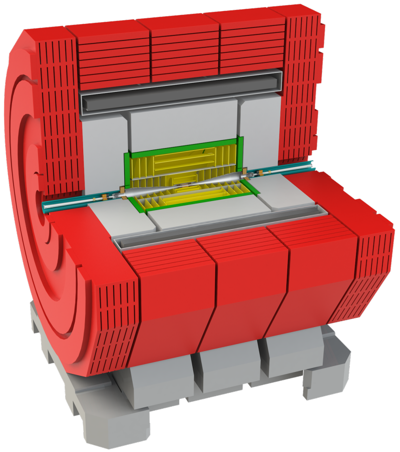


- **Lepton identification, very forward electron tagging**

CLIC detector concept





- Ultra low-mass vertex detector with ≈ 25 x 25 μm^2 pixels
- Main trackers: silicon-based (large pixels / short strips)
- Fine grained (PFA) calorimetry, 1+7.5 λ
- Strong solenoid magnet (4 T)
- Complex forward region with compact calorimeters
- Instrumented return yoke for muon ID

CLICdp-Note-2017-001

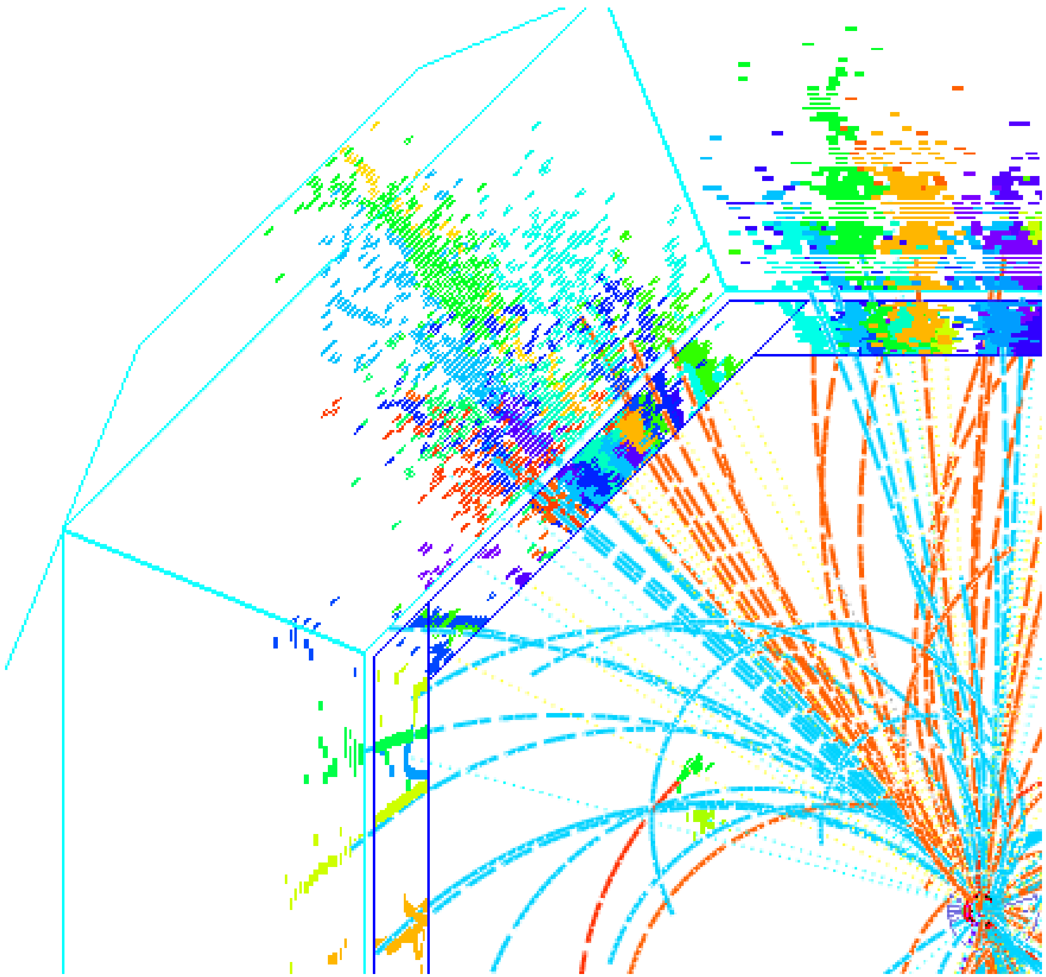
Calorimetry and PFA

Detector design driven by jet energy resolution and background rejection
→ Fine-grained calorimetry + particle flow analysis (PFA)

What is PFA?
Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutral hadrons

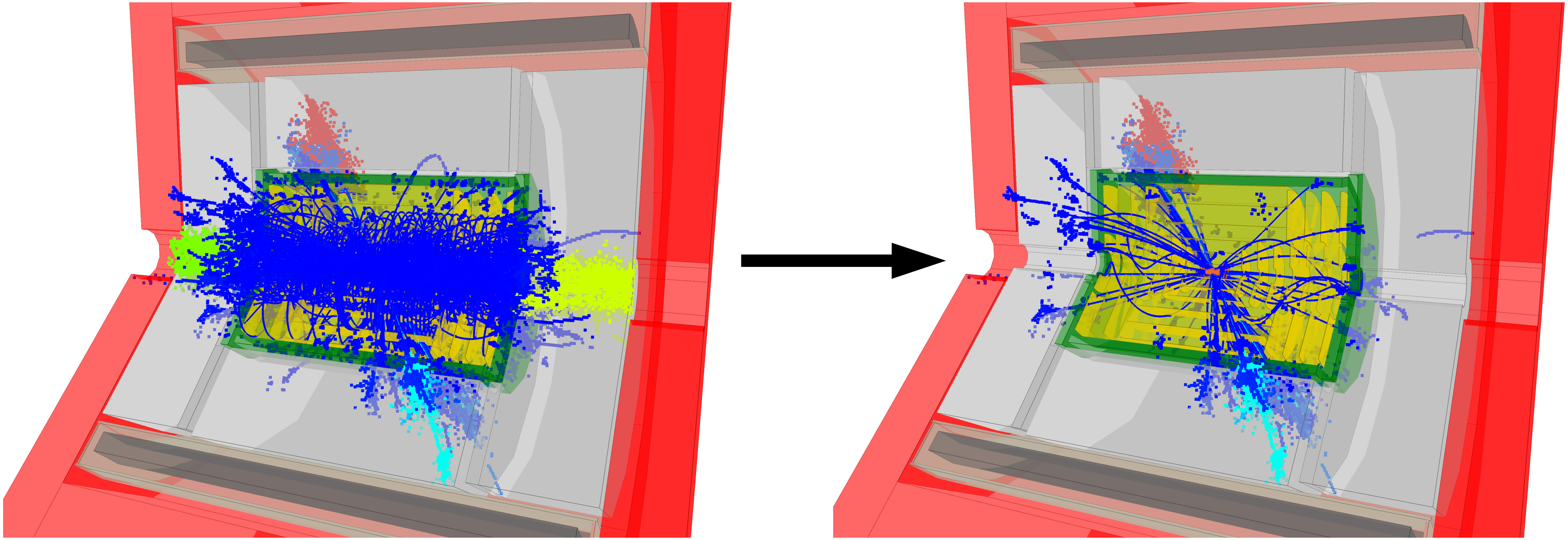
Always use the best available measurement:
- charged particles
→ tracking detectors: 🙂 🙂
- photons → ECAL: 🙂
- neutrals → HCAL: 🙁

Hardware and software!



Background suppression

Beam-induced background from γγ → hadrons can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles (= particle flow objects)

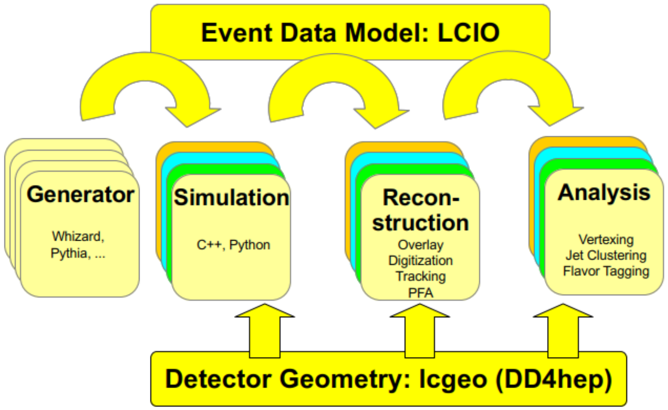


$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from γγ → hadrons overlaid

Simulation software chain

Linear Collider Software

- Linear collider community has used and developed **common software** for many years
  - Event data model (EDM) and persistency: LCIO
    - ★ podIO is being investigated in AIDA2020
  - Particle flow reconstruction: PandoraPFA
- Adopted DD4Hep geometry description to develop more common software this geometry information
- Interface generic reconstruction packages via thin wrappers to linear collider framework



André Sailer

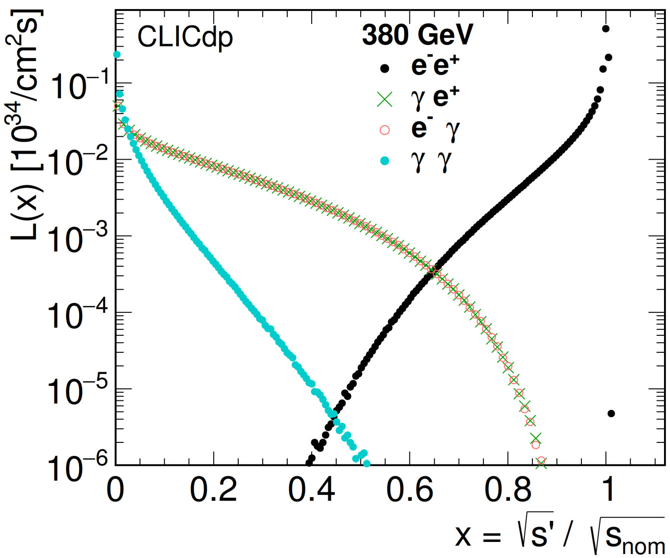
Main tool for event generation: WHIZARD

WHIZARD 1.95 (and earlier versions) used since a long time for LC physics studies (including CLIC CDR and ILC TDR)

Recently switched to **WHIZARD 2.x:**

- Automatic generation of matrix elements for arbitrary processes in e^+e^-, $e^\pm\gamma$, $\gamma\gamma$ collisions
- Beamstrahlung spectra via CIRCE2 interface or beam-beam event files
- Lepton collider ISR structure functions, EPA
- Arbitrary beam polarisation
- Output event formats: LCIO (also HepMC, LHEF, StdHEP, …)
- Using other generators for specific purposes (PYTHIA, PHYSSIM, ...)

https://whizard.hepforge.org/



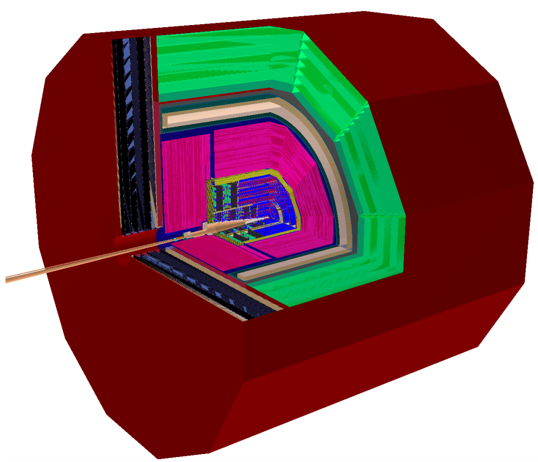
CERN-2018-005-M

Geometry description (DD4hep)

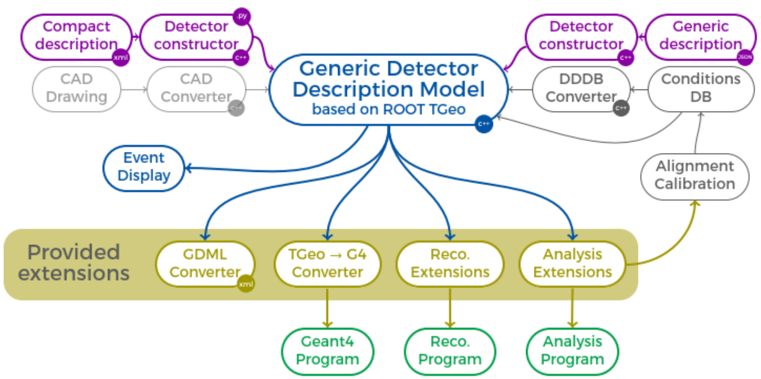
DD4hep – Overview

Complete Detector Description

- Providing geometry, materials, visualization, readout, alignment, calibration. . .
- Single source of information → consistent description
- Supports full experiment life cycle: Detector concept → development → detector optimization → construction → operation



- Use in simulation, reconstruction, analysis, etc.
- Easily write new detector drivers
- Detector geometry extensible with additional information, e.g. for reconstruction



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Tracking

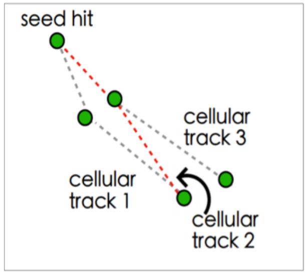
Conformal tracking = cellular automaton in conformal space

Conformal mapping: transforms circles passing through the origin in (x,y) into straight lines in (u,v)

$$u = x / (x^2 + y^2) \qquad v = y / (x^2 + y^2)$$

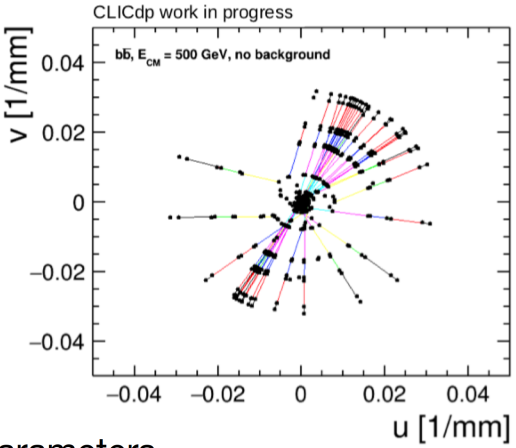
Cellular automaton based on build and extend

- build: finds set of cellular tracks from each seed hit by creating connections with nearest neighbours
- extend: extends cellular tracks to form track candidates



Pattern recognition: full chain

Algorithm	Hit collection	Configuration
Build tracks	Vertex barrel	Standard cuts
Extend tracks	Vertex endcap	Standard cuts
Build tracks	Vertex	Looser cuts (angle x 5)
Build tracks	Vertex	Looser cuts (angle x 10; χ^2 x 20)
Extend tracks	Tracker	Looser cuts (angle x 10; χ^2 x 20)
Build tracks	Vertex + Tracker	Displaced cuts



After pattern recognition: Kalman filter to get the track parameters

- prefit with 3 hits (first, middle, last) to get initial helix parameters
- fit forward and smooth backward

Emilia Leogrande

Particle flow analysis

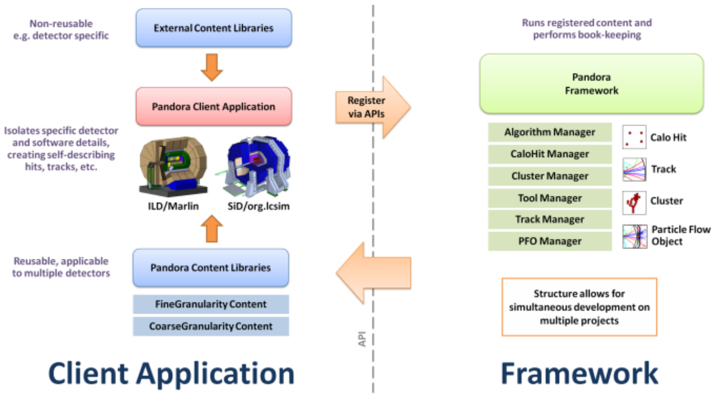
Particle Flow Reconstruction

PANDORAPFA: generic toolkit for pattern recognition algorithms in highly granular calorimeters

- Originally developed for ILC/CLIC detectors
- Extended to work in LAr-TPC reconstruction for the DUNE neutrino experiment

ClientApplication: DDMARLINPANDORA glues linear collider framework (Marlin), DD4HEP, and PANDORAPFA

- Passes DDREC `DataStructures` information, tracks, and calorimeter hits to PANDORAPFA
- Converts PANDORAPFA objects into LC EDM objects



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Distributed computing

Distributed Computing with iLCDirac

DIRAC (Distributed Infrastructure with Remote Agent Control): High level interface between users and distributed resources

- *WorkloadManagement*
- *Transformation* system for automated and centralized tasks
- *DataManagement* system including *Replica* and *Metadata Catalog*, asynchronous operations (file transfers (FTS), removal)
- *iLCDirac* extension for the linear collider community, implementing interfaces for LC applications and transformation workflows

DIRAC users can submit jobs in different ways (JDL, Ganga, python script)

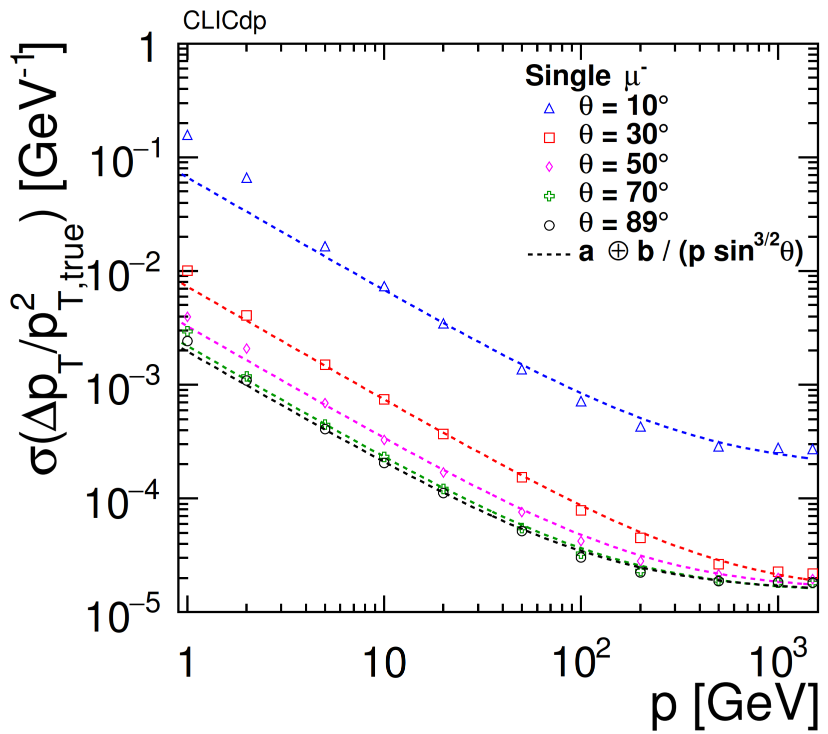
- In iLCDirac python API for existing workflow modules offer a straightforward interface

```
from DIRAC.Core.Base import Script
Script.parseCommandLine()
import UserJob, Marlin, DiracILC
d = DiracILC()
j = UserJob()
j.setOutputData("recEvents.slcio")
m = Marlin()
m.setVersion("ILCSoft-01-17-09")
m.setSteeringFile("Steering.xml")
m.setInputFile("SimEvents.slcio")
j.append(m)
j.submit(d)
```

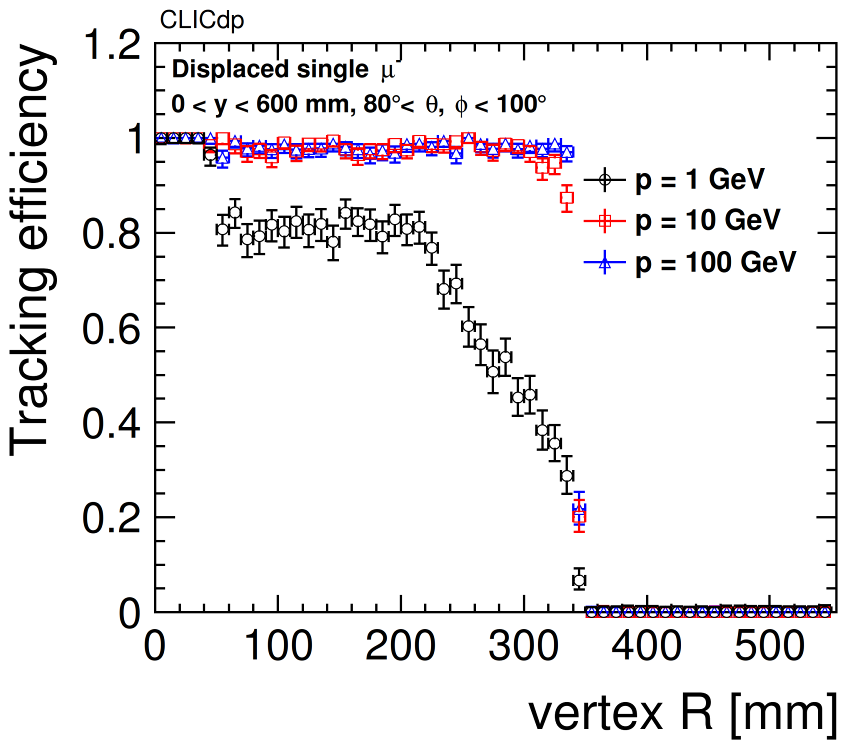
André Sailer

CLICdet performance in full simulation: tracking

Momentum resolution



Displaced tracks

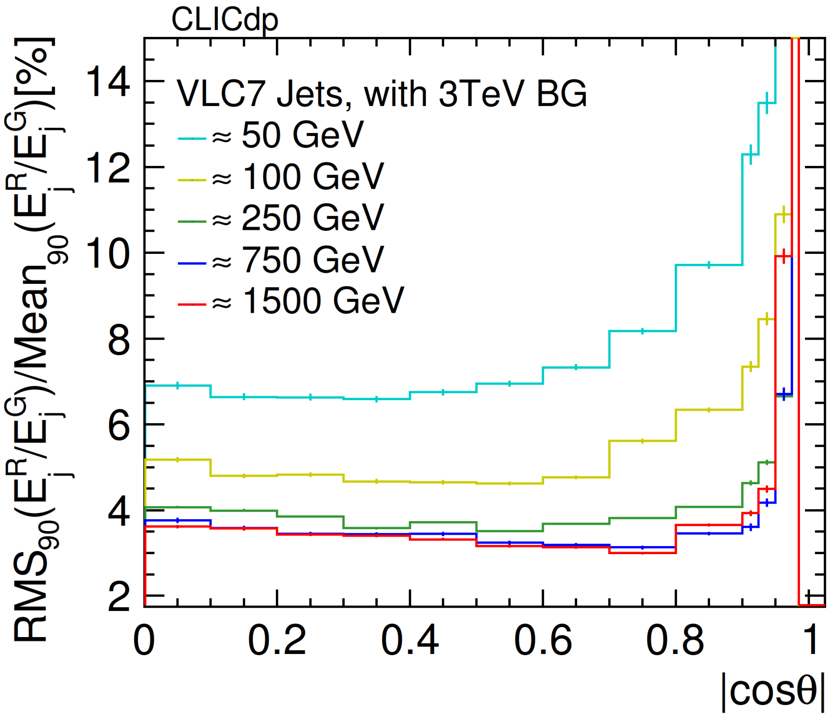


Transverse momentum resolution of 2×10^{-5} GeV^{-1} achieved for high-energy tracks in the central part of the detector

arXiv:1812.07337

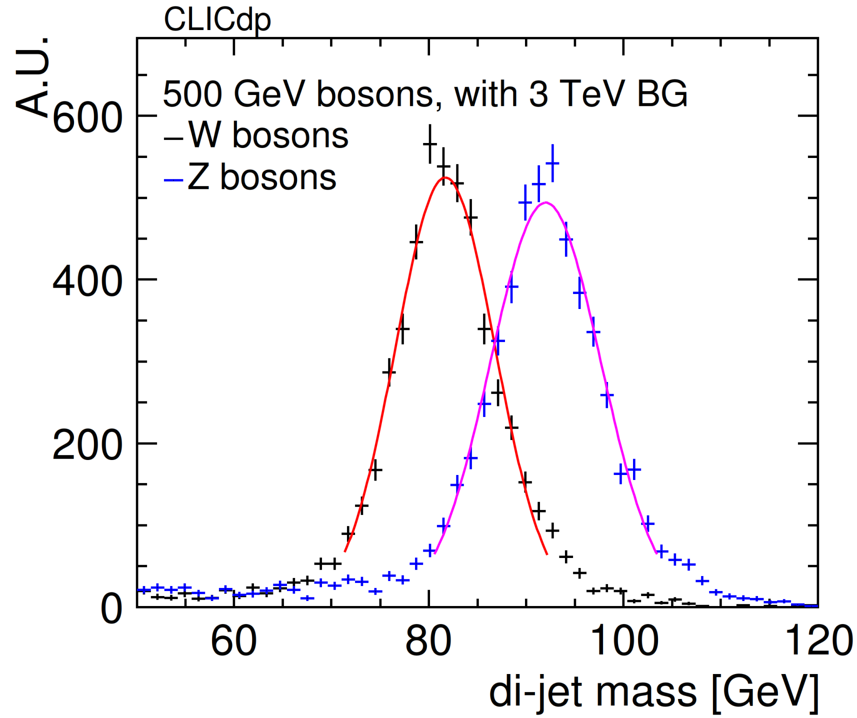
CLICdet performance in full simulation: PFA

Jet energy resolution



Jet energy resolution with pile-up at the 3 TeV CLIC stage

Hadronic W and Z decays



→ Physics projections are based on realistic full detector simulations and include the impact of beam-beam effects

arXiv:1812.07337

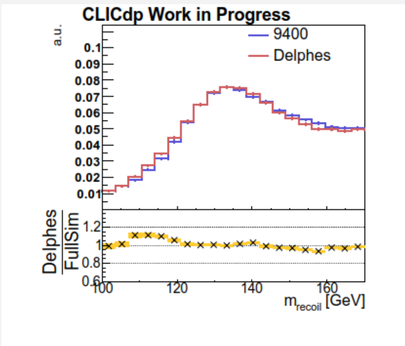
Fast simulation

CLICdet DELPHES card

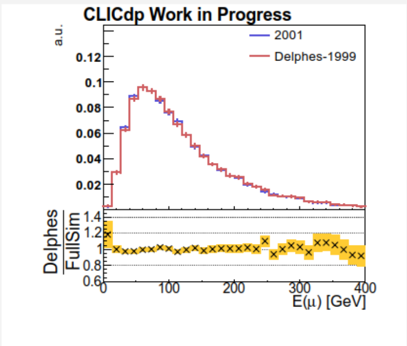
- Fast simulation based on CLICdet detector geometry and performance available in DELPHES (central repository: `https://github.com/delphes`)
- Performance parameters based on full simulation of CLICdet documented in `arXiv:1812.07337`
- Workflow includes tracking and identification efficiencies, momentum and calorimeter resolutions, jet clustering, flavor tagging, isolation, particle flow
- Linear collider jet algorithm VLC implemented in DELPHES and used in the CLICdet cards
- Separate cards for the 3 energy stages to mimic effect of beam-induced background on jet energy resolution
- Hints for using the CLICdet card:
  `https://twiki.cern.ch/twiki/bin/view/CLIC/DelphesMadgraphForBSMReport`

Validation compared to full simulation

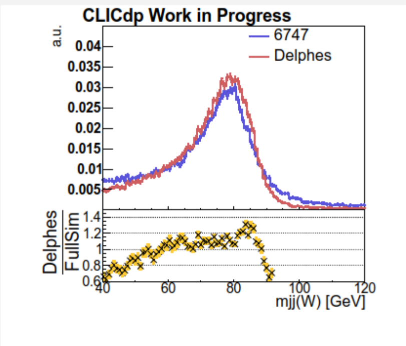
- CLICdet cards validated against full simulation for the three stages in various processes
- Good agreement found for invariant masses, energy and angular observables of jets and leptons



HZ $(Z \to q\bar{q})$ at 350 GeV



$H\nu\nu(H \to \mu\mu)$ at 1.4 TeV



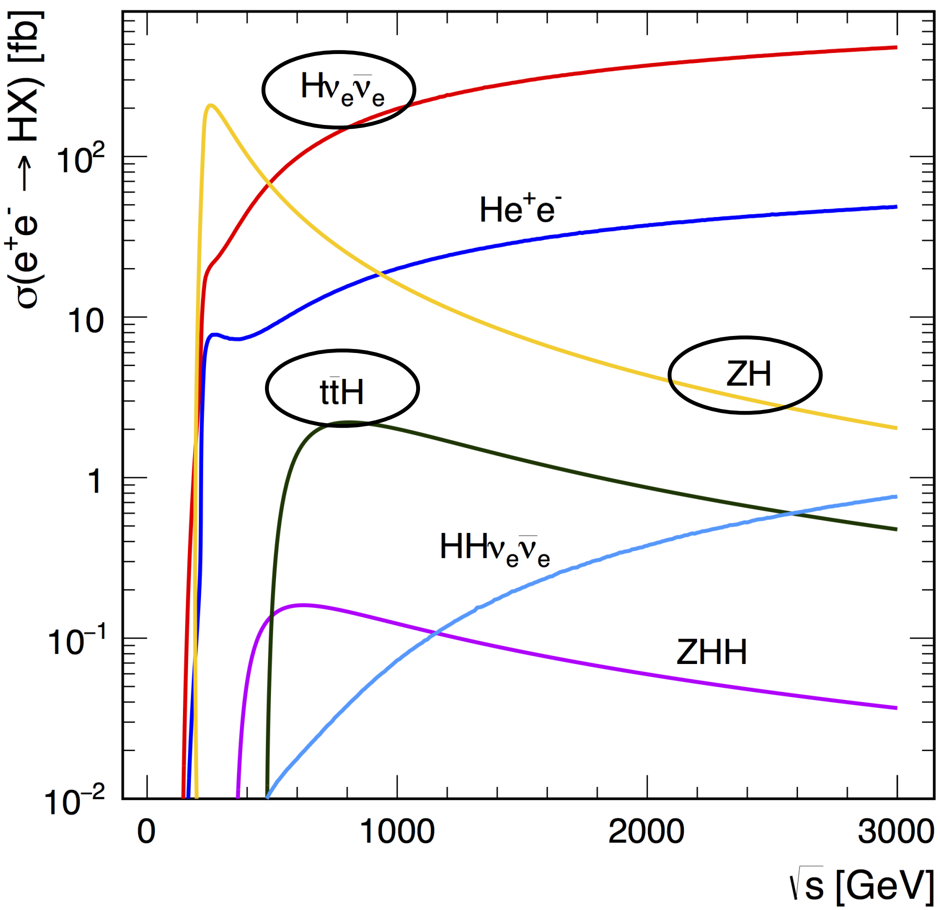
$WW \to \ell\nu q\bar{q}$ at 3 TeV

Ulrike Schnoor

Example full simulation studies:

Higgs and top physics with emphasis on reconstruction challenges and high energy

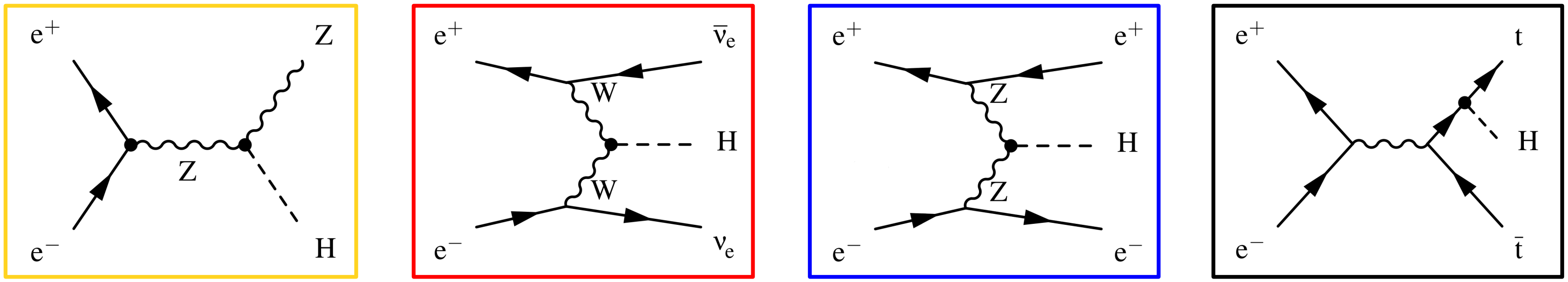
Single Higgs production



Higgsstrahlung: $e^+e^- \to ZH$
- $\sigma \sim 1/s$, dominant up to ≈ 500 GeV
- Model-independent measurement of σ(ZH) at 380 GeV

WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$
- $\sigma \sim \log(s)$, dominant above 500 GeV
- Large statistics at high energy

$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$
- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling

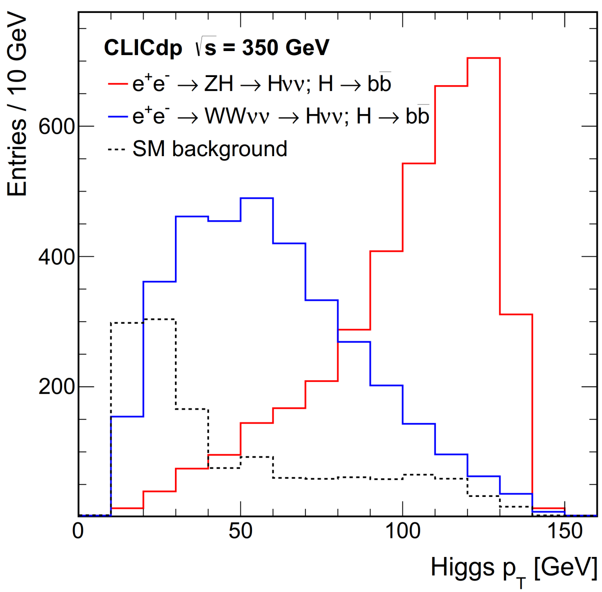


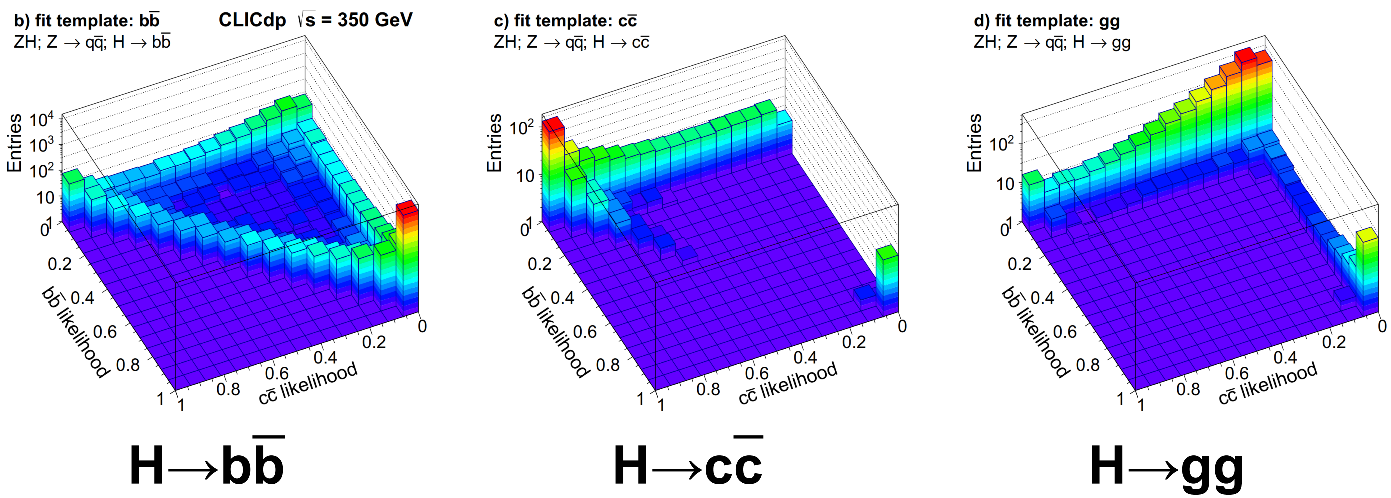
Simultaneous extraction of:
- Three decay modes: $b\bar{b}/c\bar{c}/gg$
→ precise flavour tagging
- Two production modes: ZH and WW fusion
→ Higgs p_T spectrum

Uncertainties on σ x BR

Decay	Statistical uncertainty Higgsstrahlung	Statistical uncertainty WW-fusion
$H \to b\bar{b}$	0.61 %	1.3 %
$H \to c\bar{c}$	10 %	18 %
$H \to gg$	4.3 %	7.2 %

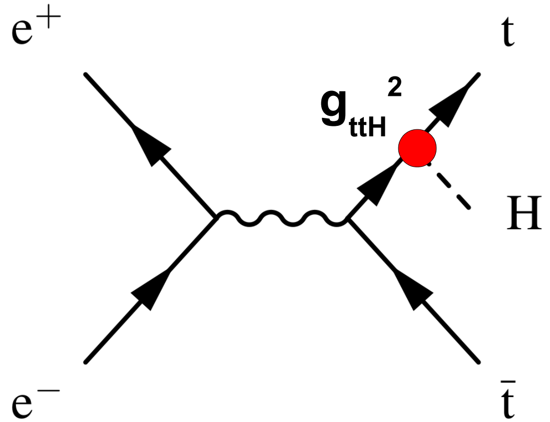
CLIC, $\sqrt{s}$ = 350 GeV, L = 1 ab^{-1}, no polarisation



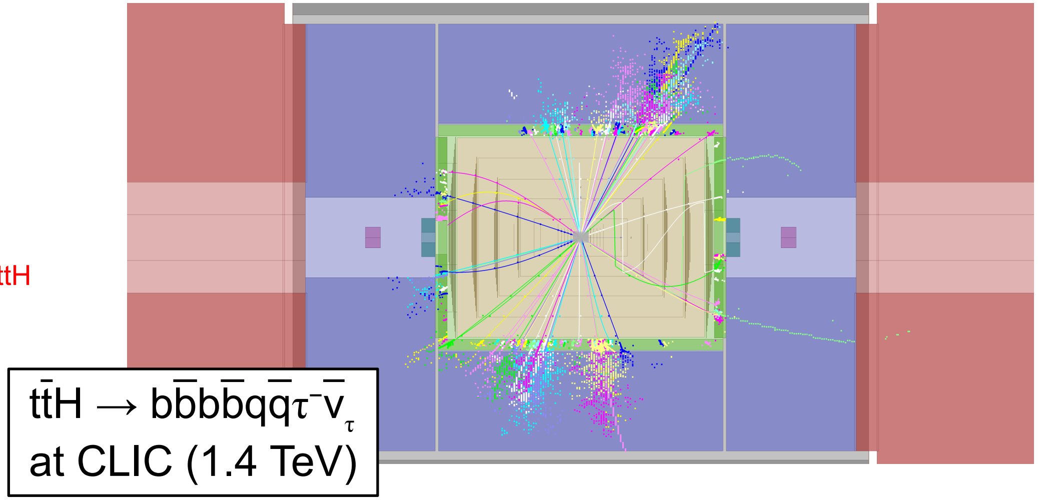


Eur. Phys. J. C 77, 475 (2017)

Top Yukawa coupling



→ σ(tt̄H) is directly sensitive to the top Yukawa coupling g_{ttH}

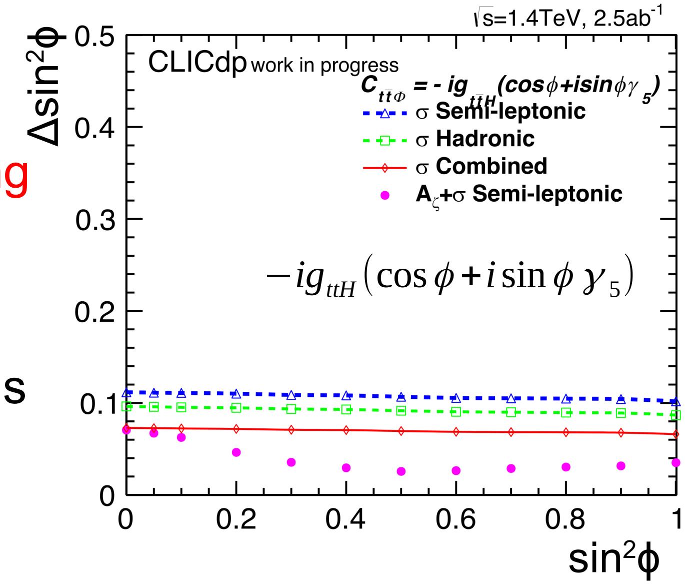


Most important final states:
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bl\nu\bar{b}b\bar{b}$
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bq\bar{q}\bar{b}b\bar{b}$
→ Roughly similar sensitivity

CLIC, $\sqrt{s}$ = 1.4 TeV, L = 2.5 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$ = 2.9%

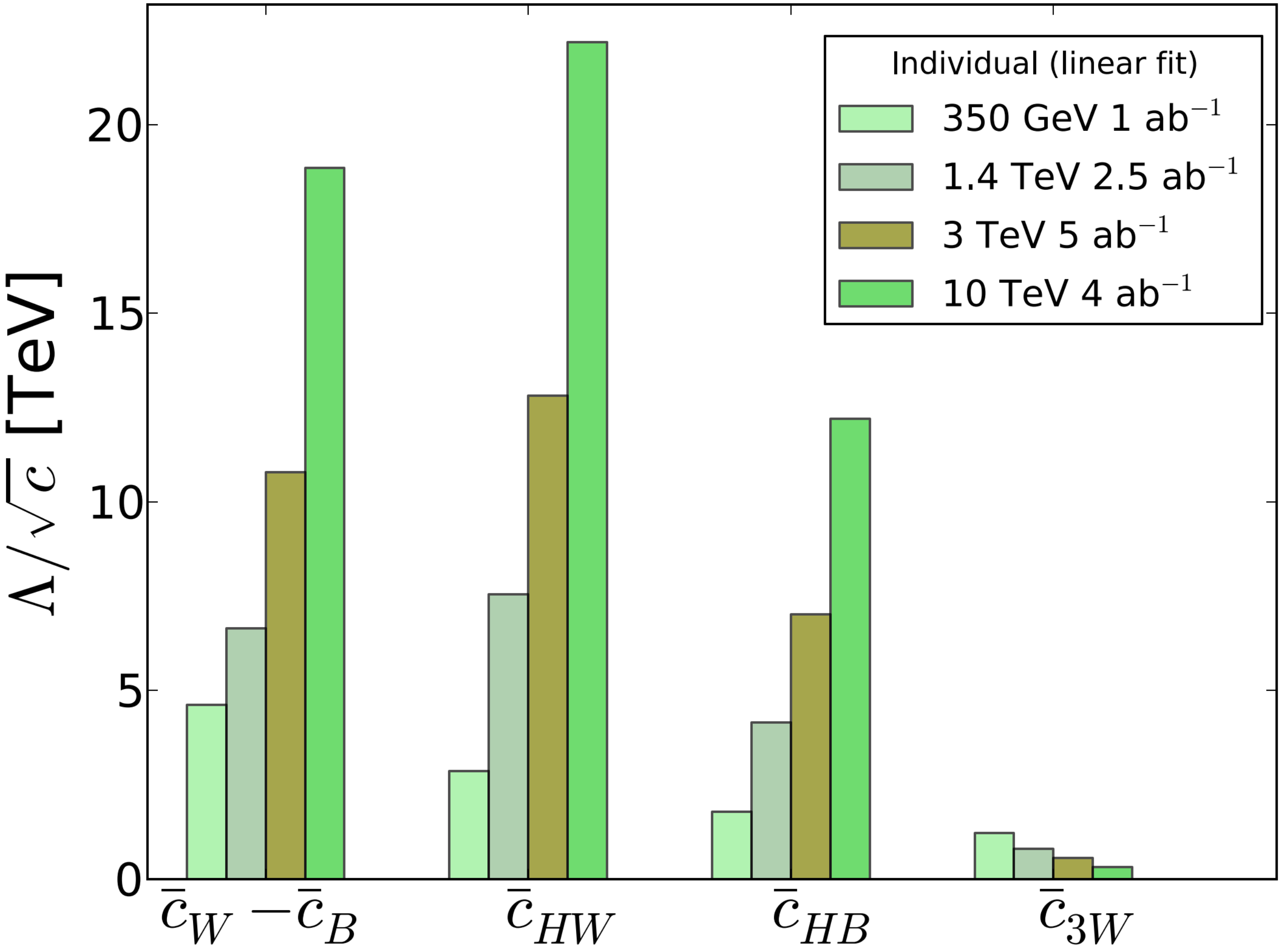
arXiv:1807.02441

- Sensitivity to CP mixing in the ttH coupling from σ(tt̄H)
- Differential distributions provide further improvement



Higgs and WW production in 10 TeV e^+e^- collisions

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

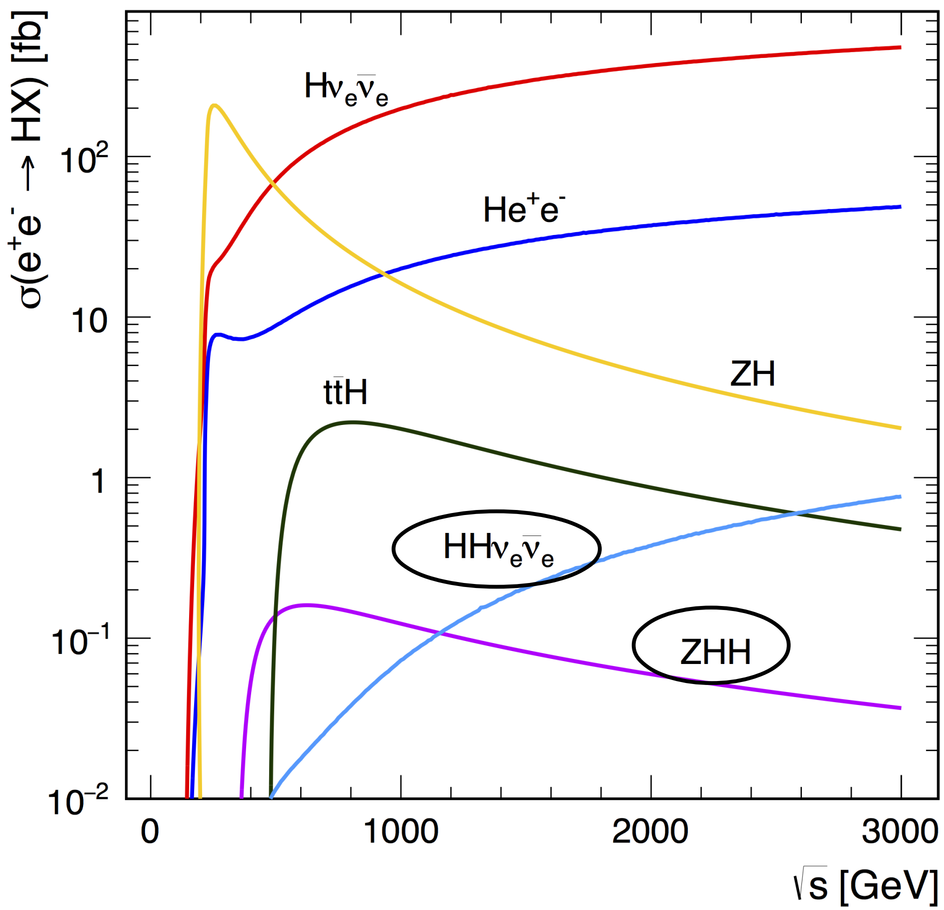


→ New physics scales well beyond the centre-of-mass energy can be reached

The 10 TeV projections were scaled from 3 TeV (assuming the same luminosity spectrum)

CERN-2018-005-M

Double Higgs production



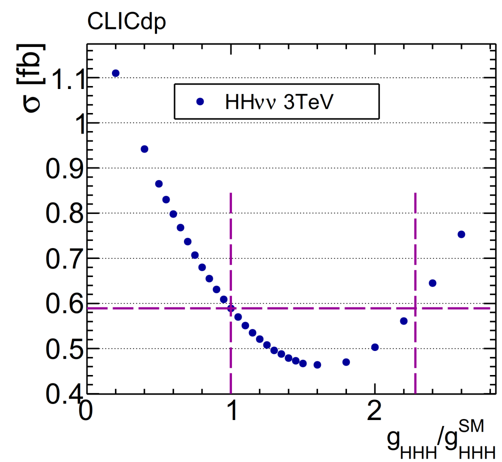
$e^+e^- \to ZHH$:

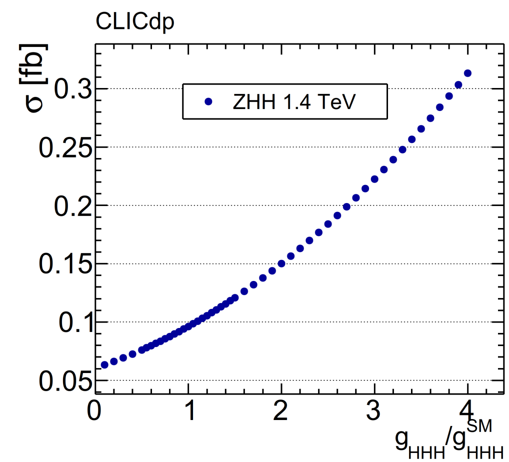
- Cross section maximum around 600 GeV

$e^+e^- \to HH\nu_e\bar{\nu}_e$:

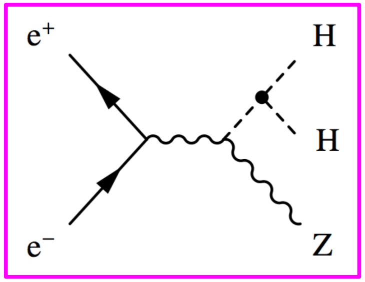
- Benefits from high-energy operation

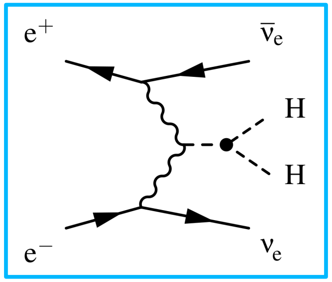
Both processes provide complementary information:





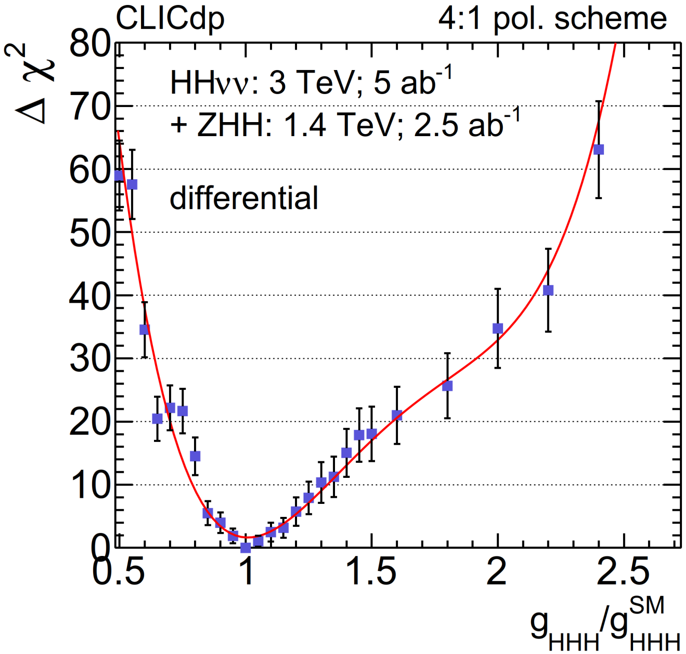
→ The ambiguity in the extraction of g_{HHH} from $\sigma(HH\nu_e\bar{\nu}_e)$ can be broken using differential distributions and / or σ(ZHH) at 1.4 TeV



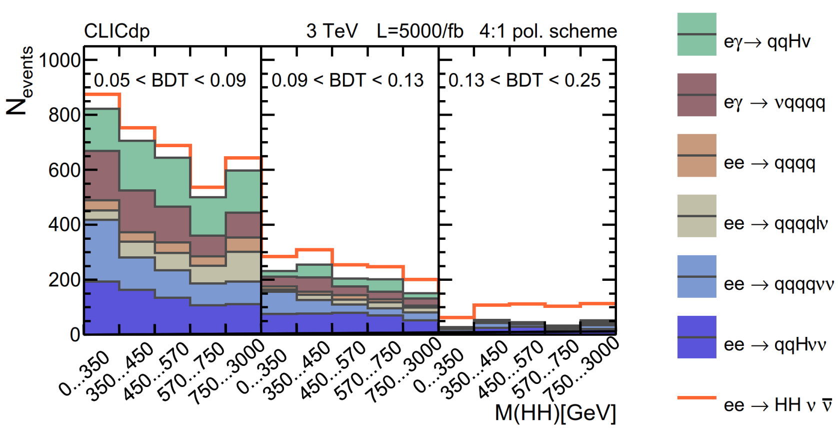


Higgs self-coupling measurements

• HH→$b\bar{b}b\bar{b}$ is the “golden channel” at CLIC, combination with HH→$b\bar{b}$WW* leads to marginal improvement



	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}e)$	> 3σ EVIDENCE Δσ/σ = 28%	> 5σ OBSERVATION Δσ/σ = 7.3%
σ(ZHH)	> 5σ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -34% +36% rate only	1.4 & 3 TeV: -7% +11% differential analysis



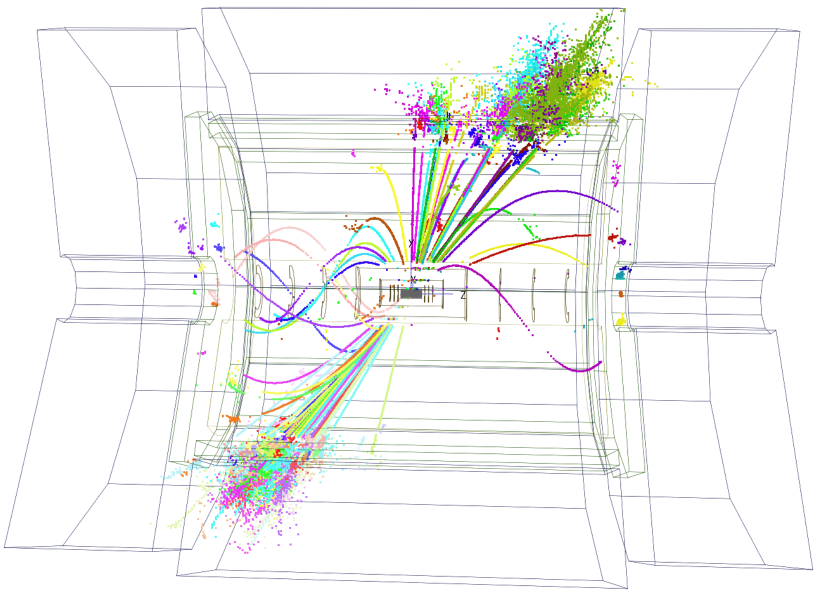
Template fit at 3 TeV
uses two variables: M(HH) and BDT score

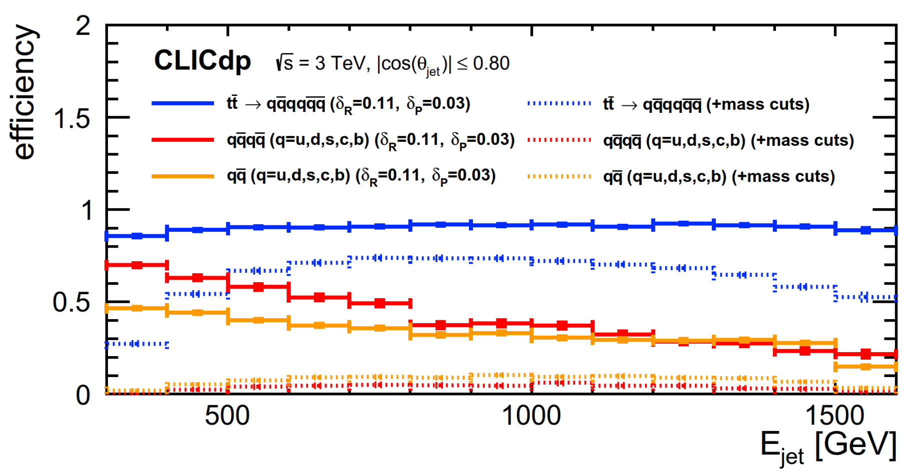
NB: ZHH not full simulation yet

arXiv:1901.05897

Boosted top reconstruction

$e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$ at $\sqrt{s}$ = 3 TeV





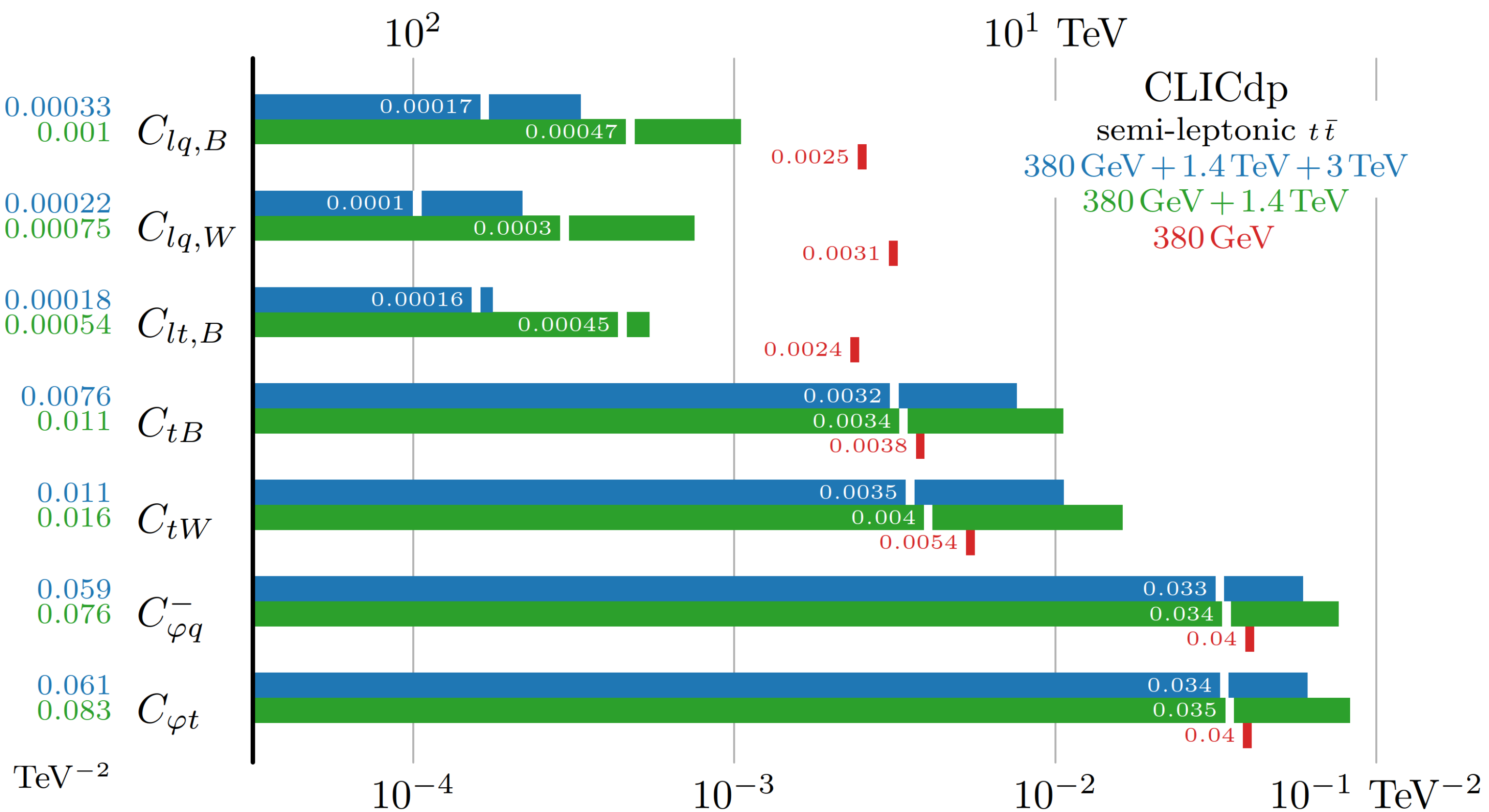
- Hadronic decays of high-energy top quarks do not lead to three well-separated jets
- Instead, reconstruction of the top in a "large" jet and identification of substructure compatible with $t \rightarrow Wb \rightarrow q\bar{q}b$
- Studied ≈10 years for the LHC, new and active effort for CLIC including different approaches
- Boosted $H \rightarrow b\bar{b}$ also under study

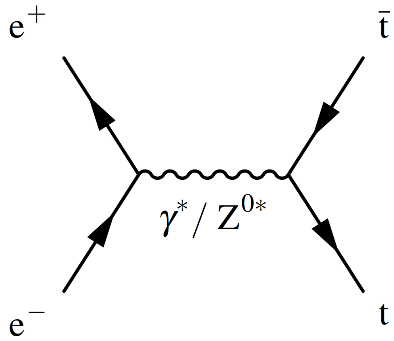
Example:

- John Hopkins top tagger
- High efficiency achieved in physics analyses (also due to moderate backgrounds in e^+e^- collisions)

arXiv:1807.02441

EFT analysis of $t\bar{t}$ production at CLIC





Bars: global fit

Ticks: individual operators

- A global fit requires at least one high-energy stage in addition to 380 GeV operation
- High-energy operation dramatically improves the sensitivity for certain (“four-fermion”) operators

arXiv:1807.02441

Much more information

https://clic.cern/european-strategy

CLIC input to the European Strategy for Particle Physics Update 2018-2020

Formal European Strategy submissions

- **The Compact Linear e+e- Collider (CLIC): Accelerator and Detector** (arXiv:1812.07987)
- **The Compact Linear e+e- Collider (CLIC): Physics Potential** (arXiv:1812.07986)

Yellow Reports

- **CLIC 2018 Summary Report** (CERN-2018-005-M, arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M, arXiv:1903.08655)
- **The CLIC potential for new physics** (CERN-2018-009-M, arXiv:1812.02093)
- **Detector technologies for CLIC** [In collaboration review]

Journal publications

- **Top-quark physics at the CLIC electron-positron linear collider** [In journal review] (arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal, arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS, arXiv.

CLICdp notes

- **Updated CLIC luminosity staging baseline and Higgs coupling prospects** (CERN Document Server, arXiv:1812.01644)
- **CLICdet: The post-CDR CLIC detector model** (CERN Document Server)
- **A detector for CLIC: main parameters and performance** (CERN Document Server, arXiv:1812.07337)

Summary and conclusions

• The CLICdet detector model is optimised to study e^+e^- collisions up to 3 TeV in the CLIC experimental conditions

• The corresponding software chain is validated for physics studies from Geant4 simulation to user analysis, access to distributed resources via (iLC)Dirac

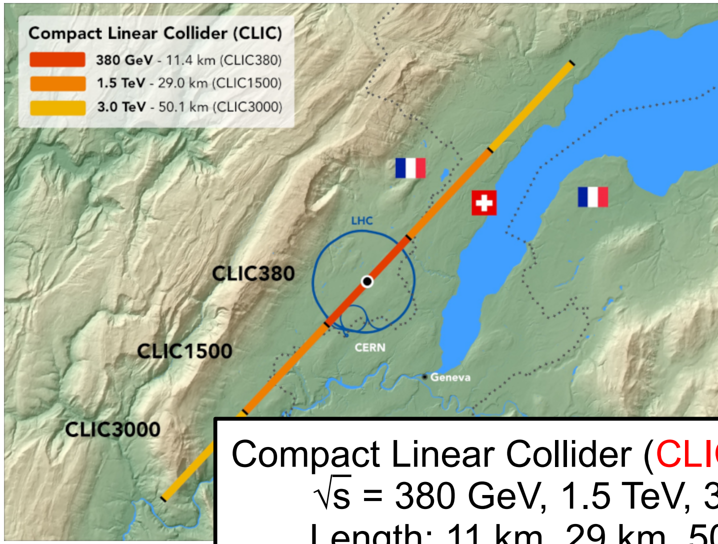
• CLIC energy-staging → optimal for physics:

380 GeV:	Optimised for precision SM Higgs and top physics
1.5 TeV & 3 TeV:	Best sensitivity for new physics searches, rare Higgs processes and decays

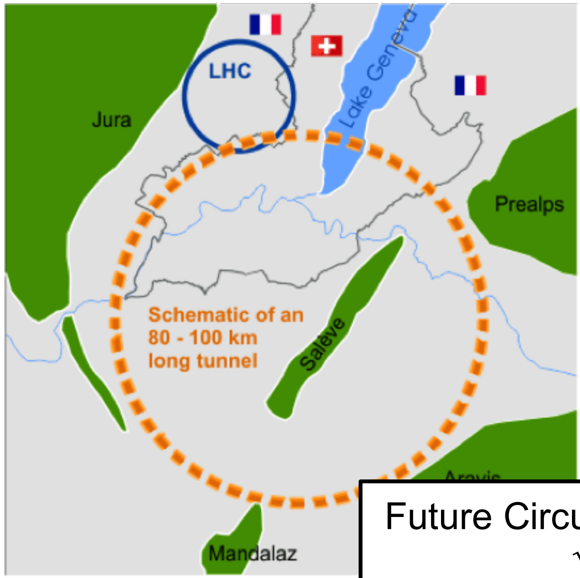
• Lots of potential synergies with muon collider studies (already visible this morning)

Backup slides

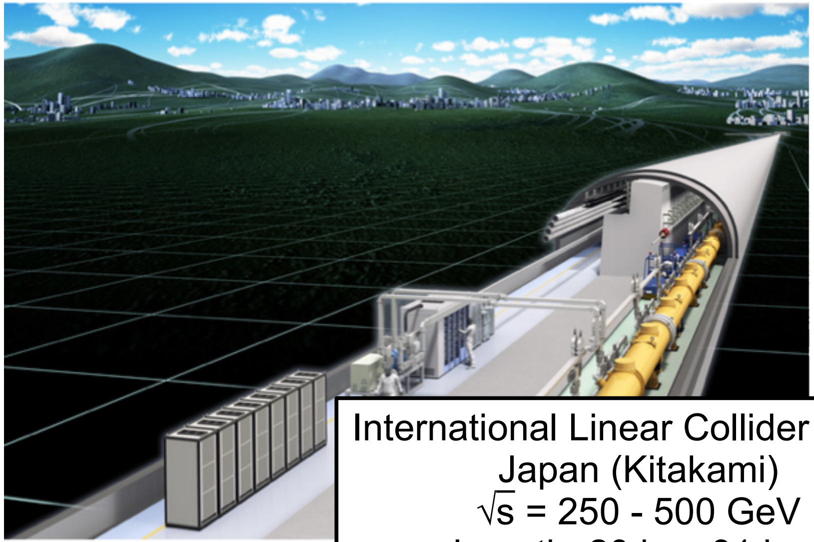
Studies of high-energy e^+e^- colliders



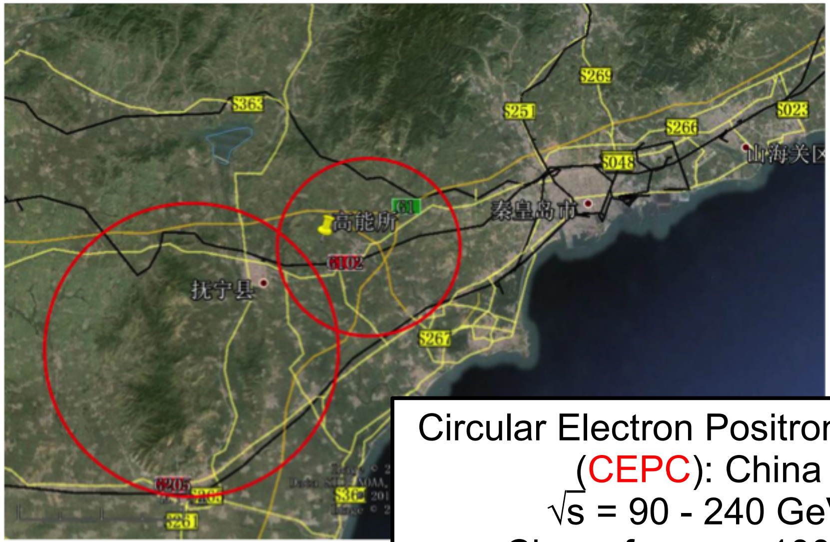
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 365 GeV
Circumference: 97.75 km

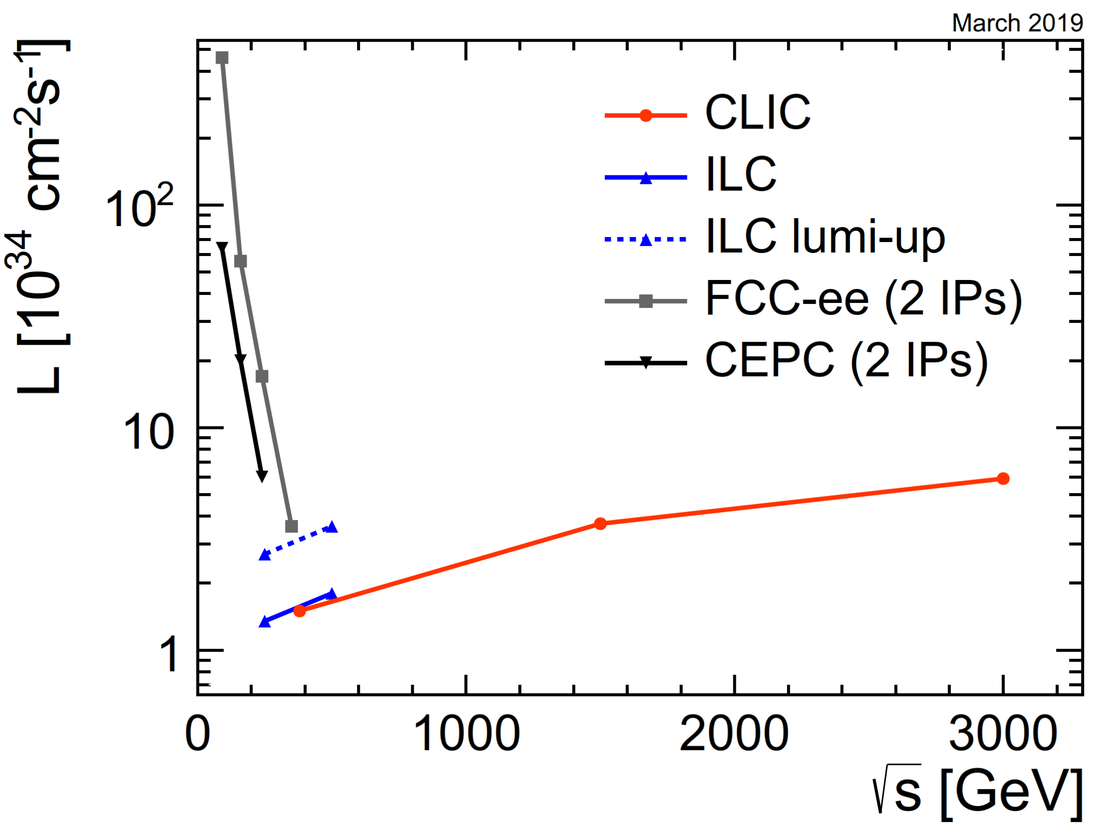


International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV
Length: 20 km, 31 km



Circular Electron Positron Collider (CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

Comparison to other e^+e^- collider options



Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies
- Potential to benefit from novel accelerator techniques

Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

NB: Peak luminosity at LEP2 (209 GeV) was ≈ 10^{32} cm^{-2}s^{-1}

Detector simulation

DDSim

- Geometry translated to GEANT4 in memory, access to `SensitiveDetectors`, `Run/Event/Stack/Step Actions`
- Simulation steerable via python program `ddsim`
- Get steering file `ddsim --dumpSteeringFile > mySteer.py`
  - Steering file includes documentation for parameters and examples
  - Configure simulation directly from commandline
- Add plugins for additional functionality

```python
from DDSim.DD4hepSimulation import DD4hepSimulation
from SystemOfUnits import mm, GeV, MeV, keV
SIM = DD4hepSimulation()
SIM.compactFile = "CLIC_o3_v06.xml"
SIM.runType = "batch"
SIM.numberOfEvents = 2
SIM.inputFile = "electrons.HEPEvt"
SIM.part.minimalKineticEnergy = 1*MeV
SIM.filter.filters ['edep3kev'] =
dict (name="EnergyDepositMinimumCut/3keV" ,
      parameter={"Cut" : 3.0*keV} )
```

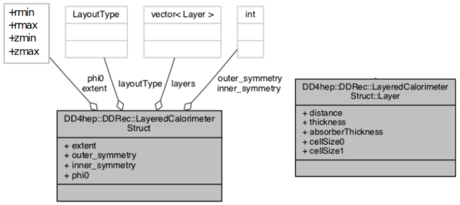
```
$ ddsim
--action.calo                    --filter.tracker        --part.keepAllParticles
--action.mapActions              -G                      --part.minimalKineticEnergy
--action.tracker                 --gun.direction         --part.printEndTracking
--compactFile                    --gun.energy            --part.printStartTracking
--crossingAngleBoost             --gun.isotrop           --part.saveProcesses
--dump                           --gun.multiplicity      --physics.decays
--dumpParameter                  --gun.particle          --physics.list
--dumpSteeringFile               --gun.position          --physicsList
--enableDetailedShowerMode       -h                      --physics.rangecut
--enableGun                      --help                  --printLevel
--field.delta_chord              -I                      --random.file
--field.delta_intersection       --inputFiles            --random.luxury
--field.delta_one_step           -M                      --random.replace_gRandom
--field.eps_max                  --macroFile             --random.seed
--field.eps_min                  -N                      --random.type
--field.equation                 --numberOfEvents        --runType
--field.largest_step             -O                      -S
--field.min_chord_step           --outputFile            --skipNEvents
--field.stepper                  --output.inputStage     --steeringFile
--filter.calo                    --output.kernel         -v
--filter.filters                 --output.part           --vertexOffset
--filter.mapDetFilter            --output.random         --vertexSigma
```

DDRec: High Level Information

High level view onto the detectors through DDRec `DataStructures` extensions for `DetElements`

- Constructors fill DDRec `DataStructures`
- `DataStructures` allow to decouple detector implementation from reconstruction algorithms

`DataStructures` contain sufficient information to provide geometry information to particle flow clustering via `PandoraPFA`

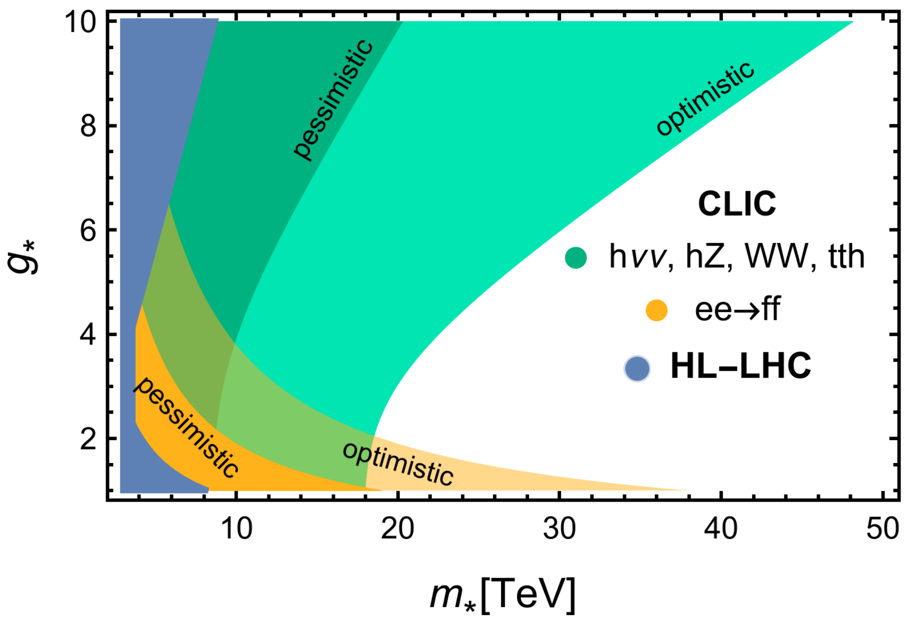


Data Structure	Detector Type
`ConicalSupportData`	Cones and Tubes
`FixedPadSizeTPCData`	Cylindrical TPC
`LayeredCalorimeterData`	Sandwich Calorimeters
`ZPlanarData`	Planar Silicon Trackers
`ZDiskPetalsData`	Forward Silicon Trackers

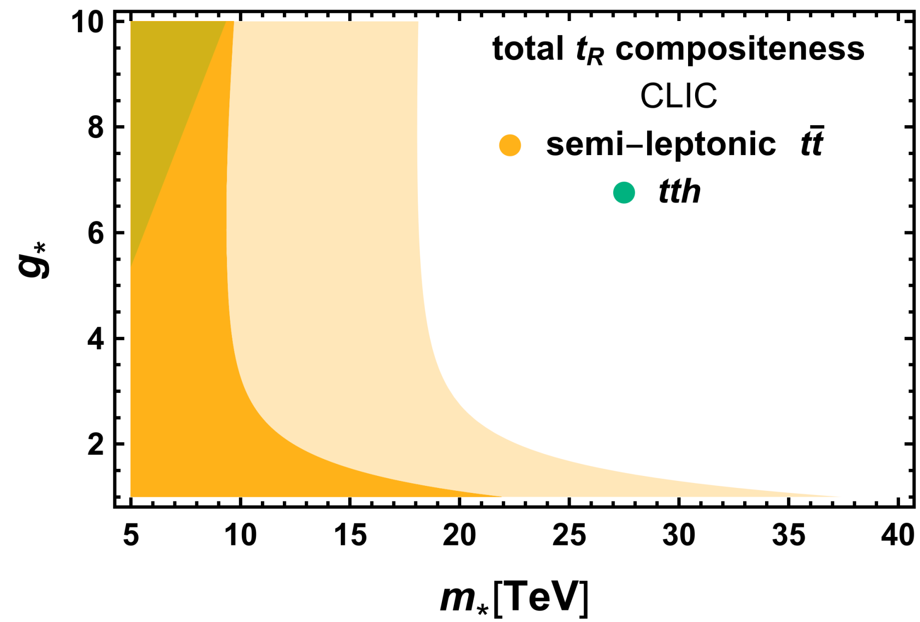
André Sailer

Compositeness at CLIC

Composite Higgs



Composite top



m_*: compositeness scale

g_*: coupling strength of the composite sector

Discovery of Higgs compositeness scale up to 10 TeV (40 TeV for $g_* \approx 8$)

Discovery of top compositeness scale up to 8 TeV (20 TeV for small g_*)

CERN-2018-009-M