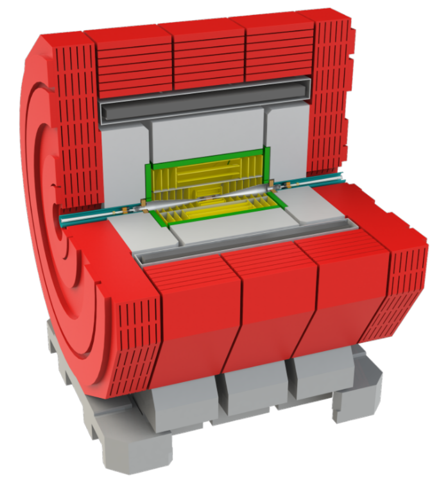
Performance of the CLIC detector and the CLD detector of FCC-ee for high-energy running

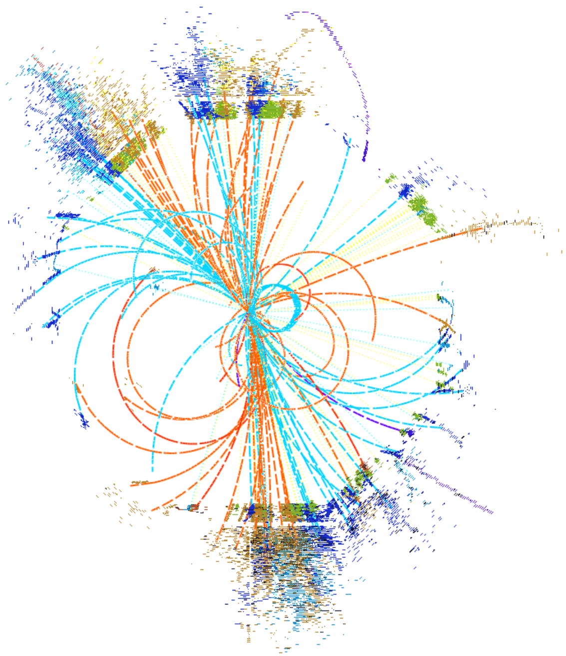
Philipp Roloff (CERN)

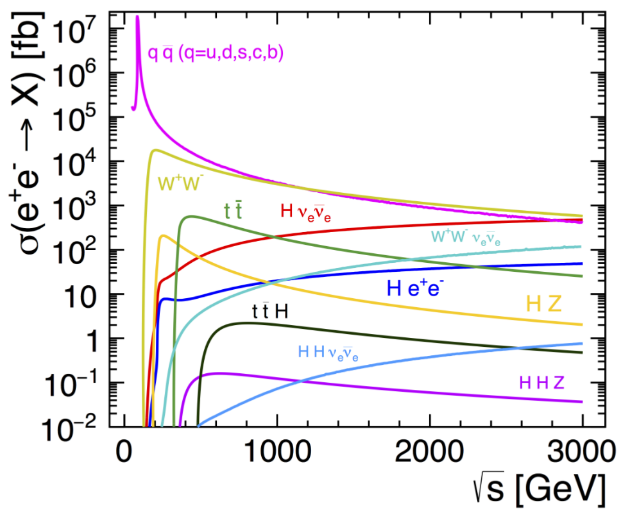
on behalf of the CLICdp collaboration and of the CLD detector study

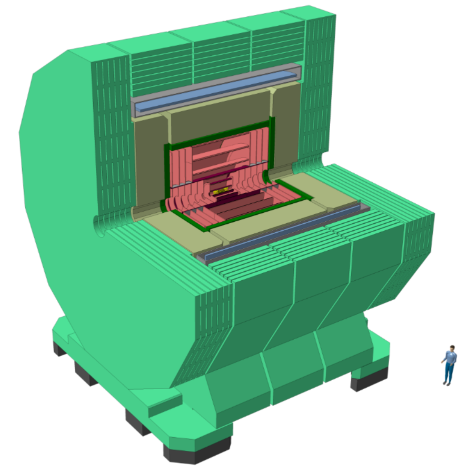


<u>27/10/2020</u>

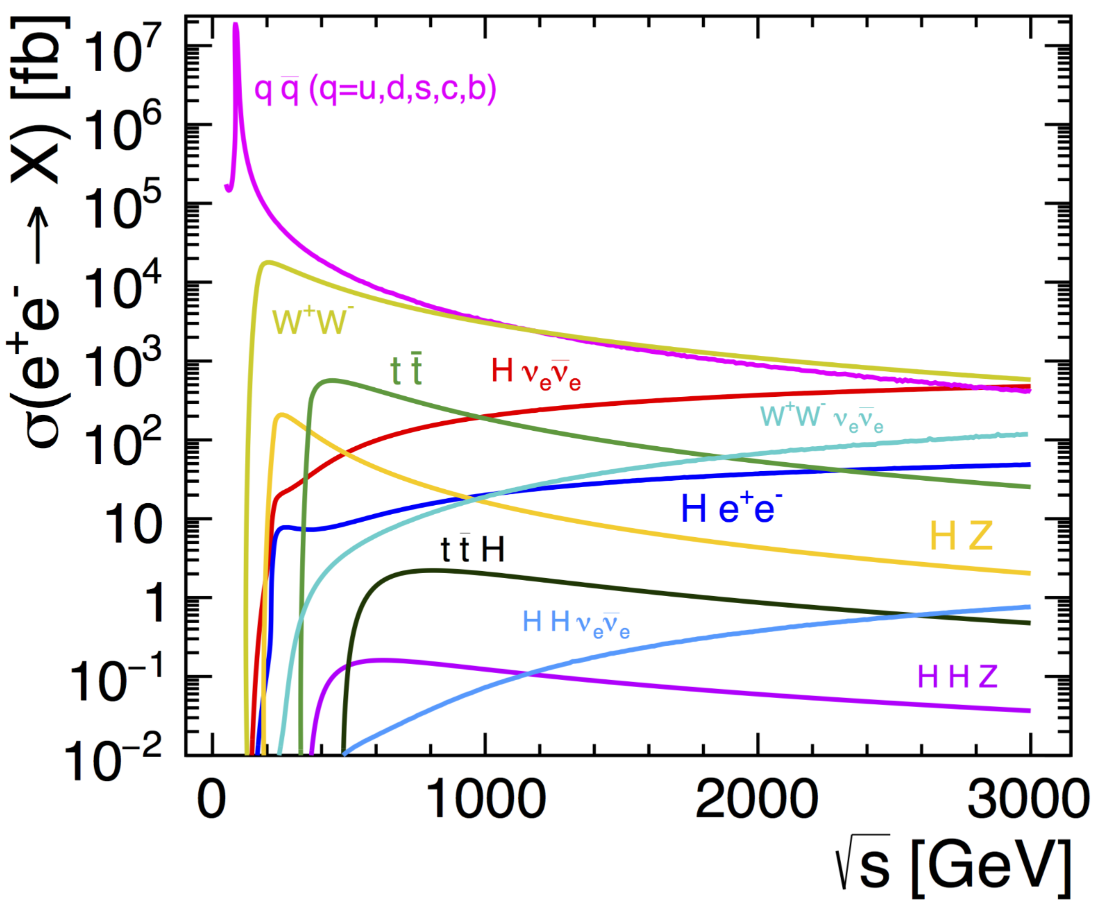
International workshop on the high energy Circular Electron-Positron Collider (CEPC)







Important processes in e^+e^- collisions



- **2-fermion production,** e.g. $q\bar{q}$
- **W-boson pair production (WW)**
- **Higgsstrahlung (HZ):** best at 240 - 380 GeV → "Higgs factory"
- **$t\bar{t}$ threshold:** 350 GeV
- **$t\bar{t}$ continuum:** ≥ 365 GeV
- **Double Higgsstrahlung (HHZ):** cross section maximum ≈ 600 GeV
- **Single and double Higgs in WW fusion ($H\nu_e\bar{\nu}_e$ and $HH\nu_e\bar{\nu}_e$):** cross section rises with energy

→ Wide range of physics opportunities, best explored in several energy stages

+ Direct searches for new particles:
highest possible energy

Physics motivations detector requirements (1)

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

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times 10^{-5}\, GeV^{-1}$$

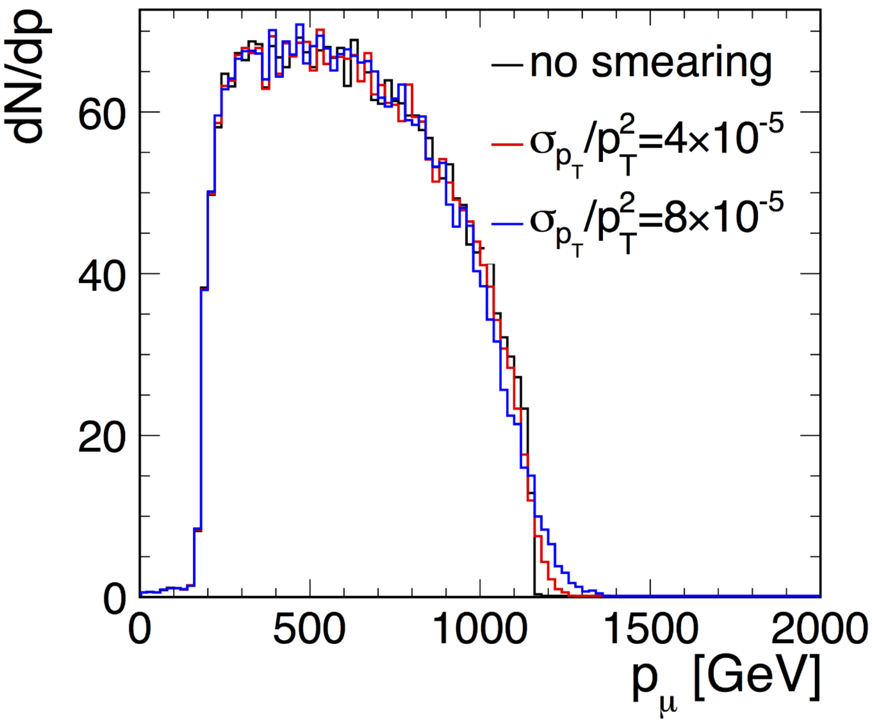
- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E \geq 50\, GeV$$

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

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 10-15\,\mu m$$

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



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

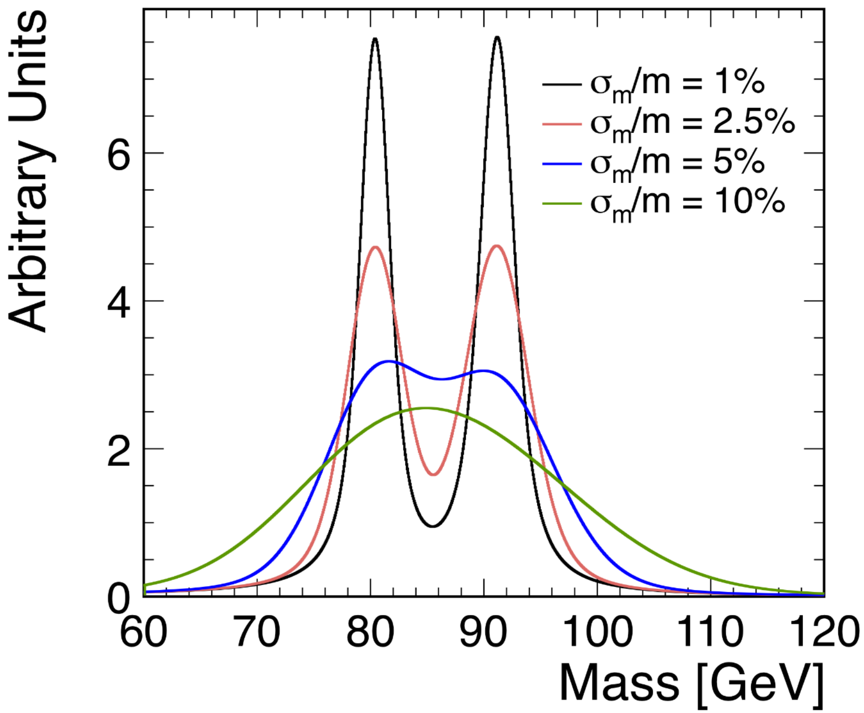
Physics motivations detector requirements (2)

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

$$\frac{\sigma(p_T)}{p_T^2} \sim 2 \times 10^{-5}\, GeV^{-1}$$

- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3.5 - 5\% \;\; for\; E \geq 50\, GeV$$

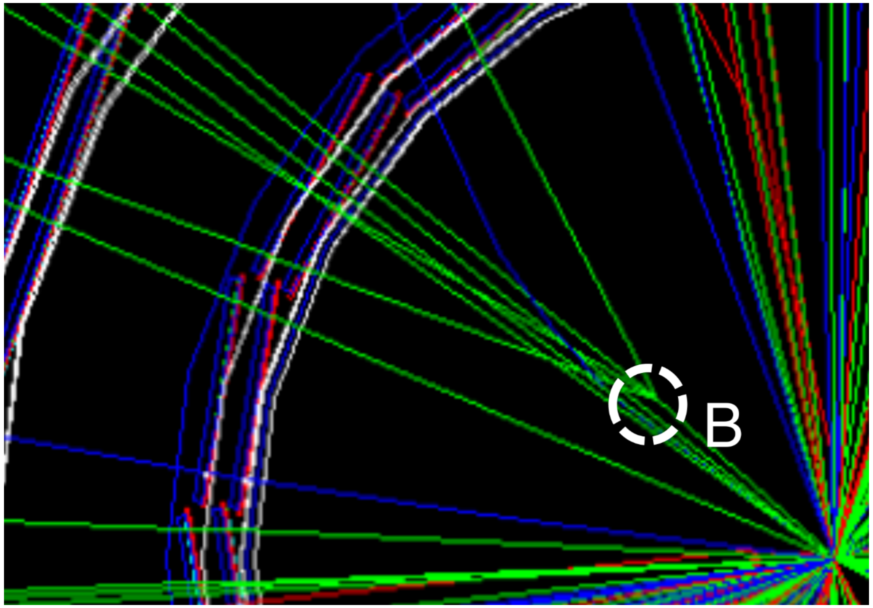


- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3\theta)},\; a \approx 5\,\mu m,\; b \approx 10 - 15\,\mu m$$

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

Physics motivations detector requirements (3)



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

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times 10^{-5}\, GeV^{-1}$$

- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E \geq 50\, GeV$$

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

For the considered vertex detector designs

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 10-15\,\mu m \rightarrow \sigma_{SP} \approx 3\,\mu m$$

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

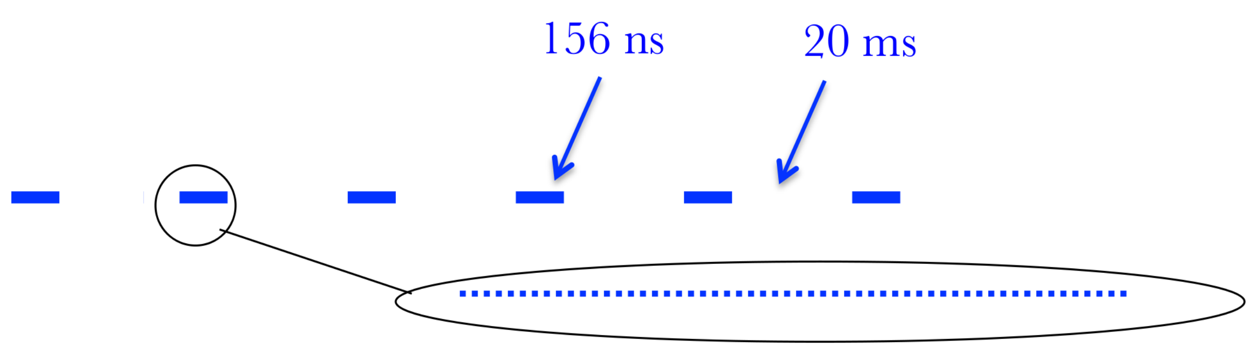
CLIC experimental conditions

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

Very low duty cycle at CLIC allows for:
- Triggerless readout
- Power pulsing



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

FCC-ee experimental conditions

	FCC-ee Z	FCC-ee Higgs	FCC-ee ttbar
$\sqrt{s}$ [GeV]	**91.2**	**240**	**365**
Luminosity per IP ($10^{34}cm^{-2}sec^{-1}$)	**230**	**8.5**	**1.7**
no. of bunches / beam	16640	393	48
Bunch crossing separation (ns)	**20**	994	3000
Beam size at IP σ_x/σ_y (μm)			
Bunch length (SR / BS) (mm) Beam size at IP σ_z (mm)	3.5 / 12.1	3.3 / 5.3	2.0 / 2.5

Example: 3 BX / 10 μs at 365 GeV FCC-ee

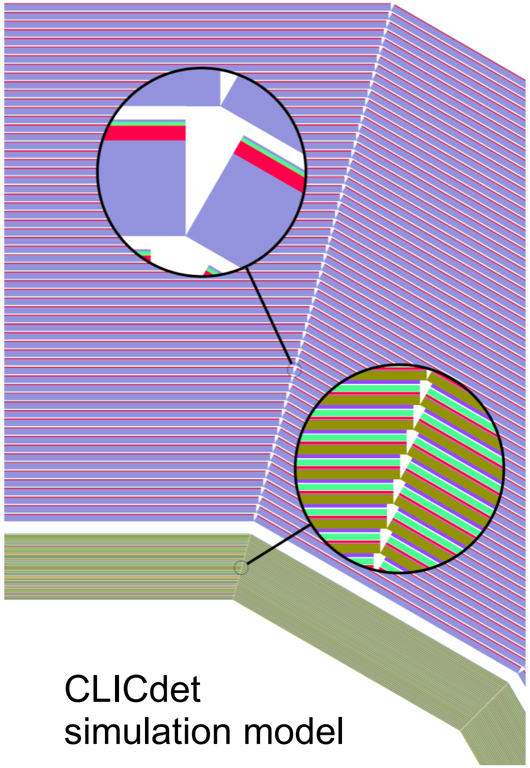
- Impact of beam-induced background to be mitigated through MDI and detector design (e^+e^- pairs dominant, $\gamma\gamma \rightarrow$ hadrons and synchrotron radiation small in the detectors)
- Tracking detectors need to achieve good resolution without power pulsing

Particle flow calorimetry

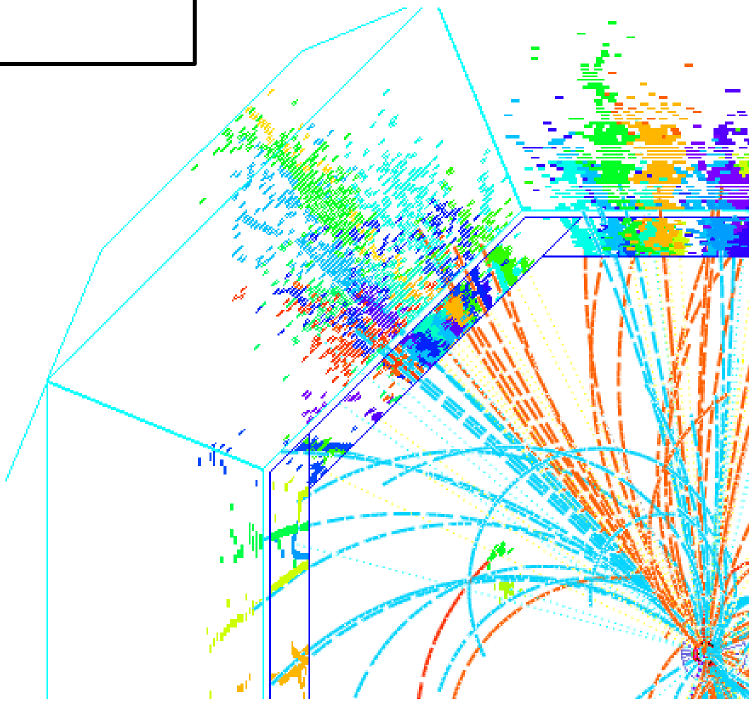
Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutral hadrons

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

Hardware and software!



CLICdet
simulation model

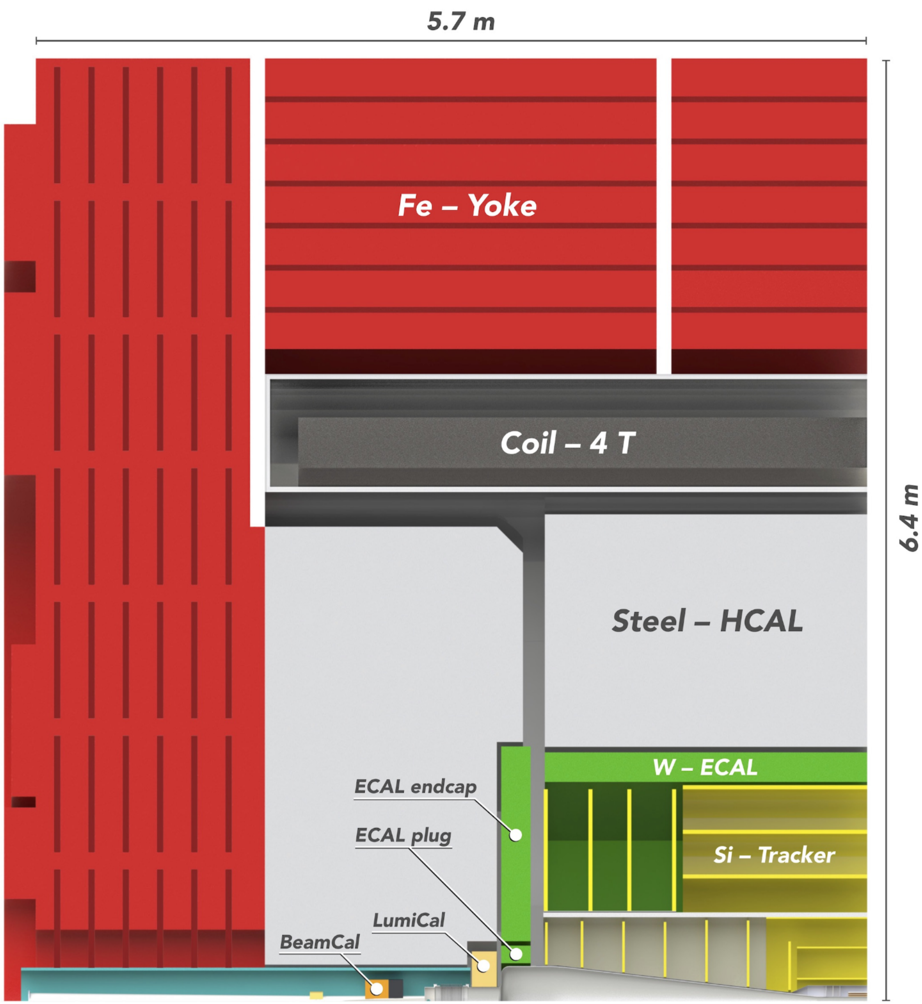


CLICdet and CLD:
- Si-W sampling ECAL,
cell size: 5 x 5 mm^2

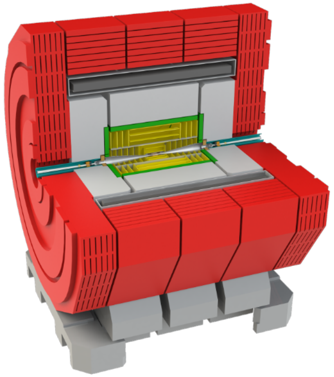
- Scintillator-steel sampling HCAL,
cell size: 30 x 30 mm^2

→ ECAL/HCAL thickness and number of layers
optimised for different conditions at CLIC and FCC-ee (see later)

CLIC detector concept: CLICdet



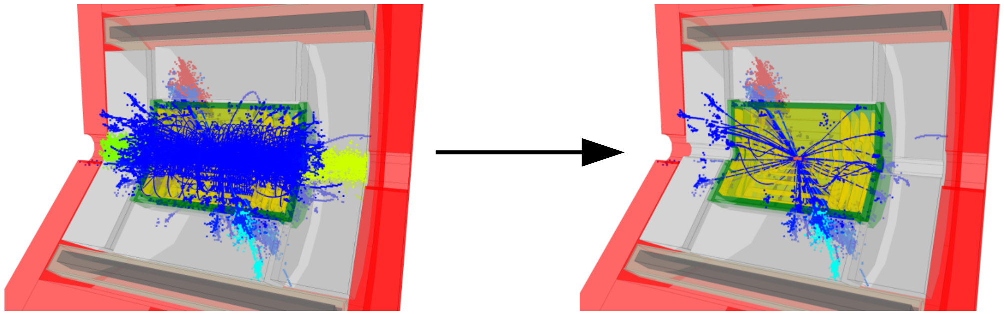
Designed for Particle Flow Calorimetry:
- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass trackers
→ reduce interactions / conversions



Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ_I)

Precise timing:
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits

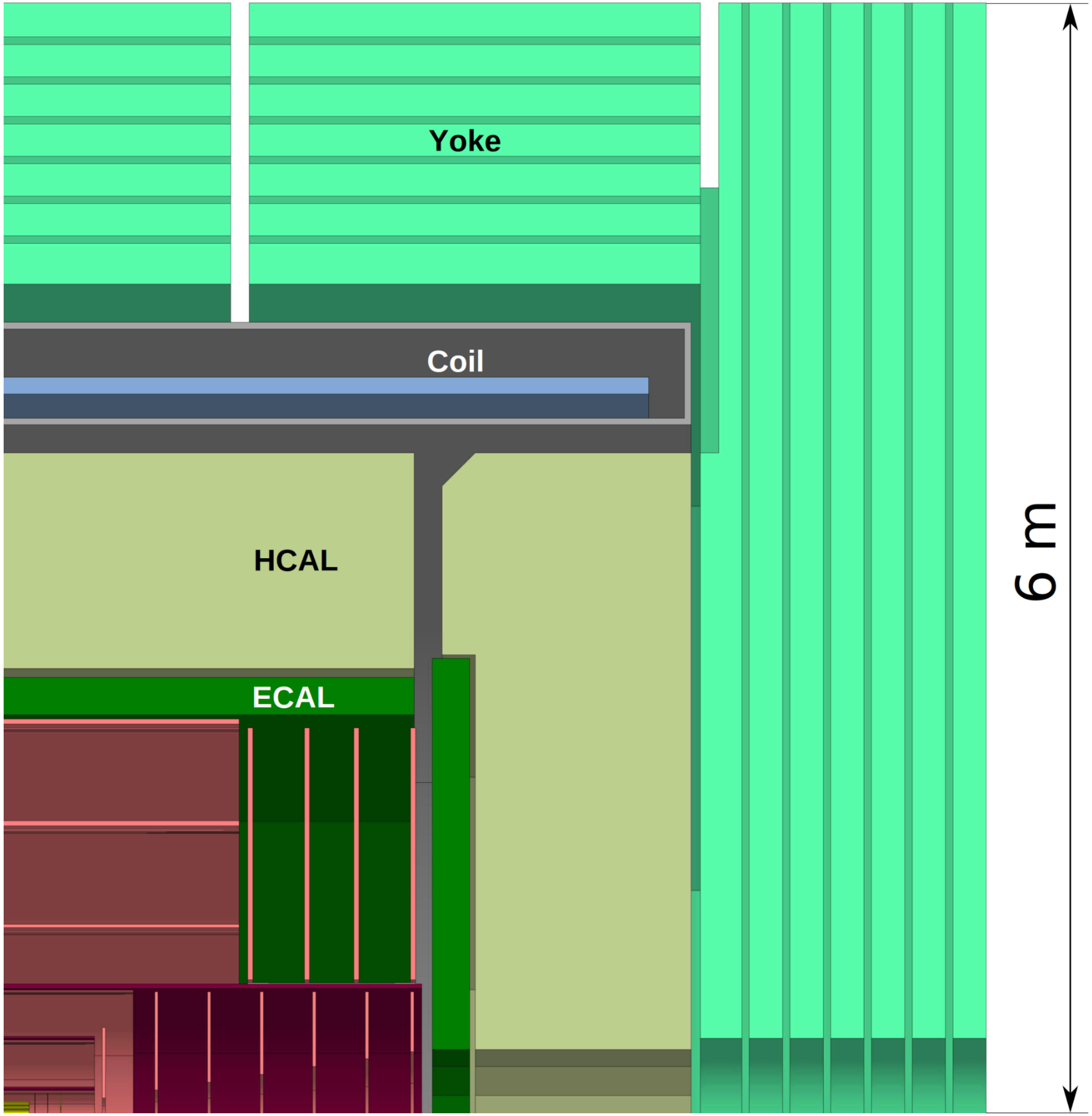
Beam-induced background can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles (= particle flow objects)



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

CLICdp-Note-2017-001
arXiv:1812.07337

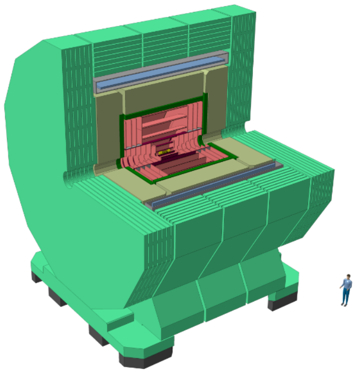
CLD detector concept



CLD concept (inspired by CLICdet):

- Smaller magnetic field (limited by luminosity goal): 2 T
- Larger tracker radius (2.15 m) to keep similar momentum resolution
- Lower $\sqrt{s}$ → HCAL less deep (44 layers, 5.5 λ_I)
- Somewhat increased material budget in the tracking detectors for cooling

arXiv:1911.12230



Detector performance studies

Basic detector performance:

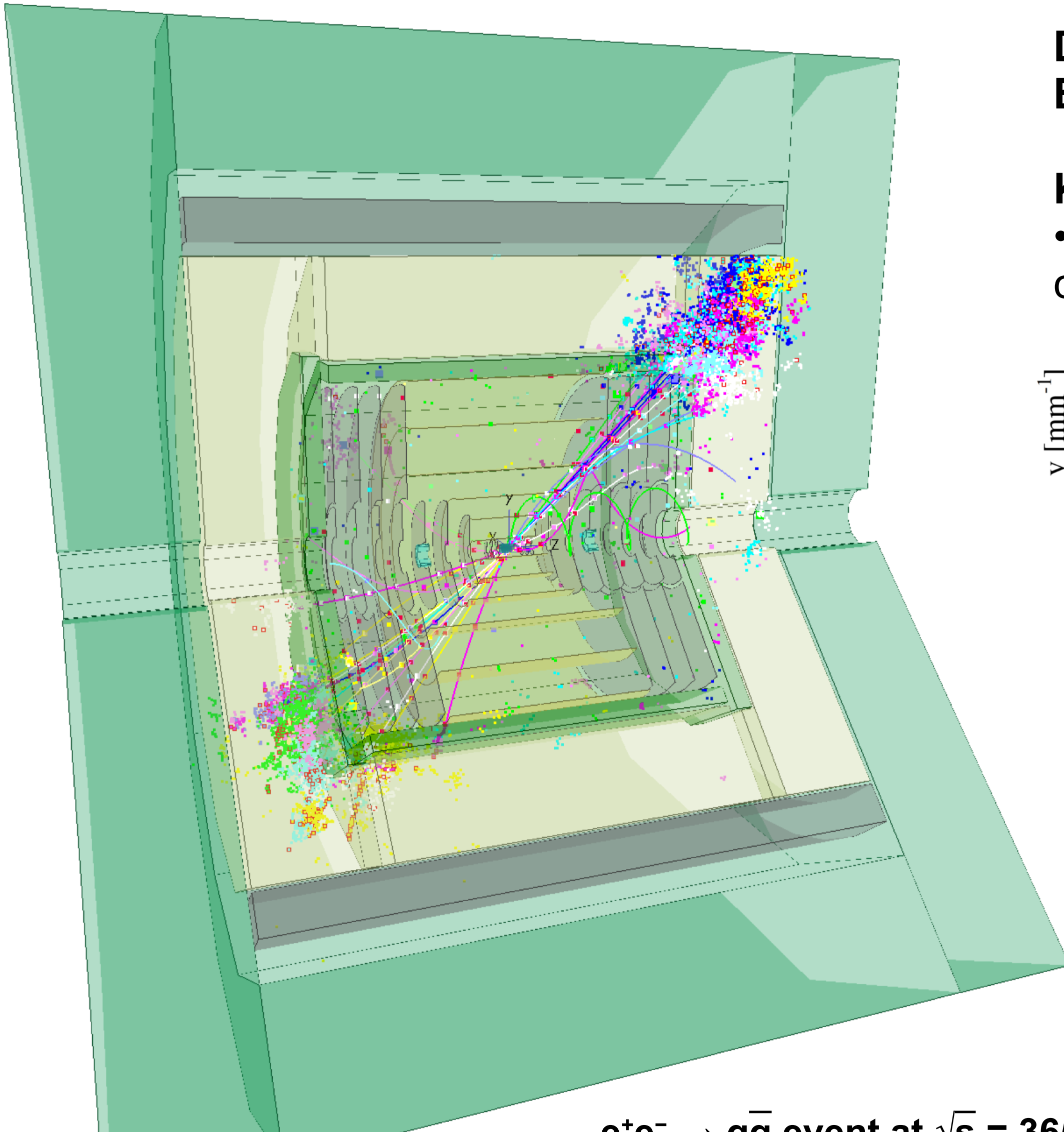
- Momentum resolution
- Impact parameter resolution
- Tracking in complex events
- PFA: photon energy resolution
- PFA: jet energy resolution

High-level physics objects:

- Flavour tagging
- W/Z separation

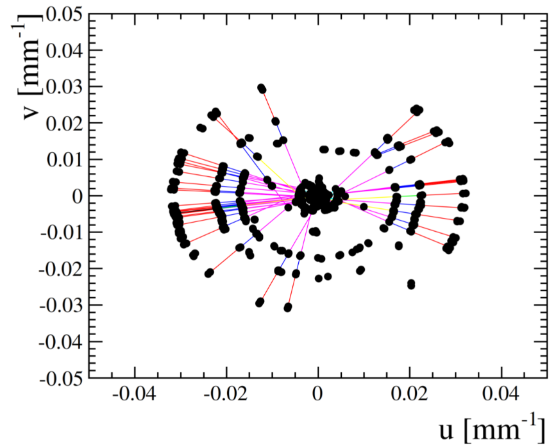
NB: all results based on full detector simulations and detailed reconstruction

Simulation software used



Detector geometries: DD4hep
Event reconstruction framework: Marlin

Key event reconstruction steps:
• “Conformal tracking”: cellular automaton in conformal space for track finding



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

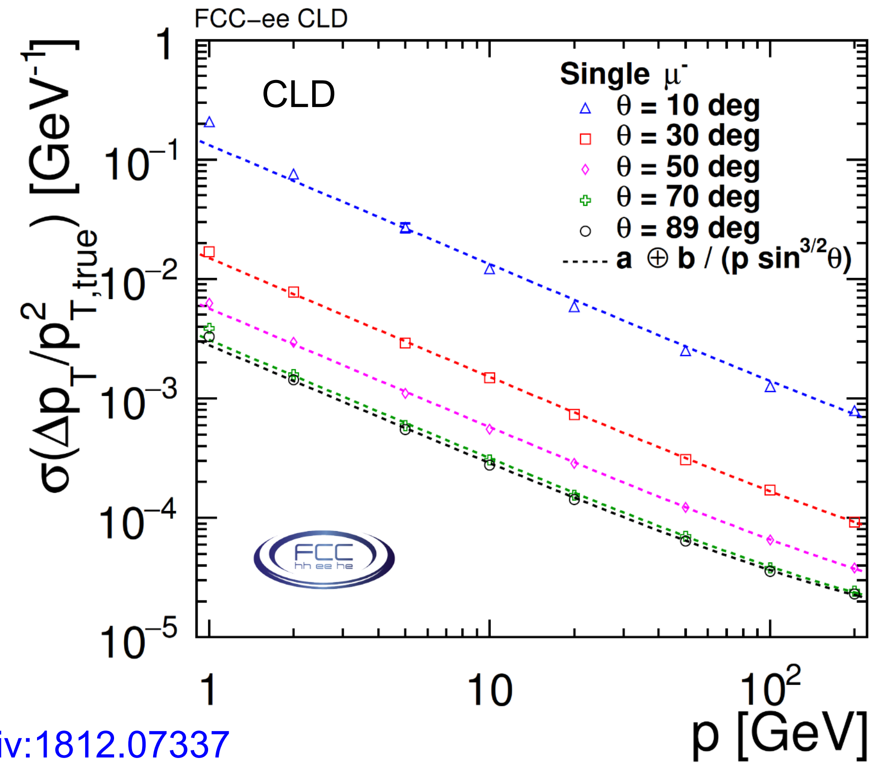
Nucl. Inst. Meth. A 956, 163304 (2020)

• Calorimeter clustering and particle flow analysis: PandoraPFA

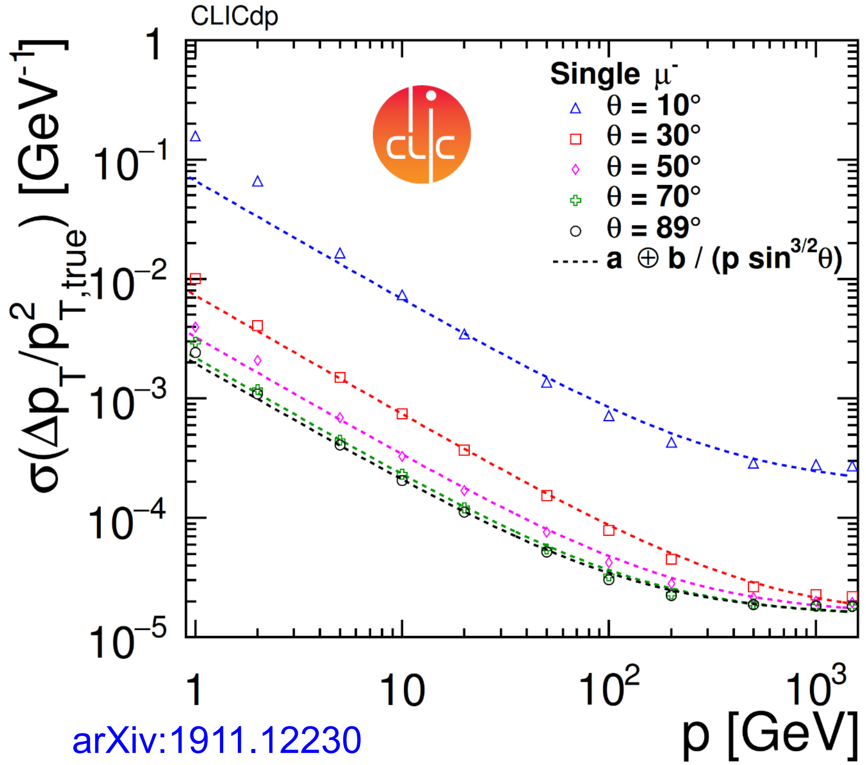
• Flavour tagging: LCFIPlus

$e^+e^- \rightarrow q\bar{q}$ event at $\sqrt{s}$ = 365 GeV
in CLD (full detector simulation)

Momentum resolution in full simulation



arXiv:1812.07337



arXiv:1911.12230

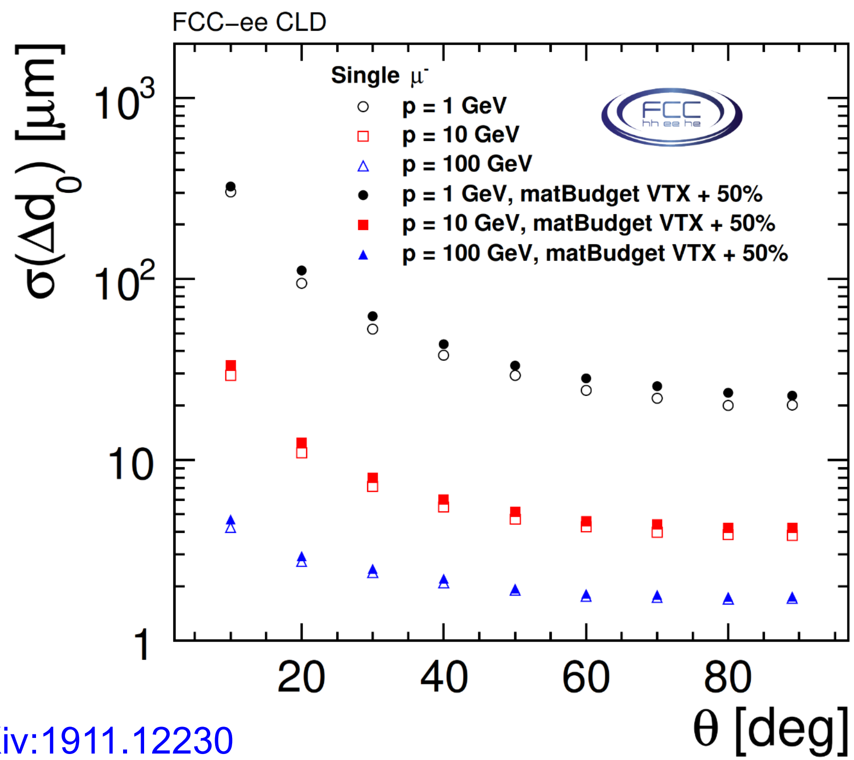
Single muon events:

- Transverse momentum resolution at 100 GeV in the barrel:

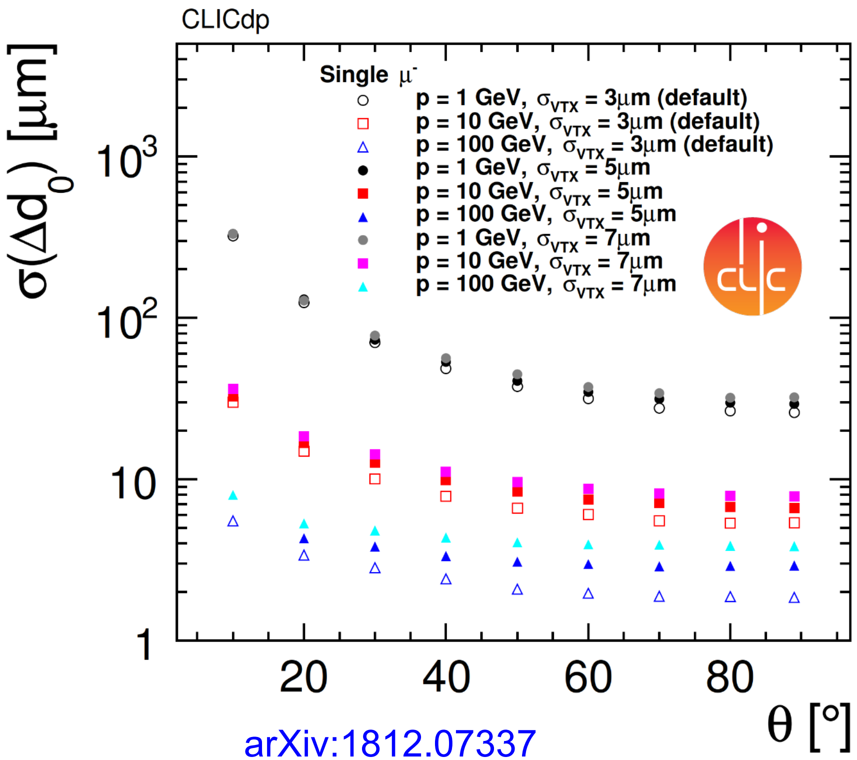
≈ 3 x 10^{-5} GeV^{-2} for both detector models

Impact parameter resolution

Optimisation example: modifications to the CLICdet and CLD vertex detectors
- Impact parameter resolution with increased material (+50%)
- Worse single point resolution (3 μm → 5/7 μm)



arXiv:1911.12230



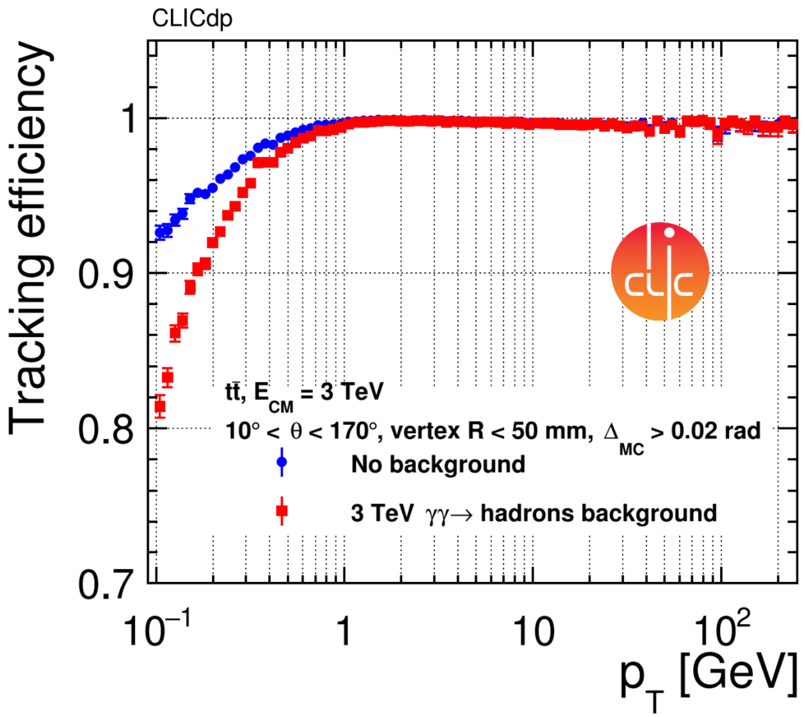
arXiv:1812.07337

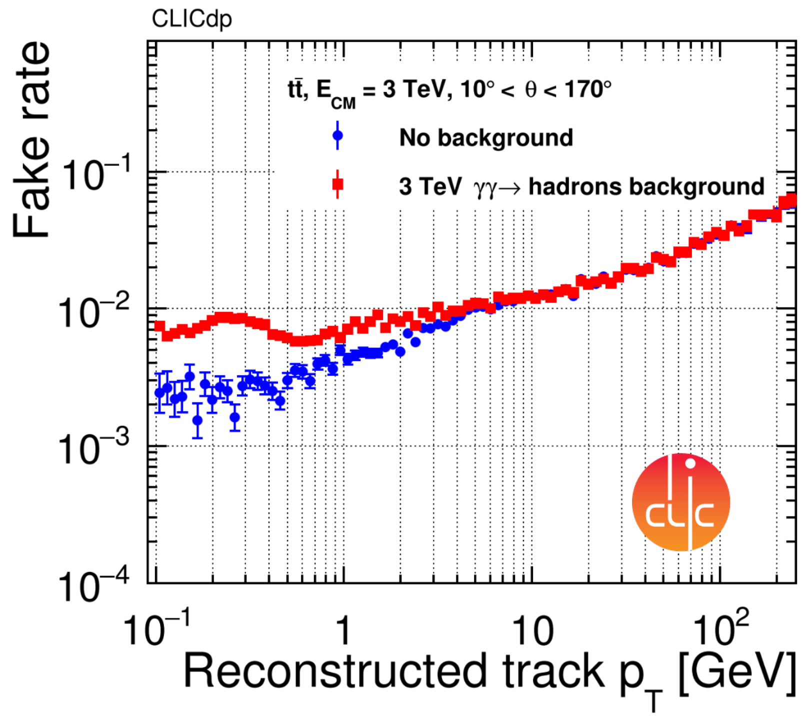
→ Small effect of increased material budget (needs refinement of flavour tagging algorithm due to increased number of secondary interactions)
→ The single point resolution has a large impact on the impact parameter resolution at high p_T

Tracking in complex events

Test case: $e^+e^- \to t\bar{t}$ events at $\sqrt{s}$ = 3 TeV

Fake rate = fraction of reconstructed tracks with purity < 75%
Purity = #hits caused by MC particle / #hits in reconstructed track





→ High efficiency over large p_T range with O(1%) level fake rate
→ Impact of beam-induced backgrounds is small

Nucl. Inst. Meth. A 956, 163304 (2020)

PFA: photon energy resolution

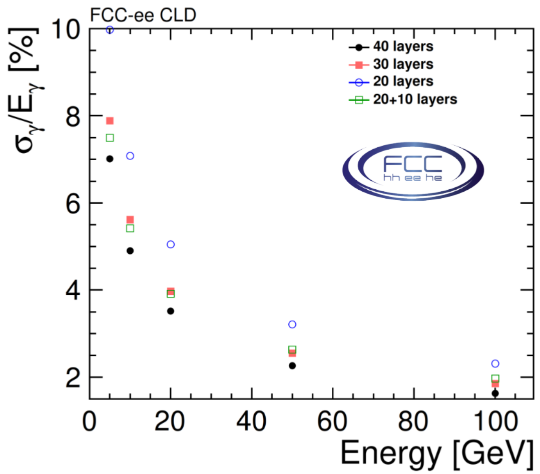
- Fine-grained sampling calorimeters with silicon technology
- Tungsten absorber to minimise Molière radius and separate showers
- Increased number of layers gives better photon energy resolution (at additional cost)
- No impact on jet energy resolution

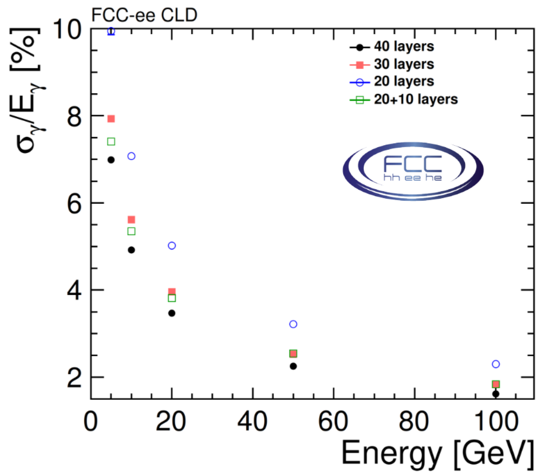
Optimisation example: ECAL options with different W layer thickness and 22 X_0 overall in CLD

Layer structure	Thickness tungsten alloy [mm]	Total thickness per layer [mm]
40 uniform	1.9	5.05
30 uniform	2.62	5.77
20 uniform	3.15	7.19
20 thin + 10 thick	1.9 + 3.8	5.05 + 6.95

Layer structure	JER [%] $\sqrt{s} = 365$ GeV	JER [%] $\sqrt{s} = 91.2$ GeV
40 uniform	3.62 ± 0.05	4.52 ± 0.06
30 uniform	3.72 ± 0.05	4.45 ± 0.06
20 uniform	3.78 ± 0.05	4.82 ± 0.07
20 thin + 10 thick	3.67 ± 0.05	4.56 ± 0.06

→ Jet energy resolution almost identical for the 4 ECAL options



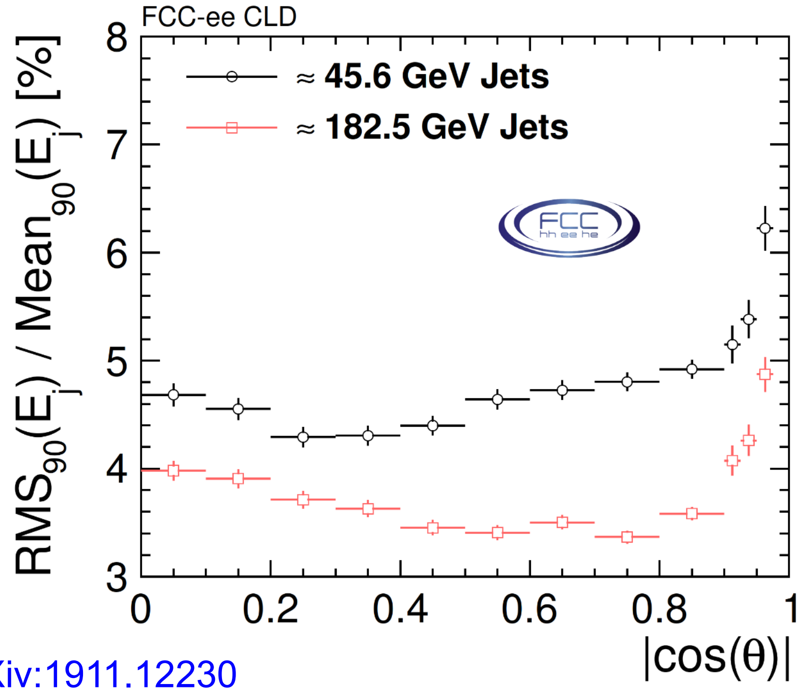


arXiv:1911.12230

PFA: jet energy resolution

Test case: $e^+e^- \rightarrow q\bar{q}$ (q = u,d,s) events

Jet energy resolution = energy sum of all reconstructed particles
RMS_{90} = smallest range of reconstructed energy containing 90% of events



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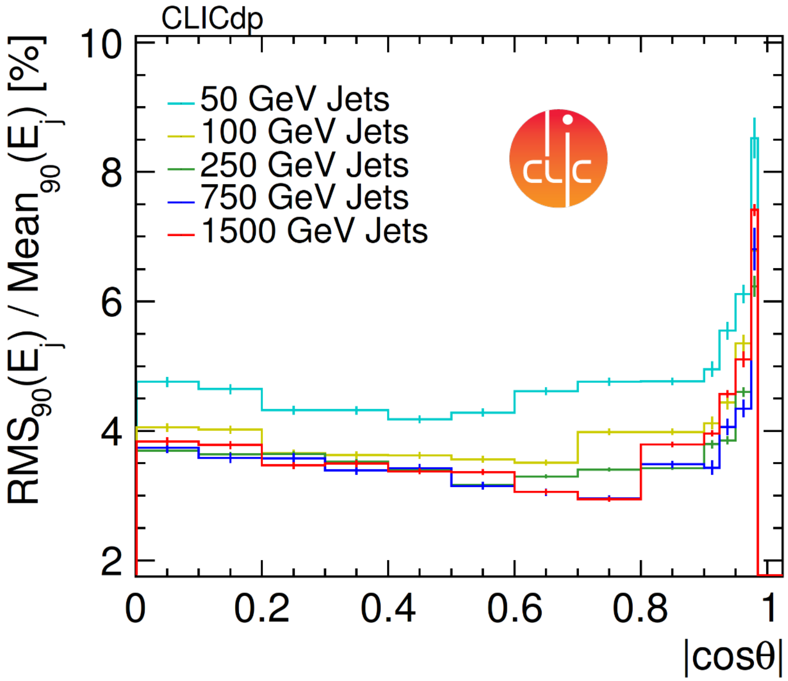


arXiv:1812.07337

→ Jet energy resolution requirement achieved except in the very forward direction)
→ Up to 10% improvement from software compensation

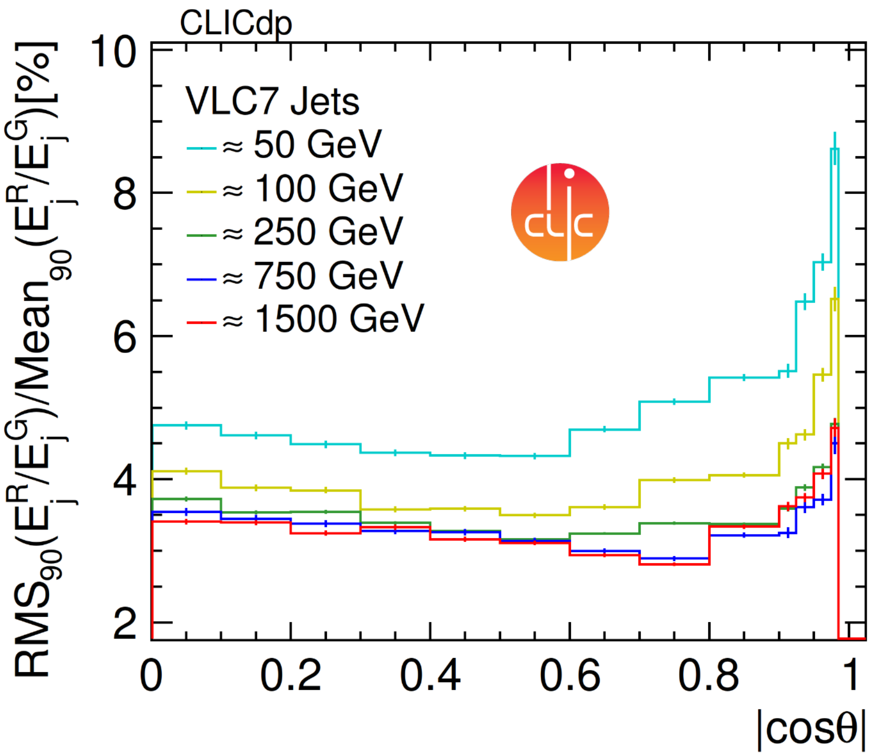
EPJ C 77, 698 (2016)

Beam-induced background: CLICdet

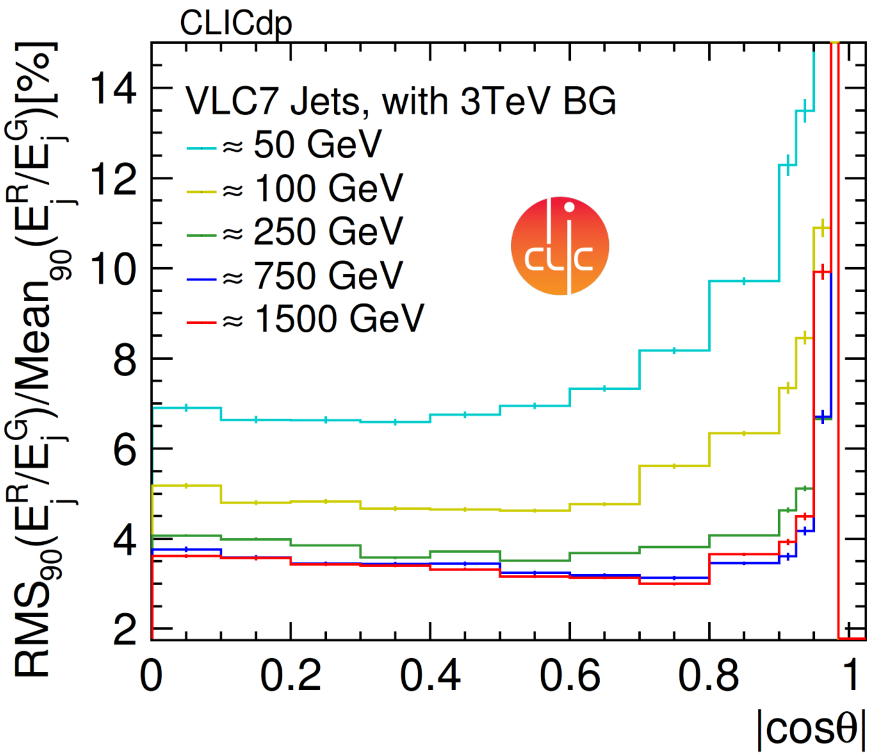
- Jets reconstructed using VLC algorithm (R = 0.7) in exclusive mode with 2 jets
- Beam-induced backgrounds suppressed with p_T-dependent timing cuts

Eur. Phys. J. C78, 144 (2018)

Without beam-induced background:



With beam-induced background:



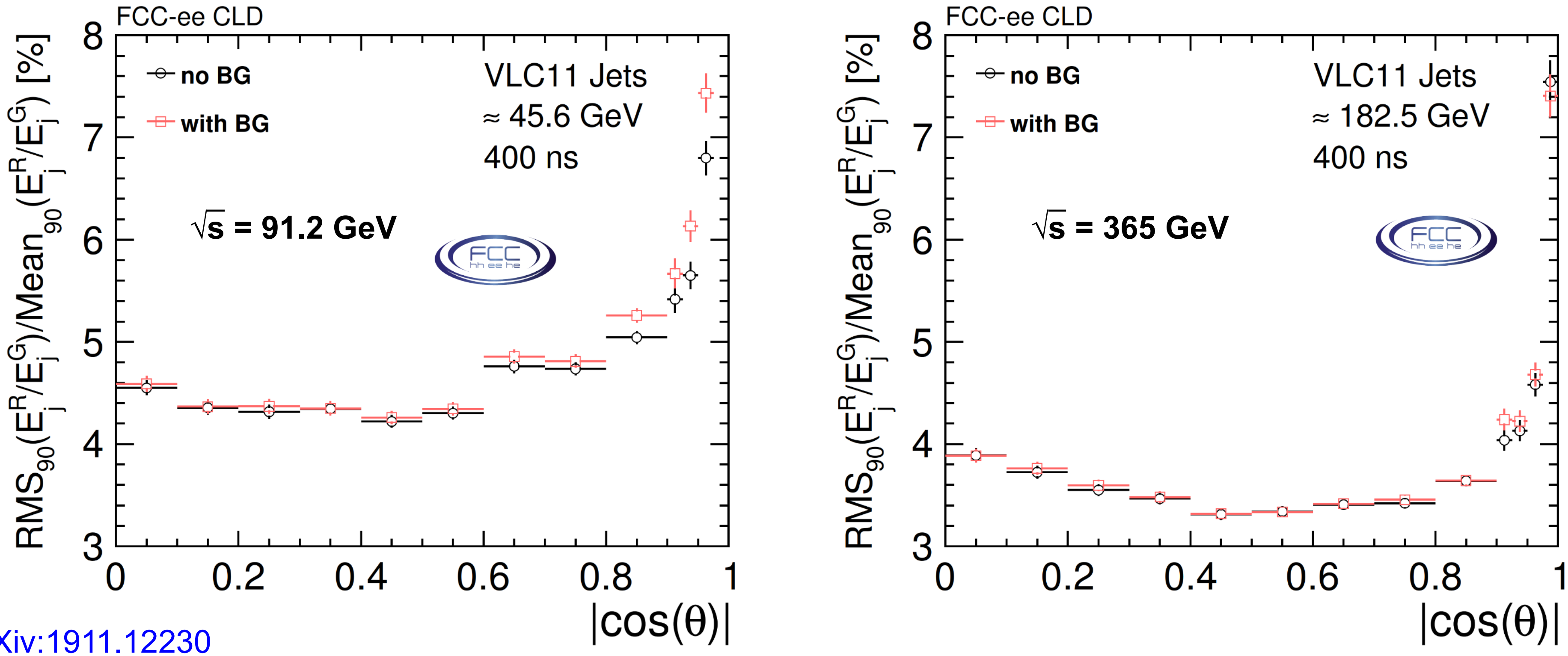
→ Beam-induced background mainly affects low-momentum jets and the forward direction

arXiv:1812.07337

Beam-induced background: CLD

- Jets reconstructed using VLC algorithm (R = 1.1) in exclusive mode with 2 jets
- 400 ns time integration window assumed at both energies

Eur. Phys. J. C78, 144 (2018)



arXiv:1911.12230

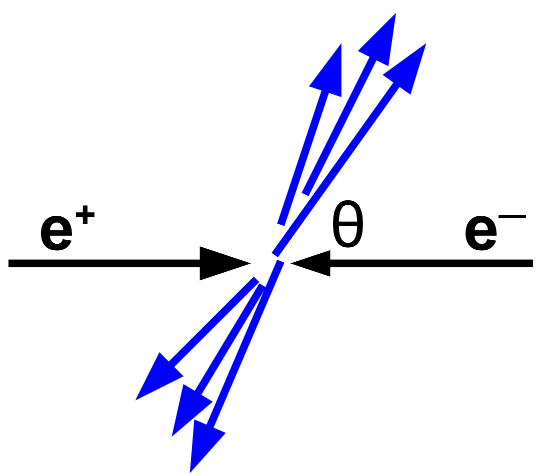
→ Generally, the impact of beam-induced background is very small
→ Largest impact in the forward direction at 91.2 GeV
→ No timing cuts applied

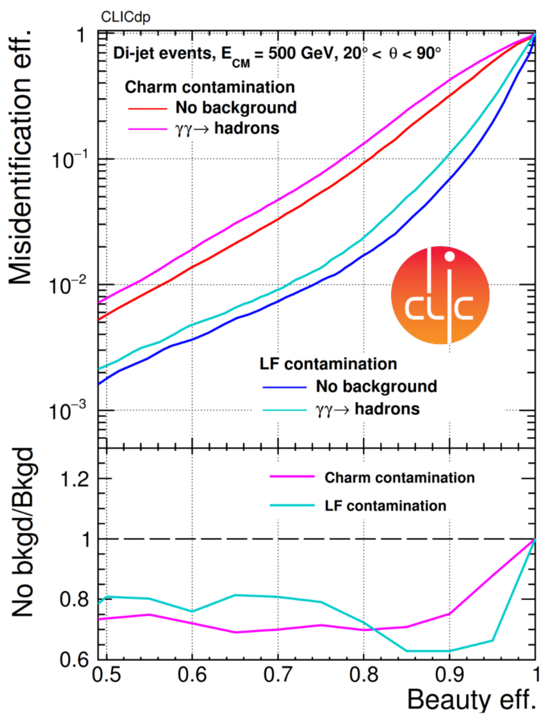
Flavour tagging

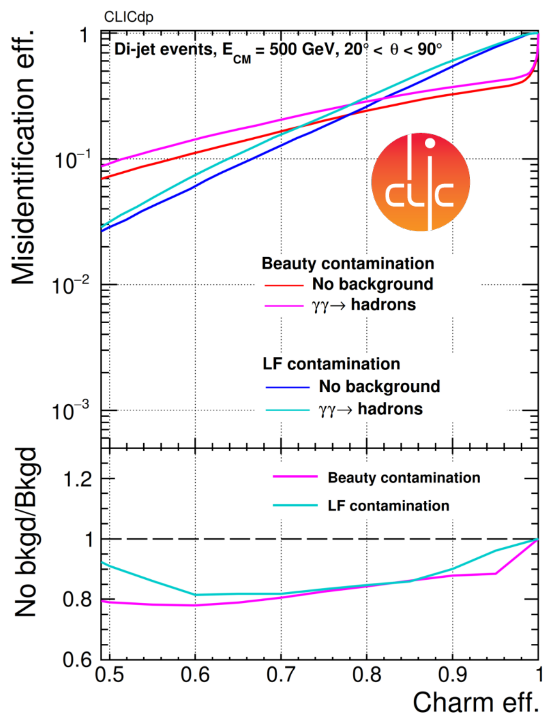
Relevant detector parameters:

- Vertex detector single point resolution
- Momentum resolution
- Vertex detector material budget
- Vertex detector geometry

Example: b- and c-tagging performance for $e^+e^- \rightarrow q\bar{q}$ events with $20° < \theta(q) < 90°$ in the CLICdet detector at $\sqrt{s} = 500$ GeV

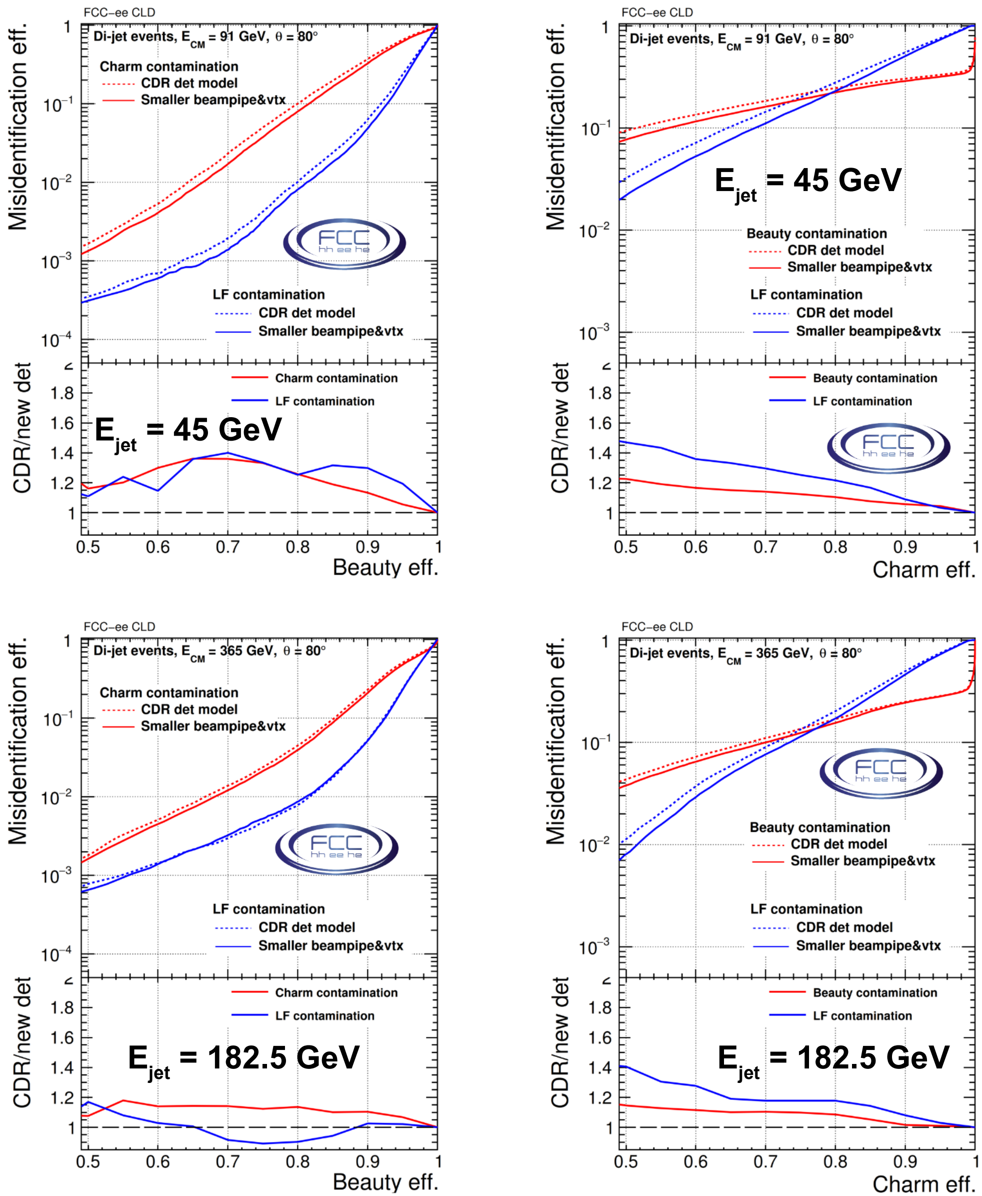






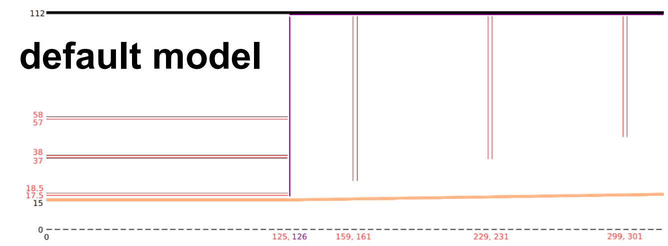
arXiv:1812.07337
Nucl. Inst. Meth. A 808, 109 (2016)

Optimisation example: smaller beam pipe in CLD



- Alternative FCC-ee interaction region with smaller beam pipe radius
- Innermost barrel layer moved from 17.5 mm to 12.5 mm, outer radius unchanged
- Vertex disks unchanged

Vertex barrel layer	Radius for the default model [mm]	Radius for the new model [mm]
Layer 1	17.5	12.5
Layer 2	18.5	13.5
Layer 3	37	35
Layer 4	38	36
Layer 5	57	57
Layer 6	58	58



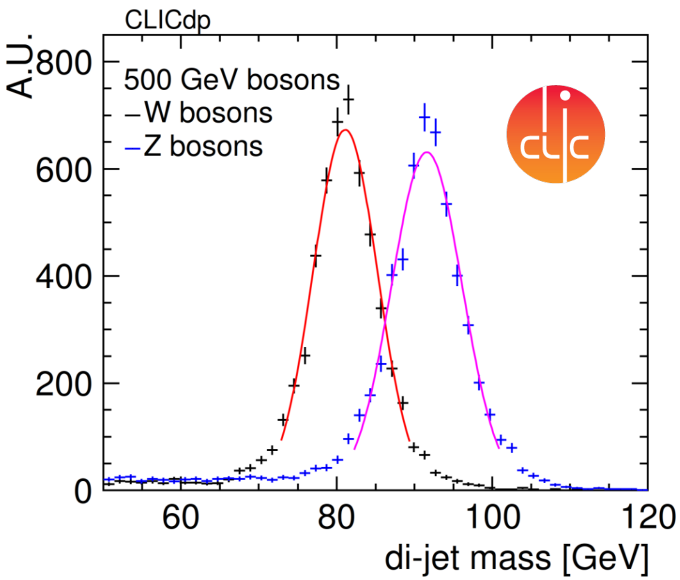
- $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 80°
- “Truth” tracking

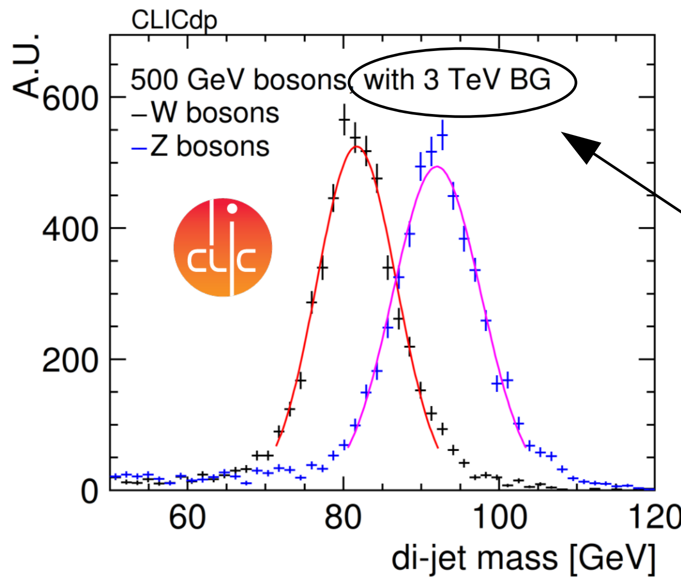
→ Visible improvement for charm at both energies and beauty at E_{jet} = 45 GeV (most decays before layer 1)

arXiv:1911.12230

W/Z separation: CLICdet

Test case: separation of hadronic W and Z boson decays in WW → qqμν_μ and ZZ → qqνν events (charged leptons excluded from jet reconstruction)





Beam-induced back-ground for 3 TeV CLIC collider included (most challenging case)

Background	$E_{W,Z}$ [GeV]	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	ε [%]	Separation [σ]
no BG	125	5.5	5.3	88	2.3
	250	5.3	5.4	88	2.3
	500	5.1	4.9	90	2.5
	1000	6.6	6.2	84	2.0
3 TeV BG	125	7.8	7.1	80	1.7
	250	6.9	6.8	82	1.8
	500	6.2	6.1	85	2.0
	1000	7.9	7.2	80	1.7
380 GeV BG	125	6.0	5.5	87	2.2

→ Separation of hadronic W and Z decays on 2σ level also with beam-induced backround over a very large energy range

Mass separation = $(m_Z - m_W) / \sigma_{av}$ with $\sigma_{av} = (\sigma_Z + \sigma_W) / 2$

arXiv:1812.07337

W/Z separation: CLD

Test case: separation of hadronic W and Z boson decays in WW → qqμν_μ and ZZ → qqνν events with $m_{WW/ZZ}$ = 250 GeV (charged leptons excluded from jet reconstruction)

Two methods compared:
- W and Z masses from mean of Gaussian fit
- Mass distribution scaled so that mean of fit is equal to the PDG values of the W and Z masses

background overlay	R	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.90	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.50	2.45

→ Effect of beam-induced background small
→ Separation on the level of 2.5 standard deviations possible

arXiv:1911.12230

Summary and conclusions

- Precision physics at future $e^{+}e^{-}$ colliders imposes challenging requirements on the detector designs

- Physics-based detector optimisation is crucial, also to provide input to the hardware R&D efforts

- The CLICdet and CLD detector concepts optimised for particle flow analysis fulfil the requirements derived from physics needs

- The reconstruction of physics objects is robust against the expected beam-induced backgrounds at CLIC and FCC-ee

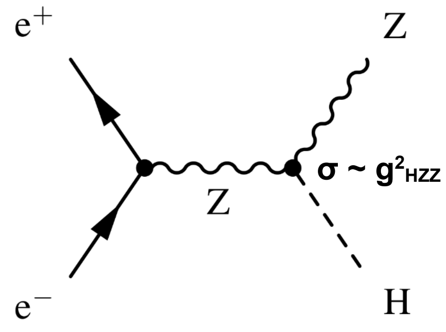
- Interesting possibilities for future improvement exist (optimisation for Z-pole operation, particle identification with timing, very long-lived particles, ...)

Thank you!

Backup slides

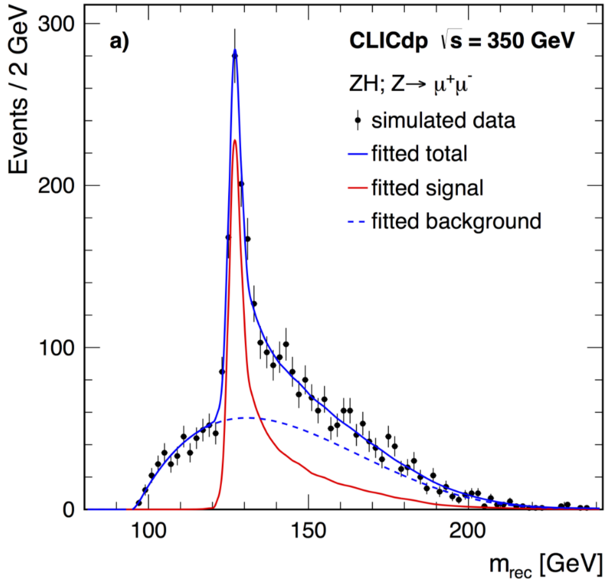
Higgs factory: $e^+e^- \rightarrow ZH$

Higgsstrahlung at e^+e^- colliders:
HZ events can be identified from the Z recoil mas
→ Model-independent measurement of the σ_{ZH} and the Higgs mass



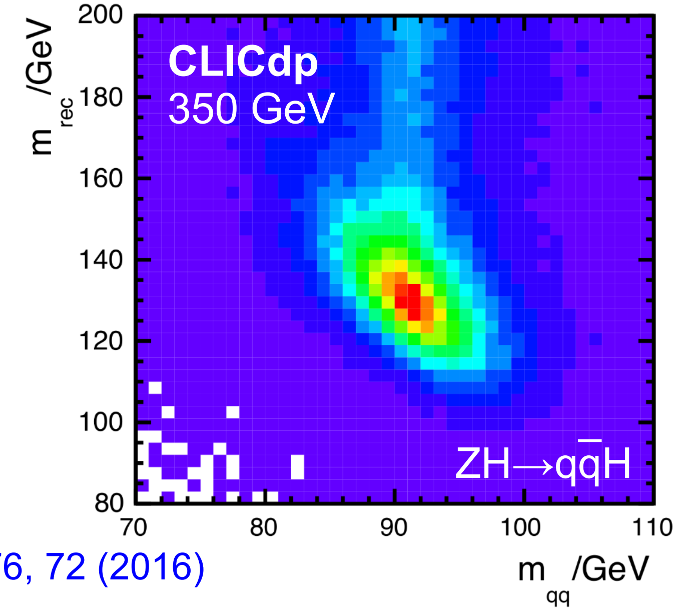
$$m^2_{recoil} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

Known at lepton collider



$Z \rightarrow e^+e^-$ or $\mu^+\mu^-$:
- Best precision at 240-250 GeV (FCC-ee)
- Cross section at maximum, impact of beam energy spectrum & ISR smallest
- Relevant detector parameter: tracking momentum resolution

$Z \rightarrow q\bar{q}$:
- Best precision at 350-380 GeV (FCC-ee & CLIC)
- Main backgrounds: WW / single-W / ZZ production
- Relevant detector parameter: jet energy resolution



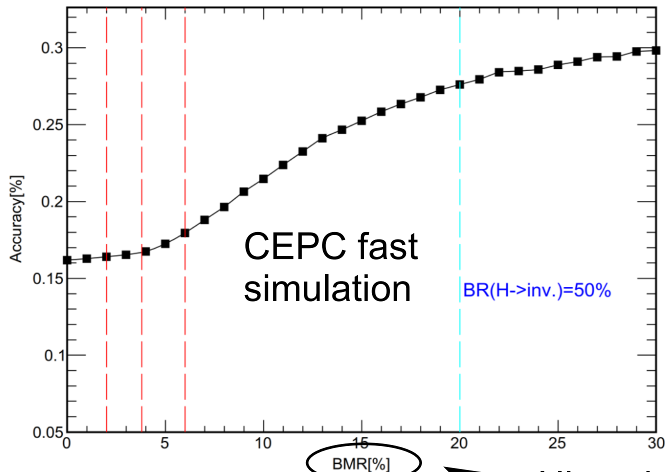
Other measurements (including at the highest energies)
→ backup slides

Eur. Phys. J. C 76, 72 (2016)

Higgs factory: other measurements

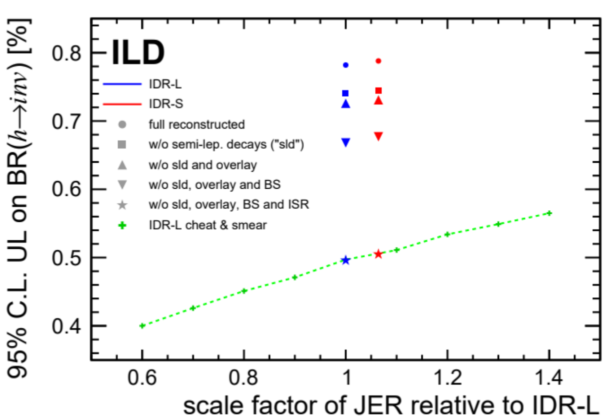
Exploration of all possible Higgs decay modes (including non-SM decays)

Example: H → inv. using ZH; Z→q$\bar{q}$



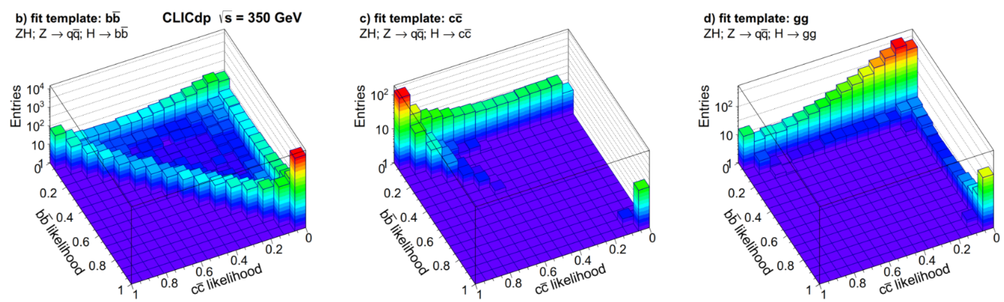
Higgs invariant mass resolution

arXiv:2001.05912



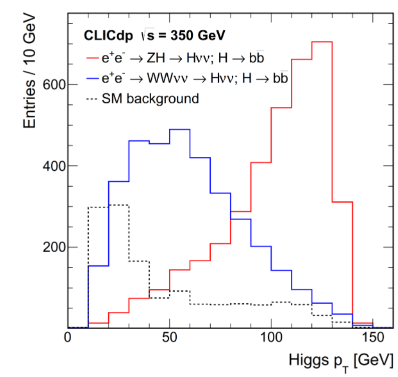
arXiv:2003.01116

Example: H → b$\bar{b}$/c$\bar{c}$/gg at $\sqrt{s}$ = 350 GeV CLIC



H→b$\bar{b}$ **H→c$\bar{c}$** **H→gg**

→ Good charm tagging capability needed (small decay length)



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

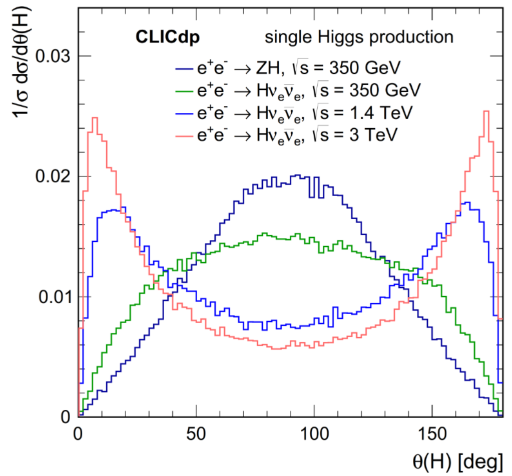
What about very high energies?

1. The forward detector region is increasingly important
Cross sections for VBF processes (e.g. single or double Higgs production) rise with energy

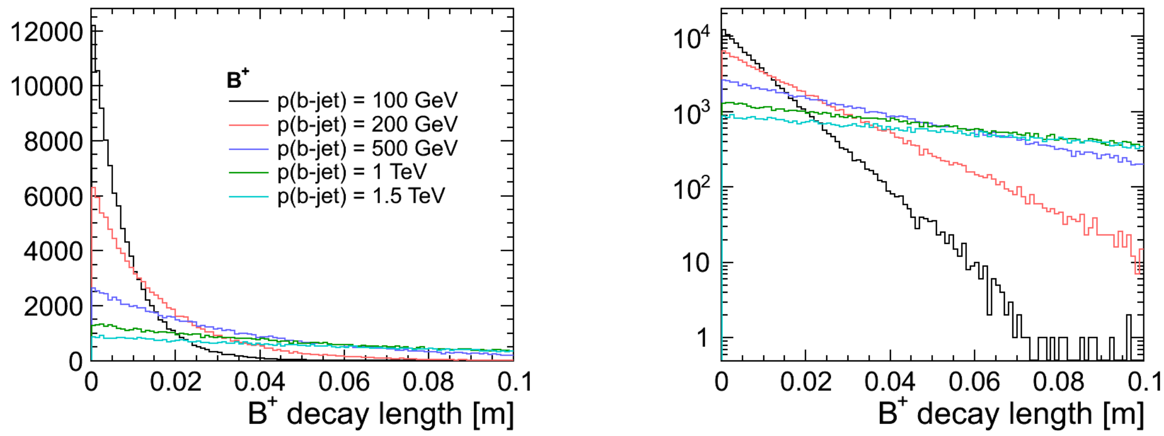
2. Boosted object reconstruction is crucial
The indirect sensitivity of 2→2 scattering processes rises very strongly with energy despite falling cross sections:

- $e^+e^- \rightarrow W^+W^-$ and ZH: tagging of boosted W/Z/H bosons arXiv:1911.02523
- $e^+e^- \rightarrow t\bar{t}$: boosted top tagging JHEP 11, 003 (2019)
- $e^+e^- \rightarrow b\bar{b}$: large secondary vertex decay lengths, very collimated decay b- and c-hadron decay products

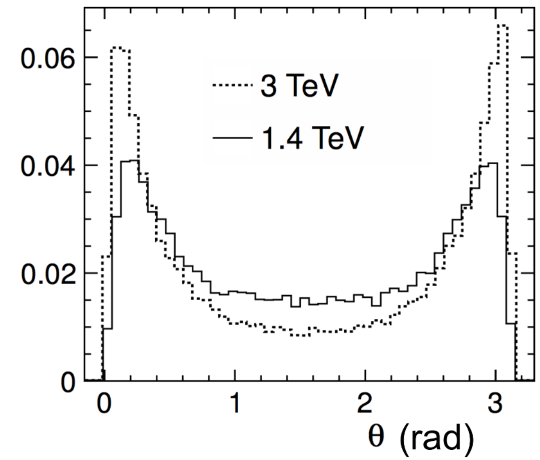
Higgs polar angle in $e^+e^- \rightarrow H\nu\bar{\nu}$ events



B^+ meson decay length for different b-jet energies



Higgs polar angle in $e^+e^- \rightarrow HH\nu\bar{\nu}$ events



Key detector parameters

	ILD (IDR_L/IDR_S)	**SiD**	**CLICdet**	**CLD**	**IDEA**	**CEPC baseline**
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

Majority of concepts based on PFA calorimetry → comparison of different choices can provide additional insight, e.g. IDR_S (TPC) vs. CLICdet (full silicon tracking), but similar magnetic field and tracker radius