Detectors for High Energy Colliders + Machine Detector Interface

Lucie Linssen (CERN)

CAS school on beam dynamics and technologies for future colliders

February 23rd 2018

With many thanks to my CLICdp, ILC, FCC-ee and FCC-hh colleagues for presentation material
pp collisions / $e^+e^-$ collisions  
to tackle the open questions in particle physics

<table>
<thead>
<tr>
<th>p-p collisions</th>
<th>$e^+e^-$ collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton is compound object</strong></td>
<td>$e^+/e^-$ are point-like</td>
</tr>
<tr>
<td>→ Initial state unknown</td>
<td>→ Initial state well defined ($\sqrt{s}$ / opt: polarisation)</td>
</tr>
<tr>
<td>→ Limits achievable precision</td>
<td>→ High-precision measurements</td>
</tr>
<tr>
<td><strong>High rates of QCD backgrounds</strong></td>
<td><strong>Cleaner experimental environment</strong></td>
</tr>
<tr>
<td>→ Complex triggering schemes</td>
<td>→ Less / no need for triggers</td>
</tr>
<tr>
<td>→ High levels of radiation</td>
<td>→ Lower radiation levels</td>
</tr>
<tr>
<td><strong>High cross-sections for colored-states</strong></td>
<td>Superior sensitivity for <strong>electro-weak states</strong></td>
</tr>
<tr>
<td><strong>Very high-energy circular pp colliders feasible</strong></td>
<td>High energies ($\geq 350$ GeV) require <strong>linear</strong> collider</td>
</tr>
</tbody>
</table>
Interesting **pp** events need to be found within a huge number of collisions.

**pp and e^+e^- collisions** provide complementary physics information. => important for our field to have both!

- **e^+e^-** events are more “clean”
Future Circular Collider (FCC-ee): CERN $e^+e^-$, $\sqrt{s}$: 90 - 350 (365) GeV; FCC-hh pp
Length: 11 km, 29 km, 50 km

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

International Linear Collider (ILC): Japan (Kitakami)
$e^+e^-$, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)

Circular Electron Positron Collider (CEPC), China
$e^+e^-$, $\sqrt{s}$: 90-240 GeV; SPPC pp,
Circumference: 100 km
high-energy pp collider studies

Super proton proton Collider (SppC), China
CEPC; SPPC vs >70 TeV
Circumference: 100 km

Future Circular Collider (FCC-hh): CERN
FCC-ee; FCC-hh vs ~100 TeV
Circumference: 97.75 km

High-Energy LHC (HE-LHC): CERN
pp vs ~27 TeV
Circumference: 27 km
Scope of the lectures

For both $e^+e^-$ and $pp$:

- **physics scope**
- **experimental conditions**
- **detector requirements**
- **detector concept**
- **performance**
- **detector technologies**

Principally explained on the basis of CERN-hosted studies:

- Future $e^+e^-$ linear collider $\Rightarrow$ CLIC
- Future $e^+e^-$ circular collider $\Rightarrow$ FCC-ee
- Future $pp$ circular collider $\Rightarrow$ FCC-hh

General detector concepts also presented for

- Future $e^+e^-$ linear collider $\Rightarrow$ ILC
- Future $e^+e^-$ circular collider $\Rightarrow$ CEPC
Part 1

$e^+e^-$ detectors

With many thanks to CLICdp, ILC and FCC-ee colleagues for presentation material
CAS school Zürich, Feb 23, 2018
CLIC physics scope and staging scenario

The CLIC program builds on energy stages:

- **380 GeV (350 GeV), 600 fb⁻¹**: precision Higgs and top physics
- **1.5 TeV, 1.5 ab⁻¹**: BSM searches, precision Higgs, ttH, HH, top physics
- **3 TeV, 3 ab⁻¹**: BSM searches, precision Higgs, HH, top physics

BSM searches: direct (up to ~1.5 TeV), indirect (>> TeV scales)

Staging scenario can be adapted, e.g. to new results from (HL-)LHC
CLIC accelerator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>380 GeV</th>
<th>1.5 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity $\mathcal{L}$ ($10^{34}$cm$^{-2}$sec$^{-1}$)</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>$\mathcal{L}$ above 99% of $\sqrt{s}$ ($10^{34}$cm$^{-2}$sec$^{-1}$)</td>
<td>0.9</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Accelerator gradient (MV/m)</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
</tr>
<tr>
<td>Site length (km)</td>
<td>11.4</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>Repetition frequency (Hz)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Beam size at IP $\sigma_x/\sigma_y$ (nm)</td>
<td>150/2.9</td>
<td>~60/1.5</td>
<td>~40/1</td>
</tr>
<tr>
<td>Beam size at IP $\sigma_z$ ($\mu$m)</td>
<td>70</td>
<td>44</td>
<td>44</td>
</tr>
</tbody>
</table>

Crossing angle 20 mrad, electron polarization ±80%

Very low duty cycle
- Allows for:
  - Triggerless readout
  - Power pulsing

1 train = 312 bunches, 0.5 ns apart
- *not to scale* -

Drives timing requirements for CLIC detector

Very small beam

CERN-2016-004
### linear $e^+e^-$ accelerator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ILC 250 GeV</th>
<th>ILC 500 GeV</th>
<th>ILC 380 GeV</th>
<th>CLIC 1.5 TeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity $\mathcal{L}$ ($10^{34}$ cm$^{-2}$ sec$^{-1}$)</td>
<td>1.35</td>
<td>1.8</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>$\mathcal{L}$ above 99% of $\mathcal{L}$ ($10^{34}$ cm$^{-2}$ sec$^{-1}$)</td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Accelerator gradient (MV/m)</td>
<td>31.5</td>
<td>31.5</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
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<tr>
<td>Site length (km)</td>
<td>~17</td>
<td>31</td>
<td>11.4</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>Repetition frequency (Hz)</td>
<td>5</td>
<td>5</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>554</td>
<td>554</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>1312</td>
<td>1312</td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Beam size at IP $\sigma_x/\sigma_y$ (nm)</td>
<td>729/7.7</td>
<td>474/5.9</td>
<td>150/2.9</td>
<td>~60/1.5</td>
<td>~40/1</td>
</tr>
<tr>
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<td>300</td>
<td>300</td>
<td>70</td>
<td>44</td>
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**ILC:** Crossing angle 14 mrad, electron polarization $\pm 80\%$, positron polarization $\pm 30\%$

Comparing experimental conditions ILC with CLIC
- Larger beam sizes and lower energies => less beamstrahlung
- Longer bunch trains (~1 ms)

Detectors do not need ns-level timing capabilities to reject background

Shin Michizono, HEP conf 2018
FCC-ee physics and staging scenario

$m_Z$, $m_W$, $m_{\text{top}}$, $\sin^2\theta^\text{eff}_W$, $R_b$, $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z m_W)$, Higgs and top quark couplings
$\Rightarrow$ Very high precision measurements of electroweak parameters
$\Rightarrow$ Exploration of very high energy scale ($\gg$ TeV) via precision measurements
$\Rightarrow$ Search for (very) weakly coupled particles

<table>
<thead>
<tr>
<th></th>
<th>luminosity/1P [10^{34} \text{cm}^{-2}\text{s}^{-1}]</th>
<th>total luminosity (2 IPs)/yr</th>
<th>physics goal</th>
<th>run time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ first 2 years</td>
<td>100</td>
<td>26 ab^{-1}/year</td>
<td>150 ab^{-1}</td>
<td>4</td>
</tr>
<tr>
<td>$Z$ later</td>
<td>200</td>
<td>52 ab^{-1}/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>30</td>
<td>7.8 ab^{-1}/year</td>
<td>10 ab^{-1}</td>
<td>1</td>
</tr>
<tr>
<td>$H$</td>
<td>7.0</td>
<td>1.8 ab^{-1}/year</td>
<td>5 ab^{-1}</td>
<td>3</td>
</tr>
<tr>
<td>machine modification for RF installation &amp; rearrangement: 1 year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>top 1st year (350 GeV)</td>
<td>0.8</td>
<td>0.2 ab^{-1}/year</td>
<td>0.2 ab^{-1}</td>
<td>1</td>
</tr>
<tr>
<td>top later (365 GeV)</td>
<td>1.3</td>
<td>0.34 ab^{-1}/year</td>
<td>1.5 ab^{-1}</td>
<td>4</td>
</tr>
</tbody>
</table>

total program duration: 14 years - including machine modifications
phase 1 ($Z$, $W$, $H$): 8 years, phase 2 (top): 6 years

P. Janot, Acad. Training, Oct 2017
M. Benedikt, Nov 2017
FCC-ee accelerator parameters

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>SR energy loss / turn (GeV)</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>SR total power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>energy spread (SR / BS) [%]</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.153</td>
<td>0.099 / 0.151</td>
<td>0.15 / 0.20</td>
</tr>
<tr>
<td>bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.3 / 7.65</td>
<td>3.15 / 4.9</td>
<td>2.5 / 3.3</td>
</tr>
<tr>
<td>bunch intensity [10^{11}]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
</tr>
<tr>
<td>no. of bunches / beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>39</td>
</tr>
<tr>
<td>Bunch crossing separation (ns)</td>
<td>20</td>
<td>160</td>
<td>830</td>
<td>8300</td>
</tr>
<tr>
<td>luminosity [10^{34} cm^{-2}s^{-1}] per IP</td>
<td>230</td>
<td>32</td>
<td>7.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Beam transverse polarisation => beam energy can be measured to very high accuracy (~50 keV)

At Z-peak very high luminosities and high cross section

⇒ Statistical accuracies at 10^{-5} level (e.g. cross sections, asymmetries)
⇒ This drives the detector performance
⇒ This also drives requirement on data rates
**e^+e^- detector requirements (from physics)**

★ **momentum resolution:**
  e.g. HZ, g_{\mu\mu}, Smuon endpoint
  \[ \sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1} \]

★ **jet energy resolution:**
  e.g. W/Z/H di-jet mass separation, ZH with Z\rightarrow qq
  \[ \frac{\sigma_E}{E} \sim 3.5 - 5 \% \] (for high-E jets, light quarks)

★ **impact parameter resolution:**
  e.g. c/b-tagging, Higgs BR
  \[ \sigma_{r\phi} = 5 \oplus 15/(p[GeV] \sin^2 \theta) \mu m \]

★ **angular coverage, very forward electron tagging**

+ requirements from experimental conditions

CAS school Zürich, Feb 23, 2018
**e^+e^- beam-induced background**

**Linear colliders:** very small beam sizes needed to achieve high luminosities e.g. CLIC bunch sizes at 3 TeV $\sigma_{x,y,z} = \{40 \text{ nm, 1 nm, 44 } \mu\text{m}\}$ => beamstahlung

**Main backgrounds** ($p_T > 20 \text{ MeV, } \theta > 7.3^\circ$):

- **Incoherent e+e- pairs**
  - 19k particles per bunch train at 3 TeV
  - High occupancies
  => **Impact on detector granularity**

- **$\gamma\gamma$ => hadrons**
  - 17k particles per bunch train at 3 TeV
  - Main background in calorimeters and trackers
  => **Impact on detector granularity and physics**

*Note: at ILC or at lower CLIC energies, beamstrahlung effect is less strong*

=> nevertheless a driver for the detector design

**Circular colliders:** beamstrahlung (BS) *(less pronounced)* + synchrotron radiation (SR)

Strongest effects at 365 GeV. Recent studies show that SR can be reduced below BS level.
In the detector region, the relevant backgrounds are incoherent pairs and $\gamma\gamma \rightarrow \text{hadrons}$.
Beamstrahlung ➞ important energy losses right at the interaction point

Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV

Experimental conditions linear $e^+e^-$

**Linear Colliders**

- **Beam-induced background:**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - High occupancies in the detector => small readout cells needed
  - Precise (ns-level) timing required at CLIC
- **Low duty cycle**
  - Power pulsing of electronics possible
  - Triggerless readout
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)
CLIC detector model

return yoke (Fe) with muon-ID detectors

superconducting solenoid, 4 Tesla

detector, (large pixels / short strips)

fine grained (PFA) calorimetry, $1 + 7.5 \Lambda_i$, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)

end-coils for field shaping

forward region with compact forward calorimeters

low-mass vertex detector, $\sim 25 \mu m$ pixels

Final beam focusing is outside the detector
Recent CLIC MDI publication

Experiment kept short along beam line
Still maximising acceptance for forward-going particles

Note: ILC detectors have final focus elements inside the detector ($L^*$ is 3.4 m)
Includes 2 compact forward calorimeters: Lumical + Beamcal

- e/\gamma acceptance to small angles
- Luminosity measurement (using Bhabha scattering)
- (possibly beam feedback)
CLIC detector occupancies from beam-induced backgrounds

Charged particles: incoherent pairs + $\gamma \gamma \rightarrow$ hadrons

CLIC vertex requirements: [CERN-2012-003](#)
CLIC tracker readout requirements: [CLICdp-Note-2017-002](#)

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CLIC silicon pixel R&D (vertex and tracker)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>vertex</th>
<th>tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit position resolution (μm)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Time stamping (ns per slice)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Material per layer ($X_0$)</td>
<td>&lt;0.2%</td>
<td>&lt;1-1.5%</td>
</tr>
<tr>
<td>Silicon thickness (μm)</td>
<td>~100 (50+50)</td>
<td>~200</td>
</tr>
<tr>
<td>Power (mW/cm², incl. power pulsing)</td>
<td>&lt;50</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Radiation level NIEL (nₑq cm⁻²/yr)</td>
<td>&lt;4×10¹⁰</td>
<td>&lt;10¹⁰</td>
</tr>
<tr>
<td>Radiation level TID (Gy/yr)</td>
<td>&lt;200</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Performance requirements for the CLIC tracking system

Layout of the CLIC vertex detector
(with spiraling discs for air cooling purposes)
First layer at ~30 mm (3 TeV), ~25 mm (380 GeV)

Layout of the CLIC tracker
Tracker radius ~1.5 m, maximum strip lengths indicated (assuming 50 μm strip width) taking into account occupancies from beam-induced background)
CLIC tracking performances

Geant4-based simulation and event reconstruction

Varying position resolution in tracker

CLICdet with nominal performances

Fit data to:

\[
\sigma \left( \frac{\Delta p_T}{p_T^{2\text{,true}}} \right) = a \oplus \frac{b}{p \sin \theta}
\]

Shows that 7 μm in tracker is needed

Geant4 simulation + reconstruction momentum resolution for muons

~2×10^{-5} GeV^{-1} achieved in central part

CLICdp-Note-2017-002

E.Leogrande @ CLIC18

CAS school Zürich, Feb 23, 2018
Si technologies pursued in CLIC R&D

Hybrid: Si sensor + ASIC (65 nm)
Bump bonded, thin 50+50 μm
TSMC process

Hybrid: HV CMOS active sensor + ASIC (65 nm)
Capacitive coupling (glue)
(recently also fully integrated HV CMOS)
AMS process

Fully integrated: HR CMOS
TowerJazz process

Fully integrated: SOI
Lapis process

Systematics R&D studies have focused on Pixel implementation, with Pixel sizes around 25×25 μm²
Studies equally valid for the main tracker, even though it will have larger cell sizes
CLIC silicon vertex and tracker R&D (1)

CLICpix (65 nm) + 50 μm sensor

Bump-bonding, 25 μm pitch

CLICpix2 ASIC (65 nm)

Planar sensor, 25 μm pitch

UBM and Indium bonds

SOI sensor design

TCAD simulations, HV-CMOS sensor

C3PD HV-CMOS sensor, thinned 50 μm

Recent presentation on vertex R&D
Recent presentation on tracker R&D

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CLIC silicon vertex and tracker R&D (2)

- Power delivery + pulsing
- TSV interconnect technology
- Flip-chip gluing (AC-coupling)
- Air cooling simulation and 1:1 scale test set up
- SOI and C3PD+CLICpix2 in Timepix3 telescope at SPS
calorimetry and PFA

Jet energy resolution + background suppression for optimal detector design

=> => 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 info you have:
60% => tracker 😊😊
30% => ECAL 😊
10% => HCAL 😞

Hardware + software!
Particle flow performance

Jet energy resolution

Full Geant4-based simulation + reconstruction using particle flow
Such a plot requires a lot of calibration/tuning efforts for all detector regions
Beam-induced background suppression

Triggerless readout of full train

- Full event reconstruction + PFA analysis with background overlaid
  - => physics objects with precise $p_T$ and cluster time information
  - Time corrected for shower development and TOF
- Then apply cluster-based timing cuts
  - Cuts depend on particle-type, $p_T$ and detector region
  - Allows to protect high-$p_T$ physics objects

+ Use well-adapted jet clustering algorithms
  - Making use of LHC experience (e.g FastJet $k_t$ or $e^+e^-$ adapted VLC algorithm)
$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\tau\bar{\nu}b\bar{b}$

CLIC 1.4 TeV

Highly granular calorimetry + precise hit timing

Very effective in suppressing backgrounds for fully reconstructed particles

General trend for $e^+e^-$ and pp options (e.g. CMS endcap calorimetry for HL-LHC)
**CLIC fine-grained calorimetry requirements**

**Fine-grained calorimetry:** ECAL, HCAL, LumiCal, BeamCal

R&D for CLIC is carried out by the CALICE and FCAL collaborations

<table>
<thead>
<tr>
<th>layers</th>
<th>cell sizes</th>
<th>active material</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>40</td>
<td>5×5 mm²</td>
</tr>
<tr>
<td>HCAL</td>
<td>60</td>
<td>3×3 cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>layers</th>
<th>Θ mrad</th>
<th>active material</th>
</tr>
</thead>
<tbody>
<tr>
<td>LumiCal</td>
<td>40</td>
<td>38 - 110 silicon</td>
</tr>
<tr>
<td>BeamCal</td>
<td>40</td>
<td>10 - 40 GaAs (tbc)</td>
</tr>
</tbody>
</table>

1 ns time resolution, 16 bit readout

Developments and beam tests of CMS HGCal are an important test bed for Linear Collider

5 ns time resolution, 32 bit readout

FCAL calorimeter module
high-granularity calorimetry

Silicon-tungsten ECAL

Silicon-tungsten ECAL

CMS HGCAL 8” silicon wafer

RPC-steel SDHCAL

Scintillator HCAL plane

Scintillator-tungsten HCAL
Jet flavour tagging

c-quark and b-quark jets involve secondary decays
• Look for displaced (secondary) vertices within jets
• Vertex detector performance is very important
• Multi-parameter identification, uses the entire detector
SiD: “Silicon Detector”
- 5 T solenoid
- All-silicon vertex detector + tracker
- Fine-grained calorimetry (PFA)
- Compact design (1:2m tracker radius)
- Final focus quadrupoles inside the detector
ILD: “International Large Detector”

- Silicon vertex detector
- Time Projection Chamber as tracker
- ... surrounded by Silicon envelope
- Fine-grained calorimetry (PFA)
- Large (L) and small (S) options under study
- Final focus quadrupoles inside the detector

<table>
<thead>
<tr>
<th></th>
<th>ILD-L</th>
<th>ILD-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-field</td>
<td>3.5 T</td>
<td>4 T</td>
</tr>
<tr>
<td>TPC outer radius</td>
<td>180 cm</td>
<td>146 cm</td>
</tr>
<tr>
<td>Coil inner radius</td>
<td>344 cm</td>
<td>310 cm</td>
</tr>
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</table>
circular $e^+e^-$
### FCC-ee physics and staging scenario

Energy stages $\sqrt{s} = 91$ GeV $Z$, 160 GeV $W$, 240 GeV $H$, 350 (365) GeV top $m_Z$, $m_W$, $m_{\text{top}}$, $\sin^2 \theta_W^{\text{eff}}$, $R_b$, $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z m_W)$, Higgs and top quark couplings

$\Rightarrow$ Precision measurements of electroweak parameters

$\Rightarrow$ Exploration of very high energy scale (>> TeV) via precision measurements

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<td>150 $\text{ab}^{-1}$</td>
<td>4</td>
</tr>
<tr>
<td>Z later</td>
<td>200</td>
<td>52 $\text{ab}^{-1}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>30</td>
<td>7.8 $\text{ab}^{-1}$/year</td>
<td>10 $\text{ab}^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>7.0</td>
<td>1.8 $\text{ab}^{-1}$/year</td>
<td>5 $\text{ab}^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>machine modification for RF installation &amp; rearrangement: 1 year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>top 1st year (350 GeV)</td>
<td>0.8</td>
<td>0.2 $\text{ab}^{-1}$/year</td>
<td>0.2 $\text{ab}^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>top later (365 GeV)</td>
<td>1.3</td>
<td>0.34 $\text{ab}^{-1}$/year</td>
<td>1.5 $\text{ab}^{-1}$</td>
<td>4</td>
</tr>
</tbody>
</table>

**total program duration: 14 years - including machine modifications**

phase 1 ($Z, W, H$): 8 years, phase 2 (top): 6 years
### FCC-ee accelerator parameters

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>SR energy loss / turn (GeV)</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>SR total power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>energy spread (SR / BS) [%]</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.153</td>
<td>0.099 / 0.151</td>
<td>0.15 / 0.20</td>
</tr>
<tr>
<td>bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.3 / 7.65</td>
<td>3.15 / 4.9</td>
<td>2.5 / 3.3</td>
</tr>
<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
</tr>
<tr>
<td>no. of bunches / beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>39</td>
</tr>
<tr>
<td>Bunch crossing separation (ns)</td>
<td>20</td>
<td>160</td>
<td>830</td>
<td>8300</td>
</tr>
<tr>
<td>luminosity $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$ per IP</td>
<td>230</td>
<td>32</td>
<td>7.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Beam transverse polarisation $\Rightarrow$ beam energy can be measured to very high accuracy ($\sim$50 keV)

---

**At Z-peak very high luminosities and high cross section**

$\Rightarrow$ Statistical accuracies at $10^{-5}$ level (e.g. cross sections, asymmetries)

$\Rightarrow$ This drives the **detector performance**

$\Rightarrow$ This also drives requirement on **data rates**
Note different x/z scales!

Incoming beam

Crossing angle 30 mrad

Beam pipe radius: 15 mm

$L^* = 2.2 \text{ m}$

Design valid for all FCC-ee centre-of-mass energies. Tantalum shield needed at highest energy. Mask tips at +/-2.1 m to protect central chamber from photons generated at 100 m from IP.
FCC-ee forward region

30 mrad beam crossing angle
Final focusing quadrupoles embedded in the detector
Emittance blow-up from detector magnetic field

- **Detector magnetic field limited to max. 2T**
- Compensating solenoid close to the IP
- Magnetic shielding around the final focus quads

Luminosity counter (makes use of Bhabha $e^+e^- \rightarrow e^+e^-$), front face at 1.0 m from IP
FCC-ee occupancy from background particles

Occupancy in the various sub-detectors from synchrotron radiation and incoherent pairs

Maximum hit density in the hottest area of each subdetector per bunch crossing

=> Synchrotron radiation can be suppressed efficiently
Dominant backgrounds

- Synchrotron radiation
- Beamstrahlung

\[ \gamma\gamma \rightarrow e^+e^- \] (shape of distribution in figure)

\[ \gamma\gamma \rightarrow \text{hadrons} \] (0.005 event / BX)

\[ \Rightarrow \text{First detector layer} \]

Reasonable assumptions

- Silicon pixel detector
  - Radius: 17 mm
  - Pixel pitch: 25×25 µm² (includes safety factor 3)

Full simulation (GuineaPig, GEANT)

Estimated occupancy ~ 5×10^{-4} / BX

Both at the top and the Z

Needs for fast electronics?

- At the Z, one bunch crossing every 20 ns
- Keep occupancy below 1% with electronics
  \[ \text{integration time} < 0.4 \, \mu\text{s} \]

P. Janot, Acad. Training, Oct 2017
**Experimental conditions $e^+e^-$**

### Linear Colliders
- **Beam-induced background:**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - High occupancies in the detector $\Rightarrow$ small readout cells needed
  - Precise (ns-level) timing required at CLIC
- **Low duty cycle**
  - Power pulsing of electronics possible
  - Triggerless readout
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

### Circular Colliders
- **Beam-induced background**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - Synchrotron radiation
- **Circulating beams**
  - Maximum detector solenoid field of 2 T $\Rightarrow$ need to increase tracker radius
  - Complex magnet shielding schemes
  - Beam focusing quadrupole closer to IP (~2.2m)
  - No power pulsing
- **High luminosity and many bunches at Z pole**
  - Moderate requirements on detector timing, high data rates
CLD is derived from the CLIC detector model
Silicon pixel vertex detector + Silicon tracker
Silicon-tungsten Ecal, Scintillator-steel HCal <= fine-grained
Superconducting solenoid, yoke with detectors for muon ID

Constraints from MDI at FCC-ee
Detector solenoidal field ↓ 2 T (4 T for CLIC)
Outer tracker radius ↑ 2.15 m (1.5 m for CLIC)
Beam pipe radius ↓ 15 mm (29 mm for CLIC)
Inner vertex radius ↓ 17 mm (31 mm for CLIC)
Max collision energy ↓ 365 GeV (3 TeV for CLIC)
Hadronic calorimeter depth ↓ 5.5 \( \lambda_I \) (7.5 \( \lambda_I \) for CLIC)
Layout respects the ±150 mrad cone for detector

Constraints from FCC-ee continuous operation
Power pulsing not possible
Increased tracker “mass” in simulation model
Track resolution for single muons

CLD work in progress !!!

![Graph showing track resolution for single muons](image)

CLD work in progress
FCC-ee CLD detector performance

Jet energy resolution

CLD work in progress !!!

Full Geant4-based simulation + reconstruction using particle flow
Such a plot requires a lot of calibration/tuning efforts for all detector regions
“IDEA” concept for FCC-ee/CEPC

IDEA “International Detector for Electron-positron Accelerator”
- Vertex detector, MAPS, $R_{\text{in}}=15\text{mm}$
- Ultra-light drift chamber with PID
- Outer silicon layer
- Thin superconducting solenoid 2T, $R=2\text{m}$
- Pre-shower
- Dual read-out calorimetry, 2m deep
- Instrumented return yoke

Optionally solenoid outside/inside calorimeter:
- a. Classical 2T solenoid around the calorimeter, 7.2m bore, 8m long
- b. Ultra light 2T solenoid around tracker, 4.0m bore, 6m long
CEPC detector

**ILD-L-inspired** detector concept studied for pre-CDR

- Shorter $L^*$ of 1.5 m → QD0 inside tracker
- Increased cooling infrastructure due to continuous operation
- Thickness of return yoke reduced for both barrel and endcap

Towards CDR:
- Study 2+ detector concepts
- ILD-like / SiD-like concepts, novel concept (→ “IDEA”)
$e^+e^- \rightarrow H\nu\nu \rightarrow b\bar{b}\nu\nu$

CLIC 1.4 TeV

same event before cuts on beam-induced background

end of the $e^+e^-$ lecture part
Detectors for High Energy Colliders
Machine Detector Interface
part 2
future pp colliders

With many thanks to my FCC-hh colleagues
Particular thank you to Werner Riegler, most of the material is his

W. Riegler, Acad.Training, Oct 2017
<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>100</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2 &amp; 2</td>
<td>2 &amp; 2</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.27</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1 (0.2)</td>
<td>1 (0.2)</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25 (5)</td>
<td>25 (5)</td>
<td>25 (5)</td>
</tr>
<tr>
<td>IP $\beta^*_{x,y}$ [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>34</td>
</tr>
<tr>
<td>peak #events/bunch crossing</td>
<td>170</td>
<td>1020 (204)</td>
<td>1070 (214)</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>synchrotron rad. [W/m/beam]</td>
<td>30</td>
<td>4.1</td>
<td>(0.35) 0.18</td>
</tr>
</tbody>
</table>

FCC-hh and HE-LHC have very similar detector requirements (resolution and radiation hardness) !!!

CAS school Zürich, Feb 23, 2018
How to specify detectors for such a collider?

The Higgs is still a key benchmark for the FCC-hh detector, => Highly forward boosted features (100 TeV, 125 GeV Higgs)

ATLAS and CMS are general purpose detectors that were benchmarked with the ‘hypothetical’ Higgs in different mass regions with tracking up to \( \eta = 2.5 \) \((\theta \approx 10^\circ)\)

Many other physics goals (see lectre by Michelangelo), for example:
Higgs self-coupling \((\lambda)\), precision Standard Model, heavy resonances, SUSY, etc.

FCC detectors must be ‘general general’ purpose detectors with very large \( \eta \) acceptance and extreme granularity

Detector acceptance goal set:
Muon detection up to \( \eta = 4 \) \((\theta \approx 2^\circ)\)
Calorimetry up to \( \eta = 6 \) \((\theta \approx 0.5^\circ)\)

\[ \eta \equiv -\ln\left[ \tan\left(\frac{\theta}{2}\right) \right] \]
FCC-hh physics scope

The present working hypothesis:
- peak luminosity baseline: $5 \times 10^{34}$, integrated luminosity $\sim 250$ fb$^{-1}$/yr
- peak luminosity ultimate: $\leq 30 \times 10^{34}$, integrated luminosity $\sim 1000$ fb$^{-1}$/yr

Total cross section and Minimum Bias multiplicity => modest increase from LHC to FCC-hh.

The cross section for interesting processes => significant increase !

→ Interesting stuff is sticking out more !!

Going from pileup of 140 at HL-LHC to pileup of 1000 at FCC-hh however reduces this possible advantage (e.g. triggering)
This is a reference detector that ‘can do the job’ and that is used to define the challenges. The question about the specific strategy for detectors at the two IPs is a different one.

W. Riegler, Acad. Training, Oct 2017
• Compared to ATLAS / CMS, the forward calorimeters are moved far out in order to reach larger $\eta$, reduce radiation load and increase granularity.
• Forward solenoid adds about 1 unit of $\eta$ to tracking acceptance.
• A large shielding (brown) stops neutrons from escaping to cavern and muon system.
Cavern length of 66 m => compatible with the opening scenario of the present detector
Cavern diameter of 20 m => similar to ATLAS cavern
Charged particle fluence at $L=30\times10^{34}\text{cm}^{-2}\text{s}^{-1}$

Central vertex/tracker:
- first IB layer (2.5 cm): $\sim1.2\times10^{10}\text{cm}^{-2}\text{s}^{-1}$
- external part: $3\times10^{6}\text{cm}^{-2}\text{s}^{-1}$

Barrel muon chambers: $\sim300\text{cm}^{-2}\text{s}^{-1}$ to $\sim500\text{cm}^{-2}\text{s}^{-1}$

Endcap Muon Chambers: $10^4\text{cm}^{-2}\text{s}^{-1}$

R $> 1\text{m}$: $5\times10^5\text{cm}^{-2}\text{s}^{-1}$
1 MeV neutron equivalent fluence for 30 ab$^{-1}$

Central tracker:
- first IB layer (2.5 cm): $\sim 5-6 \times 10^{17}$ cm$^{-2}$
- external part: $\sim 5 \times 10^{15}$ cm$^{-2}$

Forward calorimeters:
- maximum at $\sim 5 \times 10^{18}$ cm$^{-2}$ for both the EM and the HAD-calo
- $10^{16}$ cm$^{-2}$ at R=2 m

W. Riegler, Acad.Training, Oct 2017
Tracker radius 1.6 m, half-length 16 m
Hit position resolution $\sim 10 \mu$m in R-\(\phi\)

Note: resolution improves as $1/\sqrt{N_{\text{layers}}}$, material budget increases as $N_{\text{layers}}$

$12$ barrel layers, $20$ endcap disks

W. Riegler, Acad. Training, Oct 2017
FCC-hh tracker considerations

- A 1.6m x 16m long detector with 10 μm single point resolution in R-φ can achieve a 20% $\text{dpT}/p_T$ resolution for 10 TeV tracks.
- **Timing information** will be essential to identify the primary vertex within the 1000 pile-up events.
- **Tilted layout** would be very advantageous to reduce multiple scattering for pattern recognition.
- **Beampipe material** is the limiting factor for $z_0$ resolution at $|\eta| > 1.7$.
- Tracking performance in **boosted objects** is limited by detector granularity.
- A significant fraction of **displaced vertices** will be out of detector acceptance.
HL-LHC average distance between vertices at $z=0$ is
$\approx 1$mm in space and 3ps in time

For 6 times higher luminosity at FCC-hh (and HE-LHC)
$\approx 170$μm in space and 0.5ps in time

For $\eta > 1.7$ the error due to multiple scattering in beampipe is larger than average vertex distance!

Timing and very clever new are ideas are needed...
primary vertex reconstruction and pile up

Fraction of events correctly assigned to the primary vertex
No timing, 5 ps timing, 10 ps timing

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

W. Riegler, Acad.Training, Oct 2017
FCC-hh calorimetry

Overall 2-4x better granularity than e.g. ATLAS

barrel ECAL, endcap ECAL/HCAL, forward ECAL/HCAL are in LAr technology, intrinsically radiation hard

Note: Silicon ECAL and ideas for digital ECAL with MAPS are also being discussed

W. Riegler, Acad.Training, Oct 2017

CAS school Zürich, Feb 23, 2018
muon system considerations

Compare 3 options:
1. Tracker only with identification in the muon system
2. Muon system only by measuring the muon angle where it exits the coil
3. Tracker combined with the position of the muon where it exits the coil

Assume (at $\eta=0$):
- 50μm position resolution
- 70μRad angular resolution

- <10% standalone momentum resolution up to 3TeV/c
- <10% combined momentum resolution up to 20TeV

within reach of ‘standard’ muon system technology

W. Riegl, Acad.Training, Oct 2017
Experimental conditions for a ~100 TeV pp collider have much in common with conditions as we know them from HL-LHC.

**Challenge:** preserve overall detector performance, despite huge pile up, high energies, very forward-going physics and high radiation conditions

**A few extra remarks:**
- Compared to HL-LHC, **radiation levels** increase in proportion to the luminosity
- Particles (e.g. Higgs) have more **forward boost**:
  - => precision tracking needed down \( \eta=4, \theta=2^\circ \) (\( \eta=2.5, 2.5^\circ \) at LHC)
  - => calorimetry down to \( \eta=6, \theta=0.5^\circ \)
- Aim for track resolution of 10-15% up to \( p_T \) of 10 TeV
  - => central solenoid 4 T with inner radius 5 m, track hit resolution \( \sim 10 \mu m \)
  - Forward solenoids are needed to increase angular coverage

**Pile up of 1000 events?**
- FCC-hh average distance at \( z=0 \) between events is 170 \( \mu m \), 0.5 ps (1mm, 3 ps at HL-LHC)
- For tracks at \( \eta>1.7 \), multiple scattering effect due to 0.8 mm Be beam pipe is larger than average distance between two interaction vertices !
- Fine grained calorimetry required to help resolving pile up
- Excellent time (few ps) resolution required

**better ask accelerator for 5 ns bunch spacing**
a few words on detector technologies

detectors at future e+e- and pp collider face strong challenges

**Vertex/tracker**

<table>
<thead>
<tr>
<th>Property</th>
<th>e⁺e⁻</th>
<th>pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position resolution (3 μm – 10 μm)</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Small cell sizes (down to 20*20 μm)</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Very thin materials</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Excellent timing (ps-ns scale)</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Large surfaces, low cost</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>*</td>
<td>****</td>
</tr>
</tbody>
</table>

**Calorimetry**

<table>
<thead>
<tr>
<th>Property</th>
<th>e⁺e⁻</th>
<th>pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>High granularity (few cm² cells)</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Excellent timing (ps-ns scale)</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Compactness (thin active layers)</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Large surfaces, low cost</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>*</td>
<td>****</td>
</tr>
</tbody>
</table>

+ large area muon detection + DAQ/trigger + large superconducting solenoids + ...

despite differences, many challenges in common

much (not all) of the required R&D points at advanced silicon / microelectronics technologies
SPARE SLIDES
# status of the projects

<table>
<thead>
<tr>
<th>Facility</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td>• TDR/DBD in 2013&lt;br&gt;• European XFEL in operation using similar accelerator technology</td>
</tr>
<tr>
<td>CLIC</td>
<td>• CDR in 2012&lt;br&gt;• Staging baseline document in 2016&lt;br&gt;• Project Implementation Plan foreseen for 2018</td>
</tr>
<tr>
<td>CEPC-SppC</td>
<td>• Pre-CDR in 2015&lt;br&gt;• CDR planned for 2017</td>
</tr>
<tr>
<td>FCC-ee, FCC-hh, HE-LHC</td>
<td>• CDR planned for 2018</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>• Existing LHC tunnel&lt;br&gt;• Prospect to use FCC-hh magnet technology</td>
</tr>
</tbody>
</table>

- XFEL in operation since Dec 2016
- CLIC 2-beam acceleration, 100 MV/m
- 11 T superconducting dipole prototype
CLIC impact parameter resolution

![Graph showing z0 resolution and d0 resolution for different momenta (p = 1 GeV, p = 10 GeV, p = 100 GeV). The graphs display the standard deviation of impact parameter resolution as a function of the angle θ (degrees). The results indicate a resolution of approximately 6 μm for z0 resolution and 2 μm for d0 resolution.](image)

E.Leogrande @ LCWS17
Incoherent $e^+e^-$ pairs

- There are on average 84k incoherent pairs per bunch crossing at 380 GeV, 74k at 350 GeV, and 290k at 3 TeV
- In all cases only around 10% of the incoherent pairs are a source of direct background, mostly in the forward detector region, irradiating BeamCal and LumiCal subdetectors

Dominik Arominski, CLIC2018
\( \gamma \gamma \rightarrow \text{hadrons} \)

\( \gamma \gamma \rightarrow \text{hadrons overview} \)

- Over 90\% of produced hadrons have transverse momentum high enough to reach the barrel region and thus they are one of the major sources of direct background and occupancies.

- There are 0.17 \( \gamma \gamma \rightarrow \text{hadron} \) events per BX at 380 GeV, 0.16 at 350 GeV and 3.9 at 3 TeV.

Dominik Arominski, CLIC2018
Beam-induced background from $\gamma\gamma \to$ hadrons can be efficiently suppressed by applying $p_t$ cuts and timing cuts on individually reconstructed particles (particle flow objects).

$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8 \text{ jets}$$

1.2 TeV background in reconstruction window (>=10 ns) around main physics event

100 GeV background after tight cuts
Beam-induced background from $\gamma\gamma \rightarrow$ hadrons is further reduced by applying adapted jet reconstruction algorithms.

Example: squark study at $\sqrt{s} = 3$ TeV (with assumed squark mass of 1.1 TeV)

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

No $\gamma\gamma \rightarrow$ hadrons background

With $\gamma\gamma \rightarrow$ hadrons bkg from 60 bunch crossings

With $\gamma\gamma \rightarrow$ hadrons bkg from 60 bunch crossings + use of $p_t$ and timing cuts

Traditional Durham-ee jet algorithm inadequate $\iff$ use of “LHC-like” jet algorithms effective

Luminosity needs to be measured to very high accuracy
- Few $10^{-5}$ at the Z pole
- Few $10^{-4}$ at the $tt$ threshold

**Forward calorimeter to measure Bhabha scattering**, adapted from ILC/CLIC design
- Placed closer to the IP ($z < 1.2$ m) and made smaller
- Centred around the outgoing beam

Depth 10 cm (1.05 to 1.15 m)
Radius from 5.4 to 14.2 cm
30 layers ($1X_0$) of 3.5 mm W + 1 mm Si
32 × 32 Si pads in (R,φ): 3×10⁴ channels

Positioned with 1 μm accuracy

Total angular coverage: 45-95 mrad
  - Loose acceptance: 63-83 mrad
  - Tight acceptance: 68-78 mrad

$\sigma(e^+e^-\rightarrow e^+e^-) = 6-13$ nb

*P. Janot, Acad. Training, Oct 2017*
FCC-hh three solenoids