Detector requirements for future high-energy collider experiments

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Detector requirements for future high-energy \( pp, e^+e^- \) and \( \mu^+\mu^- \) collider experiments

(ep, PbPb and pPb colliders not covered in this talk)

- Facilities under study
  - Hadron (pp) and lepton (\( e^+e^- / \mu^+\mu^- \)) colliders
  - Circular and linear
- Detector design mostly driven by facility-dependent
  - Physics objectives
  - Experimental conditions
- Proposed detector concepts
  - Design choices
  - Detector challenges
Overview:
High-energy collider proposals
High-energy $e^+e^-$ collider proposals

Circular Electron Positron Collider (CEPC)

$\sqrt{s} = 90–240$ GeV; Circumference: 100 km

Compact Linear Collider (CLIC)

$\sqrt{s} = 350/380$ GeV, 1.5 TeV, 3 TeV; Length: 11 km, 29 km, 50 km

Future Circular Collider (FCC-ee)

$\sqrt{s} = 90–240$ GeV, 350–365 GeV; Circumference: 97.8 km

International Linear Collider (ILC)

$\sqrt{s} = 250$ GeV, 350/500 GeV (1 TeV); Length: 20.5 km, 31 km (40 km)
High-energy hadron collider proposals

**Future Circular Collider (FCC-hh)**

\[ \sqrt{s} = \sim 100 \text{ TeV} \]

(37.5 TeV with LHC type magnets);

Circumference: 97.8 km

**High Energy-LHC**

\[ \sqrt{s} = 27 \text{ TeV}; \]

Length: 27 km

**Super Proton Proton Collider (SppC)**

\[ \sqrt{s} = \sim 75 \text{ TeV} \]

(125–150 TeV “ultimate”);

Circumference: 100 km
High-energy muon collider proposals

Muon colliders $\sqrt{s} = \text{up to } 10\text{ TeV}$;
Circumference: few km
(+ larger pre-accelerator complex)
Example: MAP-MC: 126 GeV – 6 TeV

Low EMMittance Muon Accelerator (LEMMA):
$10^{11}$ $\mu$ pairs/sec from $e^+e^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.
### Future collider projects

#### Time lines

<table>
<thead>
<tr>
<th></th>
<th>$T_0$</th>
<th>+5</th>
<th>+10</th>
<th>+15</th>
<th>+20</th>
<th>...</th>
<th>+26</th>
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</thead>
<tbody>
<tr>
<td>ILC</td>
<td>0.5/ab 250 GeV</td>
<td>1.5/ab 250 GeV</td>
<td>1.0/ab 500 GeV</td>
<td>0.2/ab $2m_{top}$</td>
<td>3/ab 500 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td>5.6/ab 240 GeV</td>
<td>16/ab $M_z$</td>
<td>2.6/ab $2M_w$</td>
<td></td>
<td></td>
<td>SppC =&gt;</td>
<td></td>
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<tr>
<td>CLIC</td>
<td>1.0/ab 380 GeV</td>
<td>2.5/ab 1.5 TeV</td>
<td>5.0/ab =&gt; until +28 3.0 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC</td>
<td>150/ab ee, $M_z$</td>
<td>10/ab ee, $2M_w$</td>
<td>5/ab ee, 240 GeV</td>
<td>1.7/ab ee, $2m_{top}$</td>
<td></td>
<td>hh,eh =&gt;</td>
<td></td>
</tr>
<tr>
<td>LHeC</td>
<td>0.06/ab</td>
<td>0.2/ab</td>
<td>0.72/ab</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>HE-LHC</td>
<td></td>
<td>10/ab per experiment in 20y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC hh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20/ab per experiment in 25y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Near future proposals** (excluding ep colliders LHeC, EIC):
  - $e^+e^-$ colliders (ILC, CEPC, CLIC, FCC-ee)
  - Low-energy FCC-hh (using LHC-type magnets in FCC tunnel: 37.5 TeV)

- **Proposals for more distant future**
  - Hadron colliders with high-field ($\sim$ 16 T) magnets (HE-LHC, FCC-hh, SppC)
    → Require further magnet development
  - Muon colliders
    → Require further studies towards design reports
  - Linear $e^+e^-$ colliders with dielectric or plasma-wake-field acceleration
    → Require further studies towards design reports
Physics programmes

→ Detector requirements
High-energy hadron & lepton colliders

→ Aspects relevant for detector design

1) Hadrons are compound objects
   ▶ Initial state unknown
   ▶ Limits achievable precision
   → More relaxed accuracy requirements on detectors

2) High rates of QCD backgrounds
   ▶ Complex triggers
   ▶ High levels of radiation

3) Strong forward boost

4) O(10 ps) timing requirement (minimum bias)

Lepton colliders (e^+e^- / μ^+μ^-)

1) Leptons are point-like
   ▶ Initial state well-defined
   ▶ High-precision measurements
   → Very high accuracy requirements on detectors

2) Clean experimental environment
   ▶ Less/no need for triggers
   ▶ Lower radiation levels

3) Less forward boost (increase with $s$)

4) No or O(1 ns) timing requirement (beam background)
In hadron collisions, interesting events need to be found in huge number of collisions

Lepton collisions more clean

**pp cross section**

**e^+ e^- processes**

- **Factor > 10^8**
\( \mu^+\mu^- \): BSM searches and SM cross sections

- \( \mu^\pm \) less prone to synchrotron radiation: \( \Delta E \sim E^4/(m^4 \cdot R) \) \( (m_\mu = 207 m_e) \)
  \( \rightarrow \) potential to reach \( O(10 \text{ TeV}) \) in circular collider of modest circumference

**Selected SM \( \mu^+\mu^- \) cross sections**

- Similar SM cross sections in e\(^+\)e\(^-\) and \( \mu^+\mu^- \) (apart from QED-radiation and small Yukawa effects)
- Cross section for many Higgs production processes increases with \( \sqrt{s} \rightarrow \) large Higgs samples

**Equivalent parton centre-of-mass energy**

- In pp collisions, \( \sqrt{s_{\text{parton-parton}}} \ll \sqrt{s_{pp}} \)
- “Equivalent” reach at
  - \( \sqrt{s_{\mu^+\mu^-}} = 14 \text{ TeV} \) and \( \sqrt{s_{pp}} = 100 \text{ TeV} \)
- Searches in \( \mu^+\mu^- \rightarrow ff \) up to \( m_f \leq \sqrt{s_{\mu^+\mu^-}} / 2 \)
Luminosities and energy reach: $e^+e^-$

- **Circular $e^+e^-$ colliders**
  - Extremely high luminosities at low energies ($Z$, $WW$, $ZH$)
- **Linear $e^+e^-$ colliders**
  - High centre of mass energies ($t\bar{t}$, $ZH$, $H\nu\nu$, double Higgs, direct searches)
  - Beam polarisation $\rightarrow$ characterisation of new particles or processes in detail
- **Circular and linear $e^+e^-$ colliders**
  - Comparable luminosities in overlap region ($ZH$, $t\bar{t}$)

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*January 27, 2020*  
Eva Sicking: Detector requirements for future colliders
Luminosities and energy reach: $e^+e^-$ and $\mu^+\mu^-$

- Circular $e^+e^-$ colliders
  - Extremely high luminosities at low energies (Z, WW, ZH)

- Linear $e^+e^-$ colliders
  - High centre of mass energies (t\bar{t}, ZH, H\nu\nu, double Higgs, direct searches)
  - Beam polarisation $\rightarrow$ characterisation of new particles or processes in detail

- Circular and linear $e^+e^-$ colliders
  - Comparable luminosities in overlap region (ZH, t\bar{t})

- Muon collider: reach multi-TeV energies
**LC e^+e^- detector performance requirements**

- **Momentum resolution**
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - \( \sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5} \text{GeV}^{-1} \)

- **Impact parameter resolution**
  - c/b-tagging, Higgs branching ratios
  - \( \sigma_{r\phi} \sim a \oplus b/(p[\text{GeV}] \sin^{3/2} \theta) \mu m \)
  - \( a = 5 \mu m, \quad b = 10 - 15 \mu m \)

- **Jet energy resolution**
  - Separation of W/Z/H di-jets, Z and W width, HZ with Z \( \rightarrow q\bar{q} \), background reduction
  - \( \sigma_E/E \sim 3.5\% \)
    - (for high-energy jets, light quarks)

- **Angular coverage**
  - Very forward electron and photon tagging

+ Requirements from beam structure and beam-induced background
LC $e^+e^-$ detector performance requirements

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
    \[ \sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\text{GeV}^{-1} \]

- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
    \[ \sigma_{r\phi} \sim a \oplus b/(p[\text{GeV}] \sin^{\frac{3}{2}}\theta)\mu\text{m} \]
    - \( a = 5 \mu\text{m}, \ b = 10 - 15 \mu\text{m} \)

- Jet energy resolution
  - Separation of $W/Z/H$ di-jets, Z and W width, HZ with $Z \rightarrow q\bar{q}$, background reduction
    \[ \sigma_E/E \sim 3.5\% \]
    (for high-energy jets, light quarks)

- Angular coverage
  - Very forward electron and photon tagging

+ Requirements from beam structure and beam-induced background

Differences between ILC, CLIC, FCC-ee, CEPC requirements rather small
Experimental conditions
Hadron colliders: Key parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}$</td>
<td>TeV</td>
<td>14</td>
<td>14</td>
<td>27</td>
<td>100</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>97.8</td>
</tr>
<tr>
<td>Peak $\mathcal{L}$, nominal (ultimate)</td>
<td>$10^{34} \text{ cm}^{-2} \text{s}^{-1}$</td>
<td>1 (2)</td>
<td>5 (7.5)</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>2808</td>
<td>2760</td>
<td>2808</td>
<td>10 600</td>
</tr>
<tr>
<td>Goal $\int \mathcal{L}$</td>
<td>ab$^{-1}$</td>
<td>0.3</td>
<td>3</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>$\sigma_{\text{inel}}[340]$</td>
<td>mb</td>
<td>80</td>
<td>80</td>
<td>86</td>
<td>103</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}[340]$</td>
<td>mb</td>
<td>108</td>
<td>108</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>BC rate</td>
<td>MHz</td>
<td>31.6</td>
<td>31.0</td>
<td>31.6</td>
<td>32.5</td>
</tr>
<tr>
<td>Peak pp collision rate</td>
<td>GHz</td>
<td>0.8</td>
<td>4</td>
<td>14</td>
<td>31</td>
</tr>
<tr>
<td>Peak av. PU events/BC, nominal (ultimate)</td>
<td></td>
<td>25</td>
<td>130 (200)</td>
<td>435</td>
<td>950</td>
</tr>
<tr>
<td>Rate of charged tracks</td>
<td>GHz</td>
<td>59</td>
<td>297</td>
<td>1234</td>
<td>3942</td>
</tr>
</tbody>
</table>

Example: pp collisions at 100 TeV (FCC-hh)

- **Pileup:** $\sim 1000$ events/bunch crossing $\rightarrow$ spatial resolution, timing
  - Average distance between vertices: 125 $\mu$m (7 times smaller than at HL-LHC)
- **High radiation levels** $\rightarrow$ radiation hardness
  - High luminosity of $30 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
  - pp collision rate of 31 GHz
  - Charged track rate of $\sim 4$ THz
- **Forward boost** $\rightarrow$ forward coverage
Hadron colliders: Radiation levels

Assuming \( L = 30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \) and 30 ab\(^{-1}\)

**Neutron equivalent fluence**
- \( \sim 10^{18} n_{eq}/\text{cm}^2 \) close to beam pipe,
- \( 10^{15} - 10^{16} n_{eq}/\text{cm}^2 \) at \( r > 40 \text{ cm} \) (\( \sim \text{HL-LHC} \))
- Extreme fluence in forward calorimeters
  - Radiation levels 100 times larger than what present silicon sensors can sustain

**Residual dose rate**
- Dose from activation towards the end of FCC operation
- Here: 1 week of cool-down, similar picture after 1 year
  - Impact on access conditions to experiment after several years of operation
Circular vs. linear $e^+e^-$ colliders: Overview

- **Circular $e^+e^-$ colliders (CC)**
  1. Several interaction regions
  2. Continuous operation
  3. Synchrotron radiation
  4. Beam strahlung

- **Linear $e^+e^-$ colliders (LC)**
  1. One interaction region in linear colliders, alternatives: push-pull scheme or 2 beam-delivery systems (shared lumi.)
  2. Operation in bunch trains
  3. Very little synchrotron radiation in a linac
  4. Have to achieve luminosity in single pass
     → Small beam size and high beam power
     → Beamstrahlung, energy spread

- **Impact on LC/CC detector designs**
  - Shielding
  - Granularity
  - Timing
  - Cooling
Circular $e^+e^-$ colliders: Beam parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>FCC-ee (97.8 km)</th>
<th>CEPC (100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>Z</td>
<td>WW</td>
</tr>
<tr>
<td>Lumi./IP</td>
<td>$10^{34}$/cm$^2$s</td>
<td>230</td>
<td>28</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td>ns</td>
<td>16640</td>
<td>2000</td>
</tr>
<tr>
<td>Bunch sep.</td>
<td>ns</td>
<td>20</td>
<td>163</td>
</tr>
<tr>
<td>Synch.rad. power</td>
<td>MW</td>
<td>$\leq$ 50</td>
<td>$\leq$ 50</td>
</tr>
<tr>
<td>Beam $\sigma_{xy, IP}$</td>
<td>$\mu$m/nm</td>
<td>6.4/28</td>
<td>13/41</td>
</tr>
</tbody>
</table>

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

- At Z peak, **high luminosity** combined with high $e^+e^-$ cross section
  - Achieve very low statistical uncertainties ($\sim 10^{-4} - 10^{-5}$)
    → Drives detector performance req. to match systematic uncertainties
  - **High number of bunches and small distance between bunches**
    → Beam crossing angle: 30 mrad (FCC-ee)/33 mrad(CEPC)
  - **Very high data rates** (physics rates 100 kHz)
    → Requirements on readout
    → **Triggerless readout can still be possible**

- **Backgrounds**
  - **Synchrotron radiation**, beamstrahlung, backgrounds from beam losses, etc.
    → Adapt detector and machine-detector interface
Circ. $e^+e^-$ colliders: Machine-detector interface

- High luminosities: last focusing quadrupole QC1 very close to IP
  - $L^* \approx 2.2$ m @ FCC-ee and CEPC $\rightarrow$ QC1 inside detector volume
- Protect QC1 from main magnetic field of detector
  - Screening solenoid around QC1
- Compensating solenoid: prevent beam emittance blow-up in detector B field due to non-zero crossing angle

$\rightarrow$ **Lumical** at only 1 m from interaction point
  - Limits detector acceptance window

$\rightarrow$ Limits magnetic field of main solenoid: $B=2$ T at FCC-ee
  - Relatively large tracker radius to achieve good momentum resolution

$\rightarrow$ Limit on magnetic field of main solenoid varies with $\sqrt{s}$
$\rightarrow$ Larger B would require thicker main magnet coil $\rightarrow$ impact on detector
Circ. e^+e^- colliders: Machine-detector interface

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  - Limits detector acceptance window
→ Limits magnetic field of main solenoid: \( B = 2 \text{T} \) at FCC-ee
  - Relatively large tracker radius to achieve good momentum resolution

→ Limit on magnetic field of main solenoid varies with \( \sqrt{s} \)
→ Larger B would require thicker main magnet coil \( \rightarrow \) impact on detector
Circular $e^+e^-$ colliders: Shielding and cooling

- **W shielding** inside of detector region to prevent synchrotron radiation/secondary radiation to enter the sub-detectors

FCC-ee detector: 2D-top view with expanded y-coordinate

- Beam pipe
  - Heating, liquid cooled $\rightarrow$ increased material budget at the IP
  - Be in central region, then Cu
Circular $e^+e^-$ colliders: Shielding and cooling

- **W shielding** inside of detector region to prevent synchrotron radiation/secondary radiation to enter the sub-detectors

**CEPC detector: 2D-top view with expanded y-coordinate**

- Beam pipe
  - Heating, liquid cooled $\rightarrow$ increased material budget at the IP
  - Be in central region, then Cu
## Linear e^+e^- colliders: Beam parameters (1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>250</td>
<td>250(Upg.)</td>
</tr>
<tr>
<td>√s GeV</td>
<td></td>
<td>250</td>
<td>250(Upg.)</td>
</tr>
<tr>
<td>Train rep. rate</td>
<td>Hz</td>
<td>5</td>
<td>5/10</td>
</tr>
<tr>
<td>BX / train</td>
<td></td>
<td>1312</td>
<td>2625</td>
</tr>
<tr>
<td>Bunch sep.</td>
<td>ns</td>
<td>554</td>
<td>272</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>%</td>
<td>3.6</td>
<td>7.2</td>
</tr>
</tbody>
</table>

- Linear colliders operate in bunch trains
  - **Low duty cycle**
  - Possibility of power pulsing of detectors and triggerless readout

**Beam structure:** CLIC@3TeV/ILC@500GeV

![Beam structure diagram](Not to scale)
Linear $e^+e^-$ colliders: Beam parameters (2)

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>ILC</th>
<th></th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>250</td>
<td>250(Upg.)</td>
<td>500</td>
</tr>
<tr>
<td>Site length</td>
<td>km</td>
<td>20.5</td>
<td>20.5/31</td>
<td>31</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{34}/cm^2s$</td>
<td>1.35</td>
<td>2.7/5.4</td>
<td>1.8/3.6</td>
</tr>
<tr>
<td>Bunch sep.</td>
<td>ns</td>
<td>554</td>
<td>272</td>
<td>544/272</td>
</tr>
<tr>
<td>Beam $\sigma_{xy,\text{IP}}$</td>
<td>nm/nm</td>
<td>516/7.7</td>
<td>516/7.7</td>
<td>474/5.9</td>
</tr>
<tr>
<td>Beam $\sigma_{z,\text{IP}}$</td>
<td>$\mu$m</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>ILC: Crossing angle 14 mrad, electron polarization $\pm80%$, positron polarization $\pm30%$,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIC: Crossing angle 20 mrad, electron polarization $\pm80%$, upgrade positron polarization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Bunch separation** → Impact on detector design (timing, granularity)
- **Very small beams** and high beam energy → beamstrahlung
Linear $e^+e^-$ colliders: Beamstrahlung
Impact on layout, granularity, shielding

$N_{\text{Charged particles/mm}^2/\text{bunch crossing}} @ 3 \text{ TeV CLIC}$:
Zoom into vertex detector region

- Adapt detector layout, granularity, shielding, timing requirements
  - Radius of beam pipe and first vertex detector layer: $\sim 3 \text{ cm @ 3 TeV}$
  - Thicker beam-pipe in forward direction: shielding for back scattered particles
  - Timing requirements: 5 ns for CLIC vertex and tracking detectors

- Timing also useful for ILC, FCC, CEPC:
  e.g. distinguish direct energy deposits from back scattering ones
# Muon collider: Key parameters

Proton driven muon collider (MAP collaboration)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs</th>
<th>Multi-TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>1.5</td>
</tr>
<tr>
<td>Avg. Luminosity</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>0.008</td>
<td>1.25</td>
</tr>
<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.004</td>
<td>0.1</td>
</tr>
<tr>
<td>Higgs Production/10$^7$ sec</td>
<td></td>
<td>13’500</td>
<td>37’500</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>2.5</td>
</tr>
<tr>
<td>No. of IP’s</td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$\beta^{*}_{x,y}$</td>
<td>cm</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>No. muons/bunch</td>
<td>$10^{12}$</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Norm. Trans. Emittance, $\varepsilon_{TN}$</td>
<td>$\mu$m-rad</td>
<td>200</td>
<td>25</td>
</tr>
<tr>
<td>Norm. Long. Emittance, $\varepsilon_{LN}$</td>
<td>$\mu$m-rad</td>
<td>1.5</td>
<td>70</td>
</tr>
<tr>
<td>Bunch Length, $\sigma_s$</td>
<td>cm</td>
<td>6.3</td>
<td>1</td>
</tr>
<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Wall Plug Power</td>
<td>MW</td>
<td>200</td>
<td>216</td>
</tr>
</tbody>
</table>

- **Luminosity at 3 TeV similar to CLIC** (4.4 versus $5.9 \times 10^{34}$/cm$^2$/s)
- **Luminosity per wall plug power increases for muon colliders**
  \[ \rightarrow \text{reach O(10 TeV)} \]
- **Luminosity increases with energy quadratically (beam size reduction)**
- **Each $\sqrt{s}$ foreseen in individual collider of few kilometres**
Muon colliders: Neutrino background

- In-flight muon decay
  - Neutrino continue in beam direction
  - Straight sections: neutrinos emerge in spot-like area

![Diagram showing muon decay and neutrino interactions]

- Secondary hadronic interactions from initial neutrinos pose radiation hazard where the neutrino beam reaches earth surface
  → Dose in continuation of straight sections particularly high
- Radiation limit to population below 0.1 mSv/y

- Dose scales with energy following $\sim E^3$
Muons decay also near detector region
e.g. @ 750 GeV, $2 \times 10^{12} \mu$ per bunch: $4 \times 10^5$ decays/m/bunch
- $e^\pm$ inside accelerator magnets $\rightarrow$ Synchroton radiation ($\gamma$)
- El.-mag. showers from $e^\pm$ and $\gamma$ interact with the machine components
  $\rightarrow$ Photons, neutrons, electrons, charged hadrons and secondary muons reaching detector region

- Collimation, shielding and timing requirements for detector design
Detectors
FCC-hh reference detector (100 TeV)

- Silicon tracker
- Barrel ECAL LAr
- Endcap and forward HCAL/ECAL LAr
- Barrel HCAL Fe/Sci
- Central solenoid (4 T, > 10 m diameter), two forward solenoids, unshielded
- Muon system
Two tracker options studied: “Tilted” and “flat”, each $O(400 \text{ m}^2)$

- Tilted layout reduces material budget $\rightarrow$ improves reconstruction efficiency

- High occupancies
  - Small cells sizes ($\sim 25 \times 50 \mu\text{m}^2$ in inner layers)

- Two-track separation in boosted objects
  - Small cell sizes + hit resolution $< 5 \mu\text{m} + O(5 \text{ ps})$ time resolution

- High-E $\rightarrow$ significant fraction of displaced vertices outside acceptance

- Radiation levels $100\times$ higher than present silicon technologies can sustain
Calorimetry in FCC-hh detector

Requirements at 100 TeV
- Depth: $\geq 30 X_0$, $\geq 11 \lambda_I$
- High longitudinal and lateral segmentation
- Coverage up to $|\eta| = 6$
- Excellent resolution and linearity from GeV to multi-TeV (e.g. 1% mass resolution for $H \rightarrow \gamma\gamma/4e$)
- Timing $O(30 \text{ ps}) \rightarrow$ pile-up reduction by factor 6
- Dynamic range: per-cell deposits from MIPs to heavy resonances up to 50 TeV

- Sampling calorimeters for FCC-hh: Liquid Argon (LAr) and Scintillator
- LAr only known technology for extreme radiation regions, requires development towards high granularity $\rightarrow$ particle flow analysis
- Silicon alternative for lower radiation regions

arXiv:1912.09962
January 27, 2020
Linear e^+e^- collider detectors (up to 3 TeV)

- 3.5–5 T solenoids
- CLICdet and SiD: all silicon tracker; ILD: Time Projection Chamber
- Vertex and tracking detector with very low material budget and unprecedented spatial resolution
- Highly granular calorimeters
- Forward calorimeters
- Muon system in return yoke
- Power pulsing possible due to low duty circle
Circular $e^+e^-$ collider detectors (up to 365 GeV)

- 2 T FCC-ee, 2–3 T CEPC
- Large tracker radius in case of lower magnetic field
- CLD: All silicon tracker,
  Baseline: TPC, IDEA: Drift chamber
- Highly granular calorimeter or dual readout calorimeter
- Forward calorimeters
Muon collider detectors

MAP (Muon Accelerator Programme) detector

- Detector used for first background and performance studies
  - Magnetic coil 3.57 T
  - Silicon based vertex and tracking detectors
  - Dual readout calorimeter
  - Muon system

- Mitigate beam-induced backgrounds
  - Tungsten-polyethylene nozzles for background mitigation inside the detector
  - O(ps) time resolution for background suppression
### Comparison: Silicon tracking detectors

#### Silicon vertex and tracking detector parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exp.</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
<th>FCC-ee</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence ([n_{eq}/cm^2/y])</td>
<td>N x 10^{15}</td>
<td>10^{16}</td>
<td></td>
<td>10^{16}-10^{17}</td>
<td>&lt;10^{10}</td>
<td>&lt;10^{11}</td>
</tr>
<tr>
<td>Max. hit rate ([s^{-1}cm^{-2}])</td>
<td>100 M</td>
<td>2-4 G****</td>
<td></td>
<td>20 G</td>
<td>20 M ***</td>
<td>240k</td>
</tr>
<tr>
<td>Surface inner tracker ([m^2])</td>
<td>2</td>
<td>10</td>
<td></td>
<td>15</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Surface outer tracker ([m^2])</td>
<td>200</td>
<td>200</td>
<td></td>
<td>400</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>Material budget per detection layer ([X_0])</td>
<td>0.3%-2%</td>
<td>0.1%-2%</td>
<td></td>
<td>1%</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Pixel size inner layers ([\mu m^2])</td>
<td>100x150-50x400</td>
<td>~50x50</td>
<td></td>
<td>25x50</td>
<td>25x25</td>
<td>~25x25</td>
</tr>
<tr>
<td>BC spacing ([ns])</td>
<td>25</td>
<td>25</td>
<td></td>
<td>25</td>
<td>20-3400</td>
<td>0.5</td>
</tr>
<tr>
<td>Hit time resolution ([ns])</td>
<td>~25-1k)</td>
<td>~0.2**-1k)</td>
<td>~1k**</td>
<td>~10^{-2}</td>
<td>~1k***</td>
<td>~5</td>
</tr>
</tbody>
</table>

* ALICE requirement
** LHCb requirement
*** At Z-pole running
****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm^2

### Hadron colliders
- Very high radiation levels: \(\leq 10^{18} n_{eq}/cm^2\)
- Very high hit rates
- Very precise timing: \(\leq O(5 \text{ ps})\)

### Lepton colliders
- Very small single point resolution \((\leq 3 \mu m)\)
- Very low material budget \((\leq 0.2X_0/\text{layer})\)

### Remarks
- Note that ps-level timing was not part of initial HL-LHC detector requirements
- Became available through pioneering R&D on LGAD / MCP / precise timing with silicon
- Now well motivated for vertex separation / pattern reconstruction
Particle flow calorimetry

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

- Always use the best information
  - 60% → tracker
  - 30% → ECAL
  - 10% → HCAL

- Particle Flow Analysis: Hardware + Software

- **Hardware**: Resolve energy deposits from different particles
  → High granularity calorimeters
  \[ E_{\text{jet}} = E_{\text{ECAL}} + E_{\text{HCAL}} \]

- **Software**: Identify energy deposits from each individual particle
  → Sophisticated reconstruction software
  \[ E_{\text{jet}} = E_{\text{track}} + E_{\gamma} + E_{n} \]
Particle flow calorimeters

- Separate overlapping showers to reduce confusion

\[ \sigma_{\text{jet}} = \sqrt{\sigma_{\text{track}}^2 + \sigma_{\text{el.-m.}}^2 + \sigma_{\text{had.}}^2 + \sigma_{\text{confusion}}^2} \]

- JER of 3%–4% when using
  - ECAL cell size: \( \sim 5 \times 5 \text{ mm}^2 \)
  - HCAL cell size: \( \sim 30 \times 30 \text{ mm}^2 \)

  Example: Calorimeter in ILD
  - \( 10^8 \) channels, 2500 m\(^2\) Silicon
  - \( 10^7 \) channels, 7000 m\(^2\) Scintil.

- Hardware R&D for highly granular calorimeters: CALICE collaboration
- Concept by now under consideration for ILC, CLIC, FCC-ee, CEPC, FCC-hh, CMS HGCal, DUNE ND

**CALICE silicon PIN diodes**
1 \( \times \) 1 cm\(^2\) in 6 \( \times \) 6 matrices

**CALICE/CMS HGCal scint. tiles + SiPMs**
3 \( \times \) 3 cm\(^2\)

**CMS HGCal silicon pad diodes**
0.5 – 1 cm\(^2\), on 8-inch wafer
Background suppression

- Highly granular calorimeter + hit timing $O(1\,\text{ns})$
- Use combined $p_T$ and timing cuts on fully reconstructed particles to reduce out-of-time background
  - Cuts optimised for detector regions
  - Cluster timing by combining hit timing information
    $\rightarrow$ tighter cuts possible on cluster timing

Before $p_T$ and timing cuts

$e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\bar{W}\bar{b}H \rightarrow q\bar{q}b\tau\bar{b}b\bar{b}$ at 1.4 TeV at CLIC
Background suppression

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After $p_T$ and timing cuts

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbWbH \rightarrow q\bar{q}b\tau\bar{b}b\bar{b}$ at 1.4 TeV at CLIC
Summary
Summary: pp collider detector challenges

Radiation levels
- Tracker: radiation for < 40 cm radius of the tracker is 100 times larger than what present silicon sensors can sustain
- Calorimeter: Liquid Argon is only viable known technology, requires development towards high granularity; silicon or scintillator technologies could be used in regions with lower radiation levels

Activation
- Impact on access conditions after several years of operation → maximise automated access
- Engineering challenge

Pile-up and boost
- Requires much increased granularity in most regions of the detector
- High precision timing required (≈ 5 ps per track) and computing power for reconstruction, both significantly above HL-LHC
- Very accurate tracker hit position resolution (< 5 µm), for 2-track separation in boosted objects
- Forward coverage

Data rate
- High collision rate and high granularity
  → Data rate of 1-2 Pbyte/s, mostly dominated by the tracker
  → Studies to be done whether this is possible and which level of triggering is required

Magnet systems
- Very large solenoid bore diameter of 10 m (6 m in CMS)
- Unshielded coil in baseline design → Stray field in cavern
**Summary: e⁺e⁻ collider detector challenges**

**Vertex detector and silicon tracker**
- High spatial resolution ($\sim 3\,\mu m$, $\sim 7\,\mu m$), very low mass, $O(5\,\text{ns})$ hit timing (3 TeV CLIC)
- Linear Colliders: Engineering challenge to combine low mass with air cooling
- Circular Colliders: Maintain low mass for position resolution without power pulsing

**Particle Flow Calorimetry**
- Much experience gained through CALICE; CMS HGCAL will be a benchmark
- Very large area of silicon for ECAL $\rightarrow$ cost driver

**Power pulsing**
- Much experience gained with laboratory set-ups, and in CALICE prototypes
- Power pulsing not yet tested at system level for vertex and tracking detectors
- Power pulsing can become an obstacle for e.g. cosmic ray calibration

**Systematics on energy scale, luminosity measurement, calibration**
- Keep systematics below level of statistical errors
- Most challenging at Z-peak, but also for top quark mass and per-mille level Higgs couplings
Summary: $\mu^+ \mu^-$ collider detector challenges

Muon decays
- Neutrino radiation hazard on earth surface
- Muon-decay induced backgrounds in detector $\rightarrow$ shielding, timing capabilities: $O(\text{ps})$

SM event topologies
- Significant forward boost of Higgs events for $O(10 \, \text{TeV})$ collisions
  $\rightarrow$ New reconstruction challenges