Detectors for a Multi-TeV Collider: “what can be learnt from the ILC”

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Overview

★ Over last 10 years extensive studies of detector concepts for the ILC
  ▪ Recently culminated in ILC detector Letters of Intent
  ▪ Two validated detector concepts: ILD, SiD
★ Initial CLIC detector studies build on these concepts…
★ Starting point for CLIC CDR detector

This Talk
★ Discuss motivation for ILC detector concepts
★ Give very brief overview of ILD and SiD
★ Discuss requirements for a detector at CLIC
  ▪ Physics
  ▪ Machine
★ Discuss main issues for CLIC
  ▪ Backgrounds
  ▪ Vertex detector/flavour ID
  ▪ Tracking
  ▪ Calorimetry
  ▪ Bunch Crossing (BX) tagging

With reference to ILC detector concept studies
ILC Physics

- Detector design should be motivated by physics
- Full physics programme not fully defined until results from LHC
- Nevertheless, some clear candidates:
  - e.g. Precision Studies/Measurements
    - Higgs sector
    - SUSY particle spectrum (if there)
    - Top physics
- Minimum detector requirements matched to “mandatory” physics programme
- Radiation hardness not a significant problem, e.g. 1st layer of vertex detector: $10^9 \, n \, \text{cm}^{-2} \, \text{yr}^{-1}$ c.f. $10^{14} \, n \, \text{cm}^{-2} \, \text{yr}^{-1}$ at LHC

Bottom Line:
Want to design a general purpose detector to fully exploit physics in clean ILC environment
ILC Detector Requirements

★ **momentum**: \((1/10 \times \text{LEP})\)
  
  e.g. Muon momentum
  
  Higgs recoil mass
  
  \[\sigma_{1/p} < 5 \times 10^{-5} \text{ GeV}^{-1}\]

★ **jet energy**: \((1/3 \times \text{LEP/ZEUS})\)
  
  e.g. W/Z di-jet mass separation
  
  EWSB signals
  
  \[\frac{\sigma_E}{E} \approx 3 - 4\%\]

★ **impact parameter**: \((1/3 \times \text{SLD})\)
  
  e.g. c/b-tagging
  
  Higgs BR
  
  \[\sigma_{r\phi} = 5 \oplus 10/(p \sin^2 \theta) \mu m\]

★ **hermetic**: down to \(\theta = 5\) mrad
  
  e.g. missing energy signatures in SUSY
ILT: International Large Detector

“Large” : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

SiD: Silicon Detector

“Small” : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

★ Both concepts “validated” by IDAG (independent expert review)
★ Detailed GEANT4 studies show ILD/SiD meet ILC detector goals
★ Fairly conventional technology – although many technical challenges

Represent plausible/performant designs for an ILC detector
Detector design should be motivated by physics

On assumption that CLIC would be staged: e.g. 500 GeV → 3 TeV

- Must meet all ILC detector goals
- Hence ILD and SiD represent good starting points

For 3 TeV operation what are the detector goals?

- Less clear than for the ILC (for ILC Higgs physics helps define goals)
- Nevertheless can make some statements:
  - Still want to separate W/Z hadronic decays
    - Jet energy res: \( \frac{\sigma_E}{E} < 3 - 4\% \)
    - Heavy flavour-tagging still will be important; higher boost of b/c-hadrons will help. ILC goal likely(?) to be sufficient, i.e.
      \[ \sigma_{r\phi} = 5 \oplus 10/(p \sin^2 \theta) \mu m \]
  - Requirements for momentum resolution less clear, high \( p_T \) muons likely to be important...

Main detector requirements driven by CLIC machine environment
## From ILC to CLIC Detector Concepts

<table>
<thead>
<tr>
<th></th>
<th>LEP 2</th>
<th>ILC 0.5 TeV</th>
<th>CLIC 0.5 TeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L , [\text{cm}^{-2}\text{s}^{-1}] )</td>
<td>( 5 \times 10^{31} )</td>
<td>( 2 \times 10^{34} )</td>
<td>( 2 \times 10^{34} )</td>
<td>( 6 \times 10^{34} )</td>
</tr>
<tr>
<td>BX/train</td>
<td>4</td>
<td>2670</td>
<td>350</td>
<td>312</td>
</tr>
<tr>
<td>BX sep</td>
<td>247 ns</td>
<td>369 ns</td>
<td>0.5 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>50 kHz</td>
<td>5 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>( L/BX , [\text{cm}^{-2}] )</td>
<td>( 2.5 \times 10^{26} )</td>
<td>( 1.5 \times 10^{30} )</td>
<td>( 1.1 \times 10^{30} )</td>
<td>( 3.8 \times 10^{30} )</td>
</tr>
<tr>
<td>( \gamma \gamma \rightarrow X / BX )</td>
<td>neg.</td>
<td>0.2</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>( \sigma_x / \sigma_y )</td>
<td>240 / 4 mm</td>
<td>600 / 6 nm</td>
<td>200 / 2 nm</td>
<td>40 / 1 nm</td>
</tr>
</tbody>
</table>

**Note:** Integrated luminosity per BX ~ same for ILC and CLIC

- **Beam related background:**
  - Small beam profile at IP leads very high E-field;
    - beamsstrahlung
    - pair-background
    - Effects more significant at CLIC

- **Bunch train structure:**
  - **ILC:** BX separation 369 ns
  - **CLIC:** BX separation 0.5 ns

- **Two photon \( \rightarrow \) hadrons background, at CLIC:**
  - Approx three “visible” events per BX
  - Important since, sub-detectors will integrate over >1 BX (0.5 ns)
Sub-detectors: from ILC to CLIC
ILC Vertex detector

- ILD and SiD assume Silicon pixel based vertex detectors (5 or 6 layers)

**Main design considerations:**
- Inner radius: as close to beam pipe as possible for impact parameter resolution ~ 15 mm
- Layer thickness: as thin as possible to minimize multiple scattering

\[ \sigma_{r\phi} = 5 \oplus 10/(p \sin^2 \theta) \mu m \]

**Constraints:**
- Inner radius limited by pair background depends on machine + detector B-field
- Layer thickness depends on technology
- Time-stamping:
  - ILD assume integrate over ~50 \( \mu s \)
  - SiD assume single BX time-stamping (0.3 \( \mu s \))
    - how feasible
  - faster readout, implies power consumption, cooling → more material
Impact of pair background at CLIC

**CLIC Vertex Detector**

- Pair background is worse at CLIC
- Previously studied using full simulation at 3 TeV using ILD-like detector
- Conclusions depend on assumptions for detector integration times:
  - used 100 BX for ILC
  - full bunch train for CLIC

```
CLIC VTX: O(10) × more background
CLIC TPC: O(30) × more background
```

- For reasonable occupancy:
  - Inner radius of CLIC VTX detector
    ```
    31 mm
    ```
  - Still obtain good impact parameter resolution (depends on assumed point resolution)

- Pair background constrained by B-field, so does this argue for a higher B-field?
This question has been addressed by ILD study
But radius of pair background envelope scales roughly as $\sqrt{B}$

- Compare flavour tagging performance for different detector models
  - Differences of 2.5 mm in inner radius of beam pipe due to B field

**Conclude:**
- Differences are not large
- Smaller inner radius of vertex detector not a strong effect
- Earlier studies showed that going from 15 mm → 25 mm inner radius did not have a large impact on flavour tag

31 mm probably OK

Note: Vertex charge measurements more sensitive to $r_{INNER}$
Tracking at the ILC

Two options:
- ILD: Time Projection Chamber
- SiD: Silicon tracker (5 layers)

- Large number of samples
- Few very well measured points

★ Lol studies show that both result in:
  - Very high track reconstruction efficiency
  - Excellent momentum resolution: $\sigma_{1/p_T} \sim 2 \times 10^{-5}$ GeV$^{-1}$ (high p tracks)

What is the best option for CLIC?

- Robustness to background/Pattern recognition?
- Two track separation?
Background: TPC

★ For TPC, conservatively take drift velocity to be $4 \text{ cm } \mu\text{s}^{-1}$
★ Therefore fill TPC with 150 BXs of background shifted in $z$
★ Superimpose on fully-hadronic top-pair events at 500 GeV
★ Main issue “micro-curlsers”, low energy $e^+e^-$ from photon conversions
★ Removed using dedicated patrec software

150 BXs of pair background
★ Effective removal of large fraction of background hits

<table>
<thead>
<tr>
<th></th>
<th>Top (p_T&gt;1 GeV)</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw hits</td>
<td>~8,600</td>
<td>~265,000</td>
</tr>
<tr>
<td>After</td>
<td>~8,500</td>
<td>~3,000</td>
</tr>
</tbody>
</table>

★ By eye – clear that this should be no problem for PatRec
★ In practice, negligible impact on track reconstruction efficiency.
Tracking at CLIC

★ At this stage it is not clear which is the best option for CLIC

**TPC:**
- ✓ Excellent pattern recognition capabilities in dense track environment
- ✗ Integrates over all bunch-train: 312 BXs ~ 1cm drift

**Silicon:**
- ✓ May provide some time stamping capability
- ✗ Pattern recognition in dense CLIC track environment not proven  
  (SiD studies assumed single BX tagging)

★ Silicon Tracker is probably the safest option for now – but a TPC is certainly not ruled out

Needs a detailed study with full CLIC background/BX structure
Calorimetry at the ILC

★ ILD and SiD concepts designed for particle flow calorimetry, e.g. ILD*

ECAL:

- SiW sampling calorimeter
- Tungsten: $X_0/\lambda_{\text{had}} = 1/25, \ R_{\text{Mol.}} \sim 9\text{mm}$
  - Narrow EM showers
  - Longitudinal sep. of EM/had. showers
- Longitudinal segmentation: 30 layers
- Transverse segmentation: 5x5 mm² pixels

HCAL:

- Steel-Scintillator sampling calorimeter
- Longitudinal segmentation: 48 layers (6 interaction lengths)
- Transverse segmentation: 3x3 cm² scintillator tiles

Comments:

★ Technologically feasible (although not cheap)
★ Ongoing test beam studies (CALICE collaboration)

*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL
In a typical jet:
- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly $n$ and $K_L$)

Traditional calorimetric approach:
- Measure all components of jet energy in ECAL/HCAL!
- ~70% of energy measured in HCAL: $\sigma_E/E \approx 60%/\sqrt{E(\text{GeV})}$
- Intrinsically “poor” HCAL resolution limits jet energy resolution

Particle Flow Calorimetry paradigm:
- Charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20%/\sqrt{E(\text{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10% of jet energy from HCAL $\rightarrow$ much improved resolution
Particle Flow Algorithms

Reconstruction of a Particle Flow Calorimeter:
★ Avoid double counting of energy from same particle
★ Separate energy deposits from different particles
★ Performance depends on hardware + reconstruction software (Particle Flow Algorithm)

Level of mistakes, “confusion”, determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

★ Principle of Particle Flow Calorimetry now demonstrated; it can deliver at ILC energies

<table>
<thead>
<tr>
<th>$E_{\text{JET}}$</th>
<th>$\sigma_E/E$ ($\text{rms}_{90}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ILD</td>
</tr>
<tr>
<td>45 GeV</td>
<td>3.7 %</td>
</tr>
<tr>
<td>100 GeV</td>
<td>2.9 %</td>
</tr>
<tr>
<td>180 GeV</td>
<td>3.0 %</td>
</tr>
<tr>
<td>250 GeV</td>
<td>3.1 %</td>
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</tbody>
</table>

Goal < 3-4 %

★ ILD/PandoraPFA meets ILC goal for all relevant jet energies
★ SiD/IowaPFA getting close: difference = smaller detector + software
At a Multi-TeV collider, leakage of hadronic showers is a major issue.

HCAL in ILD ($6 \lambda_I$) and SiD ($4 \lambda_I$) concepts too thin to contain 1 TeV showers.

- Probably need $\sim 8 \lambda_I$ HCAL for CLIC energies
  - but needs to be inside Solenoid for PFA – cost/feasibility
    - e.g. for current ILD concept $\Rightarrow 7.4m$ diameter solenoid!
  - compact structures e.g. Replace steel with Tungsten as HCAL absorber?
  - partially instrumented solenoid?

In principle, can PFA deliver at CLIC energies?
W/Z Separation at CLIC

- **On-shell W/Z decay topology depends on energy:**
  - LEP
  - ILC
  - CLIC

- **A few comments:**
  - Particle multiplicity does not change
  - Boost means higher particle density
  - PFA could be better for "mono-jet" mass resolution

- **PandoraPFA + ILD** performance studied for:
  - 125 GeV Z
  - 250 GeV Z
  - 500 GeV Z
  - 1 TeV Z
Jet Energy Resolution

★ Is an ILD-sized detector suitable for CLIC?
★ Defined modified ILD⁺ model:
  ▪ $B = 4.0\, T$ (ILD = 3.5 T)
  ▪ $HCAL = 8\, \lambda_I$ (ILD = 6 $\lambda_I$)
★ Jet energy resolution

| $E_{JET}$   | $\sigma_E/E = \alpha/\sqrt{E_{jj}}$ | $|\cos\theta|<0.7$ | $\sigma_E/E_j$ |
|-------------|------------------------------------|---------------------|---------------|
| 45 GeV      | 25.2 %                             | 3.7 %               |               |
| 100 GeV     | 28.7 %                             | 2.9 %               |               |
| 180 GeV     | 37.5 %                             | 2.8 %               |               |
| 250 GeV     | 44.7 %                             | 2.8 %               |               |
| 375 GeV     | 71.7 %                             | 3.2 %               |               |
| 500 GeV     | 78.0 %                             | 3.5 %               |               |

★ Meet “LC jet energy resolution goal [~3.5%]” for 500 GeV ! jets
W/Z Separation

Studied W/Z separation using ILD+ MC

$e^+e^- \rightarrow WW \rightarrow u\bar{d}v\mu$

$e^+e^- \rightarrow ZZ \rightarrow d\bar{d}v\bar{v}$

- Clear separation at ILC-like energies
- CLIC-like energies: There is separation, although less clear

- Current PandoraPFA/ILD+ gives good W/Z separation for 0.5 TeV bosons
- Less clear for 1 TeV bosons – but PFA not optimized for CLIC energies

- (Perhaps surprisingly) PFlow calorimetry looks promising for CLIC
Assuming a high granularity PFlow detector for CLIC, there are some important design considerations e.g. B-field, ECAL inner radius.

Empirically find (PandoraPFA/ILD)

\[ \sigma_E = \frac{21}{\sqrt{E/\text{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{R}{1825} \right)^{-1.0} \left( \frac{B}{3.5} \right)^{-0.3} \left( \frac{E}{100} \right)^{+0.3} \% \]

\[ \text{Resolution} \uparrow \quad \text{Tracking} \uparrow \quad \text{Leakage} \uparrow \quad \text{Confusion} \uparrow \]

\[ \text{Confusion} \propto B^{-0.3} R^{-1} \quad (1/R \text{ dependence } \text{“feels right”}, \text{ geometrical factor !}) \]

Conclusions: Detector should be fairly large
Very high B-field is less important
The Alternative to PFlow

- Dual/Triple readout calorimetry
- Measure all components of hadronic shower
  - Measure EM component: Cerenkov light
  - Measure “slower” hadronic component: scintillation signal
  - Measure thermal neutron component: from timing (triple readout)
- Effectively, measure shower fluctuations
- In principle, can give very good resolution

Possible implementation:
- Totally active crystal calorimeter (ECAL + HCAL)
  - ECAL: ~100,000 5×5×5 cm³ crystals, e.g. BGO
  - HCAL: ~50,000 10×10×10 cm³ crystals
  - Readout: 500,000 Si photo-detectors
- GEANT4 simulations: 22%/$\sqrt{E}$
- It could be the “ultimate” calorimeter, but…
  - Feasible? Cost?
  - Scintillation signal slow (c.f 0.5 ns)
  - Needs significant R&D programme
The Importance of BX tagging
Two-photon → hadrons background

- **Preliminary** studies (Battaglia, Blaising, Quevillon) indicate significant two-photon background for 3 TeV CLIC operation
- Approx 40 particles per BX ($p_T > 0.15 \text{ GeV}$, $|\cos \theta| < 0.98$)
  - ~40 GeV visible energy per event
- e.g. Event display for 150 BXs (75 ns) in ILD-like detector

- Results need checking (preliminary)
- With 0.5 ns BX – will inevitably integrate over multiple BXs, how many?
- CLIC at 3 TeV may look rather different to the ILC environment
- In addition, there is also the pair background…
Reconstruction study with ILD (conservative assumptions) shows that at the ILC BX-tagging is not likely to be a significant issue.

At CLIC, physics performance likely to depend strongly on BX-tagging capability.

First studies (Battaglia, Blaising, Quevillon): suggest ~25 ns or better.

This is challenging... and places constraints on detector technologies.

This is an important issue which need careful study.
Summary/Conclusions

★ ILC detector concepts are now well studied
  ▪ meet the ILC goals
★ ILC concepts useful starting point for a possible CLIC detector
  ▪ particle flow calorimetry looks promising
★ Argument for very high B-field not that compelling
  ▪ 4 T probably sufficient – needs proper study
★ CLIC machine environment is much more challenging
  ▪ backgrounds (pairs/$\gamma\gamma\rightarrow$ hadrons)
  ▪ time structure – inevitably integrate over multiple BXs

★ Detailed simulation studies of background/impact on physics are essential
★ Need to understand the physics environment at CLIC
  ▪ detector requirements may be very different from ILC
Fin
Backup Slides
IF one assumes single BX tagging capability then background is not an issue

For ILD studies conservatively assume 30 µs / 125 µs integration times for VTX layers (0,1) and (2,3,4,5) respectively

Therefore VTX integrates over 83/333 BXs

Superimpose on fully-hadronic top-pair events at 500 GeV

200,000 background hits per event!

Also consider finite cluster size of background hits (~10 pixels)

Significantly increases occupancy
Combinatorics produce fake “ghost” tracks
In addition to some real electron/positron background tracks
Large combinatoric background challenges pattern recognition
From 83/333 BXs overlayed on $e^+e^- \rightarrow t\bar{t} \rightarrow 6$ jets:
reconstruct ~34 “ghost” tracks/event (~1/3 are genuine)
Rejected by requiring at least 1 SIT hit or >10 TPC associated hits

Left with ~0.5 GeV per event (mixture of real tracks/combinatorics)