Particle Flow Performance
At CLIC

Matthias Weber (CERN)
On behalf of the CLICdp collaboration
Compact Linear Collider

Proposed e⁺e⁻ linear collider
- Two beam acceleration scheme
- High acceleration gradient (100 MV/m)
- Staged construction up to 3 TeV
  - Higgs and top precision physics
  - BSM searches

<table>
<thead>
<tr>
<th>Stage</th>
<th>√s [TeV]</th>
<th>$\mathcal{L}_{\text{int}} [\text{ab}^{-1}]$</th>
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Overview talk by Aidan Robson
postCDR detector model CLICdet, introduced in **CLICdp-Note-2017-001**

- 4 T solenoid outside of calorimetry
- Low mass all silicon tracking system
- 40 layer SiW ECAL → 22 $X_0$
- 60 layer Steel-SiPM Hcal → 7.5 $\lambda$
- RPCs for muon ID in Fe Yoke
- Very forward sampling electromagnetic calorimeters

→ detector optimised for particle flow
Physics Performance:

- Tracking in single particle events and more complex events e.g. $t\bar{t}$ → talk by Emilia Leogrande
- Flavour Tagging
- Particle Flow identification in single particle events
- Jet and missing transverse energy performance, di-jet mass separation
- Very forward reconstruction of electrons and photons
Very small bunch size at IP:
Very strong electromagnetic field from opposite beam $\rightarrow$ Beamstrahlung
Main background in calorimeters and from $\gamma\gamma \rightarrow$ hadrons

$p_T$ and timing cuts on PFOs
Particle Flow
PandoraPFA algorithm

1. Multiple tracks associated to single cluster – split cluster.
2. Cluster energy much greater than track momentum – split cluster.

- Exploit calorimeter granularity to gradually build up picture of events
- More than 70 algorithms
  → address different topologies,
  → correct identification
  → avoid accidental splitting and merging of particles

NIM A 700 (2013) 153
Software Compensation (SWC)
Neutral Hadrons and Software Compensation

Response of electromagnetic component in hadron showers on average larger than for hadronic component → treating all hits in HCAL the same way leads to a less accurate energy measurement

Follow description of Software Compensation paper EPJC 77 (2017) 698

Electromagnetic component of shower typically denser:
Software compensation at CLIC reweights hits in HCAL depending on the hit energy density, assuming these originate from electromagnetic component
→ assume monotonic falling weight with energy density
→ Weight includes an energy dependence
→ Software compensation reweighting integrated into PandoraPFA software
Software compensation weights derived from MC using neutron and $K^0_L$ events

- Mean and resolution after software compensation largely improved
- Software compensation corrects for nonlinear response of hadrons on the fly
Software Compensation in HCal

Tune using mono-energetic single $K^0_L$ and neutron events produced flat in polar angle $\cos \theta \rightarrow$ improvement of energy response and energy resolution
Both for events with and without beam-induced background, relative improvement of jet energy resolution of about 10 % in barrel, and 7.5-3 % in endcap
Flavour tagging
c and b tagging results

b and c tagging performed using LCFIPlus flavor tagging package: 250 GeV jets

- **b-tagging**: with 3 TeV beam BG at 80 % eff.: 13% missID for c and 2% light-flavor BG
- **c-tagging**: with 3 TeV beam BG at 80 % eff.: 30% missID for b and light-flavor BG

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**b-tag**

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<th>CLICdp</th>
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**c-tag**

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Di-jet events, $E_{cm} = 500$ GeV, $20^\circ < \theta < 90^\circ$
Jet Performance
Jet Performance Studies

compare quantities of reconstructed jets with quantities of MC truth jets clustering stable particles

• Ignore neutrinos for MC particle jets
• Reconstructed jets use particle flow objects as input
  • PandoraPFOs in events without background
  • TightSelectedPandoraPFOs in events with 3 TeV $\gamma\gamma \rightarrow$ hadrons background
  • LooseSelectedPandoraPFOs for 380 GeV $\gamma\gamma \rightarrow$ hadrons
• Studied in Z/$\gamma^* \rightarrow$ qq events, with q=u,d,s
• Jet algorithm: VLC algorithm, $\gamma=\beta=1.0$, radius R=0.7, exclusive jet clustering of event in exactly two jets

• Study resolutions of reconstructed jets angularly matched to particle level jets within 10°
Jet energy: particle level vs detector level

PandoraPFOs calibrated, no further calibration on jet energy
Check if $\gamma \gamma \rightarrow$ hadrons background has large impact on energy collected in jet

Angular matching requirement between detector level recojet and particle level genjet within $10^\circ$ $\rightarrow$ raw jet energy response close to unity for both cases, no large impact of background within jet cone
Jet Energy Resolution vs $\cos \theta$: with and without BG

Compare resolution of reconstructed jets $\Rightarrow$ 3 TeV conditions for overlay
$\Rightarrow$ for 50 GeV jets increase from 4.5/5 % to 7 % in barrel
$\Rightarrow$ for 100 GeV jets increase from 4 % from 5% in barrel, 6.5 % in endcap
At high jet energies mild increase, except for very forward jets
JER vs $\cos\theta$: 380 and 3 TeV BG

Compare background levels from $\gamma\gamma \rightarrow $ hadrons of the 380 GeV machine to the 3 TeV machine

- Moderate increase in jet energy resolution for barrel jets even for 50 GeV jets, of additional 0.5 %, at 3 TeV machine increase from 5 $\rightarrow$ 7 %
- Almost no effect of background for barrel jets for energies $>100$ GeV
Theta/Phi resolutions below 1/1.5 degree for most detector regions for all jet energies, for forward region phi resolutions a bit larger for low energetic jets.
MET Resolution
Missing $E_T$ (MET) Resolution

Study two cases:
Events with fake MET: $Z/\gamma^*\rightarrow qq$ (with $q=u,d,s$) at 3 TeV, investigate 3 TeV $\gamma\gamma\rightarrow$ hadron backgrounds

Events with genuine MET: semi- and di-leptonically ttbar events at 3 TeV, check background from $\gamma\gamma\rightarrow$ hadrons at 3 TeV

True missing transverse momentum from neutrinos in semi- & dileptonic ttbar $\rightarrow$ peaks around 100-250 GeV
**MET Resolution**

\[ Z^{\gamma^{*}} \rightarrow qq,uds,3 \text{ TeV} \]

- using PFO selection cuts clearly improves resolution, tight selection cuts perform best

\[ \text{MET} \text{ spectrum above 100 GeV, clearly improves with selection cuts, restrict range of tops to avoid a bias due to jets outside of detector acceptance} \]
W and Z mass separation
W and Z di-jet mass with beam-induced background

Study di-jet mass reconstruction in WW\(\rightarrow qq\ l\nu\) and ZZ\(\rightarrow qq\ \nu\nu\) events
Dijet mass peak separation quantified using the overlap fraction \(A_O\) and the corresponding selection efficiency \(\varepsilon (=1-A_O)\), defined by the gaussian fits (Integral normalised to 1)

\[
A_O = \left( \int_{-500}^{X_{int}} \text{gauss}Z(x)dx + \int_{X_{int}}^{500} \text{gauss}W(x)dx \right) / 2
\]

With BG

No BG

CEPC EU workshop 2019, Tools and Performance, April 16, 2019
Matthias Weber
CERN
### W and Z mass separation results

<table>
<thead>
<tr>
<th>Background</th>
<th>$E_{W,Z}$ [GeV]</th>
<th>$\sigma_{m(W)}/m(W)$ [%]</th>
<th>$\sigma_{m(Z)}/m(Z)$ [%]</th>
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<td>380 GeV BG</td>
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<td>87</td>
<td>2.2</td>
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Without background overlap fraction between 10-16 %

Increase of overlap fraction to 15-20 % due to beam background effects (13% for 380 GeV backgrounds)
Conclusion

- Performance of post CDR detector model CLICdet studied in detail using full simulation
- Pandora particle flow algorithms used in reconstruction
- Software Compensation in HCal improves relative jet energy resolution by about 10 % in Barrel, 3-5 % in EndCap
- Jet energy resolution around 3-5% for all energies and all detector regions, up to 10 % for very forward jets
- $p_T$ and timing cuts on PFOs largely recover performance of missing transverse energy
- Achieve a W-Z dijet mass separation of 1.7-2.0 $\sigma$ when including beam backgrounds
BACKUP
Single Particle Performance
Photon and Kaon Energy Resolution

Photon energy resolution between 0.5-3% from 30 to 1500 GeV

Kaon energy resolution between 5.5 and 18% starting around 20 GeV

→ energy resolution distribution fitted with a Gaussian
Electron Efficiencies in $t\bar{t}$ @ 3 TeV

Electron efficiency vs electron energy

$\rightarrow$ With background around 85-90% starting at 25 GeV, 3-5% difference to efficiency without background

Electron energy 30-75 GeV

Electron efficiency vs Theta

$\rightarrow$ With background around 80% in endcaps, around 90% in barrel
Muon Efficiencies in $t\bar{t}$ @ 3 TeV

Electron efficiency vs electron energy

$\rightarrow$ With background beyond 98%
starting at 5 GeV, less than 0.5 % effect of background

Muon energy 30-75 GeV
Muon efficiency vs Theta pretty flat around 98-99%
Pion Efficiencies

Inefficiency at large energies in most central part of the detector

90-98% from 1-1000 GeV
Photon Efficiencies

Over 98 % for unconverted photons

Unconverted photons (15 % of all photons):
If photon clusters merged, then efficiencies beyond 95 % above 100 GeV, around 60 % for 25 GeV
using PFO selection cuts clearly improves resolution, tight selection cuts perform best, full MET spectrum

Angular resolution of MET vector, with selection cuts within 10 degrees of true vector above 150 GeV
Technical details

CLICdet model: CLIC-o3_v14

Tracking reconstruction: ConformalTracking

Software release: iLCSoft-18-10-11_gcc64

Software Compensation applied on HCAL clusters
LumiCal and BeamCal
BeamCal Performance

Efficiency and fake rate in mono-energetic single electron events:
Overlay of incoherent pair background (40 BX), angular and energy matching between generated electron and reconstructed cluster

Energy resolution around 10% for whole energy range, fake rate below $10^{-4}$ for all electron energies studied
Flat $\theta$ resolution of 0.2 mrad for energies over 400 GeV (3 TeV BG)
Efficiency and fake rate in mono-energetic single electron events: Overlay of Incoherent pair background (40 BX), angular and energy matching between generated electron and reconstructed cluster

Energy resolution around 8% for low energies, decreasing to 2% for high energy electrons, fake rate below 1% for all electron energies studied

θ resolution of 20 µrad at 1.5 TeV
Track Reconstruction
Conformal tracking

Coordinate transformation from xy plane (perpendicular to the beam) to u-v coordinate system:

\[ u = \frac{x}{x^2 + y^2} \quad \quad v = \frac{y}{x^2 + y^2} \]

Perform straight line search in this 2D space:
Prompt single particle tracks: study of resolution ($p_T$, $d_0$, $z_0$, $\theta$, $\varphi$)

Tracking efficiencies
Complex events: impact of background

Di-jet events at various jet energies, study impact of beam-induced backgrounds from $\gamma\gamma \rightarrow$ hadrons for 380 GeV and 3 TeV CLIC

Even with 3 TeV background levels efficiency above $p_T > 1$ GeV about 100%,
ttbar events

Displaced tracks
Tracking efficiency vs production vertex R

In 3 TeV background conditions around 60 % tracking efficiency for production radii up to 200 mm

Fake rate vs $p_T$
Below 4 % for all $p_T$, below 1 % above 1 GeV \( \rightarrow \) ongoing effort to reduce fake rate
Flavour tagging
c and b tagging results

b and c tagging performed using LCFIPlus flavor tagging package: 250 GeV jets

b-tagging: with 3 TeV beam BG at 80 % eff.: 13% missID for c and 2% light-flavor BG

c-tagging: with 3 TeV beam BG at 80 % eff.: 30% missID for b and light-flavor BG
c and b tagging: vertex single point resolution

Nominal parameter: 3 µm position resolution in vertex

At 80% b and c tagging efficiency miss-identification rate increases with worse single point resolution, by about 20% (40%) with 5 µm (7 µm) position resolutions in vertex.
c and b tagging: conformal vs truth tracking

True MC pattern recognition (truth tracking) as best possible tracking algorithm

Track reconstruction improvements in conformal tracking could lead to significantly improved mis-identification numbers → ongoing effort
Track reconstruction improvements in conformal tracking can lead to significantly improved mis-identification numbers.
Fit jet energy response by double sided Crystal Ball function, use sigma of the Gaussian core as measure for jet energy resolution.
For most energies resolution values of fit close to the RMS90 resolution measure, for high energies within 10-15%
Datasets WW→νμ qq and ZZ→νν qq, where q is a light quark
Veto for WW events where W is offshell, decaying into tb with t decaying leptonically, for Z keep offshell Z→νν (Z→qq always on shell)

• On MC truth: cluster all stable visible particles (status=1, excluding neutrinos), exclude lepton from W (and lepton daughters, e.g. FSR photons)

• On reconstructed level: use all pandora PFOs in events without background, use tightSelected PandoraPFOs when running on events with γγ→hadrons overlayed, remove PFOs around an angle of 25.8° (acos 0.9) of the isolated lepton from W’s → with very high rate this removes reconstructed muons and FSR photons and very soft “additional” neutral hadrons

• Jet Algorithm: VLC Algorithm, R=0.7, β=γ=1.0, exclusive mode with 2 jets, cross-check with k_t algorithm, R=0.7 leads to very similar mass distributions

• W and Z mass calculated from dijet distributions
W and Z overlap fraction

Overlap fraction $A_O$:

$$A_O = \frac{\int_{-500}^{500} gaussZ(x) \, dx + \int_{x_{int}} gaussW(x) \, dx}{2}$$

Efficiency: integral above/below intersection mass point divided by integral over the whole dijet mass range $\rightarrow$ average efficiency $E=1-A_O$

Ideal gaussian separation quantified by $2|\text{ROOT::Math::normal_quantile}(A_O,1)|$

Same result for separation with different approach (seems more intuitive)

$$\sigma = (Z_{mass} - W_{mass})/\sigma_{avg} \text{ with } \sigma_{avg} = (\sigma_Z + \sigma_W)/2 \text{ the averaged } \sigma \text{ of the rescaled Gaussian fits on the reconstructed } Z \text{ and } W \text{ dijet mass peaks for the different energies}$$