PFA Reconstruction at the CEPC

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On behavior of the CEPC Study Group
Science at CEPC-SPPC

- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: 1M Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: 10B Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...

- **Heavy ion, e-p collision...**

*Complementary*
CEPC High Granularity Calorimeter Studies

**Hardware**
- ECAL: USTC (Electronics) + IHEP (SiPM) + LLR
  - USTC: University of Science & Technology
  - IHEP: Institute of High Energy Physics
  - SJTU: Shanghai JiaoTong University
- HCAL: USTC+UCAS (GEM) IHEP (Scintillator) SJTU (RPC)

**Software**
- PFA: IHEP + LLR + IPNL
- Geometry Optimization: IHEP + SJTU

USTC: University of Science & Technology
SJTU: Shanghai JiaoTong University
IHEP: Institute of High Energy Physics

Each institute has 2-3 FTEs, + Students...
Arbor Reconstruction

Performance at
Lepton
Kaon
Photon
Tau
JET
Reference concept for CEPC CDR

PFA Oriented Design (Reference: ALEPH, SiD & ILD). TPC + Si-W ECAL + GRPC HCAL

Geometry optimized at Physics benchmarks
Smaller B Field (3.5 → 3T), Thinner HCAL (48 → 40 Layers), ECAL based ToF (50 ps), MDI/Yoke System, etc.
Lepton

BDT method using 4 classes of 24 input discrimination variables.

Test performance at: Electron = E\_likeness > 0.5 ; Muon = Mu\_likeness > 0.5

Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5
Kaon

Highly appreciated in flavor physics @ CEPC Z pole
TPC dEdx + ToF of 50 ps
At inclusive Z pole sample:
  Conservative estimation gives efficiency/purity of 90%/90% (2-20 GeV)
  Could be improved to 99%/99% by using optimized detector geometry & Improved
  DAQ performance
Inhomogeneity degrades the resolution significantly.
Physics requirement: constant term < 1%
Detector geometry defects degrades the mass resolution to **2.2%** (after correction);
Two catalogues:

- Leptonic environments: i.e, $ll\tau\tau(ZZ/ZH)$, $\nu\nu\tau\tau(ZZ/ZH/WW)$, $Z\rightarrow\tau\tau$;
- Jet environments: i.e, $ZZ/ZH\rightarrow q\tau\tau$, $WW\rightarrow q\nu\tau$;
**g(HTτ) measurement: preliminary**

- ZH→μμττ
- Extremely Efficient Event Selection
- Signal efficiency of 93% - entire SM background reduced by 5 orders of magnitude

\[ \delta \mu/\mu \sim 2.7\% \]

- ZH→qqττ
- Cone based tau finding algorithm, Compromise the efficiency & purity
- Signal efficiency of 51%

\[ \delta \mu/\mu \sim 1.7\% \]

*VTX system, and the understanding of background, is also crucial for this measurement*
Jets

- Boson Mass Resolution: Separate W, Z and Higgs in hadronic decay mode
  - Essential for Higgs measurement
    - Separate Higgs from Z/W (relatively easy)
    - Separate H→ZZ/WW events (challenging)
  - Appreciated in Triplet Gauge Boson Coupling measurements
    - Separate WW (Signal) from ZZ, ISR return Z, etc.
  - ...

- Jet Clustering & Single jet response
  - To understand the Degrading induced by Jet Clustering, Matching, etc
  - Search for the most suited jet clustering algorithm (Presumably channel dependent)
  - ...

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Boson Mass Spectrum

- 2-jets Samples (the majority of events with jets at Higgs operation)
  - Higgs: vvH
  - Z: vvqq and ISR return events
  - W: lvqq events
- Physics effects
  - Intrinsic Width (Z: 2.5 GeV, W: 2 GeV)
  - Neutrinos, especially those induced by heavy flavors
  - ISR photons
  - Interferences*
- Detector effects
  - Acceptance
  - Geometry defects
  - Polar angle dependence

Figure 4: The diagrams for the four fermions processes
Inclusive sample

Light jet sample

Light jet + visible ISR veto
Separation

PDF Normalized to unit Area.
Left: Inclusive Samples
Right: Light flavor Sample with Visible ISR Photon Veto
Jets

- Test on vvqq sample with ee-AntiKt algorithms
- Same Jet Clustering Set up applied for MCParticles & Reconstructed Particles
- Matching algorithm based on Min. Angle is applied
Impact of Jet Clustering: Significant

Jet Clustering is Mainly responsible for the tails

Leading jets

Parton: Quark & Gluons

GenJet: Visible Final State Particles

Sub-Leading jets

Recon Jets: From Recon Particles

Jet Clustering is Mainly responsible for the tails

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Amplitude ~ 1%
Large JES observed at Leading Jet (Correlated), and at overlap region (Increasing of Splitting)
Jet Energy Resolution

CMS Reference: CMS-JME-13-004,
Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV
PFA Oriented Reconstruction

Example Working Points & Performance for Object identification (Preliminary)

<table>
<thead>
<tr>
<th>Object</th>
<th>Efficiency</th>
<th>Purity</th>
<th>Mis-Id Probability from Main Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>99.5 – 99.9%</td>
<td>99.5 – 99.9% at Higgs Runs (c.m.s = 240 GeV), Energy dependent</td>
<td>P(π⁺⁻ → leptons) &lt; 1%</td>
</tr>
<tr>
<td>Photons*</td>
<td>99.3 – 99.9%</td>
<td>99.5 – 99.9% at Higgs Runs Energy Dependent</td>
<td>P(Neutron → γ) = 1 - 5%</td>
</tr>
<tr>
<td>Charged Kaons**</td>
<td>86 – 99%</td>
<td>90 – 99% at Z pole Runs (c.m.s = 91.2GeV, Track Momentum 2 - 20 GeV)</td>
<td>P(π⁺⁻ → K⁺⁻) = 0.3 – 1.1%</td>
</tr>
<tr>
<td>b-jets</td>
<td>80%</td>
<td>90% at Z pole runs (Z → qq)</td>
<td>P(uds → b) = 1%</td>
</tr>
<tr>
<td>c-jets</td>
<td>60%</td>
<td>60% at Z pole runs</td>
<td>P(uds → c) = 5%</td>
</tr>
</tbody>
</table>

Photon*: only considering neutron background and using ToF information
Kaon**: Performance Highly depend on DAQ & Geometry
Conclusion

- The PFA oriented detector & reconstruction: well established at the CEPC
- Reference detector + Arbor
  - High efficiency & purity for Lepton, Kaon, Photon reconstruction
  - Well established Higgs Signal in Physics benchmarks
  - The Jet energy resolution
    - 2-jets events: efficiently separate W, Z & Higgs: appreciated in TGC & Higgs properties measurements
    - Jet level: |JES| < 1%, JER ~ 3-6%
  - Jet Clustering has significant impact and need to be handled with care
    - To do: detailed study on the 4 jets events (ZH, ZZ, WW)
- Requirement to the Calorimeter
  - High Granularity + Low Power Consumption + High Homogeneity
Backup
$e^+e^- \rightarrow ZZ \rightarrow \nu \nu q\overline{q}$

CEPC Preliminary

$\sqrt{s} = 250$ GeV

Left:
Subleading $\Delta E_{\text{Gen-MCP}}$
Leading $\Delta E_{\text{Gen-MCP}}$

Right:
Subleading $\Delta E_{\text{Reco-Gen}}$
Leading $\Delta E_{\text{Reco-Gen}}$
Z->ff, Energy of Z
(SumE of di-fermion)

Single ISR along Z -> E(Z) = 141.6GeV

Peak at 125GeV: gamma gamma(II) event
Z->ff, Energy of Z
(SumE of di-fermion)
## Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CEPC_v1 (~ ILD)</th>
<th>Optimized (Preliminary)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Radius</td>
<td>1.8 m</td>
<td>&gt;= 1.8 m</td>
<td>Requested by Br(H-&gt;μμ) measurement</td>
</tr>
<tr>
<td>B Field</td>
<td>3.5 T</td>
<td>3 T</td>
<td>Requested by MDI</td>
</tr>
<tr>
<td>ToF</td>
<td>-</td>
<td>50 ps</td>
<td>Requested by pi-Kaon separation at Z pole</td>
</tr>
<tr>
<td>ECAL Thickness</td>
<td>84 mm</td>
<td>84(90) mm</td>
<td>84 mm is optimized on Br(H-&gt;γγ) at 250 GeV; 90mm for bhabha event at 350 GeV</td>
</tr>
<tr>
<td>ECAL Cell Size</td>
<td>5 mm</td>
<td>10 – 20 mm</td>
<td>Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation</td>
</tr>
<tr>
<td>ECAL NLayer</td>
<td>30</td>
<td>20 – 30</td>
<td>Depends on the Silicon Sensor thickness</td>
</tr>
<tr>
<td>HCAL Thickness</td>
<td>1.3 m</td>
<td>1 m</td>
<td>-</td>
</tr>
<tr>
<td>HCAL NLayer</td>
<td>48</td>
<td>40</td>
<td>Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV.</td>
</tr>
</tbody>
</table>
Br(H→WW)

H→WW/ZZ: Portal to Higgs width & perfect test bed for detector/reconstruction performance...

- Br(H→WW), Combined accuracy ~ 1.0% from 13 independent full simulation analyses
  - 1.45% at llH, H→WW*→inc channels, 12 independent channels.
  - ~ 1.7% at vvH, H→WW*→4q channel (Preliminary. ILC extrapolation = 2.3%)
  - 2.3% at qqH, H→WW*→2qlv channel (extrapolated from ILC full simulation)
  - Combined: 1.0%

High efficiency in event reconstruction
Validation: Arbor Branch Length

Arbor: successfully tag sub-shower structure

Samples: Particle gun event at ILD HCAL (readout granularity $1cm^2$ & layer thickness $2.65cm$)

Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighbor hits

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Requirements at the CEPC: Reconstruct all the physics objects (Lepton, Photon, Kaon, Tau, Jet, MET) efficiently & precisely.