The CEPC Simulation and tools: Software & Performance

Manqi Ruan
Performance

• Determined by
  - Detector design
  - Reconstruction algorithm

• Characterized at
  - Physics Objects
  - Higgs Signal
  - Benchmark Physics Analyses
Two classes of Concepts

- **PFA Oriented concept using High Granularity Calorimeter**
  - + TPC (ILD-like, **Baseline**)
  - + Silicon tracking (SiD-like)

- **Low Magnet Field Detector Concept (IDEA)**
  - Wire Chamber + Dual Readout Calorimeter

https://indico.ihep.ac.cn/event/6618/
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=14816
CEPC Baseline Software

Physics Models
- Whizard
- Pythia Fragmentation
- MokkaPlus G4 Simulation

Parton
- MCParticle
- Fast Simulation
- Reconstructed Particle
- Arbor (Core PFA)
- Tracks & calorimeter hits
- Tracking
- High-level Reconstruction
- Analysis
- Physics Parameters
- Physics Object

Data format & management (LCIO & Marlin)

Generators (Whizard & Pythia)

Simulation (MokkaC)

Digitizations

Tracking

PFA (Arbor)

Single Particle Physics Objects Finder (LICH)

Composed object finder (Coral)

 Tau finder

Jet Clustering (FastJet)

Jet Flavor Tagging (LCFIPLus)

Event Display (Druid)

General Analysis Framework (FSClasser)

Fast Simulation (Delphes + FSClasser)

General Software

ILCSoft

ILCSoft + Development

Developments

Status of simulation-performance study

<table>
<thead>
<tr>
<th></th>
<th>Geant4-Simulation</th>
<th>Digitization</th>
<th>Reconstruction</th>
<th>Performance-Object</th>
<th>Performance-Benchmark</th>
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<td>IDEA</td>
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</table>
Performance at
Lepton
Kaon
Photon
Tau
JET
...

Arbor

Physics Objects


10/01/19  

FCC WS@CERN
Applied on Higgs physics, et.al

Precision Higgs Physics at CEPC

Initial assessments of Higgs physics potential at the CEPC based on the white paper (to be submitted)
Pheno-studies: EFT & Physics reach

The Physics reach could be largely enhanced if the EW measurements is combined With the Higgs measurements (in the EFT)

G. Durieux, C. Grojean, J. Gu & K. Wang
Pheno-studies: High order corrections

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>LO (fb)</th>
<th>NLO Weak (fb)</th>
<th>NNLO mixed electroweak-QCD (fb)</th>
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<tr>
<td></td>
<td>σ(0)</td>
<td>σ(α)</td>
<td>σ(0) + σ(α)</td>
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<td></td>
<td>σ(ααs)</td>
<td>σ(ααs)</td>
<td>σ(ααs)</td>
</tr>
<tr>
<td></td>
<td>σ(0)</td>
<td>σ(α)</td>
<td>σ(0) + σ(α) + σ(ααs)</td>
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<tr>
<td>240</td>
<td>Total</td>
<td>223.14</td>
<td>6.64</td>
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<tr>
<td></td>
<td>L</td>
<td>88.67</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>134.46</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>223.12</td>
<td>6.08</td>
</tr>
<tr>
<td>250</td>
<td>L</td>
<td>94.30</td>
<td>3.31</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>128.82</td>
<td>2.77</td>
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</table>

- Correction at 1% level with NNLO calculation.

- Lots of efforts needed to correctly interpret the measurements at CEPC

Q. Sun, et al

10/01/19
FCC WS@CERN
Tracking

Per mille level momentum resolution -> per mille level mass resolution for H→mumu

Mingrui Zhao. CEPC CDR

CEPC-RECO-2018-003
Reconstruction of Ks(\Lambda) at Z pole (Preliminary)

<table>
<thead>
<tr>
<th>wi/wo perfect PID</th>
<th>Efficiency</th>
<th>Purity</th>
<th>Resolution</th>
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<tr>
<td>K_short</td>
<td>79%/78%</td>
<td>91%/86%</td>
<td>0.28%/0.29%</td>
</tr>
<tr>
<td>Lambda</td>
<td>82%/68%</td>
<td>94%/64%</td>
<td>0.043%/0.046%</td>
</tr>
</tbody>
</table>

Efficiency = Correctly reconstructed Ks(\Lambda)/Ks(\Lambda) with 2 tracks reconstructed
Purity = Correctly reconstructed Ks(\Lambda)/All reconstructed Ks(\Lambda)

Perfect PID = Perfect identification of pions, charged kaons, and (anti-)protons
Photons – conversion & efficiency

In the barrel region: Roughly 6-10% of the photons converts before reaching the Calorimeter.

For the unconverted photon: A critical energy of 200 MeV is observed.
Photon: resolution

- A Higgs mass resolution of 1.7/2.5% is achieved in the Higgs to di-photon final states with simplified/baseline geometry.
- The geometry defects correction could be efficiently corrected (Preliminary).

Yuqiao Shen & CEPC CDR
Clustering - Separation

Critical energy to separate an evenly decay $\pi_0$: 30 GeV

*Hang Zhao. CEPC CDR*
Tau finding at hadronic events

TAURUS (Tau ReconstrUction toolS): an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

Zhigang Wu, CEPC CDR
Jets – color singlet

• Boson Mass Resolution: Total reconstructed mass of hadronic events
  - 3.8% at baseline (benchmarked with vvH, H→gluons process)
  - Applied to event with one color singlet fragments into jets
    • W, Z, H signal separation at lvqq, ll(vv)+qq events (Appreciated in Triplet Gauge Boson Coupling measurements)
    • Analysis of qqH, Higgs decays into non-jet final states, for example, qqH, H→taus, inv, photons, muons...
  • ...

• Single Jet Response (Jet energy scale/resolution)
  - Differential measurements with jet directions
  - Applied to events with more than one color singlet fragment into jets
    • WW/ZZ/ZH event separation in 4-jet final state
    • ...

Massive Boson Separation

WW sample: using $\mu\nu qq$ sample, Plot: the visible mass without the muon

Peizhu Lai & CEPC CDR

CEPC Preliminary

CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),

An Analysis Example: $g(H\tau\tau)$ at qqH

- TAURUS: di-tau system
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: BMR < 4% (baseline of 3.8%) is crucial
- Isolated tracks are intentionally defined as tau candidate: be distinguished by the VTX

Dan Yu's thesis
Jet Energy Scale & Resolution

- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- Both Superior to LHC experiments by 3-4 times
Separation of full hadronic WW-ZZ event

- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response
Jet confusion: the leading term

- Separation be characterized by
- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2
- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - + Jet confusion – Genjet: Overlapping ratio of 53%
  - + Detector response – Recojet: Overlapping ratio of 58%

\[ \chi^2 = \frac{(M_{12} - M_B)^2 + (M_{34} - M_B)^2}{\sigma_B^2} \]

overlapping ratio = \( \sum_{\text{bins}} \min(a_i, b_i) \)
Reconstructed mass of the two di-jet system

Equal mass condition $|M_{12} - M_{34}| < 10$ GeV: At the cost of half the statistic, the overlapping ratio can be reduced from 58%/53% to 40%/27% for the Reco/Genjet
Separation of full hadronic WW-77 event

The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state. Critical to develop color singlet reconstruction: improve from the naive Jet clustering & pairing. 

Quantified by differential overlapping ratio.

Control of ISR photon/neutrinos from heavy flavor jet is important.

https://arxiv.org/abs/1812.09478
Summary

• CEPC, a super Higgs/W/Z factory, requires high efficiency, purity, and precision reconstruction of all key physics objects
  - Tracker & Calorimeter intrinsic resolution: better is better!
  - BMR < 4% is crucial: di-jet recoil mass at qqH events

• Performance of the CEPC baseline fulfills the physics requirements
  - All key physics objects tamed
    • Tracks, Clusters
    • Charged Particle & identification
    • Leptons, photons
    • Composited objects
      - Ks/Λ
      - Tau
      - Jets: WW-ZZ separation
  - Clear Higgs signature in all SM Higgs decay modes
  - 0.1% – 1% relative error in Higgs coupling measurements
Summary

- To do
  - Generator: understand the current theoretical error & roadmap to its control
  - Simulation: novel framework that supports parallel computing
  - **Reconstruction – Optimization:**
    - Enhance the engagement-iteration with the detector design
    - Jet, *vertex*-jet flavor, gluon jet, and *color singlet*
    - Machine learning...
  - Analysis:
    - Iterates with physics reach study
    - Data driven method for systematic control...
- Wishlist & Perspective for future collaboration
  - Common software: simulation framework and reconstruction algorithm/toolkits
  - Common samples: start from generator samples
  - Common toolkits/repositories to other tech. Challenges: integration, cooling, etc
Many Thanks to

See also:

Xianghu Zhao & Mingrui Zhao's talks on Software/production
Taifan Zhen's talk on Ks & Λ reconstruction
Hao Liang & Fenfen An's talks on Higgs/Flavor benchmark analysis
YueXin Wang's Poster on Alternative Calorimeter study
backup
**Leptons**

**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%

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 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)
Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

Jet Energy Resolution

Amplitude ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
Depends on the Flavor, direction and jet energy
Superior to LHC experiments by 3-4 times
Flavor Tagging

- Using LCFIPlus Package from ilcsoft
- At Higgs->2 jet samples:
  - Clear separation between different decay modes
- Typical Performance at Z pole sample:
  - B-tagging: eff/purity = 80%/90%
  - C-tagging: eff/purity = 60%/60%
An ILD-like detector at the CEPC

- Different collision environments/rates:
  - MDI design & Implementation: CEPC-SIMU-2017-001

- The CEPC Event rate is significantly higher than linear colliders, charged kaon id can strongly enhance the CEPC flavor physics program
  - TPC Feasibility: JINST-12-P07005 (2017)

- No power pulsing at CEPC detector
  - A significant reduction of the readout channel, especially the Calorimeter Granularity: JINST-13-P03010 (2018)
  - HCAL Optimization

- 3 Tesla Solenoid: requested by the Accelerator/MDI
APODIS Geometry
Missing Energy & Momentum

Width of the Light jets: 6GeV/8GeV (Left/Right Plots)
Physics Objects: Tamed

PHOTON

LEPTON

KAON

TAU

BMR

JER

JET FLAVOR

Higgs mass/GeV
Higgs Signal at APODIS

240 GeV
$\nu\nu$Higgs, Higgs $\rightarrow \mu\mu$
Mean 125
Sigma 0.240

Lepton tracks & Photon Clusters
Higgs to bb, cc, gg (Jets)

- Higgs → bb:
  - 240 GeV
  - Mean: 125 ± 0.042
  - Sigma: 4.508 ± 0.037
  - 3.6%

- Higgs → cc:
  - 240 GeV
  - Mean: 125 ± 0.034
  - Sigma: 4.796 ± 0.032
  - 3.8%

- Higgs → di-gluon:
  - 240 GeV
  - Mean: 125 ± 0.029
  - Sigma: 4.696 ± 0.025
  - 3.8%
Higgs to WW, ZZ (Jets + leptons + neutrinos)

Table 2. Benchmark resolutions ($\sigma$/Mean) of reconstructed Higgs boson mass, comparing to LHC results.

<table>
<thead>
<tr>
<th></th>
<th>$\text{Higgs} \to \mu\mu$</th>
<th>$\text{Higgs} \to \gamma\gamma, \gamma\gamma$</th>
<th>$\text{Higgs} \to bb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC (AODIS)</td>
<td>0.20%</td>
<td>2.59%$^1$</td>
<td>3.63%</td>
</tr>
<tr>
<td>LHC (CMS, ATLAS)</td>
<td>~2% [19, 20]</td>
<td>~1.5% [21, 22]</td>
<td>~10% [23, 24]</td>
</tr>
</tbody>
</table>

$^1$ primary result without geometry based correction and fine-tuned calibration. [https://arxiv.org/abs/1806.04992](https://arxiv.org/abs/1806.04992)
Particle tagging

Jet clustering

Particle Isolation

$\text{MET} = - \sum_i E_{T,i}$

PFA oriented Detector & Reconstruction
Higgs benchmark analyses

$\sigma(\mathcal{H})$ measurements

$\text{Br}(H \rightarrow \mu\mu)$

$\text{Br}(H \rightarrow WW)$

$\sigma(vvH)^* \text{Br}(H \rightarrow bb)$

$\text{Br}(H \rightarrow \tau\tau)$

$\text{Br}(H \rightarrow \gamma\gamma)$ (Asimov)