Methods & Considerations for Calibration, Alignment CEPC ECAL

Jin Wang[1]

1: Institute of High Energy Physics, CAS

17th March 2025

CEPC Meeting

Introduction

- Recommendation from IDRC: Explain how calibration for each sub-detector will be achieved through physics processes, and document specific calibration methods in the Ref-TDR

1.4 Challenges & Plan . . . 17
1.4.1 Strategy for the measurement of absolute luminosity (Ivanka Bozovic) . . . 17
1.4.2 Plan of the use of resonant depolarization for W/Z mass (Zhe Duan) . . . 18
1.4.3 Methods & Considerations for Calibration, Alignment (Jin Wang, Qun Wang, Chu Wang, Tianyu Cao) . . . 19
1.4.3.1 **Vertex Detector Calibration and Alignment** . . . 19
1.4.3.1.1 Calibration using physics processes. . . . 19
1.4.3.1.2 Dedicated calibration methods. . . . 20
1.4.3.1.3 Alignment methods. . . . 20
1.4.3.2 **Tracker Calibration and Alignment** . . . 20
1.4.3.2.1 Calibration using physics processes. . . . 20
1.4.3.2.2 Dedicated calibration methods. . . . 21
1.4.3.2.3 Alignment methods. . . . 21
1.4.3.3 **ECAL Calibration and Alignment** . . . 22
1.4.3.3.1 Calibration using physics processes. . . . 22
1.4.3.3.2 Dedicated calibration methods. . . . 24
1.4.3.3.3 Alignment methods. . . . 24
1.4.3.3.4 Summary . . . 25
1.4.3.4 **HCAL Calibration and Alignment** . . . 26
1.4.3.4.1 Calibration using physics processes. . . . 26
1.4.3.4.2 Dedicated calibration methods. . . . 26
1.4.3.4.3 Alignment methods. . . . 26
1.4.3.5 **Muon System Calibration and Alignment** . . . 26
1.4.3.5.1 Calibration using physics processes. . . . 26
1.4.3.5.2 Dedicated calibration methods. . . . 26
1.4.3.5.3 Alignment methods. . . . 27
1.4.3.6 **Summary of Calibration and Alignment Approach** . . . 27

Calibration using physics processes

- **Typical physics processes**
  - Bhabha scattering ($e+e- \rightarrow e+e-$) : high statistics, realies on tracker
  - π0: high statistics, low energy region, high photon systematics
  - $Z \rightarrow e+e-$: low statistics, high energy region, well-known scales
  - W events, $J/\psi \rightarrow e+e-$, complementary
- **E/p method for time-dependent corrections (**Bhabha, W/Z**)**
  - Calorimetric energy can be compared to the tracking momentum for monitoring time-dependent drifts of the ECAL
  - Track quality cuts: Require well-reconstructed tracks in the inner tracker to ensure good momentum resolution and minimize inefficiencies.
  - Selection of scattering angles and momentum ranges: Impose angular cuts to reduce forward or backward beam backgrounds, and restrict p_{track} to the region where the tracker has optimal performance.
  - Fit the E/p distribution: Extract calibration constants (i.e., offsets in the mean) and resolution parameters (e.g., widths, non-Gaussian tails) by comparing data with either simulation or analytical models.

Intercalibration and absolute scale calibration

- $\pi 0 \rightarrow \gamma\gamma$ calibration with neutral pions produced in hadronic events
  - High statistics, good for precise calibration of fine-grained non-uniformities.
  - Photon selection and clustering
    - Select photon candidates using electromagnetic shower characteristics, requiring minimal hadronic contamination
    - Apply isolation cuts to suppress merging of overlapping clusters
    - Use clustering algorithms to reconstruct photon showers, ensuring containment of most of the energy within the selected cluster
    - Discard clusters with significant energy leakage or those affected by dead/hot channels.
  - Invariant mass reconstruction and event weighting
    - Construct all possible photon pairs in each event.
    - Compute the invariant mass of each candidate pair

$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

Intercalibration and absolute scale calibration

- Intercalibration to equalize channel-to-channel response
  - Compute the per-event calibration factor for each π0 event

$$IC_{\text{event}} = \frac{M_{\pi^0}^{\text{true}}}{M_{\pi^0}^{\text{measured}}}$$

  - Distribute this factor across all contributing crystals in the photon clusters, weighted by their energy

$$IC_i^{\text{event}} = IC_{\text{event}} \times w_i, \quad w_i = \frac{E_i}{E_{\text{cluster}}}$$

  - Accumulate all events and compute the final per-crystal intercalibration constant as a weighted average

$$IC_i = \frac{\sum_{\text{events}} IC_i^{\text{event}} \cdot w_i}{\sum_{\text{events}} w_i}$$

  - Iterate the process until the intercalibration factors converge

Intercalibration and absolute scale calibration

- Z → e+e− events provide a clean, well-known resonance suitable for both **intercalibration** and **absolute scale calibration**
  - Electron selection - Impose track quality cuts, require ECAL clusters with energy deposit shapes consistent with electromagnetic showers, and demand opposite-charge pairs.
  - Background rejection - Exclude non-resonant e+e− production or τ decays by applying mass window cuts around the Z peak.
  - Invariant mass fit - Compare the measured mee distribution to the true Z mass. The shift in the peak (and any width change) indicates calibration offsets.
  - Regional and channel-level intercalibration - Assign a single scale factor to each η ring to align its Z mass peak with the known value. - Perform additional fine-grained intercalibration at the channel level using local variations in reconstructed electron energy.
- Weighted combination of Z and π0 intercalibration

$$IC_{\text{combined}} = \frac{IC_{\pi^0}/\sigma^2_{\pi^0} + IC_Z/\sigma^2_Z}{1/\sigma^2_{\pi^0} + 1/\sigma^2_Z}$$

- A low-energy resonance such as J/ψ serves as an extra cross-check, particularly in the few-GeV range.

ECAL Alignment

- **ECAL-tracker alignment**: minimizing the difference in the η/φ between the ECAL cluster and the extrapolated track position
  - Relative alignment of ECAL crystals with the tracker detector using $Z \rightarrow e^+e^-$ events
  - For each e^+ and e^-, the distance between its track extrapolated from the tracker and its ECAL cluster position is minimized along η and φ directions
  - Iterative corrections update the relative positions of ECAL modules, minimizing residuals and improving overall alignment
- **Mechanical monitoring**
  - Integrated strain gauges, temperature sensors, and laser trackers monitor deformations or thermal expansion in the support structures.
  - This complementary information can be incorporated into the alignment model, ensuring a stable and consistent detector geometry over long operation periods.

Dedicated calibrations

- **Crystal transparency and SiPM response calibration**
  - The response of the ECAL is affected by variations in crystal transparency and silicon photomultiplier (SiPM) performance over time.
    - LED/laser injected to selected channel to monitor these effects in-situ?
  - High-energy cosmic muons deposit near-minimum-ionizing signals (MIPs) in the ECAL, providing a continuous and natural source of calibration data, particularly during beam-off periods.
  - By comparing the energy deposition of MIPs across different channels, relative response variations due to radiation damage, temperature fluctuations, or long-term aging can be identified and corrected.

Dedicated calibrations

- **Pedestal and noise scans**
  - Pedestal and noise levels are critical for ensuring optimal ECAL performance.
  - Periodic calibration runs without beam collisions or with random triggers measure each channel's baseline (pedestal) and electronic noise.
  - These measurements are essential for:
    - defining dynamic energy thresholds to suppress electronic noise while maintaining high sensitivity
    - identifying and masking excessively noisy channels to prevent artifacts in physics data
    - providing input for time-dependent noise corrections that improve energy reconstruction in low-energy events

Dedicated calibrations

- **Pulse shape and timing calibration**
  - Precise timing and pulse shape reconstruction are crucial for optimal energy esolution, pileup mitigation, and event reconstruction.

- **Template-based pulse shape corrections**
  - Each ECAL channel has a characteristic pulse shape, typically modeled using a reference pulse template derived from high-statistics calibration events.
  - Variations in pulse shape arise from differences in crystal light collection, SiPM response, and electronics timing offsets.
  - These effects are corrected using channel-specific calibration constants. A time-dependent correction accounts for aging effects, ensuring stable pulse shape reconstruction over long data-taking periods.
- **Pileup and out-of-time corrections**
  - Dedicated out-of-time pulse shape templates are used to identify and suppress contributions from previous or subsequent bunch crossings.

Dedicated calibrations

- **Timing synchronization and corrections**
  - Inter-channel synchronization is essential to ensure consistent timing across the ECAL.
  - Timing offsets arise from differences in electronic signal propagation, clock synchronization, and temperature variations.
    - Cosmic ray muons to verify inter-channel synchronization over large detector regions
    - Well-identified prompt photons or electrons from $Z \rightarrow e^+e^-$ decays provide absolute time reference points.
  - A final per-channel time alignment correction can be applied to ensure that all signals are synchronized within tens of picoseconds, enabling precision time-of-flight measurements and background rejection.

Summary of CEPC ECAL calibration and alignment

- Time-dependent drift correction with E/p method
  - Bhabha scattering and W/Z decays.
- Channel intercalibration, absolute scale calibration, stability monitoring
  - $\pi^0 \to \gamma\gamma$ and $Z \to e^+e^-$
- Additional Cross-Checks:
  - $J/\psi \to e^+e^-$ low-energy validation of the calibration scheme
- Dedicated Calibration Methods:
  - LED Systems: Monitor selected/partial crystal transparency and SiPM response in real time.
  - Cosmic Muons (MIPs): Supply continuous, natural calibration for channel uniformity.
  - Pedestal/Noise Scans: Regularly update baselines and optimize noise thresholds.
  - Pulse Shape & Timing Calibration: correct pulse shape variations and timing drift to ensure stable performance.
- Track-Based Alignment and Mechanical Monitoring