Electroweak Physics at CEPC

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Outline

• Introduction to CEPC
• W physics
• Z pole physics
Introduction to CEPC

- CEPC is Higgs Factory \( (E_{\text{cms}} = 240\text{GeV}, 10^6 \text{Higgs}) \)
- CEPC have good potential in electroweak precision physics at Z pole.
  - \( L = 1.6 (3.2) \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}, 10^{12} \text{Z boson} \) (tera-Z)
- WW threshold scan runs are also expected.
  - Total luminosity 2.5 \( \text{ab}^{-1} \),
  - 14M WW events
CEPC detector

- **ILD-like design with some modification for circular collider**
  - No Power-pulsing

- **Tracking system (Vertex detector, TPC detector, 3.0T magnet)**
  - Expected Tracking resolution: $\delta(1/Pt) \sim 2 \times 10^{-5}(\text{GeV}^{-1})$

- **Particle Flow Algorithm (PFA) based**
  - Expected jet energy resolution: $\sigma E/E \sim 0.3/\sqrt{E}$

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Outline

• Introduction to CEPC
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• Z pole physics
Motivation of W mass measurement

- CEPC have very good potential in electroweak physics.
- Precision measurement is important
  - It constrain new physics beyond the standard model.
  - Eg: Radiative corrections of the W or Z boson is sensitive to new physics

W mass measurement

- Two approaches to measure W mass:
  
  **Direct measurement**
  - performed in ZH runs (240GeV)
  - Precision 2~3MeV

  **WW threshold scan**
  - WW threshold runs (157~172GeV)
  - Expected Precision 1MeV level

ALEPH

![Histogram](image1)

LEP

![Graph](image2)

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Consider the beam spread unc. ($E_{BS}$), beam energy unc., signal efficiency, cross section unc. and background uncertainty.

With $E_{BS}$, the $\sigma_{WW}$ becomes:

$$\sigma_{WW}(E) = \int_0^\infty \sigma_{WW}(E') \times G(E, E') dE'$$

$$\approx \int_{E-6\sqrt{2}\Delta E_{BS}}^{E+6\sqrt{2}\Delta E_{BS}} \sigma(E') \times \frac{1}{\sqrt{2\pi\sqrt{2}E_{BS}}} e^{\frac{-(E-E')^2}{2(\sqrt{2}E_{BS})^2}} dE'$$

$E_{BS} + \Delta E_{BS}$ is used in the simulation, and $E_{BS}$ is for the fit formula.

The $m_W$ insensitive to $\Delta E_{BS}$ when taking data around 162.1 GeV

By Peixun Shen (Nankai University)
WW threshold scan – run plan

- **WW threshold scan running proposal**
  - **Assuming one year data taking in WW threshold (2.5 ab-1)**
  - **Four energy scan points:**
    - 157.5, 161.5, 162.5 (W mass, W width measurements)
    - 172.0 GeV ($\alpha_{QCD}$ ($m_W$) measurement, $\text{Br (W->had)}$, CKM |Vcs|)
    - 16M WW events in total
      - 400 times larger than LEP2 comparing WW runs

<table>
<thead>
<tr>
<th>$E_{cm}$ (GeV)</th>
<th>Lumiosity (ab$^{-1}$)</th>
<th>Cross section (pb)</th>
<th>Number of WW pairs (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>157.5</td>
<td>0.5</td>
<td>1.25</td>
<td>0.6</td>
</tr>
<tr>
<td>161.5</td>
<td>0.2</td>
<td>3.89</td>
<td>0.8</td>
</tr>
<tr>
<td>162.5</td>
<td>1.3</td>
<td>5.02</td>
<td>6.5</td>
</tr>
<tr>
<td>172.0</td>
<td>0.5</td>
<td>12.2</td>
<td>6.1</td>
</tr>
</tbody>
</table>

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**WW threshold scan – physics goal**

- **Statistics is enough for Branching ratio measurement** $\text{Br (W->had)}$ and $\alpha_{\text{QCD}} (mW)$ measurements.

- **Statistics uncertainty is one of the limiting factor** for $W$ mass and $W$ width measurement with CEPC one year running plan (2.5 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Systematics</th>
<th>Statistics uncertainty</th>
<th>limiting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ mass</td>
<td>1 MeV</td>
<td>1.0 MeV</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>Beam energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W$ width</td>
<td>1 MeV</td>
<td>3.2 MeV</td>
<td>Statistics</td>
</tr>
<tr>
<td>Br (W-&gt;had) &amp; $\alpha_{\text{QCD}} (mW)$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>/</td>
</tr>
</tbody>
</table>
W mass direct measurement

• The Z, W, and Higgs bosons can be well separated in CEPC.
• Benefitted from excellent jet energy resolution and PFA based calorimeter.
• Possible to measure W mass from direct di-jet mass reconstruction.

By Peizhu Lai (NCU)
W mass direct measurement

- Reconstruct di-jet mass from WW→lvqq events in ZH run
  - Not affect by beam energy uncertainty
  - Major systematics is Jet energy scale (JES) uncertainty (2~3 MeV)
  - Calibrate JES with Tera-Z (Z→jj)

By Peizhu Lai (NCU)
Prospect of CEPC W mass measurement

- CEPC can improve current precision of W mass by one order of magnitude
  - A possible BSM physics can be discovered in the future

Future with CEPC contribution

\[ M_W = 80363 \text{ MeV} \pm 2 \text{ MeV} \]

\[ M_W = 80385 \text{ MeV} \pm 3 \text{ MeV} \]

Figure from Gfitter community (LHC+ILC)
Outline

• Introduction to CEPC
• $W$ physics
• $Z$ pole physics
Branching ratio ($R^b$)

\[
\frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{had})}
\]

- **LEP measurement**: $0.21594 \pm 0.00066$ (~0.3%)
  - Stat unc and Systematics Unc. Have similar contribution
- **CEPC**
  - Expected Stat Unc. Is neglectable
  - Expected Syst error (0.02%)
  - Expect to use 80% working points
    - 15% higher efficiency than SLD
    - 20-30% higher in purity than SLD

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>LEP</th>
<th>CEPC</th>
<th>Thing to improve</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemisphere tag correlations for b events</td>
<td>0.2%</td>
<td>0.02%</td>
<td>B tagging performance, pixel</td>
</tr>
<tr>
<td>gluon splitting</td>
<td>~0.15%</td>
<td>0.01%</td>
<td>Better granularity in Calo</td>
</tr>
</tbody>
</table>
**R^b**: hemisphere tag correlations

- Study hemisphere b tag correlations systematics with full simulation
- Two ways to reduce correlations factor -> reducing systematics
  - Using tighter cuts to choose Z->bb events
  - Use different B jet tagger (soft muon tag Vs impact parameter)
  - Correlations factors c_b need to be reduced below 0.01%

\[
C_b = \frac{\varepsilon_{2\text{jet}-tagged}}{\left(\varepsilon_{1\text{jet}-tagged}\right)^2}
\]

\[\Delta\theta(\text{jet1, jet2}) < 5^\circ\]

By Bo Li (Yantai University)
Weak mixing angle

- **LEP/SLD:** 0.23153 ± 0.00016
  - ~0.07% precision. (Stat error is limiting factor.)

- **CEPC**
  - Aim for 0.002% precision
  - Input from Backward-forward asymmetry measurement of \(Z\rightarrow\text{bb}\) and \(Z\rightarrow\text{\mu\mu}\)
Backward-forward asymmetry in $Z \rightarrow \mu \mu$

- **LEP measurement**: 1.69% $\pm$ 0.13% (PDG fit)
- **CEPC aim**: to improve it by a factor of 20~30.
  - muon angular resolution and acceptance
  - the precision of beam energy measurement
- **Full simulation studies** to understand muon angular resolution
  - Muon angular resolution can reach $1 \times 10^{-4}$ to $1 \times 10^{-5}$ level

By Mengran Li (IHEP)
Weak mixing angle (2)

- **Comparison with Fcc-ee on weakening mixing angle measurement**
  - Expect 1~2 order magnitude better than LEP results
  - consistent with FCC-ee prediction

<table>
<thead>
<tr>
<th>Improvement compared to LEP results</th>
<th>CEPC</th>
<th>FCC-ee (Paolo’s talk in CEPC Roma workshop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FB} (Z\rightarrow e\bar{e})$</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>$A_{FB} (Z\rightarrow \mu\bar{\mu})$</td>
<td>20-30</td>
<td>30</td>
</tr>
<tr>
<td>$A_{FB} (Z\rightarrow \tau\bar{\tau})$</td>
<td>NA</td>
<td>15</td>
</tr>
<tr>
<td>$A_{FB} (Z\rightarrow b\bar{b})$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Weak mixing angle</td>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>
### Status of W/Z physics study in CEPC

- The prospect of W/Z physics study in CEPC are under study
- Mainly based on projection from LEP

<table>
<thead>
<tr>
<th>Observable</th>
<th>LEP precision</th>
<th>CEPC precision</th>
<th>CEPC runs</th>
<th>$\int \mathcal{L}$ needed in CEPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$</td>
<td>2 MeV</td>
<td>0.5 MeV</td>
<td>$Z$ threshold scan</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$A_{FB}^{0,b}$</td>
<td>1.7%</td>
<td>0.1%</td>
<td>$Z$ threshold scan</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$A_{FB}^{0,\mu}$</td>
<td>7.7%</td>
<td>0.3%</td>
<td>$Z$ threshold scan</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$A_{FB}^{0,e}$</td>
<td>17%</td>
<td>0.5%</td>
<td>$Z$ threshold scan</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.3%</td>
<td>0.02%</td>
<td>$Z$ pole</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$R_\mu$</td>
<td>0.2%</td>
<td>0.01%</td>
<td>$Z$ pole</td>
<td>3.2ab$^{-1}$</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>1.7%</td>
<td>0.05%</td>
<td>$ZH$ runs</td>
<td>5ab$^{-1}$</td>
</tr>
<tr>
<td>$m_W$</td>
<td>33 MeV</td>
<td>2-3 MeV</td>
<td>$ZH$ runs</td>
<td>5ab$^{-1}$</td>
</tr>
<tr>
<td>$m_W$</td>
<td>33 MeV</td>
<td>1 MeV</td>
<td>$WW$ threshold</td>
<td>2.5ab$^{-1}$</td>
</tr>
</tbody>
</table>
Summary

• **CEPC community is working on in Conceptual Design Report.**
  – updated CEPC accelerator design on Z pole and WW runs
  – order of magnitudes larger than pre-CDR
  – Prospect of CEPC W/Z physics improved benefitted from higher design luminosity

• **Welcome to join this effort**
  – Lots of work needed to understand the systematics

• **Thanks for hard work from current team.**
  – PhD Students, and who are practically working:
    – Peixun Shen (Nankai U.), Pei-Zhu Lai (NCU), Mengran Li (IHEP), Bo Li(Yantai U.)
  – Supervisors, Conveners, Experts, who are contributing ideas:
    – Gang Li (IHEP), Zhijun Liang (IHEP), Manqi Ruan (IHEP), Bo Liu (IHEP),
    Chai-Ming Kuo (NCU), Maarten Boonekamp (CEA Saclay), Hengne Li (SCNU/UVa),
    Fuivio Piccinini (INFN), Liantao Wang (Chigago), Joao Costa (IHEP)
Open issue

• Tools needed:
  – Soft muon b jet tagger is needed for \( R_b \) measurement
  – Jet charge reconstruction is need for \( Afb_b \)

• Analyses to be covered
  – \( Afb_b \), \( Afb_e \) measurements
    • Key input to weak mixing angle measurement
  – \( W\rightarrow jj \) branching ratio and \( \alpha_{QCD} \)
  – \( Z\rightarrow ll \) off-peak runs design and \( \alpha_{QED} \) measurements
Backward-forward asymmetry

• **LEP measurement : 0.1000+0.0017 (Z peak)**
  - Method 1: Soft lepton from b/c decay (~2%)
    - Select one lepton from b/c decay, and one b jets
    - Select lepton charge ($Q_{\text{lepton}}$) and jet charge ($Q_{\text{jet}}$)
  - Method 2: jet charge method using Inclusive b jet (~1.2%)
    - Select two b jets
    - Use event Thrust to define the forward and background
    - Use jet charge difference ($Q_F - Q_B$) $Q_{\text{lepton}} - Q_{\text{jet}}$ in method 1

Arxiv: Hep-ex/0107033

$Q_F - Q_B$ in method 2

Arxiv: Hep-ex/0403041

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Backward-forward asymmetry

- **LEP measurement**: $0.1000^{+0.0017}_{-0.0017}$ (Z peak)
  - Method 1: Soft lepton from b/c decay ($\sim2\%$)
  - Method 2: jet charge method using Inclusive b jet ($\sim1.2\%$)
  - Method 3: D meson method ($>8\%$, method)

- **CEPC**
  - Focus more on method 2 (inclusive b jet measurement)
  - Expected Systematics ($0.15\%$):

<table>
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</thead>
<tbody>
<tr>
<td>hemisphere tag correlations for b events</td>
<td>1.2%</td>
<td>0.1%</td>
<td>Higher b tagging efficiency</td>
</tr>
<tr>
<td>QCD and thrust axis correction</td>
<td>0.7%</td>
<td>0.1%</td>
<td></td>
</tr>
</tbody>
</table>
Backward-forward asymmetry

**Uncertainty $A_{FB}^{b\bar{b}}$ due to QCD correction to Thrust**

- Higher order QCD effect is major systematics

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**CERN-EP/98-23**

<table>
<thead>
<tr>
<th>Error source</th>
<th>$C_{QCD}^{\text{part.}, T}$ (%)</th>
<th>$C_{QCD}^{\text{part.}, T}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{b}b$</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Theoretical error on $m_b$ or $m_c$</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>$\alpha_s(m_Z^2)$ ($0.119 \pm 0.004$)</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Higher order corrections</td>
<td>0.27</td>
<td>0.66</td>
</tr>
<tr>
<td>Total error</td>
<td>0.37</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Calorimeters:

- Concept of Particle Flow Algorithm (PFA) based
- EM calorimeter energy resolution: $\sigma_{E}/E \sim 0.16/\sqrt{E}$
- Had calorimeter energy resolution: $\sigma_{E}/E \sim 0.5/\sqrt{E}$
- Expected jet energy resolution: $\sigma_{E}/E \sim 0.3/\sqrt{E}$