Heavy-quark electroweak measurements

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Heavy-quark electroweak measurements

- Heavy quarks: charm, beauty and top
- Precision tests of the electroweak sector + Higgs boson properties
- Best suitable at FCC-ee for beauty- and charm-physics? Measurements at the $Z$-pole with $5.6 \cdot 10^{12} Z \rightarrow q\bar{q}$

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1871 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4944 ± 0.0024</td>
</tr>
<tr>
<td>$\sigma_0^\text{had}$ [nb]</td>
<td>41.544 ± 0.037</td>
</tr>
<tr>
<td>$R_e$</td>
<td>20.768 ± 0.024</td>
</tr>
<tr>
<td>$A_0^e$</td>
<td>0.01701 ± 0.00095</td>
</tr>
<tr>
<td>$A_e$</td>
<td>0.1483 ± 0.0051</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.1425 ± 0.0044</td>
</tr>
<tr>
<td>$\sin^2\theta_\text{eff}^{\text{lept}}$</td>
<td>0.2321 ± 0.0010</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.350 ± 0.056</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21642 ± 0.00073</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1674 ± 0.0038</td>
</tr>
<tr>
<td>$A_{0,b}$</td>
<td>0.0988 ± 0.0020</td>
</tr>
<tr>
<td>$A_{b,c}$</td>
<td>0.0692 ± 0.0037</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.911 ± 0.025</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.630 ± 0.026</td>
</tr>
<tr>
<td>$\sin^2\theta_\text{eff}^{\text{lept}}$</td>
<td>0.23099 ± 0.00026</td>
</tr>
<tr>
<td>$\sin^2\theta_W$</td>
<td>0.2255 ± 0.0021</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.448 ± 0.062</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>174.3 ± 5.1</td>
</tr>
<tr>
<td>$\Delta r_{\text{had}}(m_Z)$</td>
<td>0.02804 ± 0.00065</td>
</tr>
</tbody>
</table>
Heavy-quark electroweak measurements

- Heavy quarks: charm, beauty and top
- Precision tests of the electroweak sector + Higgs boson properties
- Best suitable at FCC-ee for beauty- and charm-physics?
- Measurements at the $Z$-pole with $5.6 \cdot 10^{12} \ Z \rightarrow q\bar{q}$
- Statistics allow for new methods: flavour tagging for $R_b$ and $A_{FB}^{b\bar{b}}$
Principle of the measurement

- Produce $Z \rightarrow q\bar{q}$ at $\sqrt{s} = 91$ GeV
  - $R_b$: Which $q$ is a $b$?
  - $A_{FB}^{bb}$: Where does which $b$ go?

- FCC-ee brings **unprecedented statistical precision**, but: systematic uncertainties have to keep track!

**Proposal: b-hemisphere tagger**

"Look inside the jet" and select + identify the charge of the hemispheres by exclusively reconstruct $b$-hadrons. Targets:

- Potential purity of 100 %
- Efficiency of 1 %

Exclusive $b$-hadrons as hemisphere tagger.
New $b$-quark tagger – Credits and Debits

- Current systematic uncertainty budget for $R_b$ measurement at LEP

![Pie chart showing contributions to systematic uncertainty budget]

- Improved systematic uncertainty budget for $R_b$ measurement at LEP
- Loss in efficiency, thus statistical precision ($\sim$ factor 20)
- Measurement of $A_{b\bar{b}}^{FB}$: Further loss in efficiency
- $\Rightarrow$ Stay with not-mixing $b$-hadrons ($B^+$ and $\Lambda_0 b$)

With $\varepsilon_b = 1\%$:

$$\Delta R_b (\text{stat}) = 1.9 \cdot 10^{-5}$$

(factor 45 improvement wrt. LEP)

- udsc-physics background free: Eliminates major source of systematic uncertainty
- Evaluation of the systematic uncertainties (mainly hemisphere correlation, QCD corrections)
- Measurement of $R_b$: requires knowledge about the existence of a $b$-quark (inclusion of $B^+$, $B^0$, $B_s$, $\Lambda_0 b$)
- Measurement of $A_{b\bar{b}}^{FB}$: Possibly overcome mixing dilutions + hemisphere confusion from hard gluon radiation
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- Measurement of $A_{FB}^{bb}$: Possibly overcome mixing dilutions + hemisphere confusion from hard gluon radiation
Analysis strategy for $R_b$

1. Result from PDG-search, that 1% is in reach: select decay modes with $\text{Br} > 10^{-3}$
   
   $\sum \text{Br} = 1.11\%$

   \[
   \begin{cases}
   B^+ & 50+ \text{ modes} \\
   B^0 & 100+ \text{ modes} \\
   B_s & 50+ \text{ modes} \\
   \Lambda_b & \mathcal{O}(10) \text{ modes}
   \end{cases}
   \]
Analysis strategy for $R_b$

1. Result from PDG-search, that 1% is in reach: select decay modes with a sufficiently large Br ✓

2. Perform a reconstruction of a $b$-hadron with representative decay modes: $B^+ \to \ldots$
   - Fully charged, two tracks
   - Fully charged, three tracks
   - Fully charged, four tracks
   - One $\pi^0$, two tracks,
   - Two $\pi^0$, two tracks,
   - Two leptons

Exemplarily: $B^+ \to J/\psi K^+ \to [\ell^+ \ell^-]_{J/\psi} K^+$

\[ \bar{D}^0 \pi^+ \to [K^+ \pi^-]_{\bar{D}^0} \pi^+ \]
\[ \bar{D}^0 D_s^+ \to [K^+ \pi^-]_{\bar{D}^0} [K^+ K^- \pi^+]_{D_s^+} \]
\[ \bar{D}^0 \pi^+ \to [K^+ 2\pi^- \pi^+]_{\bar{D}^0} \pi^+ \]
\[ \bar{D}^0 \pi^+ \to [K^+ \pi^- \pi^0]_{\bar{D}^0} \pi^+ \]
\[ \bar{D}^0 \pi^+ \to [K^+ \pi^- 2\pi^0]_{\bar{D}^0} \pi^+ \]
\[ J/\psi K^+ \to [\ell^+ \ell^-]_{J/\psi} K^+ \]
2. Reconstruction of representative decay modes

- $B^+ \rightarrow J/\psi K^+$ reconstruction and $J/\psi \rightarrow \ell^+ \ell^-$ with $4 \cdot 10^7 Z \rightarrow q\bar{q}$ events from winter2023 campaign
- Emulation of vertex resolution by requiring charged particles to have $< 50 \mu$m displacement

- Uncertainty from unbinned maximum likelihood fit to the $B^\pm$ mass spectrum: 5.00 MeV
- Full mass spectrum already shows two orders of magnitude suppressed background, doing better?
2. Reconstruction of representative decay modes – doing better!

- Background contamination: gluon radiation and $g \rightarrow b\bar{b}$ (proven from simulation)
  - These candidates are expected to have lower energy
- Energy spectrum of the truth-matched $B^+$ candidates confirms expectation
- Use an energy cut of $E > 20$ GeV

![Energy spectrum graph](image-url)
2. Reconstruction of representative decay modes – doing better!

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- Original $B^+$ reconstruction efficiency $= 85.7\%$ and purity $= 98.6\%$
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- Energy spectrum of the truth-matched $B^+$ candidates confirms expectation
- Use an energy cut of $E > 20$ GeV

- Original $B^+$ reconstruction efficiency = 85.7 % and purity = 98.6 % → 80.4 % and 99.9 %
Analysis strategy for $R_b$

1. Result from PDG-search, that 1% is in reach: select decay modes with a sufficiently large Br ✓
2. Perform a reconstruction of a $b$-hadron with representative decay modes: $B^+ \rightarrow \ldots$ ✓
3. Verification for the other decay modes

<table>
<thead>
<tr>
<th>Decay mode $B^+ \rightarrow \ldots$</th>
<th>Reconstruction efficiency / %</th>
<th>Purity / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{D}^0 \pi^+ \rightarrow [K^+ \pi^-]_{\bar{B}_0} \pi^+$</td>
<td>71.1</td>
<td>99.9</td>
</tr>
<tr>
<td>$\bar{D}^0 \pi^+ \rightarrow [K^+ \pi^-\pi^0]_{\bar{B}_0} \pi^+$</td>
<td>59.9</td>
<td>99.9</td>
</tr>
<tr>
<td>$\bar{D}^0 \pi^+ \rightarrow [K^+\pi^-2\pi^0]_{\bar{B}_0} \pi^+$</td>
<td>47.1</td>
<td>99.8</td>
</tr>
<tr>
<td>$\bar{D}^0 \pi^+ \rightarrow [K^+2\pi^-\pi^+]_{\bar{B}_0} \pi^+$</td>
<td>64.8</td>
<td>99.6</td>
</tr>
<tr>
<td>$J/\psi K^+ \rightarrow [\ell\ell] K^+$</td>
<td>80.4</td>
<td>99.9</td>
</tr>
<tr>
<td>$D_s^+ \bar{D}^0 \rightarrow [K^+K^-\pi^+] [K^-\pi^+]$</td>
<td>81.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Analysis strategy for $R_b$

1. Result from PDG-search, that 1% is in reach: select decay modes with a sufficiently large $\text{Br}$ ✓
2. Perform a reconstruction of a $b$-hadron with representative decay modes: $B^+ \rightarrow \ldots$ ✓
3. Verification for the other decay modes ✓
4. Determination of the hemisphere correlation from fully simulated events
4. First look on Full Simulation

- Hemisphere correlation determination requires fully simulated events in CLD (with all its ups and downs)
- Forced decays on both legs to $B^\pm \rightarrow D^0\pi^\pm \rightarrow [K^\pm\pi^\mp]_{D^0}\pi^\pm$ with EvtGen
- Usage of modified FCCAnalyses software to extract tracks and 4-vectors
  → Performed complete vertexing up to the $B^\pm$

- Resolution on the $B^+$ mass degraded by a factor 3.1
- Correlation of hemispheres about to be determined: $\rho_b = \frac{e(\text{tag } H_2 | H_1)}{e(\text{tag } H_1)}$

Special thanks to F. Bedeschi, E. Perez and X. Zuo!
Conclusions

- Presented a novel hemisphere tagger and it’s application on $R_b$ and $A_{FB}^{b\bar{b}}$

Proposal: b-hemisphere tagger

"Look inside the jet" and select+identify the charge of the hemispheres by exclusively reconstruct $b$-hadrons. Targets:

- Potential purity of 100 %
- Efficiency of 1 %

1. Result from PDG-search, that 1% is in reach ✓

2. Perform $B^+$ reconstruction in a representative decay mode ✓

3. Verification for the other decay modes ✓

4. Hemisphere correlation from fully simulated events WIP

- Strategy summarised in a rather final Internal Analysis Note
**Bigger picture**

- Combination of $R_b$ and $A_{FB}^{bb}$ with other heavy-quark measurements
- Possible anomalies translate from the $Z$-pole to top-measurements
  ⟷ Consistently described by a common set of dimension-6 operators in SMEFT

**$O(m_Z) \sim 90$ GeV**

$$\Rightarrow \text{Vertex corrections} \approx 1\% \text{ of } R_b \text{ in the SM}$$

<table>
<thead>
<tr>
<th>$O(m_t) \sim 350$ GeV</th>
</tr>
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</table>

$$\Rightarrow \text{Anomaly in e.g. the } t \text{ forward-backward asym.}$$

- About 25 observables extracted from the top-energy scale: global interpretation
Bigger picture

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- Possible anomalies translate from the $Z$-pole to top-measurements
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$O(m_t) \sim 350 \text{ GeV}$

⇒ Vertex corrections $\approx 1\%$ of $R_b$ in the SM

⇒ Anomaly in e.g. the $t$ forward-backward asym.

- About 25 observables extracted from the top-energy scale: global interpretation

Thanks a lot for the attention!
Appendix: Primary vertex resolution

- Primary vertex resolution extracted from the CLD Full Simulation sample
Appendix: $D^0$ vertex and momentum resolution

- Vertex and momentum resolution for the Full Simulation sample with the CLD detector

![Graph 1: $D^0$ vertex resolution](image1)

![Graph 2: $D^0$ momentum resolution](image2)
Appendix: $B^+$ vertex and momentum resolution

- Vertex and momentum resolution for the Full Simulation sample with the CLD detector

![Graph showing vertex and momentum resolution for $B^+$ particles](image)

**Legend:**
- $i = x$
- $i = y$
- $i = z$

**Graph 1:**
- $B^+_{vtx,i}$ (Object-level) vs. $B^+_{vtx,i}$ (Particle-level) / mm
- Entries

**Graph 2:**
- $p_i(B^\pm, Object-level) - p_i(B^\pm, Particle-level) / GeV
- Entries

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Appendix: CLD $B^+$ mass fit

- Fit of the reconstructed $B^+$ meson with a sum of three Gaussian distributions
- Fit parameters: $\mu = 5279.09$ MeV and $\sigma_{\text{comb.}} = 12.75$ MeV
Appendix: Further increasing the efficiency

- Efficiency of the tagger can be further improved by accepting also partially reconstructed candidates
- No degradation of the purity

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Fast Simulation: Decay mode $B^+ \rightarrow [K^+\pi^-]\bar{D}_0\pi^+$
Fast Simulation: Decay mode $B^+ \rightarrow [K^+\pi^-\pi^0]_{D^0}\pi^+$

![Graph showing decay modes and candidate distributions.](image_url)
Fast Simulation: Decay mode $B^+ \rightarrow [K^+\pi^-2\pi^0]_{D^0}\pi^+$
Fast Simulation: Decay mode $B^+ \rightarrow [K^+2\pi^-\pi^+]\bar{D}_0\pi^+$
Fast Simulation: Decay mode $B^+ \rightarrow [\ell^+ \ell^-]_{J/\psi} K^+$

- **Candidates / 25 MeV**
  - $B^+ \rightarrow [\ell^+ \ell^-]_{J/\psi} \pi^+$
  - Combinatorial & partially reconstructed
  - udsc-physics
  - Object-level

- **Candidates / 2.667 MeV**
  - Particle-level
  - Fit
  - Object-level

**Diagrams:**
- **Left Diagram:**
  - $m([\ell^+ \ell^-]_{J/\psi} K^+) / \text{MeV}$
  - $B^+ \rightarrow [\ell^+ \ell^-]_{J/\psi} \pi^+$
  - Combinatorial & partially reconstructed
  - udsc-physics
  - Object-level

- **Right Diagram:**
  - $m([\ell^+ \ell^-]_{J/\psi} K^+) / \text{MeV}$
  - Particle-level
  - Fit
  - Object-level

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L. Röhrig | 06/07/2023
Fast Simulation: Decay mode $B^+ \rightarrow [K^+K^−\pi^+]_{D^+_s}[K^+\pi^-]_{D^0}$
Reconstructed exclusive $b$-hadron decays as hemisphere jet charge tagger and its application for the measurement of $R_b$ and $A_{FB}^b$