Heavy-quark electroweak measurements

FCC week 2023 – London

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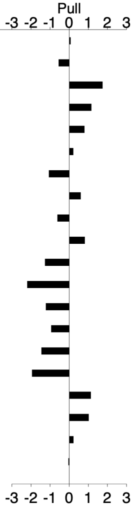
Heavy-quark electroweak measurements

- 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 $5.6 \cdot 10^{12}$ $Z \to q\bar{q}$

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



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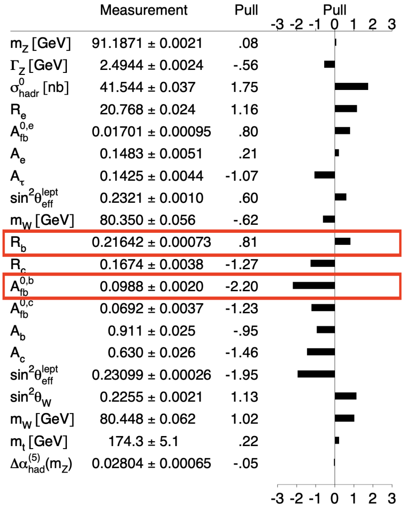
- Precision tests of the electroweak sector + Higgs boson properties
- Best suitable at FCC-ee for beauty- and charm-physics? Measurements at the Z-pole with $5.6 \cdot 10^{12}$ $Z \to q\bar{q}$
- Statistics allow for new methods: flavour tagging for R_b and $A_{\mathrm{FB}}^{b\bar{b}}$



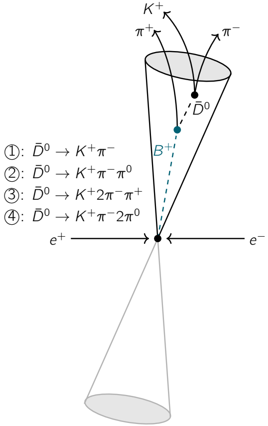
Principle of the measurement

- Produce $Z \to q\bar{q}$ at $\sqrt{s} = 91\,\text{GeV}$
  - R_b: Which q is a b?
  - $A_{\text{FB}}^{b\bar{b}}$: 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:

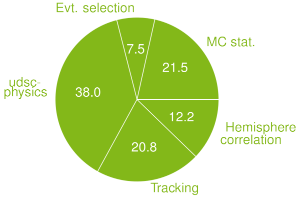
- Potential purity of 100 %
- Efficiency of 1 %



Exclusive b-hadrons as hemisphere tagger.

New b-quark tagger – Credits and Debits

- Current systematic uncertainty budget for R_b measurement at LEP



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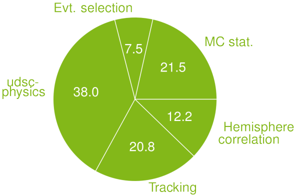

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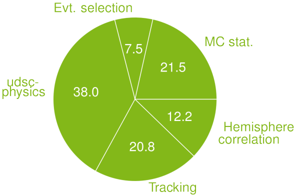

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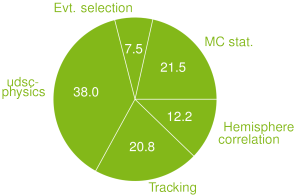

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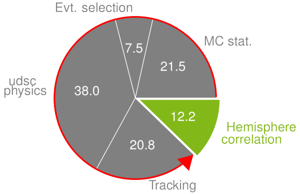

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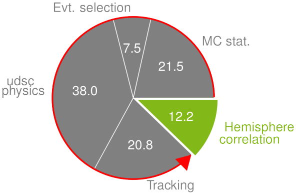

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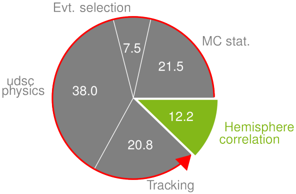

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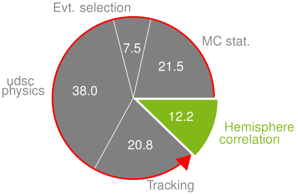

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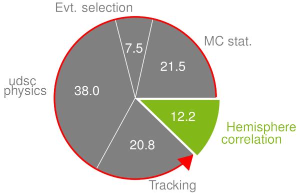

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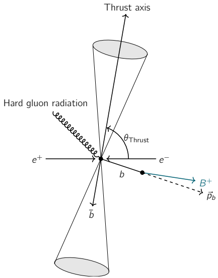

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- Measurement of R_b: requires knowledge about the existence of a b-quark (inclusion of B^+, B^0, B_s, Λ_b^0)
- Measurement of $A_{\mathrm{FB}}^{b\bar{b}}$: Possibly overcome mixing dilutions + hemisphere confusion from hard gluon radiation

Analysis strategy for R_b

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

$$\left.\begin{array}{l} \mathbf{B^+}\ \text{50+ modes} \\ \mathbf{B^0}\ \text{100+ modes} \\ \mathbf{B_s}\ \text{50+ modes} \\ \mathbf{\Lambda_b^0}\ \mathcal{O}(10)\ \text{modes} \end{array}\right\} \text{200+ decay modes: } \sum \mathrm{Br} = 1.11\,\%$$

Analysis strategy for R_b

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

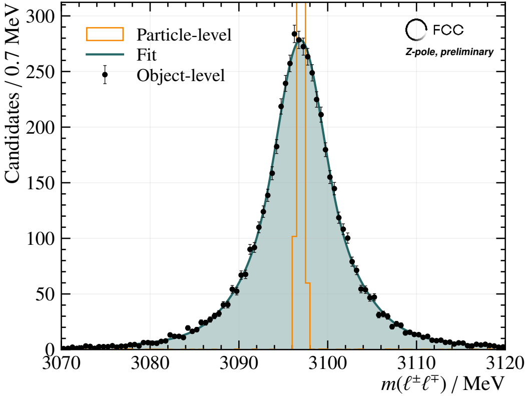
2. Perform a reconstruction of a b-hadron with representative decay modes: $B^+ \to \ldots$

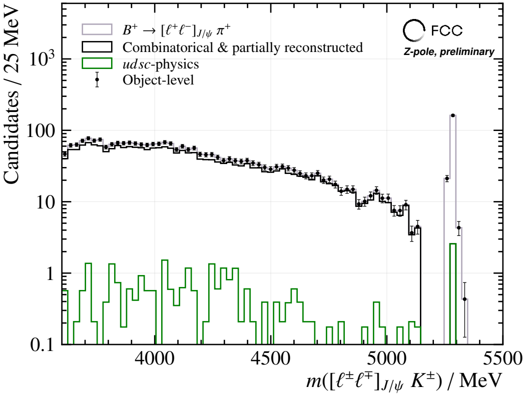
Fully charged, two tracks	$\bar{D}^0\pi^+ \to [K^+\pi^-]_{\bar{D}^0}\,\pi^+$
Fully charged, three tracks	$\bar{D}^0 D_s^+ \to [K^+\pi^-]_{\bar{D}^0}\,[K^+K^-\pi^+]_{D_s^+}$
Fully charged, four tracks	$\bar{D}^0\pi^+ \to [K^+2\pi^-\pi^+]_{\bar{D}^0}\,\pi^+$
One π^0, two tracks,	$\bar{D}^0\pi^+ \to [K^+\pi^-\pi^0]_{\bar{D}^0}\,\pi^+$
Two π^0, two tracks,	$\bar{D}^0\pi^+ \to [K^+\pi^-2\pi^0]_{\bar{D}^0}\,\pi^+$
Two leptons	$J/\psi\,K^+ \to [\ell^+\ell^-]_{J/\psi}\,K^+$

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

2. Reconstruction of representative decay modes

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

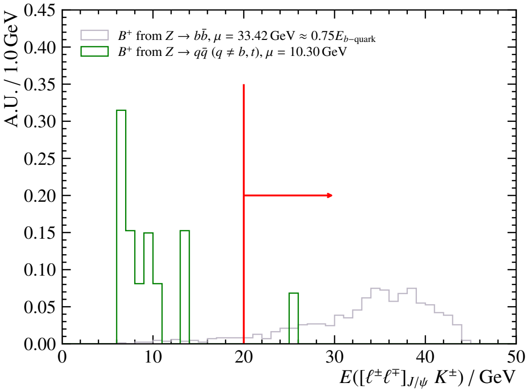




- Uncertainty from unbinned maximum likelihood fit to the $B^\pm$ mass spectrum: 5.00 MeV
- Full mass spectrum already shows two orders of magnitude suppressed background, doing better?

2. Reconstruction of representative decay modes – doing better!

- Background contamination: gluon radiation and $g \to b\bar{b}$ (proven from simulation)
  $\hookrightarrow$ 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



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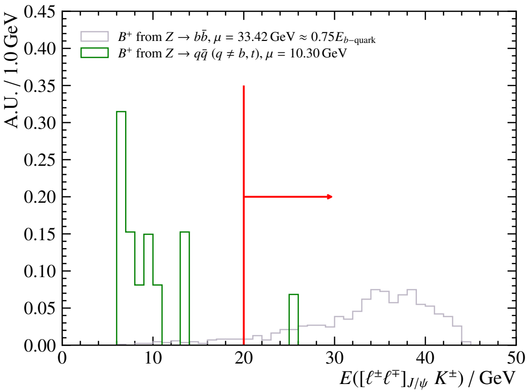

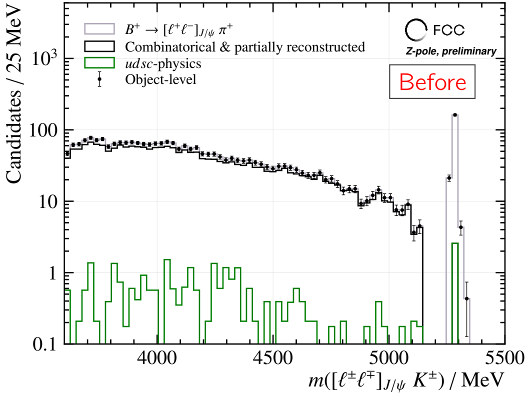

- Original B^+ reconstruction efficiency = 85.7 % and purity = 98.6 %

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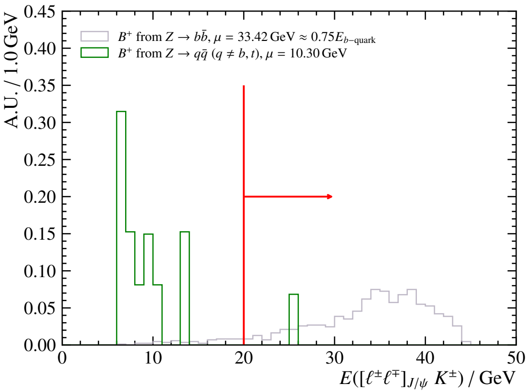

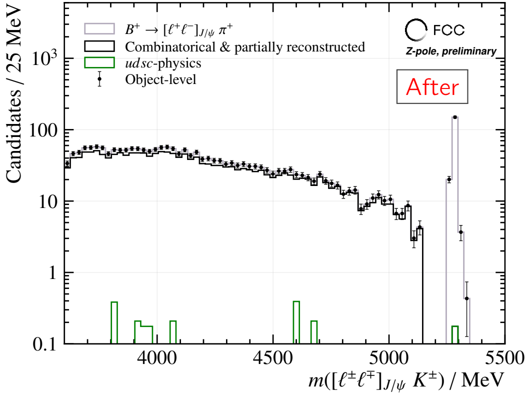

- Original B^+ reconstruction efficiency = 85.7 % and purity = 98.6 % → 80.4 % and 99.9 %

Analysis strategy for R_b

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3. Verification for the other decay modes

Decay mode $B^+ \to \ldots$	Reconstruction efficiency / %	Purity / %
$\bar{D}^0\pi^+ \to [K^+\pi^-]_{\bar{D}^0}\,\pi^+$	71.1	99.9
$\bar{D}^0\pi^+ \to [K^+\pi^-\pi^0]_{\bar{D}^0}\,\pi^+$	59.9	99.9
$\bar{D}^0\pi^+ \to [K^+\pi^-2\pi^0]_{\bar{D}^0}\,\pi^+$	47.1	99.8
$\bar{D}^0\pi^+ \to [K^+2\pi^-\pi^+]_{\bar{D}^0}\,\pi^+$	64.8	99.6
$J/\psi\,K^+ \to [\ell\ell]K^+$	80.4	99.9
$D_s^+\bar{D}^0 \to [K^+K^-\pi^+][K^-\pi^+]$	81.5	100.0

Analysis strategy for R_b

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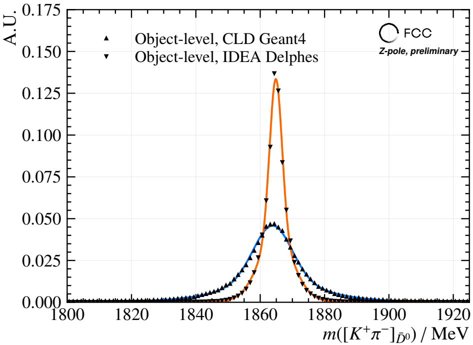
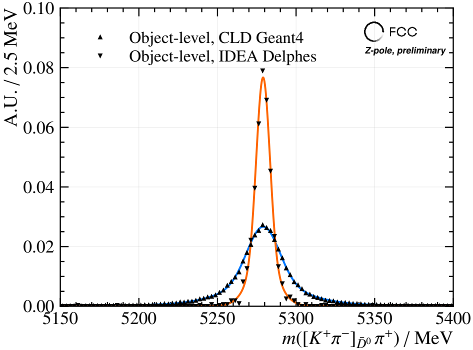
2. Perform a reconstruction of a b-hadron with representative decay modes: $B^+ \to \ldots$ ✓
3. Verification for the other decay modes ✓
4. Determination of the hemisphere correlation from fully simulated events

4. First look on Full Simulation

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

- Hemisphere correlation determination requires fully simulated events in CLD (with all its ups and downs)
- Forced decays on both legs to $B^{\pm} \to D^0 \pi^{\pm} \to [K^{\pm}\pi^{\mp}]_{D^0}\, \pi^{\pm}$ 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: $\rho_b = \frac{\varepsilon(\text{tag } H_2 \mid H_1)}{\varepsilon(\text{tag } H_1)}$

Conclusions

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

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 %
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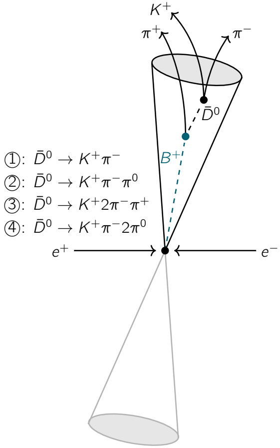


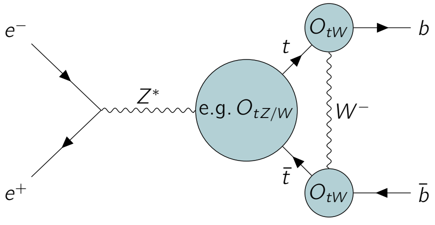
1. Result from PDG-search, that 1 % is in reach ✓
2. Perform B^+ reconstruction in a representative decay mode ✓
3. Verification for the other decay modes ✓
4. Hemisphere correlation from fully simulated events WIP

- Strategy summarised in a rather final Internal Analysis Note

Bigger picture

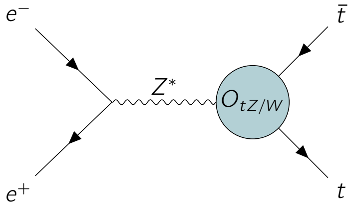
- Combination of R_b and $A_{\mathrm{FB}}^{b\bar{b}}$ with other heavy-quark measurements
- Possible anomalies translate from the Z-pole to top-measurements
  $\hookrightarrow$ Consistently described by a common set of dimension-6 operators in SMEFT

$\mathcal{O}(m_Z) \sim 90$ GeV



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

$\mathcal{O}(m_t) \sim 350$ GeV



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

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

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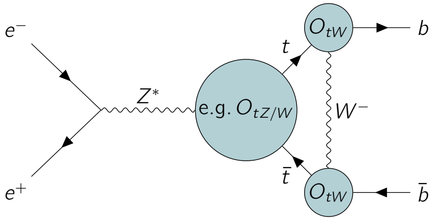

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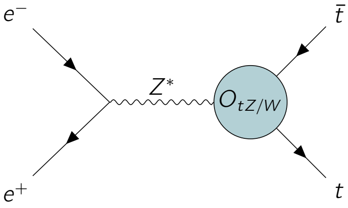

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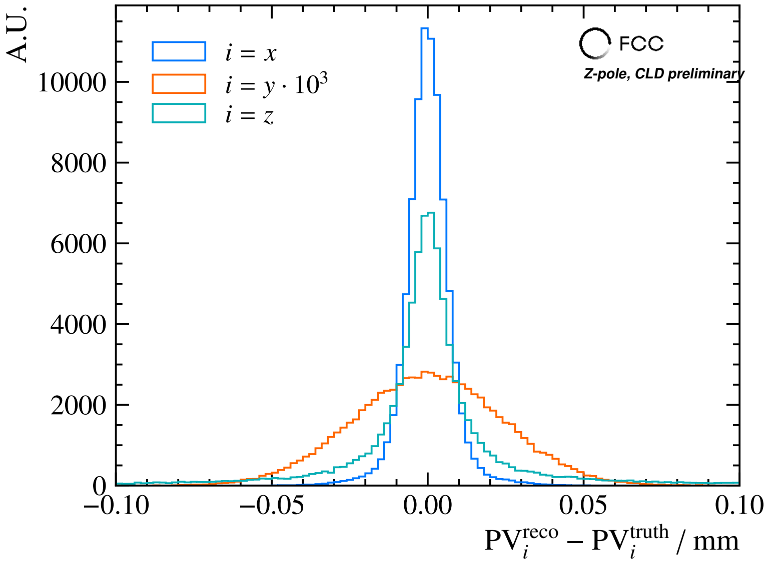
Thanks a lot for the attention!

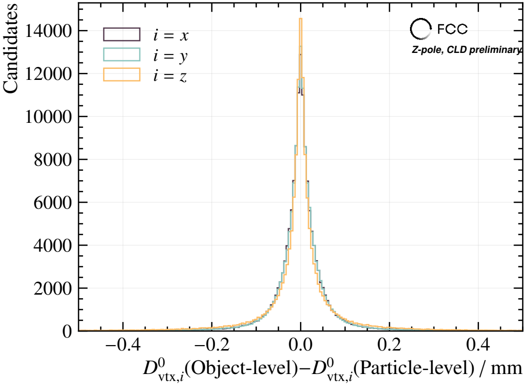
Appendix: Primary vertex resolution

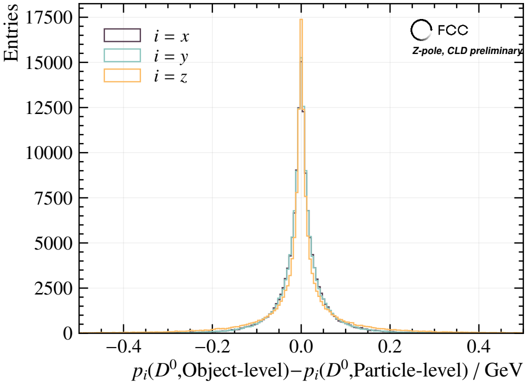
- Primary vertex resolution extracted from the CLD Full Simulation sample



Appendix: D^0 vertex and momentum resolution

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





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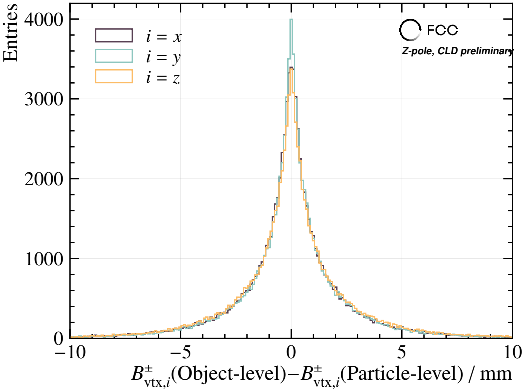
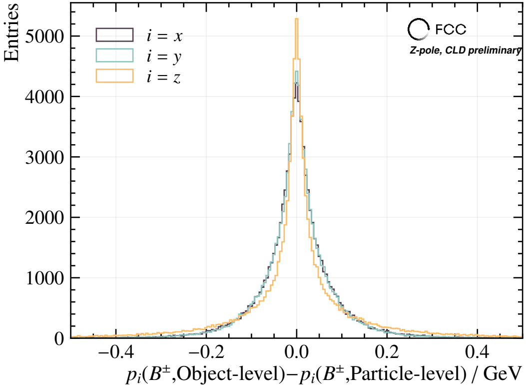
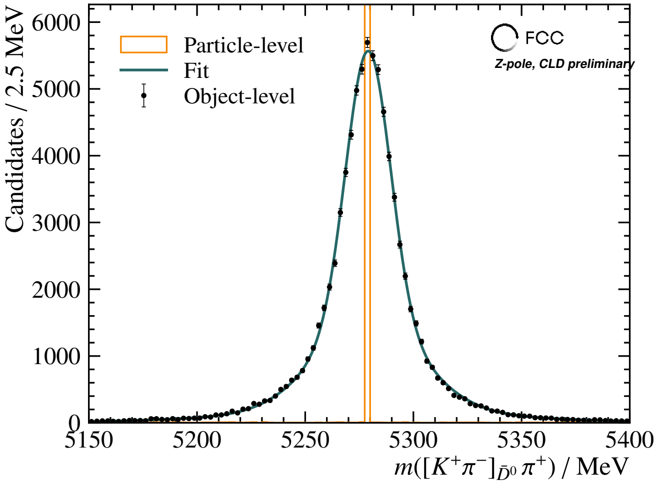




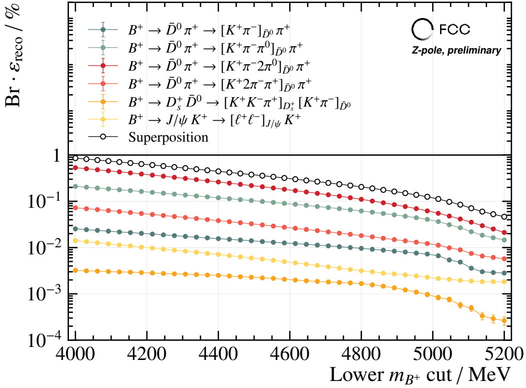
Appendix: CLD B^+ mass fit

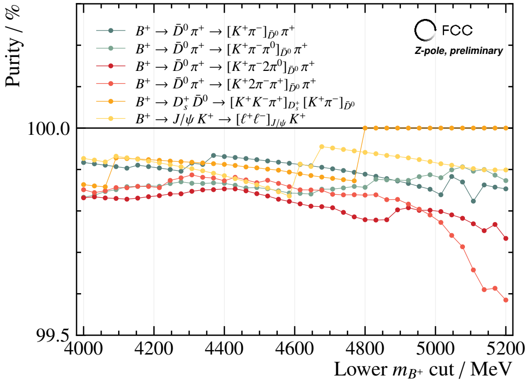
- Fit of the reconstructed B^+ meson with a sum of three Gaussian distributions
- Fit parameters: $\mu = 5279.09\,\text{MeV}$ and $\sigma_{\text{comb.}} = 12.75\,\text{MeV}$



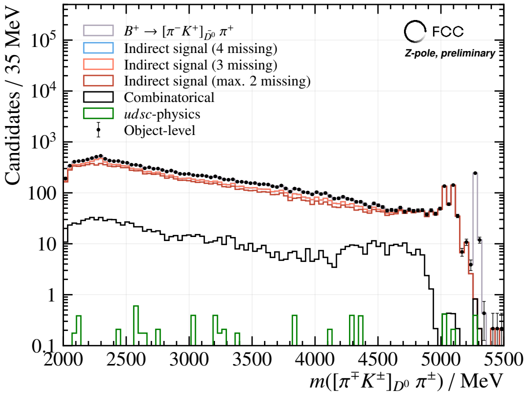
Appendix: Further increasing the efficiency

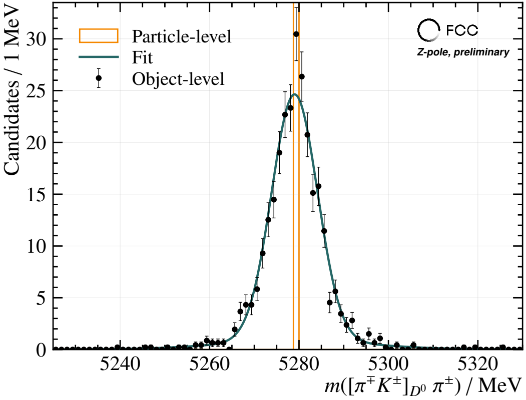
- Efficiency of the tagger can be furhter improved by accepting also partially reconstructed candidates
- No degradation of the purity



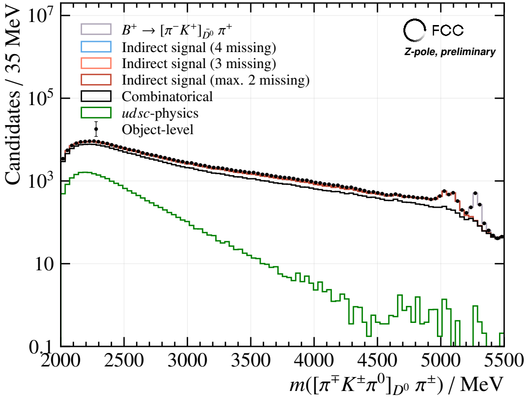


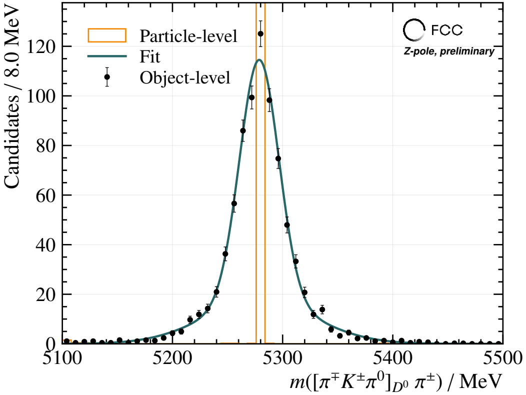
Fast Simulation: Decay mode $B^+ \to [K^+\pi^-]_{\bar{D}^0}\pi^+$





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





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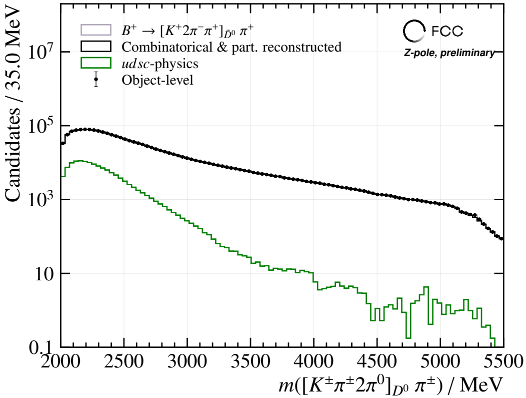

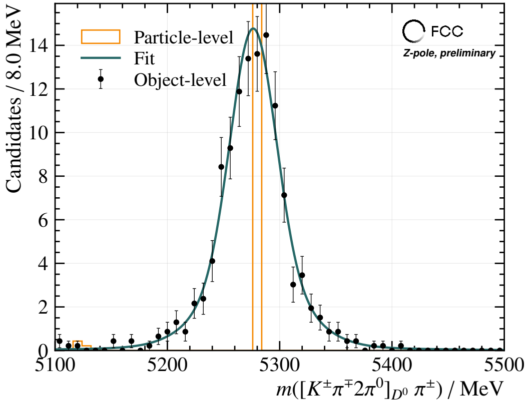

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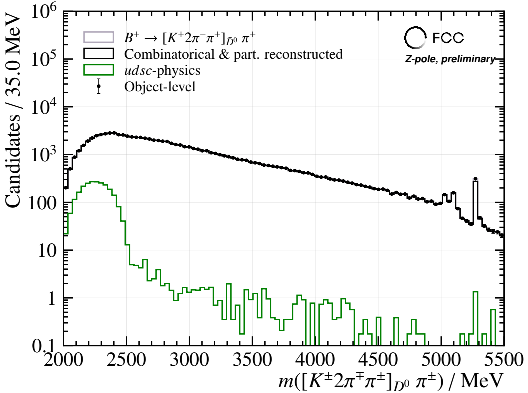
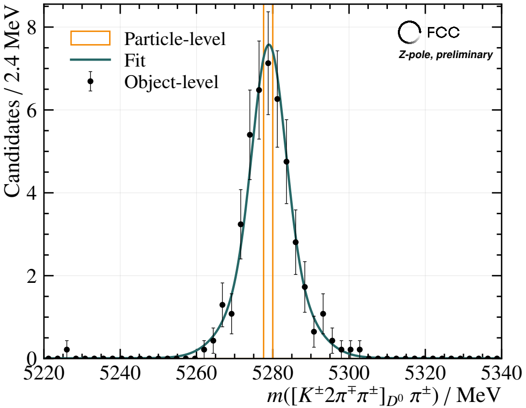
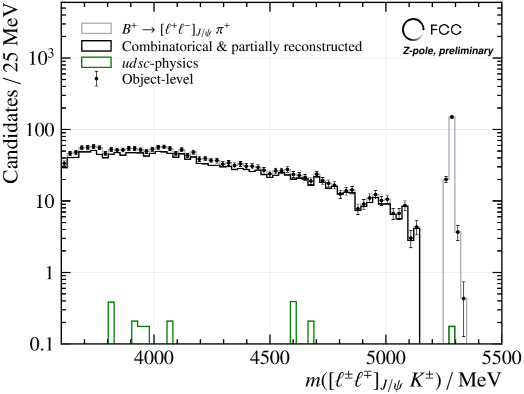
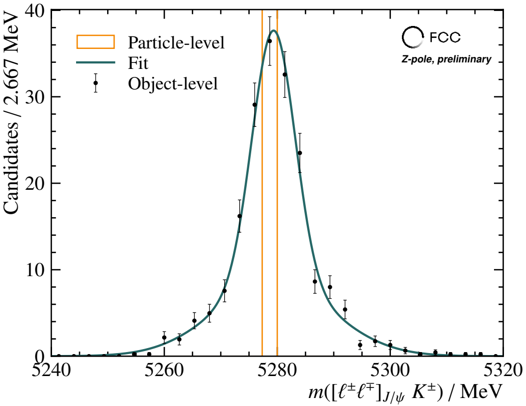


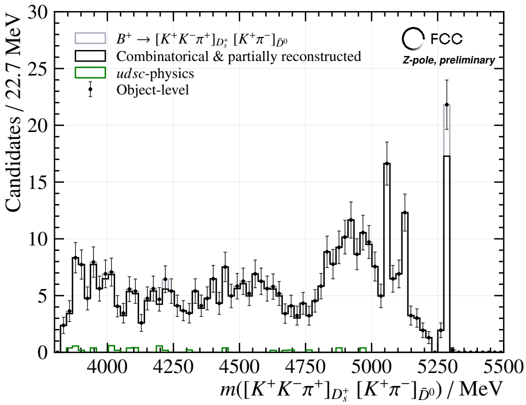


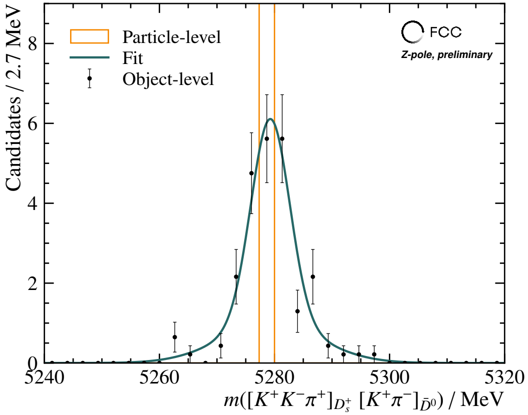
Fast Simulation: Decay mode $B^+ \to [\ell^+\ell^-]_{J/\psi} K^+$





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





Appendix: Internal Analysis Note

- Status: Fast Simulation reconstruction described in detail + Full Simulation studies to be included

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-001
FCC-ee-INT-2023-001
February 02, 2023

Reconstructed exclusive b-hadron decays as hemisphere jet charge tagger and its application for the measurement of R_b and A^b_{FB}

FCC-ee collaboration

Abstract

This paper presents a novel approach using exclusively reconstructed b-hadron decays as a hemisphere tagger and its application for the measurement of R_b, the ratio of the Z-boson coupling to b-quarks to its coupling to all quarks, as well as the b-quark forward-backward asymmetry (A^b_{FB}). By focusing on the identification and reconstruction of b-hadrons exclusively within one hemisphere of an event, the technique aims to enhance the purity of the b-quark sample and improve the precision of these measurements as important tests of the Standard Model's parameters. We present the implementation and validation of the hemisphere tagger technique, including the selection criteria, event reconstruction algorithms and the discussion of uncertainties in the experimental environment of the Tera-Z programme at the FCC-ee.

Contents

1 Introduction

Measurements of electroweak precision observables in high-energy physics requires the precise and unambiguous determination of the products emerging from the hard scattering. The products, summarised as a collection of particles sharing the same thrust in a hemisphere of the collision, are referred to as a *jet*. The determination of the jet flavour, i. e. the determination of the flavour of the originating quark, becomes complicated due many quantum chromodynamic (QCD) processes taking place before the hadronisation of the quark.

The two most prominent observables at electron-positron colliders with collision energies of $\sqrt{s} = m_Z$ requiring exquisite and unique determination of the beauty-flavour are the fraction of hadronic Z decays to b-quarks R_b and the forward-backward asymmetry of the b-quark, A^b_{FB}. While R_b is defined as

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \mathrm{had})} \tag{1}$$

and just requires the knowledge about the presence of absence of a b-quark, the forward-backward asymmetry

$$A^b_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}} \tag{2}$$

also asks for the angle and the charge of the quark wrt. the incoming electron (or of the antiquark wrt. the positron).