Measurement of R_b with an exclusive b-tagger

FCC Physics Workshop Annecy 2024

Kevin Kröninger[1], Romain Madar[2], Stéphane Monteil[2], Lars Röhrig[1,2]

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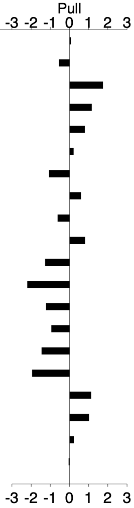
[1]Department of Physics – TU Dortmund University
[2]Laboratoire de Physique de Clermont – Université Clermont-Auvergne

Heavy-quark measurements at the Z-pole

- Best suited at FCC-ee for rich heavy-quark programme?
  $\rightarrow$ Z-pole with $N_Z = 5 \cdot 10^{12}$
- Coupling of the Z to b-quark probes fundamental SM parameters

	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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- Best suited at FCC-ee for rich heavy-quark programme?
  $\rightarrow$ Z-pole with $N_Z = 5 \cdot 10^{12}$
- Coupling of the Z to b-quark probes fundamental SM parameters
- Statistics allow for new ways: combining flavour and EWPO
  $\rightarrow$ Ultra pure beauty-flavour tagging

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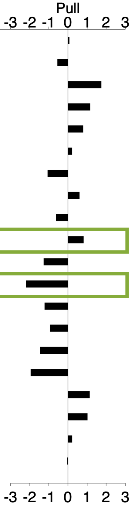
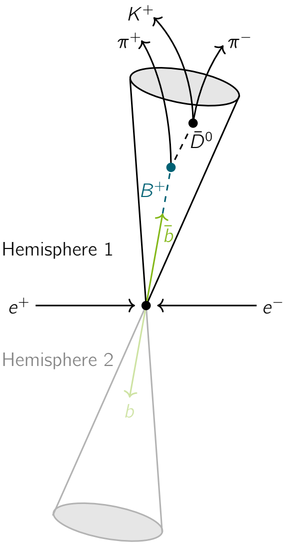
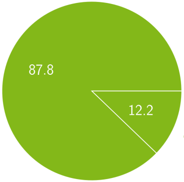


Principle of the measurement

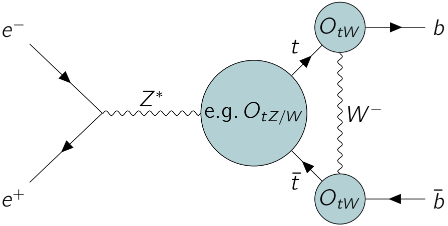
- Produce $Z \to q\bar{q}$ events at $\sqrt{s} = 91\,\text{GeV}$
- Event topology: two back-to-back particle sprays (hemispheres)
- With $N_{Z\to q\bar{q}} = 5 \cdot 10^{12}$ events: measurements limited by $\sigma_{\text{syst.}}$
- Need to reduce $\sigma_{\text{syst.}}$ to $\mathcal{O}(\sigma_{\text{stat.}})$



Principle of the measurement: R_b



- Sensitive to **vertex corrections:** $R_b = \frac{\Gamma_{Z\to b\bar{b}}}{\Gamma_{Z\to q\bar{q}}}$



- **Single tag:** $N_1 = 2N_Z \cdot (R_b\,\varepsilon_b + R_c\,\varepsilon_c + R_{uds}\,\varepsilon_{uds})$
- **Double tag:** $N_2 = N_Z \cdot (R_b\,\varepsilon_b^2\,C_b + R_c\,\varepsilon_c^2\,C_c + R_{uds}\,\varepsilon_{uds}^2\,C_{uds})$
- N_1, N_2, N_Z counted, all other unknown: measure R_b and ε_b simultaneously
- Standard LEP tools (vertex charge, lepton tag): $\sigma_{\text{syst.}}$ dominated by *udsc*-misidentification

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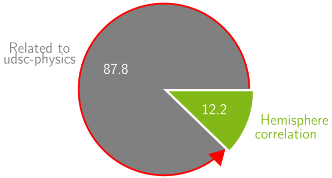
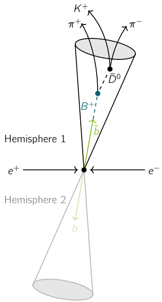


Proposal: b-hemisphere tagger

Hemisphere **flavour**- and **charge** tagging by exclusively reconstructing *b*-hadrons

- Potential purity of 100 %
- Efficiency of 1 %



→ Expected $\sigma^{\text{stat.}}(R_b) = 2.2 \cdot 10^{-5}$

Setting the stage

- Exclusive b-tagger can play **central role** to reduce $\sigma^{\text{syst.}}$

	R_b
b-hadrons	$B^+, B^0_d, B^0_s, \Lambda^0_b$
Requirements	Flavour
Advantages	Remove *udsc*-physics contribution
Remaining $\sigma_{\text{syst.}}$	Hemisphere correlation C_b

- $\varepsilon_b \geq 1.11\,\%$ with > 200 b-hadron decay modes ✓
- Validate purity on $4 \cdot 10^7$ $Z \to q\bar{q}$ (`winter2023`) on 6/200 **representative modes** (varying $N_{\text{trk.}}$, N_{π^0})
  1. Fully charged, two tracks $B^+ \to \bar{D}^0\pi^+ \to [K^+\pi^-]_{\bar{D}^0}\,\pi^+$
  2. Fully charged, three tracks $B^+ \to \bar{D}^0 D_s^+ \to [K^+\pi^-]_{\bar{D}^0}\,[K^+K^-\pi^+]_{D_s^+}$
  3. Fully charged, four tracks $B^+ \to \bar{D}^0\pi^+ \to [K^+2\pi^-\pi^+]_{\bar{D}^0}\,\pi^+$
  4. One π^0, two tracks $B^+ \to \bar{D}^0\pi^+ \to [K^+\pi^-\pi^0]_{\bar{D}^0}\,\pi^+$
  5. Two π^0, two tracks $B^+ \to \bar{D}^0\pi^+ \to [K^+\pi^-2\pi^0]_{\bar{D}^0}\,\pi^+$
  6. Two leptons $B^+ \to J/\psi\,K^+ \to [\ell^+\ell^-]_{J/\psi}\,K^+$

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Reconstruct exemplarily →

1. Fully charged, two tracks — $B^+ \to \bar{D}^0\pi^+ \to [K^+\pi^-]_{\bar{D}^0}\,\pi^+$
2. Fully charged, three tracks — $B^+ \to \bar{D}^0 D_s^+ \to [K^+\pi^-]_{\bar{D}^0}\,[K^+K^-\pi^+]_{D_s^+}$
3. Fully charged, four tracks — $B^+ \to \bar{D}^0\pi^+ \to [K^+2\pi^-\pi^+]_{\bar{D}^0}\,\pi^+$
4. One π^0, two tracks — $B^+ \to \bar{D}^0\pi^+ \to [K^+\pi^-\pi^0]_{\bar{D}^0}\,\pi^+$
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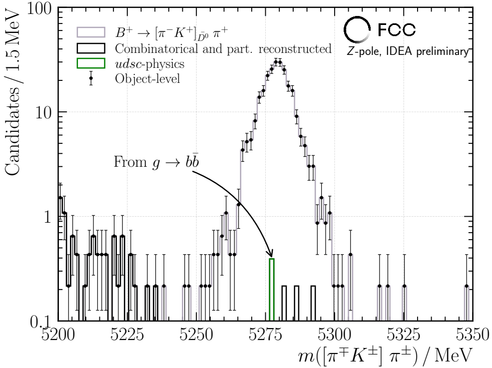
Exclusive b-hadron reconstruction

Fast Simulation (IDEA)

- Combine K and π (100 % particle-ID) tracks to D^0 candidates (emulate 50 µm vertex resolution)
- D^0 candidates + π track to B^+ candidate: cut on B^+ **flight distance** of 300 µm (boost of ~ 6)
- Observable to quantify **purity**: invariant b-hadron mass spectrum with $E_B > 20$ GeV



- First: focus on **mass-peak region** to get control on $\sigma^{\text{syst.}}$
  $\rightarrow$ Purity of 99.8 %, contamination in signal region from $q \rightarrow q + [b\bar{b}]_g$

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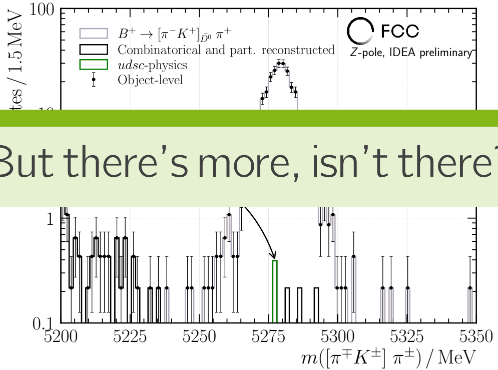

But there's more, isn't there?

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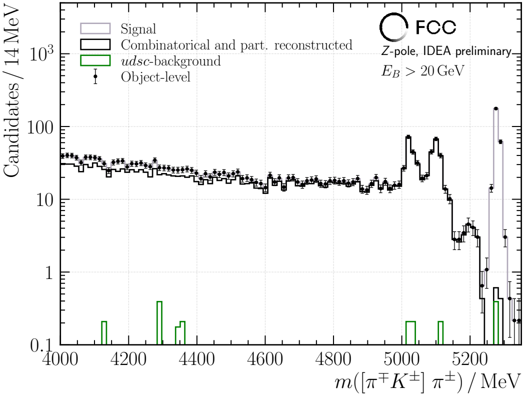
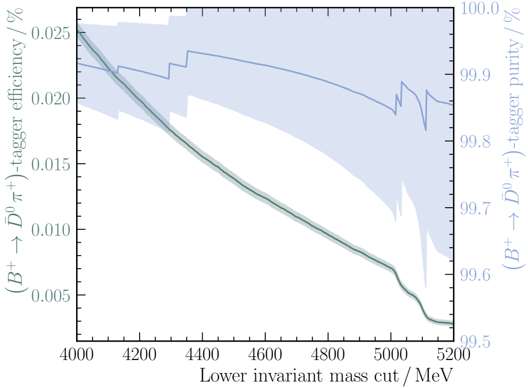
Exclusive b-hadron reconstruction

- Combine K and [partly covered] tex resolution)
- D^0 candidates + [partly covered] boost of ~ 6)

But there's more, isn't there? Yes!

- Observable to quantify **purity**: invariant b-hadron mass spectrum with $E_B > 20$ GeV



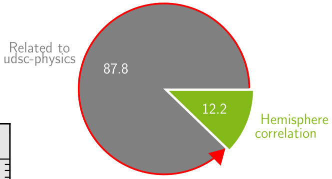


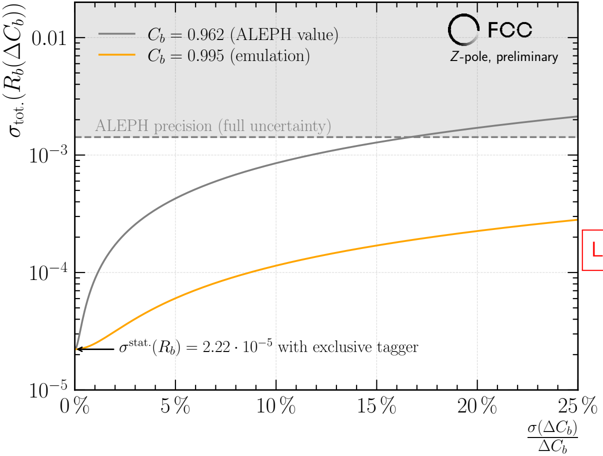
- Part. reconstructed are no background! $\rightarrow$ **efficiency gain** by enlarging mass window to no loss in purity!
- **But for now:** Examine B^+ candidates in mass-peak region

Systematic uncertainty: importance of C_b

$$N_1 = 2\, R_b\, \varepsilon_b\, N_Z$$
$$N_2 = R_b\, \varepsilon_b^2\, C_b\, N_Z$$

- Ultra-pure: hemisphere correlation dominating systematic uncertainty
  → Quantifies dependence of **tagging efficiencies in the two hemispheres**:
  → $C_b = \frac{\varepsilon_{b\bar{b}}}{\varepsilon_b \cdot \varepsilon_{\bar{b}}}$
- Control over $\Delta C_b = 1 - C_b$ crucial for R_b measurement!



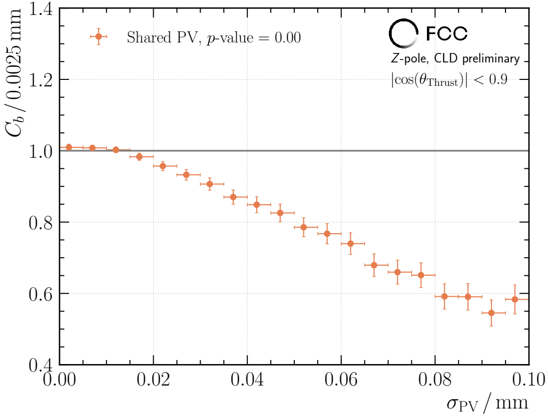


LEP+SLD $\mathcal{O}(\sigma_{\text{tot.}}(R_b)) = 10^{-4}$

Hemisphere correlation: PV measurement uncertainty

Full Simulation (CLD)

- LEP found: C_b mainly departed from 1 because of **primary-vertex measurement uncertainty** σ_{PV}



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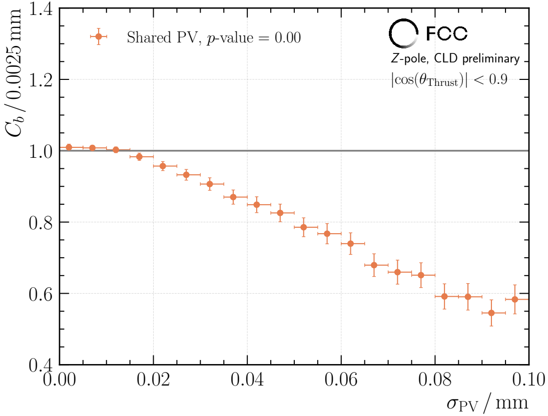
- Sample: 10^6 FullSim CLD events of $B^+ \to [K^+\pi^-]_{\bar{D}^0}\pi^+$ (forcing both legs with `EvtGen`)



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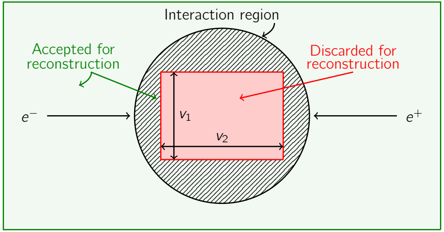
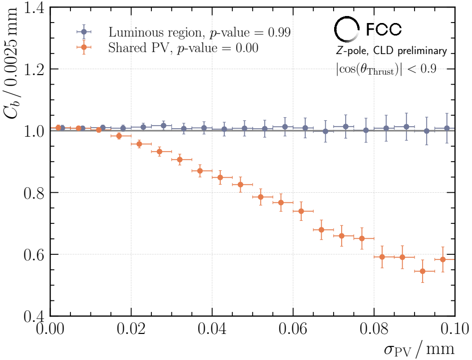
- Here: select tracks for reconstruction by using optimised cuts (v_1 and v_2) in **luminous region**





- $C_b^{\mathrm{PV}} = 0.978 \pm 0.003$ vs. $C_b^{\text{Luminous region}} = 1.009 \pm 0.003$

Results: R_b uncertainty budget

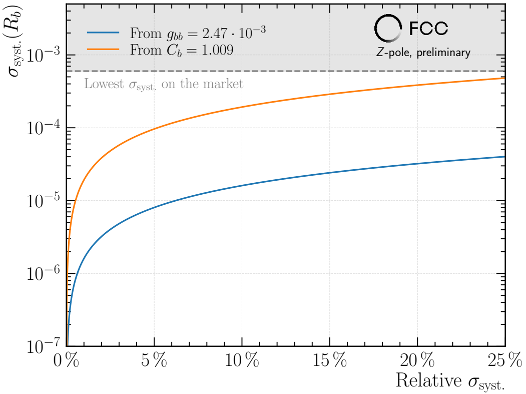
Full Simulation (CLD)

- So far: systematic uncertainty considered
  - Hemisphere correlation: $C_b = 1.009 \pm 0.003 \Rightarrow \frac{\sigma(\Delta C_b)}{\Delta C_b} \approx 33\,\%$

Full Simulation (CLD)

Results: R_b uncertainty budget

- So far: systematic uncertainty considered
  - Hemisphere correlation: $C_b = 1.009 \pm 0.003 \Rightarrow \frac{\sigma(\Delta C_b)}{\Delta C_b} \approx 33\,\%$
  - Signal region contamination from gluon splitting: $g_{b\bar{b}} = (2.47 \pm 0.56) \cdot 10^{-3} \Rightarrow \frac{\sigma(g_{b\bar{b}})}{g_{b\bar{b}}} \approx 23\,\%$
- **Target:** $\sigma^{\text{stat.}}(R_b) = 2.2 \cdot 10^{-5}$ with exclusive tagger and $\varepsilon_b = 1\,\%$



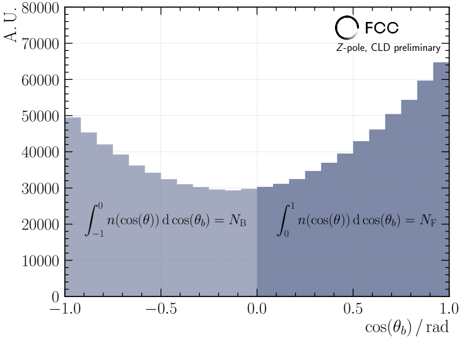
	Luminous region
Current syst. precision	$\sigma^{\text{tot.}}(R_b) = 6.4 \cdot 10^{-4}$
1 % syst. precision	$\sigma^{\text{tot.}}(R_b) = 2.9 \cdot 10^{-5}$

→ C_b dominating uncertainty

Full Simulation (CLD)

Extension for the measurement of A_{FB}^{b}

- We have an **ultra pure tagger** at hand: what else?
- As seen: exclusive b-tagger can play central role to reduce $\sigma^{\mathrm{syst.}}$
- Especially interesting for $A_{\mathrm{FB}}^{b} = \frac{N_{\mathrm{F}}-N_{\mathrm{B}}}{N_{\mathrm{F}}+N_{\mathrm{B}}}$
  $\rightarrow$ Expected $\sigma_{\mathrm{stat.}}(A_{\mathrm{FB}}^{b}) = 1.05 \cdot 10^{-5}$ (current: $\sigma_{\mathrm{tot.}}(A_{\mathrm{FB}}^{b}) = 1.6 \cdot 10^{-3}$)

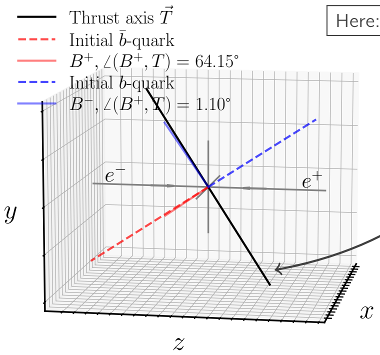


	R_b	A_{FB}^{b}
b-hadrons Requirements	$B^{+}, B_d^0, B_s^0, \Lambda_b^0$ Flavour	B^{+}, Λ_b Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	Remove *udsc*-physics contribution **Overcome mixing dilutions** and possibly reduce hemisphere confusion
Remaining $\sigma_{\mathrm{syst.}}$	Hemisphere correlation C_b	QCD corrections

Full Simulation (CLD)

Systematic uncertainty of A_{FB}^b

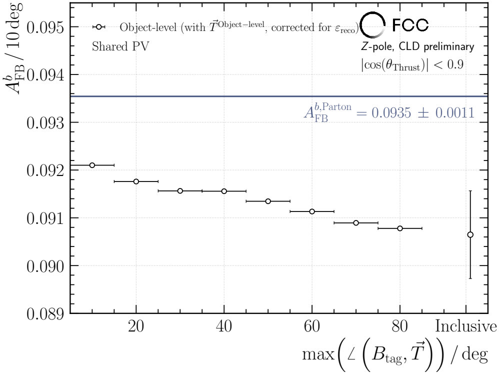
- Dominant systematic uncertainty: (hard) **gluon radiation** from b-quark (up to hemisphere confusion)
- Since b-quark direction not directly accessible: use **thrust** $\vec{T}$
- Direction of reconstructed b-hadron: **estimator for gluon emission quantity**
- The smaller the angle $\angle(\vec{B}_{\text{tag}}, \vec{T})$, the softer is the gluon radiation



Here: thrust axis not a valid direction estimator!

Gluon radiation estimator: $\angle(\vec{B}_{\text{tag}}, \vec{T})$

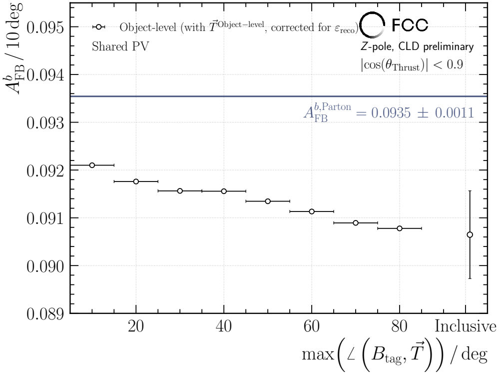
- Quantify the amount of gluon radiation by $\angle(\vec{B}, \vec{T})$
- Cut on maximally allowed angle reduces QCD-related effects by 50 %

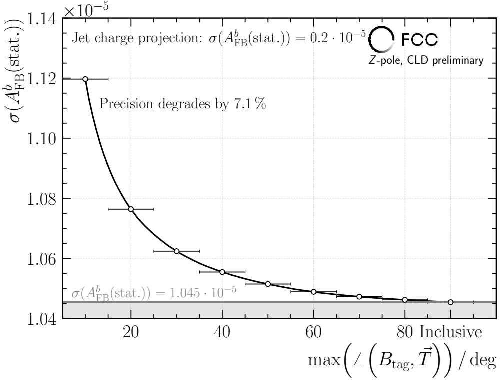


Full Simulation (CLD)

Gluon radiation estimator: $\angle(\vec{B}_{\text{tag}}, \vec{T})$

- Quantify the amount of gluon radiation by $\angle(\vec{B}, \vec{T})$
- Cut on maximally allowed angle reduces QCD-related effects by 50 %
- Slight degradation of statistical precision (~ 7 %) to $\boxed{\sigma_{\text{stat.}} = 1.12 \cdot 10^{-5}}$ (Z-pole extrapolation)





$\rightarrow$ $\sigma_{\text{syst.}}$ WIP by varying b-fragmentation fraction, renormalisation scale & parton shower model

Conclusions and Outlook

- Fruitful synergy in flavour and EWPO measurements at FCC-ee
- Use exclusive *b*-(flavour) tagger to eliminate *udsc*-physics contributions and to get $\mathcal{O}(\sigma_{\text{stat.}}) = \mathcal{O}(\sigma_{\text{syst.}})$
- R_b measurement: luminous region cut essential to reduce hemisphere correlations

$$\rightarrow \text{Now:} \quad R_b = \mu(R_b) \pm 2.2 \cdot 10^{-5}(\text{stat.}) \pm 6.4 \cdot 10^{-4}(\text{syst.})$$

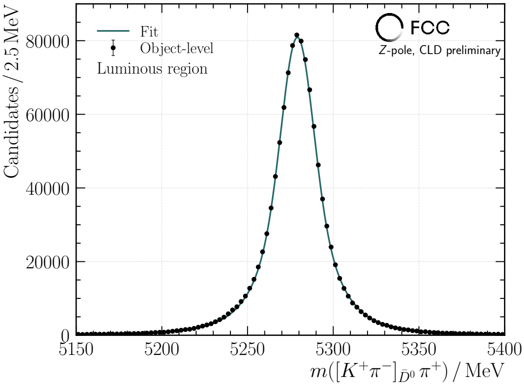
$$\rightarrow \text{With } \frac{\sigma(\Delta C_b)}{\Delta C_b} = 1\,\%: \quad R_b = \mu(R_b) \pm 2.2 \cdot 10^{-5}(\text{stat.}) \pm 1.9 \cdot 10^{-5}(\text{syst.})$$

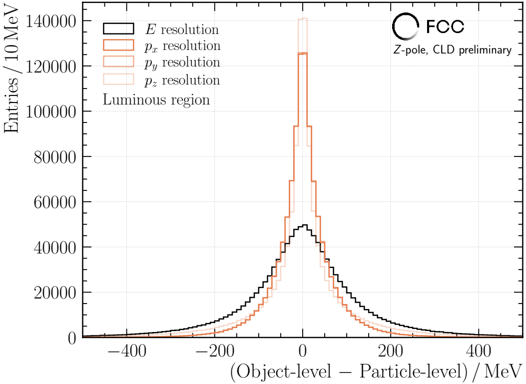
- A_{FB}^b measurement: overcome mixing dilutions by using B^+ and Λ_b^0 decays
- Cut on opening angle between thrust and *b*-hadron direction mitigates QCD effects (WIP!)
  $\rightarrow \sigma_{\text{stat.}} = 1.12 \cdot 10^{-5}$ with $\angle(B_{\text{tag}}, \vec{T}) < 10^\circ$

$B^{\pm}$ reconstruction at CLD

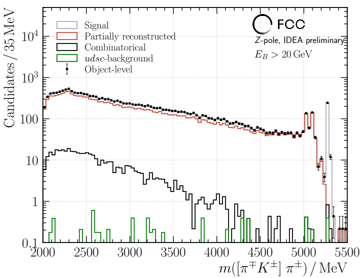
Full Simulation (CLD)

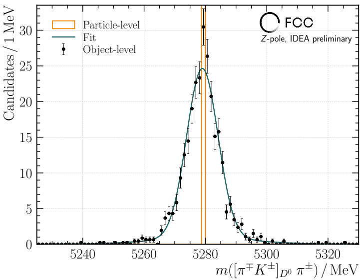
- Using the collection tracks vertexed with the DELPHES vertexing capabilities
- Recent developments allow for neutral peusdotracks, here: $\bar{D}^0 \to K^+\pi^-$

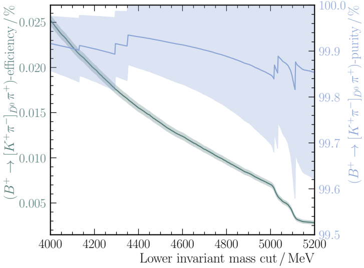




Decay mode $B^+ \to [K^+\pi^-]_{\bar{D}^0}\pi^+$







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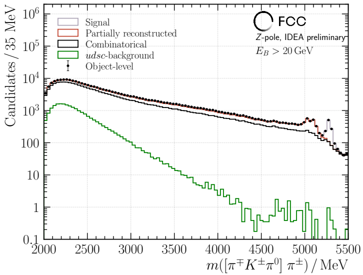
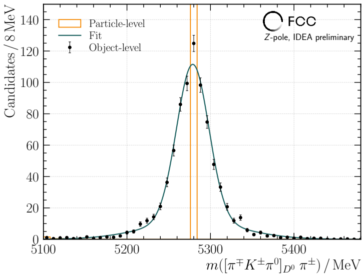
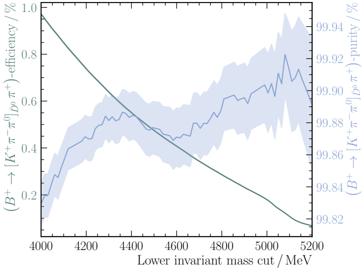
Fast Simulation (IDEA)

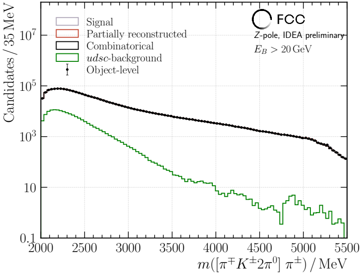


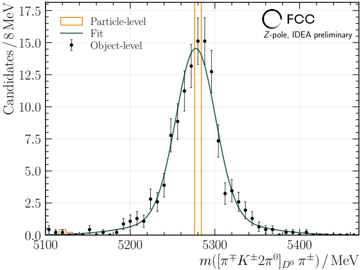


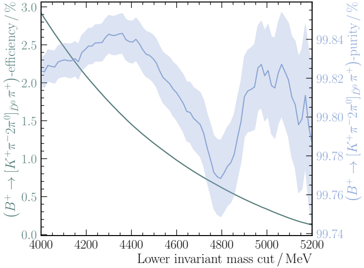


Decay mode $B^+ \to [K^+\pi^-2\pi^0]_{\bar{D}^0}\pi^+$

Fast Simulation (IDEA)

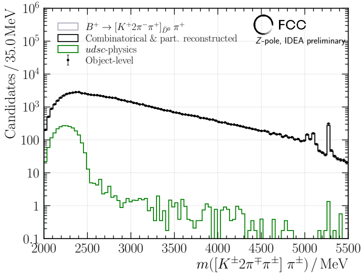


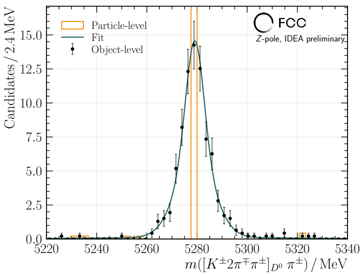


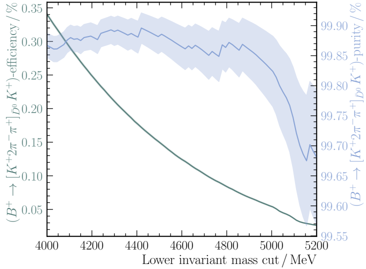


Decay mode $B^+ \to [K^+2\pi^-\pi^+]_{\bar{D}^0}\pi^+$

Fast Simulation (IDEA)

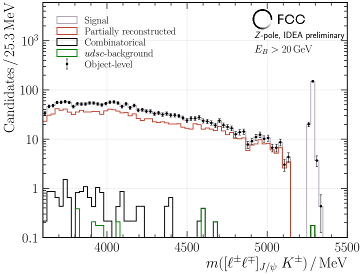


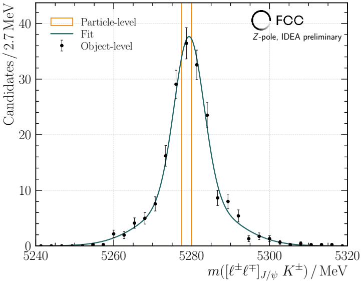


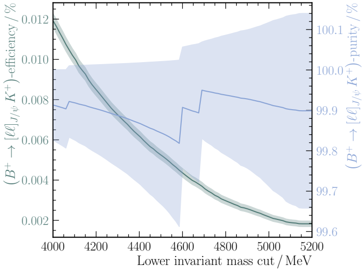


Decay mode $B^+ \to [\ell^+\ell^-]_{J/\psi} K^+$

Fast Simulation (IDEA)

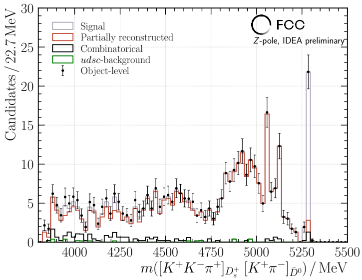


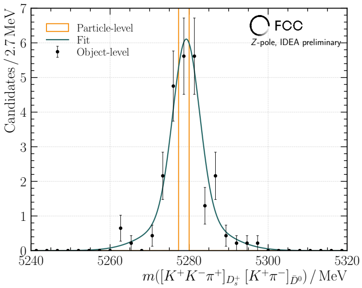


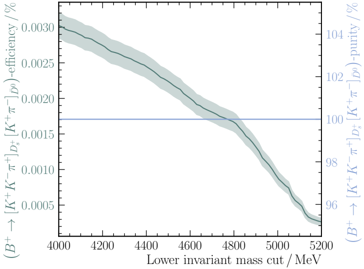


Decay mode $B^+ \to [K^+K^-\pi^+]_{D_s^+}[K^+\pi^-]_{\bar{D}^0}$

Fast Simulation (IDEA)



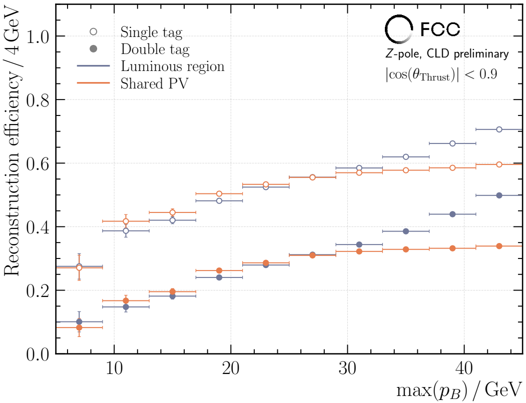


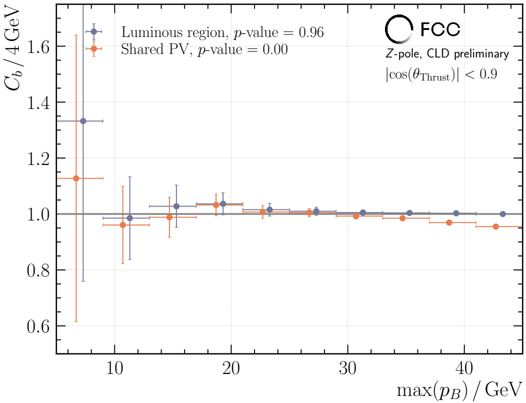


Hemisphere correlation: momentum dependence

Full Simulation (CLD)

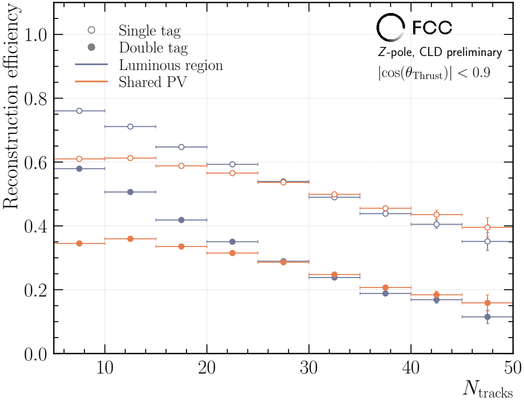
- Single-/double-tag efficiencies and C_b as function of the highest-momentum B-meson of the event
- p-value from χ^2-test with $C_b = 1$

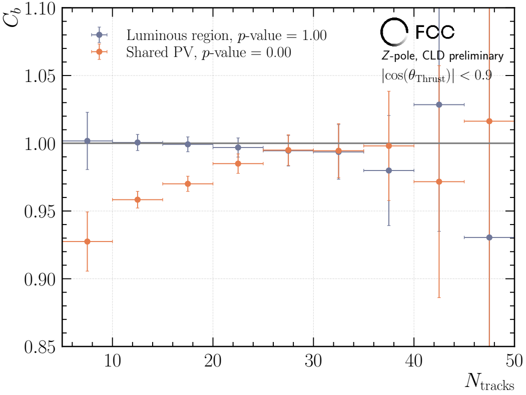




Hemisphere correlation: number of event tracks

- Single-/double-tag efficiencies and C_b as function of the number of tracks of the event
- p-value from χ^2-test with $C_b = 1$





Hemisphere correlation: $\cos(\theta_B)$

Full Simulation (CLD)

- Single-/double-tag efficiencies and C_b as function of the B-meson with highest $\cos(\theta_B)$ of the event
- p-value from χ^2-test with $C_b = 1$