Using exclusive b-hadron decays as hemisphere taggers for a precise A_{FB}^{b} and R_b determination

FCC-ee Electroweak Precision – Progress Meeting

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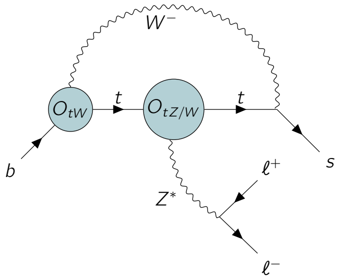
Motivation

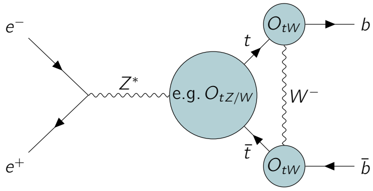
- Combination of top- and beauty energy scales to constrain dimension-6 operators in SMEFT
- Anomalies at $\mathcal{O}(m_B)$ and $\mathcal{O}(m_Z)$ **translate to higher energy scale**

$\mathcal{O}(m_B) \sim 5$ GeV



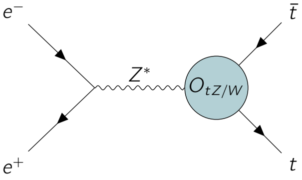
$\Rightarrow b \rightarrow s$ FCNCs

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



$\Rightarrow \approx 1\,\%$ of $R_b = \frac{\Gamma_{Z\rightarrow b\bar{b}}}{\Gamma_{Z\rightarrow q\bar{q}}}$ in the SM

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

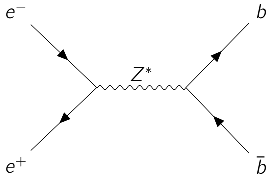


$\Rightarrow$ Modification of e. g. the t forward-backward asym.

- High precision and variety of observables is the key to extract tight constraints
  $\rightarrow$ **To which extent can FCC-ee improve them?**

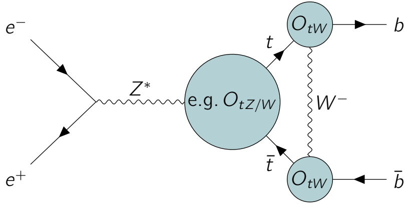
Measurements at the Z-pole: R_b and A^b_{FB}

- $\mathcal{O}(10^{12})$ $Z \to b\bar{b}$ events @FCC-ee: measurements **systematically limited**
  $\to$ need for novel approaches to reduce to the scale of the statistical one
- Prominent observables at the Z-pole: A^b_{FB} and R_b with potential for SM-deviation within current uncertainties



Tree-level contribution.

$\oplus$

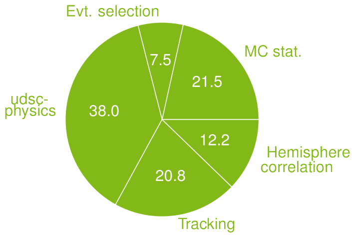


Zbb-vertex correction, contribution $\approx 1\,\%$.

$\to$ Taking Zbb-vertex corrections for R_b into account: $\frac{\Delta R_b^{\mathrm{LEP}}}{R_b^{\text{tree-level}} - R_b^{\mathrm{SM}}} \approx 40\,\%$

- Today: guide through a novel hemisphere tagger and its proof of principle
  $\to$ **Application on R_b (further discussed here) and A^b_{FB} and evaluation of the systematic uncertainties**

Novel hemisphere tagger



- À la LEP: Tagging of hemispheres based on lifetime of b-hadrons and b/c-hadron mass difference
- From ALEPH collaboration [1]:
  $R_b = 0.2167 \pm 0.0011\,(\text{stat.}) \pm 0.0013\,(\text{syst.})$
  $\rightarrow$ Systematic uncertainty dominated by light-quark and c-physics + MC statistics

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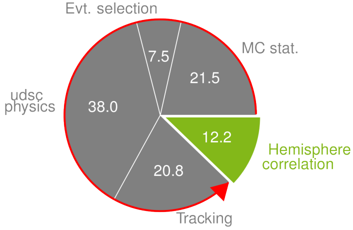
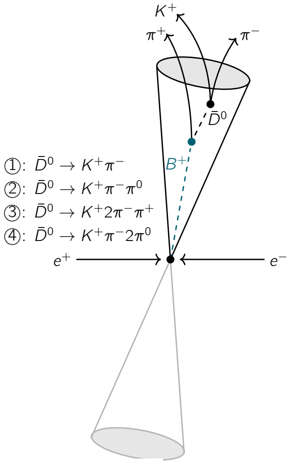


Novel approach to tag hemispheres

Tag the hemispheres by exclusively reconstruct b-hadrons with a potential purity of $P = 100\,\%$ and an efficiency of $\varepsilon \approx 1\,\%$

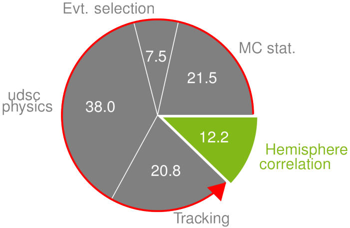


- Efficiency of $1\,\%$ in reach with a list of b-hadron ($B^+, B^0, B_s, \Lambda_b^0$) decay modes (at max. $2\pi^0$):
  1. **Charmonium modes**, e. g. $B^+ \rightarrow J/\psi\, K^+$
  2. Modes with **one and two charm-mesons**, e. g. $B^+ \rightarrow \bar{D}^0\pi^+$ and $B^+ \rightarrow \bar{D}^0 D_s^+$
  3. **Baryon decays**, e. g. $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^+2\pi^-$

$\rightarrow$ Can proof an efficiency of **1.11 %** from PDG-search ✓
$\hookrightarrow$ Reconstruction efficiencies not taken into account!

Advantages and starting point

- Exclusive b-hadron reconstruction: **No contribution from light-quark and c-physics** $\rightarrow$ Reduction of major systematic uncertainty
- Proof of principle (including all uncertainty correlations):



À la LEP with FCC-ee statistics

- Using efficiencies from ALEPH collaboration [1] by including light-quark physics
- Statistical uncertainty: $\Delta R_b(\text{stat.}) = 2.022 \cdot 10^{-6}$
- $\Delta R_b(\text{syst.}) = \Delta R_b^{\text{LEP}}(\text{syst.}) = \mathcal{O}(10^{-4})$

Exclusive b-hadron decays

- No contribution from *udsc* physics: $\varepsilon_{c,uds} \rightarrow 0.0$ and $\varepsilon_b = 1\,\%$
- Statistical uncertainty: $\Delta R_b(\text{stat.}) = 4.570 \cdot 10^{-5}$
- Reduce $\Delta R_b(\text{syst.})$ to $\mathcal{O}(\Delta R_b(\text{stat.}))$

↪ Reduction of major source of systematic uncertainty to the cost of statistical uncertainty, still: **factor 20 improvement wrt. LEP**

- Purity and reconstruction efficiency evaluated on `winter2023` samples with 10^7 events each: $Z \rightarrow b\bar{b}, Z \rightarrow c\bar{c}, Z \rightarrow s\bar{s}, Z \rightarrow ud\overline{ud}$
- Vertexing information (still) taken from MC + inclusion of partially reconstructed particles

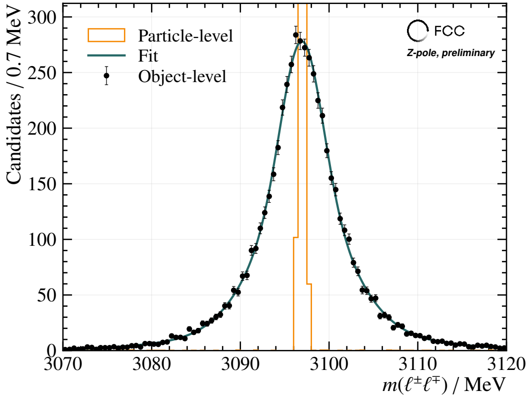
$\rightarrow$ Evaluation of the vertexing assumptions WIP

Representative decay modes

- Examined a number of representative decays: $B^+ \to J/\psi\, K^+$, $B^+ \to \bar{D}^0\pi^+$, $B^+ \to \bar{D}^0\, D_s^+$ with $\bar{D}^0 \to K^+\pi^-(\pi^0)$, $\bar{D}^0 \to K^+2\pi^-\pi^+$ and $D_s^+ \to K^+\pi^-\pi^+$
- To emulate vertexing resolution: charged particles have to have $< 50\,\mu\text{m}$ displacement
- **Flight distance cut:** B^+-PV displacement $> 300\,\mu\text{m} \to \varepsilon_{\text{PV-displacement}} = 89.59\,\%$

$B^+ \to J/\psi\, K^+ \to \ell\ell\, K^+$

- Reconstruction of the leptonic J/ψ mode: $\mu = 3096.89\,\text{MeV}$, $\sigma_{\text{comb.}} = 3.98\,\text{MeV}$



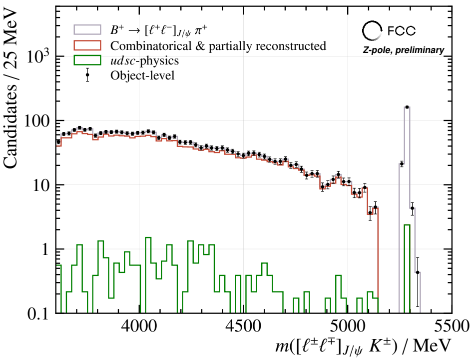
Reconstruction efficiency

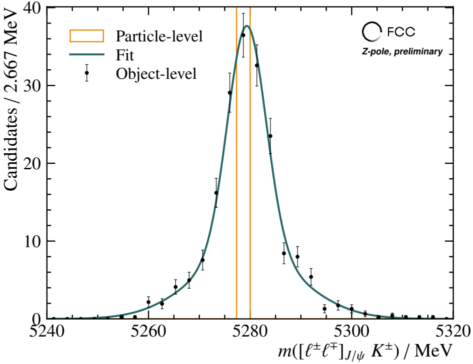
- Produced $J/\psi \to \ell\ell$ in the sample: 26 340
- Reconstructed, truth-matched $J/\psi \to \ell\ell$: 25 527

$\hookrightarrow$ $\varepsilon_{[3070,3120]\,\text{MeV}}(J/\psi \to \ell\ell) = 96.91\,\%$

$B^+ \to J/\psi\, K^+ \to \ell\ell\, K^+$ reconstruction

- J/ψ candidates accepted in $m_{\ell\ell} \in [3070, 3120]$ MeV window
- Charged kaon added to the system and vertex displacement cut applied
- Fit results to the truth-matched B^+ signal (right): $\mu = 5279.35$ MeV, $\sigma_{\text{comb.}} = 5.00$ MeV



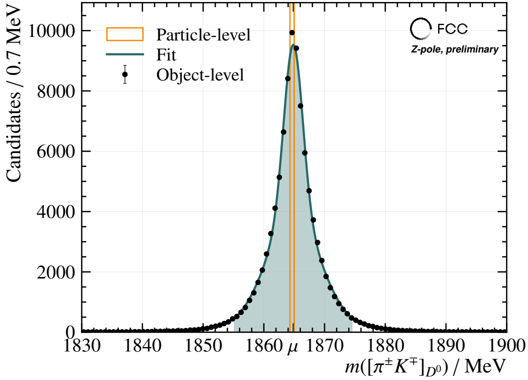


- **Reconstruction efficiency** $B^+ \to J/\psi\, K^+ \to \ell\ell\, K^+$: 85.67 %
- **Purity** $P_{B^+ \to J/\psi\, K^+} = 98.73\,\%$ within $m_{B^+} \in [5240, 5320]$ MeV

→ Purity could further be improved by also accepting also partially reconstructed candidates ($B^+ \to J/\psi\, K^0\pi^+$, $B^+ \to J/\psi\, K^+\pi^+\pi^-, \dots$)

Fully charged $\bar{D}^0$ decay: $B^+ \to \bar{D}^0\pi^+ \to K^+\pi^-\pi^+$

- Charged pion and kaon collection combined with opposite charges to emerge from the same hemisphere
- Vertexing between kaon and pion $< 50\,\mu\text{m}$
- Triple-Gaussian distribution applied to fit the mass peak and to determine 3σ intervals (colored region) $\to \mu = 1864.85\,\text{MeV}, \sigma_{\text{comb.}} = 3.72\,\text{MeV}$



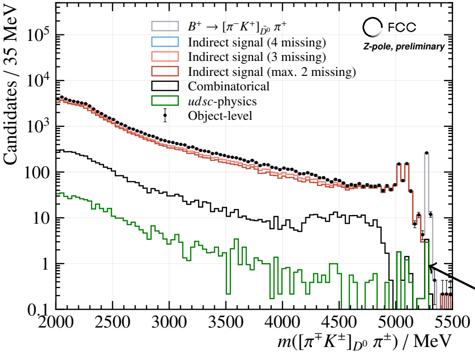
Reconstruction efficiency

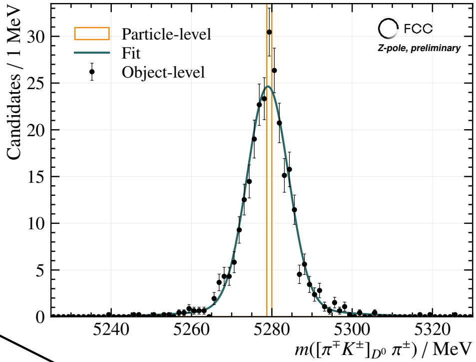
- Produced $\bar{D}^0 \to K^+\pi^-$ in the sample: 473 365
- Reconstructed $\bar{D}^0 \to K^+\pi^-$, truth-matched, within $3\sigma_{\text{comb.}}$: 425 917

$\hookrightarrow$ $\varepsilon_{3\sigma_{\text{comb.}}}(\bar{D}^0 \to K^+\pi^-) = 89.98\,\%$

Fully charged $\bar{D}^0$ decay: $B^+ \to \bar{D}^0\pi^+ \to K^+\pi^-\pi^+$

- $\bar{D}^0$ candidates accepted within 5σ interval
- Distinguished partially reconstructed particles in different categories: 2/3/4 particles missing
- Fit results to the truth-matched B^+ signal (right): $\mu = 5279.01\,\text{MeV}$, $\sigma_{\text{comb.}} = 5.00\,\text{MeV}$



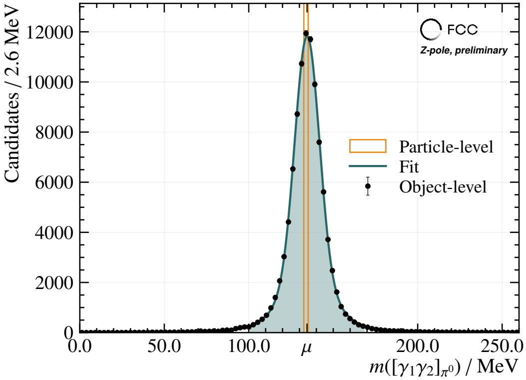


- **Reconstruction efficiency** $B^+ \to \bar{D}^0\,\pi^+ \to K^+\pi^-\pi^+$: 76.41 %
- **Purity** $P_{B^+\to\bar{D}^0\,\pi^+} = 98.89\,\%$ within $m_{B^+} \in [5240, 5320]\,\text{MeV}$

Background entering the signal region from gluon splitting

$\bar{D}^0$ decay with one π^0: $B^+ \to \bar{D}^0\pi^+ \to K^+\pi^-\pi^0\pi^+$

- π^0 reconstruction: Combine two photons with angle $< 45°$
  $\to \mu = 134.53\,\text{MeV}, \sigma_{\text{comb.}} = 6.74\,\text{MeV}$



- **Reconstruction efficiency**
  $\varepsilon_{5\sigma_{\text{comb.}}}(\pi^0 \to \gamma\gamma) = 94.06\,\%$

$\bar{D}^0$ decay with one π^0: $B^+ \to \bar{D}^0 \pi^+ \to K^+ \pi^- \pi^0 \pi^+$

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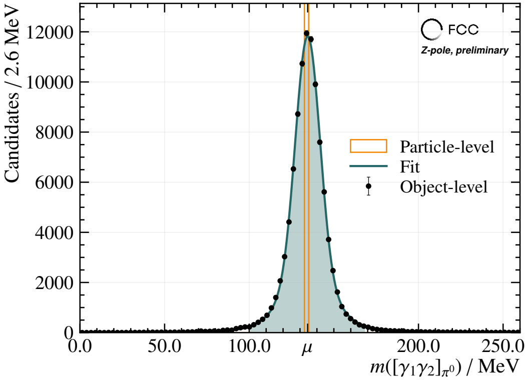
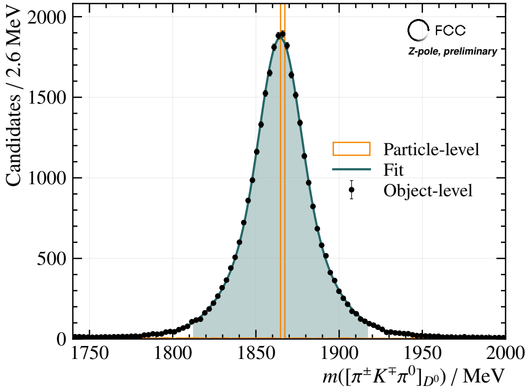


- **Reconstruction efficiency**
  $\varepsilon_{5\sigma_{\text{comb.}}}(\pi^0 \to \gamma\gamma) = 94.06\,\%$

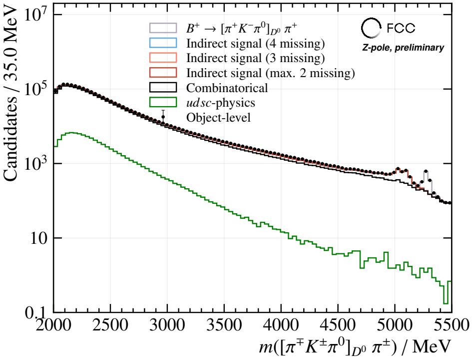
- <u>D^0 reconstruction:</u> Triple-Gaussian distribution applied to fit the truth-matched mass peak
  $\to \mu = 1864.61\,\text{MeV}$, $\sigma_{\text{comb.}} = 22.82\,\text{MeV}$

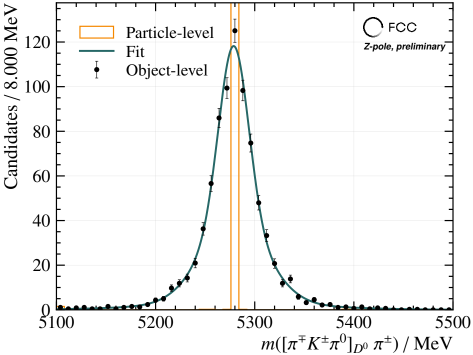


- **Reconstruction efficiency**
  $\hookrightarrow$ $\varepsilon_{2\sigma_{\text{comb.}}}(\bar{D}^0 \to K^+ \pi^- \pi^0) = 77.06\,\%$

$\bar{D}^0$ decay with one π^0: $B^+ \to \bar{D}^0\pi^+ \to K^+\pi^-\pi^0\pi^+$

- $\bar{D}^0$ candidates accepted within 5σ interval
- Distinguished partially reconstructed particles in different categories: 2/3/4 particles missing
- Fit results to the truth-matched B^+ signal (right): $\mu = 5278.74\,\text{MeV}$, $\sigma_{\text{comb.}} = 26.59\,\text{MeV}$





- **Reconstruction efficiency** $B^+ \to \bar{D}^0\,\pi^+ \to K^+\pi^-\pi^+$: 64.54 %
- **Purity** $P_{B^+\to\bar{D}^0\,\pi^+} = 98.30\,\%$ within $m_{B^+} \in [5100, 5500]\,\text{MeV}$

R_b: Concluding remarks

- Efficiency can be improved by constant purity by accepting also partially reconstructed particles $\rightarrow$ set a lower mass cut in the B^+ spectrum
- Vertexing assumptions with the updated `FCCAnalyses` to be evaluated

Summary of the reconstruction efficiencies (so far):

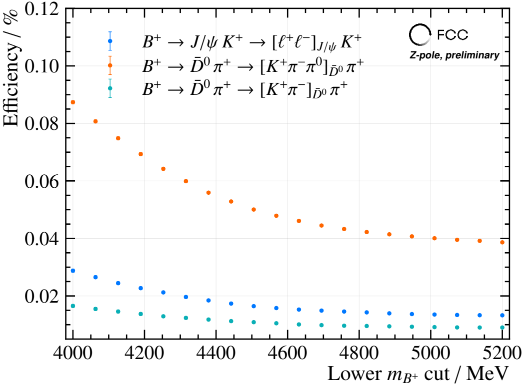
$B^+ \rightarrow J/\psi\, K^+ \rightarrow \ell\ell\, K^+$: $\varepsilon = 85.67\,\%$

$B^+ \rightarrow \bar{D}^0\pi^+ \rightarrow K^+\pi^-\pi^+$: $\varepsilon = 76.41\,\%$

$B^+ \rightarrow \bar{D}^0\pi^+ \rightarrow K^+\pi^-\pi^0\pi^+$: $\varepsilon = 64.54\,\%$

$B^+ \rightarrow \bar{D}^0\pi^+ \rightarrow K^+2\pi^-\pi^+\pi^+$: WIP

$B^+ \rightarrow \bar{D}^0 D_s^+ \rightarrow K^+\pi^-K^+K^-\pi^+$: WIP

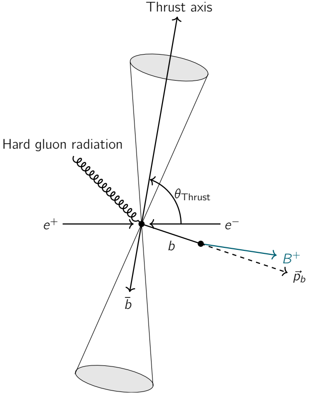


$\rightarrow$ Evaluation of the hemisphere correlation uncertainty from a full simulation sample with the CLD detector

A_{FB}^{b} in detail

For A_{FB}^{b}, things look a bit different [2]:

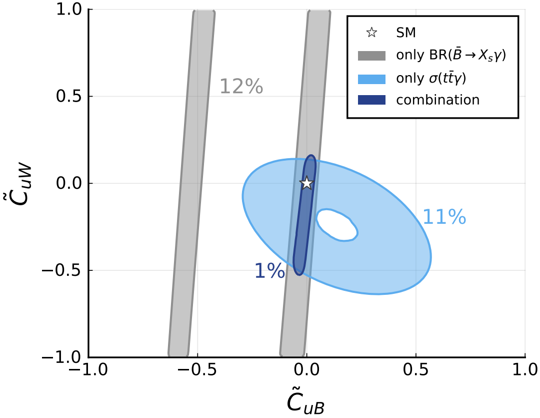
- R_b asks, *if* a b-quark was produced, regardless of its charge or direction
- Forward-backward asymmetry needs an estimator of the **charge** and the **direction:** definition of *forward / backward*
- **Overcoming LEP-limitations** with exclusive b-hadron tags:
  1. **Mixing dilution** with lepton tags: $B^0_{(s)} \leftrightarrow \bar{B}^0_{(s)}$ mixing confuses the lepton charge. Consider B^+ and Λ_b^0 reconstruction for tagging
  2. **Contamination** from light-quark and c-physics
  3. **Gluon radiation** alters angle up to confusion of the hemispheres $\rightarrow$ new angle from $\vec{p}_{B^+}$ potentially mitigating the effect



Measurement	Result	Uncertainties total systematic	QCD related	
ALEPH [3]	$0.0998 \pm \ldots \pm 0.0017\,(\text{syst.})$	1.7 %	0.6 %	$\mathcal{O}(1\,\%)$
OPAL [4]	$0.0989 \pm \ldots \pm 0.0013\,(\text{syst.})$	1.3 %	1.1 %	

Conclusions and Outlook

- **Goal:** Exploit SM-deviations consistently at different scales with EFT operators
  $\rightarrow$ Combination of the top- and beauty scale at FCC-ee for global interpretation



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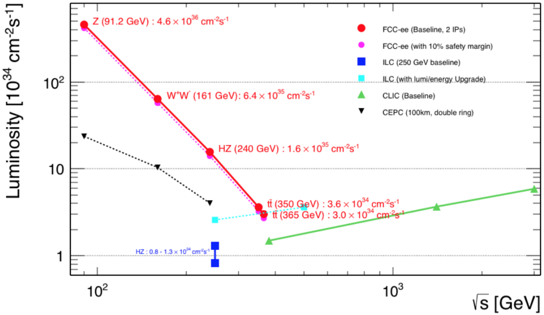

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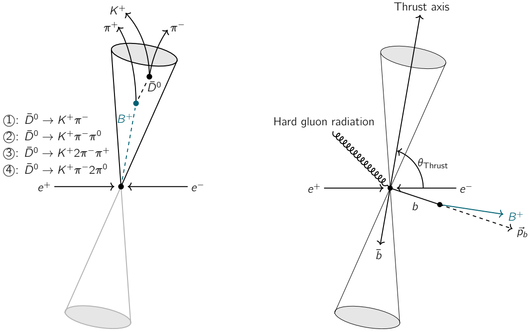
- For (b-)tagging-based observable measurements: presented the promising idea of using **exclusively reconstructed b-hadrons as tagger**
  → Reduction of major sources of systematic uncertainties to the cost of statistical precision



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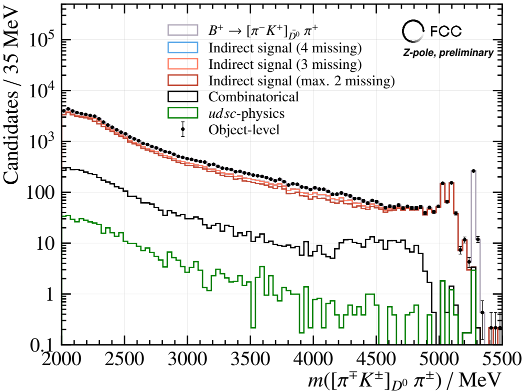

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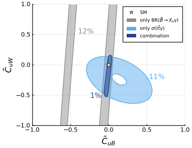
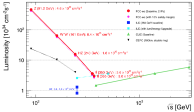
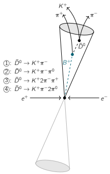
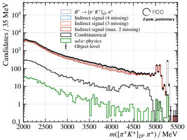








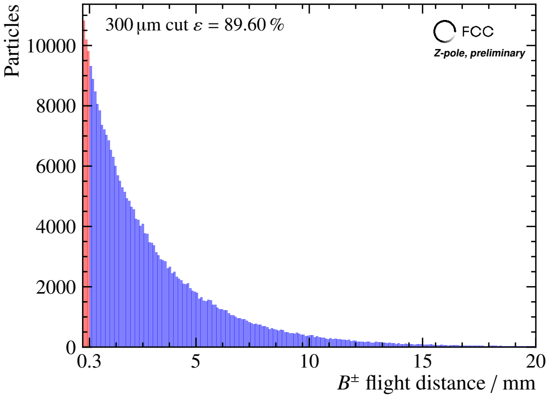
Appendix I

- B^+ mean flight-distance via $\langle L \rangle = \langle \beta\gamma \rangle c\tau$. With $\langle E_{B^+} \rangle \approx 0.75 \langle E_{b\text{-quark}} \rangle = 0.75 \cdot 45.2\,\text{MeV}$

$$\langle \beta\gamma \rangle = \frac{\langle p \rangle}{m_{B^+}} = \frac{\sqrt{0.75^2 \langle E_{b\text{-quark}} \rangle^2 - (5279.23\,\text{MeV})^2}}{5279.23\,\text{MeV}} \approx 6.57$$

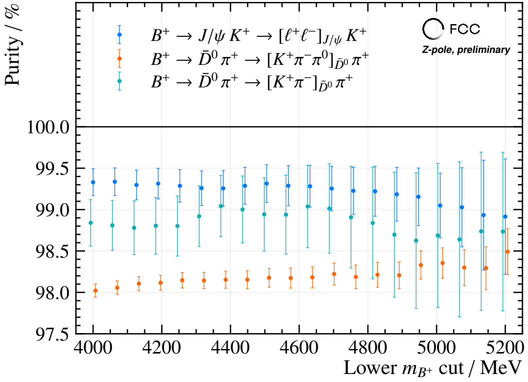
With $\tau = 1638 \cdot 10^{-15}\,\text{s} \rightarrow \langle L \rangle = 3\,\text{mm}$. Distance cut of $d > 300\,\mu\text{m}$: $\text{e}^{-\frac{300\,\mu\text{m}}{\langle L \rangle}} \approx 90.5\,\%$ remain

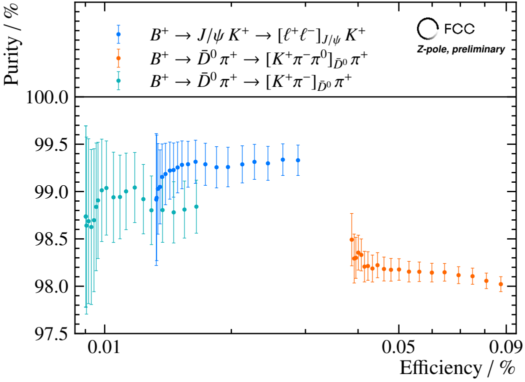
- Proof from simulation



Appendix II

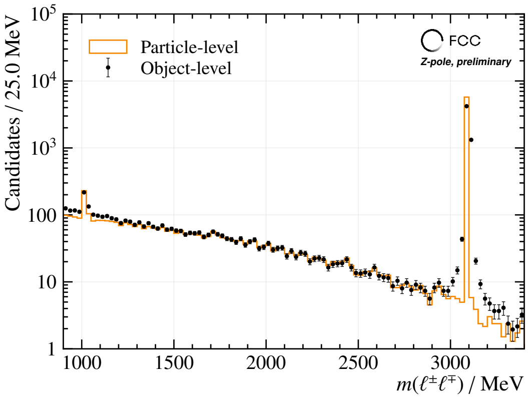
- With a lower mass cut in the m_{B^+} spectrum, the purity can be kept constant



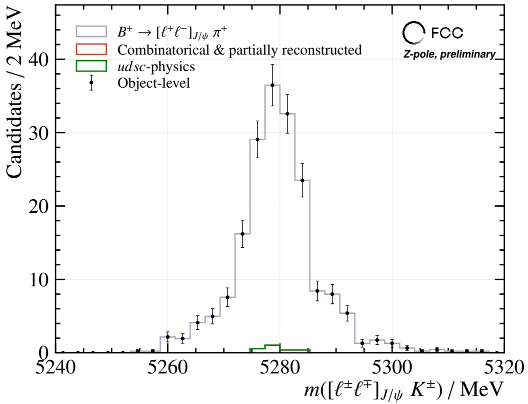


Appendix III

- Full range invariant mass distribution for the $\ell^{\pm}\ell^{\mp}$ pairs

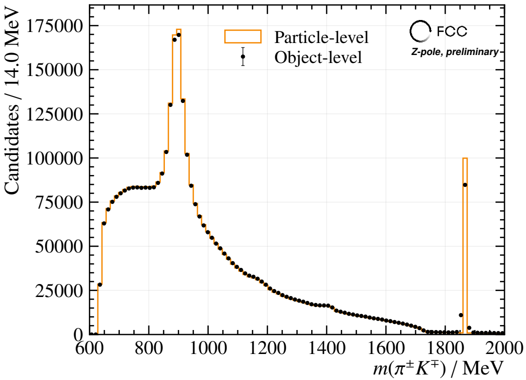


- Linear representation of the B^{+} mass range with all backgrounds included

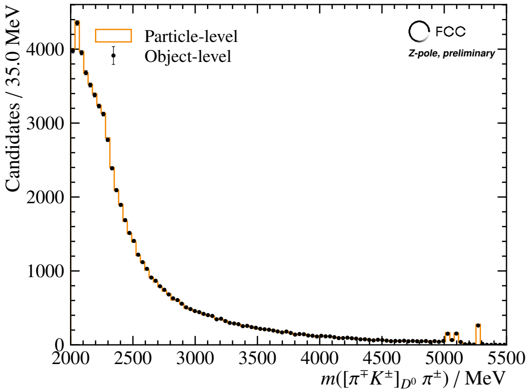


Appendix IV

- Full range invariant mass distribution for the $K^{\pm}\pi^{\mp}$ pairs

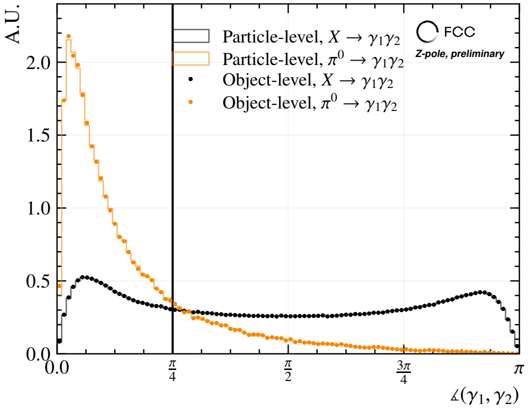


- Linear representation of the full mass range with all backgrounds included

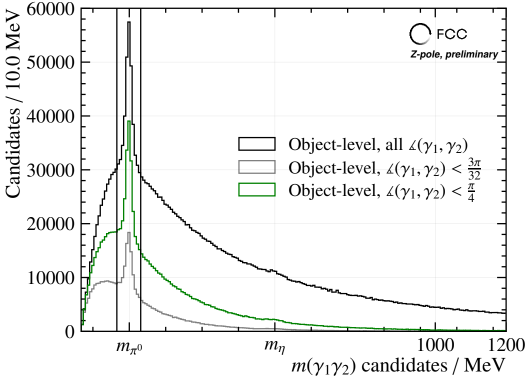


Appendix V

- Photon angle distribution of truth-matched (π^0's) and all particles

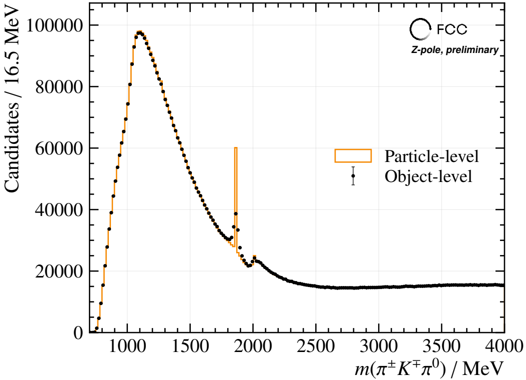


- Angular cuts applied in the $m_{\gamma\gamma}$ mass spectrum, chosen $\measuredangle(\gamma_1, \gamma_2)$: $\frac{\pi}{4}$



Appendix VI

- Full range invariant mass distribution for the $K^{\pm}\pi^{\mp}\pi^{0}$ pairs



- Linear representation of the full mass range with all backgrounds included