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Novel b-hemisphere jet charge and flavour taggers at FCC-ee

Second ECFA Workshop on e^+e^- Higgs/EW/Top Factories – Paestum

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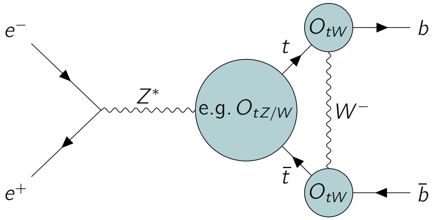
Motivation I

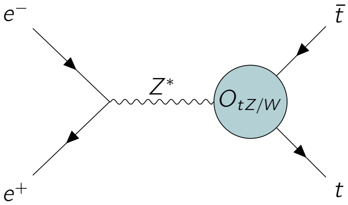
- **Connect energy scales** at future e^+e^- collider to access SM deviations globally
- Possible anomalies translate over a range of energy scales: from Z-pole to top threshold
- Heavy-quark EW measurements as a **probe for new physics** with a common set of dimension-6 operators

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



⇒ Vertex corrections ≈ 1 % of R_b in the SM

$\mathcal{O}(m_t) \sim 350$ GeV to 365 GeV



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

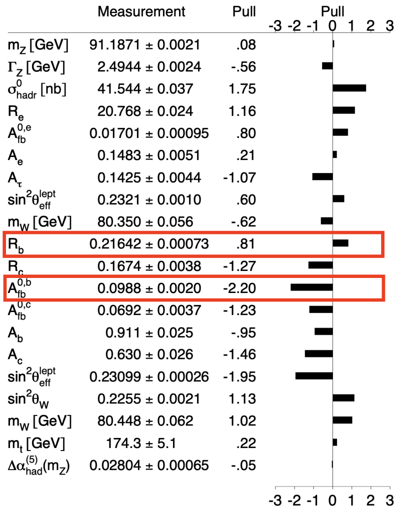
- **Tight constraints** on Wilson coefficients:
  1. Very precise measurements at the Z-pole
  2. Variety of observables at the top-threshold

Motivation II

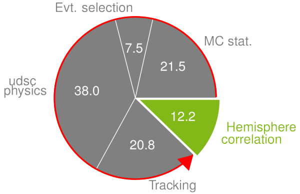
- Today: place focus on b-quark observables at FCC-ee with BSM potential from **vertex corrections**
- Measurements at the Z-pole with $4.2 \cdot 10^{12}$ $Z \to q\bar{q}$ (4 IPs):
  - $R_b = \frac{\sigma_{b\bar{b}}}{\sigma_{\mathrm{had.}}}$
  - $A^b_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$

  $\rightarrow$ Likely **dominated by systematic uncertainties**
- Interesting terrain for new methods to improve measurement

  $\rightarrow$ Explore Tera-Z regime with **exclusive b-hadron decay reconstruction as new tagger**

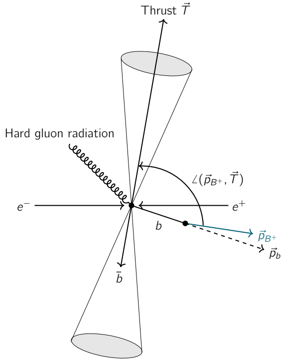


Exclusive b-hadron decays



- LEP $\sigma_{\text{syst.}}$ dominated by *udsc*-physics and hemisphere correlations
- With Tera-Z $\sigma_{\text{stat.}}$ in reach: measurement limited by systematic uncertainties
- Reconstruct exclusive b-hadron: determine quark-flavour with 100 % purity
  $\rightarrow$ Stick to **ultra-pure mass region** to assess remaining systematic uncertainties $\rightarrow \varepsilon_b = 1\,\%$

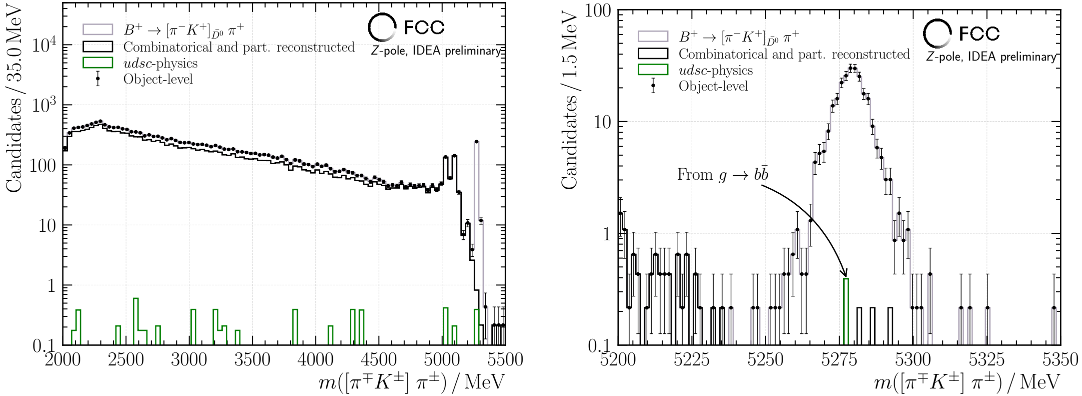
Observable	R_b	A_{FB}^b
b-hadrons	$B^+, B_d^0, B_s^0, \Lambda_b^0$	B^+, Λ_b
Knowledge of...	Flavour	Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	Remove *udsc*-physics contribution; Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{\text{syst.}}$	Hemisphere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



- C_b and QCD corrections evaluated on **Full Simulation sample** and forced decays ($B^\pm \rightarrow [K^+\pi^-]_{\bar{D}^0}\,\pi^+$)

Performance I

- Include > 200 b-hadron decay modes
  $\rightarrow$ Evaluate tagger performance from **six representative decay modes** (varying track mult., N_{π^0}, ...)
- Purity & reconstruction efficiency evaluated on 10^7 $Z \rightarrow q\bar{q}$ **Fast Simulation events** with IDEA detector
- Here: $B^+ \rightarrow [K^+\pi^-]_{\bar{D}^0}\,\pi^+$ with $E_B > 20\,\text{GeV}$ to reduce background

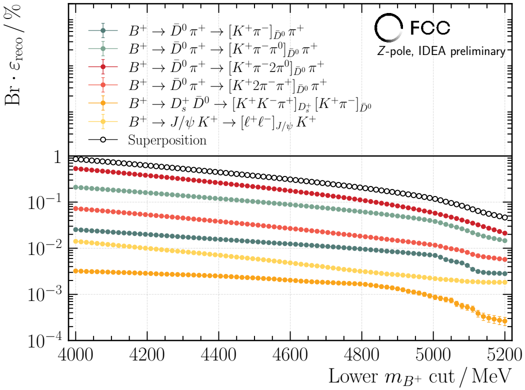


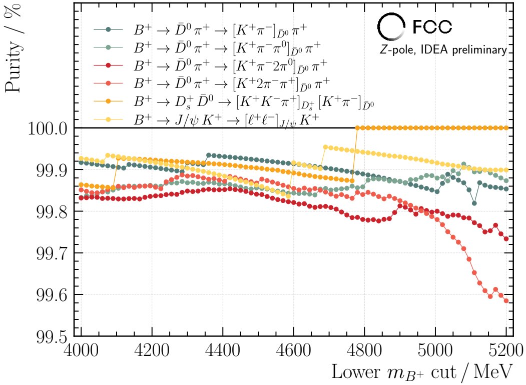
- **Purity:** 99.8 %, **reconstruction efficiency:** 77 %
- Background suppressed by three orders of magnitude, contamination in signal region from $g \rightarrow b\bar{b}$

Performance II

- Evaluate actual tagger efficiency (Br · $\varepsilon_{\text{reco}}$) for the six modes when increasing the acceptance range

→ **Enlarging mass window** highly increases the tagger-efficiency by keeping purity constant



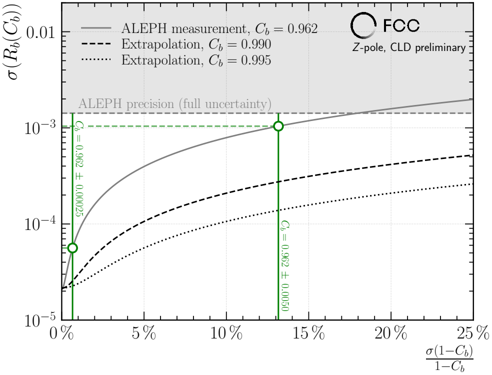


- Focus on mass peak region to control systematic uncertainties

Measurement of R_b: Importance of hemisphere correlation

- State of the art (ALEPH): $R_b = 0.2159 \pm 0.0009$
- With conservative tagger efficiency of 1 %: $\sigma_{\text{stat.}}(R_b) = 2.2 \cdot 10^{-5}$ (**factor 45** w. r. t. ALEPH)
- $\sigma_{\text{syst.}}$ reduces to **hemisphere efficiency correlation**

  → Quantifies dependence of tagging efficiencies in the two hemispheres: $C_b = \frac{\varepsilon_{b\bar{b}}}{\varepsilon_b \cdot \varepsilon_{\bar{b}}}$
- Its precise knowledge is **the key** for the measurement of R_b



Green Uncertainty on C_b scaled

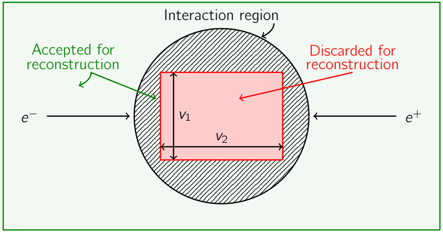
Gray C_b values extrapolated

- Two handles: Uncertainty on C_b and difference to $C_b = 1$

Understanding C_b: The PV resolution

- **Goal:** Find regions of the phase-space which increase C_b (kinematically + event-variables)
  $\rightarrow$ LEP found: mainly driven by **PV measurement uncertainty**
  $\rightarrow$ LEP did: PV-separation. Here: cut on **luminous region** from beam spot constraints

Cut on the luminous region:



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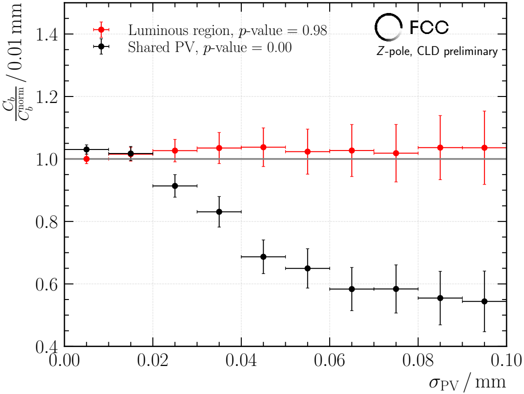
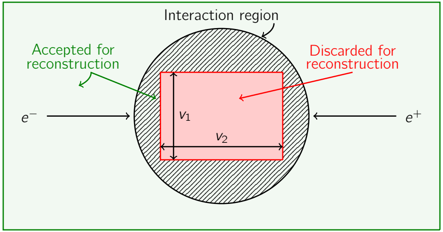
- Focus placed on **differential analysis** of C_b to reduce systematic uncertainties
- All distributions normalised to inclusive C_b value



Cut on the luminous region:

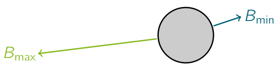


$\rightarrow$ $\sigma_{\text{PV}} = \sqrt{\sum_{i\in[x,y,z]} \left(\text{PV}_i^{\text{Object-level}} - \text{PV}_i^{\text{Particle-level}}\right)}$

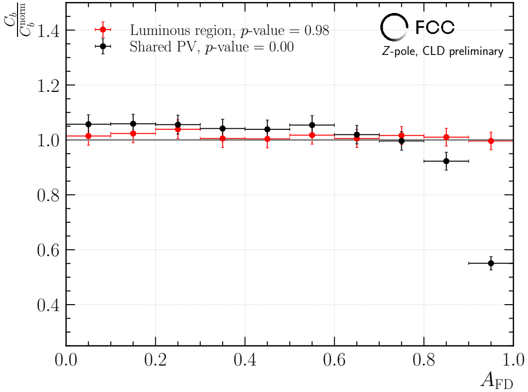
$\rightarrow$ **Strongly dependend** for the shared PV approach

$\rightarrow$ **Resolved** with optimised cut on luminous region

Understanding C_b: The flight-distance asymmetry



- Linked to the PV resolution: flight-distance asymmetry $A_{\text{FD}} = \frac{\text{FD}_{B_{\text{max}}} - \text{FD}_{B_{\text{min}}}}{\text{FD}_{B_{\text{max}}} + \text{FD}_{B_{\text{min}}}}$
- One B-meson far away $\rightarrow$ **Reduce PV measurement precision** (captures more tracks) $\rightarrow$ Increase C_b

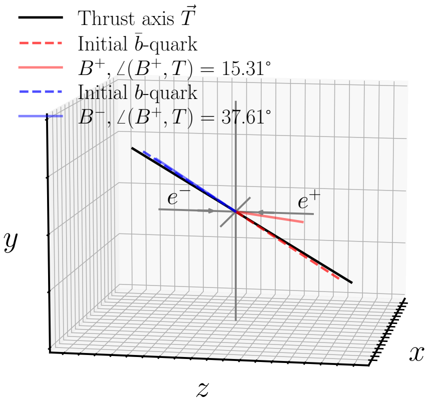


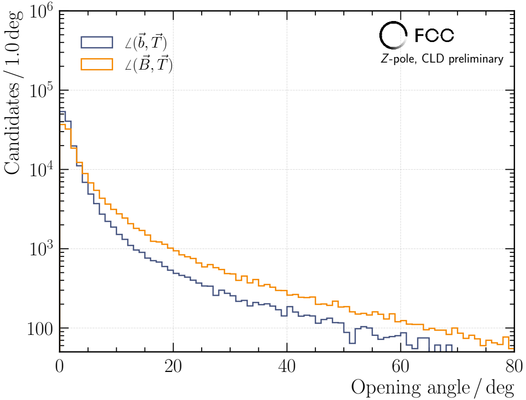
- Large asymmetries: correlation decreases
- Flat distribution for luminous region

- R_b conclusions:
  1. Crucial to minimise the remaining systematic uncertainty on R_b
  2. Handle to reduce C_b differentially: luminous region approach minimises PV dependencies
  3. Larger FullSim sample in order to make quantitative statements

Measurement of A_{FB}^{b}

- Forward/backward determined from thrust-axis $\vec{T}$, charge from reconstructed B-candidate
- **Remove mixing dilution** by using B^+ and Λ_b^0 decays
- Hard gluon radiation can still confuse hemispheres, **but:** direction of B^+ is known



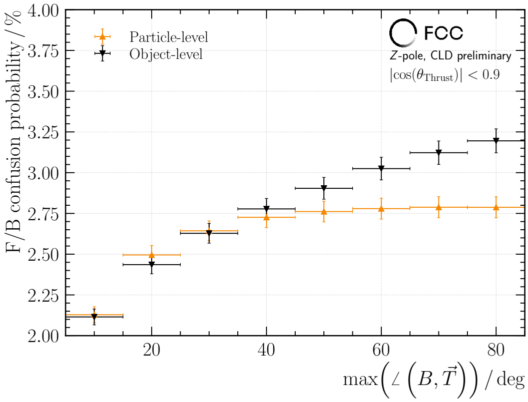


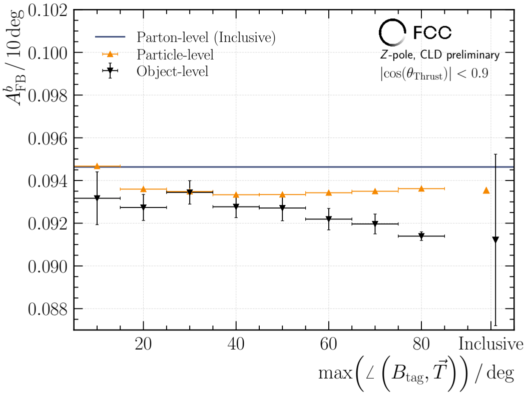
→ B-meson direction estimator altered through gluon emission + fragmentation

→ Use this information to **minimise QCD corrections**

Controlling the gluon radiations?

- Control g-radiation through $\angle(B^{\pm}, \vec{T})$
  $\rightarrow$ Hard gluon emission **increases opening angle** between $\vec{T}$ and B-meson
- Evaluate A_{FB}^{b} by cutting events with large opening angles





$\rightarrow$ Removing events with large $\angle(B^{\pm}, \vec{T})$: **closer to parton-level** A_{FB}^{b}

Conclusions and Outlook

- Novel b-hemisphere charge and flavour taggers for application at Tera-Z programme
- Promising performance: purity above 99.6 % for representative modes
- R_b and A_{FB}^b: overcome syst. limitations from *udsc*-quark physics by reconstructing exclusively b-hadrons

R_b
1. Overcome syst. limitations from *udsc*-quark physics
2. Reduction of C_b through cut on the luminous region

A_{FB}^b
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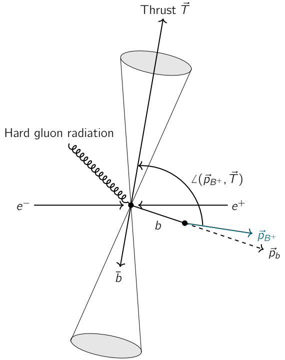
2. Remove mixing dilutions by considering B^+ and Λ_b^0
3. Gluon radiation control with angle between B-meson and $\vec{T}$?



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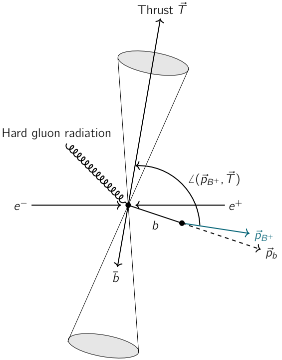
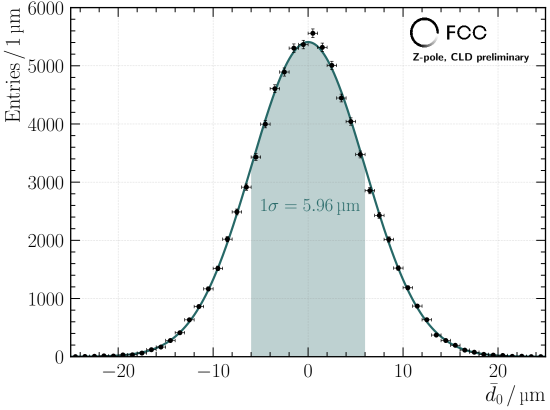


Thanks for your attention!

Luminous region

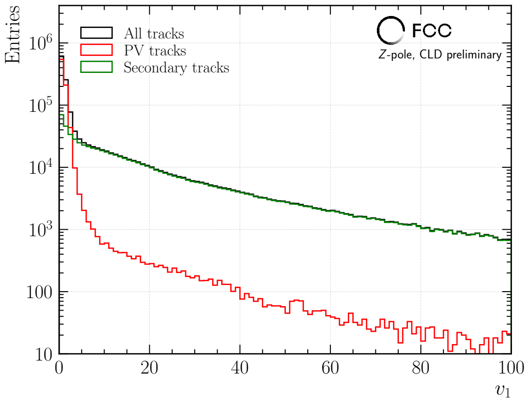
- $\bar{d}_0 = \text{sign}(\text{PV}_z^{\text{Particle-level}}) \cdot \sqrt{\left(\text{PV}_x^{\text{Particle-level}}\right)^2 + \left(\text{PV}_y^{\text{Particle-level}}\right)^2}$

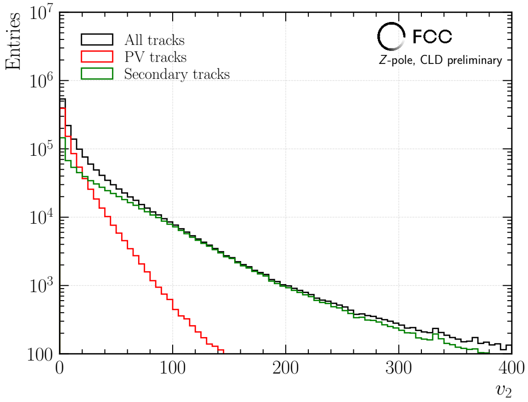


- $v_1 = \frac{d_0 - \mu(\bar{d}_0)}{\sqrt{\sigma(d_0)^2 + \sigma(\bar{d}_0)^2}}$ and $v_2 = \frac{z_0 - \mu(\bar{d}_0)}{\sqrt{\sigma(z_0)^2 + \sigma(\bar{d}_0)^2}}$, d_0 and z_0 are the track parameters

Luminous region: primary and secondary

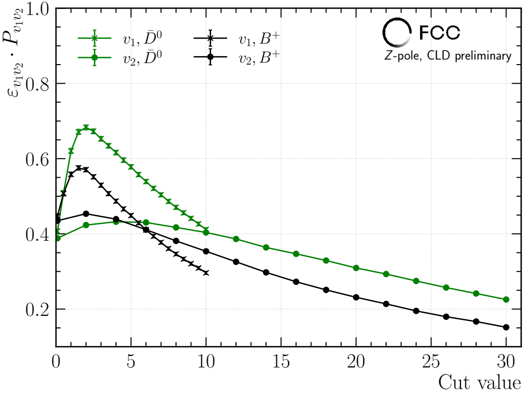
- Is there a possibility to distinguish between primary and secondary tracks? →Yes!
- Use truth-matched tracks to compute v_1 and v_2 distributions

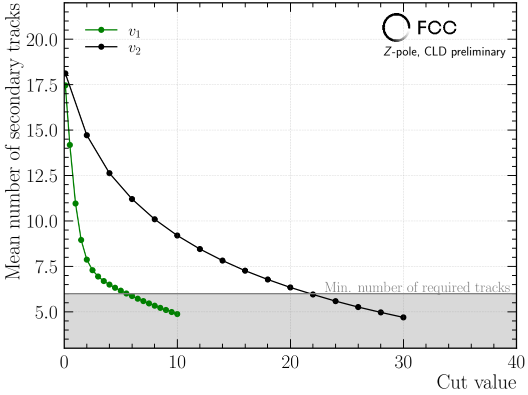




Optimising the luminous region cuts

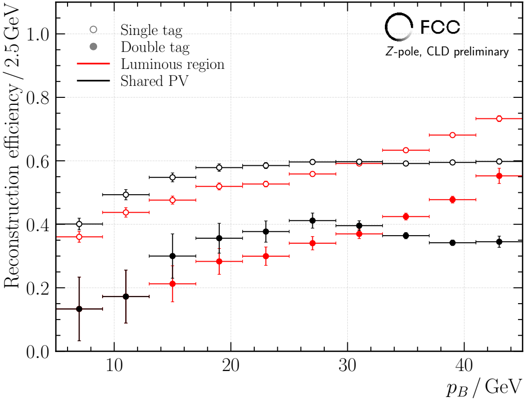
- Scan over a range of v_1 and v_2 independently
- Evaluate product of purity and efficiency of the D^0- and B-mesons & mean number of secondary tracks
- $P_{v_1 v_2} = \frac{N_{\text{sig}}}{N_{\text{sig}}+N_{\text{bkg}}}$, N_{bkg} estimated and scaled from the sidebands
- $\varepsilon_{v_1 v_2} = \frac{N_{\text{sig}}}{N_{\text{total}}}$, $N_{\text{total}} = (10^4 \cdot N_B)$ and $N_B = 2$

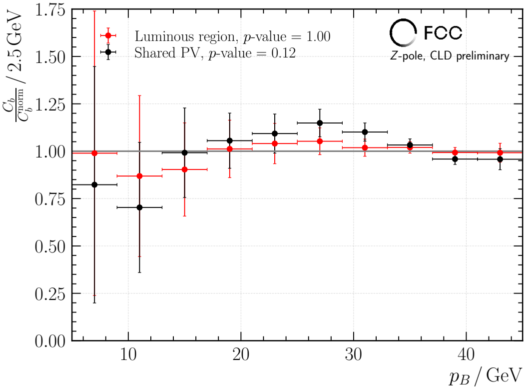




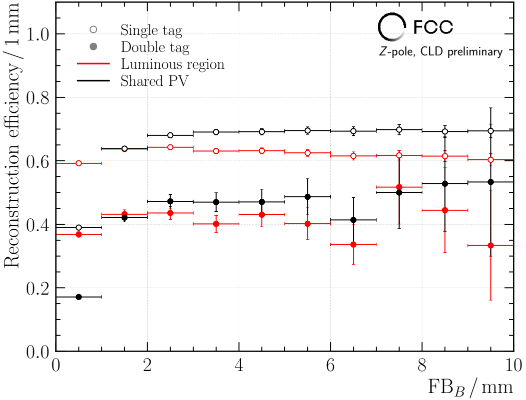
→ Choose maximum for v_1 from $P_{v_1 v_2} \cdot \varepsilon_{v_1 v_2}$, v_2 taken from the mean number of tracks

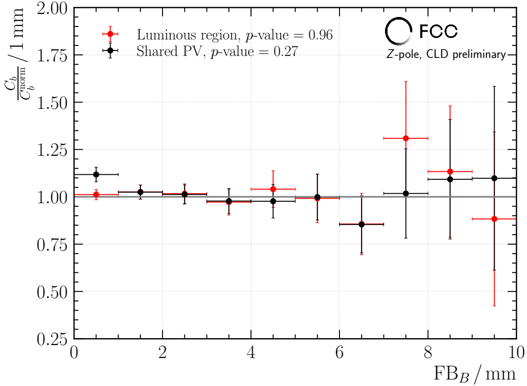
Differential hemisphere correlations: B-momentum



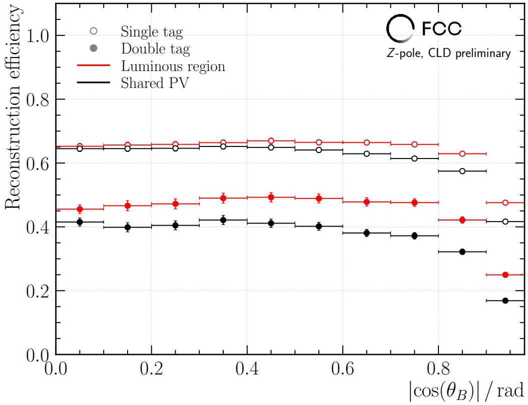


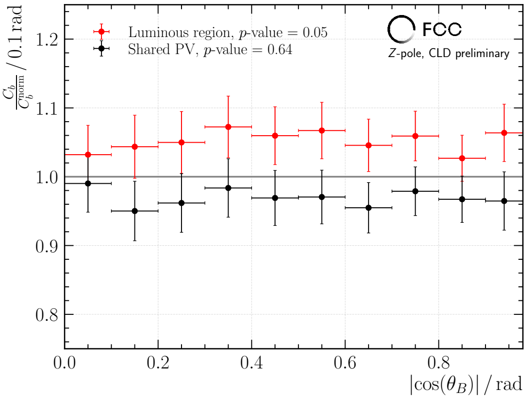
Differential hemisphere correlations: *B*-flight distance





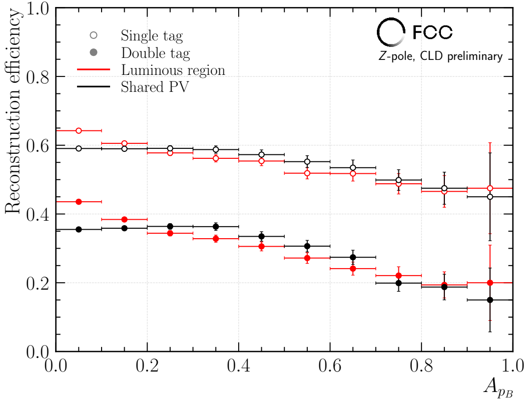
Differential hemisphere correlations: B-polar angle

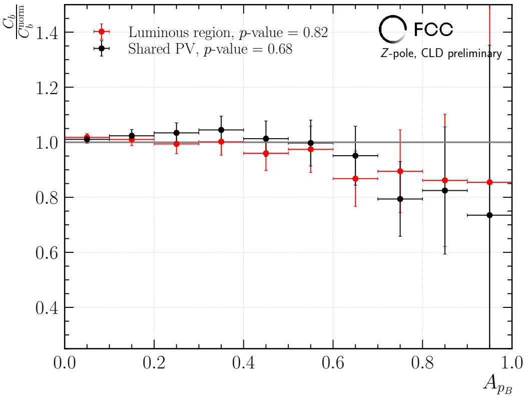




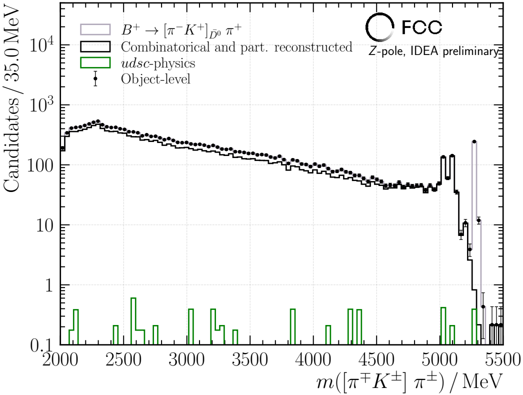
Differential hemisphere correlations: B-momentum asymmetry

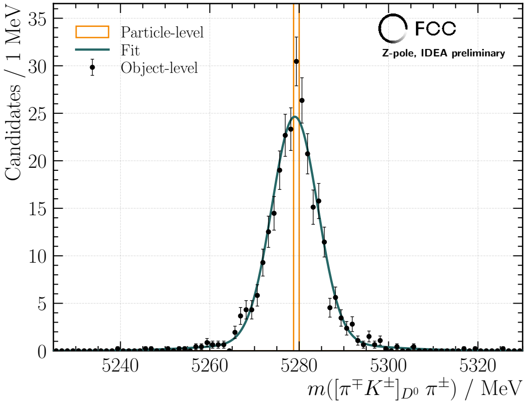
- $A_{p_B} = \frac{p_{B_{\max}} - p_{B_{\min}}}{p_{B_{\max}} + p_{B_{\min}}}$





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





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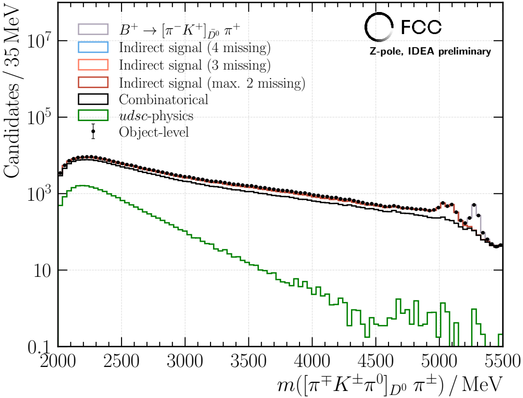
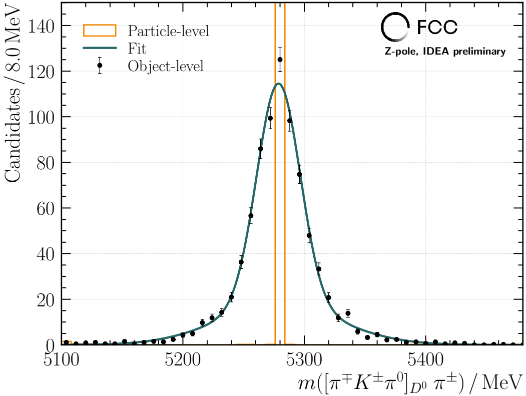
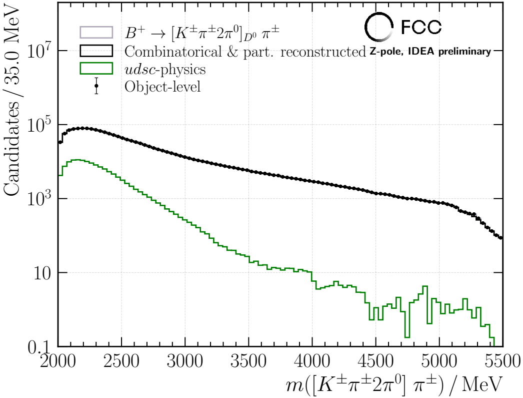
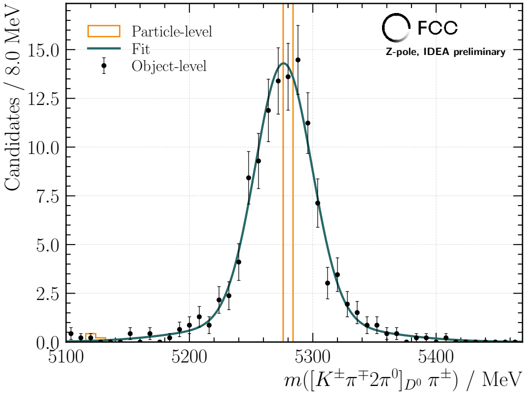




Fast Simulation: Decay mode $B^+ \to [K^+\pi^-2\pi^0]_{\bar{D}^0}\pi^+$





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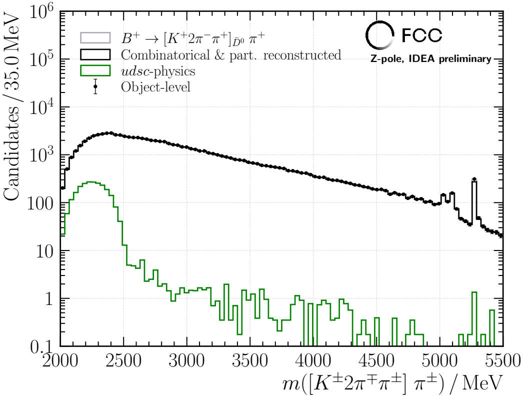
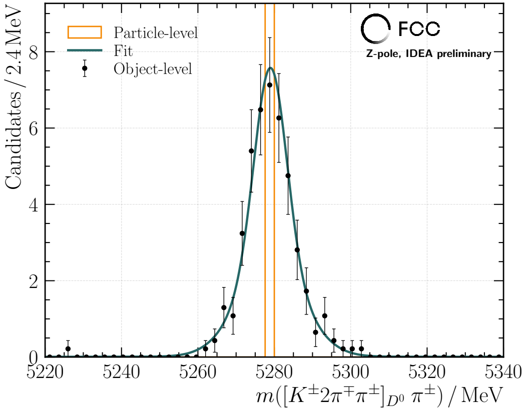
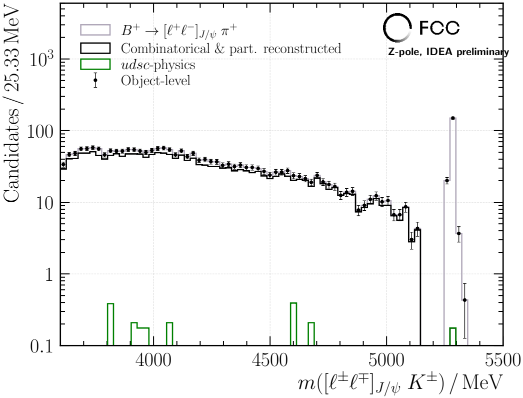
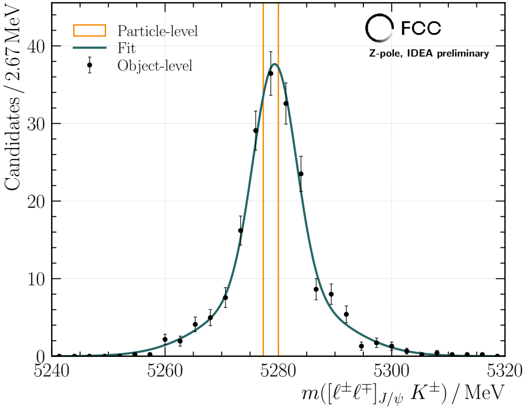




Fast Simulation: Decay mode $B^+ \to [\ell^+\ell^-]_{J/\psi} K^+$





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