Studies of $B^0 \rightarrow [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}$ at FCC-ee

CPV Working Group meeting

Charlie Wild, Guy Wilkinson

University of Oxford

31 March 2026

Preview and progress

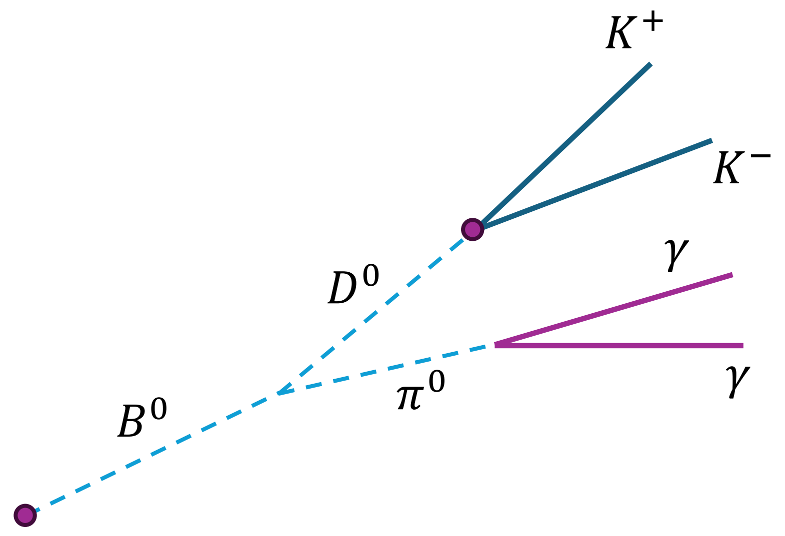
- The study of $\boldsymbol{B^0 \to [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}}$ and other similar decay at FCC-ee was motivated in Guy's talk.
  - *"Prospects for Penguin-free measurements of ϕ_d (and ϕ_s) at FCC-ee"*
- To study the feasibility of these measurements we have used simulations with the **IDEA detector concept** at 91 GeV (thanks to Xunwu Zuo).
- Simulated samples of **exclusively $\boldsymbol{B^0 \to [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}}$** and $B_s^0 \to [K^+K^-]_{D^0}K_s^0$ using **EvtGen**.
- Presenting progress in the analysis of $B^0 \to [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}$ decays today, this should be the most challenging as the only charged tracks are the daughters of the D^0 decay.
- Today I will cover progress so far:
  - Development of a **reconstruction algorithm.**
  - **Pre-selection criteria** to resolve the signal in these exclusive samples.
  - Ran this reconstruction and selection on **inclusive $\boldsymbol{Z \to b\bar{b}}$ and $\boldsymbol{Z \to c\bar{c}}$** centrally produced samples.
  - Calculated the **flight distance** and **impact parameters** of the reconstructed D^0.
  - Began work on **fitting the $\boldsymbol{B^0}$ decay vertex** using stable final state particles.

$B^0 \to [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}$ Reconstruction

Start with Reconstructed tracks and vertices, use no MC truth information.

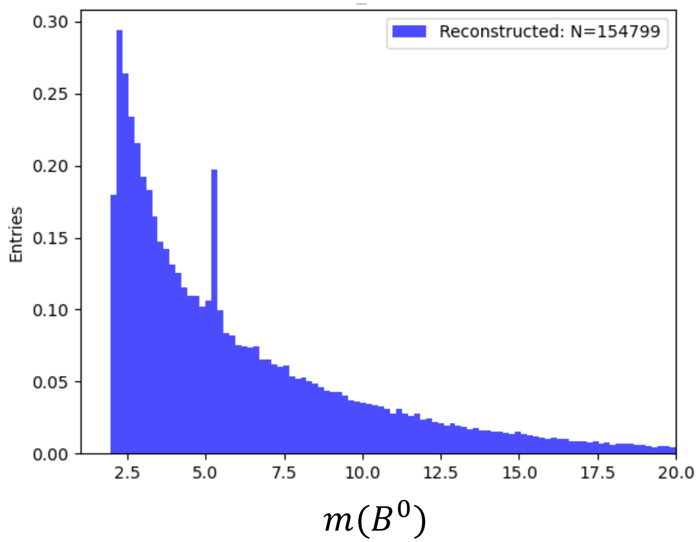
1. **D^0 candidates:**
   - Require vertex that isn't primary vertex.
   - Require exactly two tracks from the vertex.
   - Require two oppositely charged kaons at vertex.
   - Combine these kaons to form D^0 candidate.
   - Remove any D^0 candidates with mass further than 12 MeV from PDG mass.
2. **π^0 candidate:**
   - Remove any photons with Energy less than 30 MeV
   - Combine all iterations of two photons to make π^0 candidates
   - Select π^0 candidates within $115 \leq m_{\pi^0} \leq 150$ MeV.
3. **B^0 candidates:**
   - Form B^0 candidates from all possible combinations of D^0 and π^0candidates.

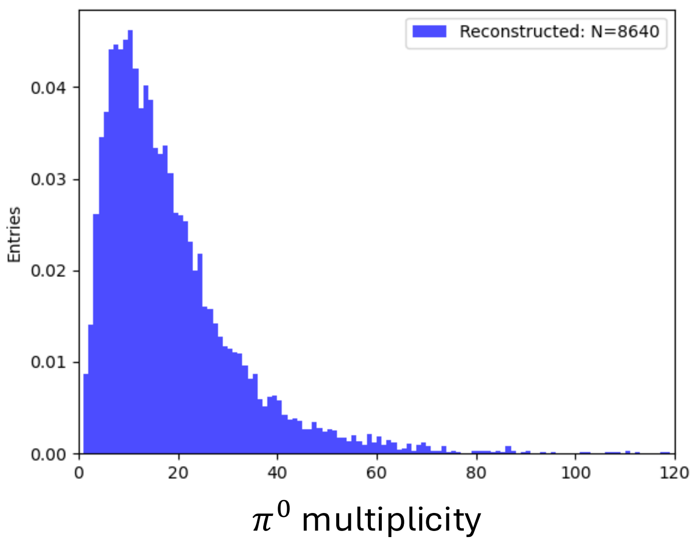
Events were no B^0 candidates are found are removed.

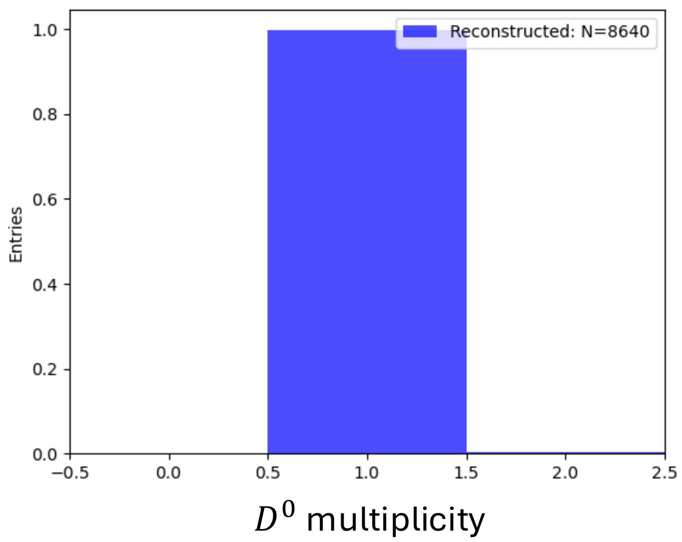


Preliminary results and issues

- Run reconstruction on 10,000 MC events generated exclusively in the signal decay.
- Observe **a clear signal peak** but **large combinatorial contributions**.
- High multiplicity driven by **high multiplicity of reconstructed pions**.
- Ability to vertex the D^0 reduces the combinatorial contributions and therefore has a low multiplicity.
- Background likely from combining real D^0 with **soft combinatorial pions**.
- Aim to remove this contribution **using selection cuts on the momenta** of the reconstructed pions and B^0.



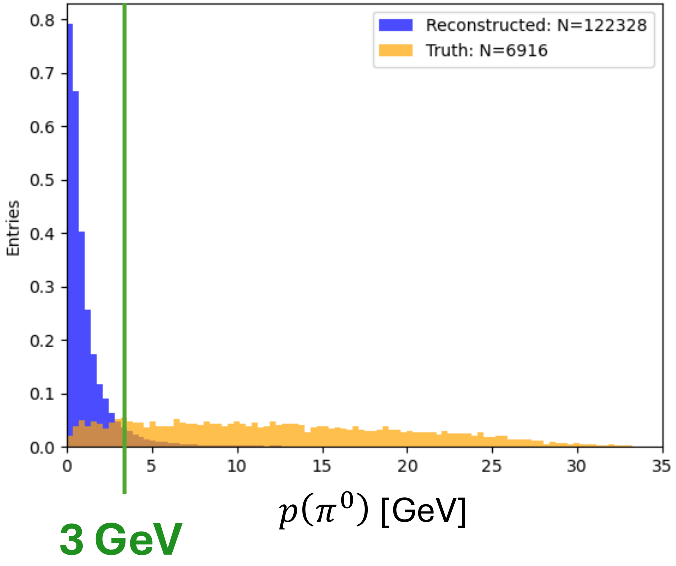


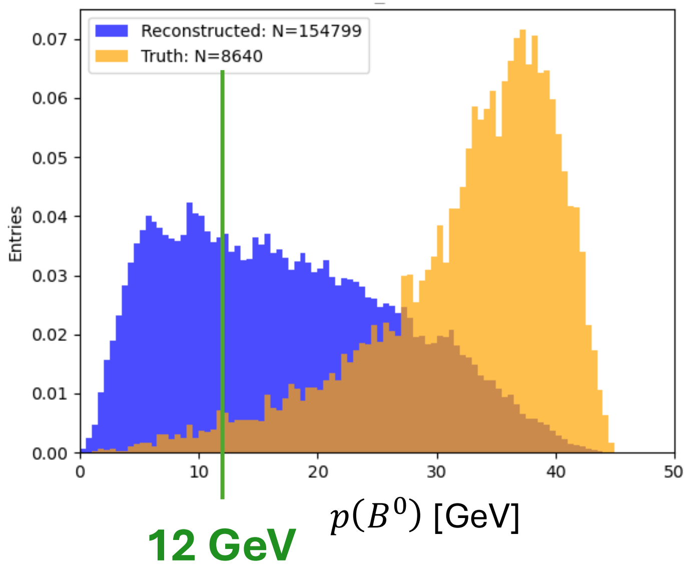


Pre-selection requirements

- No vertex for the $\pi^0 \rightarrow \gamma\gamma$ as this just leaves hits in the calorimeter need pre-selection criteria to reduce background.
- Comparing kinematic distributions of reconstructed π^0 and B^0 particles to MC truth distributions developed **pre-selection criteria**.

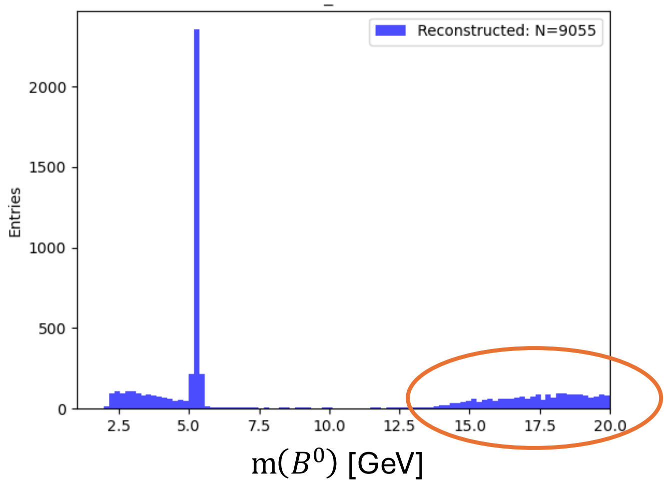
Selection criteria	Explanation
$p(\pi^0) \geq 3$ GeV	π^0 must pass this selection to form a B^0 candidate
$p(B^0) \geq 12$ GeV	B^0 candidates failing this are removed

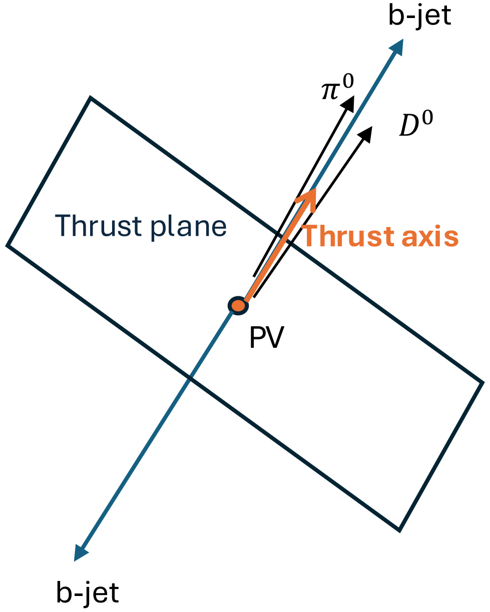




Hemisphere selection cut

- After applying these selection criteria observed a more significant signal peak but with a **bump at large B^0 invariant mass**.
- Likely due to combination of D^0 and π^0 candidates in **different b-jets**.
- Remove this contribution by requiring that both are in the same jet.
- The **thrust axis** is axis that maximises the dot product of reconstructed particle momenta with itself, so will be along the b-jet directions.
- Use the event thrust axis to define **two hemisphere separated by the plane perpendicular to this axis**.
- Require that **both candidates are in the same hemisphere** to form a B^0 candidate.
- Effectively requiring that both candidates are in the same b-jet, except for Mercedes events.

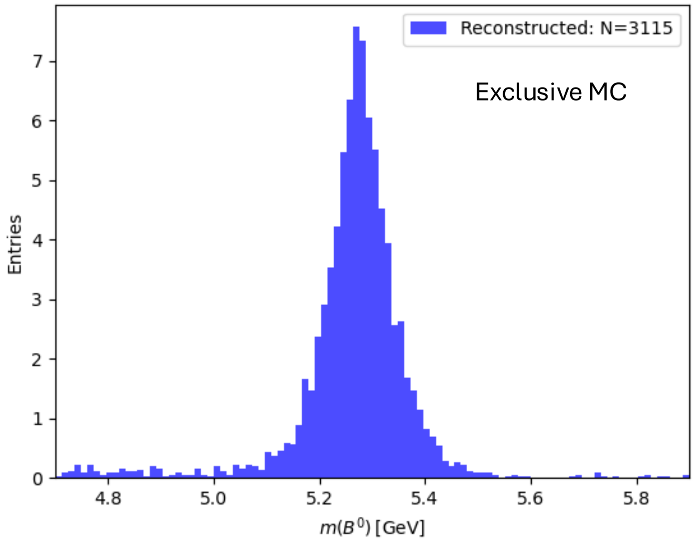




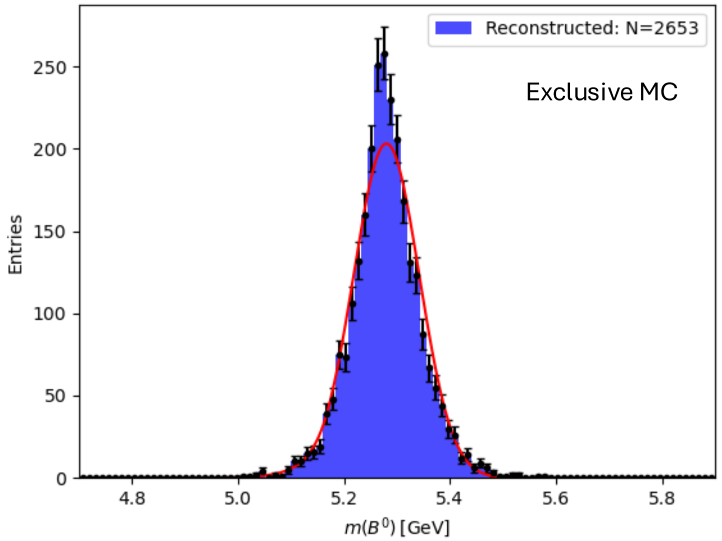
Results after pre-selection – Invariant mass

- **Raw invariant mass of B^0 candidates** using calorimeter simulation in Delphes, from a subset of the exclusive MC sample (10,000 events).
- To evaluate features of the signal mass shape used **a Crystal Ball to fit the truth matched B^0 candidates**.
  - The shape is too simple to capture the narrow peak and wider tails, however, is sufficient to get **estimate of the width of the resonance**.
  - Resolution is not very good, likely can be improved using a vertex fit where the daughter masses are constrained.

All reconstructed



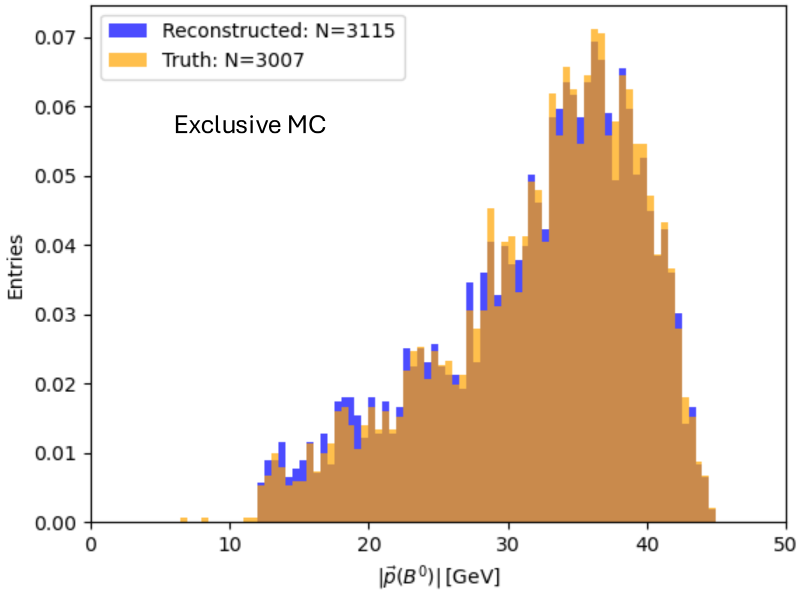
Truth matched candidates

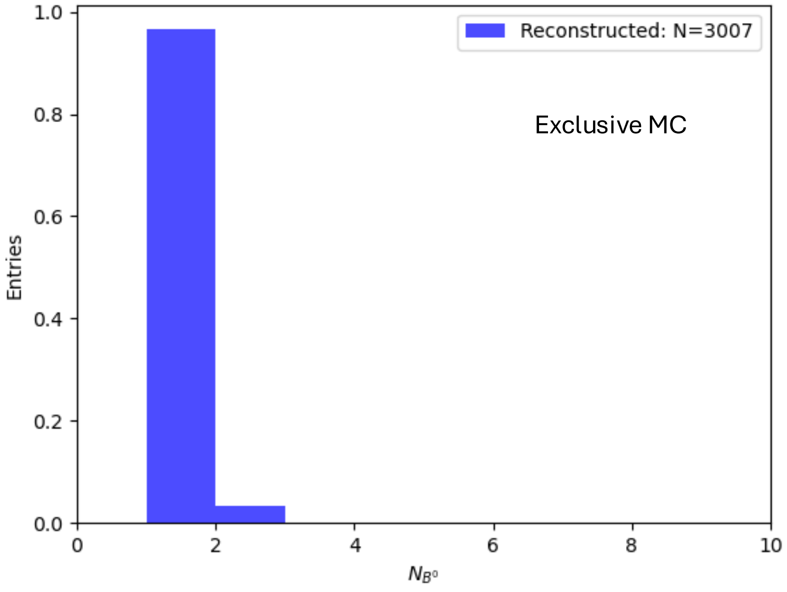


Parameter	Value
N	2653 ± 52
μ [GeV]	5.2800 ± 0.0013
σ [GeV]	0.06201 ± 0.00098
β	1.82 ± 0.16
m	42.65 ± 27.93

Results after pre-selection - B^0 kinematics

- Results from a subset of the exclusive MC sample (10,000 events).
- Plot on the left is the **momentum** and on the right the **multiplicity** of B^0 candidates.
- Blue histogram is the **reconstructed distribution** and the orange is the **MC Truth distribution**.
- After the application of selection cuts in slide 5 and 6, observe very similar distributions between the truth and reconstructed, and reduced multiplicity of reconstructed B^0 candidates.



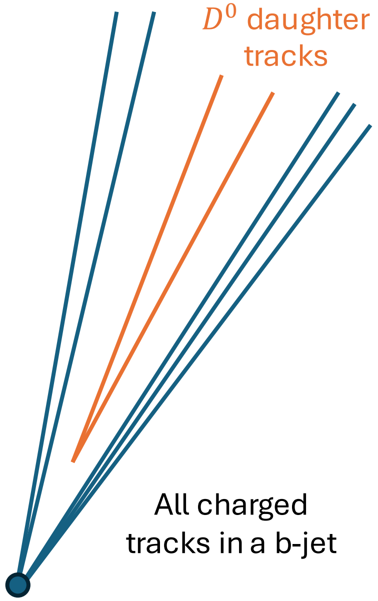


Expected Number signal of events - $Z \rightarrow b\bar{b}$

- The $\boldsymbol{Z \rightarrow b\bar{b}}$ MC root file stored:
  - $\mathbf{N = 438,738,637 \pm 20,946}$ **events.**
- Taking **HFLAV** calculations for the **rate of production of B^0 mesons** in $Z \rightarrow b\bar{b}$ events (need to multiply by two to include conjugate mesons):
  - $\boldsymbol{R(B^0) = 0.407 \pm 0.007}$
- This along with PDG Z branching fraction recovers rates in *"Heavy-quark opportunities and challenges at FCC-ee"* (*G.Wilkinson and S.Monteil)*
- Using **PDG branching fractions**:
  - $\boldsymbol{\mathcal{B}(B^0 \rightarrow [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}) = (1.07 \pm 0.04) \times 10^{-6}}$
- And from 10,000 generated $B^0 \rightarrow [K^+K^-]_{D^0}[\gamma\gamma]_{\pi^0}$ events **2653 MC truth matched reconstructed B^0 decays survive selection**:
  - $\boldsymbol{\varepsilon = 0.2653 \pm 0.0044}$
- Giving a final yield of:
  - $\boldsymbol{N \approx 101 \pm 5}$
- Scaling this by 1686.65 ± 0.08, obtain an estimated yield in the tera-Z sample (7.4×10^{11}):
  - $\boldsymbol{N_{tera-Z} \approx (1.7 \pm 0.1) \times 10^5}$, close to Guy's scaled estimate of BaBar/Belle analysis.
- Observe $\mathbf{131 \pm 12}$ truth matched in the final Zbb sample.

$Z \to b\bar{b}$ results

- Ran over the full 439 M events in the inclusive $Z \to b\bar{b}$ sample.
- The **background rate is much higher** than in the exclusive MC.
- Evaluate the signal to background ratio in a region $\pm 3\sigma$ around signal using fitted values $(5.094 < m(B^0) < 5.466)$ in slide 9.
  - $\frac{N_{truth-matched}}{(N - N_{truth-matched})} \approx 3\%$
- Combinatorial background needs to be diagnosed and reduced:
  - D^0 mass plot shows clear peak with little background, so, this contribution is **real D^0 particles**.
  - Any b-jet that contains a real D^0 may also contain a **non-signal reconstructed pion** that can pass our selection.
  - Although our selection removes this efficiently in the exclusive sample, the branching fraction of the signal decay is much less than likelihood of getting a D^0 inside a b-jet.
  - Current selection is only places requirements on momenta of the π^0 and B^0 candidates.
  - Have no requirements on the **environment of the D^0**:
    - Signal events will have two **isolated kaon tracks** within the b-jet as every other particle in the decay is neutral.
    - We currently place no constraints on the **quality of fit of a B^0 decay vertex**.
  - Constraining the daughter masses in a B^0 decay vertex fit will likely improve the resolution in the B^0 invariant mass spectrum, narrowing the signal region and improving this ratio.
  - Next step is to train an **MVA that will be able to distinguish signal and background** in the exclusive MC sample exploiting these features of our signal.

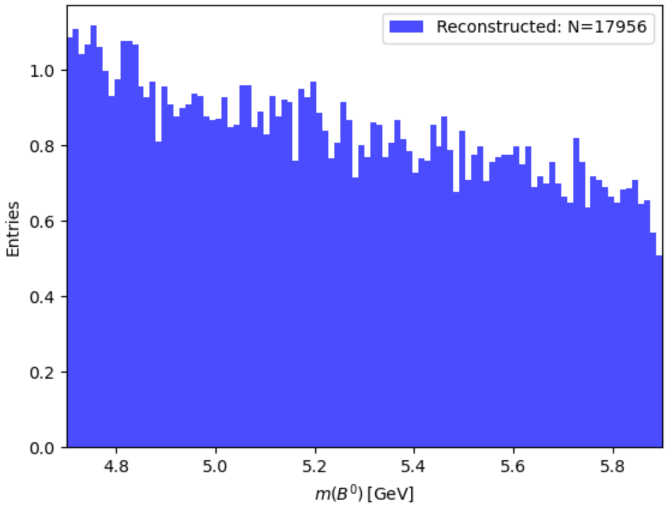


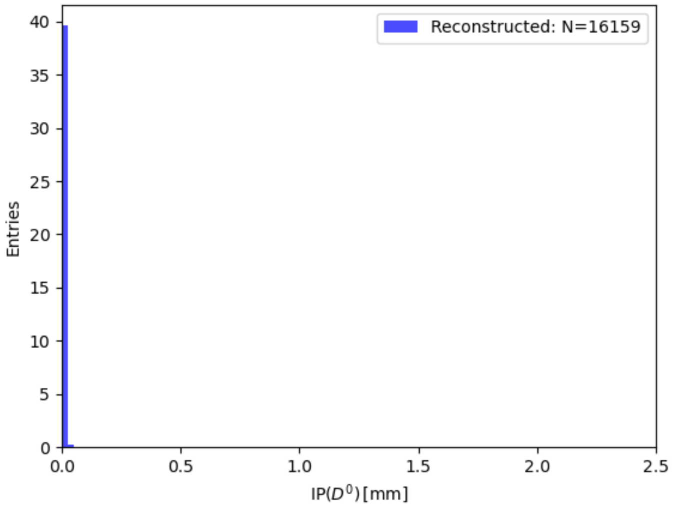
$Z \to c\bar{c}$ results

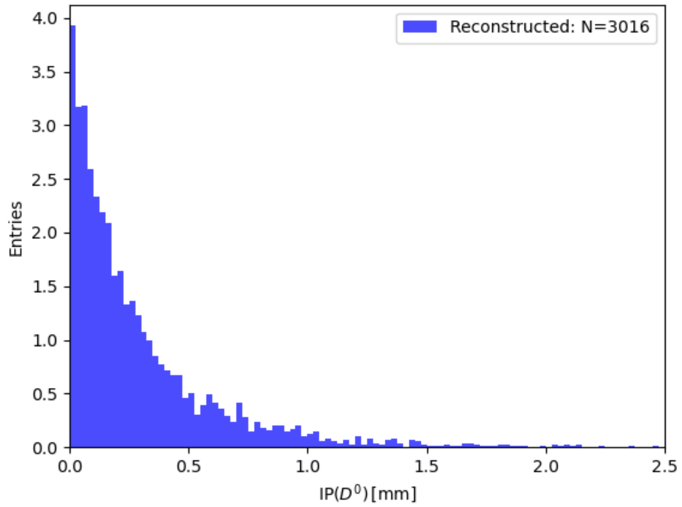
- Running over 330 M events of the inclusive $Z \to c\bar{c}$ there is **large background rate**.
- However the D^0 **Impact parameter** provides a strong discrimination between this and displaced D^0 particles present in our signal.
- Suggest this background can be effectively removed with an **IP selection cut**.

$Z \to c\bar{c}$

$B^0 \to D^0\pi^0$

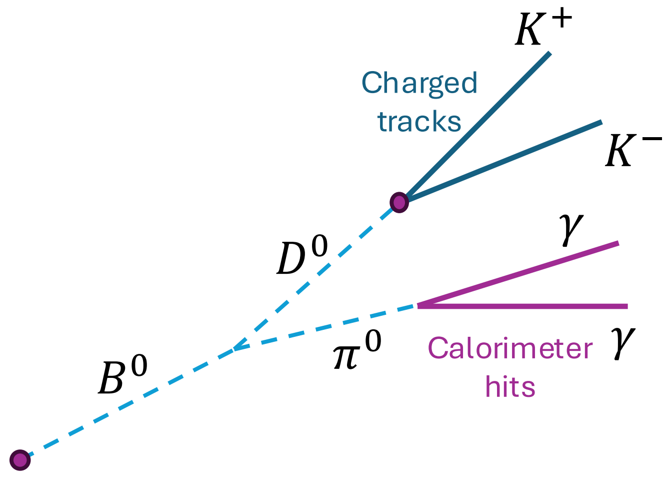






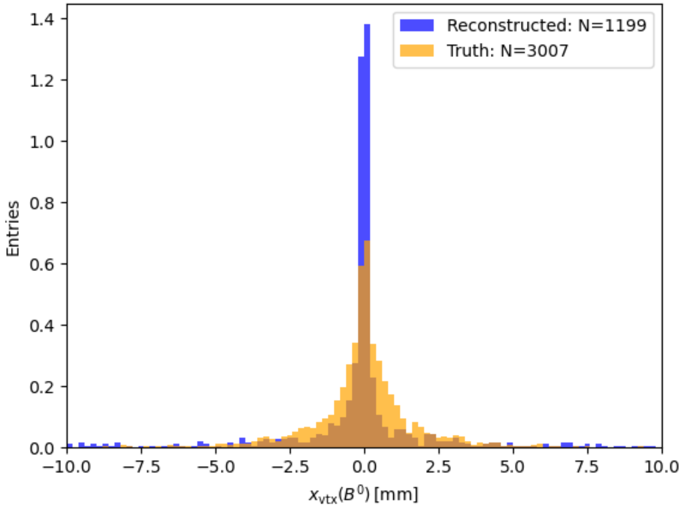
B^0 Vertex fitting

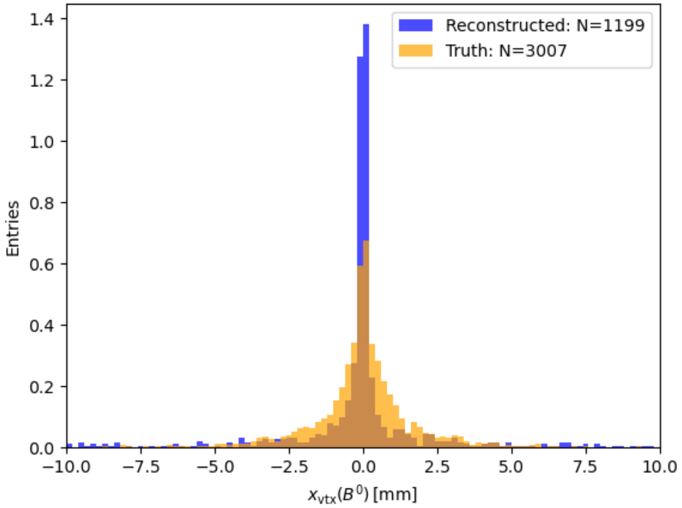
- To perform **a time dependant analysis**, need to calculate the proper time of the B^0.
- In $Z \to b\bar{b}$ production, proper time calculated using PV and the fitted decay vertex of the B^0.
- Vertex fit could also be used to discriminate signal against background in the inclusive MC sample.
- Fit complicated as **no charged tracks present at B^0 vertex nor at π^0 decay**.
- Very few constraints in the fit when performing standard FCC-ee leaf-by-leaf vertex fitting.
- Leaf-by-leaf procedure for each reconstructed B^0:
  1. Take the two kaon daughters and perform a **mass constrained fit to get D^0 pseudo-track**.
  2. Take the **two photons and create fake tracks** for each.
  3. Perform mass constrained fit with the two fake photon tracks to get a **π^0 pseudo-track**.
  4. Fit the D^0 and π^0 pseudo-tracks to **calculate the B^0 decay vertex**.
- More accurate method would be to use a ‘global decay chain fit’ like **Decay Tree Fitter** (DTF) used at B-factories and LHCb
  - The **whole decay chain** is fit at the same time.
  - Employ **mass constraints** and **momentum conservation** at vertices.
  - Beneficial especially for invisible decays as **‘mothers’ can be used to constrain downstream vertices**.
  - The main motivation for DTF use at BaBar was $B^0 \to K_S^0\pi^0$ studies.
- I cannot see an implementation of DTF or similar software in the **FCCAnalyses code**.

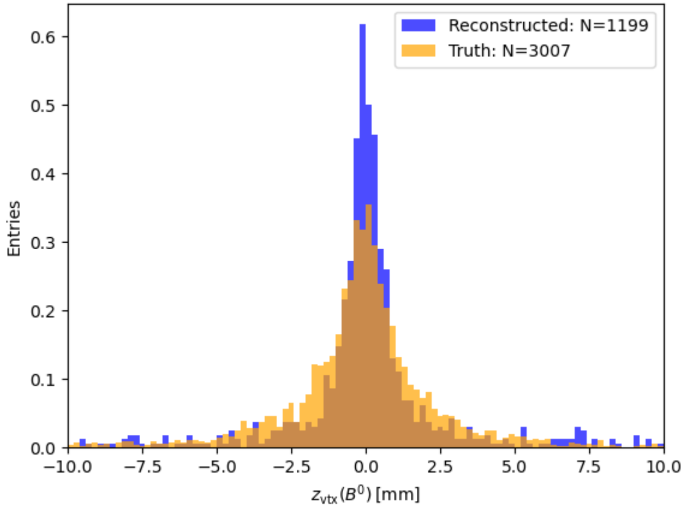


B^0 Vertex fitting - performance

- Study the performance of the **leaf-by-leaf vertexing** using the exclusive MC sample.
- See that the **vertexing fails $\sim 2/3$ of the time** reducing our signal efficiency.
- Dependent on the **inflated errors assigned to the fake photon tracks**.
- The reconstructed distributions seem to have a **smaller width** than the truth distributions suggesting inaccuracies in this vertexing procedure.
- For better accuracy and fit convergence may need to implement a **global decay chain fit**.







Next Steps

- **Increase the signal-to-background ratio in the inclusive $Z \to b\bar{b}$ sample:**
  - Develop a **BDT** that will be able to exploit features of the signal events, such as the **isolation of the D^0 tracks**.
- **Improve the convergence and accuracy of the Vertex fitting:**
  - Investigate implementing a **global decay chain vertex fitting** method.
  - Motivate the inflated errors assigned to fake-photon tracks using knowledge of the calorimeter cluster.
  - Implement **mass constraints** in the fit to improve $m(B^0)$ resolution.
- **Calculate the lifetime resolution using the PV and fitted B^0 vertex.**
- **Long term aims:**
  - Use the measured lifetime resolution in **toy studies**.
  - Calculate **sensitivity to ϕ_d** using toy studies.
- **Repeat procedure in other decay modes such as $B_s^0 \to [K^+K^-]_{D^0}K_s^0$:**
  - The **current decay is the most challenging** due to the lack of charged tracks.