Prospects for searches of invisible B-meson decays at FCC-ee

Paula Álvarez Cartelle[1,†], Matthew Kenzie[1,‡], Ritwik Mangrulkar[1,§], Aidan R. Wiederhold[2,*], Ella Wood[1,+]

[1]University of Cambridge, [2]University of Manchester

October 21, 2024

[†]paula.alvarez@cern.ch [‡]matthew.kenzie@cern.ch [§]rrm42@cam.ac.uk [*]aidan.richard.wiederhold@cern.ch [+]ella.wood@cern.ch

Introduction

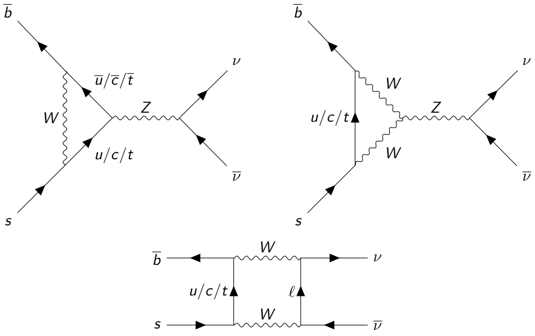
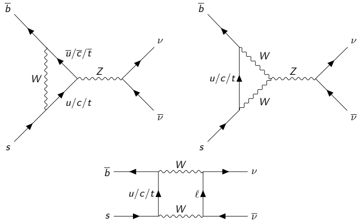


Figure: Some lowest-order Feynman diagrams corresponding to the decay $B_s^0 \to \nu\overline{\nu}$ in the Standard Model.

- As part of flavour studies at FCC-ee, we aim to estimate the improved sensitivity to completely invisible decays of $B^0_{(s)}$ mesons.
- Experimentally manifests as a search for the decays $B^0_{(s)} \to \nu\overline{\nu}$ in the Standard Model (SM).
- Provides an excellent null test of the Standard Model (SM) as well as an unambiguous probe for New Physics (NP).

SM Expectation



Helicity suppression introduces a factor in the branching fraction (BF), [1, 2]

$$\mathcal{B}\left(B^0_{(s)} \to \nu\overline{\nu}\right) \propto \left(\frac{m_\nu}{m_{B_{(s)}}}\right)^2 \tag{1}$$

giving theoretical predictions [2]

$$\mathcal{B}(B^0_d) \sim \mathcal{O}(10^{-25}), \quad \mathcal{B}(B^0_s) \sim \mathcal{O}(10^{-24})$$

Current limits of 2.4×10^{-5} for B^0_d [3] and 5.6×10^{-4} for B^0_s [4] – suggest great potential for refinement.

Advantages and drawbacks

- Theoretically clean signal.
- Discovery at high BF $\implies$ evidence for NP.
- Non-discovery $\implies$ SM validation + improved limits on viable BSM theories.
- However, experimentally and computationally difficult to distinguish from background.
- Neither initial nor final state can be detected at any stage in a conventional collider.
- Cannot perform fits of invariant mass, intermediate candidate states, etc.

Analysis pipeline

This analysis adopted the approach used in two previous studies, $b \to s\nu\overline{\nu}$ [5] and $B_c^+ \to \tau^+\nu_\tau$ [6].
Importantly, the same set of assumptions are used during the analysis: (a) perfect PID and (b) perfect vertex seeding. In addition, this analysis also uses true parent and grandparent PIDs in certain places for detailed investigation.

Workflow:

1. Identify well-separated features to use as preselection cuts.
2. 2 BDTs, first using event level branches and the second using granular features (in this case without fitting candidates).
3. Mapping BDT efficiencies and optimising cuts to reach a desired sensitivity.
4. BDTs trained using XGBOOST, with 4-fold cross-validation and early stopping. Optimum hyperparameters found using gridsearch on a subset of the training set.

Signal and background samples[1]

Classification	Process	Sample name
Signal†	$B_s^0 \to \nu\overline{\nu}$	`p8_ee_Zbb_ecm91_EvtGen_Bs2NuNu`
Background	$Z \to b\overline{b}$	`p8_ee_Zbb_ecm91`
Background	$Z \to c\overline{c}$	`p8_ee_Zcc_ecm91`
Background	$Z \to s\overline{s}$	`p8_ee_Zss_ecm91`
Background	$Z \to q\overline{q}$, $q \in \{u, d\}$	`p8_ee_Zud_ecm91`

Table: List of the signal and inclusive background samples used in the analysis.

† $B_d^0 \to \nu\overline{\nu}$ samples are not available in the `winter2023` dataset, so only invisible B_s^0 decays considered for now.

[1] https://fcc-physics-events.web.cern.ch/FCCee/delphes/winter2023/idea/

Vertexing[2]

- During collection of the ntuples, noticed an issue with the vertexing leading to immense slowdown of the analysis scripts.
- Believe it is due to older DELPHES version which fails to populate track covariances.
- Quality of the vertexing unaffected here (as they are seeded) but meant that only 50% of the available background data could be used.

```
CheckDefPos: found <= 0 eigenvalue E(2) = 0
CheckDefPos: input matrix NOT posite definite. Printing normalized matrix.

5x5 matrix is as follows

     |      0    |      1    |      2    |      3    |      4    |
---------------------------------------------------------------------
   0 |          0          0          0          0          0
   1 |          0          0          0          0          0
   2 |          0          0          0          0          0
   3 |          0          0          0          0          0
   4 |          0          0          0          0          0

CheckDefPos: found <= 0 eigenvalue E(3) = 0
CheckDefPos: input matrix NOT posite definite. Printing normalized matrix.

5x5 matrix is as follows

     |      0    |      1    |      2    |      3    |      4    |
---------------------------------------------------------------------
   0 |          0          0          0          0          0
   1 |          0          0          0          0          0
   2 |          0          0          0          0          0
   3 |          0          0          0          0          0
   4 |          0          0          0          0          0

CheckDefPos: found <= 0 eigenvalue E(4) = 0
CheckDefPos: input matrix NOT posite definite. Printing normalized matrix.

5x5 matrix is as follows

     |      0    |      1    |      2    |      3    |      4    |
---------------------------------------------------------------------
   0 |          0          0          0          0          0
   1 |          0          0          0          0          0
   2 |          0          0          0          0          0
   3 |          0          0          0          0          0
   4 |          0          0          0          0          0
```

```
================================== SUMMARY ===================================
Elapsed time (H:M:S):    00:58:58
Events processed/second: 28
Total events processed:  100,000
No. result events:       100,000
Reduction factor local:  1.0
==============================================================================
```

[2] The issue is documented here: https://github.com/HEP-FCC/FCCAnalyses/issues/378

Representative event displays

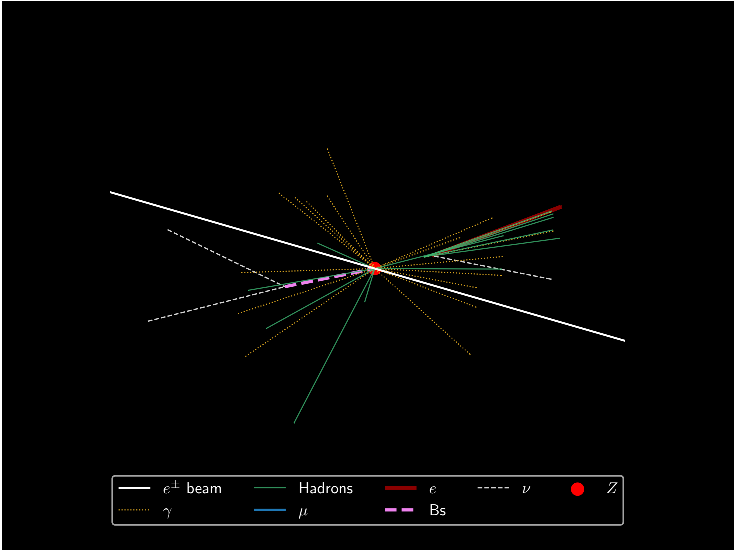


Figure: An example of a signal event

Representative event displays

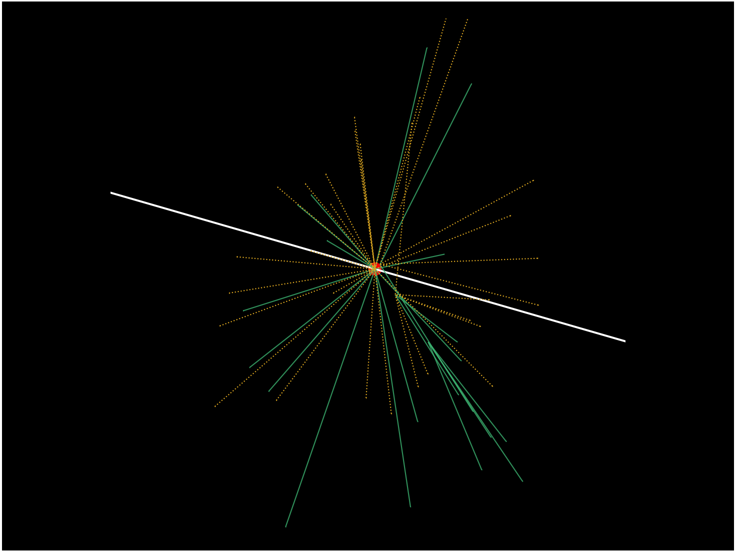


Figure: A normal $Z \to b\overline{b}$ background event

Representative event displays

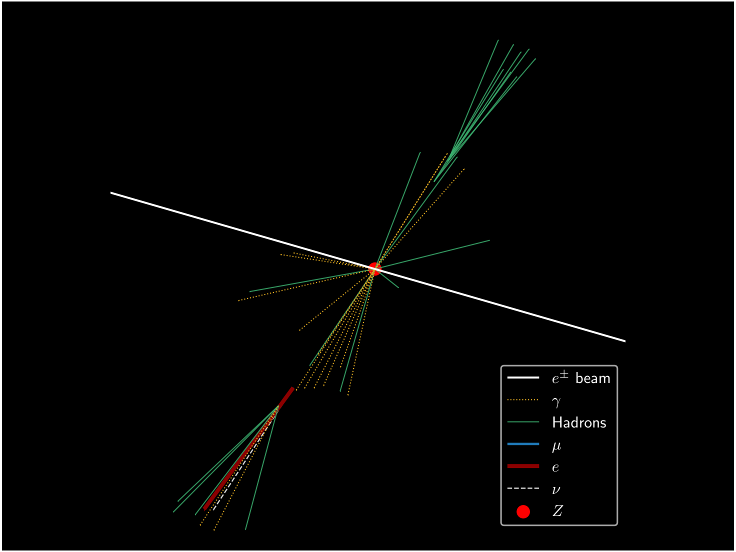


Figure: A $Z \rightarrow b\overline{b}$ background event with a cut on the energy of the “signal" hemisphere

Representative event displays

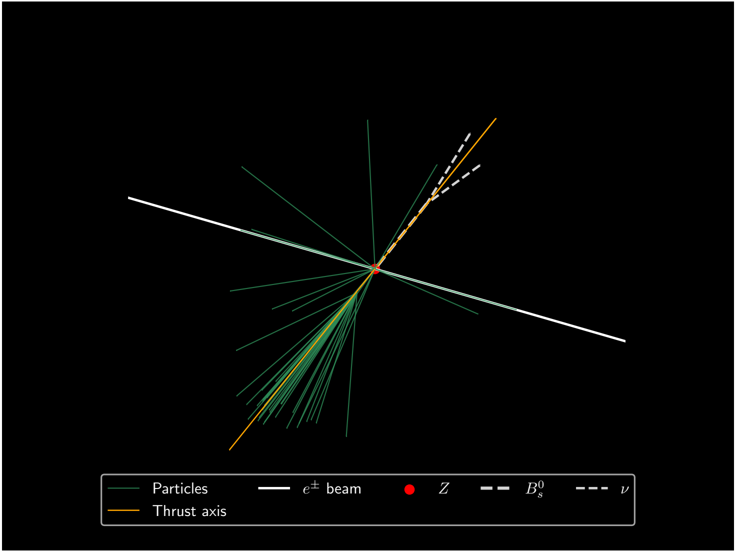
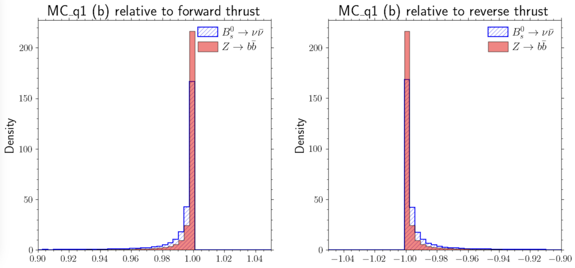
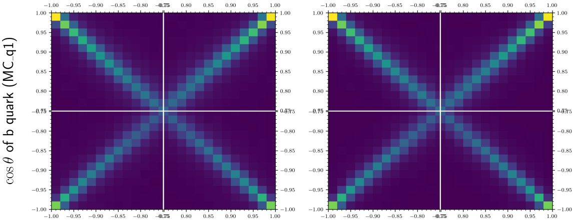


Figure: A signal event showing the thrust axis direction. Visually, the thrust direction is as expected, in spite of the fewer particles in the signal hemisphere.

Confidence in thrust computation

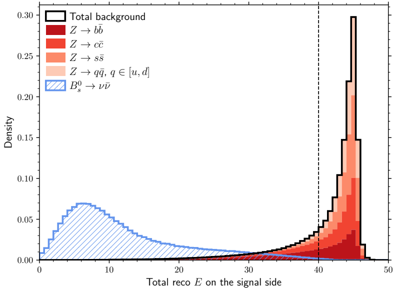


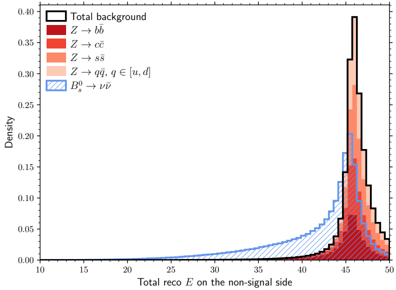
Thrust axis vs b without cut (left) and with cut (right)



Various angular parameters were plotted to ensure that the thrust direction was faithful to the original axis of the $q\overline{q}$ pair, despite missing momenta on the signal side.

Preselection





Preselection efficiencies

1. First preselection cut: Energy of the signal side < 40 GeV.
2. Since backgrounds with semileptonic decays survive this, second cut: 0 charged leptons on the signal side.
3. Two "common sense" cuts: at least one charged particle on signal side and at least one PV.
4. After the first BDT was trained on a smaller sample, a loose cut of $BDT1 > 0.2$ was also included.

Sample	**Efficiency (%)**
$B_s^0 \to \nu\overline{\nu}$	89
$Z \to b\overline{b}$	0.87
$Z \to c\overline{c}$	0.56
$Z \to s\overline{s}$	0.79
$Z \to q\overline{q},\ q \in \{u, d\}$	0.21

Custom functions and maps

Additional functions were defined specific to this analysis. These were primarily used in BDT2. Some examples include:

1. Inverse maps from the space of reconstructed vertices to the space of reconstructed particles.
2. Branches to identify highest energy particles and their properties.
3. Identification of $\tau \to \pi hh\nu$ vertices, where h is a charged hadron. This was added because a large fraction of the surviving background ($\sim 50\%$ of $b\overline{b}$ and $\sim 20\%$ of $c\overline{c}$) contained a 3 track τ vertex.

Maximum energy members

- In the signal, hardest K will come from hadronisation as the B_s^0 partner; low energy and originates from PV.
- In most backgrounds, hardest K will be from a decay; high energy and originates from a displaced vertex.
- Motivated the creation and use of such branches, including those for charged leptons and pions.

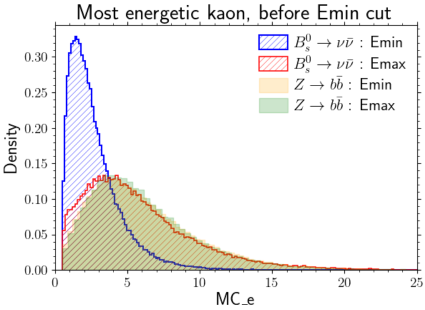
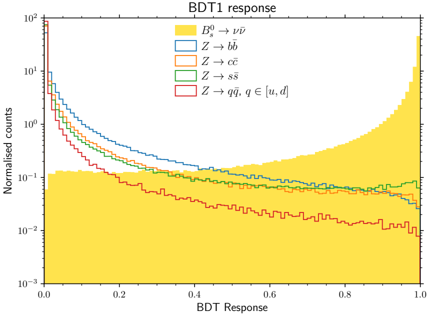
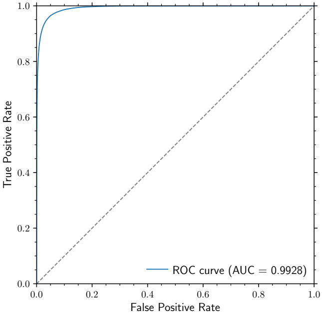


Figure: Different maximum K energies in the two hemispheres. The blue histogram indicates the softer K on the signal side, while the red indicates the K on the non-signal side. The non-signal hemisphere and both background hemispheres appear identical before any preselection cuts.

BDT1

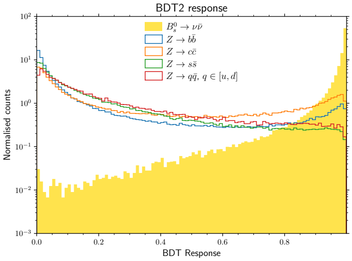
Uses 25 “event level" features, such as the energies of both hemispheres, the number of displaced vertices and the number of tracks from the PV.

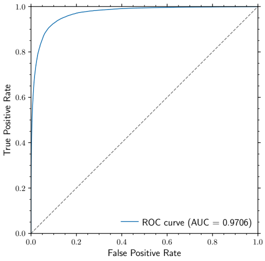




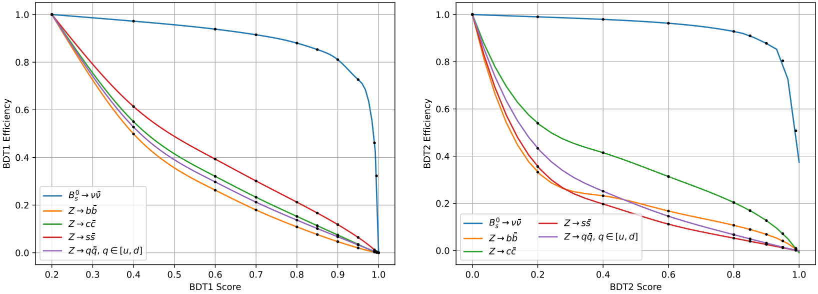
BDT2

- Uses 57(!) features containing vertex and particle level information.
- Actually contains 29 independent features, using statistical aggregates increases the total number.
- Includes the angular distributions of particles, maximum distance from the PV to a vertex, average transverse IP to the PV, etc.
- Includes the aforementioned “max energy members" and their properties.





Sensitivity estimation



Using these efficiencies, define the signal expectation value, S and the total background expectation value, B for a given signal BF.
We can define a figure of merit (FoM) $= S/\sqrt{S+B}$.

$$S = 2N_Z\mathcal{B}(Z \to b\overline{b})f_{B_s}\mathcal{B}(B_s^0 \to \nu\overline{\nu})\epsilon^s_{\text{pre}}\epsilon^s_{\text{BDT}}, \quad B = N_Z \sum_{\{q\}} \mathcal{B}(Z \to q\overline{q})\epsilon^q_{\text{pre}}\epsilon^q_{\text{BDT}} \tag{2}$$

Predicted response curves

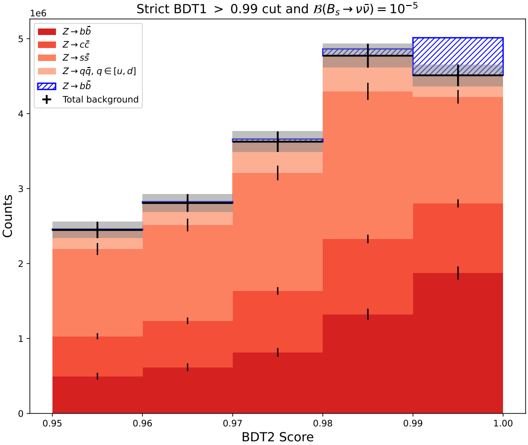


Figure: Signal and background expectations for a given BDT1 cut and signal BF. This shows that sensitivity to $\mathcal{B}(B_s^0 \to \nu\overline{\nu}) = 10^{-5}$ is almost achieved already.

A deceptive figure

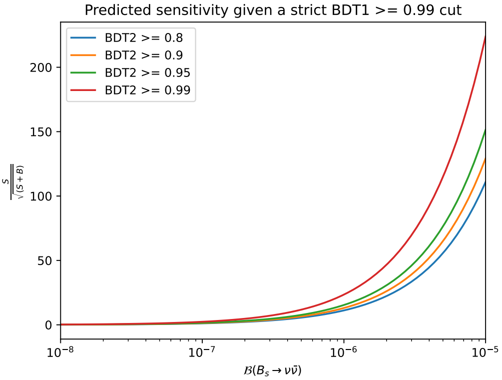


Figure: Plot of the "signal-to-noise" ratio as a function of the signal branching fraction. According to this plot, a strict BDT1 and BDT2 cut will achieve very high sensitivity at current limits (even after adjusting for the idealised assumptions).

However! If we propagate the errors in the signal and background expectations, S and B, from the errors in the efficiency calculations, it turns out that the error in this figure of merit is larger than the value itself (by a factor of ~ 100)!

Sample Statistics

Sample	Fraction saved	Number saved	After preselection	After BDT1>0.99 and BDT2>0.99
$B_s^0 \to \nu\overline{\nu}$	1	2M	1.77M	576k
$Z \to b\overline{b}$	0.5	219M	1.9M	453
$Z \to c\overline{c}$	0.5	250M	1.4M	322
$Z \to s\overline{s}$	0.5	250M	1.9M	374
$Z \to q\overline{q}$, $q \in \{u, d\}$	0.5	249M	523k	44

Table: Number of events of each sample type in the dataset at various stages of the analysis.

Conclusions

- It is clear that, although both BDTs are performing very well, more samples are required to achieve statistical significance.
- Some more fine-tuning is required to go below $\mathcal{O}(10^{-5})$.
- This ties in to necessary improvements to BDT2 and reducing the correlated features.
- Inclusion of $B_d^0 \to \nu\overline{\nu}$ samples, may want to restrict to a single combined $B_{(s)}^0 \to \nu\overline{\nu}$ estimate.
- These planned stages are currently in progress, carried out by Ella Wood[3].
- Hope to have a full Internal Note in place for the next review process.

[3] ejnw2@cam.ac.uk

References

[1] B. Aubert and BABAR. Collaboration, *Search for B0 Decays to Invisible Final States and to nu nubar gamma*, Phys. Rev. Lett. **93** (2004) 091802, arXiv:hep-ex/0405071.

[2] B. Bhattacharya, C. M. Grant, and A. A. Petrov, *Invisible widths of heavy mesons*, Phys. Rev. D **99** (2019) 093010.

[3] T. B. Collaboration, *Improved Limits on B^{0} decays to invisible $(+\gamma)$ final states*, Phys. Rev. D **86** (2012) 051105, arXiv:1206.2543.

[4] G. Alonso-Álvarez and M. Escudero, *The first limit on invisible decays of B_s mesons comes from LEP*, Eur. Phys. J. C **84** (2024) 553, arXiv:2310.13043.

[5] Y. Amhis, M. Kenzie, M. Reboud, and A. R. Wiederhold, *Prospects for searches of $b \to s \nu \bar{\nu}$ decays at FCC-ee*, 2023. doi: 10.17181/6k4q7-veh06.

[6] Y. Amhis *et al.*, *Prospects for $$ {B}_c^{+} $$ $\to \tau + \nu\tau$ at FCC-ee*, J. High Energ. Phys. **2021** (2021) 133.

Backups

Details about vertexing

- The `VertexFitterSimple::get_PrimaryTracks` and `VertexFitterSimple::VertexFitter_Tk` algorithms were used to fit the primary tracks and the primary vertex.
- The beamspot constraint was, in accordance with previous analyses, $(x, y, z) = (0, 0, 0)$ with $(\sigma_x, \sigma_y, \sigma_z) = (4.5, 0.02, 300)$ μm [6].
- An alternative, `VertexFinderActs::VertexFinderAMVF`, was tested but no improvements were observed.

Signal and background expectations: S, B

The error in the figure of merit $S/\sqrt{S+B}$ is:

$$\sigma^2_{FoM} = \frac{\sigma^2_S}{4}\frac{(S+B(2-S))^2}{(S+B)^3} + \frac{\sigma^2_B}{4}\frac{S^2(1+S)^2}{(S+B)^3} \quad (3)$$

Errors in S and B are calculated assuming the errors in the efficiency dominate. Efficiency errors are treated using Bayesian statistics in a pure counting experiment[4],

$$\sigma^2_\epsilon = \frac{(k+1)(k+2)}{(n+2)(n+3)} - \left(\frac{k+1}{n+2}\right)^2 \quad \text{for efficiency, } \epsilon = \frac{k}{n} \quad (4)$$

where k is the number of events after the cut and n is the number of events in the sample.

[4]Motivated by https://indico.cern.ch/event/66256/contributions/2071577/attachments/1017176/1447814/EfficiencyErrors.pdf

Version Info

1. 2022-12-23 release of the Key4hep stack used during generation, 2024-04-12 release used during analysis.

2. Crucially, the 6.28/10 release of ROOT was used by `fccanalysis`. This is not forward-compatible with the latest release, especially so when saving XGBOOST models to TMVA files.

3. The 1.6.2 version of XGBOOST was used to train the BDTs, which is also incompatible with later releases and had noticeably worse execution times.