Prospects for searches of $b \to s\nu\overline{\nu}$ decays at FCC-ee

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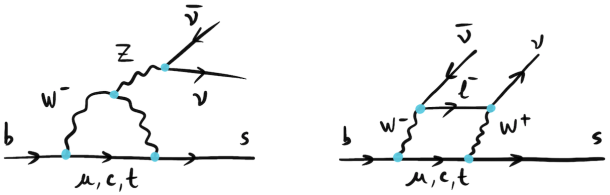
- Considerable interest in the flavour community in $b \to s\ell^+\ell^-$ and $b \to c\ell^-\overline{\nu}$ transitions
  - $b \to s\nu\overline{\nu}$ transitions are complementary probes (ℓ^+ and ν share a weak doublet)
- **SM predictions are clean:**
  - Dominant uncertainties from hadronic form-factors and CKM elements
  - No long-distance contributions from (in)famous charm loops
  - Sensitive to a variety of NP scenarios *e.g.* Z', leptoquarks *etc.*



$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{ij} (C_L^{ij} O_L^{ij} + C_R^{ij} O_R^{ij}) + h.c,$$

- In the SM, $C_L^{ii} = -6.35(7)$ and $C_R^{ij} = 0$ [1, 2, 3, 4]

FCC-ee as a flavour factory

- FCC-ee is a **dream** environment for heavy flavour
  - Get all the benefits of both Belle II and LHCb
  - Provides a *unique* opportunity for semileptonic flavour physics
- The Monteil-Wilkinson tick-list [5]

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

- **Tera-Z** run at the Z^0-pole:
  - 6×10^{12} Z^0 (across 4 experiments)

Species (both flavours)	B^0	B^+	B_s^0	Λ_b^0	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (billions)	740	740	180	160	3.6	720	200

- **Giga-W** run at W^+W^- threshold:
  - 2.4×10^8 $W^\pm$ pairs (across 4 experiments)
- Do LEP in ONE MINUTE!

Experimental state-of-the-art

- In the SM $b \to s\nu\overline{\nu}$ BF predictions are $\mathcal{O}(10^{-5})$
  - Recently evidence at Belle II 3.5σ [6]
  - 2.7σ enhancement w.r.t SM prediction
- From the underlying $b \to s\nu\bar{\nu}$ transition:

Decay	B-factories	FCC-ee	Current Limit	SM prediction
$B^+ \to K^+\nu\overline{\nu}$	✔	✔	Seen	$(4.0 \pm 0.5) \times 10^{-6}$
$B^+ \to K^{*+}\nu\overline{\nu}$	✔	✔	$< 4.0 \times 10^{-5}$	$(9.8 \pm 1.1) \times 10^{-6}$
$B^0 \to K^0_S\nu\overline{\nu}$	✔	✔	$< 2.6 \times 10^{-5}$	$(3.7 \pm 0.4) \times 10^{-6}$
$B^0 \to K^{*0}\nu\overline{\nu}$	✔	✔	$< 1.8 \times 10^{-5}$	$(9.2 \pm 1.0) \times 10^{-6}$
$B^0_s \to \phi\nu\overline{\nu}$	✗	✔	$< 5.4 \times 10^{-3}$	$(9.9 \pm 0.7) \times 10^{-6}$
$\Lambda^0_b \to \Lambda^0\nu\overline{\nu}$	✗	✔	–	–
$\Lambda^0_b \to \Lambda^0\nu\overline{\nu}$	✗	✔	–	–
$B^+_c \to D^+_s\nu\overline{\nu}$	✗	✔	–	–

- Decays with intermediate vectors are consierably easier experimentally
  - single track is hard, final state neutral needs good $K^0_S/\ \Lambda^0$ reco
- Decays with intermediate scalars are cleaner for theory
- With 2 neutrinos in the final state, decays are (probably) impossible at the LHC

Detector requirements for flavour

Tracking

- Good p resolution is required for most physics at FCC
  - Ability to reconstruct down to low momentum important for flavour

Vertexing

- Essential for huge parts of flavour program
  - Resolve TD oscillations of B_s^0 so $\sigma_t \sim 50\,\text{fs}$
  - Semi-leptonic and decays to τ, $\sigma_v \sim 5\,\mu\text{m}$ for 3-track vertex

Calorimetry

- Low multiplicity allows study of flavour with neutrals
  - Anything with π^0 or γ incredibly challenging at LHCb
  - Need performance maintained at low energy

Particle ID

- Vital for any heavy flavour program
  - Need effective kaon-pion separation across wide range of momentum
  - Non-signal momenta $\sim 10\,\text{GeV}/c$, signal momenta $\sim 30\,\text{GeV}/c$

- Published in JHEP last week! [7]

JHEP

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Prospects for searches of $b \to s\nu\bar{\nu}$ decays at FCC-ee

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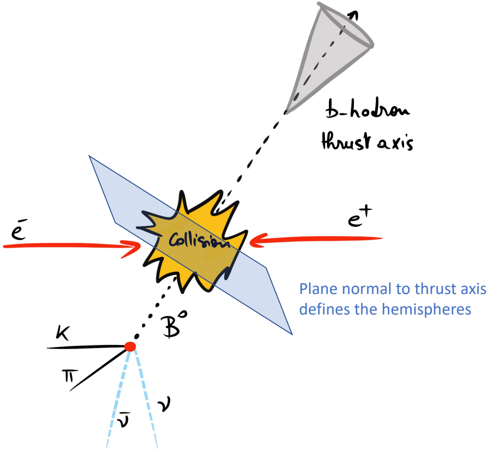
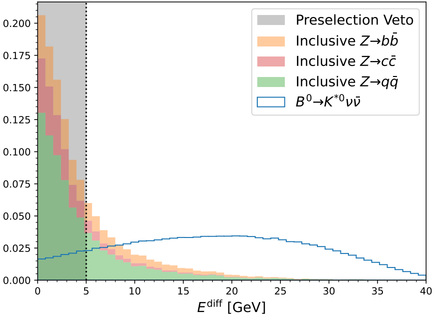
ABSTRACT: We investigate the physics reach and potential for the study of various decays involving a $b \to s\nu\bar{\nu}$ transition at the Future Circular Collider running electron-positron collisions at the Z-pole (FCC-ee). Signal and background candidates, which involve inclusive Z contributions from $b\bar{b}$, $c\bar{c}$ and uds final states, are simulated for a proposed multi-purpose detector. Signal candidates are selected using two Boosted Decision Tree algorithms. We determine expected relative sensitivities of 0.53%, 1.20%, 3.37% and 9.86% for the branching fractions of the $B^0 \to K^{*0}\nu\bar{\nu}$, $B^0_s \to \phi\nu\bar{\nu}$, $B^0 \to K^0_S\nu\bar{\nu}$ and $\Lambda^0_b \to \Lambda\nu\bar{\nu}$ decays, respectively. In addition, we investigate the impact of detector design choices related to particle-identification and vertex resolution. The phenomenological impact of such measurements on the extraction of Standard Model and new physics parameters is also studied.

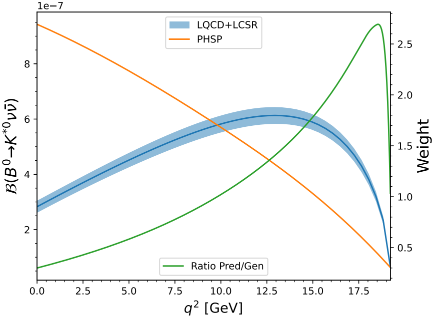
Event topology

- Use the thrust axis for $Z^0 \rightarrow q\bar{q}$ to define event hemispheres
- Due to missing energy in the signal decay the two hemispheres have different energy distributions



- Background sample from inclusive $Z^0 \to q\bar{q}, c\bar{c}, b\bar{b}$ using PDG branching fractions
- Signal sample from `EvtGen` with *e.g.* $B^0 \to K^{*0}\nu\bar{\nu}$ or $B_s^0 \to \phi\nu\bar{\nu}$ with reweighted q^2 distribution
- Many thanks to `IDEA` and `FCCAnalysis` developers
- Easy initial win from cut on E_{diff}





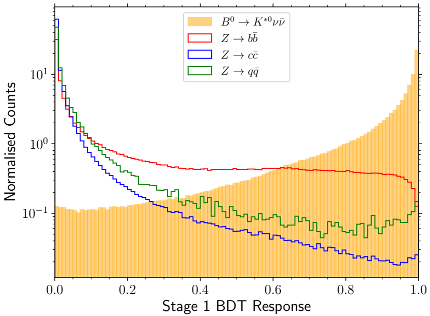
- Train two MVAs, one "Event-level" and one "Decay-level"

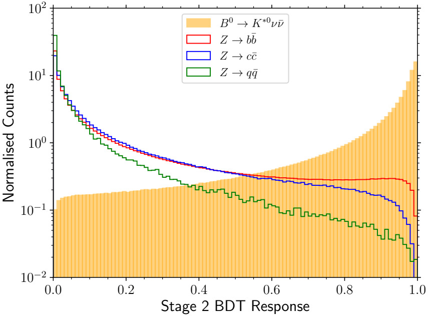
Event-level MVA inputs

- Event energy distributions
- Event vertex information

Decay-level MVA inputs

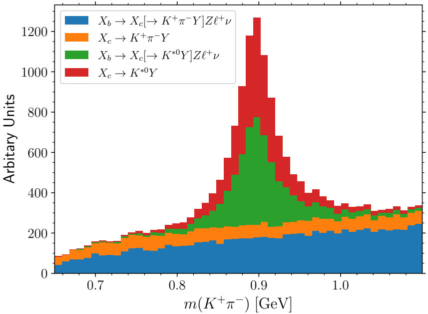
- Intermediate candidate kinematics
- Intermediate candidate topology
- The nominal B-meson energy ($m_Z - E_{\text{rec}}$)

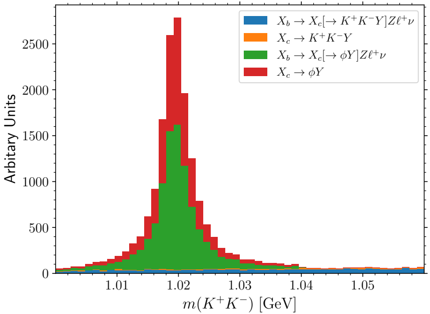




- Use multivariate splines to build efficiency maps across the (BDT1, BDT2) plane

- For modes with an intermediate resonance the serious backgrounds are those with real K^{*0} or ϕ
- In a "real-life" analysis would fit in intermediate candidate mass to remove fakes





Sensitivity estimate

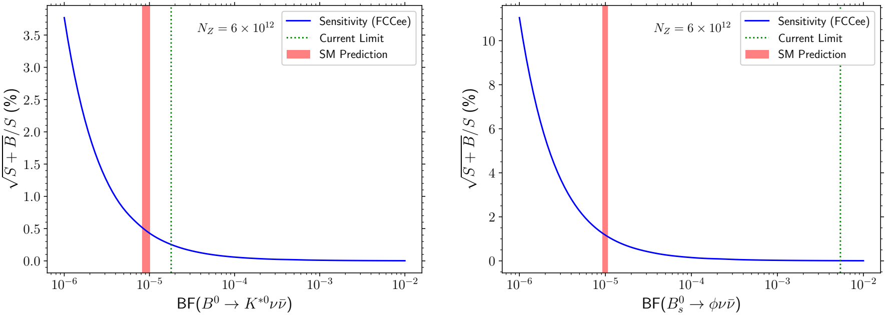
- Signal expectation is computed as

$$S = N_Z\,\mathcal{B}(Z \to b\bar{b})\,2\,f_B\,\mathcal{B}(B \to Y\nu\bar{\nu})\,\mathcal{B}(Y \to f)\,\epsilon^{s}_{\text{pre}}\,\epsilon^{s}_{\text{BDTs}},$$

- Background expectation computed as

$$B = \sum_{f\in\{b\bar{b},c\bar{c},q\bar{q}\}} N_Z\,\mathcal{B}(Z \to f)\,\epsilon^{b}_{\text{pre}}\,\epsilon^{b}_{\text{BDTs}},$$

  assuming
  - 6×10^{12} Z^0 in FCC-ee operation
  - known / predicted production fractions and branching ratios
  - analysis efficiencies
- Run full analysis for $B^0 \to K^{*0}\nu\bar{\nu}$ and $B^0_s \to \phi\nu\bar{\nu}$
- Extrapolate to estimate for $B^0 \to K^0_{\text{S}}\nu\bar{\nu}$ and $\Lambda^0_b \to \Lambda\nu\bar{\nu}$

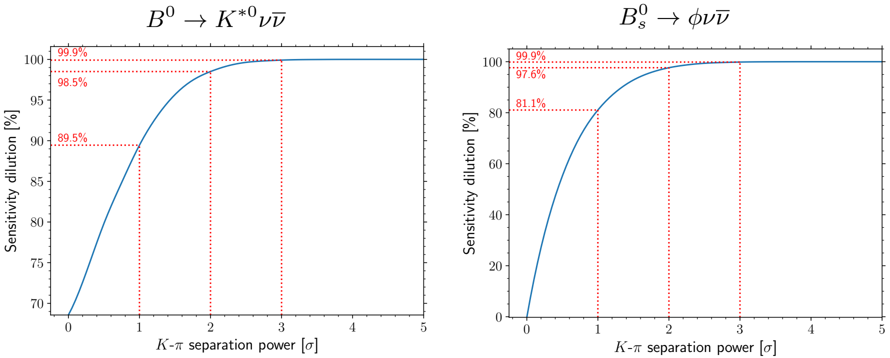


- Sensitivity at the SM prediction

Mode	N_S	N_B	ϵ^s	$\epsilon^{b\bar{b}}$	$\epsilon^{c\bar{c}}$	$\epsilon^{q\bar{q}}$	S/B	$\sqrt{S+B}/S$
$B^0 \to K^{*0}\nu\bar{\nu}$	231 K	1.27 M	3.7%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.17	0.53%
$B_s^0 \to \phi\nu\bar{\nu}$	61 K	0.48 M	7.4%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.13	1.20%

- Extrapolates to 3.37% for $B^0 \to K_S^0\nu\bar{\nu}$ and 9.86% for $\Lambda_b^0 \to \Lambda\nu\bar{\nu}$
- Could measure F_L at $\sim 2.5\%$ in $B^0 \to K^{*0}\nu\bar{\nu}$ and $\sim 5\%$ in $B_s^0 \to \phi\nu\bar{\nu}$

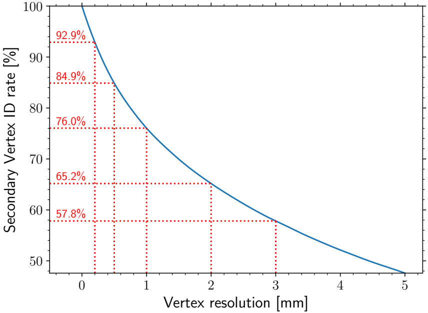
- For serious flavour analysis at FCC-ee - hadronic PID separation is vital
- Our analysis assumes *perfect* PID
- Naively investigate this by making random swaps (no momentum dependence)



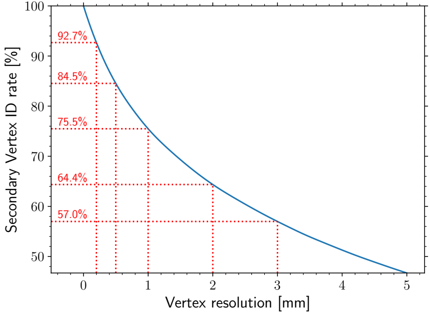
- K-π separation of 2σ would have negligible impact on the sensitivity

- For serious flavour analysis at FCC-ee - precision vertexing is essential
- Our analysis assumes *perfect* vertex seeding
- Naively investigate this by making random swaps

$B^0 \to K^{*0}\nu\overline{\nu}$

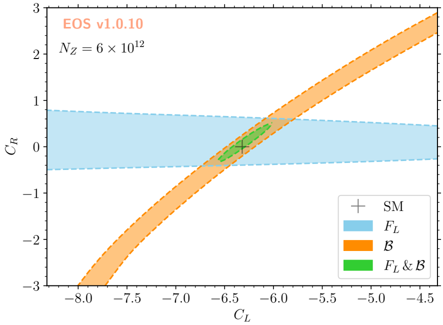


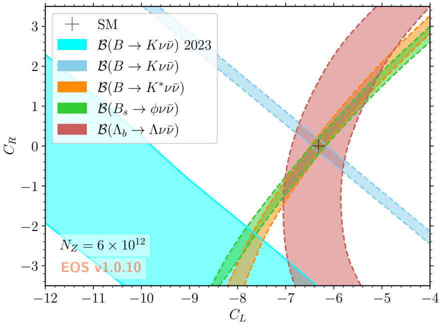
$B_s^0 \to \phi\nu\overline{\nu}$



- Need $< 0.2\,\mathrm{mm}$ resolution to mitigate vertex mis-id
  - But this is already above the requirements for vertex precision anyway

- Extrapolate predicted sensitivities to Wilson coefficients



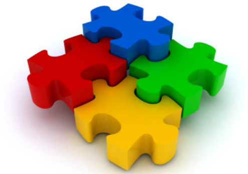


- See the exceptional potential of FCC-ee to model-independet New Physics

Summary and thoughts on future studies

So where is this heading (just some of my own thoughts)

- This was a very enjoyable experience!
- Would like to review and improve the software for flavour studies
  - MC-truth level decay descriptor matching
  - Incoporate latest improvements for neutral reconstruction
- Can of course expand and improve physics case studies
  - Would be interesting to see how FCC-ee does with $B^+ \to K^+ \nu \overline{\nu}$
  - Could also consider the rarer $b \to d \nu \overline{\nu}$ transitions
- Emphasis towards detector design
  - Vertexing requirements
  - PID requirements
  - Implementation in simulation



[1] J. Brod, M. Gorbahn, and E. Stamou, *Two-Loop Electroweak Corrections for the $K \to \pi\nu\bar{\nu}$ Decays*, Phys. Rev. D **83** (2011) 034030, arXiv:1009.0947.

[2] G. Buchalla and A. J. Buras, *The rare decays $K \to \pi\nu\bar{\nu}$, $B \to X\nu\bar{\nu}$ and $B \to l^+l^-$: An Update*, Nucl. Phys. B **548** (1999) 309, arXiv:hep-ph/9901288.

[3] A. J. Buras, J. Girrbach-Noe, C. Niehoff, and D. M. Straub, *$B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond*, JHEP **02** (2015) 184, arXiv:1409.4557.

[4] M. Misiak and J. Urban, *QCD corrections to FCNC decays mediated by Z penguins and W boxes*, Phys. Lett. B **451** (1999) 161, arXiv:hep-ph/9901278.

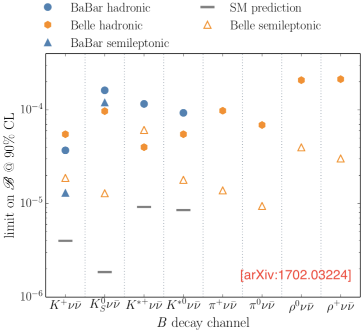
[5] S. Monteil and G. Wilkinson, *Heavy-quark opportunities and challenges at FCC-ee*, Eur. Phys. J. Plus **136** (2021) 837, arXiv:2106.01259.

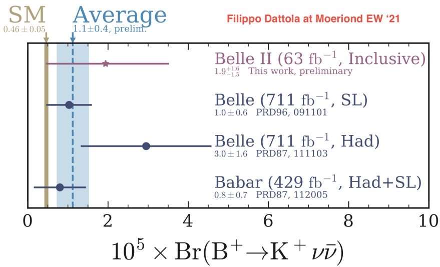
[6] Belle-II, I. Adachi *et al.*, *Evidence for $B^+ \to K^+\nu\bar{\nu}$ Decays*, arXiv:2311.14647.

[7] Y. Amhis, M. Kenzie, M. Reboud, and A. R. Wiederhold, *Prospects for searches of $b \to s\nu\overline{\nu}$ decays at FCC-ee*, JHEP **01** (2024) 144, arXiv:2309.11353.

BACK UP

- Searches at B-factories use B-mesons produced via $e^+e^- \to \Upsilon(4S) \to B^+B^-$
- Event is *tagged* either *inclusively* or using specific hadronic or semileptonic decays of the other B.
- Belle II results: BR($B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5}$ at 90% C.L. [arXiv:2104.12624].
- Expect to reach $\sim 10\%$ precision on B^+/B^0 with 50 ab^{-1} [arXiv:1808.10567]





- **FCC-ee** is the **only foreseen experiment** that **can improve Belle-II measurement** in the (far) future (apart from maybe CEPC)!

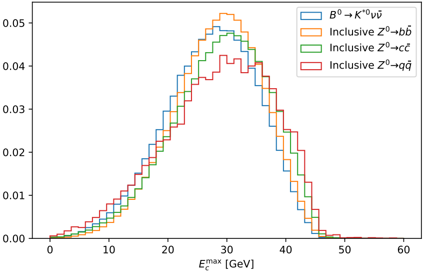
Some places we cheat

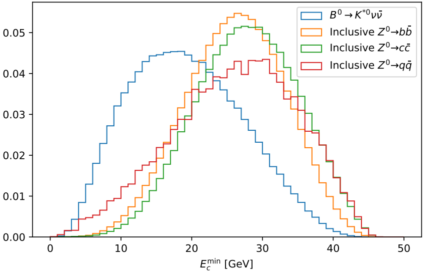
Relevant for detector design

- Use the same vertexing procedure developed for $B_c^+ \to \tau^+ \nu_\tau$ (see this talk for details) which assumes *perfect* vertex seeding
  $\to$ implies we will have **excellent vertex resolution**
- We also truth match the kaon and pion daughters to have the correct mass hypothesis (with the reconstructed momentum)
  $\to$ implies we will have **excellent PID**
- When we get a bit more advanced it would be nice to understand the impact of relaxing these requirements.
- Also assume the K^{*0} in the signal mode is pure $K^*(892)^0$

None of this is particularly relevant for the event level MVA we have trained so far (and show today) but it will be important for the next stage MVA

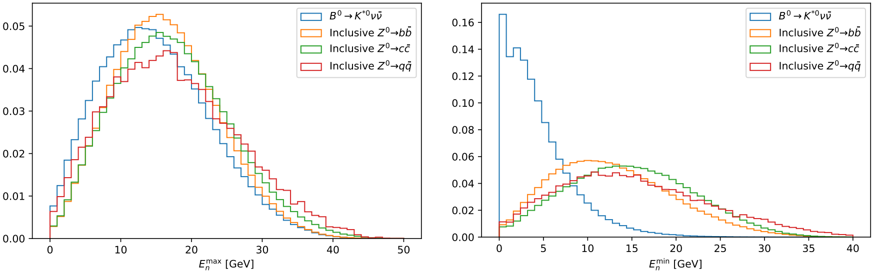
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay





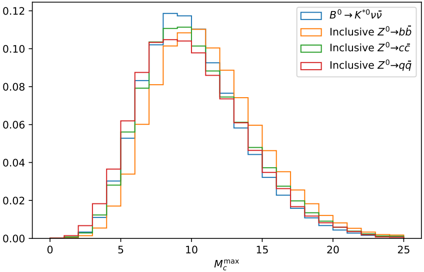
Neutral energy in each hemisphere

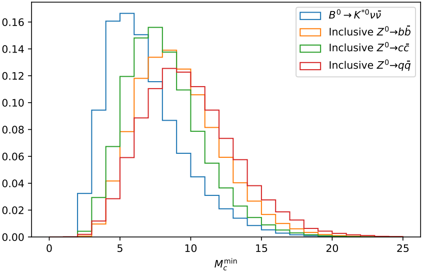
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay



Charged multiplicity in each hemisphere

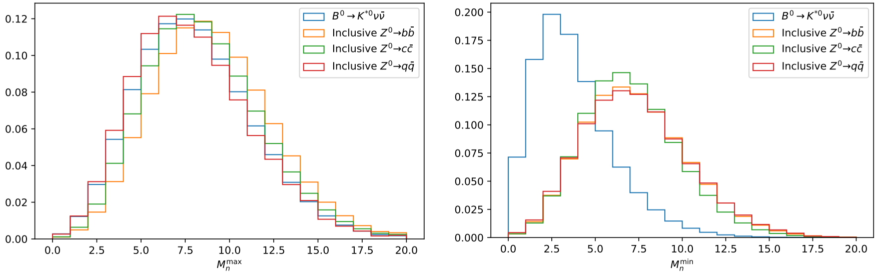
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay





Neutral multiplicity in each hemisphere

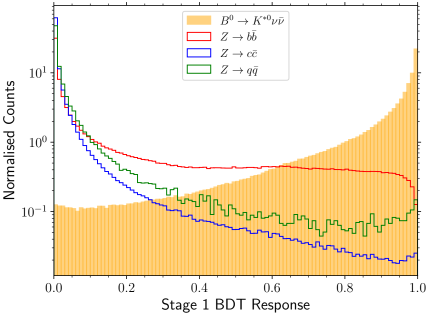
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

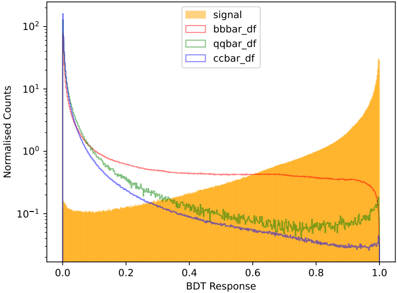


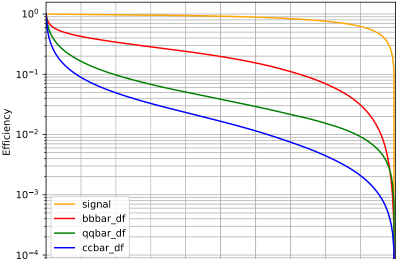
Stage 1 Inputs

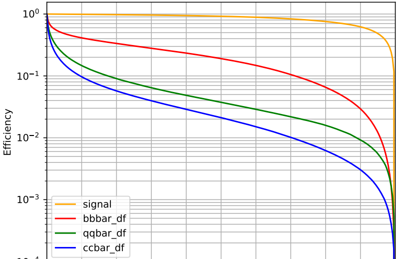
- The total reconstructed energy in each hemisphere,
- The total charged and neutral reconstructed energies of each hemisphere,
- The charged and neutral particle multiplicities in each hemisphere,
- The number of charged tracks used in the reconstruction of the primary vertex,
- The number of reconstructed vertices in the event,
- The number of candidates in the event
- The number of reconstructed vertices in each hemisphere,
- The minimum, maximum and average radial distance of all decay vertices from the primary vertex.

Stage 1 BDT

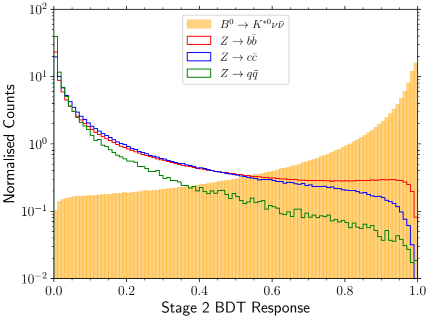

$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 1 BDT Response


signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts
BDT Response

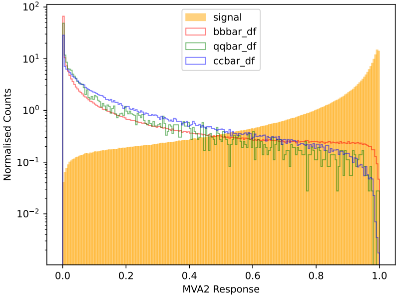

Efficiency
signal
bbbar_df
qqbar_df
ccbar_df


Efficiency
signal
bbbar_df
qqbar_df
ccbar_df

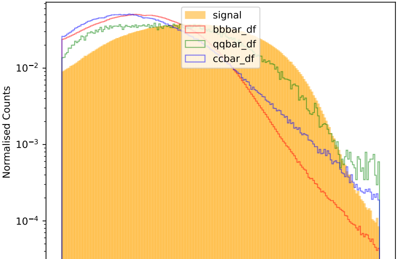
Stage 2 BDT



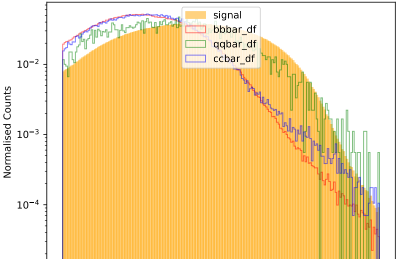
$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 2 BDT Response



signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts
MVA2 Response



signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts

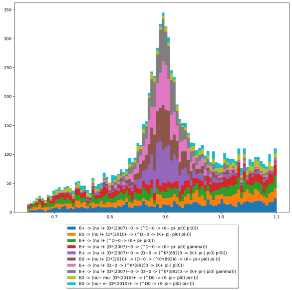


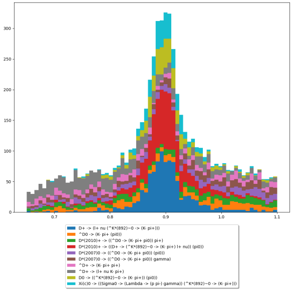
signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts

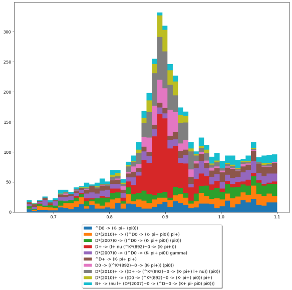
Stage 2 Inputs

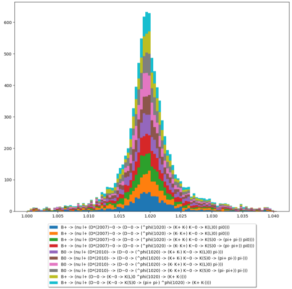
- The intermediate candidate's reconstructed mass
- The number of intermediate candidates in the event
- The candidate's flight distance and flight distance χ^2 from the primary vertex
- The x, y and z components of the reconstructed candidate's momentum
- The scalar momentum of the candidate
- The transverse and longitudinal impact parameter of the candidate
- The minimum, maximum and average transverse and longitudinal impact parameters of all other reconstructed vertices in the event
- The angle between the intermediate candidate and the thrust axis
- The mass of the primary vertex
- The nominal B candidate energy, defined as the Z mass minus all of the reconstructed energy apart from the candidate children

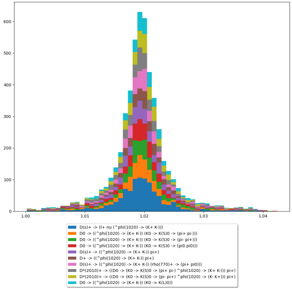
Backgrounds

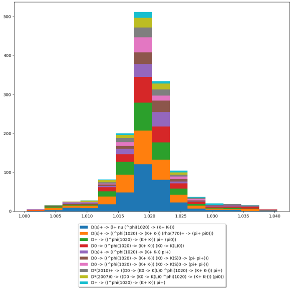




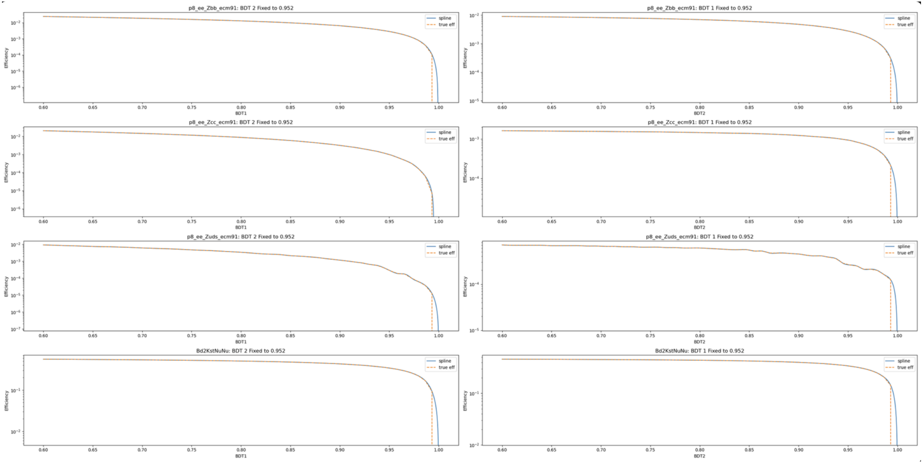






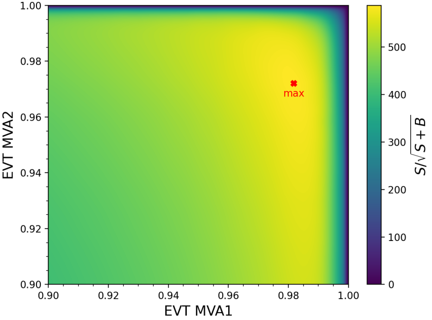


Spline Drop Off



- Train a second BDT on variables related to the candidate properties:
  - Intermediate candidate kinematics
  - Intermediate candidate topology
  - The nominal B-meson energy (Z mass minus E_{rec})
- Use multivariate splines to build efficiency maps across the (BDT1, BDT2) plane
- Then maximise the FOM, $S/\sqrt{S+B}$, as a function of the BDT cuts for a range of BF values

$B^0 \to K^{*0}\nu\bar{\nu}$



$B_s^0 \to \phi\nu\bar{\nu}$