Prospects for searches of $b \to s\nu\bar{\nu}$ decays

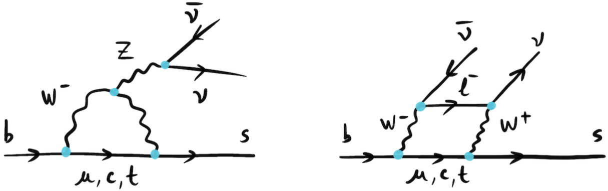
Yasmine Amhis [1,2], Matthew Kenzie [3], Méril Reboud [1,4],
Olcyr Sumensari [1], Aidan Wiederhold [5]

[1] *Orsay*, [2] *CERN*, [3] *Cambridge*, [4] *Durham*, [5] *Warwick*

FCC Week 2023, London

7th June 2023

- 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]

Experimental state-of-the-art

- FCC-ee provides a (possibly *unique*) opportunity for semileptonic flavour physics
  - A *beauty/charm* factory at the Z gets the best of both LHCb and B-factories
  - e^+–e^- collision, high production rate, access to high mass states, hermetic detector
- In the SM $b \to s\nu\bar{\nu}$ BF predictions are $\mathcal{O}(10^{-5})$
- Not yet seen experimentally
- From the underlying $b \to s\nu\bar{\nu}$ transition we can study:

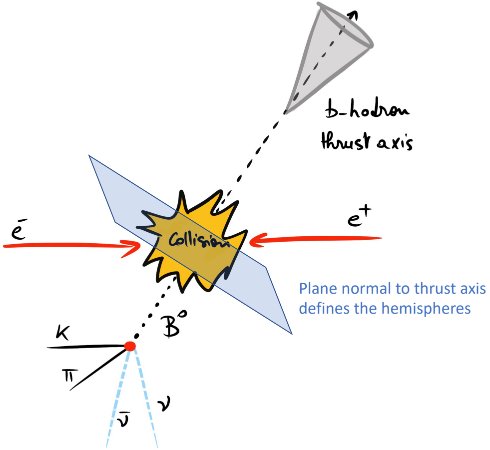
Decay	B-factories	FCC-ee	Current Limit	SM prediction
$B^+ \to K^+\nu\bar{\nu}$	✔	✔	$< 1.6 \times 10^{-5}$	$(4.0 \pm 0.5) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔	$< 4.0 \times 10^{-5}$	$(9.8 \pm 1.1) \times 10^{-6}$
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔	$< 2.6 \times 10^{-5}$	$(3.7 \pm 0.4) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔	$< 1.8 \times 10^{-5}$	$(9.2 \pm 1.0) \times 10^{-6}$
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔	$< 5.4 \times 10^{-3}$	$(9.9 \pm 0.7) \times 10^{-6}$
$\Lambda^0_b \to \Lambda^0\nu\bar{\nu}$	✗	✔	–	–

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

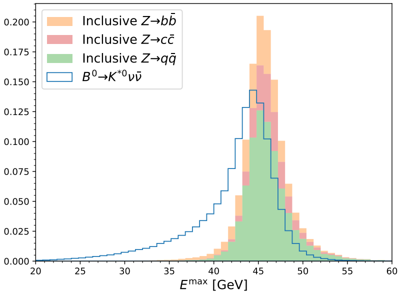
Event topology

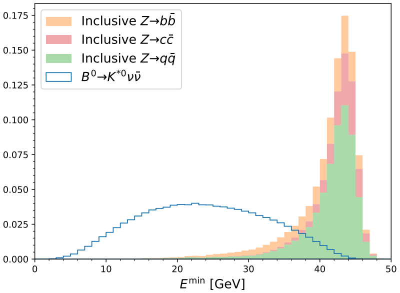
We have studied the prospects for $B^0 \to K^{*0}\nu\overline{\nu}$ and $B_s^0 \to \phi\nu\overline{\nu}$

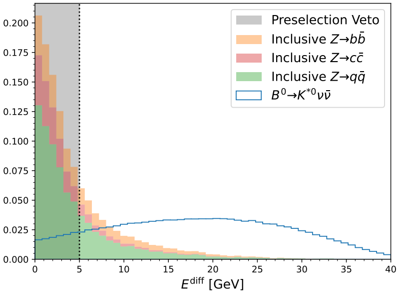
- Use the thrust axis for $Z^0 \to q\overline{q}$ to define event hemispheres
- Due to missing energy in the signal decay the two hemispheres have different energy distributions



Energy in each hemisphere

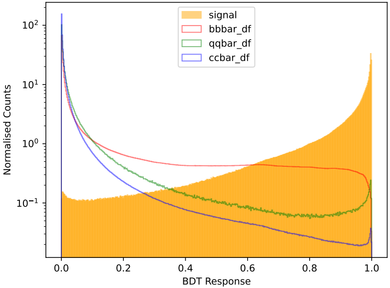


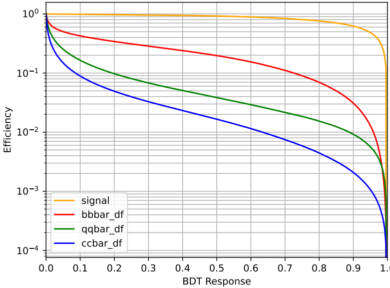




Event-level MVA

- Background sample from inclusive $Z^0 \to q\overline{q}, c\overline{c}, b\overline{b}$ using PDG branching fractions
- Input variables are the event energy distributions and vertex information



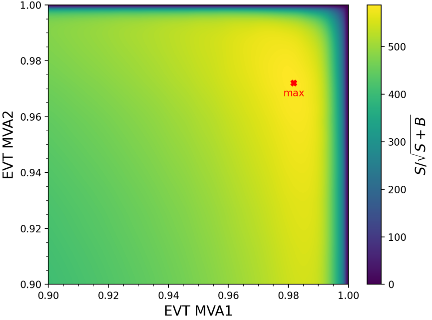


- Powerful seperation - cut at 0.6 has $> 90\%$ signal efficiency and $\sim 90\%$ background rejection
- Very similar for the $B_s^0 \to \phi\nu\overline{\nu}$ mode

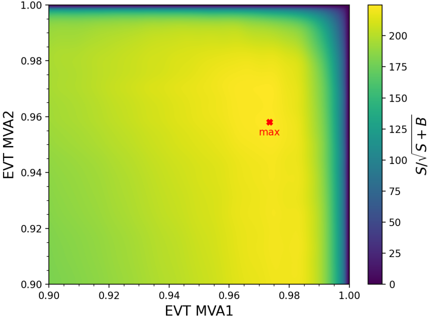
Analysis-level MVA

- 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

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



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



Signal 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

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

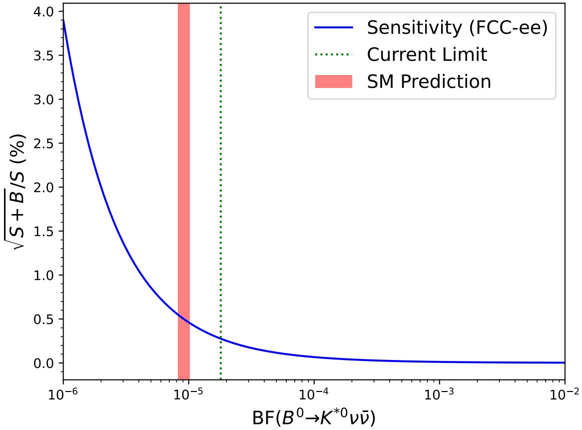
assuming

- 3×10^{12} Z^0 in FCC-ee operation (needs updating to 2×10^{12})
- known / predicted production fractions and branching ratios
- analysis efficiencies

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

For optimal cuts at the SM prediction:

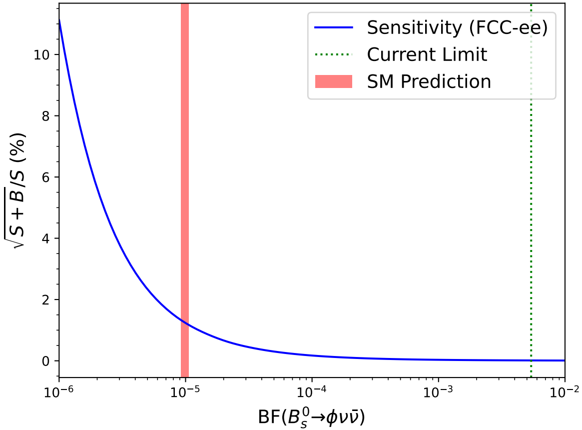
- Signal efficiency $\sim 10\%$
- $b\bar{b}$ efficiency $\sim 10^{-5}$
- $c\bar{c}$ efficiency $\sim 10^{-6}$
- $q\bar{q}$ efficiency $\sim 10^{-8}$
- S/B ratio $\sim 1:20$
- Sensitivity $\sim 0.5\%$



$B_s^0 \to \phi\nu\overline{\nu}$ Efficiency and Sensitivity

For optimal cuts at the SM prediction:

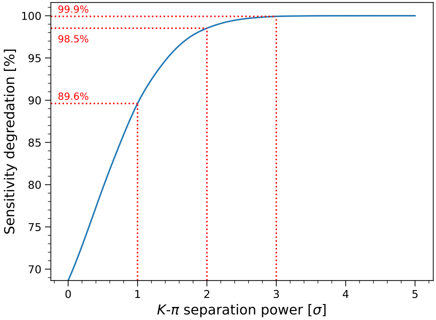
- Signal efficiency $\sim 11\%$
- $b\overline{b}$ efficiency $\sim 10^{-6}$
- $c\overline{c}$ efficiency $\sim 10^{-8}$
- $q\overline{q}$ efficiency $\sim 10^{-9}$
- S/B ratio $\sim 1:9$
- Sensitivity $\sim 1.3\%$
- CEPC at $\sim 1.8\%$ [5]



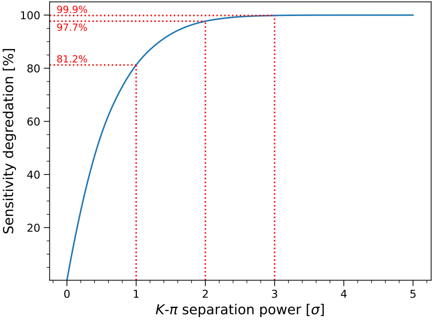
PID requirements of the detector

- 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)

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



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

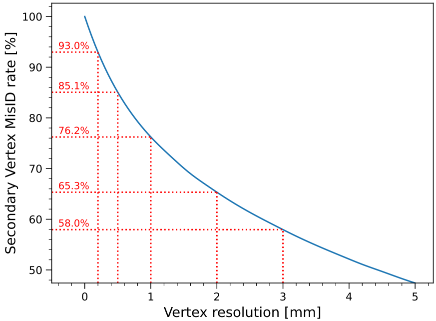


- K-π separation of 2σ would have negligible impact on the sensitivity

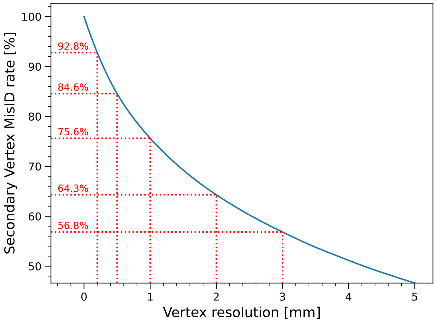
Vertexing requirements of the detector

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

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



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

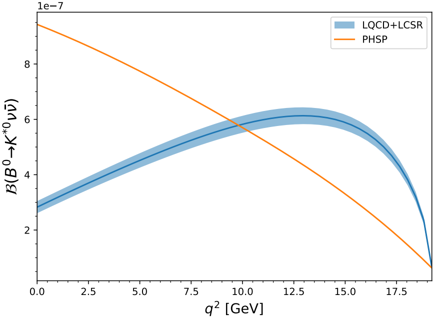


- Need < 0.2 mm resolution to mitigate vertex mis-id
  - But this is already above the requirements for vertex precision anyway

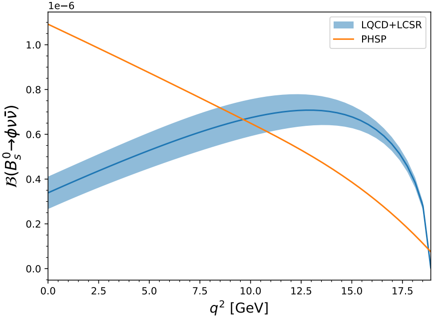
q^2 distribution and reweighting

- Our simulation uses phase space (PHSP) generation models
- We need to reweight the q^2 distribution to match the latest theory predictions (from MR and OS)

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



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



Summary and Outlook

- We are now at fairly advanced stages (we have an almost complete paper draft)
- Sensitivity to $b \to s\nu\overline{\nu}$ BFs of $\mathcal{O}(1\%)$
- Need to finish the pheno interpretation (sensitivity to Wilson coeffs)
- In parallel considering neutral modes not shown here
- Precise vertexing is vital
  - Average flight distance of a B^0 at FCC-ee is ~ 3mm
  - Our analysis assumes both the production (PV) and decay (SV) vertices of the B are perfectly seeded
  - Need resolution $\mathcal{O}(100 - 200\,\mu\text{m})$ to mitigate vertex mis-id
- Powerful particle identification is required
  - Sensitivity begins to rapidly degrade for separation $< 2\sigma$

Thanks to the authors of Ref. [6] for the inspiration and example codes

[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, *$B \to K^{(*)}\nu\overline{\nu}$ decays in the Standard Model and beyond*, JHEP **02** (2015) 184, arXiv:1409.4557.

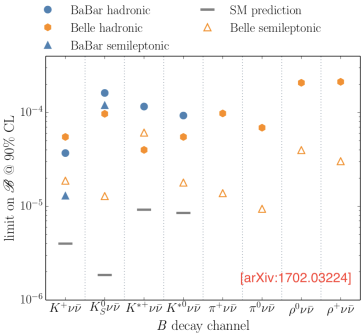
[4] M. Misiak and J. Urban, *QCD corrections to FCNC decays mediated by Z penguins and W boxes*, Phys. Lett. B **451** (1999) 161, arXiv:hep-ph/9901278.

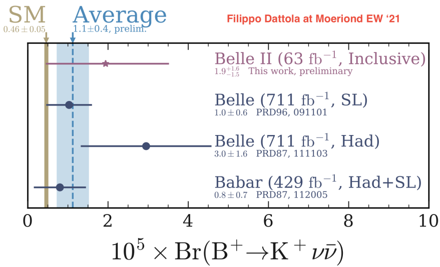
[5] L. Li, M. Ruan, Y. Wang, and Y. Wang, *Analysis of $B_s^0 \to \phi\nu\nu$ at CEPC*, Phys. Rev. D **105** (2022) 114036, arXiv:2201.07374.

[6] Y. Amhis *et al.*, *Prospects for $B_c^+ \to \tau^+\nu_\tau$ at FCC-ee*, JHEP **12** (2021) 133, arXiv:2105.13330.

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

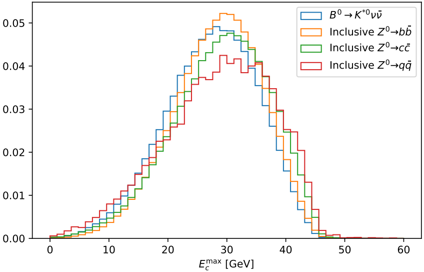
Relevant for detector design

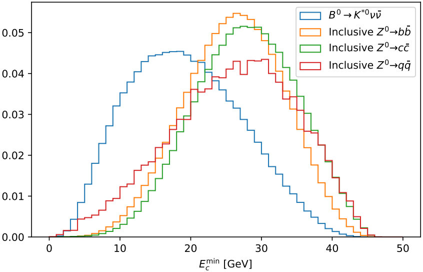
- Use the same vertexing procedure developed for $B_c^+ \to \tau^+ \nu_\tau$ (see this talk for details) which assumes *perfect* vertex seeding
  $\to$ implies we will have **excellent vertex resolution**
- We also truth match the kaon and pion daughters to have the correct mass hypothesis (with the 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

Charged energy in each hemisphere

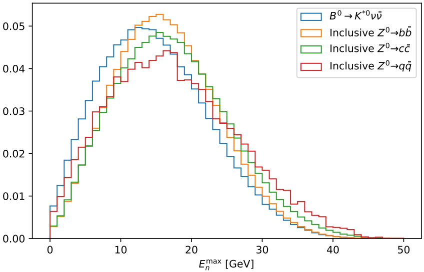
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

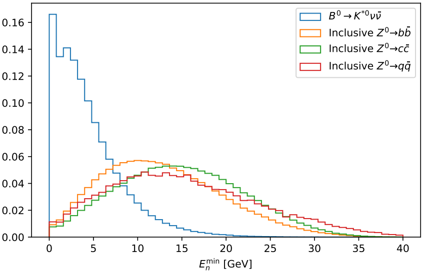




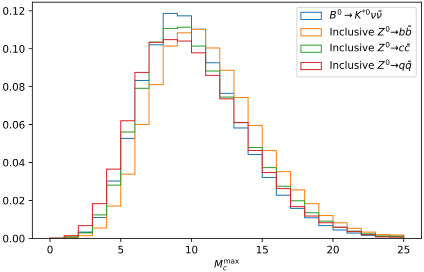
Neutral energy in each hemisphere

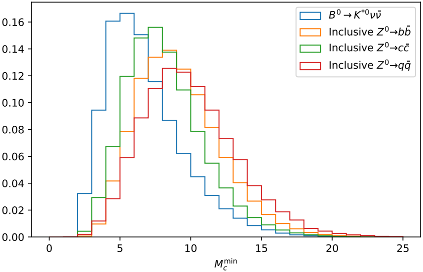
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay





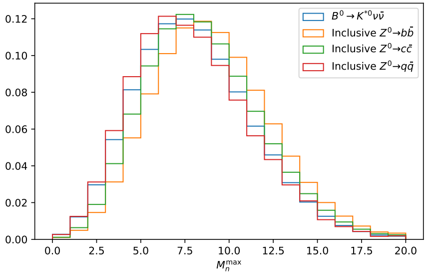
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

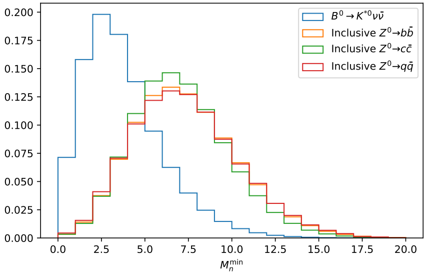




Neutral multiplicity in each hemisphere

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

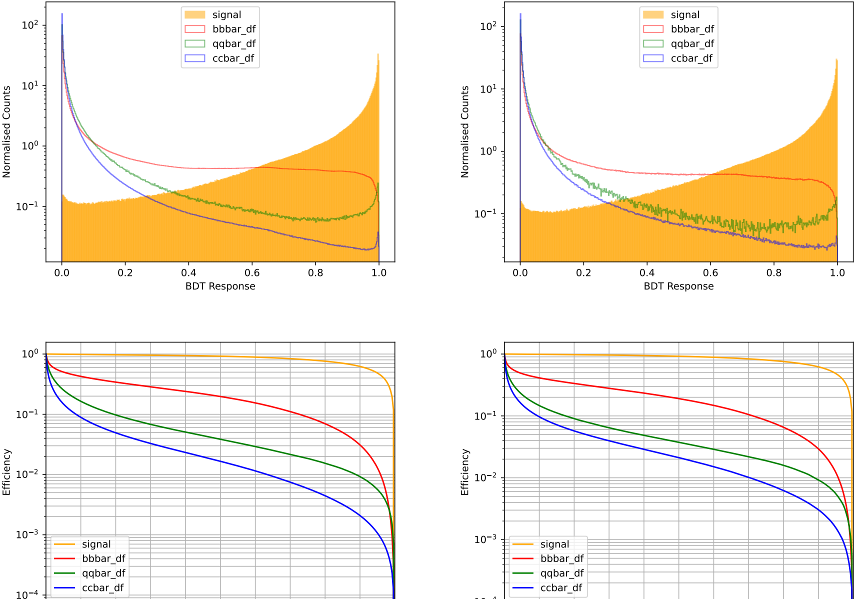




Stage 1 Inputs

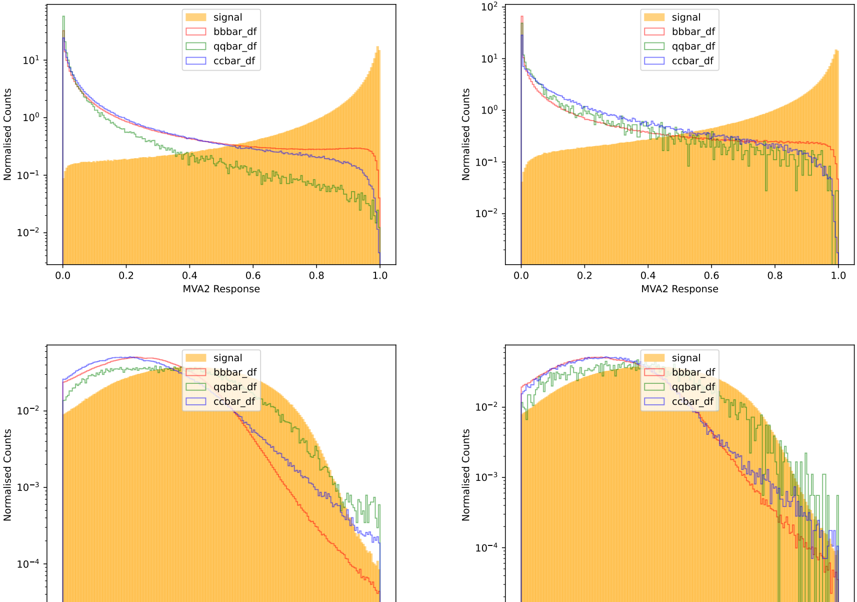
- The total reconstructed energy in each hemisphere,
- The total charged and neutral reconstructed energies of each hemisphere,
- The charged and neutral particle multiplicities in each hemisphere,
- The number of charged tracks used in the reconstruction of the primary vertex,
- The number of reconstructed 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



signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts
BDT Response
Efficiency

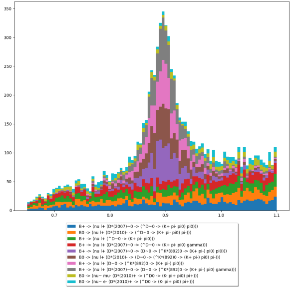
Stage 2 BDT

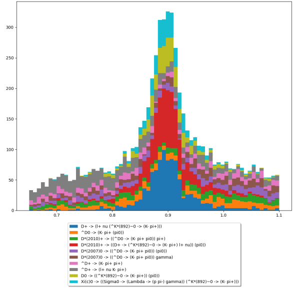

signal
bbbar_df
qqbar_df
ccbar_df
Normalised Counts
MVA2 Response

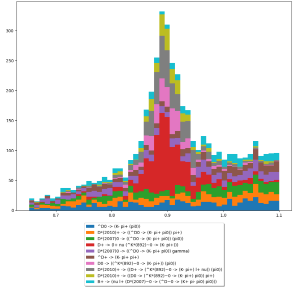
Stage 2 Inputs

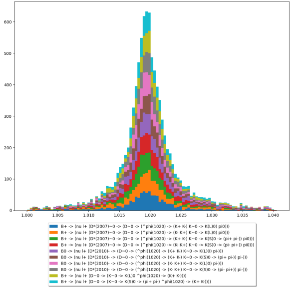
- The intermediate candidate's reconstructed mass
- The number of intermediate candidates in the event
- The candidate's flight distance and flight distance χ^2 from the primary vertex
- The x, y and z components of the reconstructed candidate's momentum
- The scalar momentum of the candidate
- The transverse 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

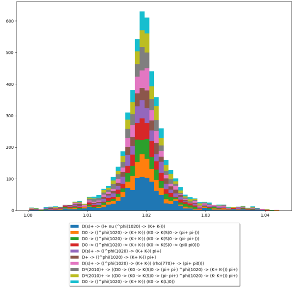
Backgrounds

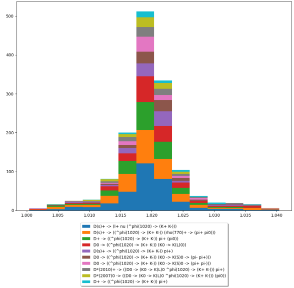












Spline Drop Off