First studies of $b \to s\nu\bar{\nu}$

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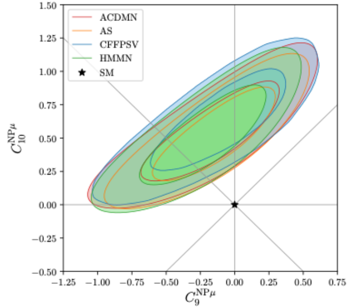
Introduction

- FCC-ee provides a fantastic (possibly *unique*) opportunity for semi-leptonic flavour physics
- Have already seen the physics case for $B_c^+ \to \tau^+ \nu_\tau$ that can only be efficiently probed at FCC-ee [JHEP **12** (2021) 133]
- Considerable interest in the flavour community in $b \to s\ell\ell$ and $b \to c\ell\nu$ transitions ("*flavour anomalies*")
- Model independent NP interpretations of these anomalies also contribute to the $b \to s\nu\nu$ transition due to SM gauge invariance, see *e.g.* [Phys.Lett.B 809 (2020)]



fit to LFU observables + $B_s \to \mu\mu$

Stolen from P. Stangl's talk at the Flavour Anomaly Workshop

$b \to s\nu\bar{\nu}$ as a probe of New Physics

The effective Hamiltonian for $b \to s\nu\bar{\nu}$ transitions is

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

where the operators are defined as

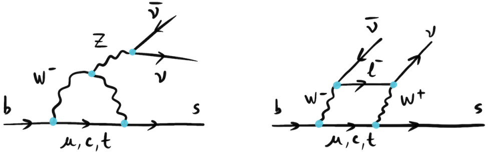
$$O_L^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\nu}_i \gamma^\mu (1-\gamma_5)\nu_j)\,,$$
$$O_R^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\nu}_i \gamma^\mu (1-\gamma_5)\nu_j)\,,$$

where i, j are neutrino flavor-indices.

- In the SM, $C_L^{ii} = -6.35(7)$ and $C_R^{ij} = 0$ [arXiv:1409.4557]
- $b \to s\nu\overline{\nu}$ allows us to probe operators with $\nu_{L\tau}$ (which are related to τ_L via gauge invariance) – important independent test of the $b \to c\tau\nu$ anomalies
- **SM predictions are clean:** only uncertainties come from hadronic form-factors
- No long-distance contribution from (in)famous charm loops (see $b \to s\mu\mu$ literature)

Experimental state-of-the-art

- In SM expected branching ratio $\mathcal{O}(10^{-5})$, see e.g. [arXiv:1409.4557].



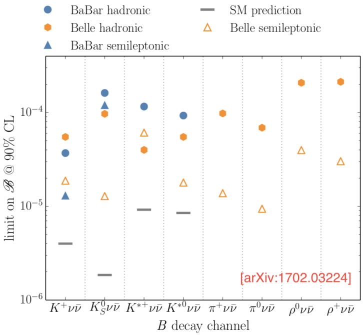
- $b \to s\nu\bar{\nu}$ decays have not yet been observed.
- From the underlying $b \to s\nu\bar{\nu}$ transition we can reconstruct:

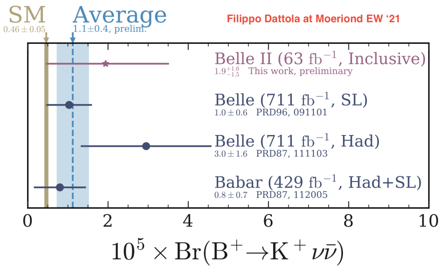
Decay	B-factories	FCC-ee
$B^+ \to K^+\nu\bar{\nu}$	✔	✔
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔
$\Lambda^0_b \to \Lambda^{(*)0}\nu\bar{\nu}$	✗	✔

- With 2 neutrinos in the final state, decays are (probably) impossible at the LHC.

Searches at B-factories

- 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)!

Story so far

- A few months ago we started taking a look at the $B^0 \to K^{*0}\nu\overline{\nu}$ but also intend to look at $B_s^0 \to \phi\nu\overline{\nu}$ and $B^+ \to K^+\nu\overline{\nu}$ (perhaps could consider $B^+ \to K^{*+}\nu\overline{\nu}$ and $B^0 \to K_S^0\nu\overline{\nu}$ also.)
- Have written `DecFiles` for all the "signal modes" within `EvtGen` using `PHSP` models. Pushed to the FCC-config github repo
  - Events generated with `Pythia`, EvtGen and `Delphes` in `EDM4hep`
  - Our MC (so far) only includes $K^*(892)^0$ so we assume tight cuts around that
  - We have re-used the inclusive samples of $Z \to b\bar{b}, c\bar{c}, q\bar{q}$ that were generated for the $B_c^+ \to \tau^+\nu$ analysis.
- Fixed a "feature" / bug in the `FCCAnalyses` code that hard-coded all tracks to have the pion mass hypothesis
- Many thanks to Clement Helsens for generating the samples and to Donal Hill for the discussions to get us started.
- We have taken **much inspiration** from the $B_c^+ \to \tau^+\nu_\tau$ analysis

Some places we cheat

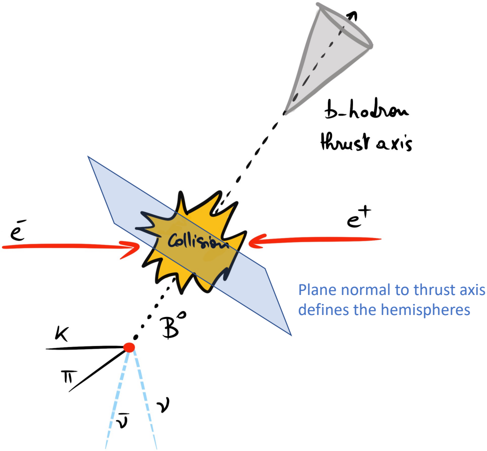
Relevant for detector design

- 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

Event topology

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

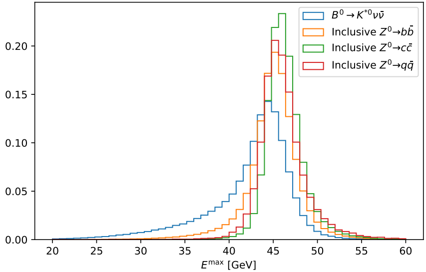


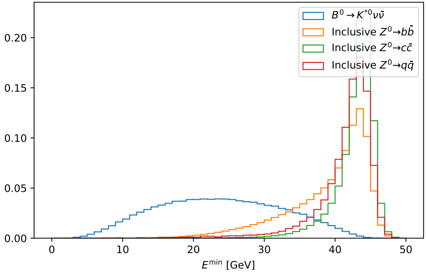
A look at some event variables

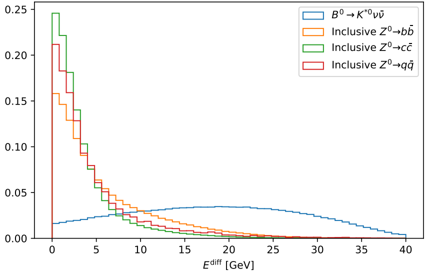
Variable	Description
E^{diff} [GeV]	Max. – Min. hemisphere energy
E^{max} [GeV]	Max. hemisphere energy (higher of the two)
E^{min} [GeV]	Min. hemisphere energy (lower of the two)
$E_c^{\text{max(min)}}$ [GeV]	Charged energy in max. (min.) hemisphere
$E_n^{\text{max(min)}}$ [GeV]	Neutral energy in max. (min.) hemisphere
$M_c^{\text{max(min)}}$	Charged multiplicity in max. (min.) hemisphere
$M_n^{\text{max(min)}}$	Neutral multiplicity in max. (min.) hemisphere

Energy of hemispheres

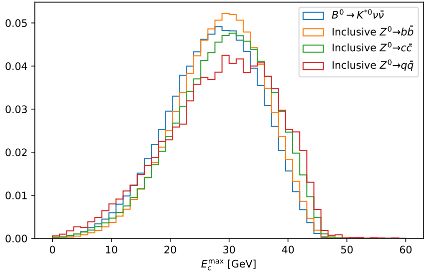
- Clear difference in event hemisphere energy distributions

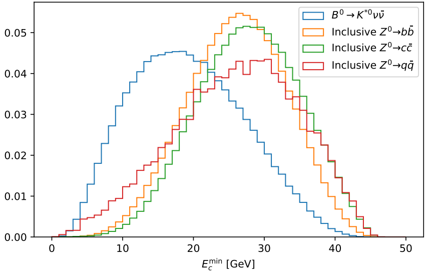






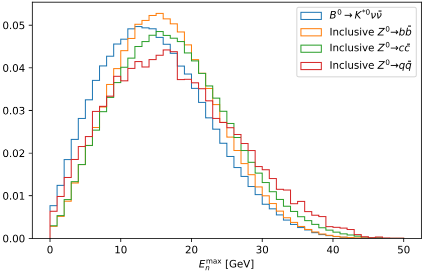
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

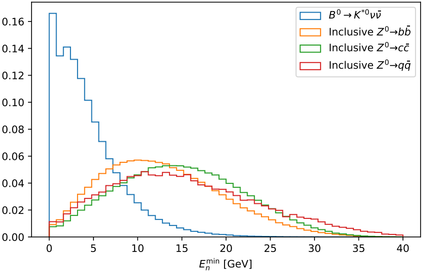




Neutral energy in each hemisphere

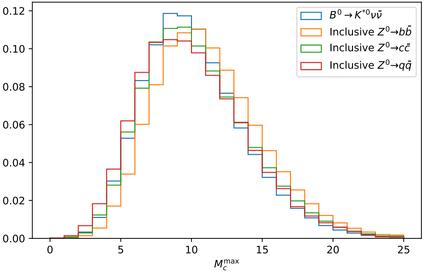
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

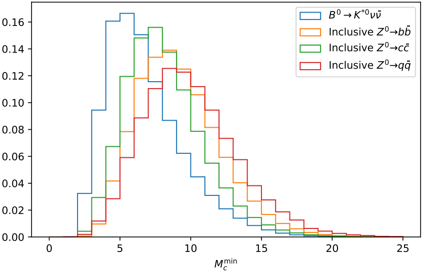




Charged multiplicity in each hemisphere

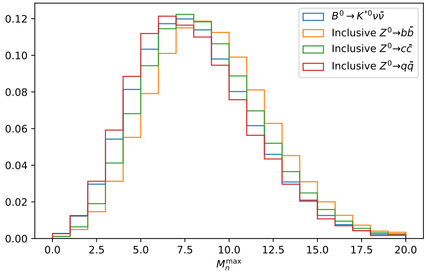
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

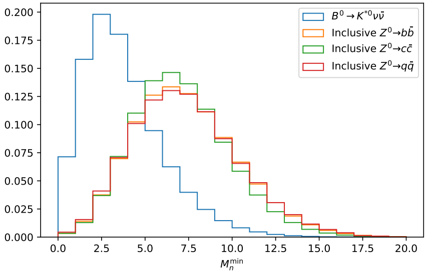




Neutral multiplicity in each hemisphere

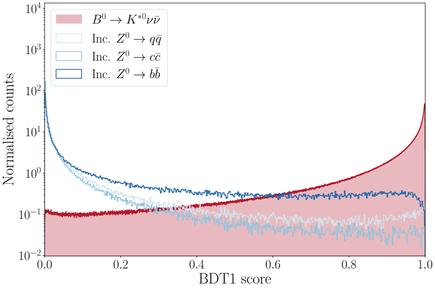
- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

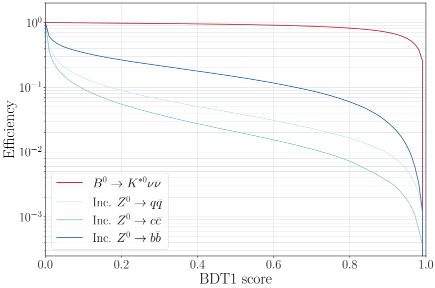




Event level MVA

- Essentially a copy from the $B_c^+ \to \tau^+ \nu_\tau$ analysis but re-trained with our signal MC
- Create a background sample from inclusive $Z^0 \to q\bar{q}, c\bar{c}, b\bar{b}$ using PDG branching fractions
- Use `XGBClassifier` from `XGBoost` (`n_estimators`=400, `learning_rate`$= 0.3$, `max_depth`$= 3$)
- 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

Signal estimate

- Assume 3×10^{12} Z^0 in FCC-ee operation
- Using $\mathcal{B}(Z^0 \to \text{hadrons}) = 70\%$ gives 4.2×10^{12} inclusive background decays
- $N(B^0 \to K^{*0}\nu\overline{\nu}) \approx 1.8M$ using

$N(Z^0)$	3×10^{12}
$\mathcal{B}(Z^0 \to b\overline{b})$	0.1512
B^0 production fraction	0.4
$\mathcal{B}(B^0 \to K^{*0}\nu\overline{\nu})$	1×10^{-5}

Before any cuts the signal purity is $\approx 4 \times 10^{-7}$

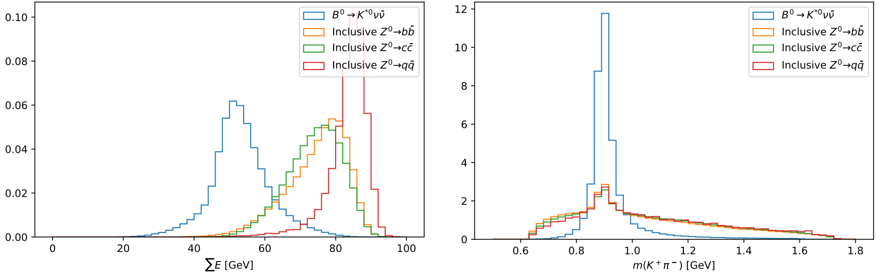
- If we target 1000 signal and 1000 background events for a $\sim 4\%$ precision BF measurement
- Require a background rejection of 4.2×10^9
- For a signal efficiency of 5×10^{-4}

Clearly still some work to do

- Will require a second stage BDT looking at signal candidate variables
- But seems feasible we can get well below the 10% uncertainty projected at Belle-II

Next steps

- Need to figure out (from the inclusive samples) what specific backgrounds we will encounter
- Requires some truth matching setup which we (I) haven't figured out yet
- Then probably generate exclusive samples of these
- Start taking a look at candidate specifc information
- Train a second stage BDT, optimise the cuts, fit in some discriminating variable
- Olycr can then help us with the interpretation



Summary and Outlook

- We are at the very early stages
- But thanks to the work done on $B_c^+ \to \tau^+ \nu_\tau$ we have managed to make some good progress (with relatively little effort)
- Now is to get into the nuts and bolts of the analysis (in particular understanding backgrounds)
- Next stage BDT to be developed
- Then perform analysis on potential BF limits that could be achieved or indeed sensitivity to particular wilson coefficients

Thoughts on detector designs

- The organisers asked me to say a few words on this
- Mostly already covered in the talk but summarised here
- These are true for **this analyis** but also hold for **most flavour analyses**

1. Precise vertexing is vital
   - Average flight distance of a B^0 at FCC-ee is ~ 3mm
   - Our analysis so far assumes both the production (PV) and decay (SV) vertices of the B are perfectly seeded
2. Powerful particle identification is required
   - Particularly for cases like these flavour studies (in which the final state contains both kaons and pions)