Heavy flavour and Searches

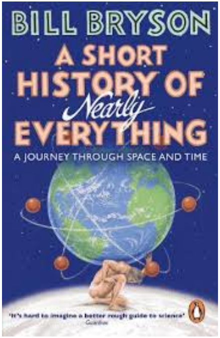
Matt Kenzie

University of Cambridge

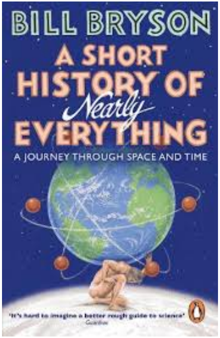
ECFA-UK Meeting, Durham

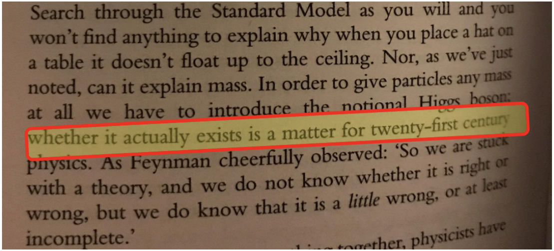
23^{rd} September 2024

Making history


BILL BRYSON
A SHORT HISTORY OF Nearly EVERYTHING
A JOURNEY THROUGH SPACE AND TIME

- The Higgs discovery does not appear in "A Short History of Nearly Everything"!





Search through the Standard Model as you will and you won't find anything to explain why when you place a hat on a table it doesn't float up to the ceiling. Nor, as we've just noted, can it explain mass. In order to give particles any mass at all we have to introduce the notional Higgs boson; whether it actually exists is a matter for twenty-first century physics. As Feynman cheerfully observed: 'So we are stuck with a theory, and we do not know whether it is right or wrong, but we do know that it is a *little* wrong, or at least incomplete.'

together, physicists have

Why Heavy Flavour?

The SM generates many unanswered questions connected to flavour

- Why do we have three generations?
- Why do the quark masses and CKM matrix exhibit such a distinctive hierachy?
- Why don't we see sufficient CP violation in the CKM sector?
- Strong CP problem, what makes θ so small?
- How is this connected to other BSM phenomena (neutrinos, dark matter *etc.*)?

Why Heavy Flavour?

The SM generates many unanswered questions connected to flavour

- Why do we have three generations?
- Why do the quark masses and CKM matrix exhibit such a distinctive hierachy?
- Why don't we see sufficient CP violation in the CKM sector?
- Strong CP problem, what makes θ so small?
- How is this connected to other BSM phenomena (neutrinos, dark matter *etc.*)?

Flavour observables have a strong track record as a powerful discovery apparatus

- Loops receive NP contributions
- Natural entry point for massive particles
- The key to the physics reach is **precision**
- Can probe scales up to $\mathcal{O}(100\ \text{TeV})$

Why Heavy Flavour?

The SM generates many unanswered questions connected to flavour

- Why do we have three generations?
- Why do the quark masses and CKM matrix exhibit such a distinctive hierachy?
- Why don't we see sufficient CP violation in the CKM sector?
- Strong CP problem, what makes θ so small?
- How is this connected to other BSM phenomena (neutrinos, dark matter *etc.*)?

Flavour observables have a strong track record as a powerful discovery apparatus

- Loops receive NP contributions
- Natural entry point for massive particles
- The key to the physics reach is **precision**
- Can probe scales up to $\mathcal{O}(100\;\text{TeV})$

Precision works as a discovery tool

- Consistency in flavour observables $\rightarrow$ NP unlikely at the LHC
- GIM mechanism $\rightarrow$ discovery of charm
- CP violation in K^0_{L} decay $\rightarrow$ CKM mechanism $\rightarrow$ discovery of bottom and top
- EW precision fit $\rightarrow$ discovery of Higgs

Why Heavy Flavour?

The SM generates many unanswered questions connected to flavour

- Why do we have three generations?
- Why do the quark masses and CKM matrix exhibit such a distinctive hierachy?
- Why don't we see sufficient CP violation in the CKM sector?
- Strong CP problem, what makes θ so small?
- How is this connected to other BSM phenomena (neutrinos, dark matter *etc.*)?

Flavour observables have a strong track record as a powerful discovery apparatus

- Loops receive NP contributions
- Natural entry point for massive particles
- The key to the physics reach is **precision**
- Can probe scales up to $\mathcal{O}(100\ \text{TeV})$

Precision works as a discovery tool

- Consistency in flavour observables $\rightarrow$ NP unlikely at the LHC
- GIM mechanism $\rightarrow$ discovery of charm
- CP violation in K^0_L decay $\rightarrow$ CKM mechanism $\rightarrow$ discovery of bottom and top
- EW precision fit $\rightarrow$ discovery of Higgs

Direct searches for long lived BSM particles have similar detector requirements

- Clearly any long lived direct signal is a BSM smoking gun

Why kind of collider?

This is what we said in the Euro Strategy 2020

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- A **dream** environment for heavy flavour
- Running at Z-pole or on-shell production of W^+W^-
- Get all the benefits of **both** Belle II and LHCb

Heavy flavour at the $W^{\pm}$ and Z^0

- The Monteil-Wilkinson tick-list [*EPJ+* **126** (2021) 8]

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

- Production rate countered by **huge luminosity**
- **Tera-Z** run at the Z^0-pole:
  - 6×10^{12} Z^0 (across 4 experiments)

Species (both flavours)	B^0	B^+	B^0_s	Λ^0_b	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)

Heavy flavour at the $W^\pm$ and Z^0

- Huge luminosity competes with pp cross section, $10^5 Z/s$, $10^4 W/h$, $10^3 H, t/d$
  - Representative numbers based on nominal FCC-ee running
- Hundreds of billions of b-hadrons
- Clean environment, no pile-up, controlled beam background
- E and p constraints
- Minimal trigger losses
- Do LEP in ONE MINUTE!

  $\rightarrow$ many flavour (and EW) observables are still dominanted by LEP
- Boost at the Z $\rightarrow$ $\langle E_B \rangle \approx 70\% \times E_{\text{beam}}$ $\langle \beta\gamma \rangle \approx 6$
  - b fragmentation allows topological reconstruction
  - the "other" b gives constraint on missing energy
- Large sample of W^+W^- (on-shell and boosted) will give access to all CKM element **magnitudes**

Detector requirements for flavour

Tracking

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

Vertexing

- Essential for huge parts of flavour program and for displaced vertex searches
  - 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

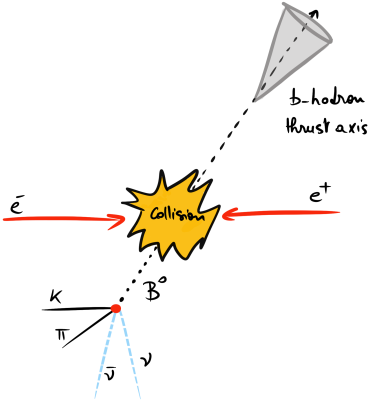
- Vital for any heavy flavour program
  - Need effective kaon-pion separation across a wide range of momenta
  - Non-signal momenta $\sim 10\,\text{GeV}/c$, signal momenta $\sim 30\,\text{GeV}/c$
  - Can this be done *without* specific PID / Cherenkov systems (dE/dx, cluster counting, ToF)?

Heavy Flavour

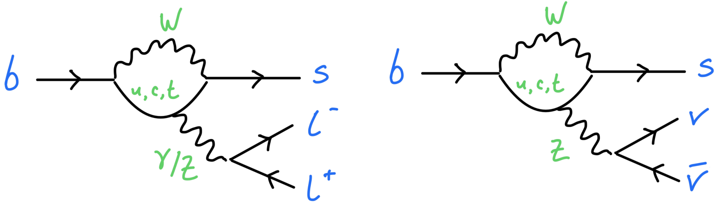
Fig 1. A heavy flavour

- Z decays at rest so decay products ($Z \to q\bar{q}$) are back-to-back
- Thrust axis ($q\bar{q}$ decay axis) is *very accurately* reconstructed using visible particle momenta

$$T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|} \tag{1}$$



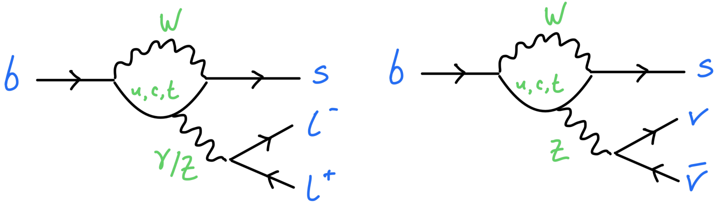
- FCNC, loop suppression in SM, gives natural entry point for additional amplitudes from NP
- A huge part of the global heavy flavour effort in this sector



- Intepretation of results can be done with EFT in a **model independent** way (Wilson coefficients)
- **Tera-Z** running in clean environment opens up unique opportunities with τ and ν final states
- **SM predictions are clean** (particularly in *e.g.* $b \to s\nu\overline{\nu}$)
  - Dominant uncertainties from hadronic form-factors and CKM elements
  - No long-distance contributions from (in)famous charm loops
  - Sensitivte to variety of NP scenarios (Z', leptoquarks *etc.*)

$\Delta F = 1$ *e.g.* $b \to s$ transitions

- A huge part of the global heavy flavour effort in this sector



- Final states with muons, $b \to s\mu^+\mu^-$, are well covered by LHCb
- Final states with electrons more challenging (although not impossible) at LHCb
- Final states with taus and neutrals are much more difficult
- Belle-II has a clean enough environment for these but suffers from production rate and has no access to B_s^0, B_c^+ or Λ_b^0
  - Makes interpretation of results (in EFT framework) harder

Current state-of-the-art on $b \to s\nu\overline{\nu}$

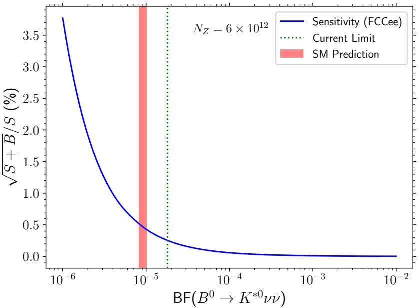
- In the SM $b \to s\nu\overline{\nu}$ BF predictions are $\mathcal{O}(10^{-5})$
- $B^+ \to K^+\nu\overline{\nu}$ has **recently been seen** by Belle II [PRD **109** (2024) 112006] - $\mathcal{B} = (2.3 \pm 0.7) \times 10^{-5}$
  - 2.7σ enhancement from SM prediction
- From the underlying $b \to s\nu\overline{\nu}$ transition we can study:

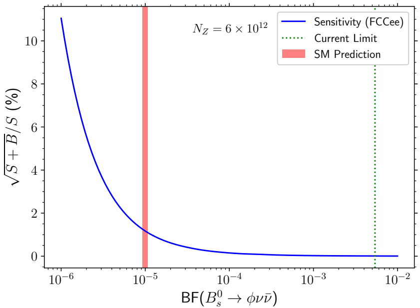
Decay	B-factories	FCC-ee	Current Limit	SM prediction
$B^+ \to K^+\nu\overline{\nu}$	✔	✔	$< 1.6 \times 10^{-5}$	$(4.0 \pm 0.5) \times 10^{-6}$
$B^+ \to K^{*+}\nu\overline{\nu}$	✔	✔	$< 4.0 \times 10^{-5}$	$(9.8 \pm 1.1) \times 10^{-6}$
$B^0 \to K^0_S\nu\overline{\nu}$	✔	✔	$< 2.6 \times 10^{-5}$	$(3.7 \pm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

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

Projections for $b \to s\nu\overline{\nu}$

- Studies on sensitivity at FCC-ee [JHEP **01** (2024) 144] and at CEPC [PRD **105** (2022) 114036]

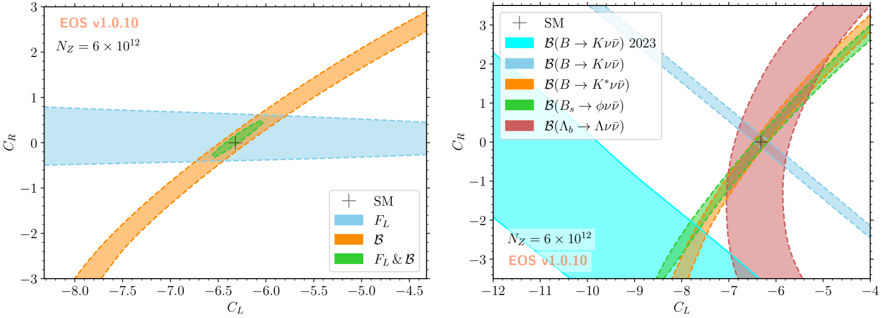




- This kind of precision means that differential measurements will be possible

Wilson coefficient interpretations

- Direct measurements of longitundinal polarisation (F_L) possible at $\mathcal{O}(5\%)$ [JHEP **01** (2024) 144]



- Opens up highly interesting measurements of

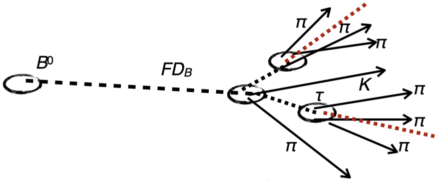
$$R_Y^{\ell/\nu} = \frac{\mathcal{B}(B \to Y\ell^+\ell^-)}{\mathcal{B}(B \to Y\nu\bar{\nu})} \quad (2)$$

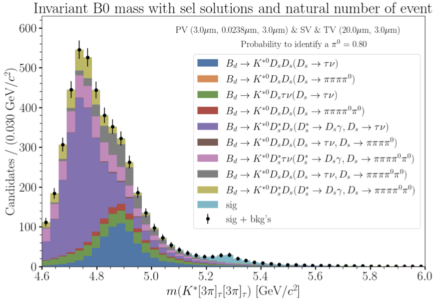
- These benefit from numerous uncertainty cancellations (both theory and experiment)
- Would allow us to quantify the shift due to long-distance effects (charm loops)
- Future e^+e^- **the only place** that can do this

Flavour with taus

- Many semileptonic B decays with taus are beyond the reach of the current experimental program
- Future facilities with exquisite vertex resolution and neutral identification can reconstruct 3-prong tau decays

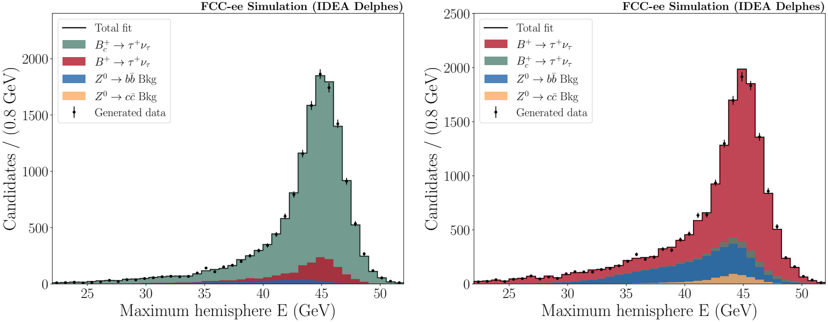
[arXiv:2207.11055]





- Some other possibilities with theoretically clean semileptonic decays with B^+ and B_c^+
- New physics probe with lepton ratios (a la R_D) and also as measurements of V_{ub} and V_{cb}

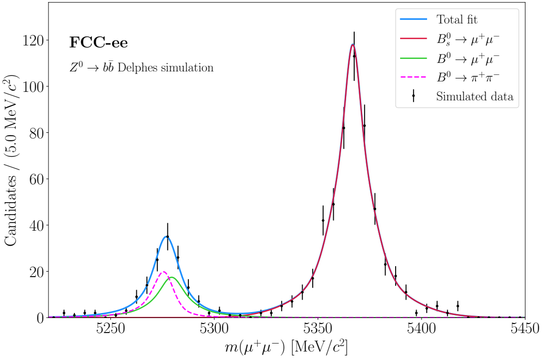
[EPJC **84** (2024) 87]



$\Delta F = 1$ processes, *e.g.* $B^0_{(s)} \to \mu^+\mu^-$ or $B \to \nu\bar{\nu}$

- Effective lifetimes and CP asymmetries in $B^0_{(s)} \to \ell^+\ell^-$

[*EPJ+* **126** (2021) 8]



- Ongoing studies on $B \to$ invisible decays suggest limits at 10^{-7} level

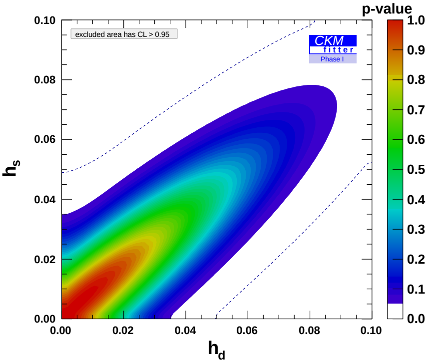
CKM metrology and $\Delta F = 2$ processes

Predict sizeable (order of magnitude or more) improvements using b- and c-tagging in W^+W^- threshold runs

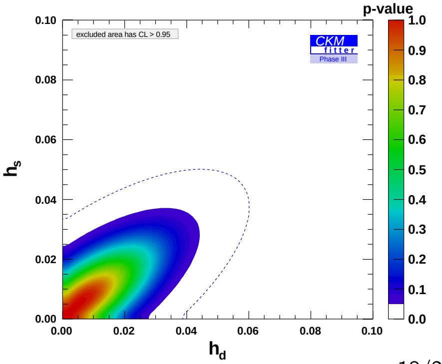
- Measurements of V_{cb}, V_{cs} and V_{ub}
- Semileptonic asymmetries, a^q_{sl}
- NP constraints in B^0 and B^0_s oscillation

[PRD **102** (2020) 056023]

Current forecast (LHCb + Belle II)



Forecast with FCC-ee expectation



A smorgasbord of possibilties

- No time to mention possible charm and strange programs
- FCNC in the charm sector are complementary probes to beauty and strange
  - up-type gives access to different NP
  - very small CPV in charm
  - FCNC transition time much longer than decay time
- Driving performance of b- and c-tagging will be key
- Also many possibilities with taus in their own right
  - third generation lepton
  - tests of LFU
  - precision measurements not available / possible with current facilities

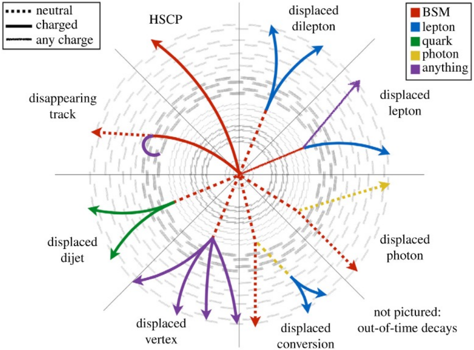
Long-lived BSM searches

Fig 2. A long-lived person (LLP)

LLPs as NP signals

LLPs that are semi-stable or decay downstream (in sub-detectors) predicted by various BSM models

- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- Dark Photons
- Axion-like particles (ALPs)
- Other dark sector models

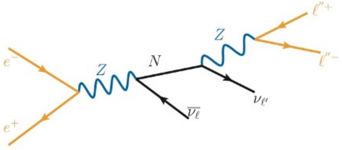


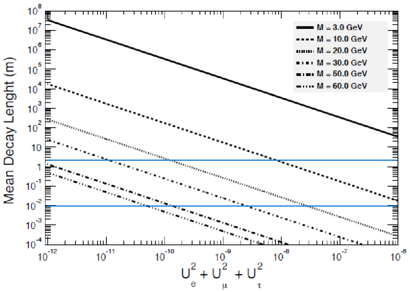
Wide variety of different signatures

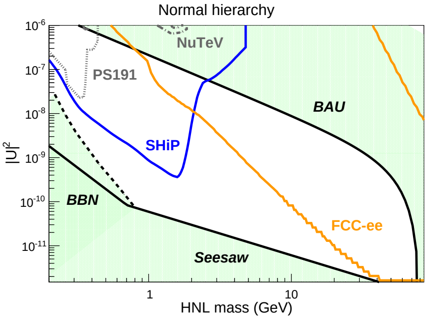
- Detector designs need to cover broad physics reach

- Displaced vertex signature

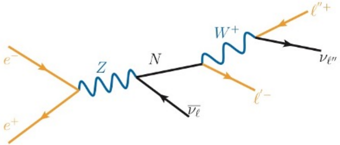
[arXiv:1411.5230]





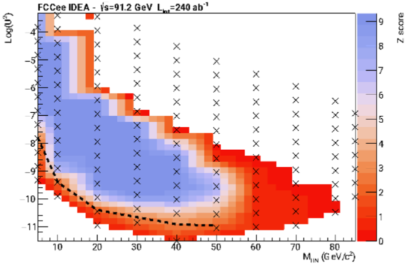


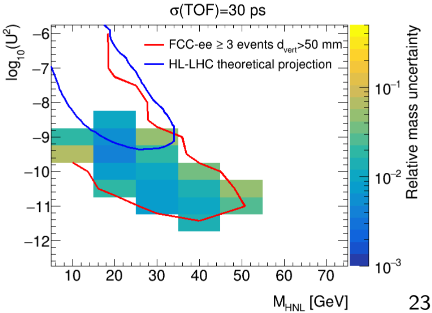
- Searches with final state jets



- Combine prompt analysis (high HNL mass) with long-lived analysis (low HNL mass)
- Additional use of vertex timing

[arXiv:2406.05102]

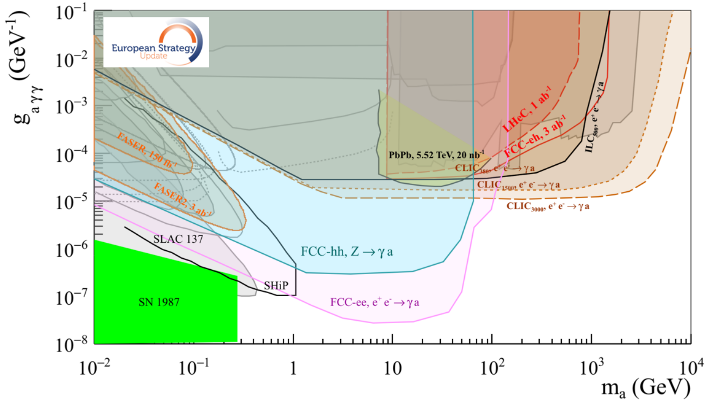




Axion-like Particles

- Small couplings and light ALPs give LLP signature

[arXiv:2203.06520]



Exotic Searches

- Complementary requirements for HNL, ALPs and exotic Higgs
- Typically (almost) background-free analyses
- Checking assumptions against different detector configurations is important
- A vast program of possibilities
- Want to design our detectors accordingly
- Allow for the possibility to characterise not just discover new signals

Fig 3. Exotic Higgs

Summary

- Precision flavour measurements set powerful constraints on NP
- Explaining flavour anomalies is how we built the SM
- Future e^+e^- machines offer an unparalled opportunity in heavy flavour measurements
  - Beauty, charm, strange and tau physics (I only really mentioned the first)
  - Operating at the Z-pole and W^+W^-
  - It is the perfect environment for flavour physics
- Detector designs are often complementary for many long-lived searches
- e^+e^- will improve on almost all key flavour observables
  - In certain sectors by orders of magnitude
- Pushes NP reach up to $10^2 - 10^4$ TeV
- UK is playing a leading role already in these physics studies
- **We should be pushing to get this machine built**