Flavour physics at FCC-ee

Donal Hill* (EPFL)

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Introduction

- Flavour physics measurements have played a major role in the construction of the Standard Model

- Now complete, the SM poses several questions that are closely related to flavour:

  - Why three fermion generations, and why the particular mass hierarchy and CKM structure?

  - What additional sources of CP violation are there beyond the SM to explain the matter-dominated universe?

- Flavour is a powerful tool for discovery, since loop amplitudes contributing to many processes provide natural entry points for new massive particles

  - Flagship experiments: LHCb at the LHC, and Belle II e^+e^- $\Upsilon(4S)$

Looking to the future: FCC-ee

- An e^+e^- facility such as FCC-ee operating at the Z-pole can combine most advantages of LHCb and Belle II [arXiv:2106.01259]
- Huge luminosity can counter low cross-section, and deliver 5×10^{12} Z^0's
  - $b\bar{b}$ sample 15 times larger than Belle II, with all b-hadron types
  - Very large prompt charm and τ samples also anticipated - **FCC-ee is expected to have unparalleled reach in τ measurements**
- Collect data at several collision energies: CKM measurements with 10^8 on-shell W^+W^- production

Feature	Belle II $\Upsilon(4S)$	LHCb	FCC-ee Z-pole
All hadron species		✓	✓
High boost		✓	✓
Large production cross-section		✓	
Negligible trigger loss	✓		✓
Low combinatorial bkg.	✓		✓
Initial energy knowledge	✓		(✓)

Flavour landscape at the dawn of FCC-ee

- LHCb Upgrade II at HL-LHC during 2030s
  - 300 fb^{-1} envisaged, 50 times higher statistics than Run 1 + 2 LHCb measurements
  - ATLAS and CMS will also continue to contribute strongly in areas such as $B^0_{(s)} \to \mu^+\mu^-$ and ϕ_s
- 50 ab^{-1} anticipated from Belle II by 2031
- Advances in theory e.g. lattice QCD calculations also anticipated
  - In tandem with LHCb and Belle II results, expect excellent precision on CKM parameters and suppressed flavour-changing neutral-current (FCNC) processes
- What can FCC-ee bring at this point?

CP violation - CKM and ϕ_s

- CKM angles and weak mixing phase ϕ_s can be measured with similar or better precision than previous experiments [Eur. Phys. J. C 79 (2019) 474]
- Exploit modes with neutrals that have poor reconstruction efficiency at LHCb, with a much larger sample size than Belle II
- Access wide range of charm modes in time-integrated $B^{\pm} \to D^{(*)}K^{\pm}$ decays
  - SM tree-level γ can be measured with $< 10^{-6}$ theoretical uncertainty
- Time-dependent modes such as $B_s^0 \to D_s^- K^+$ can benefit greatly from much higher tagging efficiency than at LHCb
  - Access to $2\beta_s$, which can be compared to NP-sensitive ϕ_s

CP violation - $|V_{cb}|$ and $a_{sl}^{d,s}$

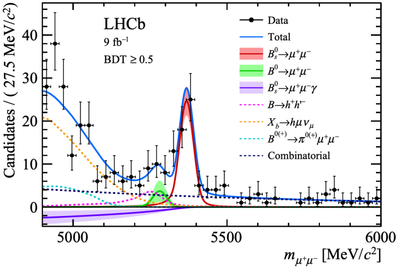
- Sides of CKM Unitarity Triangle are normalised to $|V_{cb}|$, and knowledge of this parameter will limit NP sensitivity of LHCb and Belle II results

- W^+W^- run at FCC-ee using b-tagged and c-tagged jets can **improve $|\mathbf{V_{cb}}|$ by an order of magnitude** [arXiv:1306.6327]

- Charge asymmetry $a_{sl}^{d,s}$ in flavour-specific semileptonic neutral B decays are small (10^{-4} – 10^{-5}) and precisely known in SM
  - Sensitive to NP contributions through mixing box diagrams
  - LHCb expects to reach $\sigma_{stat} \sim 10^{-4}$, but systematics from production and detection asymmetries extremely difficult to control at this level
  - **Solenoidal FCC-ee detector can reach total uncertainty of $\mathcal{O}(\mathbf{10^{-5}})$** [arXiv:2106.01259]

Rare FCNC processes - $B^0 \to \mu^+\mu^-$

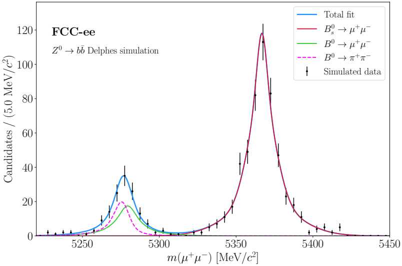
- Very rare decay ($\mathcal{B} = 1.07 \times 10^{-10}$ in SM) which is sensitive to NP contributions
- Not observed yet, but $\mathcal{B}$ measurements by LHC experiments
- Recent LHCb limit $\mathcal{B} < 2.6 \times 10^{-10}$ at 95% C.L. [arXiv:2108.09284]
  - Limit is consistent with SM, but theory error is 0.1×10^{-10} [arXiv:1208.0934]
- Well-motivated to push for observation and ~ 10% $\mathcal{B}$ precision



[arXiv:2108.09284]

Rare FCNC processes - $B^0 \to \mu^+\mu^-$

- With 5×10^{12} Z^0's at FCC-ee, expect around 500 $B_s^0 \to \mu^+\mu^-$ and 70 $B^0 \to \mu^+\mu^-$
- Superb mass resolution to clearly resolve the B_s^0 and B^0 signals, while e^+e^- environment results in negligible combinatorial background
  - $\pi \to \mu$ misidentification must be minimised with excellent PID to control $B^0 \to \pi^+\pi^-$ background
- B^0/B_s^0 ratio offers a powerful test of minimal flavour violation



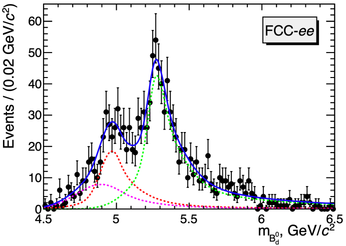
[arXiv:2106.01259]

Rare FCNC processes - $B^0 \to K^{*0}\tau^+\tau^-$

- Tauonic equivalent of $B^0 \to K^{*0}\ell^+\ell^-$, critical to fully explore the $b \to sll$ lepton universality picture
  - $\mathcal{B} \sim 10^{-7}$, but rate and angular properties can be strongly altered by NP contributions

- By using $\tau \to 3\pi\nu$ decays, can constrain τ flight vectors and fully solve the system to reconstruct $m(B^0)$

- Approach requires high-precision vertex reconstruction superior to LHCb Upgrade II
  - Expected rate is too low for Belle II, unless very large NP enhancement



[Eur. Phys. J. C 79 (2019) 474]

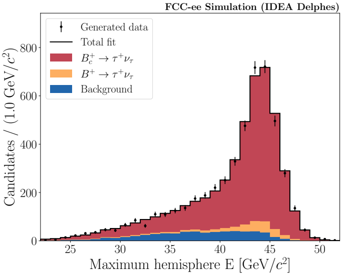
Favoured modes that are experimentally challenging

- Fully leptonic B decays have reliable SM predictions, and are very sensitive to NP mediators such as charged Higgs or leptoquarks
    - Tauonic modes of particular interest, given that such NP will couple preferentially to third generation
- Belle II expected to measure $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ with 5% precision (current precision is 22%)
- $B_c^+ \to \tau^+ \nu_\tau$ is also of great interest, since it involves the same vertex factors as $B \to D^{(*)} \tau^+ \nu_\tau$ and is less CKM-suppressed than $B^+ \to \tau^+ \nu_\tau$
    - No B_c^+ mesons produced at Belle II, and lack of reconstructed final state information renders a measurement impossible at LHCb

$B_c^+ \to \tau^+\nu_\tau$ - FCC-ee or nothing

- Can use same $\tau^+ \to 3\pi\nu_\tau$ reconstruction techniques as $B^0 \to K^{*0}\tau^+\tau^-$ to measure $(B_c^+ + \tau^+)$ flight distance
  - Highly suppress $B^+ \to \tau^+\nu_\tau$ background since $\tau(B^+) > \tau(B_c^+)$
- Harness full event reconstruction and known centre-of-mass energy to measure missing momentum and reject background

- High purity final sample containing $\sim 4000\ B_c^+ \to \tau^+\nu_\tau$ is achievable with $5 \times 10^{12}\ Z^0$'s
  - Constrain remaining $B^+ \to \tau^+\nu_\tau$ from expected Belle II result
  - **$\mathcal{B}(\mathbf{B_c^+} \to \tau^+\nu_\tau)$ precision at the $\mathbf{4-5}\%$ level possible**
  - Highly constraining for 2HDM and LQ models



[arXiv:2105.13330]

Detector considerations for heavy flavour

- Layouts considered thus far (such as IDEA) have been designed with higher-energy requirements in mind like Higgs programme
- With 4 IPs under consideration, a dedicated flavour experiment is possible and would diversify the FCC-ee detector attributes
    - Design studies are now of high importance

Attribute	Some key applications
High-precision vertexing	Crucial for modes exploiting $\tau \to 3\pi\nu$, lifetime resolution in B_s^0 mixing
Particle ID	K vs. π for CP violation studies, hadron rejection in $B_{(s)}^0 \to \mu^+\mu^-$
Calorimetry	π^0 reconstruction to surpass LHCb, high resolution photons for $\tau^+ \to \mu^+\gamma$

Summary

- FCC-ee represents a unique opportunity for flavour physics, with 5×10^{12} Z^0's leading to high rates of heavy flavour production
- Physics reach competitive with LHCb and Belle II, and can extend well beyond for modes with neutrals and missing energy
- Performance studies are ongoing, and have shown promise for channels like $B_c^+ \to \tau^+ \nu_\tau$ and $B^0 \to K^{*0} \tau^+ \tau^-$ which are impossible to measure elsewhere
- Dedicated design studies for flavour to be undertaken, covering areas such as vertexing, PID, and calorimetry
  - Stay tuned for more!

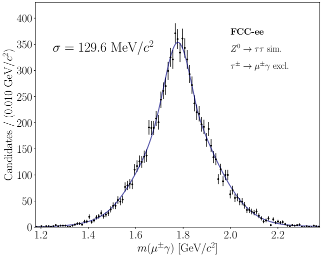
Backup

τ decays - $\tau^+ \to \mu^+\gamma$

- 1.7×10^{11} $\tau^+\tau^-$ pairs expected from 5×10^{12} Z^0's at FCC-ee
  - Perfect knowledge of both τ momenta at production
- $\tau^+ \to \mu^+\gamma$ is a lepton flavour violating decay with unobservable rate in SM
- NP scenarios predict it to have the highest $\mathcal{B}$ of all LFV modes [arXiv:0908.2381]
- Current best limits $\mathcal{B} < 4.4 \times 10^{-8}$ from B-factories
- Challenging due to lack of τ vertex (only one charged track) and presence of photon

τ decays - $\tau^+ \to \mu^+\gamma$

- Anticipate ~ 400 events with 5×10^{12} Z^0's (prior to selection cuts)
- Observation possible down to 6×10^{-11} level, whereas Belle II projected upper limit is 10^{-9}
- Mass peak reconstruction has limited resolution due to lack of photon direction information (assumed to point to PV)
    - High-granularity calorimetry with good tower depth could open the possibility of photon direction measurements, and greatly improve the resolution



[D. Hill, FCC Workshop Nov. 2020]

$B_c^+ \to \tau^+\nu_\tau$ NP sensitivity

- Can consider the ratio $R_c = \mathcal{B}(B_c^+ \to \tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, which has ~ 4% expected experimental precision
  - $|V_{cb}|$ independent
  - Can assume no NP in the muonic mode for theory calculation
- R_c measurement at FCC-ee can strongly constrain both 2HDM and leptoquark parameter space in a complementary manner to other key observables
  - Leptoquark couplings can cause $\mathcal{O}(10 - 100)$ variations!