# Heavy Flavours @ FCC-ee: physics opportunities and challenges†

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## Outline

- Opportunities (sketch of) from heavy flavours Physics.
- Detector challenges related to these opportunities.
- Explore challenges through opportunities with Case Studies.
- Disclaimer: similar to FCCWS@CERN w/ one actual Clermont projection.

† Embodies discussion with G.Wilkinson, R. Aleksan, P. Collins, C. Helsens, D. Hill, R. Suarez, M. Chrzaszcz, M. Dams, P. Azzi, E. Perez, L.Li …

# Heavy Flavours: physics opportunities.

## 1) Heavy Flavours Production

| Particle specie at FCC-$ee$ | $B^0$ | $B^+$ | $B^0_s$ | $\Lambda_b$ | $B_c^+$ | $c\bar{c}$ | $\tau^-\tau^+$ |
|---|---|---|---|---|---|---|---|
| Yield ($\times 10^9$) [for $5.10^{12}$ $Z$] | 310 | 310 | 75 | 65 | $1.5^\dagger$ | 600 | 180 |

$^\dagger$ $B_c$ hadronisation fraction assumed to be $f_{B_c} = 2.10^{-3}$.

- 15 times Belle II $B^{0,+}$ statistics, mode / mode comparison in order w/ LHCb
- All species of weakly-decaying b-flavoured particles around.
- Statistics similar or better than the upgrades of current experiments.
- Significant boost, as LHCb (invincible, though). Vertexing capabilities in a clean and hermetic experimental environment.
- Neutrals and flavour tagging for *CP* violation possible, as Belle II.

# Heavy Flavours: physics opportunities

- Categories to explore — the hierarchy does not tell the importance:

    1) Rare *b*-flavoured particles decays (EWP & friends).
    2) Di-leptonic decays (*e.g.* $B^0 \to \mu^+\mu^-$, $B_s \to \tau^+\tau^-$).
    3) (Semi-)leptonic decays (*e.g.* $R_{D,D^*}$, to $B_c \to \tau^+\nu$ …)
    4) ***CP* violation study program at large.**
    5) Mass and lifetime properties, spectroscopy.
    6) Charm physics.

## 1) Rare *b*-flavoured particles decays (EWP & friends):

this is related to the current Flavour anomalies. Should they be NOT confirmed, the relevance of their study remains as a third generation couplings fundamental test. Here we think that FCC-ee is unique in that:

- the modes with tau lepton are key to sort out the models addressing the flavour problem(s).
- FCC-ee is the only place where SM values can be reached. Exploratory work ($B^0 \to K^{*0}\ \tau^+\tau^-$) promising. Comprehensive treatment of background in realistic detector simulations in order to provide sound sensitivity (see arXiv:2012.00665).
- Lepton Flavour Violating *b*-flavoured particles decay modes are necessary to have, per se, as null tests of the SM, to complete the model constrains in case the Flavour anomalies remain significant.

2) Di-leptonic decays (*e.g.* $B^0 \to \mu^+\mu^-$, $B_s \to \tau^+\tau^-$).

Again fundamental tests. Particularly important in the context the Flavour anomalies but also beyond. FCC-*ee* is especially expected for $B_s \to \tau^+\tau^-$ .

- For the former, LHCb UpgradeII shall do good. Yet invariant-mass resolution at FCC-ee is an asset.
- For the latter, more complex experimentally because of the absence of the secondary vertex to be used in topological reconstructions. Ideas to mitigate this absence, such as using the quark direction in the other hemisphere.
- Similar techniques employed as for ElectroWeak penguins with $\tau$. That should be part of the same collective exploration.

3) (Semi-)leptonic decays (*e.g.* from $R_{D,D^*}$ up to $B_c \to \tau^+\nu$ ...)

Fundamental tests of lepton universality. Again connection to the Flavour anomalies but mainstream measurements. FCC-ee is especially expected for $B_c \to \tau^+\nu$.

- Beyond LFU tests, these can be used to measure CKM elements $V_{ub}$ ($B^+ \to \tau^+\nu$) and $V_{cb}$. Introduced as a case study for devising granularity of the calorimeter.
- Already promising existing studies in the context of CEPC — hep-ex:2007.08234. Exploration started for FCC-ee (see Donal and Yasmine in this session).

4) *CP* violation study program at large.

- Inevitable must-do part of the Flavour program.
- Yet no obvious flagship measurement where FCC-*ee* is unique w.r.t. the Belle II or LHCb U2 anticipated precisions.
- FCC-*ee* competes potentially favourably though everywhere (offers redundancy for sole measurements). See Roy's talk.
- A high energy-resolution calorimeter and excellent PID are in order.

4) *CP* violation study program at large.

- There is probably one flagship measurement, the specific exploration (already started at FCC-ee) of semileptonic asymmetries in neutral *B* mixing.
- Unobserved to date and small in the SM.
- Those are delicate measurements and likely systematic limited. Lightest detector helps.
- They enter as an important exploration of BSM amplitudes in mixing processes. I give a glimpse of it here. See there and article here hep-ph: 2006.04824.

# Heavy Flavours: physics opportunities and challenges

## 4) *CP* violation study program at large.

Bottlenecks in the interpretation of CKM profile meas. identified (true already for LHCb U2) (2006.04824): $V_{cb}$ and QCD mixing parameters.

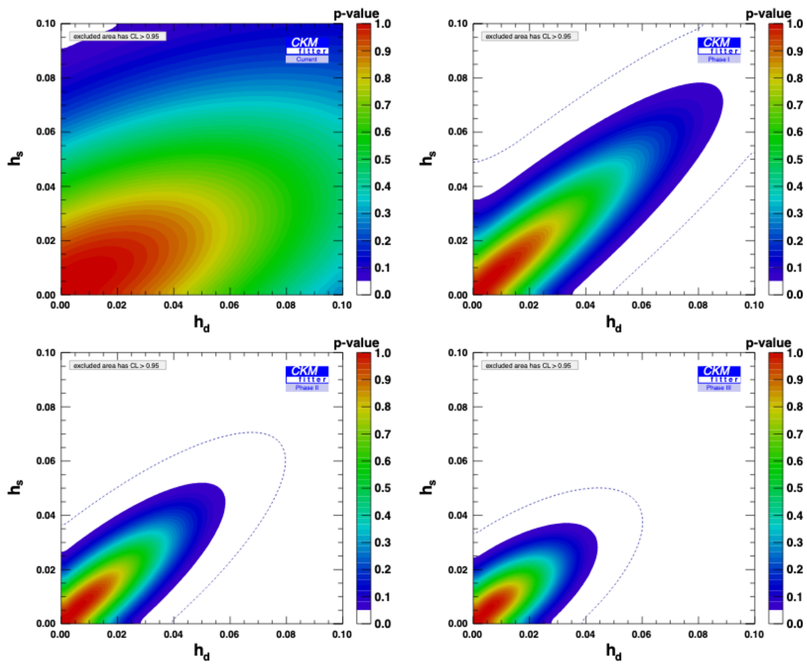



FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in $B_d$ and $B_s$ mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL ($3\sigma$) contours.

A flavour of what can be expected for $V_{cb}$ measurements at *WW* threshold in Paolo Azzuri's talk here.

- Hierarchised in categories to explore:

  5) Mass and lifetime properties, spectroscopy.

  6) and Charm physics.

  Both categories are not touched yet to my knowledge on the experimental side but are a must-do.

  - The invariant-mass resolution at FCC-ee for narrow states shall make marvels in spectroscopy.
  - For charm, significant phenomenological works do exist for FCC-ee. One of the last in line : https://arxiv.org/pdf/2010.02225.pdf.

# Heavy Flavours: detector challenges

Flavour physics requires trivially (writing them is trivial):

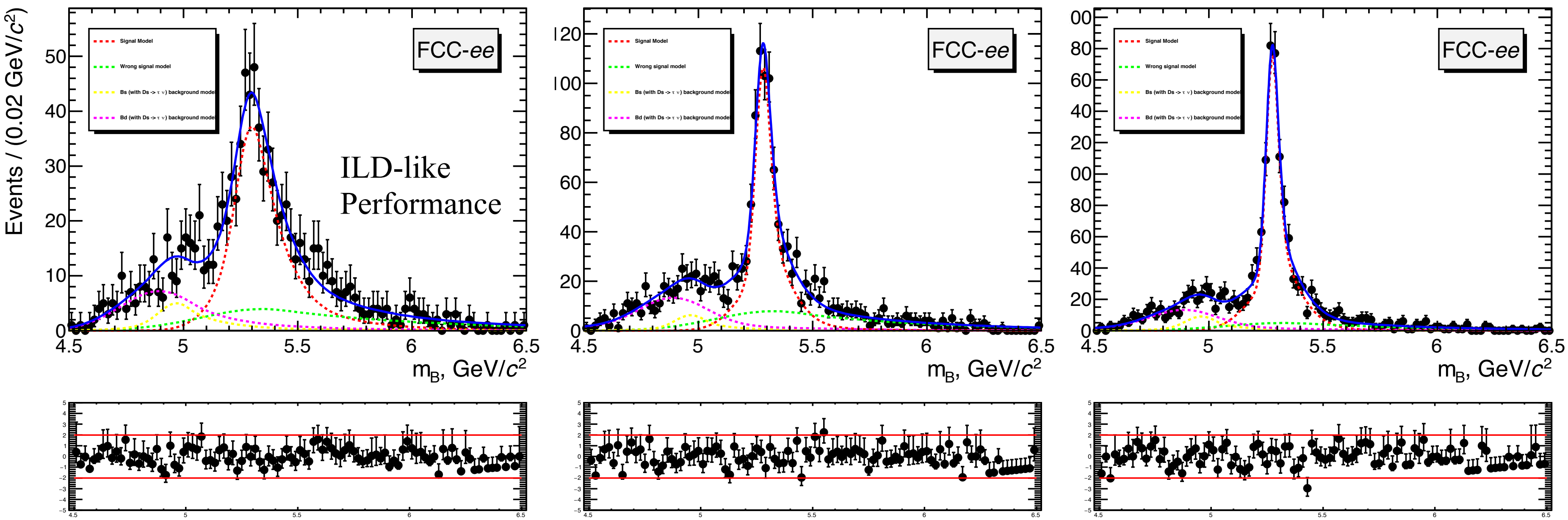
- Measurements of short-lived particles decay vertices to measure lifetimes, resolve oscillations, identify tertiary short-lived particle decay vertices in decay chain.
- Hadron particle identification (PID) to reconstruct the final state of interest under the correct mass hypotheses, and remove background contamination.
- Flavour tagging (in the sense of the charge of the quark): identification of leptons in jets, low momenta particles close in phase space w/ the decay ( $B^*(B\pi)$, $D^*(D\pi)$ ) …
- High momentum resolution to resolve the invariant-mass of exclusive decays. Precision calorimetry to resolve $\pi^0$ and $\gamma$ (radiative decays) energy (invariant-mass again / background suppression).
- Long-lived particle tracking ($K_S$ and $\Lambda$) and $K_L$ stopping for CPV studies

# Heavy Flavours: detector challenges

Some comments in order:

- If most of these requirements do meet those of the overall physics program, PID, calorimetry and vertexing performance are not obviously given, or shall be obtained with a compromise and envisaged in a global design.
- A PID detector if needed has to fit before the calorimeter and will degrade electron & $\gamma$ reconstruction.
- This is the kind of questions one wants to answer in the current phase of the FCC project.
- Case Studies are envisaged to guide the requirements for the detector design.

# $B^0 \to K^{*0}\ \tau^+\tau^-$ : Case studies @Clermont — Vertex.




| Performance / Conditions | ILD-like | ILD /2 | ILD / 4 |
|---|---|---|---|
| Efficiency of the identification of the correct solution (%) | 42,3 | 52,6 | 62 |
| Invariant mass resolution (core) [MeV/$c^2$] | 42(1) | 36(1) | 27(1) |

Invariant-mass resolution is key to beat the backgrounds. Not guaranteed at state of the art performance … Very challenging assumptions in this exploration.

# Heavy Fl.: Case studies — Rare decays & Vertex.

The semileptonic transitions with taus in the final states $b \rightarrow s\, \tau^+\tau$ (and $B_s \rightarrow \tau^+\tau^-$ and LFV decay modes) performance (branching fraction and why not angular analysis) are demanding likely more than the state-of-the-art. To go further, they can be used to:

- Understand the requirements to beampipe design and location of the first layer, as well as its geometry (bending).
- Understand the impact of the hit resolution.
- Review the impact of the material density.
- Requires: a) comprehensive and realistic background sources (beyond the current study), b) understand the critical points of the detector design upon the topological methods.
- The case study with the developing FCC sw is launched in Clermont / Dortmund Master internship.

# Heavy Fl.: Case studies — CPV and other detectors

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, starting w/ charged hadron particle identification PID.

- *p* / *K* / $\pi$ separation is capital to suppress background of *CP*-eigenstates and mandatory to eliminate the cross-feeding signals of companion modes.
- It has been already touched for $B_s \to D_s K$ (see Roy's talk).
- It is to be extended to $B \to DK$, multibody *b*-hadron decays (including baryons), etc…
- It is also a necessary ingredient for flavour tagging (in the sense of the quark charge taggin) via same side and opposite soft kaon identification.
- PID considerations can't be thought alone (entangled w/ the global design).

# Heavy Fl.: Case studies — CPV and other detectors

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, continuing w/ calorimetry:

- A comprehensive program of *CP* violation must include the study of modes w/ $\pi^0$, *e.g.* $B^0 \to \pi^0\pi^0$, $B^0 \to \pi^+\pi^0\pi^-\pi^0$, …critical to measure the CKM alpha angle as an example (though theory limited at that time).
- High resolution at low energy is the key here.
- Some other calorimetry cases discussed by Roy next.
- Radiative decays following $b \to s\gamma$, provides the same requirements. Critical for charm studies as well.
- Isolation criteria (the missing energy flow) likely instrumental in $B^+_c \to \tau^+\nu$.

# Heavy Fl.: Case studies — CPV and other detectors

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, coming back to vertexing :

- The knowledge of the $V_{cb}$ CKM matrix element — governing the normalisation of the UT sides— becomes a bottleneck to interpret the CKM profile(s). Powerful *b*- and *c*-jets tagging is in order to benefit from the breathtaking statistics of 3 $10^8$ *WW (both* on-shell and boosted).
- Last but not least, semileptonic asymmetries, as measures of *CP* violation in the *B* meson mixings (unobserved to date) is at reach if charged particle detection asymmetry is controlled (up to few $10^{-5}$ to meet SM values): another challenge to global detector design.

# Summary

- Significant opportunities provided by Flavour Physics at FCC-ee.
- In turn, demanding detector requirements:
  - Vertex detector (possibly beyond hit resolution).
  - Calorimetry for *CP* violation and missing energy.
  - Particle identification (has been considered in the two detector sessions this afternoon and tomorrow morning).
- Not only demanding sub-detector requirements but a challenge for the global detector design.
- Questions to be instrumented through two Case Studies, which are developing here and there.
- Significant (and enthusiast studies) are emerging.