Flavours at FCC-*ee*: beyond CDR studies with plans for the short / middle terms

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Outline

- Motivation and method for building the Flavours case.
- Executive Summary of the CDR results.
- New: search for CP violation in the mixing.
- Plans / ideas for the future studies.

1) Motivation and method: Flavour Physics case.

- Focus on the third generation Physics (but direct top).
- Start from the anticipated Flavour Physics landscape after Belle II and LHCb U1/2 experiments.
- Identify challenging flagship processes where FCC-ee is unique (in for a penny, in for a pound).
- Selection of modes which tells detector requirements.

Rare b-hadron decays — electroweak penguins

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix} \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$$

$$\begin{pmatrix}u\\ d\end{pmatrix} \quad \begin{pmatrix}c\\ s\end{pmatrix} \quad \begin{pmatrix}t\\ b\end{pmatrix}$$

Lepton Flavour Violating (LFV) Z decays

cLFV tau decays

CKM measurements —CPV in B mixings

2) Recap: executive summary CDR — Flavours

https://cernbox.cern.ch/index.php/s/9ZuIudM8cUATaZD

The following slides can be taken and used from the above link.

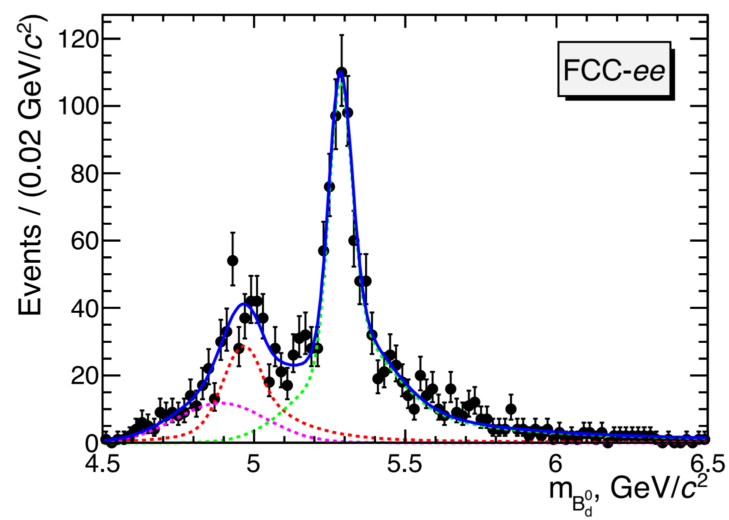
1) Heavy Flavours Production — Comparison w/ Belle II

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

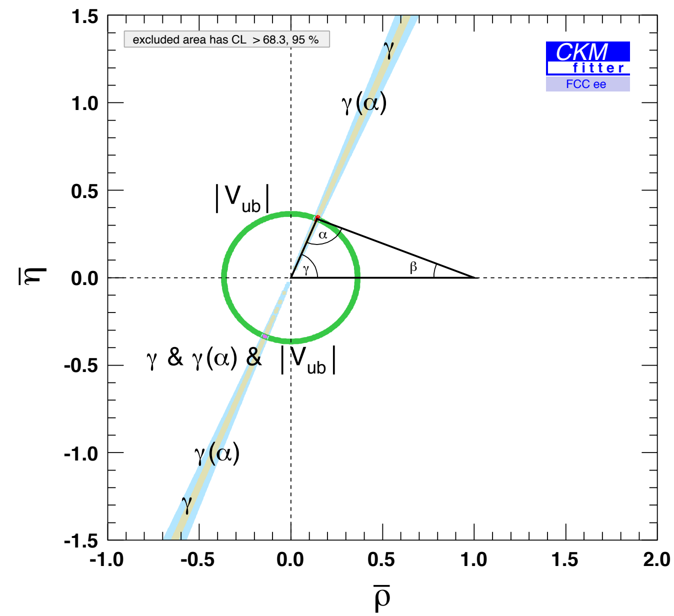
2) Flavour anomalies — $b \to s\ell\ell$ yields and $B^0 \to K^{*0}\ \tau^+\tau^-$.

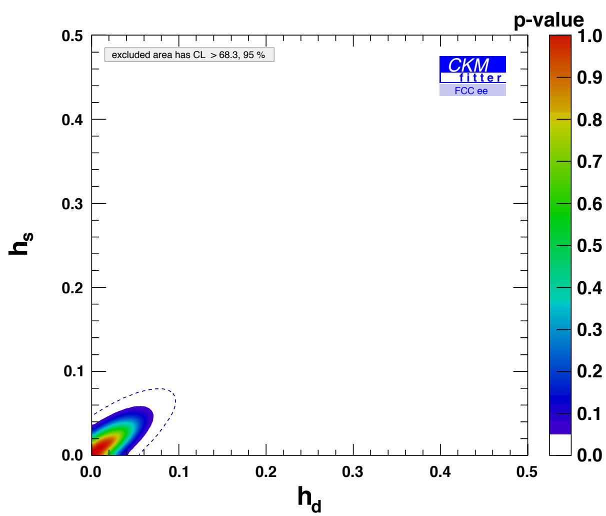
Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	∼ 2 000	∼ 10	n/a (5)
LHCb Run I	150	-	∼ 15 (–)
LHCb Upgrade	∼ 5000	-	∼ 500 (50)
FCC-ee	∼ 200000	∼ 1000	∼1000 (100)



3) CKM and *CP* violation in quark mixings

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2





$$\Lambda_{\rm NP}(\Delta F = 2) > 20\ \text{TeV}$$

2) Executive summary — Flavours at FCC-*ee*

4) Tau Physics

Visible Z decays	3×10^{12}
$Z \to \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

CLFV *Z* decays:

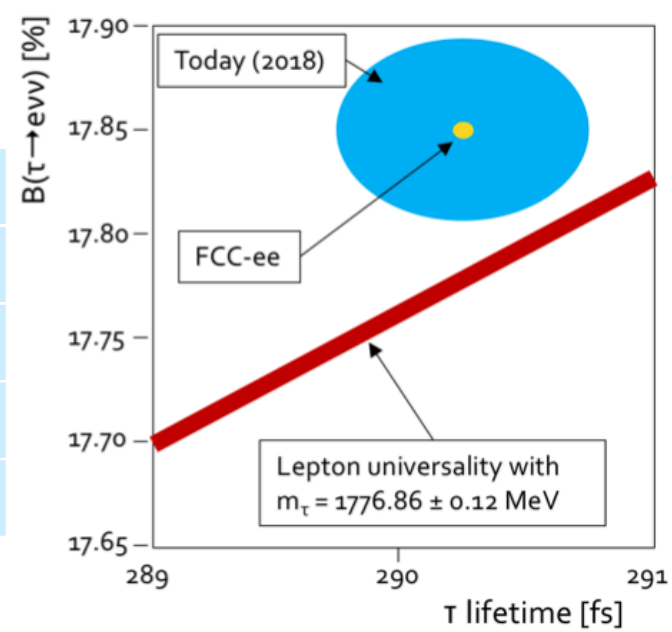
Decay	Current bound	FCC-ee sensitivity
$Z \to e\mu$	0.75×10^{-6}	10^{-8}
$Z \to \mu\tau$	12×10^{-6}	10^{-9}
$Z \to e\tau$	9.8×10^{-6}	10^{-9}

CLFV *τ* decays:

Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

Tau properties

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04



3) Search for *CP* violation in *B* mixing

- A source of *CP* violation not measured so far.
- Part of the consistency check of the CKM paradigm.
- There are several ways to measure this at FCC-*ee*. It has been chosen in this exploration (Dennis Arogancia, Jan Maratas, MSU-IIT, SM) to focus on the *Bs* mixing.
- with a method inline with the one used at LHCb.
- This is work in progress.

3) Search for *CP* violation in *B* mixing

- Setting the scene: *CP* violation in mixing can be measured by looking at flavour-specific decays and the *CP*-violating observable defined by:

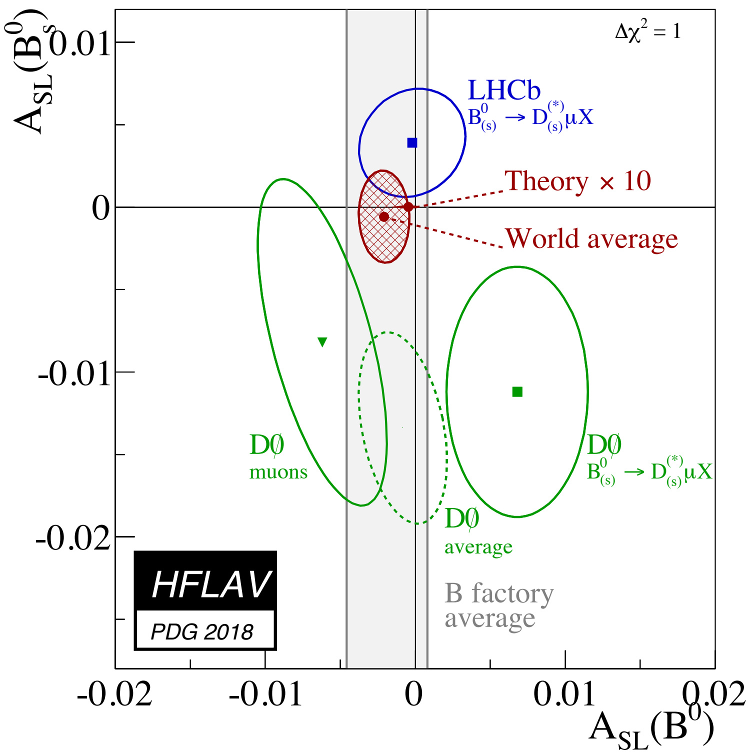
$$a_{\rm fs} = \frac{\Gamma(\bar{B}^0_q \to B^0_q \to f) - \Gamma(B^0_q \to \bar{B}^0_q \to \bar{f})}{\Gamma(\bar{B}^0_q \to B^0_q \to f) + \Gamma(B^0_q \to \bar{B}^0_q \to \bar{f})}$$

- The SM predictions reads:

$$a^d_{\rm sl} = -(4.7 \pm 0.6) \times 10^{-4} \,,$$
$$a^s_{\rm sl} = +(2.22 \pm 0.27) \times 10^{-5}.$$

- Focus here on B_s (in for a penny…)

- The state of the art is at the level of few per mil precision.



3) Search for *CP* violation in *B* mixing

- Signal: $B_s \to D_s^{-(*)} \ell^+ \nu_\ell$ w/ $D_s^+ \to KK\pi$ as the generation proxy. Statistics scaled to fully reconstructible D_s modes forming a decay vertex,

- Backgrounds: a variety of backgrounds involving double charmed mesons in decays of B^0, B_s and Λ_b, where one meson is the $D_s^{-(*)}$ and the other one decays semileptonically. Modes considered:

Background	Branching fraction (%)
$B^0 \to \bar{D}^0 D_s^{(*)-} X$	5.7 ± 1.2
$B^0 \to \bar{D}^- D_s^{(*)-} X$	4.6 ± 1.2
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$	4.5 ± 1.4
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)-} X$	10.3 ± 2.1

- Generation: Pythia + EvtGen + momentum / vertexing smearing (ILD).

3) Search for *CP* violation in *B* mixing

- Backgrounds generation: EvtGen cocktail with a variety of D^0, D_s, D^+ and Λ_c semileptonic decays (scaled to the inclusive semileptonic BF)

Decay mode	Branching fraction
$D^0 \to K^- \mu^+ \nu_\mu$	$(3.31 \pm 0.13)\%$ (PDG 2018)
$D^0 \to K^{*-} \mu^+ \nu_\mu$	$(1.86 \pm 0.24)\%$ (PDG 2018)
$D^0 \to K_1^- \mu^+ \nu_\mu$	0.000076 (decay file)
$D^0 \to K_2^{*-} \mu^+ \nu_\mu$	0.00110 (decay file)
$D^0 \to \pi^- \mu^+ \nu_\mu$	$(2.37 \pm 0.24) \times 10^{-3}$ (PDG 2018)
$D^0 \to K^- \pi^0 \mu^+ \nu_\mu$	0.00040 (decay file)
$D^0 \to K_1^- \pi^+ \pi^- \mu^+ \nu_\mu$	0.00120 (decay file)

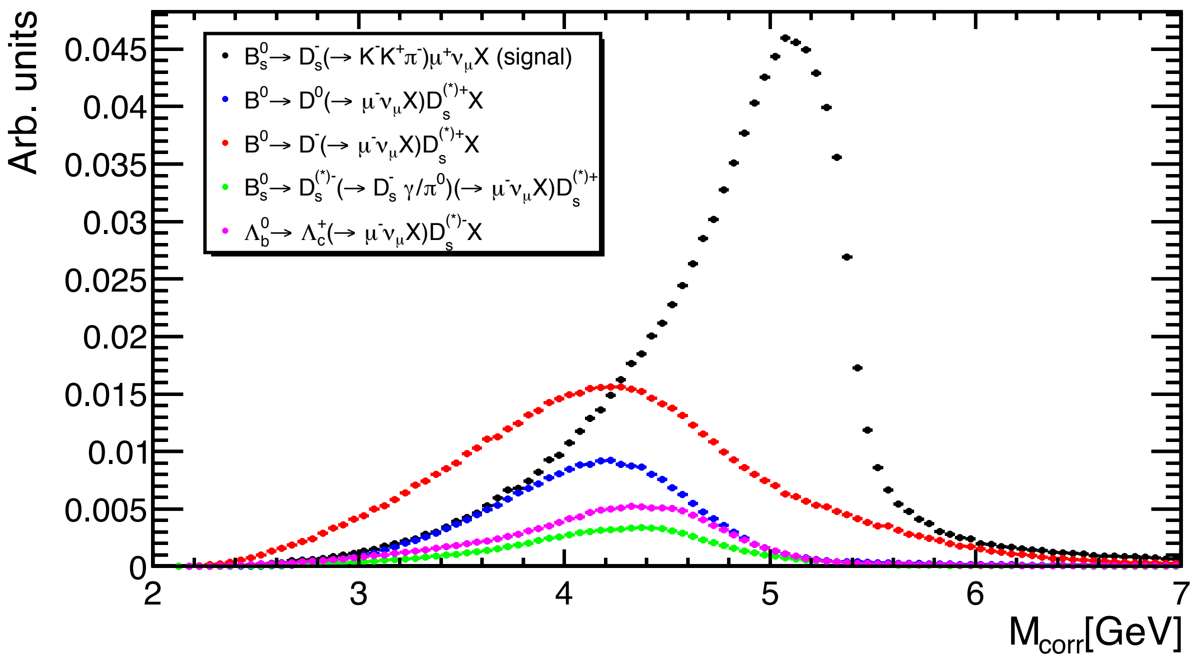
Decay mode	Branching fraction
$\Lambda_c^+ \to \mu^+ \nu_\mu \Lambda$	$(3.5 \pm 0.5)\%$ (PDG 2018)
$\Lambda_c^+ \to \mu^+ \nu_\mu \Sigma^0$	0.01000
$\Lambda_c^+ \to \mu^+ \nu_\mu \Sigma^{*-}$	0.01000
$\Lambda_c^+ \to \mu^+ \nu_\mu n$	0.00600
$\Lambda_c^+ \to \mu^+ \nu_\mu \Delta^0$	0.00400
$\Lambda_c^+ \to \mu^+ \nu_\mu \pi^+ \pi^-$	0.01200
$\Lambda_c^+ \to \mu^+ \nu_\mu n \pi^0$	0.01200

Decay mode	Branching fraction
$D^+ \to \mu^+ \nu_\mu$	$(3.74 \pm 0.17) \times 10^{-4}$ (PDG 2018)
$D^+ \to \bar{K}^{*0} \mu^+ \nu_\mu (\bar{K}^{*0} \to K^- \pi^+)$	$(3.52 \pm 0.10)\%$ (PDG 2018)
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$(8.74 \pm 0.19)\%$ (PDG 2018)
$D^+ \to K_1^0 \mu^+ \nu_\mu$	2.77×10^{-3} (decay file)
$D^+ \to K_2^{*0} \mu^+ \nu_\mu$	2.93×10^{-3} (decay file)
$D^+ \to \pi^0 \mu^+ \nu_\mu$	4.05×10^{-3} (decay file)
$D^+ \to \eta \mu^+ \nu_\mu$	1.14×10^{-3} (decay file)
$D^+ \to \eta' \mu^+ \nu_\mu$	2.2×10^{-3} (decay file)
$D^+ \to \rho^0 \mu^+ \nu_\mu$	$(2.4 \pm 0.4) \times 10^{-3}$ (PDG 2018)
$D^+ \to \omega^0 \mu^+ \nu_\mu$	1.82×10^{3} (decay file)
$D^+ \to K^- \pi^+ \mu^+ \nu_\mu$	$(3.65 \pm 0.34)\%$ (PDG 2018)
$D^+ \to \bar{K}^0 \pi^0 \mu^+ \nu_\mu$	1.5×10^{-3} (PDG 2018)

Decay mode	Branching fraction
$D_s^+ \to \mu^+ \nu_\mu$	$(5.5 \pm 0.23) \times 10^{-3}$ (PDG 2018)
$D_s^+ \to \phi \mu^+ \nu_\mu$	$(1.9 \pm 0.5)\%$ (PDG 2018)
$D_s^+ \to \eta \mu^+ \nu_\mu$	$(1.1 \pm 0.5)\%$ (PDG 2018)
$D_s^+ \to \bar{K}^0 \mu^+ \nu_\mu$	0.00390 (decay file)
$D_s^+ \to \bar{K}^{*0} \mu^+ \nu_\mu$	0.00180 (decay file)

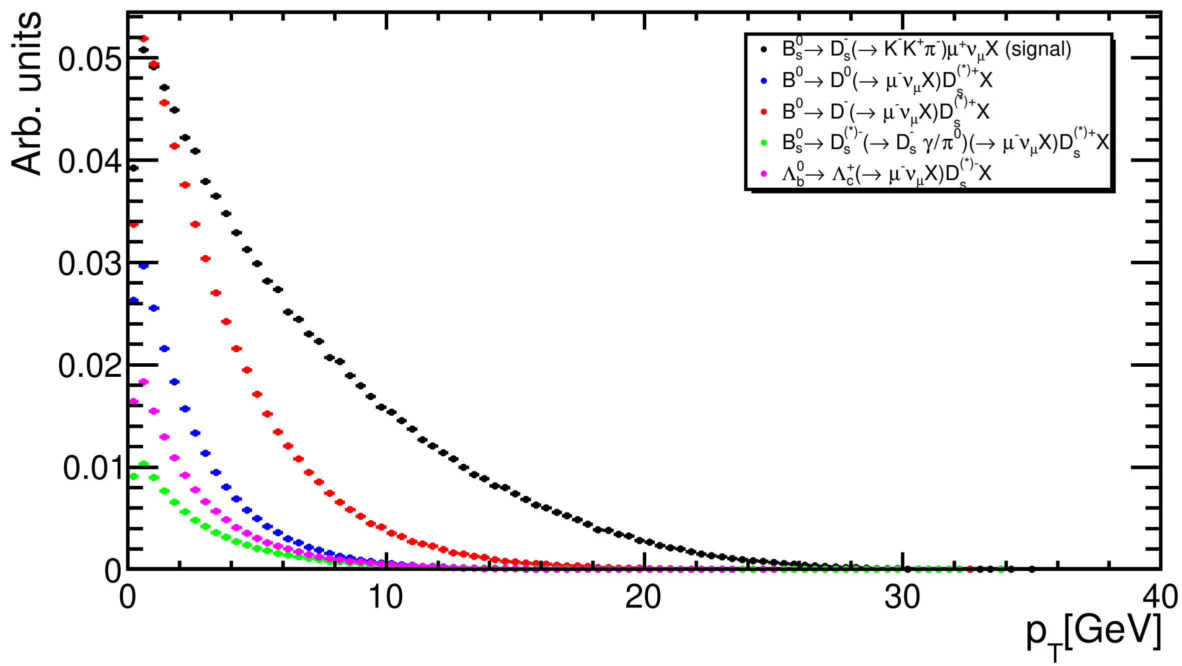
- A relevant variable to characterise the signal: the corrected *b*-hadron mass formed from the $D_s\ell$ mass and the missing momentum transverse to the *b*-hadron direction inferred from vertexing.

$$M_{\mathrm{corr}} = \sqrt{M^2_{D_s\mu} + |p_T^{\mathrm{miss}}|^2} + |p_T^{\mathrm{miss}}|$$



3) Search for *CP* violation in *B* mixing

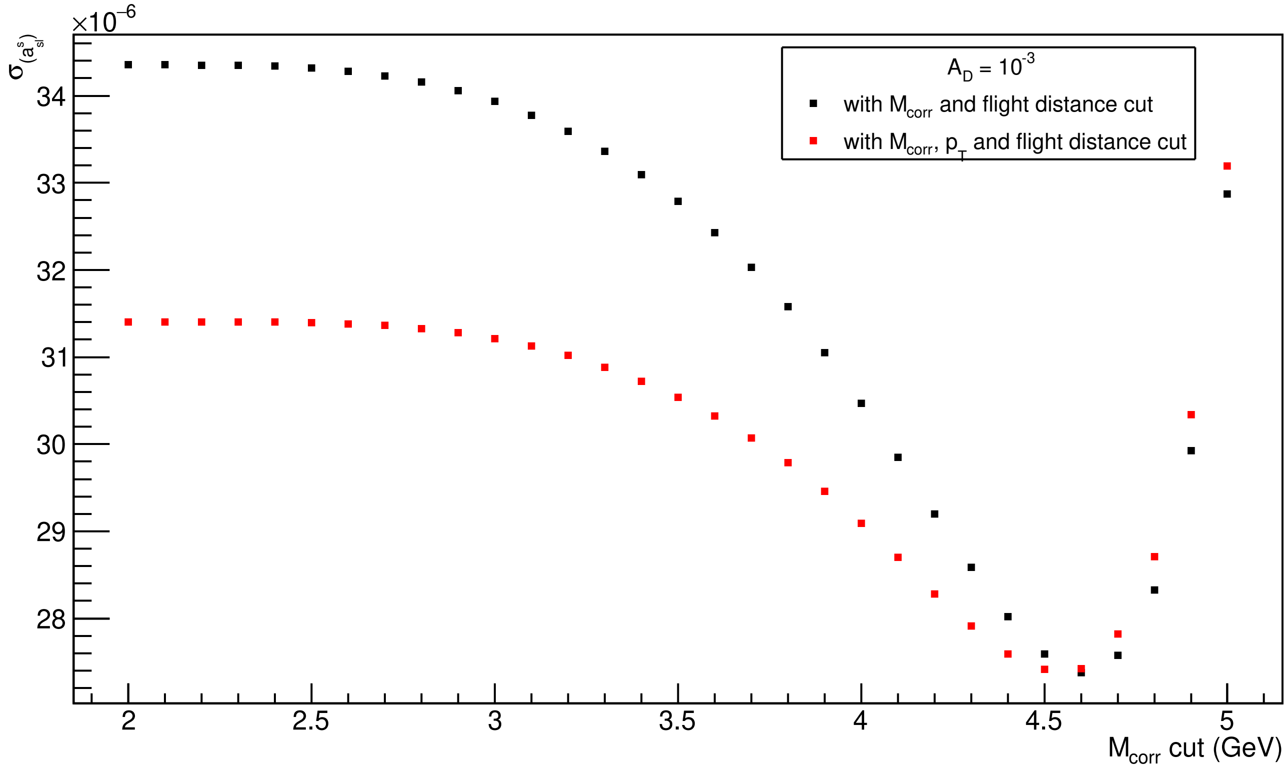
- The measured lepton transverse momentum can be additionally discriminative:



- Most toxic backgrounds come from the $D^{+/-}$. If needed, vertex ordering can further decrease this background.

3) Search for *CP* violation in *B* mixing

- Uncertainty scaling with one dimensional cut:



- Order of magnitude of the precision is at the level of the SM prediction. The actual numbers must still be ironed further. *E.g.*, dependence with the detection asymmetry precision has still to be determined.

3) Search for *CP* violation in *B* mixing

- The most challenging flavour specific asymmetry seems at reach if SM prediction is considered (actual numbers must still be ironed further but the order of magnitude is there).

- Precision about 10 times better than the back of the envelope computation reported in the CDR and further used in the ΔF=2 model-independent NP constraints.

- Outlook #1: make another pass on the ΔF=2 model-independent NP constraints.

- Outlook#2: document the study with an internal note.

4) Plans for the short term

- Where we are expected A/: the search for the decay $B_s \to \tau^+\tau^-$, as the next rare (helicity-suppressed) dileptonic decay.
- Produced number of events at FCC-ee: $O(10^5)$ (*) at SM value. Can be studied with a topological reconstruction of the kinematics of the decay.
- Contrarily to $B^0 \to K^{*0}\ \tau^+\tau^-$, the kinematics of the decay cannot be fully solved analytically from the measured topological properties of the decay. We are missing here the decay vertex of the B_s.
- The direction of the b-hadron must be approximated. Obvious ideas are to use the global missing energy of the hemisphere of the decay and / or the quark / b-hadron direction of the opposite hemisphere.
- Both approaches require the use of several sub-detectors information from vertexing to calorimetry.

4) Plans for the short term

- Where we are expected B/: the search for the leptonic decay $B^+_c \to \tau^+\nu_\tau$.
- Used to be interesting per se for probing *e.g.* charged scalar couplings.
- Diagrammatically similar to the presently anomalous decay $B^0 \to D^{(*)}\tau^+\nu_\tau$. Another way to tackle tree level anomalies, should they be confirmed. Expect $O(10^6)$!
- Again requires the use of several sub-detectors information simultaneously from vertexing to calorimetry (absence of the secondary vertex). Use of excited B_c would provide a further kinematical constraint.
- A good mode to benchmark the handling of missing energy (search for a true absence in the calorimeter).
- Already got expression of interest for these two explorations. Hope this happens soon. The hands-on tutorial of September might be instrumental for this.

4) Plans for the short term: detector concepts.

- How Flavour Physics can help to exercise the detector concepts?

- Topological reconstruction (full kinematical solution) à la $B^0 \to K^{*0}\ \tau^+\tau^-$: demanding vertexing performance.

- Tau Physics (standard Branching Fractions per se or in view of the tau polarisation optimal measurement) : we were reminded on Tuesday this week that current best precision for modes with π^0 were driven by the calorimeter design / performances.

- LFV Z decays search pose tracking requirements.

- The quark flavour program relies for a significant part on Hadronic Particle Identification. A canonical mode to benchmark PID detector concepts can be $B_s \to D_s K$. Exploratory study was engaged showing the necessity of PID. To be continued with actual detectors.

- …

4) Wishlist / plans for the middle term

- All explored subjects in the CDR will benefit of full simulations of different detector concepts and should be reviewed in the light of realistic detection performance.
- The CKM profile has been explored with simple extrapolations / scaling of either LHCb or Belle analyses. Providing a solid assessment of the precision reach with full sim. is in order.
- There is a terrain that would be nice to cover: *exotic* spectroscopy with baryons. Identification of states and quantum properties measurements in clean environment. (Note: most cited papers in LHCb with the anomalies).
- Charm Physics is overlooked so far. Though statistics is modest w.r.t. LHCb, radiative decays as an obvious starting point to be studied.
- I believe that the model of building small groups of experimentalist and theorist in view of a focussed note / paper is a valid one though we had only two occurrences of that in the WG during the Design Study.

5) Summary

- Exploration phase for Flavour Physics was successful / promising:
  - FCC-ee can compete favourably with each of the ultimate precisions of LHCb and Belle II experiments.
  - There are processes for which FCC-ee is unique. The explored subjects in the CDR will benefit of full simulations of different detector concepts and should be reviewed in the light of realistic detector performance.
  - 5 10^{12} Z decays are needed (most of the measurements reported here are statistically limited).
- The initial case can be strengthened with two additional flagship studies and the consolidation of the CKM profile.
- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The next phase of the program should entangle the Physics performance and detector concepts.