

Flavour Physics in Feasibility Report and future prospects

Stéphane Monteil,
Clermont University, LPCA-IN2P3-CNRS.

Outline

1. Setting the Scene
2. Feasibility Report achievements
3. Some opportunities before Venise
4. Some ideas and views for the pre-TDR phase
5. Summary

Most materials can be found in the Flavour document for ESPP: <https://doi.org/10.17181/jnzpp-1fw39>

1) FCC-ee ABCD specifics for Flavour Physics.

A- Particle production at the Z pole:

- About 15 times the nominal Belle II anticipated statistics for B^0 and B^+ .
- All species of b -hadrons are produced.

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$
\sqrt{s} (GeV)	88, 91, 94		157, 163		240	340–350 365
Lumi/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	70	140	10	20	5.0	0.75 1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36 0.58
Run time (year)	2	2	2	–	3	1 4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW \rightarrow H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW \rightarrow H

Particle species	B^0	B^-	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^- \tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

Table 1: Particle abundances for $6 \cdot 10^{12}$ Z decays. Charge conjugation is implied.

1) FCC-ee ABCD specifics for Flavour Physics.

B- The Boost at the Z: $\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$

- Fragmentation of the b -quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

C- Versatility : the Z pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the operation at and above WW threshold will enable to collect several 10^8 W decays on-shell AND boosted. Direct access to CKM matrix elements.

D- Comparison w/ LHC and B-factory. Advantageous attributes:

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

1) FCC-ee ABCD specifics for Flavour Physics.

D- Comparison w/ LHC and B-factory. Advantageous attributes:

Important note: there's a hole in this table. The Heavy Quarks production at the LHC is invincible. The exquisite luminosity at the Z pole and the high geometrical acceptance mitigates this LHC(b) advantageous attribute to a certain extent. The watershed lies around three- to four-body fully charged decays, depending on the modes. $5 \cdot 10^{12}$ Z makes a fantastic sample but more are welcome!

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All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
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Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

2) Achievements during the Feasibility Study

Several avenues explored with (mostly) fast simulation studies:

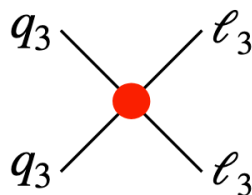
- Semileptonic decays $b \rightarrow s\tau^+\tau^-$ [1705.11106](#), [2505.00272](#)
- Semileptonic decays $b \rightarrow s\nu\bar{\nu}$ [2309.11353](#)
- Leptonic decays $B_c^+, B^+ \rightarrow \tau^+\nu_\tau$ [2105.13330](#), [2305.02998](#)
- CKM CPV observables (γ and ϕ_s) [2402.09987](#), [2205.07823](#), [2107.02002](#)
- CKM m.e. w/ on-shell W decays ($|V_{cs}|, |V_{cb}|$) e.g. [2405.08880](#)
- Tau physics [2505.00272](#), [2401.07564](#)
- EWK observables for heavy quarks with exclusive decays [2502.17281](#)
- Hopefully conveys that these studies are getting published. Worth to join the effort!

2) Achievements during the Feasibility Study (Flash)

Several avenues explored with (mostly) fast simulation studies:

- Study of $b \rightarrow s$ transitions with tau's and neutrinos is a must do (see A. Greljo and L. Allwicher talks here). Breakthrough : SM values can be measured.

3rd family semileptonic transitions

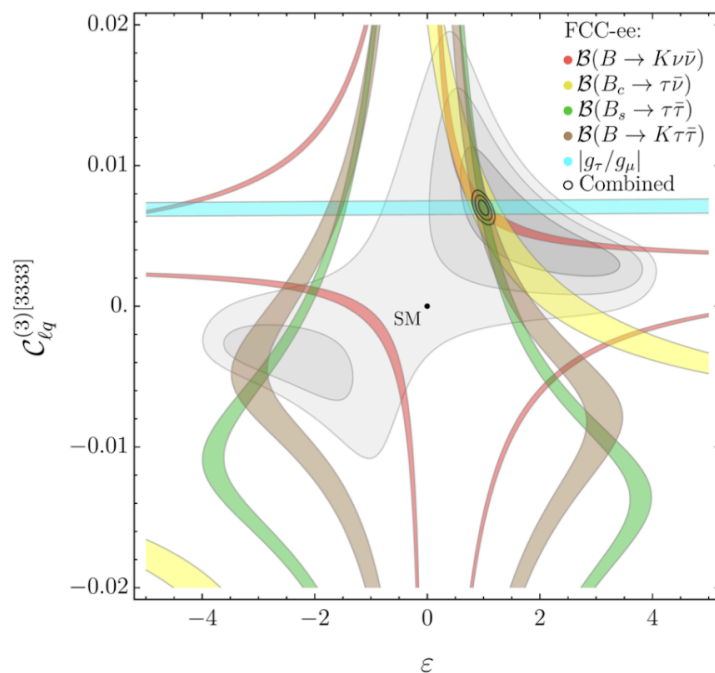


$$Q_{\ell q}^{(3)[3333]} = (\bar{\ell}^3 \gamma_\mu \sigma^a \ell^3) (\bar{q}^3 \gamma^\mu \sigma^a q^3)$$

Mixing: Irreducible prediction of a flavor-protected SMEFT: $\epsilon \sim \mathcal{O}(1)$

$$q_3 \text{ --- } \times \text{ --- } q_i \quad i = 1, 2$$

ϵV_{ti}



Allwicher et al, 2503.17019

2) Achievements during the Feasibility Study (Flash)

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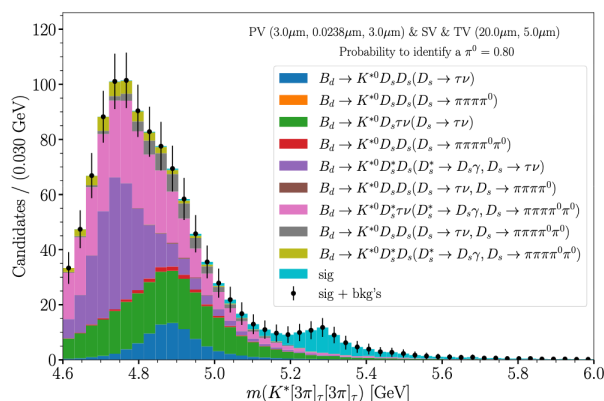


Fig. 53: Distribution of the mass of the B candidates after the full selection, assuming that the secondary and tertiary vertices can be reconstructed with a resolution of $5 \mu\text{m}$ ($20 \mu\text{m}$) in the transverse (longitudinal) direction. The normalisation corresponds to a total of 6×10^{12} produced Z bosons.

- Place vertex and PID requirements

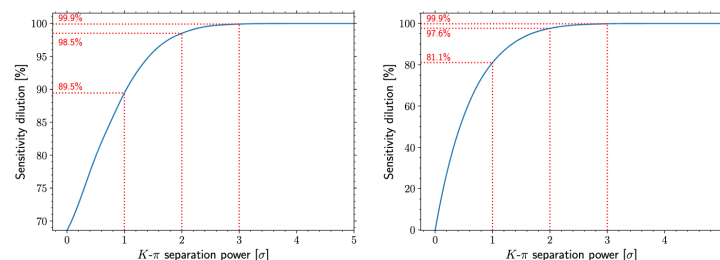
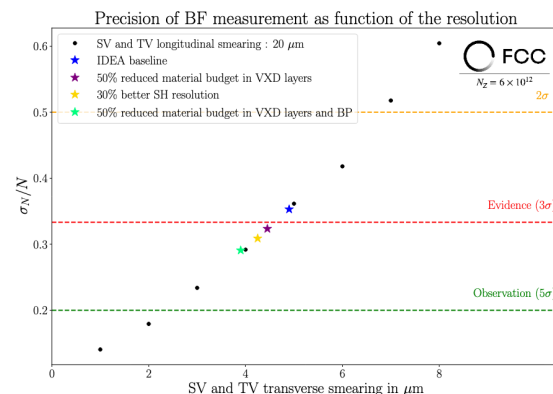


Fig. 58: Sensitivity to the $B \rightarrow K^+ \nu \bar{\nu}$ (left) and $B_s \rightarrow \phi \nu \bar{\nu}$ (right) branching fractions, as a function of the π/K separation power, with respect to the sensitivity assuming perfect PID.

Several avenues explored with (mostly) fast simulation studies:

- **Tau lepton physics: LFU and LFV.** Breakthrough : one to two orders of magnitude improvement in either precision or limits.

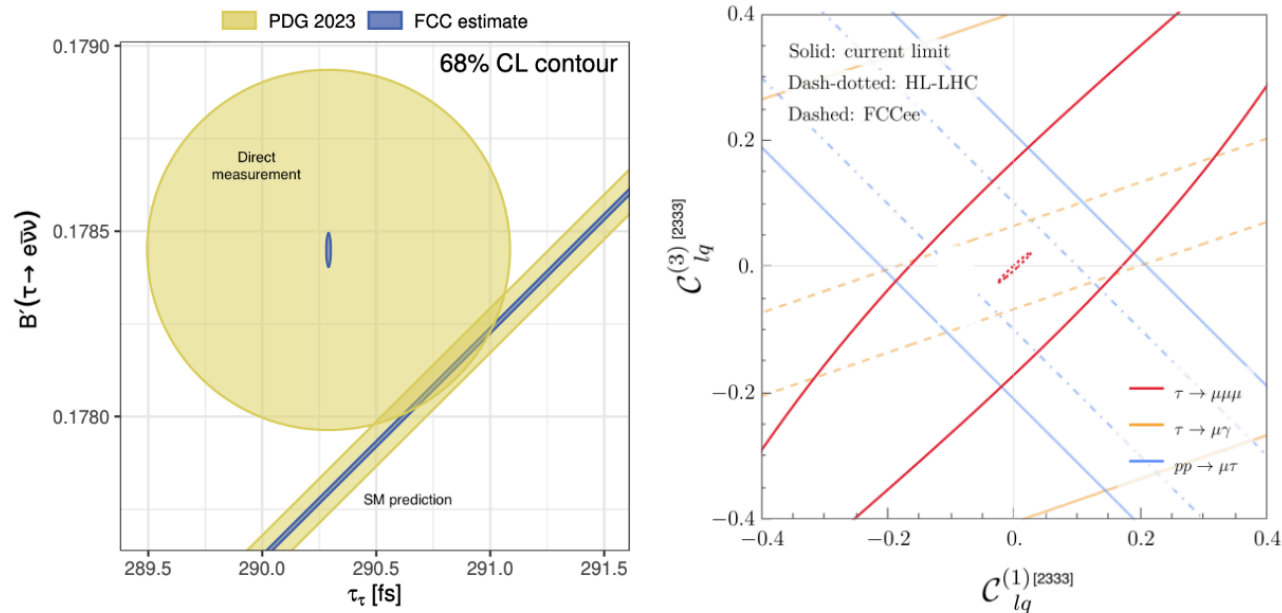


Fig. 34: Left: Direct measurements of $\mathcal{B}(\tau \rightarrow \ell\nu\bar{\nu})$ branching fraction and τ lifetime (ellipse) compared to the SM prediction (band); the width of the SM band is determined by the τ mass uncertainty. From Ref. [195]. Right: FCC-ee impact in constraining, at 95% CL, the coefficients of representative dimension-six LFV operators normalised to the 1 TeV scale. Adapted from Ref. [197], scaled to the baseline FCC-ee luminosities.

2) Achievements during the Feasibility Study (Flash)

Several avenues explored with (mostly) fast simulation studies:

- **CKM:** at Horizon 2040, one can expect the *CPV* observables γ, β, ϕ_s to be already measured at sub-degree precision. FCCee can confirm these values with similar precision.
- The bottlenecks in the interpretation of the CKM profile are therefore reduced to the hadronic parameters (determined by latticeQCD) and the matrix element V_{cb} , as the normalisation of the UT triangle [[2006.04824](#)]
- The several 10^8 *WW* pairs produced at threshold and beyond offer the opportunity of a breakthrough in precision by one order of magnitude.

© Marzocca et al.,
[2405.08880](#)

$ V_{ij} $	Current (PDG)		FCC-ee ($\delta_\epsilon = 1\%$)	FCC-ee ($\delta_\epsilon = 0.1\%$)	FCC-ee (Stat. only)
$ V_{cs} $	0.975 ± 0.006	(0.6%)	0.36%	0.05%	0.008%
$ V_{cb} $	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.52%	0.16%	0.14%

Table 1. The first column shows the current values of $|V_{cs}|$ and $|V_{cb}|$ from PDG [1]. The second, third and fourth columns show the relative precision projected for FCC-ee by assuming 1%, 0.1% and zero relative systematic uncertainty on the tagger parameters, respectively.

3) Some activities have started in the recent months

- They were not in time to feed the FS report but they should soon complement the Flavour case developed so far. Triggers the study charm physics case (one of the recommendation of the FS mid-term review).
- Charm semileptonic decays with neutrinos in the final state
- CP violation in $D^0 \rightarrow \pi^0 \pi^0$
- CP violation in charm mixing.
- Semileptonic decays $b \rightarrow s$ with pair of electrons in the final state
- I'm flashing next preliminary results of two of those studies.

3) Some activities have started in the recent months

- They were not in time to feed the FS report but they should soon complement the Flavour case developed so far.
- Charm semileptonic decays with neutrinos in the final state: this is advanced and documented ! Publication to follow shortly.

© T. Hachaney et al., the analysis note is on cds

Process	Reconstruction [10 ⁻²]	Preselection [10 ⁻³]	BDT1 [10 ⁻²]	BDT2 [10 ⁻²]	Overall
$Z \rightarrow c\bar{c}$	75.5	25.0	10.5	0.32	6.41×10^{-6}
$Z \rightarrow b\bar{b}$	84.2	1.7	3.0	0.75	3.24×10^{-7}
$Z \rightarrow u\bar{u}$	42.6	0.59	2.6	0.22	1.43×10^{-8}
$Z \rightarrow d\bar{d}$	44.9	0.60	2.5	0.30	2.01×10^{-8}
$Z \rightarrow s\bar{s}$	62.6	0.57	3.1	0.27	3.02×10^{-8}
$Z \rightarrow \tau^+\tau^-$	9.9	0.082	90.7	0.64	4.72×10^{-8}
Signal	58.5	784.4	92.2	15.4	6.53×10^{-2}

Table 2: Efficiencies at different selection steps for all inclusive background samples and signal. The selection efficiencies are calculated relative to the previous step by summing over the candidate PID-weights w .

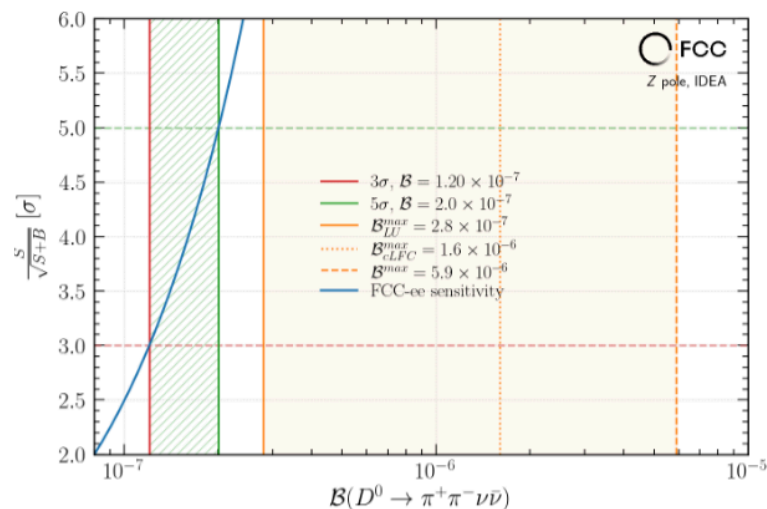
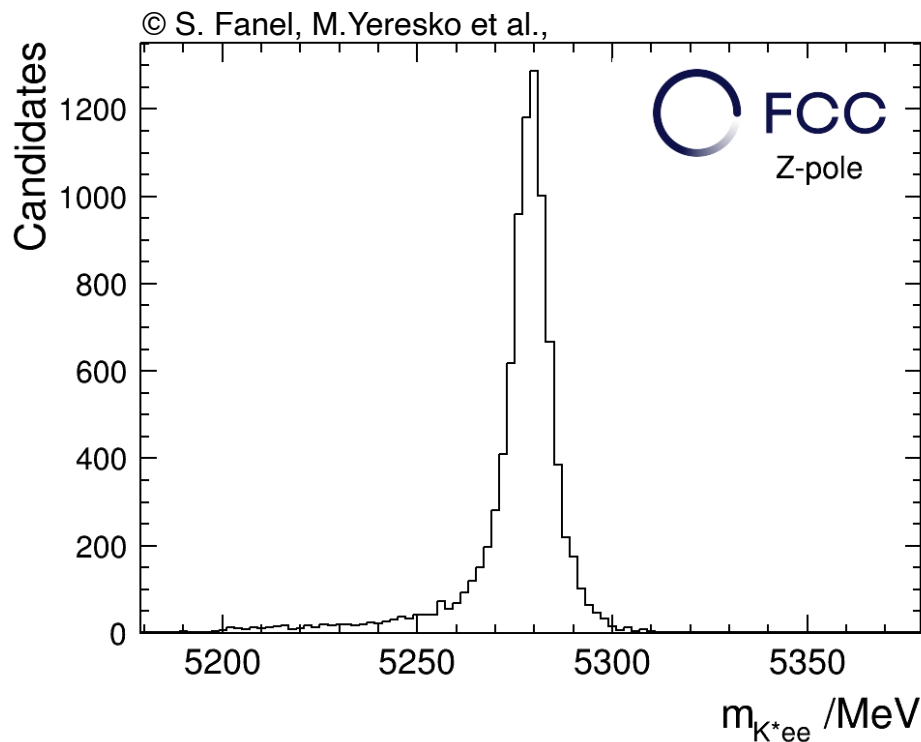


Figure 5: Sensitivity estimate as a function of the branching fraction of $D^0 \rightarrow \pi^+\pi^-\nu\bar{\nu}$ (blue) with the 3σ (red) and 5σ (green) threshold. The expected theoretical maximum branching fraction for different flavour structure assumptions is marked with the orange bands.

3) Some activities have started in the recent months

- They were not in time to feed the FS report but they should soon complement the Flavour case developed so far.
- Semileptonic decays $b \rightarrow s$ with pair of electrons in the final state : about 250 (500) kevents for $B^0 \rightarrow Ke^+e^-$ ($B^0 \rightarrow K^*(892)e^+e^-$)



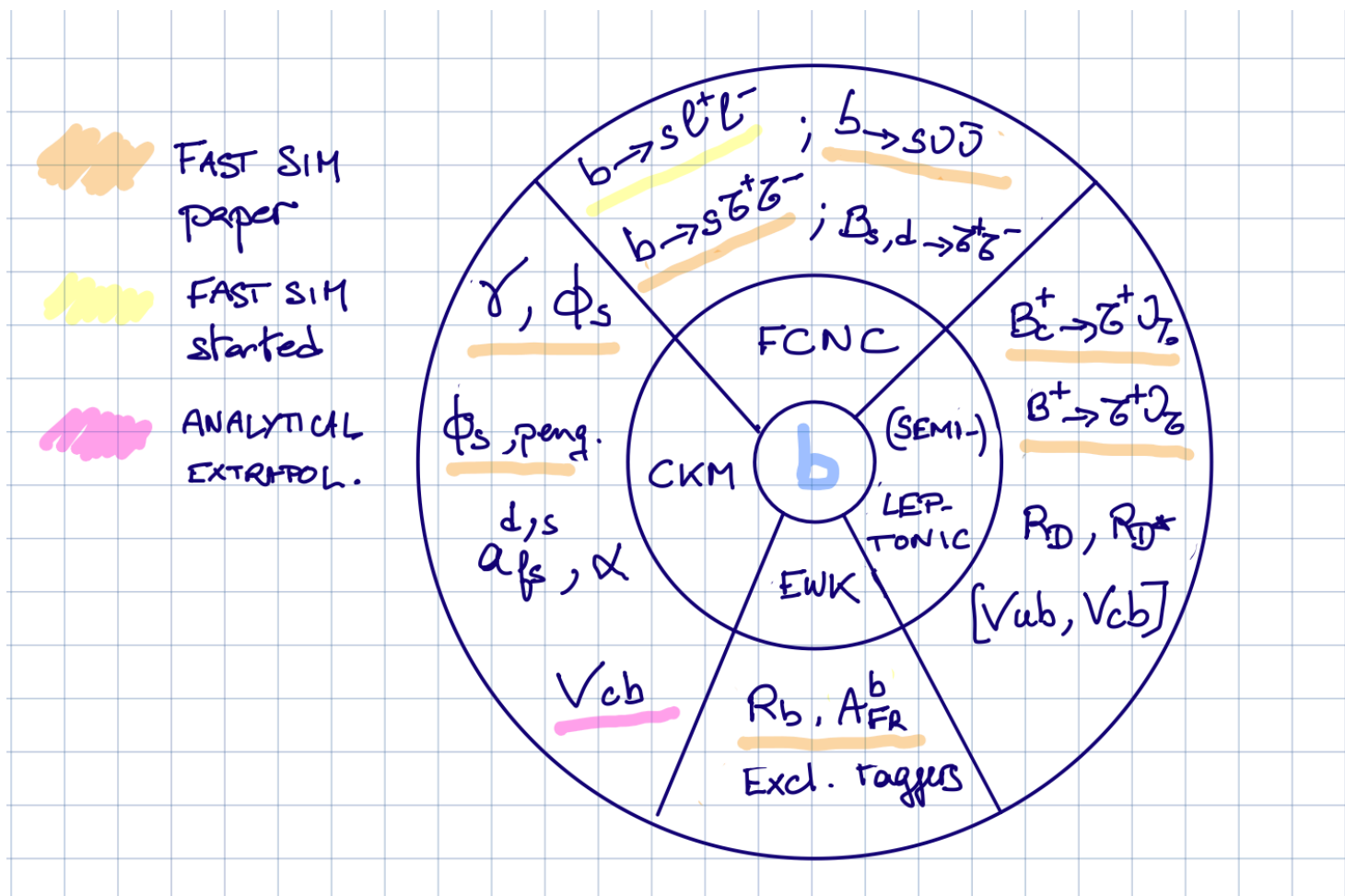
4) What would be useful in the pre-approval phase?

The following two objectives are desirable imo:

- Refine the narrative for Flavours with a more complete program on the several Flavour factories /sources (b, c, and tau)
- Refine the detector requirements : automated benchmarks for detector designs and address comprehensively the electromagnetic calorimeter requirements.

4) What would be useful in the pre-approval phase?

- Refine the narrative for Flavours with a more complete program on the several Flavour factories / sources (b, c, and tau) with more than fast simulations



4) What would be useful in the pre-approval phase?

- **Refine the narrative for Flavours with a more complete program on the several Flavour factories / sources (b, c, and tau)**
- Complete and document the charm studies:
 - Rare decays $c \rightarrow u\nu\bar{\nu}$ in conjunction with $c \rightarrow u\ell^+\ell^-$ (TUDO, Clermont, BNL)
 - CPV compl. to LHCb: direct $D^0 \rightarrow \pi^0\pi^0$ (Clermont, Orsay) and mixing $D^0 \rightarrow K_S\pi^+\pi^-\pi^0$ (CERN, Oxford).
- Engage (at last) the study of the golden (and most challenging!) mode $B_s^0 \rightarrow \tau^+\tau^-$ (Florida U., KIT, EPFL, Clermont).
- There's one potential flagship measurement in the CKM sector : the so-called semileptonic asymmetries $a_{fs}^{d,s}$. The name of the game is there the control of the charge detection efficiency asymmetries.

4) What would be useful in the pre-approval phase

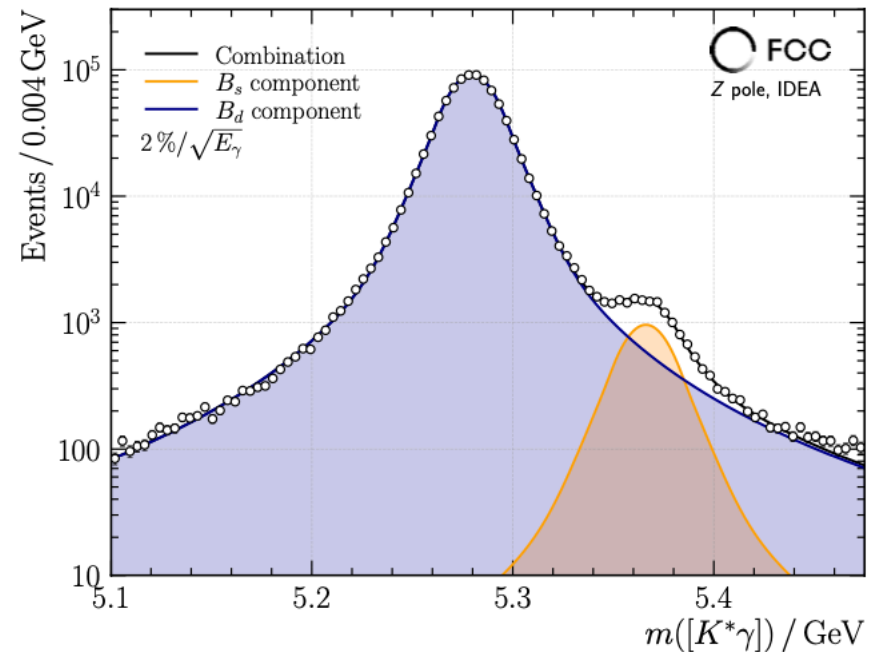
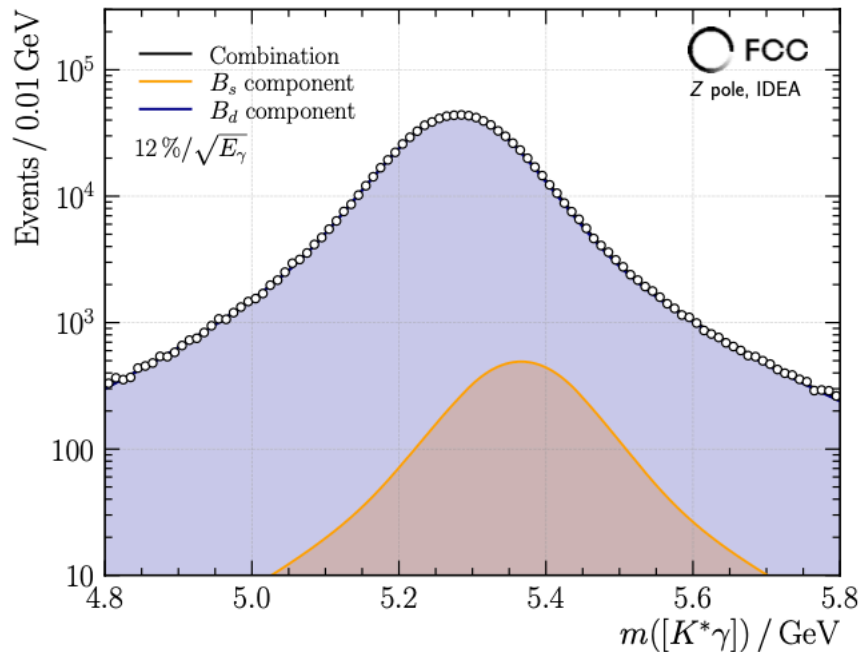
- Foster the detector requirements / connect physics benchmarks with detector design in a more automated way, *e.g.* get the first layer of VD on the beam pipe, even better, remove the beam pipe: how many more $B^0 \rightarrow K^{*0}(892)\tau^+\tau^-$?
- For Calorimetry:
 - So far, academic exercise in the FS report w/ $B_{d,s} \rightarrow K^*\gamma$
 - Much more to study w/ *e.g.* :
 - $D^{*+} \rightarrow D^0(\rightarrow \pi^0\pi^0)\pi^+$
 - $B^0 \rightarrow \pi^0\pi^0(\rightarrow e^+e^-\gamma)$ for the CKM α measurement
 - $b \rightarrow se^+e^-$

5) Summary

- Flavours at FCCee can be the continuation of a vibrant physics programme at the current and foreseen experiments Belle II and LHCb.
- In particular, high complementarity of the LHCb Upgrade II (invincible $b\bar{b}$ cross-sections) and FCCee programmes (neutrinos in the final state, neutral reconstructions, lightweight detectors for systematic-limited measurements in CKM) established.
- Tau physics is unique (boost) and deserves to be systematically explored with full simulations.
- The charm physics case at FCCee reaches adolescence: first solid results on rare decays. Not impossible that interesting findings in CPV can be obtained at FCCee in the modes with neutrals.
- Foster the detector requirements and connect physics benchmarks with detector design, *be it in vertexing or calorimetry* where most demanding requirements are placed.

6) Back-up: les renforts !

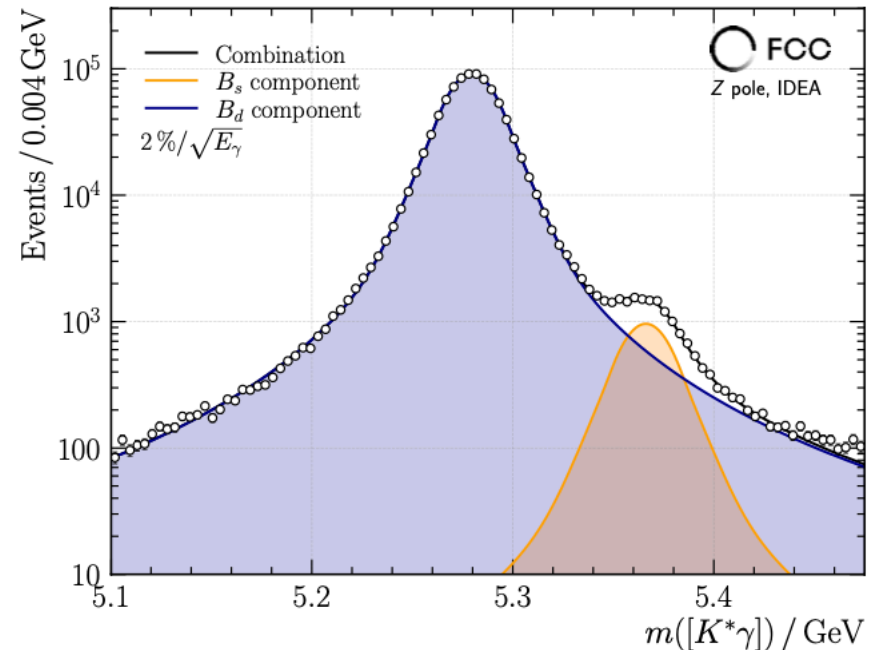
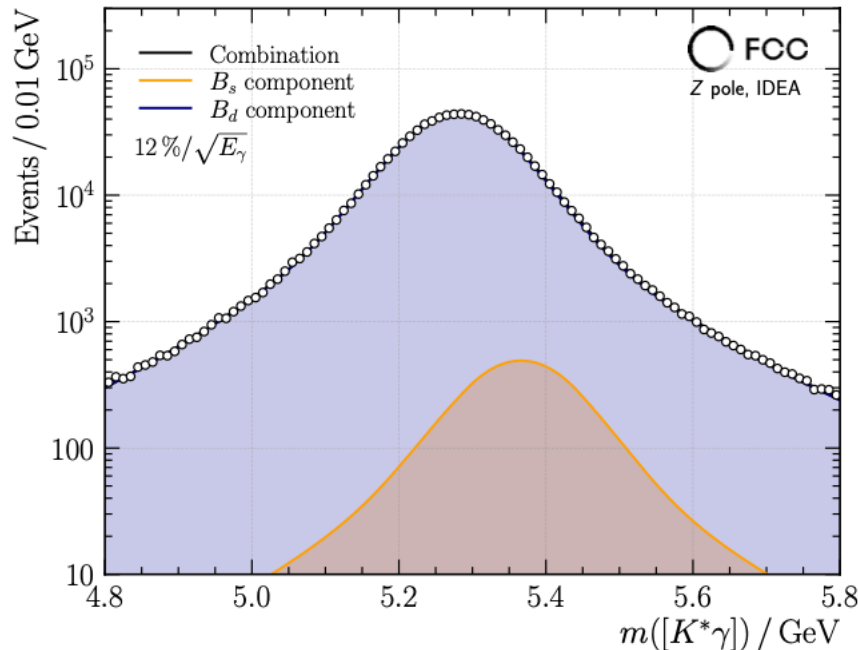
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- There's a difference! addressing or not this Physics. Target: 2%!

Flavour Physics requires in addition high energy-resolution, e.g. Radiative decays: separation of $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$. *Academic exercise w/ $B^0 \rightarrow K^*\gamma$.*

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- There's a difference! **addressing or not this Physics. Target: 2%!**