Flavour Physics in Feasibility Report and future prospects

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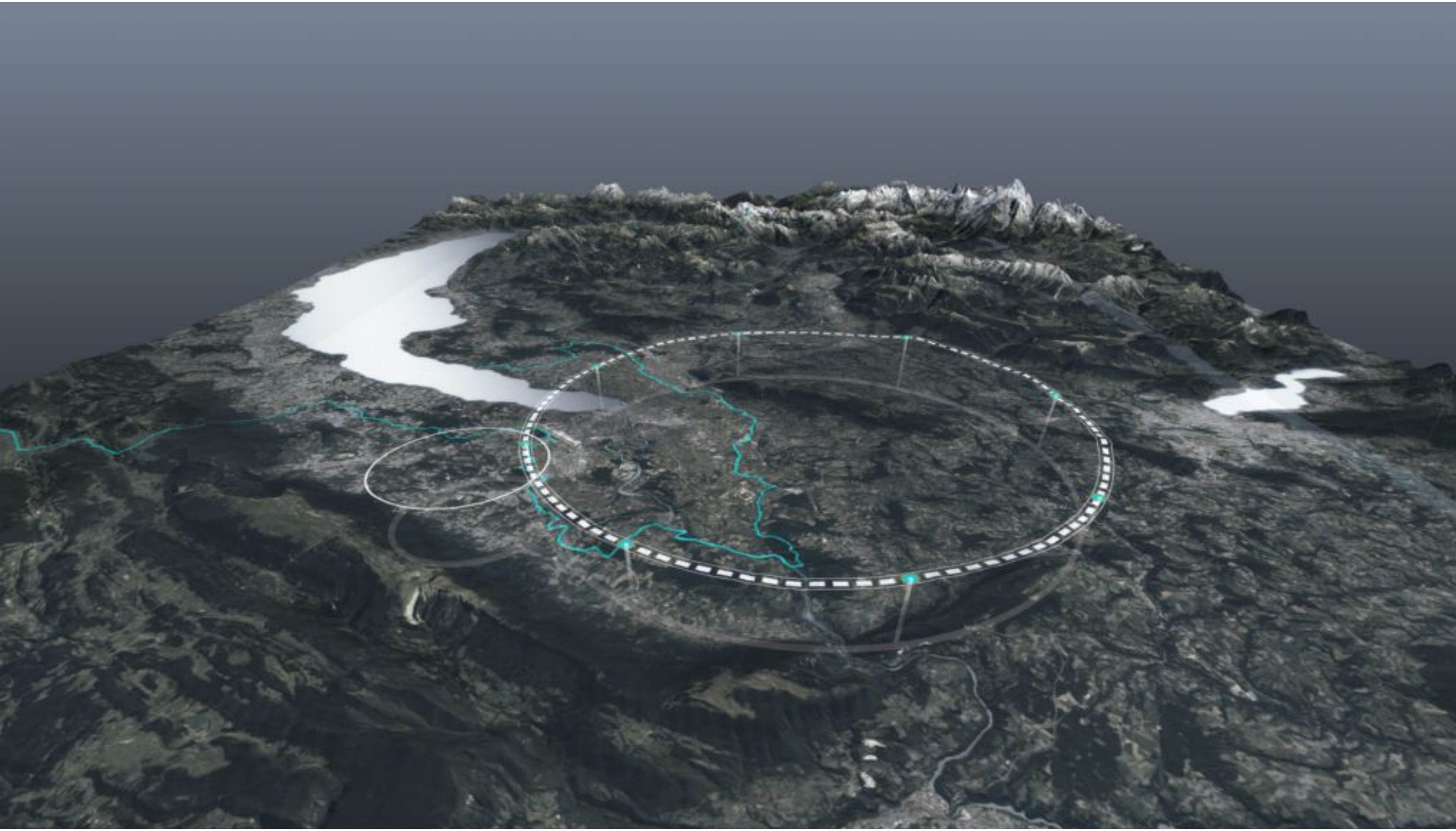
Outline

1. Setting the Scene: the FCC project
2. Setting the Scene: the case for Flavours
3. Feasibility Report achievements in Flavours
4. Some opportunities
5. Summary

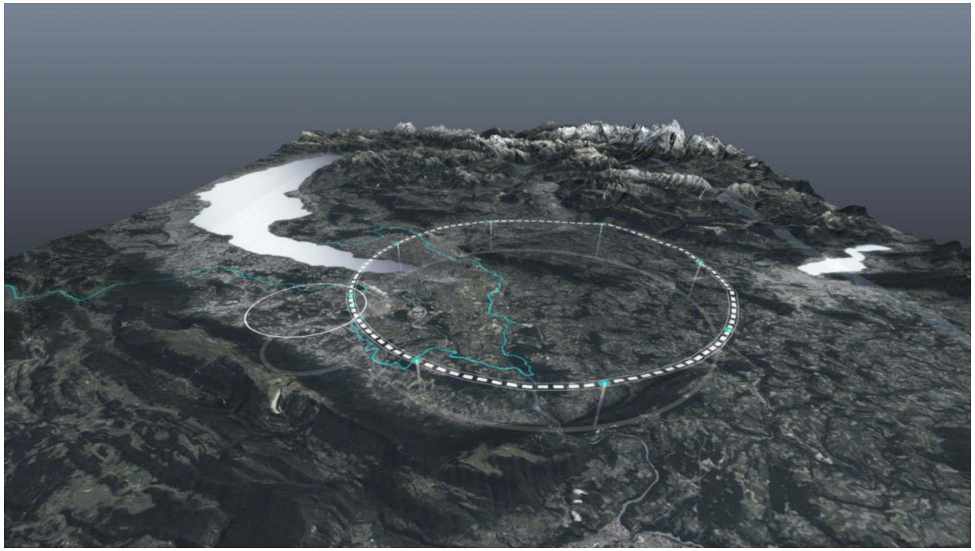
Most materials can be found in the Flavour document for ESPP: https://doi.org/10.17181/jnzpp-1fw39



1) Setting the Scene : the FCC integrated project

- A 90 km tunnel hosting first an e+e- machine in the mid-2040 crossing the four (five?) relevant electroweak thresholds: Z pole, *WW* pair production, (*H* pole), *HZ* and *top* quark pair production.

- The FCC electron machine can be followed in the 2060 decade by a hadron collider with the highest B fields magnet available at that time. Target: at least 14T, 20T desirable.



1) Setting the Scene : the FCC-ee in a glance

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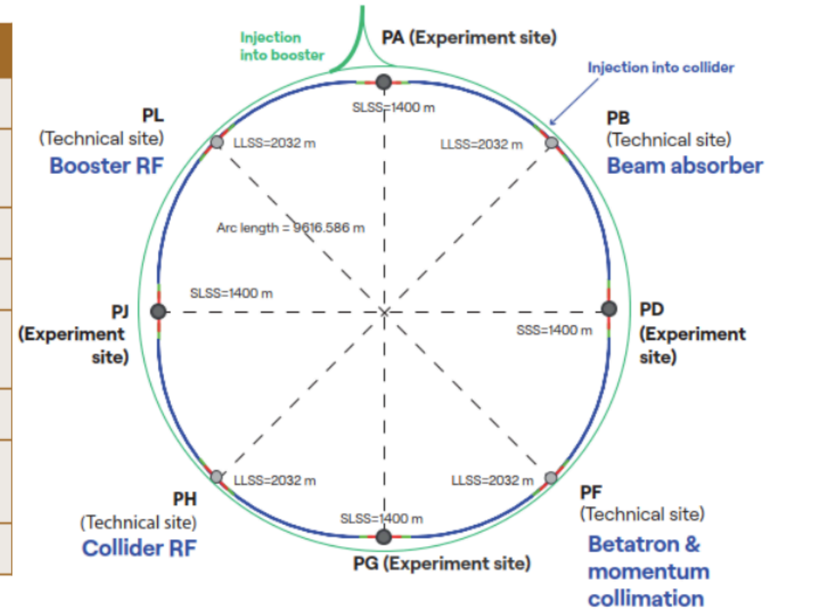
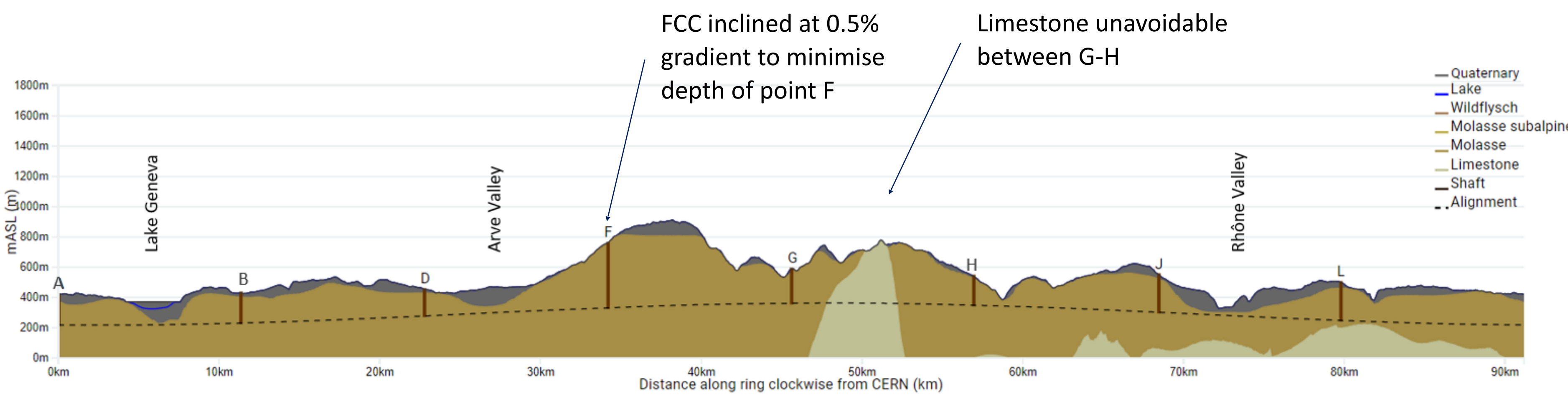
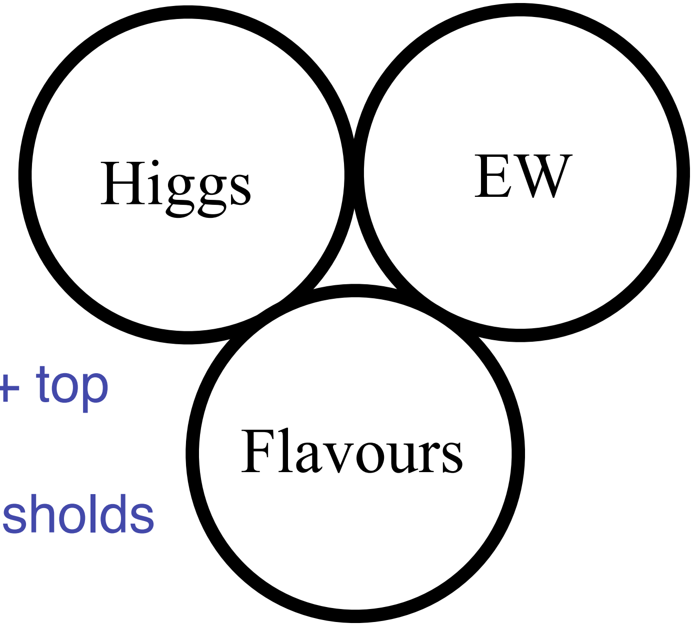
parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10



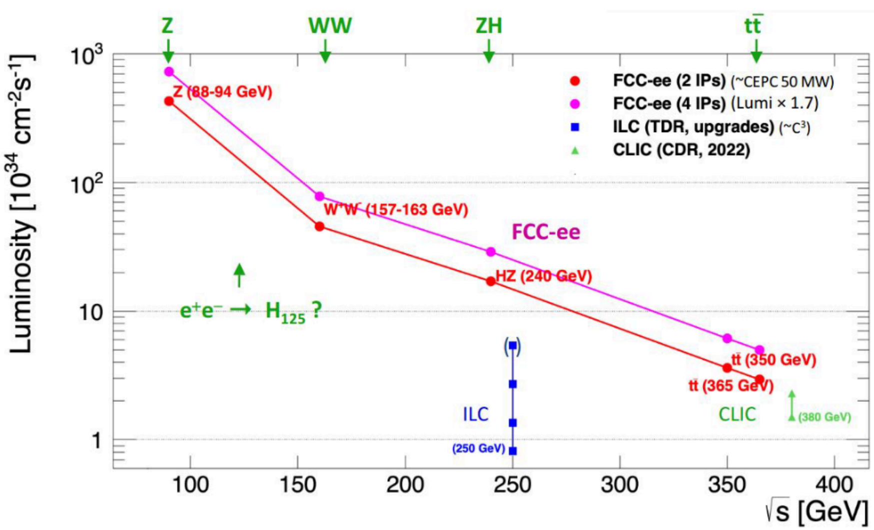


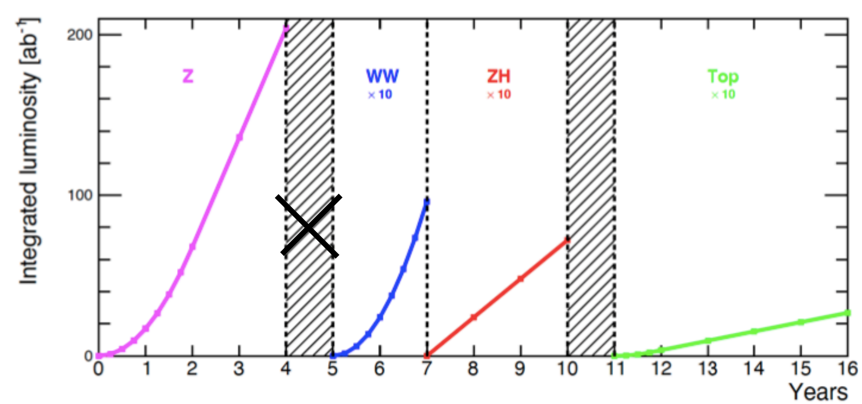
1) Setting the Scene : the FCC-ee in a glance

Three intertwined pillars:



- Higgs factory: several millions in 3 years.
- EW factory: 6 10^{12} Z , 5 10^{8} in 5 years
- Flavour factories: b, c, τ , ν (about 10^{12} each) + top
- Navigate seamlessly b/w the first 3 energy thresholds





1) Setting the Scene : EW and Higgs in 2 tables

Higgs

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

EW

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration

2) 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 ($10^{34}\,cm^{-2}s^{-1}$)	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 $\to$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\to$ 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.

2) FCC-ee ABCD specifics for Flavour Physics.

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

- 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	✓		(✓)

2) 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. 10^{12} *Z* makes a fantastic sample but more are welcome!

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	✓		(✓)

3) Achievements during the Feasibility Study

Several avenues explored with (mostly) fast simulation studies:

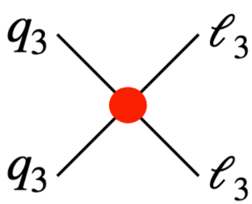
- Semileptonic decays $b \to s\tau^+\tau^-$ 1705.11106, 2505.00272
- Semileptonic decays $b \to s\nu\bar{\nu}$ 2309.11353
- Leptonic decays $B_c^+, B^+ \to \tau^+\nu_\tau$ 2105.13330, 2305.02998
- CKM *CPV* observables (γ and ϕ_s) 2402.09987, 2205.07823, 2107.02002
- CKM m.e. w/ on-shell *W* decays ($|V_{cs}|, |V_{cb}|$) *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!

3) Achievements during the Feasibility Study (Flash)

Several avenues explored with (mostly) fast simulation studies:

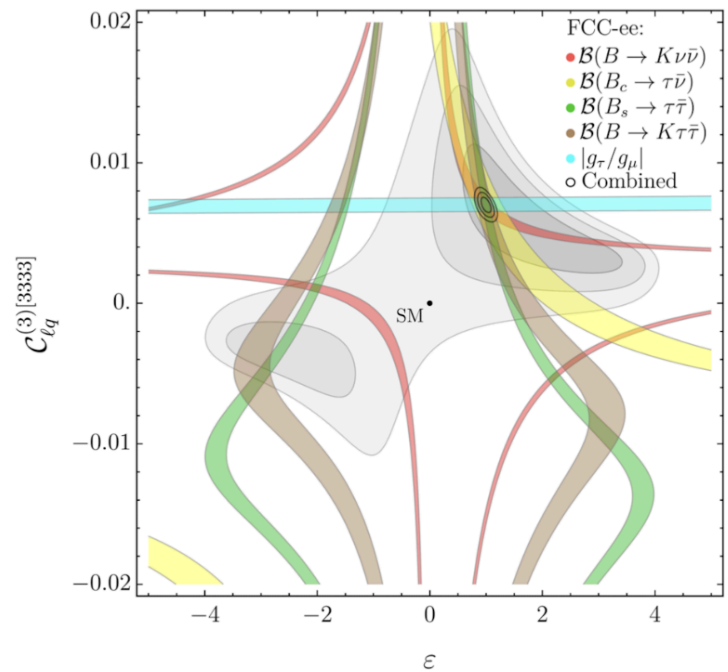
- Study of b->s transitions with tau's and neutrinos is a must do.
  Breakthrough : SM values can be measured.

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: $\epsilon \sim \mathcal{O}(1)$



Allwicher et al, 2503.17019

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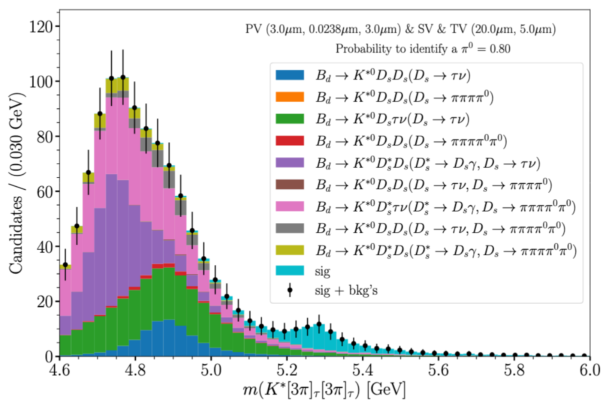
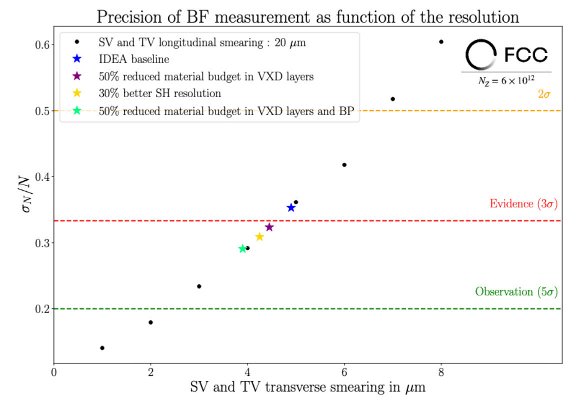


Fig. 53: Distribution of the mass of the B candidates after the full selection, assuming that the secondary and tertiary vertices can be reconstructed with a resolution of 5 μm (20 μm) in the transverse (longitudinal) direction. The normalisation corresponds to a total of 6×10^{12} produced Z bosons.



- Place Vertex and PID requirements

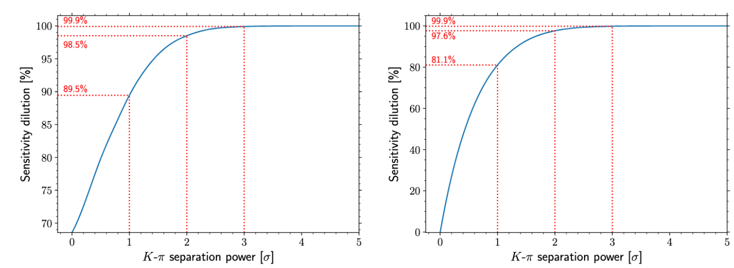


Fig. 58: Sensitivity to the $B \to K^* \nu\bar{\nu}$ (left) and $B_s \to \phi\nu\bar{\nu}$ (right) branching fractions, as a function of the π/K separation power, with respect to the sensitivity assuming perfect PID.

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.

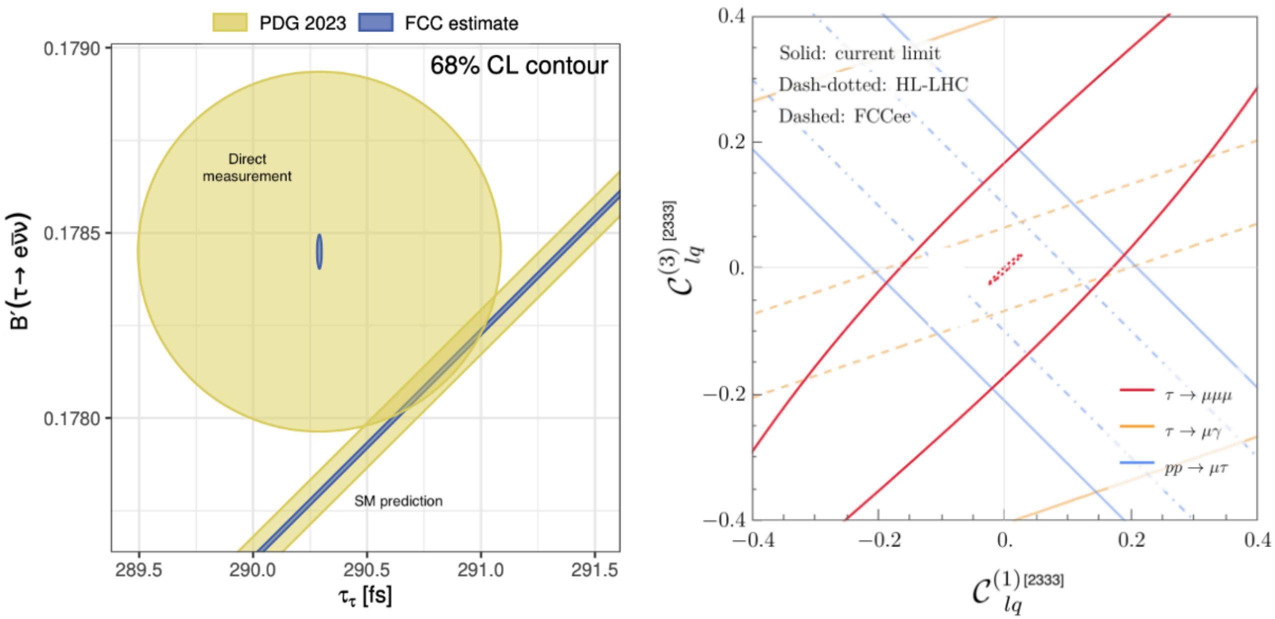


Fig. 34: Left: Direct measurements of $\mathcal{B}(\tau \to \ell\nu\bar{\nu})$ branching fraction and τ lifetime (ellipse) compared to the SM prediction (band); the width of the SM band is determined by the τ mass uncertainty. From Ref. [195]. Right: FCC-ee impact in constraining, at 95% CL, the coefficients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

3) 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.

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$\|V_{ij}\|$	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.

4) Recent activities to illustrate opportunities

- 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 recommandation of the FS mid-term review).

- Charm semileptonic decays with neutrinos in the final state

- *CP* violation in $D^0 \to \pi^0\pi^0$

- *CP* violation in charm mixing $D^{*+} \to D^0(\to K_S\pi^+\pi^-(\pi^0))\pi^+$.

- Semileptonic decays $b \to s$ with pair of electrons in the final state

- I'm flashing next preliminary results of two of those studies.

4) Recent activities to illustrate opportunities

- 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.

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Process	Reconstruction $[10^{-2}]$	Preselection $[10^{-3}]$	BDT1 $[10^{-2}]$	BDT2 $[10^{-2}]$	Overall
$Z \to c\bar{c}$	75.5	25.0	10.5	0.32	6.41×10^{-6}
$Z \to b\bar{b}$	84.2	1.7	3.0	0.75	3.24×10^{-7}
$Z \to u\bar{u}$	42.6	0.59	2.6	0.22	1.43×10^{-8}
$Z \to d\bar{d}$	44.9	0.60	2.5	0.30	2.01×10^{-8}
$Z \to s\bar{s}$	62.6	0.57	3.1	0.27	3.02×10^{-8}
$Z \to \tau^+\tau^-$	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}

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

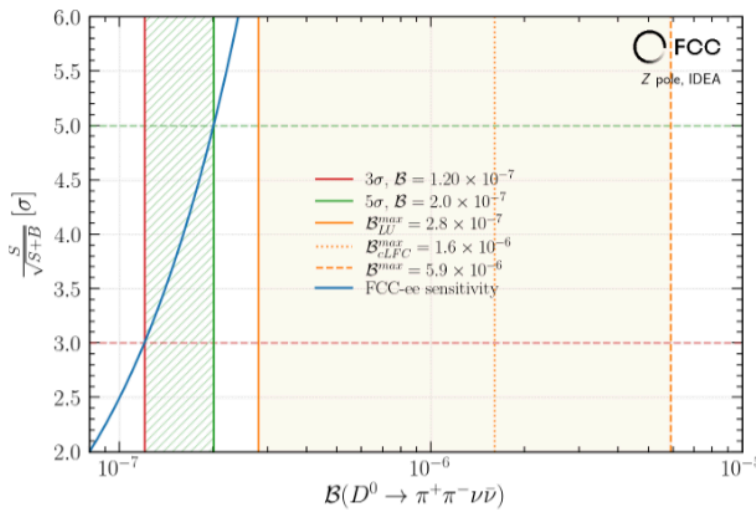

Figure 5: Sensitivity estimate as a function of the branching fraction of $D^0 \to \pi^+\pi^-\nu\bar{\nu}$(blue) with the 3σ (red) and 5σ (green) threshold. The expected theoretical maximum branching fraction for different flavour structure assumptions is marked with the orange bands.

4) Recent activities to illustrate opportunities

- They were not in time to feed the FS report but they should soon complement the Flavour case developed so far.

- Semileptonic decays $b \to s$ with pair of electrons in the final state : about 250 (500) kevents for $B^0 \to Ke^+e^-$ ($B^0 \to K^*(892)e^+e^-$). No background seen in 10^7 inclusive events.

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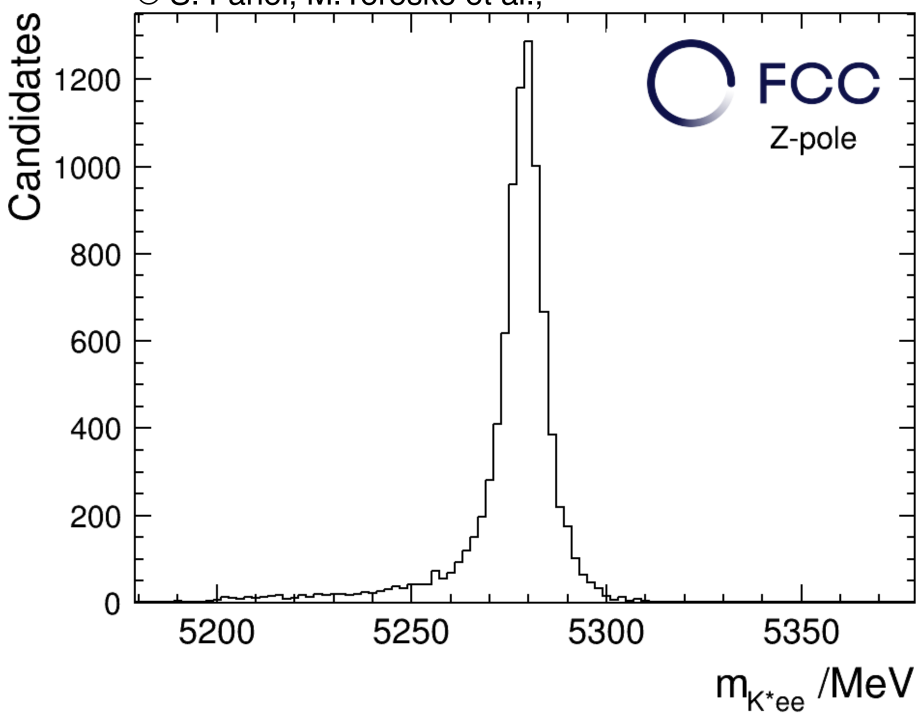
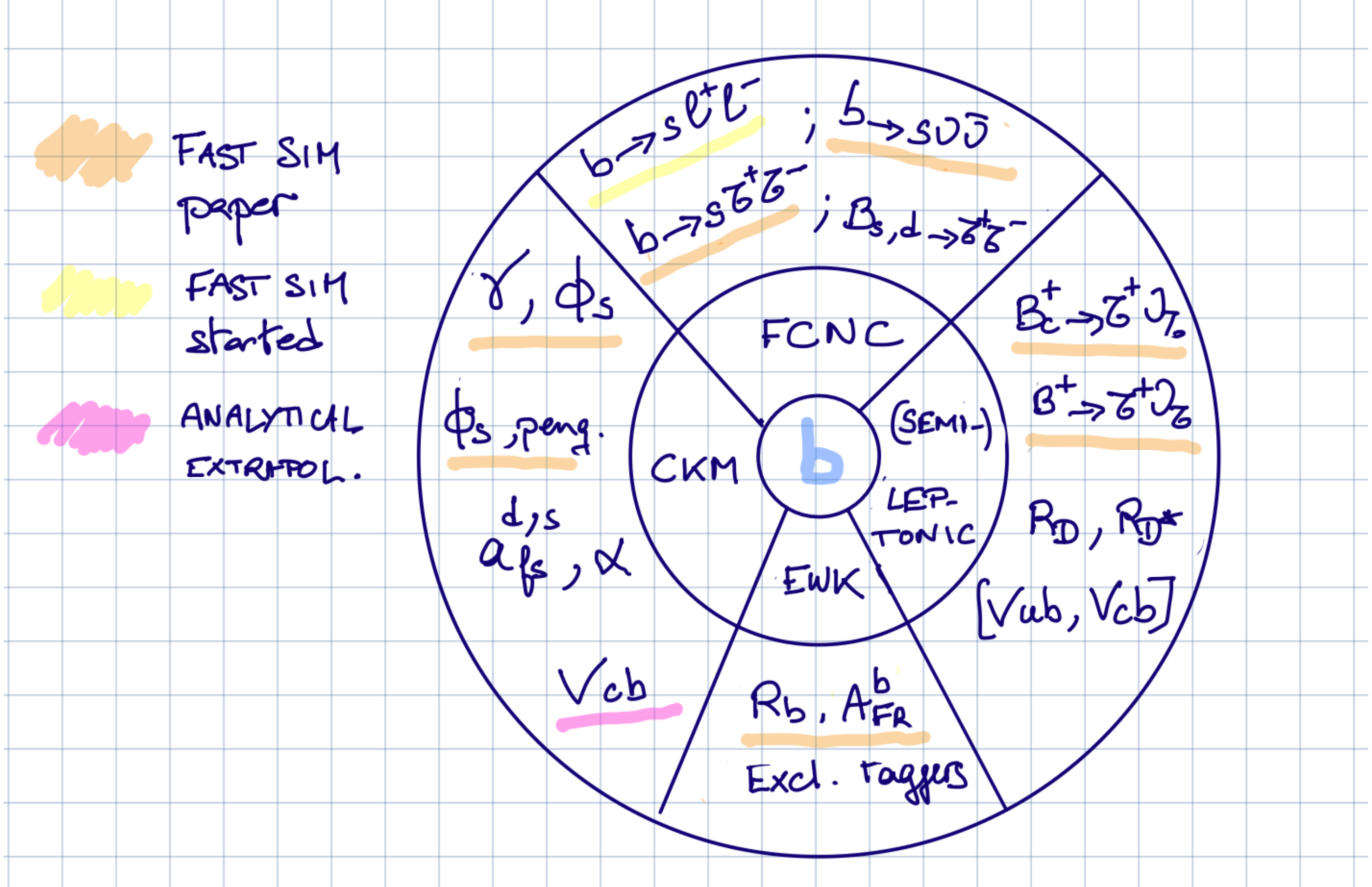


4) Opportunities

- 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) Selected opportunities

- 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:

  - Close unexplored rare *b* modes, *e.g* $B_s^0 \to \tau^+\tau^-$
  - Complete the charm studies
  - Complete the tau studies (BF, LFV,…)
  - Open spectroscopy studies

- Refine the detector requirements :

  - Complete designs of tracking systems do exist
  - Particle identification systems are yet to be established
  - Electromagnetic calorimeters (see Ianina’s talk) are still to be designed for meeting Higgs and Flavour physics requirements.

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 bbar 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.