Flavour Physics opportunities and detector challenges at FCC-ee

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

w/ A. Lusiani (Flavour perf.), J. Kamenik and
G. Isidori (Flavour prog.)

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Outline

- Flavours@FCC-ee: setting the scene.
- Overview of selected studies performed so far
  - Rare decays.
  - CKM profile.
  - Tau Physics.
  - Connecting dots.
- Outlook.

1) FCC-ee specifics for Flavour Physics.

FCC

A- Particle production at the Z pole:

- About 15 times the Belle II anticipated statistics for B^0 and B^+.
- All species of b-hadrons are produced.
- Expect ~4.10⁹ B_c-mesons assuming $f_{B_c}/(f_{B_u} + f_{B_d}) \sim 3.7 \cdot 10^{-3}$

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 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	300	300	80	80	600	150

1) FCC-ee specifics for Flavour Physics.

B- The Boost at the *Z*:

$$\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$$

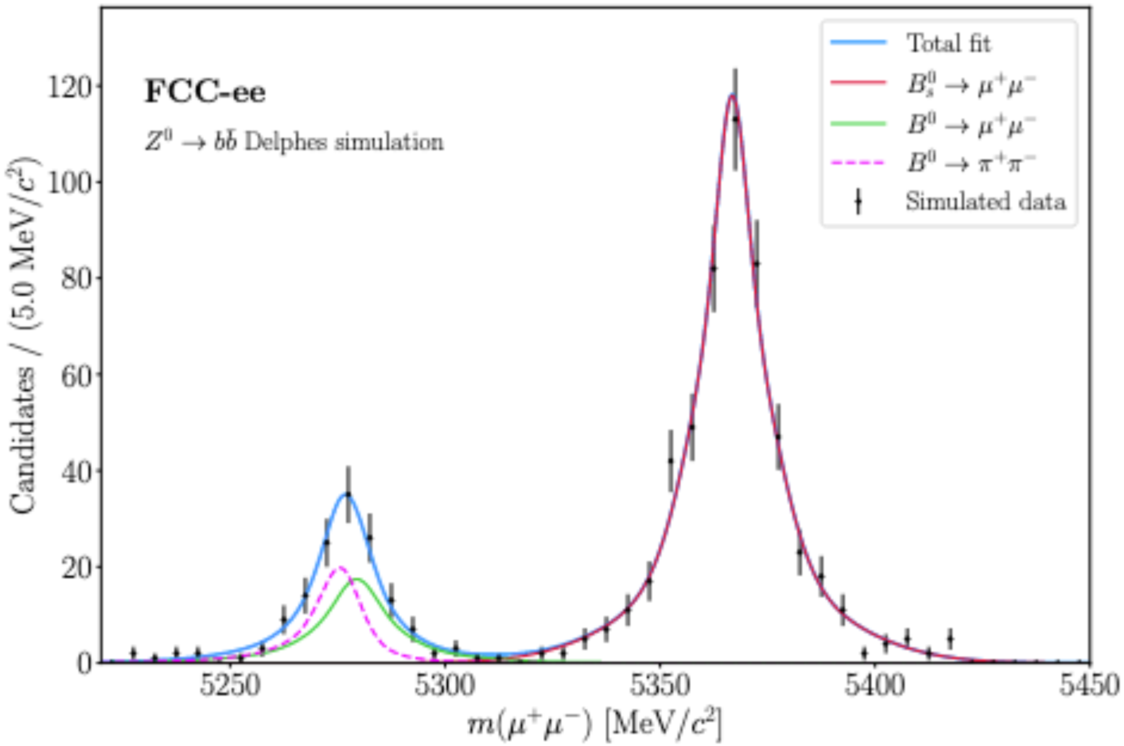
- Fragmentation of the *b*-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

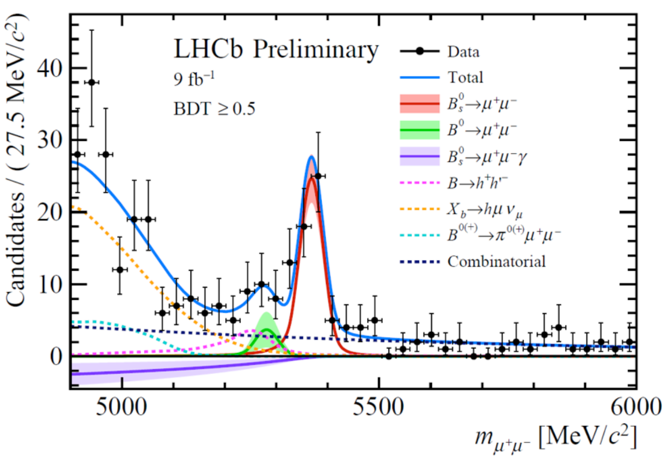
C- Comparison w/ LHCb and Belle II. Advantageous attributes:

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

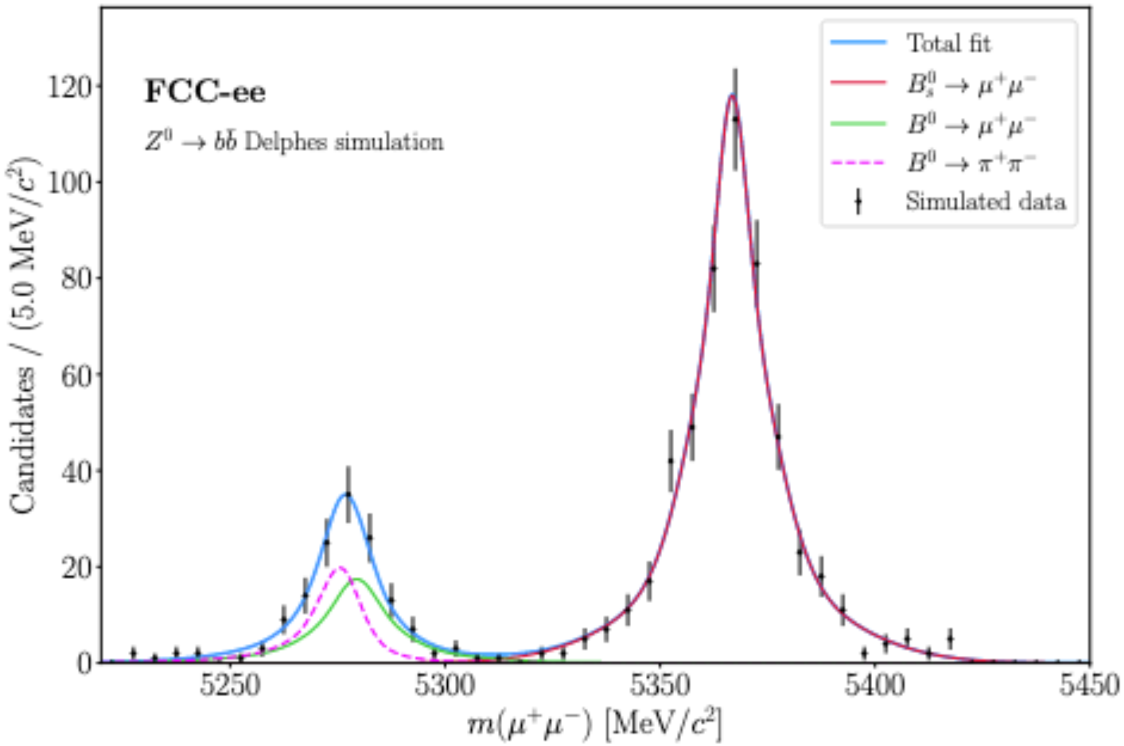
D- Versatility : the *Z* pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the *WW* operation will enable to collect several 10^8 *W* decays on-shell AND boosted.

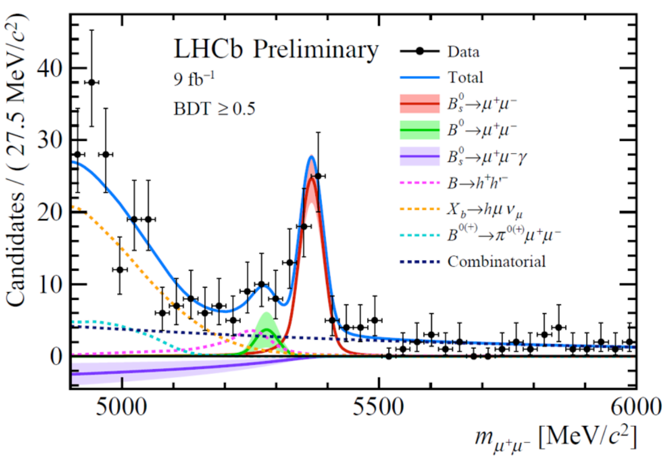
1) FCC-ee specifics for Flavour Physics.





E- Detector performance: exquisite tracking is necessary and at reach.
Invariant-mass resolution as it is in the current state of IDEA fast simulation:





Ultra-high resolution calorimetry and vertexing are in addition highly desirable. Performance to be determined in the Feasibility Study Phase.

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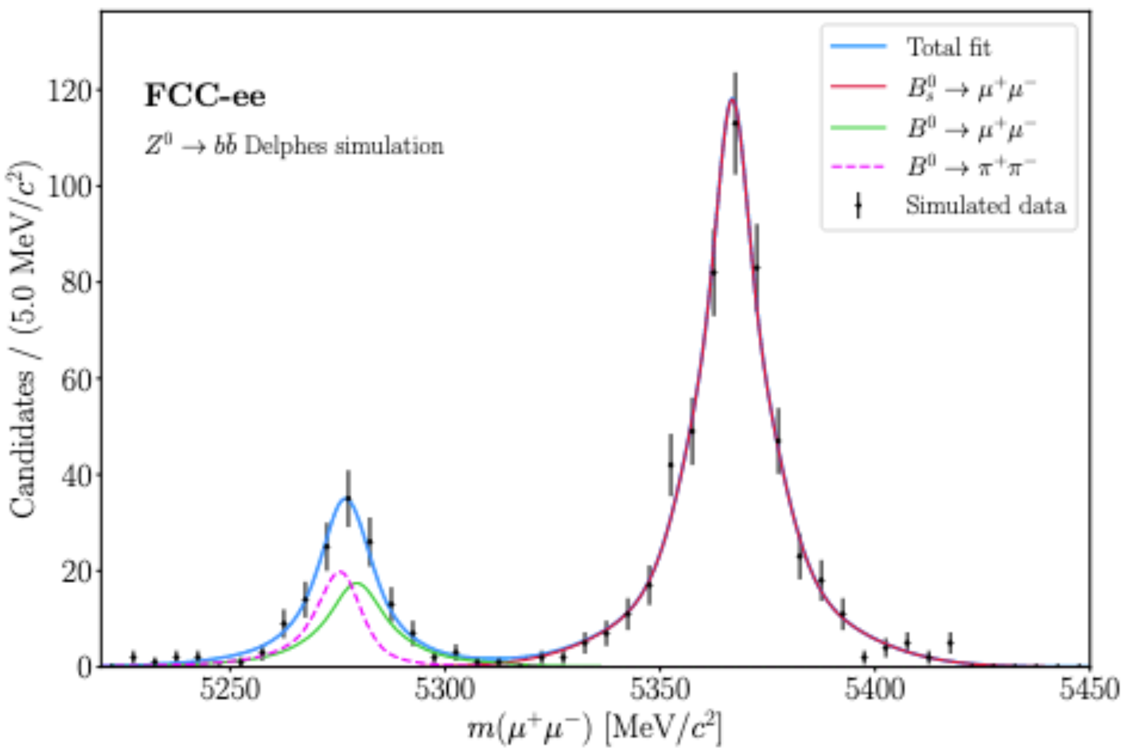

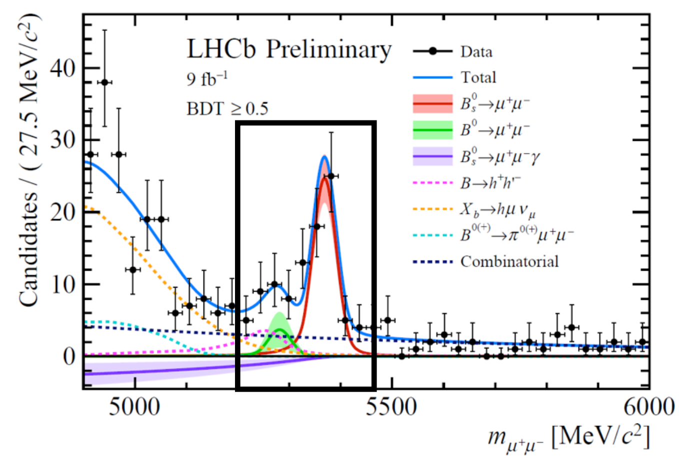

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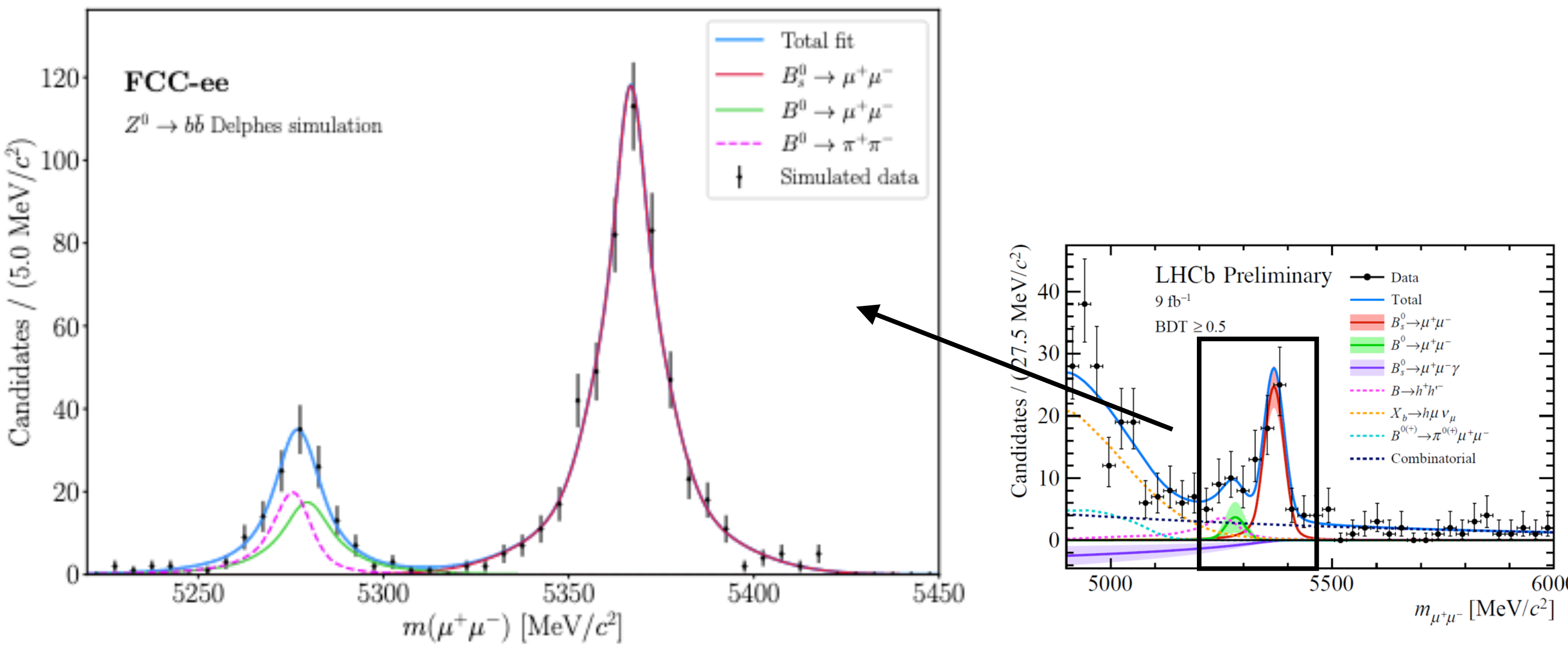
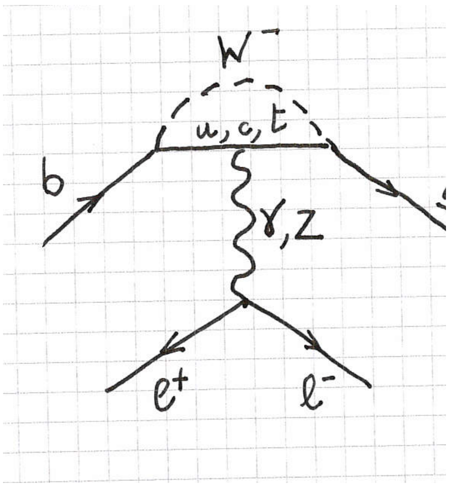
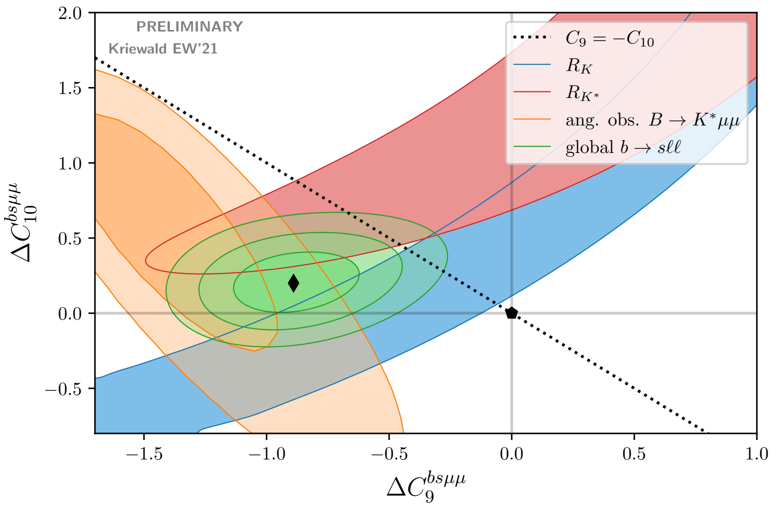
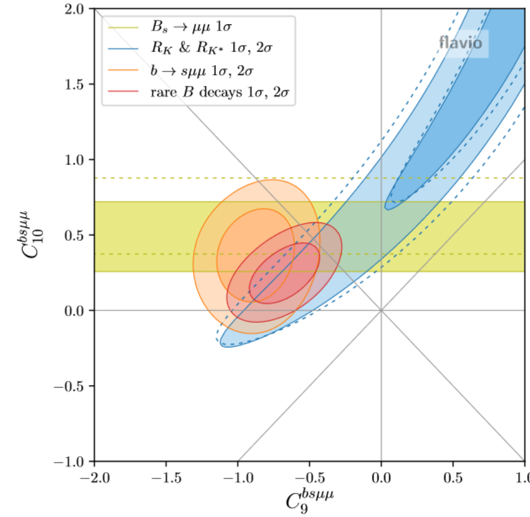


Ultra-high resolution calorimetry and vertexing are in addition highly desirable. Performance to be determined in the Feasibility Study Phase.

2) Overview of the studies: Rare decays & Friends







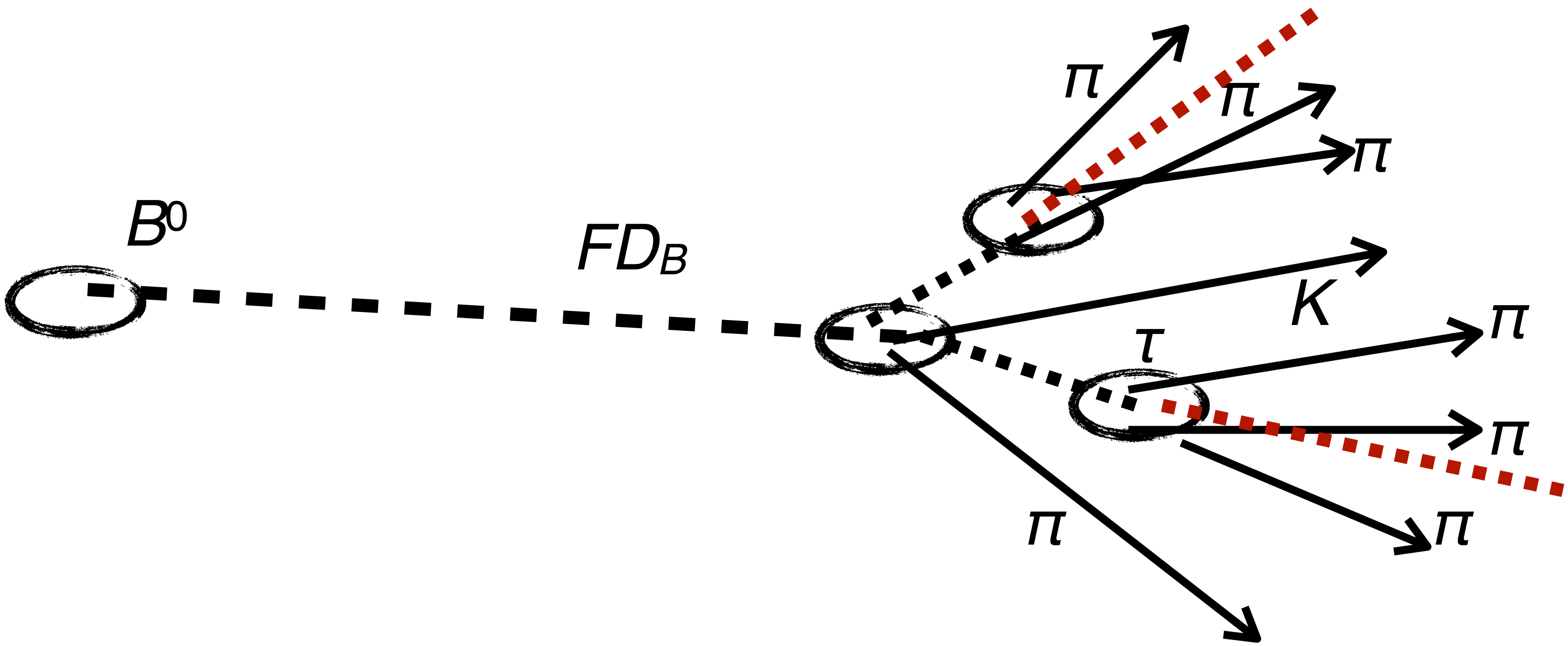
- Multiple global fits in the literature (I picked here 2012.13241 and arXiv:2103.13370, many others around). Intriguing consistent pattern pointing towards a C_9 modification.

- How to go further with indirect measurements ? Belle II and LHCb will refine these measurements. But final states with tau lepton is a promising way forward. FCC-ee unique. Two flashed here $B^0 \to K^{*0}\ \tau^+\tau^-$ and $B_c \to \tau^+\nu$. Other modes (relevant as well) are under study, e.g. $b \to s\nu\nu$.

- These transitions with third generation particles are a must to study.

2) Overview of the studies: Rare decays & Friends

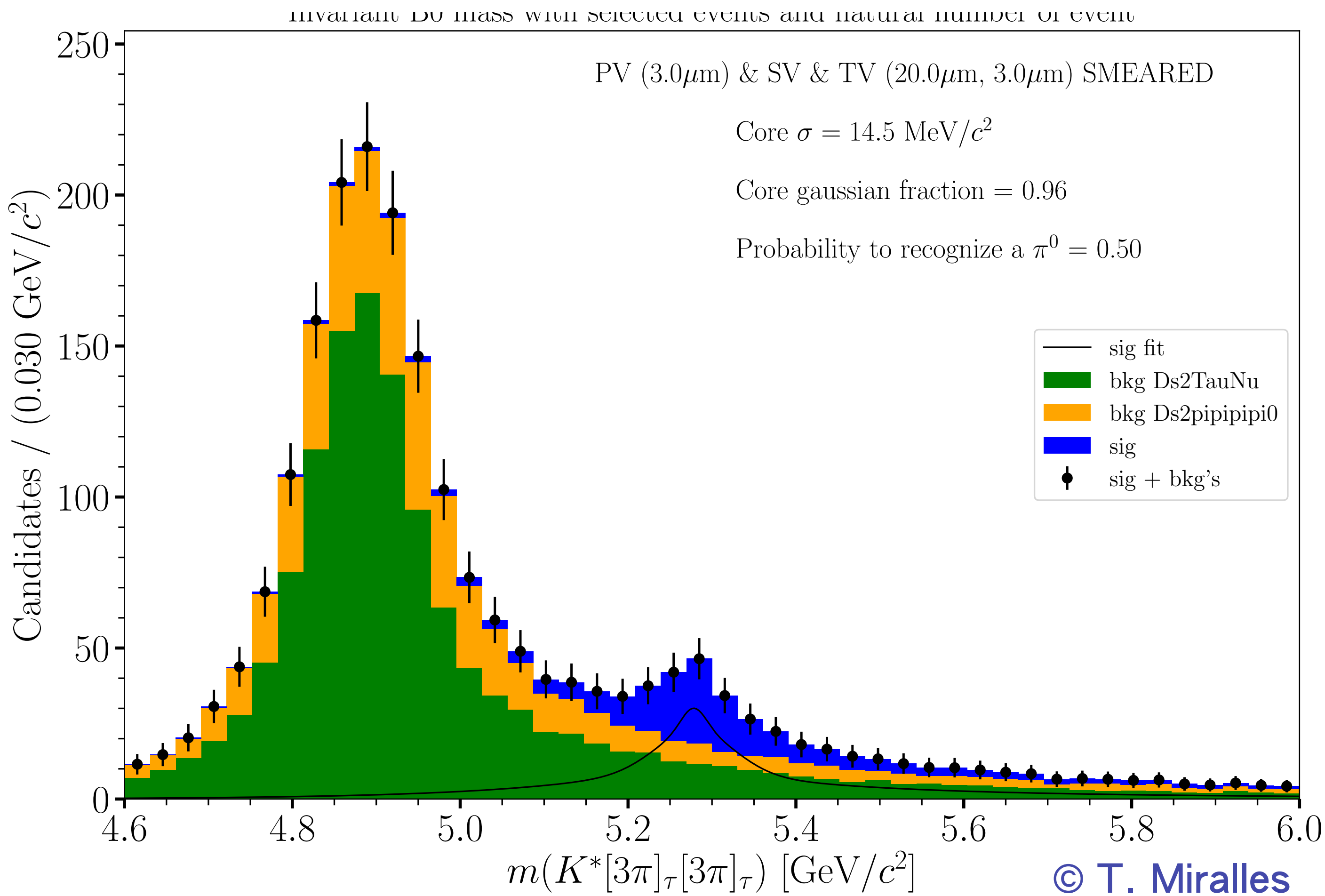
- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$.



- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - The system is in principle over-constrained.

2) Overview of the studies: Rare decays & Friends

- $B^0 \to K^{*0}\ \tau^+\tau^-$: a couple of backgrounds that an adequate vertexing can discriminate.



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2) Overview of the studies: Rare decays & Friends

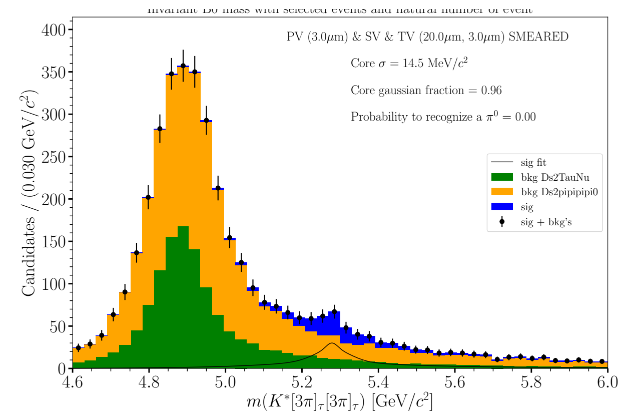
- $B^0 \to K^{*0}\ \tau^+\tau^-$: executive summary

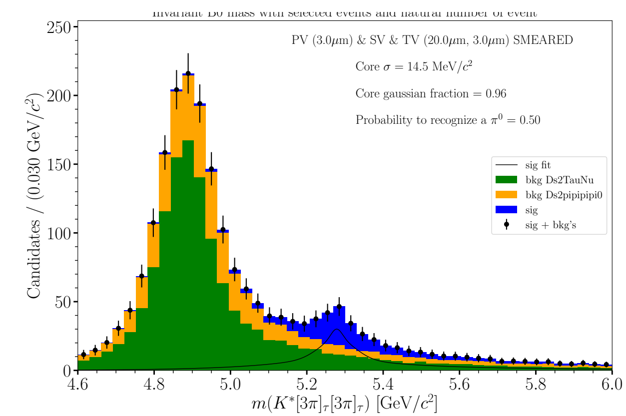
- IDEA Delphes card for *p* resolution. Vertexing performance from smearing: allows to assess the required performance.

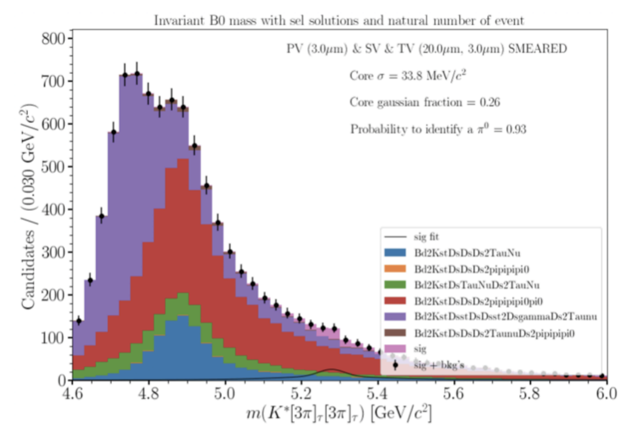
- Study w/ background has started. Initial look promising [O(200) events at SM value]. Some overwhelming backgrounds (with several pi0 discovered.

- A selection is in order.

- Outlook: attempt at a “comprehensive" bkg estimate (getting to it). Actual vertex detector geometries to be assessed as a function of the precision.

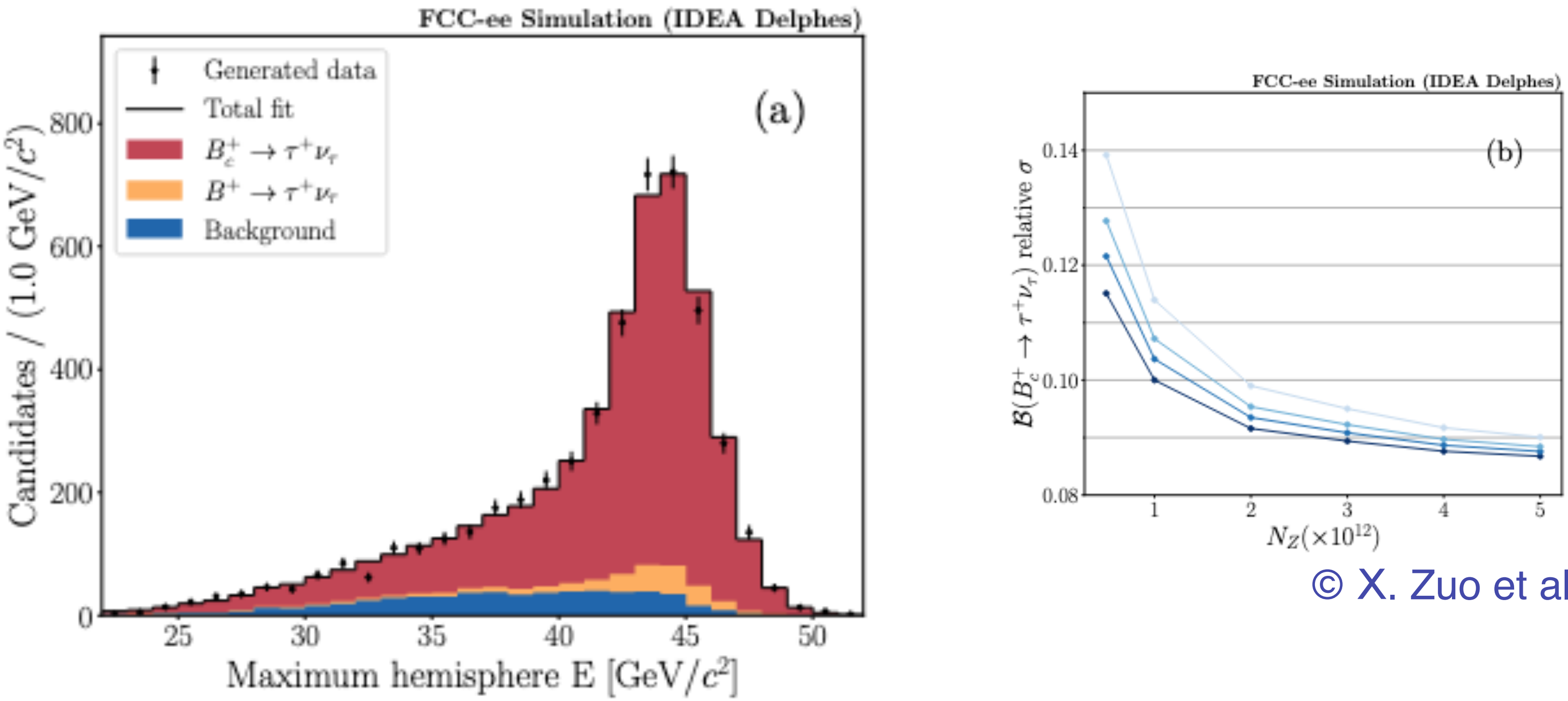






2) Overview of the studies: Rare decays & Friends

- $B_c \to \tau^+\nu$: another fundamental test of lepton universality. Counterpart of R_{D,D^*}. A promising study lies here [2105.13330, see also 2007.08234]



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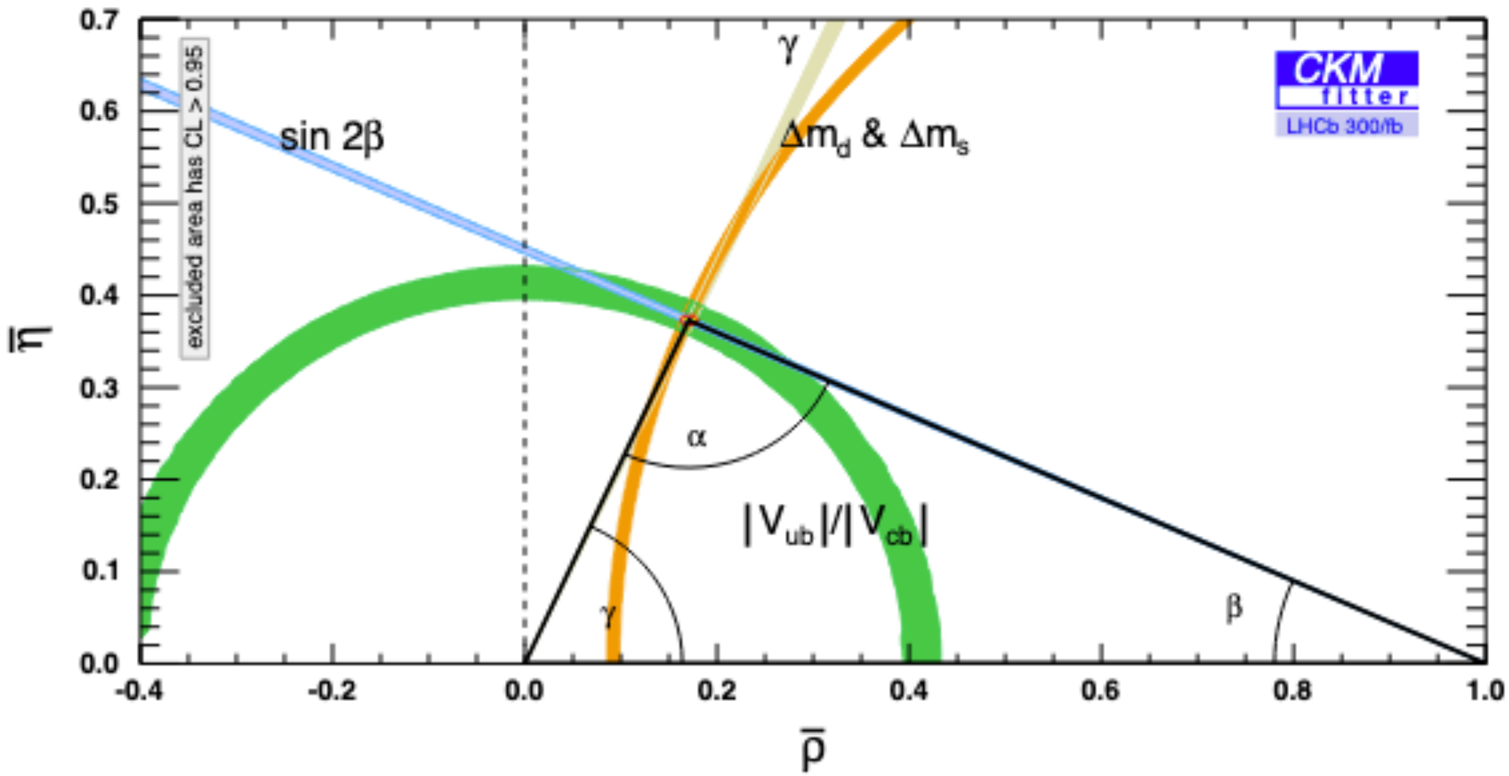
Bottomline: few percent precision mostly limited yet by the knowledge of the normalisation BF ($J/\psi\mu\nu$).

2) Overview of the studies: CKM profile & Friends

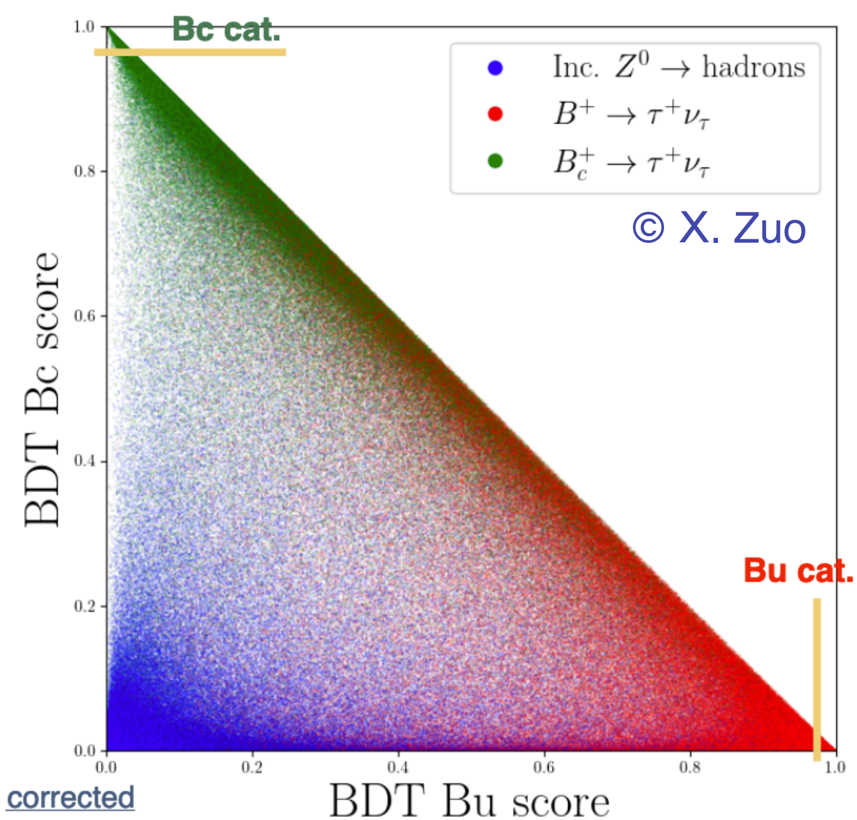
- CKM profile is at the heart of the Flavour programme. Possible status of the CKM profile in the late 2030s assuming SM is valid (Lattice-QCD expected improvements in; LHCb-biased view).



- Belle II will add up to this. The question is: can we do better ?

2) Overview of the studies: CKM profile & Friends

- *$B^+ \rightarrow \tau^+\nu$:* access $|V_{ub}|$ with the only knowledge of the decay constant. Work in progress building on [hep-ex:2105.13330].



Bottomline: similar yields / purities as for *$B_c \rightarrow \tau^+\nu$.*

2) Overview of the studies: CKM profile & Friends

- Another projection is the model-independent search for BSM CPV phases in mixing processes

hep-ph 2006.04824

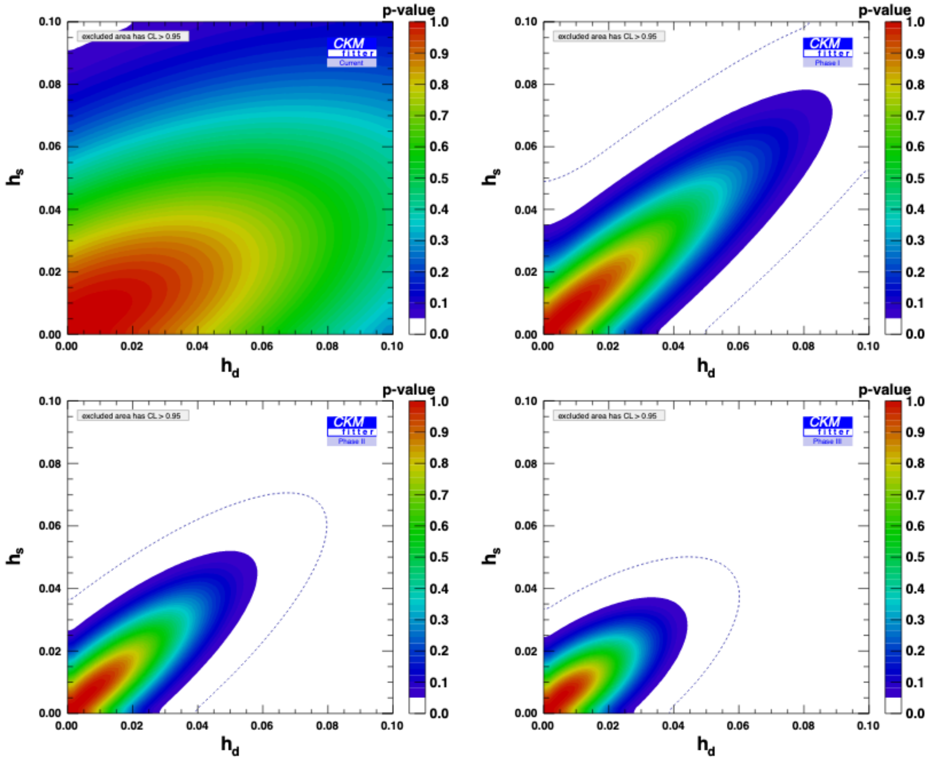


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ)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

- Bottleneck in precision: V_{cb} and Lattice-QCD mixing parameters

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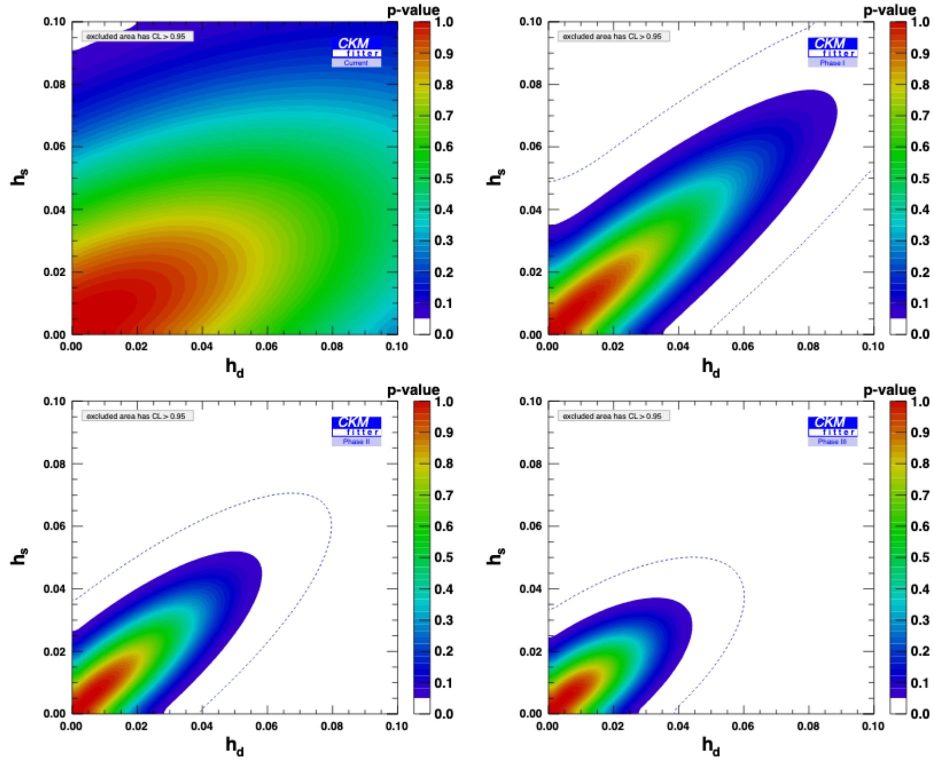
rescaled to SM — Now,



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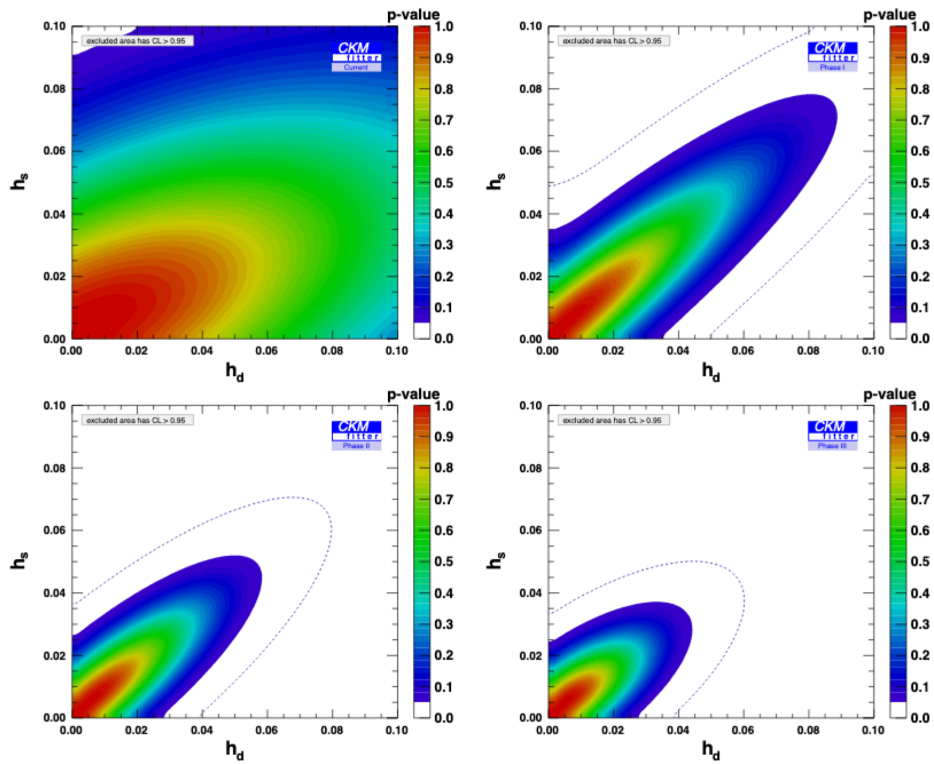

after LHCb-U1 and Belle II — 2030

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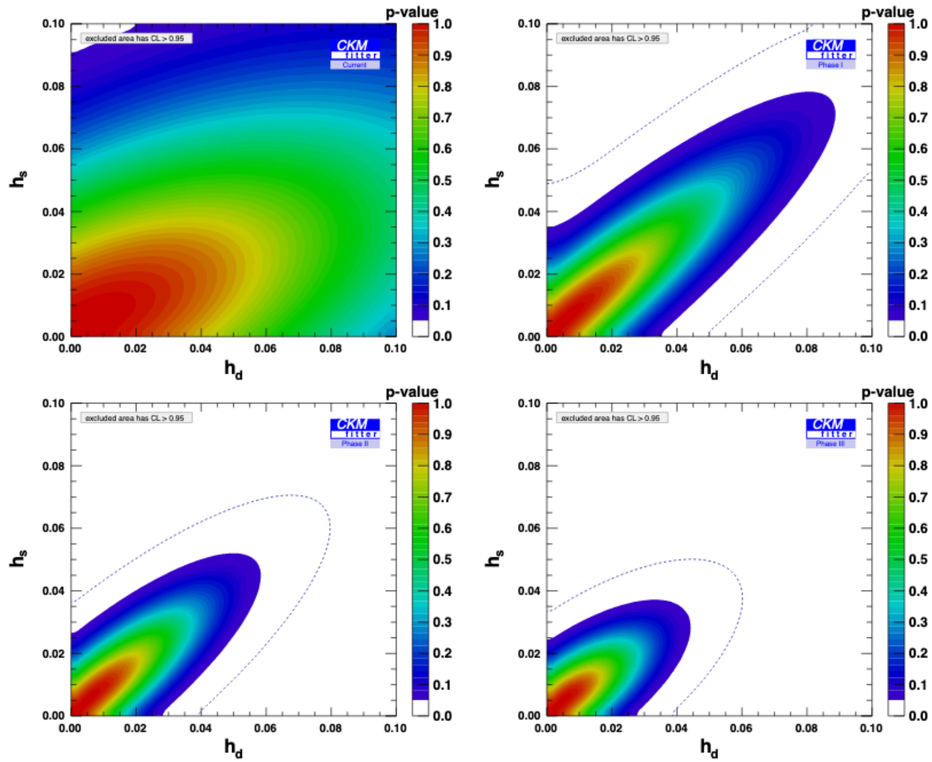

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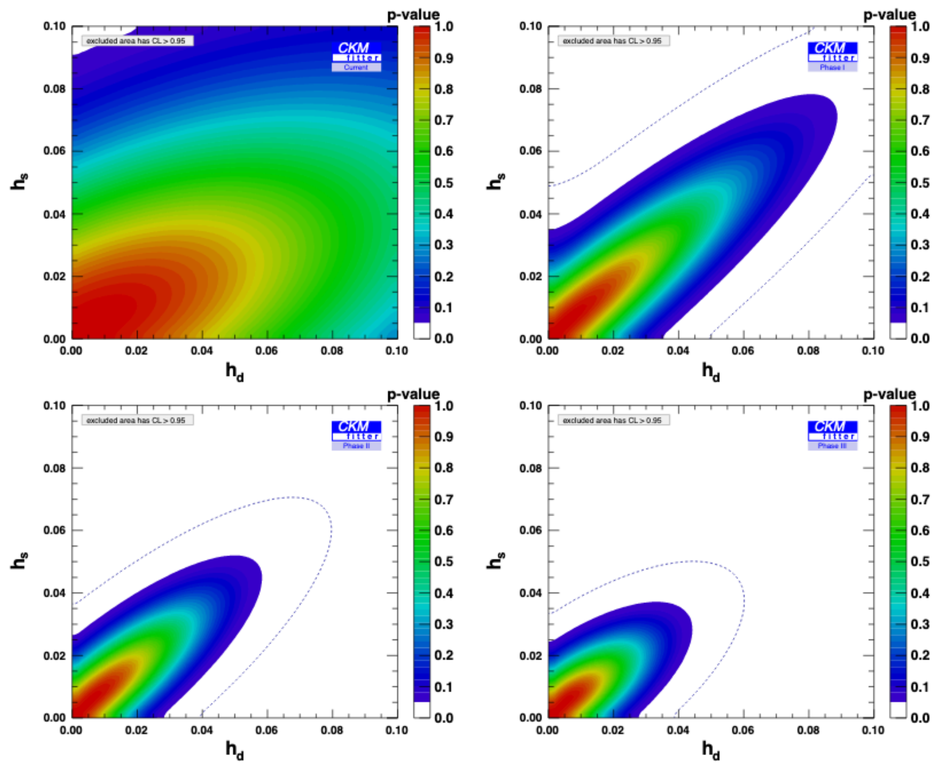
FCC-ee. Vcb in. LQCD not



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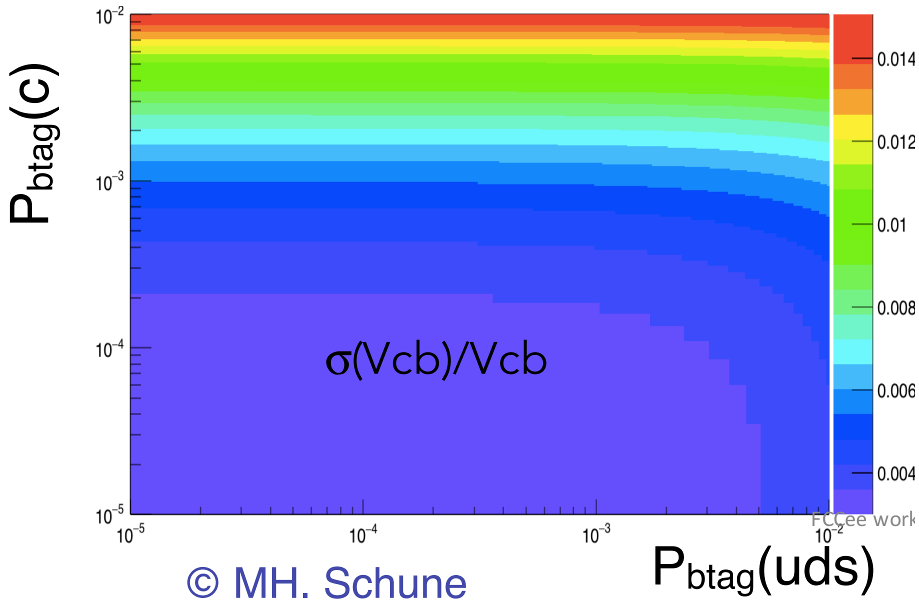
2) Overview of the studies: CKM profile & Friends

- $|V_{cb}|$ measurement: the WW threshold. First look here.

Eff. \ *q*-jet	*b*-jet	*c*-jet	*uds*-jet
b-tag	25 %		
c-tag	10 %	50 %	2 %

- Numbers picked from *Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging* — Tomohiko Tanabe. ILD@ILC. IAS Program on High Energy Physics 2017, HKUST



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- With these state-of-the-art inputs, precision on $|V_{cb}|$ improves from 1.9% (current) to 0.4%. Ultimate statistical precision is $O(10^{-4})$.
- Actual study in order. A driver for the *b*- and *c*- tagging performance.

2) Overview of the studies: CKM profile & Friends

- Sub-degree gamma angle measurement at reach :

Measurement of CP violation with $B_s \to D_s K$

$\int Ldt = 150\ ab^{-1}$

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$

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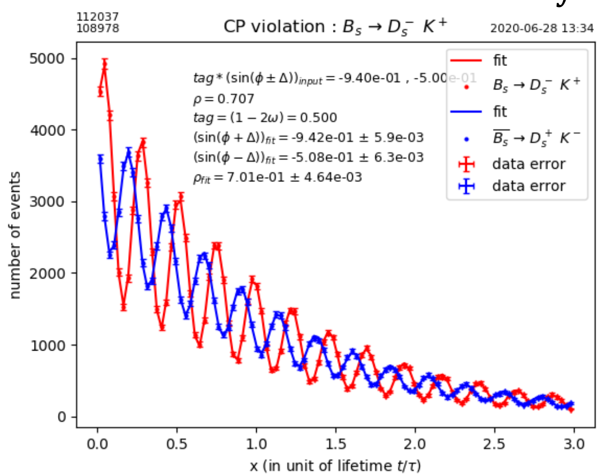
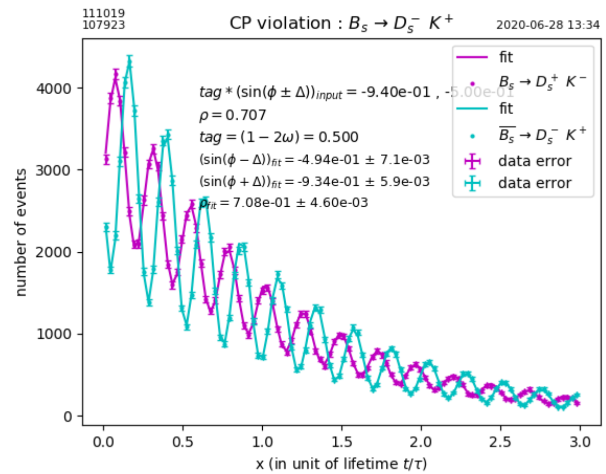




Result 3 :
$\delta(\rho) \approx 3.2 \times 10^{-3} (stat.)$
$\delta(sin^2\phi_{CKM}) \approx \delta(sin^2\gamma) \approx 5 \times 10^{-3} (stat.) \ \cong \delta(\gamma) \approx 0.4° \ (stat.)$

Potential statistical gain of factor 4-5 with $D_s^\pm \to K^{*0}K^\pm, \phi\rho^\pm$, … but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \to D_s^{*\pm}K^\mp, D_s^\pm K^{*\mp}, D_s^{*\pm}K^{*\mp}$, most modes including γ(s)

- A lot more to do with neutrals !

- Several null tests of the SM accessible w/ unprecedented precision, *e.g.* semileptonic asymmetries, ϕ_s in penguin-dominated diagrams …

2) Overview of the studies: CKM profile & Friends

- Degree alpha measurement : a study to get started.

- The alpha angle can be measured through an isospin analysis from *$B^0 \rightarrow (\pi\pi)^{+-/00}$*. The knowledge of parameter S^{00} , that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.

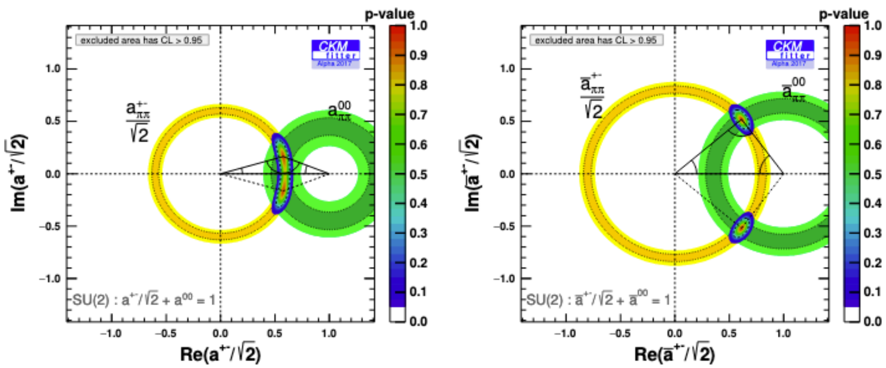


Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.*

- Accessible through Dalitz decays of the π^0 in $B^0 \rightarrow (\pi^0\pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible case study for EM calo. design.

2) Overview of the studies: others

- Many other categories to explore. To cite two of them that shall be addressed in the feasibility study.

  —) Mass and lifetime properties, spectroscopy, exotics.

  —) Charm physics.

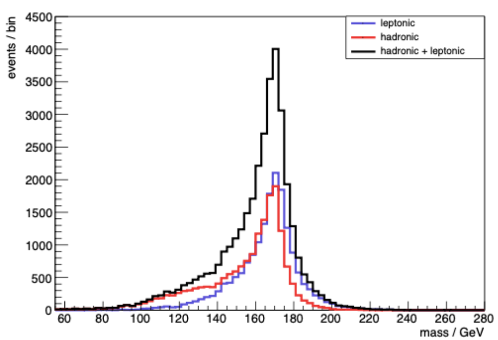
  Both categories are not touched yet to my knowledge on the experimental side but are a must-do.

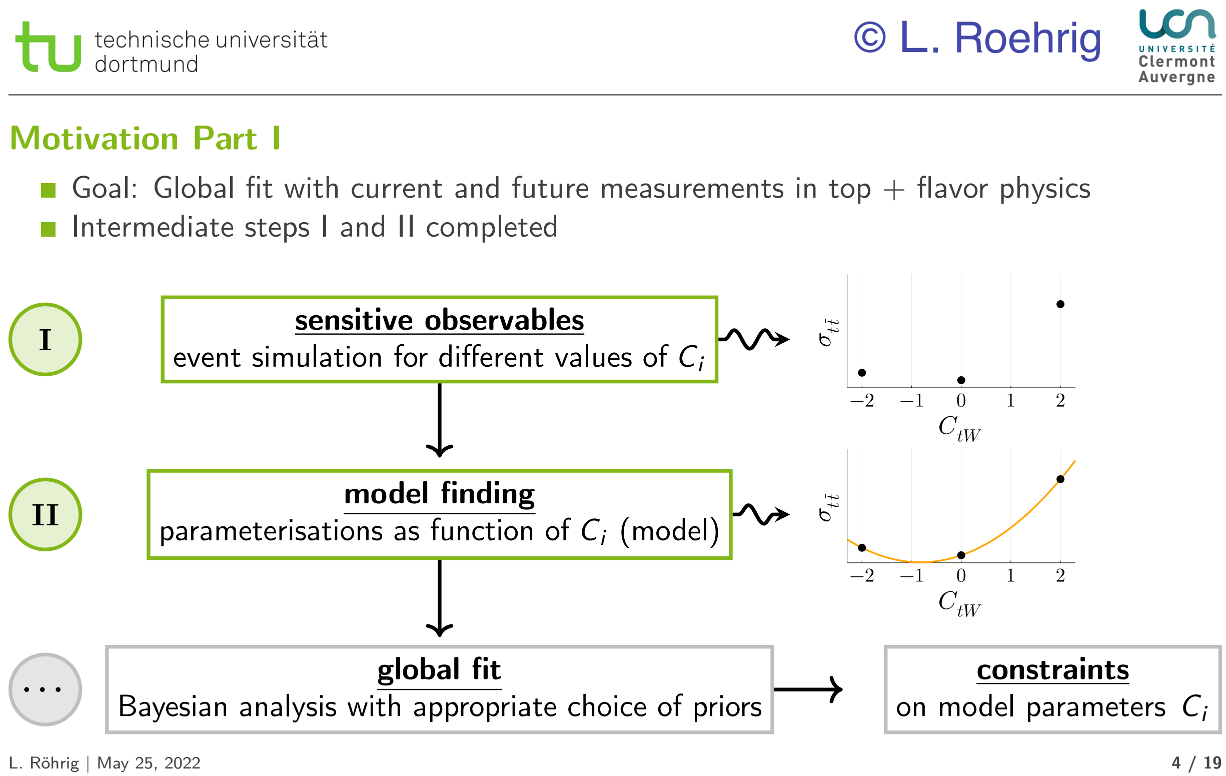
  - The invariant-mass resolutions, charged and hopefully neutrals as well, at FCC-ee for narrow states shall make marvels in spectroscopy.
  - For charm, significant phenomenological works do exist for FCC-ee. One of the last in line : https://arxiv.org/pdf/2010.02225.pdf. The exploration shall be launched.

2) Overview of the studies: connecting some dots

- Embrace top quark, *Z* pole and Flavour observables to operate a SMEFT analysis. Exercised first with top quark:

Very first look at simulated ttbar events





2) Overview of the studies: Tau lepton physics

- Touched so far through the lepton universality studies and Lepton Flavour violating decays (LFV Z and tau directly).

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04–0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
$B(\tau\to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
$B(\tau\to\mu\nu\nu)$ [%]		17.39 ± 0.05			

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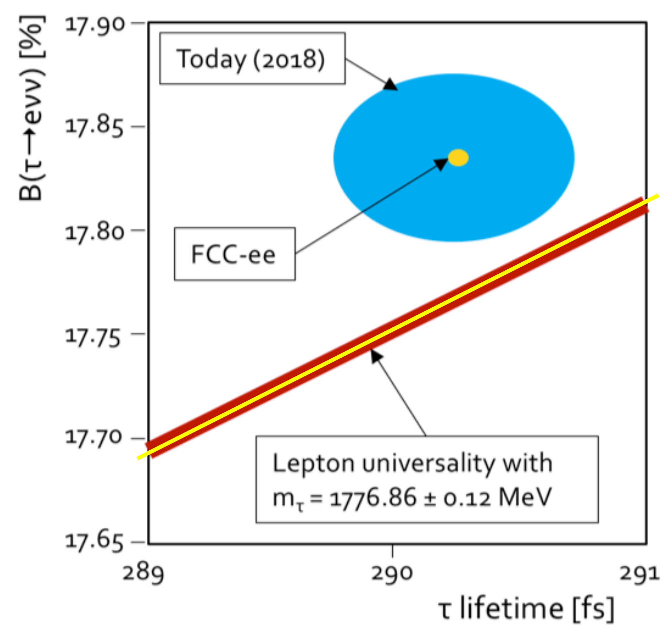
Necessary ingredients:

- Mass
- Lifetime
- Leptonic branching fractions



2) Overview of the studies: Tau lepton physics

- A non-exhaustive Tau Physics advantages and prospects :
  - About 200 billions of tau pairs at the *Z* pole.
  - About 3 times the Belle II anticipated statistics but with a 25 boost !
  - Beyond EWPO (polarisation), stringent lepton universality tests. Global improvement can be two orders of magnitude w.r.t. state of the art.
  - 2-3 orders of magnitude w.r.t. state of the art in sensitivity for LFV Z decays. 1-2 orders of magnitude for actual LFV tau decays.
  - Hadronic branching fractions, spectral functions, strong coupling constant: the QCD program with tau is rich.

3) Outlook

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. Flavour physics places most demanding requirements for vertexing and calorimetry.

- The feasibility study will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

- Four experiments can as well allow for different experiment designs, including a flavour-oriented concept.

3) Outlook

- A flavour physics working group has been set up and will get up and running before this Summer. Here to subscribe:
  - https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours
  - First meeting of the Flavour performance WG is soon to be announced.

FUTURE
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4) Back-ups

3) Outlook — Feasibility Study

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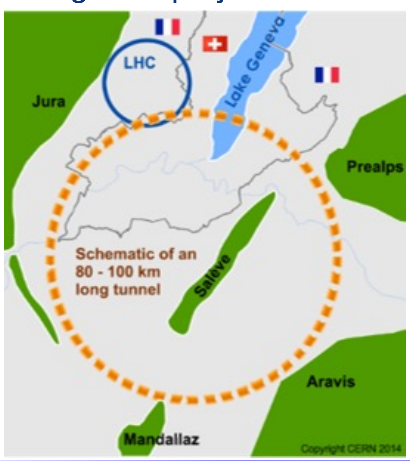
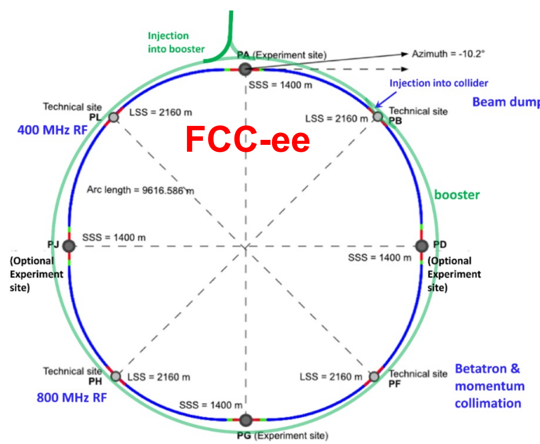
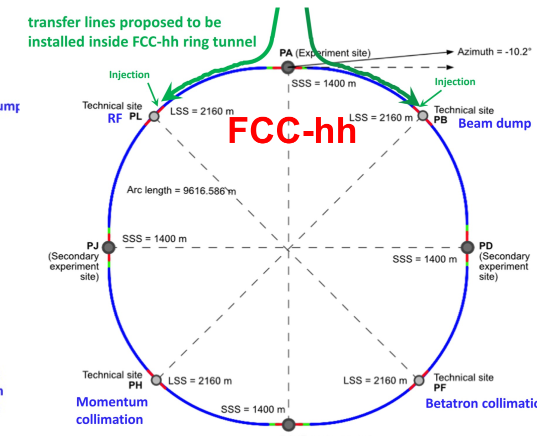
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program



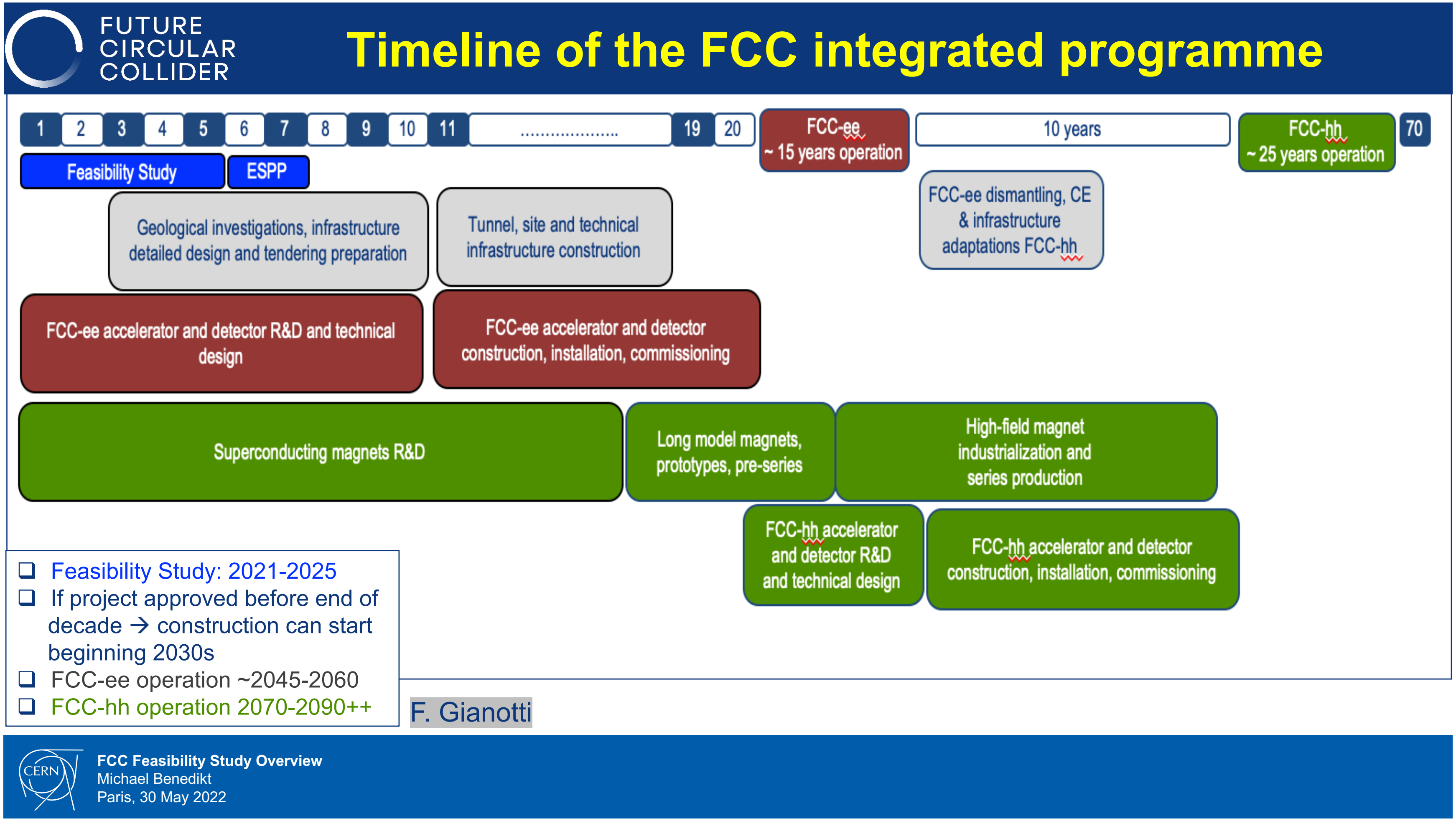




2020 - 2040 | 2045 - 2060 | 2070 - 2090++

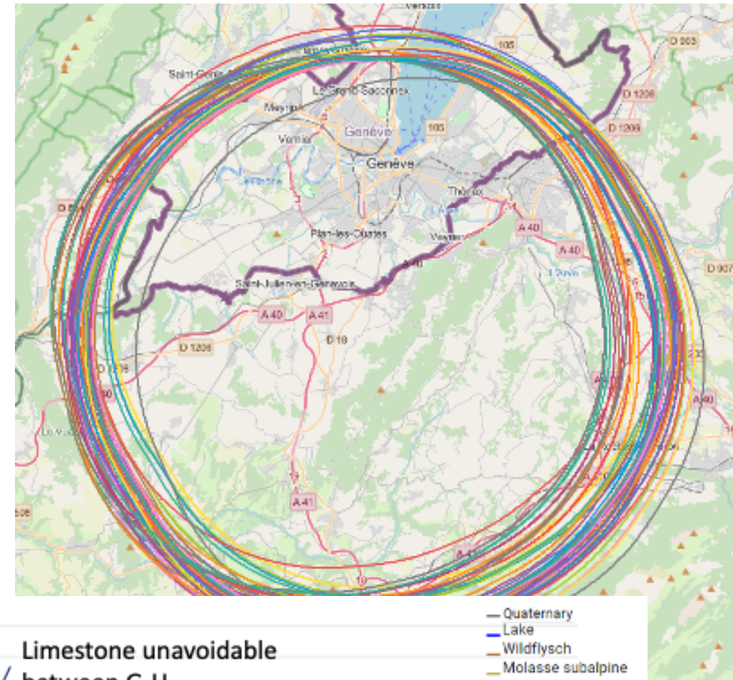
FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022

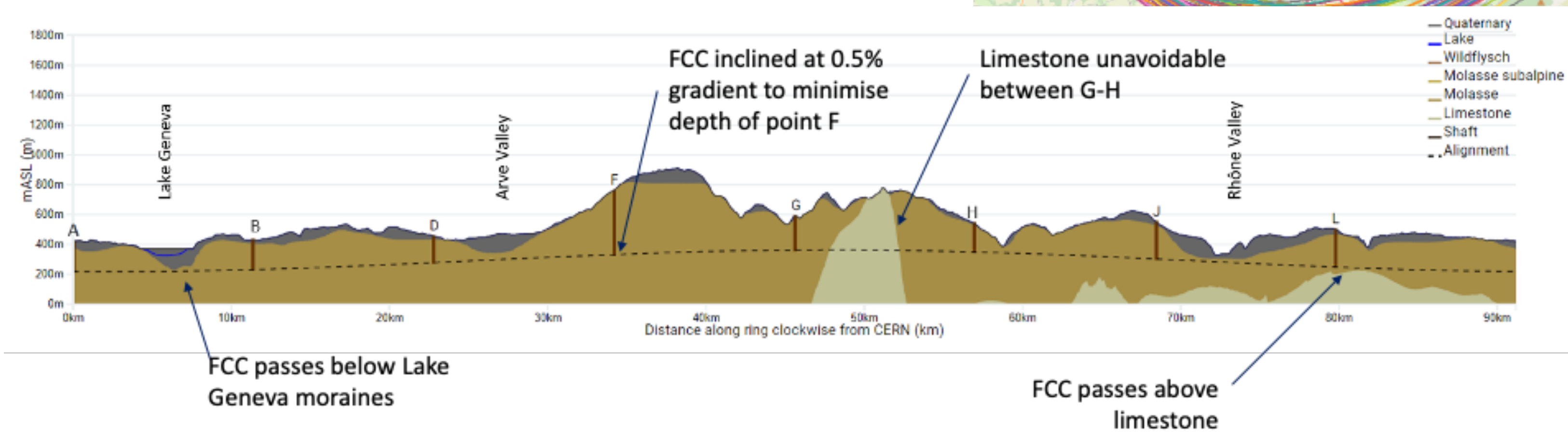
3) Outlook — Feasibility Study — Backups.



3) Outlook — Feasibility Study

- Civil engineering and infrastructures



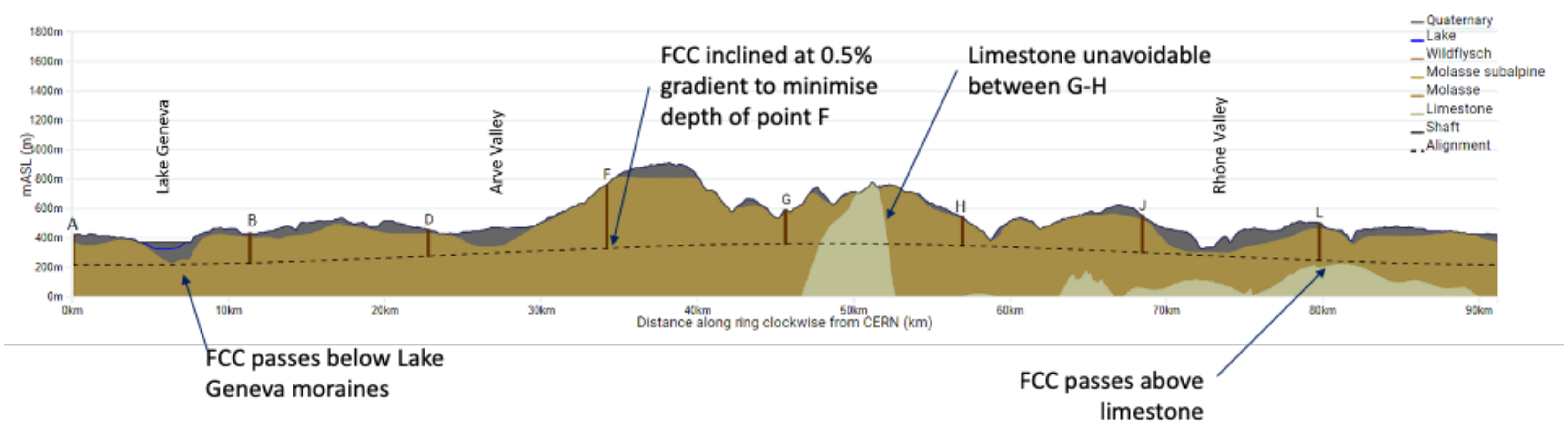


Shaft depth:

A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

3) Outlook — Feasibility Study

- Civil engineering and infrastructures



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3) Outlook — Feasibility Study

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