Perspectives for $b \to s\ell^+\ell^-$ studies at the Future Circular Colliders project (FCC-ee)

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The scientific materials are taken from the CDR references available here:
https://fcc-cdr.web.cern.ch/

Outline of the talk

- Few words to introduce the Future Circular Colliders project
- Operation at the Z pole and statistics
- Studies so far in the design study
- Other opportunities he Flavour Physics in the FCC landscape.

1. Introduction to FCC project:

- Starting from the former European HEP strategy 2013

Summary: European Strategy Update 2013
Design studies and R&D at the energy frontier

…."to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update":

d) CERN should undertake design studies for accelerator projects in a global context,

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- http://cds.cern.ch/record/1567258/files/esc-e-106.pdf

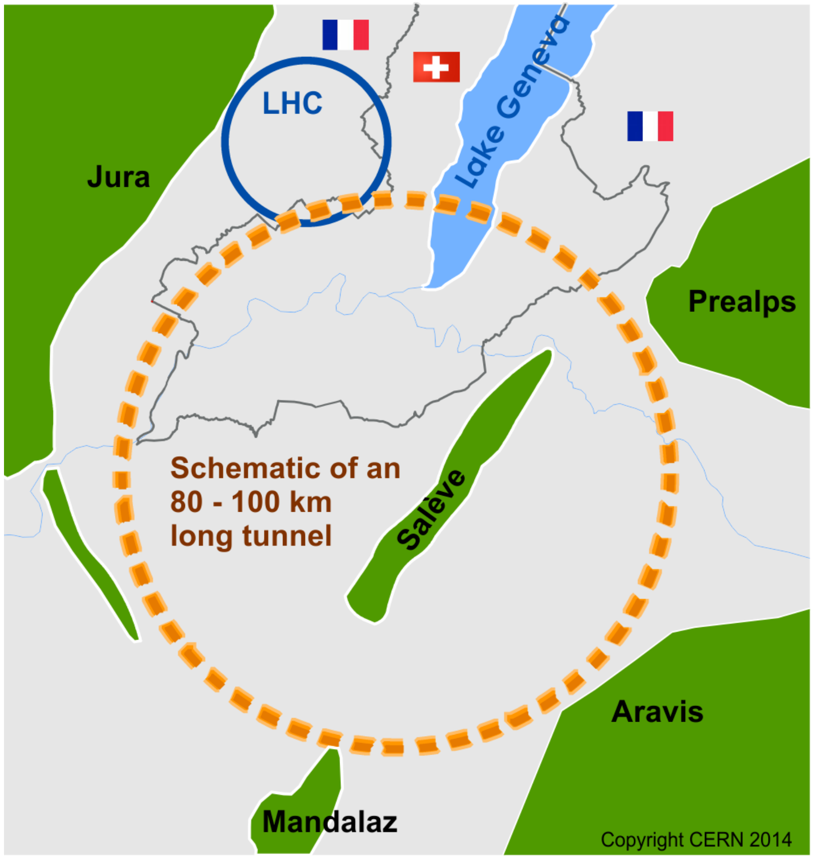
Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
3

- At the time the LHC Run II will have delivered its results, have an educated vision of the reach of future machines for the next round of the European Strategy in 2019.

1. Introduction to FCC: the scope of the project

Forming an international coll. (hosted by Cern) to study:

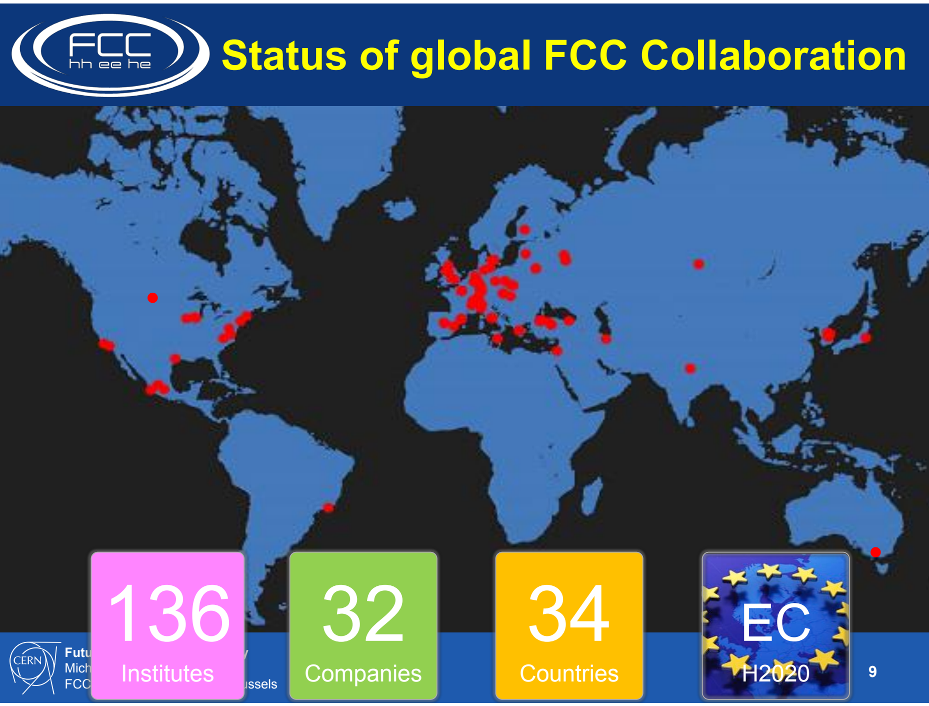
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



- Conceptual design report and cost review for the next european strategy → 2019.

1. Introduction to FCC: the scope of the project

The Design Study is completed and fulfilled the mandate



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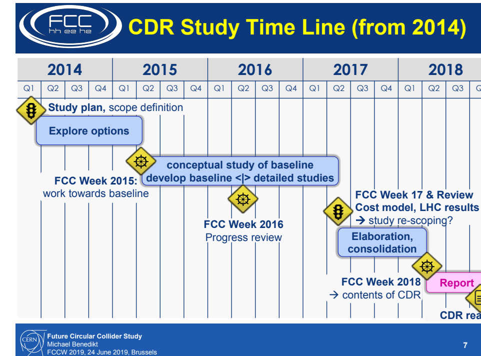
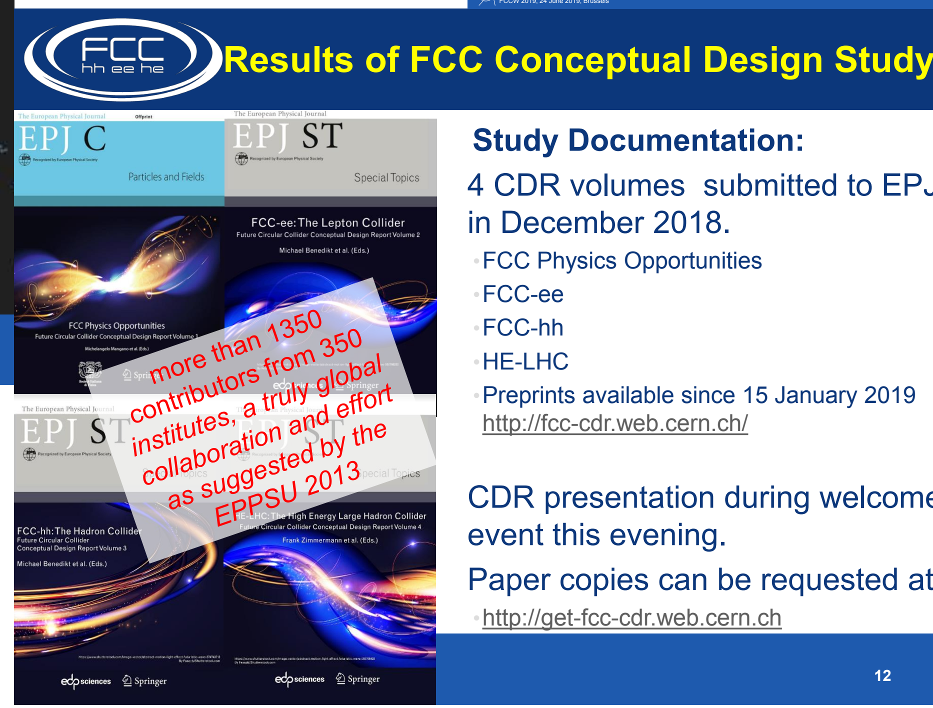
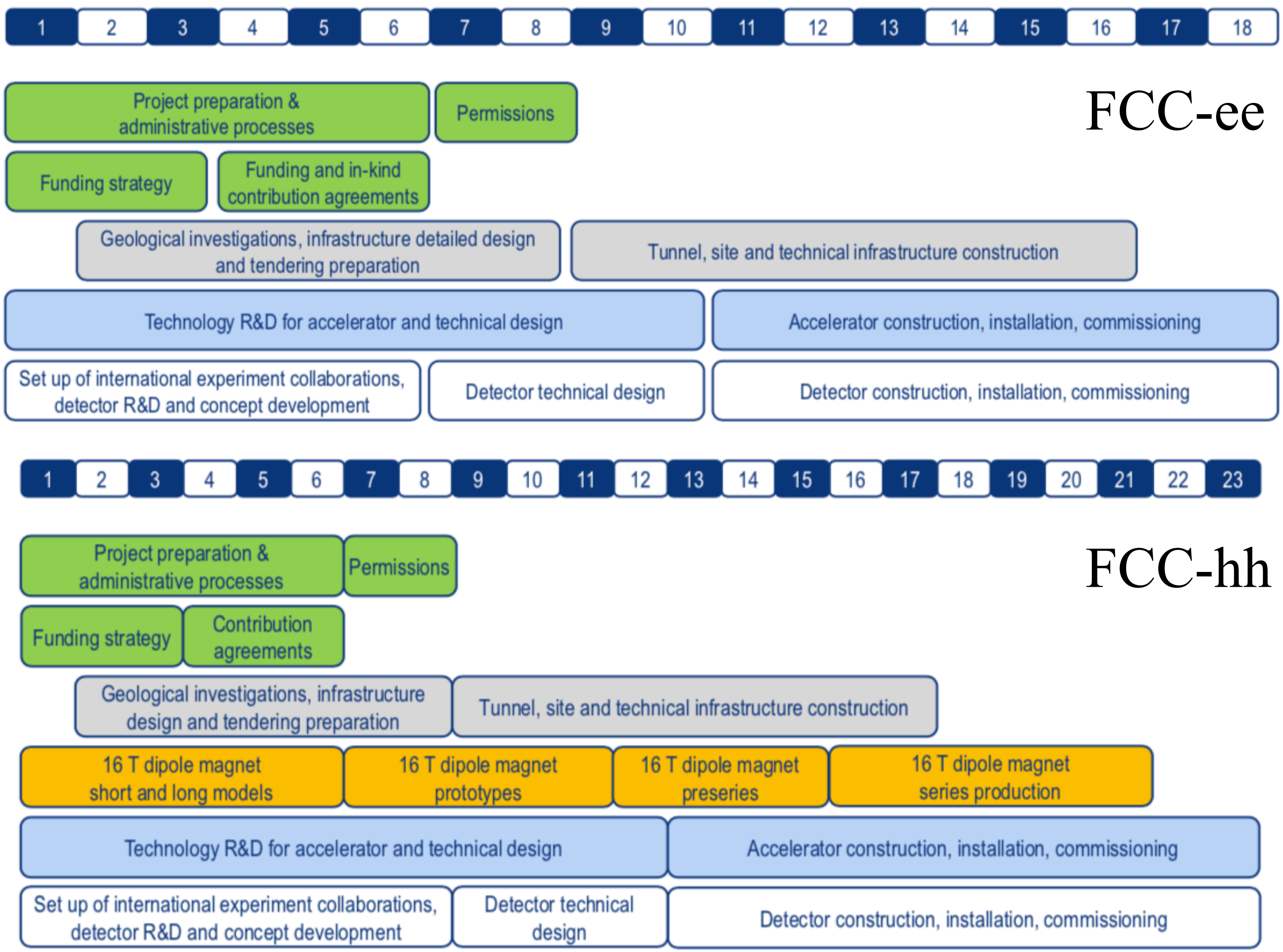




Next stages (CDR+, TDR) are subjected to the ESPP update outcome.

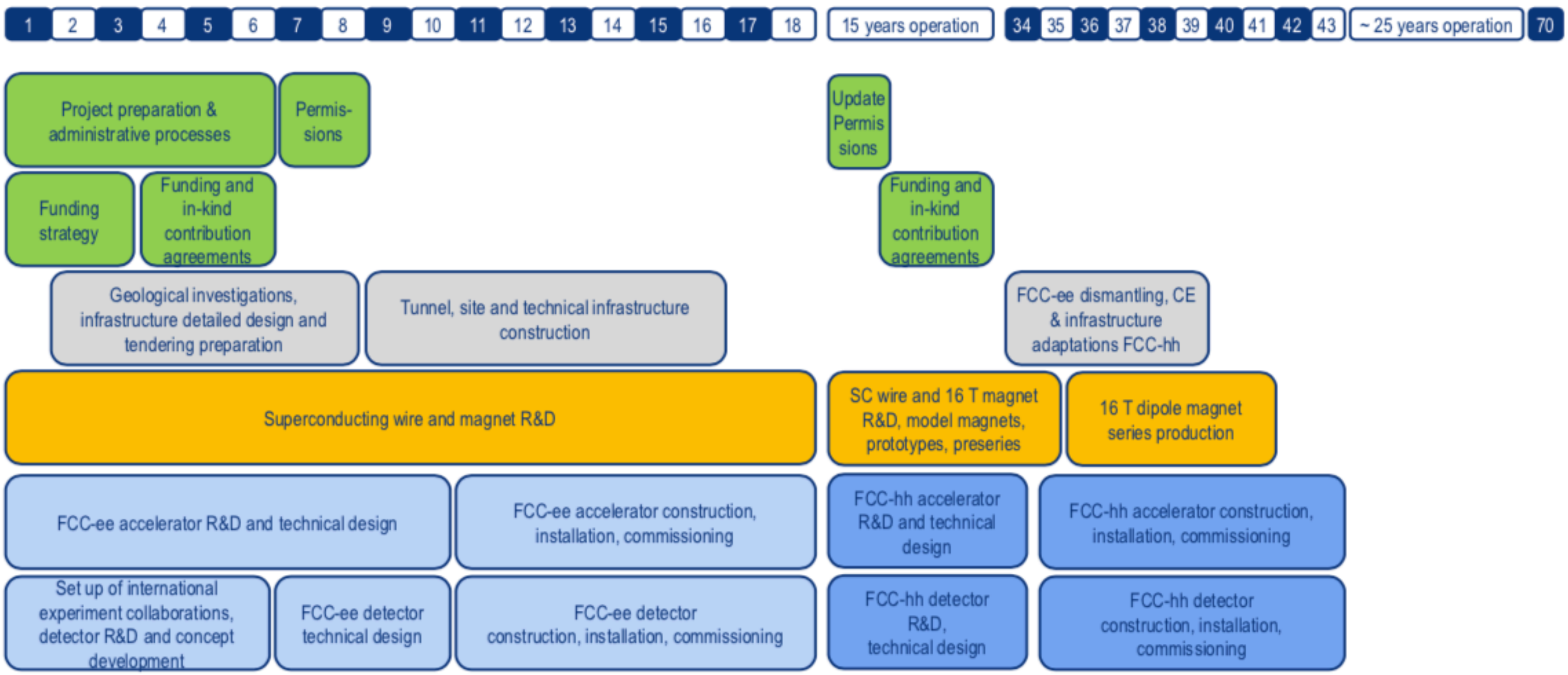
1. Introduction to FCC: timelines of implementation

- Eighteen years towards Physics. No overlap in Physics between the end of HL-LHC and FCC-*ee*



1. Introduction to FCC: timelines of implementation

- Eighteen years towards Physics. No overlap in Physics between the end of HL-LHC and FCC-*ee.* The big picture.



- Is it crazy to plan a Physics program for seventy years?

1. Introduction to FCC: timelines of implementation

- Is it reasonable to plan a Physics program for seventy years? It was.
- The previous HEP European planning was only for … 60 years !

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field, H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann, K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter, C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

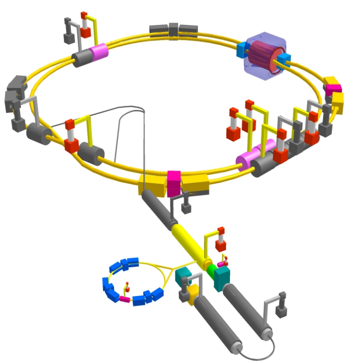
1. The FCC e^+e^- machine. Baseline design

- Physics from the *Z* pole to top pair production (90 - 400 GeV), crossing *WW* and *ZH* thresholds with unprecedented statistics everywhere.

- Two rings (top-up injection) to cope with high current and large number of bunches at operating points up to *ZH*.

- Description of the machine parameters(relagated in back-up) next slide.

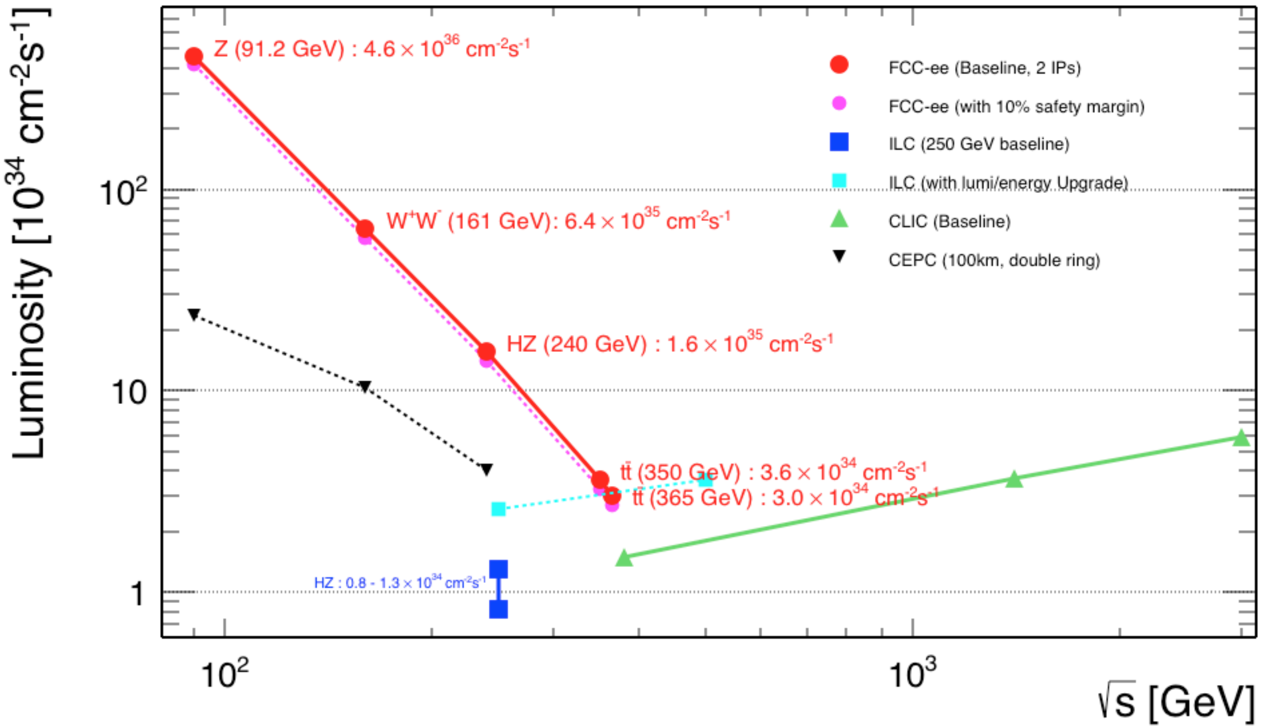
- To some extent, SuperKEKB is already meet some of the challenges of FCC-*ee:*



Some SuperKEKB parameters :

- β^*_y : 300 μm
  - FCC-ee (H) : 1 mm
- σ_y : 50 nm
  - FCC-ee (H) : 50 nm
- $\varepsilon_y/\varepsilon_x$: 0.25%
  - FCC-ee (H) : 0.2% to 0.1%
- e^+ production rate : 2.5×10^{12} / s
  - FCC-ee (H) : < 1×10^{11} / s
- Off-momentum acceptance at IP : ±1.5%
  - FCC-ee (H) : ±2.0% to ±2.5%
- Beam Lifetime : 5 minutes
  - FCC-ee (H) : 20 minutes
- Centre-of-mass energy: ~10 GeV
  - FCC-ee (H) : 240 GeV

1. The FCC e^+e^- machine. Luminosity figure



- The FCC-ee offers the largest luminosities in its whole energy range.

- We‘re speaking here of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, without trigger.

2. Operation at the *Z* pole and statistics

- The time / energy allocation of the machine has been worked out …

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}

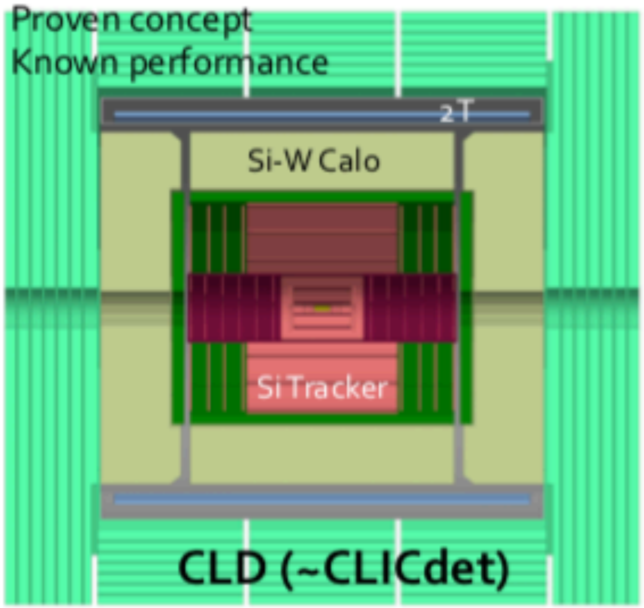
- … we're speaking here of 5.10^{12} *Z*, 10^8 *WW*, 10^6 *H* and 10^6 top pairs.

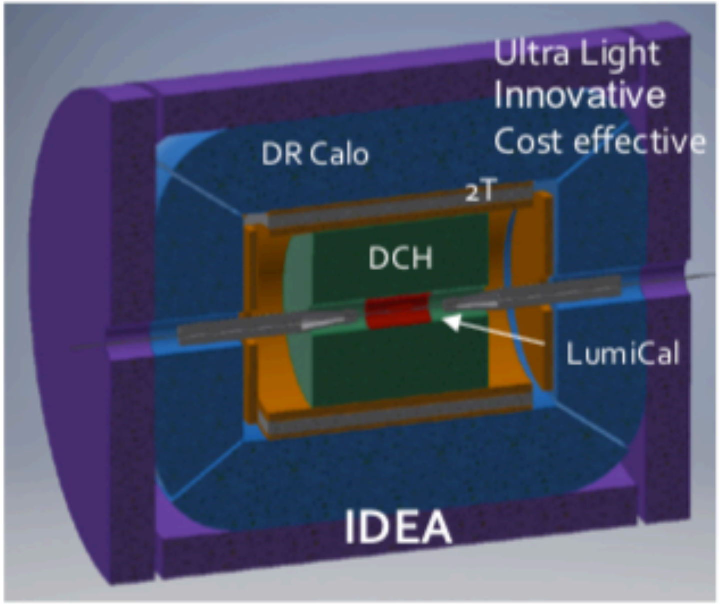
- Relevant production yields for Flavour Physics (2 IPs — 4 are considered):

Particle production (10^9)	B^0	B^-	B^0_s	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

- Direct comparison with LHCb yields requires a mode by mode approach to take into account trigger and reconstruction efficiencies.

2. The e^+e^- experiments.





- Two designs have been studied so far.
- Robust towards performance, intricate MDI, beam backgrounds.
- The key point for all the Physics program is the lightness …
- Personal note: FCC project aims at providing four detector proposals by 2026. Among those proposals, there is room for a dedicated design for Flavours, in particular for hadron identification.

3. The Flavours case to introduce $b \to s\ell^+\ell^-$

- Now part of the program in its own right.

- The Design Study considered a limited number of subjects in which FCC-*ee* has unique distinctive features, with the idea *In for a pound, in for a penny* (*qui peut le plus peut le moins*). Comprise taus, LFV *Z* decays, Heavy Neutral leptons, and of course b-hadron decays.

- Among the distinctive experimental features, one finds:

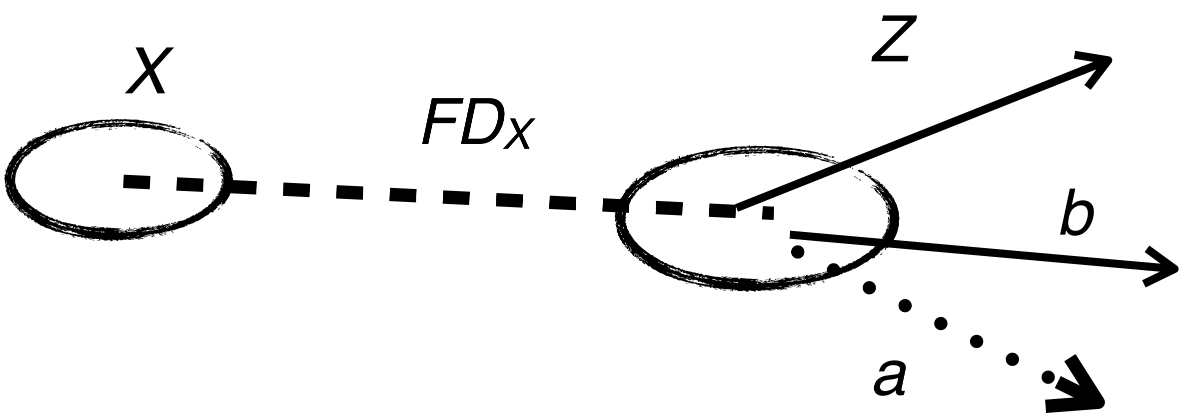
  - The boost experienced at the *Z* pole in conjunction with excellent vertexing (average -hadron energy is 35 GeV) .
  - The precise reconstruction of EM objects (nothing in front of the calo!)
  - The other hemisphere (useful for EWPT as well)
  - The knowledge of the missing energy (particle flow).
  - Triggerless: absolute branching fractions

- I'm flashing the main results of the experimental prospectives.

3. The vertexing capabilities for $b \to s\tau^+\tau^-$

- The expected vertexing performance at FCC-*ee* (detector at 2 cm from the interaction point) allows to reconstruct precisely the missing momentum in decays inferred from the decay flight distances.

- Example: $X \to Y\,(\,Y \to [a]b\,)\,Z$ with a not reconstructed.



- Three momentum components to be searched for:
  - The measurement of X momentum direction fixes 2 d.o.f.
  - An additional constraint closes the system: m_Y or a tertiary vertex.
  - Usually, quadratic form of the constraints: solution up to an ambiguity.

3. Search for $B^0 \to K^{*0} \tau^+\tau^-$.

- The FCC-*ee* statistics and the capacity to fully reconstruct the decay even in the absence of the neutrinos allows to address FCNC transitions with tau in the final state. The reconstruction of the mode $B^0 \to K^{*0} \tau^+\tau^-$ as a benchmark has received a special attention in the FCC-*ee* context.

- Should the LFU anomalies be confirmed, these modes are invaluable model killers.

- A lot is still to be done to address the rare decays Physics case in a more comprehensive way but this indicates the potential.

- Note that the expected number of decay mode $B^0 \to K^{*0} e^+ e^-$

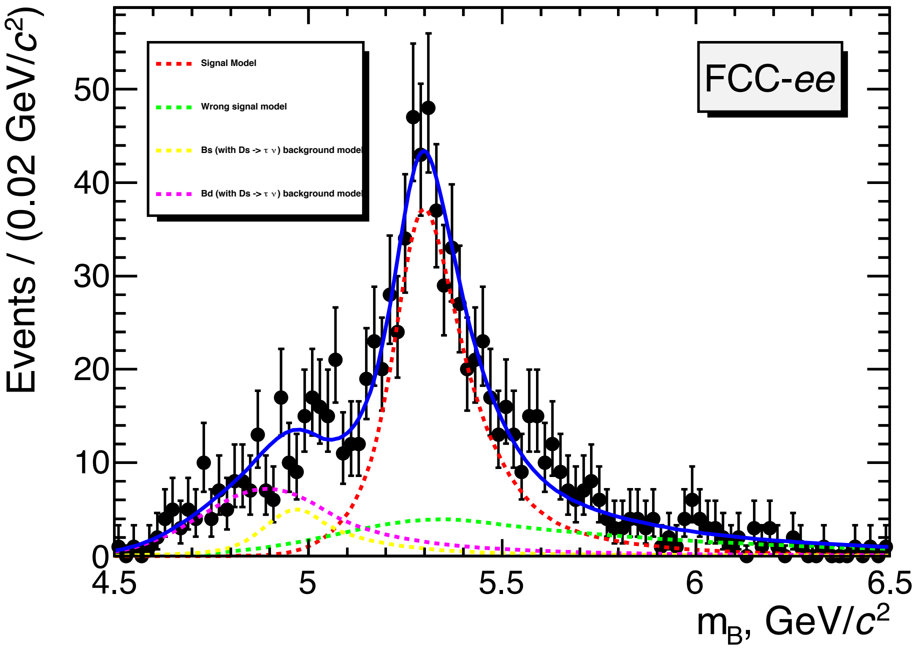
Decay mode	$B^0 \to K^*(892) e^+ e^-$	$B^0 \to K^*(892) \tau^+ \tau^-$	$B_s(B^0) \to \mu^+ \mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)

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

- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance

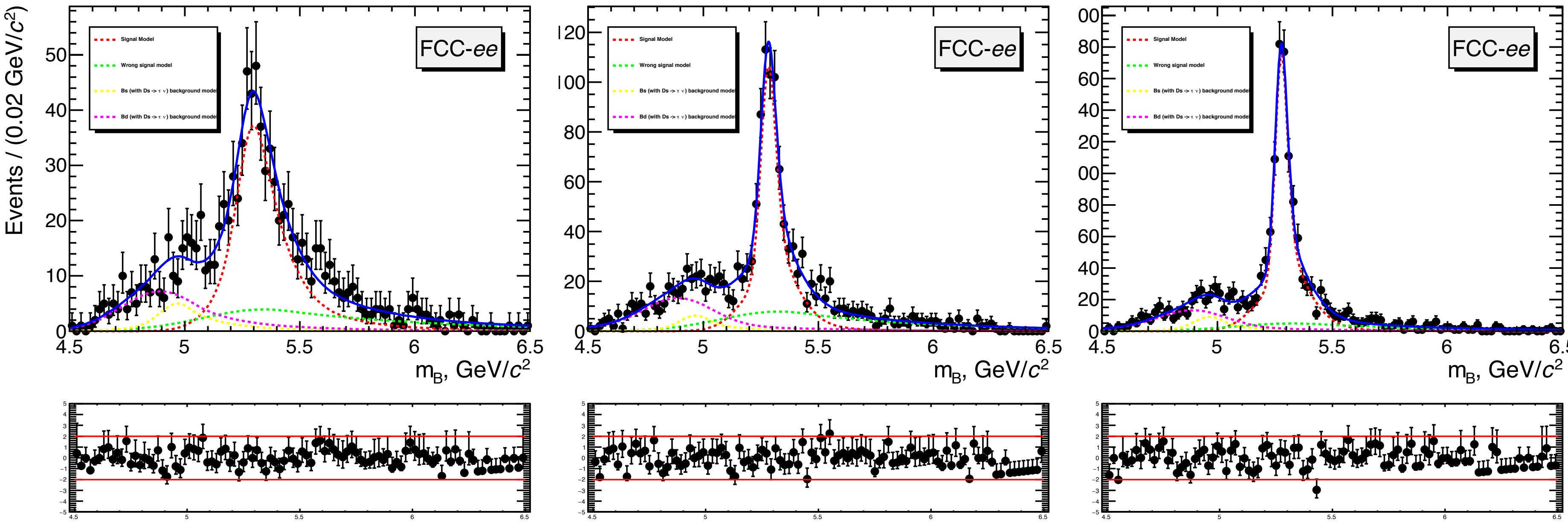
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um

- Backgrounds: (pink - DsK*taunu and DsDsK*) [signal in red+green].



- At baseline luminosity, under SM hypothesis, more than 10^3 events of reconstructed signal. Angular analysis possible. Tau polarisation can be used. O(5%) on BF.

3. Search for $B^0 \to K^{*0} \tau^+\tau^-$.



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)

4. Next opportunities

- The next phase of the Study must go through full simulations of actual detector proposals.

- This will allow to have realistic inputs (in particular from calorimetric objects) to evaluate the sensitivity on a series of outstanding observable measurements:

    - Semileptonic b-hadron decays
    - The electroweak penguins $X_b \to X \nu \nu$
    - The leptonic decay $B_c \to \tau^+ \nu_\tau$
    - The dileptonic B^0, $B_s \to \tau^+ \tau^-$
    - Not forgetting the dileptonic B^0, $B_s \to \mu^+ \mu^-$
    - CKM profile(s)
    - Tau Physics at large.
    - etc…

- The standard Heavy Flavour program: lifetimes, branching fractions, spectroscopy, exotic states etc…

5. Summary

- $B^0 \to K^{*0}\ \tau^+\tau^-$ has been chosen as a benchmark. The secondary vertex reconstruction makes the partial reconstruction

- O(5%) BF measurements [at SM value !] can be attained on the decay mode $B^0 \to K^{*0}\ \tau^+\tau^-$. Tau polarisation features allows new angular observables to be devised (e.g L. Vale et al. arXiv:1705.1110)

- Everything to do on dileptonic $B^0, B_s \to \tau^+\tau^-$. Here, the absence of the SV complicates the study. There are perspectives though !

- Escaping the $b \to s\ell^+\ell^-$, much more to do on the leptonic decay, in particular $B_c \to \tau^+\nu_\tau$

5) References as a conclusion:

- CDR(s):
  - https://fcc-cdr.web.cern.ch
- FAQs about FCC:
  - https://arxiv.org/pdf/1906.02693.pdf
- Join the Study (a model):
  - https://www.cern.ch/fcc-ee (then join us item and provide your preferences)
  - A successful approach in Flavours has been to gather small groups of experimentalists and theoreticians targeting at a paper. The unique opportunities offered by FCC-*ee* can trigger new ideas / new areas of thinking.
- Software is up ! Hands-on tutorials available here:
  - https://indico.cern.ch/event/839794/
- Should you have a project / interest to implement: monteil@in2p3.fr.