Flavours in the landscape of FCC

Future Circular Colliders —> Frontier Circular Colliders

Would fit pretty well with this conference's spirit.

Focus on the first step: electron machine

Stéphane Monteil,
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Outline

- The Future Circular Colliders.
- Motivation and method for building the Flavours case.
- Executive Summary of the Conceptual Design Report exploration study.
- Much more to devise at the next stage of the study in an integrative program with EWPT.
- Implementation as the outlook.

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
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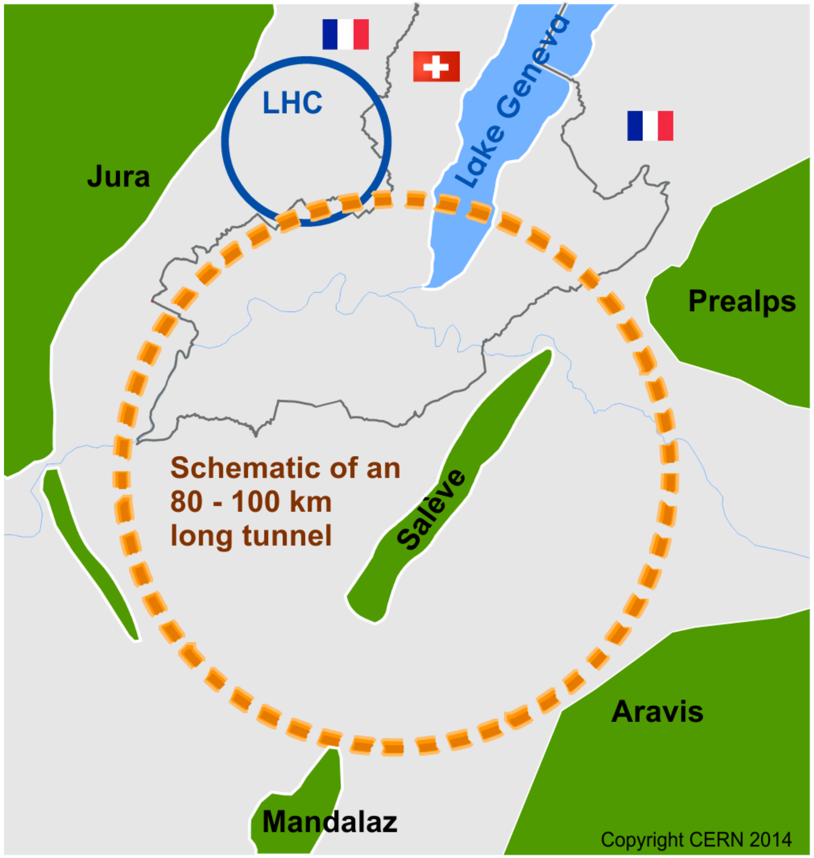
- At the time the LHC Run II will have delivered a significant part of its results, have an educated vision of the reach of future machines for the next round of the European Strategy in 2020.

1. Introduction to FCC: the scope of the project

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

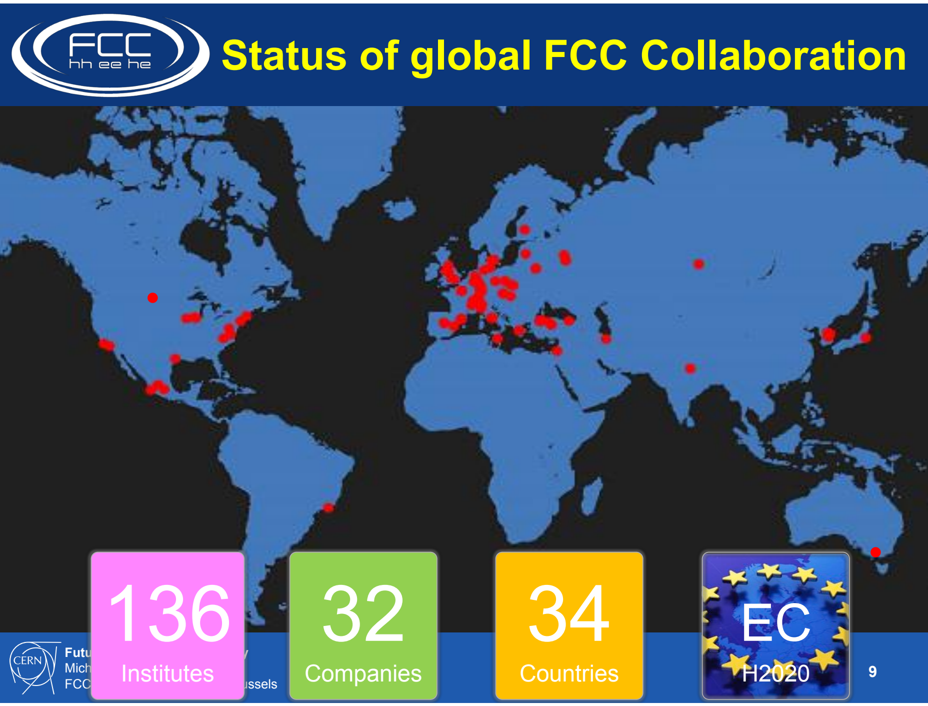
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.

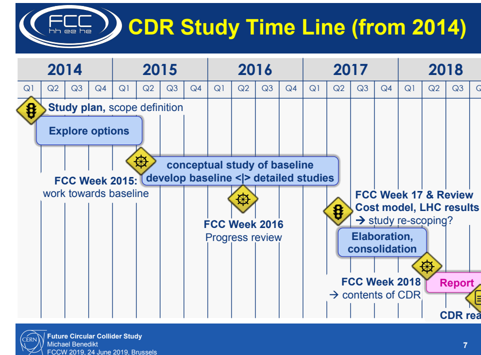


- Conceptual design report and cost review for the next european strategy → 2020.

1. Introduction to FCC: the completion of the CDR

The Design Study is completed and fulfilled the mandate





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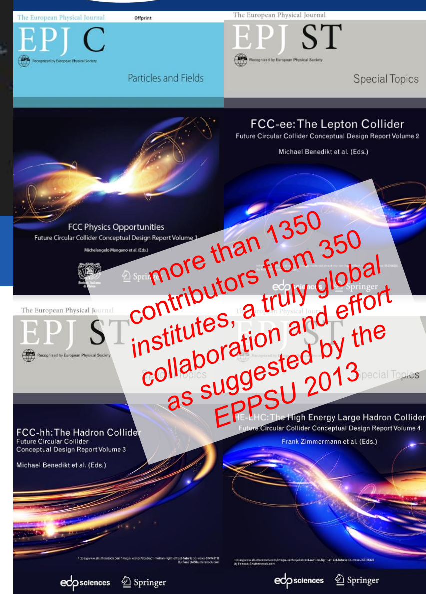
Results of FCC Conceptual Design Study



Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019 http://fcc-cdr.web.cern.ch/

CDR presentation during welcome event this evening.

Paper copies can be requested at

- http://get-fcc-cdr.web.cern.ch

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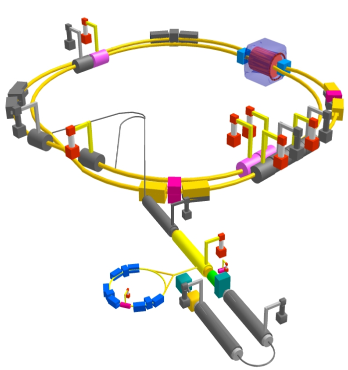
Next stages (CDR+, TDR) are subjected to the ESPP update outcome.

1. Introduction to FCC: FCC-*hh*

- Flavour Physics at FCC-*hh* is simultaneously appealing and subjected to in depth studies in light of LHCb U2.
- Link to the slide.
- Focus on the electron machine in the following.

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

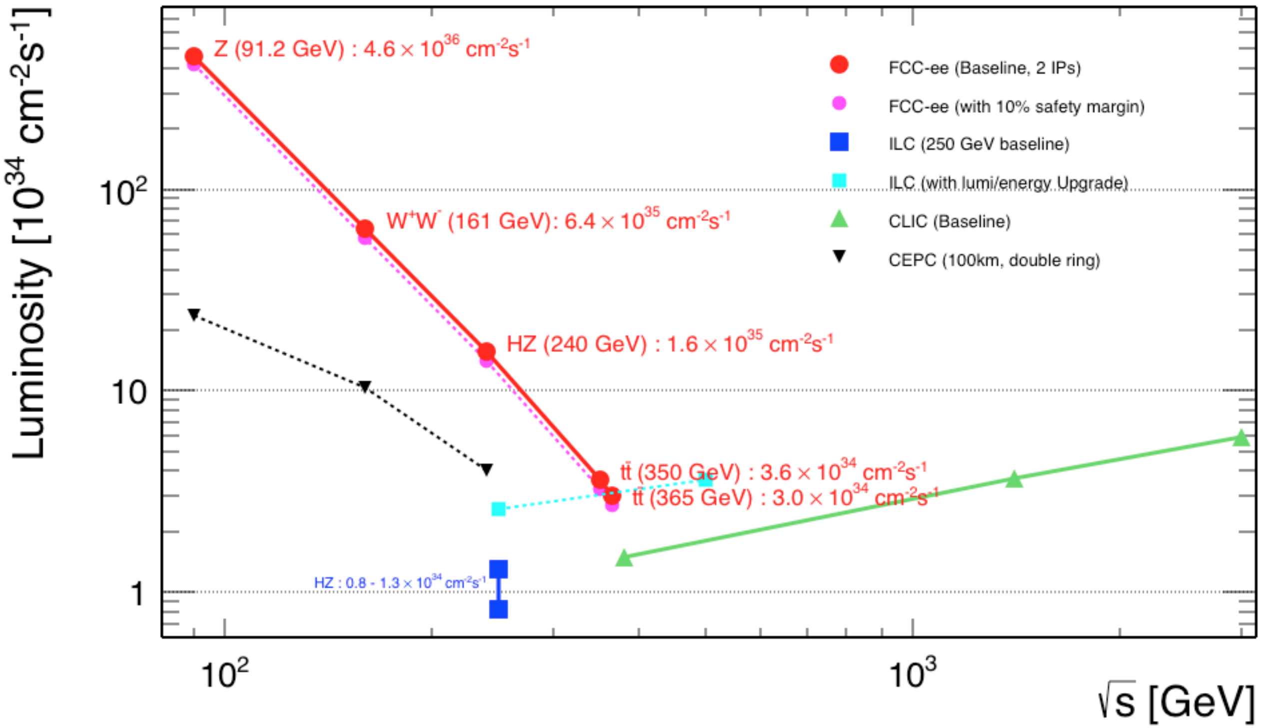
- Physics from the *Z* pole to top pair production (90 - 400 GeV), crossing *WW* and *ZH* thresholds with unprecedented statistics everywhere.
- Two rings (top-up injection) to cope with high current and large number of bunches at operating points up to *ZH*.
- Description of the machine parameters (relagated in back-up)
- To some extent, SuperKEKB is already meeting or about to 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) : $< 1 \times 10^{11}$ / 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.

1. The FCC e^+e^- machine. Time allocation at Z pole

- 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.

- Of particular relevance for the Flavour Physics is the Z pole

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

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

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

1. The FCC e^+e^- machine. Characteristics

- Of particular relevance for the Flavour Physics is the *Z* pole

1. The FCC e^+e^- machine. Main Characteristics

- Amongst the main characteristics for Flavour Physics is the boost experienced at the *Z* pole (fragmentation of the *c*,*b*-quark provides ~75% of the beam energy to the *b*-hadron). Conversely, the excellent capacity of reconstructing detached vertices is a decisive feature for the studies presented here. Link to partial reconstruction.

- Of particular relevance for the Flavour Physics is the *Z* pole

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- The energy spread of the beams (~ 50 MeV) to determine event-by-event the actual initial conditions energy-wise.

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- 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 …

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- Amongst the main characteristics for Flavour Physics is the boost experienced at the *Z* pole (fragmentation of the b-quark provides is ~75% of the beam energy to the *b*-hadron).

- You make the whole LEP … in a minute! Not a trivial scaling.

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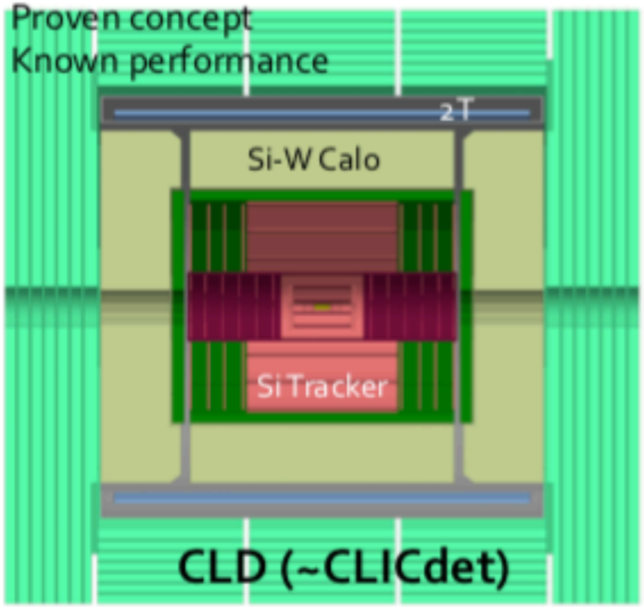
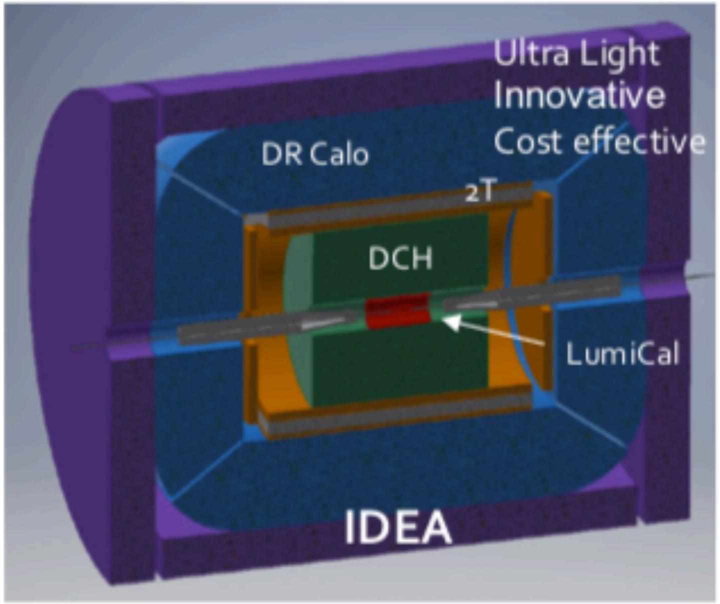
1. A word on FCC e^+e^- detectors





- 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.

1. EW and SSB Physics case in 2 slides. THE FIRST

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

Z pole / WW thr. / tt thr.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
$A_{FB}^b, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
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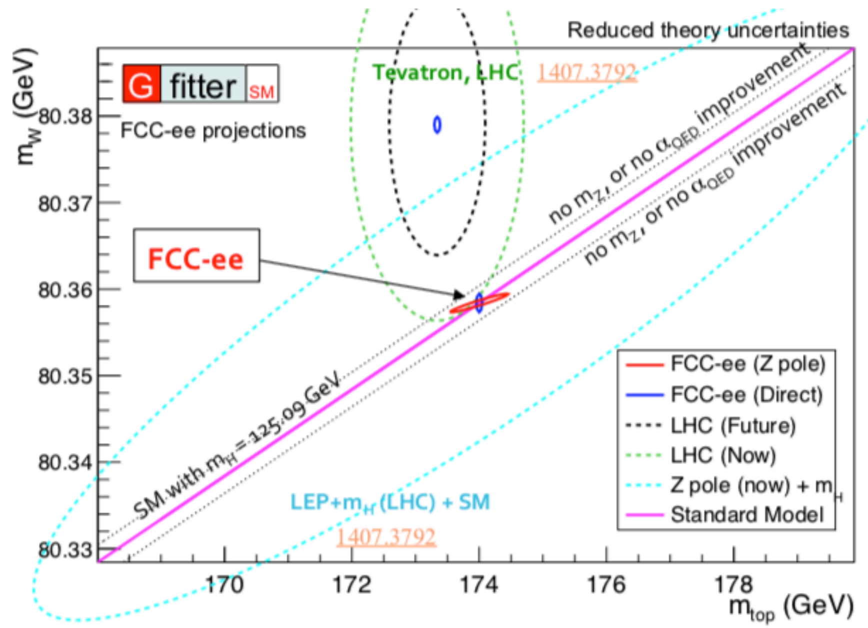
N_ν($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run



- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program.

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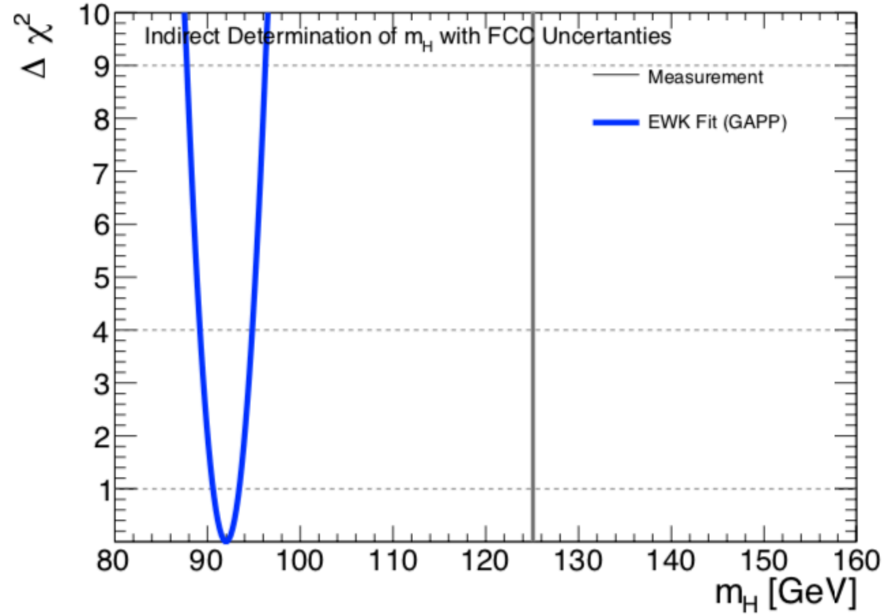
Z pole (rows m_Z to $A_{FB}^{pol,\tau}$)

WW thr. (rows m_W to N_ν)

tt thr. (rows m_{top} to ttZ couplings)



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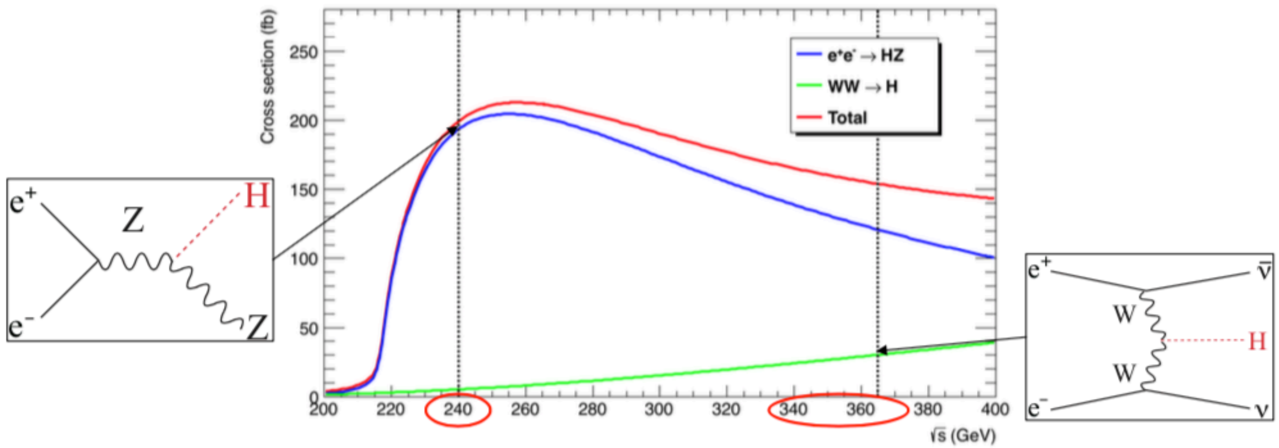
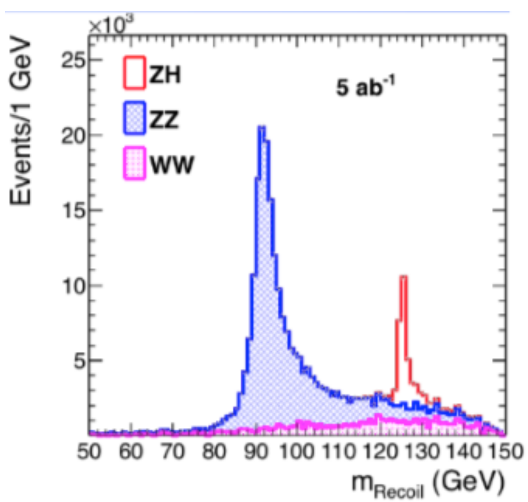
1. EW and SSB Physics case in 2slides. SECOND

- Two energy points (240 and 360 GeV) for the program



- Invincible precision on the absolute couplings and width. Interplay with HL-LHC.



Collider	HL-LHC	FCC-ee		
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC
Years	25	3	**+4**	-
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0

2. 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 tell detector requirements.

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

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

Lepton Flavour Violating (LFV) Z decays

Rare *b*-hadron decays — electroweak penguins

cLFV tau decays

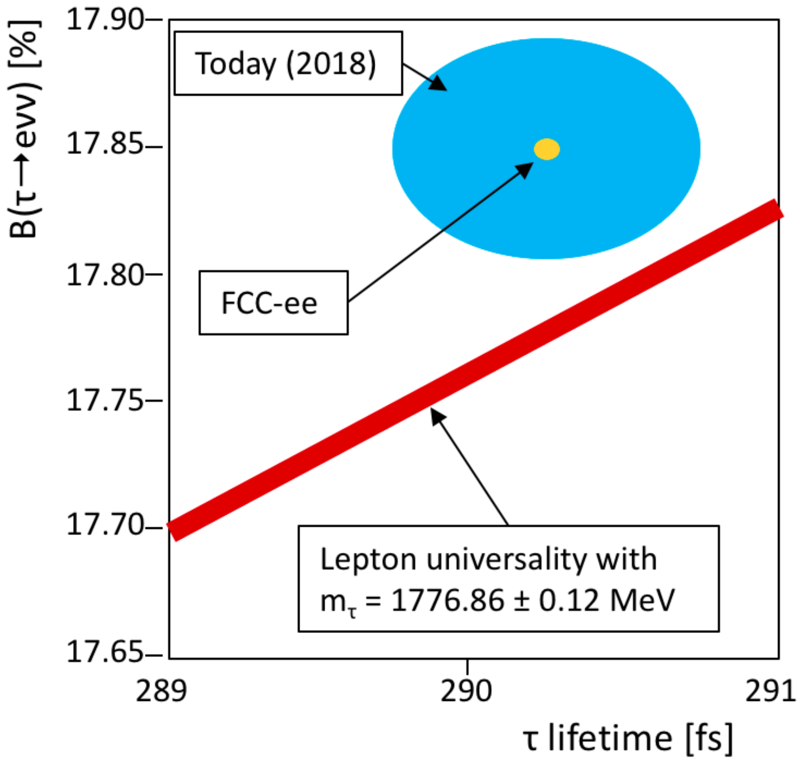
CKM measurements —CPV in *B* mixings

2. Tau lepton Physics (selection of)

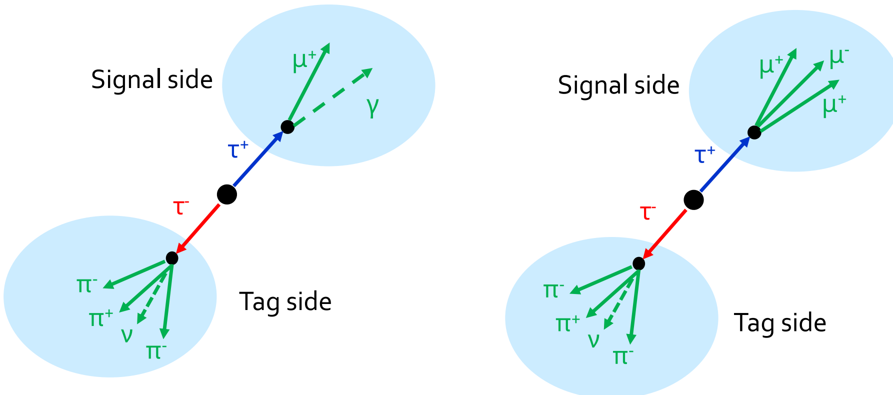
- Unprecedented statistics of boosted tau decay topologies.
- Lifetime measurement in addition to branching fractions.
- Highly competitive Lepton Flavour Universality tests program in its own right.

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

Note: systematics are kind of state-of-the-art. A decade to exercise the experimentalists' cleverness on this.



2. Tau lepton Physics (selection of) — cLFV



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	?

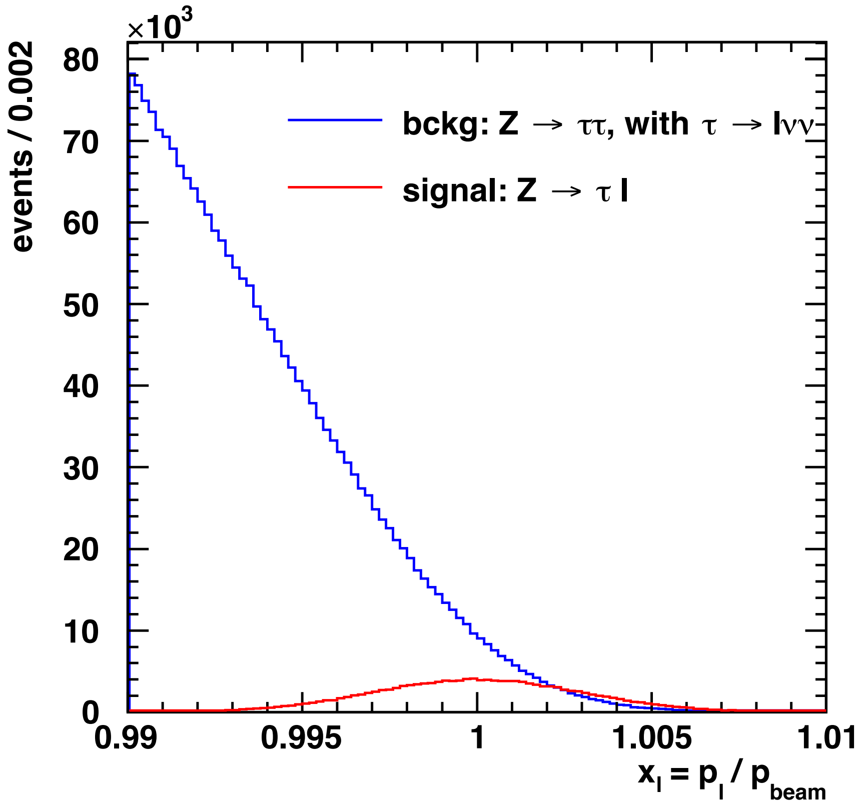
- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

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}

Bottomline: the current limits can be pushed by one to two orders of magnitude.

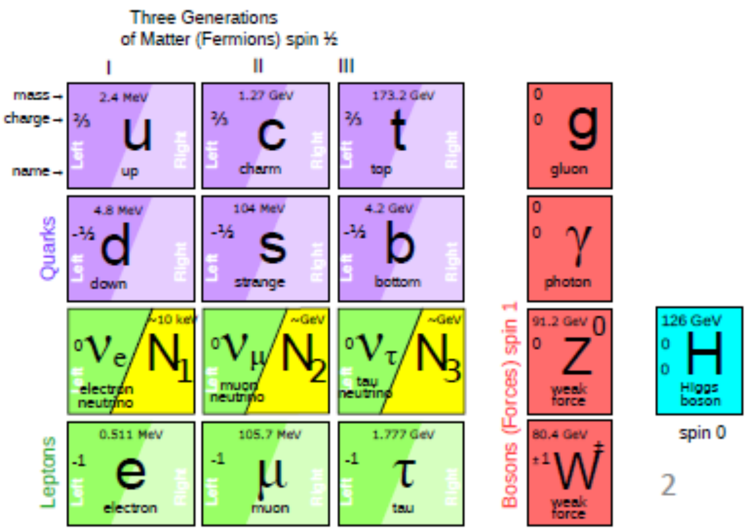
2. Lepton-flavour-violating decays (*Z* decays)

- Lepton Flavour-Violating *Z* decays in the SM with lepton mixing are typically < 10^{-50}.
- Any observation of such a decay would be an indisputable evidence for New Physics. FCC-*ee* exploration [JHEP 1504 (2015) 051].
- The dominant background is ($Z \to \tau\tau$), where one tau decays into a close to beam energy lepton. The search is limited by the momentum resolution.
- A lot of phenomenology to explore yet.



Bottomline: With the expected tracking performance at FCC-*ee* , the current limits are pushed by three orders of magnitude.

2. Direct search of Heavy Neutral Leptons.



arXiv:1411.5230

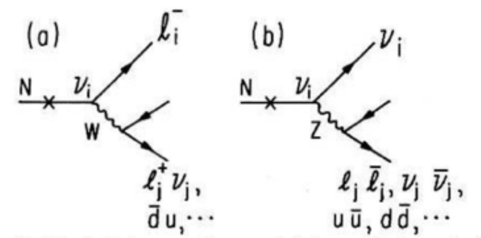
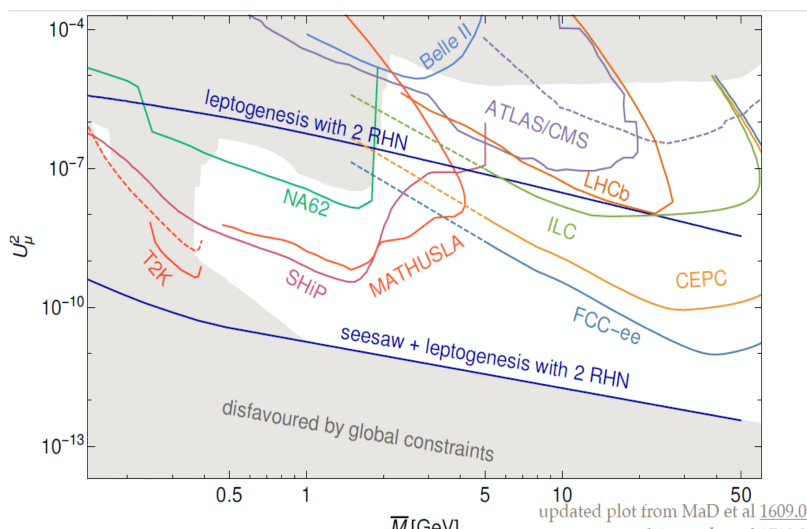


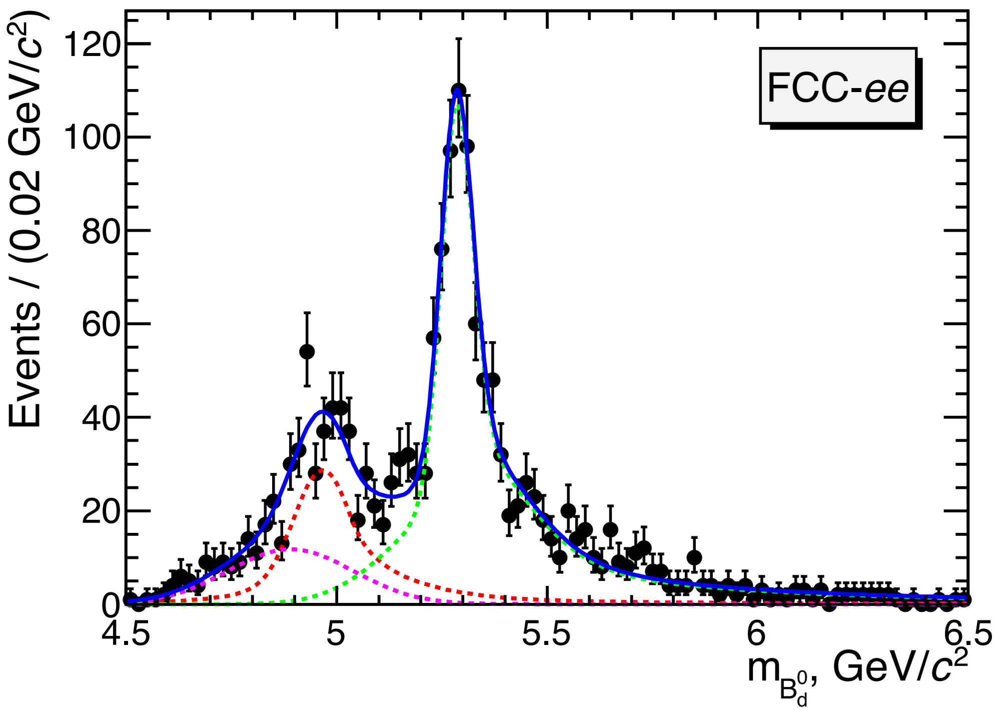
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.



updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

2. Rare decays (& Flavour anomalies) — $B^0 \to K^{*0}\ \tau^+\tau^-$.

- Topological reconstruction of the missing energy with meas. of the decay vertices.
- Background estimates from generic double-charmed decays at SM values w/proxies (no meas. available).
- Vertex detector as close as 1.7 cm. Yet, considered ILD-like vertexing performance.
- Focus here on three-prongs decays of the taus.



Bottomline: several thousands of decays can be reconstructed, if the branching fraction is at SM value. *O*(5%) precision on BF. Angular analyses can be performed [arXiv:1705.11106].

2. *CP* violation in *B*-meson mixings

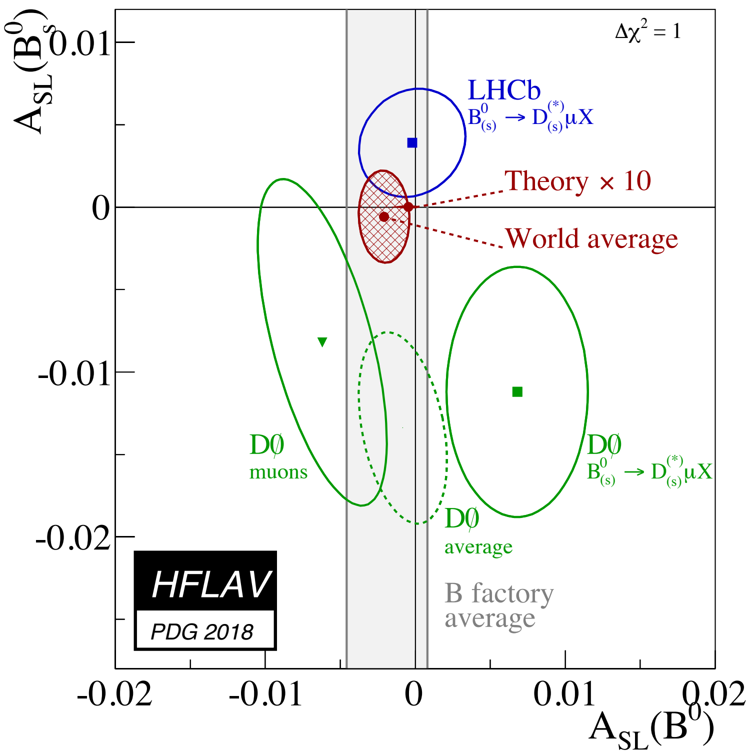
- Setting the scene: *CP* violation in mixing can be measured by looking at flavour-specific decays and the *CP*-violating observable defined by:

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

- The SM predictions reads:

$$a_{\rm sl}^d = -(4.7 \pm 0.6) \times 10^{-4}\,,$$
$$a_{\rm sl}^s = +(2.22 \pm 0.27) \times 10^{-5}.$$

CKMfitter



- Focus here on B_s (in for a penny…)

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

2. *CP* violation in *B*-meson mixings

- **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).

- 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
$D^+ \to \mu^+\nu_\mu$	$(3.74 \pm 0.17) \times 10^{-4}$ (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)

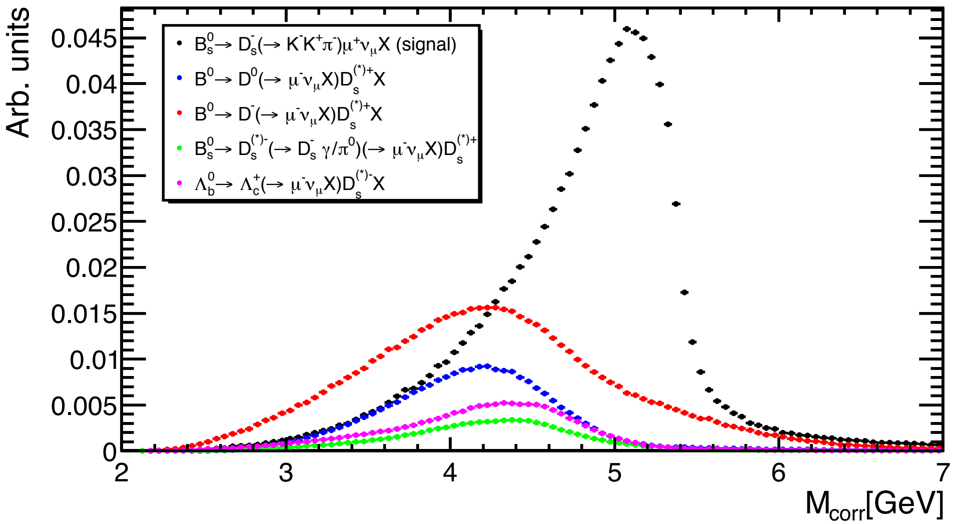
Decay mode	Branching fraction
$D_s^+ \to \mu^+\nu_\mu$	$(5.5 \pm 0.23) \times 10^{-3}$ (PDG 2018)
$D_s^+ \to \phi\mu^+\nu_\mu$	$(1.9 \pm 0.5)\%$ (PDG 2018)
$D_s^+ \to \eta\mu^+\nu_\mu$	$(1.1 \pm 0.5)\%$ (PDG 2018)
$D_s^+ \to \bar{K}^0\mu^+\nu_\mu$	0.00390 (decay file)
$D_s^+ \to \bar{K}^{*0}\mu^+\nu_\mu$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

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

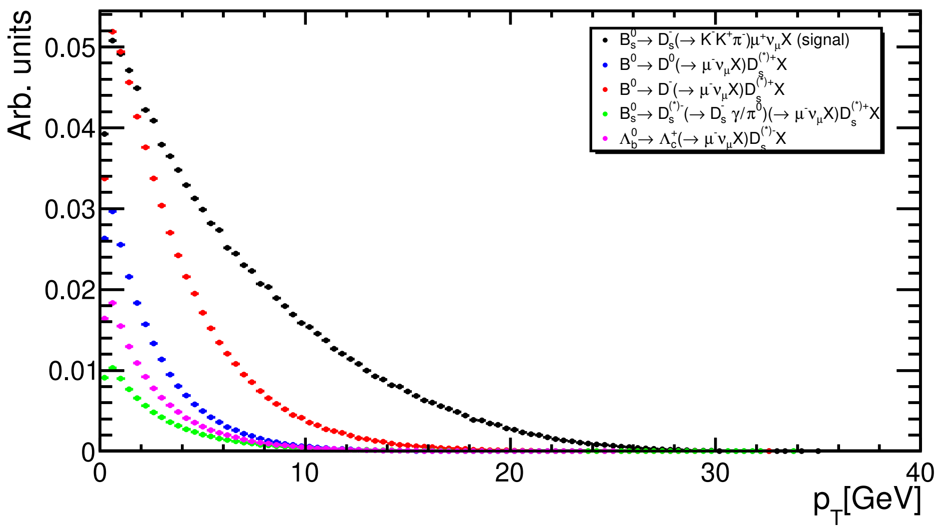
2. *CP* violation in *B*-meson mixings

- 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.

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



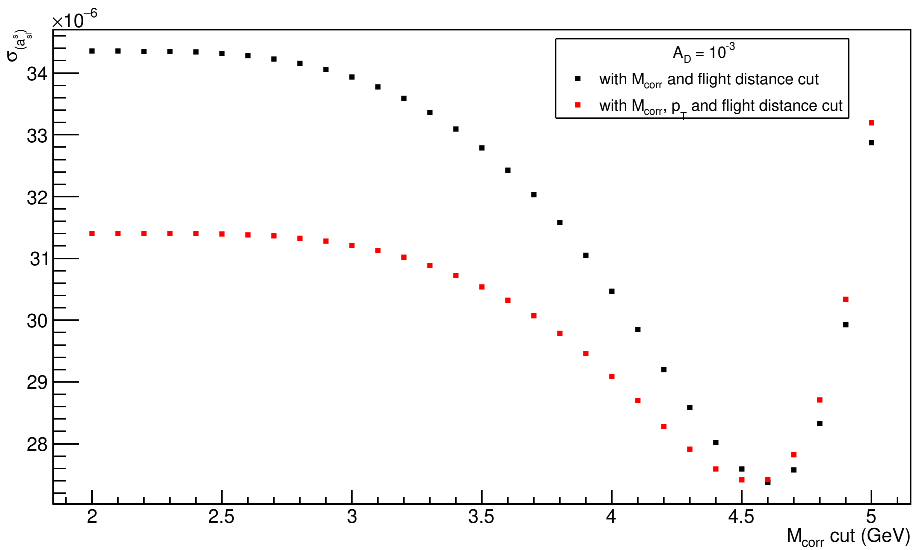
- The measured lepton transverse momentum can be additionally discriminative:



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

2. *CP* violation in *B*-meson mixings

- 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.

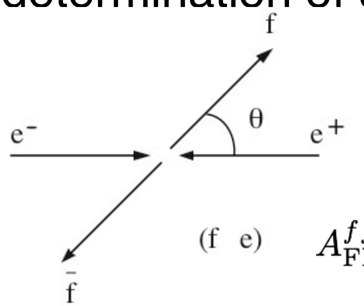
- The most challenging flavour specific asymmetry seems at reach if SM prediction is considered (actual numbers must still be ironed further but the order of magnitude is there).

- 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 with this.

- The measurement of the forward-backward asymmetry of the *b* quark in *Z* decays is primarily meant for *Ab* determination, since muons will drive the determination of $\sin^2\theta_W$.

$$\frac{\mathrm{d}\sigma^f}{\mathrm{d}\cos\theta} = \sigma^f_{\mathrm{tot}} \cdot [\frac{3}{8}(1+\cos^2\theta) + A^{f\bar{f}}_{\mathrm{FB}}\cos\theta]$$



$$A^{f\bar{f}}_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B} \text{ with } N_F = \int_0^1 \frac{\mathrm{d}\sigma_{f\bar{f}}}{\mathrm{d}\cos\theta} \cdot \mathrm{d}\cos\theta$$

$$A^{f\bar{f}}_{\mathrm{FB}} \propto A_e \cdot A_f \propto \frac{g^e_V g^e_A}{(g^e_V)^2 + (g^e_A)^2} \cdot \frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

- Explore exclusive *b*-hadron decays (B^+ *or* Λ_b) reconstruction to benefit of the *Z* pole statistics, *e.g.* $B^- \to D^0\pi^-$, $D^0\pi^-\pi^+\pi^-$ [10^{-2}] followed by $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K_S^0\pi^+\pi^-$ [15.10^{-2}], $\Lambda_b \to \Lambda_c\pi^+$, $\Lambda_c\pi^+\pi^-\pi^-$ [10^{-2}] followed by $\Lambda_c \to p K^-\pi^+$ [7. 10^{-2}] —> A billion of them.

- Limitations of LEP-like measurements of A_{FB}(b) are overcome: mixing dilution with lepton tags, purity of the sample, QCD corrections (gluon radiations).

- Same rationale / virtues for the Z —> bb partial width (for correlations systematics).

3. Much more to quantitatively assess (and start projects)

- 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 (some comments in back-up):

  - Semileptonic b-hadron decays
  - The electroweak penguins $X_b \to X \nu\nu$
  - The leptonic decay $B_c \to \tau^+ \nu_\tau$
  - The dileptonic $B^0, B_s \to \tau^+ \tau^-$
  - CKM profile(s)
  - Tau Physics at large.
  - Charm Physics (@Uli: $D^0 \to K_S K_S$ *CP* asym; yields about 10^7)
  - etc…

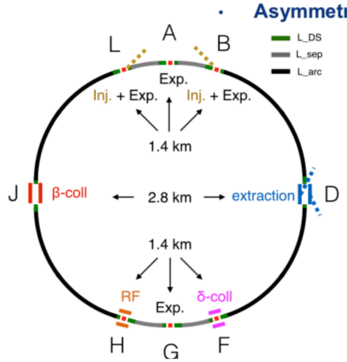
- The standard Heavy Flavour program: lifetimes, branching fractions, spectroscopy, exotic states etc…

4. The FCC implementation — Civil engineering

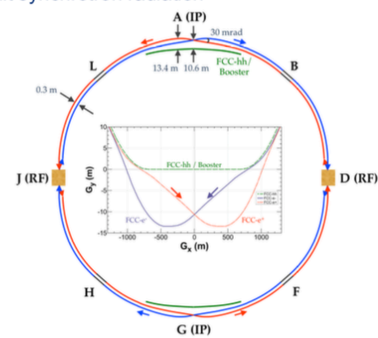
- Machine footprints, experimental caverns, geological studies

FCC-hh

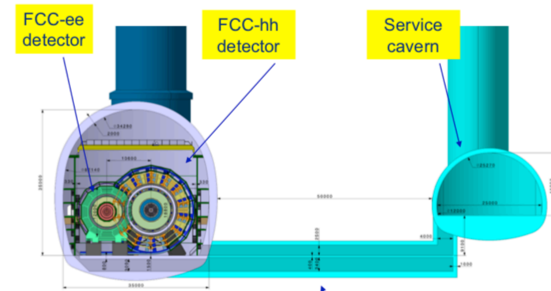
- **Common footprint except around IPs**
- **Asymmetric IR layout** to limit synchrotron radiation

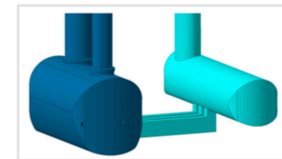


FCC-ee

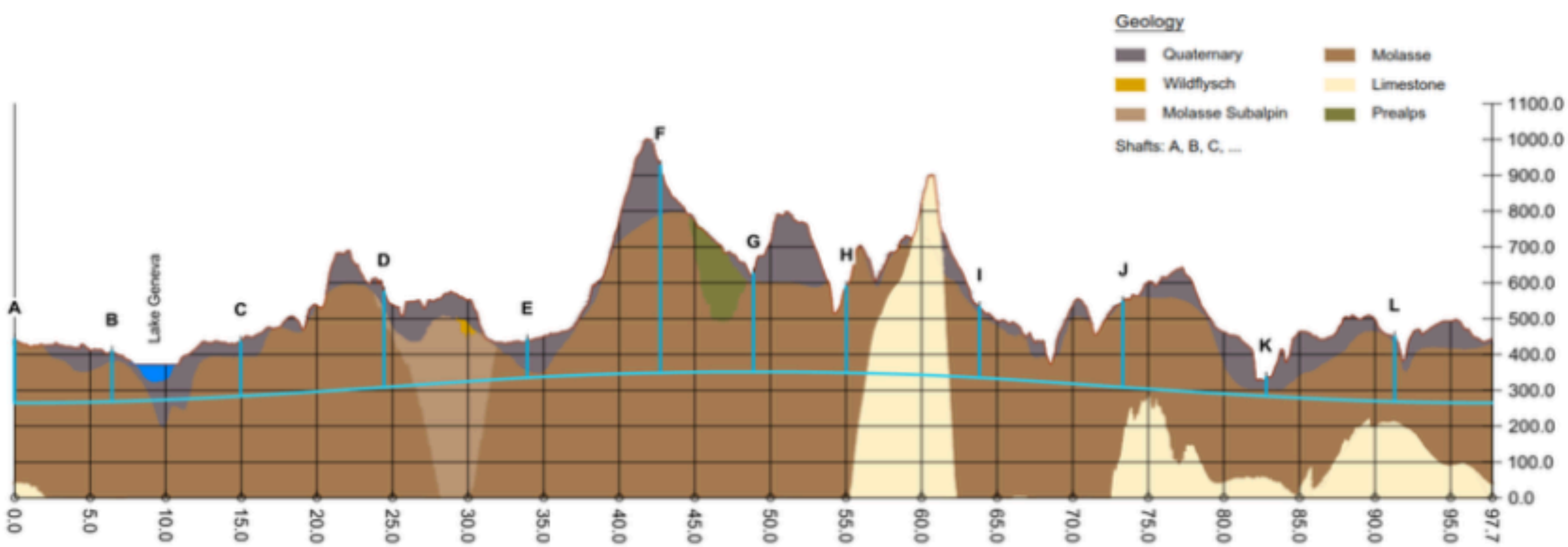


Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



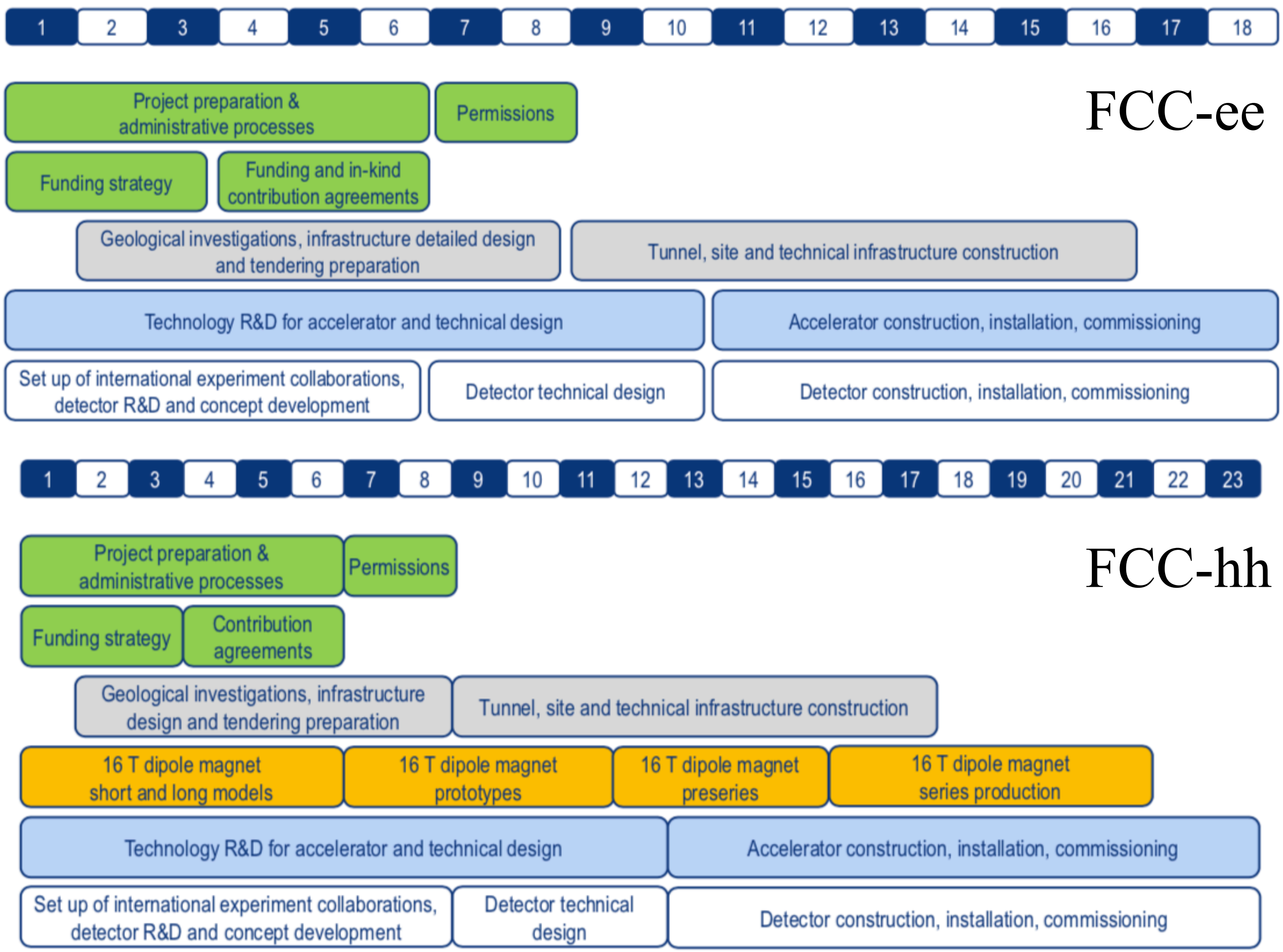


Preliminary design of access and cable paths



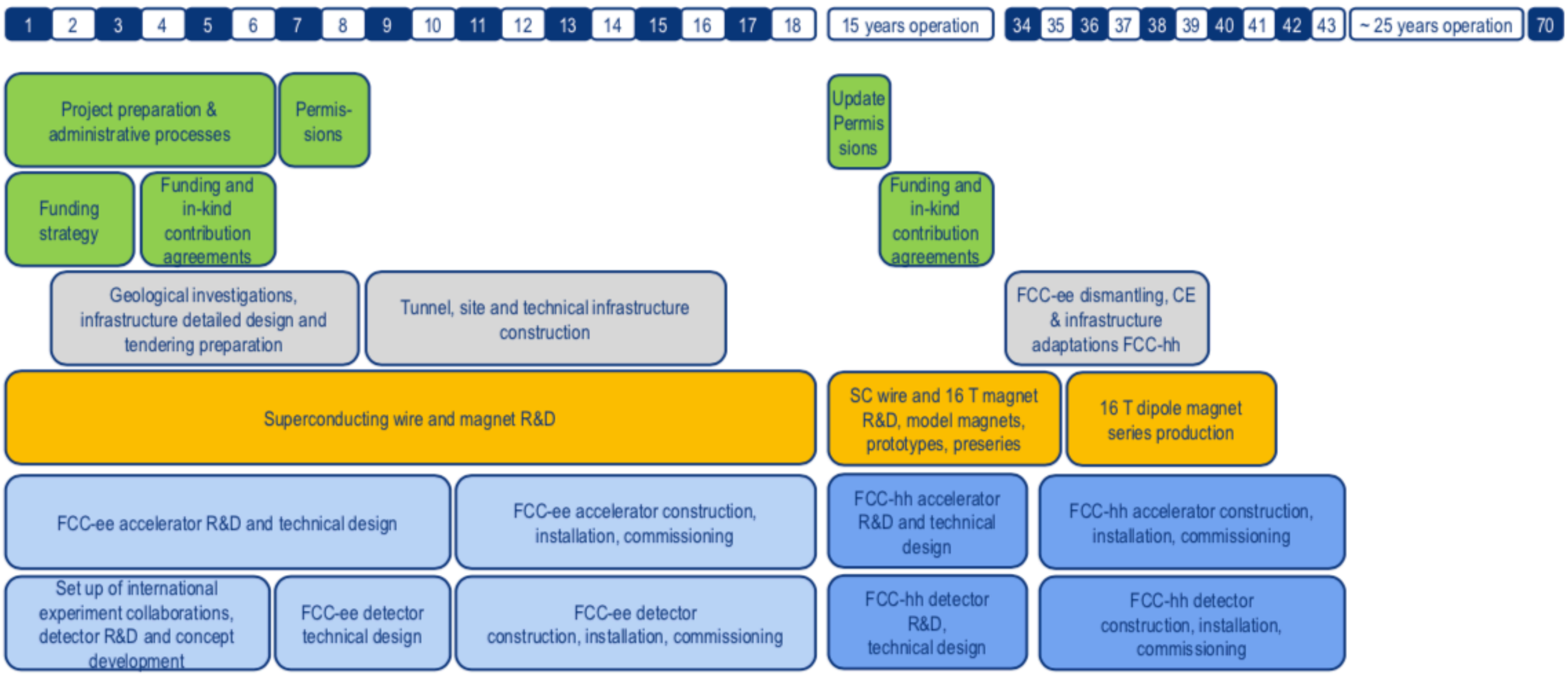
4. The FCC implementation — Timelines

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



4. The FCC implementation — Timelines

- 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?

4. The FCC 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

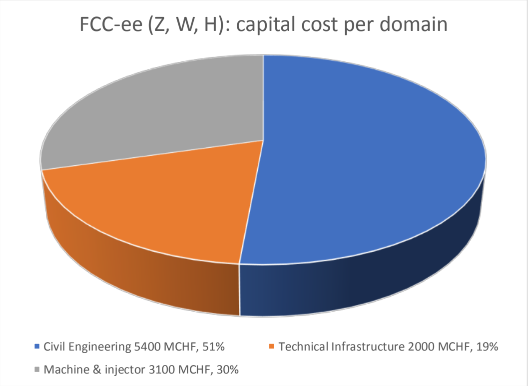
ABSTRACT

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

FCC-ee cost estimate

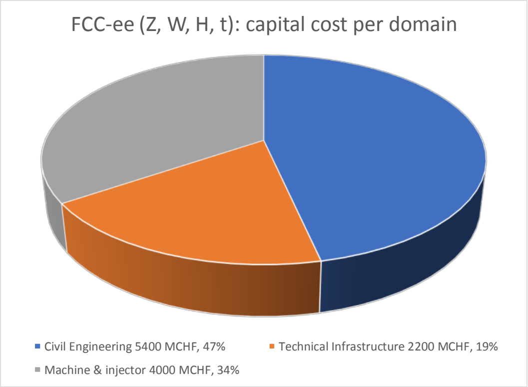
Total construction cost phase1 (Z, W, H) amounts to 10,500 MCHF

- 5,400 MCHF for civil engineering (51%)
- 2,000 MCHF for technical infrastructure (19%)
- 3,100 MCHF accelerator and injector (20%)



Complement cost for phase2 (tt) amounts to 1,100 MCHF

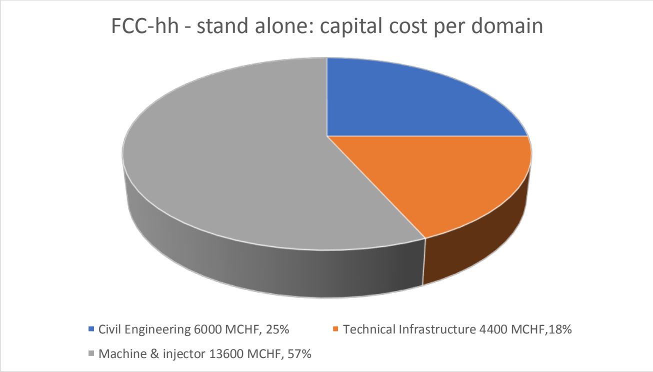
- 900 MCHF for RF, 200 MCHF for associated technical infrastructure



FCC-hh cost estimate

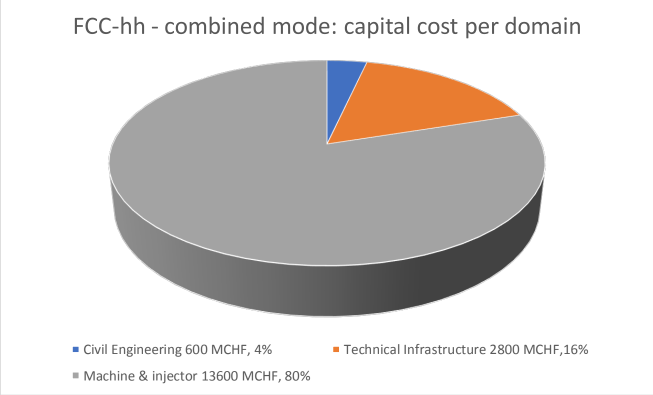
Total construction cost in “stand-alone” is 24,000 MCHF

- 13,600 MCHF accelerator and injector (57%)
  - Major part corresponds to the 4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,400 MCHF, at cost target of 2 MCHF/magnet.
- 6,000 MCHF construction cost for surface and underground civil engineering (25%)
- 4,400 MCHF for technical infrastructures (18%)



Total construction cost in “combined mode” following FCC-ee is 17,000 MCHF.

- CE and TI from FCC-ee re-used
- 600 MCHF for additional CE structures:
  - Two experiment caverns for the lower luminosity experiments
  - Beam dump tunnels and the two transfer lines from LHC
- 2,800 MCHF for additional TI, driven by cryogenics infrastructure



Future Circular Collider Study
Michael Benedikt
Physics at FCC, 4 March 2019
20

6. Outlook - FCC-*hh* and Flavours.

- The *bb* cross-section receives about a factor 5 enhancement at 100 TeV w.r.t. 14 TeV.

- The distinctive feature of FCC-*hh* is however that high-pt Physics is enhanced by a far larger factor (~100).

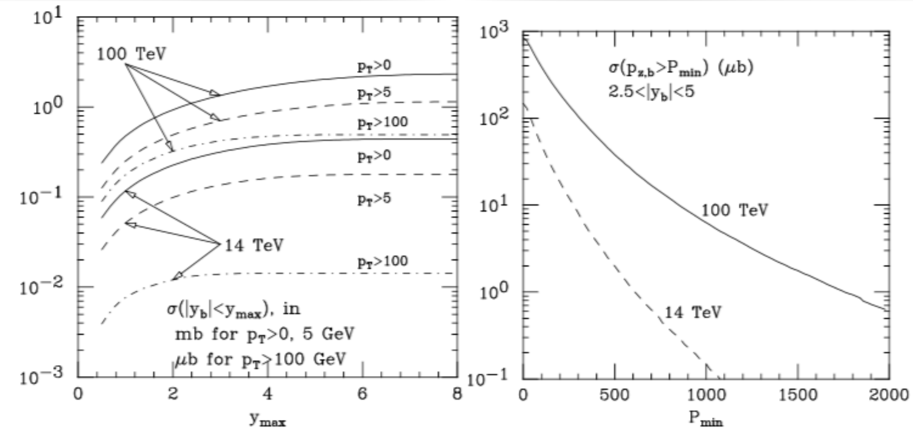


Figure 7.4: Left: production rates for b quarks as a function of detection acceptance in y, for various p_T thresholds (rates in μb for p_T > 100 GeV, in mb otherwise). Right: forward b production rates, as a function of the b longitudinal momentum.

Back

- It was still an early stage to devise a Flavour Physics case for the FCC-*hh* in the CDR. It will be part of the next stage of the Study.

- The progresses in data acquisition and triggering systems of the LHCb upgrades (to cope with high pile-up) will be invaluable in that respect.

6) Summary

- The project is mature. FCC can be done ! The FCC software and detector full simulations are getting up. A good moment to contribute.
- The Flavour Physics case was not yet examined in the initial studies. It is now part of the program in its own right.
- Unique flagship modes have been studied. The core of the program is to be assessed quantitatively. FCC-*ee* precision shall meet or increase the precision of each and both of Belle II and LHCb upgrades (super-complementarity).
- Four interaction points are studied. Plenty of opportunities for dedicated Flavour specifics detector developments.
- The continuation towards Technical Design Report is subjected to the completion of the ESPP update. This happens now.

7) References:

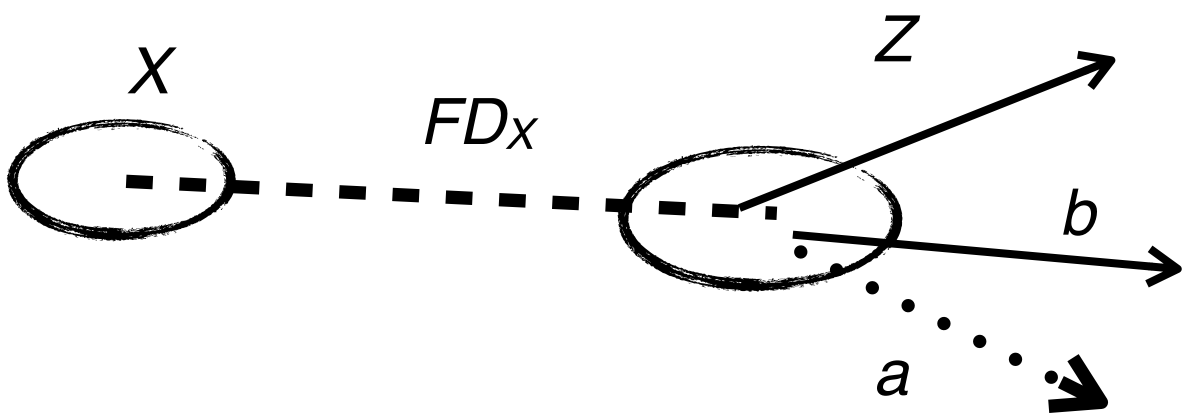
- CDR(s):
  - https://fcc-cdr.web.cern.ch
- FAQs about FCC:
  - https://arxiv.org/pdf/1906.02693.pdf
- Join the Study (a model):
  - https://www.cern.ch/fcc-ee (then join us item and provide your preferences)
  - A successful approach in Flavours has been to gather small groups of experimentalists and 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.

00) Back-up slides

00) Back-up: Vertexing

- One of the most demanding requirement for vertex detectors comes from the missing momentum reconstruction inferred from the decay flight distances.

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



Back

- 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.

00) Back-ups: comments on some modes.

- Where FCC-ee is expected: 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.

00) Back-ups: comments on some modes.

- An obvious unique territory: 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.

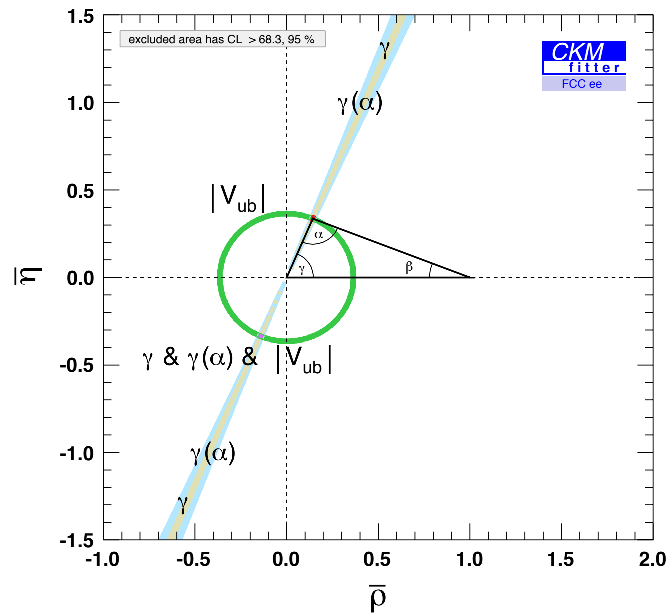
00) Back-ups: machine parameters.

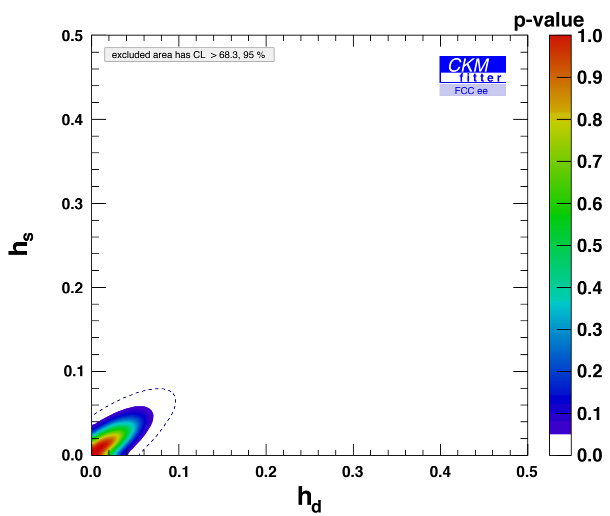
parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS ("weak") [min]	> 200	20	20	25

00) Back-up slides

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_{fs} (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
a^s_{fs} (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2





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