Future Flavours: Prospects for Beauty, Charm and Tau Physics

Future Circular Colliders project (FCC):

a long term vision for Particle Physics including Flavours

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Outline

- The SM in a glance and the open questions.
- Introduction to the Future Circular Colliders project.
- The electron machine and some prototype detectors.
- Physics case at large.
- Flavours Physics in the FCC landscape and detector challenges.
- Implementation as an outlook.

Scientific context: SM became a theory

The free parameters of the SM:

- $SU(2)_L \otimes U(1)_Y$ unification:
  - the weak and electromagnetic coupling constants $\boldsymbol{G_F / g_W}$ **and** α_{EM}.
- After the spontaneous breaking of the symmetry:
  - The nine masses of the fermions: $\boldsymbol{m_f}$.
  - The masses of the electroweak gauge bosons: $\boldsymbol{m_Z}$ **and** $\boldsymbol{m_W}$.
  - The scalar sector parameters: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$

    $\boldsymbol{v}$ **(the v.e.v) and** $\boldsymbol{m_H}$ **.**

1) Scientific context: SM became a theory

The free parameters of the SM

- The CKM matrix elements : it's a 3X3 complex and unitary matrix and hence can be described by means of only **4 independent parameters**. As the masses of the fermions (except for the top quark), these 4 parameters are decoupled from the rest of the theory.

- If you like QCD in (and you do), just add α_s (and $\theta^{S}{}_{CP}$).

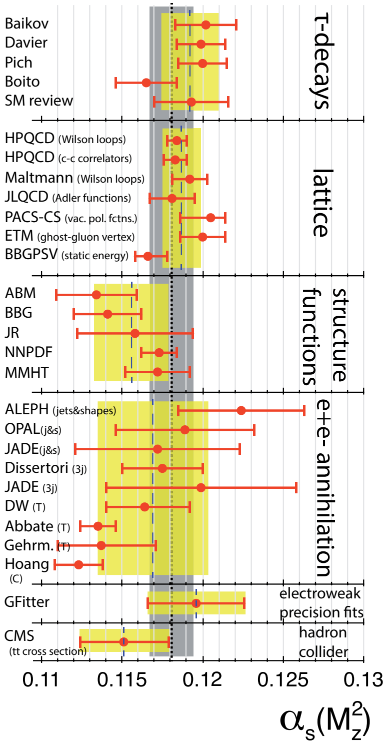
- Neutrino oscillations are implying neutrinos to be massive and to mix → 7 parameters to minimally describe them.

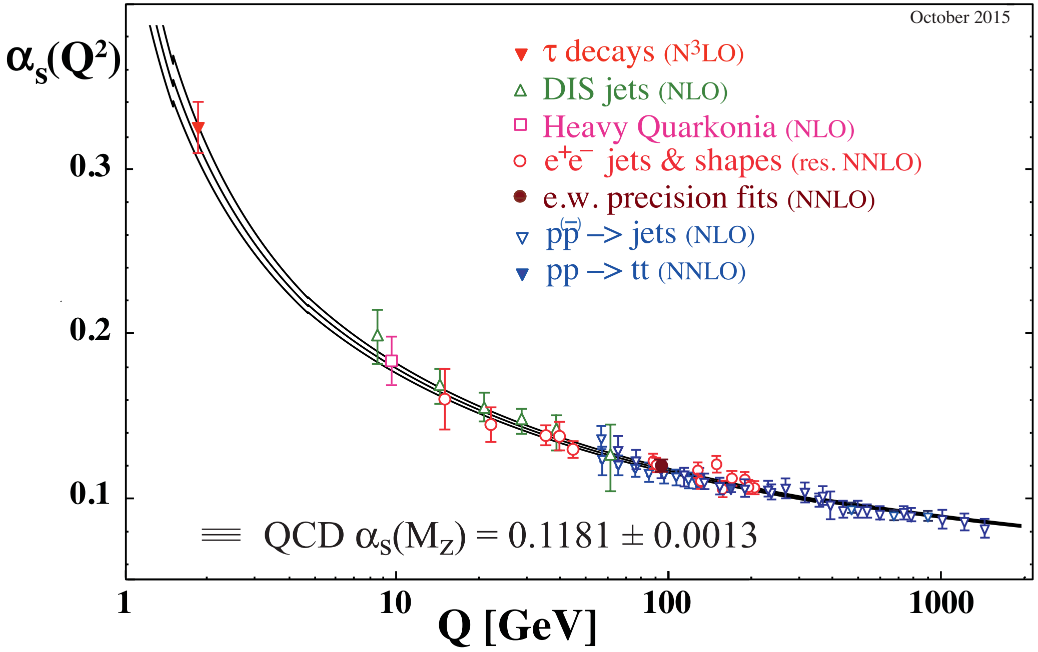
- The number of parameters amounts to 20 (28 w/ neutrinos and strong CP). Not all of them are independent though.

1) Scientific context: SM became a theory

Reorganisation:

- QCD and α_s : LEP and others did great already. Limitation of the consistency test is not yet fully on the theory side for most of the determinations.



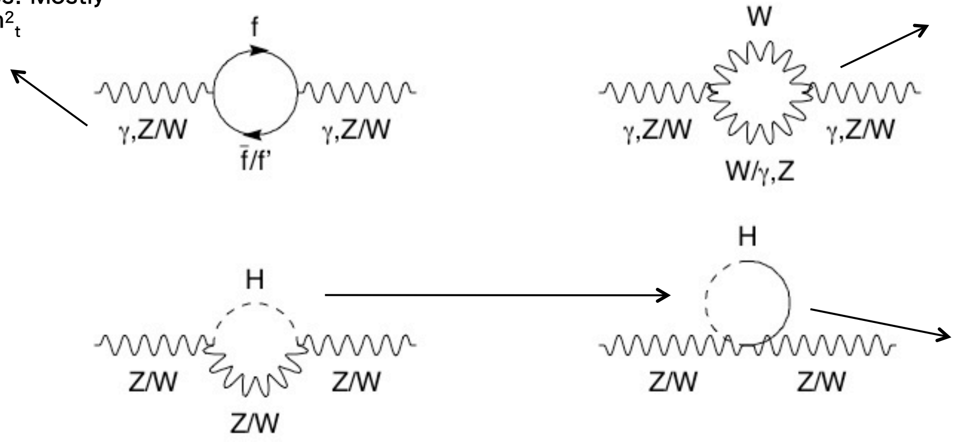


- A better α_s determination is desirable, and in order for advanced predictions (QCD x-sections, Higgs decays, top mass, *Z* width, R_b, R_l).

1) Scientific context: SM became a theory

Reorganisation:

- The nine masses of the fermions: $\boldsymbol{m_f}$.
- They are for 8 of them decoupled from the rest of the SM parameters.
- Nothing much to do here as well till the moment a theory comes with a prediction.
- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular), *e.g.*



Top dominates. Mostly sensitive to m^2_t

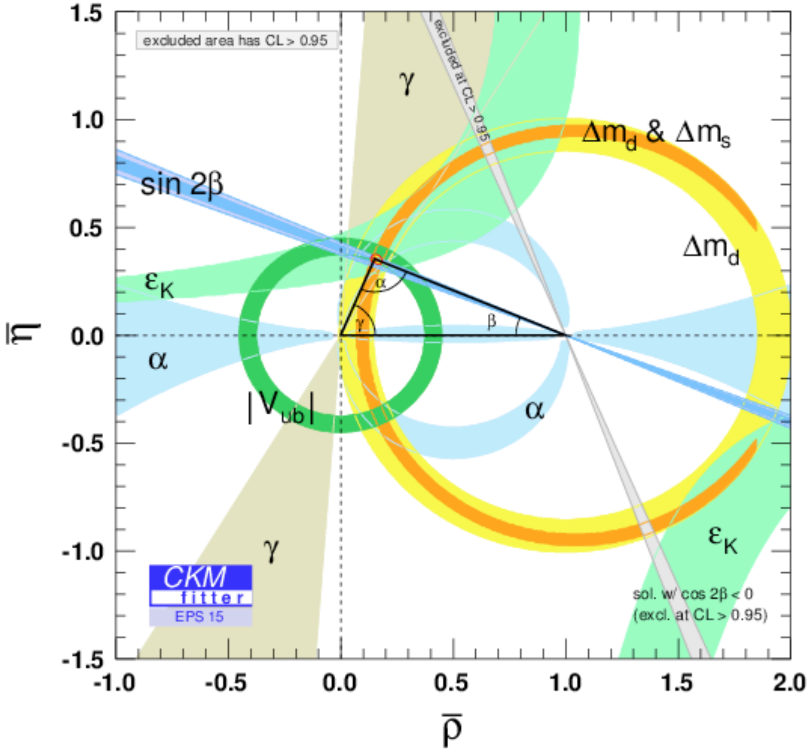
Non abelian structure of the EW theory. TGC.

Scalar sector. Contains Higgs mass info.

1) Scientific context: SM became a theory

Reorganisation:

- The (4) CKM matrix elements (decoupled from the rest of the theory). The consistency check of the SM hypothesis in that sector is a pillar of the SM:



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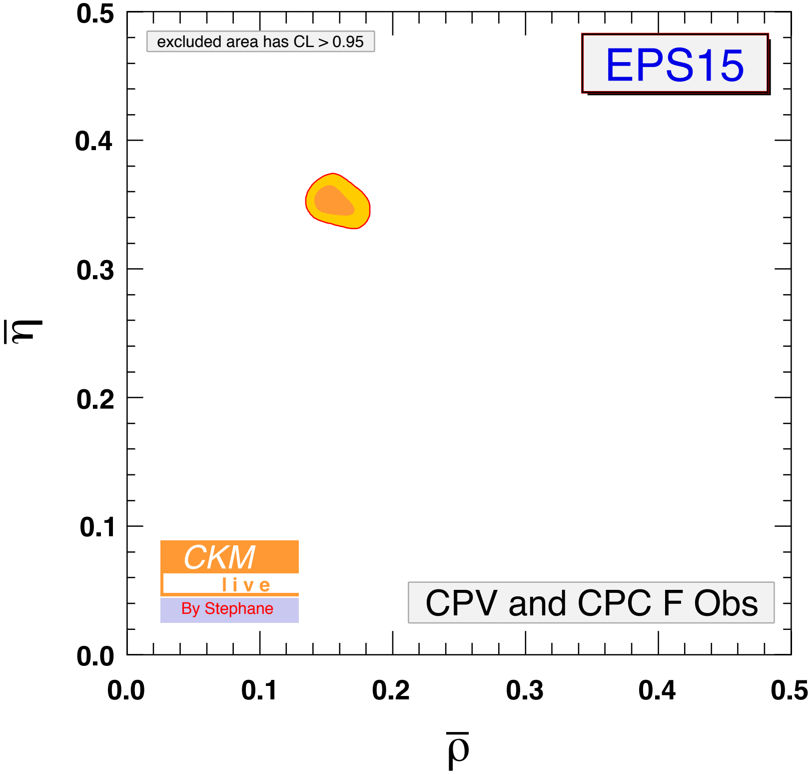
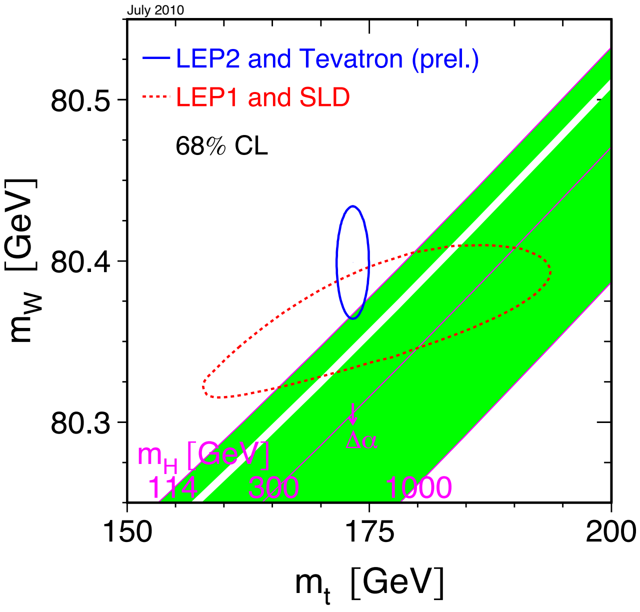
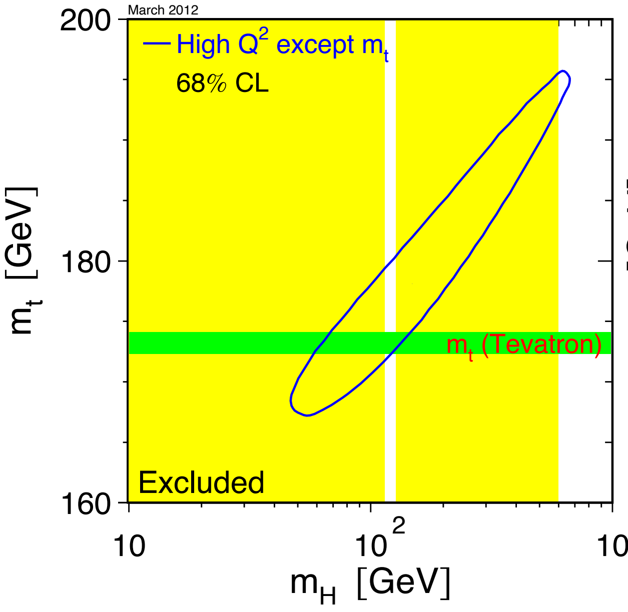


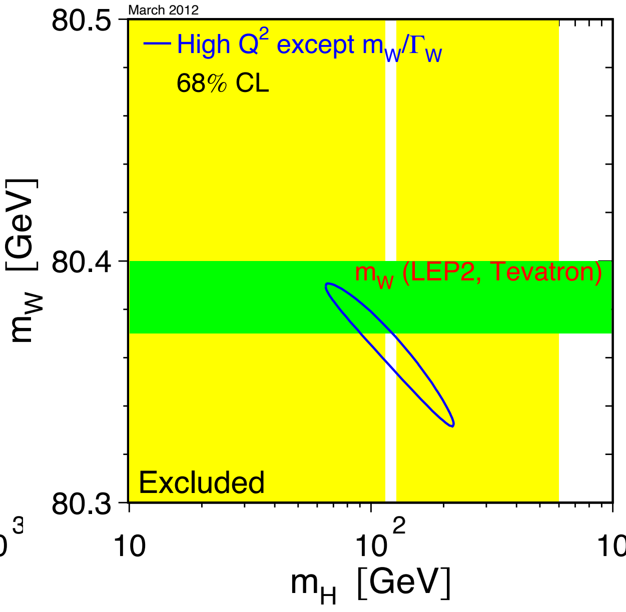
1) Scientific context: SM became a theory

Reorganisation:

- The rest of the free parameters are part of the so-called electroweak precision observables consistency check. This is the other pillar of the SM. Fix G_F, α_{EM} and m_Z at their measured value and produce a prediction of m_{top}, m_W and m_H. A tremendous success !



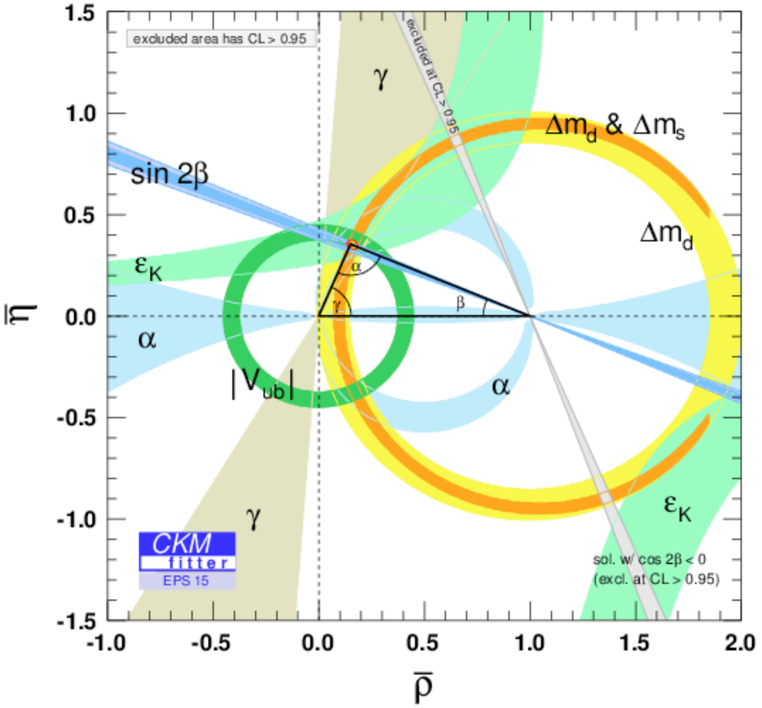


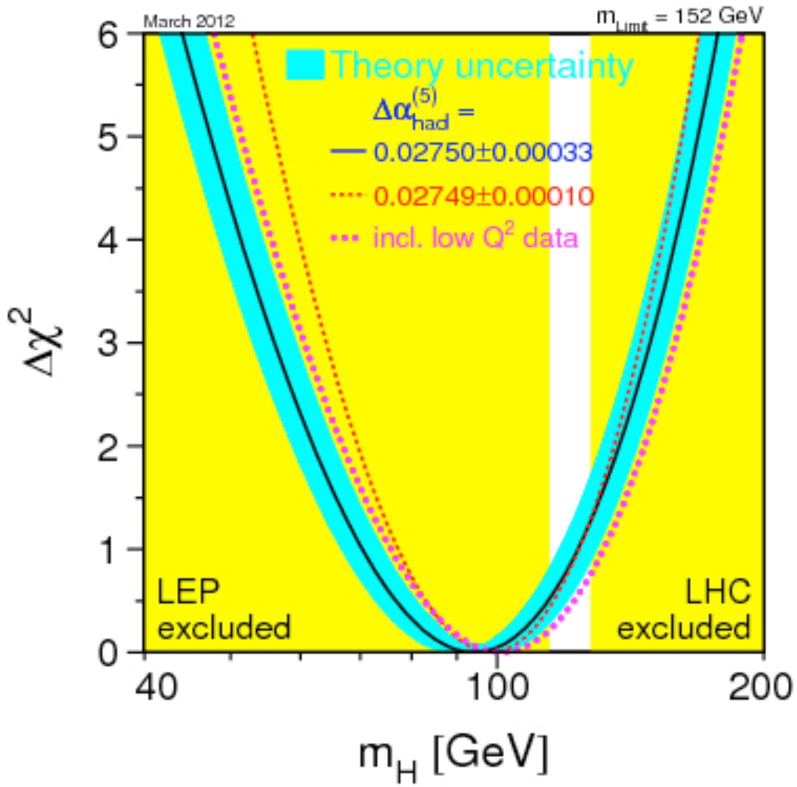


1) Scientific context: SM became an (invincible) theory

Recap:

- Two pillars: EWPT and Flavours.





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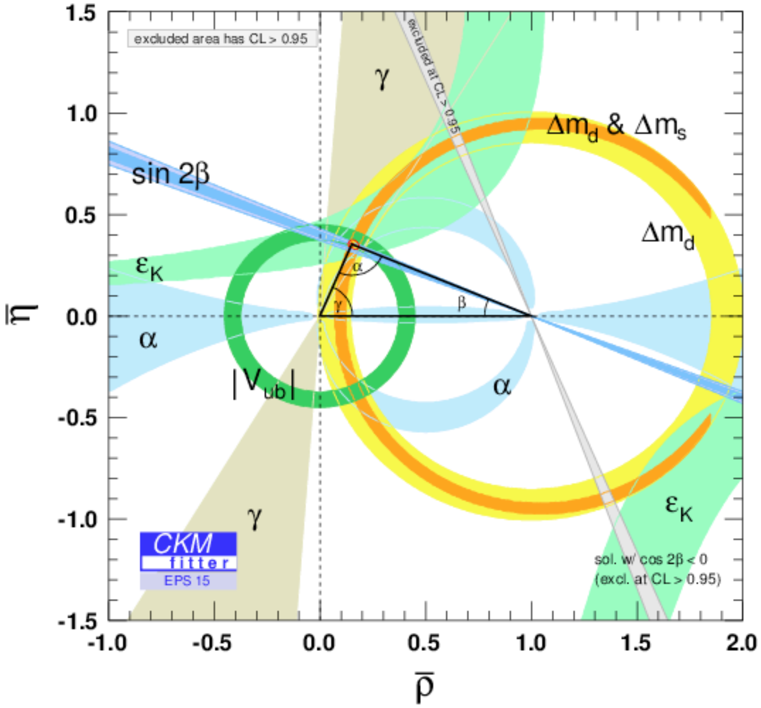

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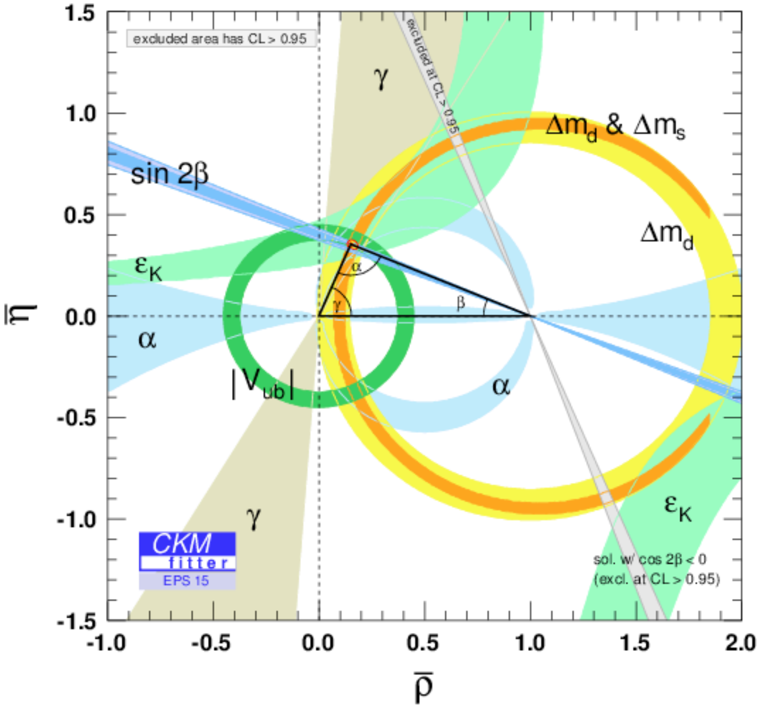

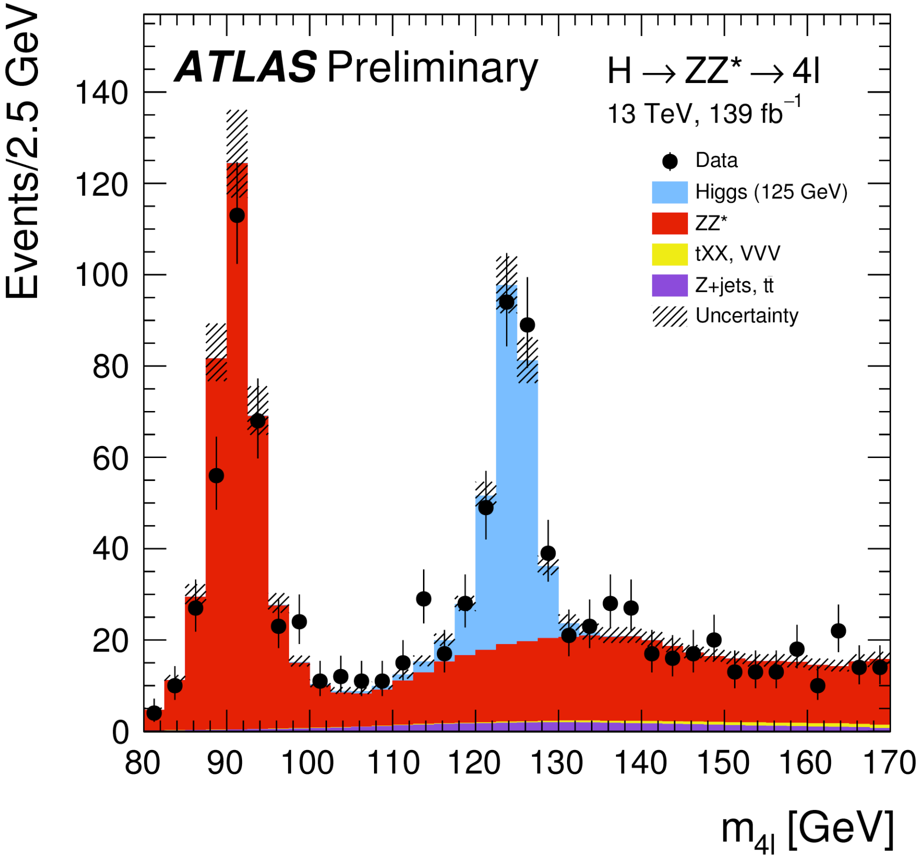

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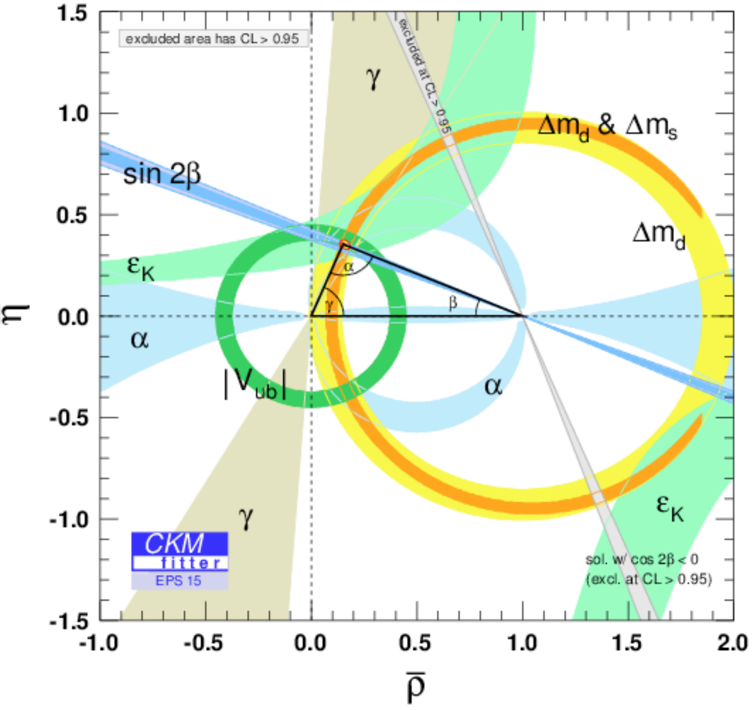

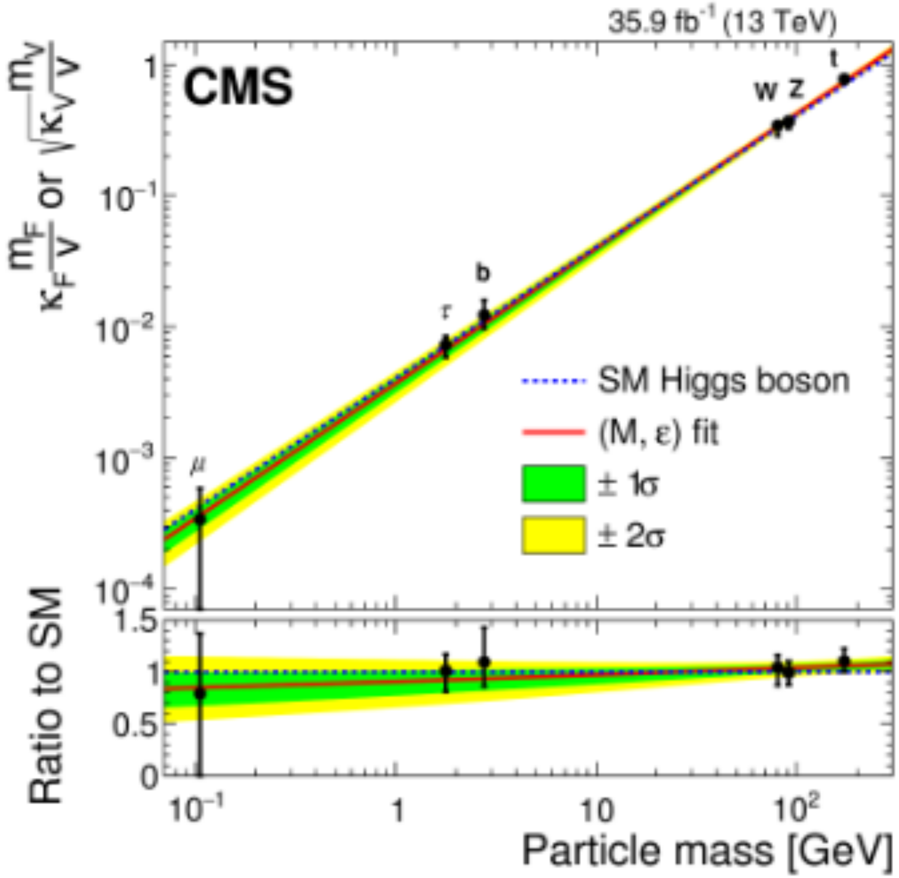

1) Scientific context: SM became an invincible theory

Lessons

- The SM has cleared so far the attacks from LEP, TeVatron, *B*-factories, LHC and single-observables experiments.
- There are compelling beauty arguments for Beyond Standard Model (BSM) Physics. I will overlook them.
- Instead, three indisputable measurements/observations are crying for BSM:
  - The neutrinos have a mass. Though several ways exist theoretically, it's tempting / natural to enhance the neutral particle content with right-handed states.
  - Dark matter: a nice (recent-ish) evidence for cosmological dark matter is the observation of a low surface brightness galaxy [ArXiv:1606.06291].
  - Baryonic asymmetry in the Universe.

1) Scientific context: scenarii

1) Find a new heavy particle at the Run III of LHC:
   - HL-LHC can study it to a certain extent.
   - If mass is small enough (and couples to electrons), CLIC can be the way.
   - Larger energies are needed to study (find) the whole spectrum.
   - The underlying quantum structure must be studied.

2) Find no new particle, but non-standard *H* properties
   - HL-LHC can study it to a certain extent.
   - Higgs factory.
   - *Z*, *W*, top factories for the quantum structure.
   - Energy frontier (also for precision measurements)

3) Find no new particle, standard H properties but flavour observables departing from SM:
   - *Z*, *W*, top factories for the quantum and flavour structure.
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1) From Scientific context to the introduction to FCC

2. 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

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FCC Kick-Off 2014

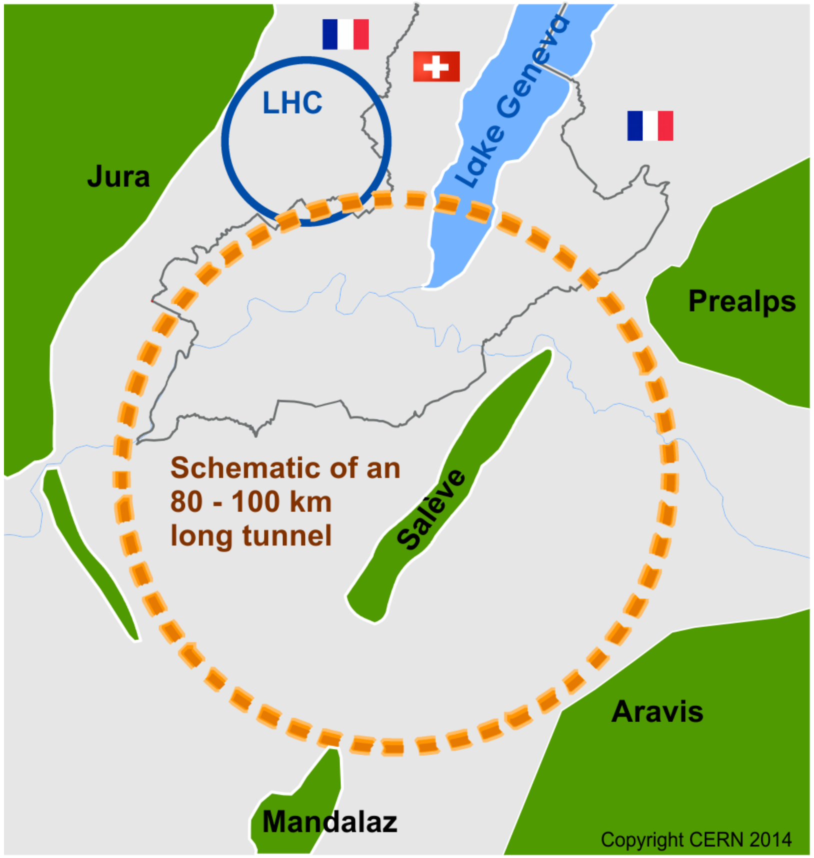
3

- 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.

2. Introduction to FCC: the scope of the project

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

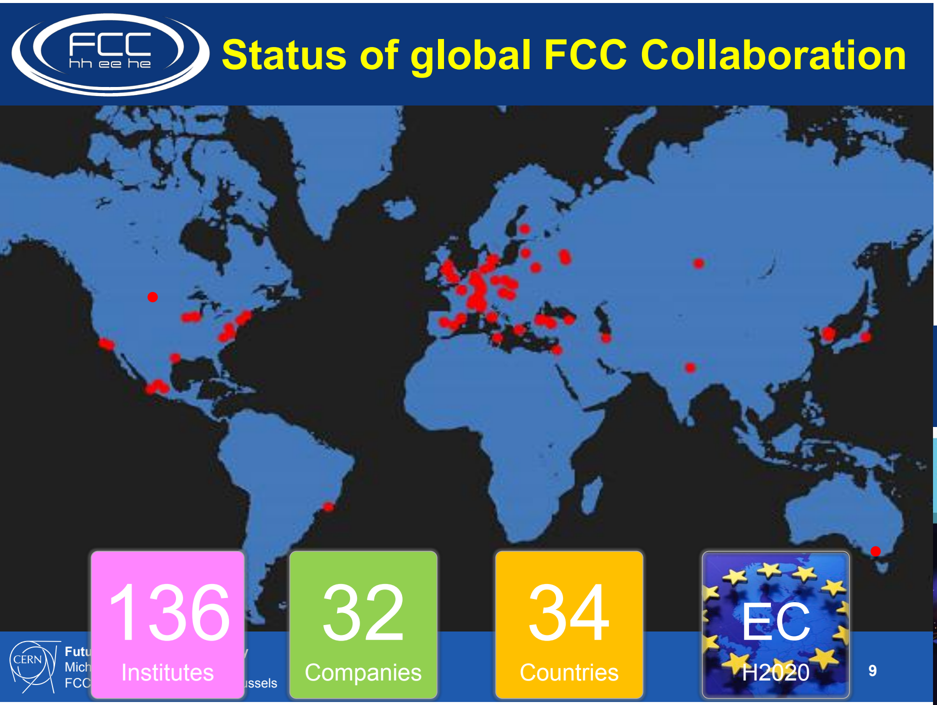
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



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

2. Introduction to FCC: the completion of the CDR

The Design Study is completed and fulfilled the mandate



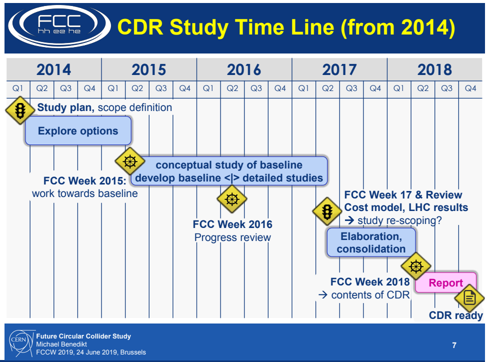
Status of global FCC Collaboration

136 Institutes

32 Companies

34 Countries

EC H2020



CDR Study Time Line (from 2014)

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FCCW 2019, 24 June 2019, Brussels

7

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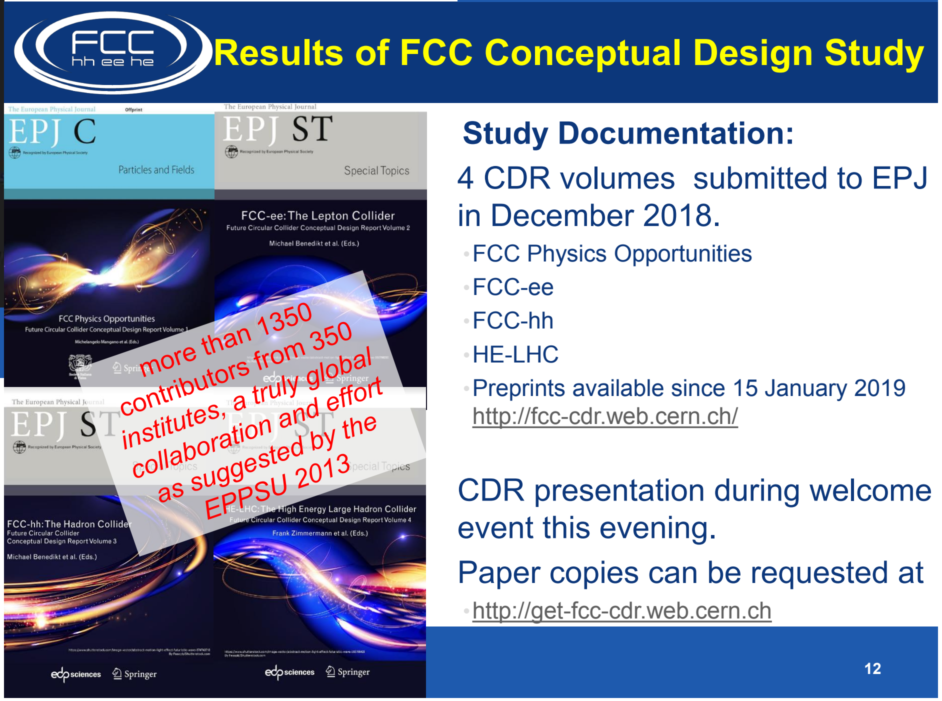


Results of FCC Conceptual Design Study

more than 1350 contributors from 350 institutes, a truly global collaboration and effort as suggested by the EPPSU 2013

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.

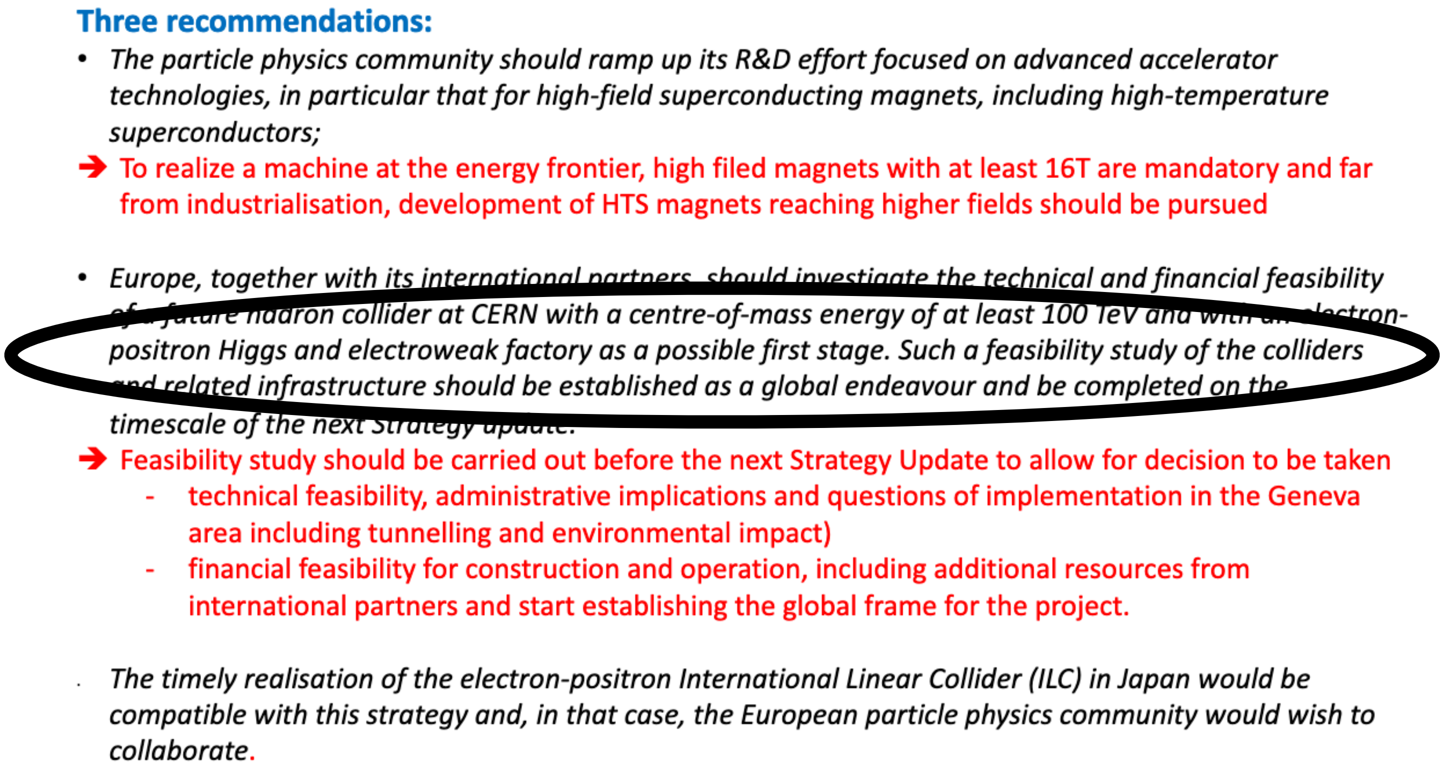
Paper copies can be requested at

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

12

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

2. Introduction to FCC: the ESPP update



Three recommendations:

- *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*

➔ To realize a machine at the energy frontier, high filed magnets with at least 16T are mandatory and far from industrialisation, development of HTS magnets reaching higher fields should be pursued

- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

➔ Feasibility study should be carried out before the next Strategy Update to allow for decision to be taken
  - technical feasibility, administrative implications and questions of implementation in the Geneva area including tunnelling and environmental impact)
  - financial feasibility for construction and operation, including additional resources from international partners and start establishing the global frame for the project.

- *The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.*

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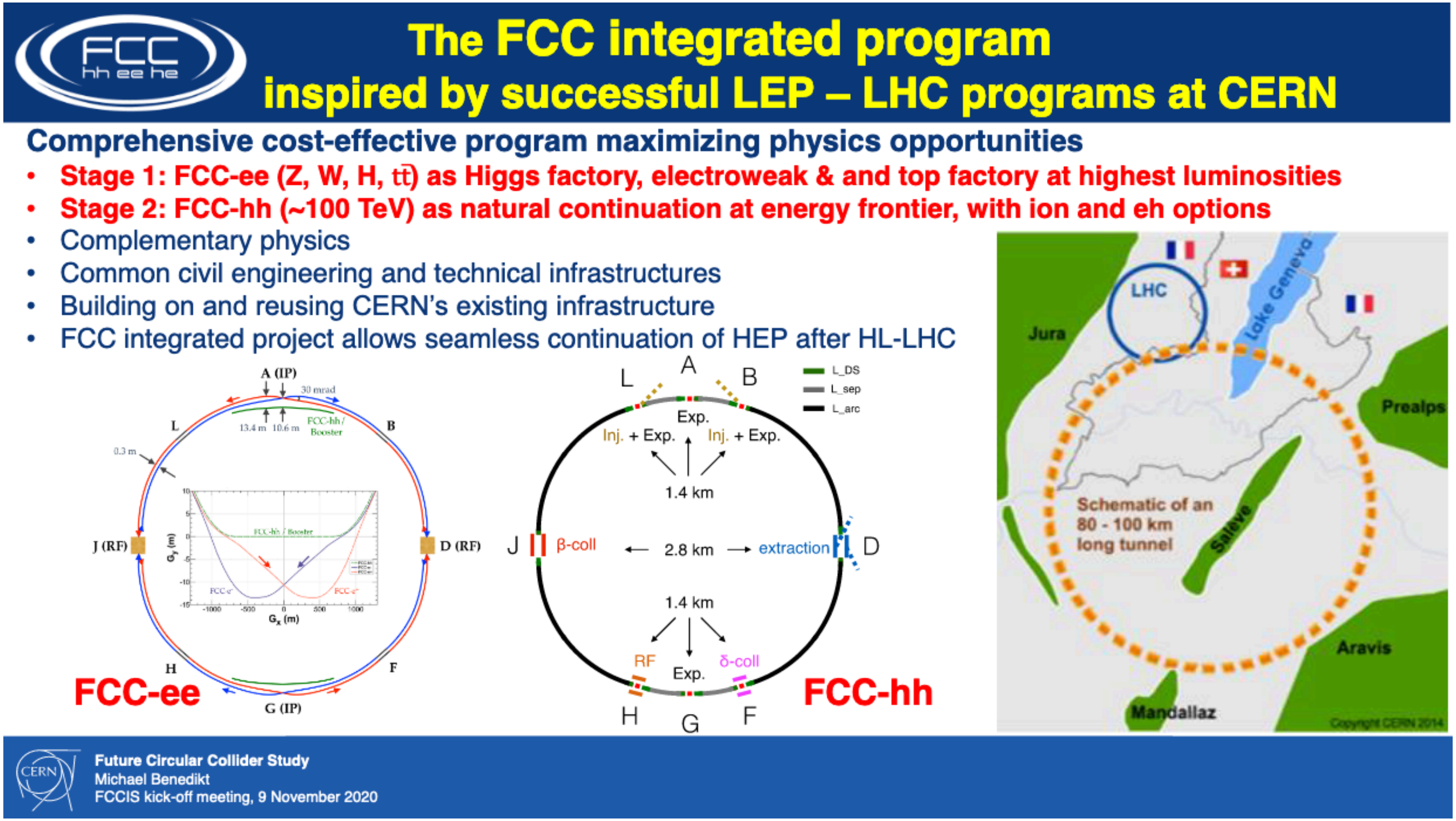
Note that everything is written in such a way that proponents of each and every large scale projects can read it happily. Yet,

“the vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC ” ESPP 2020 d’après d’Hondt.

2. Introduction to FCC: same scope after ESPP



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

Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and 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 HL-LHC

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FCCIS kick-off meeting, 9 November 2020

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2. Additional comments:

“the vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC ” ESPP 2020 d’après d’Hondt.

- FCC-*ee* can’t happen before the completion of the HL-LHC program.
- FCC-*ee* shall happen seamlessly after HL-LHC.
- FCC-*hh* is foreseen after FCC-ee. The Higgs Physics program is inclusive (FCC-*hh* invincible for trilinear *H* couplings). The Flavour Physics program at FCC-*hh* is simultaneously appealing but subjected to in depth studies in light of LHCb U2.
- Link to the slide.
- Focus on the electron machine in the following.

2) From Introduction to FCC to the machine elements & detectors

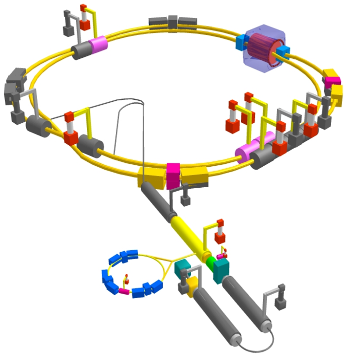
3. The FCC e^+e^- machine. Baseline design

- 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 (given next slide).

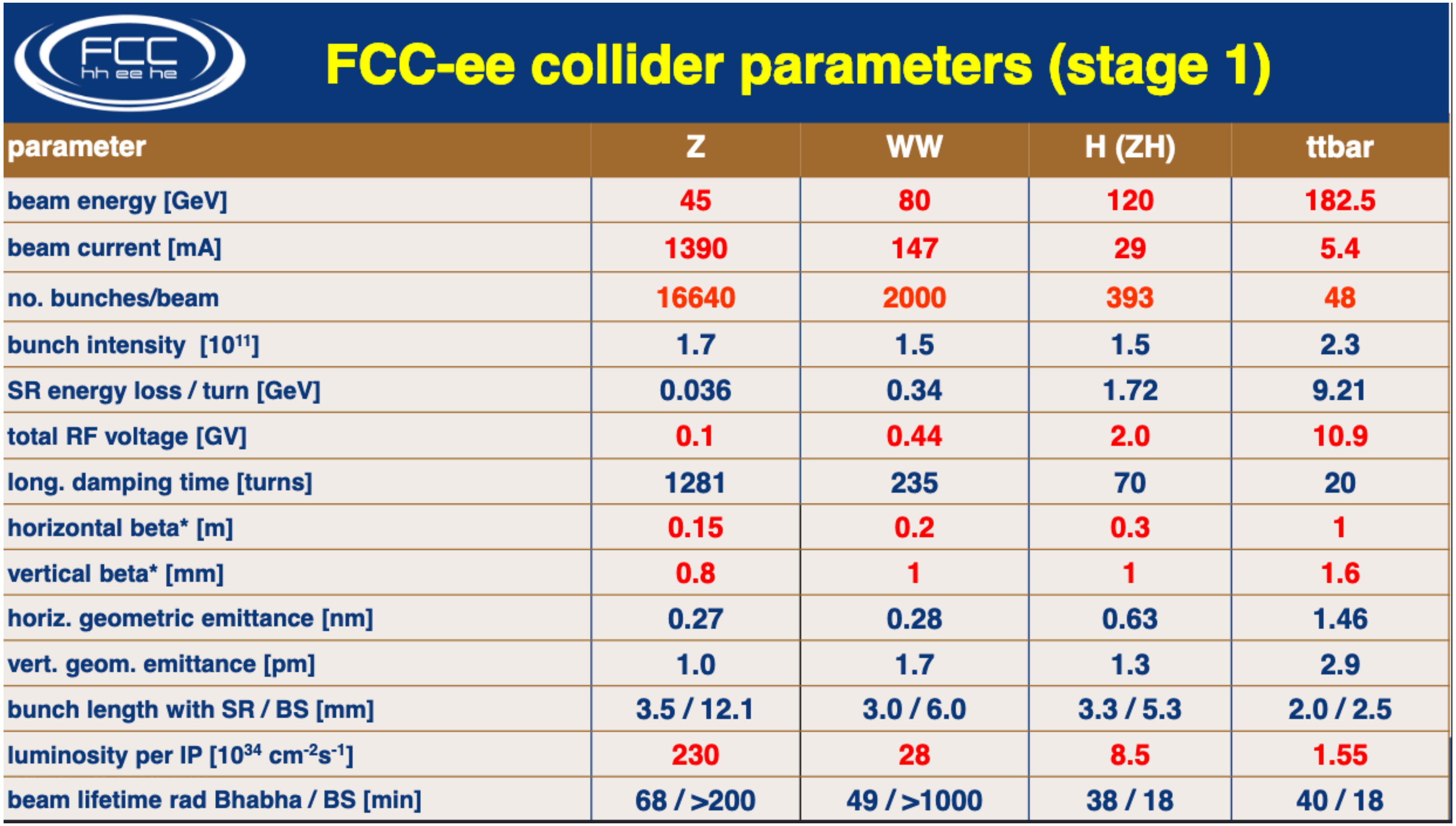
- To some extent, SuperKEKB is already meeting or about to meet some of the challenges of FCC-*ee:*



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

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

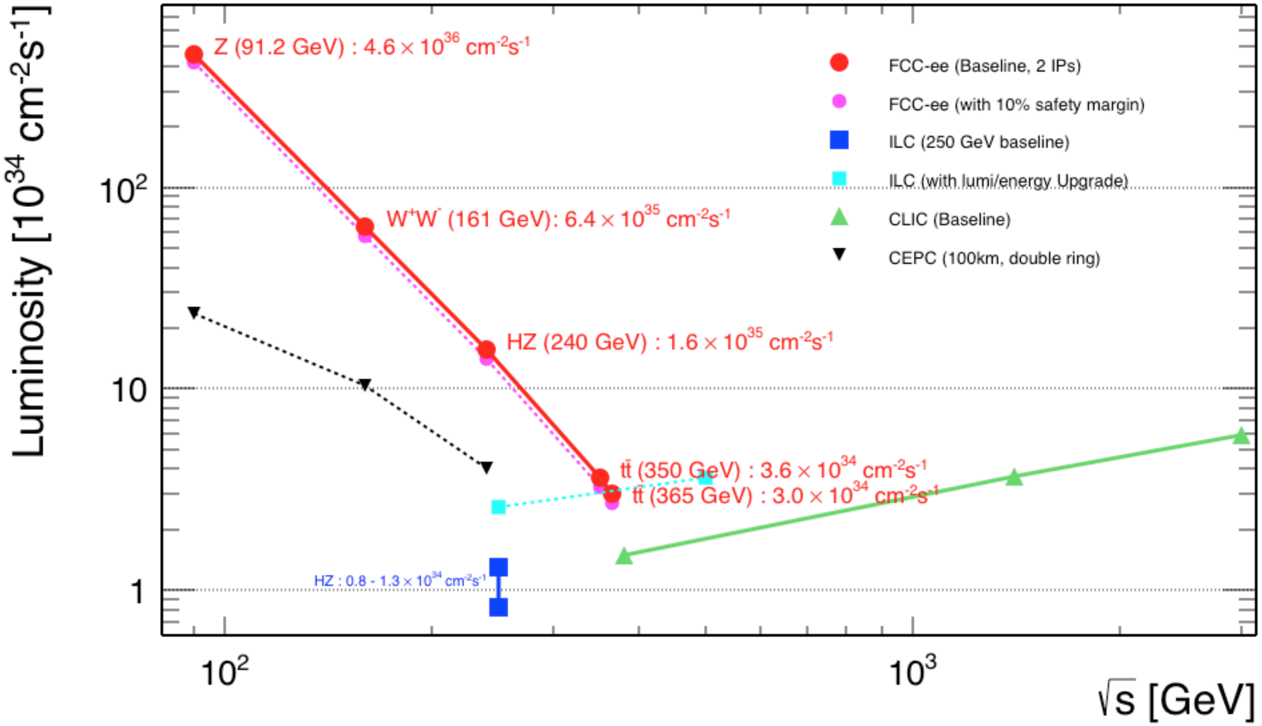


FCC-ee collider parameters (stage 1)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

- There seem to be several machines actually.

3. 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. In particular, you do the LEP in a minute!

3. 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.

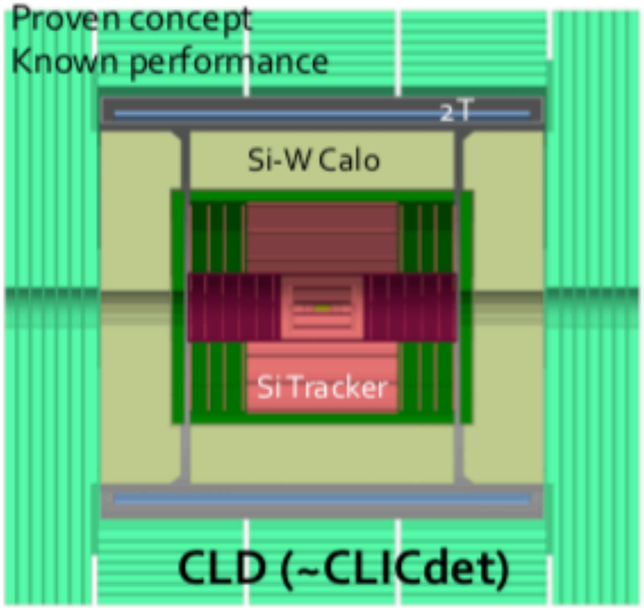
- Of particular relevance for the Flavour Physics is the Z pole (2 IPs — 4 are considered):

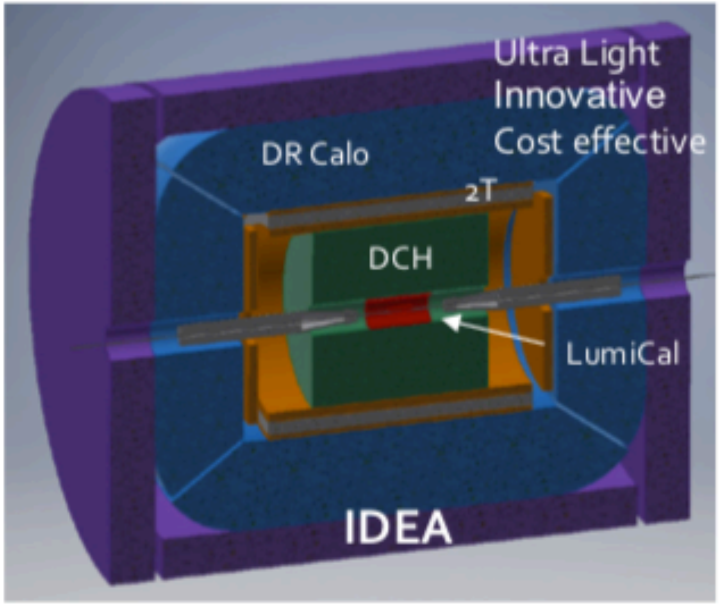
Particle specie at FCC-ee	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$) [for 5.10^{12} Z]	310	310	75	65	$1.5^\dagger$	600	180

- 20 times Belle II for B^0 and B^+

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

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





- Two designs have been studied so far (and used to assess performances)
- 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, vertexing and calorimeter.

3) From machine & detectors to the Physics case / reach

Be it only for the accurate study of the Higgs-boson decays, an electron collider is the way to go.

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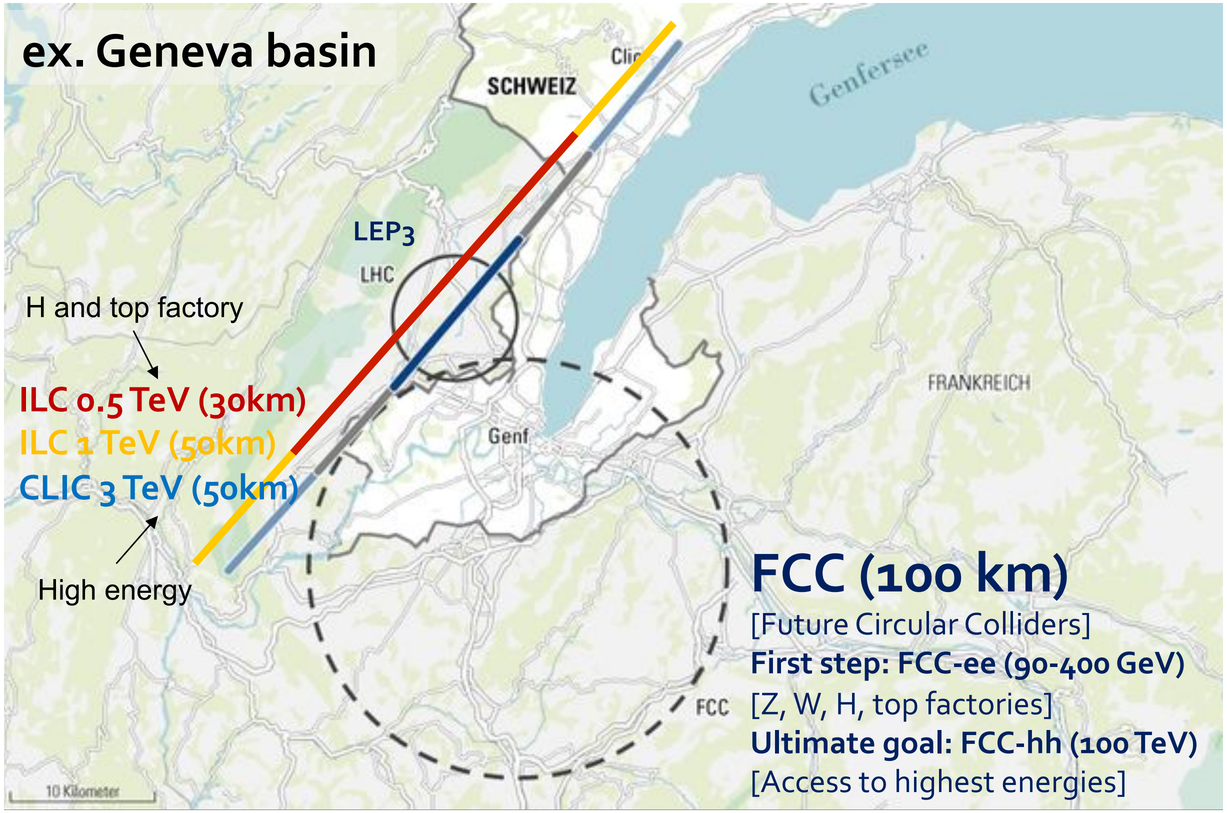
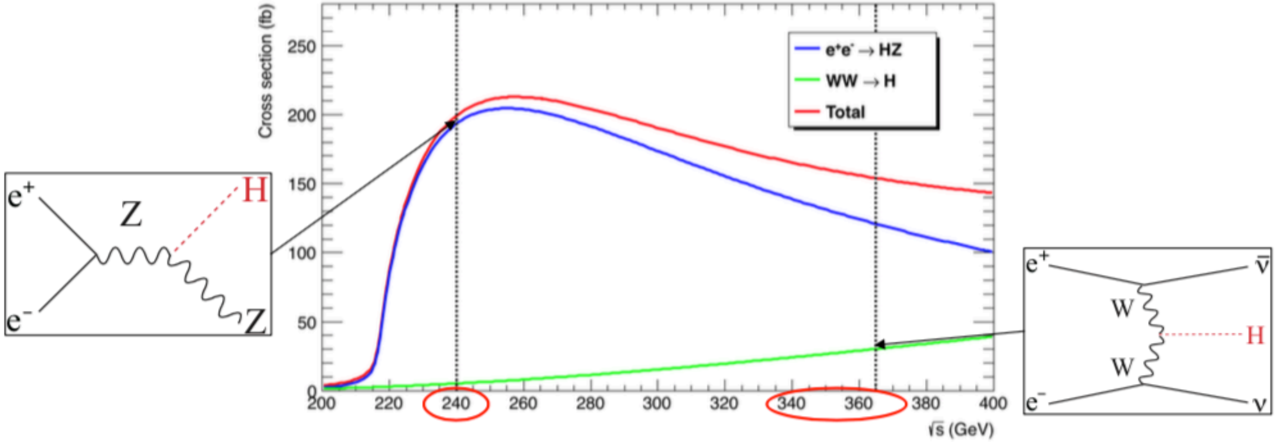
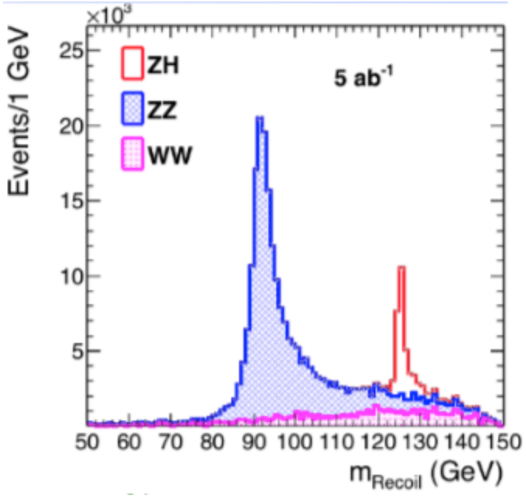


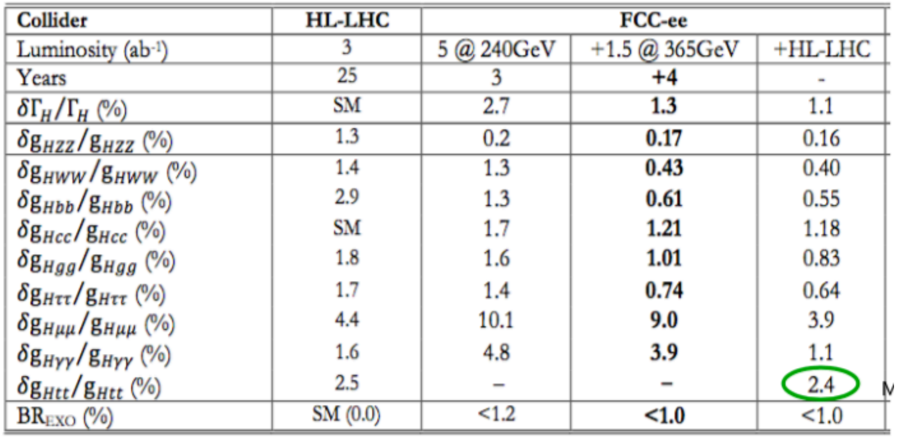
4) Physics case — Higgs chapter

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



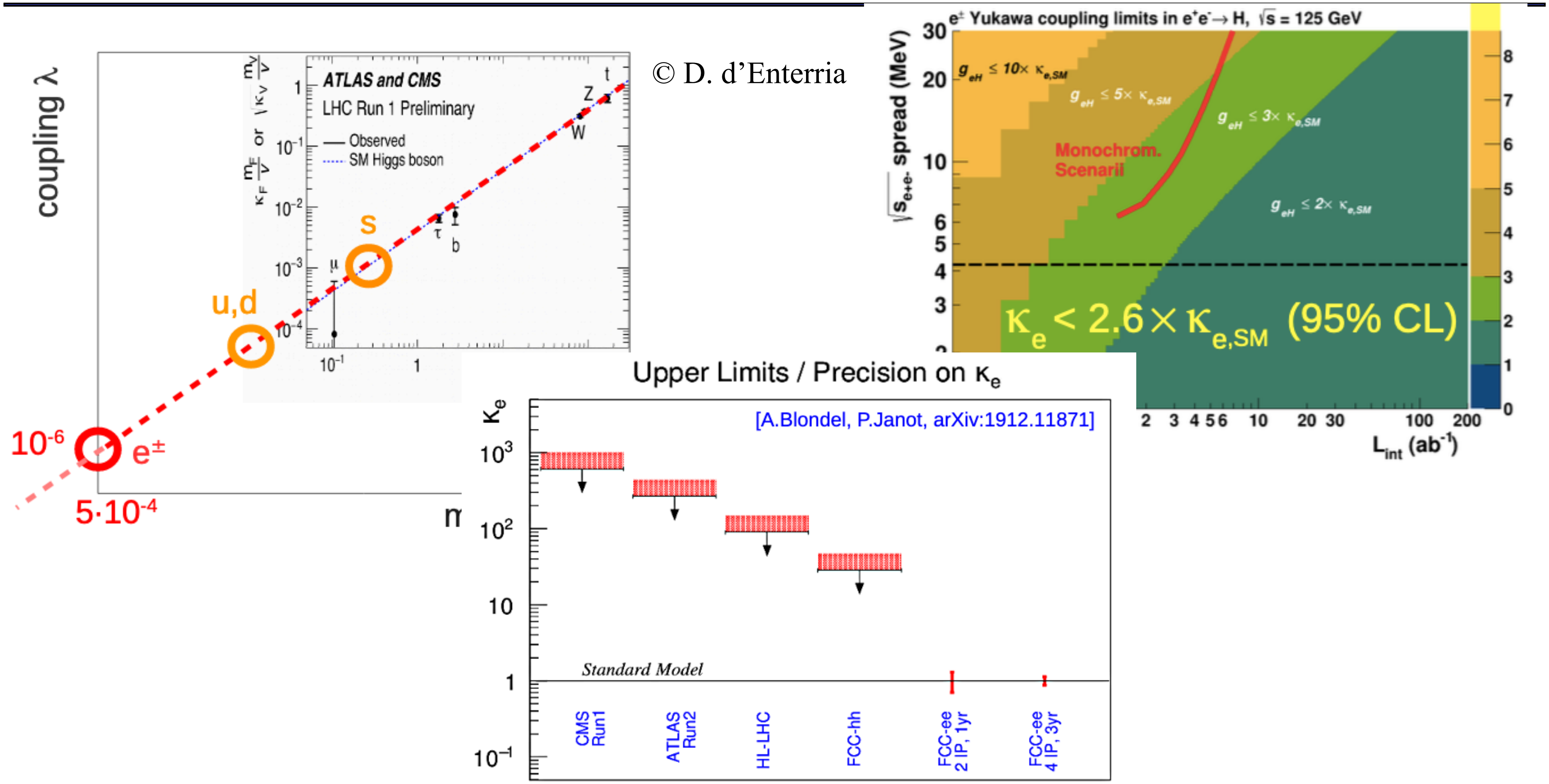
- Invincible precision on the absolute couplings and width. Interplay with HL-LHC.





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

4) Physics case — Higgs chapter — Even the electron Yukawa?



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[A.Blondel, P.Janot, arXiv:1912.11871]

- The name of the game is to control the beam energy to touch the natural width of the Higgs boson. Monochromatisation technique.
- Tells you how exquisite can be the luminosity.

4) Physics case — EWPT chapter (including WW and top thr.)

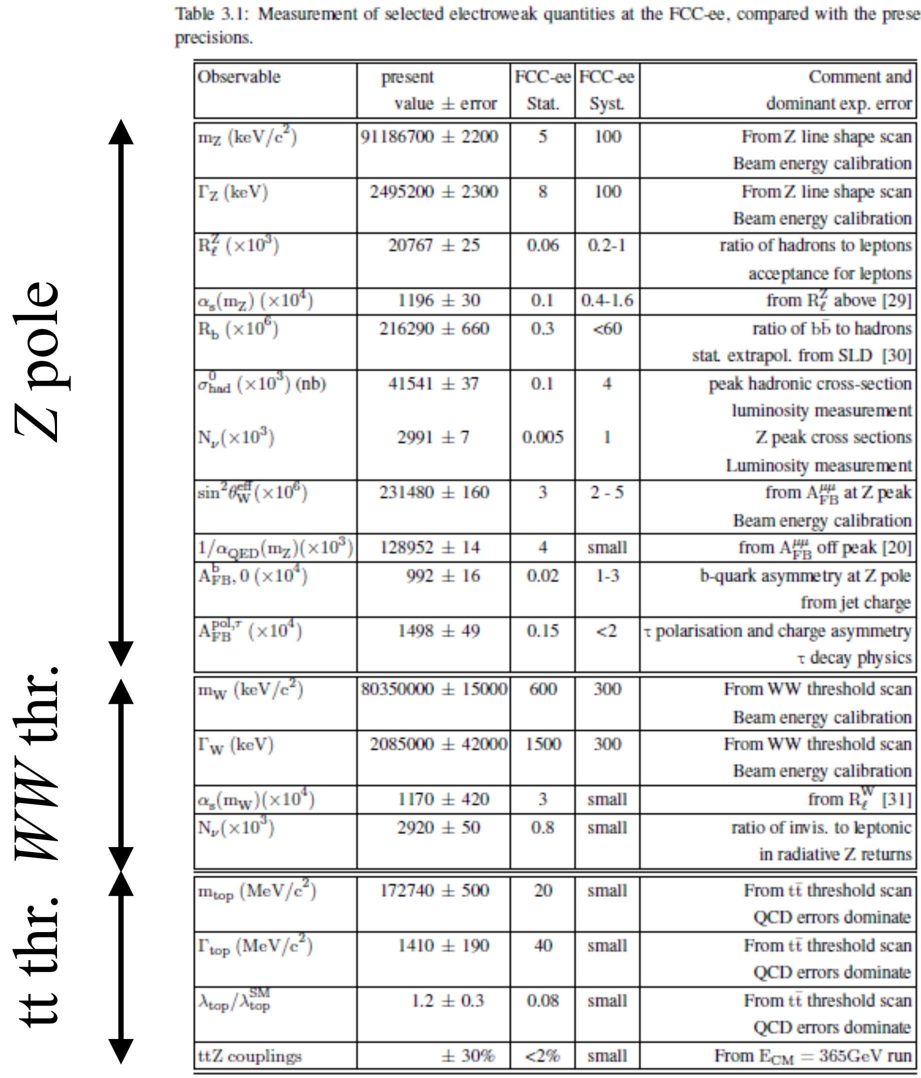
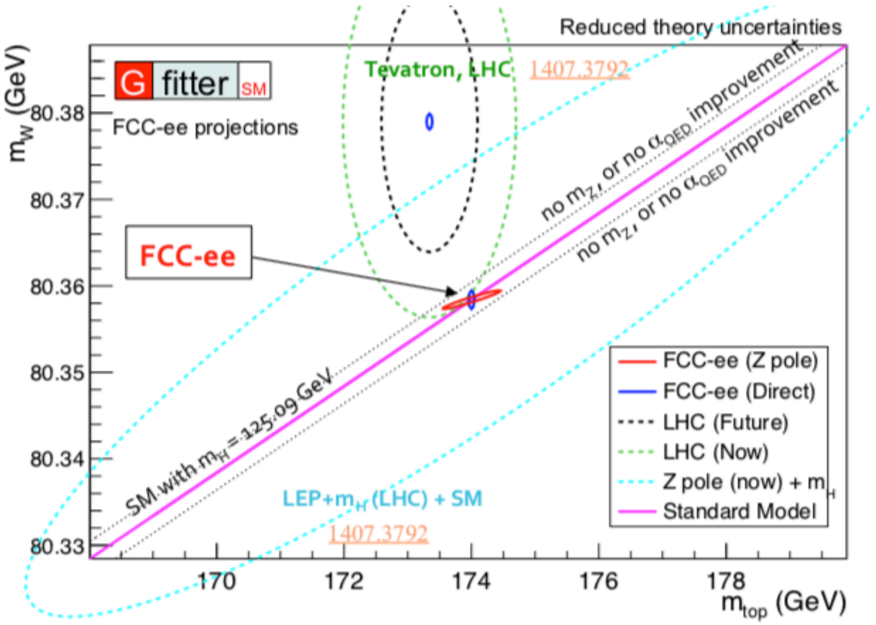


Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

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
$\alpha_s(m_W)$($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
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



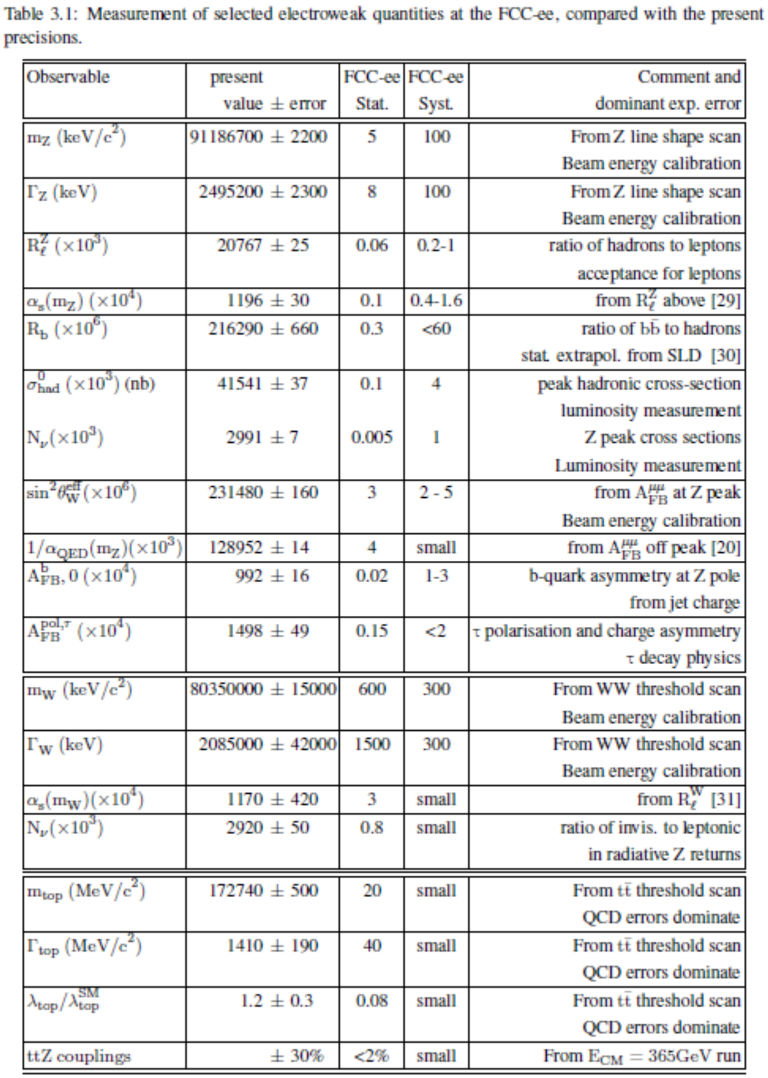
- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program.

4) Physics case — EWPT chapter

Z pole

WW thr.

tt thr.



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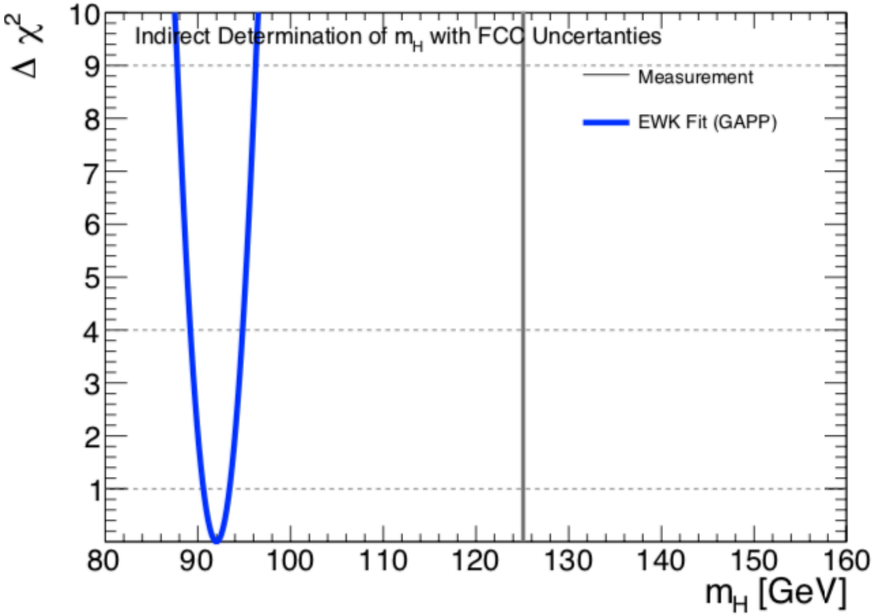
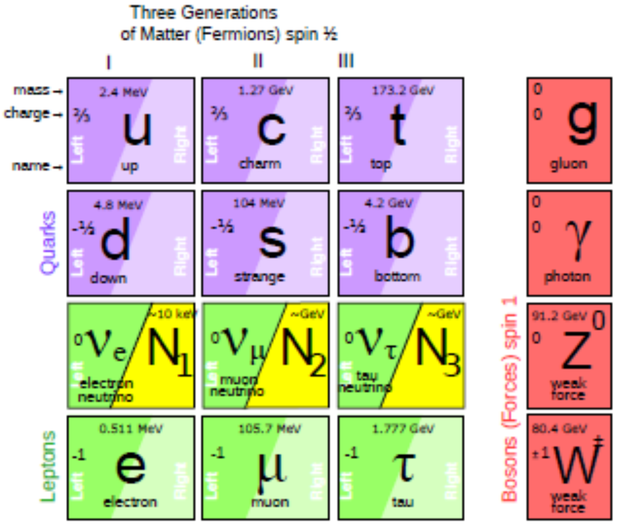
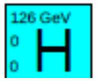


- Ultimate quantum completeness consistency test of the SM.
- The improvements in theory prediction precision is part of the FCC program. Precision 1.4 GeV.

4) Physics case — Miscellanea chapter; some favourites.

- Higgs, top and EWK precision physics do not saturate the case.
- Many BSM direct searches thanks to the exquisite luminosity.
- Here are direct searches for heavy neutral leptons.





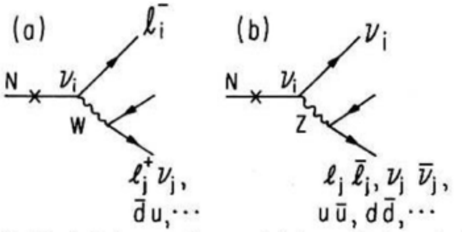
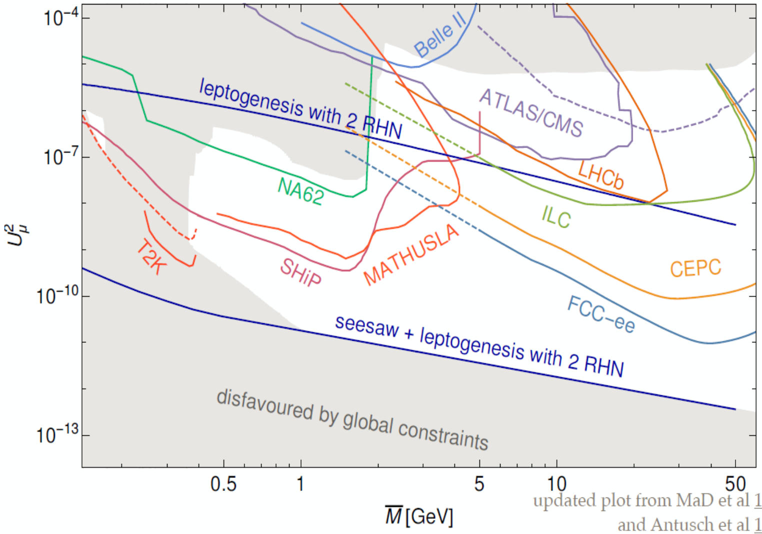


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

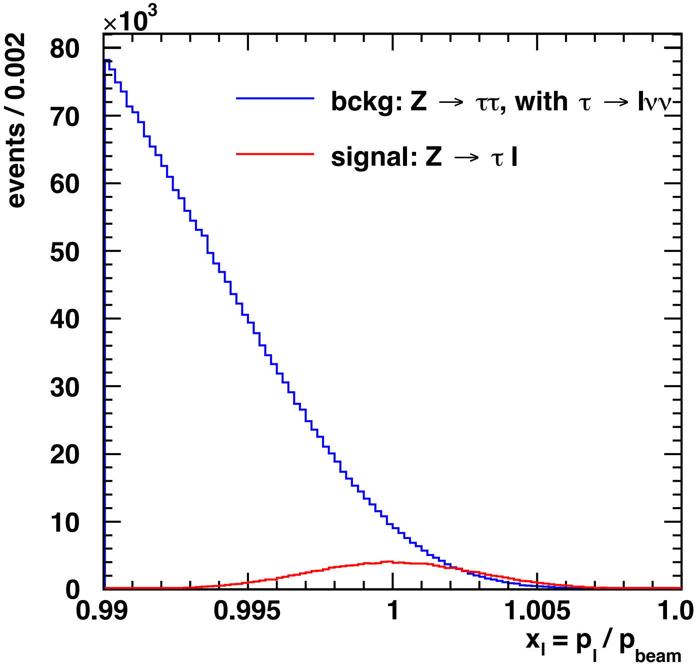


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

4) Physics case — Miscellanea chapter; some favourites.

- Higgs, top and EWK precision physics do not saturate the case.
- Many BSM direct searches thanks to the exquisite luminosity.
- Lepton Flavour violating *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]. $Z \rightarrow \tau\mu/e$ is unique at FCC.
- The dominant background is ($Z \rightarrow \tau\tau$), 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* (beam spread equivalent resolution at 45 GeV), the current limits are pushed by three orders of magnitude.

4) From general Physics case to Flavours

4. Distinctive features of FCC-ee at *Z* pole (Flavours)

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

Some first mitigation comments:
vs LHC the modest cross-section partly compensated by the exquisite luminosity.
vs KEKB the initial energy constraint is diluted by the quark fragmentation; incoherent production of the b quarks.

4) Heavy Flavours: physics opportunities.

1) Heavy Flavours Production

Particle specie at FCC-ee	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$) [for 5.10^{12} Z]	310	310	75	65	$1.5^\dagger$	600	180

† B_c hadronisation fraction assumed to be $f_{B_c} = 2.10^{-3}$.

- All species of weakly-decaying b-flavoured particles around.
- Statistics similar or better than the upgrades of current experiments.
- Significant boost, as LHCb (invincible, though). Vertexing capabilities in a clean and hermetic experimental environment.
- Neutrals and flavour tagging for *CP* violation possible, as Belle II.

4) Heavy Flavours: physics opportunities.

- 2) Categories to explore — the hierarchy does not tell the importance:

  1) Rare *b*-flavoured particles decays (EWP & friends).
  2) Di-leptonic decays (*e.g.* $B^0 \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau^+\tau^-$).
  3) (Semi-)leptonic decays (*e.g.* R_{D,D^*}, to $B_c \rightarrow \tau^+\nu$ …)
  4) ***CP* violation study program at large.**
  5) Mass and lifetime properties, spectroscopy.
  6) Charm physics. Heavy Flavours Production

4) Heavy Flavours: physics opportunities.

1) Rare *b*-flavoured particles decays (EWP & friends):

this is related to the current Flavour anomalies. Should they be NOT confirmed, the relevance of their study remains as a third generation couplings fundamental test. Here we think that FCC-ee is unique in that:

- the modes with tau lepton are key to sort out the models addressing the flavour problem(s).
- FCC-ee is the only place where SM values can be reached. Exploratory work ($B^0 \rightarrow K^{*0} \tau^+\tau^-$) promising, arXiv:1705.11106. Comprehensive treatment of background in realistic detector simulations in order (See arXiv:2012.00665)
- *b*-flavoured particles Lepton Flavour Violating decay modes are necessary to have, per se, as null tests of the SM, to complete the model constrains in case the Flavour anomalies remain significant.

4) Heavy Flavours: physics opportunities.

2) Di-leptonic decays (*e.g.* $B^0 \to \mu^+\mu^-$, $B_s \to \tau^+\tau^-$).

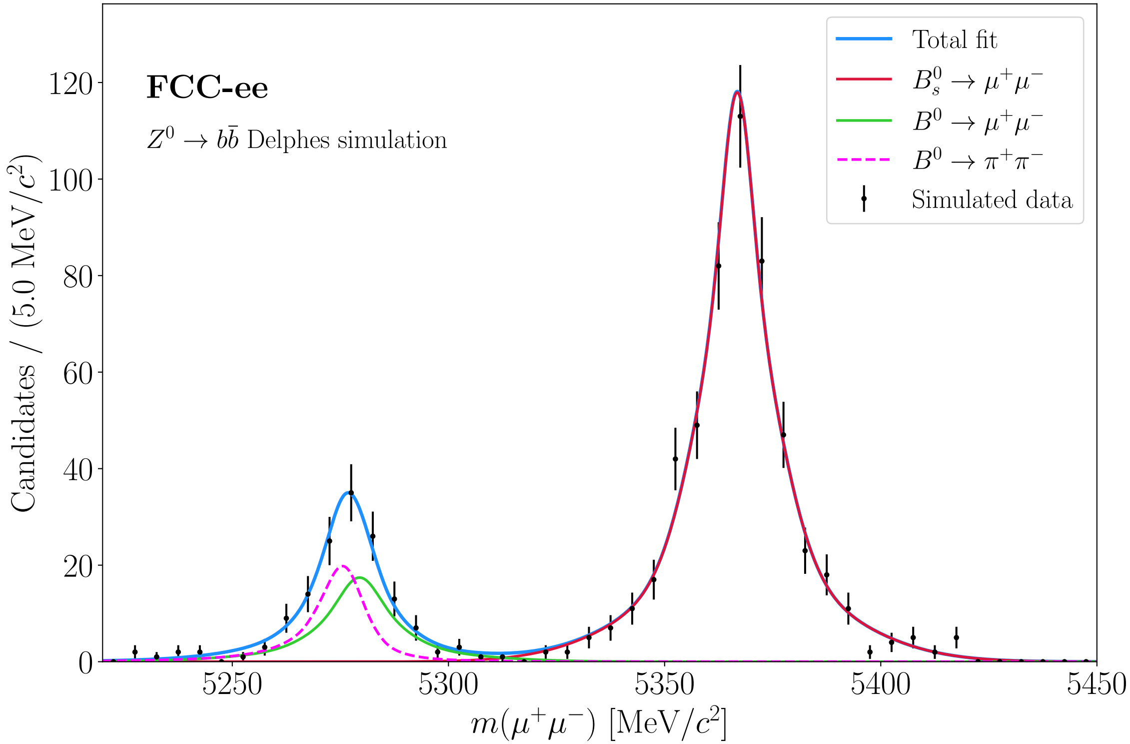
Again fundamental tests. Particularly important in the context the Flavour anomalies. FCC-*ee* is especially expected for $B_s \to \tau^+\tau^-$.

- More complex experimentally because of the absence of the secondary vertex to be used in topological reconstructions. Ideas to mitigate this absence, such as using the quark direction in the other hemisphere.
- Similar techniques employed as for ElectroWeak penguins with τ. That should be part of the same collective exploration.

4) Heavy Flavours: physics opportunities.

2) Di-leptonic decays (*e.g.* $B^0 \rightarrow \mu^+\mu^-$, $B_s \rightarrow \tau^+\tau^-$).

A flavour of the potential: note the exquisite invariant-mass resolution. The probability of a pion to punch through and be identified as muon is taken as ALEPH performance.



© hep-ex:2106.01259

4) Heavy Flavours: physics opportunities.

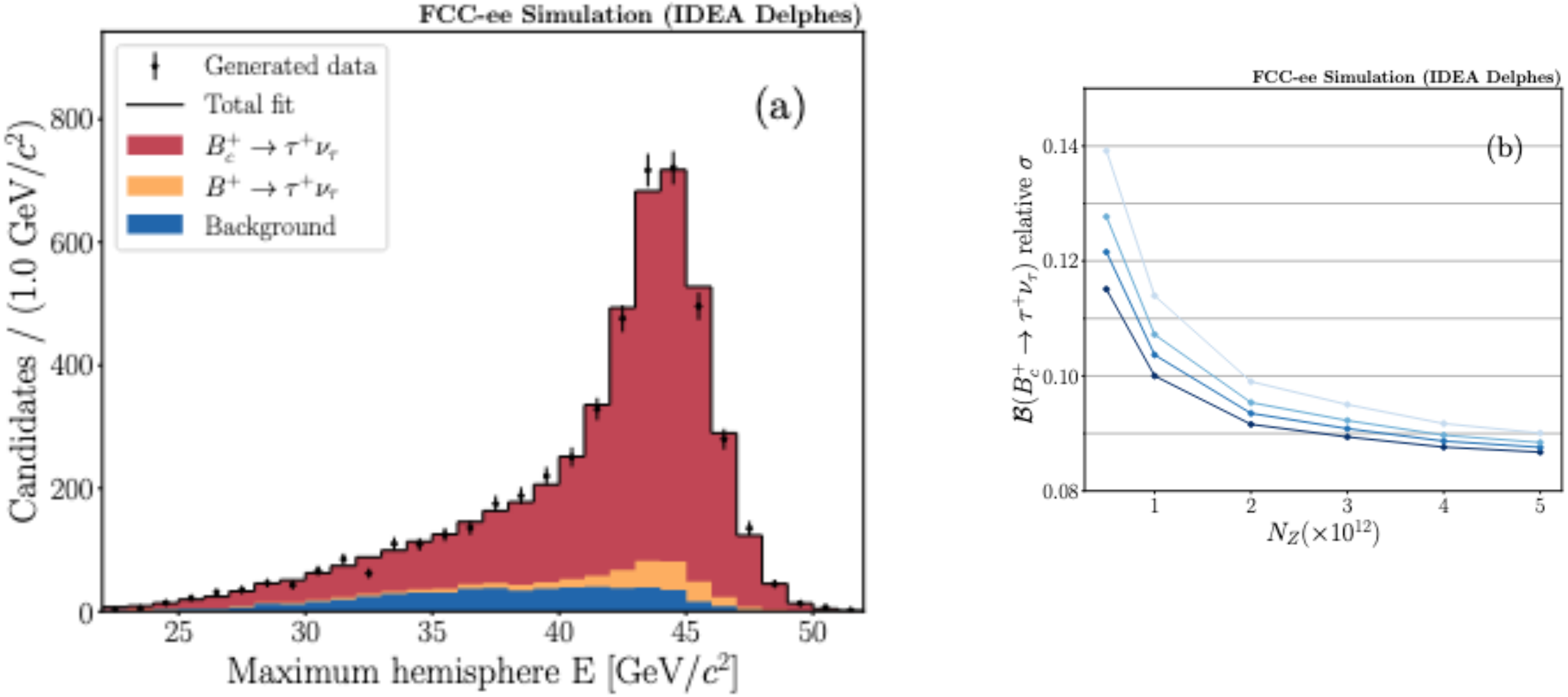
3) (Semi-)leptonic decays (*e.g.* from R_{D,D^*} up to $B_c \rightarrow \tau^+\nu$ …)

Fundamental tests of lepton universality. Again connection to the Flavour anomalies but mainstream measurements. FCC-ee is especially expected for $B_c \rightarrow \tau^+\nu$.

- Beyond LFU tests, these can be used to measure CKM elements V_{ub} ($B^+ \rightarrow \tau^+\nu$) and V_{cb}. Introduced as a case study for devising granularity of the calorimeter.
- Already promising existing studies in the context of CEPC and FCC-ee.
- Reminder: most precise knowledge is still LEP

4) Heavy Flavours: physics opportunities.

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



Bottomline: few percent precision mostly limited by the knowledge of the BF Bu2JPsimunu.

4) Heavy Flavours: physics opportunities.

4) *CP* violation study program at large.

- Inevitable must-do part of the Flavour program.
- Yet no obvious flagship measurement where FCC-*ee* is unique w.r.t. the Belle II or LHCb U2 anticipated precisions.
- FCC-*ee* competes potentially favourably though everywhere (offers redundancy for sole measurements).
- A high energy resolution calorimeter and excellent PID are in order.

4) Heavy Flavours: physics opportunities.

4) *CP* violation study program at large.

- There is probably one flagship measurement, the specific exploration (already started at FCC-ee) of semileptonic asymmetries in neutral *B* mixing.
- Unobserved to date and small in the SM.
- Those are delicate measurements and likely systematic limited.
- They enter as an important exploration of BSM amplitudes in mixing processes. Prospective studies discussed in here — hep-ph: 2006.04824.

4) Heavy Flavours: physics opportunities.

- Model-independent approach to constrain BSM Physics in neutral meson mixing processes

$$\begin{aligned}\langle B_q \,|\, \mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2} \,|\, \bar{B}_q \rangle &\equiv \langle B_q \,|\, \mathcal{H}^{\mathrm{SM}}_{\Delta B=2} \,|\, \bar{B}_q \rangle \\ &\times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))\end{aligned}$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

Assumptions:

✓only the short distance part of the mixing processes might receive NP contributions.

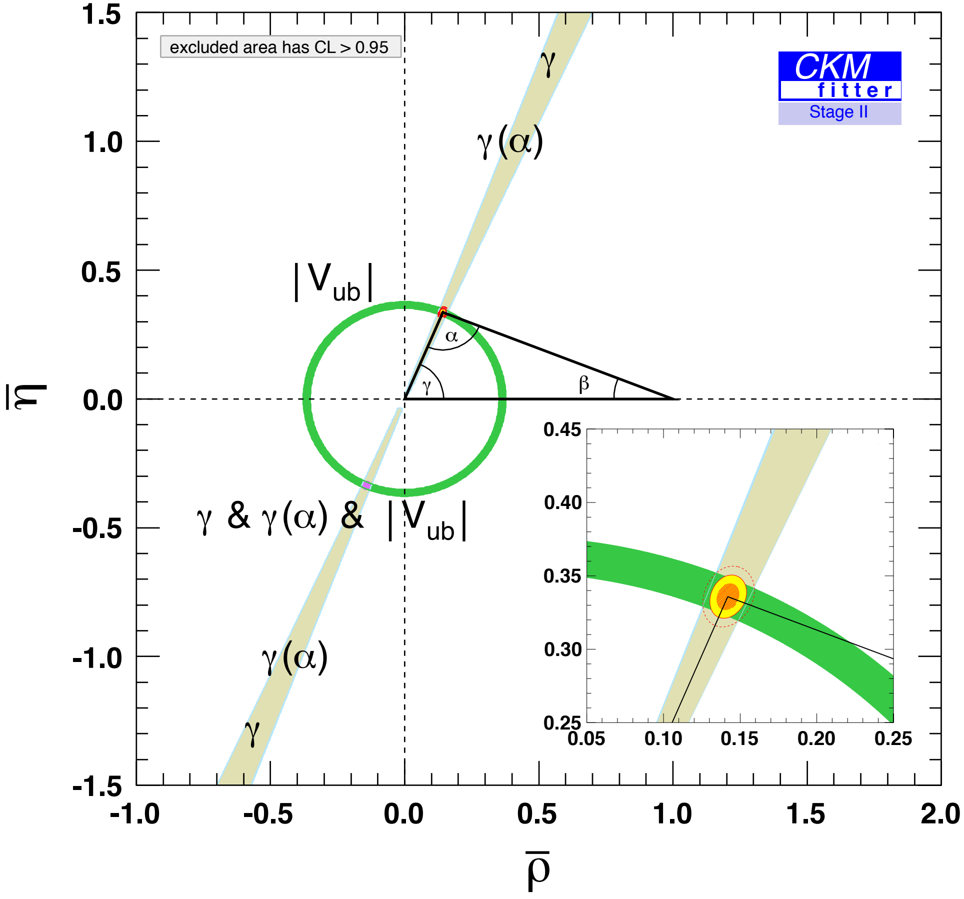
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

✓ tree-level processes are not affected by NP (so-called SM4FC: b→$q_i q_j q_k$ (i≠j≠k)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

4) Heavy Flavours: physics opportunities.

- The unitarity triangle: fixing CKM parameters w/ Vub, Vcb and gamma . This is the anticipated landscape after Belle II and LHCb upgrade I.



arXiv:1309.2293 [hep-ph]]

4) Heavy Flavours: physics opportunities.

- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as $\Delta_q = |\Delta_q| e^{i2\Phi_q^{\rm NP}}$).

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\rm NP}\rvert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = {\rm Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\rm SM}} \times \frac{\sin(\Phi_{12,q}^{\rm SM}+\Phi_q^{\rm NP})}{\lvert\Delta_q^{\rm NP}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\rm SM} + \Phi_q^{\rm NP})$

4) Heavy Flavours: physics opportunities.

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$

$$\sigma = \arg\left(C_{ij}\,\lambda^{t*}_{ij}\right),$$

hep-ph 2006.04824

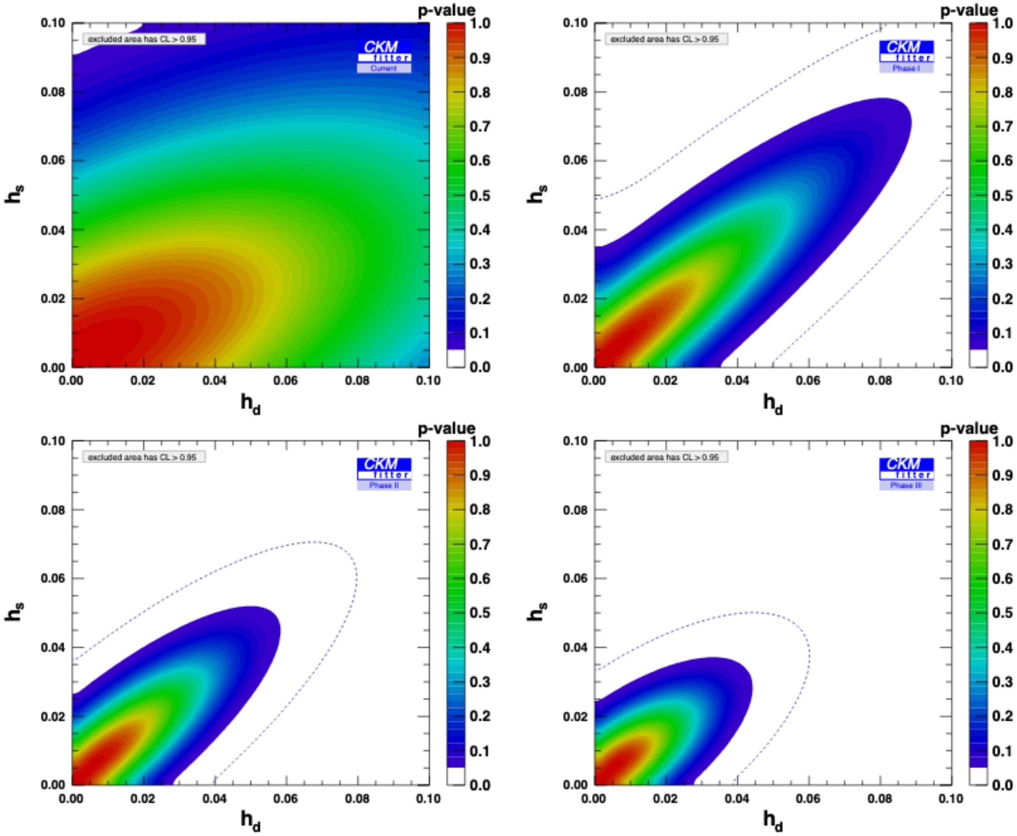
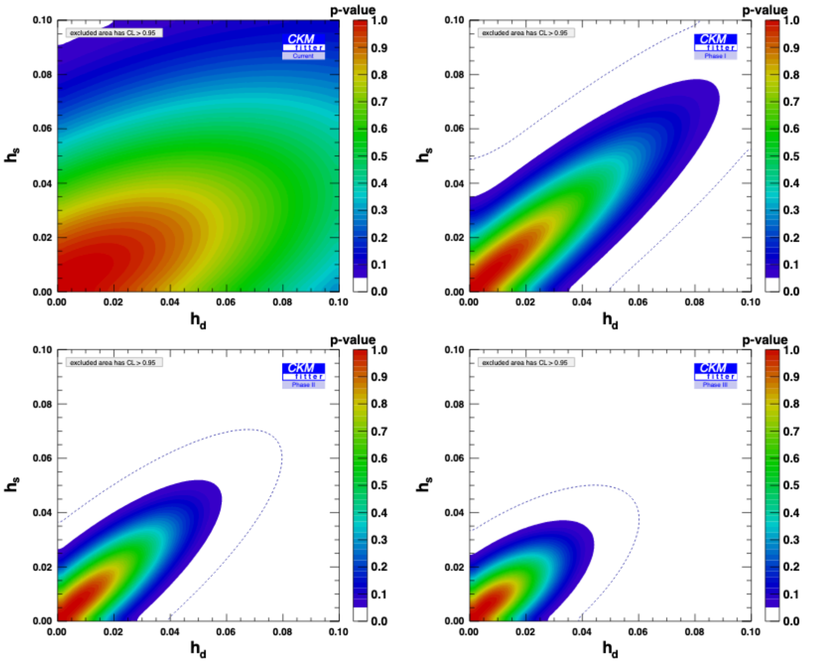


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ)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

4) Heavy Flavours: physics opportunities.

4) *CP* violation study program at large.

Bottlenecks in the interpretation of CKM profile meas. identified (true already for LHCb U2) (2006.04824): V_{cb} and QCD mixing parameters.



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Ongoing study at FCC-ee to get a flavour of what can be expected for V_{cb} measurements at *WW*: O(4 10^{-3} possible).

4) Heavy Flavours: physics opportunities.

4) *CP* violation study program at large: a conclusion

- By contrast with the rare decays, there is no clear-cut flagship CKM observable at FCC-*ee* w.r.t. the anticipated precisions of the upgrades of LHCb and Belle II.
- FCC-*ee* competes favourably though everywhere.
- Yet, it has been shown that the interpretation of the CKM profiles is limited, at the timescale of LHCb U2 (and hence FCC-*ee*) by the knowledge of V_{cb} and QCD mixing parameters.
- FCC-*ee* can provide a breakthrough in V_{cb} precision, thanks to the direct W decays on-shell and boosted.

4) Heavy Flavours: physics opportunities.

- Hierarchised in categories to explore:

  5) Mass and lifetime properties, spectroscopy.

  6) and Charm physics.

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

  - The invariant-mass resolution 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.

4) Heavy Flavours: detector challenges.

Flavour physics requires (trivially):

- Measurements of short-lived particles decay vertices to measure lifetimes, resolve oscillations, identify tertiary decay vertices in decay chain.
- Hadron particle identification (PID) to reconstruct the final state of interest under the correct mass hypotheses, and remove background contamination.
- Flavour tagging (in the sense of the charge of the quark): identification of leptons in jets, low momenta particles close in phase space w/ the decay ($B^*(B\pi)$, $D^*(D\pi)$) …
- High momentum resolution to resolve the invariant-mass of exclusive decays. Precision calorimetry to resolve π^0 and γ (radiative decays) energy (invariant-mass again / background suppression).
- Long-lived particle tracking (K_S and Λ) and K_L stopping for CPV studies

4) Heavy Flavours: detector challenges.

Some comments in order:

- If most of these requirements do meet those of the overall physics program, PID and calorimetry performance (vertexing as well) are not obviously given, or shall be obtained with a compromise and envisaged in a global design.
- A PID detector if needed has to fit before the calorimeter and will degrade electron & γ reconstruction.
- This is the kind of questions one wants to answer in the current phase of the FCC project.
- Case Studies are envisaged to guide the requirements for the detector design.

4) Heavy Flavours: detector challenges / Case studies.

The semileptonic transitions with taus in the final states $b \rightarrow s \tau^{+}\tau$ (and $B_s \rightarrow \tau^{+}\tau^{-}$ and LFV decay modes) performance (branching fraction and why not angular analysis) are demanding likely more than the state-of-the-art. To go further, they can be used to:

- Understand the beampipe design and location of the first layer, as well as its geometry.
- Understand the impact of the hit revolution.
- Review the impact of the material density.
- Requires: a) comprehensive and realistic background sources (beyond the current study), b) understand the critical points of the detector design upon the topological methods.

4) Heavy Flavours: detector challenges / Case studies.

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, starting w/ charged hadron particle identification PID.

- p / K / π separation is capital to suppress background of *CP*-eigenstates and mandatory to eliminate the cross-feeding signals of companion modes.
- It is has been already touched for $B_s \to D_s K$.
- It is to be extended to $B \to DK$, multibody *b*-hadron decays (including baryons), etc…
- It is also a necessary ingredient for flavour tagging (in the sense of the quark charge) via same side and opposite soft kaon identification.
- PID considerations can't be thought alone (entangled w/ the global design).

4) Heavy Flavours: detector challenges / Case studies.

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, continuing w/ calorimetry:

- A comprehensive program of *CP* violation must include the study of modes w/ π^0, *e.g.* $B^0 \to \pi^0\pi^0$, $B^0 \to \pi^+\pi^0\pi^-\pi^0$, …critical to measure the CKM alpha angle as an example (though theory limited at that time).
- High resolution at low energy is the key here.
- Some other calorimetry cases discussed here.
- Radiative decays following $b \to s\gamma$, provides the same requirements. Critical for charm studies as well.
- Isolation criteria (the missing energy flow) likely instrumental in $B^+_c \to \tau^+\nu$.

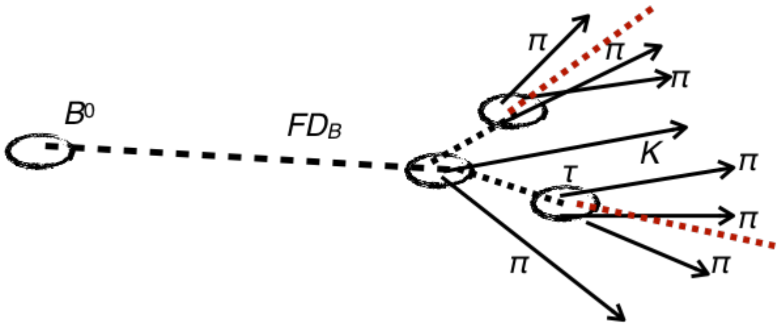
4) Heavy Flavours: detector challenges / Case studies.

The span of relevant observables to understand further the *CP* symmetry breaking is large. Let's distinguish a few of them, coming back to vertexing :

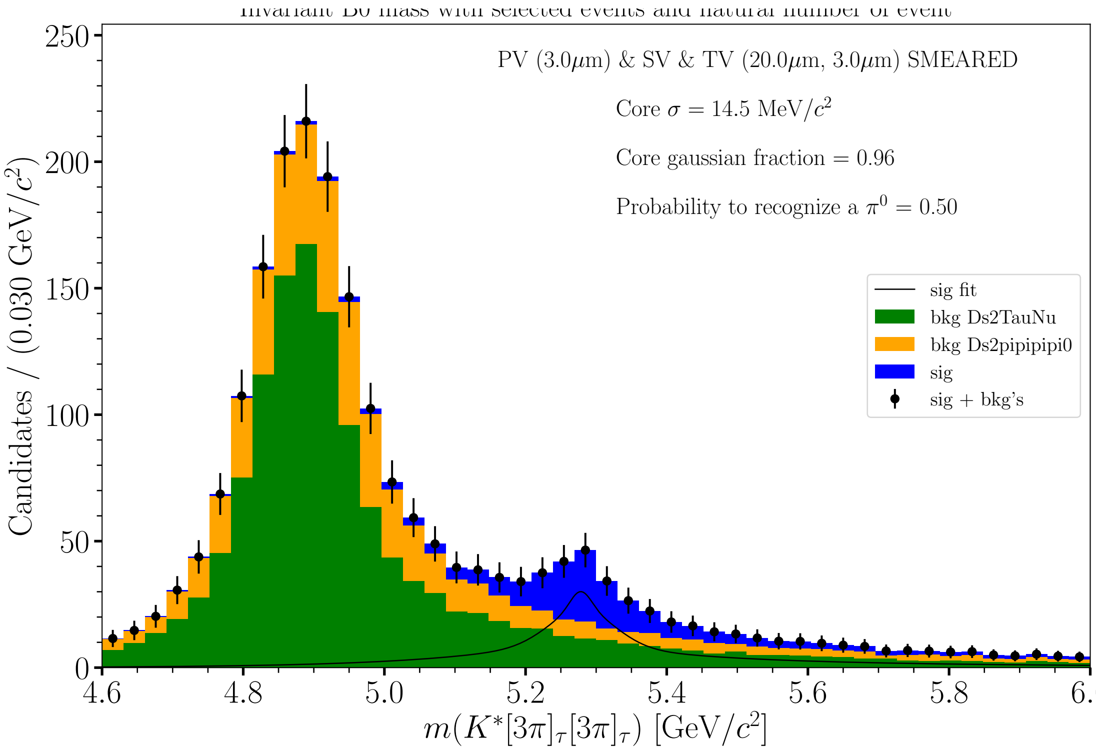
- The knowledge of the V_{cb} CKM matrix element — governing the normalisation of the UT sides— becomes a bottleneck to interpret the CKM profile(s). Powerful *b*- and *c*-jets tagging is in order to benefit from the breathtaking statistics of 2 10^8 *WW* on-shell.
- Last but not least, semileptonic asymmetries, as measures of *CP* violation in the *B* meson mixings (unobserved to date) is at reach if charged particle detection asymmetry is controlled (up to few 10^{-5} to meet SM values): another challenge to global detector design.

4) Heavy Flavours: some examples of studies.

$B^0 \rightarrow K^* \tau^+\tau$

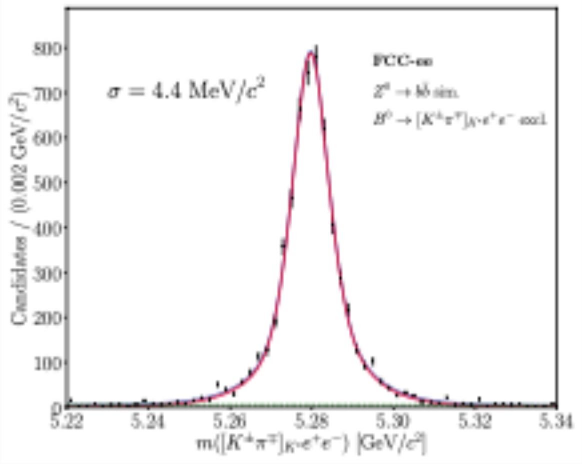


- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - The system is in principle over-constrained.
- Likely the most demanding for vertexing !



4) Heavy Flavours: some examples of studies.

$B^0 \rightarrow K^* \tau^+\tau^-$



$B^0 \rightarrow K^* e^- e^+$

LHCb $\sigma = 75$ MeV/c^2

Belle $\sigma = 5$ MeV/c^2
[arXiv: 1904.02440]

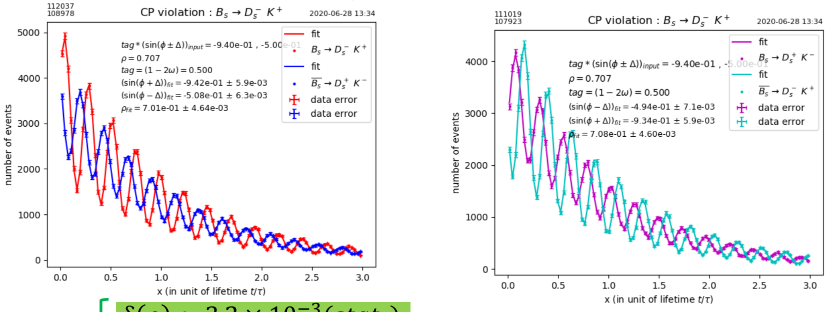
© D. Hill

© R. Aleksan

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

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

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$



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

Some others around here:
https://indico.in2p3.fr/event/23012/

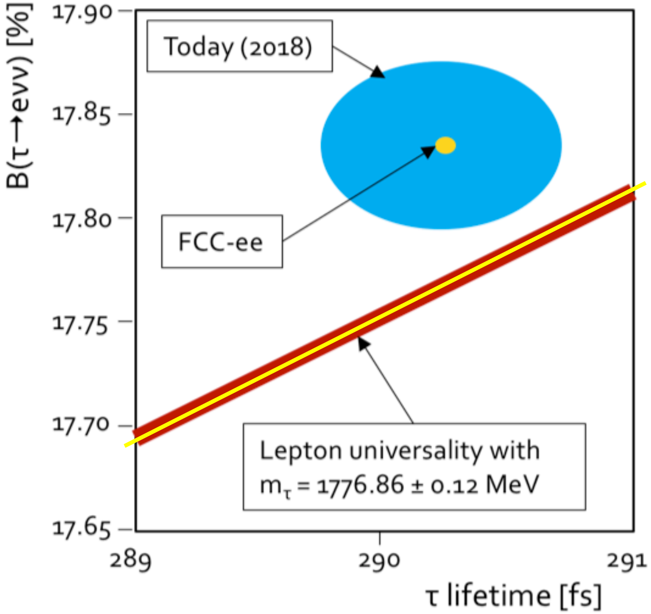
4) Heavy Flavours: don’t forget tau leptons!

- 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 (?)**	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			

Necessary ingredients:

- Mass
- Lifetime
- Leptonic branching fractions



4) Heavy Flavours: physics opportunities conclusions

- FCC-ee gathers most of the advantages of each of the Flavour factories environment (pp, Upsilon).
- In turn, lots of physics opportunities and some likely unique physics cases and reach.
- They can't be met with any detector performance (vertexing beyond state-of-the-art, high resolution ECAL, PID).
- In particular if 4 IP are to be designed, it can be conceived that one experiment has a flavour-oriented design.
- Assessing the detector performance is the name of the game for the next five years.
- Convenient simulation tools have been set up. The fun can start.

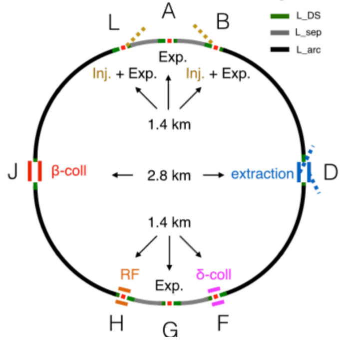
5. The FCC implementation as an outlook

5. The FCC implementation: civil engineering.

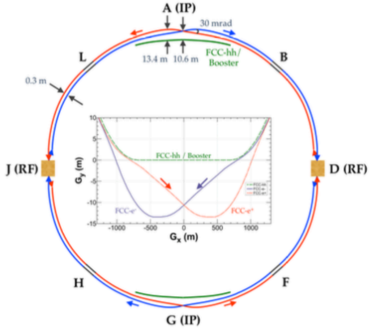
- Machine footprints, experimental caverns, geological studies

FCC-hh

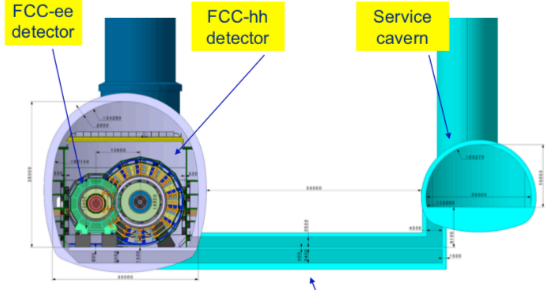
- **Common footprint except around IPs**
- **Asymmetric IR layout** to limit synchrotron radiation



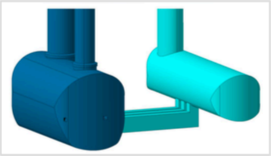
FCC-ee

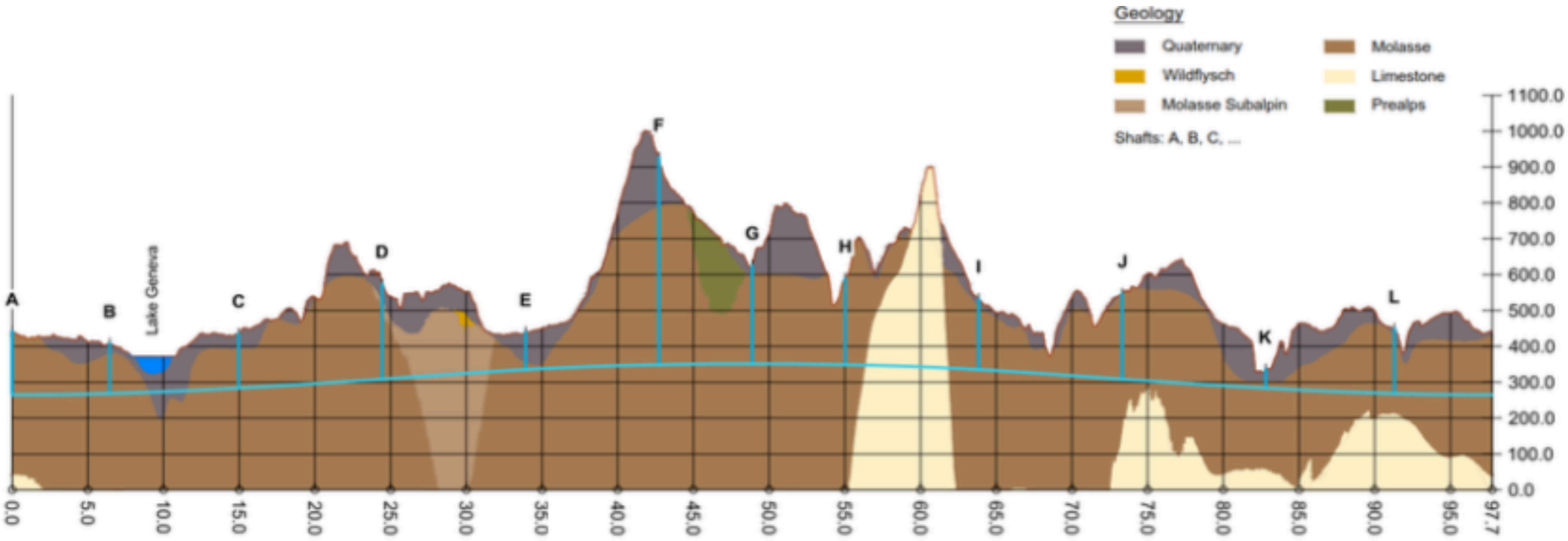


Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



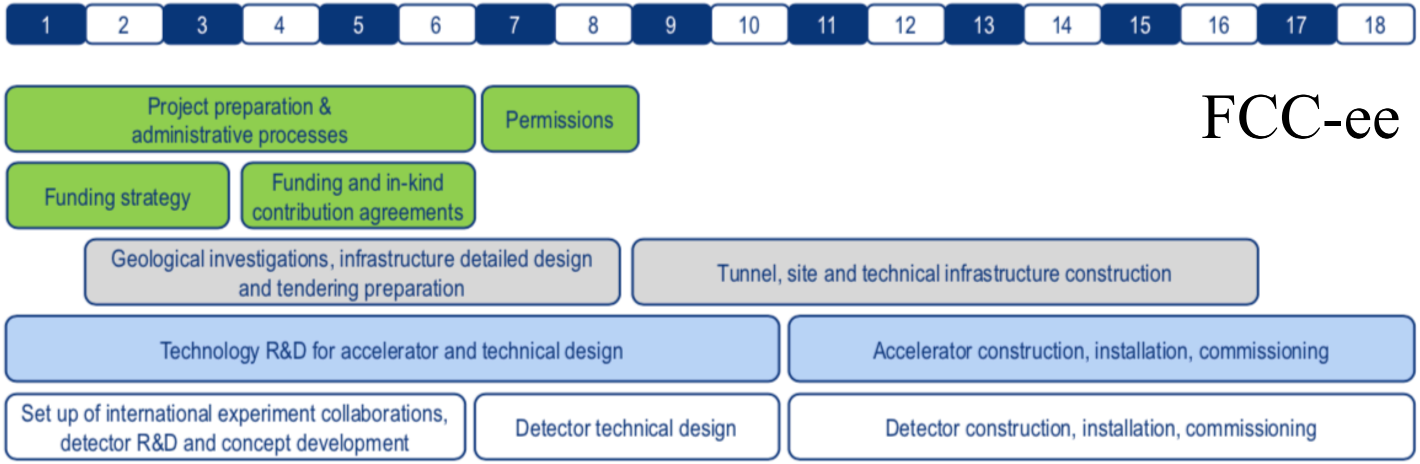
Preliminary design of access and cable paths





5. The FCC implementation: timeline.

- Eighteen years towards Physics. No gap in Physics between the end of HL-LHC and FCC-*ee* (unless external constraints).



FCC-ee

Project preparation & administrative processes

Permissions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

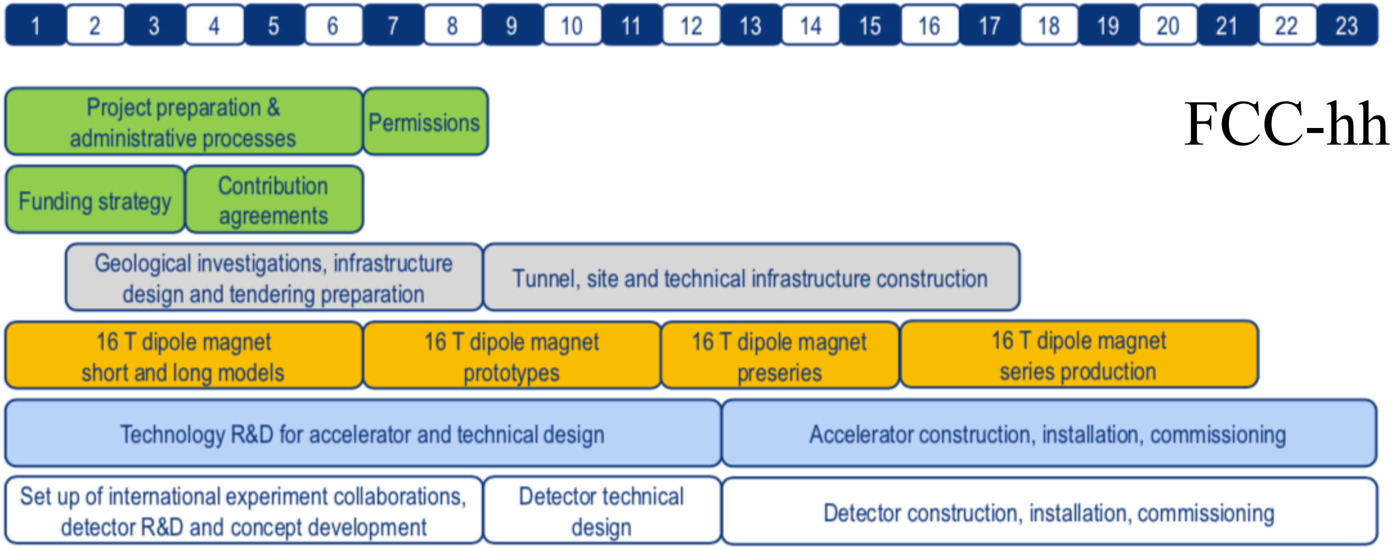
Technology R&D for accelerator and technical design

Accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

Detector technical design

Detector construction, installation, commissioning



FCC-hh

Project preparation & administrative processes

Permissions

Funding strategy

Contribution agreements

Geological investigations, infrastructure design and tendering preparation

Tunnel, site and technical infrastructure construction

16 T dipole magnet short and long models

16 T dipole magnet prototypes

16 T dipole magnet preseries

16 T dipole magnet series production

Technology R&D for accelerator and technical design

Accelerator construction, installation, commissioning

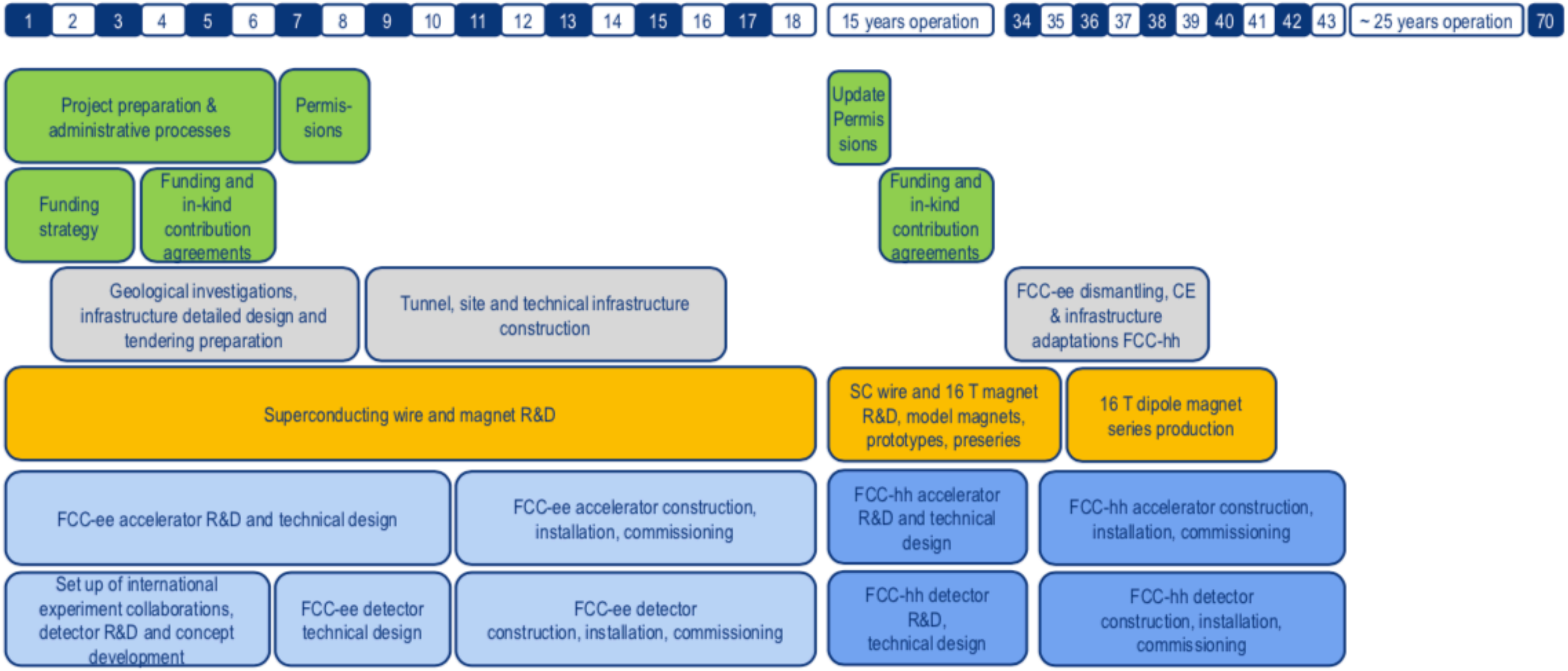
Set up of international experiment collaborations, detector R&D and concept development

Detector technical design

Detector construction, installation, commissioning

5. The FCC implementation: timeline.

- Eighteen years towards Physics. The big picture.



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Update Permis sions

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

Superconducting wire and magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

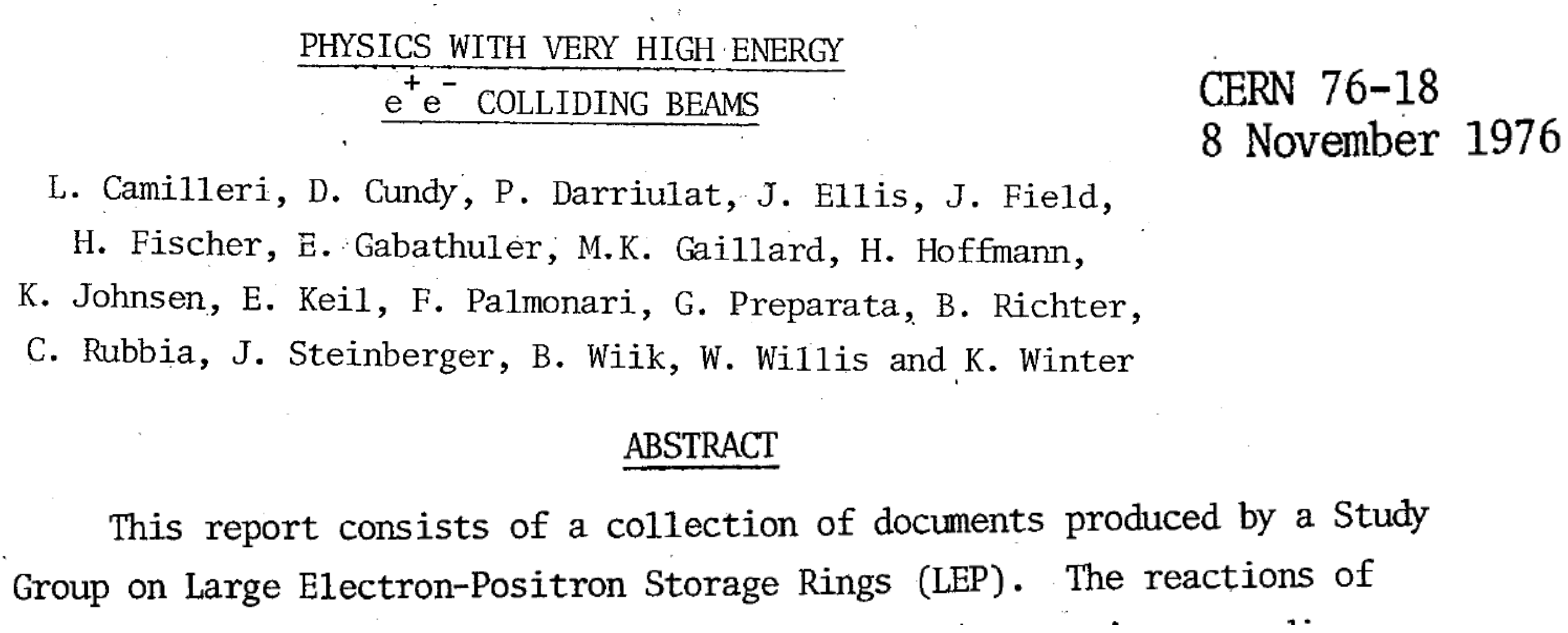
FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

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

5. The FCC implementation: timeline

- 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

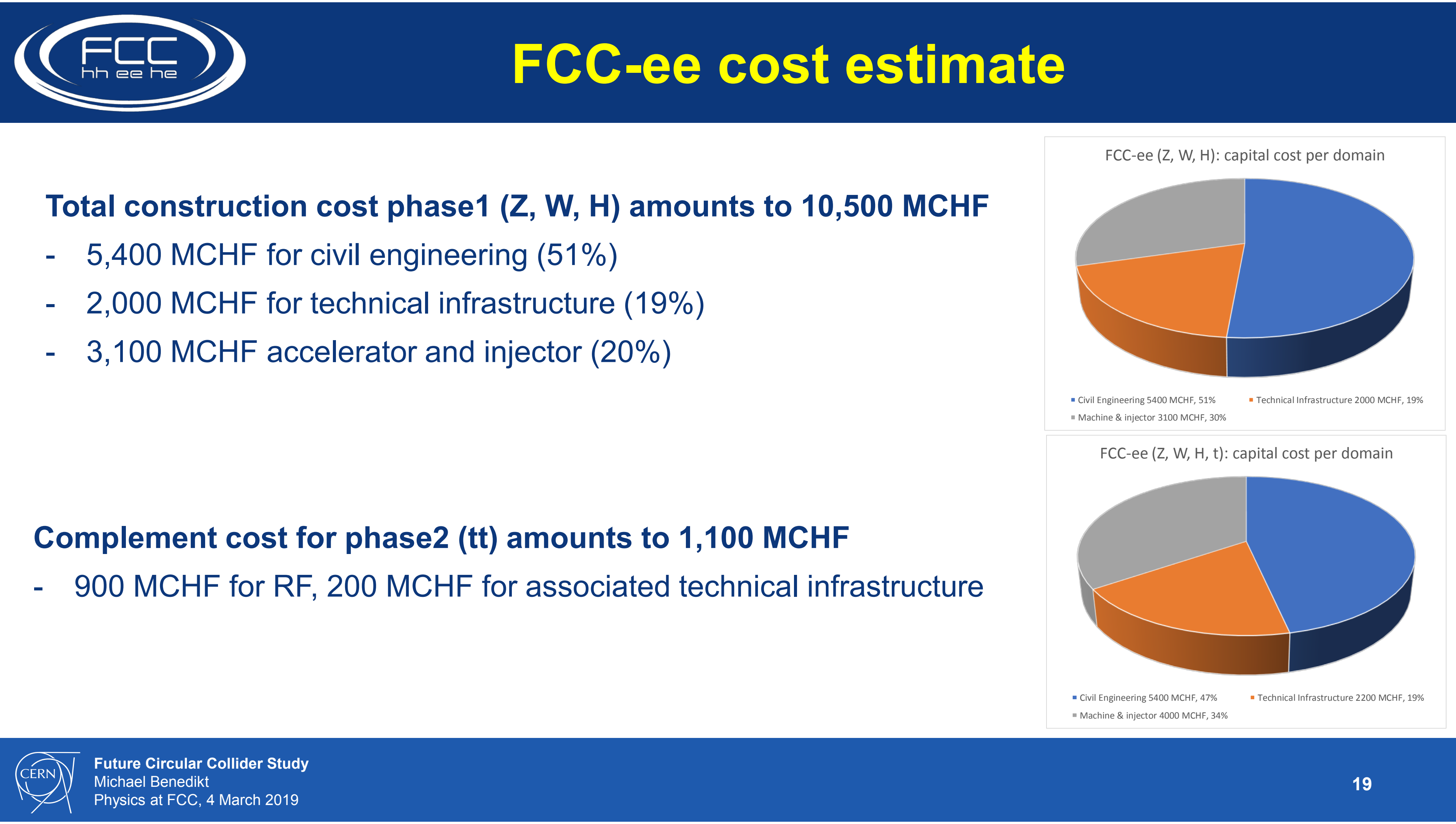
CERN 76-18
8 November 1976

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

5. The FCC implementation — Cost



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%)

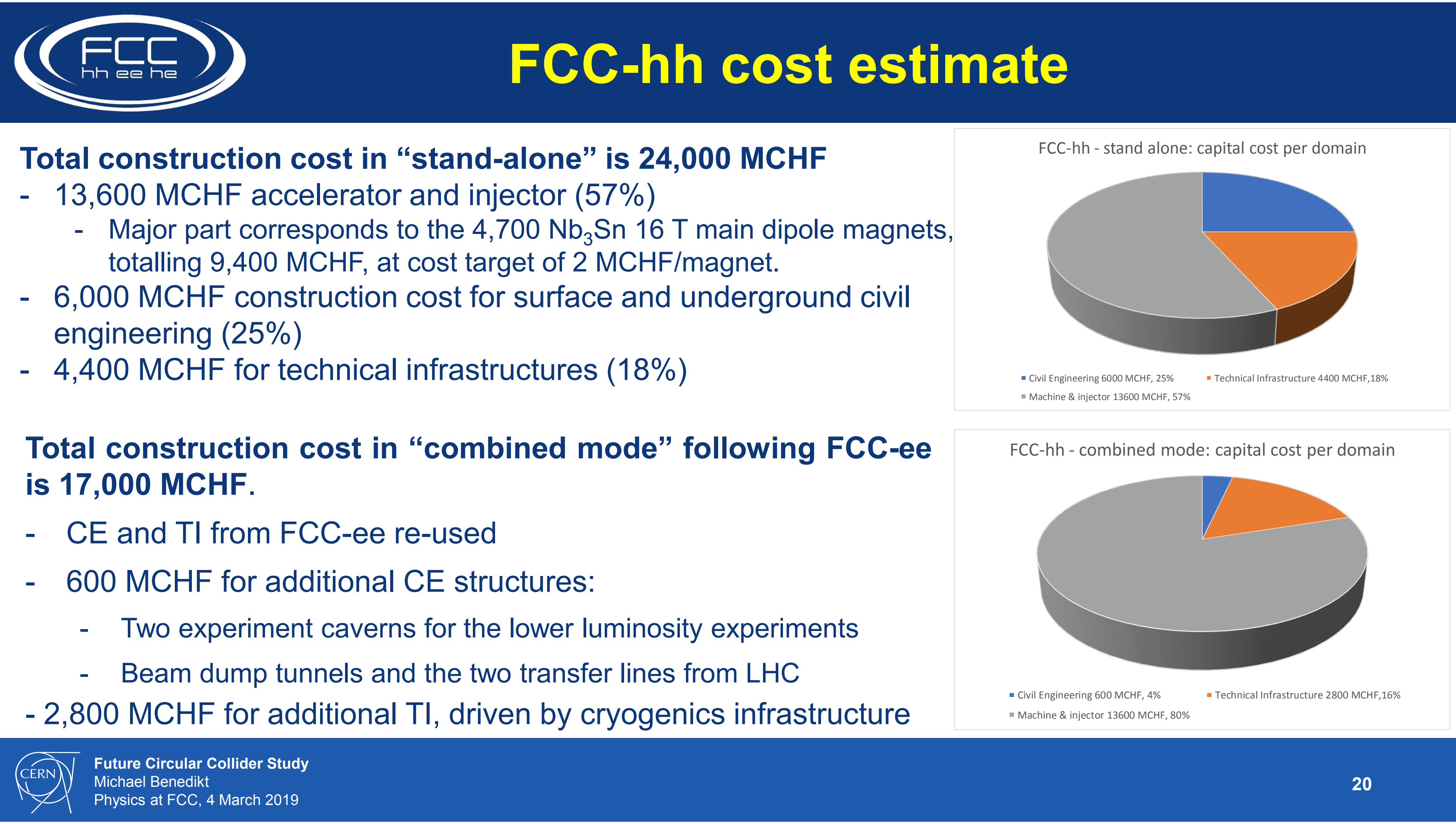
Complement cost for phase2 (tt) amounts to 1,100 MCHF

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

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

19

5. The FCC implementation — Cost



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%)

FCC-hh - stand alone: capital cost per domain

■ Civil Engineering 6000 MCHF, 25%
■ Technical Infrastructure 4400 MCHF,18%
■ Machine & injector 13600 MCHF, 57%

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

FCC-hh - combined mode: capital cost per domain

■ Civil Engineering 600 MCHF, 4%
■ Technical Infrastructure 2800 MCHF,16%
■ Machine & injector 13600 MCHF, 80%

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Physics at FCC, 4 March 2019

20

6) Summary

- The project is mature. FCC can be done ! The FCC software and detector full simulations are getting up. Please check:
  - https://hep-fcc.github.io/FCCeePhysicsPerformance/
- Fantastic tool for Higgs, top, and EWPT tests.
- Unique flagship modes in Flavours have been identified. The core of the program is yet 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).
- The Flavour Physics case is now part of the FCC program in its own right. There are exciting times ahead with Flavours with the present data and this to come. It can be a lot of fun to think of these prospectives and some serious studies (though part-time !) to be conducted.

00) Back-up slides

Wish list for today:

- FCC tunnel.
- Visit Bangalore.

My place
Clermont behind
the dome

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).

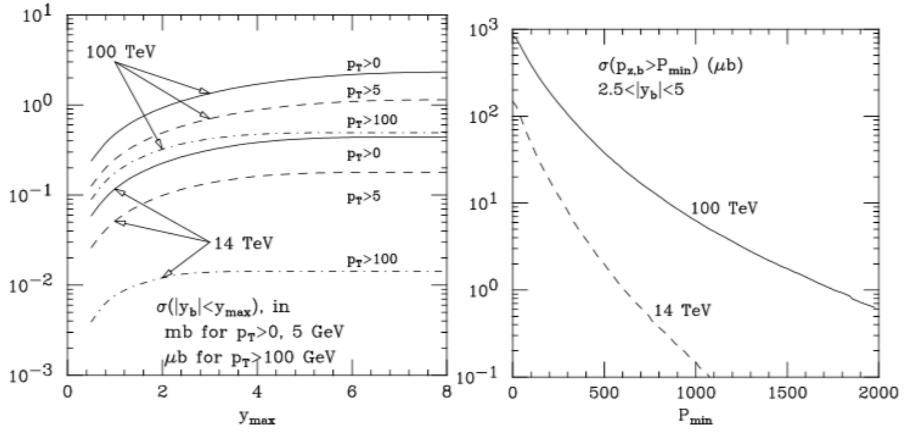


Figure 7.4: Left: production rates for b quarks as a function of detection acceptance in y, for various p_T thresholds (rates in μb for $p_T > 100$ GeV, in mb otherwise). Right: forward b production rates, as a function of the b longitudinal momentum.

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.

7) References:

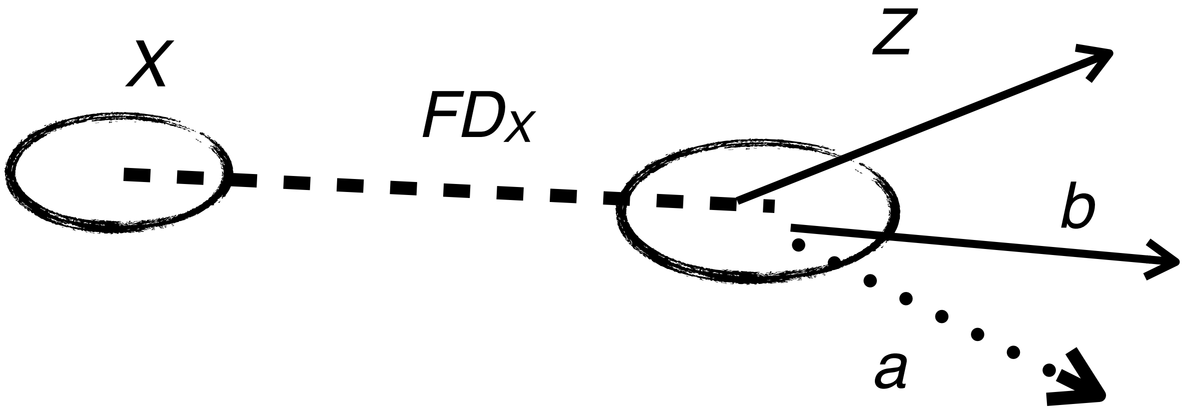
- CDR(s):
  - https://fcc-cdr.web.cern.ch

- FAQs about FCC:
  - https://arxiv.org/pdf/1906.02693.pdf

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.