Future Circular Colliders project (FCC): a long term vision for Particle Physics

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Outline of the talk

- Scientific context
- Introduction to the Future Circular Colliders project
- The Physics reach of FCC-hh
- Few words about the e^+e^- machine and
- FCC-ee Physics case at large.
- The Flavour Physics in the FCC landscape.

Scientific context

- The Standard Model is a theory: gauge, flavour, scalar field.
- Timelines of LHC and other medium / large experiments.
- Anticipation scenarii for Physics after LHC Run III.
- The European FCC Design Study.

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: $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$

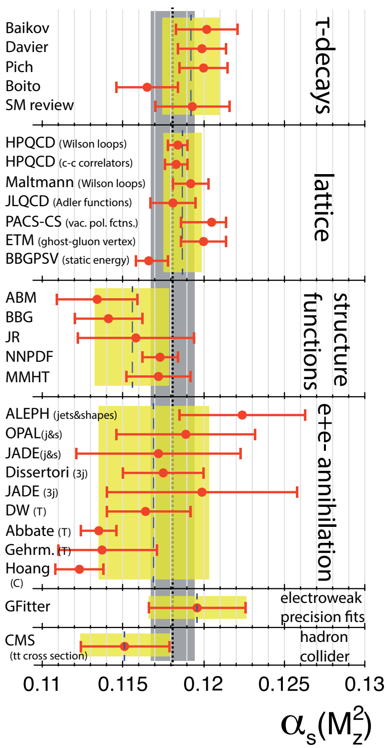
    $\boldsymbol{v}$ **(the v.e.v) and** $\boldsymbol{m_H}$.

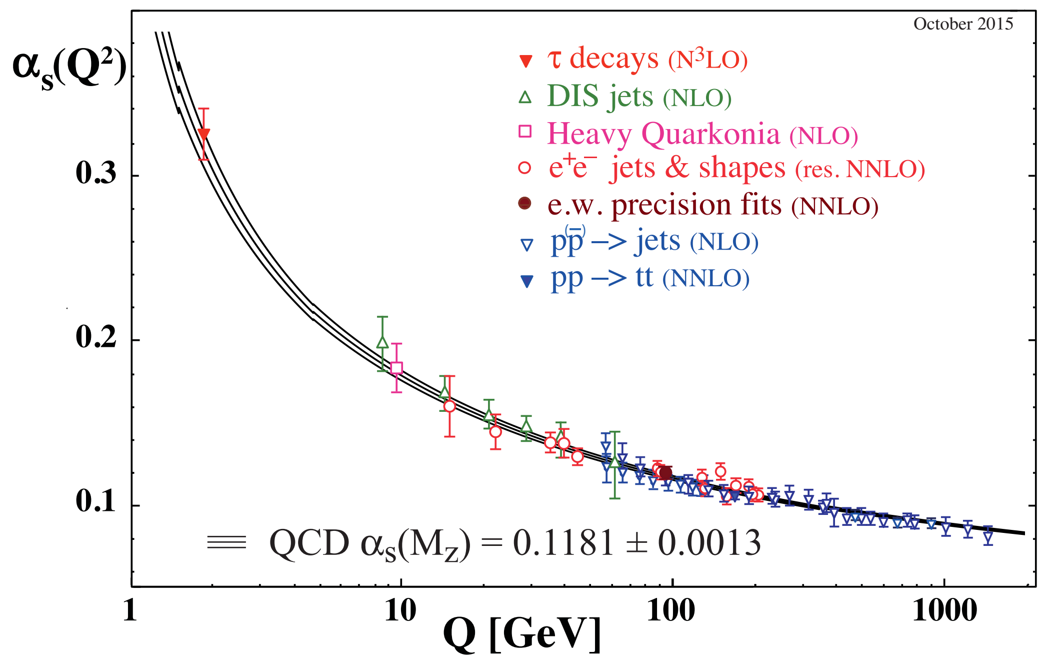
The free parameters of the SM

- 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.

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.

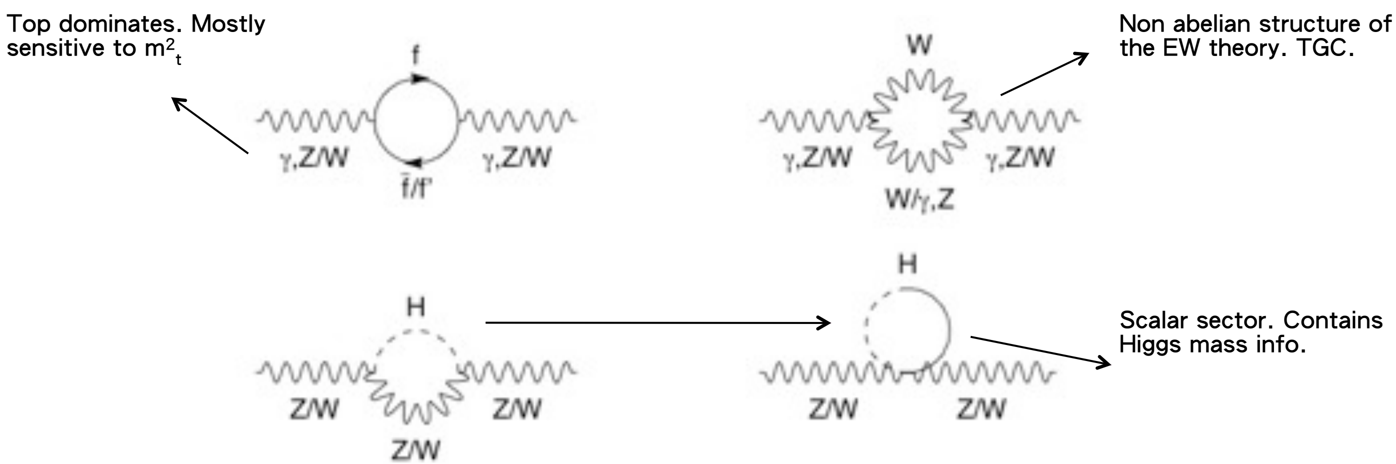




Scientific context: SM became a theory

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.*



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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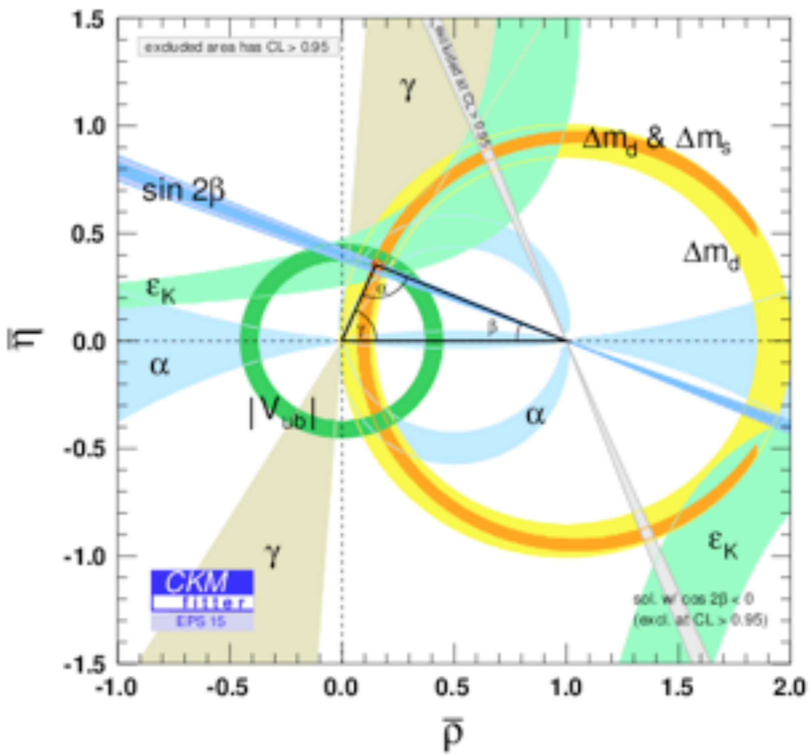
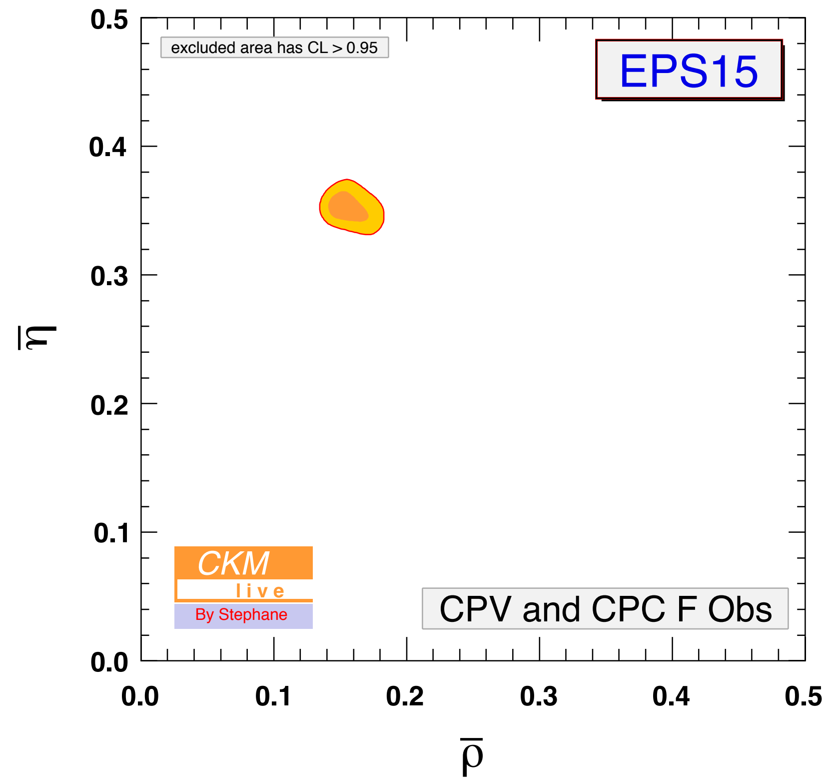
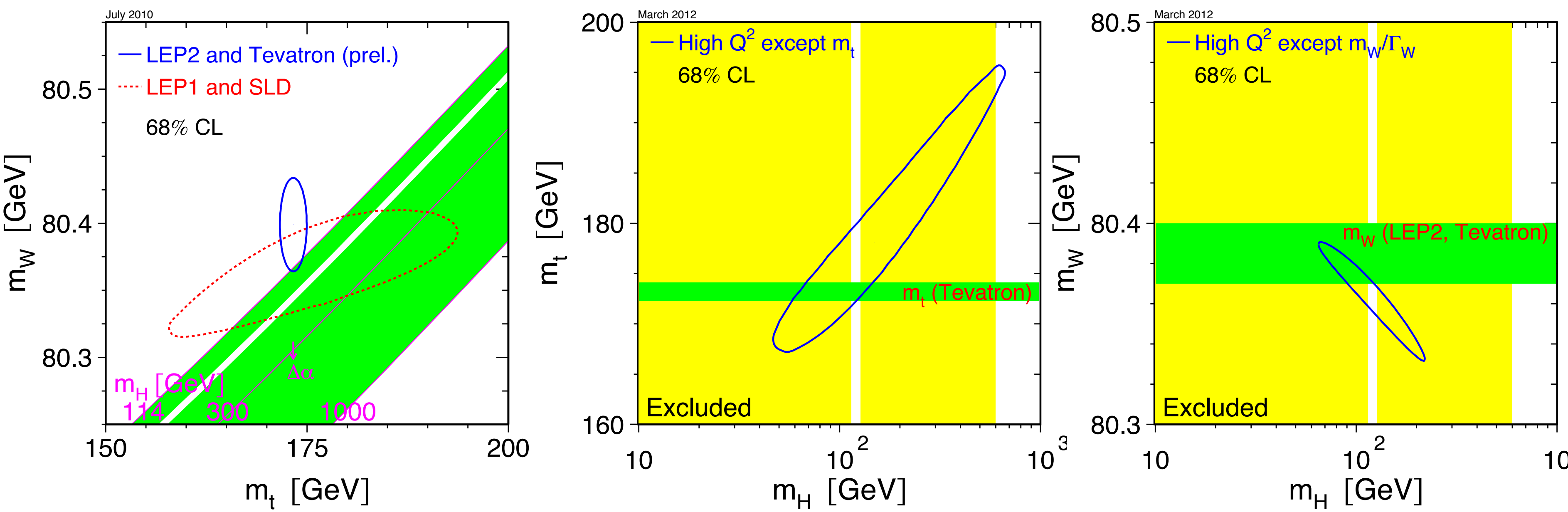




Scientific context: SM became a theory

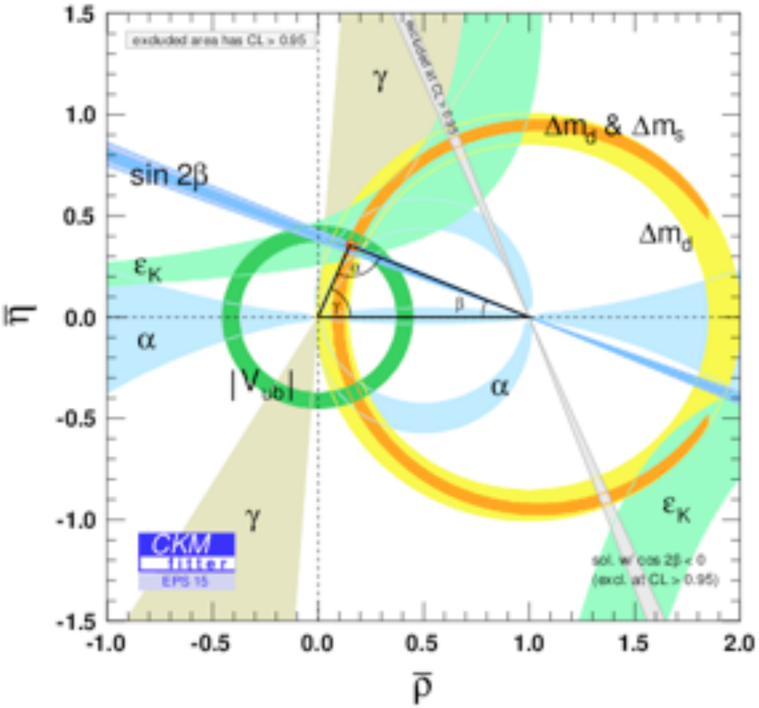
Reorganisation:

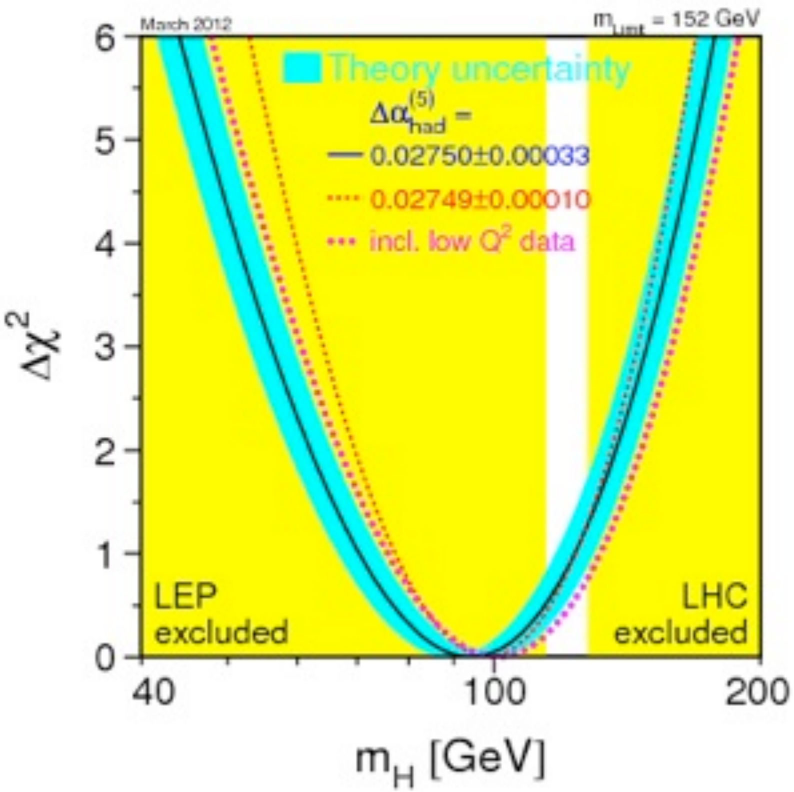
- The rest of the free parameters are part of the so-called electroweak precision observables consistency check. This is the other pillar of the SM. Fix $\boldsymbol{G_F}$, α_{EM} and $\boldsymbol{m_Z}$ at their measured value and produce a prediction of $\boldsymbol{m_{top}}$, $\boldsymbol{m_W}$ and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



Recap:

- Two pillars: EWPT and Flavours.

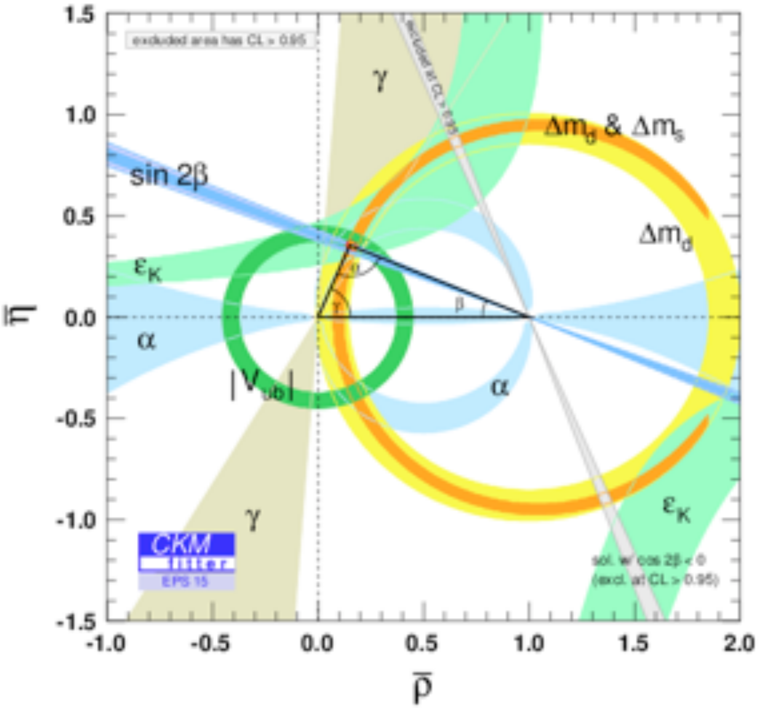




Scientific context: SM became an invincible theory

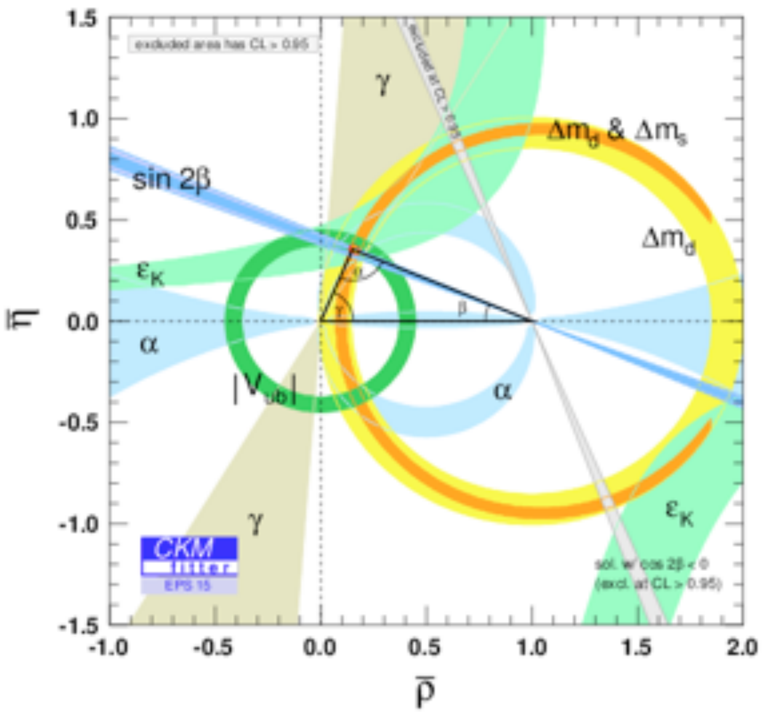
Recap:

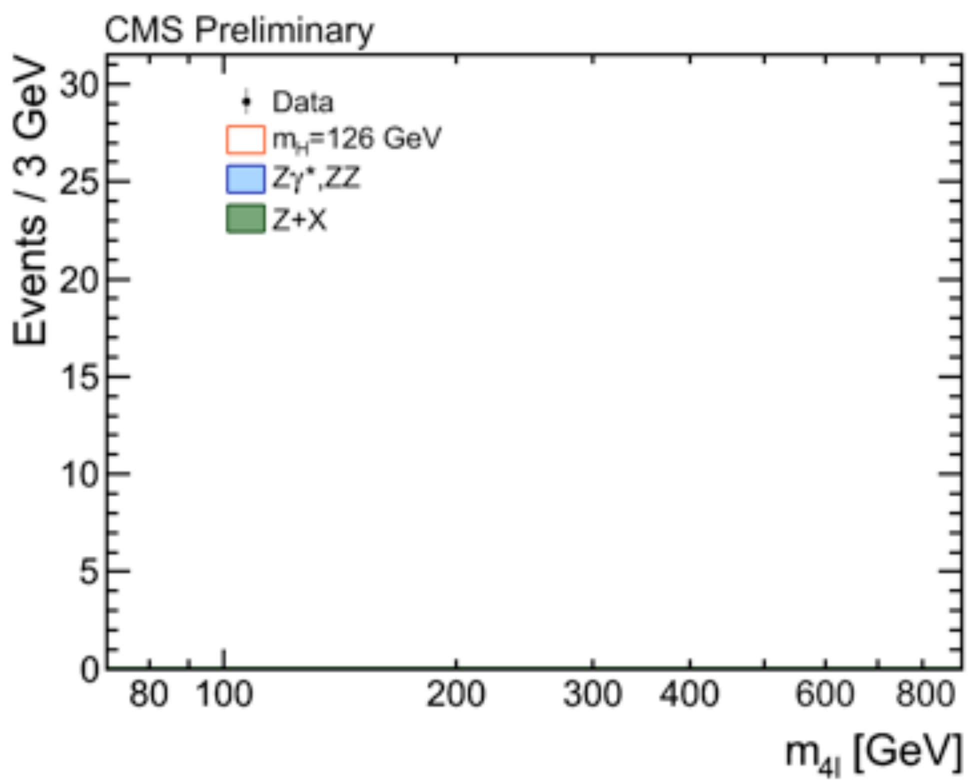
- Two pillars: EWPT and Flavours.



Recap:

- Two pillars: EWPT and Flavours.





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: the last evidence for cosmological dark matter is the observation of a low surface brightness galaxy [ArXiv:1606.06291].

  - Baryonic asymmetry in the Universe.

A selection of experiment timelines for running projects, on track projects and foreseeable projects

Scientific context: LHC timeline (GPD-wise)

LHC Run I	LHC Run II	LHC Run III	HL-LHC
2015 - 20 /fb	2021 - 50 /fb	2025 - 300 /fb	2035 - 3000 /fb

Legend and disclaimer:

- on track or running
- foreseen projects
- timeline, lumi, omissions are mine.

Scientific context: landscape of future flavour factories

LHC(b)

LHC(b) upgrade(s)

Beyond LHCb

FCC injectors & FCC

2019 - 8 /fb

~2025 - 50 /fb

2035 - 500 /fb

5000 /fb

2025 - 50 /ab

2035 - 150 /ab

Belle II

Comet - Meg & friends.

KOTO - NA62 ...

FCC-*ee*

Legend and disclaimer:

- on track or running
- foreseen projects
- timeline, lumi, omissions are mine.

Scientific context: theoretical / historical timelines

1964 Electroweak unification

Neutral current discovery in 1973 by Gargamelle (CERN).

1979 Glashow, Salam and Weinberg get the Nobel.

1971 EW loops and RN

Top quark mass predicted by LEP, CERN (from M_Z and other EWPO).

Top quark discovered by CDF, FNAL.

1999 t'Hooft and Veltman get the Nobel.

1973 *CP* violation

The *B*-factories establish that the KM paradigm is the dominant source of *CP* violation in *K* and *B* particle systems.

2008 Kobayashi and Maskawa get the Nobel.

1964 Fundamental Scalar

Higgs boson mass cornered by LEP (EWPO) and Tevatron (top and *W* mass).

An alike Higgs boson discovered where said at LHC.

2013 Englert and Higgs get the Nobel.

[B]SM Scenarii

Scientific context: scenarii

1) Find a new heavy particle at the Run II 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.
   - Energy frontier to find the corresponding spectrum.

4) Find no new particle, standard H properties and flavour observables in SM:
   - Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision.
   - Push the energy frontier to the best of our knowledge.

By anticipation of the conclusion of the seminar

1) Find a new heavy particle at the Run II 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 [FCC-hh].
- The underlying quantum structure must be studied [FCC-ee].

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

3) Find no new particle, standard H properties but flavour observables departing from SM:
- Asymptotic *Z*, *W*, top factories to fix the energy scale [FCC-ee].
- Energy frontier to find the corresponding spectrum [FCC-hh].

4) Find no new particle, standard H properties and flavour observables in SM:
- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision [FCC-ee].
- Push the energy frontier to the best of our knowledge [FCC-hh].

Introduction to the FCC project

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

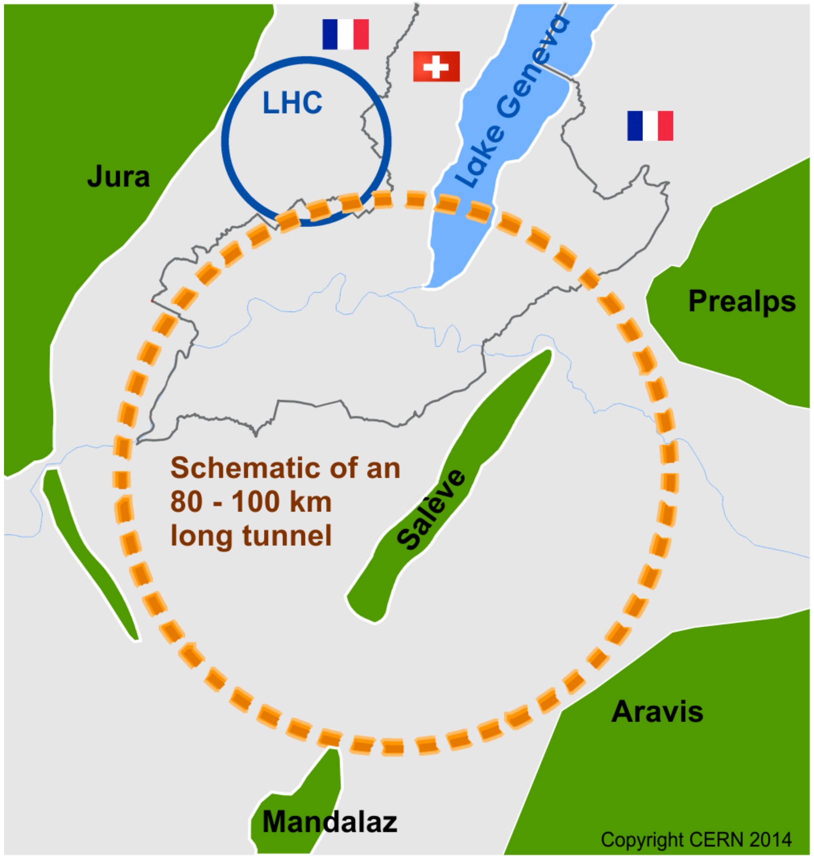
CERN **Future Circular Collider Study**
Michael Benedikt
FCC Kick-Off 2014 3

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

1. Introduction to FCC: the scope of the project

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

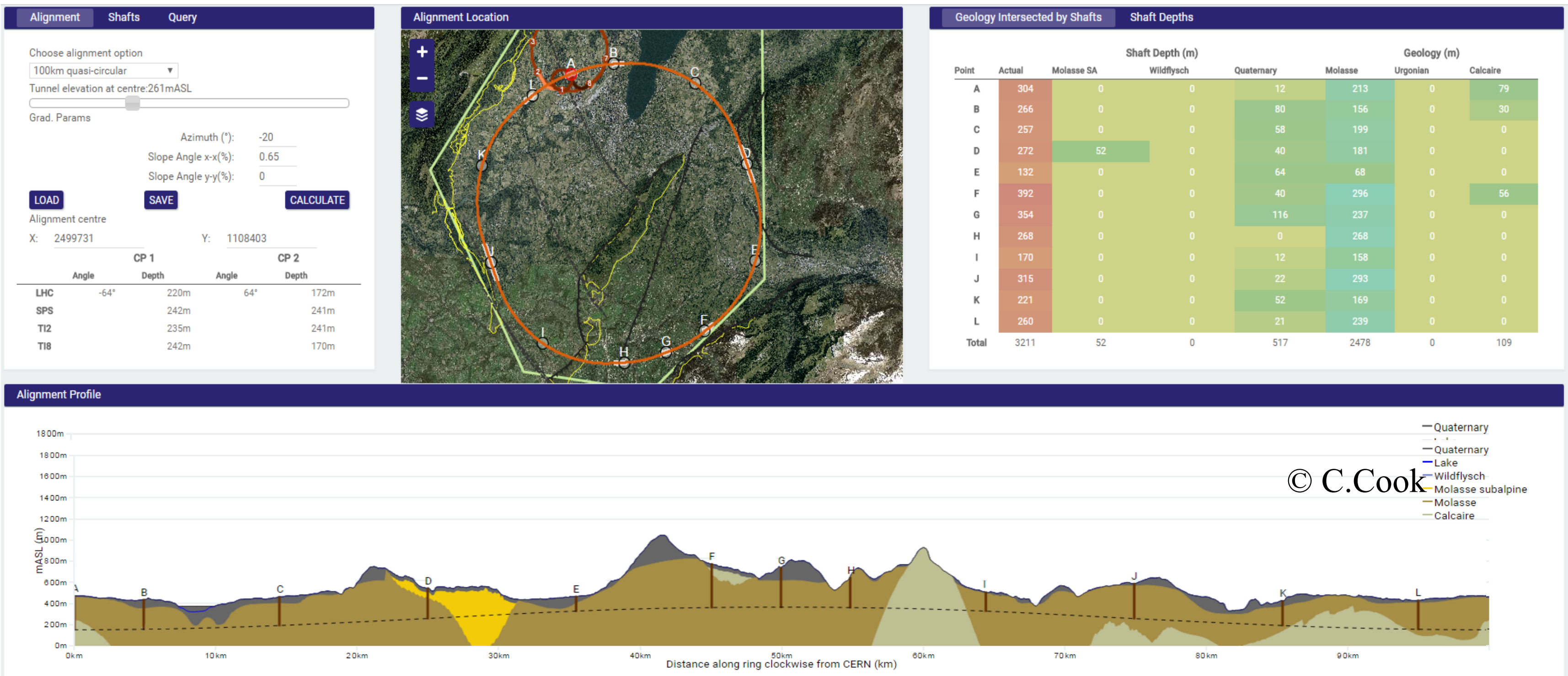
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



- Conceptual design report and cost review for the next european strategy → 2019 / 2020.

1. Introduction to FCC - Civil engineering.

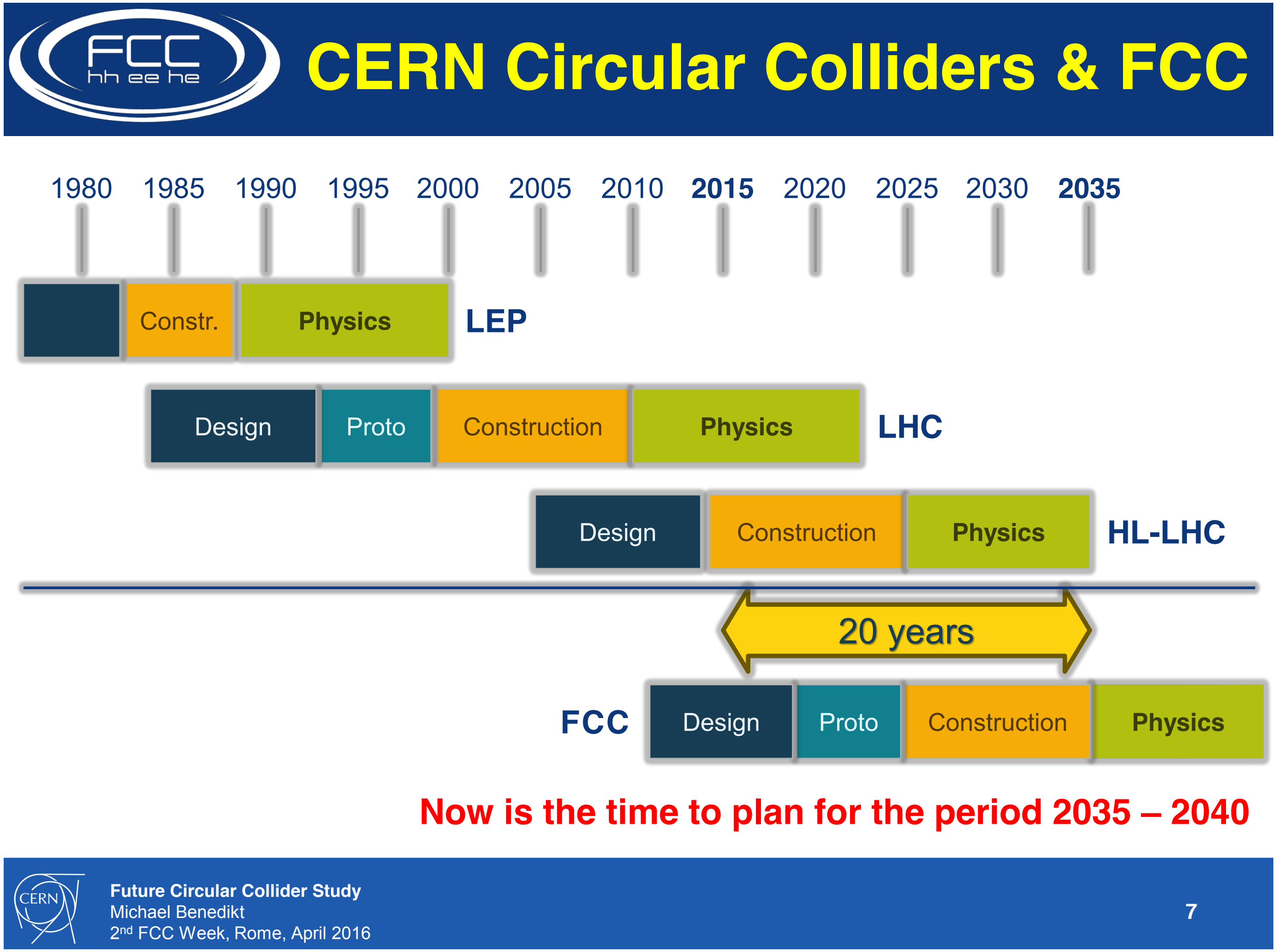
- Infrastructure studies well advanced. A 93 km planar racetrack:



	Shaft Depth (m)				Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

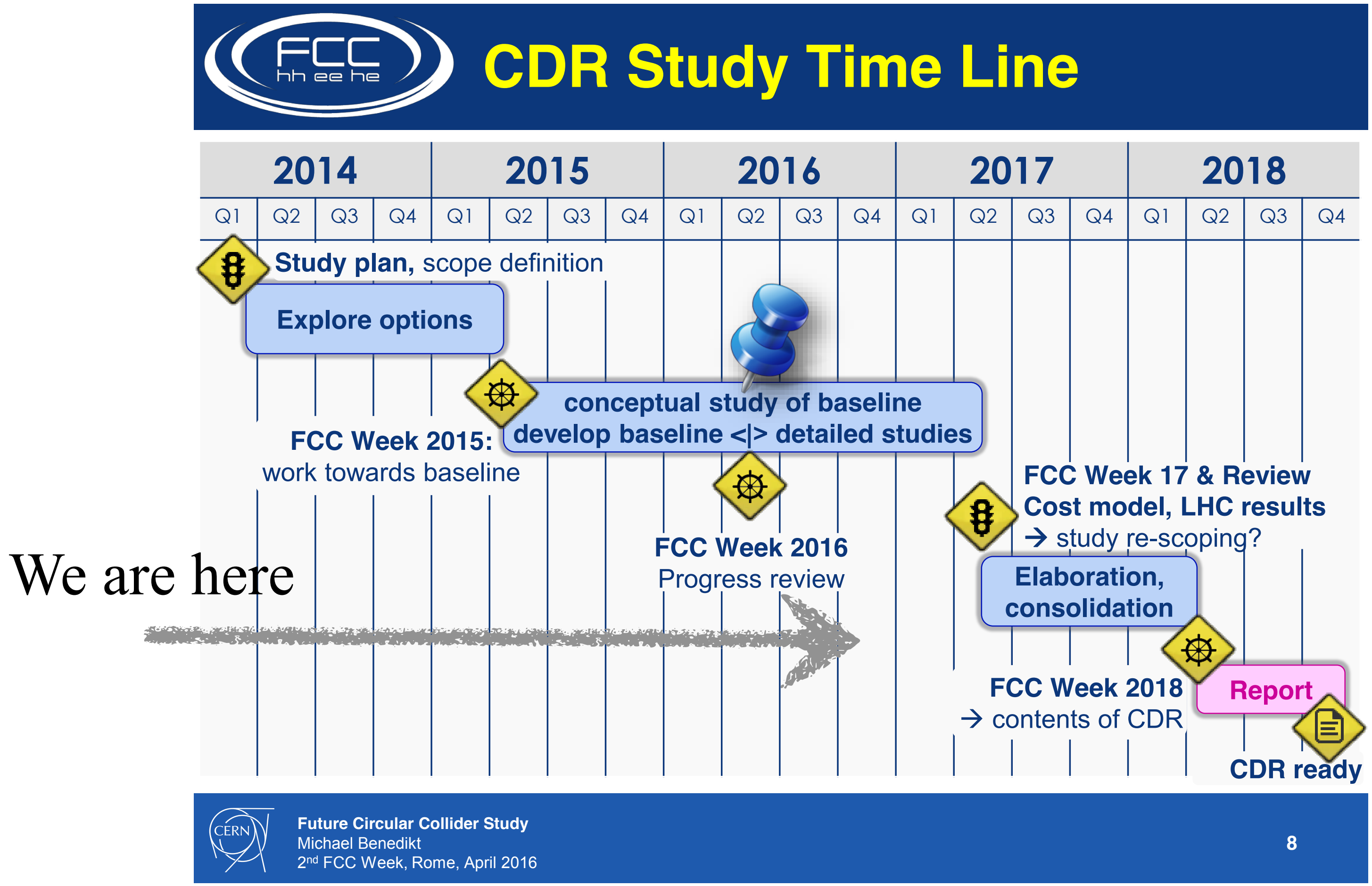
- Challenges:
  - 7.8 km tunnelling through Jura *limestone*.
  - Up to 300 - 400 m deep shafts + caverns in *molasse*.

1. Introduction to FCC - Timeline



1. Introduction to FCC: the design study timeline

- Applies to all machine and experiment designs:



Disclaimer: I'm not participating to this part of the Design study. Relevant information can be taken from:

https://indico.cern.ch/event/438866/

FCC-*hh:* preliminary machine parameters

Parameter	LHC (HL-)	FCC-*pp*
E (TeV)	14	100
R (km)	26.7	100
B dipole (T)	8.3	16
Lumi (10^{34} $cm^2.s^{-1}$)	1 (5)	5 → 100
Bunch (ns)	25	25 [5]
Events / BX	30 (150)	170 → 3500

- Machine challenges (in no particular order) are immense: civil engineering, dipoles, power consumption, cryogenics ...
- The energy and the luminosity coupled to high production rates provides both discovery and precision potential for the Physics opportunities.
- The operation distributed in two phases: Phase1 (10 years, 2.5 ab^{-1}) Phase2 (10 years, 25 ab^{-1}).

FCC-*hh:* Physics reach

- The energy and the luminosity coupled to high production rates provides both discovery and precision potential for the Physics opportunities.

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

- New dynamical regimes (energy) but also high precision. The huge production rates allow to make tighter kinematical cuts and reduce backgrounds.

FCC-*hh:* the detector challenges

Likely much more demanding than HL-LHC:

- Highly granular detectors (calorimeters, tracking and vertexing):
  - Deal with the large pile-up to figure out which *pp* vertex it is.
  - Also there is need of fast timing detector.
  - The *Z*, *W*, *H* tops are boosted.

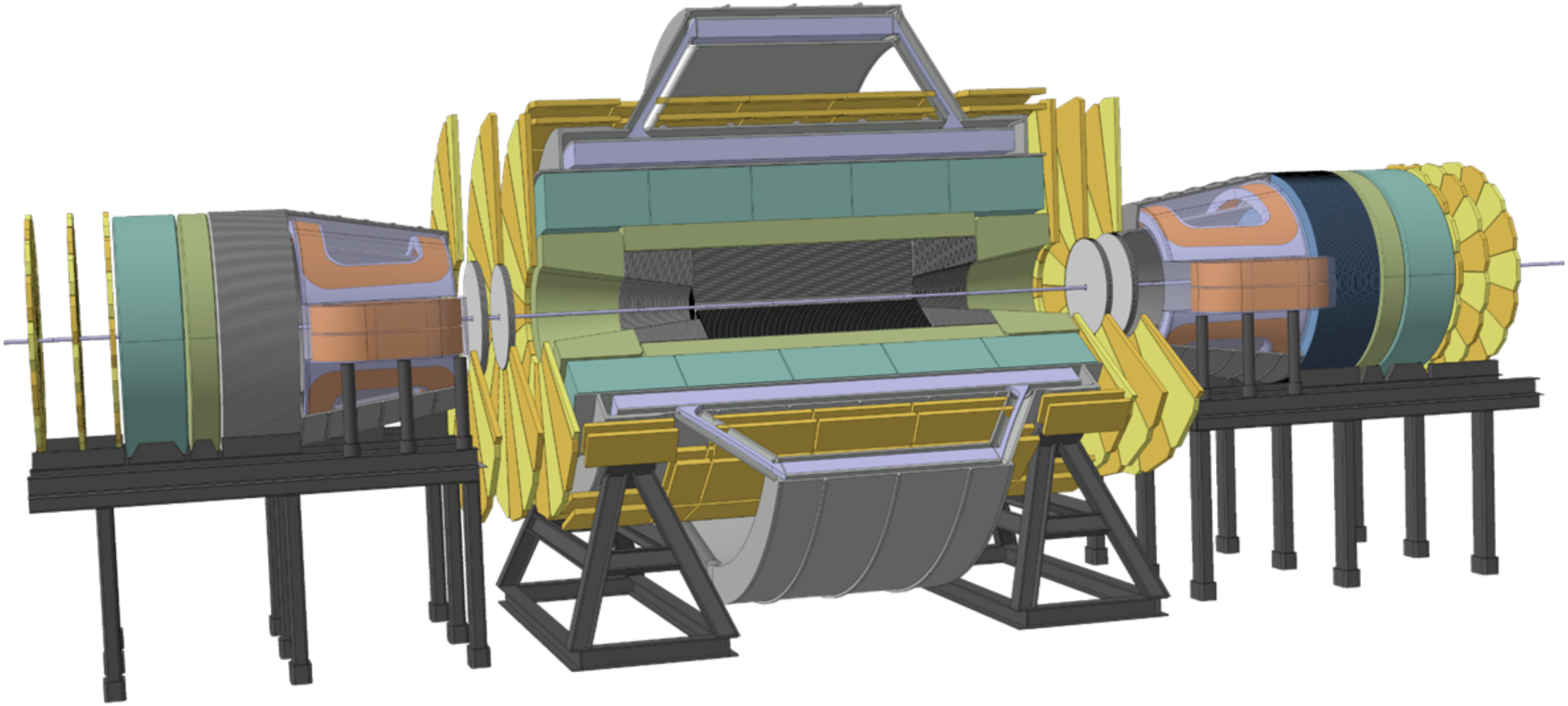
- Large coil and tracker: precise momentum resolution up to multiTeV charged particles.

- Thick calorimeters: energy containment of the boosted jets.

- Forward coverage: to deal with large longitudinal boost.

Need a larger, thicker, faster Atlas/CMS in the central region and two LHCb in the forward regions ... not a mere extrapolation of what we have.

FCC-*hh:* the detector challenges



• Twin Solenoid 6T, 12m, Dipoles 10Tm, for engineering challenge.
• The coil radius makes the cost of the detector. Likely to go down at the end of the Design Study.

FCC-*hh:* physics reach by selected examples.

Disclaimer: not a Physics case yet. It will come at the end of the Design Study in the light of the obtained results at LHC, SuperKEKB, DM searches etc...

1) Direct search for new particles: SUSY

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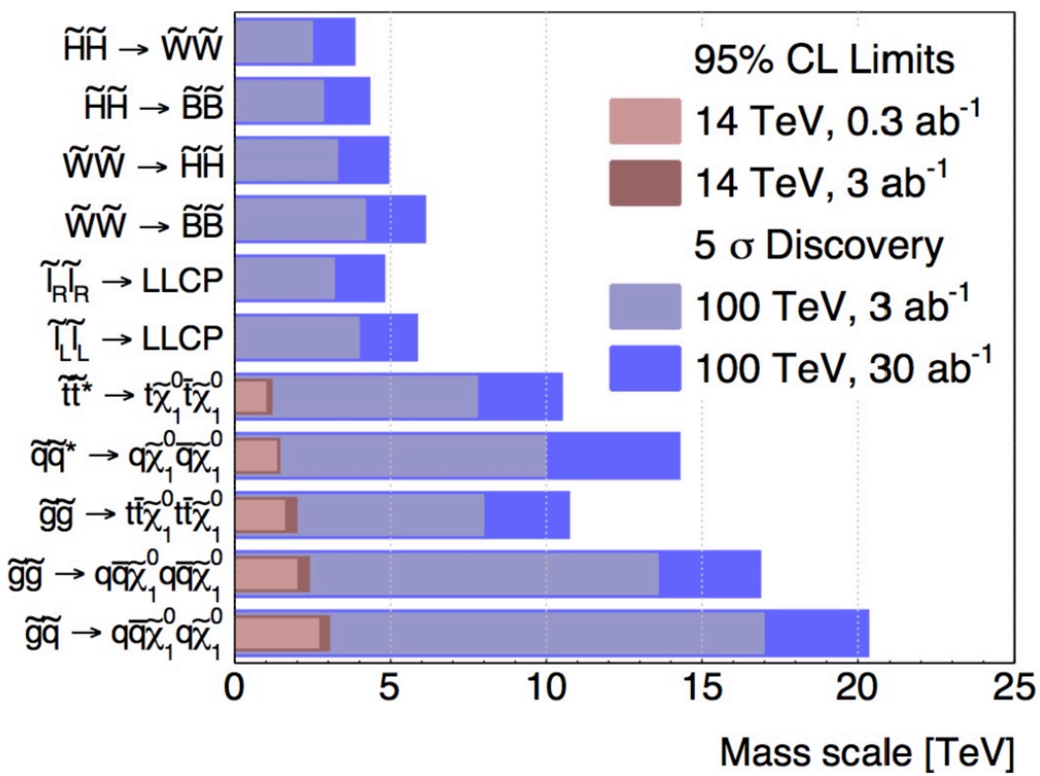
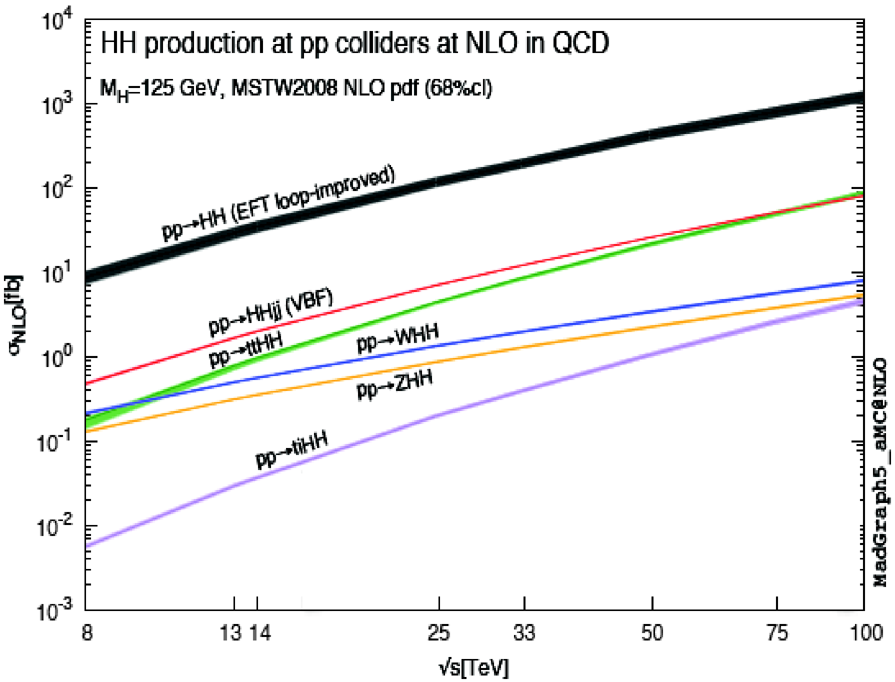


2) Trilinear (quadrilinear) Higgs couplings. FCC-*pp* is the place to be.

Cross section for HH (HHH) production 1.9 pb (5fb)

© Contino et al. [arXiv:1606.09408]



process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

- Few percents precision for HHH.
- One of the ultimate null test of the SM hypothesis.
- No competition.

FCC-*hh:* physics reach by selected examples.

3) Rare decays (examples of). With the anticipated integrated luminosity:

- $O(10^{10})$ H decays: can address FCNC probes $H \rightarrow e\mu$
- $O(10^{12})$ top quarks: can address FCNC probes $t \rightarrow cZ, cH$ ...
- As a consequence, $O(10^{12})$ W and b from top quarks ...
- Also $O(10^{11})$ τ from top quarks: LFV decays
- Search for Majorana neutrinos in top decays / WW

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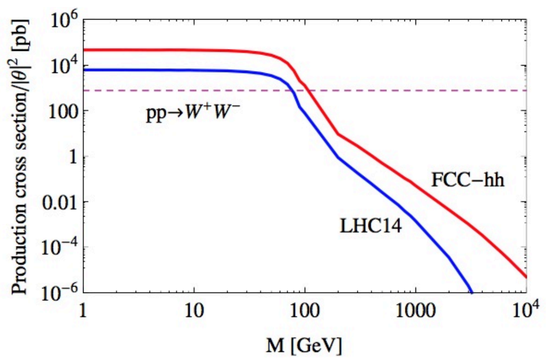

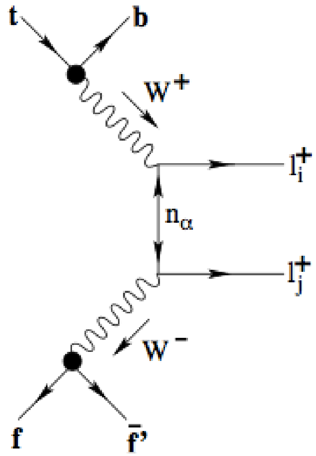

FCC-*hh:* physics reach by selected examples.

- From M. Mangano @ FCC week 2016

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)
- *

input to forthcoming simulations and studies of detector design and performance assessment

Program for next three years

* *Flavour physics at FCC-hh will be the subject of a future dedicated study and report*

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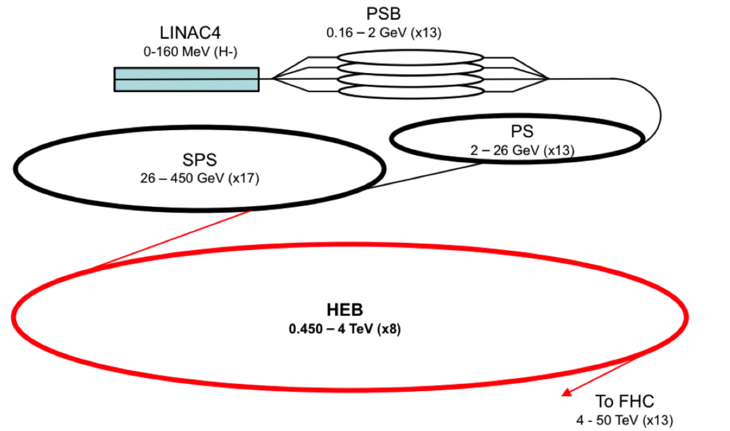


Fig. 1: Schematic view of the CERN accelerators system viewed as injectors of the future FCC-hh collider (FHC).

input to forthcoming simulations and studies of detector design and performance assessment

Program for next three years

* *Flavour physics at FCC-hh will be the subject of a future dedicated study and report*

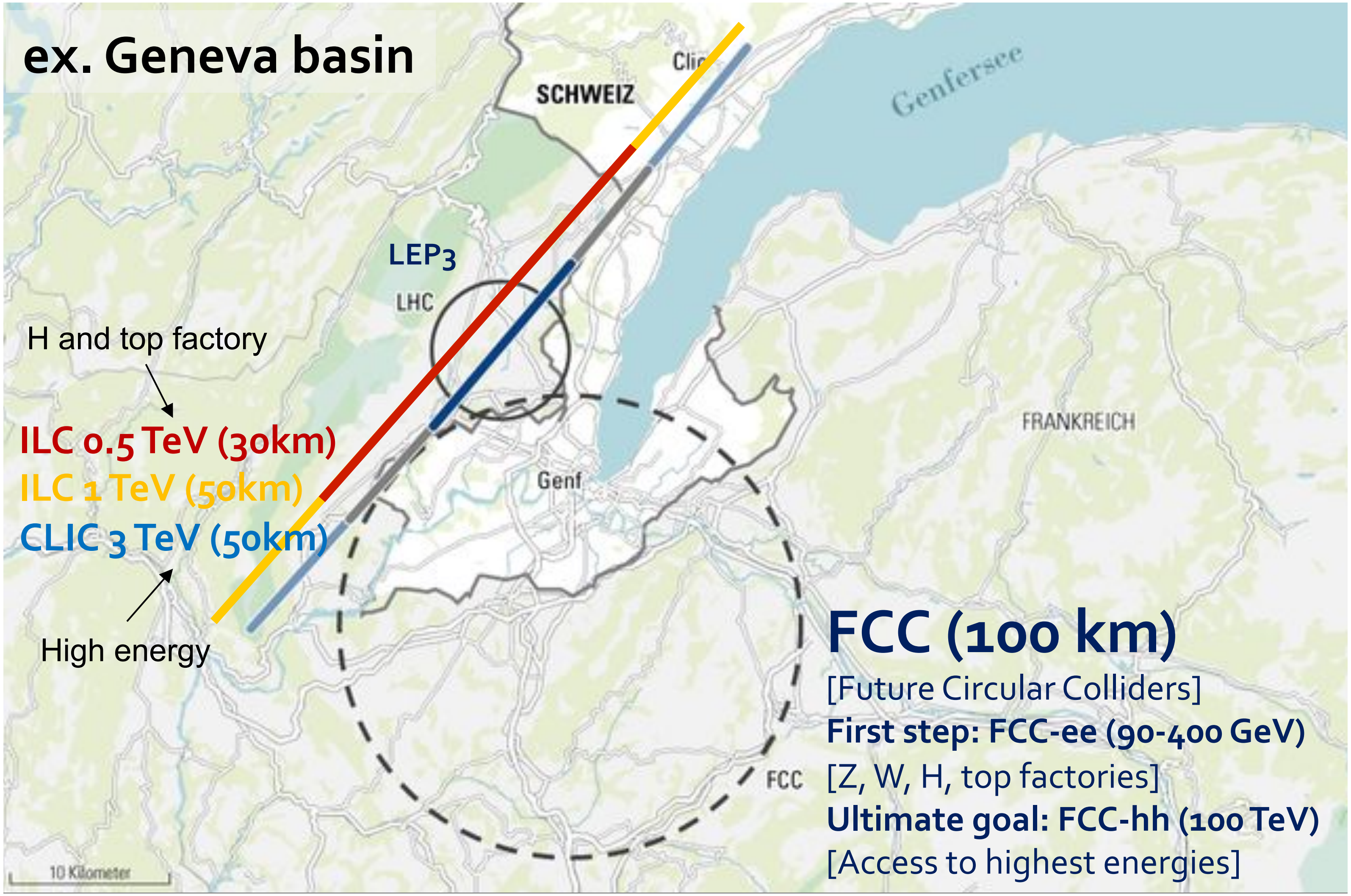
FCC-*ee*

- Generalities, competition, timelines.
- The machine parameter and design.
- The Physics case at large.
- Clermont's contributions.
- Detector design(s).

The timescale for FCC-*hh* is > 2045. The HL-LHC won't likely answer most of the outstanding questions of the field.

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

If we say that the next large scale machine must be an electron collider: what are the other large scale projects in the world?

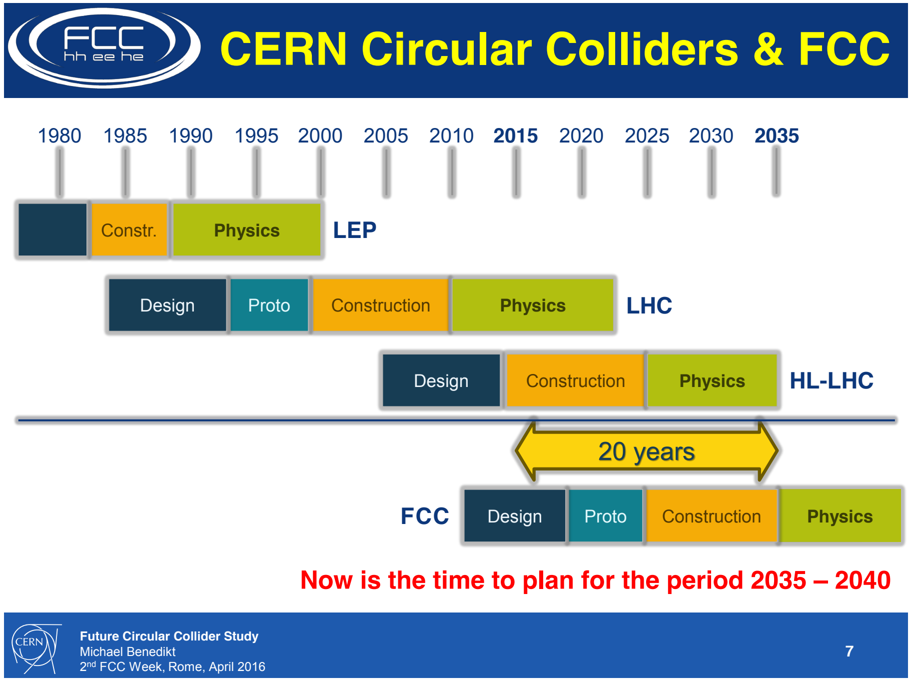

ex. Geneva basin
SCHWEIZ
Genfersee
LEP3
LHC
H and top factory
ILC 0.5 TeV (30km)
ILC 1 TeV (50km)
CLIC 3 TeV (50km)
High energy
Genf
FRANKREICH
FCC
FCC (100 km)
[Future Circular Colliders]
First step: FCC-ee (90-400 GeV)
[Z, W, H, top factories]
Ultimate goal: FCC-hh (100 TeV)
[Access to highest energies]
10 Kilometer

FCC-*ee*

- CepC: e^+e^- collisions at 240 GeV.
- SppC: *pp* collisions at 50-70 TeV.

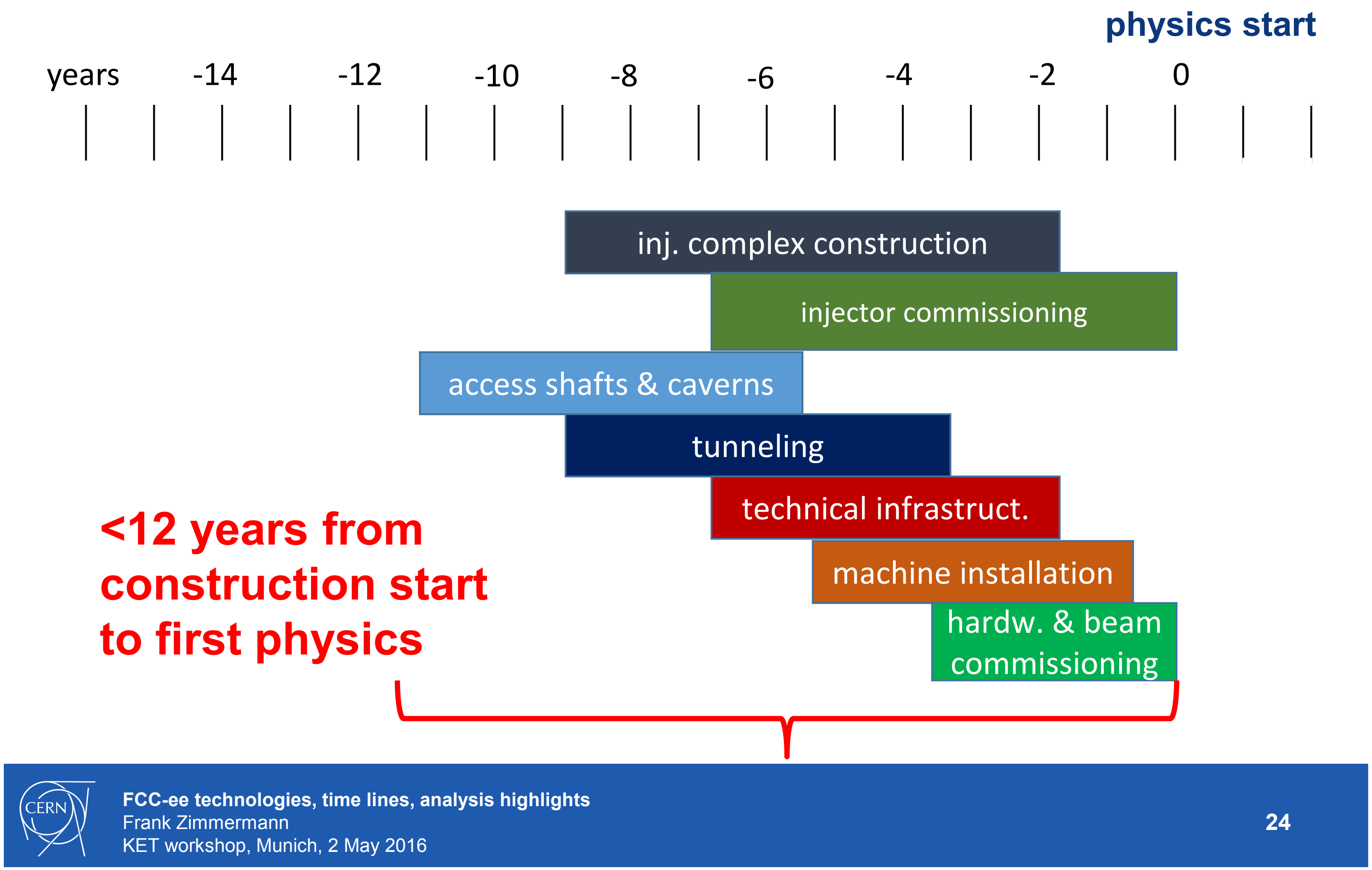
- ILC: longstanding project. Decision from Japan before 2020?

FCC-*ee* timeline and related comments



- It is often said that the FCC is far away in time. I'd like to highlight few points related to that statement
- The re-commissioning of the LHC as injector of the FCC-*hh* shall take *O*(10 y).
- On the contrary, the installation of the electron machine in the FCC tunnel can go in parallel with the operation of HL-LHC. Start of Physics: 2035 !
- Continuous particle Physics at colliders in Europe in contrast with the previous decade.
- The FCC-*ee* and ILC projects can be compared in time ...

FCC-*ee*: tentative timeline for FCC-ee construction



Machine parameters, design and luminosities

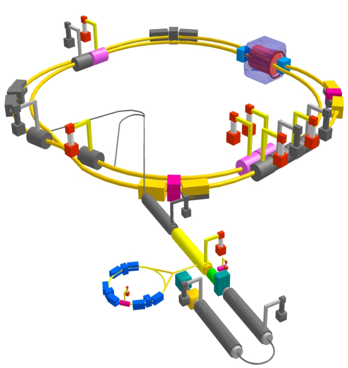
The FCC e^+e^- machine. Baseline design

- 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: next slide.

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



Some SuperKEKB parameters :

β^*_y : 300 μm
FCC-ee (H) : 1 mm

σ_y : 50 nm
FCC-ee (H) : 50 nm

$\varepsilon_y/\varepsilon_x$: 0.25%
FCC-ee (H) : 0.2% to 0.1%

e^+ production rate : 2.5×10^{12} / s
FCC-ee (H) : $< 1 \times 10^{11}$ / s

Off-momentum acceptance at IP : ±1.5%
FCC-ee (H) : ±2.0% to ±2.5%

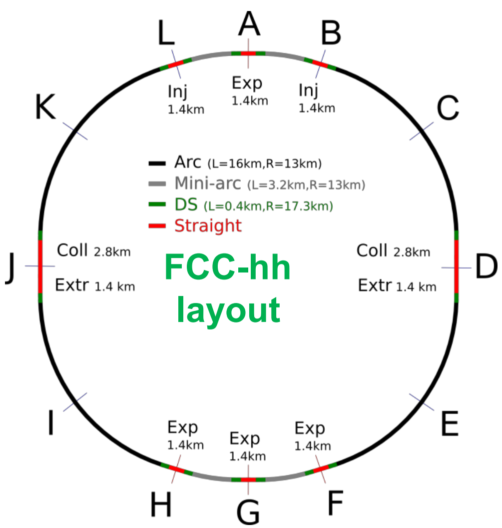
Beam Lifetime : 5 minutes
FCC-ee (H) : 20 minutes

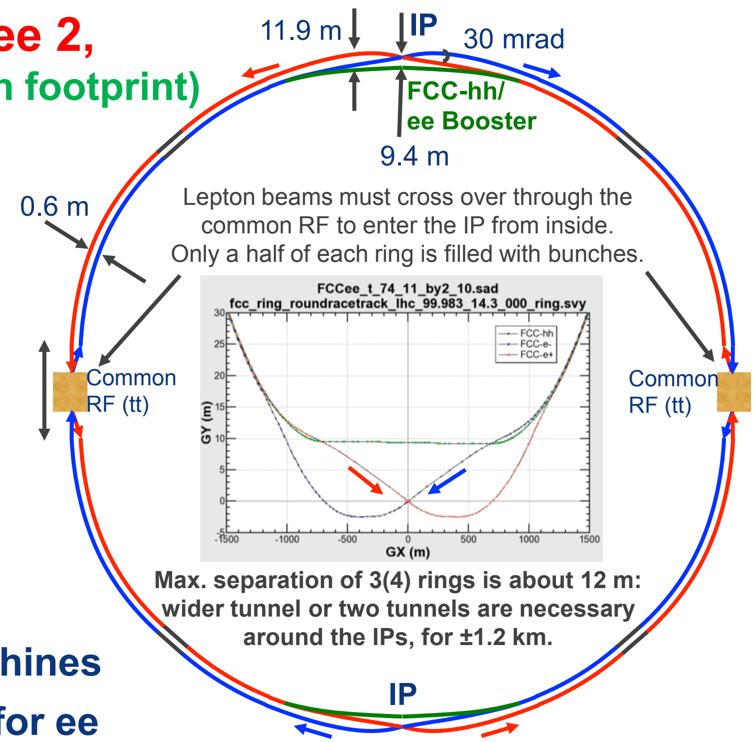
Centre-of-mass energy: ~10 GeV
FCC-ee (H) : 240 GeV

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

common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)





- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

K. Oide, D. Schulte, A. Bogomyagkov, B. Holzer, et al.

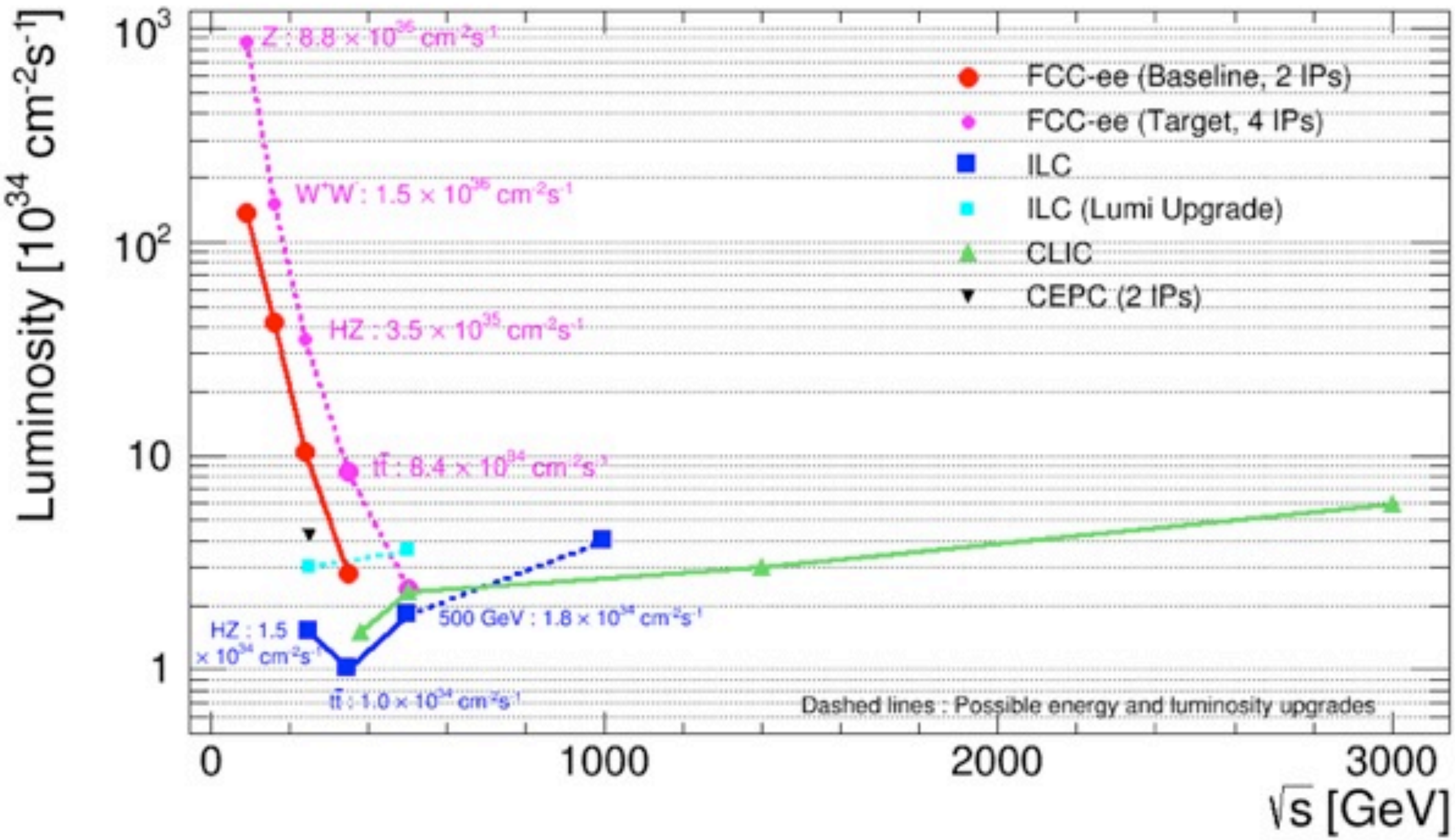
CERN
FCC-ee technologies, time lines, analysis highlights
Frank Zimmermann
KET workshop, Munich, 2 May 2016

The FCC e^+e^- machine. Baseline parameters

© F. Zimmermann

parameter	FCC-ee					LEP2
physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	210	**90**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	3.5
rms cm *E* spread SR [%]	0.03	**0.03**	**0.05**	**0.07**	**0.10**	0.11
rms cm *E* spread SR+BS [%]	0.15	**0.06**	**0.07**	**0.08**	**0.12**	0.11

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



- The time / energy allocation of the machine is to be worked out; still ...
- ... we're speaking here of $10^{12}/10^{13}$ *Z*, 10^8 *WW*, 10^6 *H* and 10^6 top pairs.

The Physics case at large

FCC-*ee*: organisation of the Design Study (Expt)

FCCs: Implementation at CERN (5)

- **Lepton experimental studies – Coordinators A. Blondel, P. Janot**
  - **Study the properties of the Higgs and other particles with unprecedented precision**

EW Physics (Z pole)	Diboson physics, m_W	H(126) Properties	Top Quark Physics
R. Tenchini F. Piccinini	R. Tenchini F. Piccinini	M. Klute K. Peters	P. Azzi

QCD and $\gamma\gamma$ Physics	Flavour Physics	New Physics
D. d'Enterria P. Skands	S. Monteil J. Kamenik	M. Pierini C. Rogan

- **Develop the necessary tools** — **Understand the experimental conditions**

Physics Software	Online & Trigger	Exp'tal Environment
C. Bernet B. Hegner	E. Perez C. Leonidopoulos	N. Bacchetta
Common with FCC-hh/eh, Synergies with LHC, LC		Synergy with FCC-hh and Linear Colliders

- **Set constraints on the possible detector designs to match statistical precision**

Detector Designs
A. Cattai
G. Rolandi

Synergy with Linear Collider detectors and others

Patrick Janot — Journée "Futur de la physique des particules" 23 Janvier 2015 — 7

FCC-*ee*: the e^+e^- Physics case at large.

First look at the physics case of TLEP

JHEP01(2014)164

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s] C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G. Sguazzoni,[u] M. Antonelli,[v] M. Boscolo,[v] U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G. Venanzoni,[v] M. Zobov,[v] J. van der Bij,[w] M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,[z] A. Butterworth,[z] C. Bernet,[z] C. Botta,[z] F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d'Enterria,[z] G. Ganis,[z] B. Goddard,[z] G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C. Lourenço,[z] L. Malgeri,[z] E. Meschi,[z] F. Moortgat,[z] P. Musella,[z] J. A. Osborne,[z] L. Perrozzi,[z] M. Pierini,[z] L. Rinolfi,[z] A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà,[z] A. Valassi,[z] C.S. Waaijer,[z] J. Wenninger,[z] H. Woehri,[z] F. Zimmermann,[z] A. Blondel,[aa] M. Koratzinos,[aa] P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E. Castaneda Miranda,[ad] E. Bulyak,[ae] D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P. Faccioli,[ah] J. R. Ellis,[ai] M. Campanelli,[aj] Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am] H. Owen,[am] H. Maury Cuna,[an]

Abstract: The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

- This initial study focused primarily on the Higgs Physics (w/ full simulation but CMS detector).
- EWK precision tests were examined from LEP (Z, W) or LC (top) extrapolations.
- The Design Study aims at reaching a fully educated view of the Physics Case from realistic detector simulation studies (We are here now).
- Explore all the Physics possibilities including Flavours. The latter is not *a priori* at the heart of the project but can be a *supplément d'âme*.

FCC-*ee*: Physics case at large / one slide synthesis

Physics reach related to the luminosity figure:

✓ ElectroWeak Precision tests:

Z pole, *WW* and top pairs thresholds.

At *Z*: you get the statistics of one LEP experiment in a minute or so!

✓ Higgs Precision test.

✓ Higgs direct production in study.

✓ Note: higher order EW calculations required.

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, ll	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	(−0.8, +0.3)	(−0.8, +0.3)	(−0.8, +0.2)	(same)	(0, 0)	(0, 0)	(−0.8, 0)	(−0.8, 0)	(−0.8, 0)
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

FCC-*ee*: the Physics case at large

Key points:

✓ Beam energy measurement: use the resonant depolarization for few bunches. Syst: 100 keV !

✓ Almost everywhere systematics limited: invent new methods, *e.g.* exclusive *b*-hadron decays for the FB asymmetry.

✓ Interpretation of the results: major theory effort required. Breakthrough with EM coupling constant measurement [arXiv: 1512.05544].

✓ Note: 100 kHz of Z decays.

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$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	(0, 0)	(0, 0)	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
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BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

Flavours in the big picture

FCC-*ee*: lepton flavours

- With the advent of the discovery of a SM-like BEH boson, there is a strong case for the existence of right-handed neutrinos possibly below or at the electroweak scale.

- A high-luminosity Z factory with 10^{12} / 10^{13} Z offers the opportunity to scan their parameter space below the electroweak scale.

- The sterile neutrinos can be searched for directly through their decays or indirectly through the charged lepton flavour-violating Z decays. Will give examples of both.

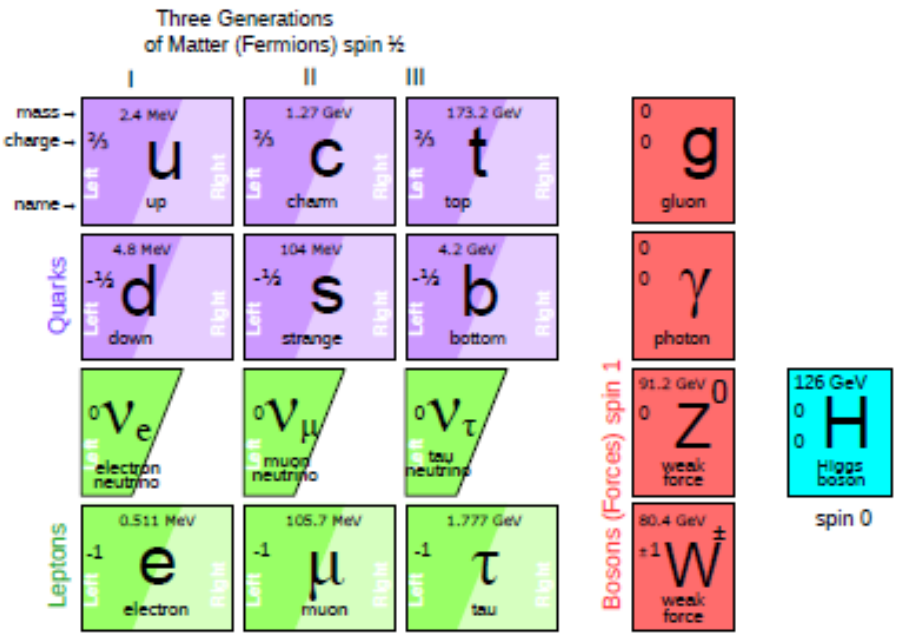
- Yukawa for charged fermions

$$\mathcal{L}_Y = Y^d_{ij}\bar{Q}_{Li}\phi d_{Rj} + Y^u_{ij}\bar{Q}_{Li}\tilde{\phi} u_{Rj} + Y^\ell_{ij}\bar{L}_{Li}\phi\ell_{Rj} + +\text{h.c.}$$

- Most general Lag. form for neutrals $\mathcal{L}_N = \frac{M_{ij}}{2}\bar{N}^c_i N_j + Y^\nu_{ij}\bar{L}_{Li}\phi N_j$

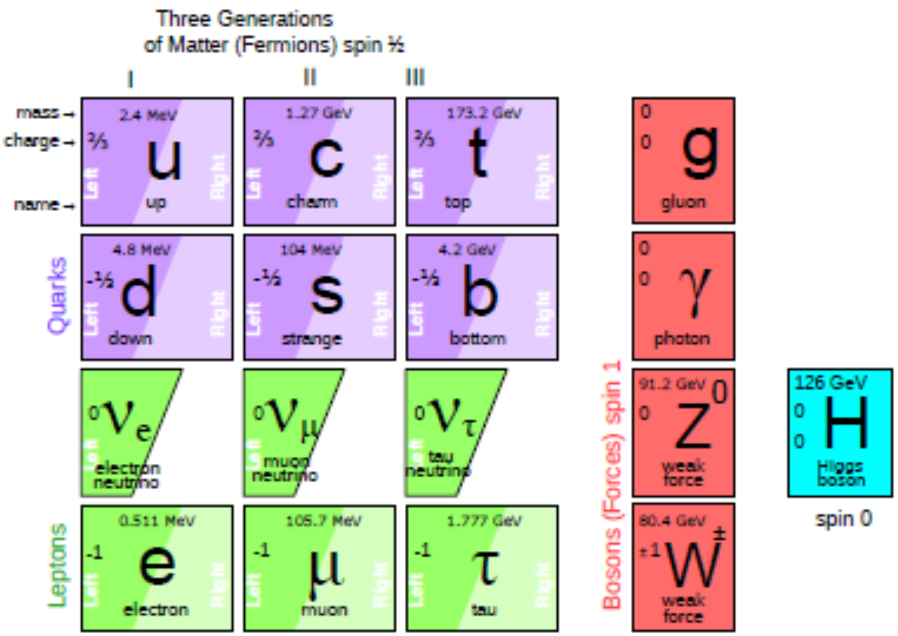
FCC-*ee*: lepton flavours

- Most general form for neutrals L $\mathcal{L}_N = \frac{M_{ij}}{2} \bar{N}_i^c N_j + Y_{ij}^{\nu} \bar{L}_{Li} \phi N_j$



- Most general form for neutrals L $\mathcal{L}_N = \frac{M_{ij}}{2}\bar{N}_i^c N_j + Y_{ij}^{\nu}\bar{L}_{Li}\phi N_j$

- Somehow, the only (provocative) question is how many?



FCC-*ee*: lepton flavours

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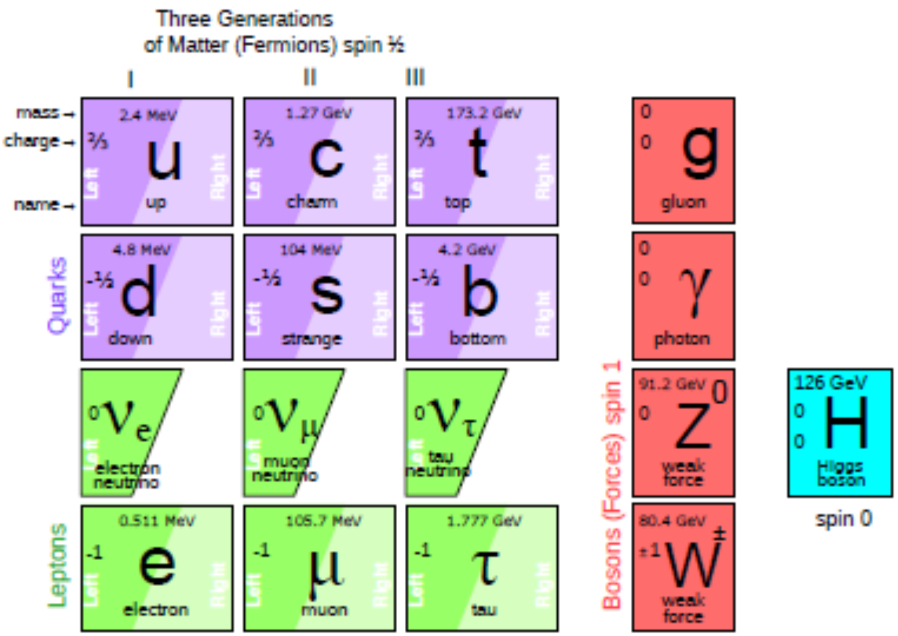
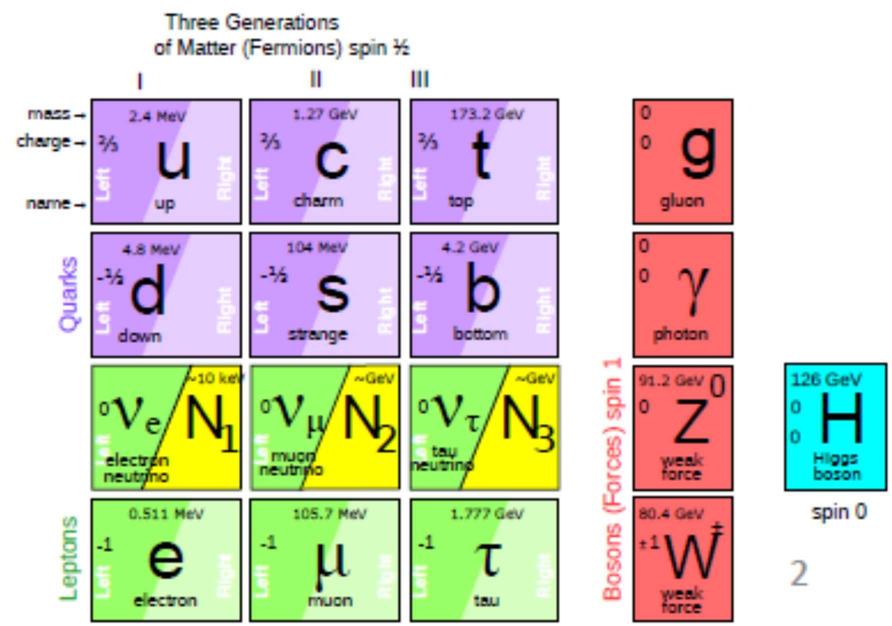




FCC-*ee*: lepton flavours

- Lepton Flavour-Violating Z decays in the SM with lepton mixing are typically

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

- Any observation of such a decay would be an indisputable evidence for New Physics.

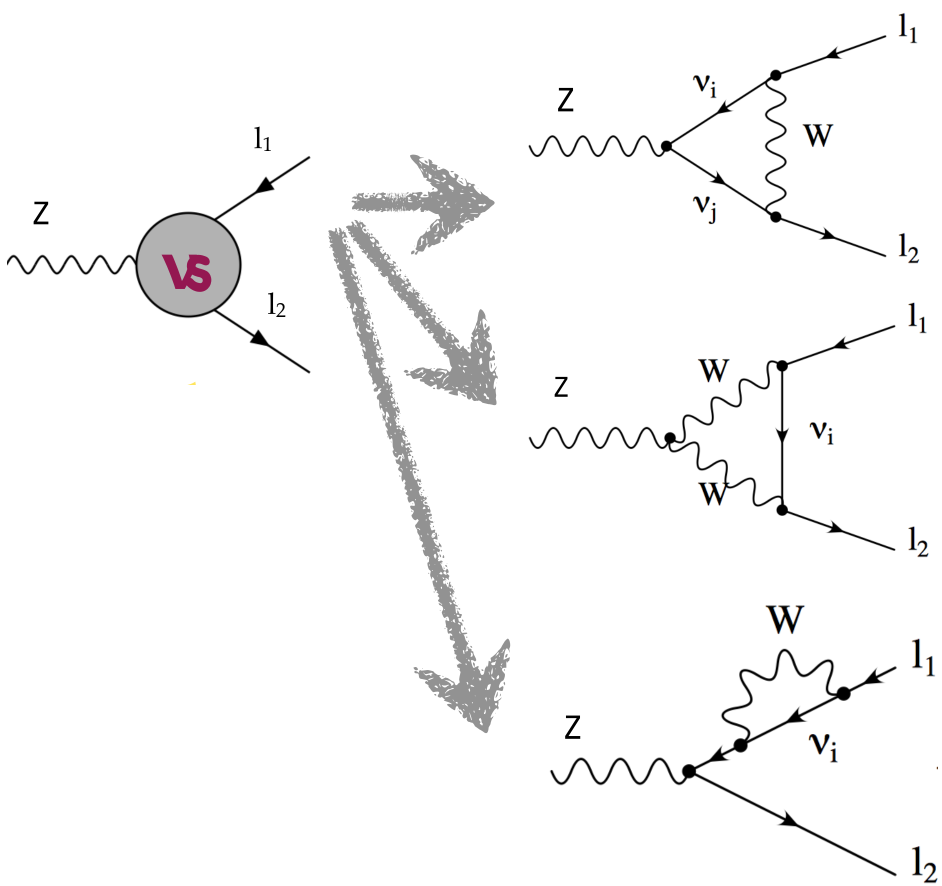
- Current limits at the level of ~10^{-6} (from LEP and recently Atlas, *e.g.* DELPHI, Z. Phys. C73 (1997) 243 ATLAS, CERN-PH-EP-2014-195 (2014))

- The FCC-*ee* high luminosity Z factory would allow to gain up to six orders of magnitude ...

- Complementary to the direct search for steriles.

- The following plots are based on a work from V. De Romeri et al.

FCC-*ee*: LFV in rare Z-decays



Studies for the Giga-Z (Wilson, DESY-EFCA LC workshop (1998-1999), J. I. Illana and T. Riemann, Phys. Rev. D63 (2001) ... are revisited taking into account:

- θ_{13} and other neutrino data
- new contributions of sterile states are already severely constrained:

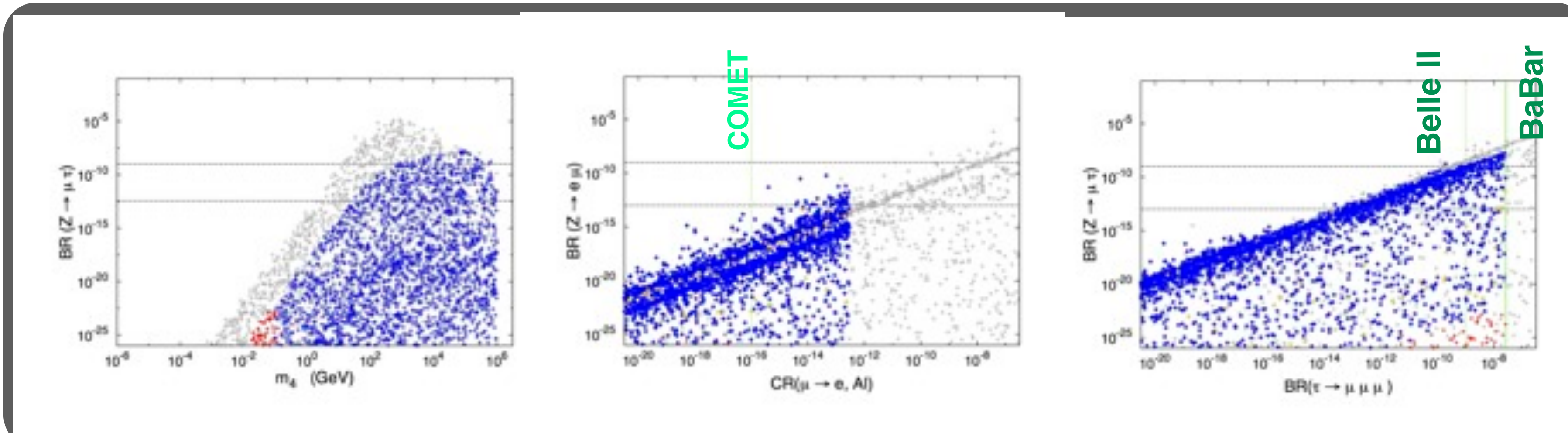
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double β decays
  - invisible Z-width

  ....

FCC-*ee*: LFV in rare Z-decays: “3+1” toy model

3+1 model is a convenient ad-hoc extension; 4th state encodes contributions of arbitrary number of sterile νs

exp. excluded ●
cosmo X ●
cosmo OK ●



V. De Romeri et al. JHEP 1504 (2015) 051

- Steriles with mass > 80 GeV and mixings *O*(10^{-5}-10^{-4}) within FCC-*ee* reach.

- Low-energy experiments (COMET ...) at work to probe the electron-muon sector.
- FCC-*ee* provides the stringent constraint in tau-mu sectors.
- Experimental study ongoing.

FCC-*ee*: Flavours at the *Z*: the lepton Physics Case

- Direct search (Serra, Blondel, Graverini, Shaposhnikov) based on nuMSM model from Asaka and Shaposhnikov arXiv:050501. Explored in arXiv:1411.5230.

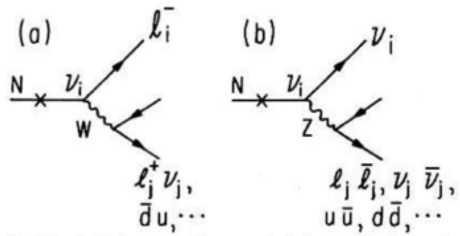
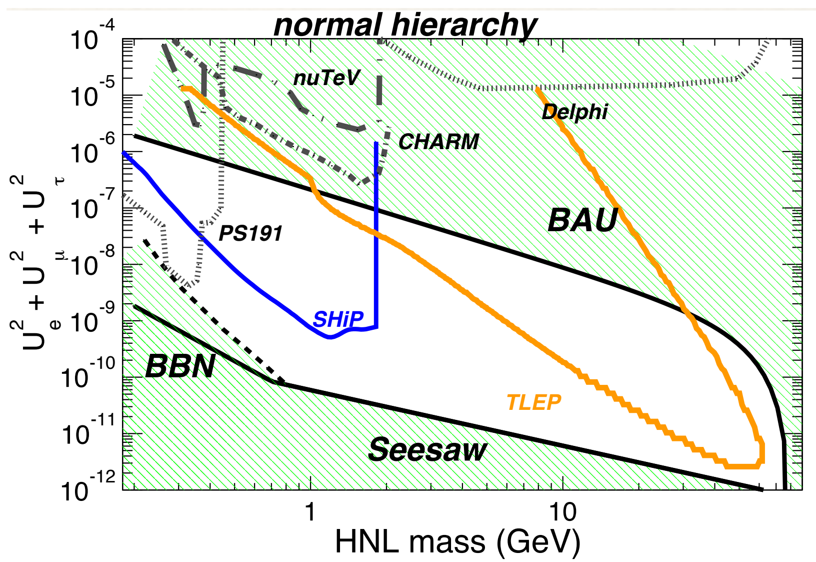


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

- The sterile neutrinos are produced from mixing with active neutrinos out of the *Z* decay.

- The *N* decay lifetime depends on the mass of the sterile and the mixings

- Branching fraction almost saturated with the final states: $N \to \ell^+ \ell'^- \nu, N \to q\bar{q}'\ell, N \to q\bar{q}\nu$



N. Serra et al. arXiv:1411.5230.

FCC-*ee*: the EWP decays as a first exploration.

- The rare decays $b \to s\ \ell^+\ell^-$ are receiving increasing experimental and phenomenological interests:
  - good laboratory for new quark/lepton transitions operators.
  - possibly clean theoretical (QCD) uncertainties.
  - some signs of departures of the data w.r.t. the SM/QCD predictions.
  - Lepton universality is challenged.

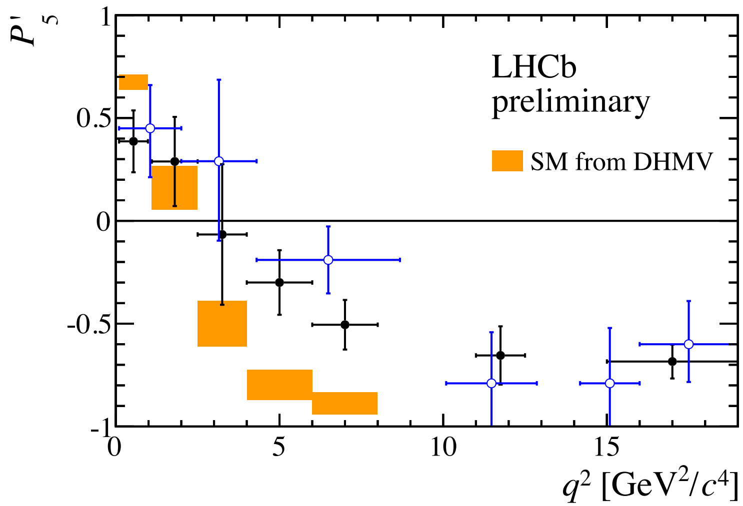


Figure 17: The observable P'_5 in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the $1\,\text{fb}^{-1}$ analysis from Ref. [7].

FCC-*ee*: the EWP decays as a first exploration.

- The rare decays $b \to s\ \ell^+\ell^-$ are receiving increasing experimental and phenomenological interests:
  - good laboratory for new quark/lepton transitions operators.
  - possibly clean theoretical (QCD) uncertainties.
  - clear experimental signatures.
  - some signs of departures of the data w.r.t. the SM/QCD predictions in the muon final states.

- The electron final states allows a dedicated study at low q^2. O(10^5) events! Exploration started at LHCb: O(10^2) events (RunI).
- The tau lepton final states is unexplored so far but is necessary to complete the landscape, whatever the NP scenario is there or ruled out.

- Experimentally, aim at:
  - measuring the **branching fraction**,
  - studying the **angular distributions**.

In both cases, FCC-*ee* provides a possibly unique access to these territories.

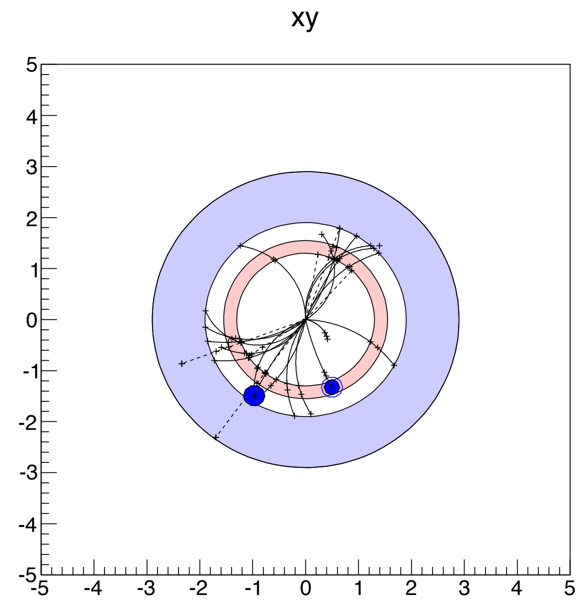
FCC-*ee*: The EWP decays as a first exploration.

- The transition $B^0 \rightarrow K^{*0}\, \tau^+\tau^-$ can be fully solved.

- Two neutrinos missing
  → six momentum coordinates to find.

- The secondary vertex is determined from
  → the resonant $K^{*0} \rightarrow K^- \pi^+$

- Limit ourselves to the τ^- decays in three prongs
  → $\tau^- \rightarrow a_1^- \nu_\tau$



- **Constraints:**
  - B flight distance → 2 d.o.f.
  - τ flight distances → 4 d.o.f.
  - τ masses → 2 d.o.f.
  - saturate the d.o.f. of the problem.

This is a Physics with :

- One primary vertex
- No trigger (neither hw or sw).

FCC-*ee*: FCNC (EWP) in *b*-hadron decays. $B^0 \to K^{*0}\,\tau^+\tau^-$.

- Backgrounds:

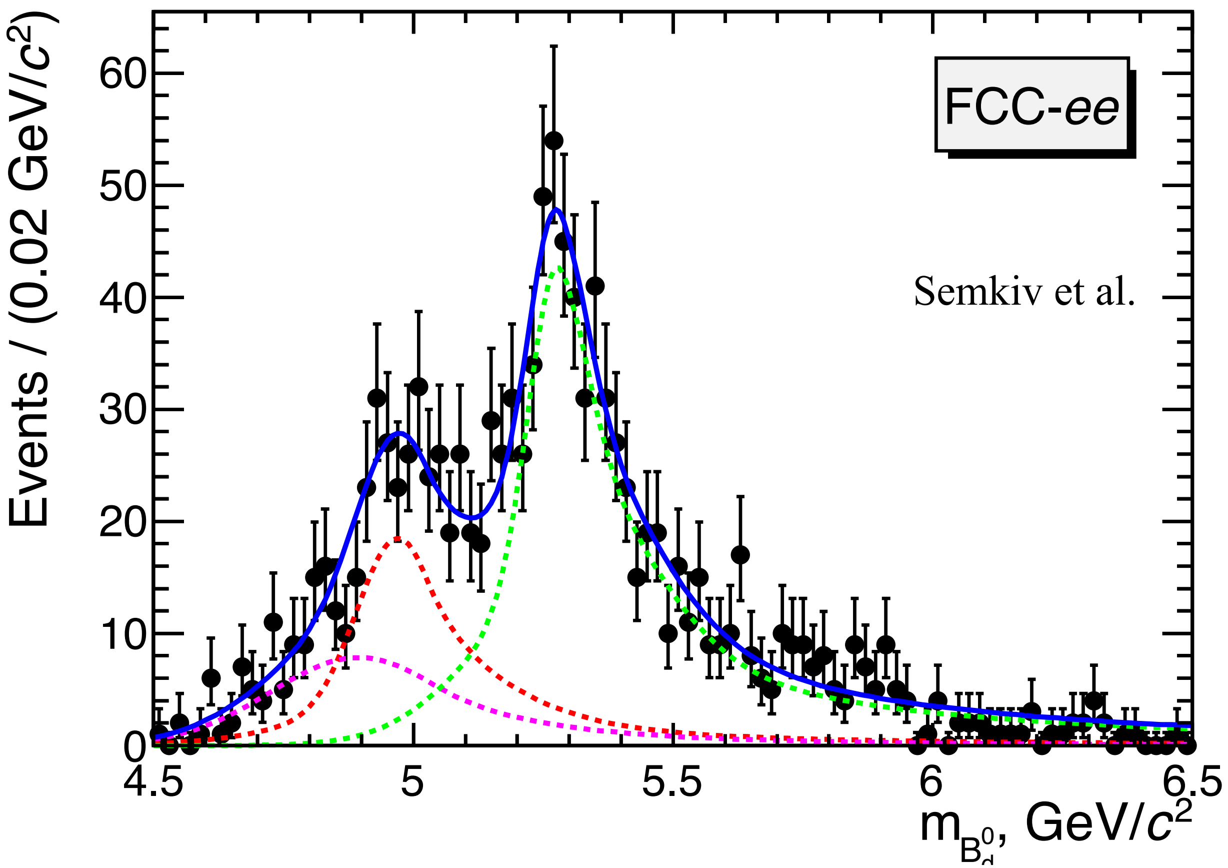
$\bar{B}^0 \to D_s^+ \bar{K}^{*0} \tau^- \bar{\nu}_\tau$

(pink)

$\bar{B}_s \to D_s^- D_s^+ K^{*0}$

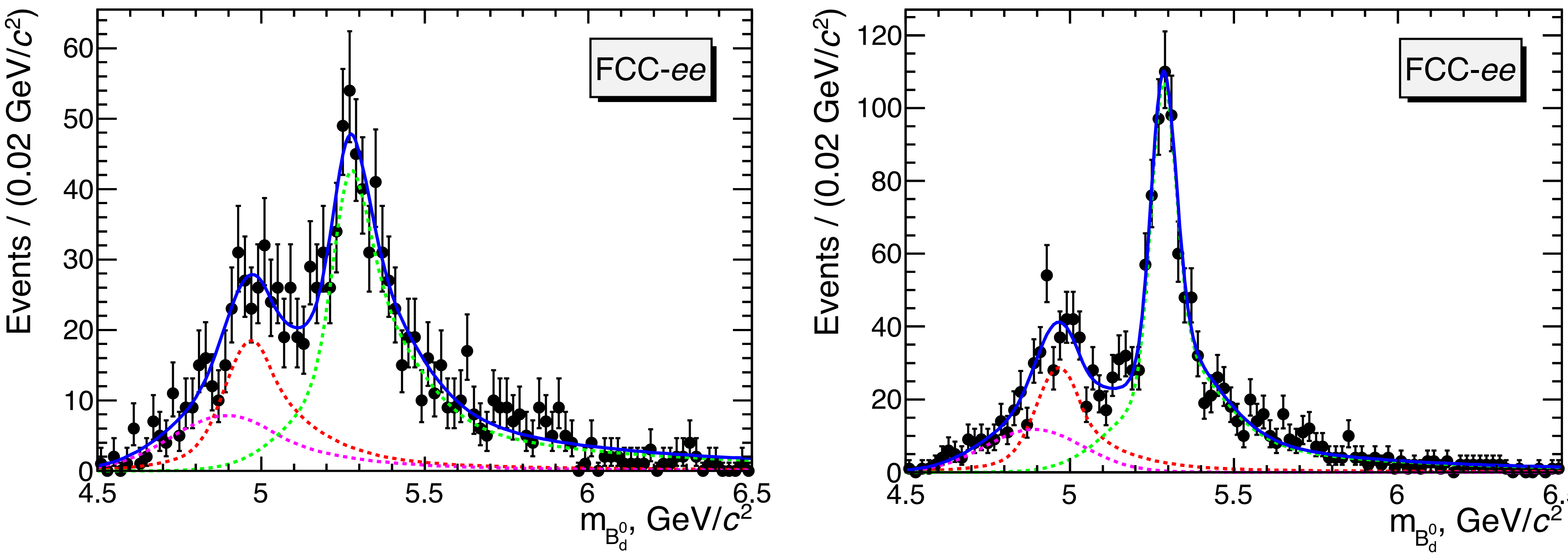
(red)

(signal in green).



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

FCC-*ee*: FCNC (EWP) in *b*-hadron decays. $B^0 \to K^{*0}\,\tau^+\tau^-$.



Conditions:

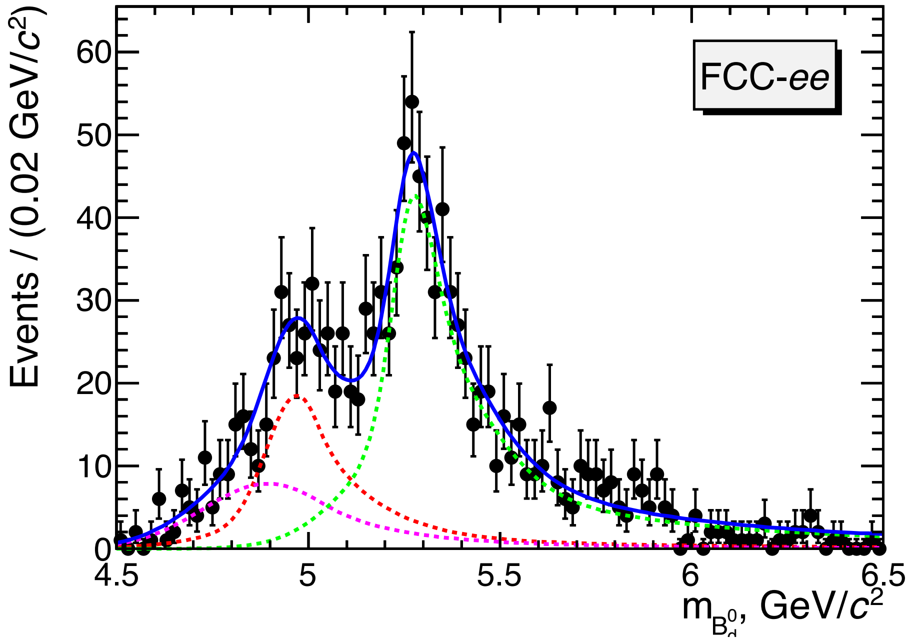
- Target luminosity
- Left: vertexing performance as ILD.
- Right: vertexing performance twice better than ILD. Pretty realistic: initial studies tell that the vertex detector can be as close as 2 cm from IP.

FCC-*ee*: FCNC (EWP) in *b*-hadron decays. $B^0 \rightarrow K^{*0}\,\tau^+\tau^-$.

Few comments are in order:

- At target luminosity, we can expect about 10^3 events of reconstructed signal. Angular analysis possible. And more w/ τ polarization.

- With an ALEPH-like vertex detector performance, the signal peak can't be resolved.

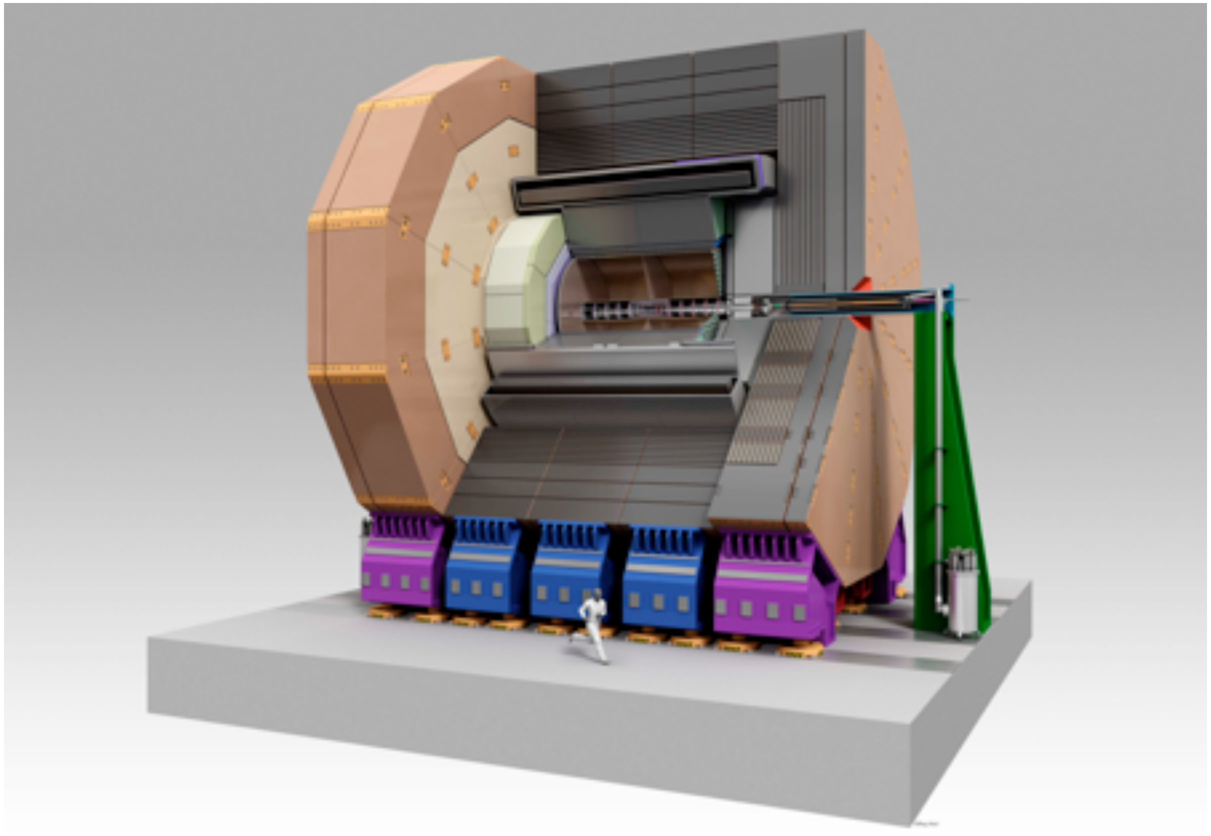


This mode can serve as a benchmark for partial reconstruction techniques and hence vertexing. The next step of the study is to attack the more challenging mode $B^0_s \rightarrow \tau^+\tau^-$.

The FCC-ee detectors

FCC-*ee*: detectors

- There have been a lot of developments in the two past decades on electron colliders (mostly ILC) detectors. They can serve as an educated basis for the full simulation studies, *e.g.*



FCC-*ee*: detectors

- There is however the need of working out a dedicated detector because there are smarter things to do:
- *B* field required for containing the beam backgrounds is only 2 T (4 for ILC or CLIC). Relaxed constraints.
- The vertex detector can be as close as 2 cm from the interaction point.
- The momentum resolution should match the beam energy spread at 45 GeV (50 MeV).
- We must be light for the Flavour (b, tau ...) Physics.
- We want hadron Particle Identification detectors.
- If you feel you can / wish participate to this, please join and think. This happens now.

Summary

Scientific context: scenarii

1) Find a new heavy particle at the Run II 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.
- Energy frontier to find the corresponding spectrum.

4) Find no new particle, standard H properties and flavour observables in SM:
- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision.
- Push the energy frontier to the best of our knowledge.

Summary

1) Find a new heavy particle at the Run II 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 [FCC-hh].
- The underlying quantum structure must be studied [FCC-ee].

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

3) Find no new particle, standard H properties but flavour observables departing from SM:
- Asymptotic *Z*, *W*, top factories to fix the energy scale [FCC-ee].
- Energy frontier to find the corresponding spectrum [FCC-hh].

4) Find no new particle, standard H properties and flavour observables in SM:
- Asymptotic *Z*, *W*, *H*, top factories for asymptotic precision [FCC-ee].
- Push the energy frontier to the best of our knowledge [FCC-hh].

Summary

1) There are scenarii for which any continuation of the particle Physics requires FCC project.

2) There is no scenario in which FCC project does not bring an invaluable path.

3) The timeline is commensurate with the other world scale projects.

FCC References and links as a Conclusion.

- The project is getting mature. The FCC software and detector simulation are getting up. A good moment to contribute.

- Aim at gathering small teams of experimentalists and theoreticians on benchmark subjects. At work for LFV *Z* decays and $B^0 \to K^{*0} \tau^+\tau^-$, on track for $B^0_s \to \tau^+\tau^-$ and foreseen for $B^0 \to K^{*0} e^+e^-$. More are welcome.

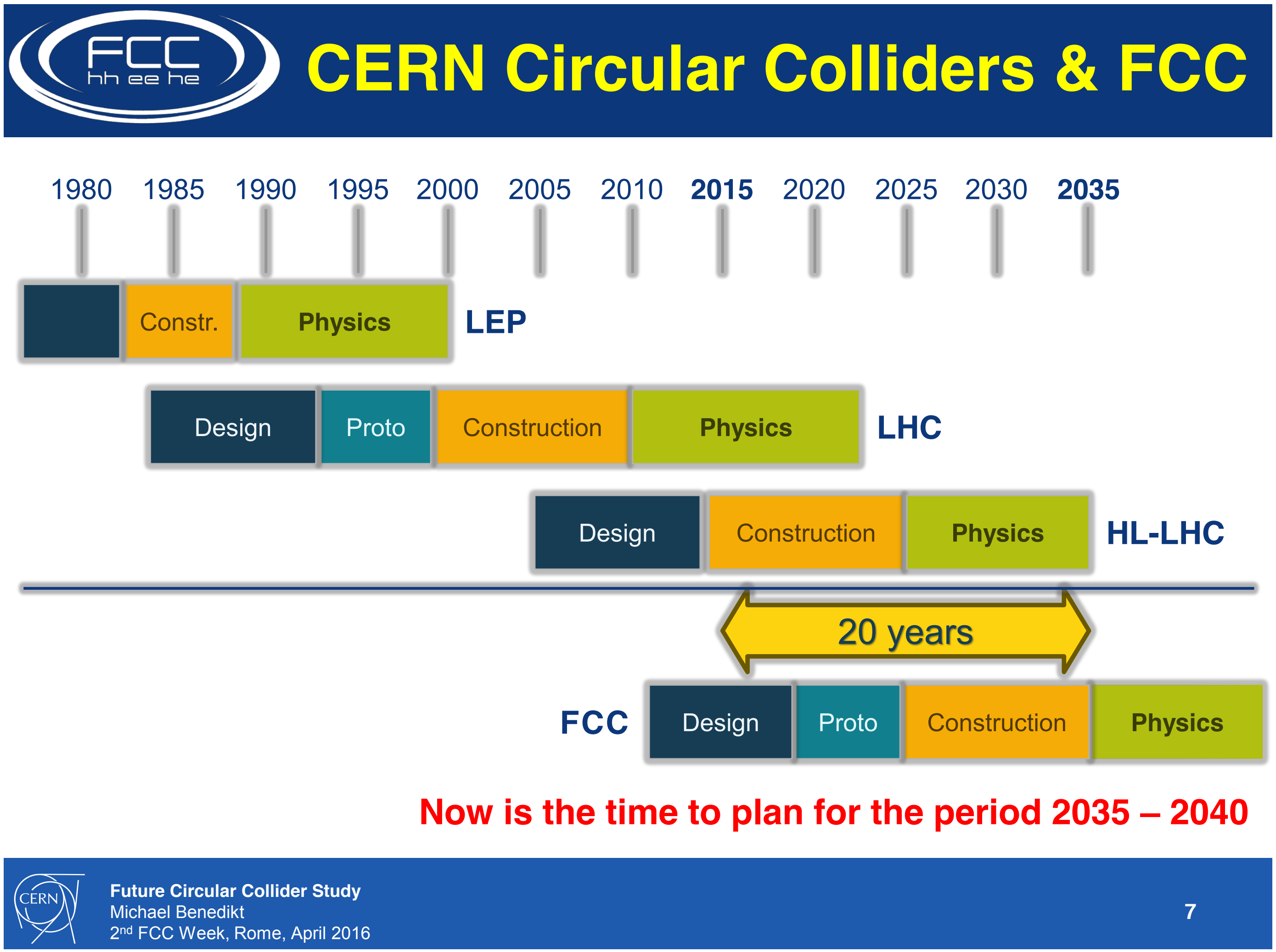
- Information on FCC and FCC-*ee* can be found there : http://tlep.web.cern.ch/

- A dedicated *e*-list for the Flavours WG is set-up here with self-subscription for CERN users: https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10116182&tab=3

- Otherwise get in touch with us: jernej.kamenik@ijs.si or monteil@in2p3.fr.

Back-up slides.

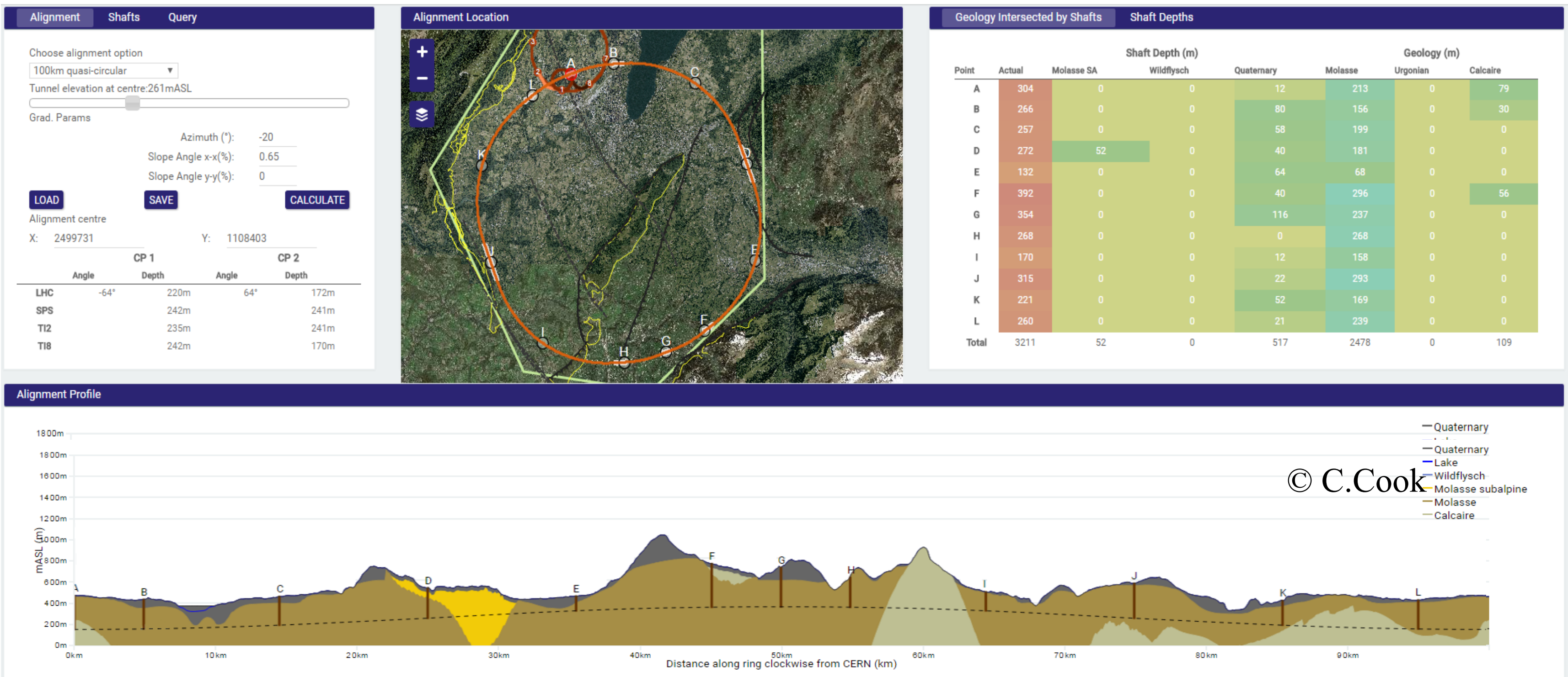
Back-up slides.



- 80-100 km infrastructure in Geneva area: A flavour of the location:

1. Introduction to FCC

- Infrastructure studies ongoing. A 93 km planar racetrack:



- Challenges:
  - 7.8 km tunnelling through Jura limestone
  - Up to 300 - 400 m deep shafts + caverns in molasse

2. The 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*.

- Not a straightforward extrapolation of LEP. Many Challenges:

  - Brehmsstrahlung@IP limits the beam lifetime at top energy.

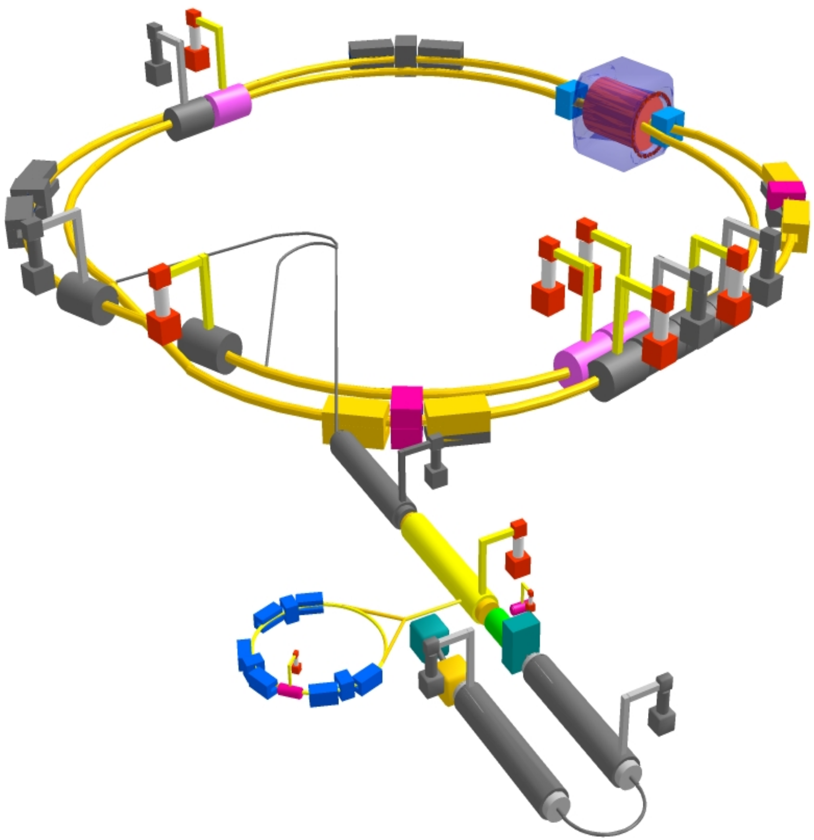
  - Polarization of the beams (at least natural one for beam energy measurement - EWK precision measurements). Note: latest explorations seem to indicate that the Physics program can be made without polarization (both for top and *Z* pole)

  - RF system must deal w/ contradictory requirements (high gradients (top) / high currents (*Z*) .

- Baseline design is a target. Not an actual working machine.

2. The e^+e^- machine. Challenges

- To some extent, SuperKEKB is a testbench for FCC-*ee:*



Some SuperKEKB parameters : ©P. Janot

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

2. The e^+e^- machine. Baseline parameters.

	LEP1	LEP2	Z	W	H	tt
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittance ε						
- Horizontal [nm]	20	22	29.2	3.3	0.94	2
- Vertical [pm]	400	250	60	7	1.9	2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP β^*						
- Horizontal [m]	2	1.2	0.5	0.5	0.5	1
- Vertical [mm]	50	50	1	1	1	1
Beam size at IP σ^* [μm]						
- Horizontal	224	182	121	26	22	45
- Vertical	4.5	3.2	0.25	0.13	0.044	0.045
Energy spread [%]						
- Synchrotron radiation	0.07	0.16	0.04	0.07	0.10	0.14
- Total (including BS)	0.07	0.16	0.06	0.09	0.14	0.19

2. The e^+e^- machine. Baseline parameters.

	LEP1	LEP2	Z	W	H	tt
Bunch length [mm] - Synchrotron radiation - Total	 8.6 8.6	 11.5 11.5	 1.64 2.56	 1.01 1.49	 0.81 1.17	 1.16 1.49
Energy loss / turn [GeV]	0.12[(1)]	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3[(1)]	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time τ_E [turns]	371	31	1320	243	72	23
Energy acceptance RF [%]	1.7	0.8	2.7	7.2	11.2	7.1
Synchrotron tune Q_s	0.065	0.083	0.65	0.21	0.096	0.10
Polarization time τ_p [min]	252	4	11200	672	89	13
Hourglass factor H	1	1	0.64	0.77	0.83	0.78
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	0.002	0.012	28.0	12.0	6.0	1.8
Beam-beam parameter - Horizontal - Vertical	 0.044 0.044	 0.040 0.060	 0.031 0.030	 0.060 0.059	 0.093 0.093	 0.092 0.092
Luminosity lifetime [min][(2)]	1250	310	213	52	21	15
Beamstrahlung critical	No		No	No	Yes	Yes

(1) Does not take into account the contribution of damping and emittance wigglers.
(2) The luminosity lifetime corresponds to 4 IPs.

4. Scope of the FCC-*ee* Flavour Physics working

- Understand the experimental precision with which rare decays of *c*- and *b*-hadrons and CP violation in the heavy-quark sector could be measured with 10^{12} Z, as well as the potential sensitivity to new physics, and compare to the ultimate potential of the (soon to be) running LHCb upgrade and Belle II experiments. Examine the relevance of a dedicated PID (π / K / p separation) detector,

- The very same objective stands for the rare lepton decays.

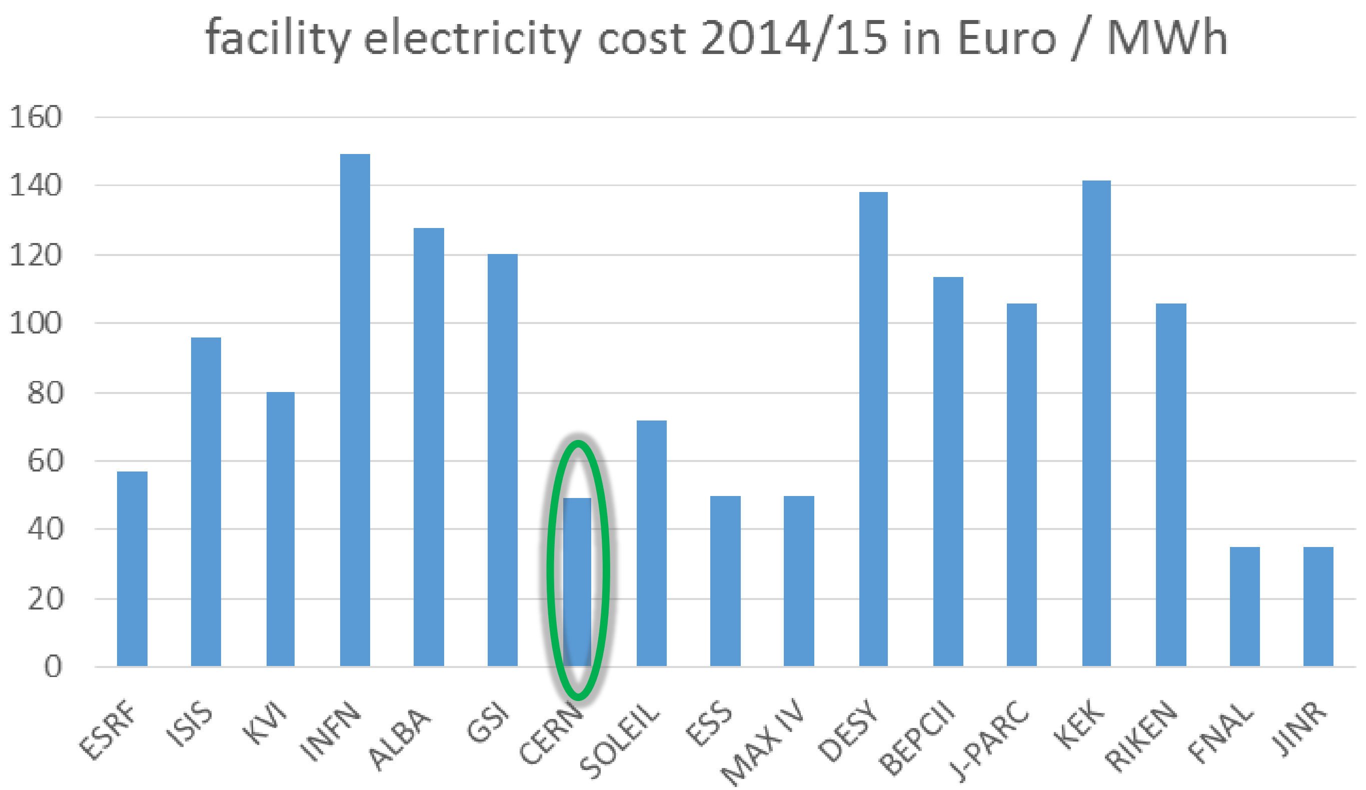
- Examine the physics reach of lepton flavour violating processes and neutrino-related Physics unique to the FCC-*ee*.

- Have a platform to think of beyond standard observables.

- "What would like to do/see with/in 10^{12} / 10^{13} Z?" makes a nice playground to start with.

The general numbers it is good to have in mind when one speaks about these kinds of projects.

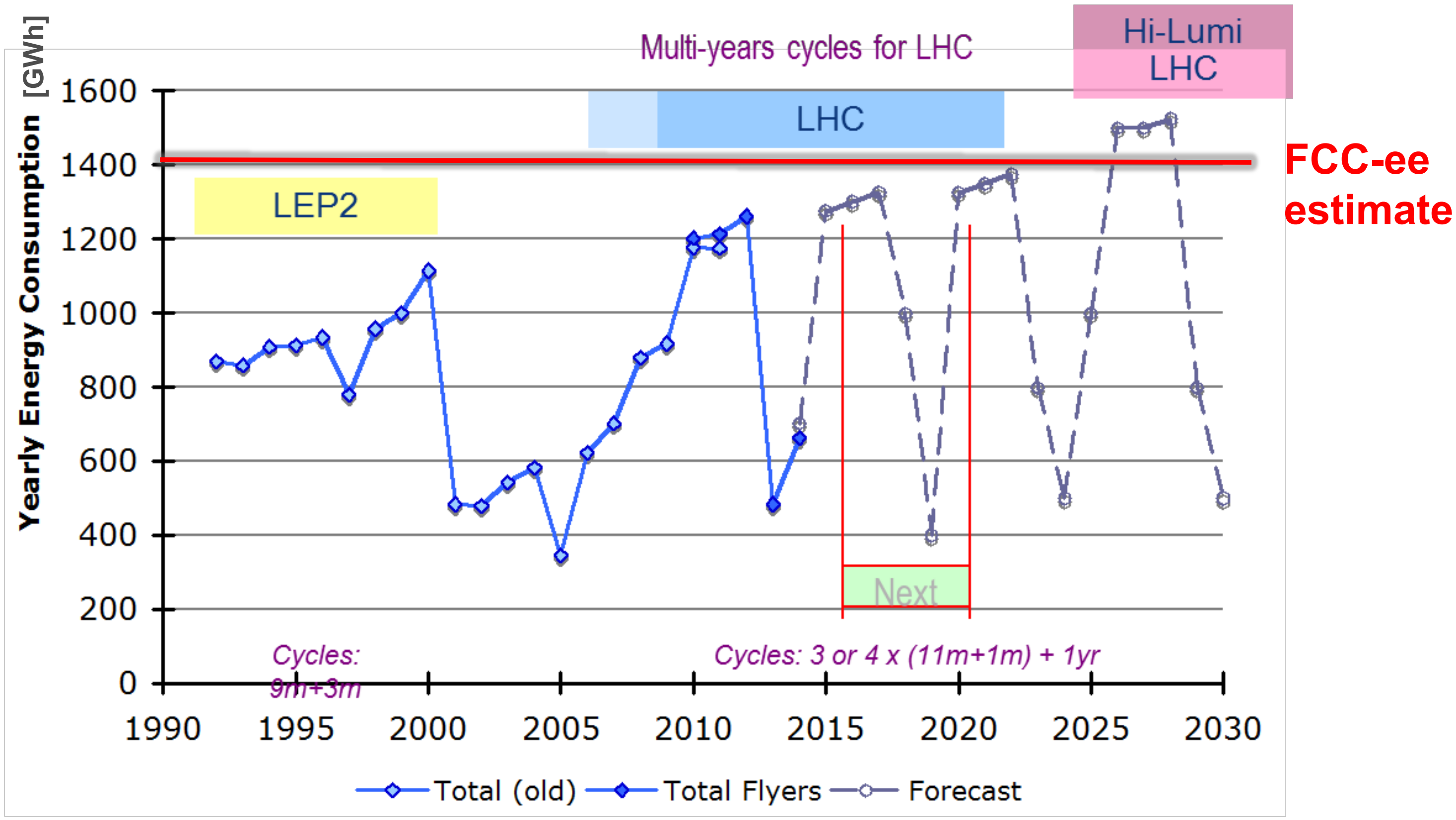
Electricity cost



Courtesy: M. Seidel, EuCARD-2, V. Shiltsev, K. Oide, Q. Qin, G. Trubnikov, and others

1400 GWh / yr → ~70 MEuro / yr

Electricity cost



S. Claudet - CERN
Procurement Strategy

3rd Energy Workshop 29-30 October 2015

Higgs couplings

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee	FCC-hh
m_H [MeV]	40	0.06	40	30	5.5	8	
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04	
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15	
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2	
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4	
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5	
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5	
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7	
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8	
g_{Htt} [%]	4.0	-	4.5	18	-	-	1
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2	1
g_{HHH} [%]	30	-	24	-	-	-	5

© M. Klute

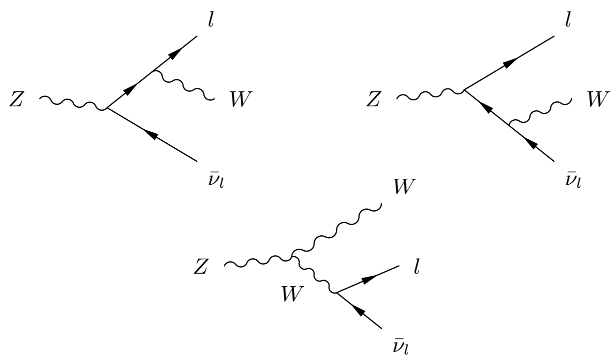
* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2

For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

FCC-*ee*: LFV in rare Z-decays: analysis

- Signal event topology: one high energy light lepton in one hemisphere, a tau decay in the other with 1, 3 or 5 prongs. This seems very clean experimental environment but keep in mind that we are chasing 10^{-13} sensitivity.

- Among the background sources:
  - $Z \rightarrow qq$ with low multiplicity.
  - $Z \rightarrow W^* \ell \nu$



- The latter (as a signal) is appealing *per se* as a SM candle and/or NP probe. [Durieux et al. arXiv:1512.03071]. The final state is the same as CLFV (with an additional neutrino) and the authors find a SM branching fraction of $1.4\ 10^{-8}$! Need to devise more than a counting experiment to make the most of the statistics. Assessment of the experimental sensitivity ongoing.

FCC-*ee*: the quarks Physics Case

- The *CP* violation and rare *b*-decays landscape has to be examined from the anticipated results of both the LHCb upgrade and the Belle II experiments.

- LHCb sees all species of *b*-particles (and charm in abundance) and is especially good at rare decays with muons and fully charged decay modes. Less efficient for electrons, neutrals, missing energy, hadronic multibody decays.

- Belle II should explore deeply/widely the B_d and B_u meson systems. Might also run above the $\Upsilon(5S)$ threshold but can't resolve the oscillation of B_s meson.

- The latter highs and lows define a path to complete the picture in the event nothing new is observed meanwhile.

- I will only show one example of the work ongoing.

4.2 Flavours at the *Z*: the quarks Physics Case

- A possible/appealing realm for FCC-*ee* in the classic flavours is therefore provided by the following triptych most likely unique to FCC-*ee*:

  1) Any leptonic or semileptonic decay mode involving B_s, B_c or *b*-baryon (those are coming polarized), including electrons.

  2) Any decay mode involving B_s, B_c or *b*-baryon with neutrals.

  3) Multibody (means 4 and more) hadronic *b*-hadron decays.

- We highlighted flagship modes for each category in order to build the Physics Work Packages.

4.2 Flavours at the *Z*: the quarks Physics Case

1) Any leptonic or semileptonic decay mode involving B_s, B_c or *b*-baryon, including electrons, in no particular order:

- $B_{d,s} \to ee, \mu\mu, \tau\tau$: if the second will be mostly covered by LHCb and CMS, the first can be searched for with a similar precision. The latter $B_s \to \tau\tau$ is most likely unique to FCC-*ee* and subjected to third family specific couplings.

- Leptonic decays in direct annihilation $B_{u,c} \to \mu\nu_\mu, \tau\nu_\tau$. The latter is a chance to get $|V_{cb}|$ with mild theoretical uncertainties.

- If the baseline machine is to be confirmed with the crab-waist option, the flavours scope with 10^{13} *Z* is likely to change dramatically. For instance, it would be possible to get $|V_{ub}|$ theory-free (well, strong isospin symmetry only ...) out of ratios of rare decays (B. Grinstein @ CKM06). Not mentioning that the large boost at the *Z* can be beneficial for classical methods.

4.2 Flavours at the *Z*: the quarks Physics Case

2) Any decay mode involving B_s, B_c or *b*-baryon with neutrals.

- $B_{d,s} \to \gamma\gamma$: theoretically difficult.
- $B_s \to K_S K_S$: *CP* violation studies. Also interesting for downstream tracking of V^0 in general.
- $B \to Xll$ ($s\tau\tau$ at first): rare FCNC complementing LHCb and Belle II.

3) Multibody (4 and more) hadronic *b*-hadron decays.

- $B_s \to \psi\eta'$ or $\eta_c\Phi$: flavour tagging required for weak mixing phase.
- $B_s \to D_s K$: PID definitely required to isolate the signal.
- Modes to be used to define the Particle Identification needs.

5. Summary

- An effort for a design study of large *pp* and *ee* colliders is structured in order to provide an educated view of the Physics reach, machine and detectors of such a facility for the next update of the HEP European strategy (2019).

- Flavour physics studies at *pp* collider is starting. On the contrary, Physics opportunities at the injector have been already envisaged.

- The *ee* circular collider is meant to provide experiments with an unprecedented luminosity from the *Z* pole to the top pair threshold.

- The Flavour Physics, as an indissociable part of the electroweak symmetry breaking understanding, is a natural and obvious contributor.

- Baseline studies have been devised. We are just starting to explore the possibilities, in particular with 10^{12} / 10^{13} *Z.*