Future Circular Colliders project
Flavour Physics possibilities at FCC-*ee*

Stéphane Monteil,
Clermont University.

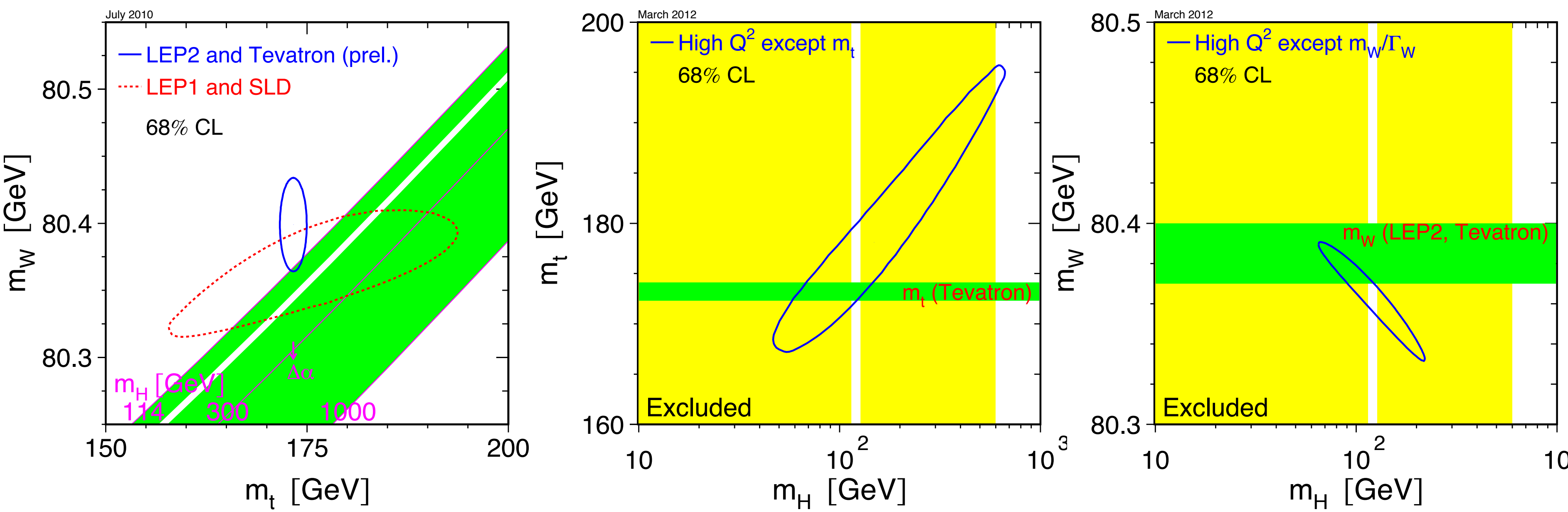
Outline of the talk

- Scientific context
- Introduction to the Future Circular Colliders project
- One slide about FCC-pp
- 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 (SM) became a theory

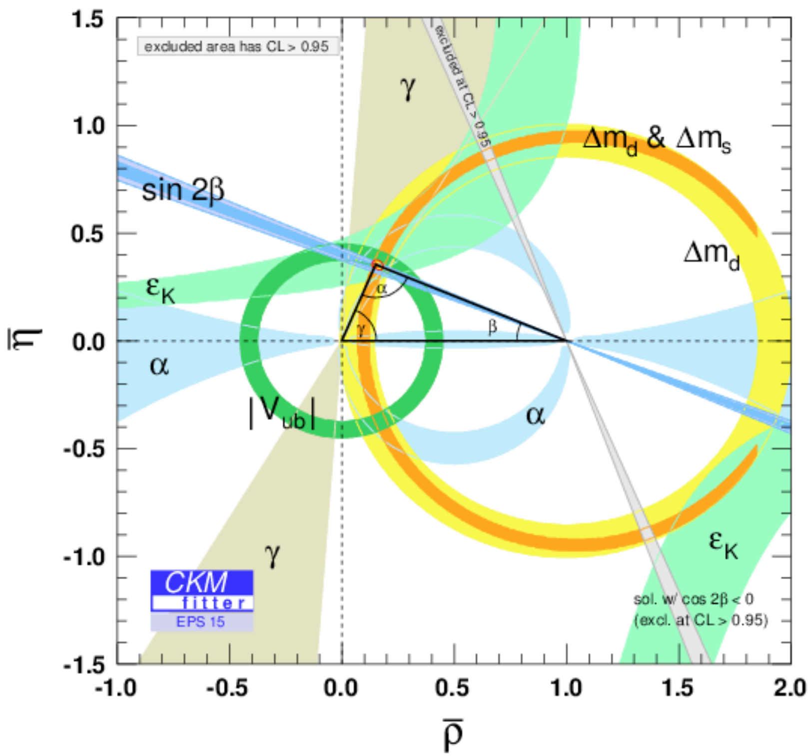
There are two pillars of the SM:

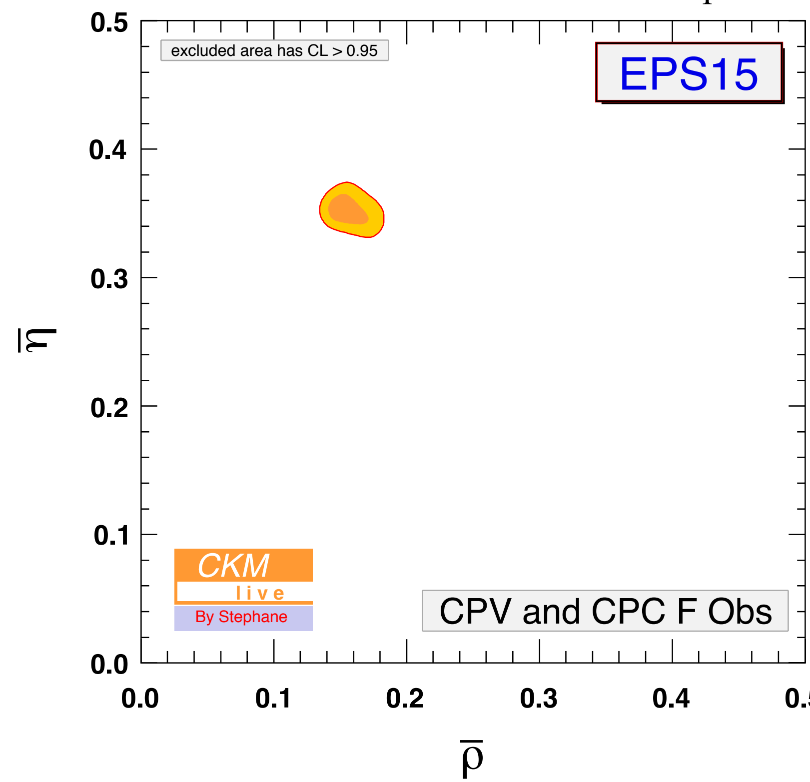
- The first pillar of the SM is the so-called electroweak precision observables consistency check. Fix $\boldsymbol{G_F}$, α_{EM} and $\boldsymbol{m_Z}$ at their measured value and produce a prediction of $\underline{\boldsymbol{m_{top}}}$, $\boldsymbol{m_W}$ and $\underline{\boldsymbol{m_H}}$. A tremendous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



There are two pillars of the SM:

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





There are two pillars of the SM:

- The success is immense but some modesty is in order.

- The successful profile of the CKM matrix has some fragility, that we experienced in the recent past, *i.e.* the single measurement (at the level of its observation) of branching fraction B($B^+ \to \tau^+$ nu) shook the consistency.

- The prediction of the BEH boson mass is mostly based on two precision parity-violating observables: the SLD left-right asymmetry and the forward-backward asymmetry in $Z \to bb$. *They are still in marginal agreement.*

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

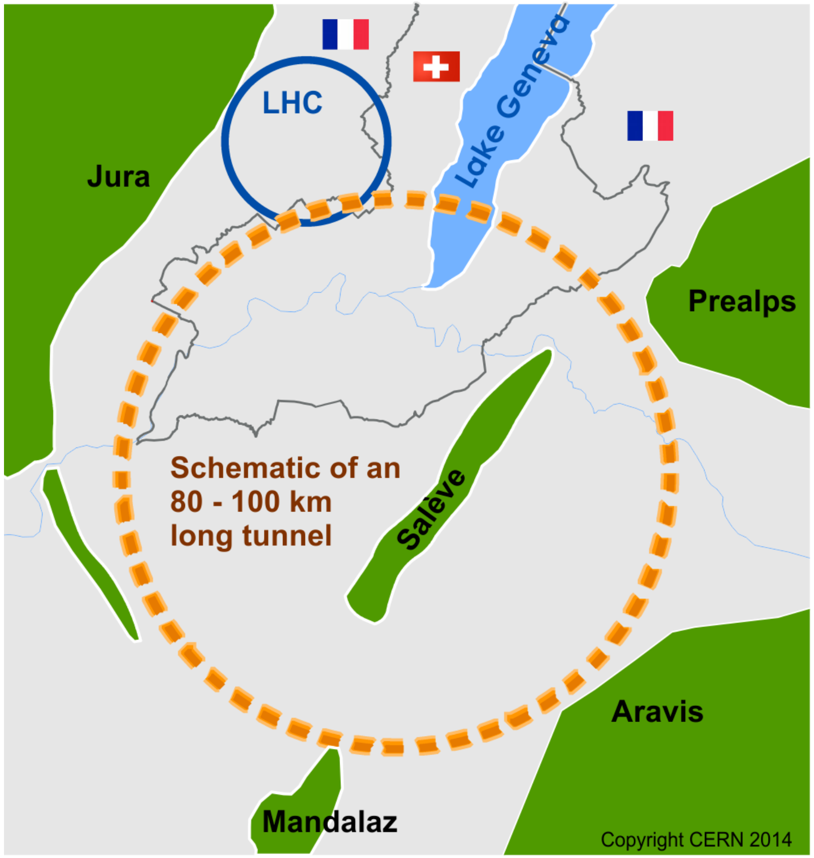
CERN
Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
3

- 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:

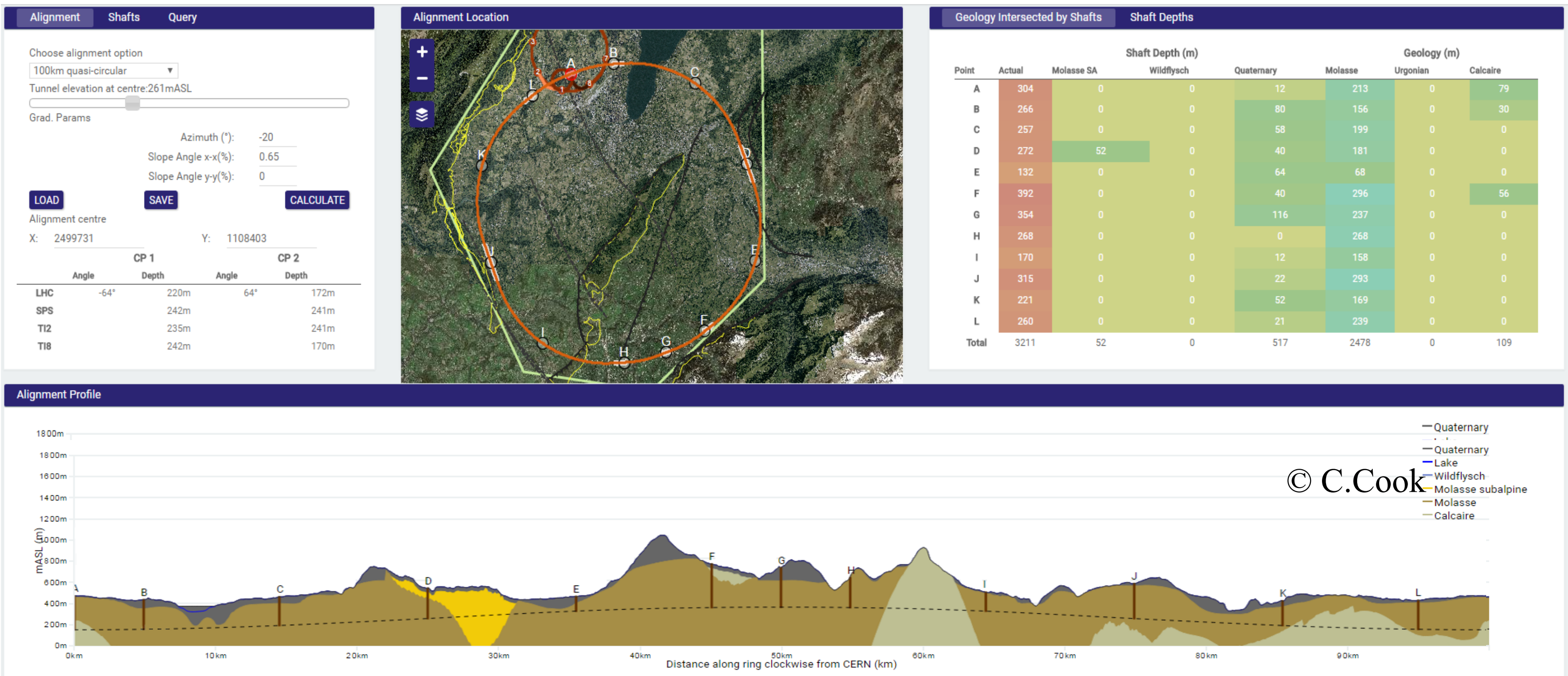
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- *e⁺e⁻* collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



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

1. Introduction to FCC - Civil engineering.

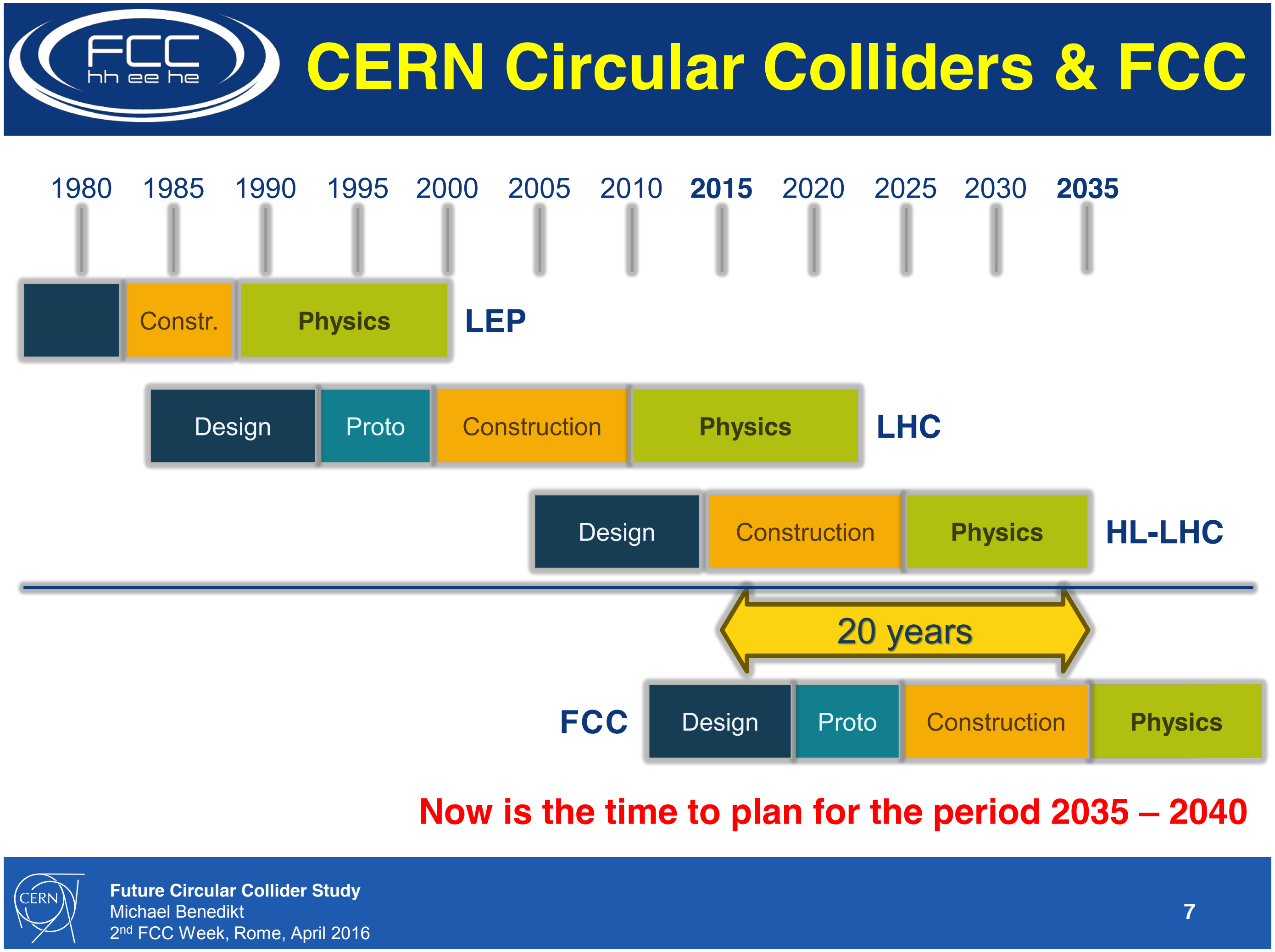
- Infrastructure studies well advanced. A 100 km planar racetrack:



- Challenges:

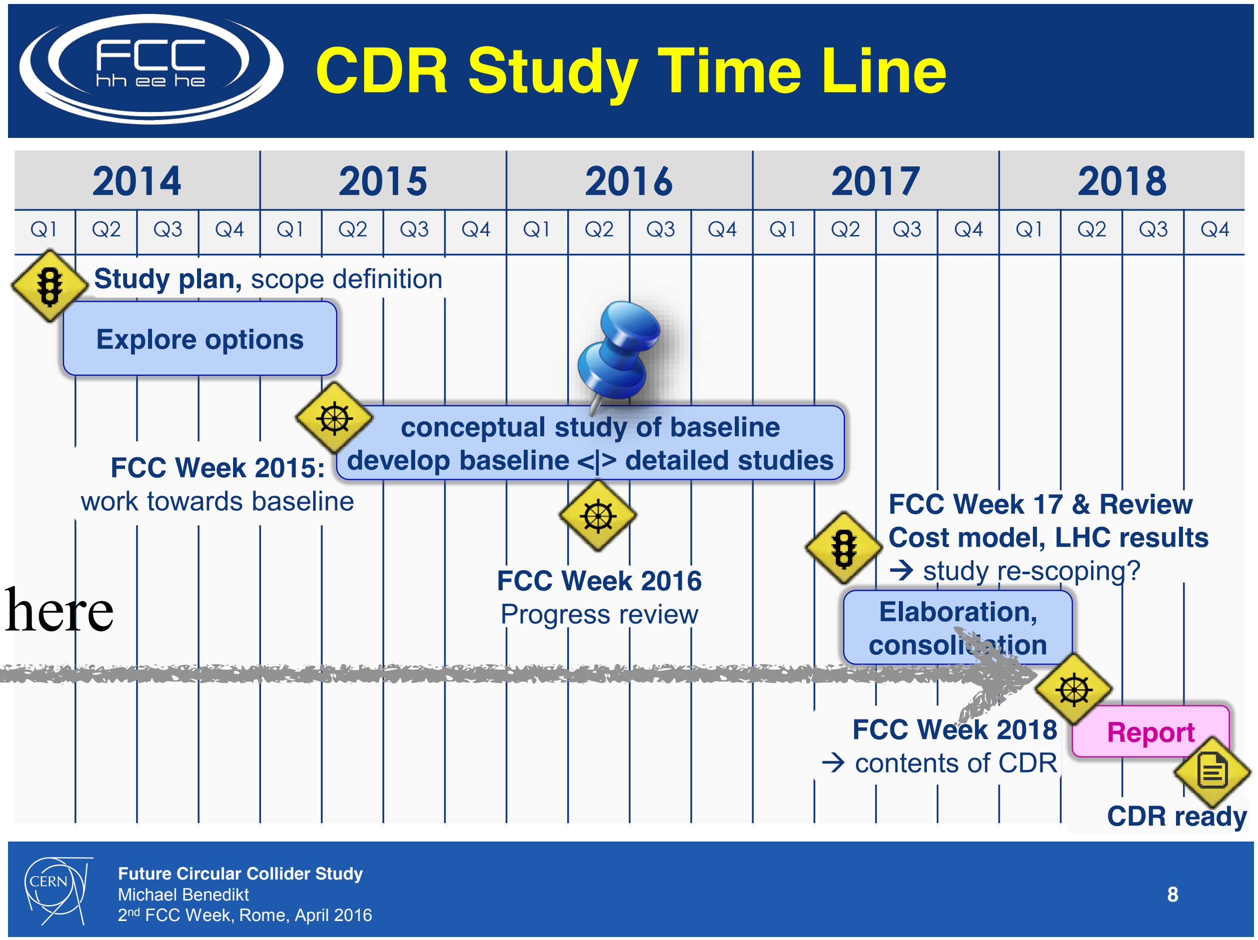
  - 7.8 km tunnelling through Jura *limestone*.

1. Introduction to FCC - Timeline



1. Introduction to FCC: the design study timeline

- Applies to all machine and experiment designs:



We are here

FCC— in a couple of slide.

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

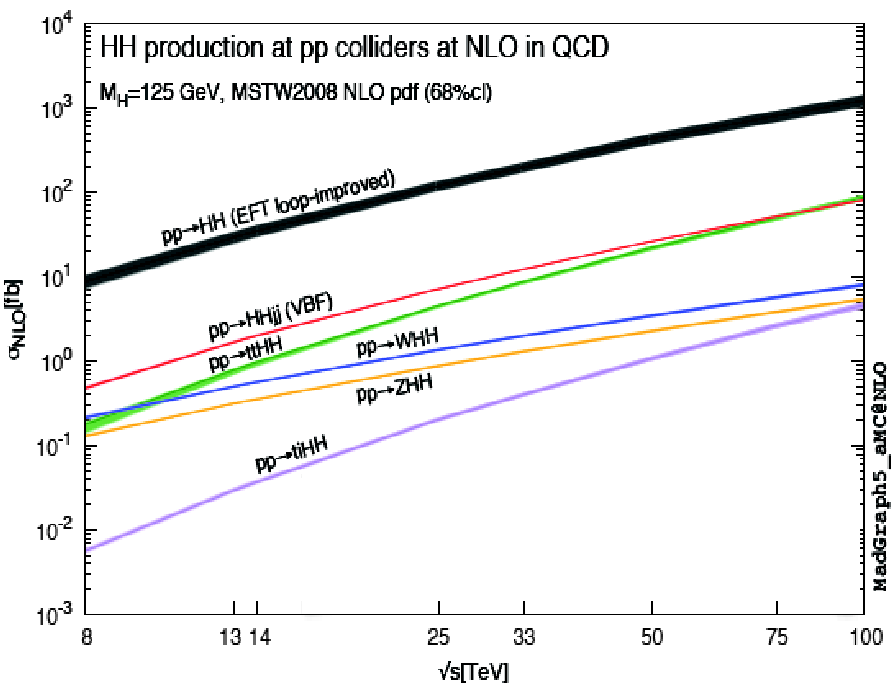
- New dynamical regimes (energy) but also high precision. The huge production rates allow to make tighter kinematical cuts and reduce backgrounds.

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

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]



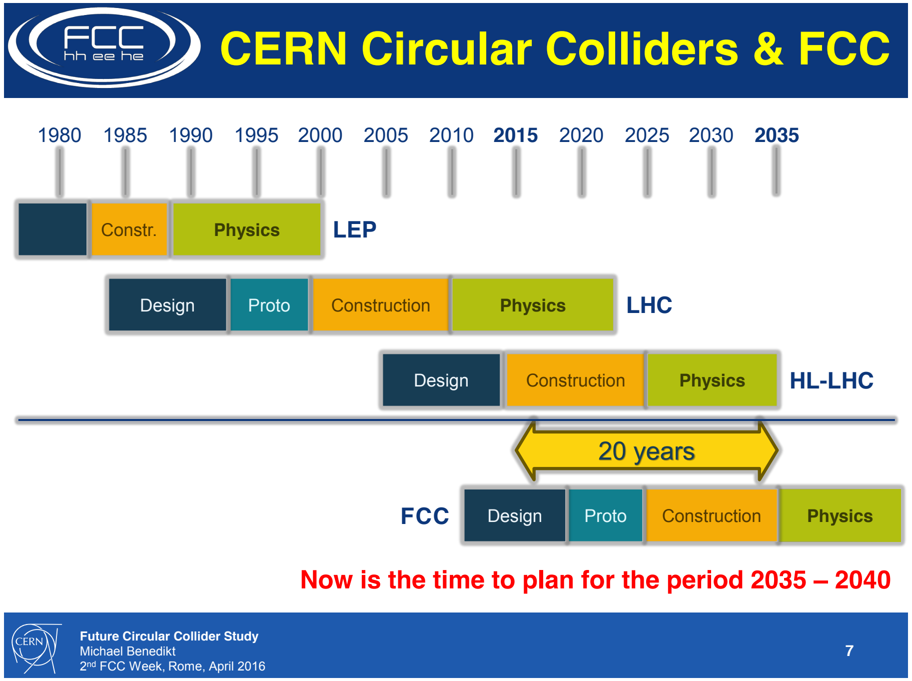
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in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

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

FCC-*ee*

- Generalities, timelines.
- The machine parameters and design.
- The Physics case at large.
- The Flavours as a *supplément d'âme*
- Detector design(s).

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

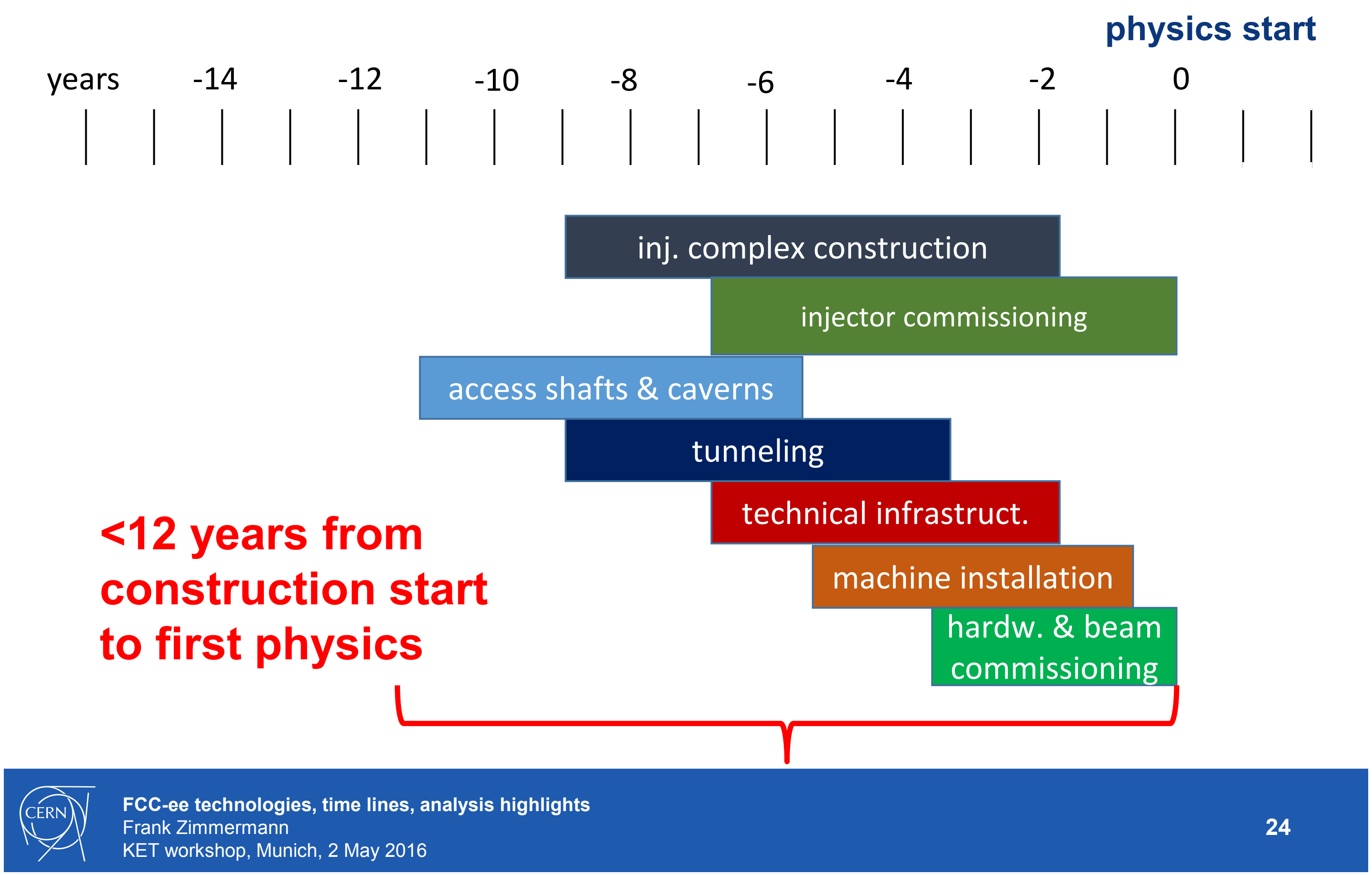
- The re-commissioning of the LHC as injector of the FCC-*hh* shall take *O*(10 y).

- 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: End of HL_LHC (2038) !

- Continuous particle Physics at colliders in Europe in contrast with the previous decade.

- The FCC-*ee* and other large scale projects can be compared in time ...

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



Machine parameters, design and luminosities

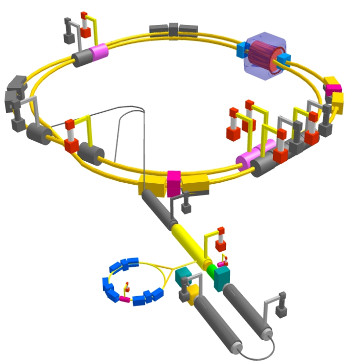
The FCC e^+e^- machine. Baseline design

- 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.

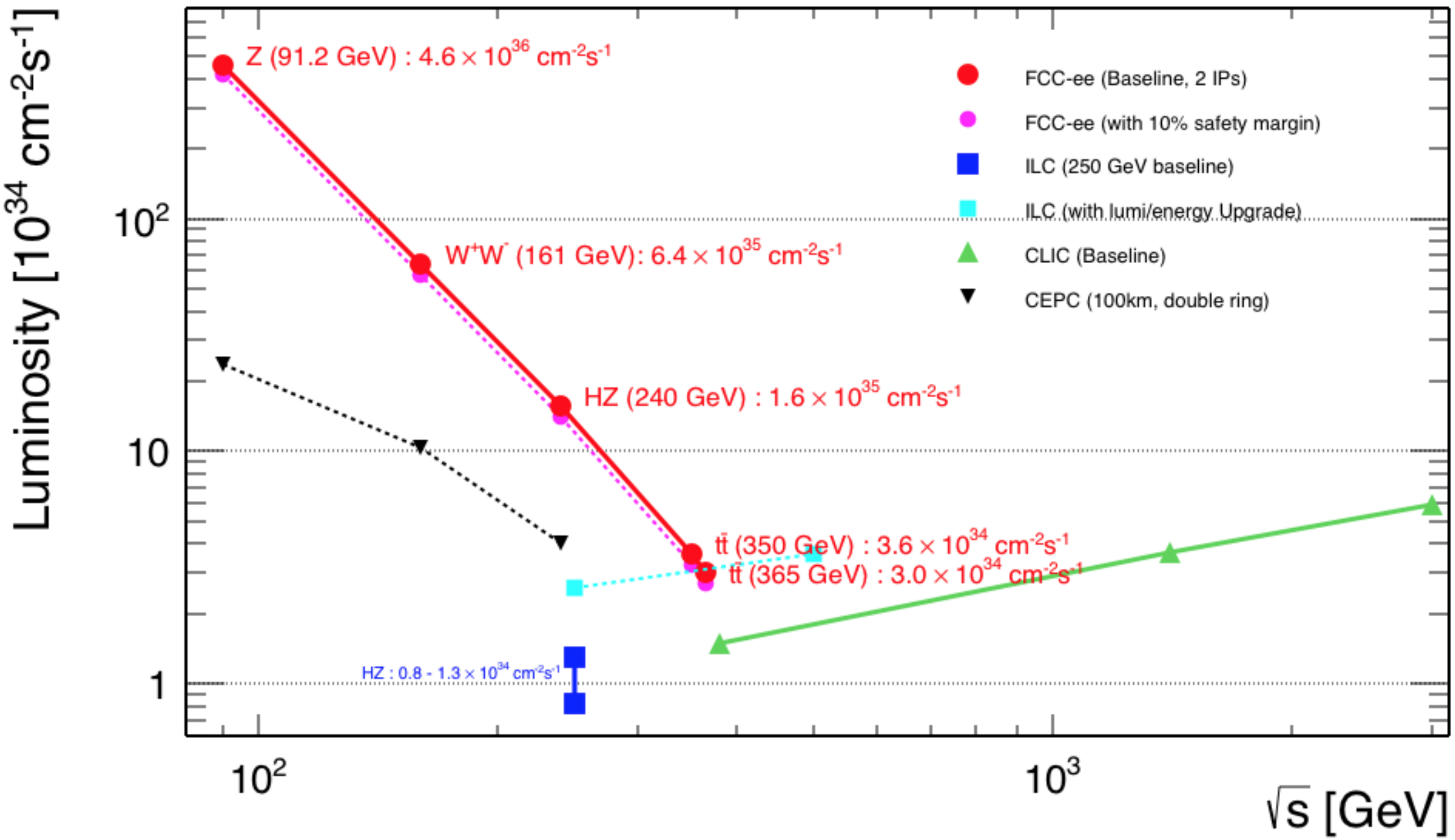
- To some extent, SuperKEKB shall already meet some of the challenges of FCC-*ee:*



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) : < 1×10^{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. Luminosity figure



- The time / energy allocation of the machine has been worked out;
- ... we're speaking here of 6.5 10^{12} *Z*, 10^8 *WW*, 10^6 *H* and 10^6 top pairs.

The Physics case at large

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	$g \to bb$
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 $e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	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 depolarisation 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.

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	$g \to bb$
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 $e^+e^- \to \gamma Z$, $Z \to \nu\nu$, 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%			

Flavours in the big picture. Three examples:

1) LFV Z decays.
2) Search for $B^0 \rightarrow K^{*0}\, \tau^+\tau^-$
3) BSM in $\Delta F = 2$ quark transitions

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		

Note: 100 kHz of *Z*. This is a real triggerless apparatus !

Particles	B^0/B^+	B^0_s	Λ_b	B_c	$Z \to \tau^+\tau^-$
Yields (FCC-*ee* 150 ab^{-1})	10^{12}	$2.5\ 10^{11}$	$2.5\ 10^{11}$	$2.5\ 10^{9}$	$5.\ 10^{11}$
Yields (Belle II 50 ab^{-1})	10^{11}	10^{7-8}	$-$	$-$	$5.\ 10^{10}$

FCC-*ee*: 1) LFV *Z* decays

- 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 more recently Atlas, *e.g.* [DELPHI, Z. Phys. C73 (1997) 243] [ATLAS, CERN-PH-EP-2014-195 (2014)])

- The FCC-*ee* high luminosity *Z* factory allows in principle to gain several orders of magnitude ... Complementary to the direct search for steriles.

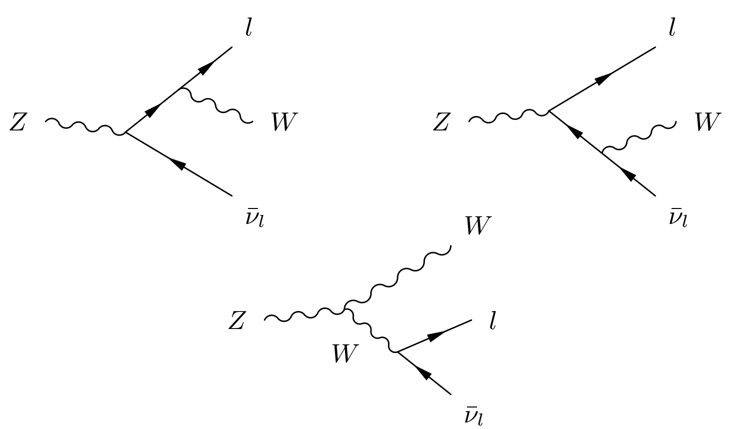
- Explored with FCC-*ee* in mind for additional neutrinos in [De Romeri et al. JHEP 1504 (2015) 051]. It happens that the final states with taus are the most appealing (see Ana's talk).

FCC-*ee*: 1) LFV *Z* decays

- There are actually three processes competing in the ball park FCC-*ee* can address with a final state with a tau and a beam energy light lepton

  - The lepton Flavour-Violating *Z* decays
  - The SM $Z \to \tau^+\tau^-$
  - The SM $Z \to l^+l^-$ ($l \to W^*\nu$ and $W^* \to \tau\,\nu$)

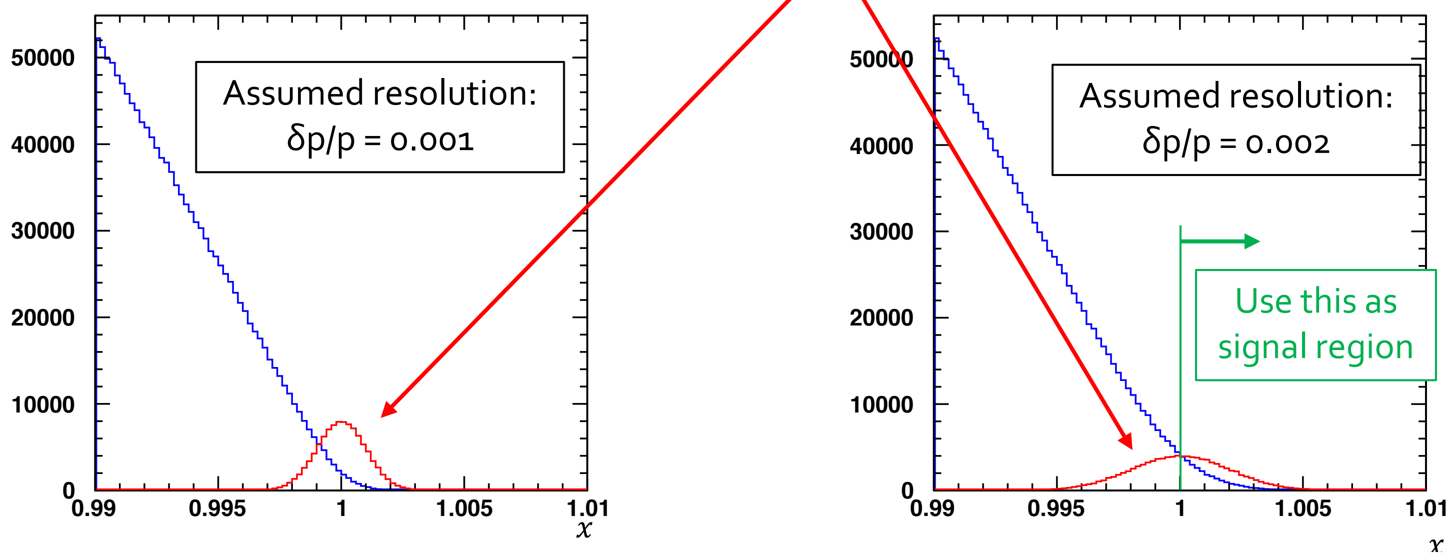
- The latter process in the list [Durieux et al. arXiv:1512.03071] is interesting per se (BSM enhancements). The final state is the same as cLFV (with an additional neutrino) and the authors find a SM branching fraction of 1.4 10^{-8} ! It can be however distinguished from the two others by its kinematical properties.



FCC-*ee*: 1) LFV *Z* decays

- The other SM $Z \rightarrow \tau^+\tau^-$ ($\rightarrow \mu\nu\nu$) is more annoying. The endpoint of the distribution mimics a beam-energy like lepton.

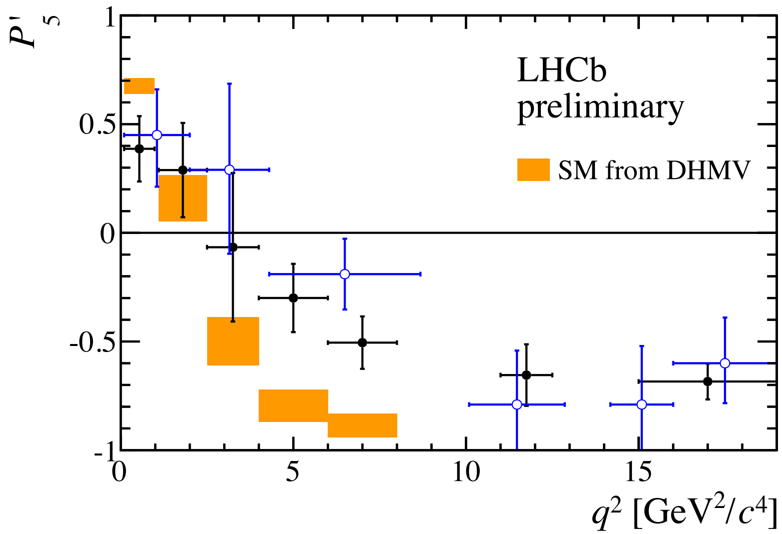
© M. Dam

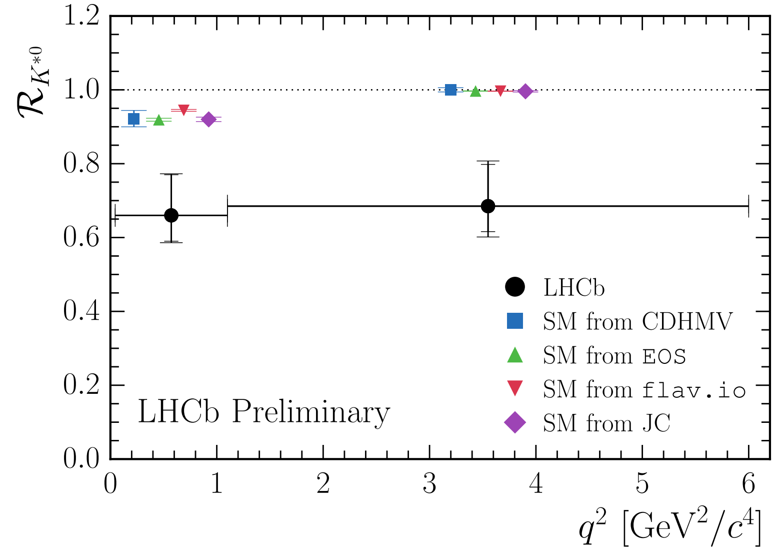


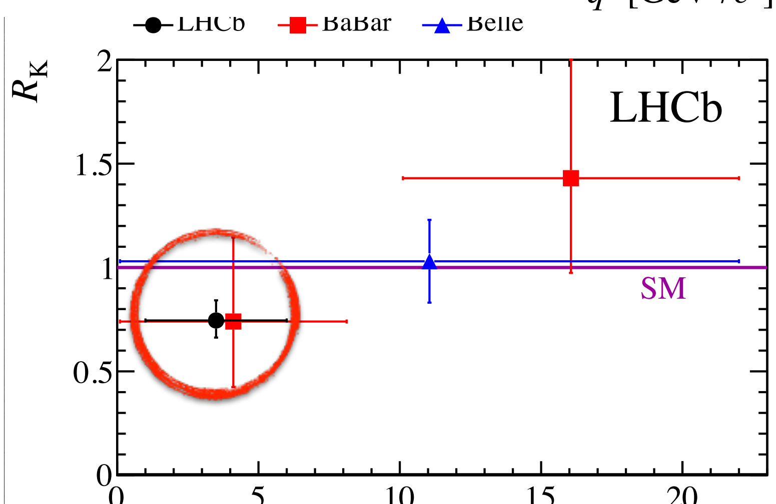
- Following the study reported here : $Z \rightarrow \tau^+\tau^-$ provides a limit on cLFV process which goes linearly with the momentum resolution. And which is asymptotically limited in turn by the beam energy spread (~ 30 MeV at 45 GeV, ~20 MeV at 90°). This makes the former limit pretty fundamental.

$$\mathcal{B}(Z \rightarrow \tau^{\pm}\mu^{\mp}) < 10^{-9} - 10^{-10}$$

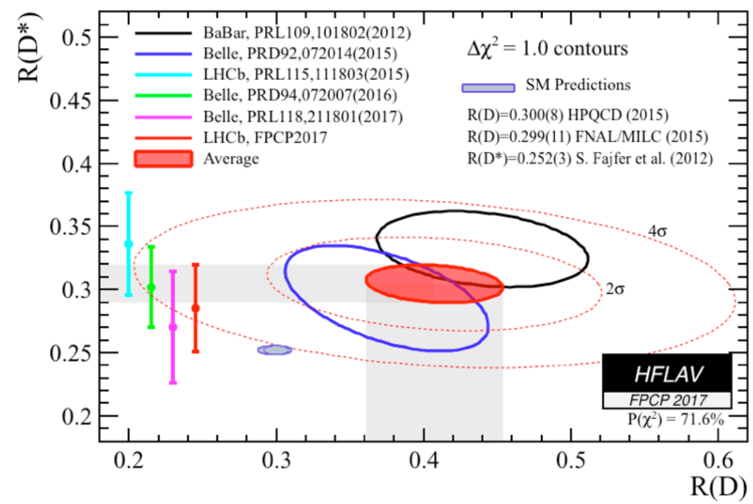
FCC-*ee*: 2) anomalies / LFUV in quark transitions







- [PRL 113 (2014) 151601]
- [PRD 86 (2012) 032012]
- [PRL 103 (2009) 171801]



FCC-*ee*: 2) anomalies / LFUV in quark transitions

- The companion decay modes $B^0 \to K^{*0}\ e^+e^-$ (angular analysis) and mostly $B^0 \to K^{*0}\ \tau^+\tau^-$ are important ingredients to interpret the discrepancies, should they be confirmed: likely unique at FCC-*ee*.

- The available statistics for the former at FCC-*ee* is beyond competition.

- The latter requires partial reconstruction, *i.e.* the use of the production and decay vertices to solve the kinematics of the decay (it is in principle fully solvable). But the SM branching fraction can likely only be attained at FCC-*ee*.

- Data-driven model-independent approaches provide very significant enhancement of arXiv:1712.01919 of $b \to s\tau^+\tau^-$ transitions.

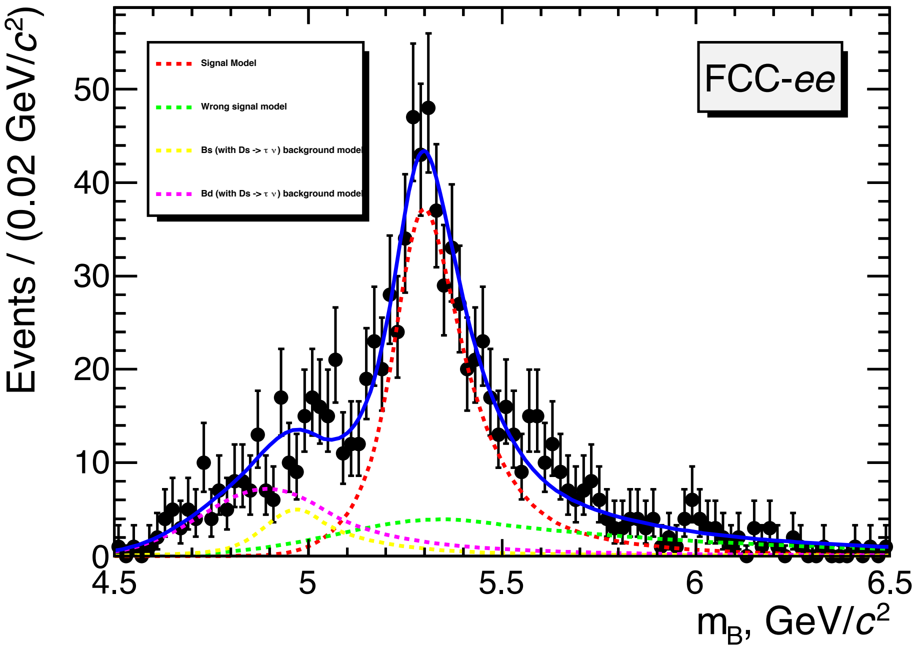
- The mode $B^0 \to K^{*0}\ \tau^+\tau^-$ has received a special attention in the FCC-*ee* context.

FCC-*ee*: 2) The search for $B^0 \to K^{*0}\tau^+\tau^-$

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

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

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

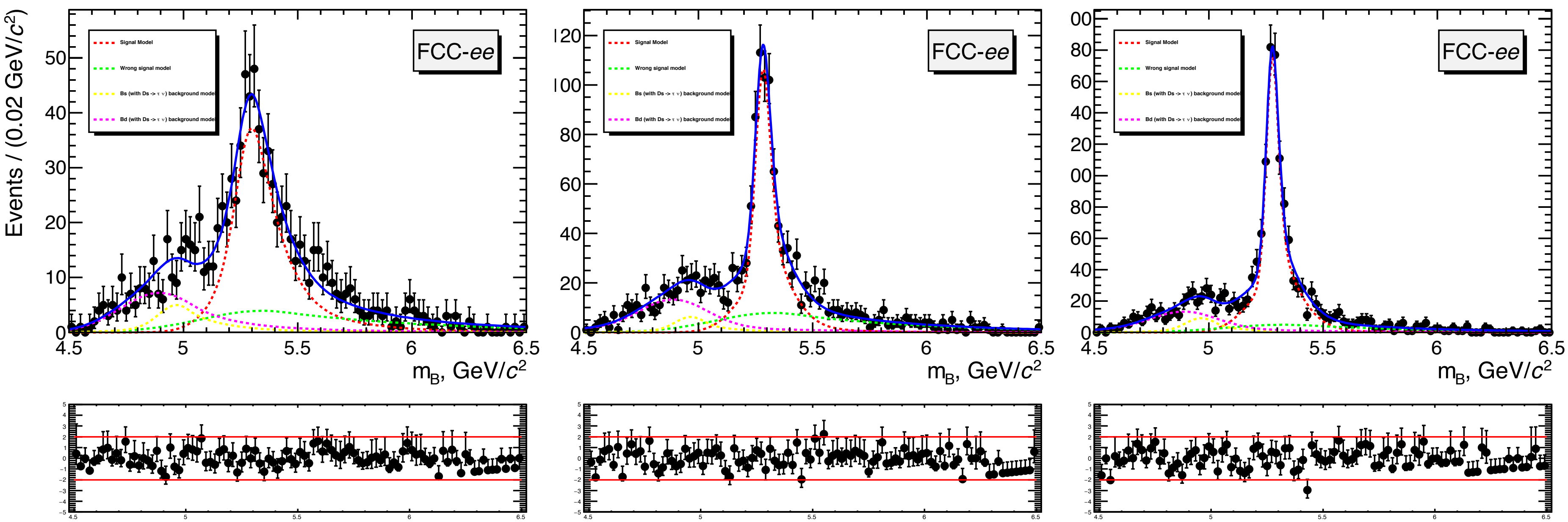


Comments in order:

- At baseline luminosity, under SM hypothesis, more than 10^3 events of reconstructed signal. Angular analysis possible.

- Another interesting and more challenging mode is $B_s \to \tau^+\tau^-$ (analysis ongoing - Marseille)

FCC-*ee*: 2) The search for $B^0 \to K^{*0}\tau^+\tau^-$



Performance / Conditions	ILD-like	ILD /2	ILD / 4
Efficiency of the identification of the correct solution (%)	42,3	52,6	62
Invariant mass resolution (core) [MeV/c^2]	42(1)	36(1)	27(1)

FCC-*ee*: 3) BSM in $\Delta F = 2$ quark transitions

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

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

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

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)

<u>Assumptions:</u>

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

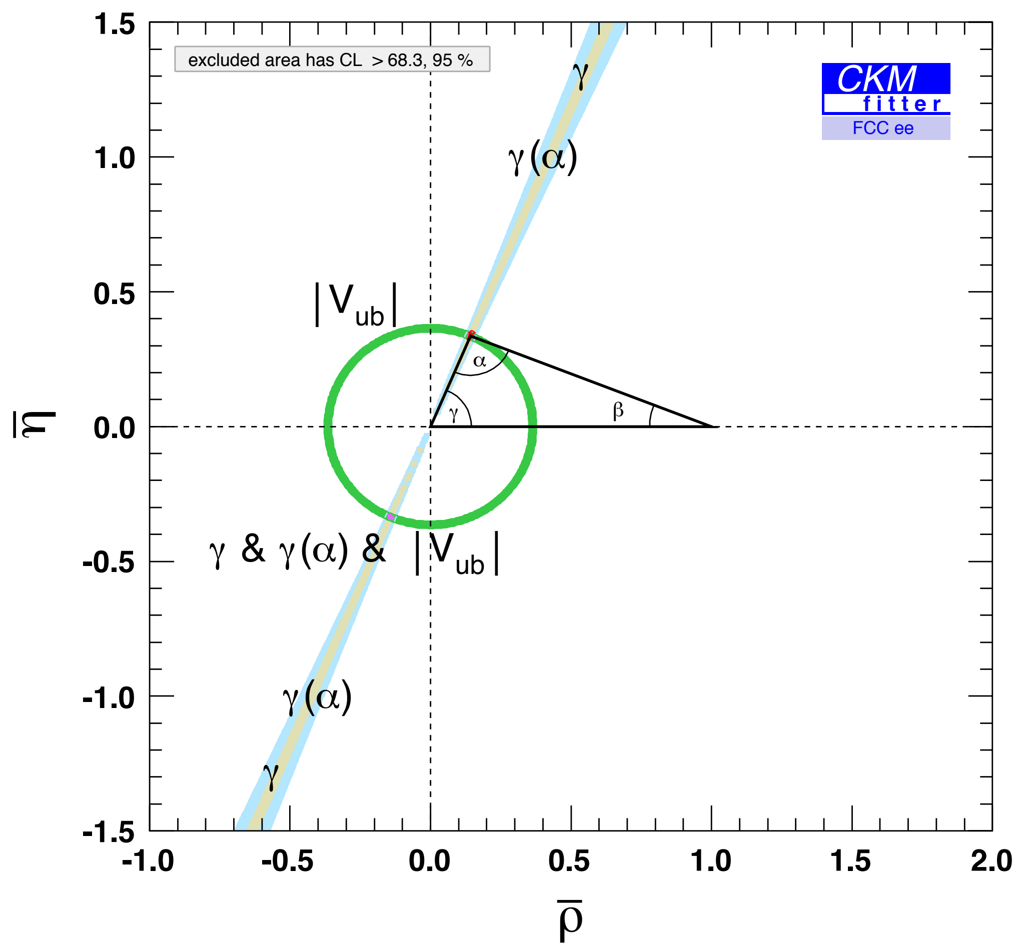
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

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

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

FCC-*ee*: 3) BSM in $\Delta F = 2$ quark transitions

- The universal unitarity triangle: fixing CKM parameters.



FCC-*ee*: 3) BSM in $\Delta F = 2$ quark transitions

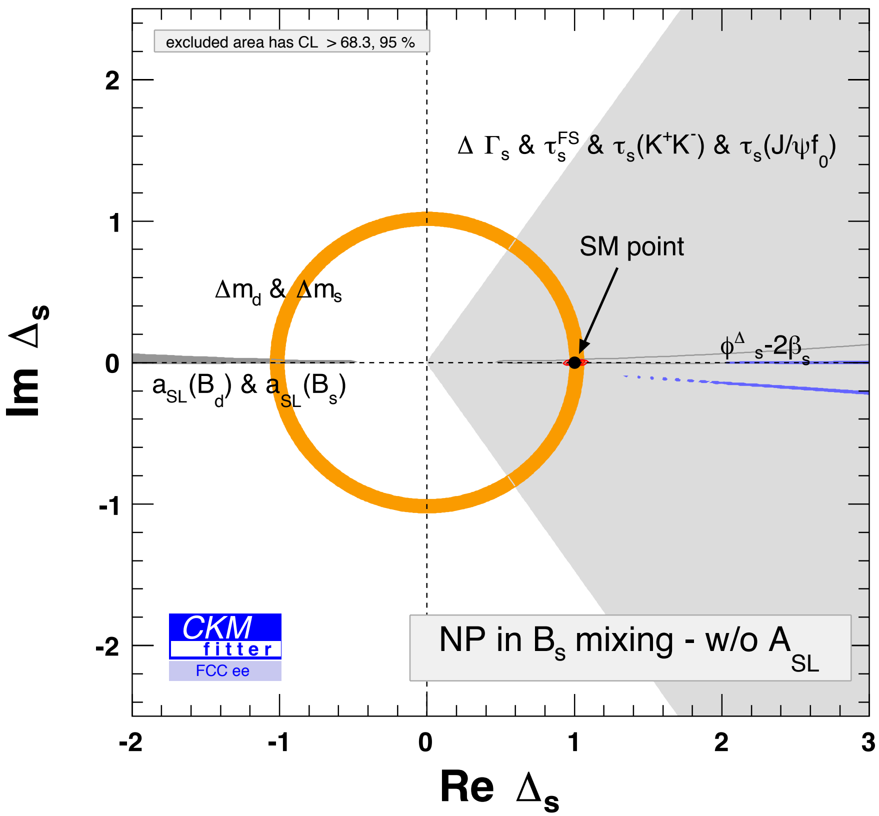
- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as $\Delta_q = |\Delta_q| e^{i2\Phi_q^{\rm NP}}$).

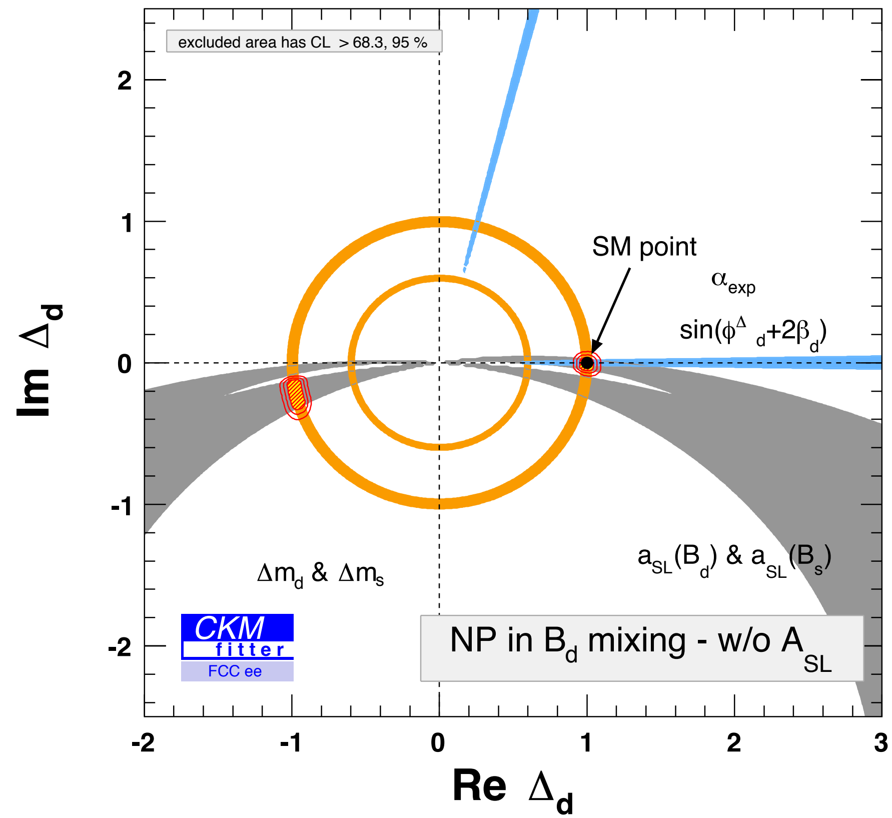
parameter	prediction in the presence of NP
Δm_q	$\vert\Delta_q^{\rm NP}\vert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = {\rm Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$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

- The improvements considered here do concern the semileptonic asymmetries, phi_s and gamma.

FCC-*ee*: 3) BSM in $\Delta F = 2$ quark transitions

- Work in progress

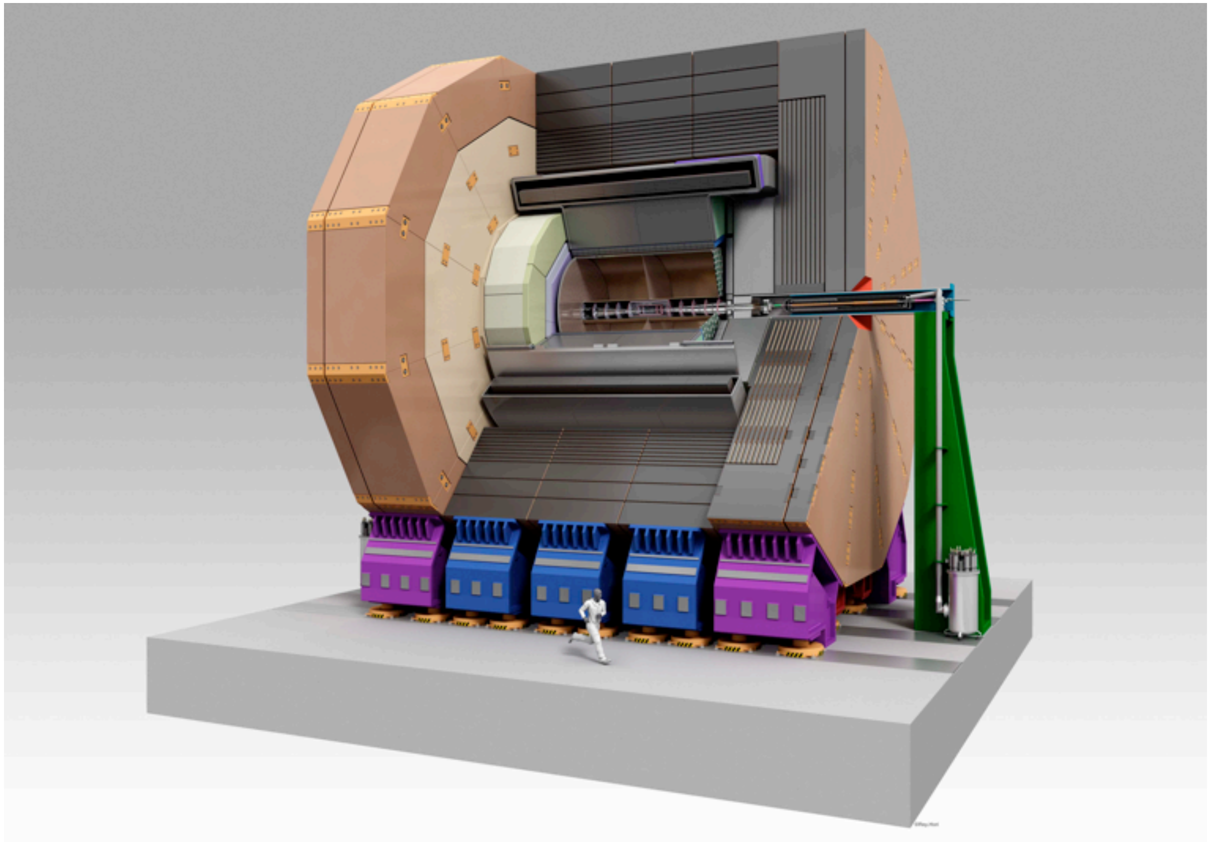




The FCC-ee detectors

FCC-*ee*: detectors

- There have been a lot of developments in the two past decades on electron colliders (mostly for linear) 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.

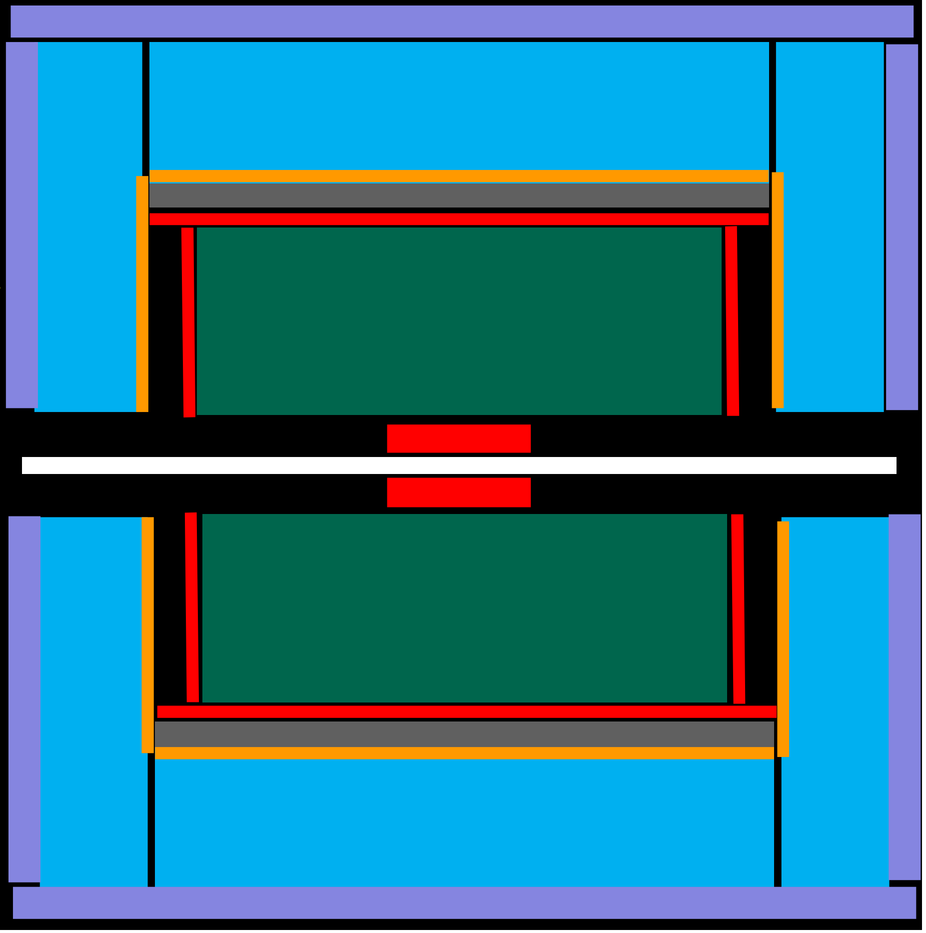
- The vertex detector can be as close as 1.7 cm (!) from the interaction point.

- The momentum resolution should match the beam energy spread at 45 GeV (50 MeV)[See LF-violating Z decays.

- We must be light … in particular for the Flavour (b, tau ...) Physics.

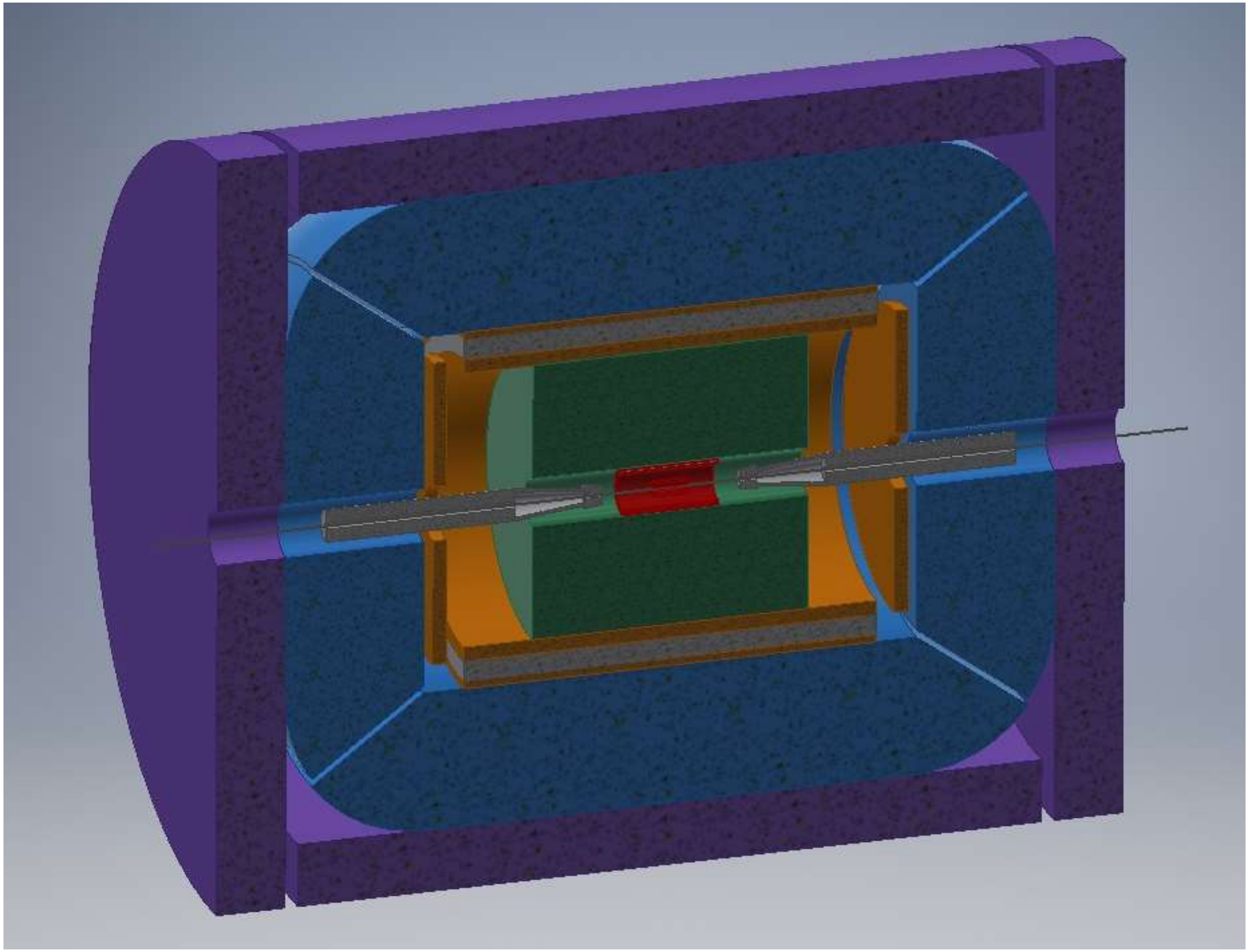
FCC-*ee*: the IDEA detector concept

- Beam pipe (R~1.5 cm)
- VTX: 4-7 MAPS layers
- DCH: 4 m long, R 30-200 cm
- Outer Silicon Layer
- SC Coil : 2 T, R~2 m
- Preshower: ~ 1-2 X_0
- DR calorimeter: 2 m/10 λ_{int}
- Yoke + muon chamber



©Bedeschi

FCC-*ee*: the IDEA detector concept



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 program 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 $B^0 \rightarrow K^{*0} \tau^+\tau^-$, on track for $B^0_s \rightarrow \tau^+\tau^-$ and foreseen for $B^0 \rightarrow K^{*0} e^+e^-$. 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 the Flavour group:
  jernej.kamenik@ijs.si or monteil@in2p3.fr.

Back-up slides.

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

sHip

FCC-*ee*

Comet - Meg & friends.

KOTO - NA62 ...

Legend and disclaimer:

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

Scientific context: theoretical / historical timelines

1964 Electroweak unification	1971 EW loops and RN	1973 *CP* violation	1964 Fundamental Scalar
	Top quark mass predicted by LEP, CERN (from M_Z and other EWPO).	The *B*-factories establish that the KM paradigm is the dominant source of *CP* violation in *K* and *B* particle systems.	Higgs boson mass cornered by LEP (EWPO) and Tevatron (top and *W* mass).
Neutral current discovery in 1973 by Gargamelle (CERN).	Top quark discovered by CDF, FNAL.		An alike Higgs boson discovered where said at LHC.
1979 Glashow, Salam and Weinberg get the Nobel.	1999 t'Hooft and Veltman get the Nobel.	2008 Kobayashi and Maskawa get the Nobel.	2013 Englert and Higgs get the Nobel.

Scientific context: the 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 persistent [and possibly consistent] anomalies in Flavour Physics though.

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

    - Baryonic asymmetry in the Universe.

1. Introduction to FCC

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

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:

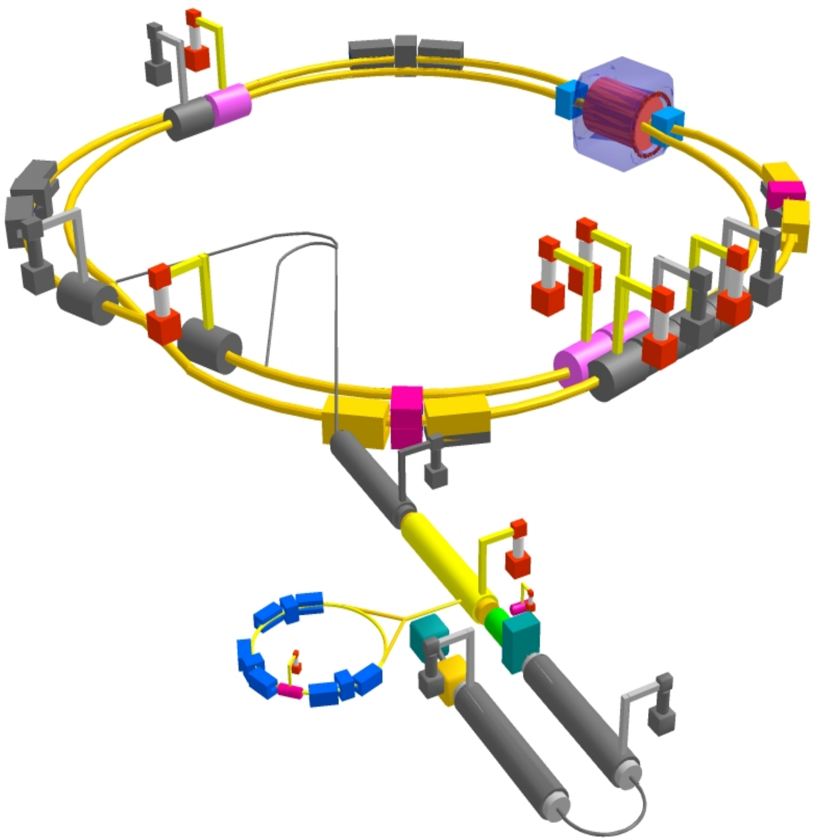
  - Brehmsstrahlung@IP limits the beam lifetime at top energy.

  - 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*) .

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

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



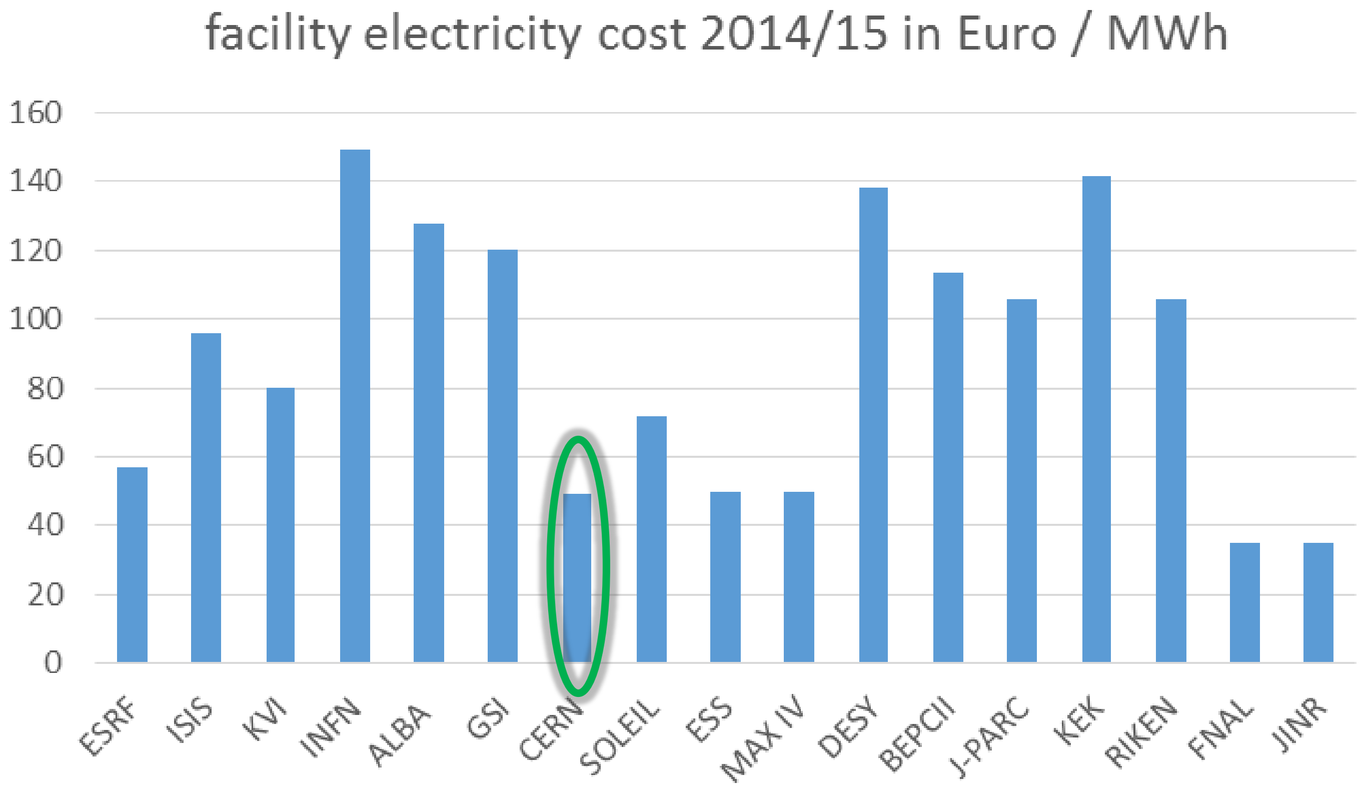
Some SuperKEKB parameters : ©P. Janot

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

FCC-*ee:* general numbers

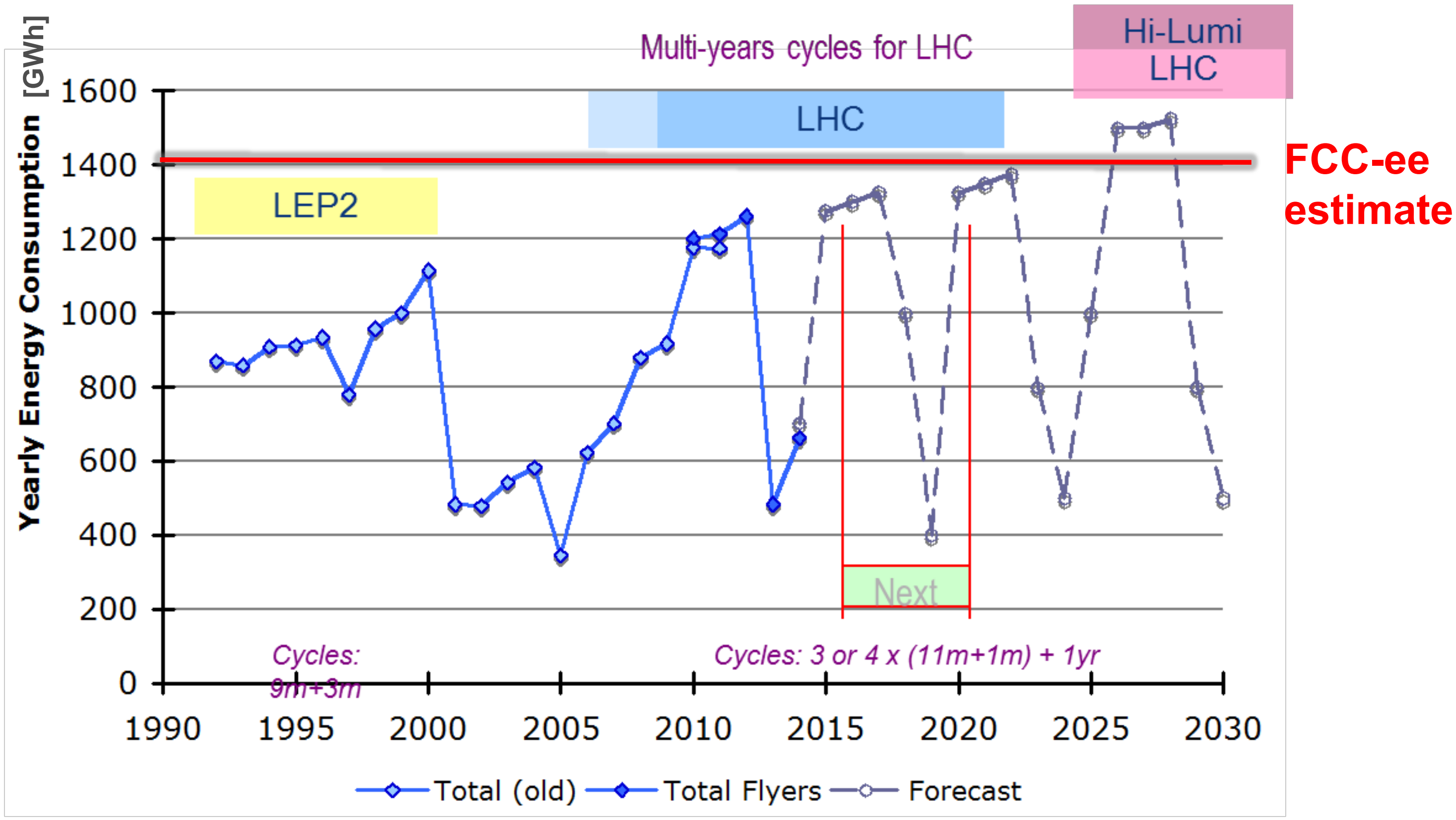
The general numbers it is good to have in mind when one speaks about these kinds of projects.



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

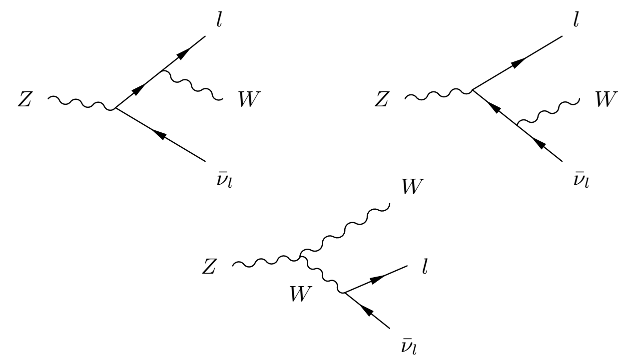
* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2

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

© M. Klute

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:
  - $Z \to qq$ with low multiplicity.
  - $Z \to W^* \ell\nu$

- 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.

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.

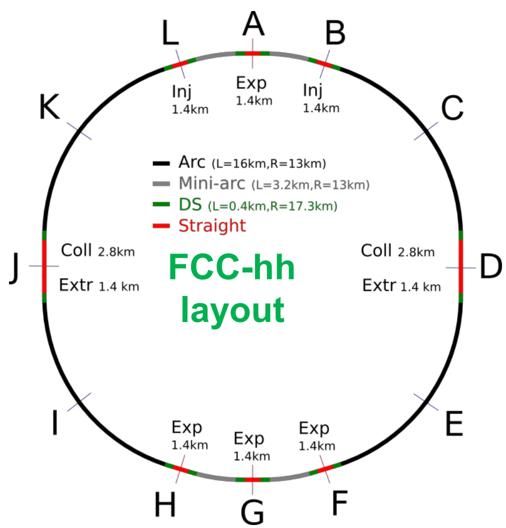
- The Flavour Physics, as an indissociable part of the electroweak symmetry breaking understanding, is a natural and obvious contributor.

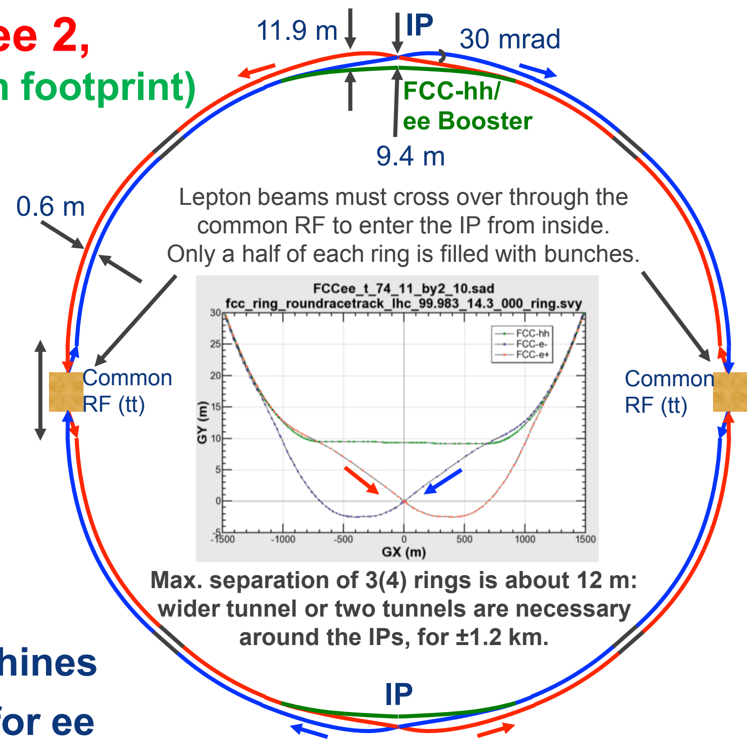
- Baseline studies have been devised. We are just starting to explore the possibilities, in particular with 10^{12} / 10^{13} *Z.*

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.

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

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

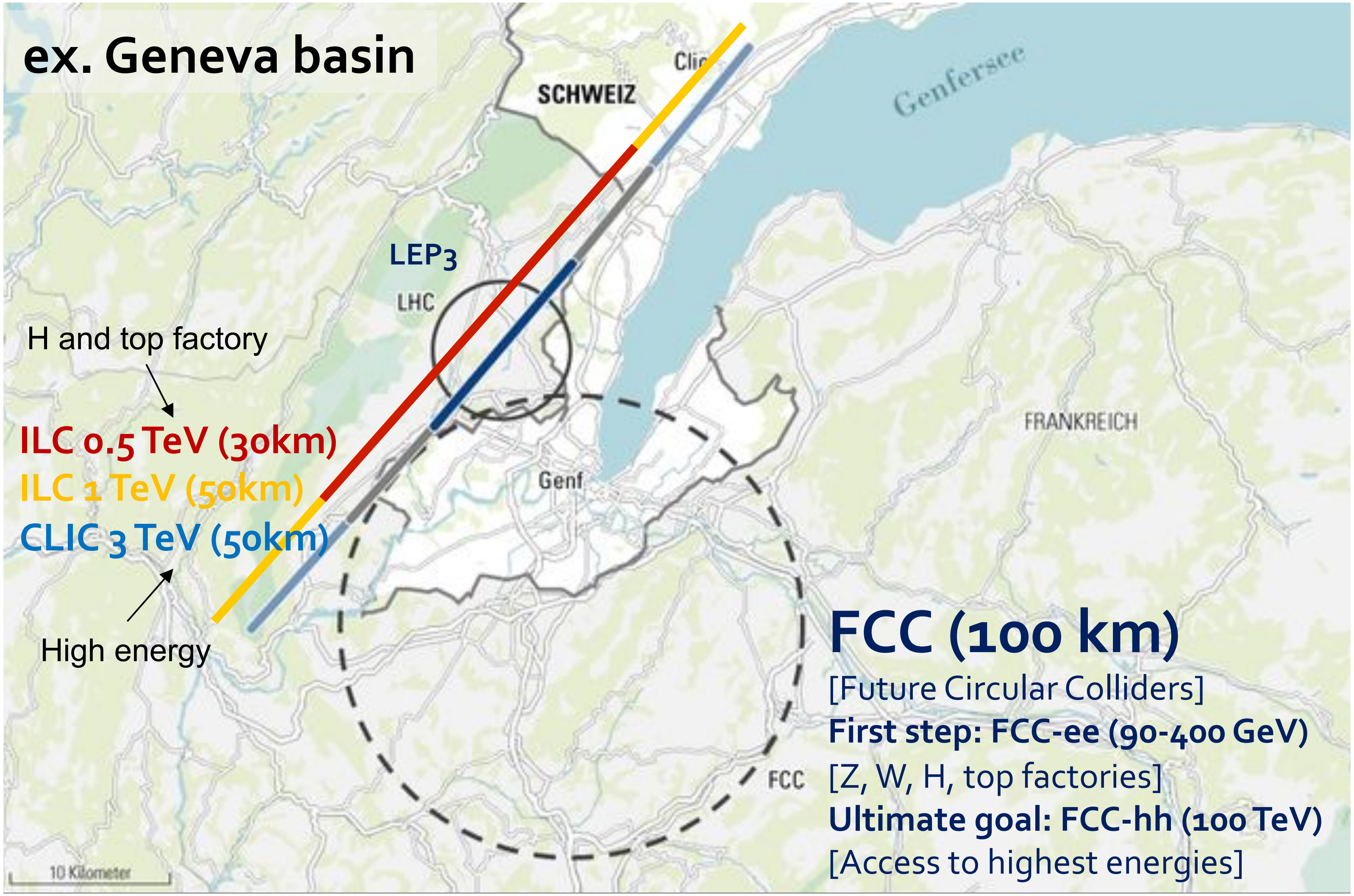
parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1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

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?

© P. Janot


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
10 Kilometer
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]

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

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