Flavour Physics possibilities at FCC-*ee*

S. Monteil,
Université Blaise Pascal,
LPC Clermont-In2p3-Cnrs,

On behalf of the FCC-*ee* design study

Outline of the talk

- Introduction to the FCC project
- Few words on the e^+e^- machine
- The Physics case at large.
- The Flavour Physics case:
    - Leptons
    - Quarks

1. Introduction to FCC:

- Starting from the former European HEP strategy 2013

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

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

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

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

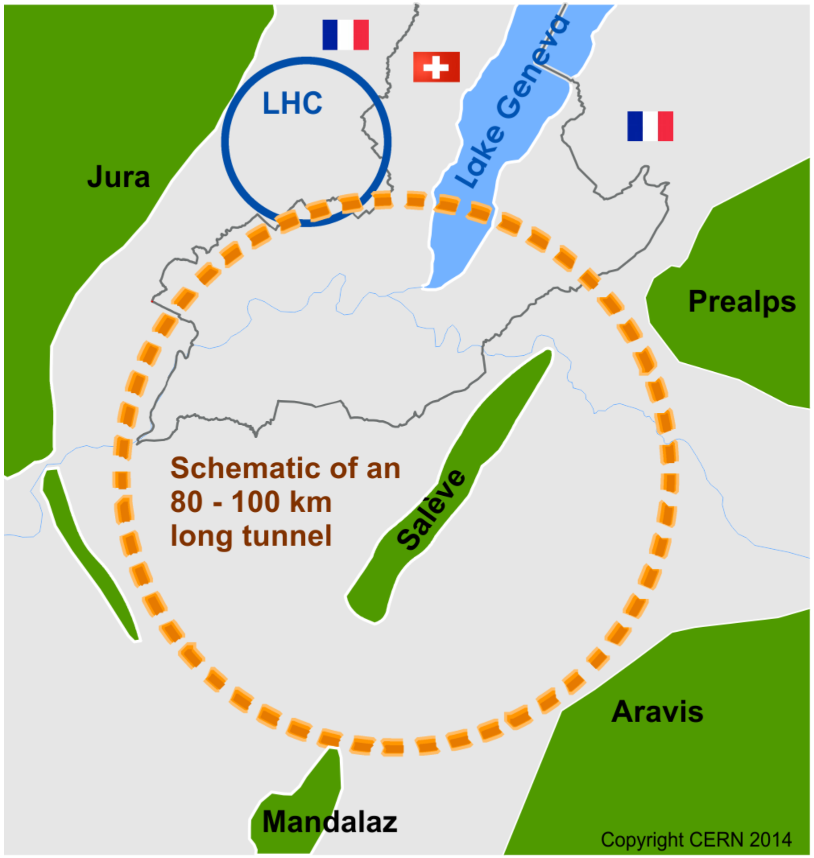
- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

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

- At the time the LHC Run II will have delivered its results, have an educated vision of the reach of future machines for the next round of the European Strategy in 2018/19.

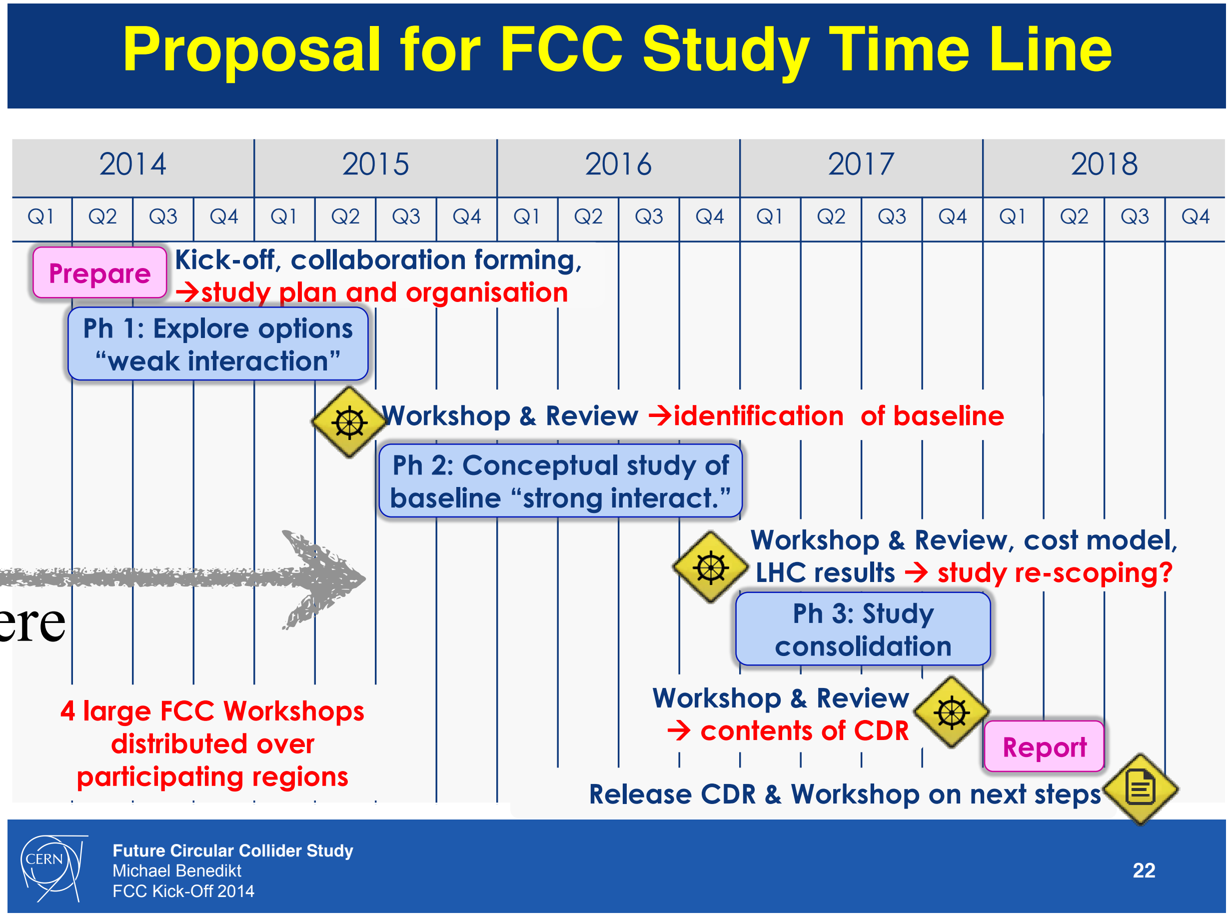
1. Introduction to FCC: the scope of the project

- Forming an international collaboration 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 → 2018/19.

- Applies to all machine and experiment designs:



We are here

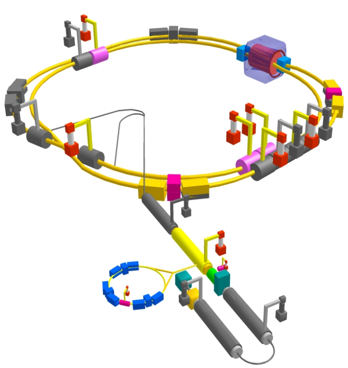
2. The e^+e^- machine. Baseline design

- 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*.

- Description of the machine in M. Koratzinos's poster.

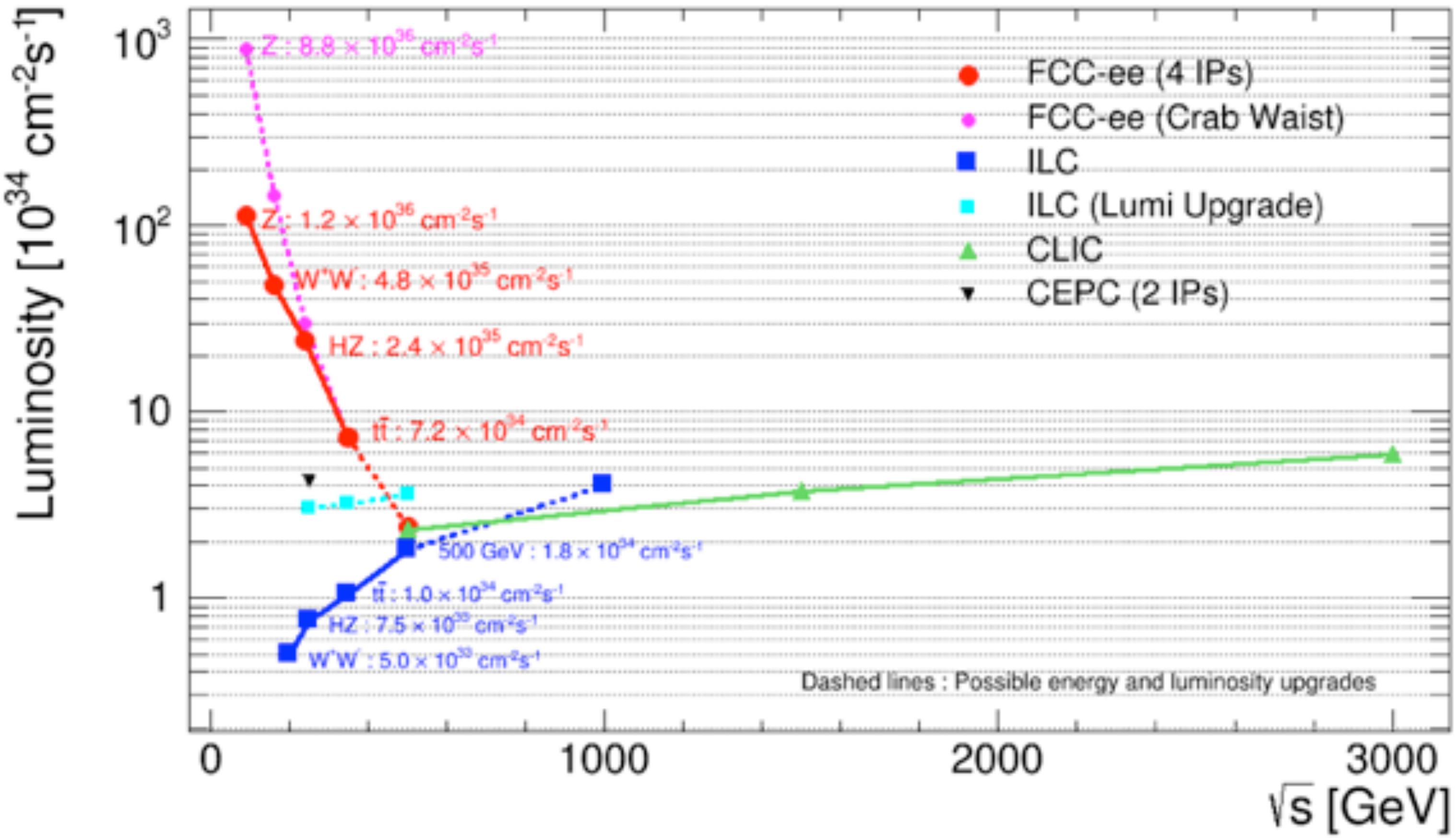
- To some extent, SuperKEKB shall already meet some of the challenges of FCC-*ee:*



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

2. The e^+e^- machine: luminosity figure.



- The 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.

3. The e^+e^- Physics case at large.

First look at the physics case of TLEP

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]

JHEP01(2014)164

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 examined from LEP (Z, W) or LC (top) extrapolations so far.

- The Design Study aims at reaching a fully educated view of the Physics Case from realistic detector simulation studies.

- Explore all the Physics possibilities including Flavours. The latter is not at the heart of the project but can be a *supplément d'âme*.

3. The e^+e^- Physics case at large: examples

Physics reach related to the luminosity figure:

✓ ElectroWeak Precision tests:

Z pole, *WW* and top pairs thresholds.

See M. Dam's and P.Janot's talks here.

✓ Higgs.

See M. Klute 's talk here.

✓ Summary.

See A. Blondel's poster here.

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%			

4. The Flavours in the big picture.

- Is there a Flavour case in this big picture?
- At least, there are obvious flavour-related questions to be examined, in the light of the anticipated precision that Flavour Physics experiments can reach (Belle II, LHCb upgrade and LFV experiments).
- I'd like to convince you that the answer is definitely yes.
- Illustrations starting with leptons.

4.1 Flavours at the Z: the lepton Physics Case

- 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.

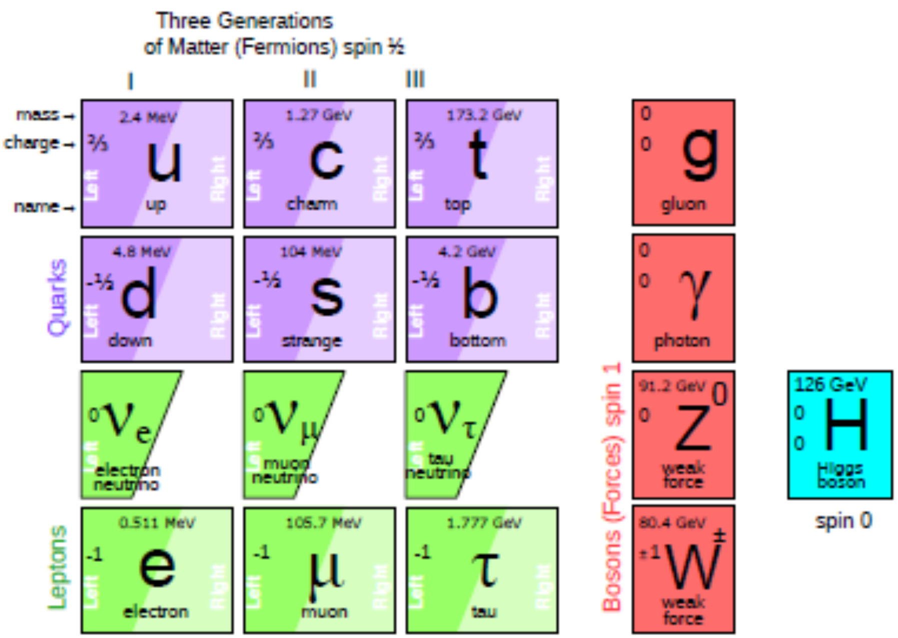
- Yukawa for charged fermions

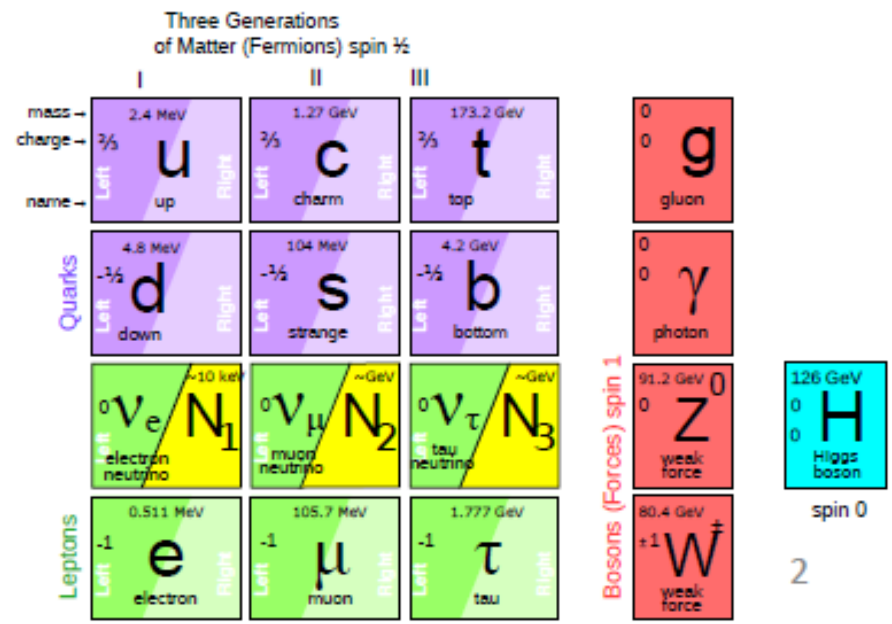
$$\mathcal{L}_Y = Y^d_{ij}\bar{Q}_{Li}\phi d_{Rj} + Y^u_{ij}\bar{Q}_{Li}\tilde{\phi}u_{Rj} + Y^\ell_{ij}\bar{L}_{Li}\phi\ell_{Rj} + +\text{h.c.}$$

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

4.1 Flavours at the *Z*: the lepton Physics Case

- 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?





4.1 Flavours at the Z: the lepton Physics Case

- 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.

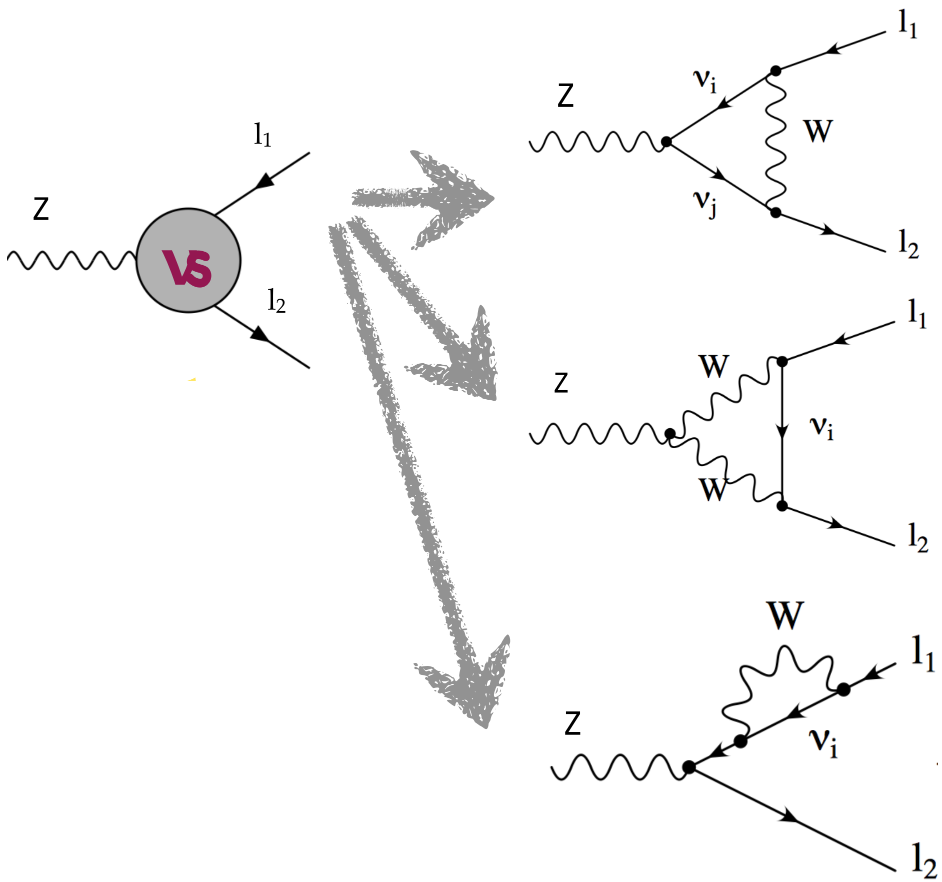
- Current limits at the level of ~10^{-6} (from LEP and recently Atlas, *e.g.* DELPHI, Z. Phys. C73 (1997) 243 ATLAS, CERN-PH-EP-2014-195 (2014))

- 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.

4.1 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:

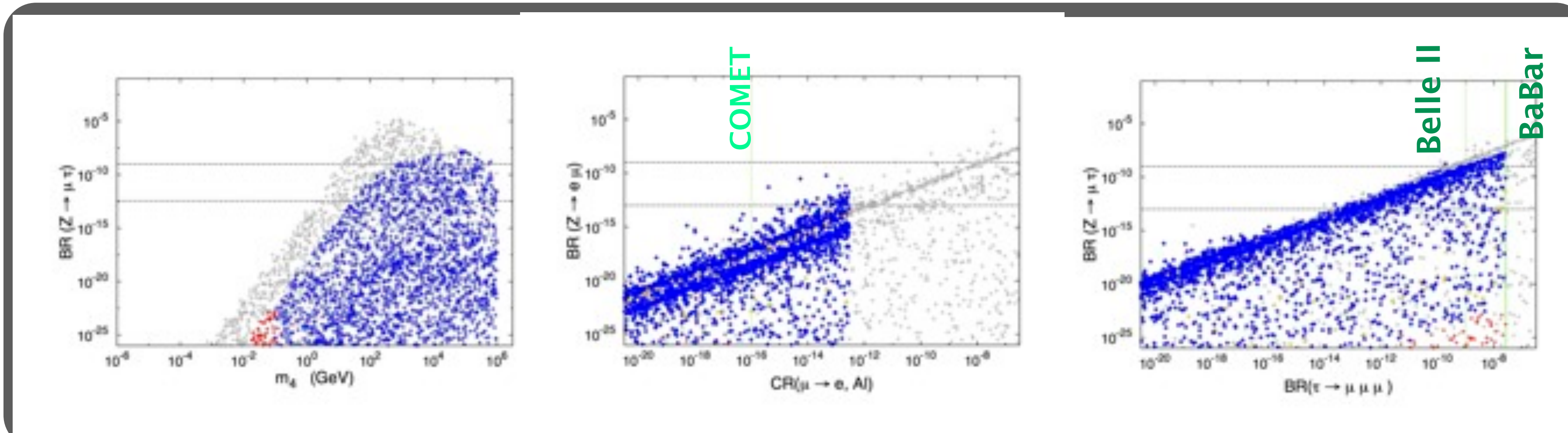
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double β decays
  - invisible Z-width

  ....

4.1 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 sterileνs

exp. excluded ●
cosmo X ●
cosmo OK ●



V. De Romeri et al. JHEP 1504 (2015) 051 and a talk here

- Steriles with mass > 80 GeV and mixings $O(10^{-5}\text{-}10^{-4})$ 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.

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

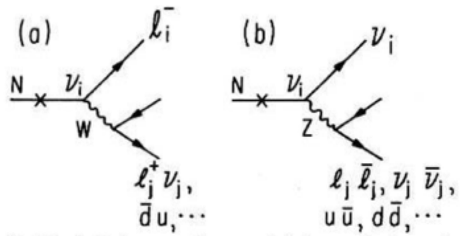


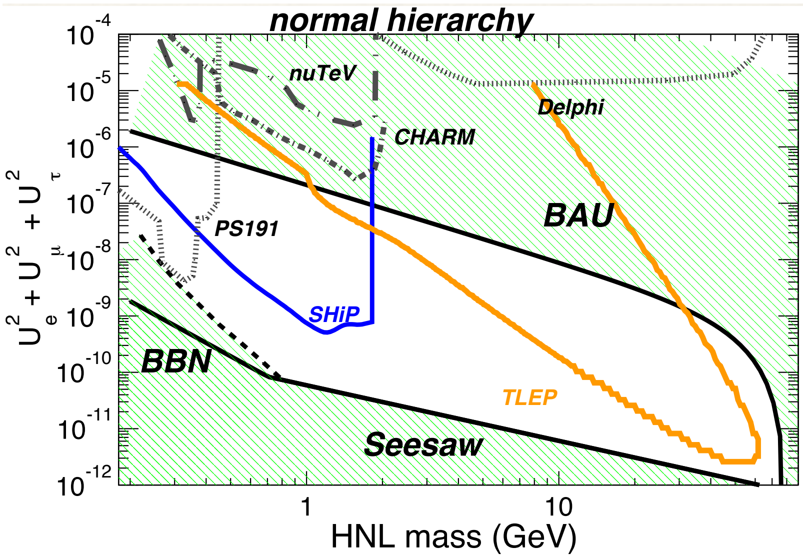
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

- 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.

4.2 Flavours at the *Z*: 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.

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.

4.2 The radiative 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.

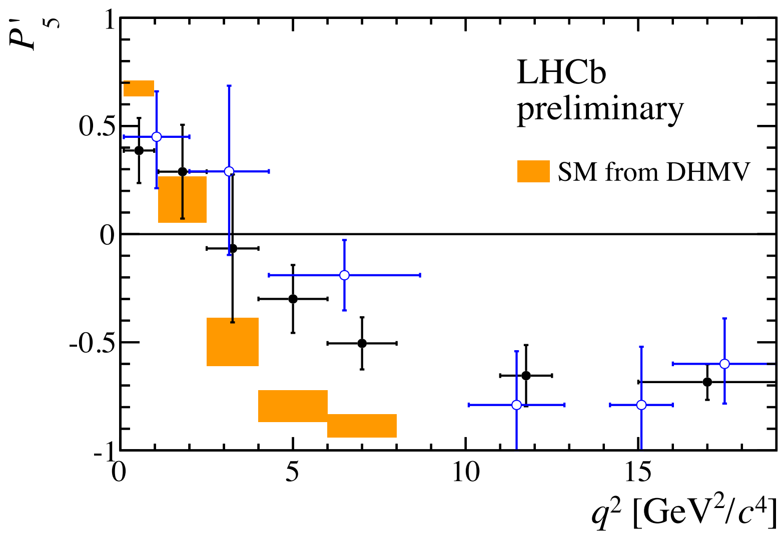


Figure 17: The observable P_5' in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the $1\,\mathrm{fb}^{-1}$ analysis from Ref. [7].

4.2 The radiative 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.

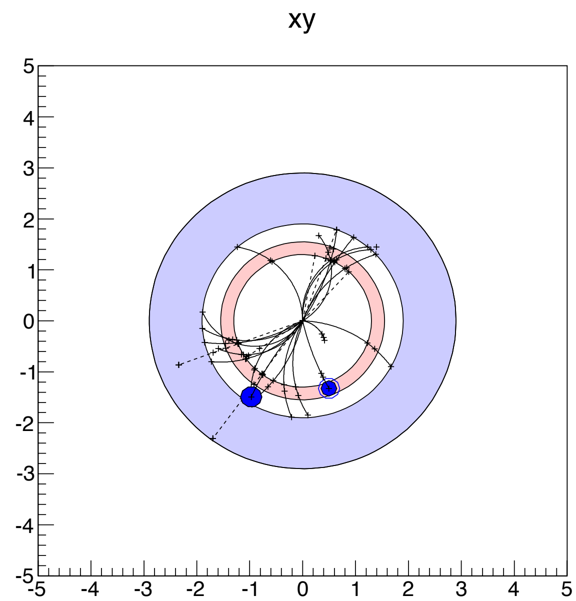
- Experimentally, aim at:
  - measuring the **branching fraction**,
  - studying the **angular distributions**.

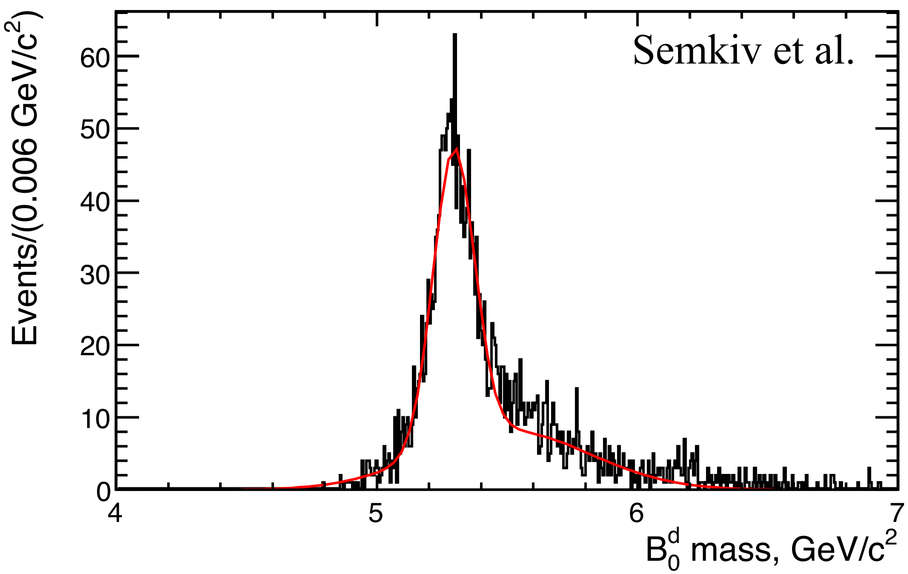
In both cases, FCC-ee provides a unique access to these territories.

4.2 The radiative decays as a first exploration.

- The transition $B^0 \to K^{*0}\, \tau^+\tau^-$ can be fully solved.
- Two neutrinos missing → six momentum coordinates to find.
- The secondary vertex is determined from the resonant $K^{*0} \to K^- \pi^+$
- Limit ourselves to the τ^- decays in three prongs: $\tau^- \to a_1^- \nu_\tau$

- **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.





Performance of the partial reconstruction. Introduce typical detector resolutions on **Momentum, PV, SV and TV.**

Efficiency ~ 40% and typical core **resolution** is at the level of **~ 80 MeV.**

5. Summary

- An effort for a design study of a large *pp* and *ee* collider is structured in order to provide an educated view of the Physics reach of such a facility for the next update of the HEP European strategy (2018/19).

- The *ee* collider should 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.

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

5. References and links as a Summary

- The project is getting mature. The FCC software is 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 $B^0 \rightarrow K^{*0} \tau^+\tau^-$, planned for $B^0_s \rightarrow \tau^+\tau^-$ and $B^0 \rightarrow K^{*0} e^+e^-$. 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 us: jernej.kamenik@ijs.si or monteil@in2p3.fr.

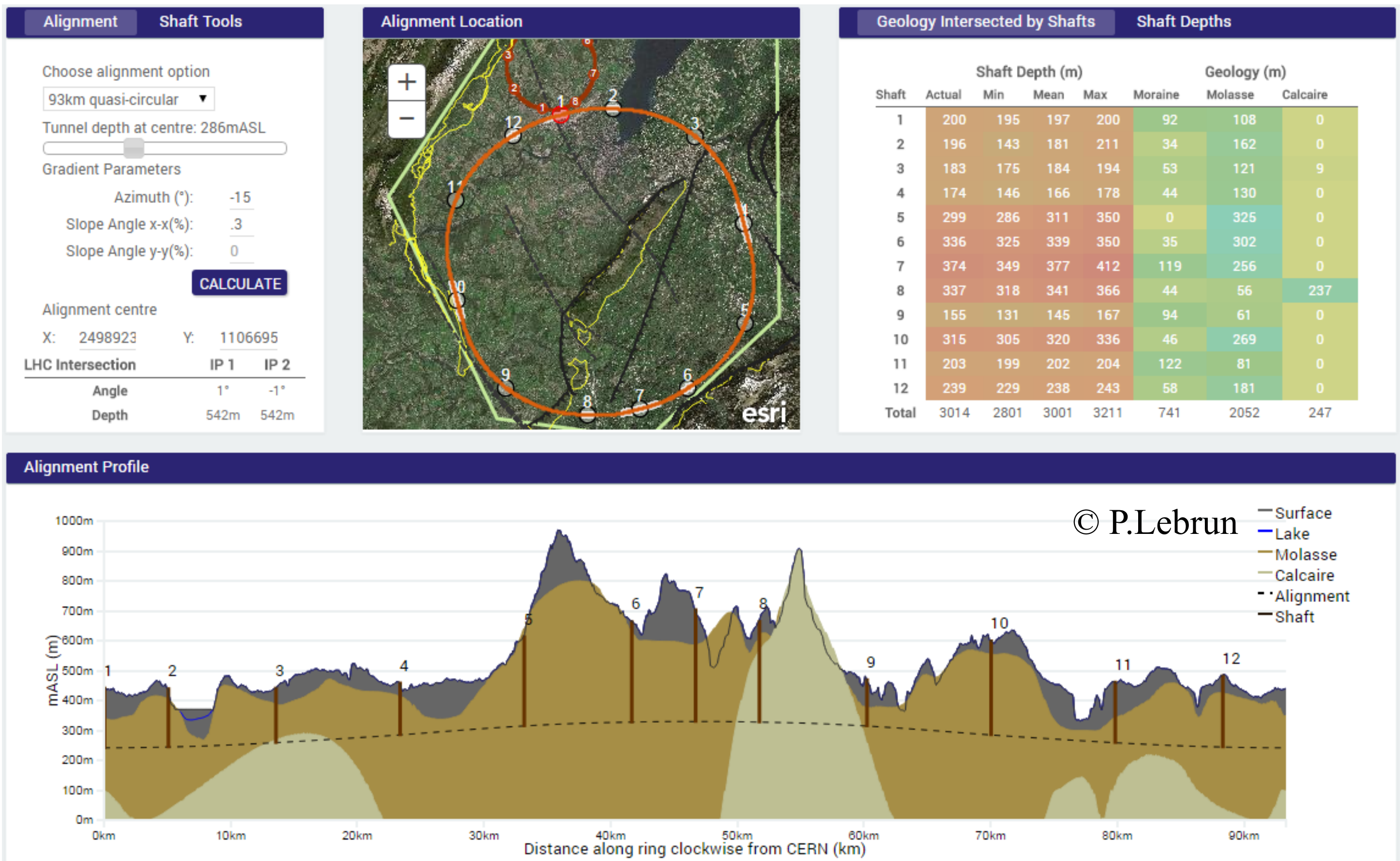
Back-up slides.

1. Introduction to FCC

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

1. Introduction to FCC

- In Geneva area.
- Infrastructure studies ongoing. A 93 km planar racetrack:



Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

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.

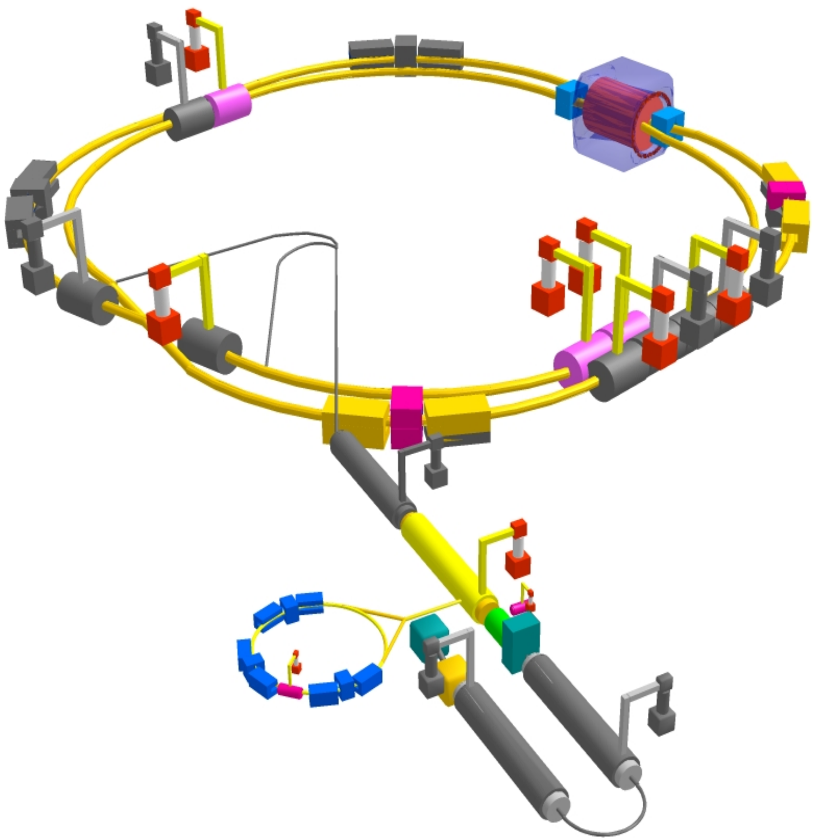
  - Polarization of the beams (at least natural one for beam energy measurement - EWK precision measurements)

  - 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) : < 1×10^{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

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.

2. The e^+e^- machine: luminosity figure.