About the future: visions for Particle Physics

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Outline of the lecture

- Scientific context I: what we think we know.
  Scientific context II: how do we know what we think we know?

- Lepton flavours at large: magnetic moments, lepton flavour violation, neutrinos & friends.

- Quark flavours at large: kaons and CKM, charm, beauty.

- Dark matter, dark matter, dark matter, dark matter ...

- Introduction to the Future Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

Exergue for this part of the lecture - Nietzsche.

Impregnare il passato e portare avanti il futuro, tale è il mio presente ...

Féconder le passé et enfanter l'avenir, que tel soit mon présent.

Die Vergangenheit befruchten und die Zukunft zeugen - das sei mir Gegenwart!

Scientific context: SM became a theory

The free parameters of the SM:

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

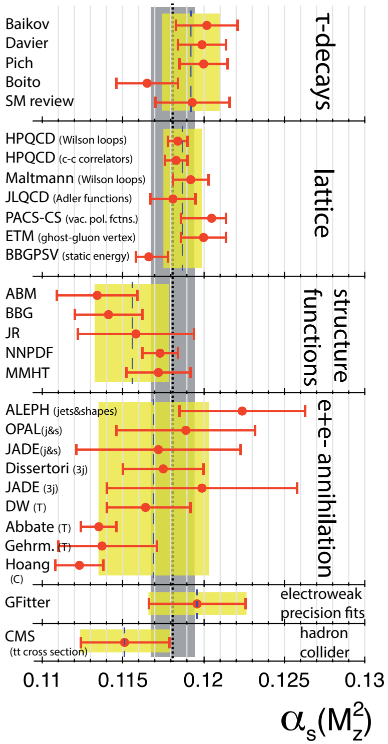
    v **(the v.e.v) and** m_H .

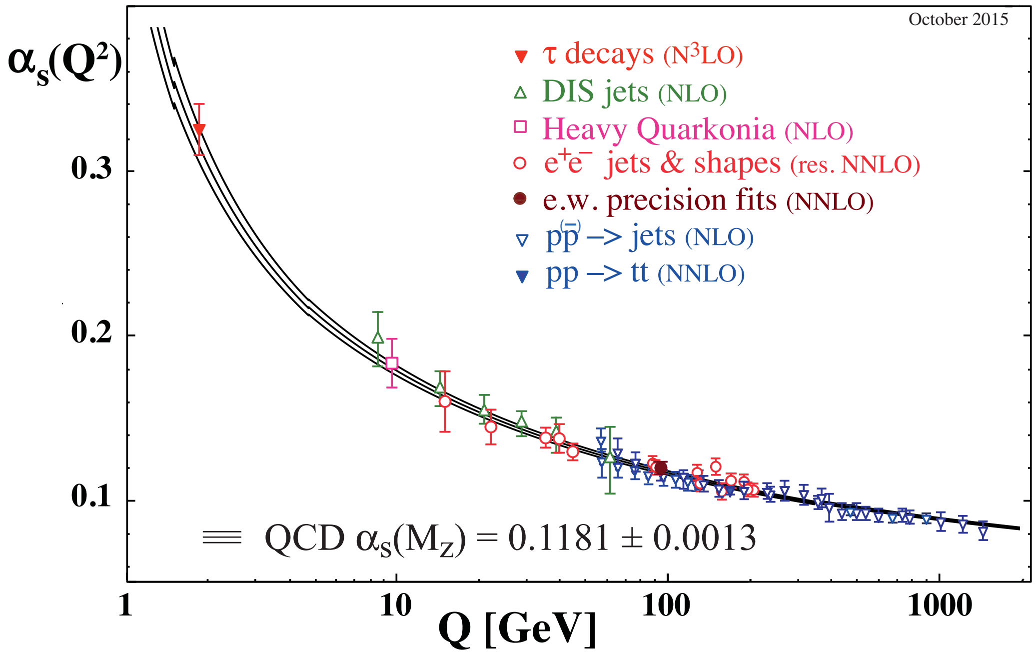
The free parameters of the SM

- 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.

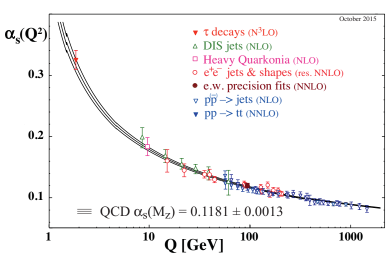




Scientific context: SM became a theory

Reorganisation:

- QCD and α_s/ homework: how to measure α_s from e^+e^- collisions?



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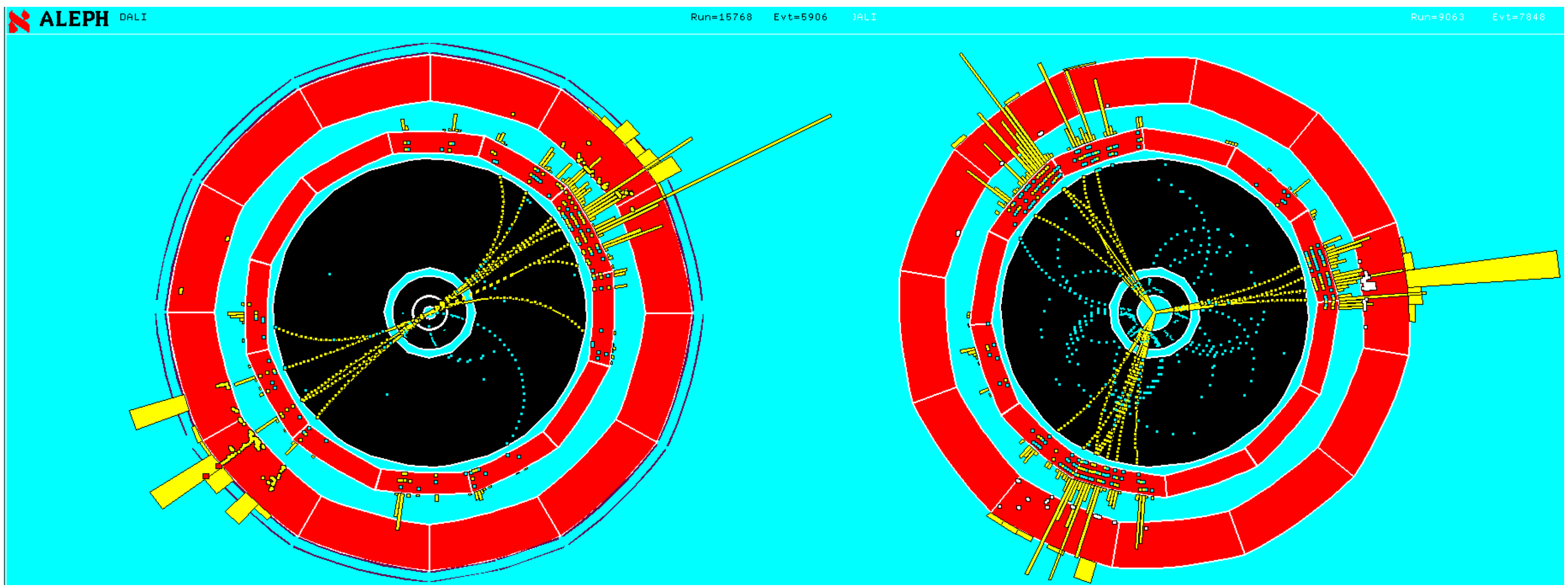

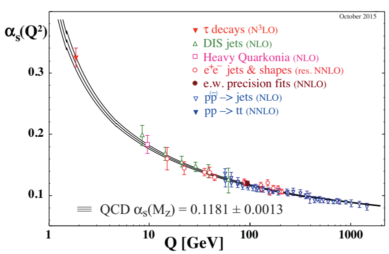

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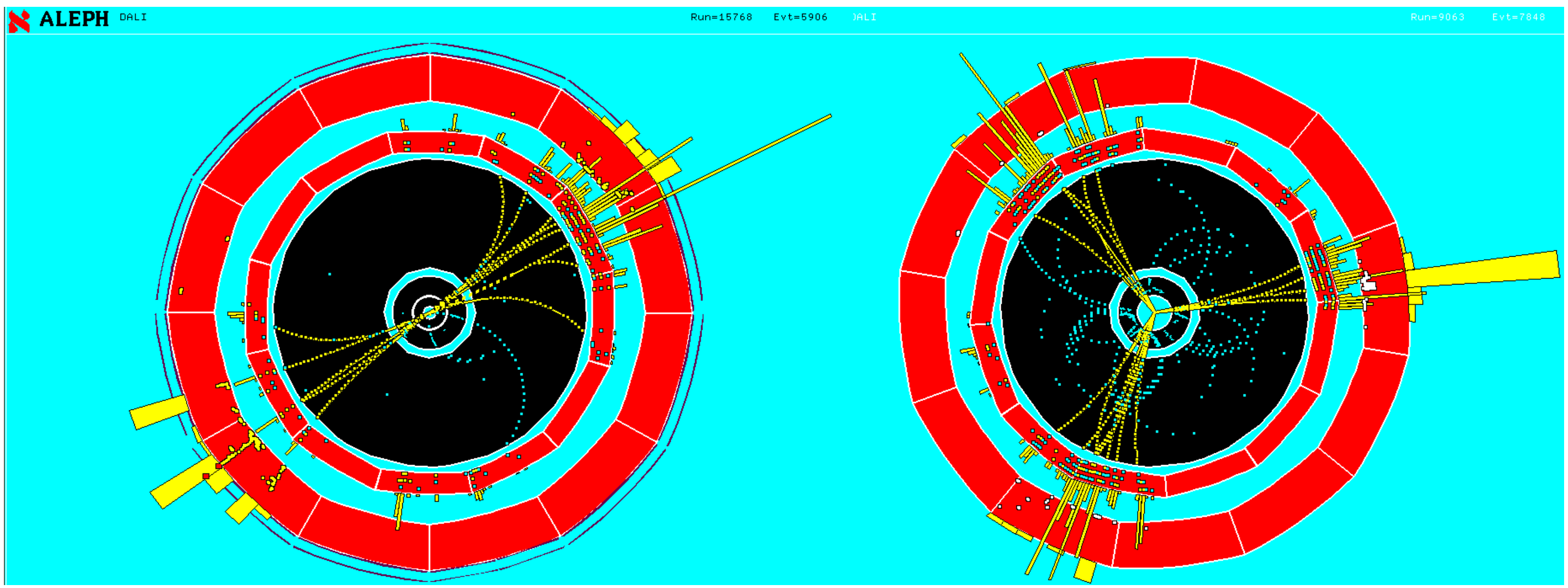
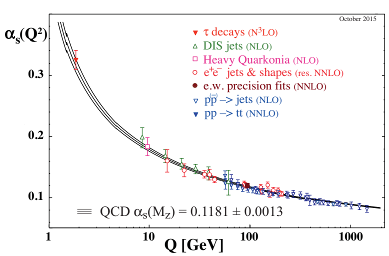




$$R = \frac{\sigma_{3\ \mathrm{jets}}}{\sigma_{2\ \mathrm{jets}}} \sim \alpha_S$$

Scientific context: SM became a theory

Reorganisation:

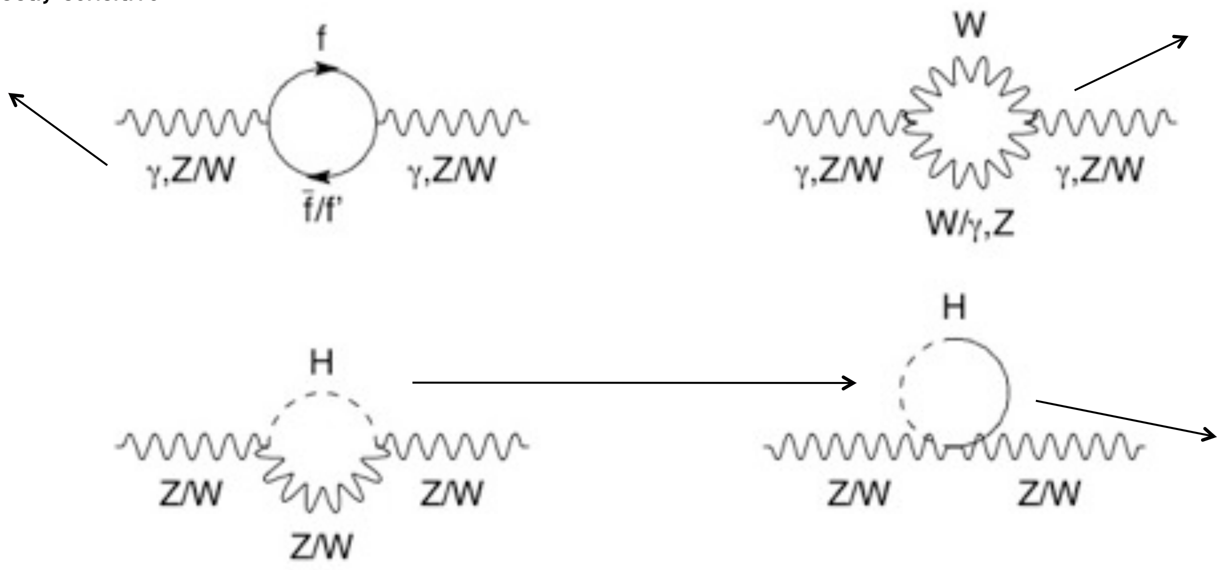
- The nine masses of the fermions: $\boldsymbol{m_f}$.
- They are for 8 of them decoupled from the rest of the SM parameters.
- Nothing much to do here as well till the moment a theory comes with a prediction.
- They are however understood from the Yukawa couplings. We'll come back there.
- The top deserves a special mention.

Reorganisation: the specific status of the top quark.

- The top quark has a specific status because it enters dominantly in the radiative corrections of the intermediate bosons mass propagators (in particular), *e.g.*

Top dominates. Mostly sensitive to m^2_t

Non abelian structure of the EW theory. TGC.



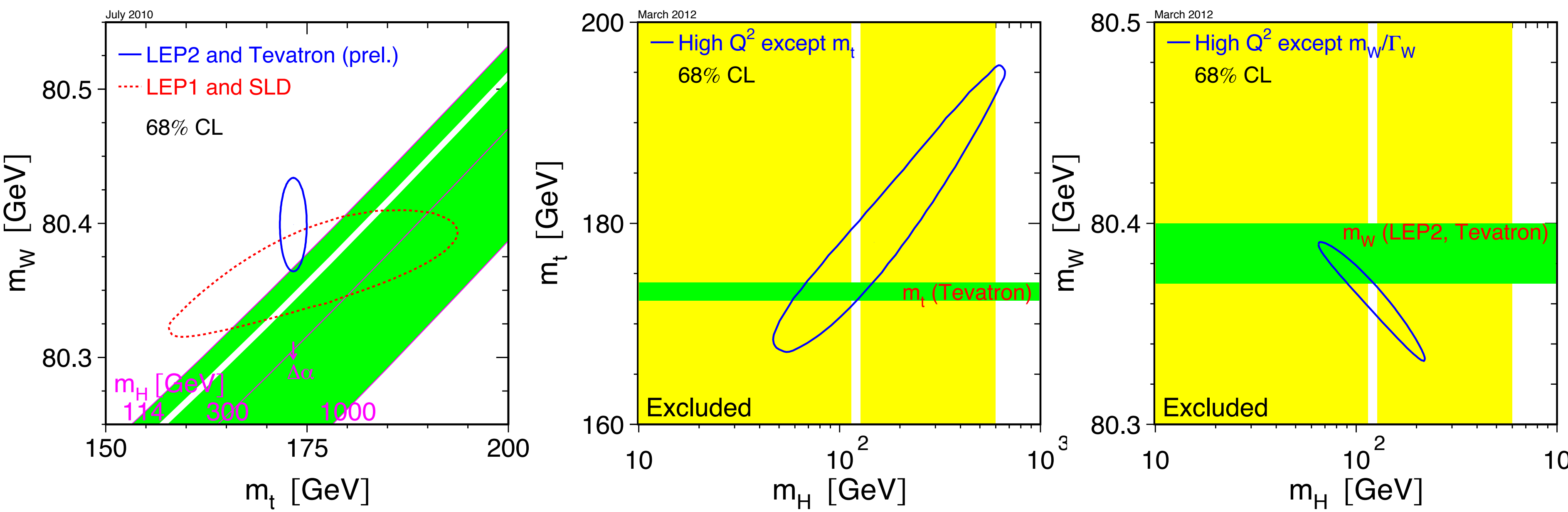
Scalar sector. Contains Higgs mass info.

- In turn, a prediction of its mass in the SM is possible in the consistency fit of the SM hypothesis against the electroweak precision observables.

Scientific context: SM became a theory

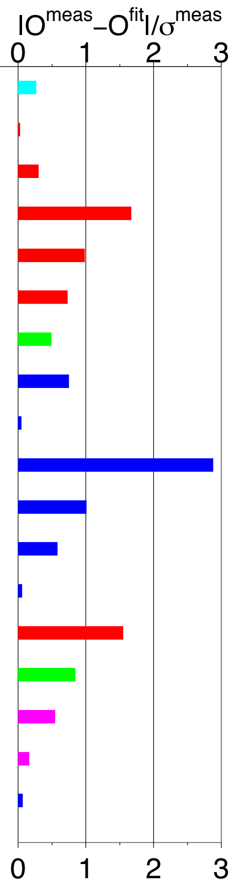
Reorganisation:

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



Reorganisation: spelling out the predictions.

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

- The SM EW global fit has a remarkable χ^2_{min}/d.o.f = 1.40 (p-value=15%).

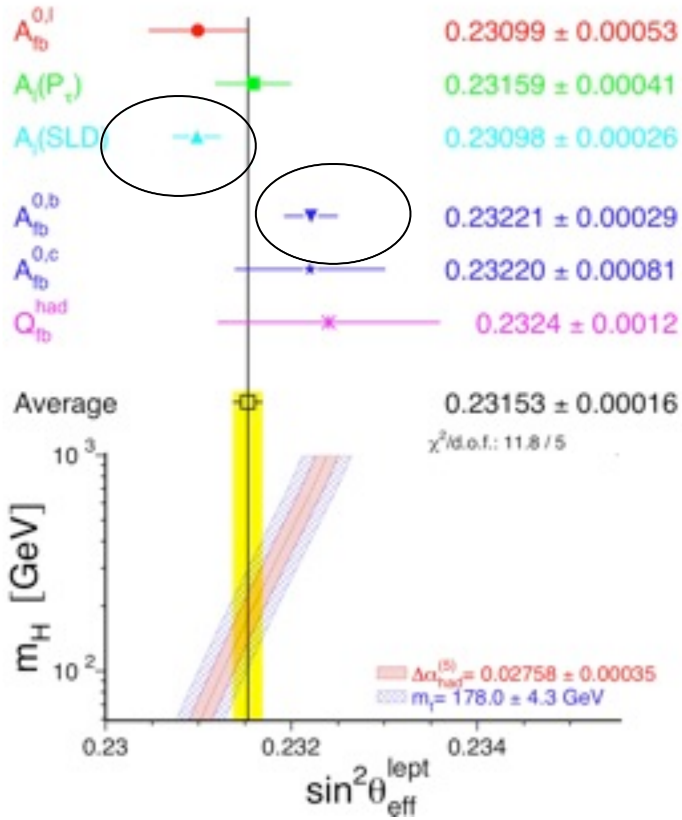
- The SM hypothesis passes the test. It does not mean that SM IS the Nature. In Science, one can usually only say NO...

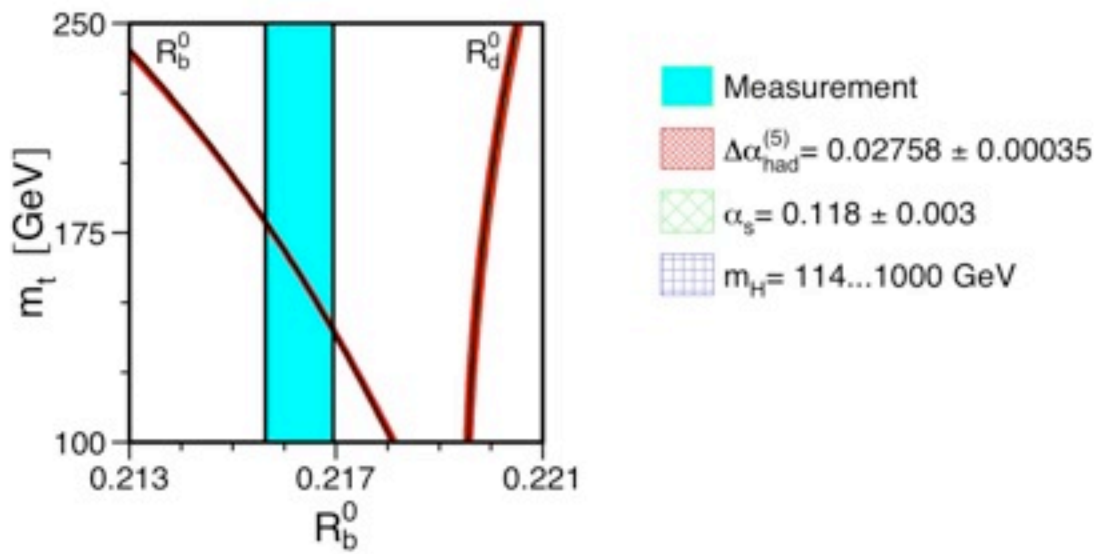
- Two observables depart « with some significance » from their prediction. It happens they are the two most important for the constraint on the Higgs boson.

- One can go one step further and make the metrology of the parameters.

Reorganisation: spelling out the predictions.

- The information on the top quark is basically brought by $\sin^2\theta_{eff}$ (A_{LR} and A_{FB} – propagator corrections), m_W (again propagator corrections) and R_b (vertex corrections).





Scientific context: SM became a theory

Reorganisation: spelling out the predictions.

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- Putting all these observables together (and some others) yields a top quark mass prediction of :

$$m_{top} = 172.6 \begin{array}{l} +13.3 \\ -10.2 \end{array} \text{GeV}/c^2 \text{ [(indirect – LEP1)].}$$

- basically obtained (w/ three times the current uncertainty) from 1993.

- actually presented at Moriond 1994.

Reorganisation: spelling out the predictions.

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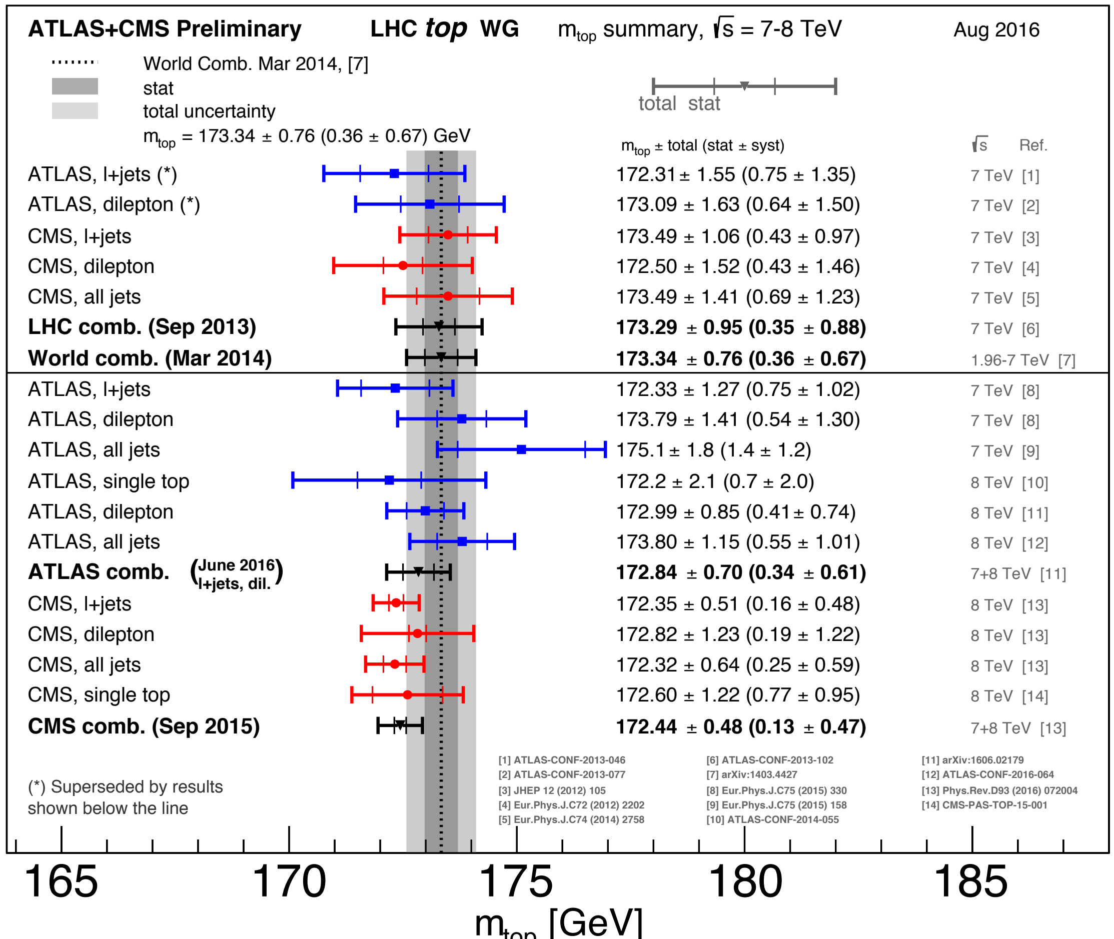


Scientific context: SM became a theory

Reorganisation: spelling out the predictions.

- We must now compare the direct and indirect determinations:

$$m_{\mathrm{top}} = 173.18 \pm 0.96 \ \mathrm{GeV}/c^2, \ [\mathrm{direct} - \mathrm{Tevatron}]$$

$$m_{\mathrm{top}} = 172.6^{+13.2}_{-10.2} \ \mathrm{GeV}/c^2, \ [\mathrm{indirect} - \mathrm{LEP1}]$$

$$m_{\mathrm{top}} = 172.44 \pm 0.48 \ \mathrm{GeV}/c^2, \ [\mathrm{direct} - \mathrm{LHC}]$$

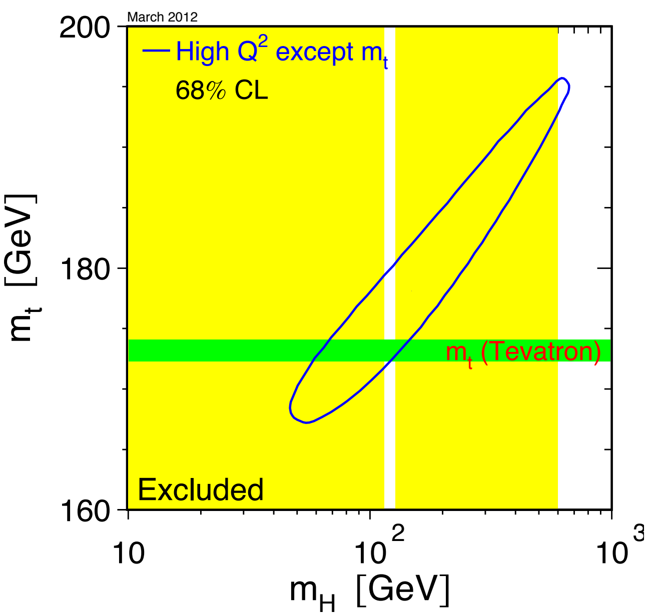
- The agreement is simply remarkable.

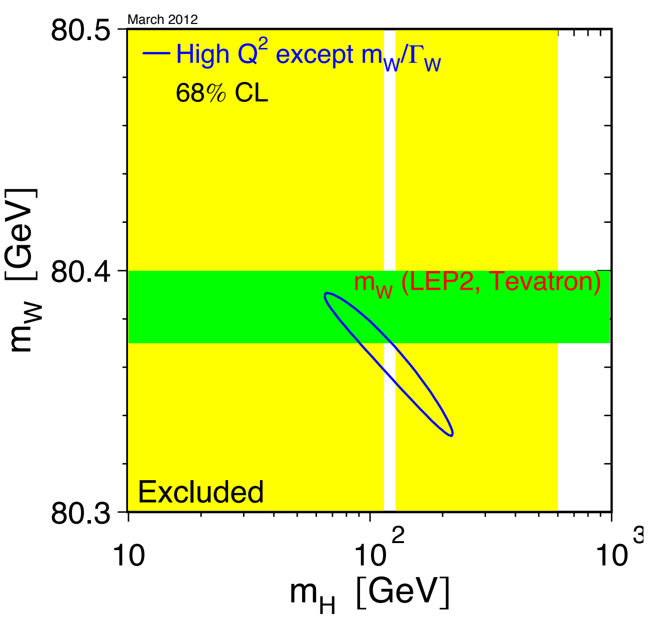
- LEP/SLD + SM predicted the top quark mass.

- This is simultaneously a triumph of the Standard Model and the HEP physics experiments. Probe quantum corrections of the electroweak theory to predict the existence of a particle in the Nature.

Reorganisation: spelling out the predictions.

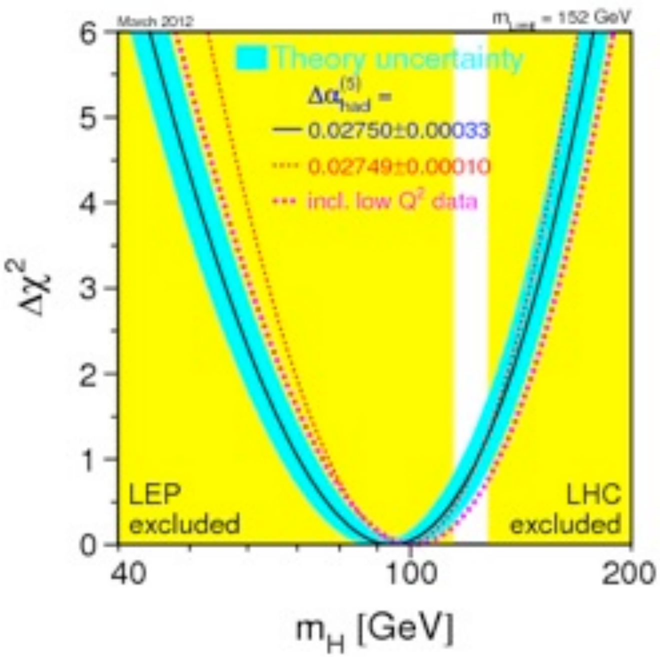
- Once the top quark is known, it can enter in the EWP consistency and constrain further the rest of the parameters, the Higgs boson.





Reorganisation: spelling out the predictions.

- Once the top quark is known, it can enter in the EWP consistency and constrain further the rest of the parameters, and bound the Higgs boson mass.



$$m_{\rm BEH} < 152 \text{ GeV}/c^2 \quad 95\% \text{ CL.}$$

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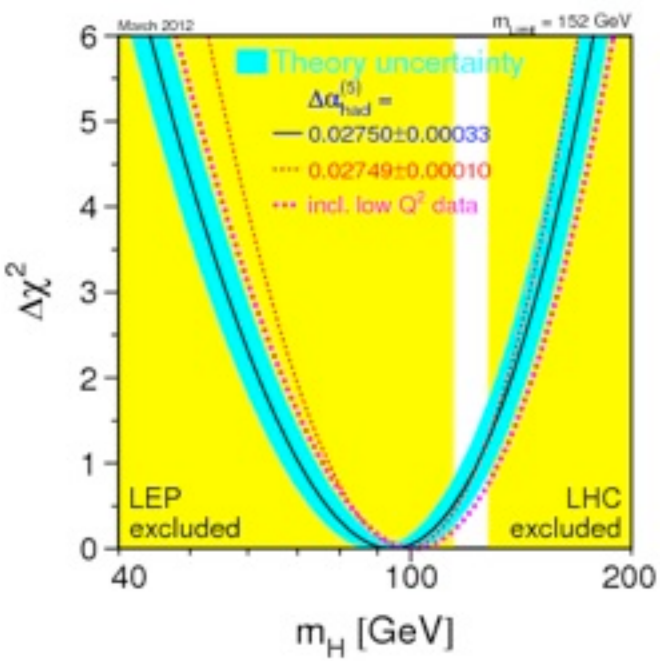

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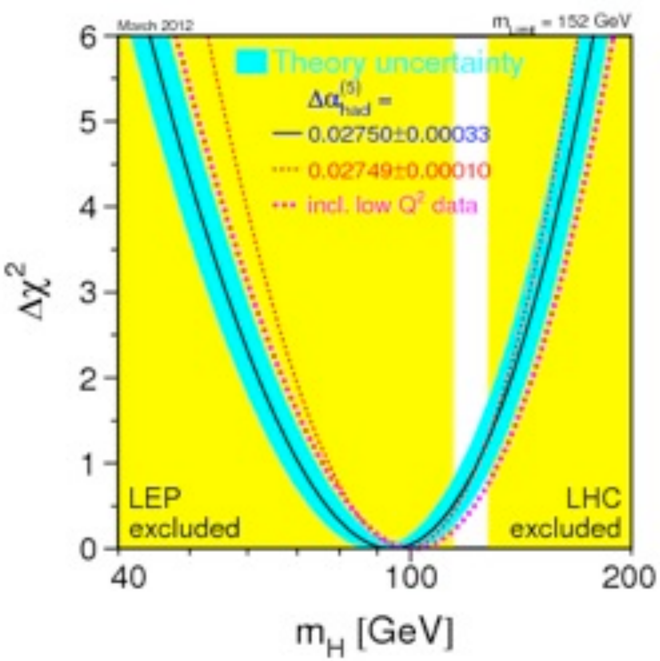

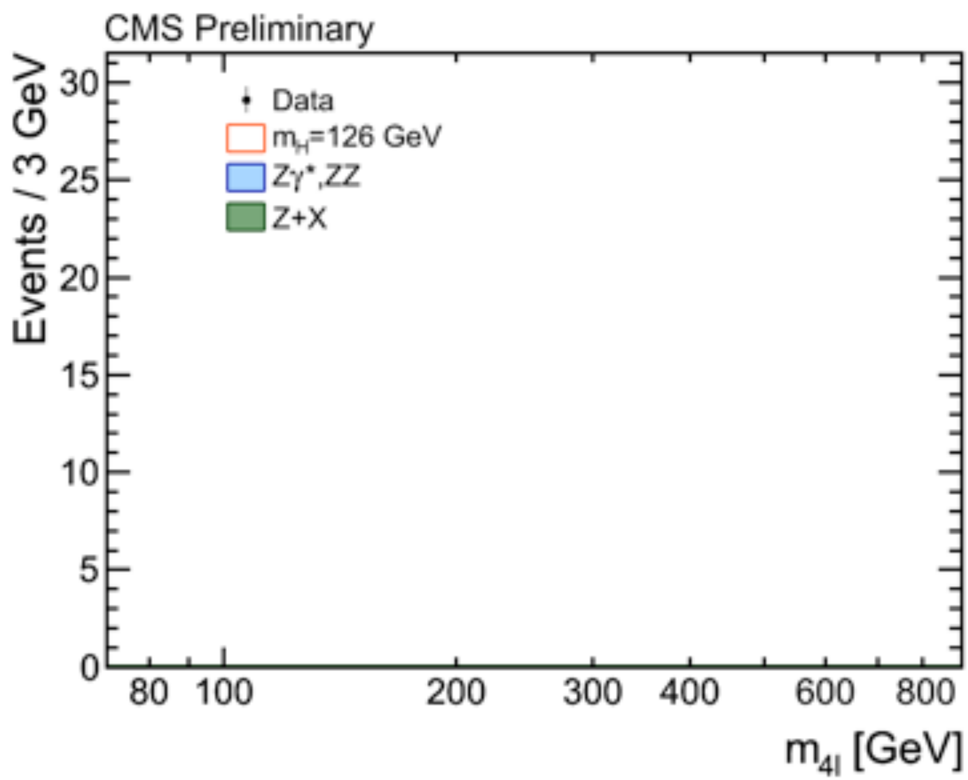

Scientific context: SM became a theory

Reorganisation: the narrow bosonic resonance.

- The mass starts to be accurately measured.

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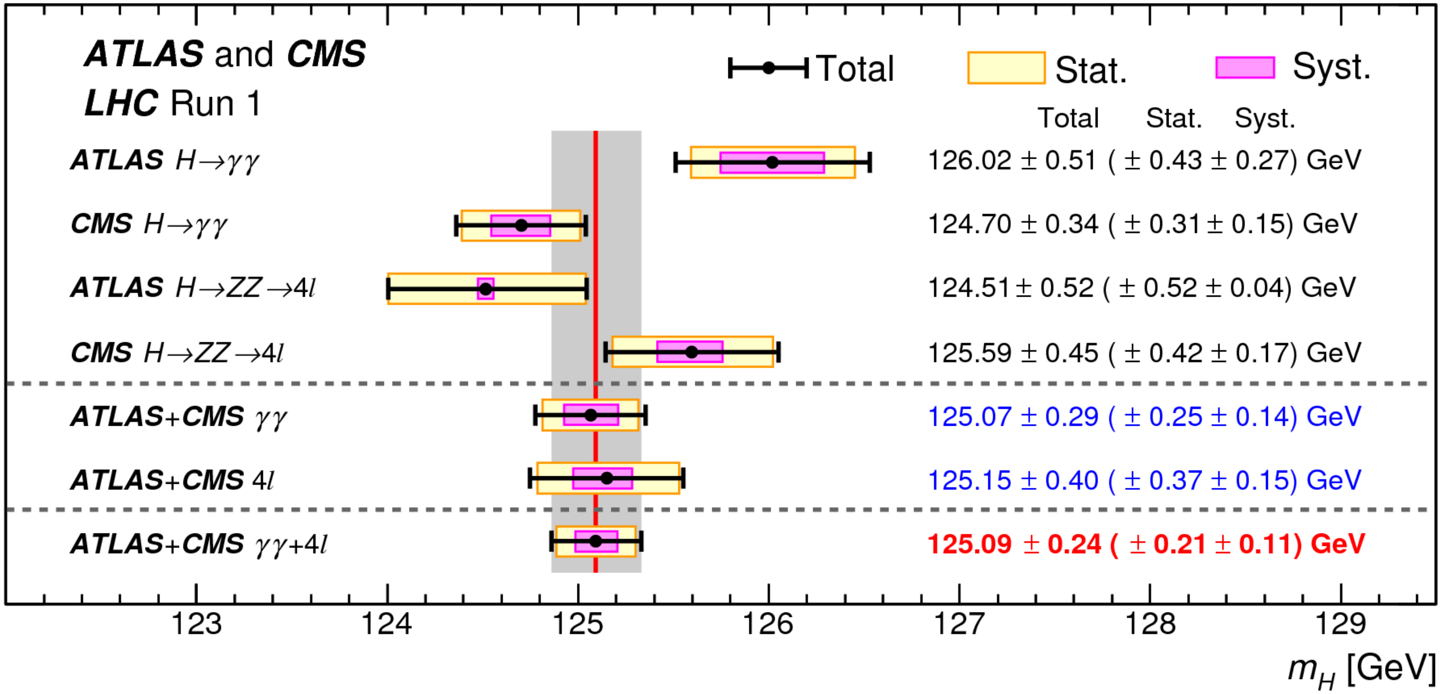
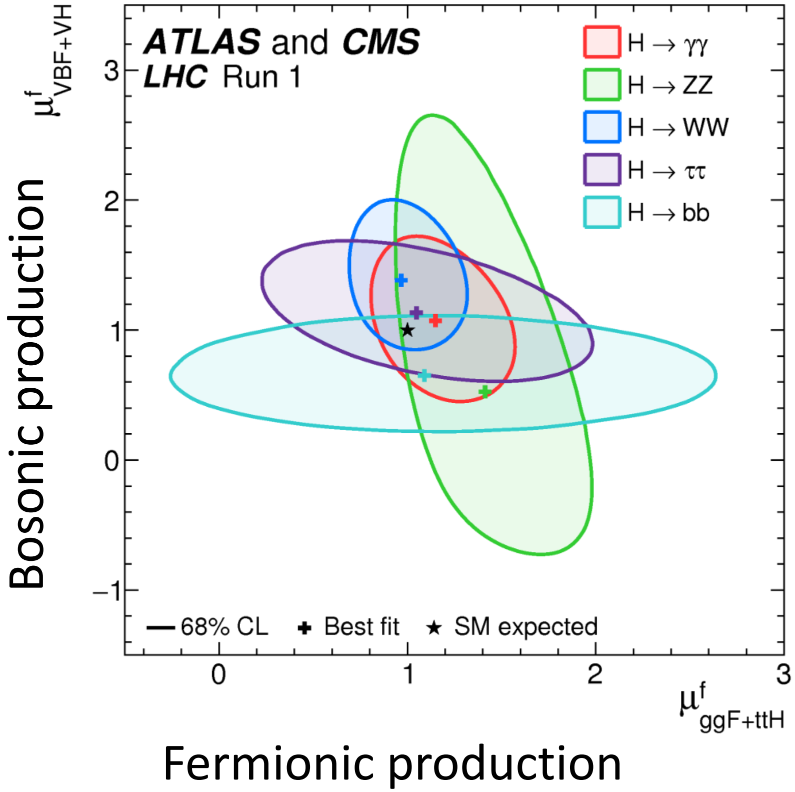


- It is likely a scalar particle (spin /parity properties determined form *ZZ** signal events.

Reorganisation: the narrow bosonic resonance.

- The couplings are so far (with a modest precision though) in good agreement with the SM predictions.



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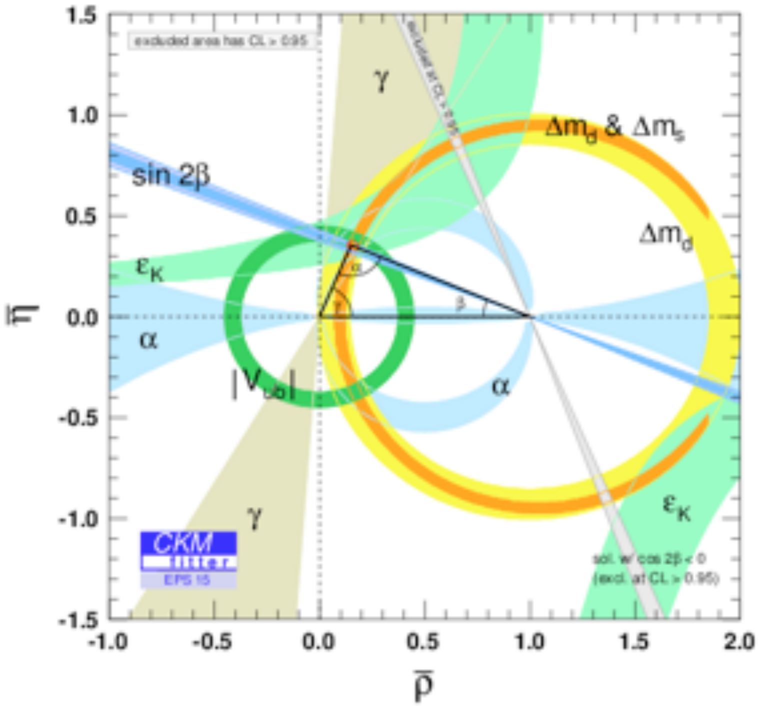
Reorganisation: coming back to quark masses and mass mixing matrix.

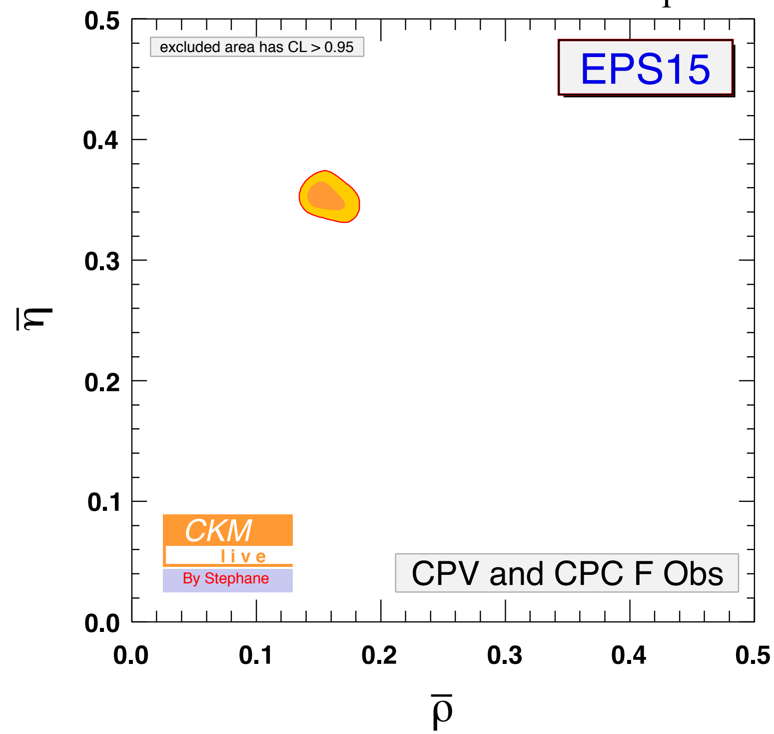
- See the Flavour Physics lecture in this School.
- Again, the name of the game consists in a global consistency check from a fit of the SM hypothesis against the relevant Flavour data observable measurements.
- Most of the constraints are coming from *b*-hadron decays and neutral *B*-meson mixings. These can be *CP*-conserving or *CP*-violating observables.
- The global fit relies heavily, as far as *CP*-conserving observables are concerned, on QCD predictions, mostly numerically established (Lattice QCD).
- The observables related to the strange flavour (*K* decays and K^0 mixing) are also consistently described, though suffering from large(r) hadronic uncertainties (long distance physics where LQCD does not apply straightforwardly).

Scientific context: SM became a theory

Reorganisation: coming back to quark masses and mass mixing matrix.

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





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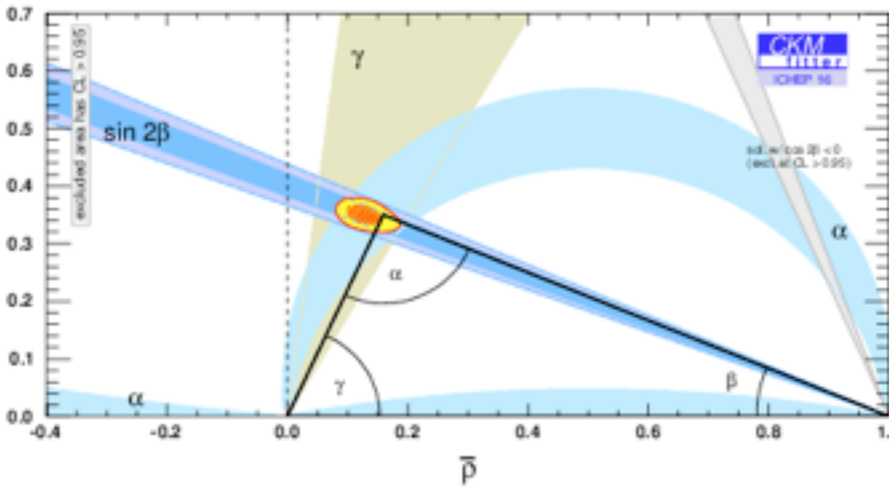
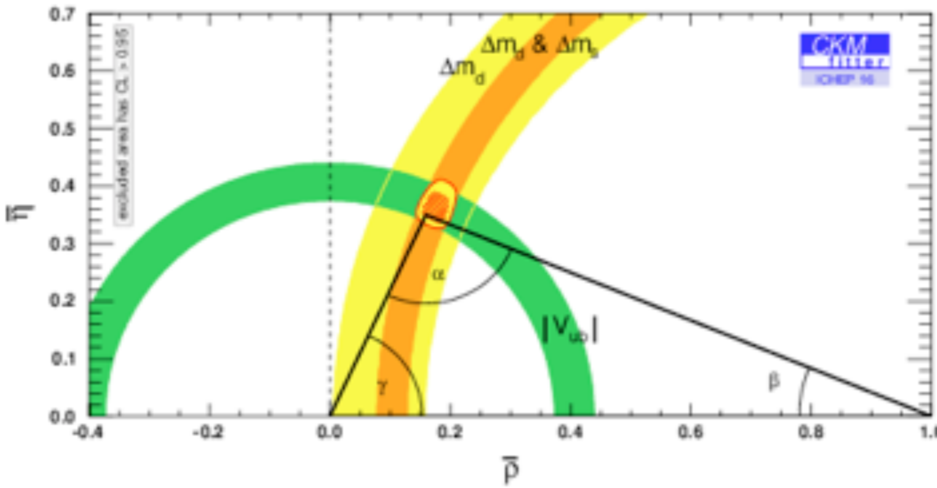


Angles - No theory uncertainty



Sides - Theory uncertainty dom.

Scientific context: SM became a theory

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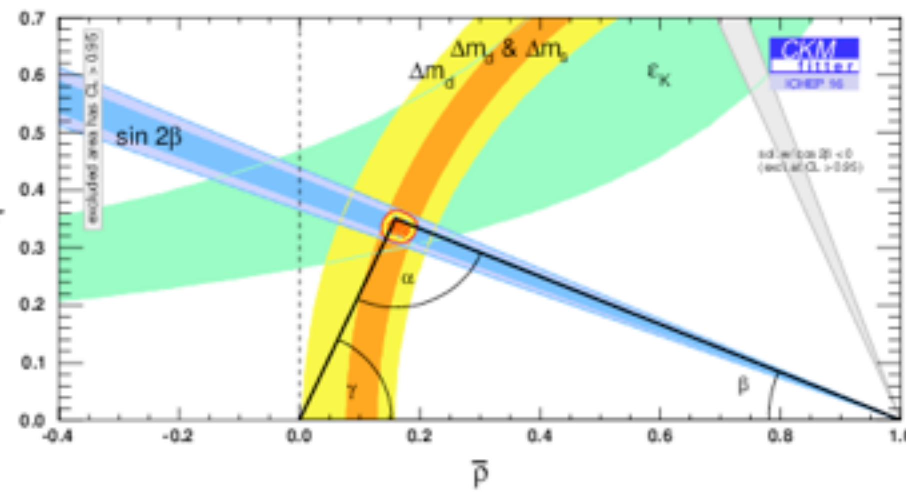

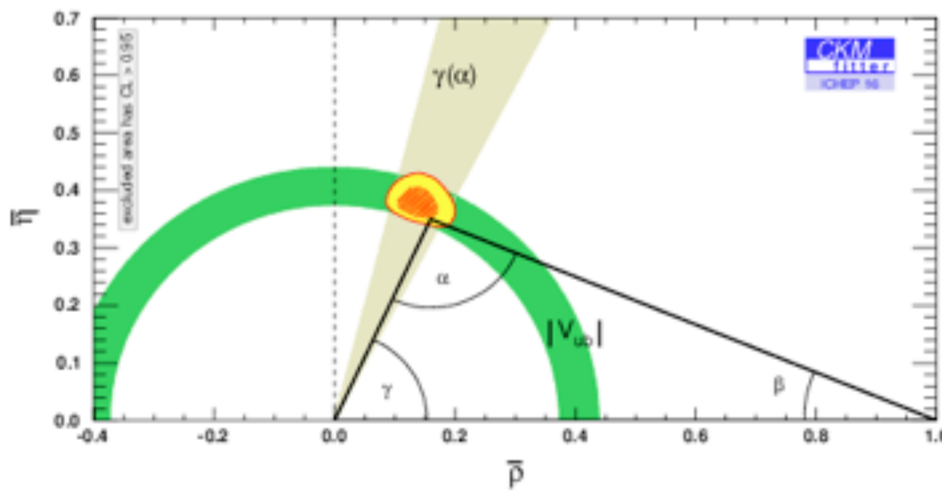

Loops -

Trees -

Recap
the two pillars of the SM:
EWPT and quark flavours.

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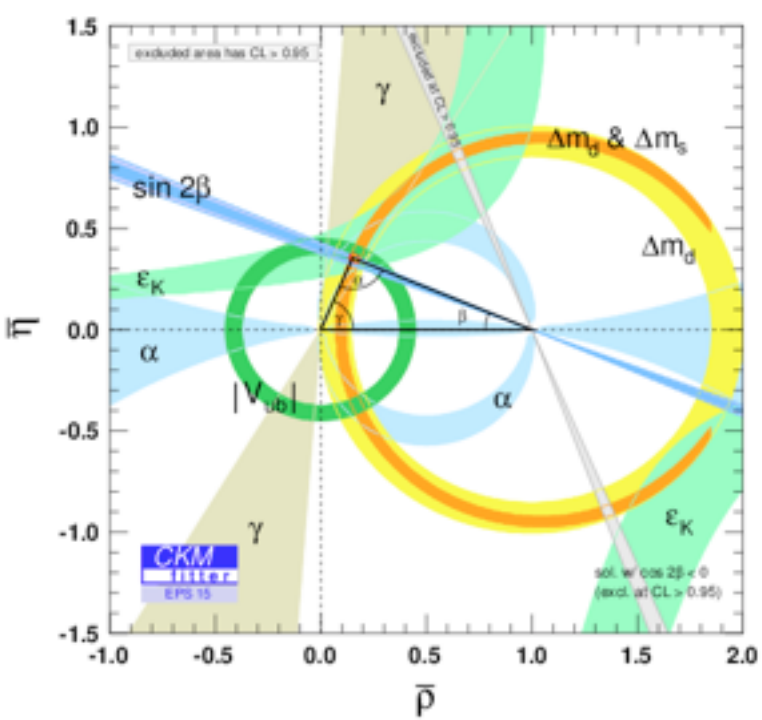
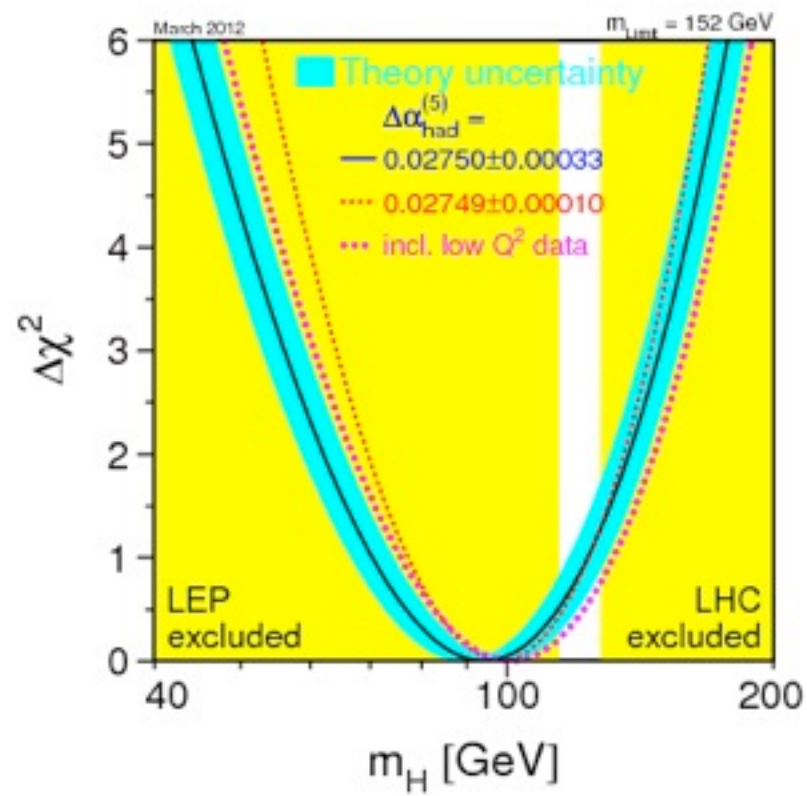
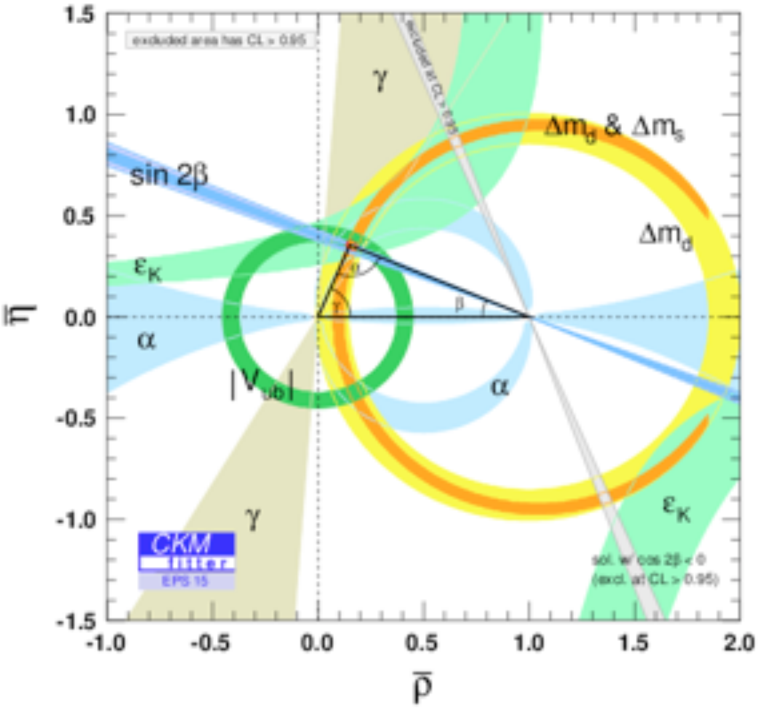




Scientific context: SM became an invincible theory

Recap: the two pillars of the SM: EWPT and quark flavours.



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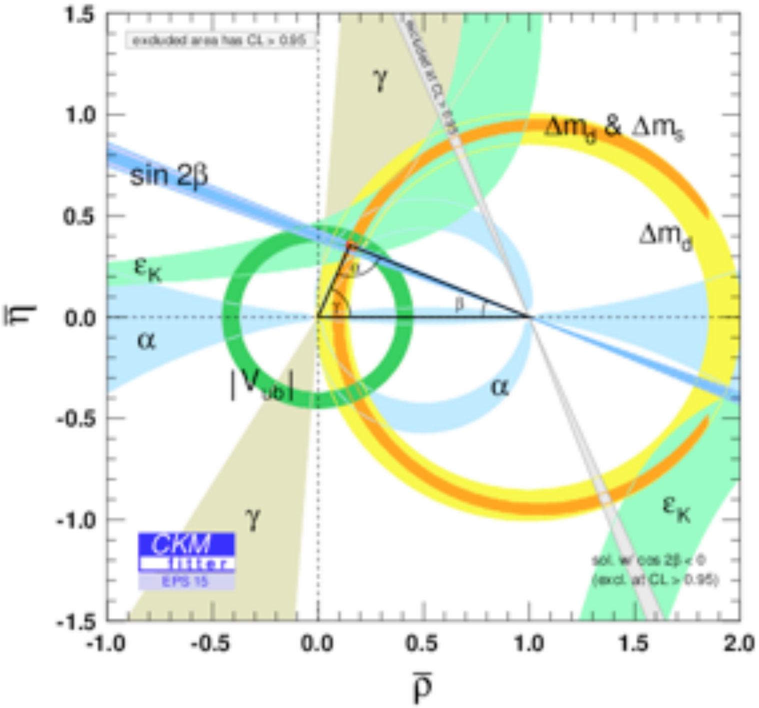

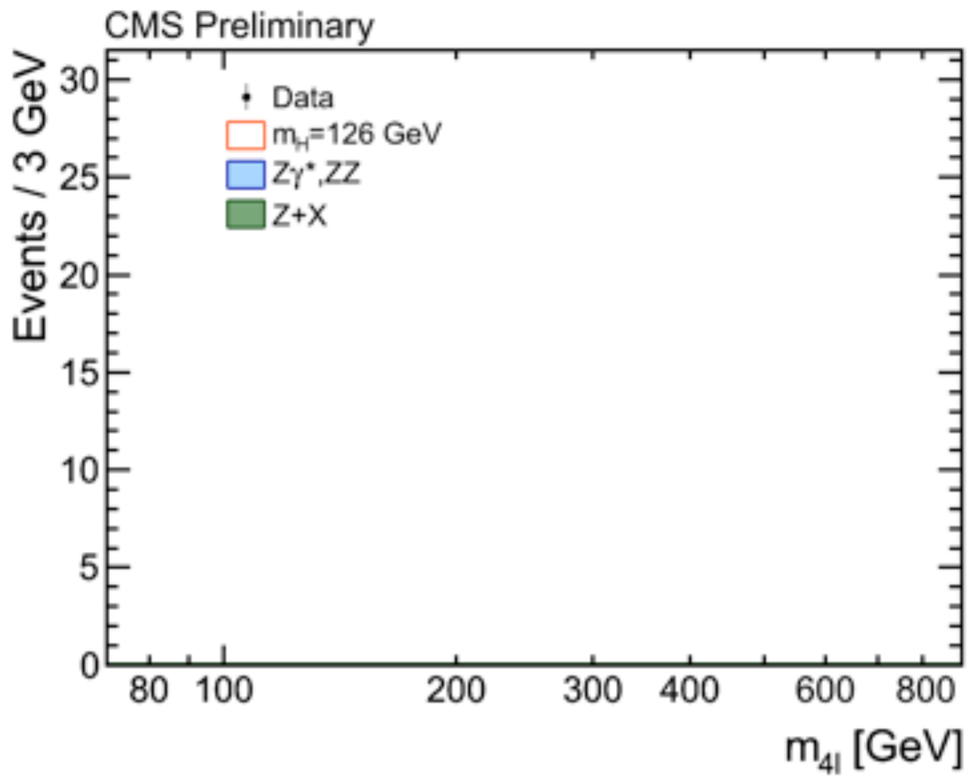

Lessons

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*

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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 lecture

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].

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- Scientific context I: what we think we know.
  Scientific context II: how do we know what we think we know?
- Lepton flavours at large: magnetic moments, lepton flavour violation, neutrinos & friends.
- Quark flavours at large: kaons and CKM, charm, beauty.
- Dark matter, dark matter, dark matter, dark matter ...
- Introduction to the Future Circular Colliders project or a long term vision for the Particle Physics. The fundamental scalar of the Nature and the electroweak thresholds.

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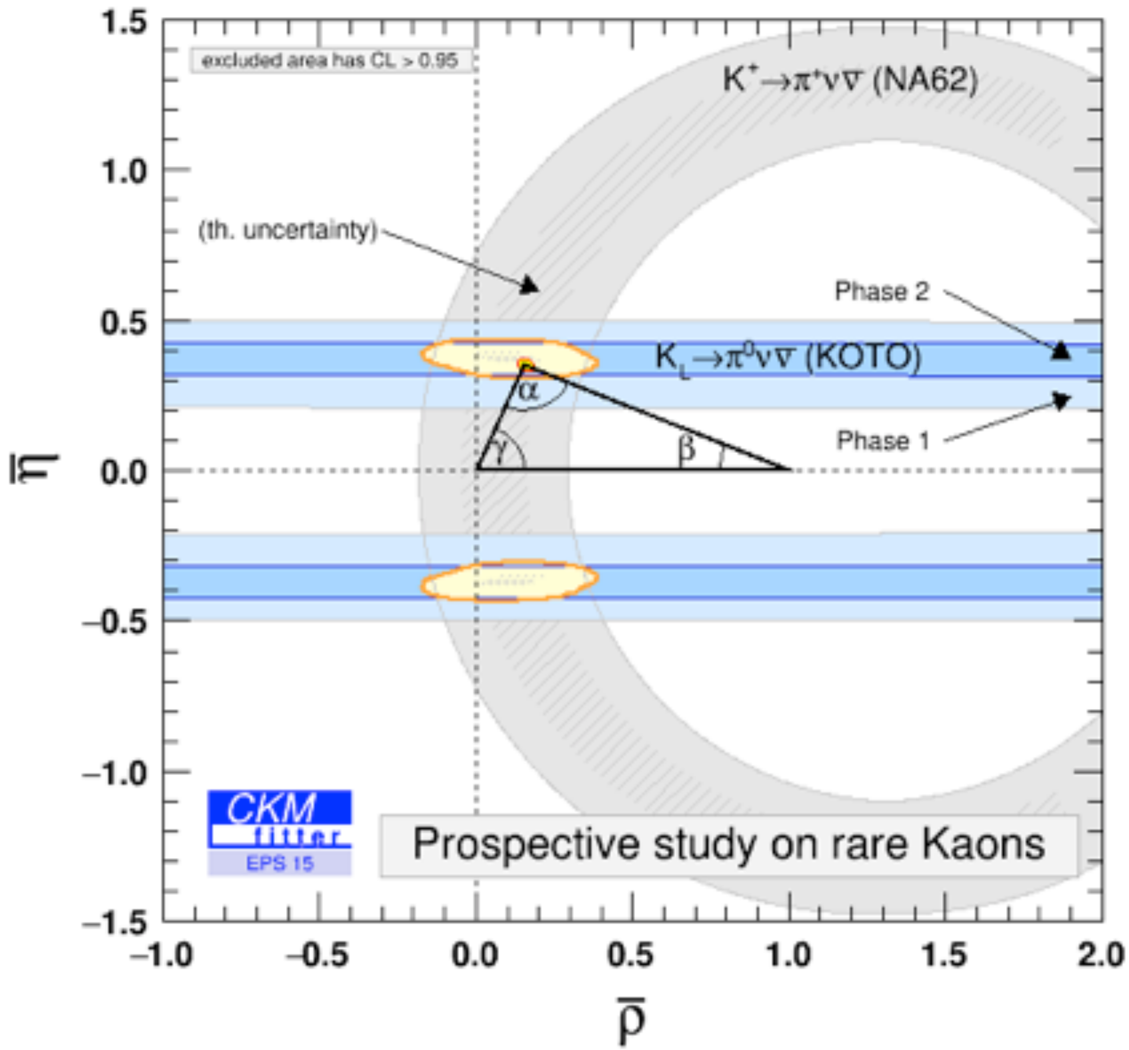
- Dark matter... See J. Brod

- FCC project for the rest of the lecture.

Kaons and CKM

- NA62 (CERN)

- KOTO (JPARC)



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

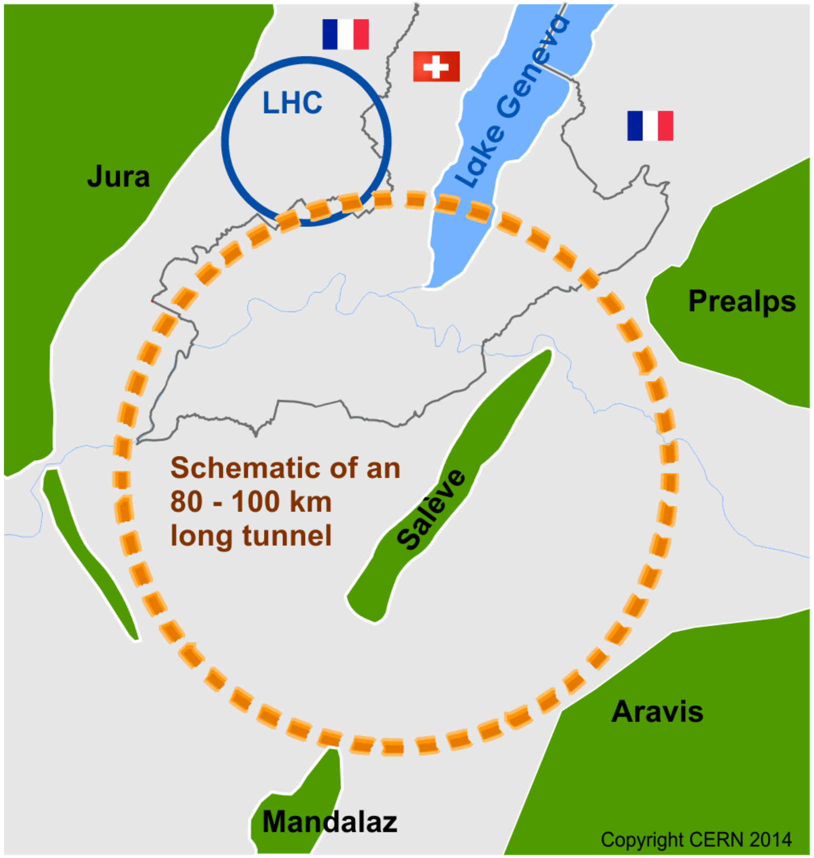
Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014 3

- 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:

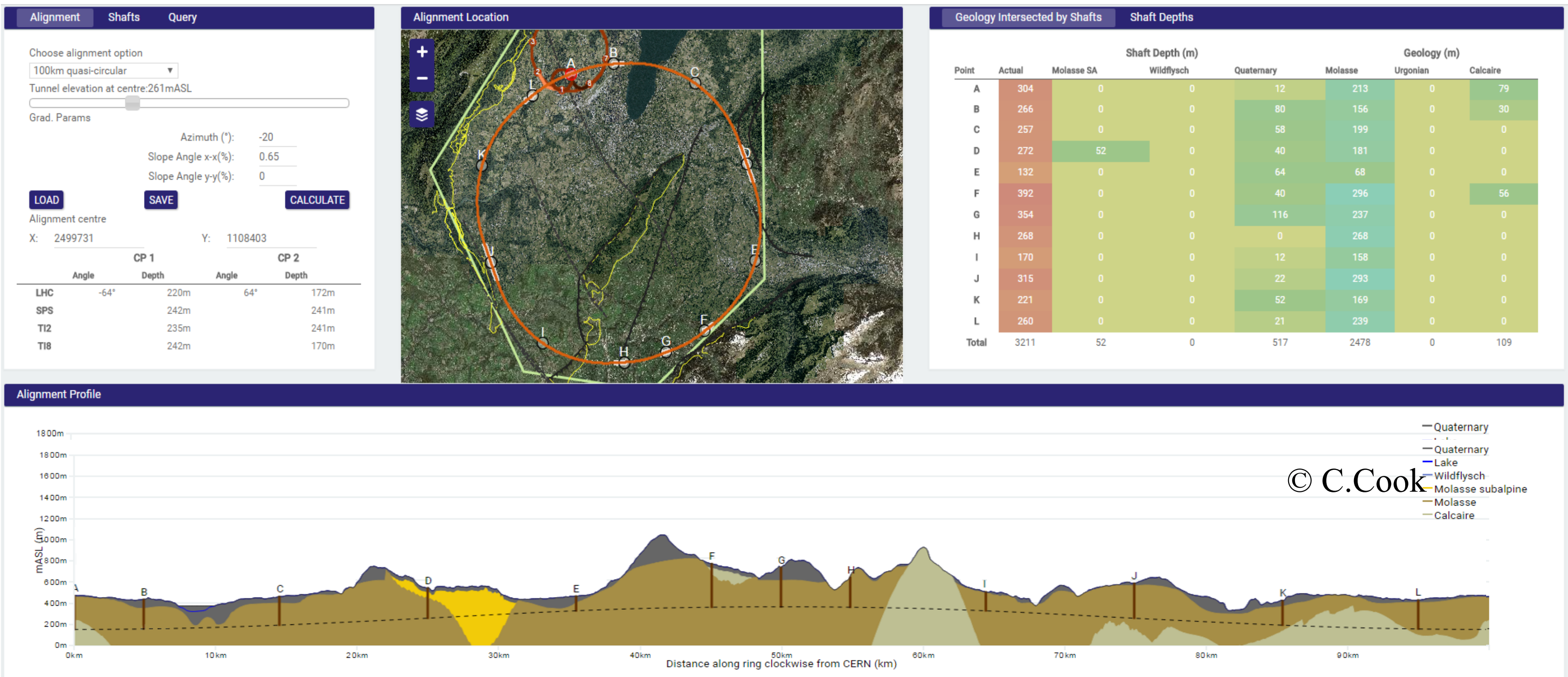
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



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

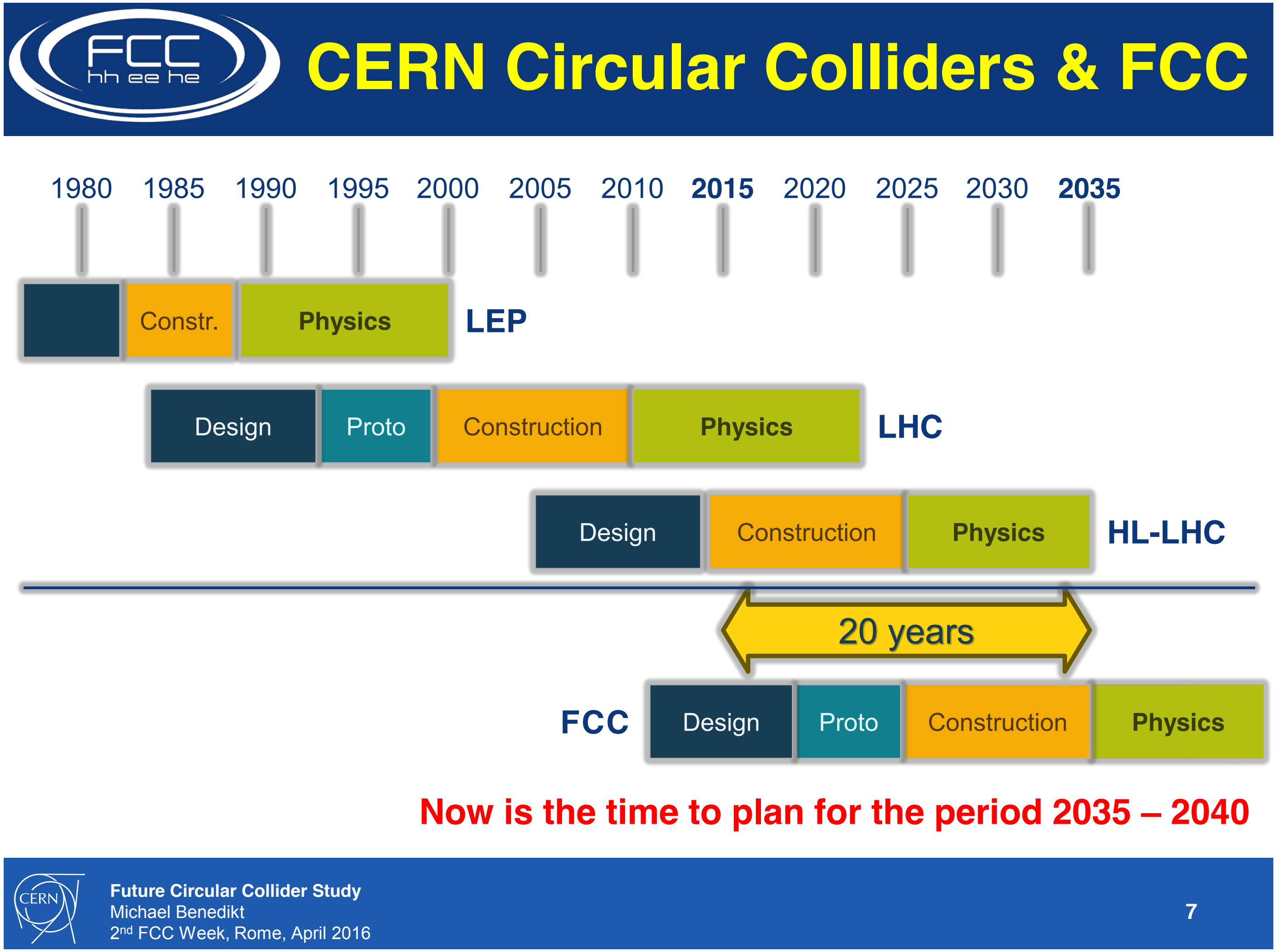
1. Introduction to FCC - Civil engineering.

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



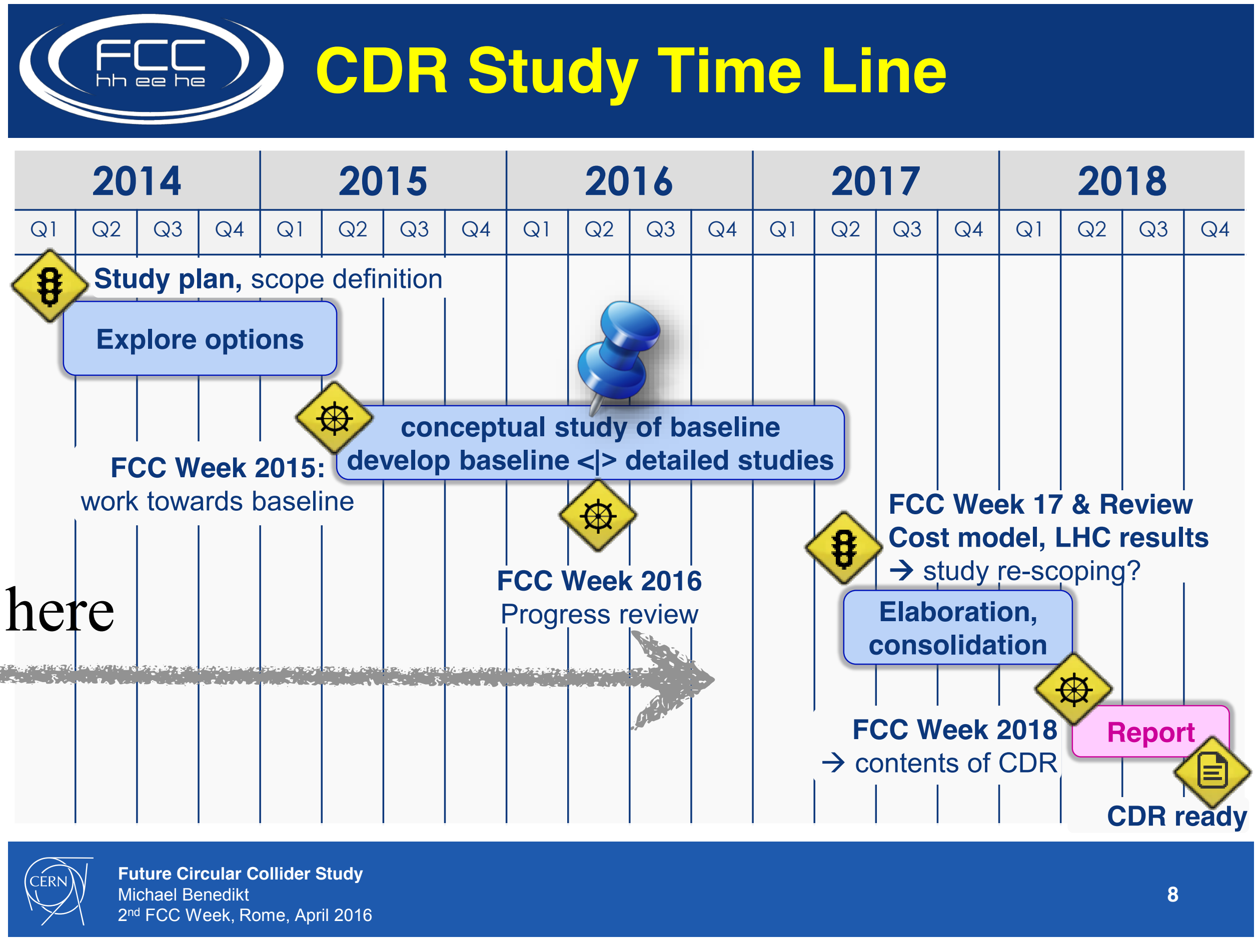
- Challenges:
  - 7.8 km tunnelling through Jura *limestone*.
  - Up to 300 - 400 m deep shafts + caverns in *molasse*.

1. Introduction to FCC - Timeline



1. Introduction to FCC: the design study timeline

- Applies to all machine and experiment designs:



We are here

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.

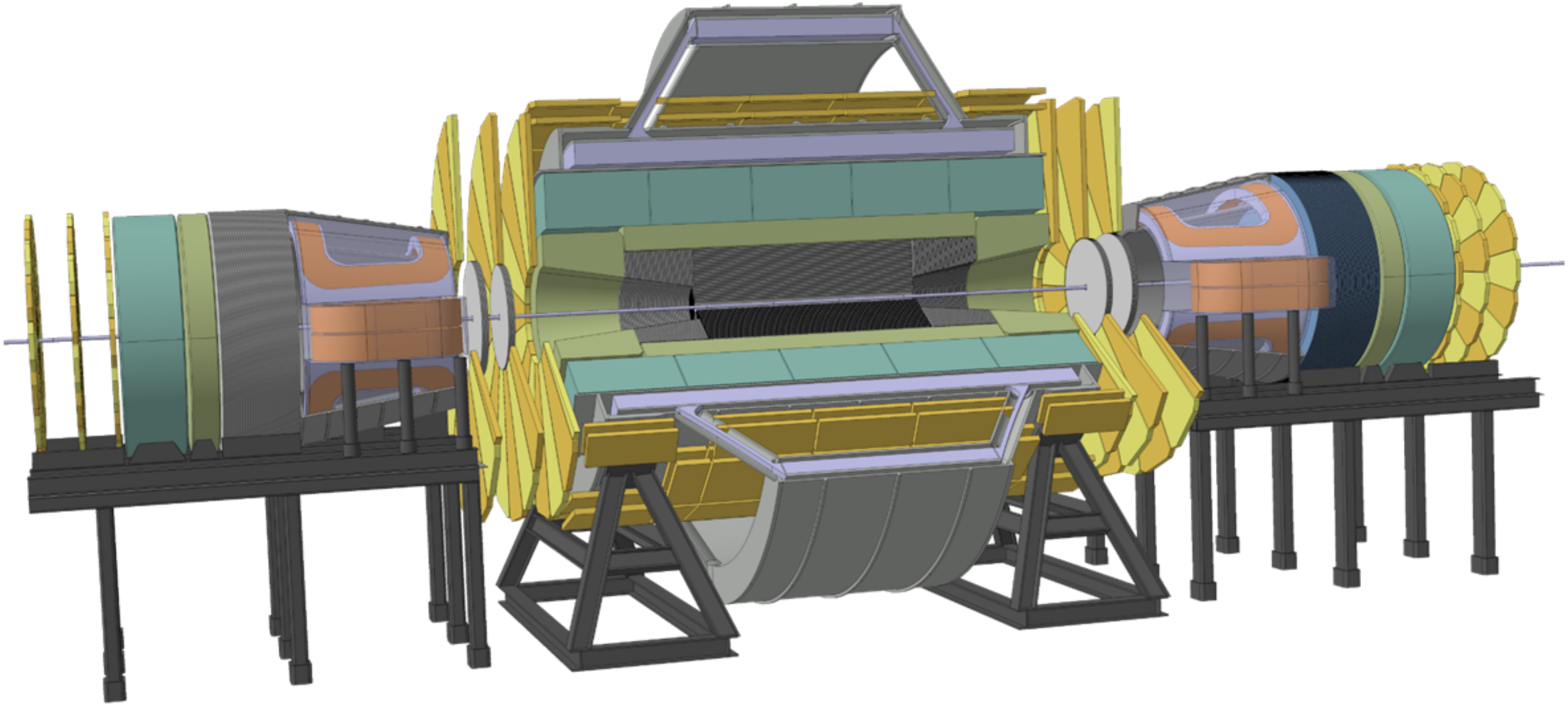
- Large coil and tracker: precise momentum resolution up to multiTeV charged particles.

- 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



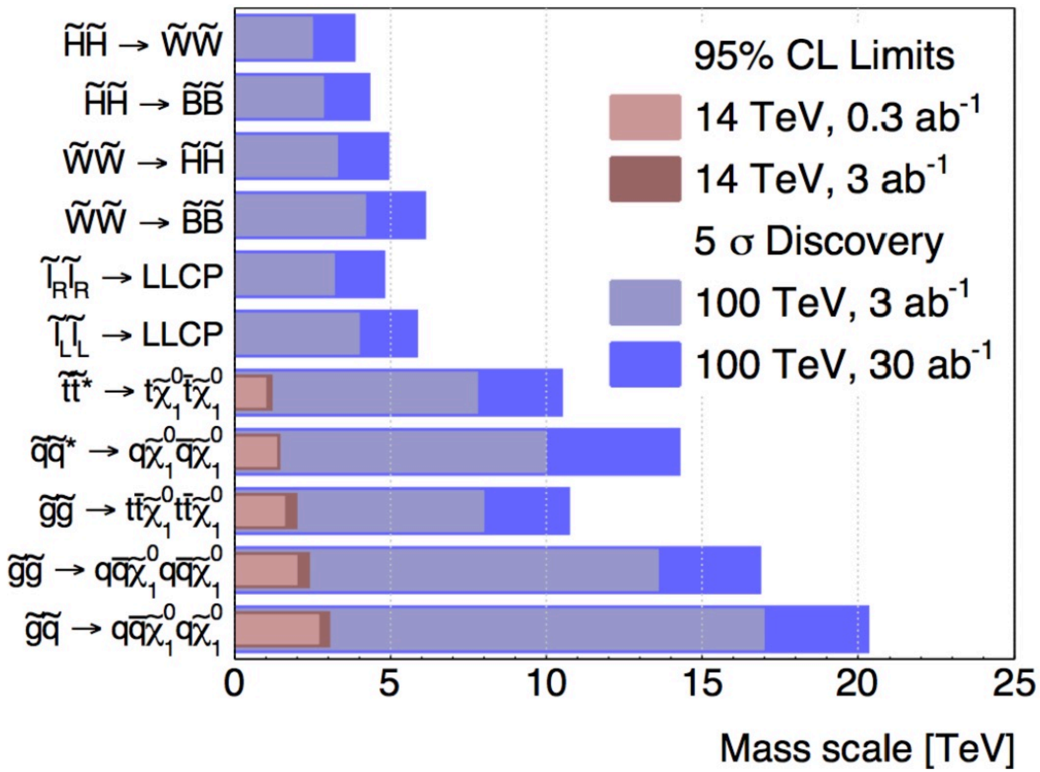
- Twin Solenoid 6T, 12m, Dipoles 10Tm, for engineering challenge.
- The coil radius makes the cost of the detector. Likely to go down at the end of the Design Study.

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

© M. Mc Cullough

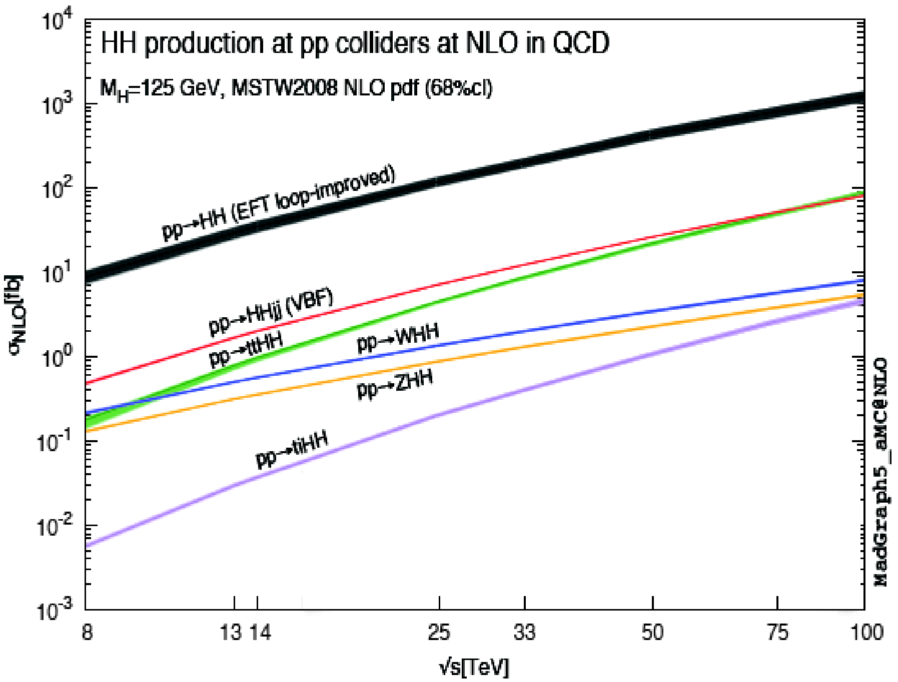


FCC-*hh:* physics reach by selected examples.

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]



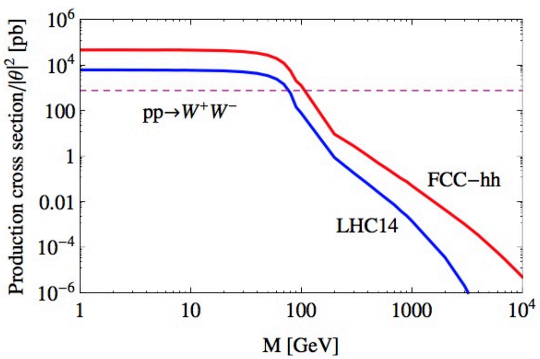
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in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

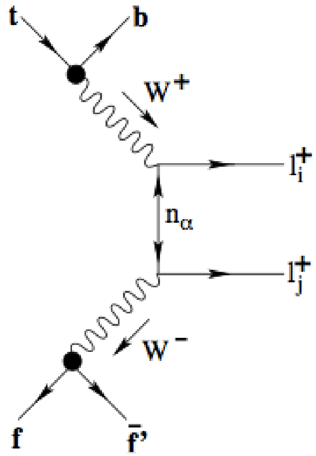
- Few percents precision for HHH.
- One of the ultimate null test of the SM hypothesis.
- No competition.

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

- $O(10^{10})$ H decays: can address FCNC probes $H \to e\mu$
- $O(10^{12})$ top quarks: can address FCNC probes $t \to cZ, cH$ ...
- 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*

© O. Fischer





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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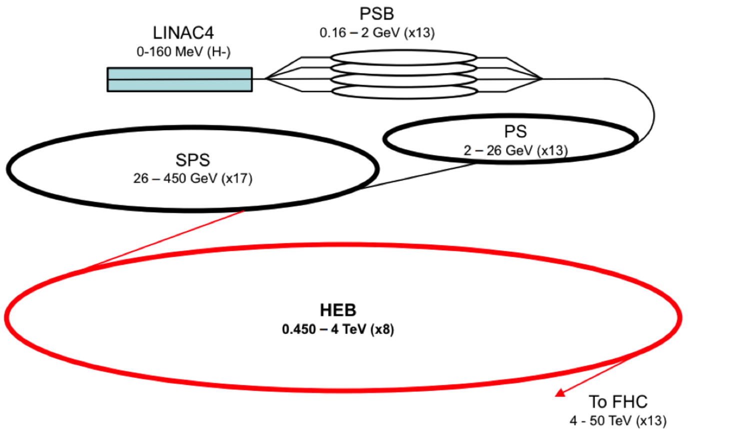


Fig. 1: Schematic view of the CERN accelerators system viewed as injectors of the future FCC-hh collider (FHC).

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).

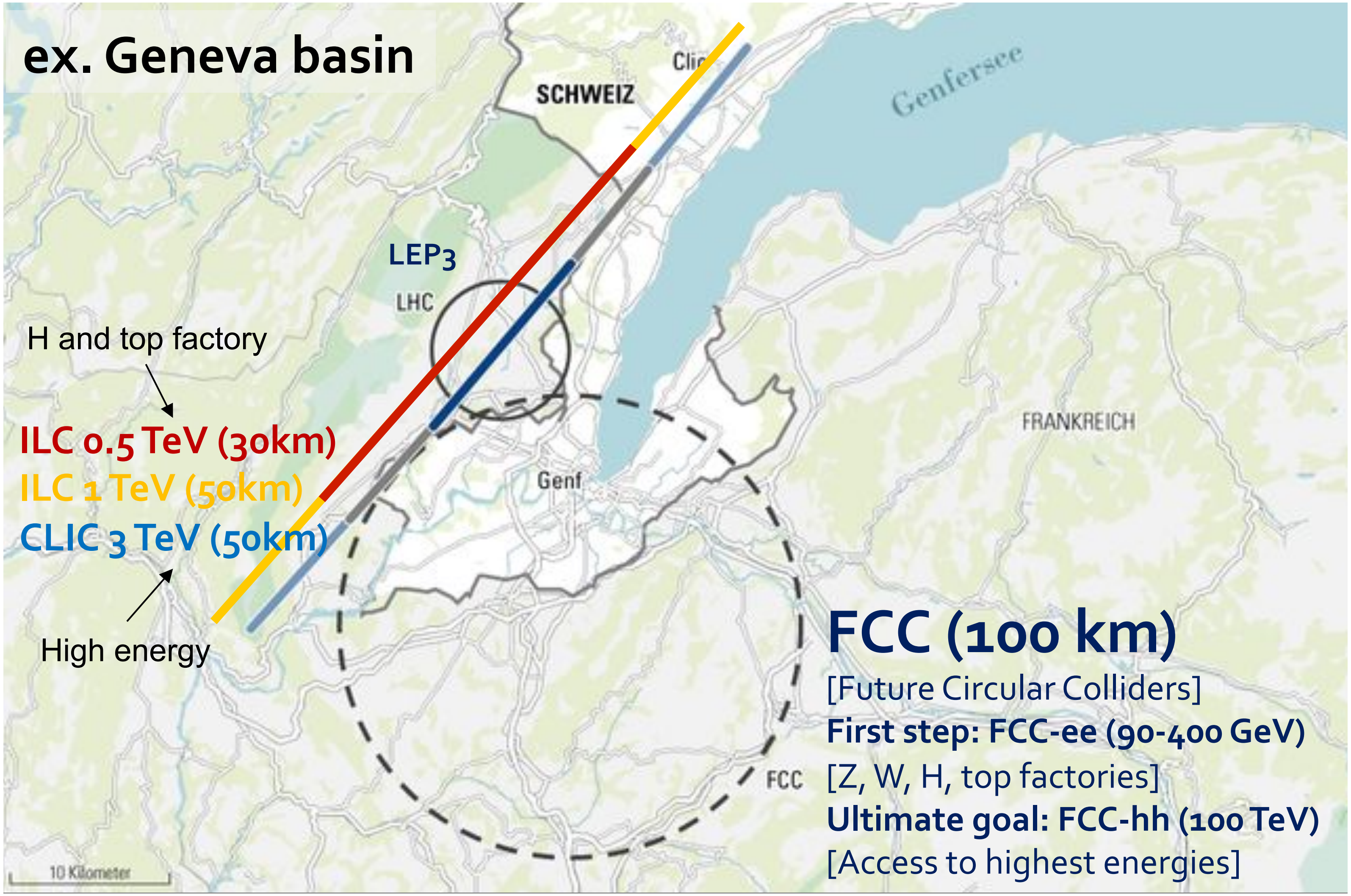
The timescale for FCC-*hh* is > 2045. The HL-LHC won't likely answer most of the outstanding questions of the field.

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?

FCC-ee

© P. Janot

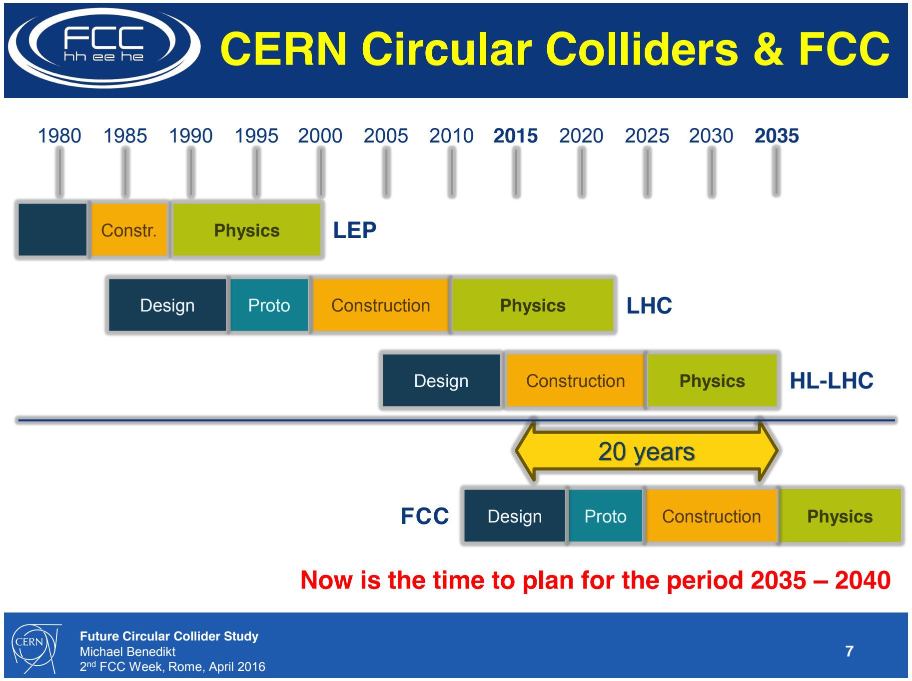


FCC-*ee*

- 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

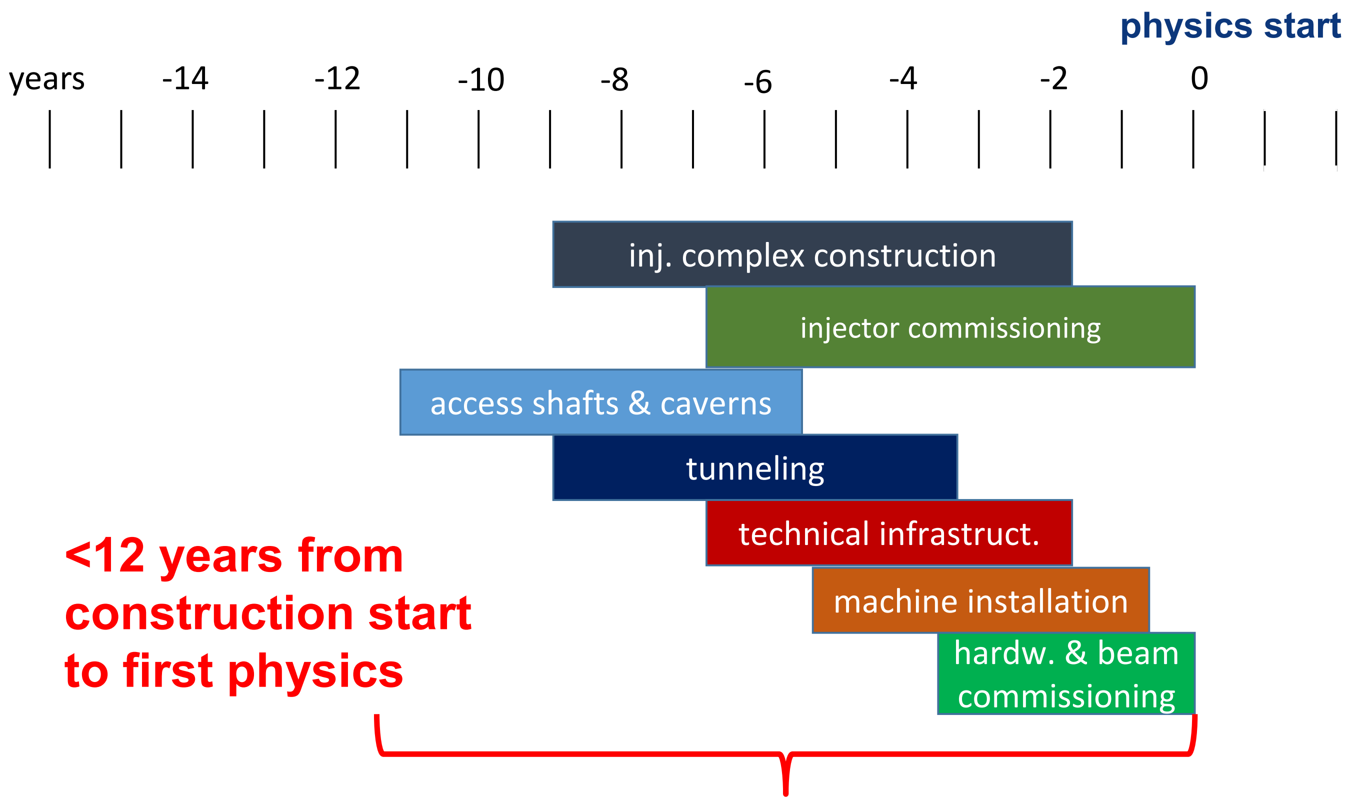
- The re-commissioning of the LHC as injector of the FCC-*hh* shall take *O*(10 y).

- 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



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

24

Machine parameters, design and luminosities

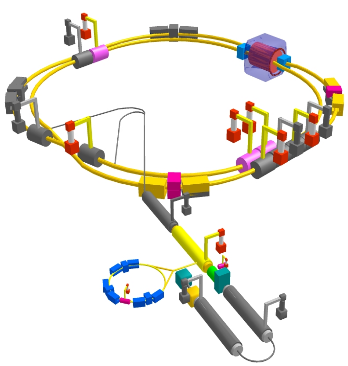
The FCC e^+e^- machine. Baseline design

- 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.

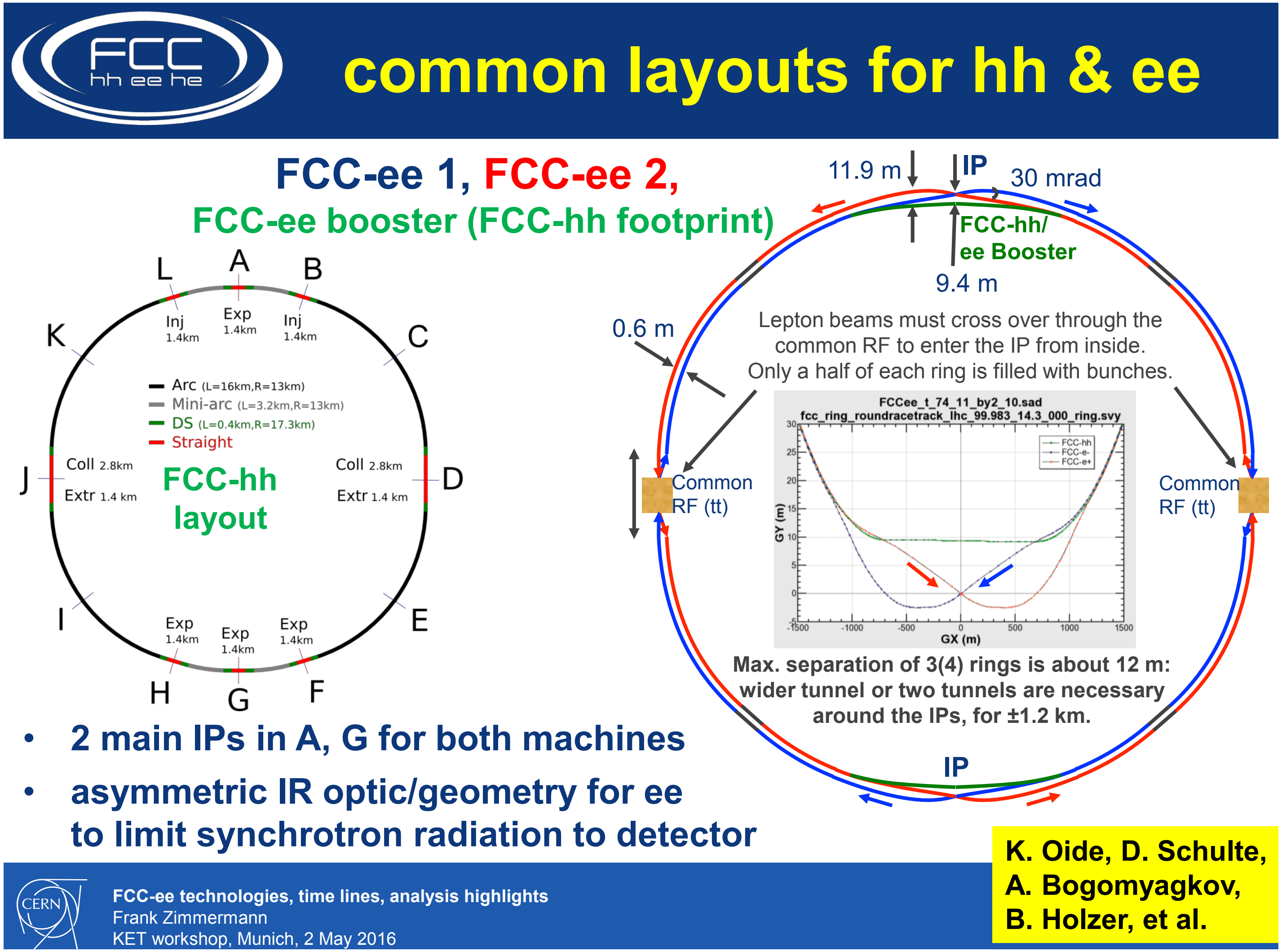
- To some extent, SuperKEKB shall already meet some of the challenges of FCC-*ee:*



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. Baseline design

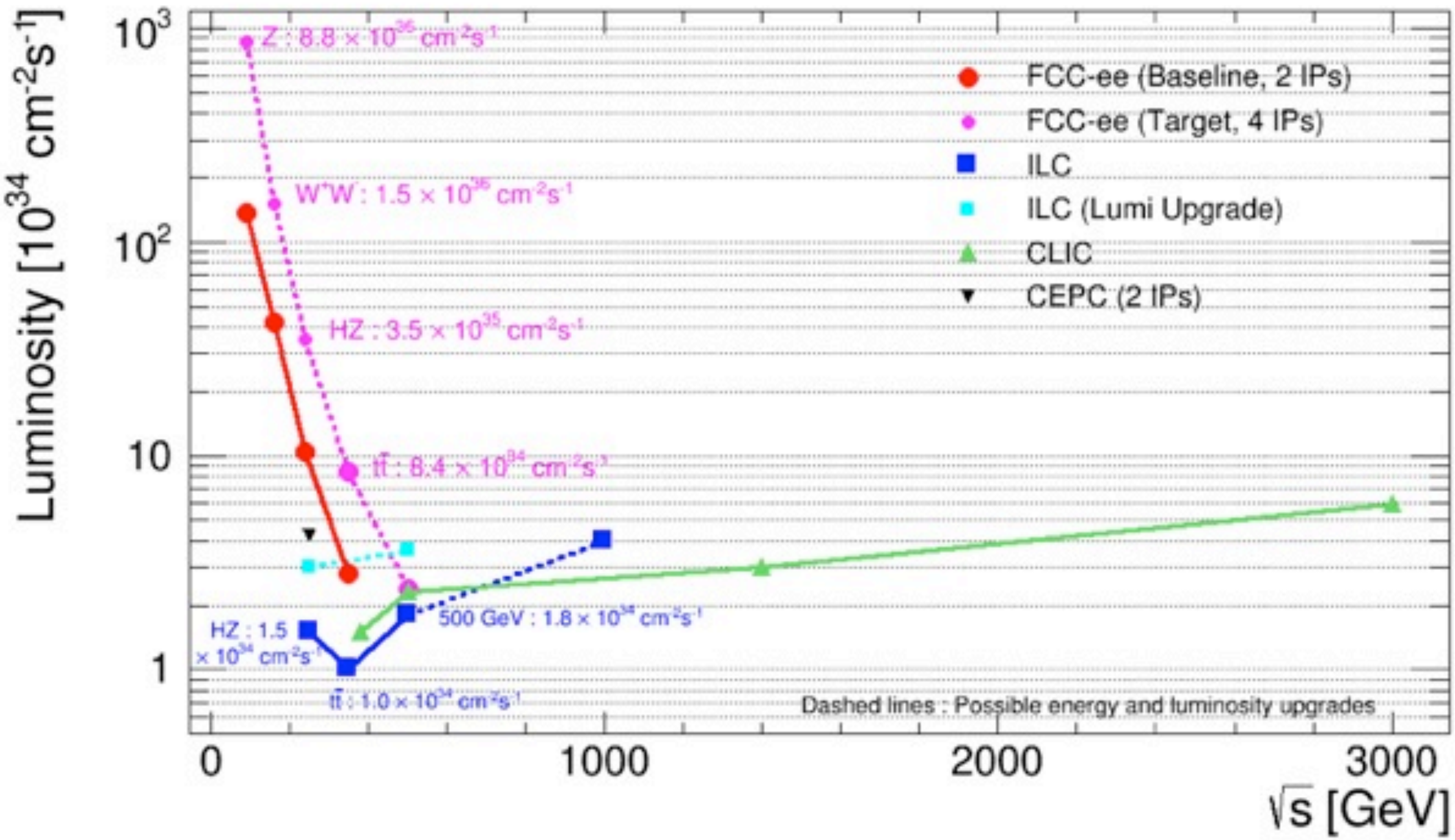


The FCC e^+e^- machine. Baseline parameters

© 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

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 γγ 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

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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	$g \to bb$
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 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.

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%			

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.

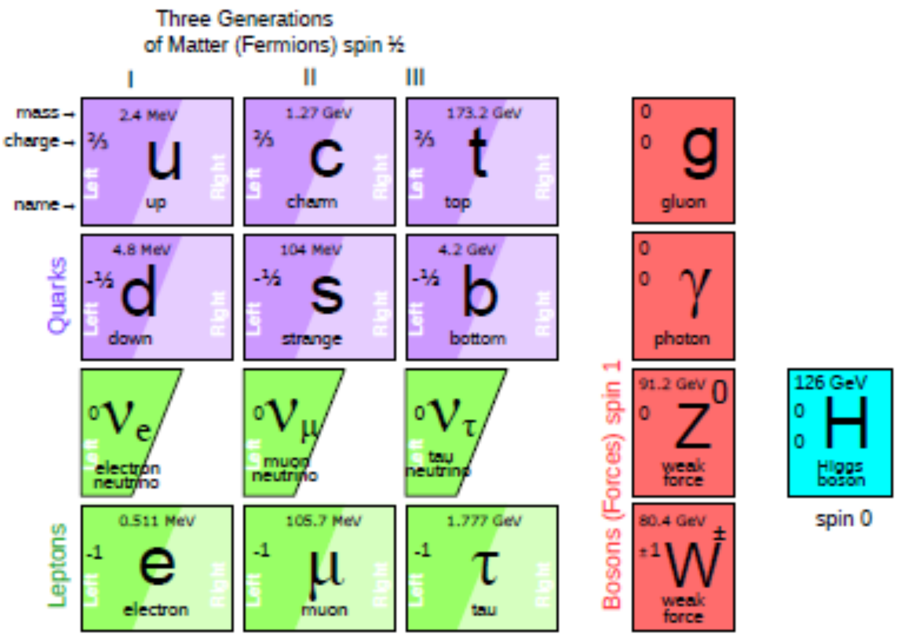
- Yukawa for charged fermions

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

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

FCC-*ee*: lepton flavours

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



FCC-*ee*: lepton flavours

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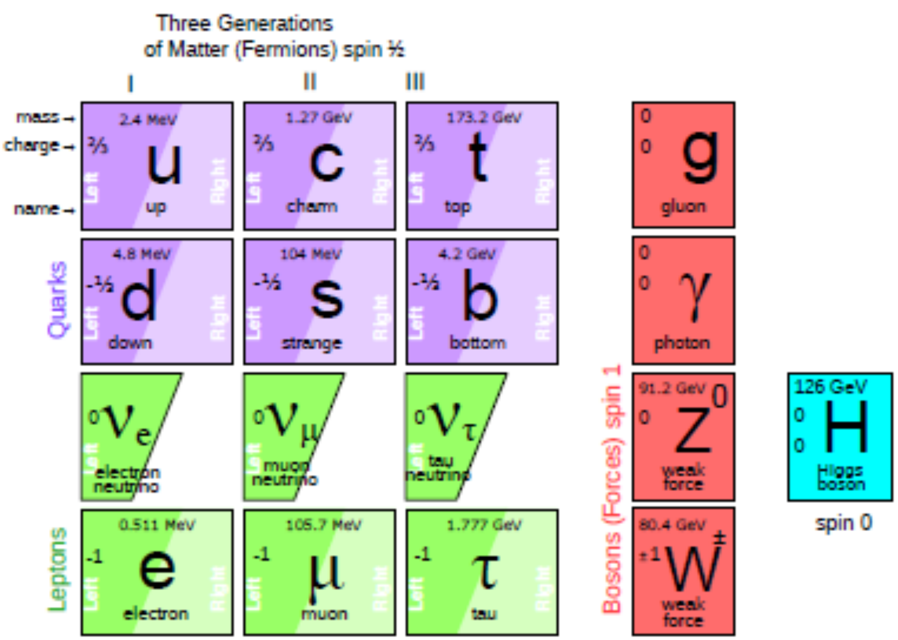
- Somehow, the only (provocative) question is how many?



FCC-*ee*: lepton flavours

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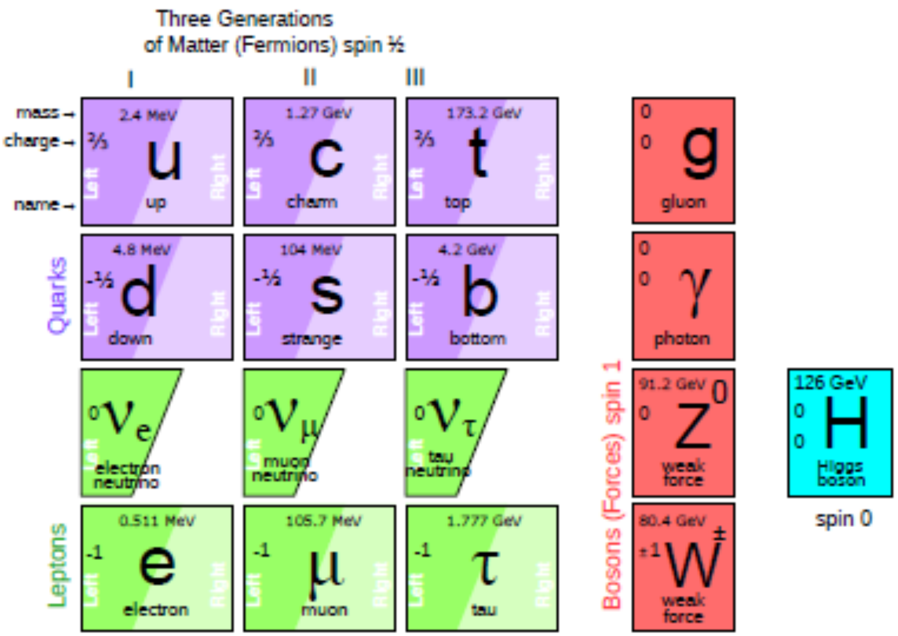
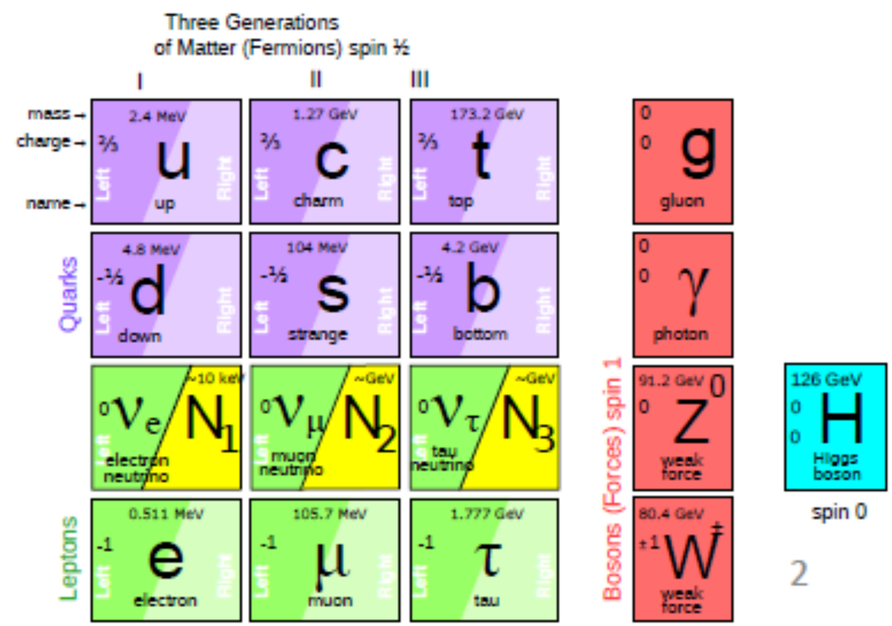




FCC-*ee*: lepton flavours

- 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.

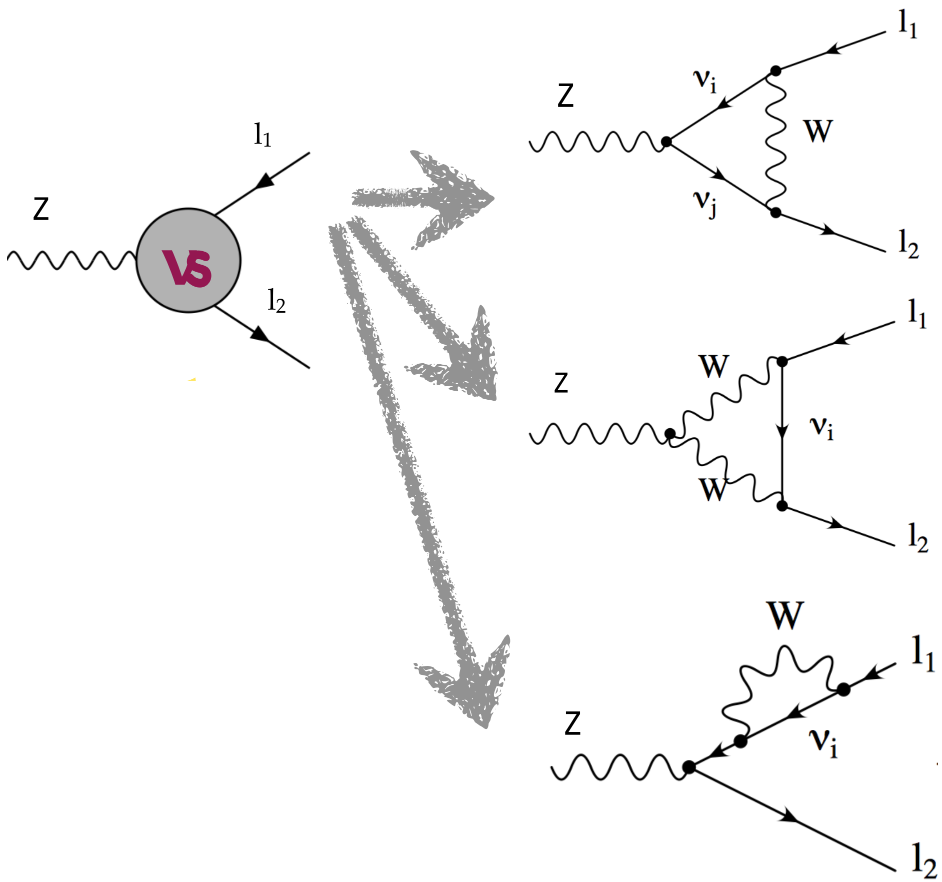
- Current limits at the level of ~10^{-6} (from LEP and recently Atlas, *e.g.* DELPHI, Z. Phys. C73 (1997) 243 ATLAS, CERN-PH-EP-2014-195 (2014))

- 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:

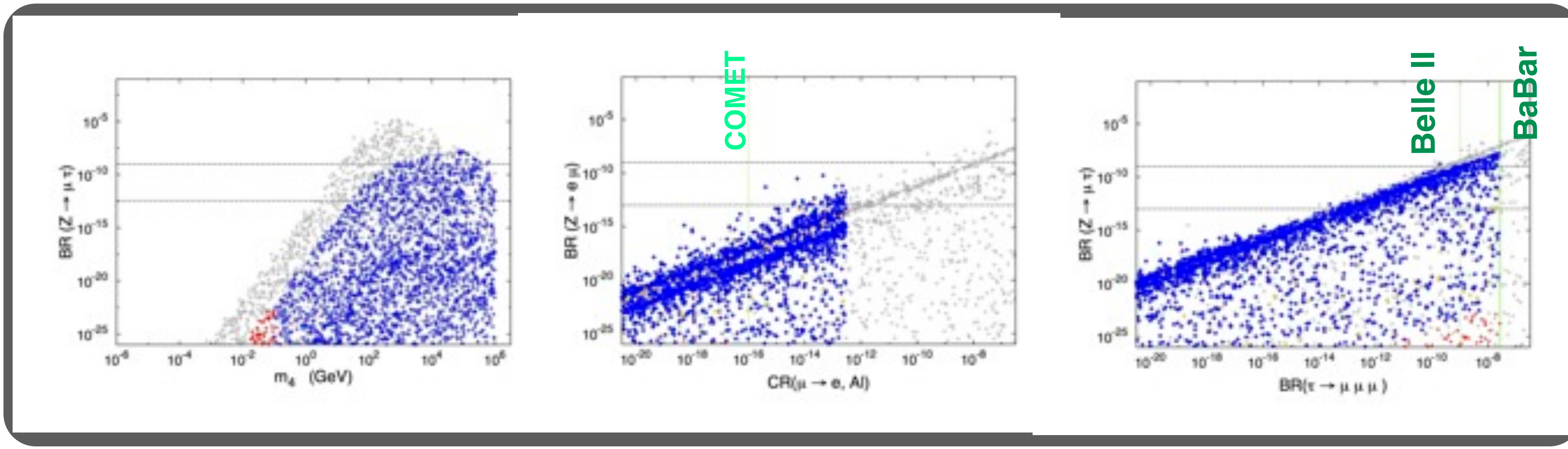
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double β decays
  - invisible Z-width

  ....

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.

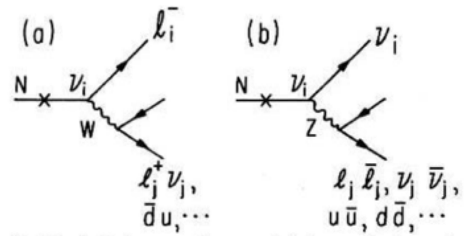
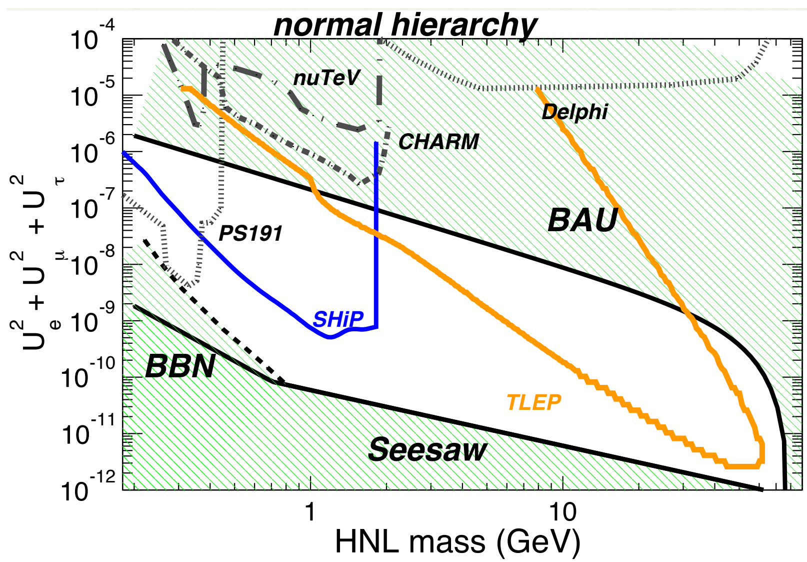


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

- 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.

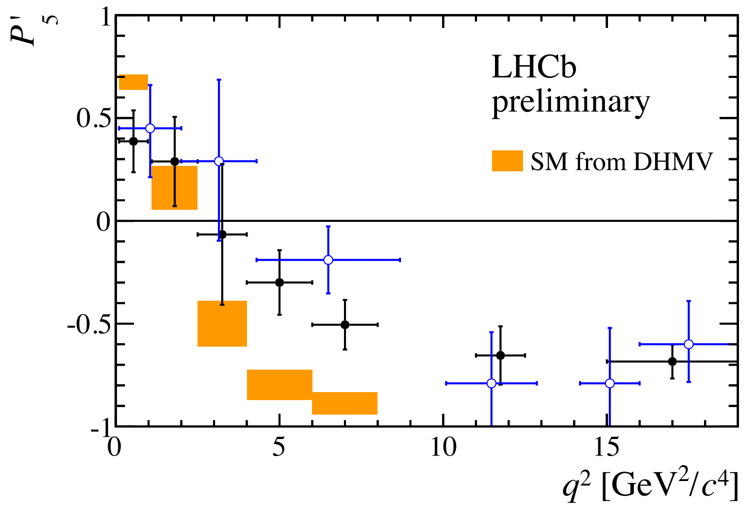


Figure 17: The observable P'_5 in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the 1 fb^{-1} analysis from Ref. [7].

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.

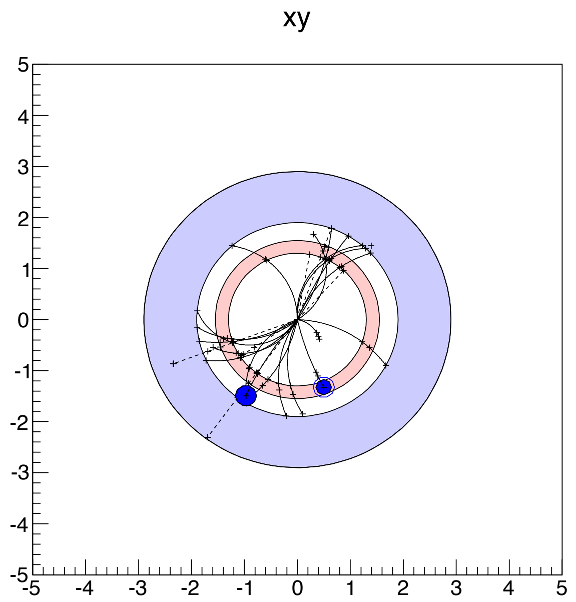
FCC-*ee*: The EWP decays as a first exploration.

- 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:

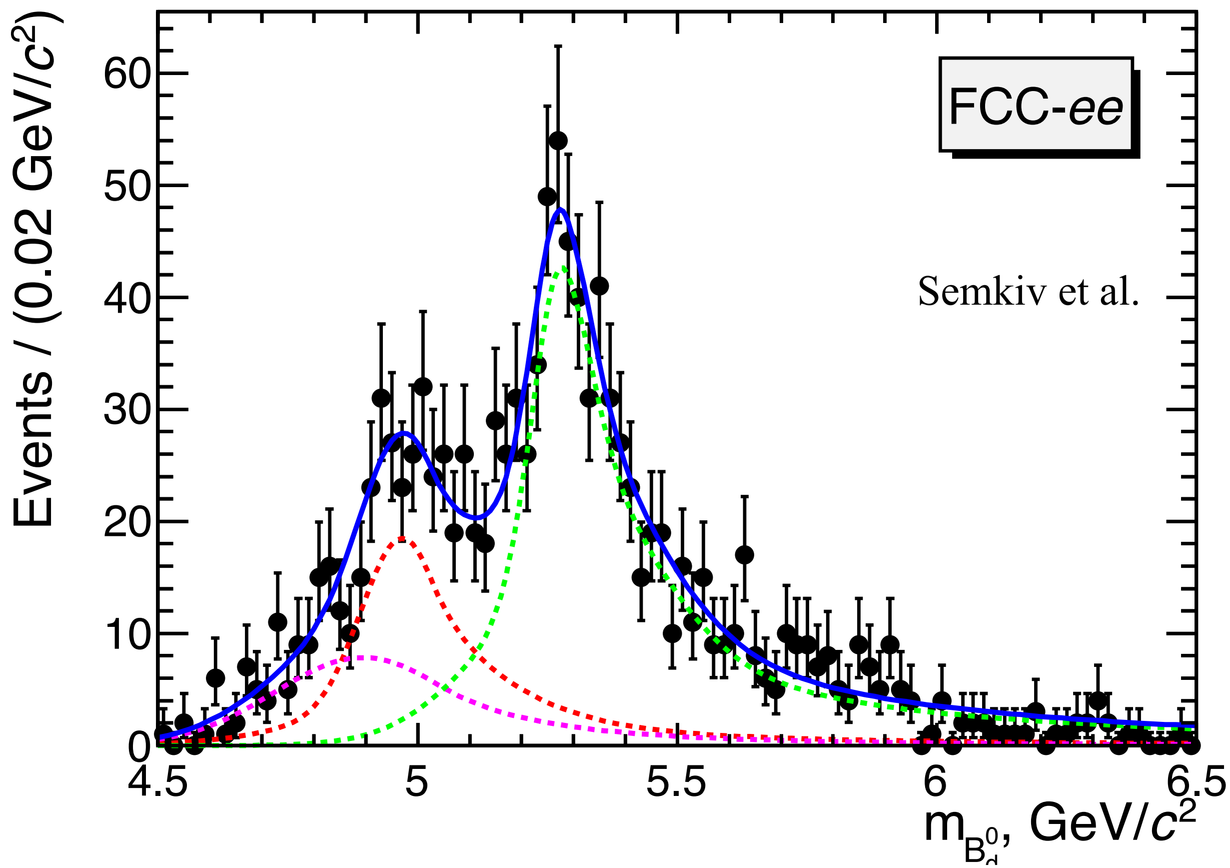
$\bar{B}^0 \to D_s^+ \bar{K}^{*0} \tau^- \bar{\nu}_\tau$

(pink)

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

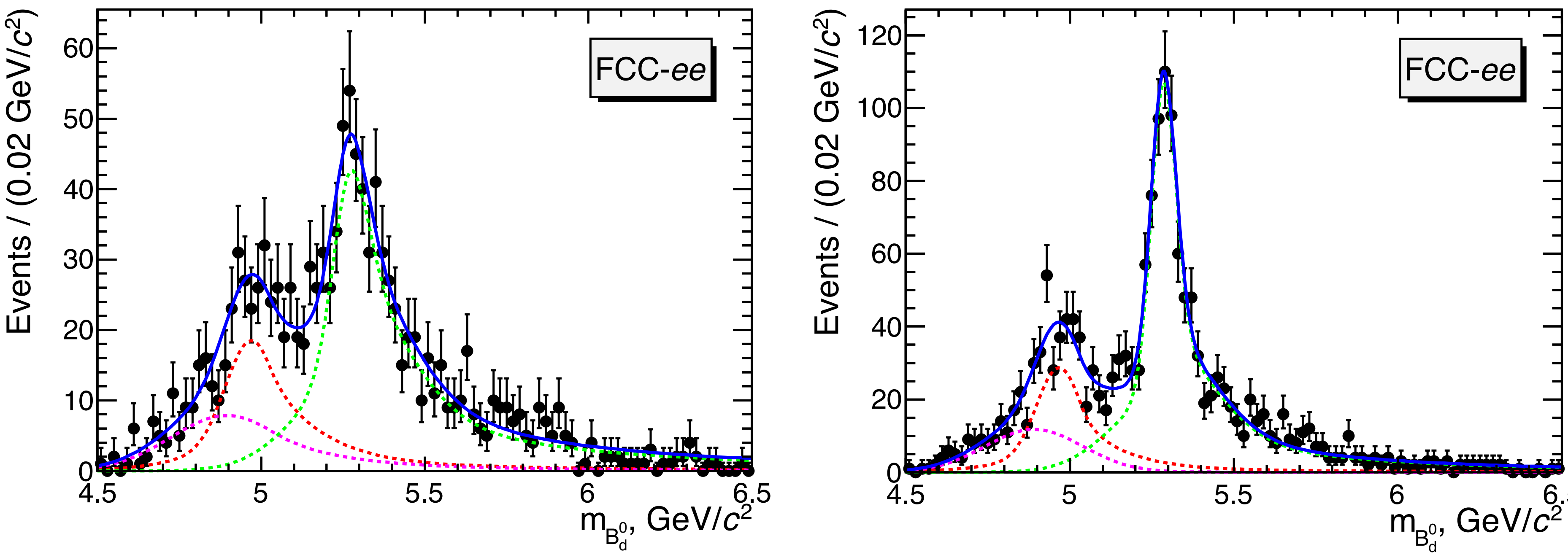
(red)

(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. $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$.



Conditions:

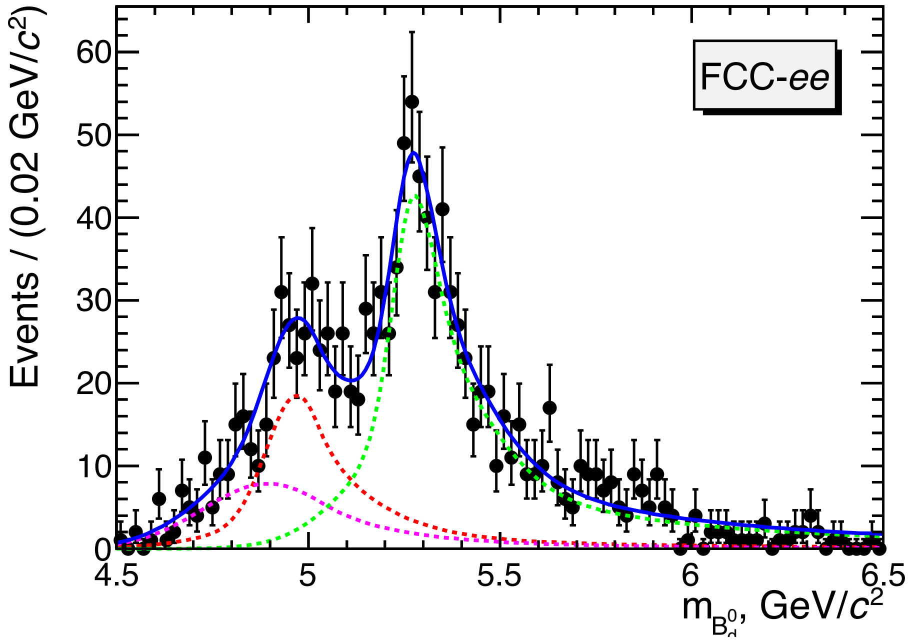
- Target luminosity
- Left: vertexing performance as ILD.
- Right: vertexing performance twice better than ILD. Pretty realistic: initial studies tell that the vertex detector can be as close as 2 cm from IP.

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

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.

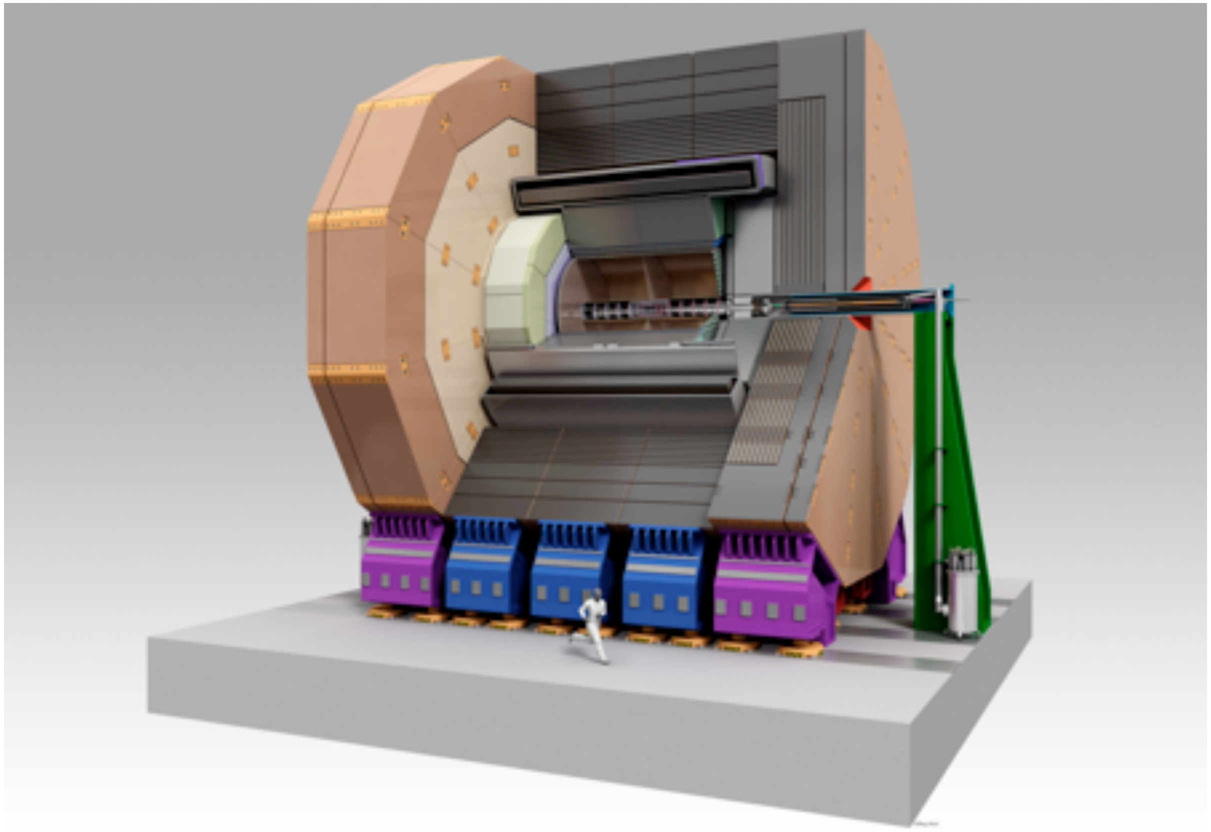


This mode can serve as a benchmark for partial reconstruction techniques and hence vertexing. The next step of the study is to attack the more challenging mode $B^0_s \to \tau^+\tau^-$.

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.