About the futures

What do we know and how do we know what we (think) we know?

- The Standard Model (SM) of particle Physics in a blink of an eye.
- The free parameters. An experimental status.
- The unescapable limitations of the SM and the remaining questions
- How to answer those questions ? A biased review of the foreseeable projects.

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About the futures - the free parameters of the SM.

The free parameters of the SM:

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

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

About the futures - the free parameters of the SM.

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 θ^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.

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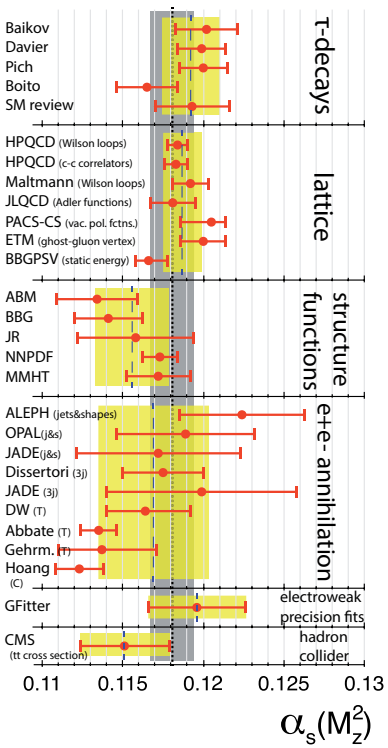
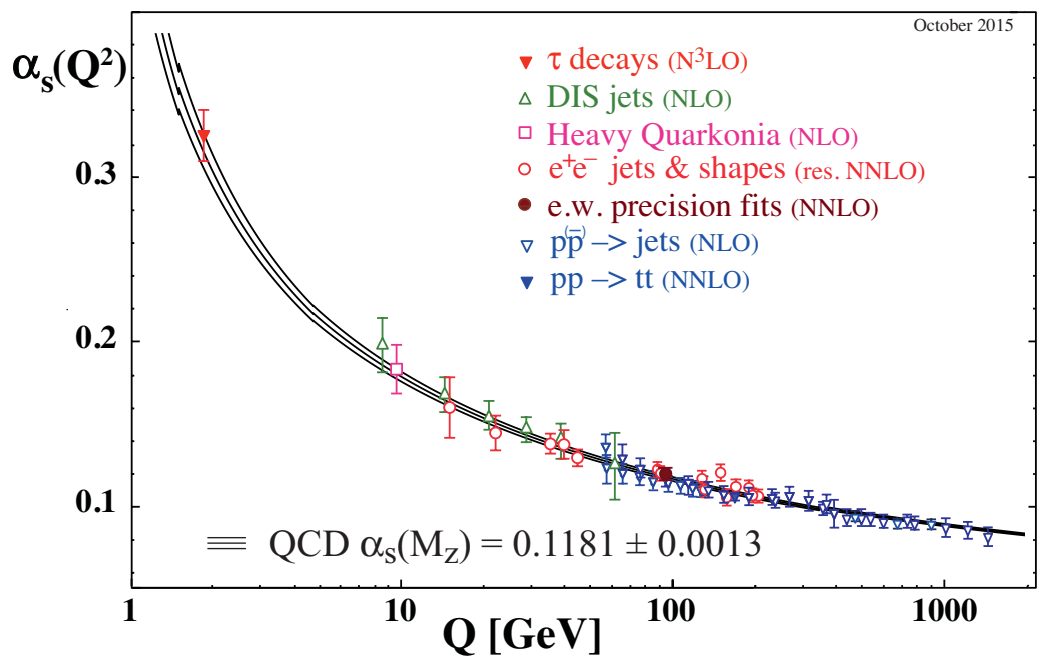
About the futures - strong interaction and QCD

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.

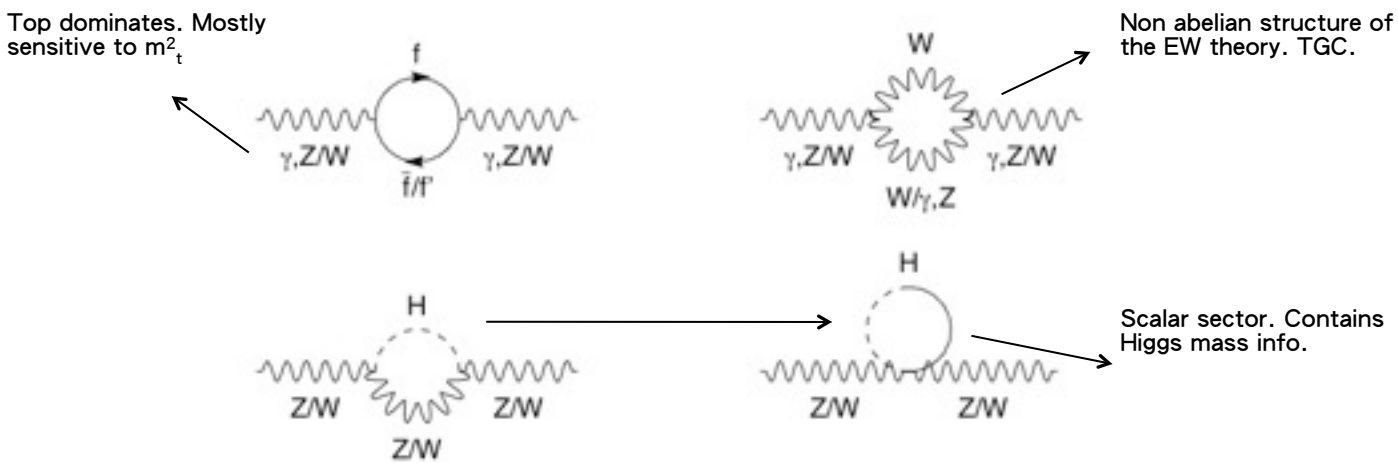




About the futures - The Z and W unraveling higher energies

Reorganisation:

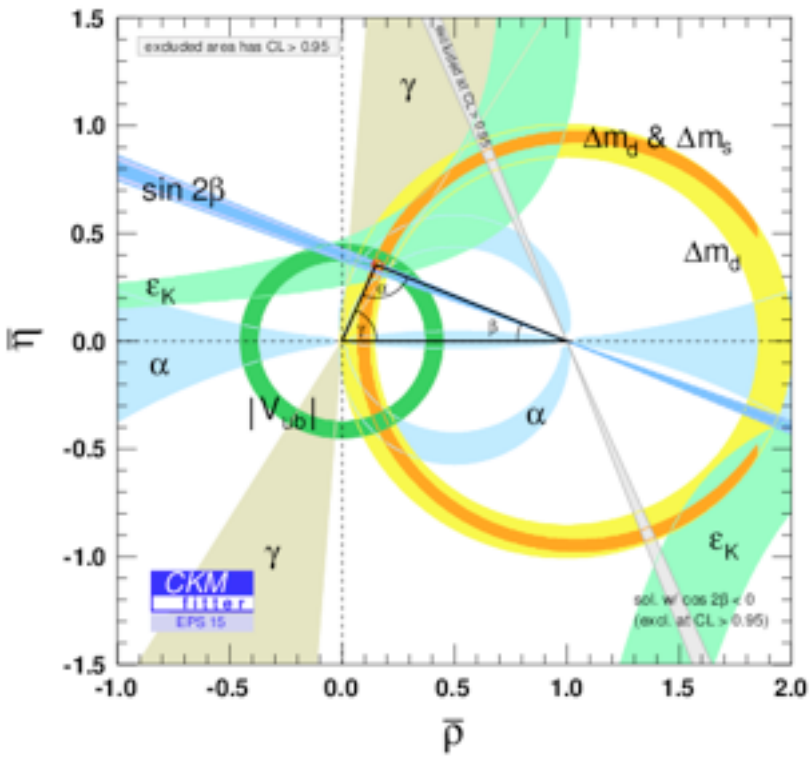
- The nine masses of the fermions: $\boldsymbol{m_f}$.
- They are for 8 of them decoupled from the rest of the SM parameters.
- Nothing much to do here as well till the moment a theory comes with a prediction.
- The top quark has a specific status because it enters dominantly in the radiative corrections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



About the futures - quarks and quark mass mixing

Reorganisation:

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



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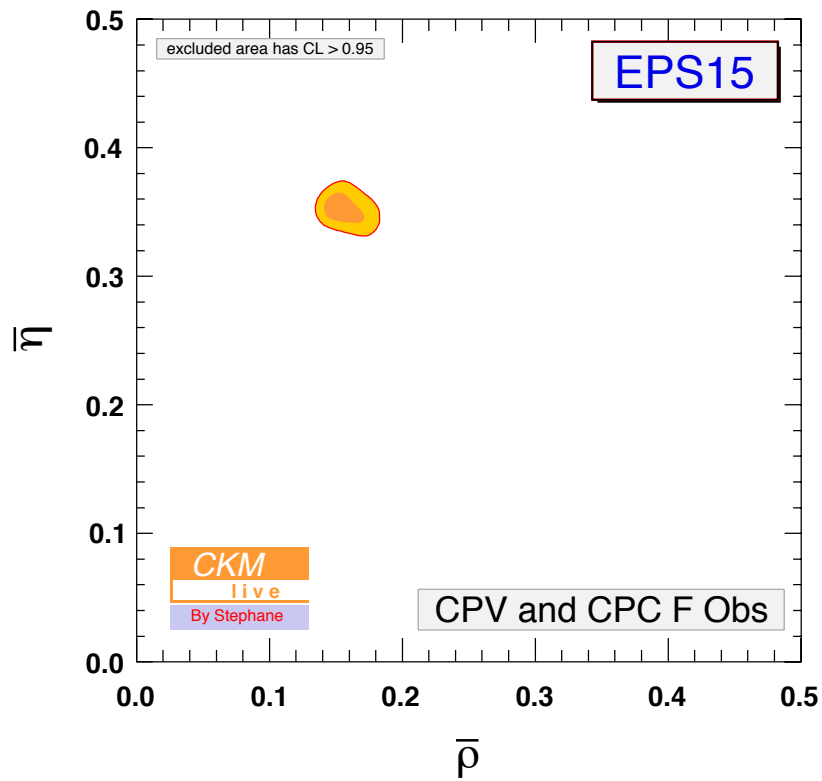
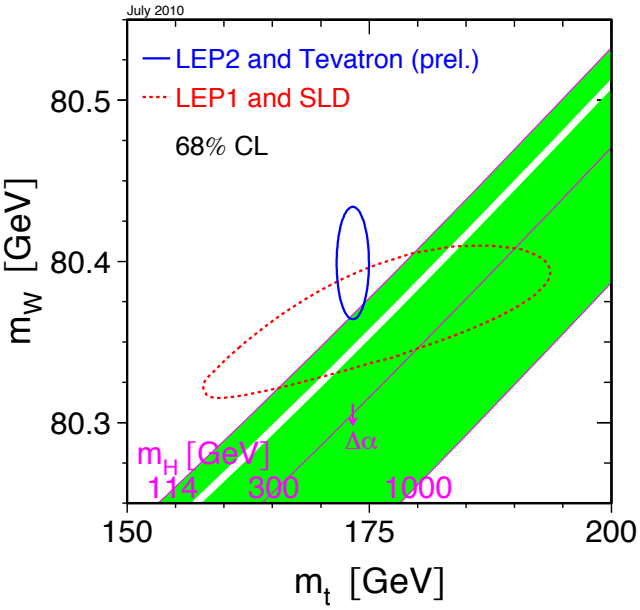
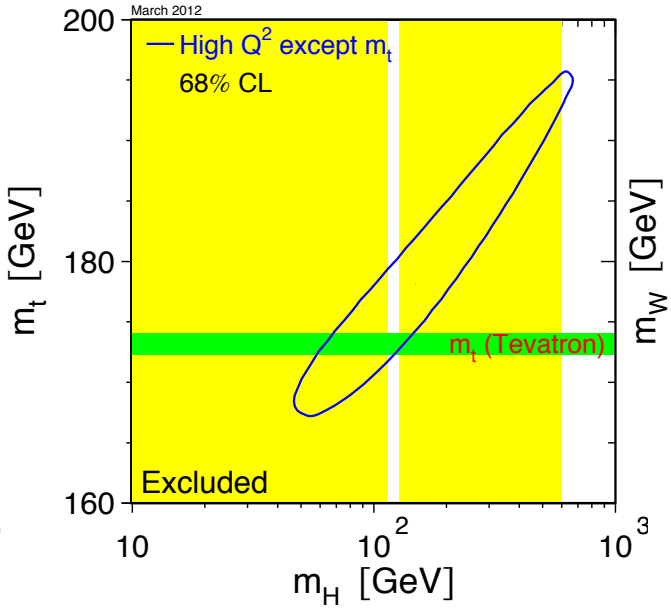


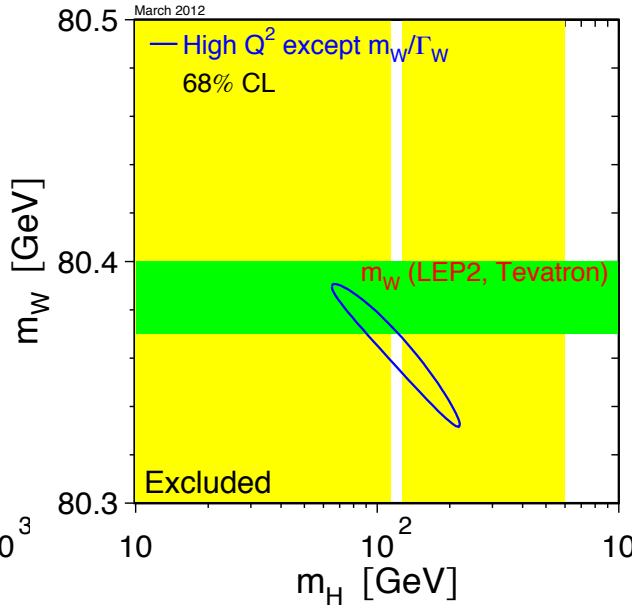
About the futures - global consistency checks

Reorganisation:

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



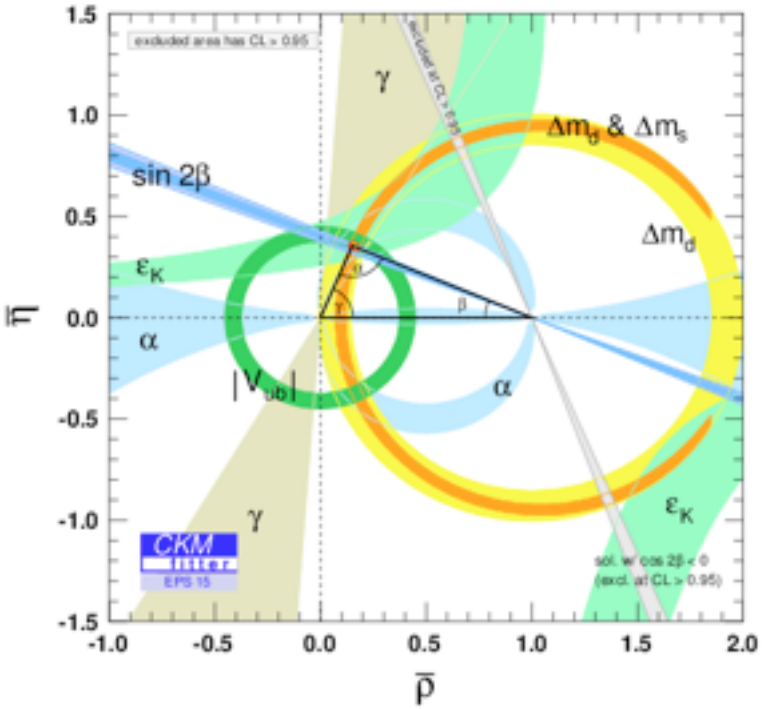




About the futures - the pillars

Recap:

- Two pillars: EWPT and Flavours.



About the futures - the pillars

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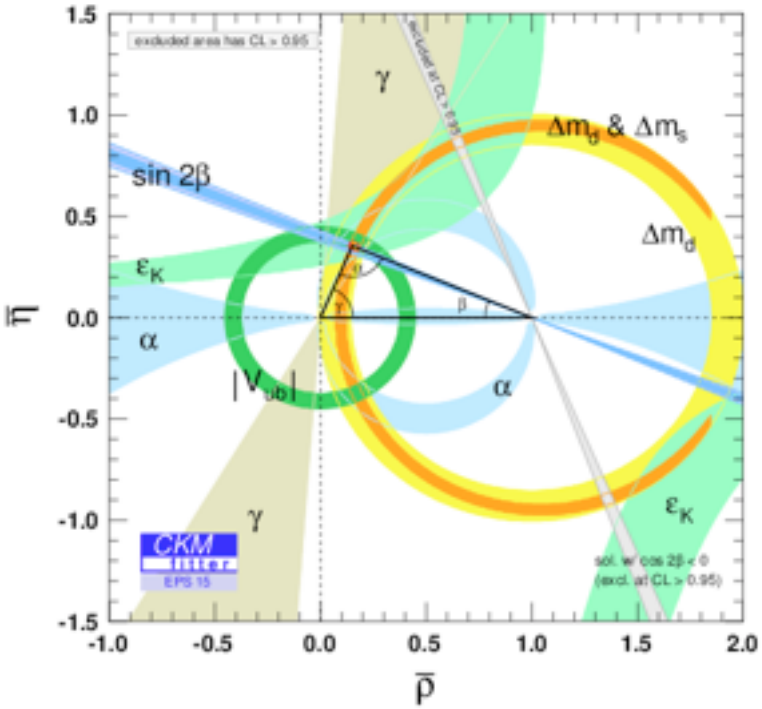

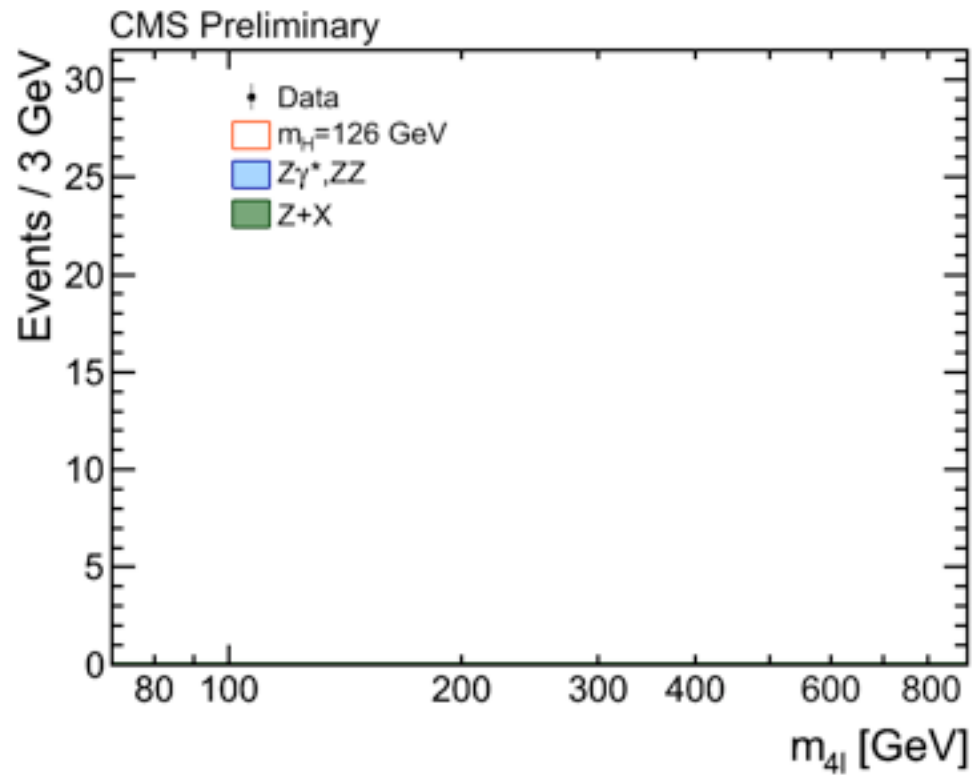

About the futures - the pillars

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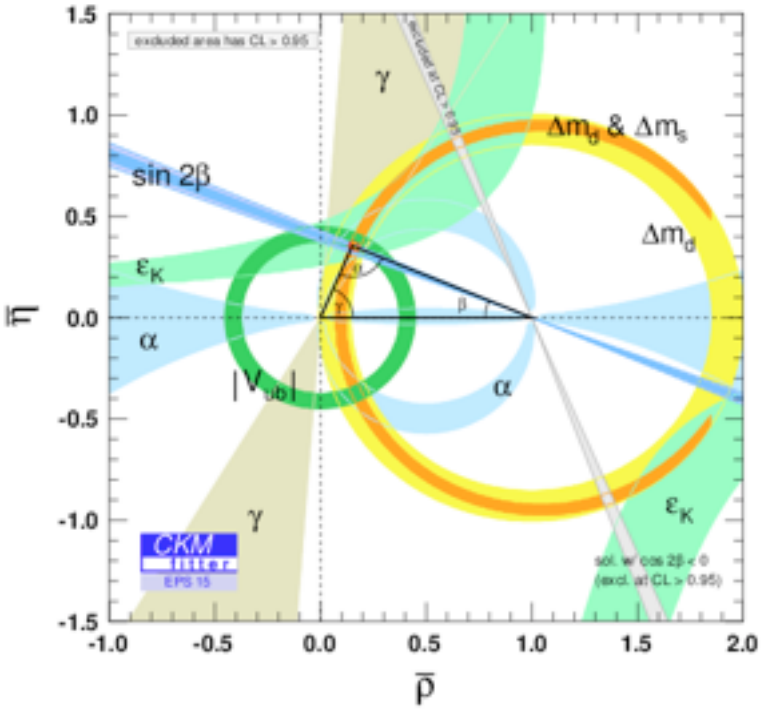

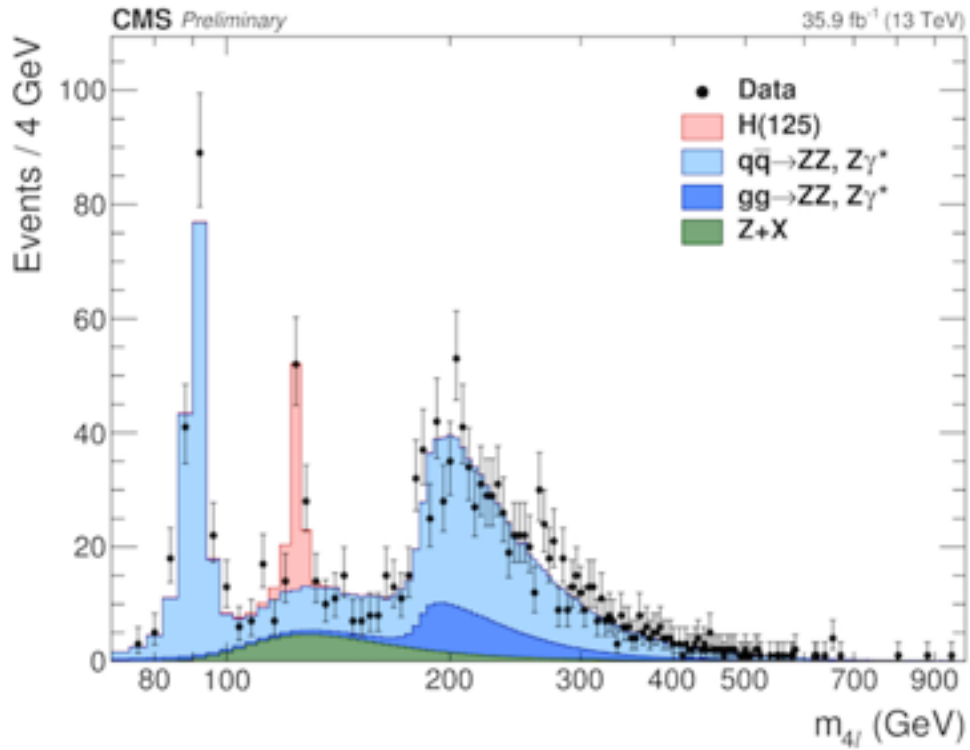

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About the futures - Lessons

- 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. Sébastien described some of them. I disregard these.
- 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.

About the futures

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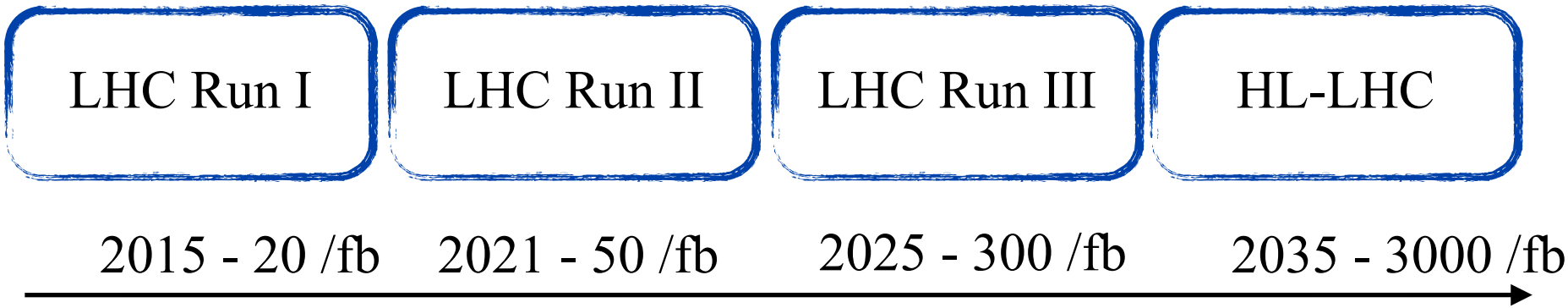
About the futures - known timelines



Legend and disclaimer:

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

About the futures - timelines and future projects

LHC(b)

LHC(b) upgrade(s)

Beyond LHCb

FCC injectors & FCC

2019 - 8 /fb

~2025 - 50 /fb

2035 - 500 /fb

5000 /fb

2025 - 50 /ab

2035 - 150 /ab

Belle II

Comet - Meg & friends.

KOTO - NA62 ...

FCC-*ee*

Legend and disclaimer:

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- timeline, lumi, omissions are mine.

About the futures : 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.

About the futures - (my) 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.

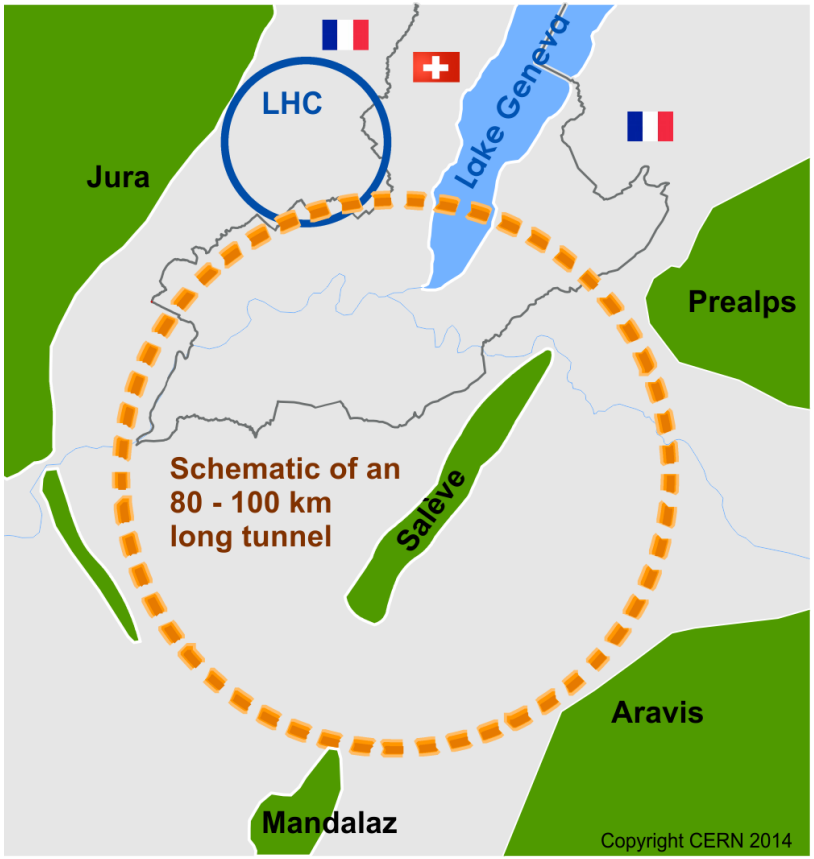
About the futures

My favourite project

About the futures

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

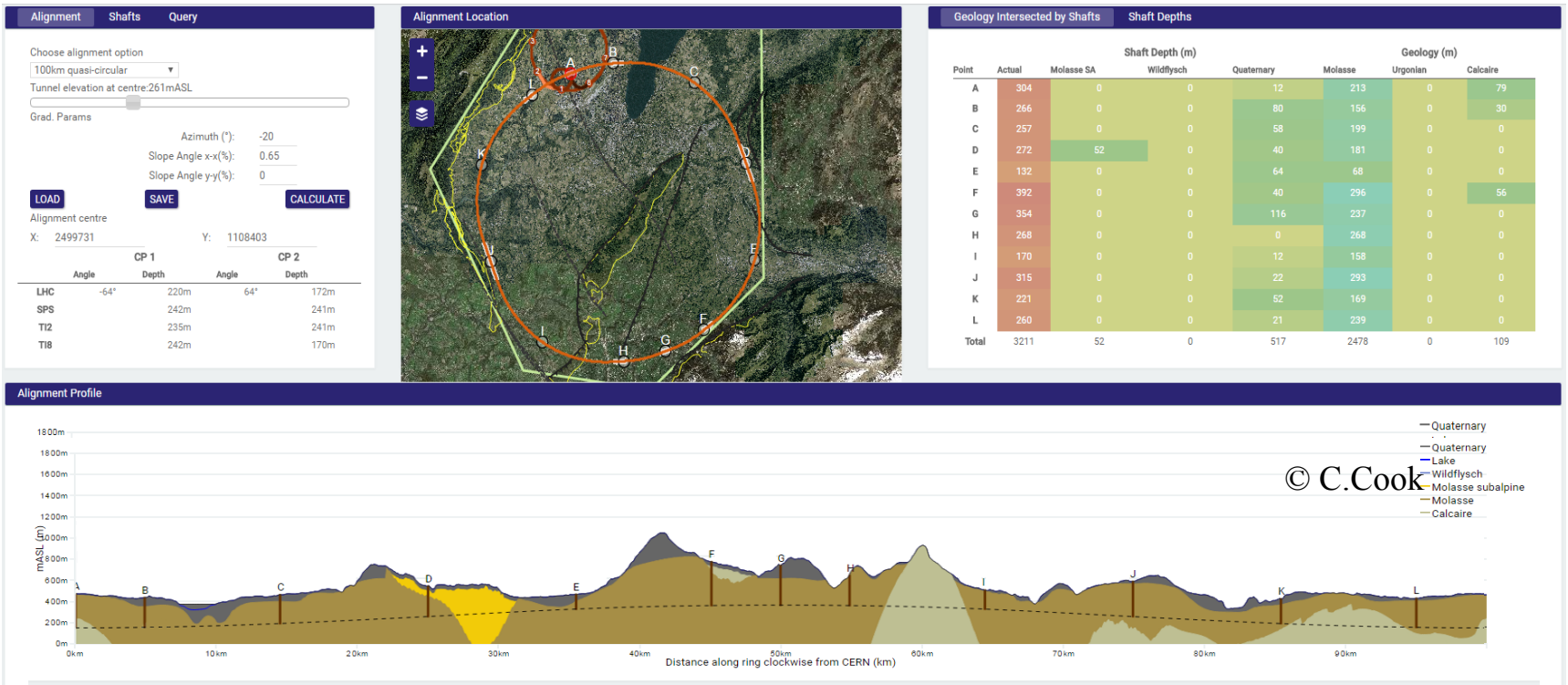
- 100 TeV *pp*-collider (FCC-*hh*) as long term goal, defining infrastructure requirements.
- e^+e^- collider (FCC-*ee*) as potential first step.
- *p-e* (FCC-*he*) as an option.
- 80-100 km infrastructure in Geneva area.



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

About the futures

- 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*.

About the futures