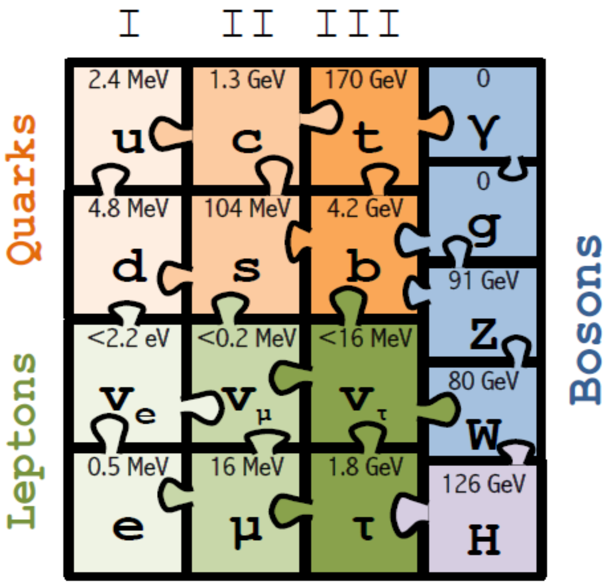
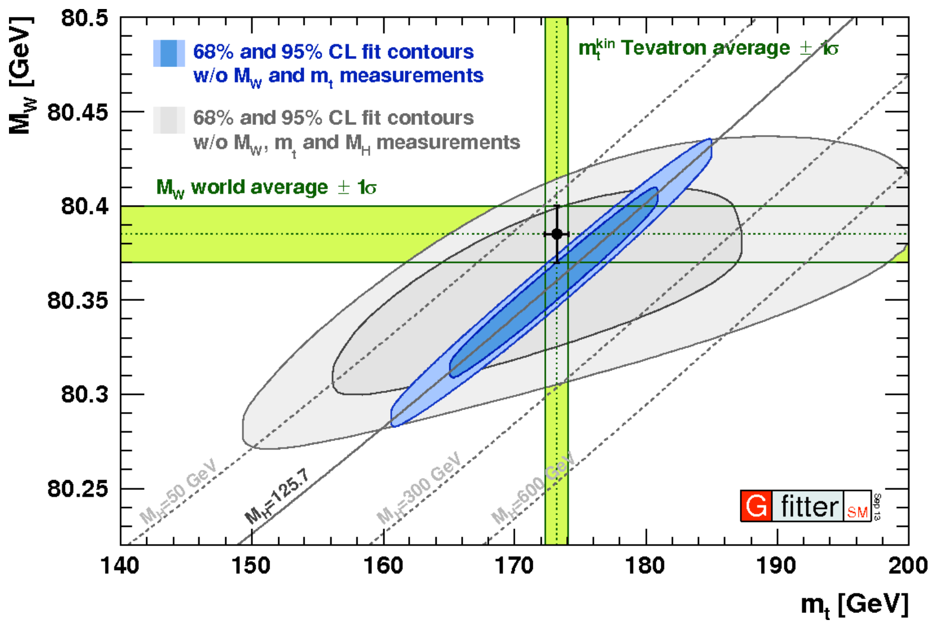
"The Standard Model is complete"

- **Completed by the last pieces of the puzzle in the past 30 years**
  - 1983: W and Z boson discovery
  - 1995: Top quark discovery
  - 2012: Higgs boson discovery



With masses predicted without new physics !



  - Indeed, no new physics has been found (yet) at the LHC Run1

- **So.... Why bother with new colliders ?**

Why bother ?

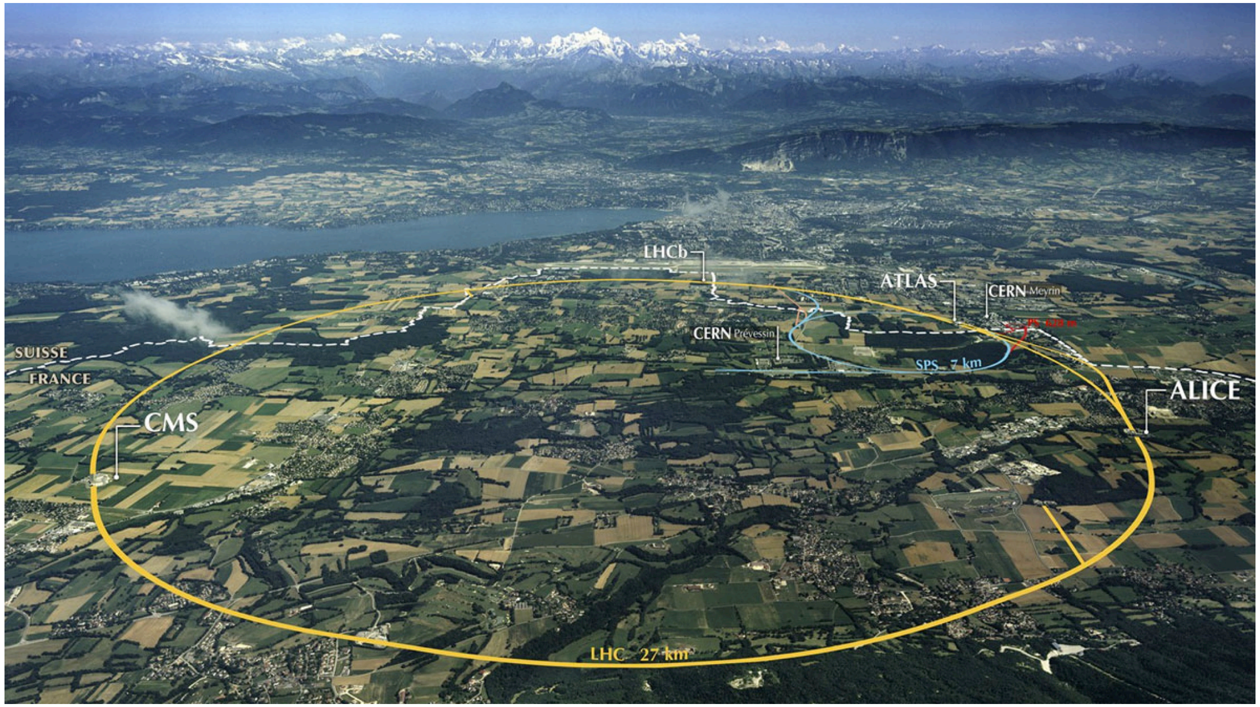
- **Because there is something beyond the standard theory**
  - **Many experimental proofs, e.g.,**
    - **Cosmological dark matter (DM)**
    - **Baryon asymmetry of the Universe (BAU)**
    - **Non-zero, but very small, neutrino masses**
  - **A mathematical hint : the small Higgs boson mass.**
- **Often heard: new physics must be "around the corner"**
  - **Problem: there is no corner (so far) … and not much of theoretical guidance**
  - **Is new physics at larger masses ? Or at smaller couplings ? Or both ?**
    - **Only way to find out: go look, following the historical approach:**
      - ➨ **Direct searches for new heavy particles**

        Need colliders with <u>larger energies</u>
      - ➨ **Searches for the imprint of new physics on W, Z, top quark, Higgs boson**

        Need colliders / measurements with <u>unprecedented accuracy</u>

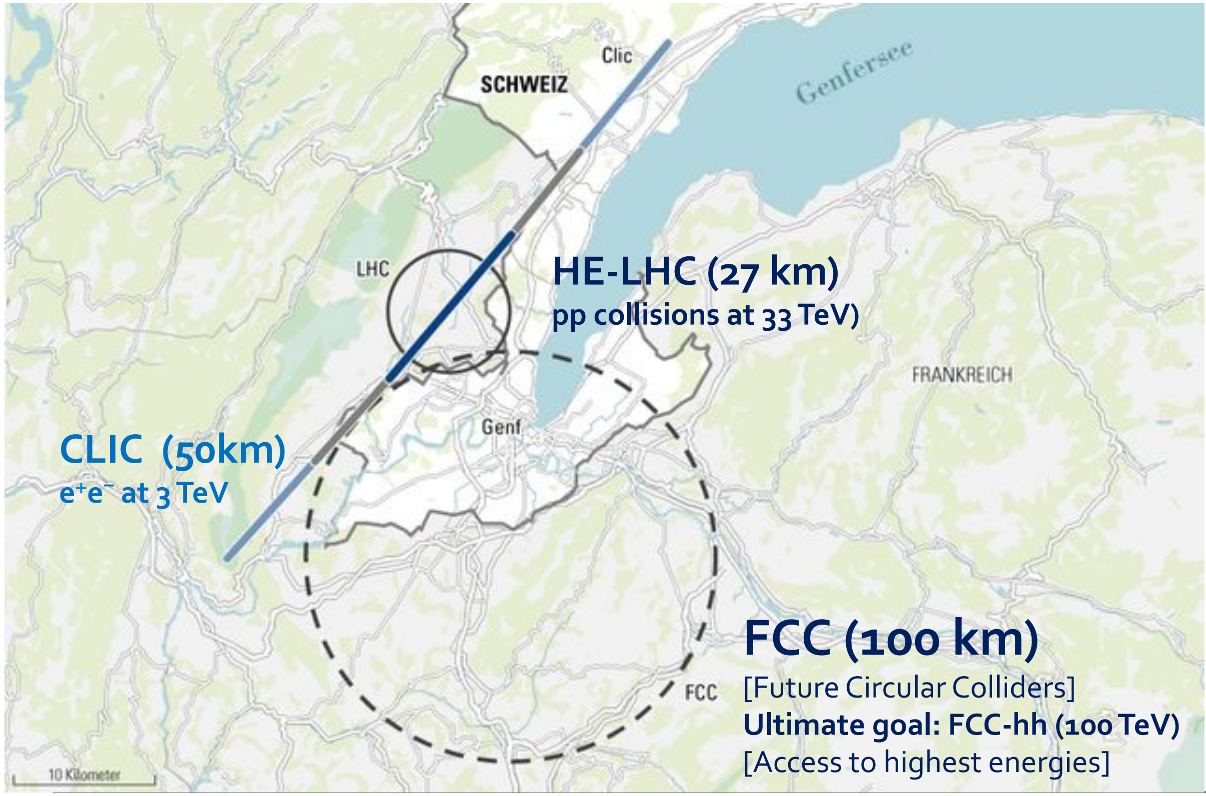
Short-term perspectives (2020-2035)

- **In May 2013, European Strategy said (very similar statements from US)**
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: project)
      - ➨ A first step towards both energy and precision frontier

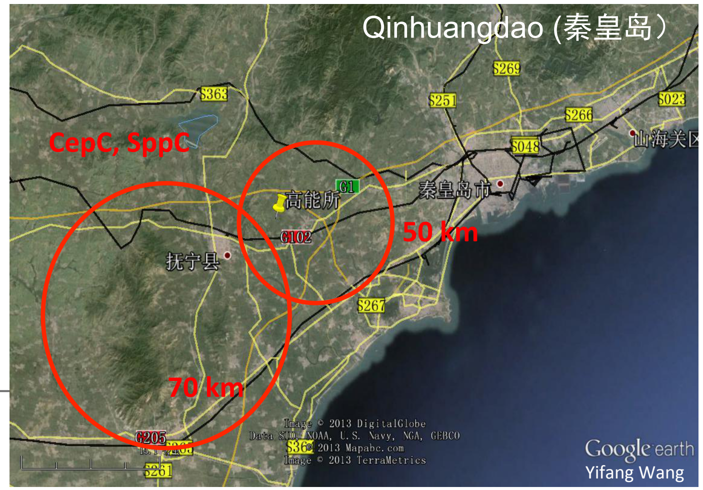


Long-term perspectives (2045-2060)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



Similar circular projects (50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV



Mid-term perspectives (2030-2045)

- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics case of e^+e^- colliders with intermediate $\sqrt{s}$
    - Participate in ILC if Japan government moves forward with the project
    - In the context of the FCC, perform accelerator R&D and design studies
      - ➨ In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step

FCC (100 km)

First step: FCC-ee (91-400GeV)

[Use the tunnel ultimately aimed at FCC-hh]

Note: CLIC can also run at $\sqrt{s}$ ~ 350 GeV in ~2035-2040

Mid-term perspectives (2030-2045)

- **The verbatim statement of the European Strategy**

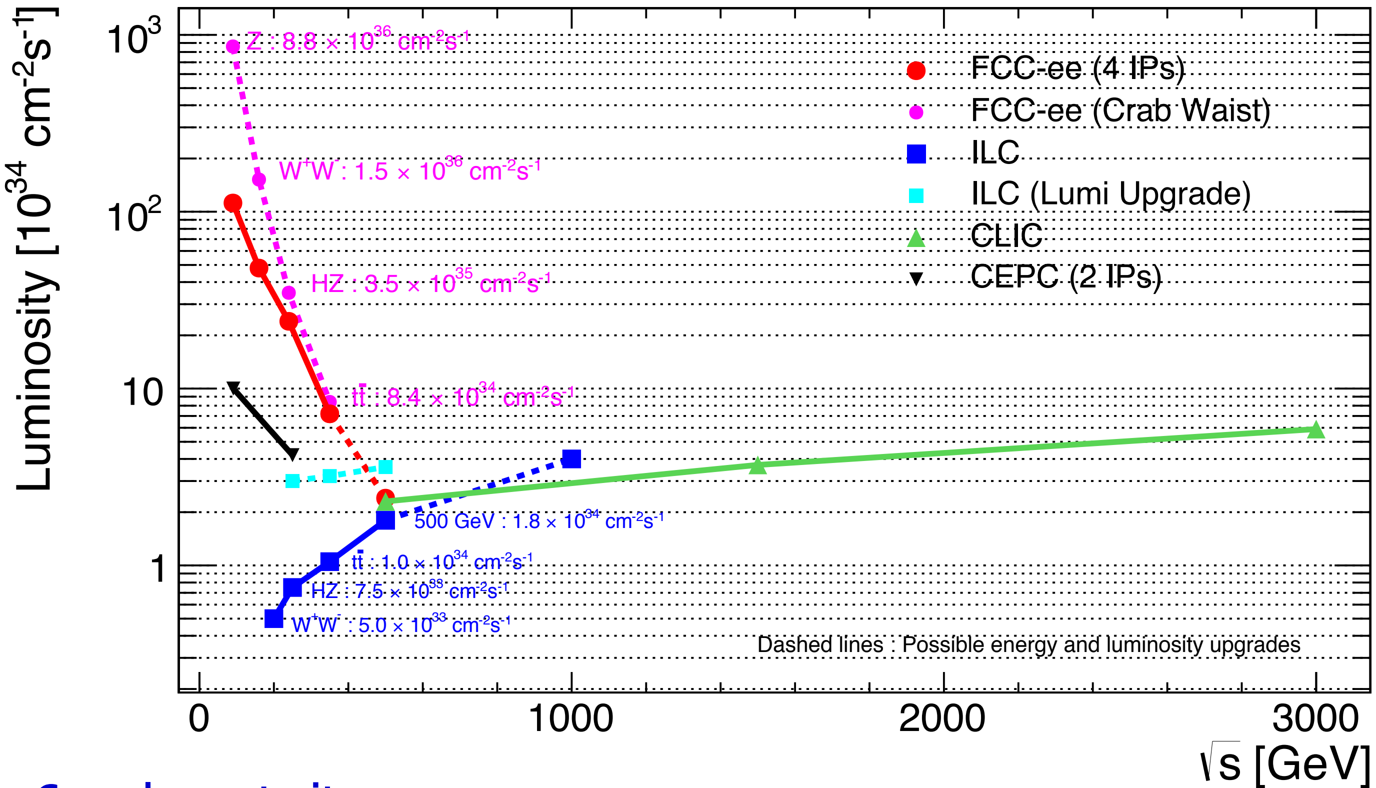
e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

- **There are only so many particles to study**
  - **Study the properties of the Higgs boson**
  - **Study the properties of the W and Z gauge bosons**
  - **Study the properties of the top quark**
    - **With unprecedented precision**

➨ **Calls for the largest luminosity at appropriate centre-of-mass energies**

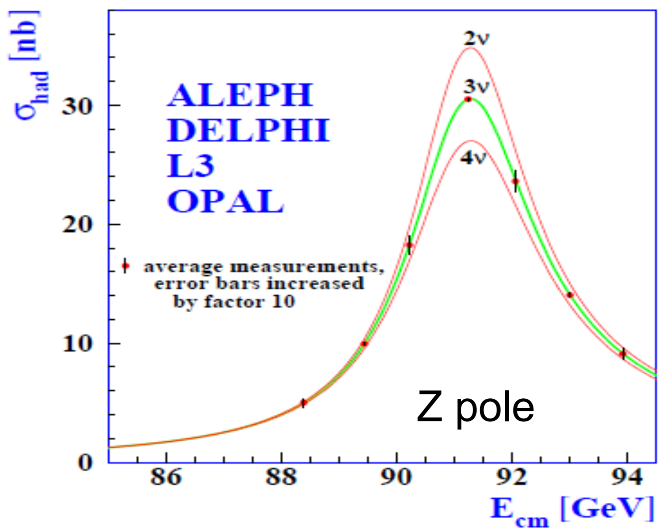
Linear or Circular ? (6)

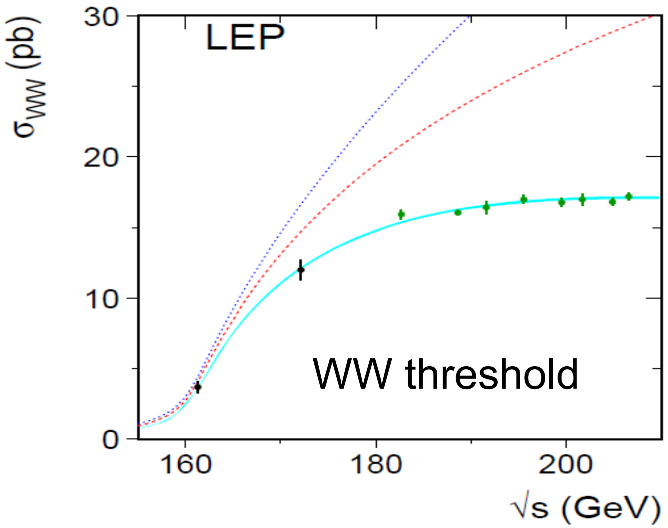
- **Performance target for e⁺e⁻ colliders**

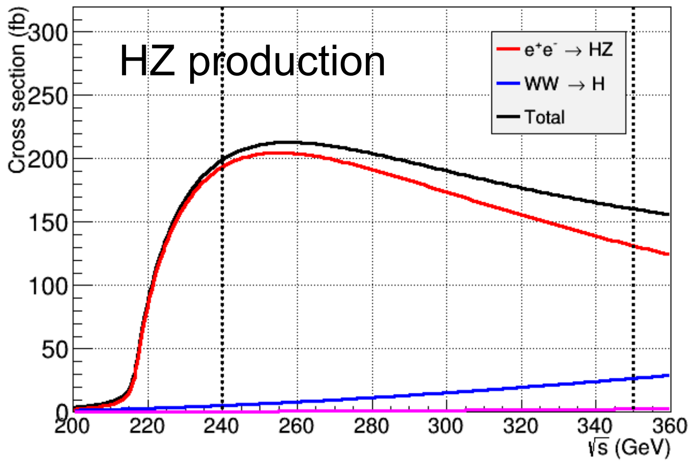


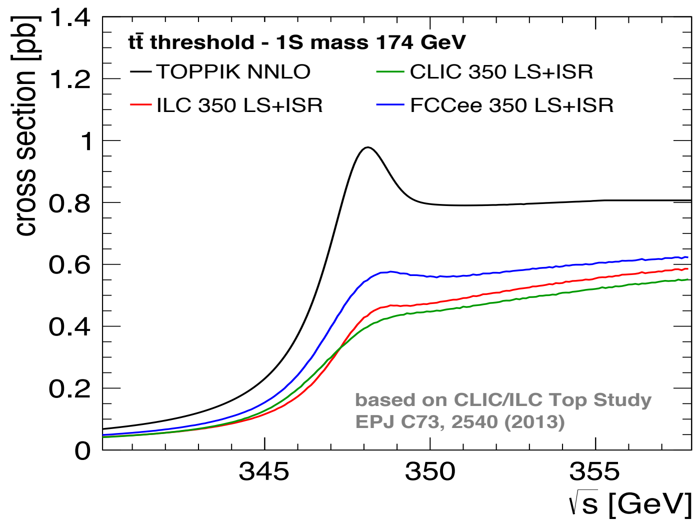
- **Complementarity**
  - **Ultimate precision measurements with circular colliders (FCC-ee)**
    - ➨ **10 to 10000 more luminosity than the linear option for √s = 90 to 400 GeV**
  - **Ultimate e⁺e⁻ energies with linear colliders (CLIC)**

The physics programme of FCC-ee (1)









The physics programme of FCC-ee (2)

- **A very rich physics menu !**

See arXiV:1308.6176, "First Look at the Physics Case of TLEP"
FCC-ee physics meetings, https://indico.cern.ch/category/5259/

- Core physics programme
  - The Z pole scan, $\sqrt{s}$ = 88-95 GeV
    - m_Z, Γ_Z to < 100 keV, $\sin^2\theta_W$ to 5×10^{-6}, $\alpha_{QED}(m_Z)$ to 2×10^{-5}, $\alpha_s(m_Z)$ to 2×10^{-4}, …
    - Rare decay/process searches and flavour physics with up to 10^{13} Z
  - The WW threshold scan, $\sqrt{s}$ = 160-165 GeV
    - m_W to 300 keV, $\alpha_s(m_Z)$ to 10^{-4}, …
  - The Higgs factory, $\sqrt{s}$ = 240 GeV and above
    - Improve HL-LHC precision on Higgs couplings by an order of magnitude
    - Measure the Higgs width to better than 1%, and BR_{invis} to 0.1%
  - The top threshold scan, $\sqrt{s}$ = 340-350 GeV
    - m_{top} to 10 MeV
  - Set constraints on new physics scale to 100 (10) TeV if weakly (Higgs) coupled
    - Possibly discover very-weakly-coupled new physics through rare processes

Well matched to FCC-hh discovery range

- And also …
  - Top electroweak couplings at $\sqrt{s}$ = 365-370 GeV (as part of the top threshold scan)
  - The Hee coupling at $\sqrt{s}$ = 125 GeV
  - The highest centre-of-mass energy $\sqrt{s}$ = 500 GeV (physics case ?)

The physics programme of FCC-ee (3)

- **How much time to complete the FCC-ee core programme ?**
  - With 4 IP's and in the crab-waist optics scheme :

$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350 (WW→H)
	$N_Z=10^{(12)13}$				
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
# years	(0.3) 2.5	1	3	0.5	3
Events@LC (*)	3×10^{9}	2×10^{6}	1.4×10^{5}	10^{5}	3.5×10^{4}
LC @ FCC-ee	1 day	1 week	2 months	3 months	1.5 year

(*) LC = 500 fb^{-1} @ 500 GeV (6 y), 200 fb^{-1} @ 350 GeV (2 y), 500 fb^{-1} @ 250 GeV (5 y)
100 fb^{-1} @ 90 GeV (>3 y), 500 fb^{-1} @ 160 GeV (>5 y)
with ±80% / ±30% polarization for e^-/e^+ beams

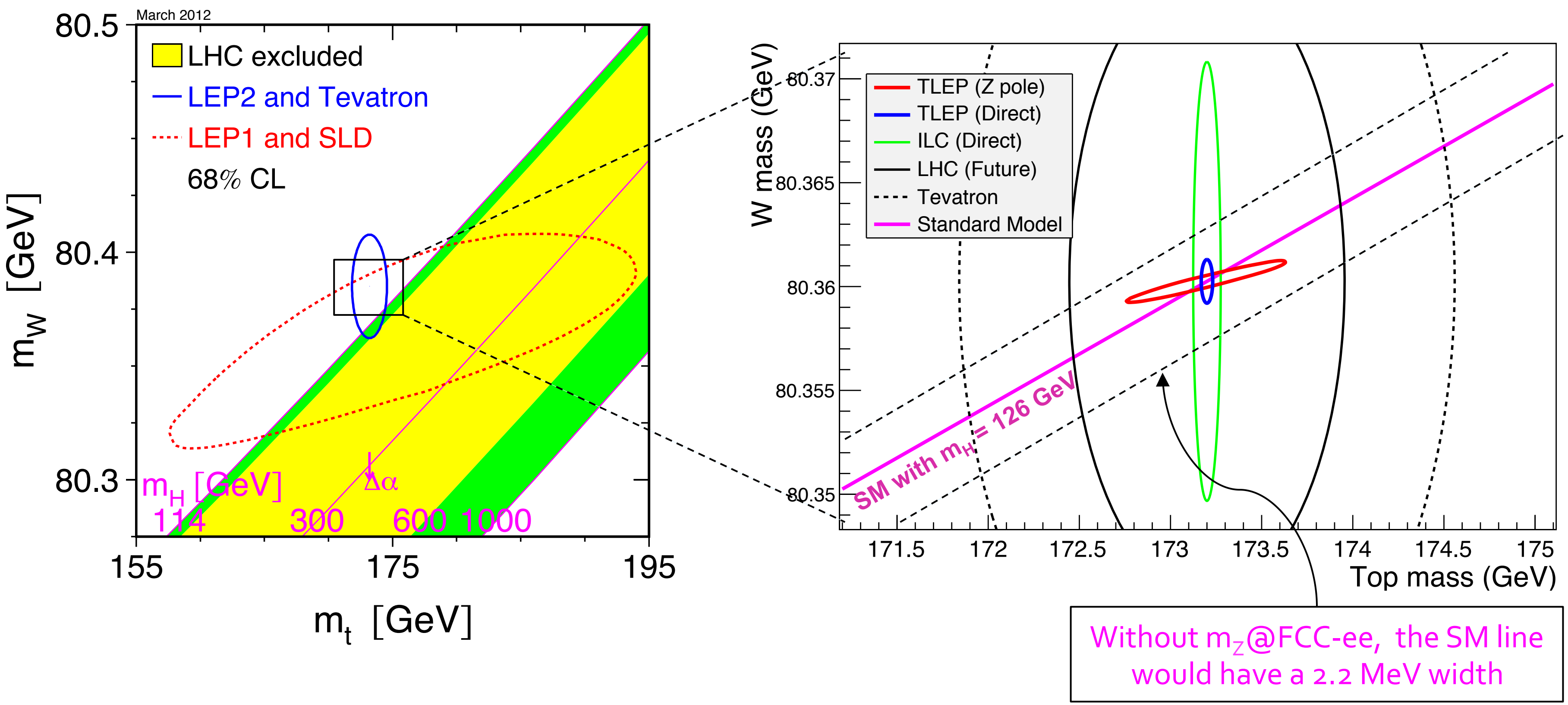
See e.g., arXiV:1506.07830 "ILC Operating Scenarios"

>21 years
(1 y = 10^7 s)

  - The FCC-ee core programme can be completed in about 8 to 10 years
    - For the "LC" physics programme, less than 2 years are needed at the FCC-ee

Sensitivity to heavy new physics (1)

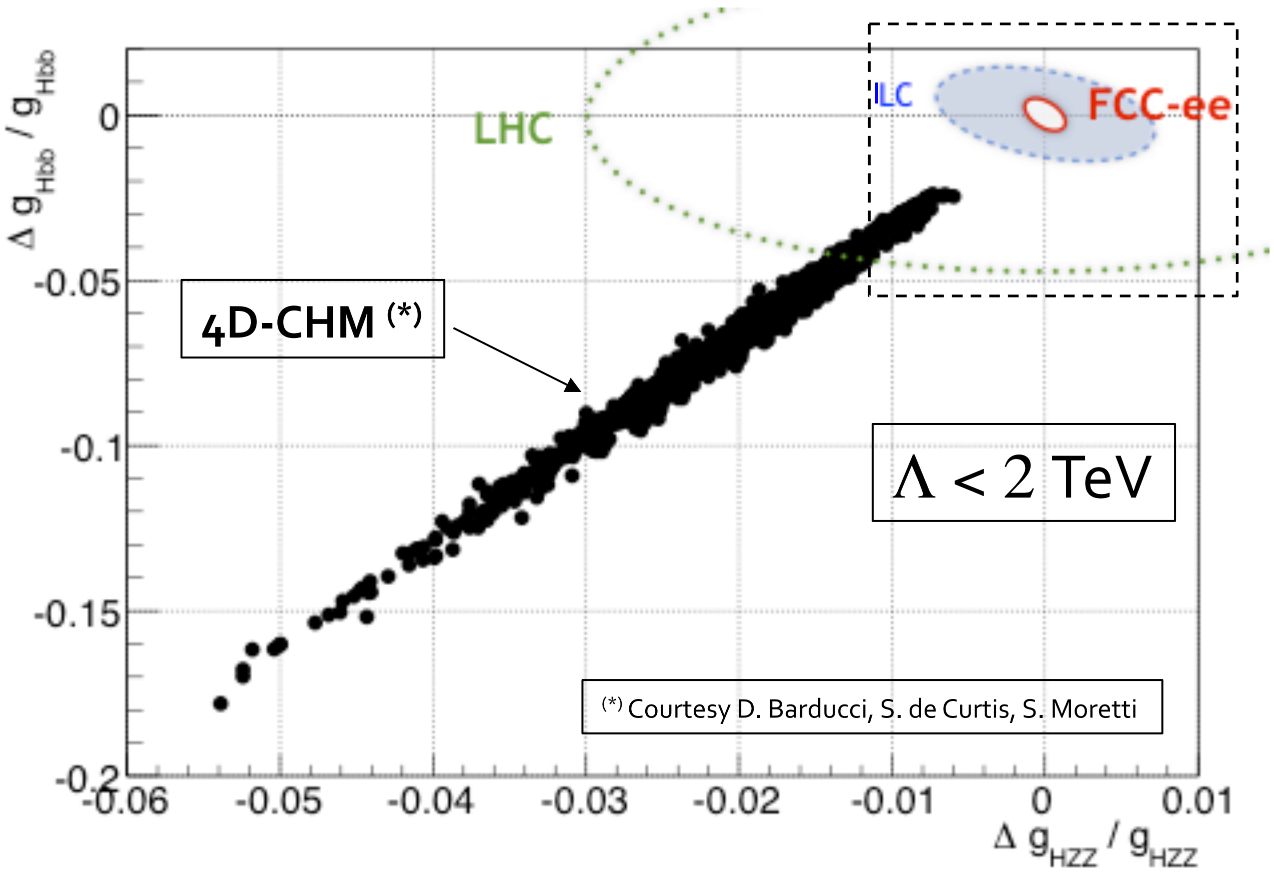
- **Combination of all precision electroweak measurements (Z, W, top)**
  - **In absence of new physics, the (m_{top}, m_W) plot would look like this**



- **Constraints on heavy new physics : Precision ⟺ $1/\Lambda_{NP}^2$**
  - **Set generic lower limits on Λ_{NP} up to 100 TeV !**

Sensitivity to heavy new physics (2)

- **Higgs couplings are affected by new physics**
  - **Example: Effect on κ_Z and κ_b from 4D-Higgs Composite Models**



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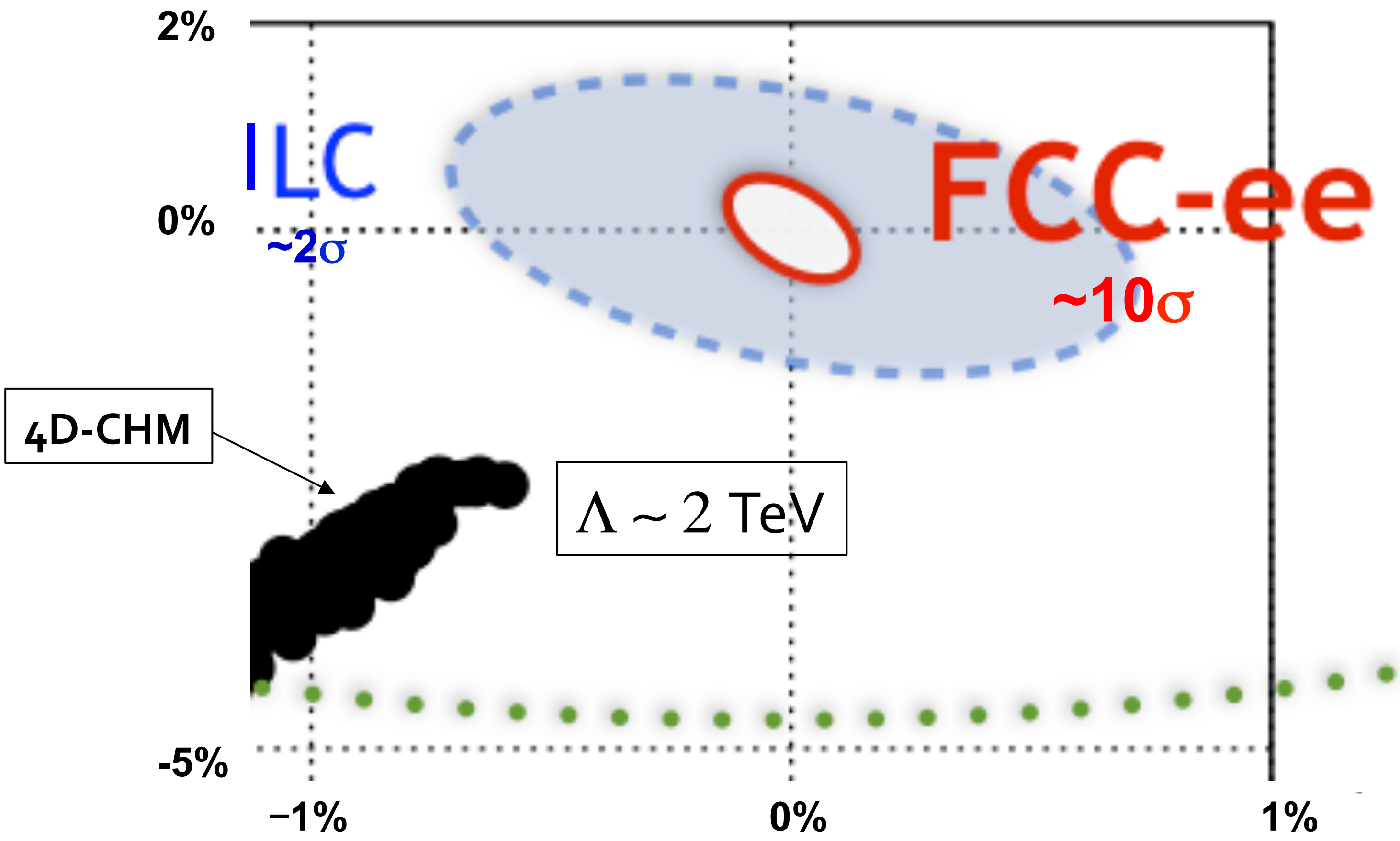
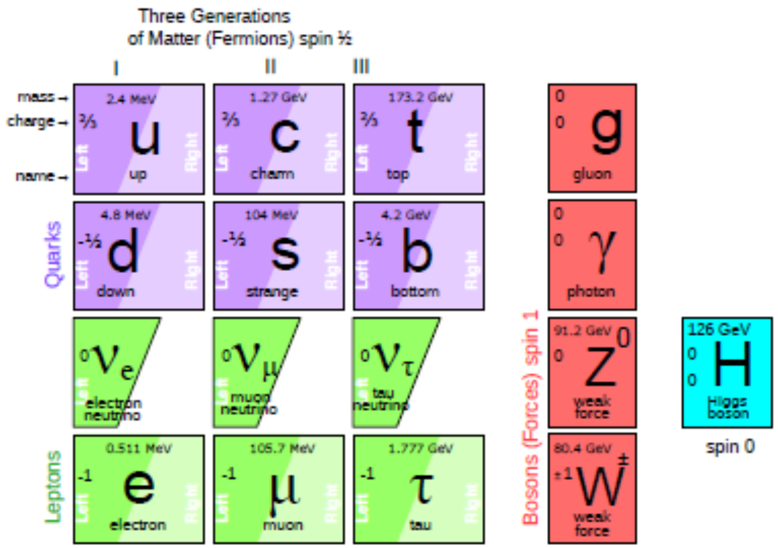
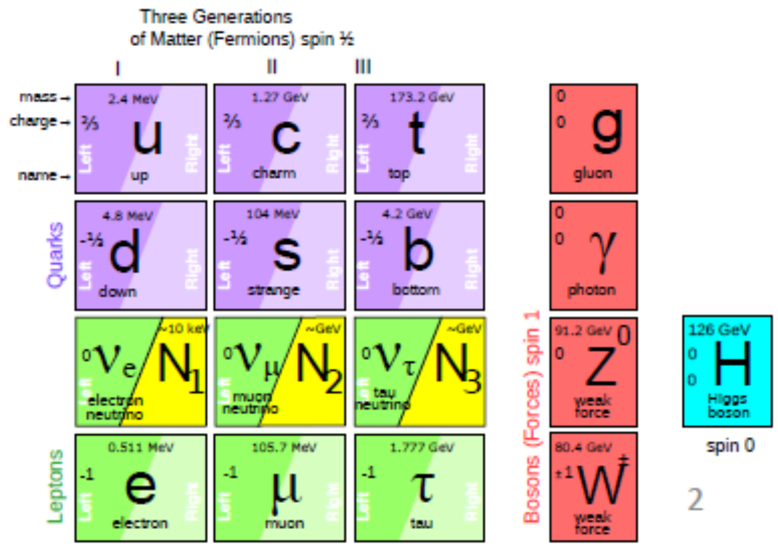


Sensitivity to very weakly coupled physics (1)

- **The standard model is complete, you said ?**





- **Obviously three pieces are missing: Three right-handed neutrinos ?**
  - **Extremely small couplings, nearly impossible to find, but could explain it all !**
    - ➨ **Small m_ν (see-saw), DM (light N_1), and B.A.U. (leptogenesis)**

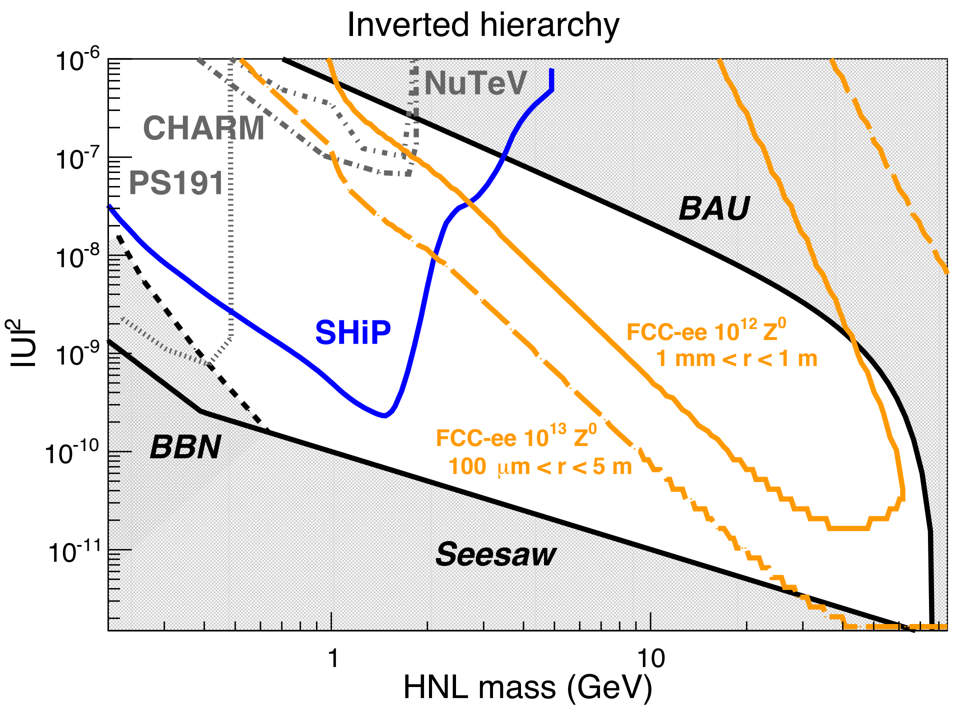
- **Need very-high-precision experiments to unveil**
  - **Possibly measurable / detectable in precision e^+e^- colliders**
  - **Almost certainly out of reach for hadron colliders (small couplings)**

Sensitivity to very weakly coupled physics (2)

- **Opportunities for direct searches for new physics through rare decays**
  - 10^{12} (10^{13}) Z, 10^{11} b, c or τ : A fantastic potential that remains to be explored.
  - E.g, search for right-handed neutrino in Z decays

$$\boxed{Z \rightarrow N\nu_i, \text{ with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j}$$

- Number of events depend on mixing between N and ν, and on m_N



Hand-waving anticipation (1)

- **With the 14 TeV LHC Run2 data, we may**
  - Find a new heavy particle (or new heavy particles)
    - The (HL-) LHC will study this (these) particles to some extent
    - If m < 3 TeV, CLIC become interesting (if copiously produced in e^+e^- collisions)
    - Larger energies might be needed to find & study the whole new spectrum (FCC-hh)
    - An e^+e^- Z factory (FCC-ee) is useful to study the underlying quantum structure
      - ➨ Note: m_H and m_{top} were predicted without new physics

        New physics will probably be very difficult to find anyway
  - Find no new particle, but finds a hint for non-standard Higgs properties
    - The (HL-) LHC will improve the precision on these measurements to some extent
    - e^+e^- factories for Higgs (ILC, FCC-ee) and Z (FCC-ee) become very interesting machines
    - Push the energy frontier to its limits (CLIC, FCC-hh)
  - Find no new particle, standard Higgs properties
    - Push precision measurements to their limits (FCC-ee)
    - Possibly push energy frontier to its limits (CLIC, FCC-hh)
- **FCC (ee+hh) might be the right combination, after all !**

Hand-waving anticipation (2)

- **Exquisite complementarity of FCC-ee with (HL-LHC and) FCC-hh**

The combination of FCC-ee and the FCC-hh offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market.

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First look at The Physics Case of TLEP
arXiv:1308.6176v2 [hep-ex] 22 Sep 2013

"The FCC exploring power will be invincible"

From a referree of the Swiss National Science Foundation