The future of Particle Physics and the role of young researchers

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Standard Model: how stubborn is it?

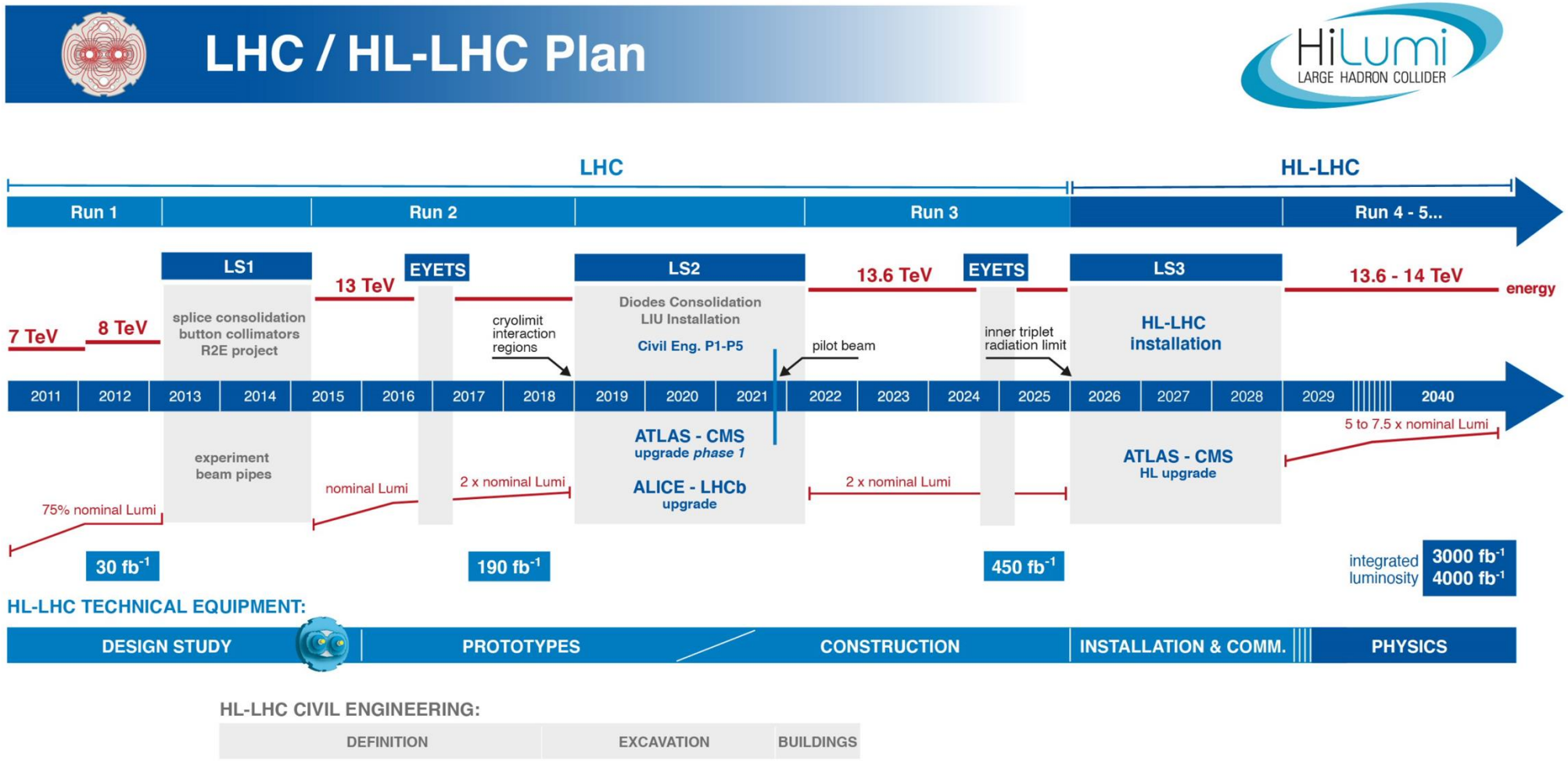
- Why three generations of leptons and quarks?
- Why such a huge difference in the masses of fundamental particles?
- What's the origin of the structure of flavour couplings?
- Why is the universe made of "matter" and not "antimatter"?
- What stabilises the Higgs mass?
- What's the nature of dark matter?
- And what about gravity?
- …

The Standard Model is certainly incredibly stubborn, but we know it can't be the ultimate theory!

General considerations on our present understanding of fundamental reality

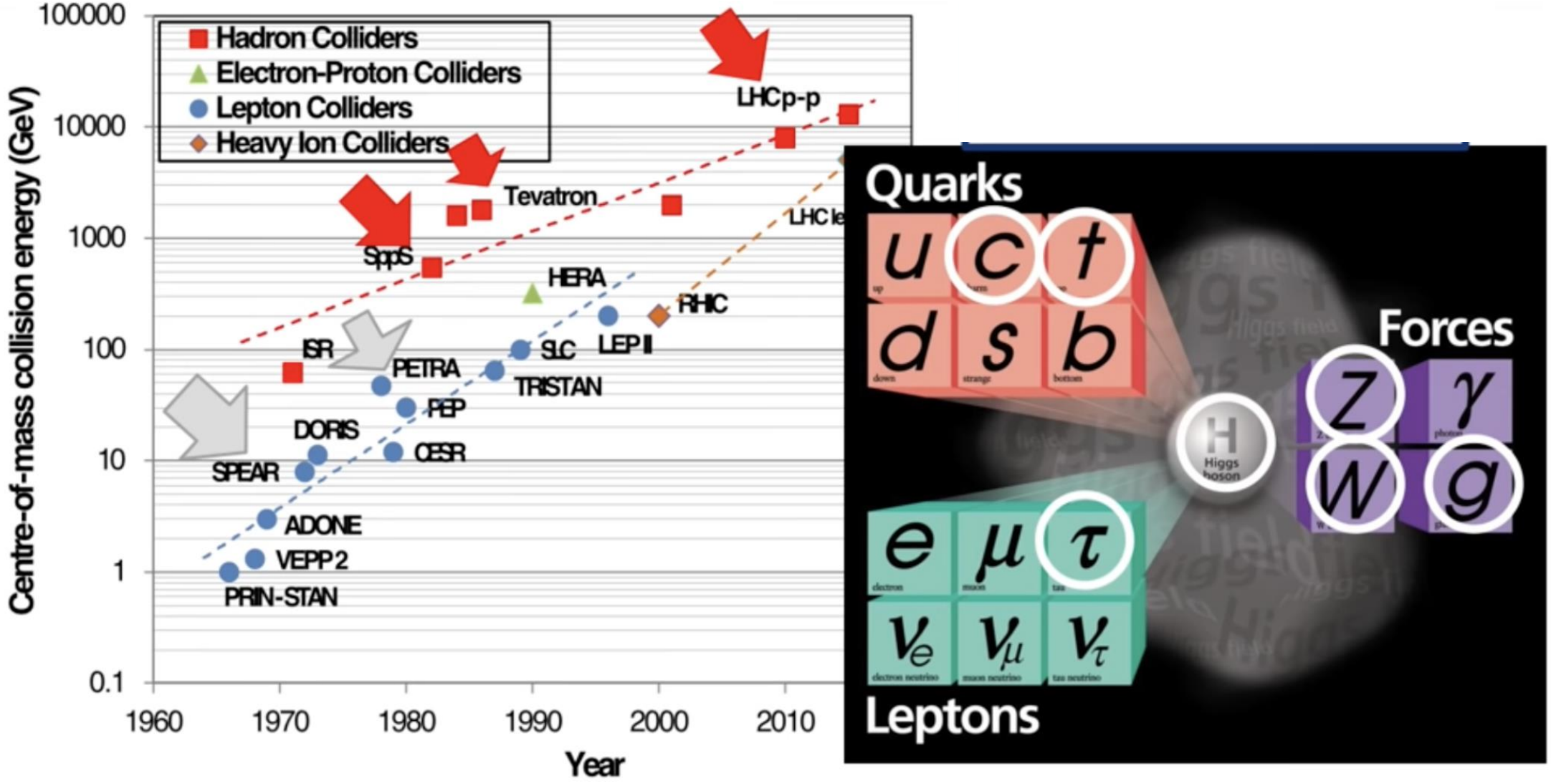
- We are living a stunning contradiction in modern days: we have developed the most successful theory of reality ever made and checked it in a wide number of ways for decades, but we have at the same time developed the awareness that it can't be complete
  - Incidentally, have you ever reflected on why the Standard Model has been named a "model", even without the full awareness of its incompleteness that we have reached today?
- I don't even want to discuss about the multiverse hypothesis, for how brilliant and ingenuous, simply because it is an excessively cheap way to escape the contradiction
- It's not time to give up, and in general I believe that in fundamental research it's never a good idea to give up, if you want a metaphore of life
  - Explore new routes, build new tools

The most powerful tool we have got today



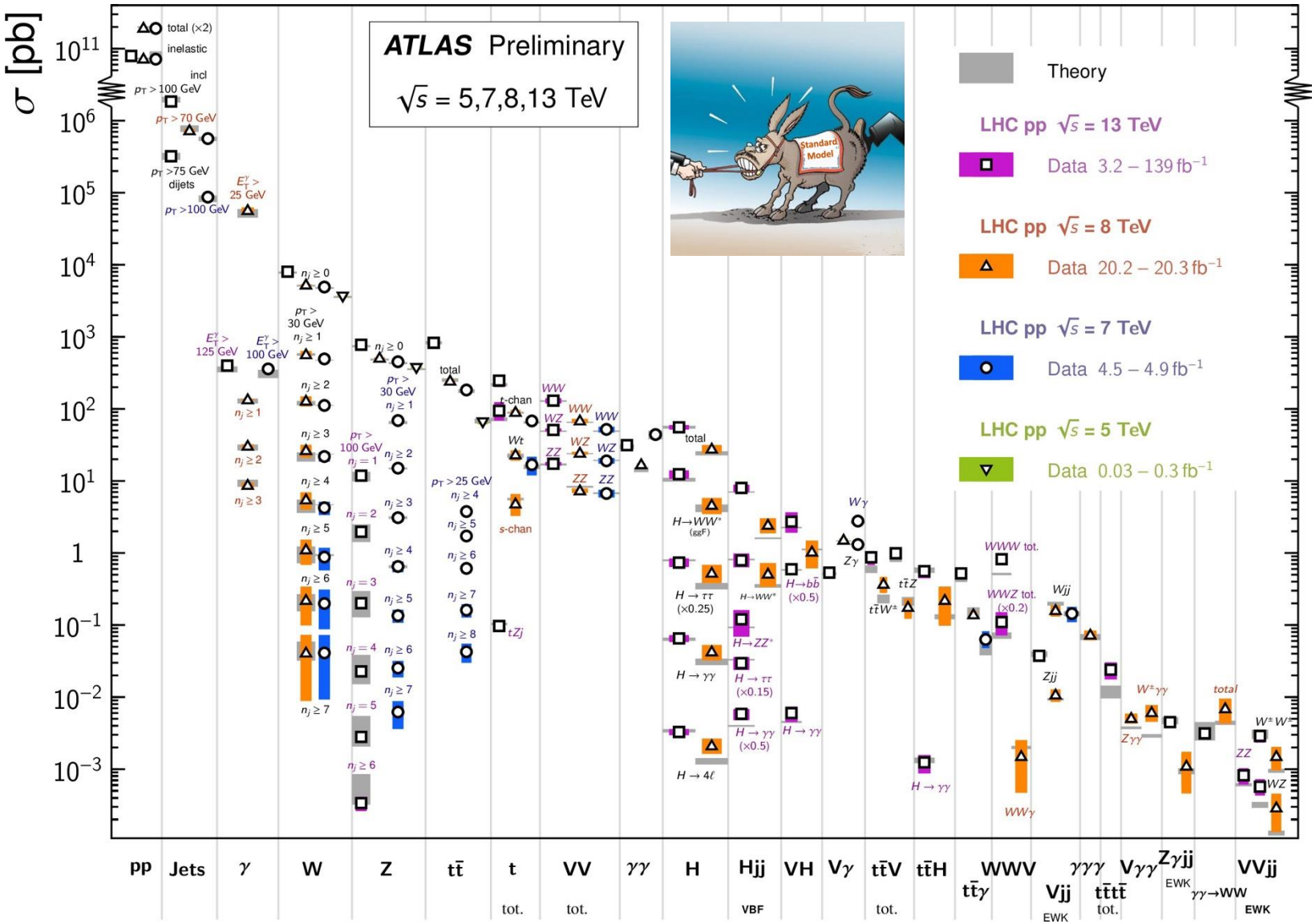
- It took 20 years of design, construction and commissioning
- It has been in operation since 15 years, and will remain in operation for another 15 years or more after a major upgrade at the next long shutdown

Colliders and discoveries



powerful instruments for discovery and precision measurement

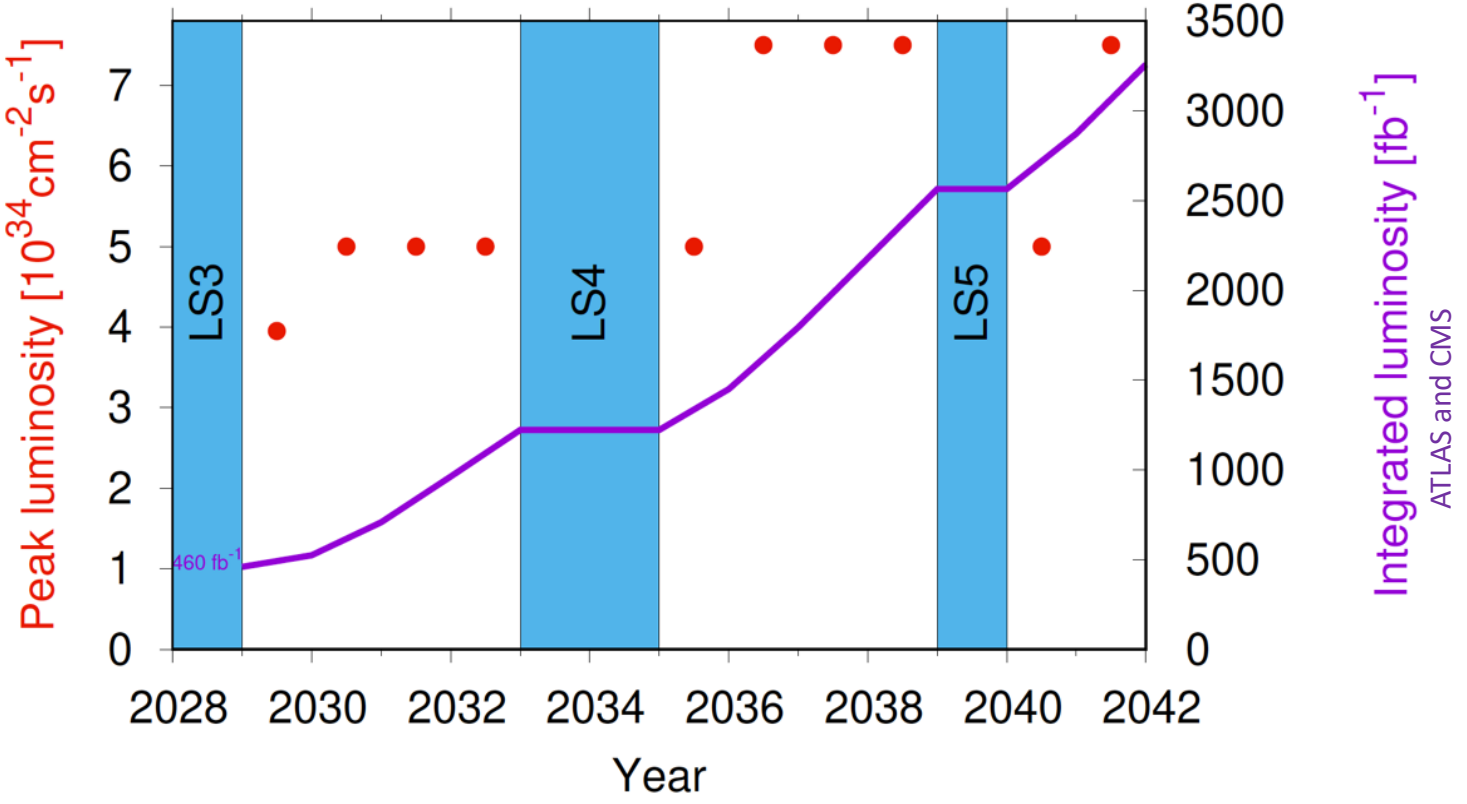
We have never seen anything like this!



- What to say to a plot like this?
- 10 orders of magnitude of agreement between cross sections from the Standard Model and experiment!
- Involving a plethora of different processes, ranging from *pp* elastic scattering, to inclusive inelastic, jets and photon production, gauge bosons, top quarks, Higgs, …, with all the possible couplings

The High-Luminosity LHC

- This will be a major machine upgrade to increase the peak luminosity → implies a larger number of simultaneous *pp* collisions (pileup) at each crossing of the LHC proton bunches
- The ATLAS and CMS detectors will also need immediate major upgrades, so-called Phase-II upgrades, to cope with a pileup of about 200 simultaneous interactions per crossing at 40 MHz collision rate!



Phase-II upgrades of ATLAS and CMS now being in the production phase, to be installed during Long Shutdown 3. Further upgrades of ALICE and LHCb foreseen for Long Shutdown 4

What have we learned from the LHC (so far)?

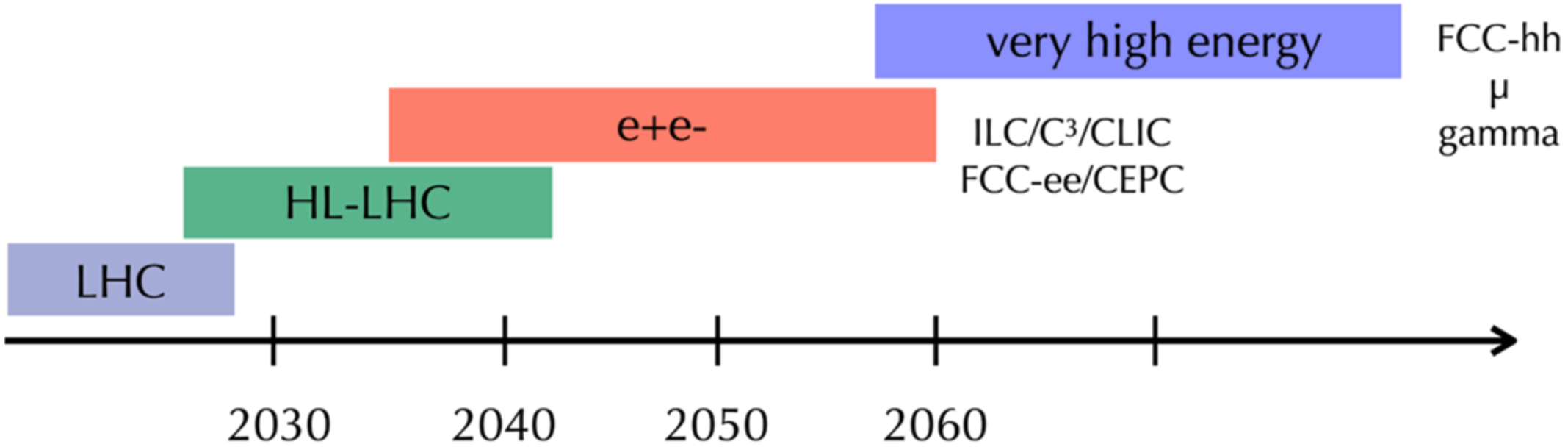
- The SM works pretty well… goddamn it!
- The Higgs boson, and then the Higgs field and the mechanism for generating particle masses, are real
- Huge amount of LHC data fits SM predictions at am amazing level of accuracy, but no real hint of BSM yet
  - Bounds on new heavy states predicted by many BSM models widely extended
- Flavour physics has strengthened constraints, but with no clear evidence of discrepancies from the SM
- Let's see what we will get with the HL phase

How to proceed beyond the HL-LHC?

- Colliders are still the most powerful instruments that we know to probe physics at smaller length scales
- Four main strategies
  - Explore the characteristics of the Higgs sector to possibly spoil the SM picture
  - Keep searching for new heavy states coupled to the SM
  - Look for new “dark” states, meaning new states which are not coupled to the SM at tree level, either producing them or looking for them in heavy-particle decays (Higgs, top)
  - Try harder with indirect searches, read flavour physics

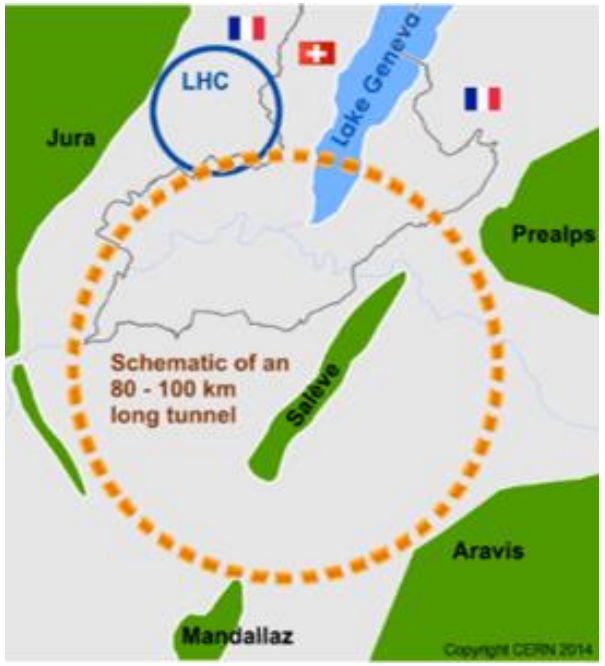
What's next?

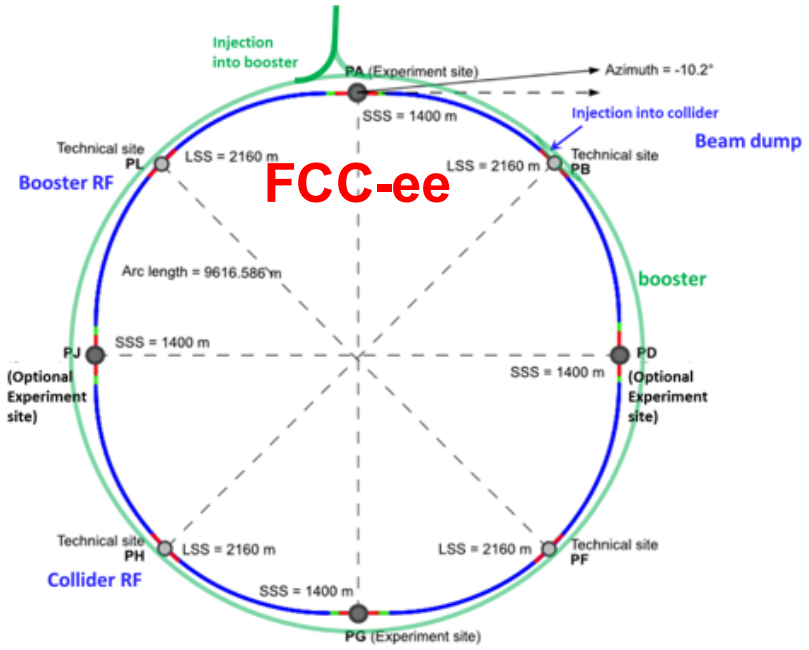
- Several options in consideration beyond HL-LHC
  - Precision studies with Higgs Factories
  - Discovery physics on the >TeV scale



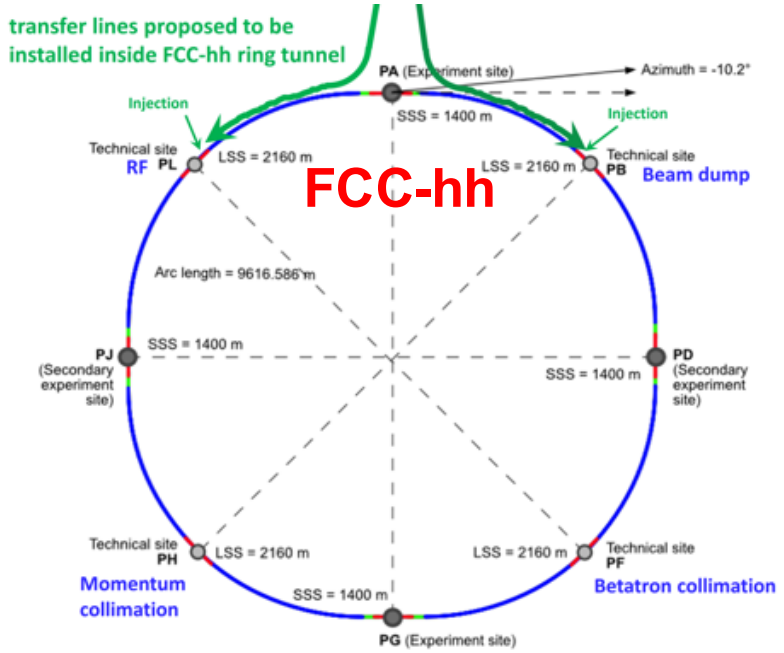
The FCC programme

- Long-term programme maximising physics opportunities
  - Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak and top factory, flavour physics
  - Stage 2: FCC-hh (~100 TeV) for energy frontier exploration
- Building on and reusing CERN's existing infrastructure
- Plan to start with FCC-ee a few years after the end of HL-LHC → ESPP update next year!





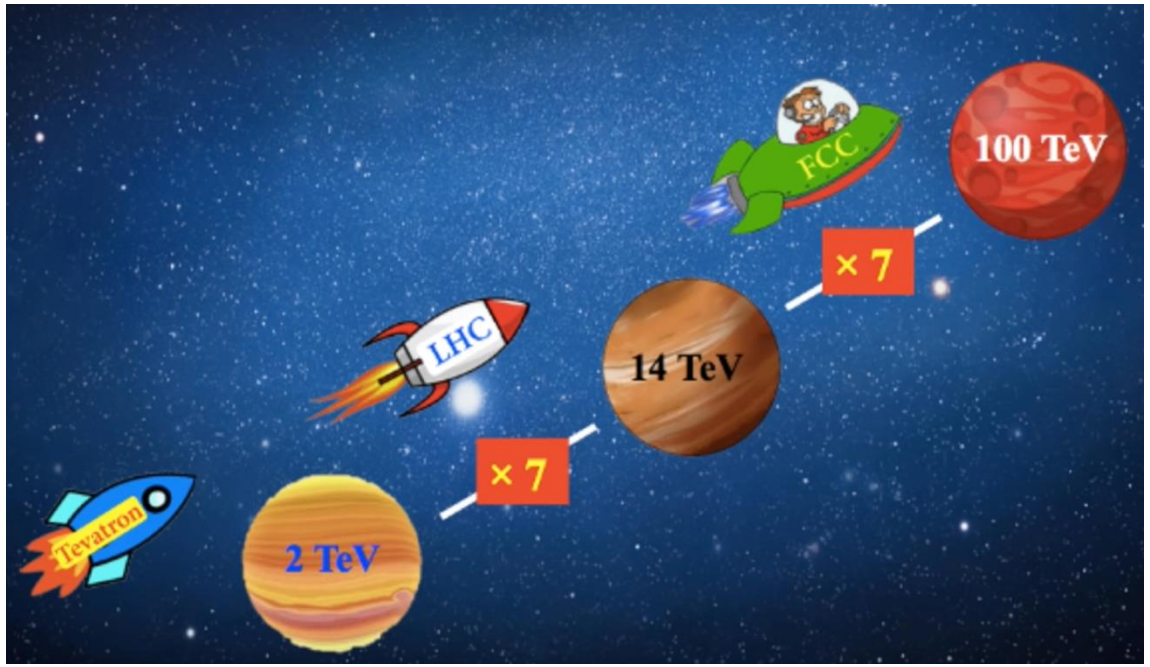
2045 - 2060



2070 - 2095

- A similar project CEPC/SPPC is being studied and proposed in China

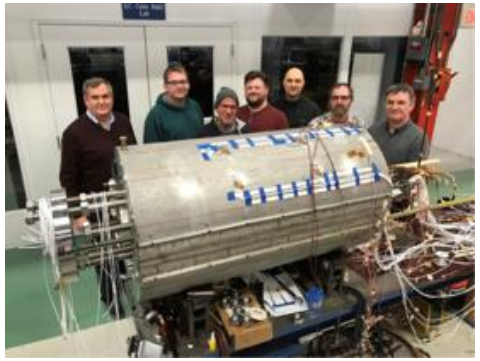
FCC-hh: highest collision energy



- Order of magnitude performance increase in both energy and luminosity wrt LHC
  - 100 TeV collision energy vs 14 TeV for LHC
  - 20 ab^{-1} per experiment over 25 years of operation vs 3 ab^{-1} for LHC
- Key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

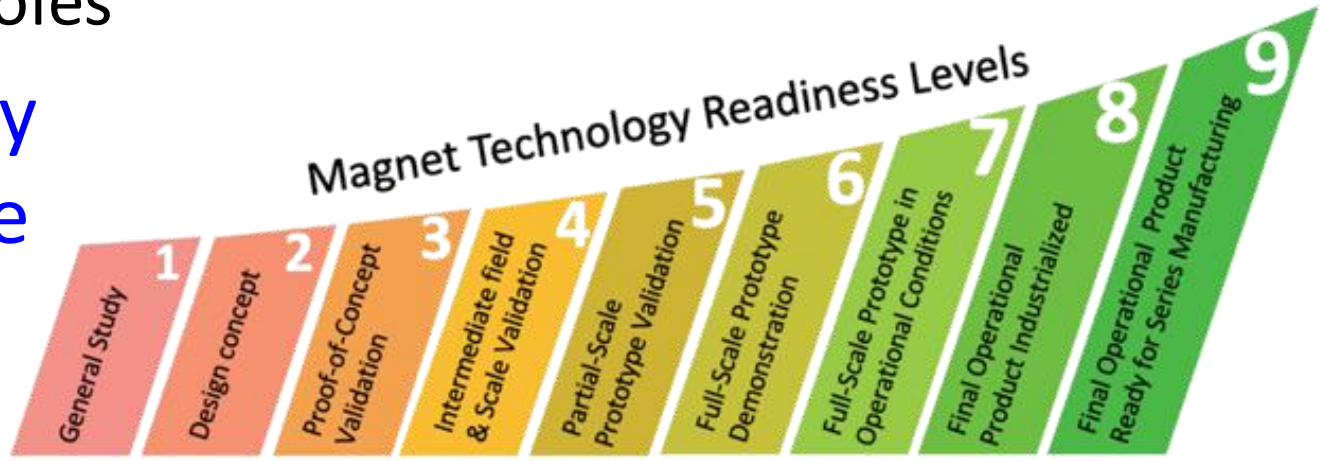
via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole
demonstrator
14.5 T Nb_3Sn

R&D on superconducting magnets

- Nb_3Sn in an intermetallic compound of Nb and Tin which is superconductor below 18 K and 30 T → State of the art Nb_3Sn strands can carry up to J_C(16 T, 4.2 K)=1200 A/mm^2
- 12 T dipoles are close to demonstration (TRL 6–7), while 14-16 T dipoles still need ~5 years of R&D (TRL 4–5)
  - To compare with NbTi 8 T LHC dipoles
- However, the question is not only to make them, but also to reduce production costs
- Making progress in this area is of paramount importance for the future of High Energy Physics



What can we do without young researchers?

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Nothing!

Several opportunities to learn and contribute to the global growth!

- Physics analysis, including advanced machine learning methods
- Theoretical progress, including understanding ”well known” theories, like QCD
- Detectors development, including picosecond timing
- Physics software development, exploiting modern computing architectures
- Electronics development, including next-generation radiation-resistant ASICs
- Offline computing, including exploitation of supercomputing centres
- …

Not only physics

- Every new generation of researchers becomes more and more open to international cooperation
  - Initiatives like IMAPP are exactly what we need for a better integration!
- Equally important to physics is the need to keep people from all over the world cooperate on a common subject for the benefit of everybody
  - Physics is a universal language!
- Today's world looks problematic and scary, but you have the opportunity to contribute to a better future for the entire humankind → Never underevaluate this aspect, it's definitively not just rethorics
- Focus on your aspirations, be ambitious and never give up!

Good luck to everyone!