Future physics challenges

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Trans-European School of High Energy Physics 2024

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Future physics challenges?

- Very interesting title potentially involving a broad range of topics
  - High-p_T physics
  - Flavour physics
  - Neutrino physics
  - Dark matter searches
  - Heavy ion physics
  - Astrophysics
  - Gravitational waves
  - Future accelerators
  - …
- Not sure I would be able to cover all of this in the proper way, but certainly not in a single lecture and not today…

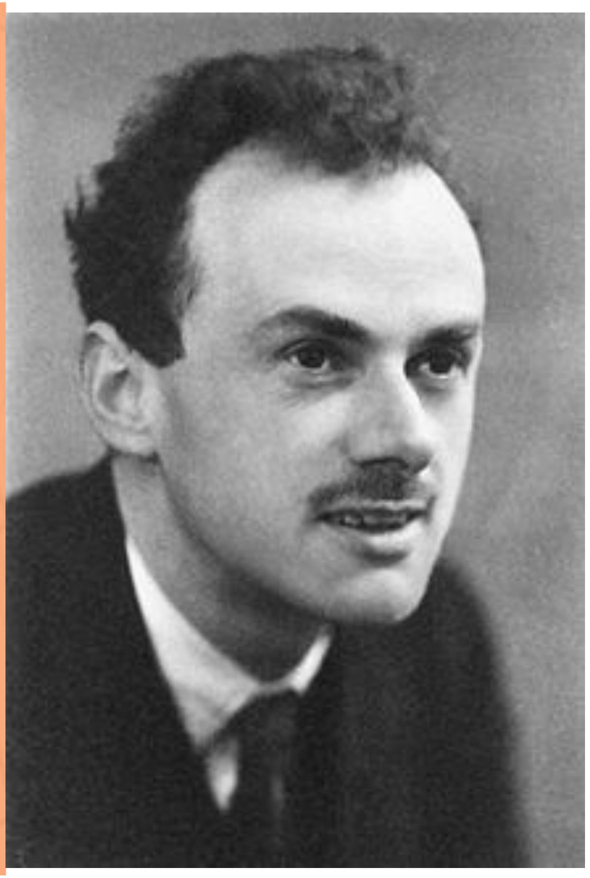
Standard Model: how stubborn is it?

- 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 it can't be the ultimate theory…

First thoughts on BAU: Dirac dixit…

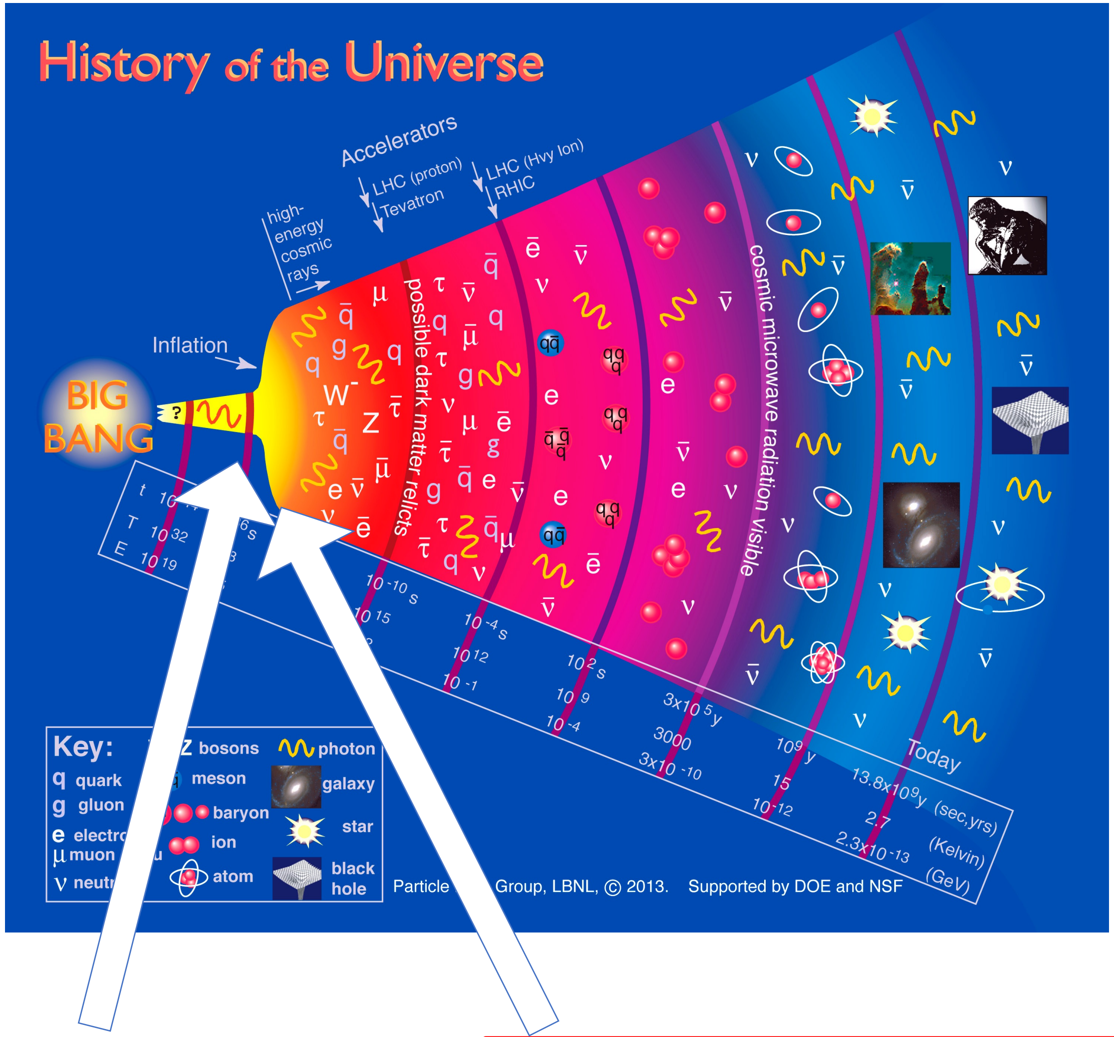
> “If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.”



- Excerpt of Dirac’s Nobel lecture in 1933
- At the time we were starting to wonder where had antimatter gone…

Matter-dominated universe

- We observe that there's no evidence of primary antimatter on the scale of the observable universe today
- What led to the disappearance of antimatter assuming an initial symmetric state?
- How big the asymmetry should have been to lead to what we observe?



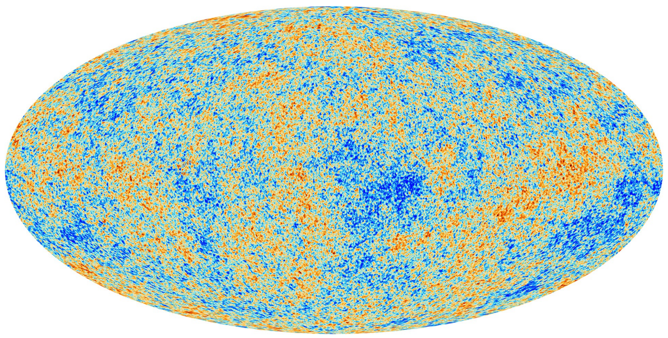
Symmetric matter-antimatter initial state?

Symmetry broken soon after inflation?

Mainstream explanation

- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over

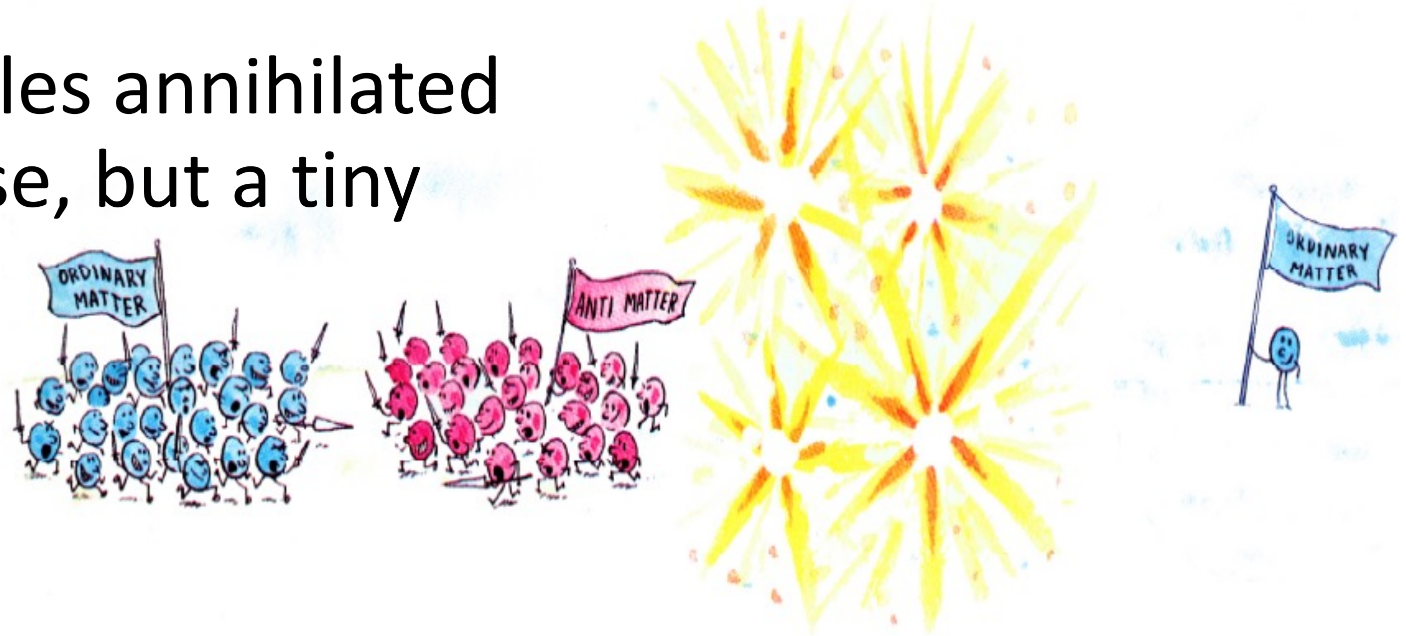
- The radiation produced by the initial annihilation is what we see today as the big bang afterglow: the cosmic microwave background (CMB)
  - By measuring photon and baryon number densities in the universe we can determine how much matter survived the annihilation with respect to matter-antimatter annihilations

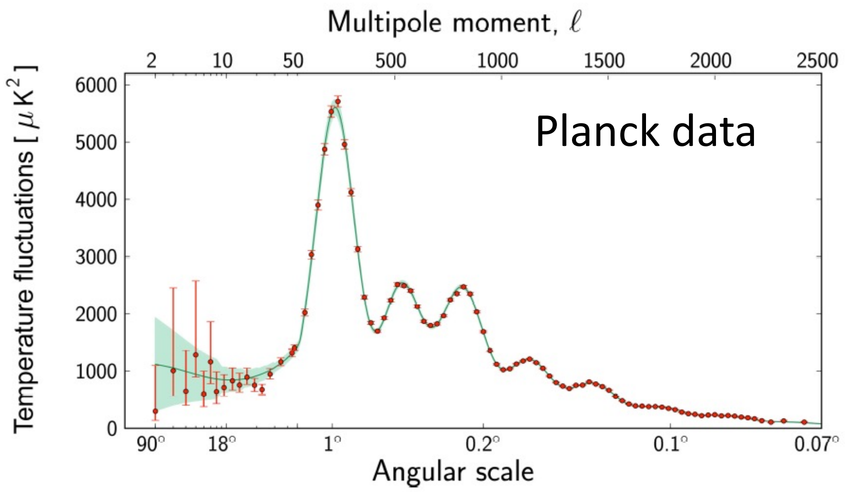


Planck data

Mainstream explanation

- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over





- The ratio of baryon to photon number densities is nowadays very well known, precisely measured in the framework of ΛCDM cosmological model

Every 10^{10} particle-antiparticle annihilations only a handful of matter particle survived

$$\eta = (6.04 \pm 0.08) \times 10^{-10}$$

Can we explain the asymmetry by Standard Model physics?

- Qualitatively: yes
  - The Standard Model in principle contains all the necessary ingredients
- It is possible to derive an expression of the ratio η

$$\eta = \frac{n_B}{n_\gamma} \sim \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,2J}{M^{12}}$$

where $J \approx 3\times10^{-5}$ is the Jarlskog invariant* quantifying the size of *CP* violation in the Standard Model and M≈100 GeV is the electroweak scale at which the baryon asymmetry freezes out

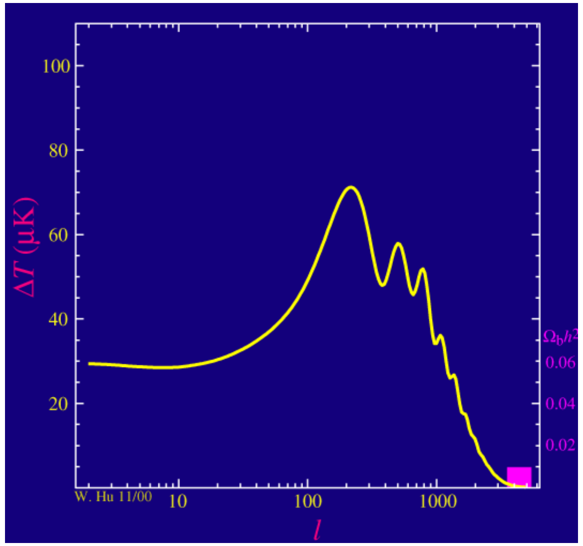
*Phys. Rev. Lett. 55 (1985) 1039

Can we explain the asymmetry by Standard Model physics?

- Quantitatively: no
- The previous equation gives $\eta \approx 10^{-19}$, which is off by 10 orders of magnitude with respect to the experimental observation
- *CP* violation in the Standard Model is too small
- Either we are missing something subtle and fundamental, or there should be new sources of *CP* violation in some beyond-the-SM physics…

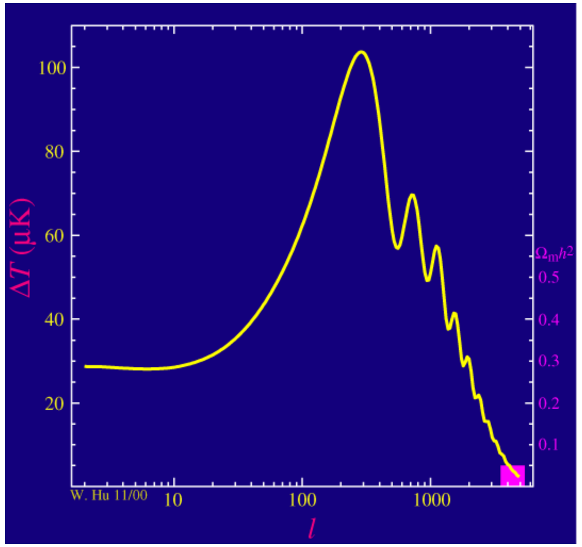
What else we learn from the CMB

Ordinary matter



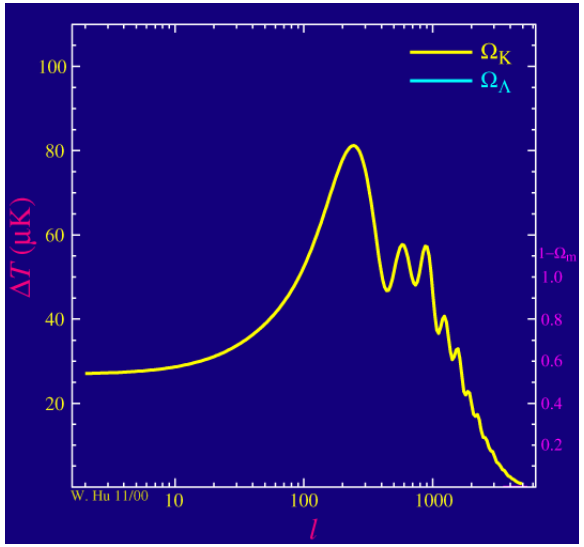
Increasing the density of ordinary matter, odd peaks increase with respect to even peaks

Dark matter



If we increase dark matter density, the amplitudes of all peaks decrease

Spatial curvature and dark energy

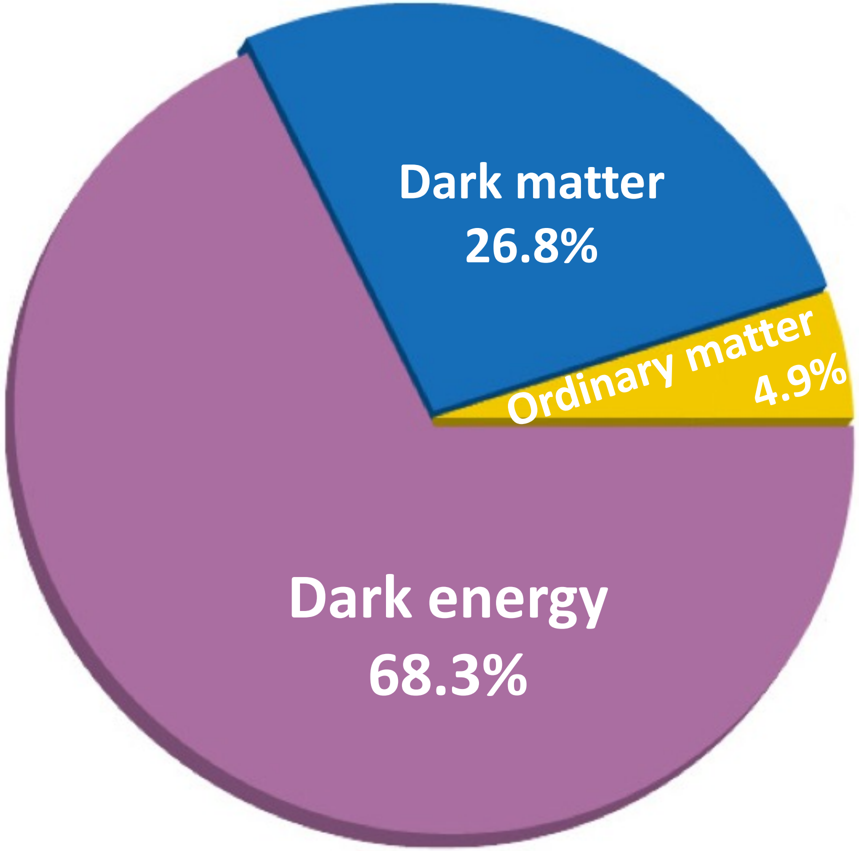


If we increase space curvature and dark energy density, the peaks move to the right or to the left

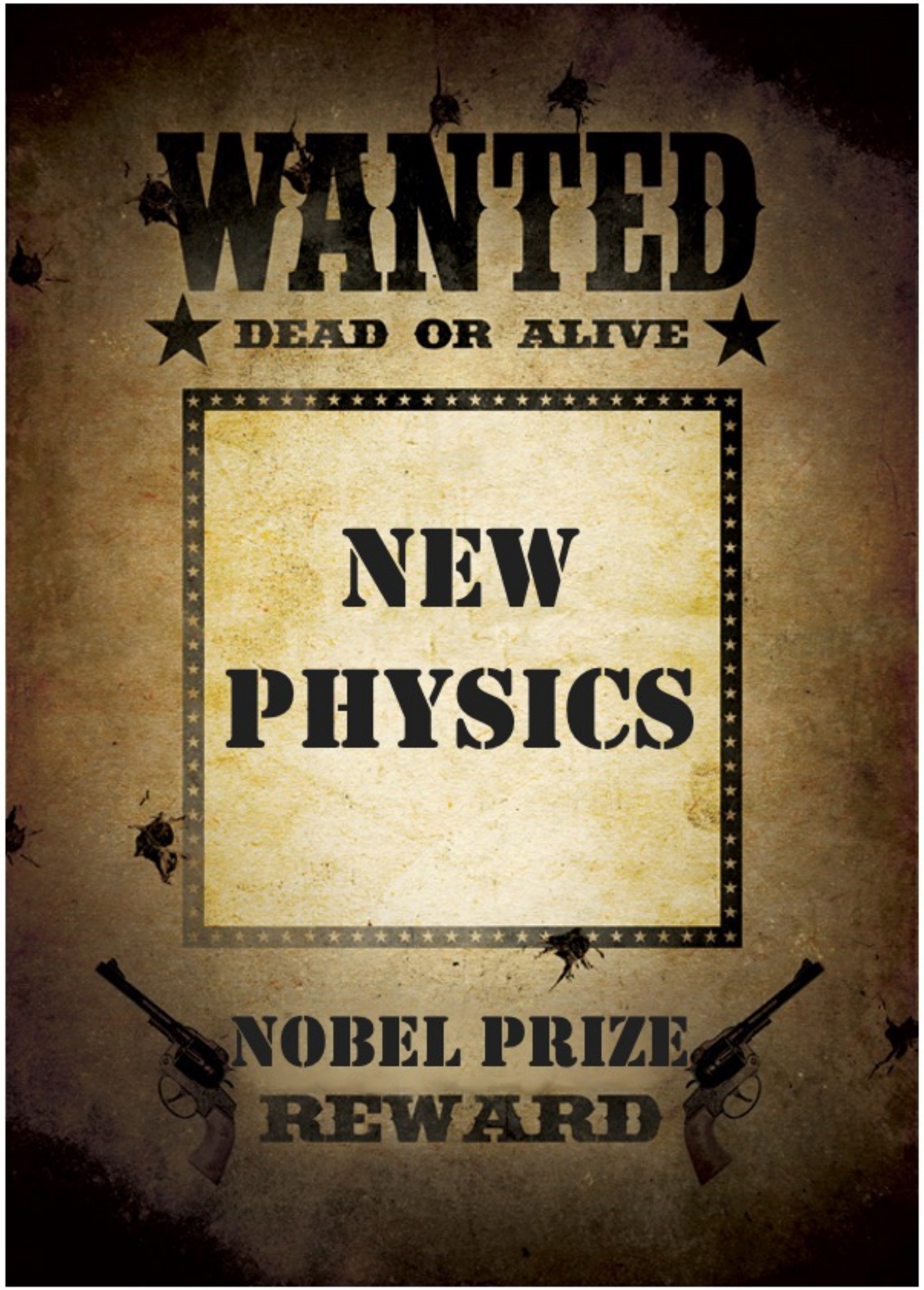
Wayne Hu, University of Chicago

Abundance of ordinary matter, dark matter and dark energy from CMB

- Ordinary matter is just ~5% of the total energy density in the Universe



New Physics is out there, but "where is everybody"?

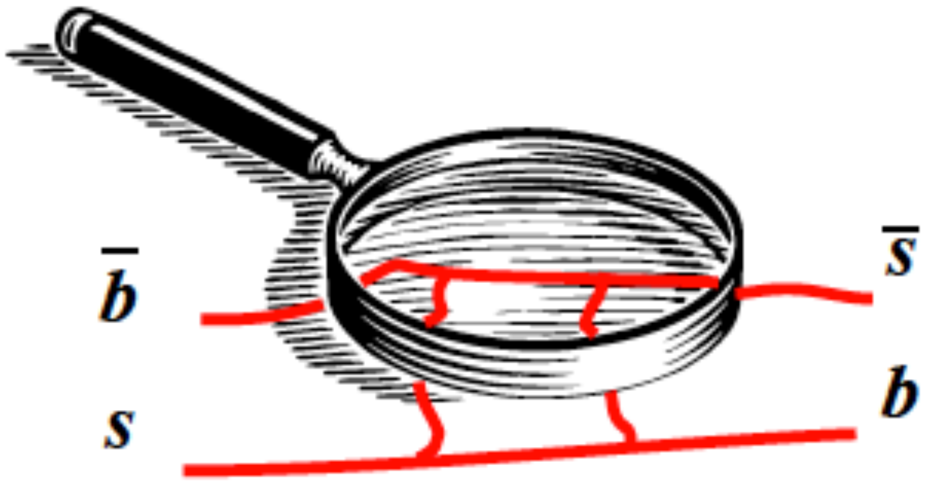


NP general considerations

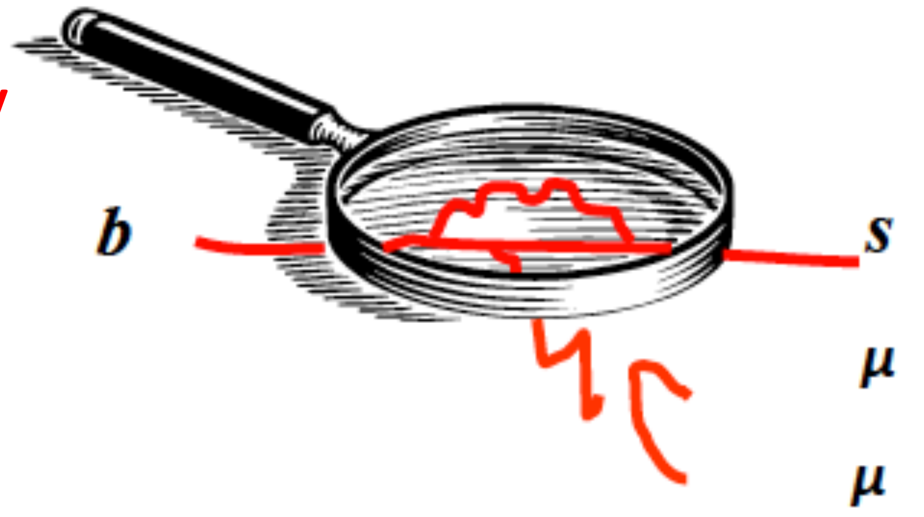
- We are living a stunning contradiction in modern days: we have developed the most successful theory of reality ever made and checked it in a wide number of ways for decades, but we have at the same time developed the awareness that it can't be complete
  - Incidentally, have you ever reflected on why the Standard Model has been named a "model", even without the full awareness of its incompleteness that we have reached today?
- I don't want even to discuss about the multiverse hypothesis, for how brilliant and ingenuous, and worth speculating, simply because that is a 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

Complementarity between low-energy and high-energy measurements

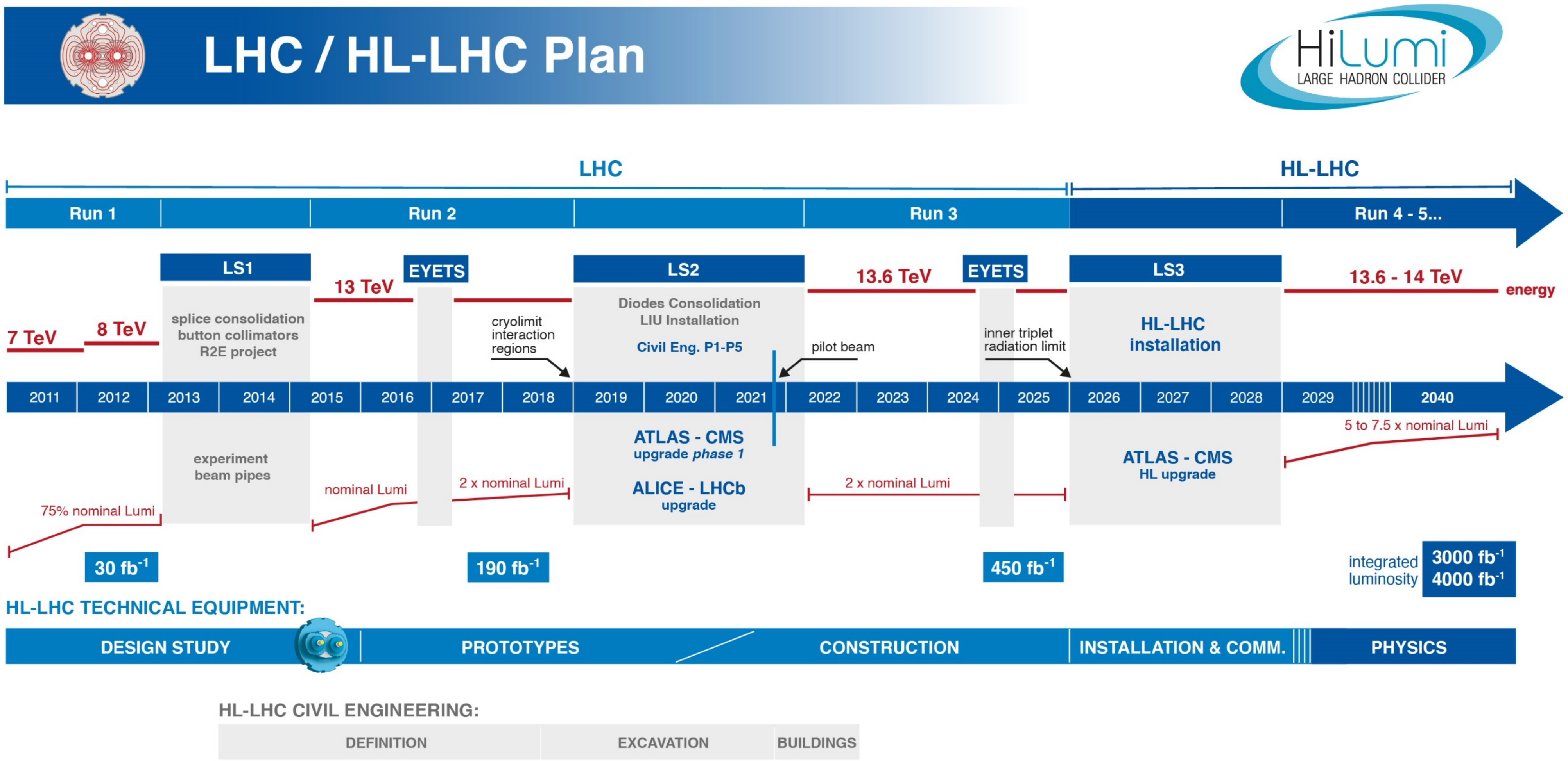
- Experiments like ATLAS and CMS look for the direct production of new heavy particles
  - Obviously, they can be produced and then revealed if the LHC energy is large enough with respect to their masses



- Dedicated flavour-physics experiments, like LHCb, operate instead in a low-energy regime, studying processes involving beauty, charm and strange quarks
  - Looking for indirect effects of virtual new physics particles entering Feynman graphs

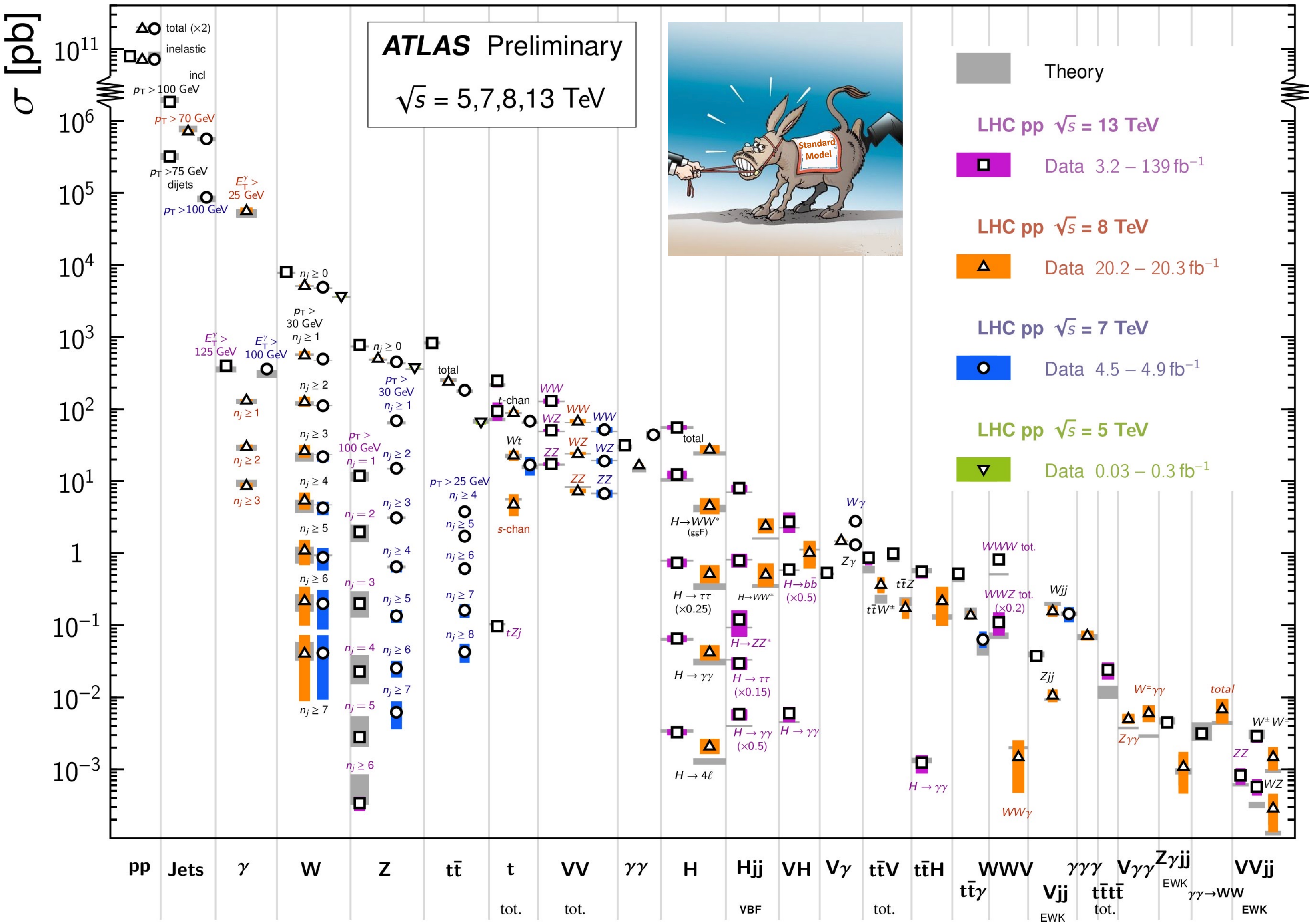


The most powerful tool we have got today



- 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

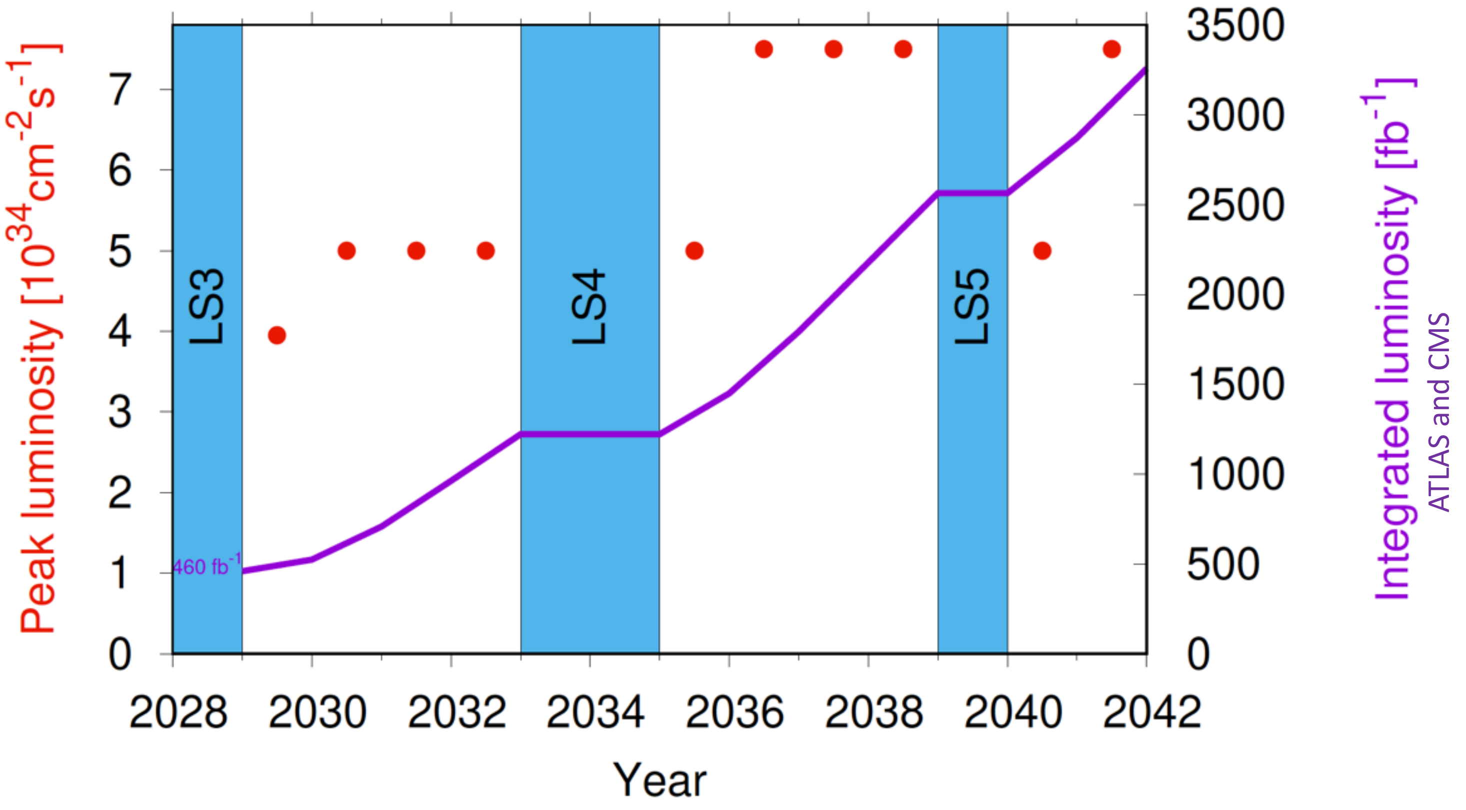
We have never seen anything like this!



- 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

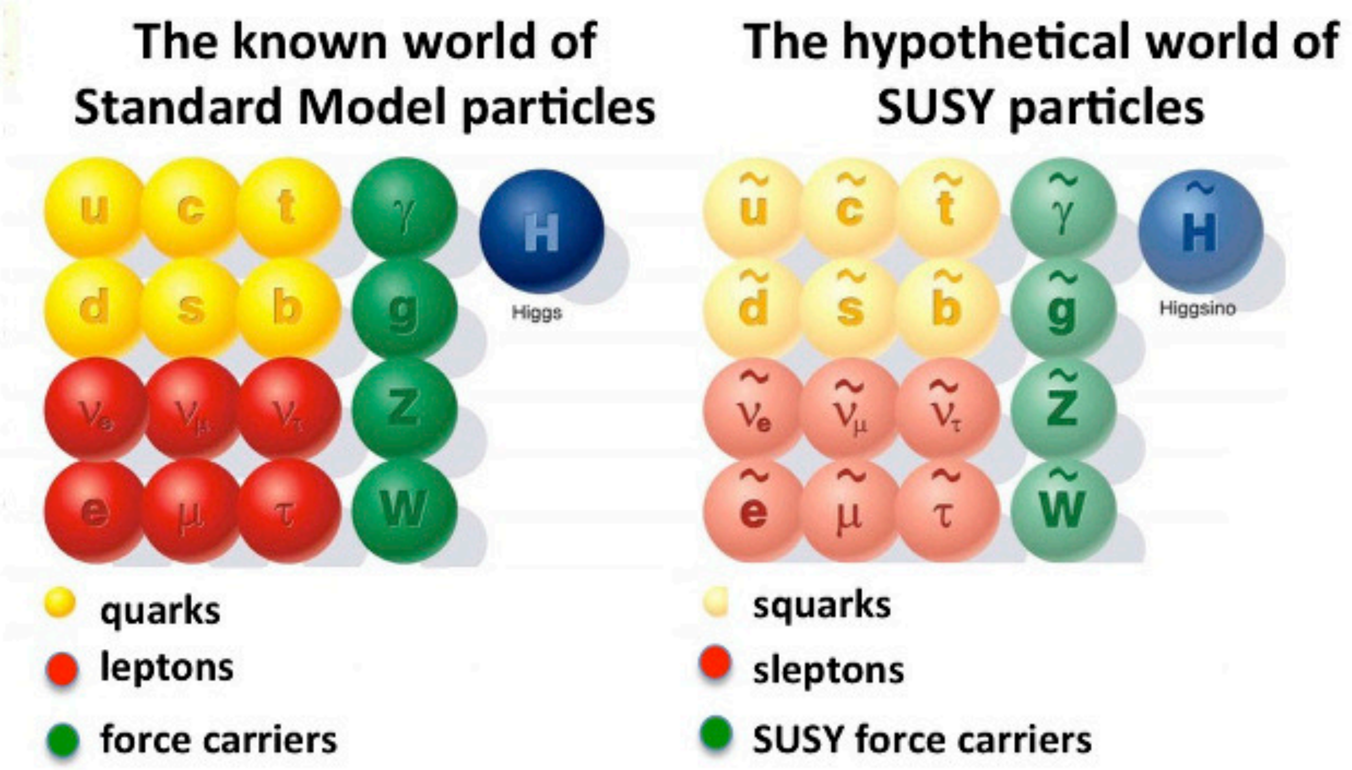
The High-Luminosity LHC

- 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!

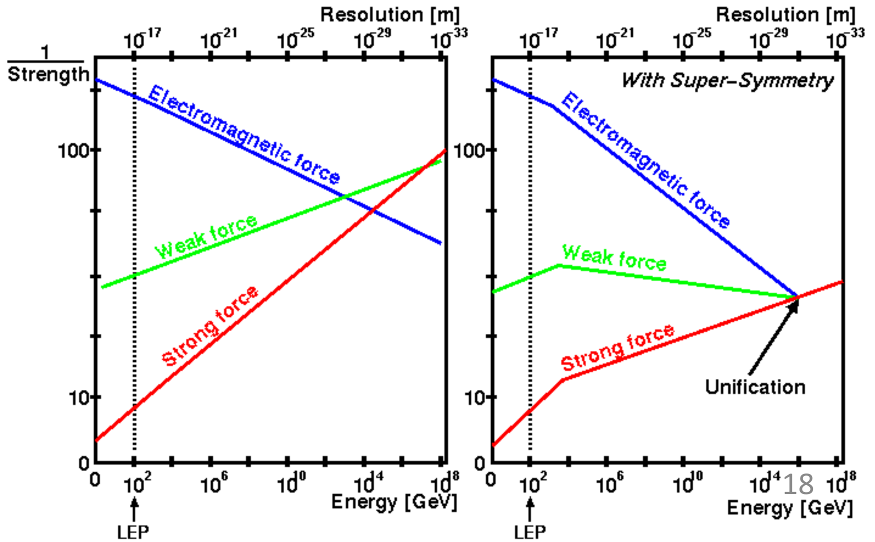


Phase-II upgrades of ATLAS and CMS now being in the production phase, to be installed during Long Shutdown 3. Further upgrades of ALICE and LHCb foreseen for Long Shutdown 4

What about supersymmetry?

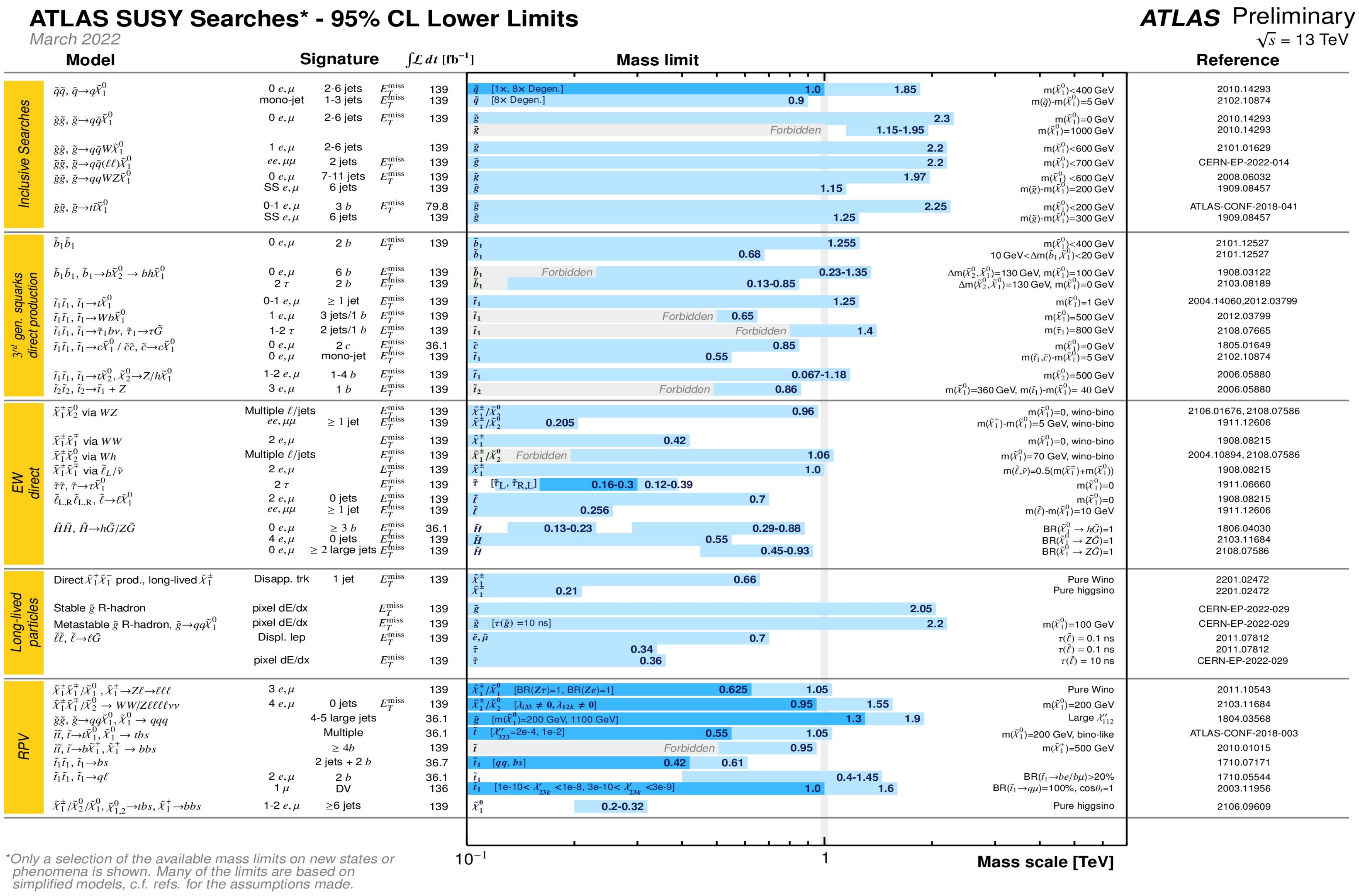


- SUSY predicts massive shadow copies of Standard Model particles on the basis of a spacetime symmetry
- It's a long-shot and very elegant idea developed since long time in the context of GUTs, attempting to unify EM, weak and strong forces

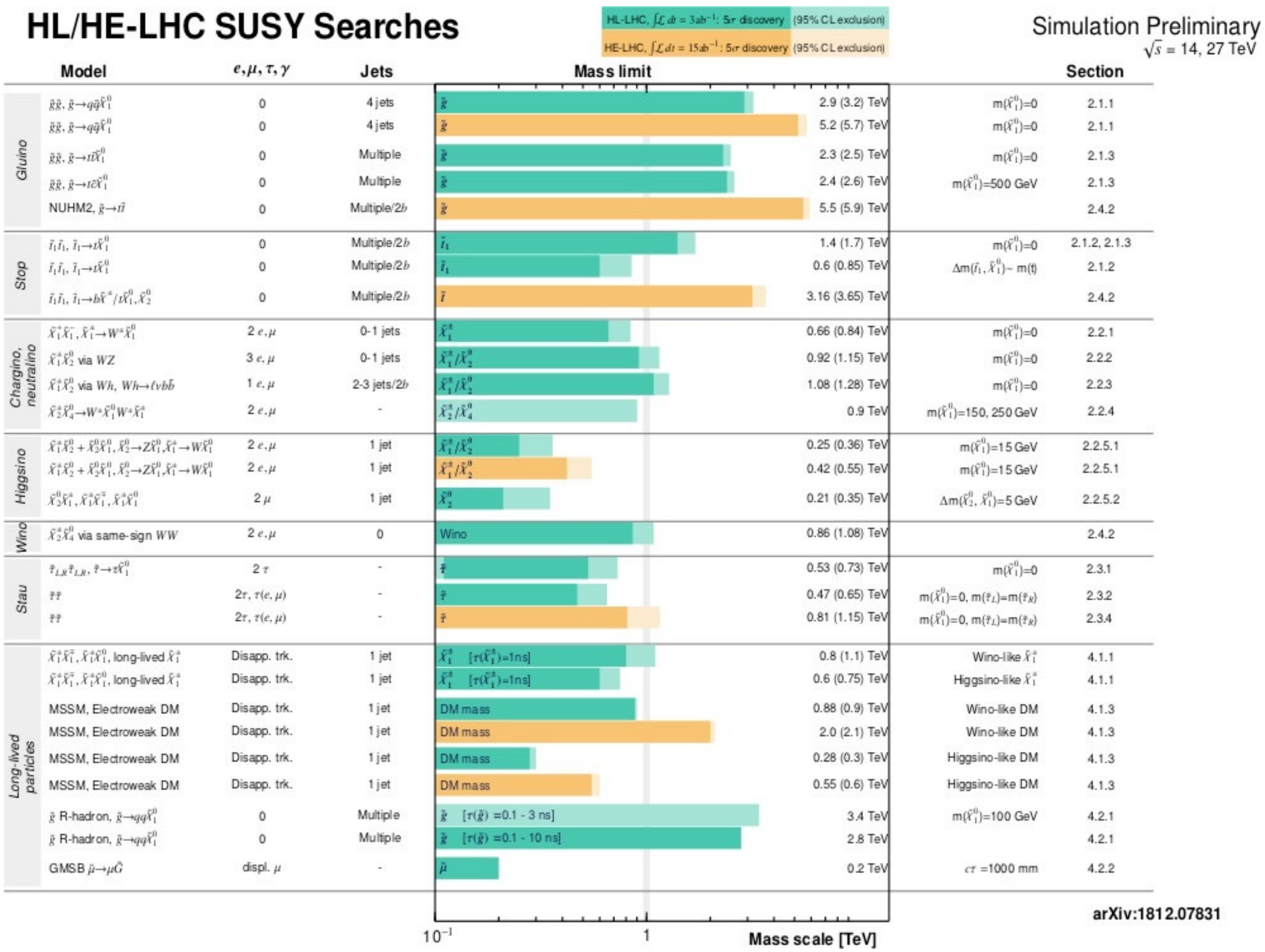


- This was for long considered as one of the holy grails of the LHC beyond the Higgs
- But there are dozens of SUSY models, and searches must be very specialised

But unsuccessful searches so far…



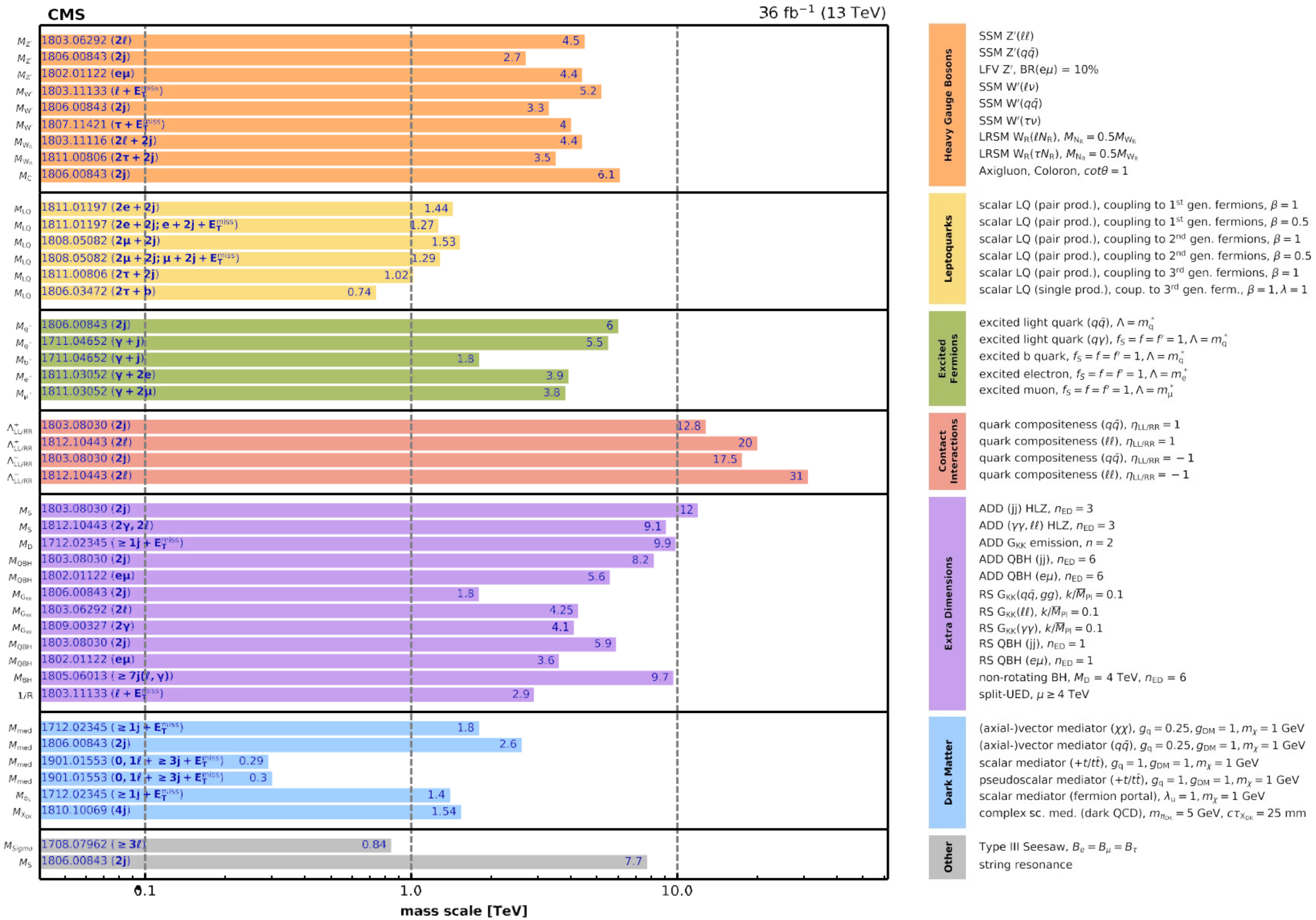
But the HL-LHC is at the gates and the quest continues



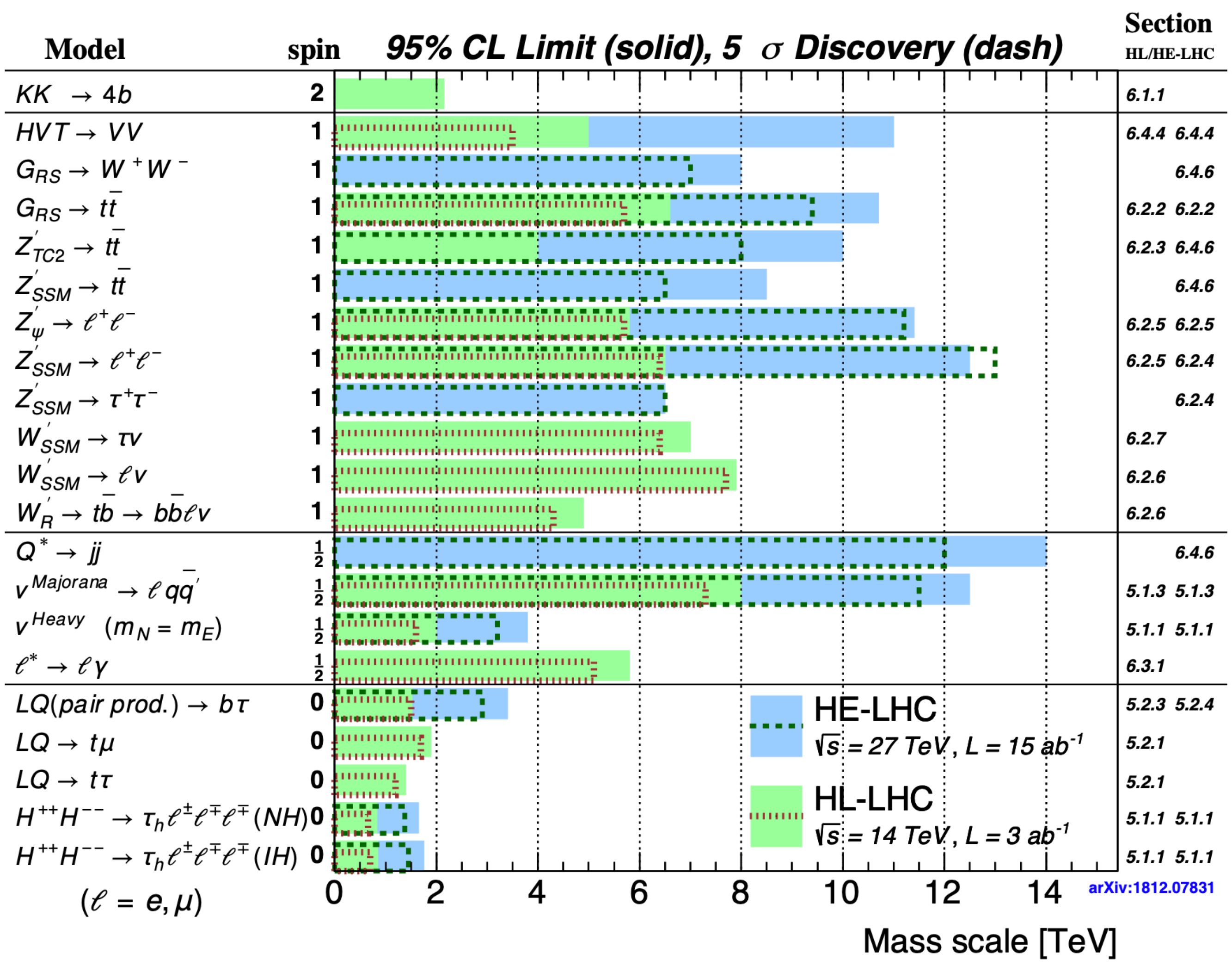
- Reachable mass scale will be raised by roughly a factor 2-ish
- You may correctly argue that the increment in mass scale is limited and we would need to be lucky if it will be so “simple” (not to be excluded though)
- And this means we must prepare for further efforts if nothing pops up at that stage

There's not only supersymmetry

- Other "exotics" being looked for, like heavy gauge bosons, leptoquarks, extradimensions, dark sector, …



And also here, the HL-LHC will improve further

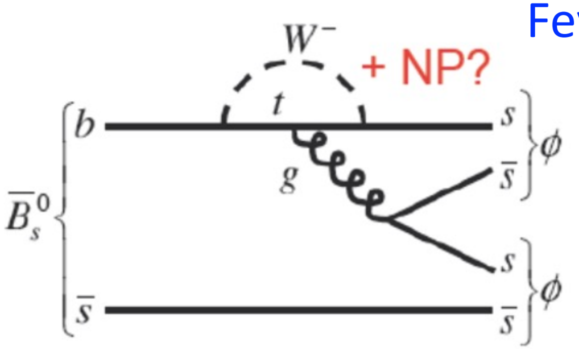


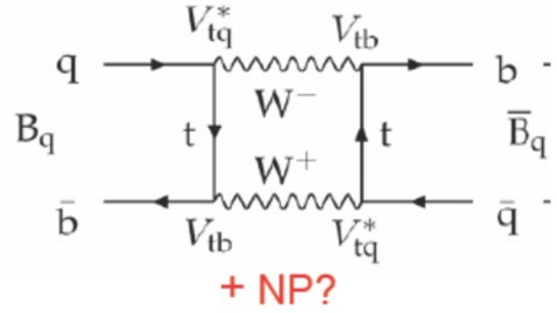
- E.g., Z' up to 6 TeV, W' up to 8 TeV, leptoquarks up to 2 TeV, charged Higgs up to 1 TeV
- Similar considerations on the increase in mass scale hold, although one also needs to consider continuous progress in analysis techniques which can easily transform a factor 2 into a factor 4!
- If you are interested on the subject, a comprehensive review is available here https://arxiv.org/abs/1812.07831

First pit stop

The indirect way to New Physics

Feynman diagrams with closed loops : new-physics virtual particles can circulate





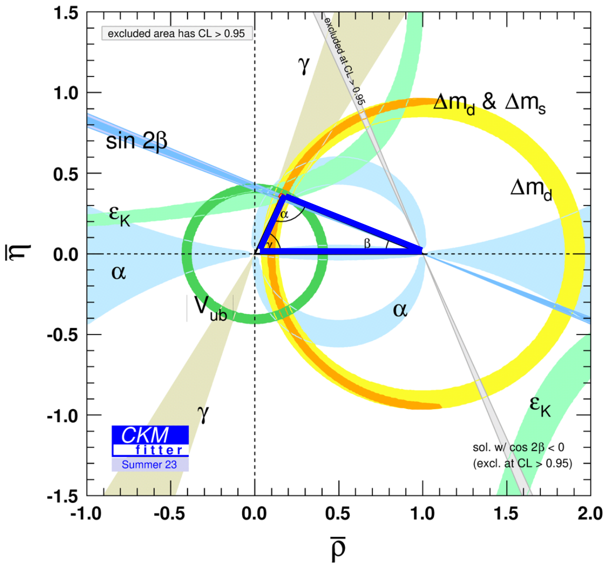
$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- General decomposition of a transition amplitude in terms of couplings and scales
- Must know the Standard Model contribution precisely, otherwise it could hide small new-physics effects
  - Need to go to high precision measurements of observables that can be calculated in the Standard Model with the smallest possible uncertainty
- The plus is that new-physics virtual particles of arbitrarily large mass can enter loops in Feynman diagrams and produce observable effects → the existence of particles with much larger masses than the energy made available by the LHC could be unveiled

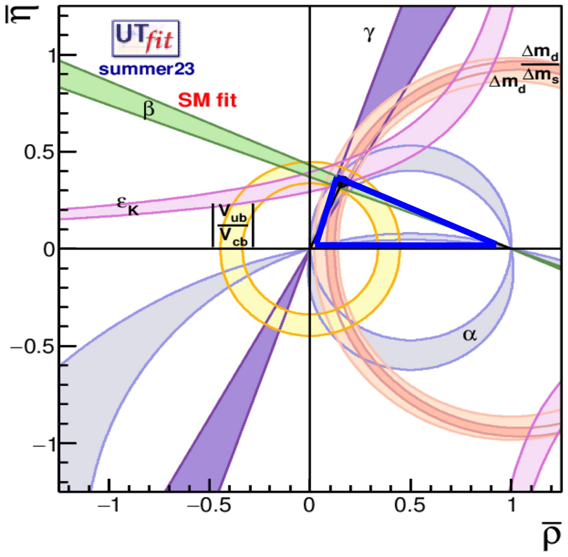
Consistency of global CKM fits

- Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process

http://ckmfitter.in2p3.fr

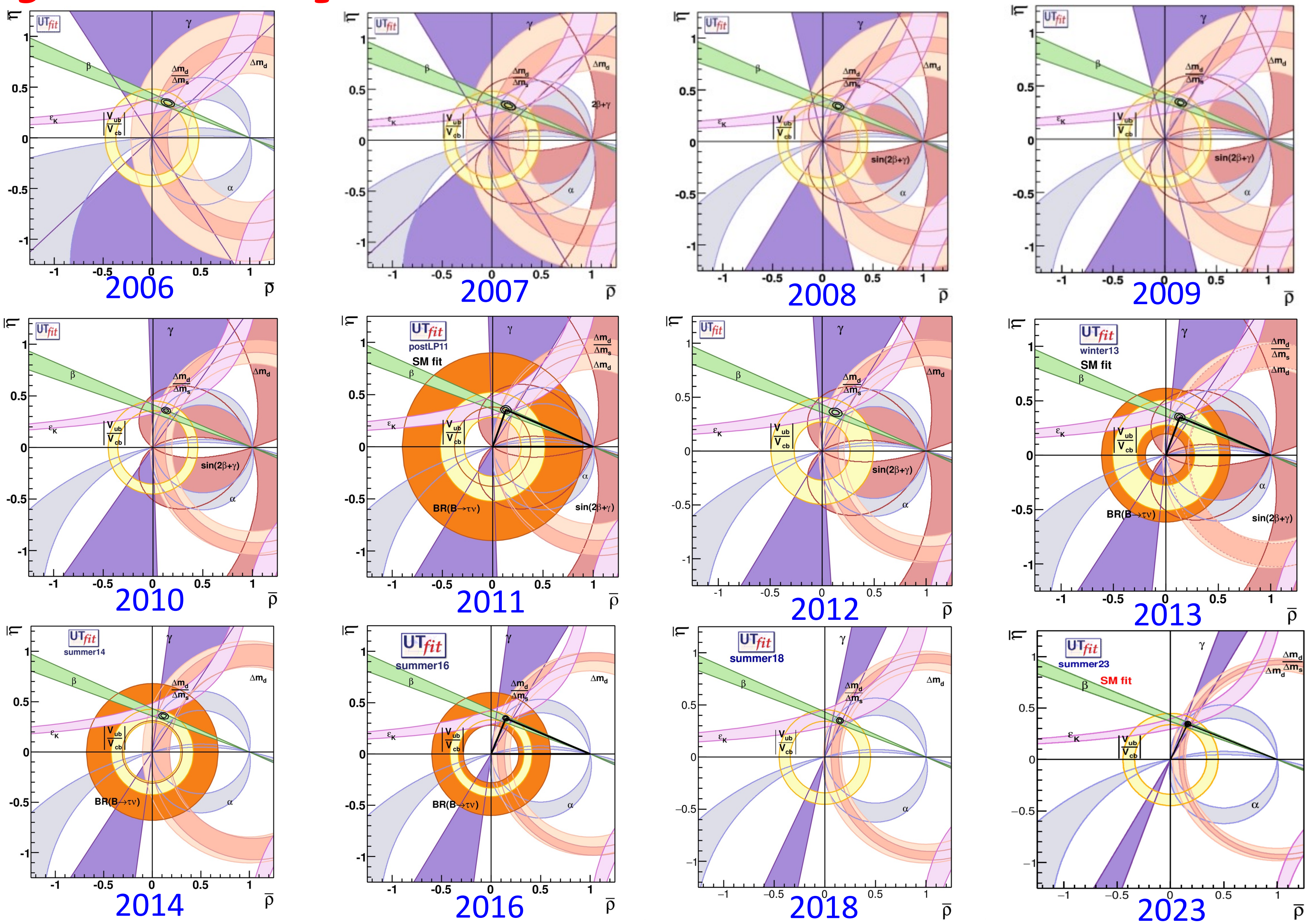


http://www.utfit.org

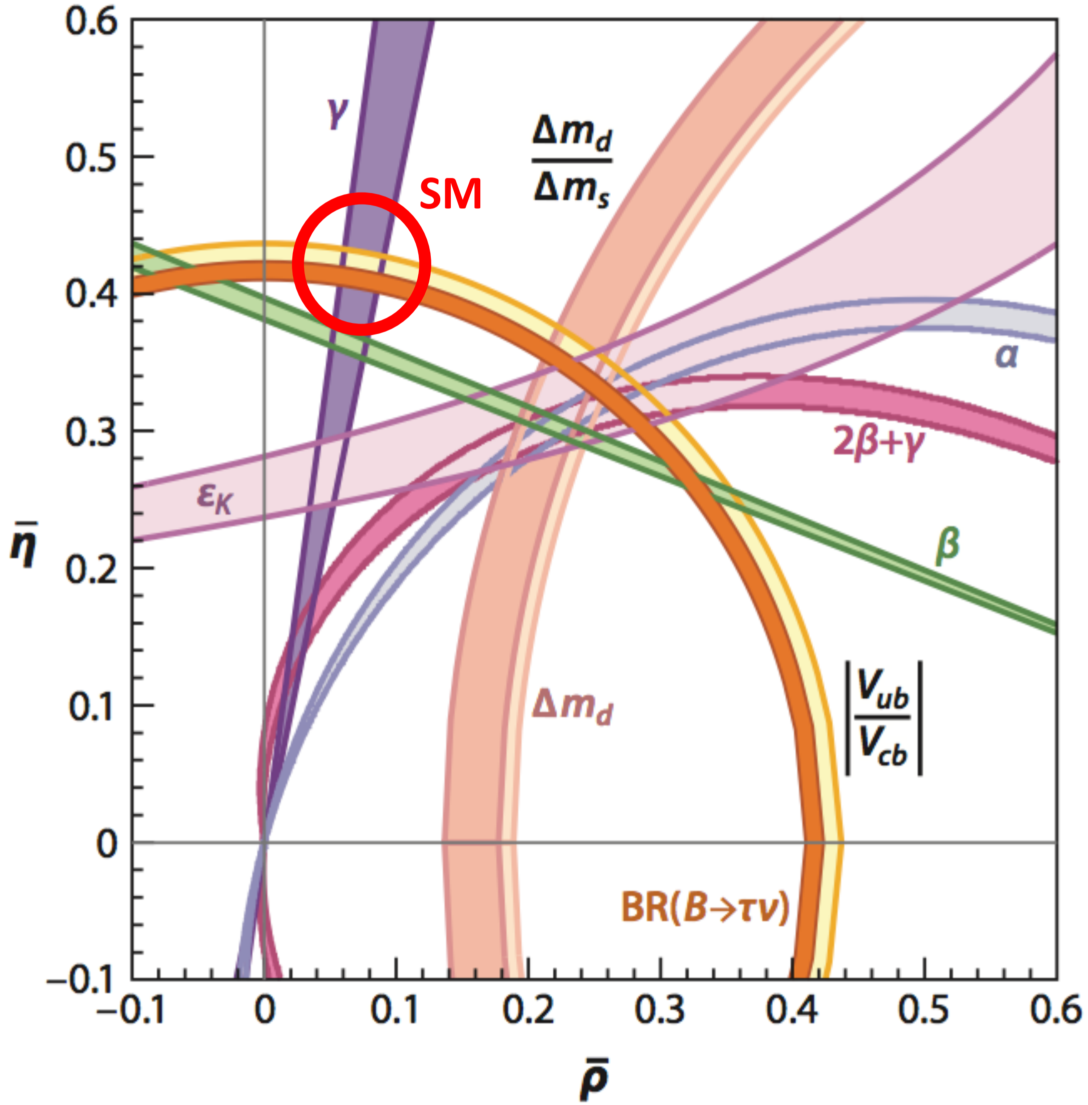


- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is generally well described by the CKM mechanism, but there's still room for new physics contributions at the ~10% level

Long journey to reach here…



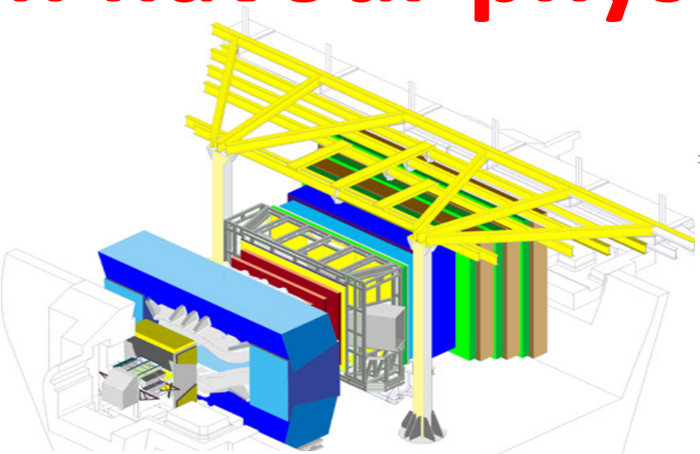
What’s the aim?

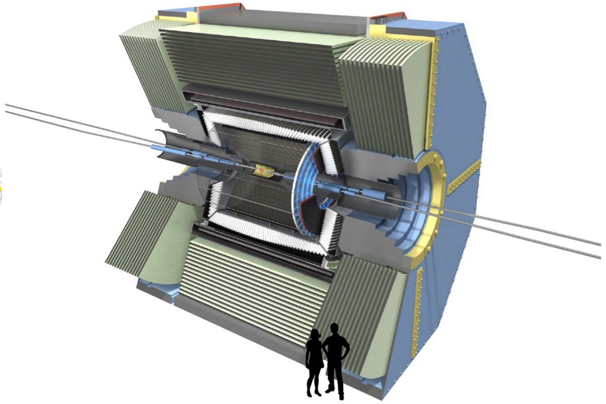


Dream scenario, for illustration only

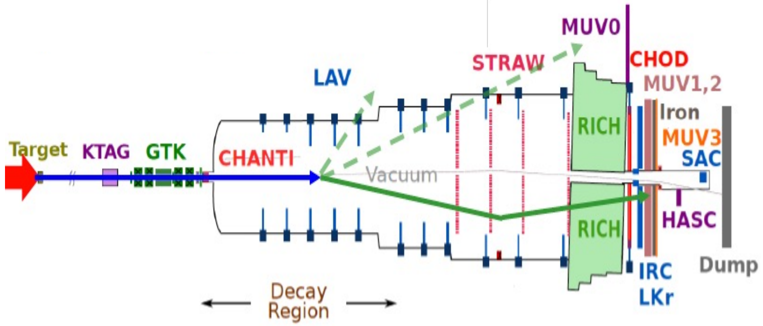
Main players in flavour physics today

- LHCb and Belle II: dedicated detectors for flavour physics with wide range of measurements

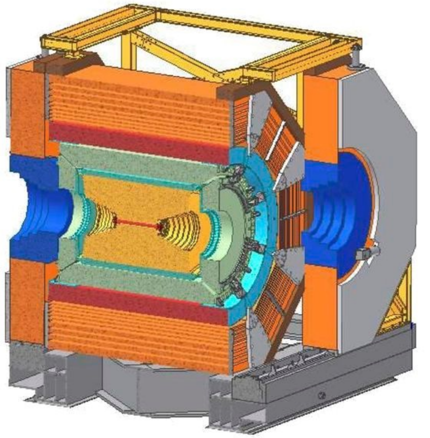




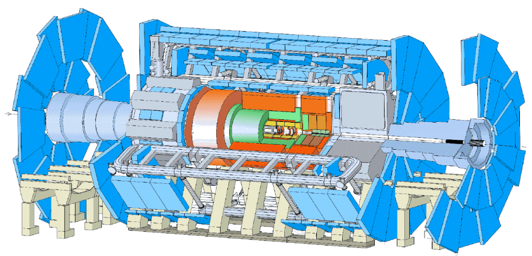
- NA62: measure the SM branching fraction of $K^+ \rightarrow \pi^+ \nu\nu$ with 10% precision

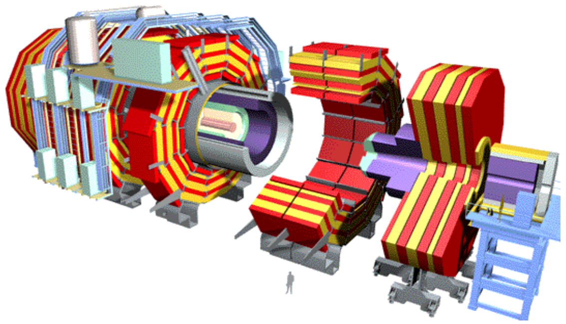


- BESIII: mainly charm and charmonium spectroscopy, but not only



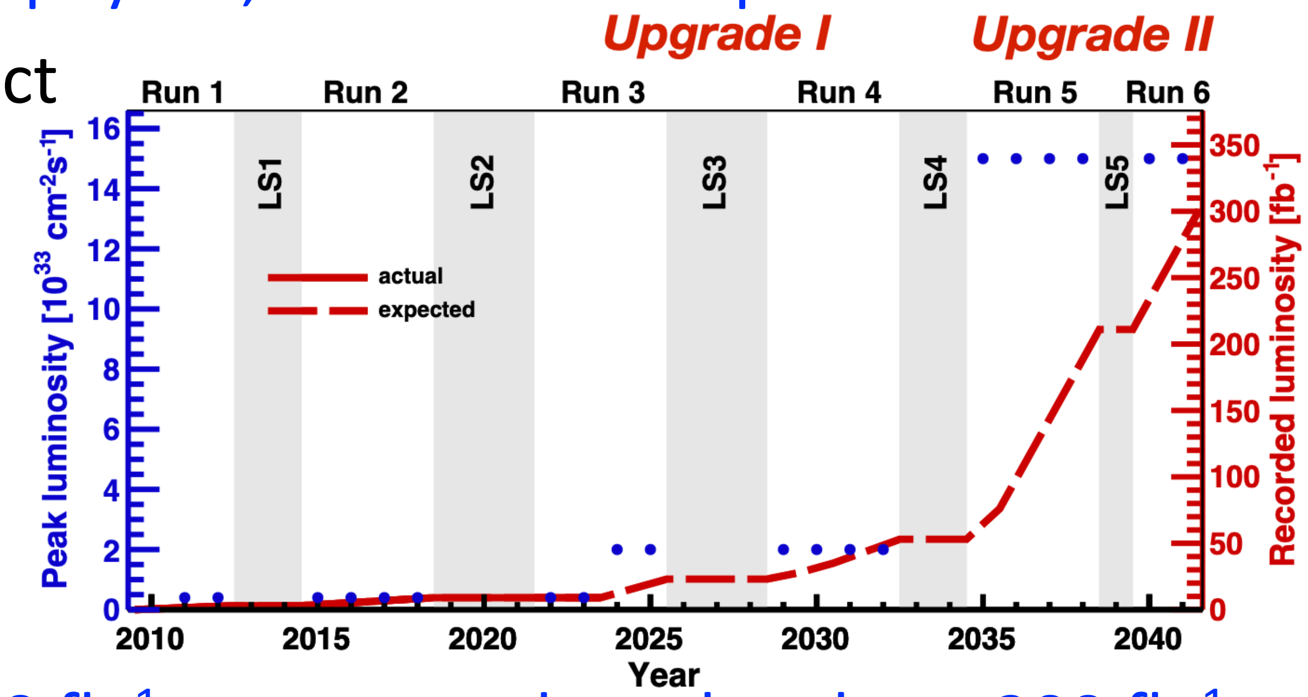
- ATLAS and CMS : measure some relevant B-physics channels, mainly with muons in the final state → but also new prospects eagerly awaited with parked data





Future challenges at LHCb

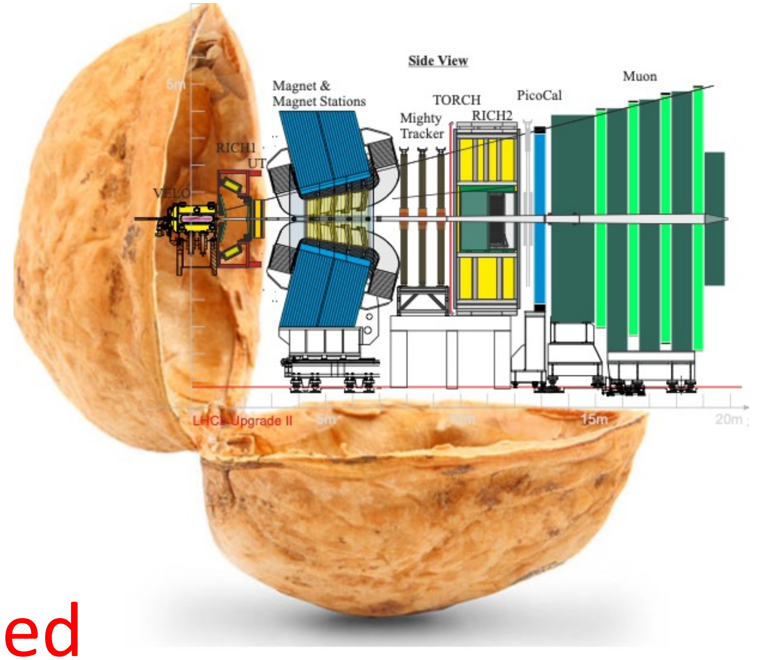
- European Strategy Update 2020: "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited"
- LHCb Upgrade I was designed to collect 50 fb^{-1} by end of Run 4, but there is the opportunity to operate the experiment until the end of HL-LHC
  - With this in mind, the LHCb Upgrade II detector is being designed to accumulate the maximum possible integrated luminosity



- The proposed baseline is to achieve 50 fb^{-1} per year and reach at least 300 fb^{-1} at the end of Run-6
- That will allow for unprecedented samples and a compelling physics programme

LHCb Upgrade II in a nutshell

- Unique scientific programme with BSM discovery potential with unprecedented sensitivity for *B* and *D* physics
- Furthermore, broad programme on spectroscopy, EW precision measurements, top and Higgs physics, dark sector searches, heavy ions and fixed target, all made with a unique and fully instrumented forward acceptance



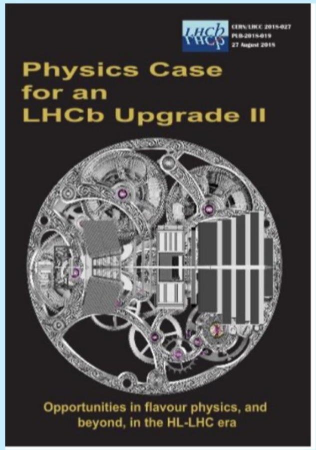
- Besides the luminosity increase and the necessary detector modifications to allow for higher multiplicity and radiation damage, it is also proposed to add further sub-detectors to expand the original programme
- Technology-wise, it provides an exciting technology roadmap with novel detectors and electronics

LHCb Upgrade II: approval steps so far

EoI

[LHCC-2017-003]

Physics case



[LHCC-2018-027]

Accelerator study [CERN-ACC-2018-038]

CERN Research Board September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

LHCC-2021-012

FTDR approved on March 2022

- Detector design and technology options
- R&D program and schedule
- Cost for baseline and options
  National interests

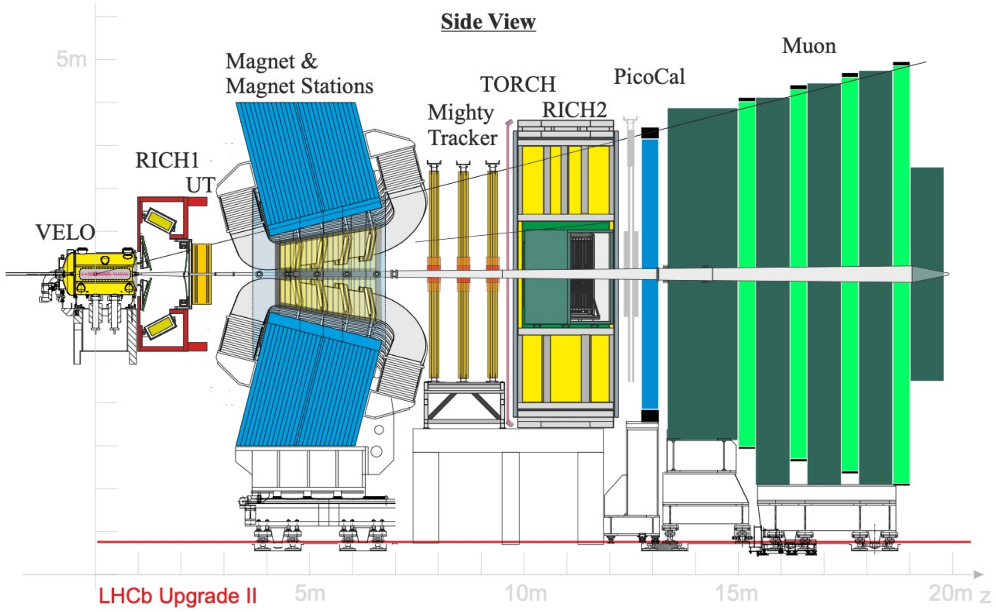
"The **LHCC recommends** that LHCb continue the R&D necessary to complete technical design reports on the proposed schedule, …"

"The **LHCC recommends** the continued investigation of descoping and other cost-saving possibilities. …"

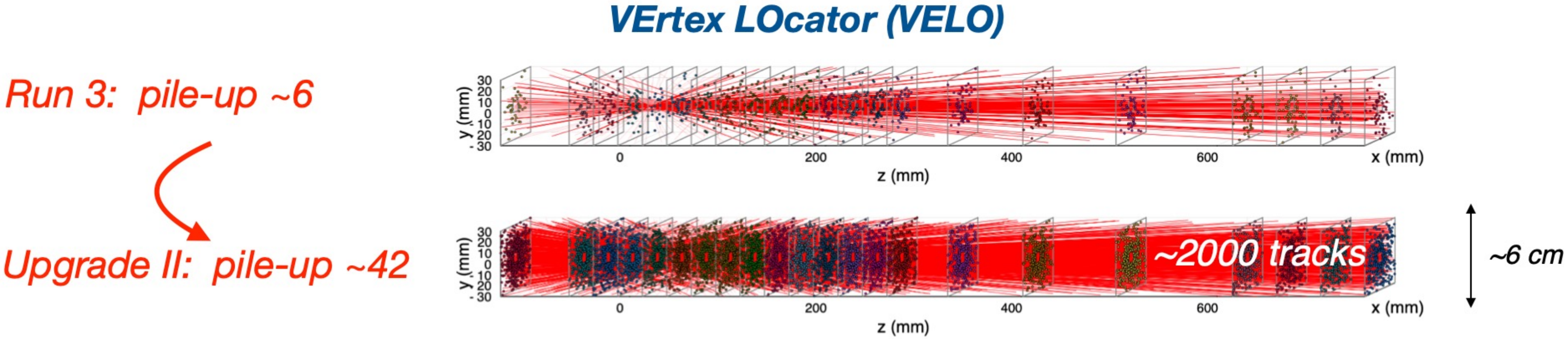
"The **LHCC recommends** that a well-defined process to establish the financial envelope prior to the preparation of TDRs be set up and notes that close coordination with funding agencies will likely be required in this process.

The new detector

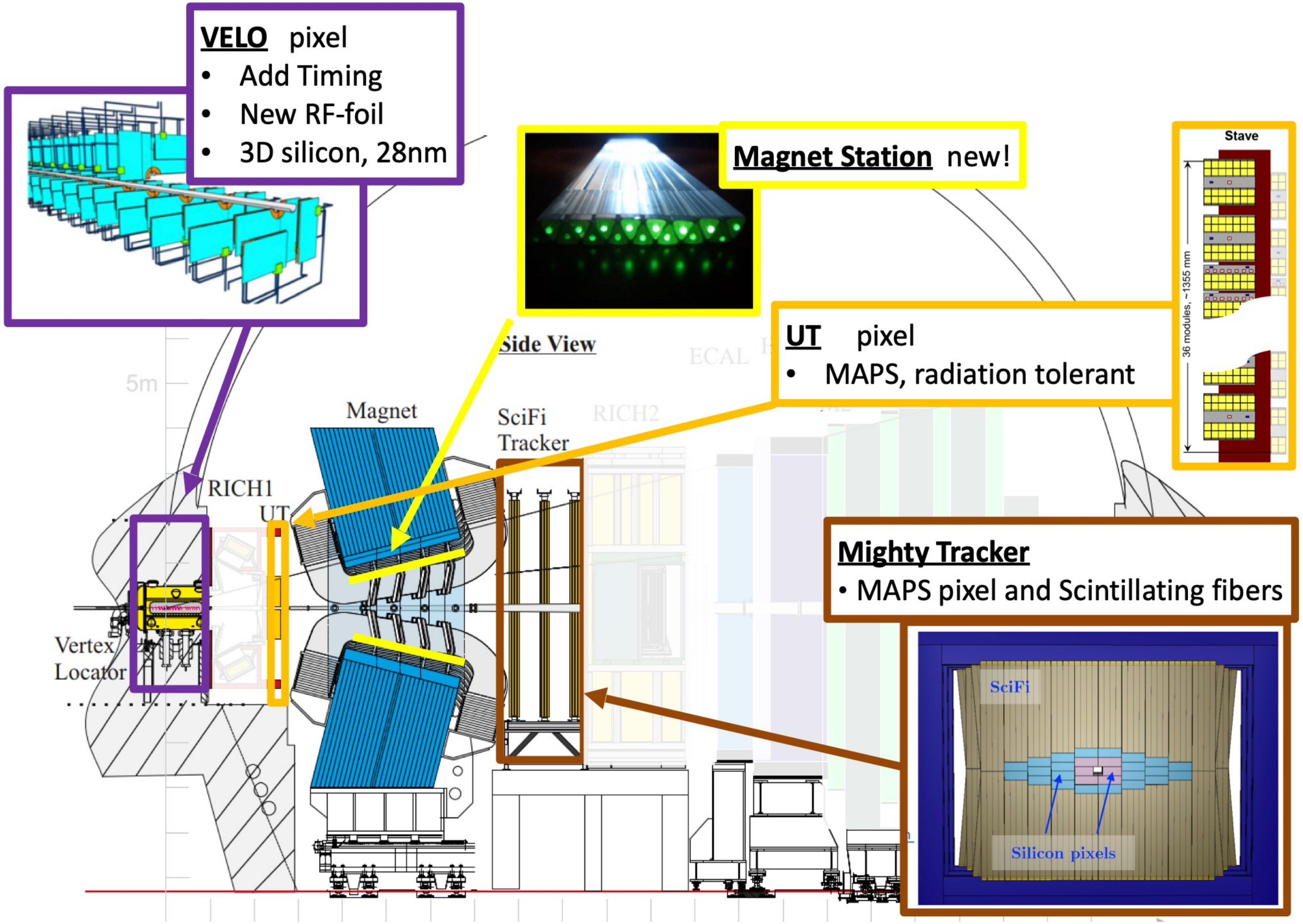
- Targeting the same performance, or even better in certain areas, as in Run-3, but with an increased pile-up of an order of magnitude
- Same footprint of the spectrometer, but with innovative technology for sub-detectors and data processing



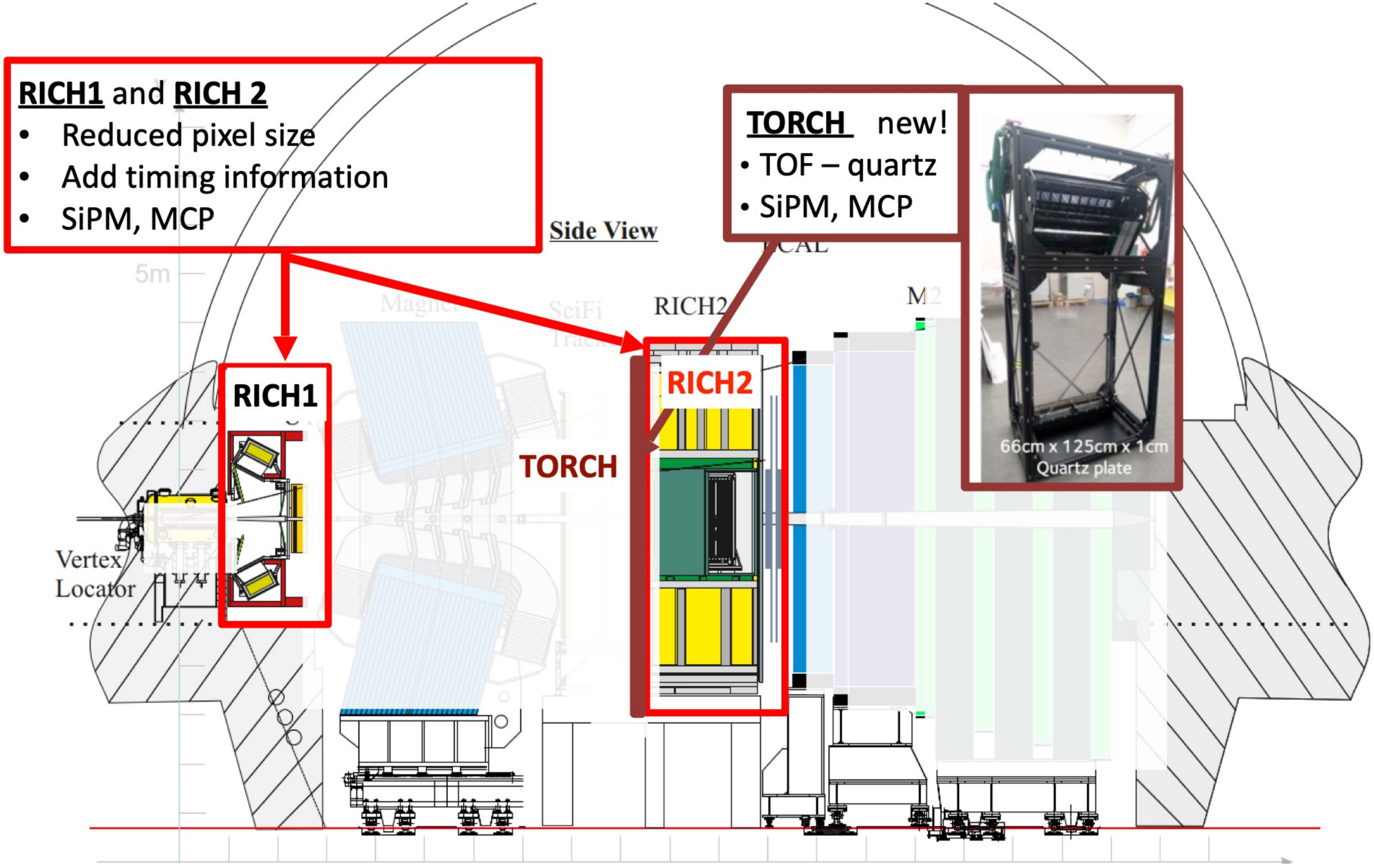
- Key ingredients
  - High granularity
  - Fast timing (few tens of ps)
  - Radiation hardness (up to few 10^{16} neq/cm^2)



New tracking detectors

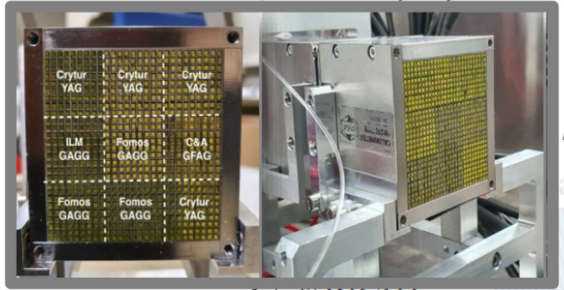


New PID detectors

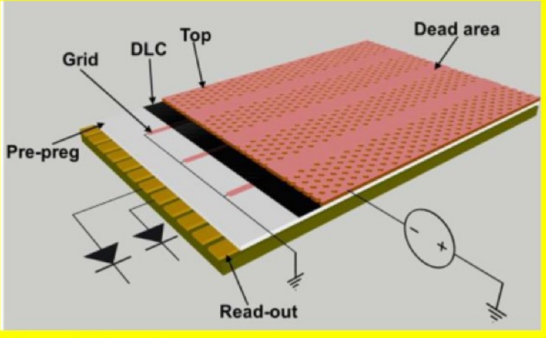


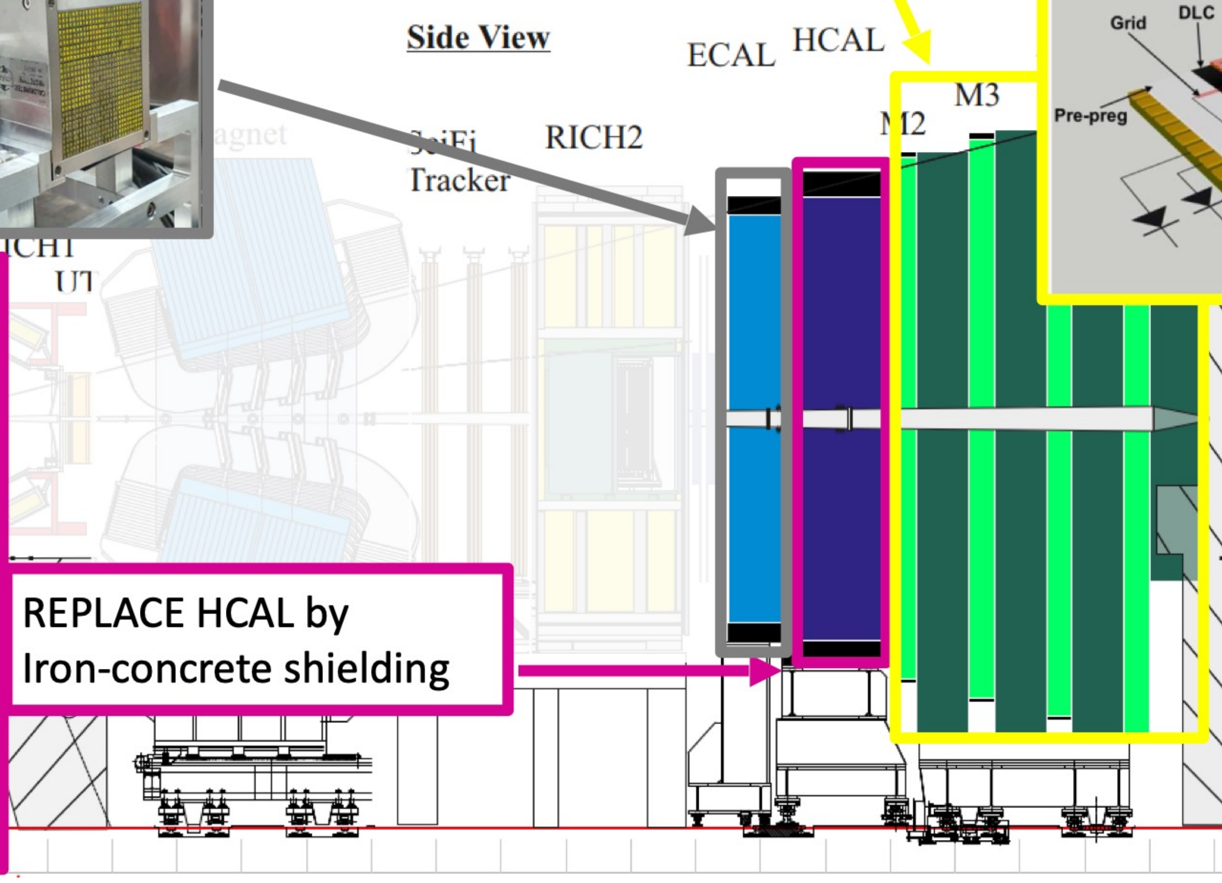
New PID detectors

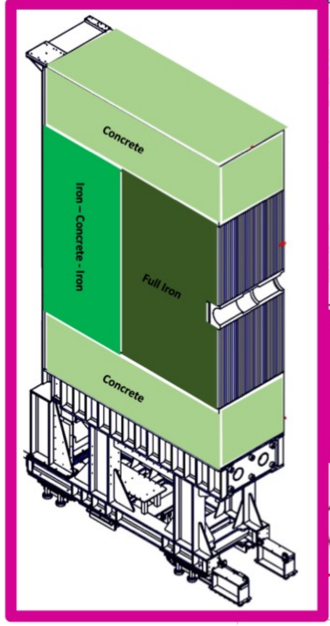
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals



Muon
- µRWELL for inner regions
- MWPC for outer regions (recycles)



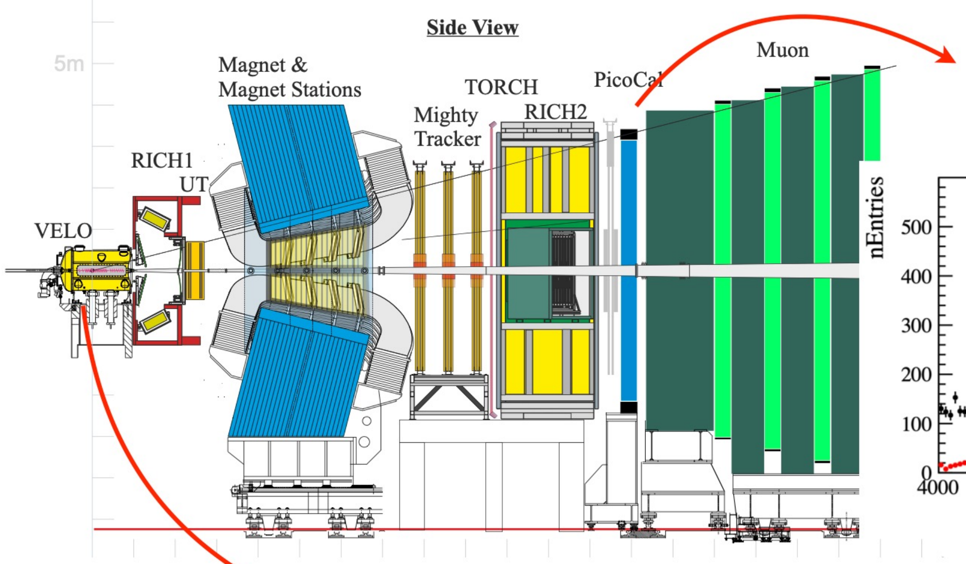




REPLACE HCAL by
Iron-concrete shielding

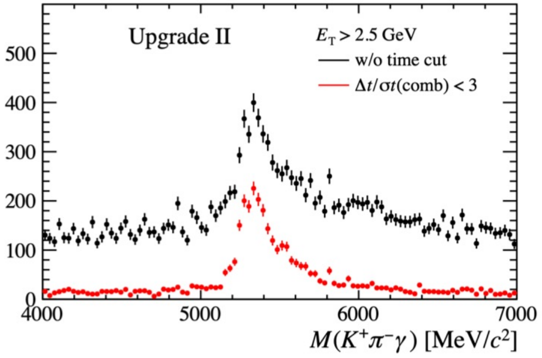
The importance of precision timing

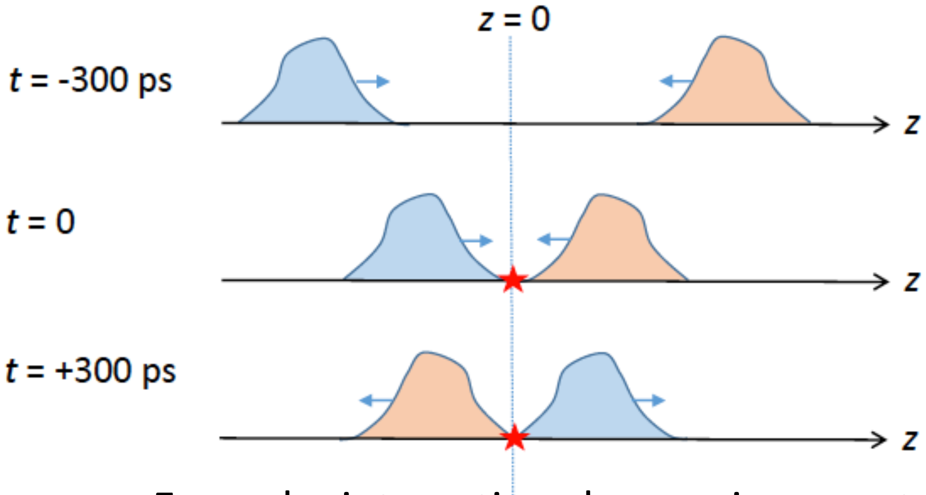
- Timing capability with a resolution of a few tens of picoseconds is a key to reduce background and associate signal decays to correct p-p primary vertices



precision timing in calorimeter

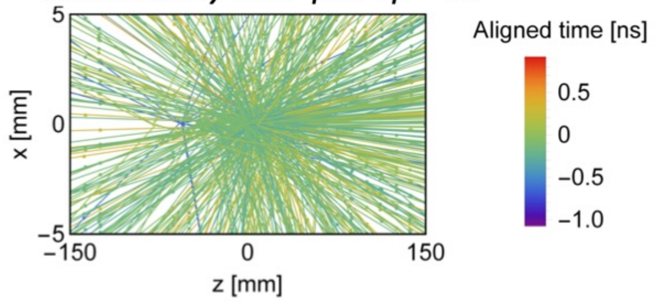
precision timing in VELO



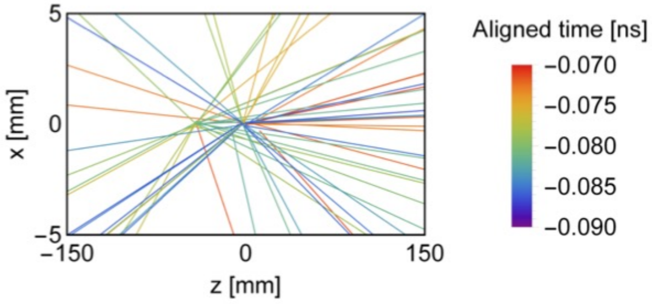


Example: interactions happening are at same *z* but separated by 300 ps in time

track density with pile-up ~40



20 ps time window applied

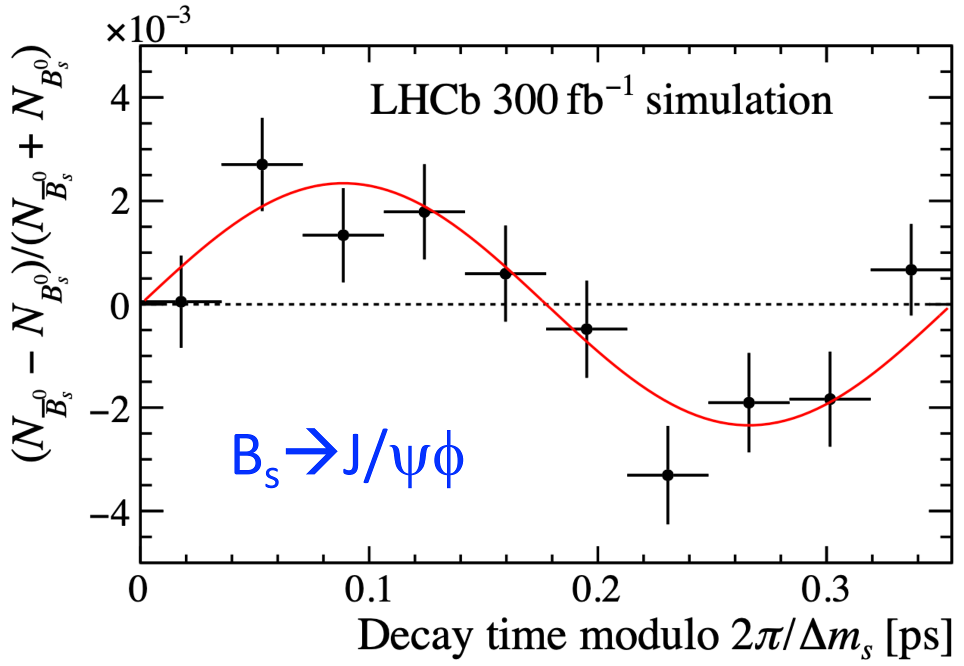


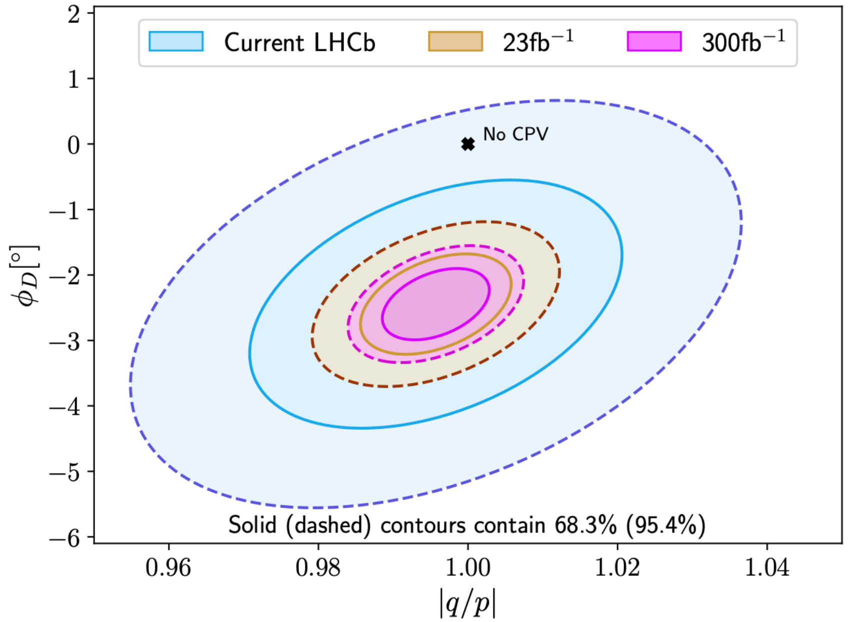
The programme requires strong R&D on sensors, already ongoing, and dedicated efforts for the design of new FEE ASICs

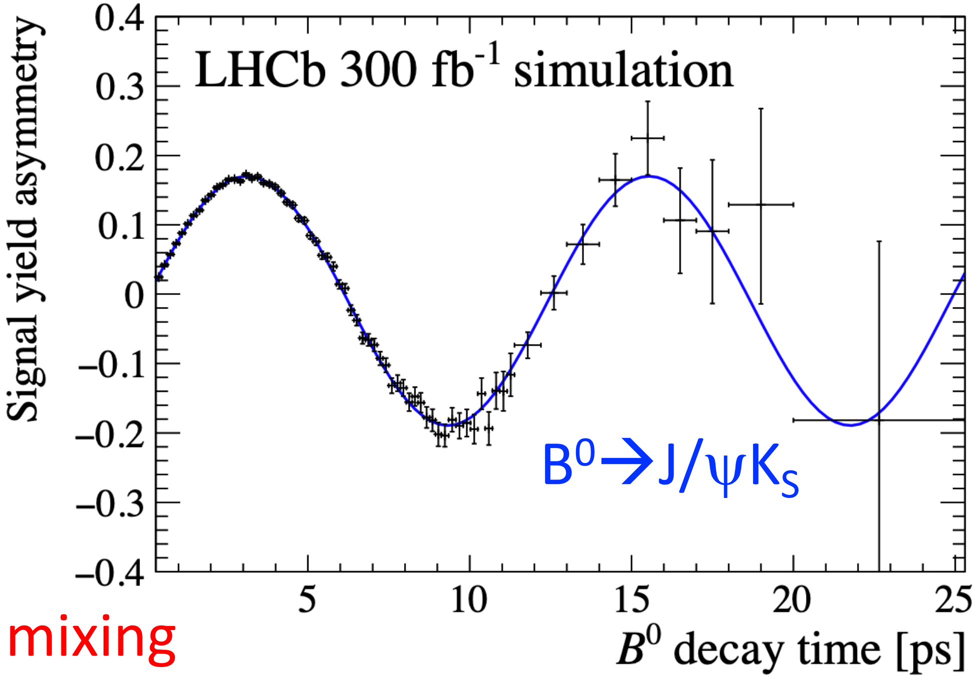
LHCb Upgrade II Physics Case: *CP* violation

- σ(γ): 0.4°
- σ(φ_s): 4 mrad
- σ(sin2β): 0.003
- σ(Charm CPV): $O(10^{-5})$

Impressive precision on CP violation phases



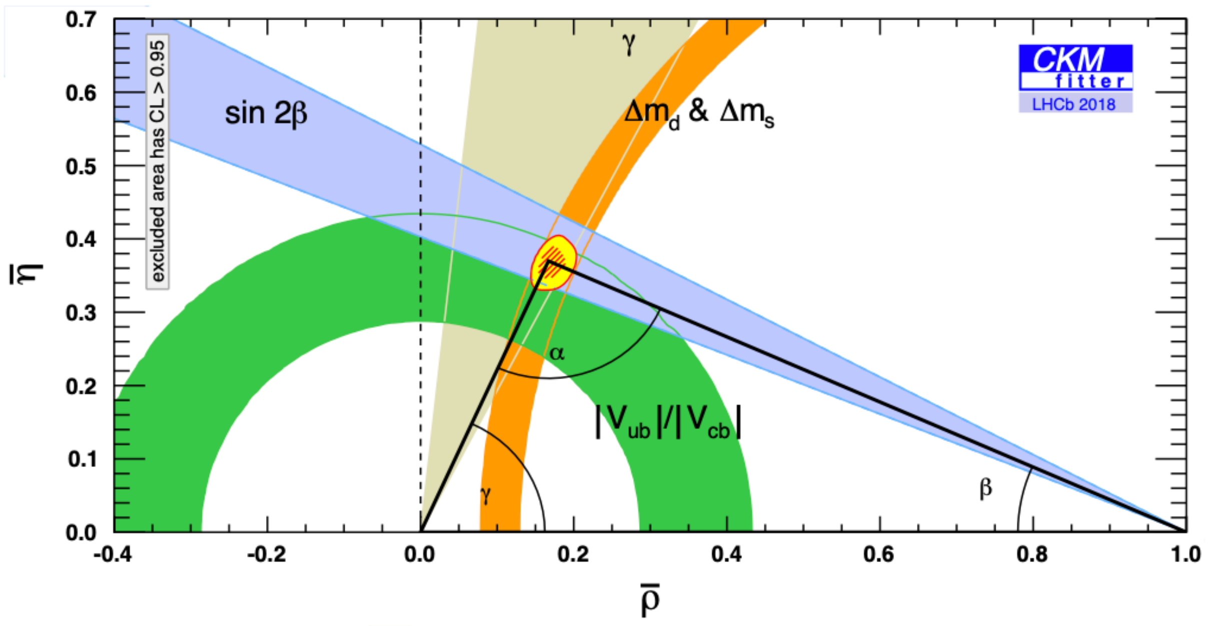


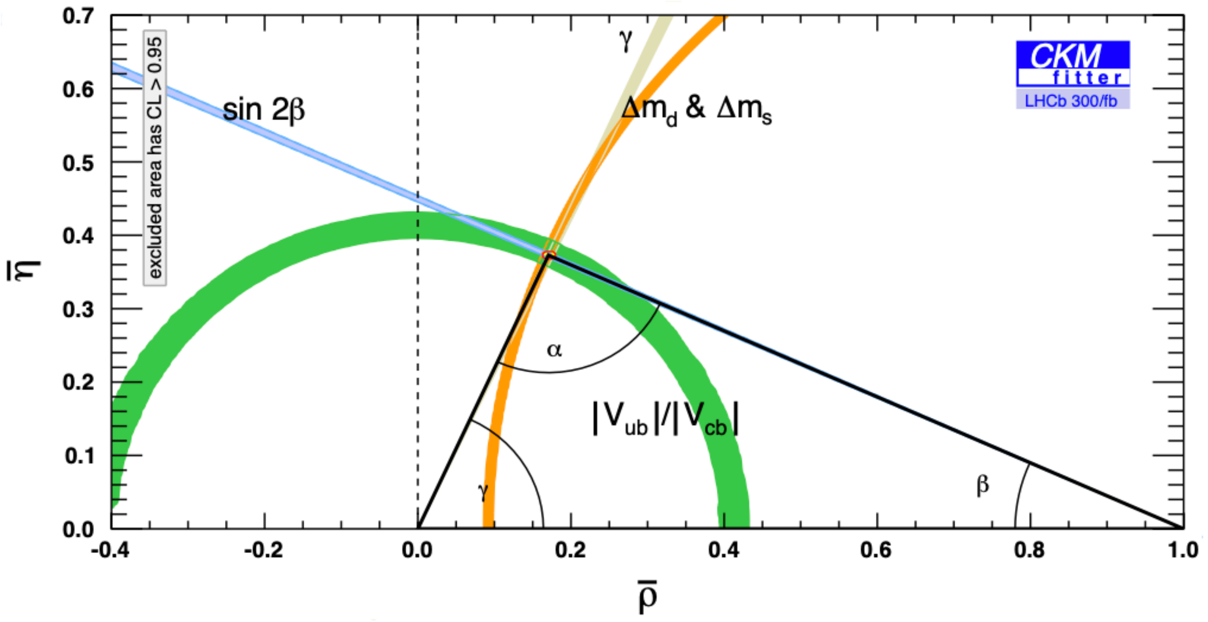


LHCb Upgrade II is the only planned facility with the realistic possibility to observe *CP* violation in charm mixing

Unitarity Triangle improvements after Upgrade II

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy





Two independent measurements of triangle apex: ($\Delta m_d/\Delta m_s$, sin 2β) and (V_{ub}, γ)

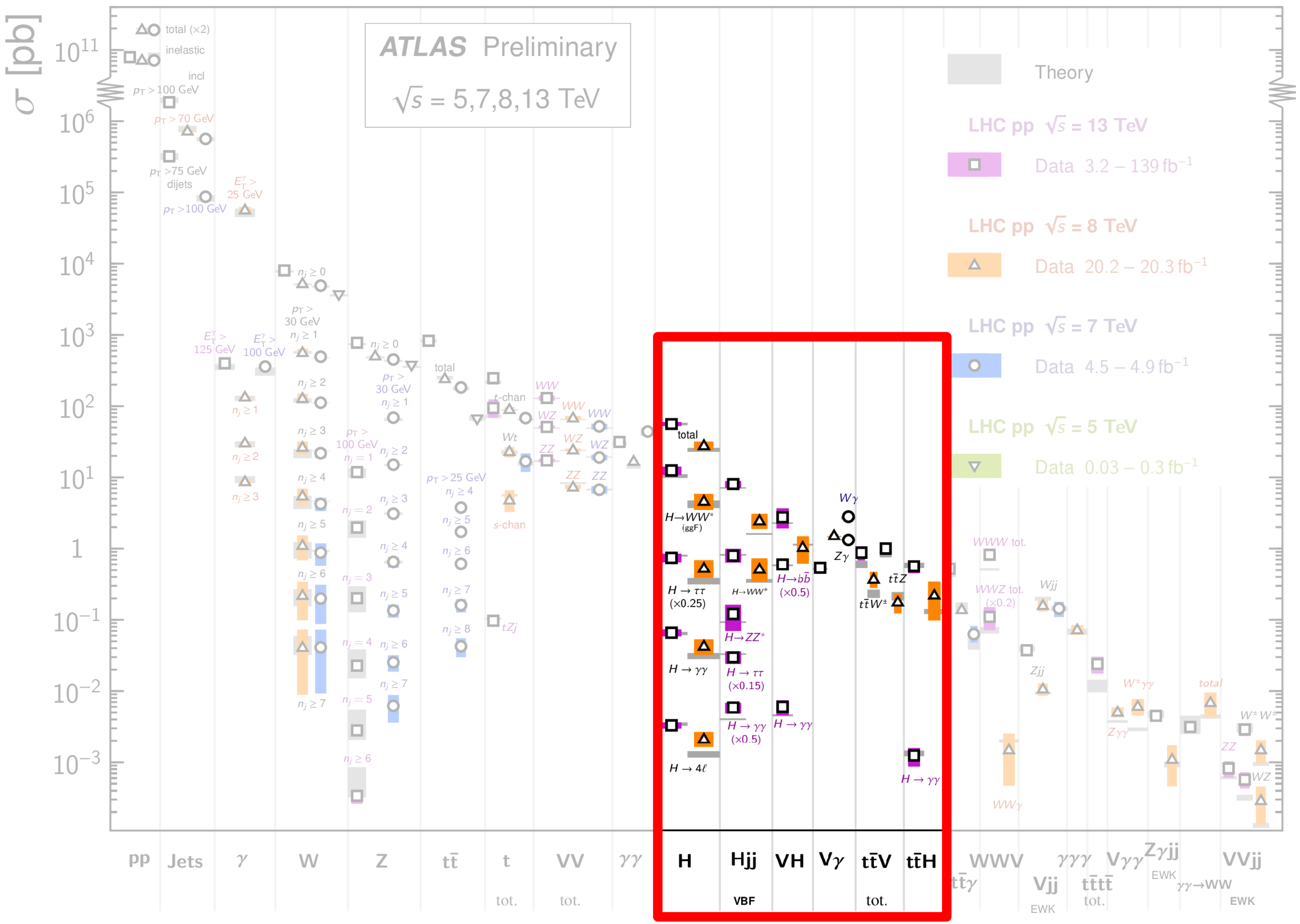
Both pairs require Upgrade 2 for statistics (sin 2β and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

- Permit tree-level observables (SM benchmarks) to be assessed against loop contributions (new physics sensitive)

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

- The SM works ☹
- The Higgs boson, and then the Higgs field and the mechanism for generating particle masses, is real, and now we know its mass
- Huge amount of LHC data fits SM predictions at am amazing level of accuracy with no real hint of BSM
- 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 focus on the Higgs

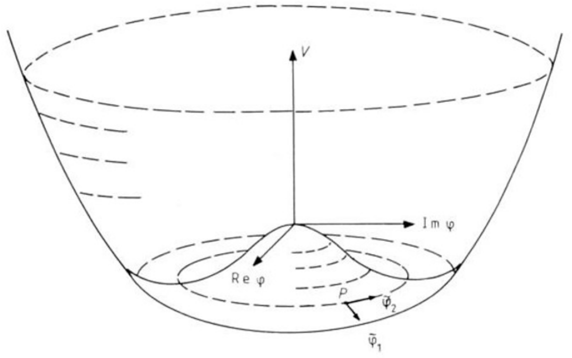


What’s so interesting about the Higgs

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) - \bar{\psi}_L\Gamma\psi_R\phi - \bar{\psi}_R\Gamma^\dagger\psi_L\phi^\dagger$$

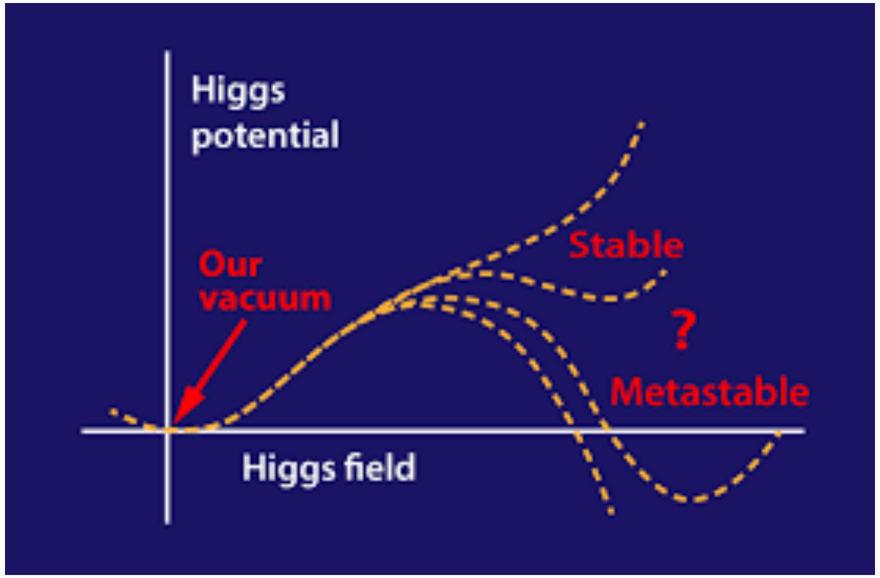
$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

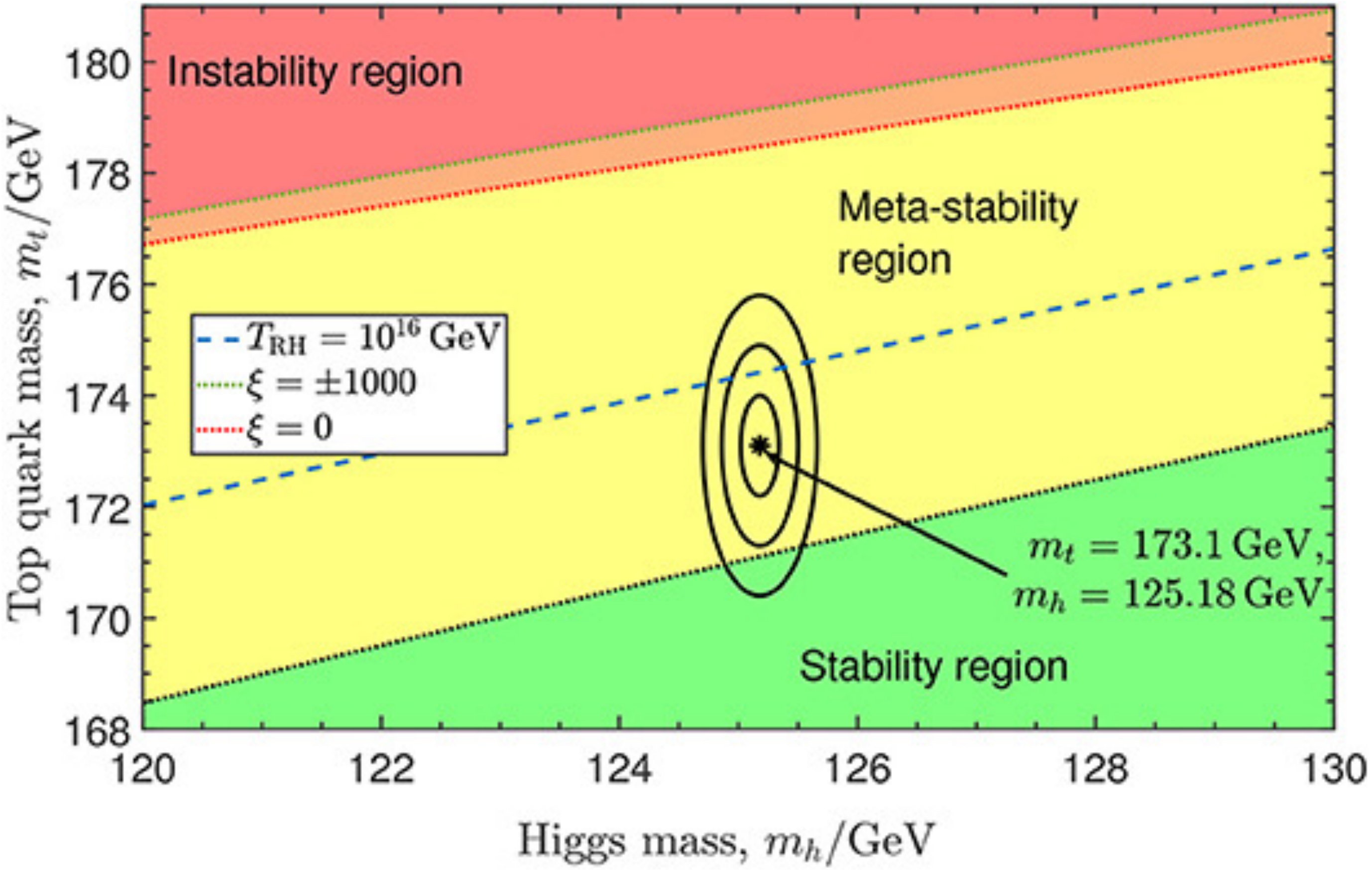
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \frac{1}{2}\lambda(\phi^\dagger\phi)^2$$



- It is the only fundamental scalar particle
  - Is it really fundamental or composite?
- It has too many different couplings, fixed by the experimental masses of the fundamental particles
  - Proliferation of free parameters with a wide hierarchy, who ordered that?
- The λ parameter determines the shape and the evolution of the Higgs potential, and has consequences on the stability of the electroweak vacuum

Electroweak vacuum stability





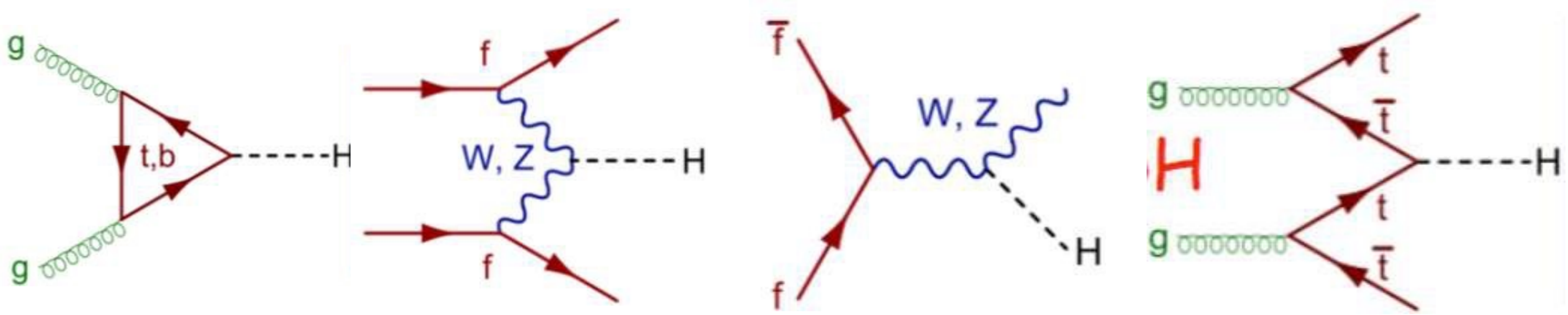
- If the Higgs potential develops a different lower minimum, a transition from the “false” minimum to the “real” one can happen somewhere in the Universe with a finite probability
- According to the measurements of the Higgs and top masses, and assuming the SM, we live at the border between metastable and stable regions

Time to worry?

- Probably not… and in any case the true vacuum bubble would expand at the speed of light, and we could never notice the end while approaching
- But more seriously, as quantum and thermal fluctuations in the Higgs field were much larger when the universe was a baby and much hotter than today, most of the Universe would have had to be falling into the true vacuum minimum and not the present one
- On the other hand, we exist as we are, and the question is why? (forgetting about multiverse and anthropic-principle explanations)
- More interestingly, this argument constitutes a hint of BSM physics, that could drastically change the stability regions, rendering the picture of the SM incorrect
- Stated otherwise, we need to find BSM if we want to sleep well!

What's so challenging about the Higgs

- Very difficult to study experimentally!
- The very small cross-sections for direct production from light states (that we have at our disposal with accelerators) call for the need to excite heavy states (t, W, Z), which then radiate a Higgs boson



- These processes have small cross-sections anyway, so it's difficult to make measurements due to large background pollution
- Still the Higgs boson is one of the best portals that we have to New Physics as of today

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

ESPP and P5

ESPP 2020

“An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.”

“Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update. Which is now coming in January 2026

“The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.”

P5 Panel 2024

“In the area of colliders, the panel endorses an off-shore Higgs factory, located in either Europe or Japan, to advance studies of the Higgs boson following the HL-LHC

“The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a 10 TeV parton center-of-momentum (pCM) collider to search for direct evidence and quantum imprints of new physics at unprecedented energies.”

“This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.”

- You may notice that the two visions are not perfectly aligned, but still both push for a next generation machine

Can the four main strategies be followed together?

- At our present level of comprehension, each of the four are of the utmost important to make further progress
- In particular, e^+e^- colliders can have great opportunities in all sectors, thanks to the clean experimental and theoretical environments and to the experimental precision achievable
- There's quite a good consensus that an e^+e^- Higgs factory should be the next collider, also considering involved costs
  - This can be an intermediate step towards a hadron machine at a later stage, to achieve 100 TeV physics within this century, following the example of LEP/LHC
- By contrast, some others think it would be better to bet immediately on a new hadron collider, although not reaching 100 TeV as a first stage
- But neither way is so easy, these toys cost billions and the obvious objection at the political level is that we are living a period of other planetary emergencies…

One example that it is not easy

nature

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NEWS | 06 June 2024

CERN's $17-billion supercollider in question as top funder criticizes cost

Germany has raised doubts about the affordability of the Large Hadron Collider's planned successor.

By Davide Castelvecchi

Plans for a 91-kilometre European particle accelerator are facing a serious challenge after the German government said that the project was unaffordable.

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BMBF's take on a future collider at CERN

Federal Ministry
of Education
and Research

FCC: Alternatives and Plan B

"The cost estimates in the feasibility study are subject to a large number of uncertainties, the effects of which are still largely unknown. ***The financing plan is extremely vague*** *and requires a high level of* ***commitment from external partners****, which is neither assured nor even in prospect at the present time.*

Under the current economic conditions, ***Germany is not in a position to provide the planned funding****. In view of all these points, the* ***FCC has to be considered as not affordable****.*

Hence, CERN has to ***diversify its efforts and prepare for different scenarios*** *including one without the FCC-ee."*

If FCC planning does not show significant changes, it cannot become succesfull.

→ German community should prepare for alternative scenarios!

Last ESPP: „*Full exploitation of HL-LHC*"

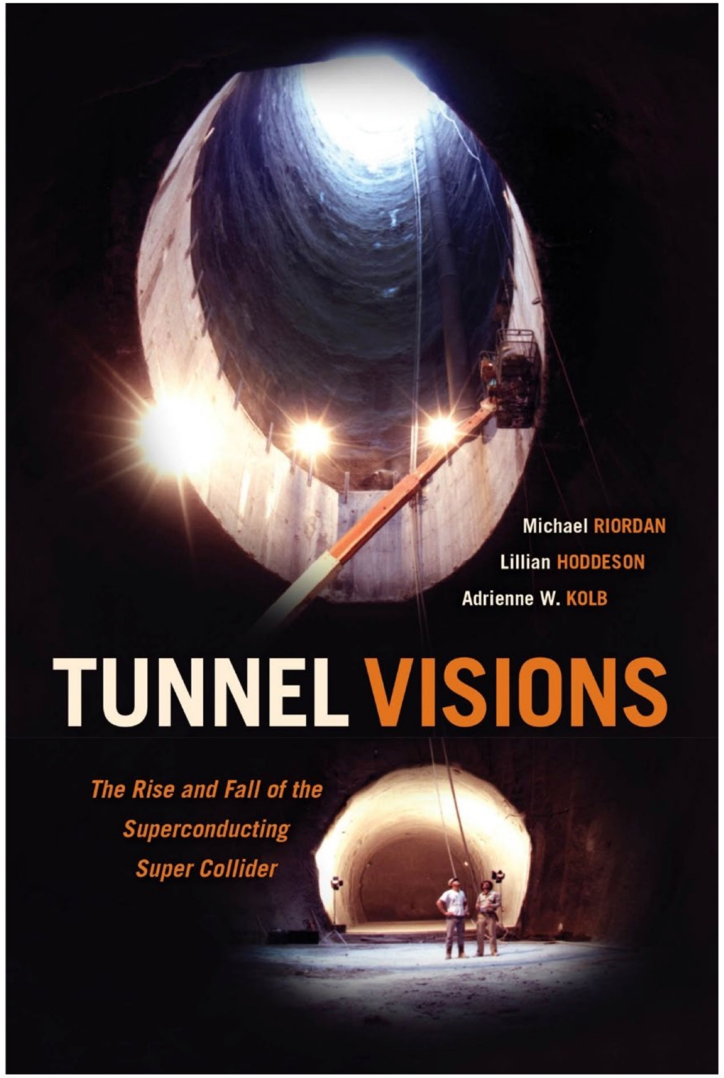
→ Primary goal might be: finish HL-LHC work and start physics

→ Watch for the Chinese decision on CEPC first

And with a scary prediction…

Federal Ministry
of Education
and Research

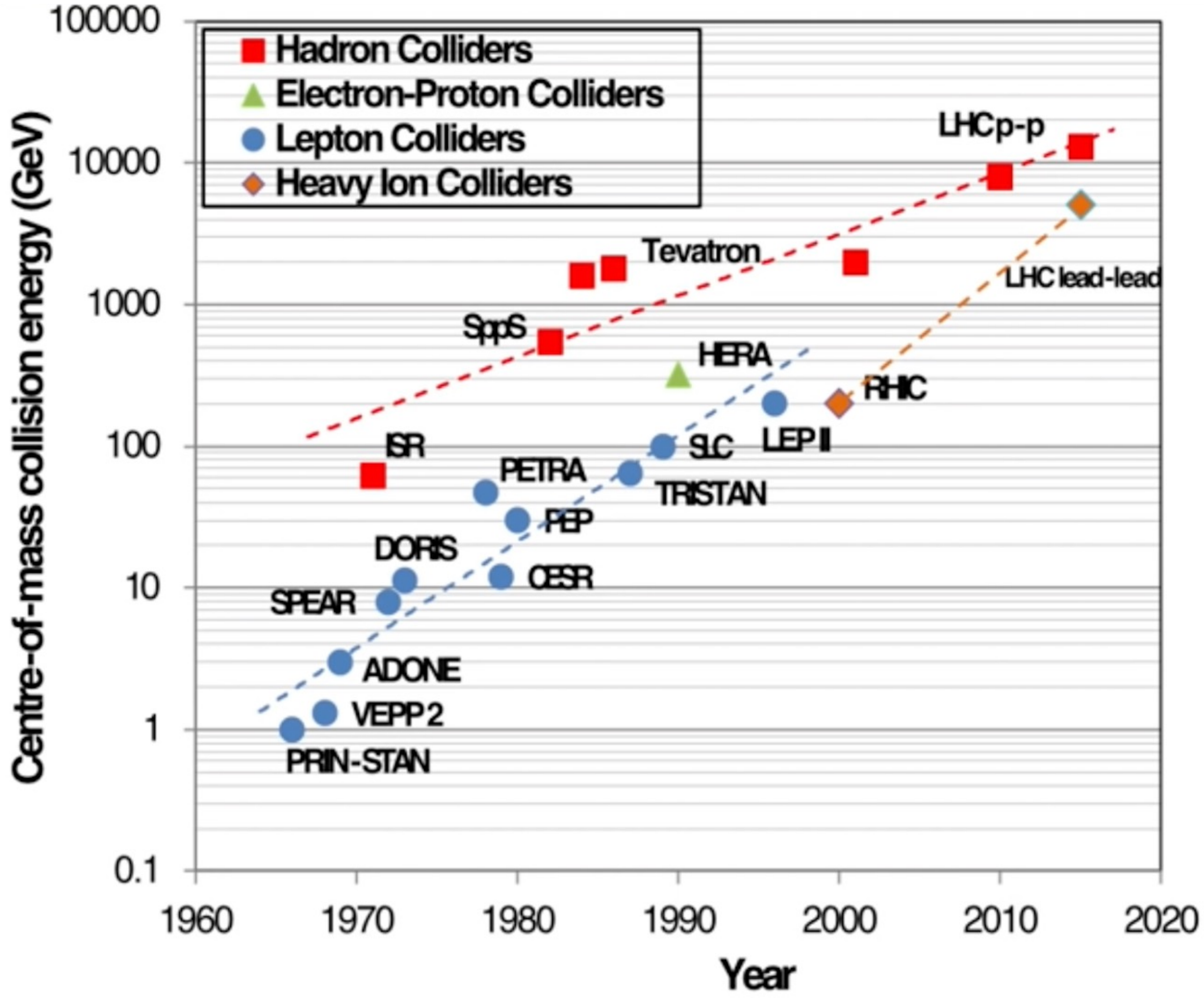
Outlook



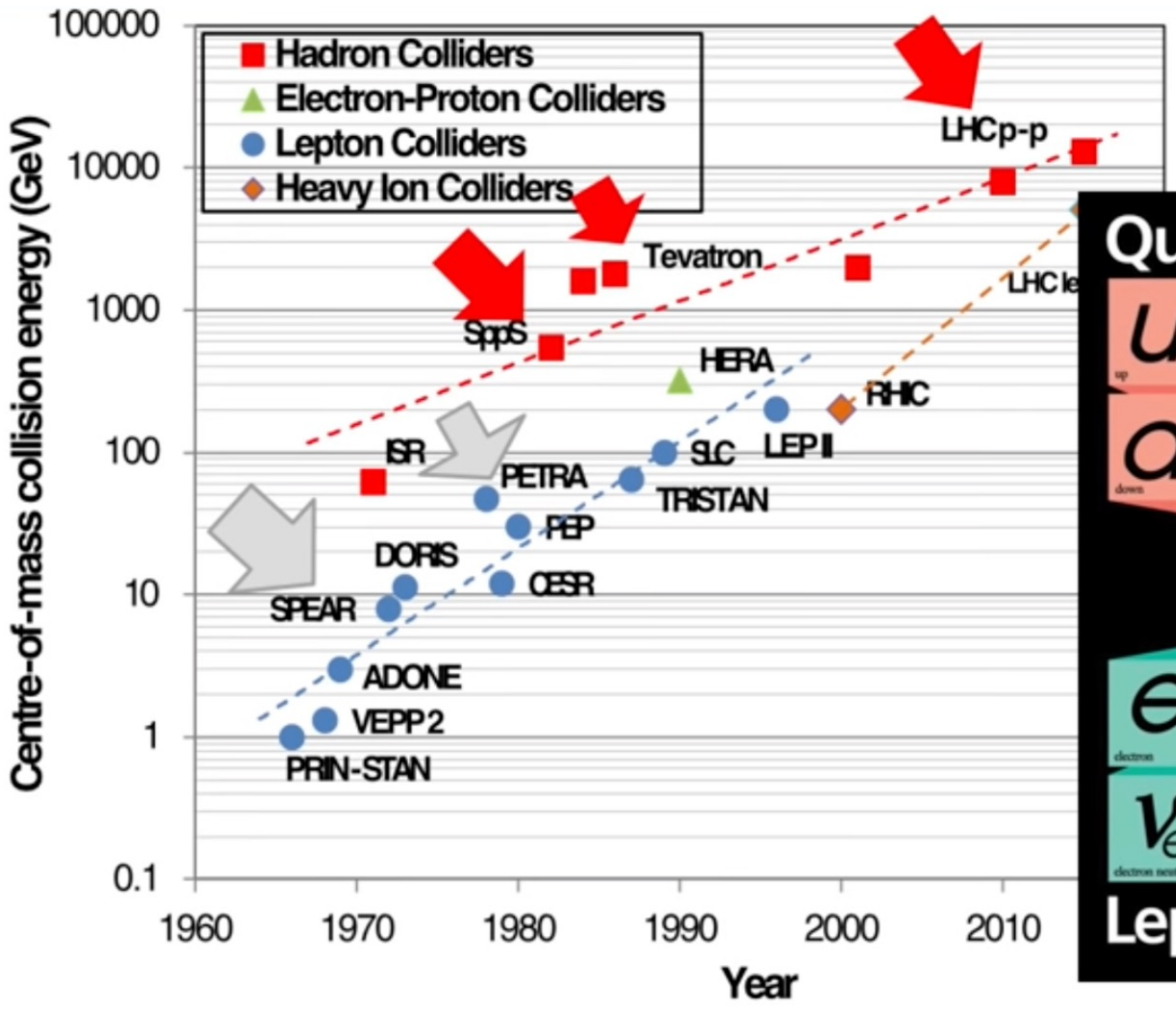
Source:
Tunnel Visions
The Rise and Fall of the Superconducting Super Collider
Michael Riordan, Lillian Hoddeson, and Adrienne W. Kolb

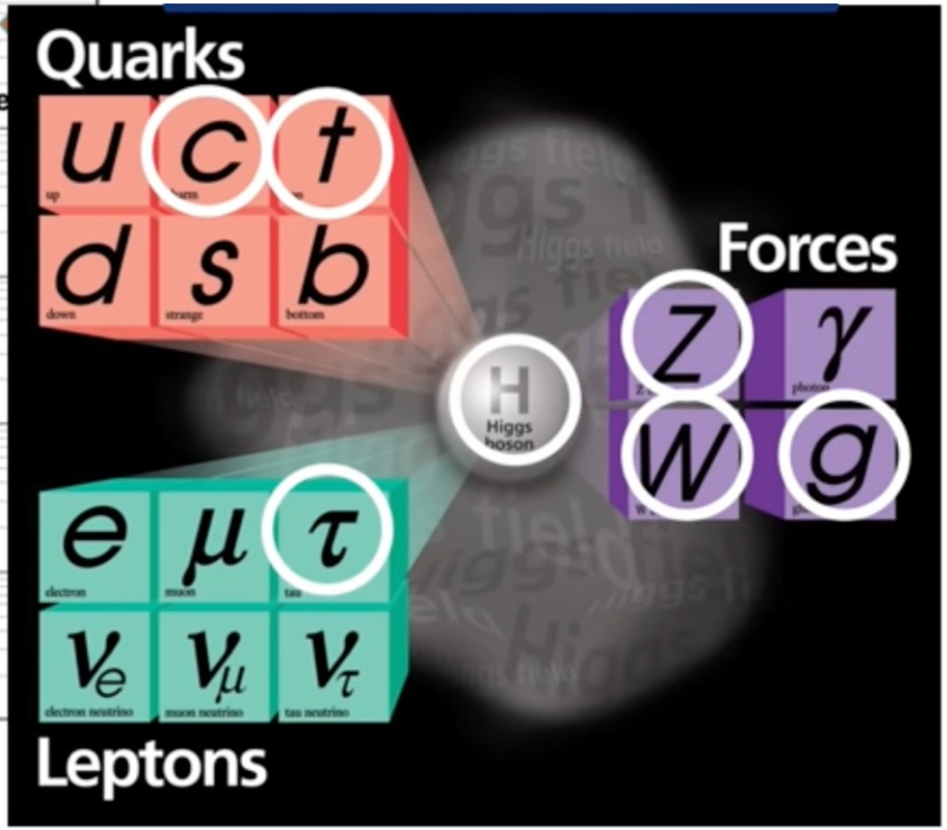
Second pit stop

The exponential growth of colliders' energies



Colliders and discoveries

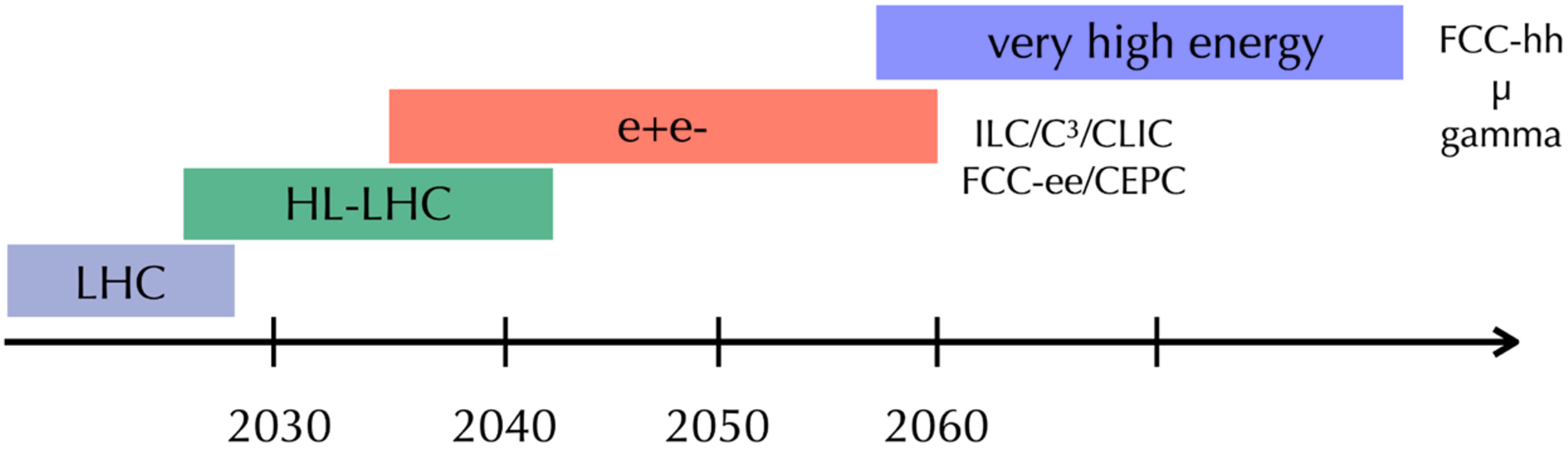




powerful instruments for discovery and precision measurement

What's next?

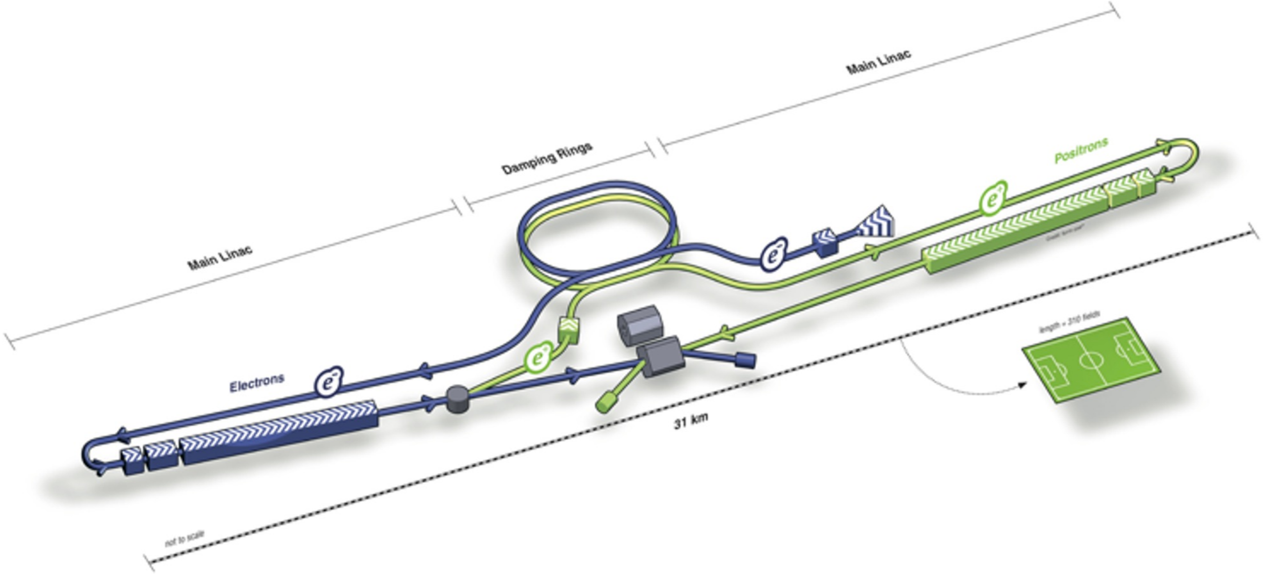
- Many options in consideration beyond HL-LHC
- Precision studies with Higgs Factories
- Discovery physics on the >TeV scale



Linear versus circular

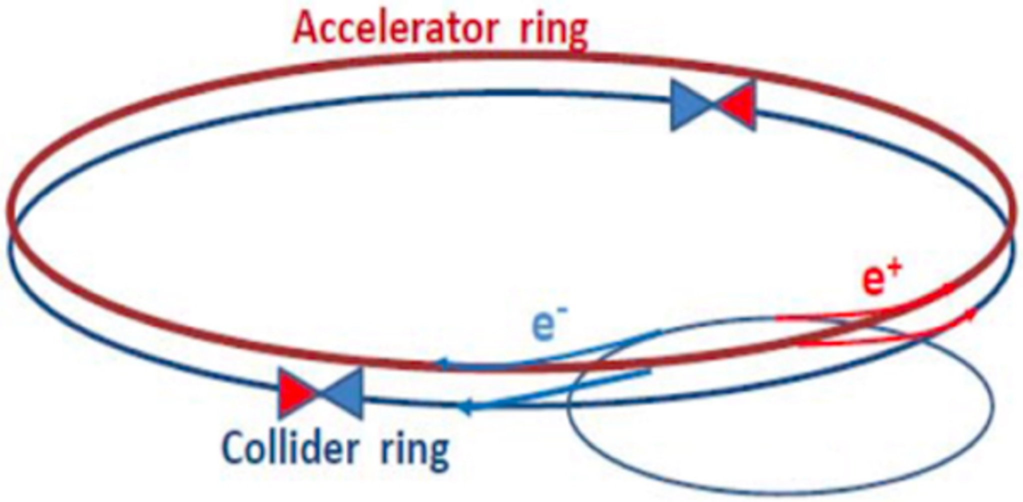
Linear e^+e^- colliders: ILC, C^3, CLIC

- Reach higher energies (~TeV), and can use polarized beams
- Relatively low radiation
- Collisions in bunch trains
- Single collision point



Circular e^+e^- colliders: FCC-ee, CEPC

- Higher luminosity
- Limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision
- Multiple collisions points possible



Reminder: synchrotron radiation

$$\Delta E \text{ (energy loss per turn)} = \frac{4\pi}{3}(\alpha\hbar c)\frac{\gamma^4}{R} \quad = \quad \frac{4\pi}{3}\left[\frac{\alpha\hbar c}{m^4}\right]\frac{E^4}{R}$$

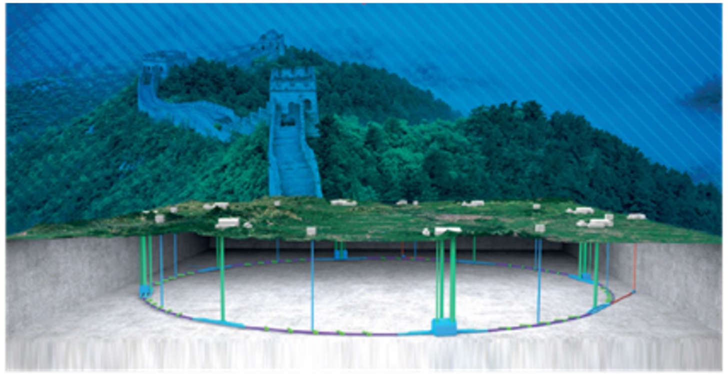
$e^{\pm}$ $$\Delta E \text{ (GeV/turn)} = (8.85 \times 10^4)\,\frac{E^4}{R} \qquad (E \text{ in TeV}, R \text{ in km})$$

$\mu^{\pm}$ $$\Delta E \text{ (GeV/turn)} = (4.84 \times 10^{-5})\,\frac{E^4}{R}$$

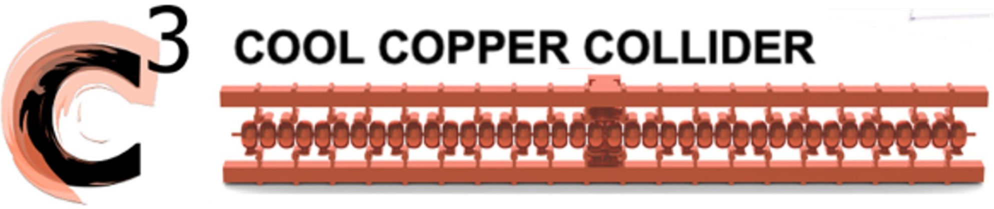
$p, \bar{p}$ $$\Delta E \text{ (GeV/turn)} = (7.78 \times 10^{-9})\,\frac{E^4}{R}$$

Higgs Factories being proposed

ILC
250/500 GeV

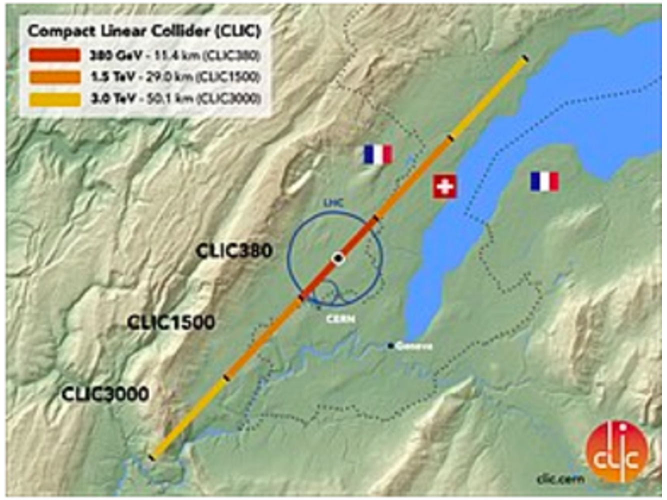


CEPC
240 GeV

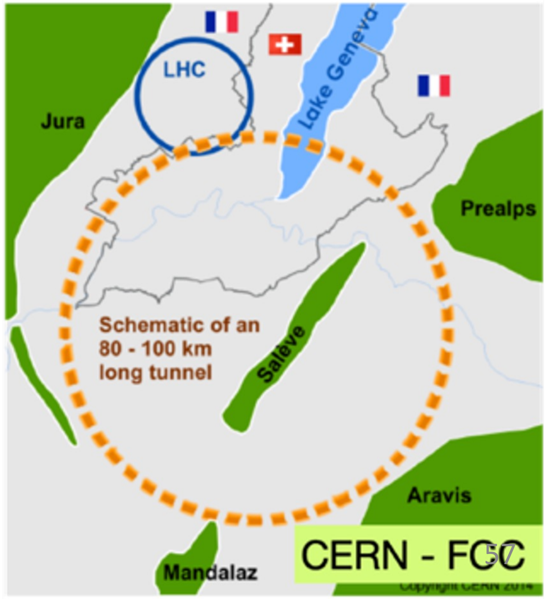


250/550 GeV
... > TeV

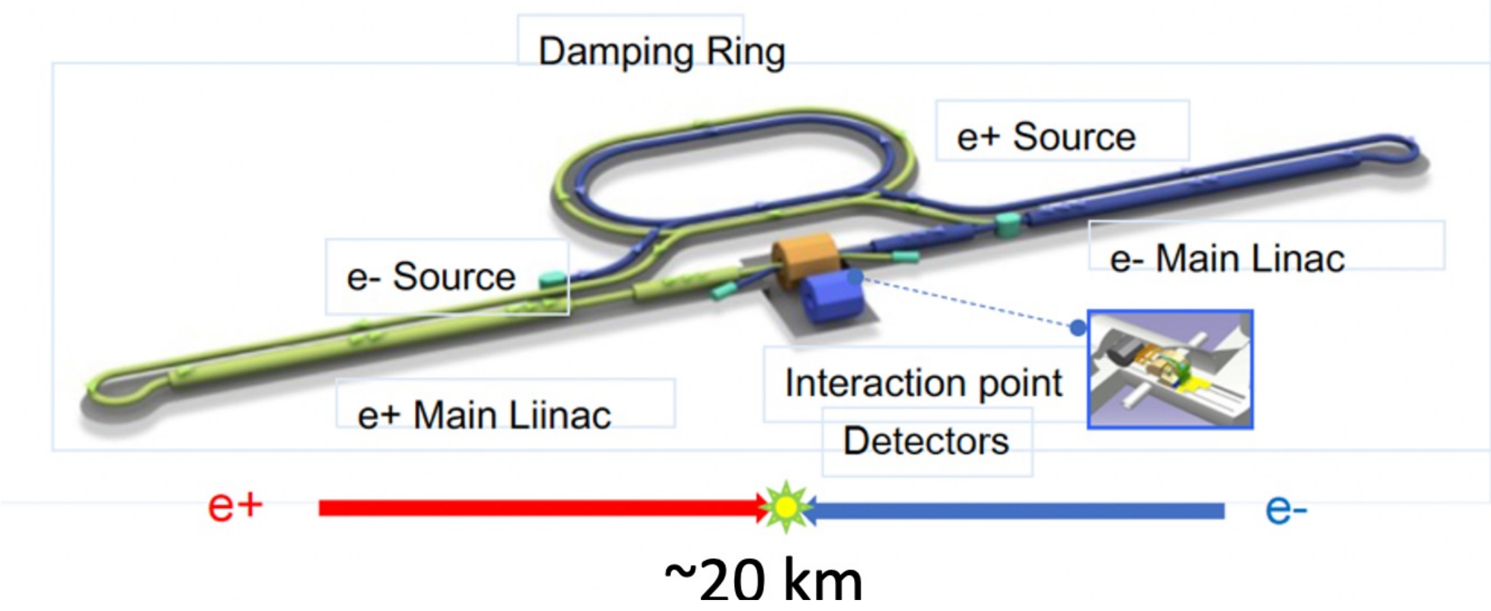
CLIC 380/1000/3000 GeV

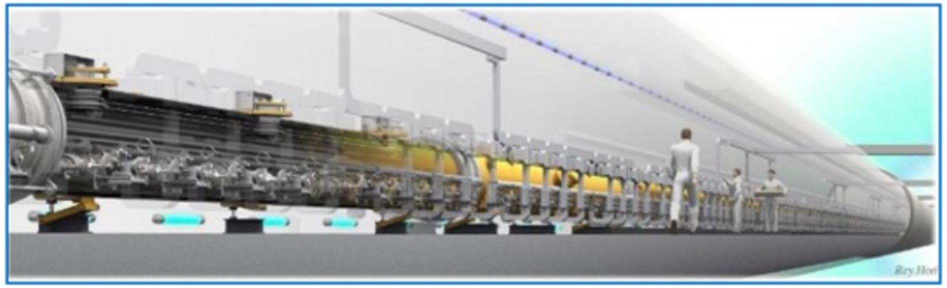


FCC-ee
240/365 GeV



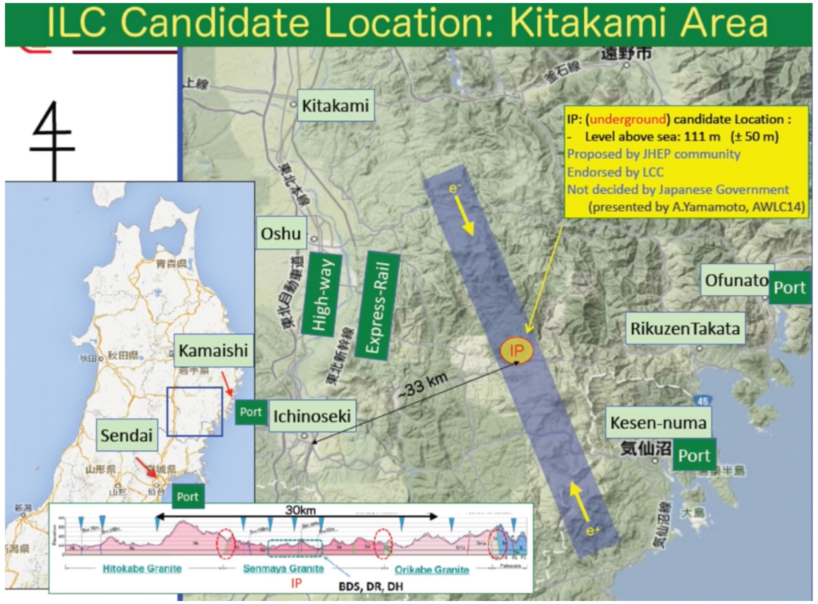
International Linear Collider (ILC)





Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	7.7 nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) Q_0 = $1x10^{10}$
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

- A few years ago it looked like it was very likely to be built, but then it lost momentum

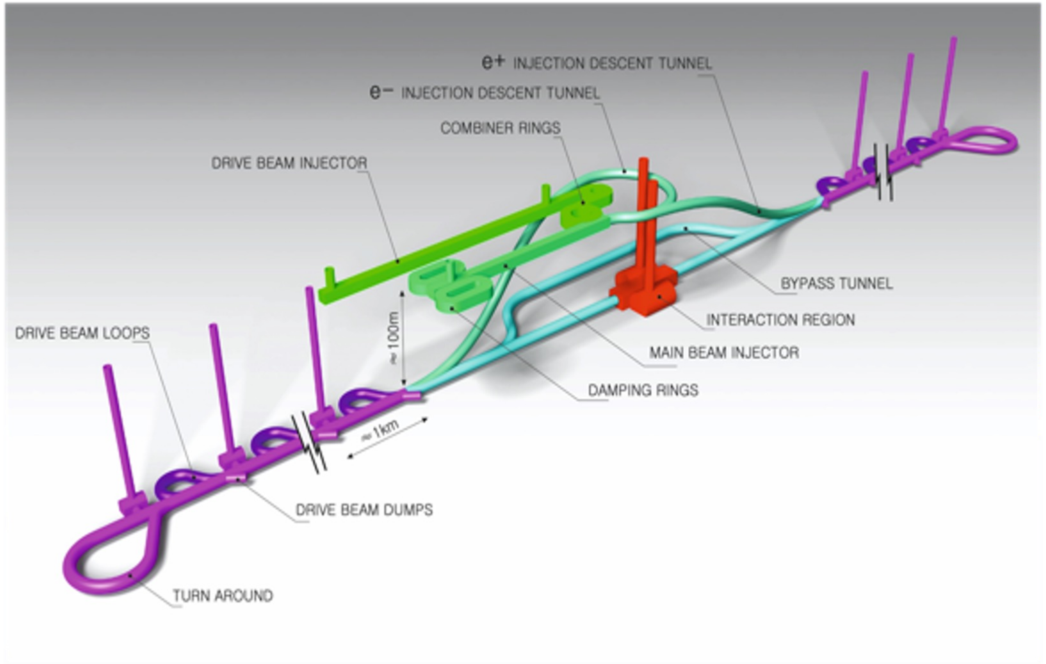


European XFEL (Hamburg)

10% scale model of ILC,
serve 10,000s scientists:

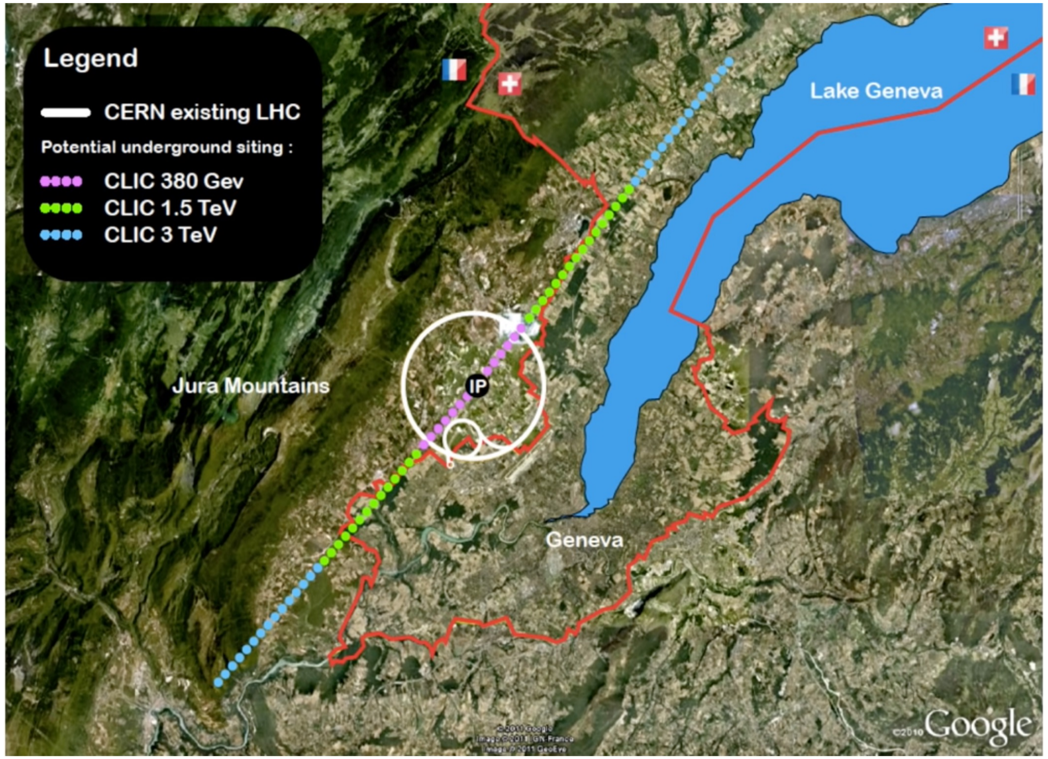
- condensed matter
- materials
- structural biology
- biomedicine
- chemistry
- ...

The Compact Linear Collider (CLIC)



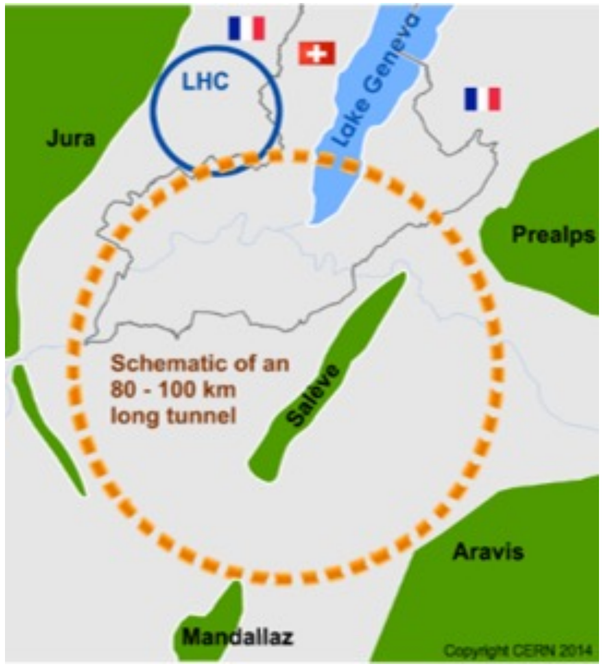
- e+e- linear collider at CERN
- Two-beam accelerating technique with high-gradient room temperature RF cavities
- Staged programme from 380 GeV (Higgs and top production) up to 3 TeV

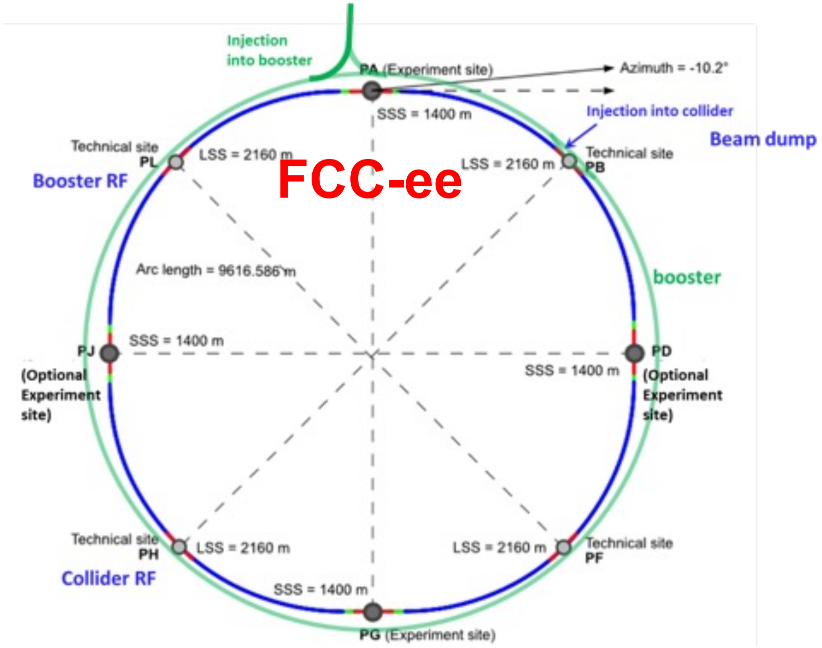
Mature project, but at the moment it is not CERN's first choice

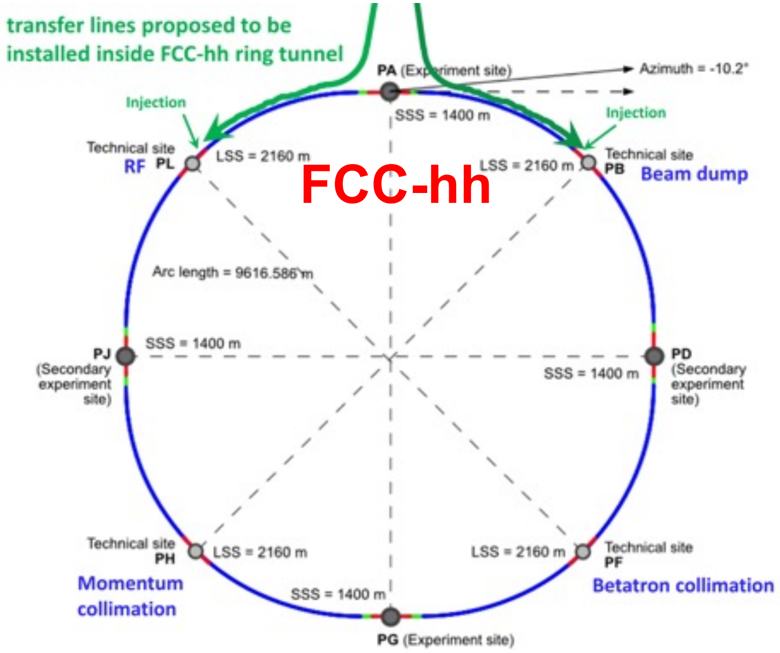


The FCC programme

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



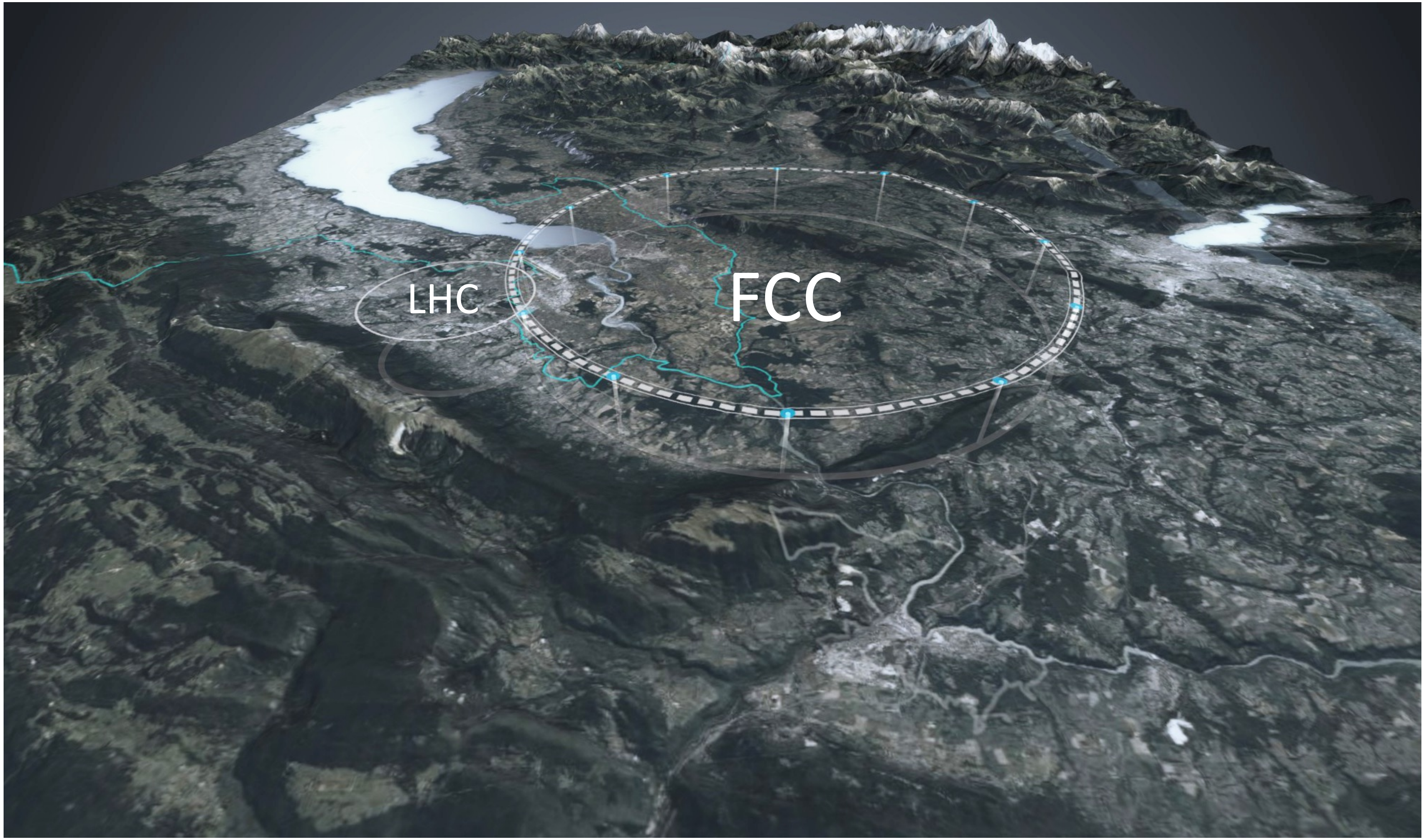




2045 - 2060 **2070 - 2095**

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

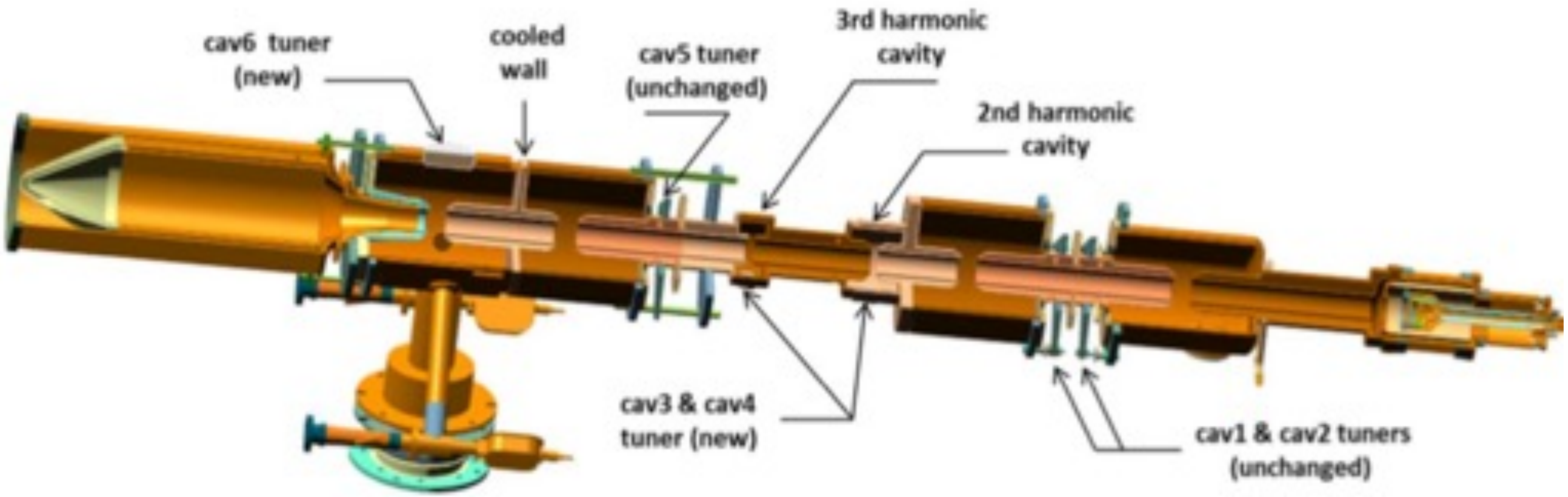
FCC's challenging civil engineering



FCC-ee developments

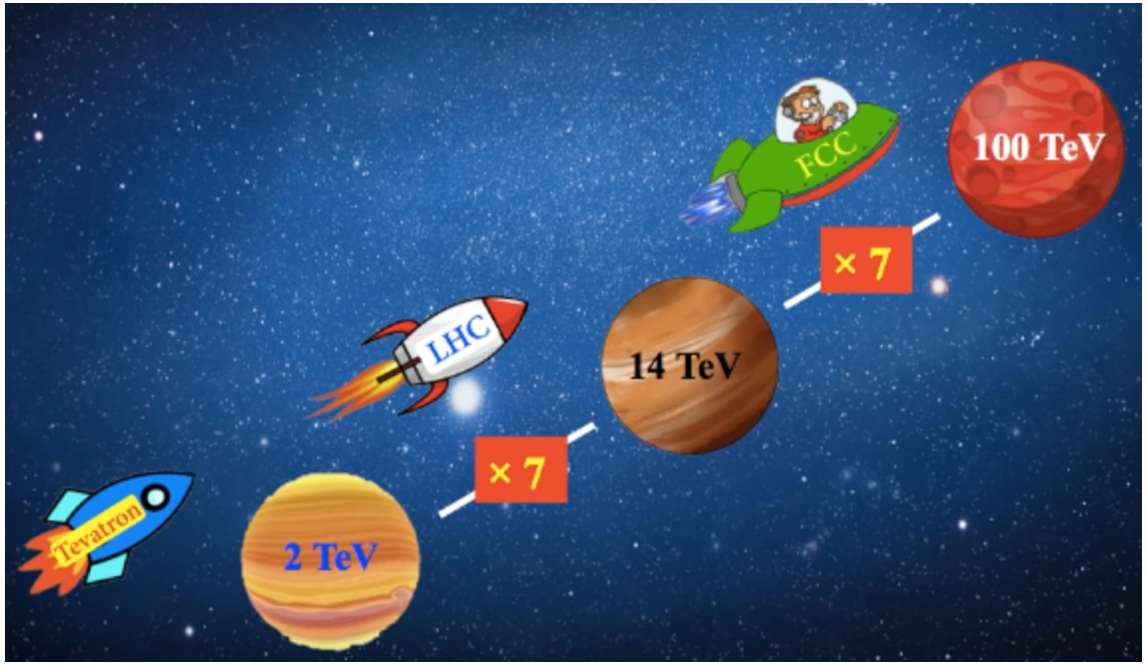
- Strong R&D programme, as for example

RF power sources
(400 & 800 MHz)



Superconducting cavities Nb/Cu, 4.5 K

FCC-hh: highest collision energy

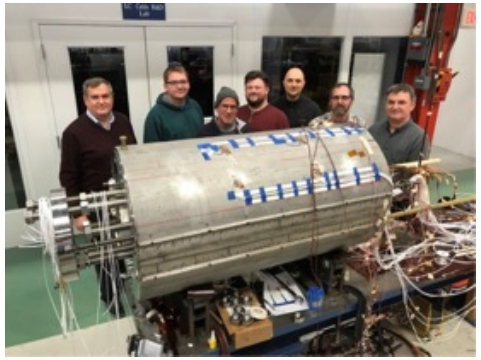


- Order of magnitude performance increase in both energy and luminosity wrt LHC
- 100 TeV collision energy vs 14 TeV for LHC
- 20 ab^{-1} per experiment over 25 years of operation vs 3 ab^{-1} for LHC

- Similar performance increase as from Tevatron to LHC
- Key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

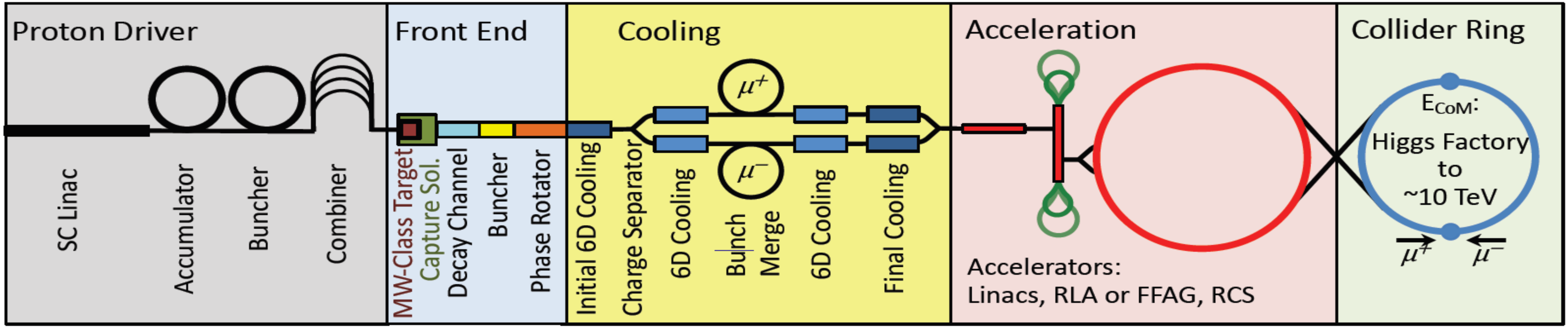
via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole
demonstrator
14.5 T Nb_3Sn
(2019)

Muon Collider concept

- Exploiting $m_\mu \sim 200\ m_e$, $P_\gamma \propto 1/m^4$ → can reach high energies with limited radiation!
- Leading concept is a proton driven target for muon production followed by cooling to reduce the beam emittance (read: area occupied by the beam in a position-momentum phase space)
- Would be easy if the muons did not decay after a lifetime of γ x 2.2 μs



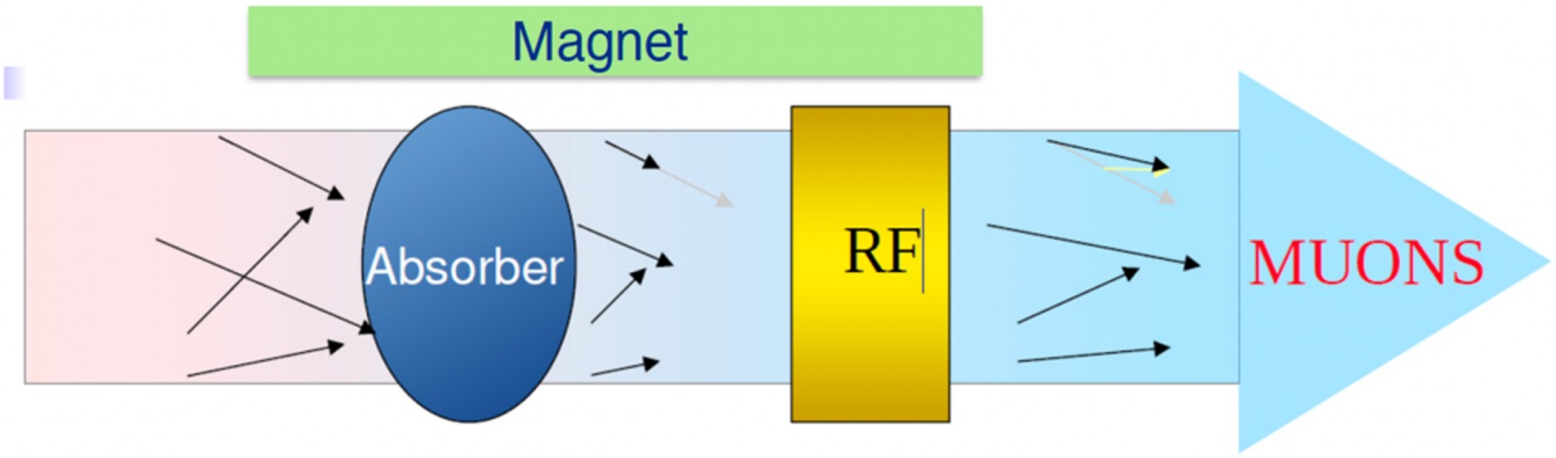
Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Big challenge: muon cooling

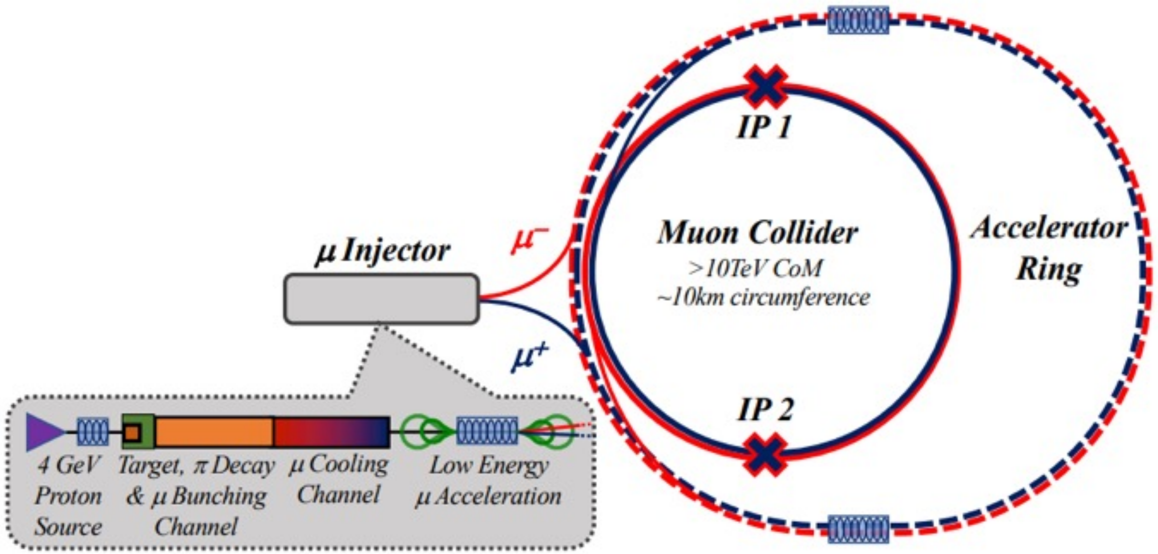


- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
  - Normal conducting rf that can provide high-gradients within a multi-T fields
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)

Target parameters for Muon Collider

- Accelerator R&D areas
  - High power proton driver
  - Short lifetime of muons in injector (~µs)
  - Cooling to reduce emittance
  - Injection and acceleration
  - Mitigating radiation

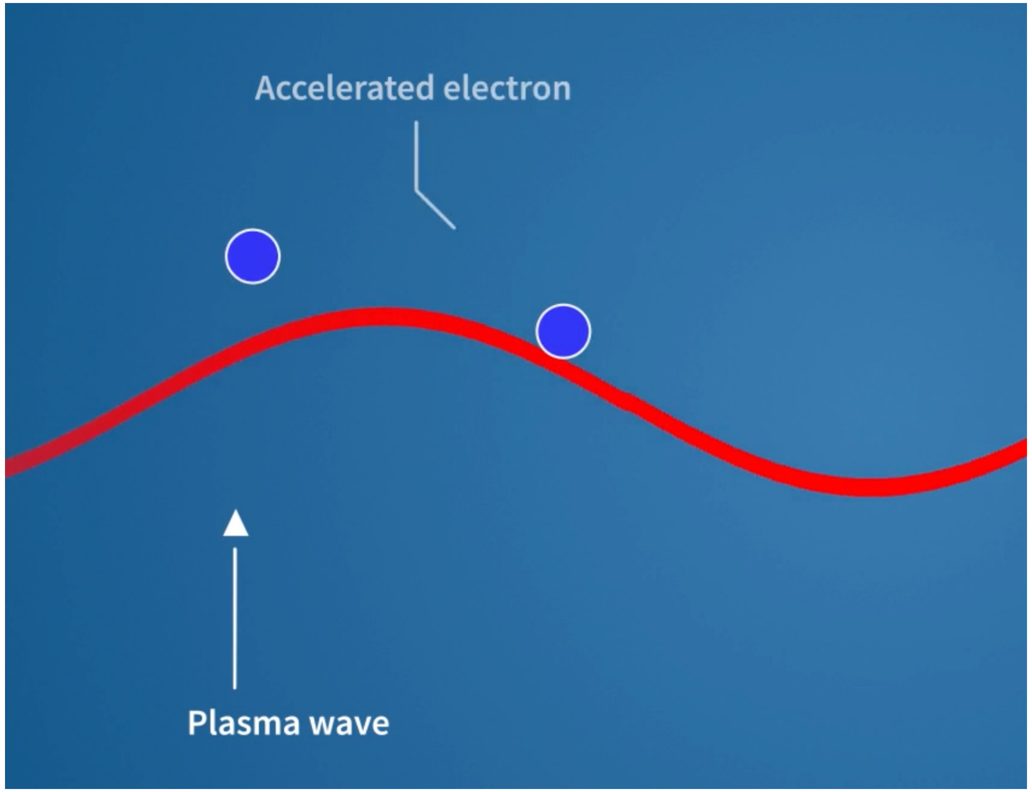
Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\,cm^{-2}\,s^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeV m	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63



- Interesting and innovative concept, allowing high energies to be reached with limited ring sizes, but still early to predict when the technology could be ready
- It's probably not the first future collider to be built

What if we could make a pocket accelerator?

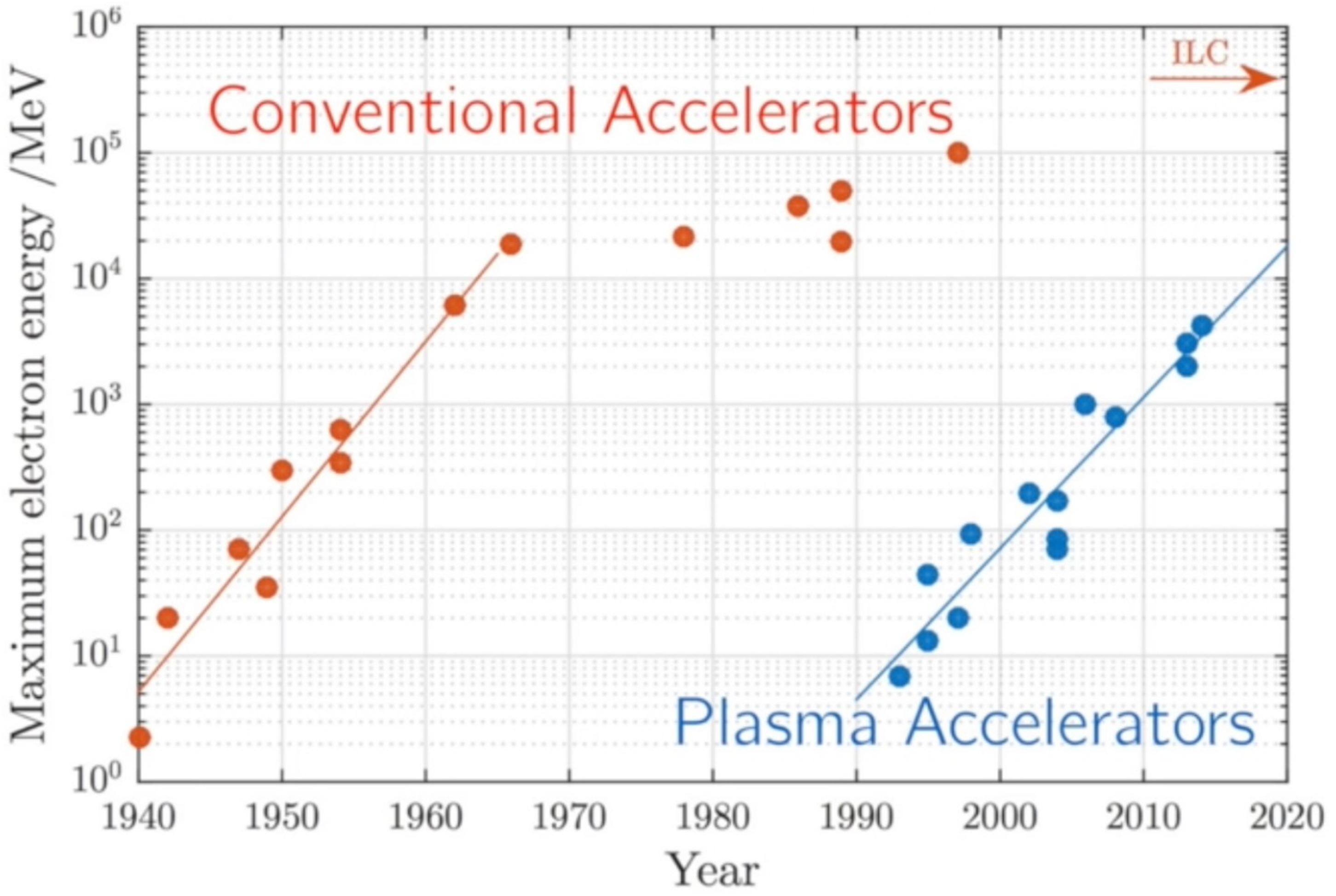
- This is even farther to come, at least at the energy frontier, but wakefield acceleration promises to achieve acceleration strengths that are up to a thousand times greater than what could be provided by today's most powerful machines, enabling much more compact systems
- The technique of wakefield acceleration consists in using a laser or a particle beam to create a plasma wave inside a fine capillary



- The laser or beam pulses strip electrons from the molecules, and electrons in the wake of the pulse can be accelerated by the positively charged plasma wave in front of them
- Ultra-large gradients achievable 1-100 GeV/m!

Progress in plasma-based accelerators

- Demonstrators have achieved energies of several GeV in a few cm of space, equivalent to electric fields of 10 GV/m!
- Still very far to reach quality, intensity and energy of a traditional accelerator, probably 50 years behind, but interesting to watch out

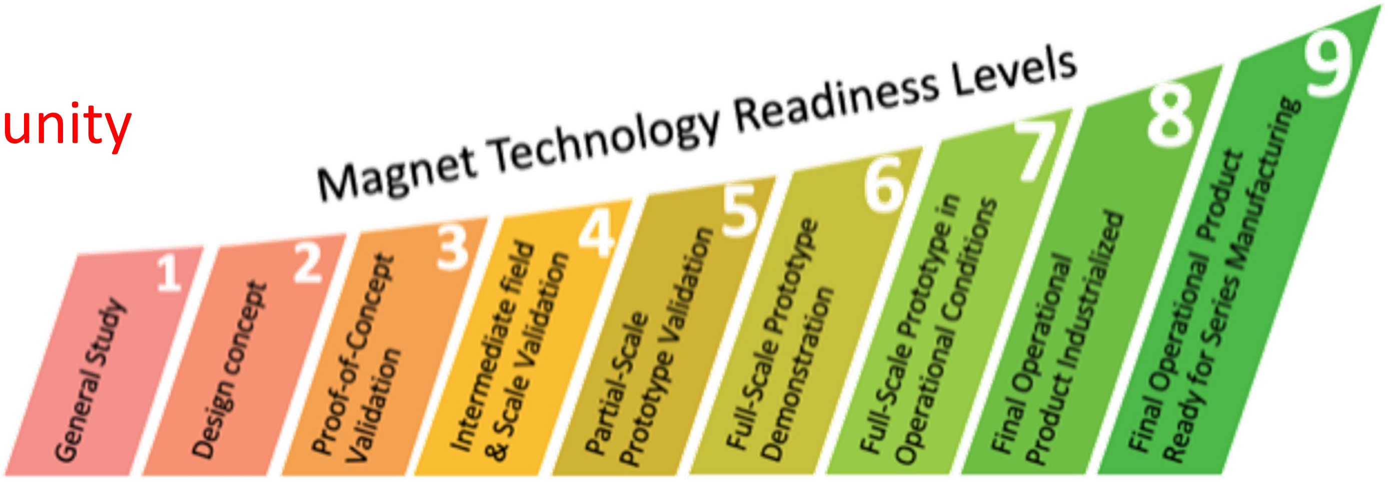


R&D on SC magnets

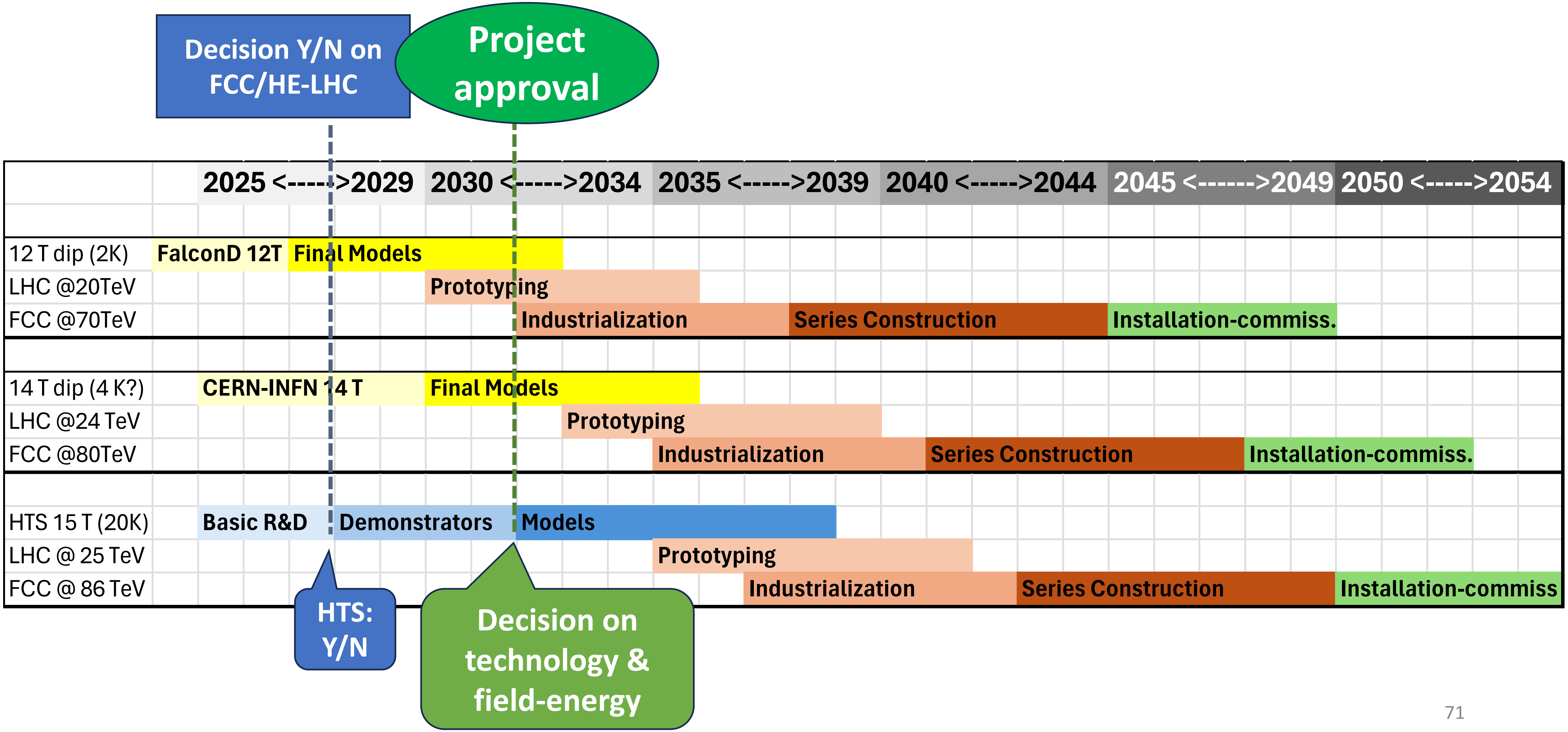
ESPP 2020

"The particle physics community should ***ramp up its R&D effort*** *focused on advanced accelerator technologies, in particular that for* ***high-field superconducting magnets****, including* ***high-temperature superconductors****"*

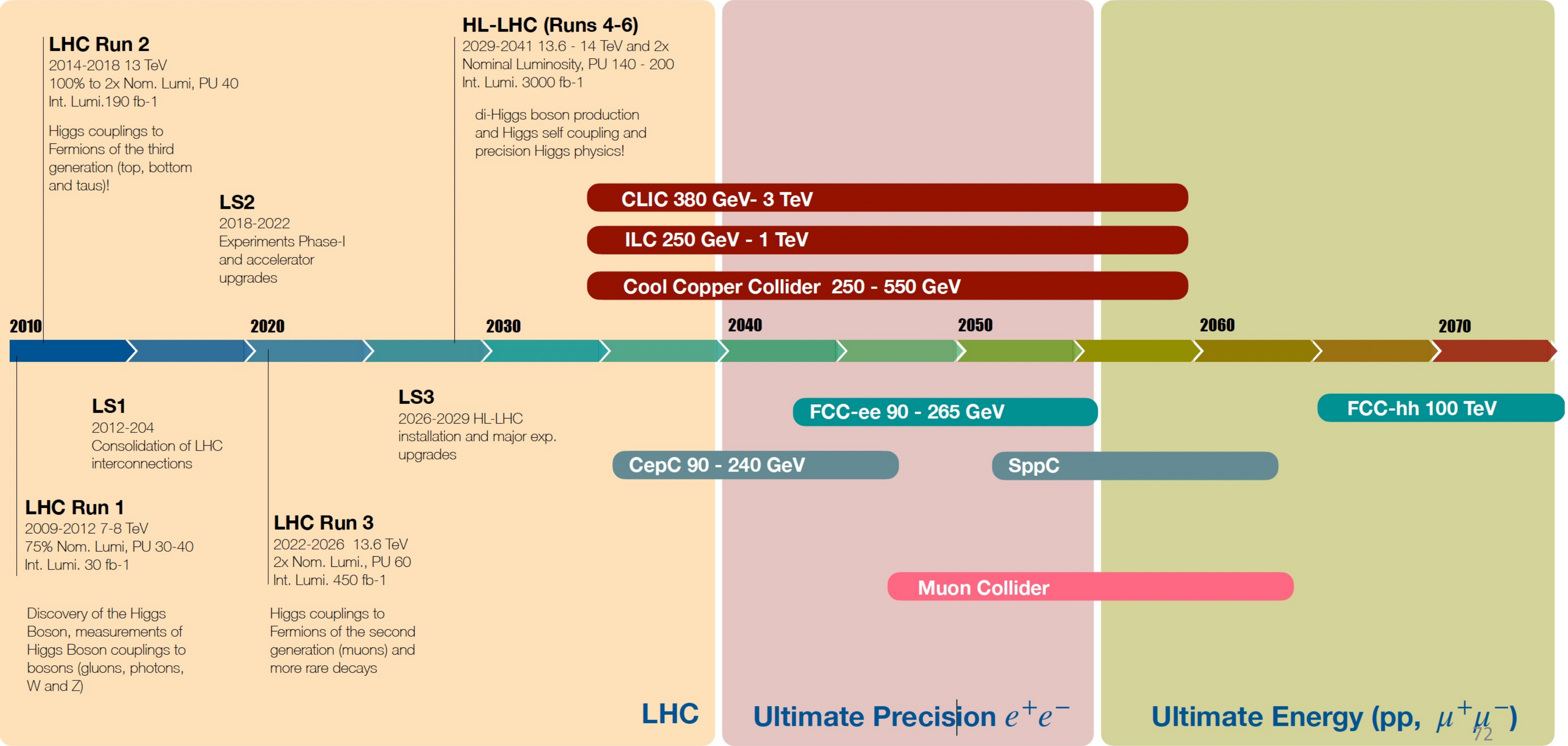
- Nb_3Sn in an intermetallic compound of Nb and Tin which is superconductor below 18 K and 30 T
- State of the art Nb_3Sn strands can carry up to J_C(16 T, 4.2 K)=1200 A/mm^2
- 12 T dipoles are close to demonstration (TRL 6–7), while 14-16 T dipoles still need ~5 years of R&D (TRL 4–5)
  - To compare with NbTi 8 T LHC dipoles
- It is conceivable that if the HEP community settles for 12 T, magnets for FCC-hh could be ready by 2045–2050
- However, the question is not only to make them, but also to reduce production costs



SC magnets timeline for FCC/HE-LHC



Roadmap to this century’s particle accelerators



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