CERN, LHC and the Higgs

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Fysikdagarna Lund 16/6 2022

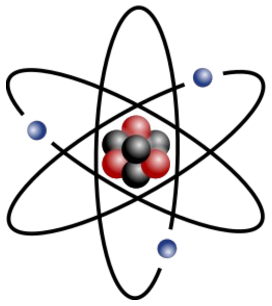
A complex world

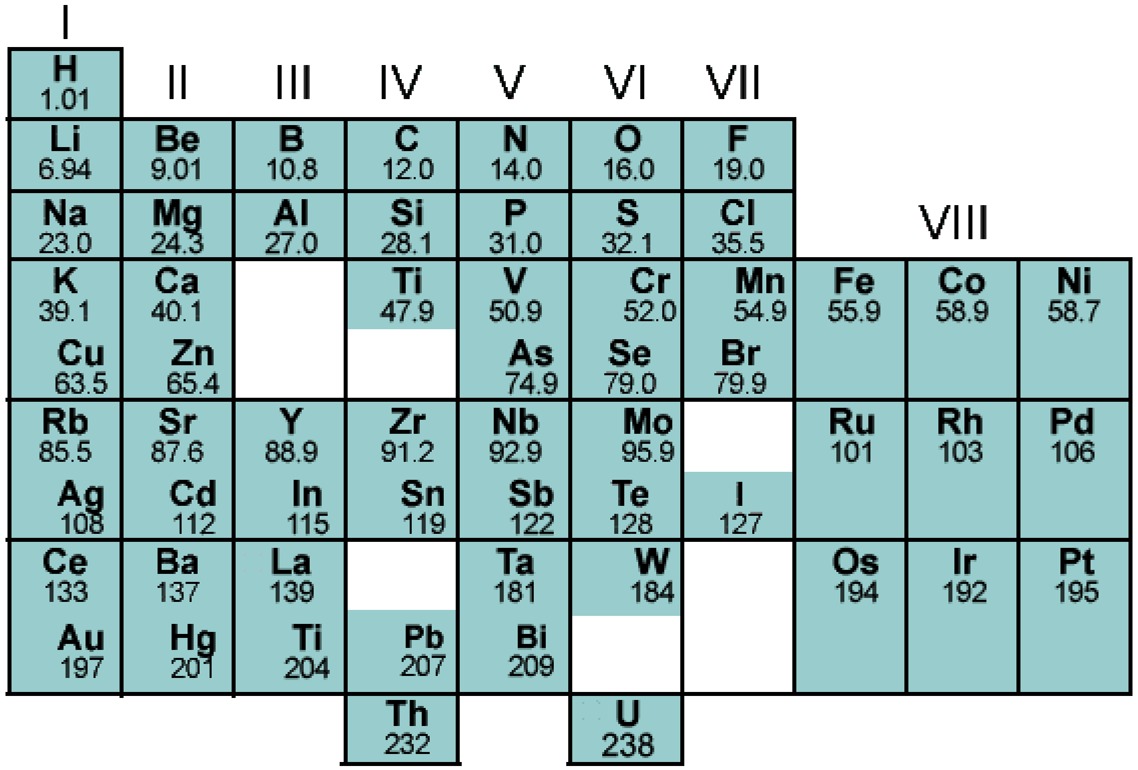
Credit: pikisuperstar - www.freepik.com

In the early days

- In the early days, four elements.
- The electron was discovered in 1897 in studies of atoms.
  - We now know this is also the first elementary particle discovered.

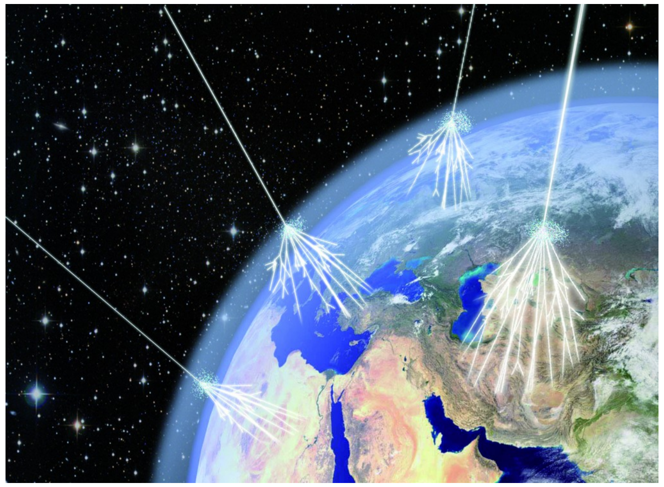
- With discoveries of the proton (1919) and neutron (1932) the atoms and the periodic table could be fully understood.
- Incredibly successful theory!
  - Could explain all known elements, and be used to predict as of then undiscovered elements.





I	II	III	IV	V	VI	VII	VIII		
H 1.01									
Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
K 39.1 Cu 63.5	Ca 40.1 Zn 65.4		Ti 47.9	V 50.9 As 74.9	Cr 52.0 Se 79.0	Mn 54.9 Br 79.9	Fe 55.9	Co 58.9	Ni 58.7
Rb 85.5 Ag 108	Sr 87.6 Cd 112	Y 88.9 In 115	Zr 91.2 Sn 119	Nb 92.9 Sb 122	Mo 95.9 Te 128	I 127	Ru 101	Rh 103	Pd 106
Ce 133 Au 197	Ba 137 Hg 201	La 139 Ti 204	Pb 207	Ta 181 Bi 209	W 184		Os 194	Ir 192	Pt 195
			Th 232		U 238				

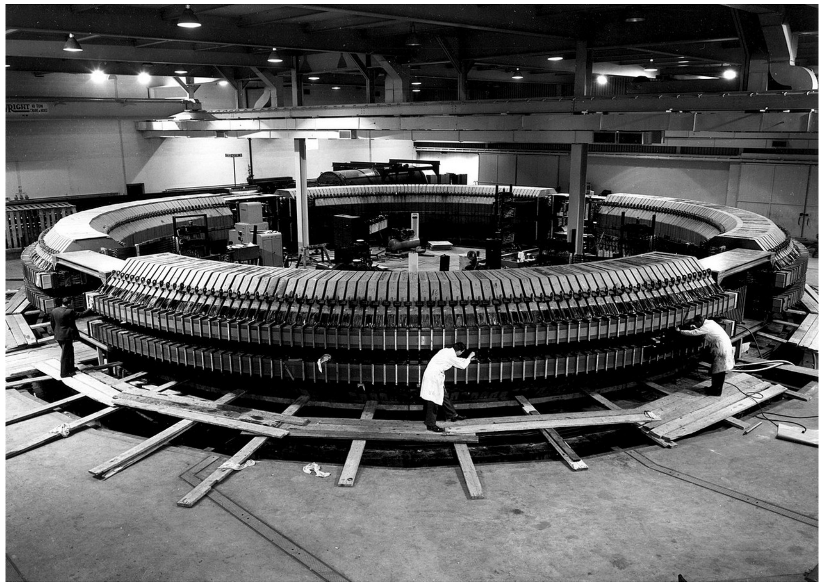
The unexpected

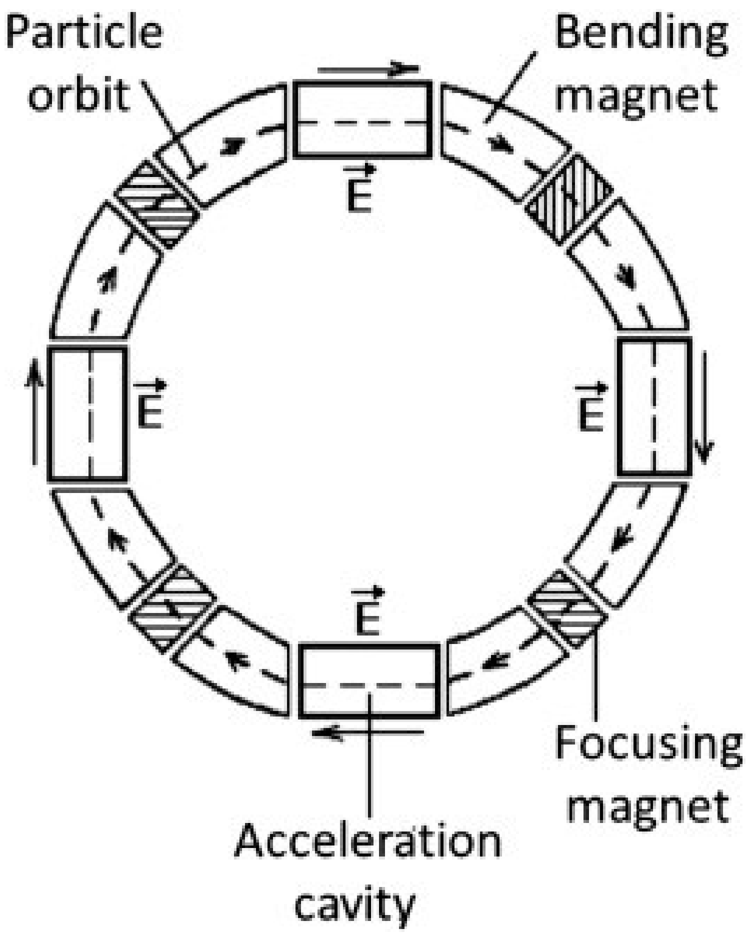


- Despite having a ”theory of everything”, scientists continued to explore the unknown.
    - One area was the study of cosmic radiation.
    - Detectors were placed on high mountains to look at the particles from space.
- Soon discovered a new particle, μ, different from the proton, neutron and electron, which played no role in the atoms.
    - Like a heavier electron, and unstable.
    - The discovery was so unexpected that Nobel laureate I.I. Rabi exclaimed “Who ordered that??”
    - Soon more new particles were discovered, with varying properties.
    - Were given names like π, K, Ω …
    - So many they were referred to as the particle zoo.

Particle accelerators

- To be able to study this myriad of new particles, physicists wanted to recreate large quantities of them in the laboratory.
- They started building particle accelerators, where the energy in the collisions could be converted to mass: $E = mc^2$.
- To study what came out of the particle collisions, detectors were built around the collision points.
- Cyclotrons developed at UC Berkeley in the 1930s and 1940s.
- 1952 the Cosmotron at Brookhaven Lab came online.
- $E=3.3$ GeV which is similar to that of cosmic rays.





- The study of particles using accelerators marked the birth of particle physics.

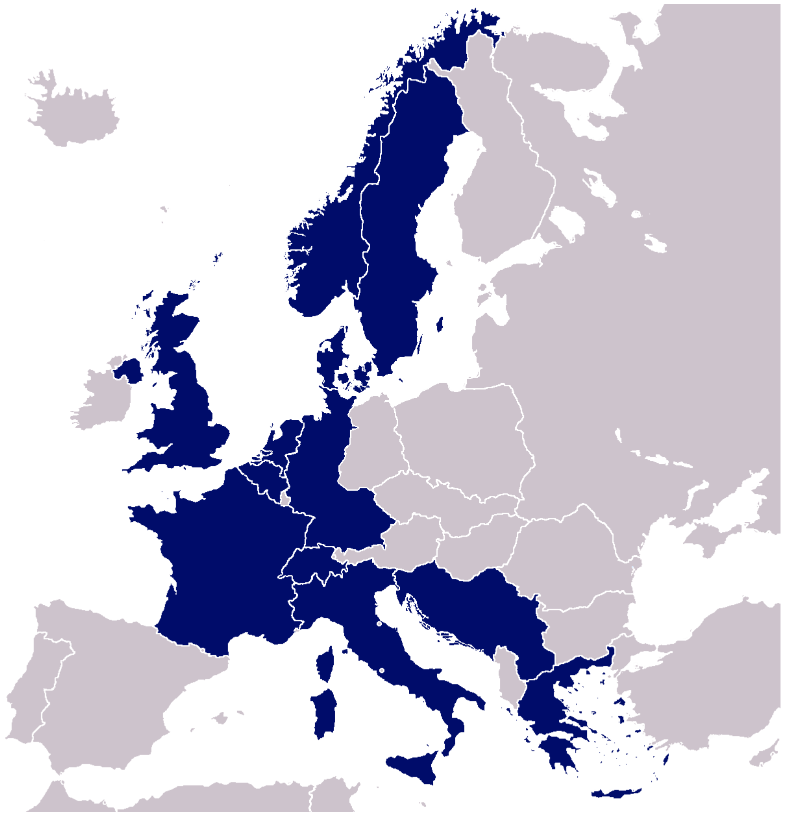
The birth of CERN

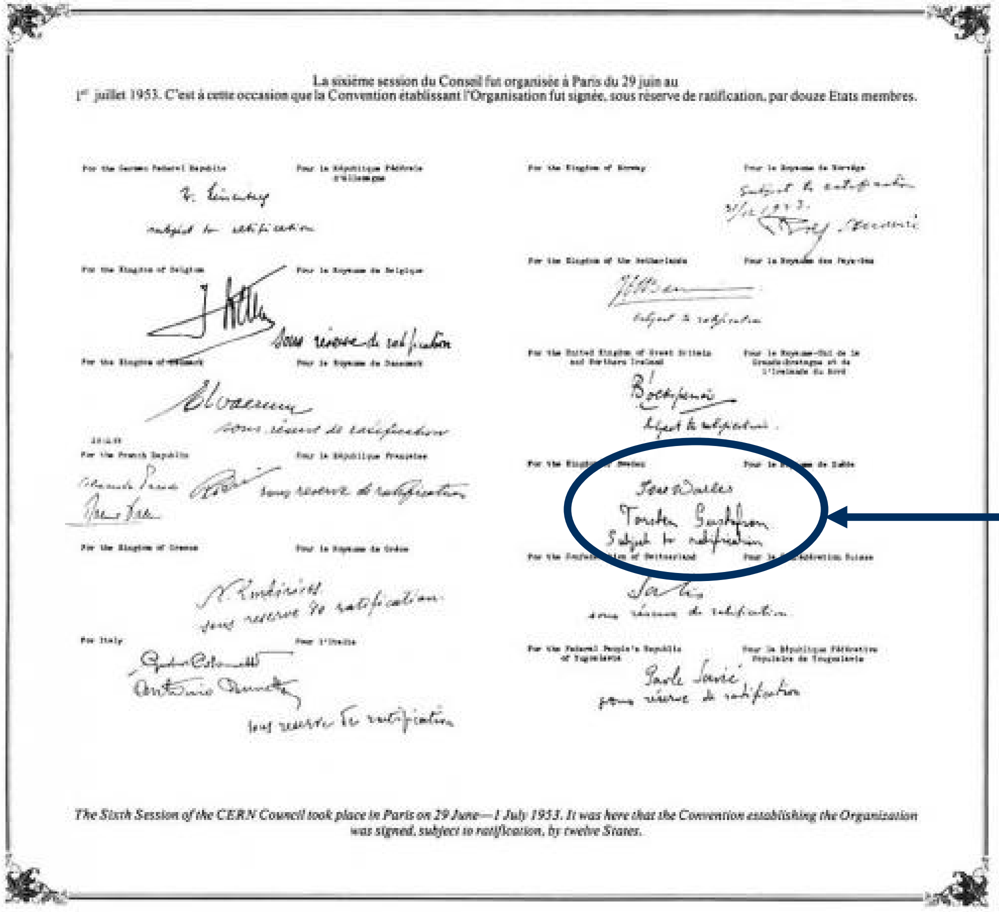
- At end of WW2, European science was no longer world-class.
  - Many leading scientists had fled to the US (Bethe, Einstein...).
  - US was leading the game, building first particle accelerators.
- A handful of visionary scientists imagined creating a European nuclear physics laboratory.
  - Would unite European scientists,
  - and allow them to share increasing costs of nuclear physics facilities.

- 1949: Proposal by French physicist Louis de Broglie at the European Cultural Conference in Lausanne.
- 1951: The first resolution concerning the establishment of a *"Conseil Européen pour la Recherche Nucléaire"* (CERN) was adopted at an intergovernmental meeting of UNESCO.

The birth of CERN

- 1953: At the sixth session of the Council, the convention was signed by 12 states: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and Yugoslavia.
- 1954: Ratification in all member states → CERN was born.
- CERN has since then changed its name to *"Organisation Européenne pour la Recherche Nucléaire"*, but the acronym CERN was kept.





La sixième session du Conseil fut organisée à Paris du 29 juin au 1^{er} juillet 1953. C'est à cette occasion que la Convention établissant l'Organisation fut signée, sous réserve de ratification, par douze Etats membres.

Torsten Gustafson
Subject to ratification

The Sixth Session of the CERN Council took place in Paris on 29 June—1 July 1953. It was here that the Convention establishing the Organization was signed, subject to ratification, by twelve States.

Torsten Gustafson

Swedish physicist and informal advisor to Tage Erlander.

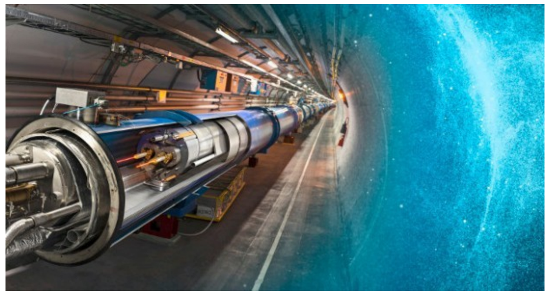
Delegate in CERN's Council 1953-1964.

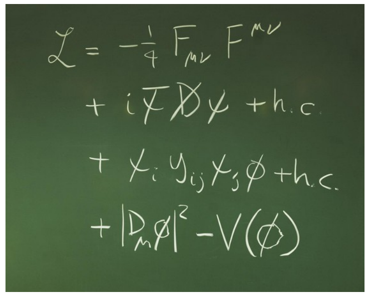
CERN today

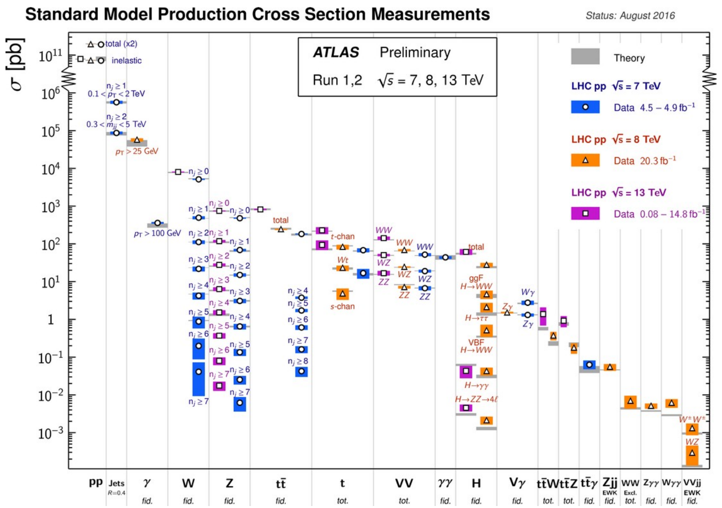
- 23 member states: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Serbia, Sweden, Switzerland, United Kingdom.
- Pre-state membership: Cyprus, Estonia, Slovenia.
- Associate members: Croatia, India, Latvia, Lithuania, Pakistan, Turkey, Ukraine.
- About 2,300 staff and over 12,000 users of 110 nationalities.

CERN's mission

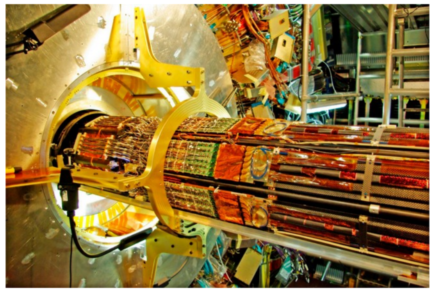
1) **Push** forward the frontiers of knowledge.

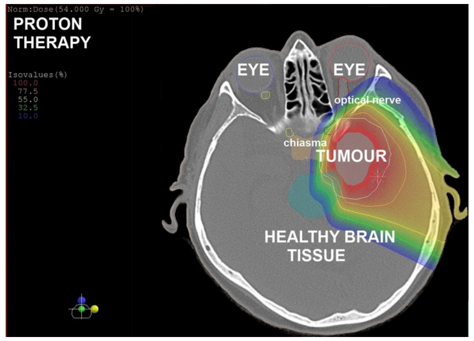




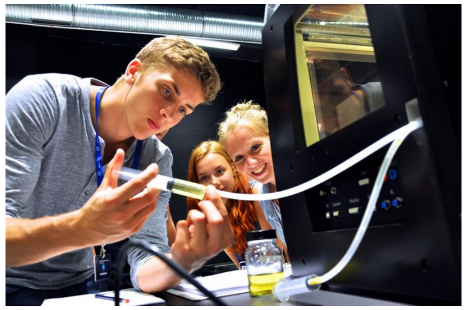


2) **Develop** new technologies for accelerators and detectors.





3) **Train** scientists and engineers of tomorrow.



4) **Unite** people from different countries and cultures.

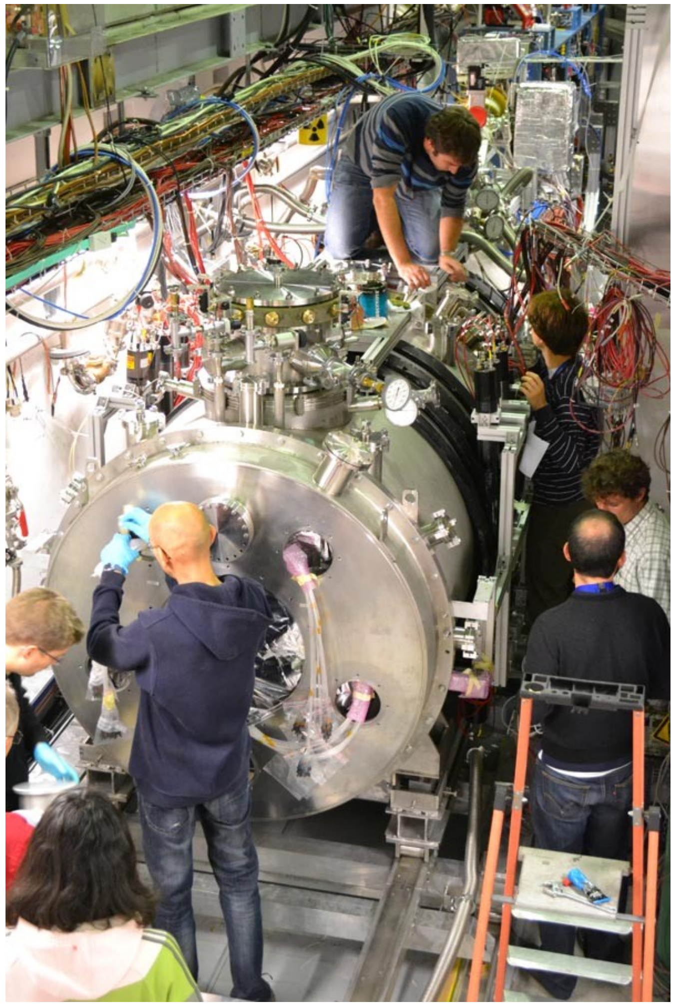
More than particle physics

Antimatter

- ALPHA, ATRAP
  - Trapping and spectroscopy
- AEGIS
  - Gravity on antimatter

Astroparticle

- CAST
  - Search for axions
- AMS
  - Dark matter search on board International Space Station

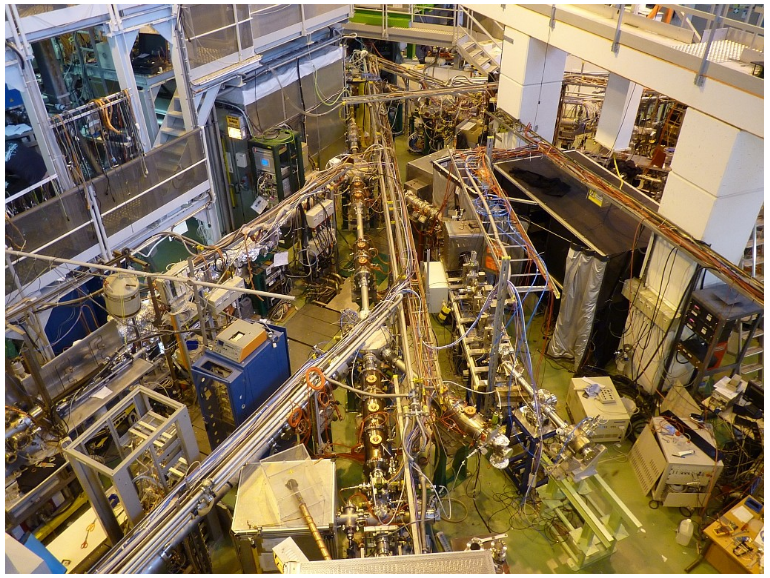


Environmental physics

- CLOUD
  - Study effects of cosmic rays on cloud formation

ISOLDE

- Radioactive ion beams
  - Nuclear physics
  - Astrophysics
  - Solid state physics
  - Medical applications



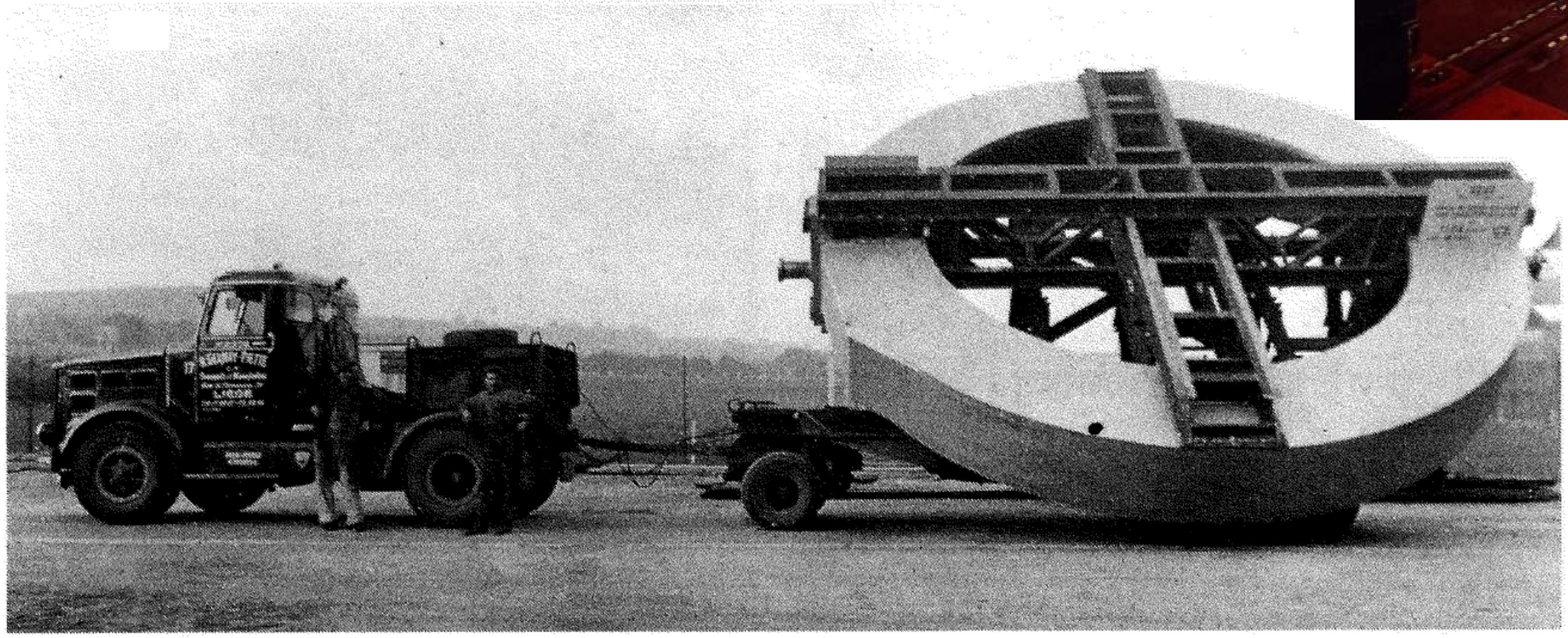
CERN’s accelerators

Our workhorses!

Synchrocyclotron (SC)

- Completed in 1957 and was CERN's first accelerator.
- Accelerated ions to an energy of 600 MeV (about ten thousand times less than today's energy frontier).
- Made precise measurements of the muon and could conclude that it behaved like a heavier version of the electron.
- SC was closed down in 1990, after 33 years service.

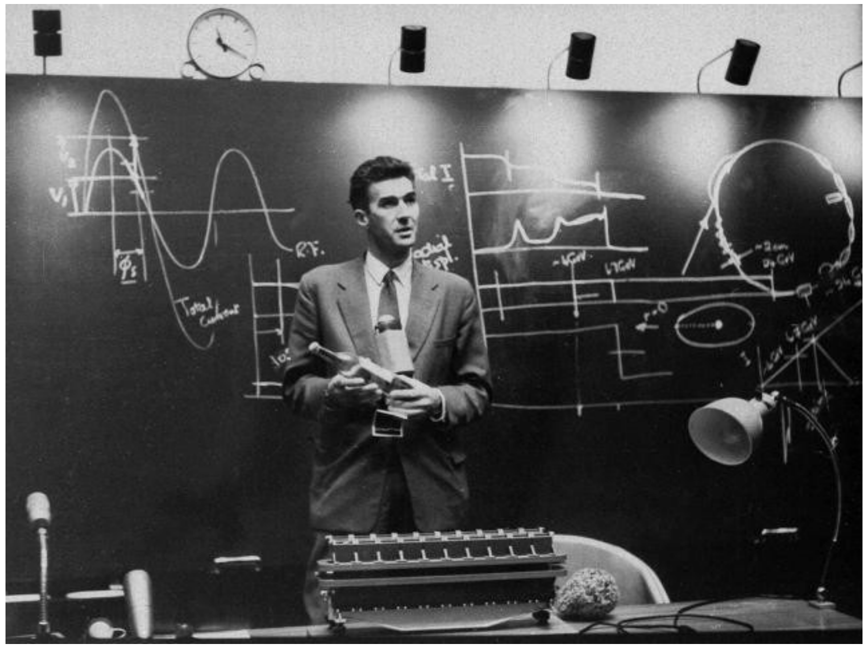
1957: construction finished



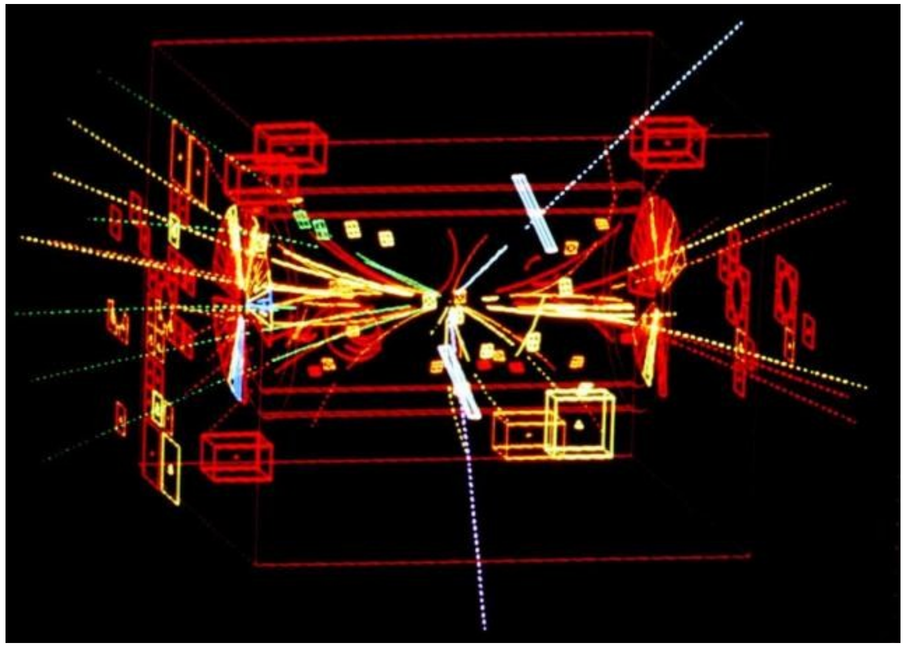
1955: magnet arrives

First synchrotrons

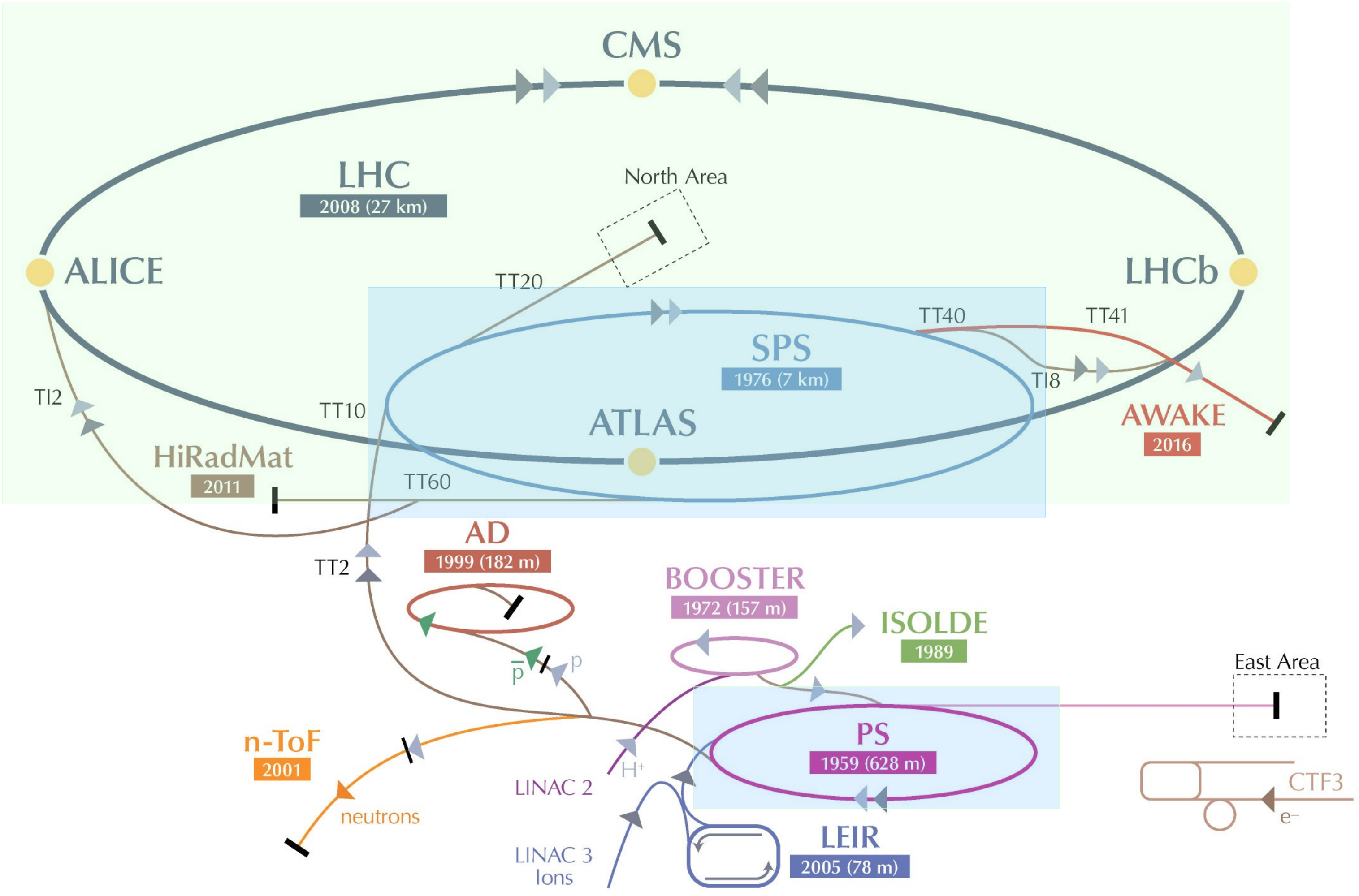
- **Proton Synchrotron (PS):** was completed in 1959. Accelerates protons to 28 GeV (0.4% of today’s energy frontier).
- Discovery of weak neutral currents in Gargamelle bubble chamber experiment.
- **Super Proton Synhcrotron (SPS):** CERN's first underground accelerator (7 km circumference, 40 m below ground).
- Started operations in 1976. 400-450 GeV (7% of today’s energy).
- Nobel Prize to Rubbia and Van der Meer 1984 for the discovery of the W and Z bosons.


PS design energy reached 1959


SPS tunnel ready 1974


Discovery of W and Z bosons 1983

CERN's Accelerator Complex



▶ p (proton) ▶ ion ▶ neutrons ▶ $\bar{p}$ (antiproton) ▶ electron ▶+▶ proton/antiproton conversion

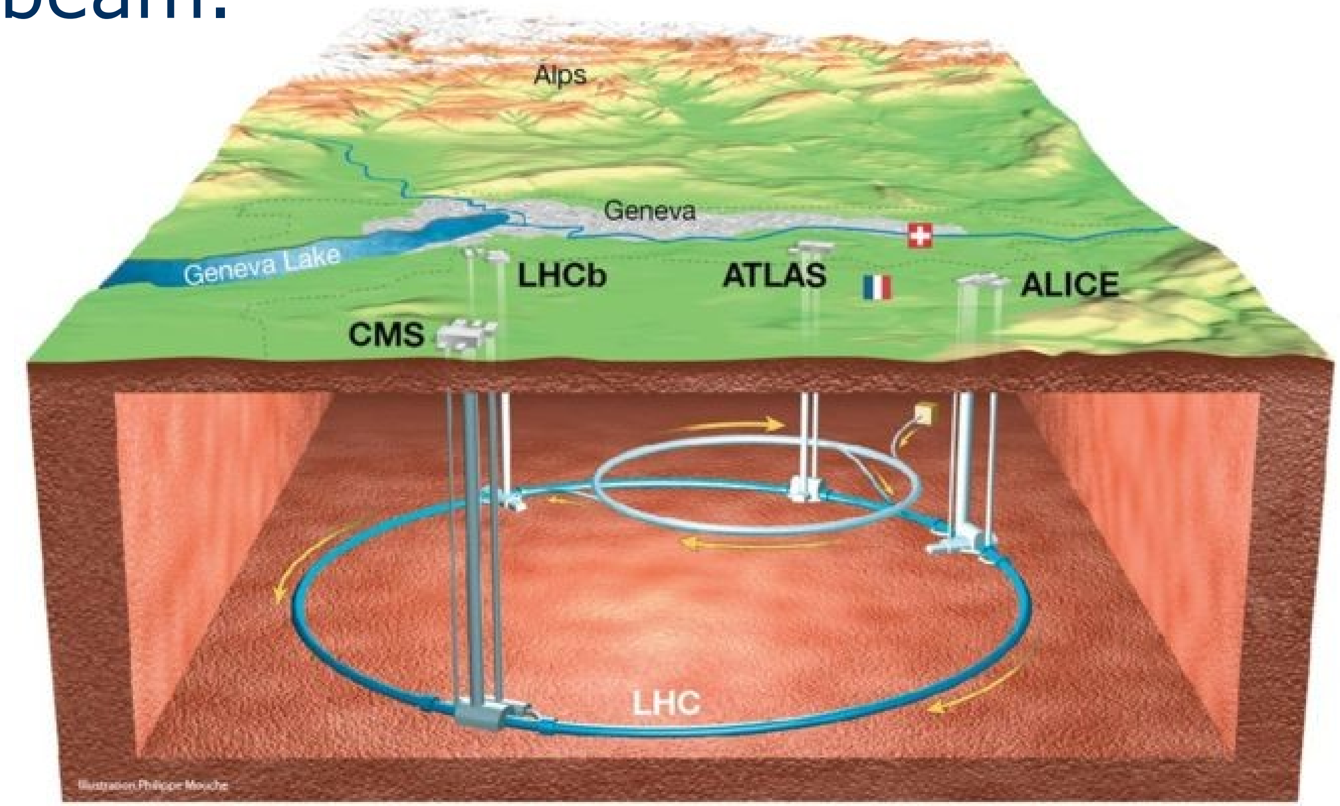
LHC Large Hadron Collider **SPS** Super Proton Synchrotron **PS** Proton Synchrotron

AD Antiproton Decelerator **CTF3** Clic Test Facility **AWAKE** Advanced WAKefield Experiment **ISOLDE** Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring **LINAC** LINear ACcelerator **n-ToF** Neutrons Time Of Flight **HiRadMat** High-Radiation to Materials

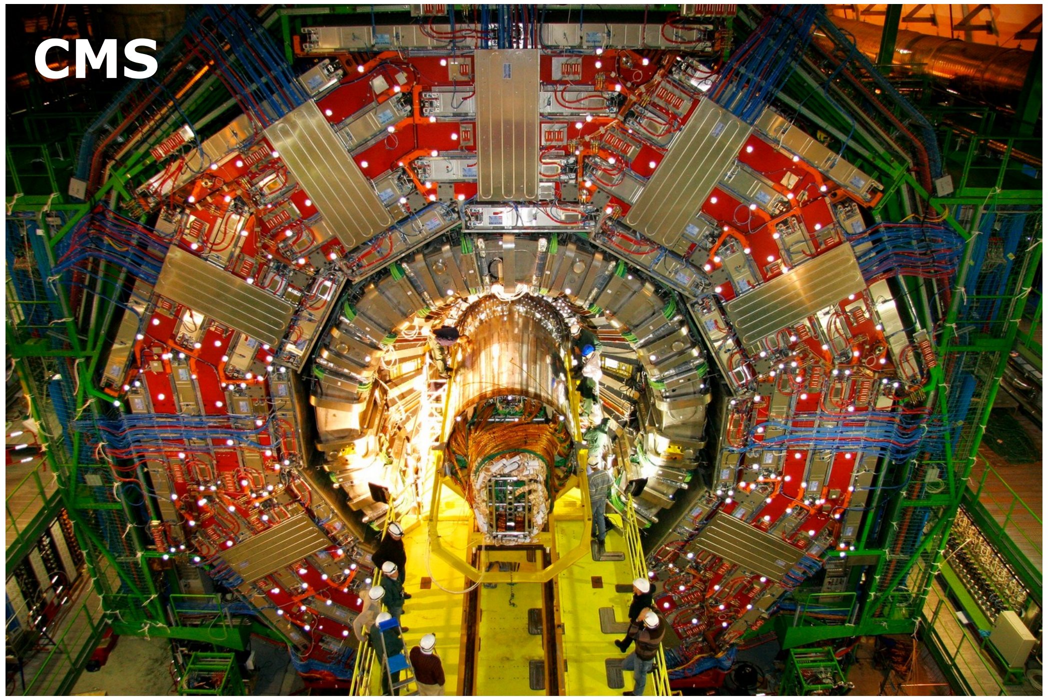
Large Hadron Collider

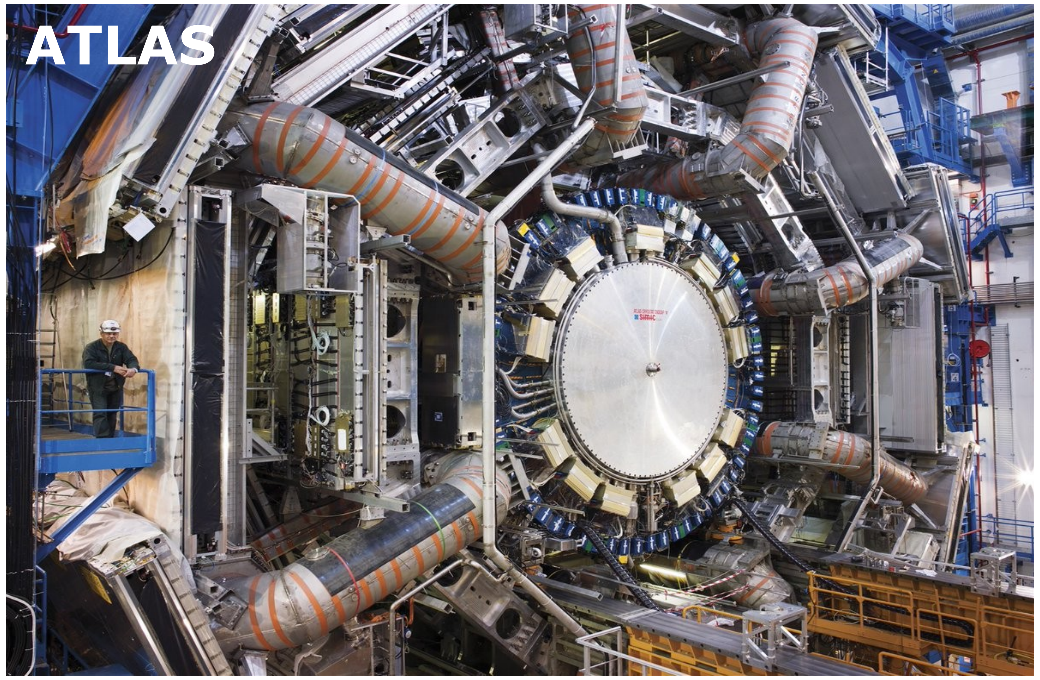
- CERN’s current flag ship. Accelerates protons to 6.8 TeV → E_{CM} = 13.6 TeV. → **Can produce heavy particles**.
- 27 km in circumference, 100 m under ground.
- About 2800 bunches of 10^{11} protons each travel at 99.999999% of the speed of light (11 245 turns around the ring per second).
- 40 million bunch crossing per second, ~40 *pp* collisions per bunch crossing. → **Can study rare processes**.
- 8 accelerating RF cavities per beam.
- 1232 dipole magnets to bend the beams in circular paths.
  - Cooled with liquid helium down to 1.9 K.
  - 8.4 T magnetic field from a current of 11 700 A.
- 392 quadrupole magnets to focus the beams.

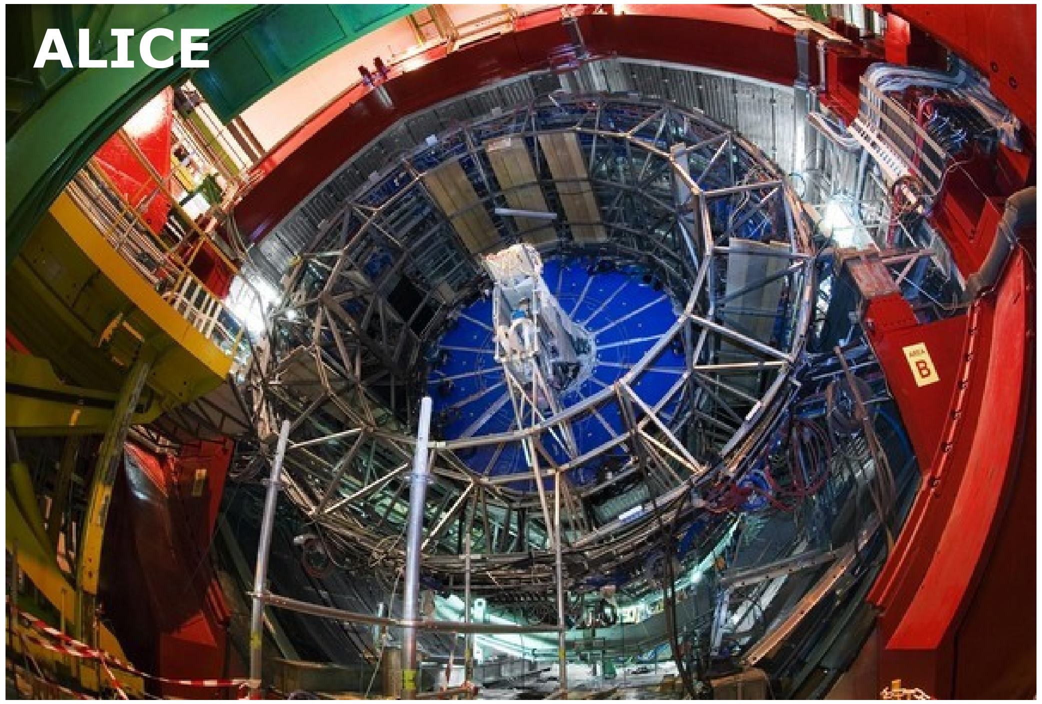


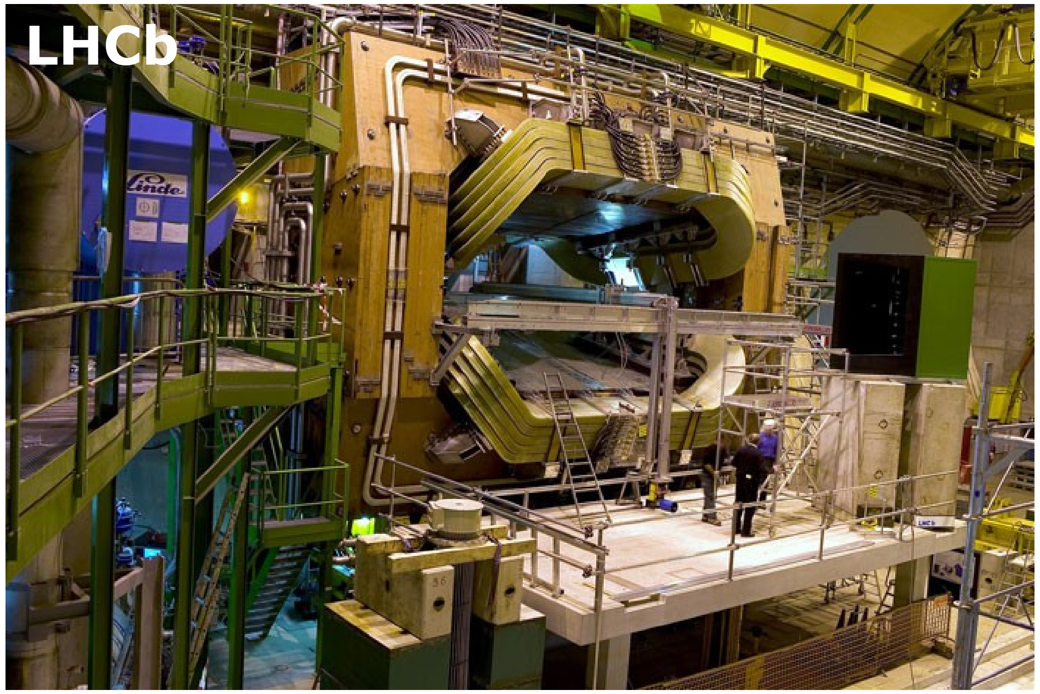
The four big experiments

- Four big and several smaller experiments study the collisions.



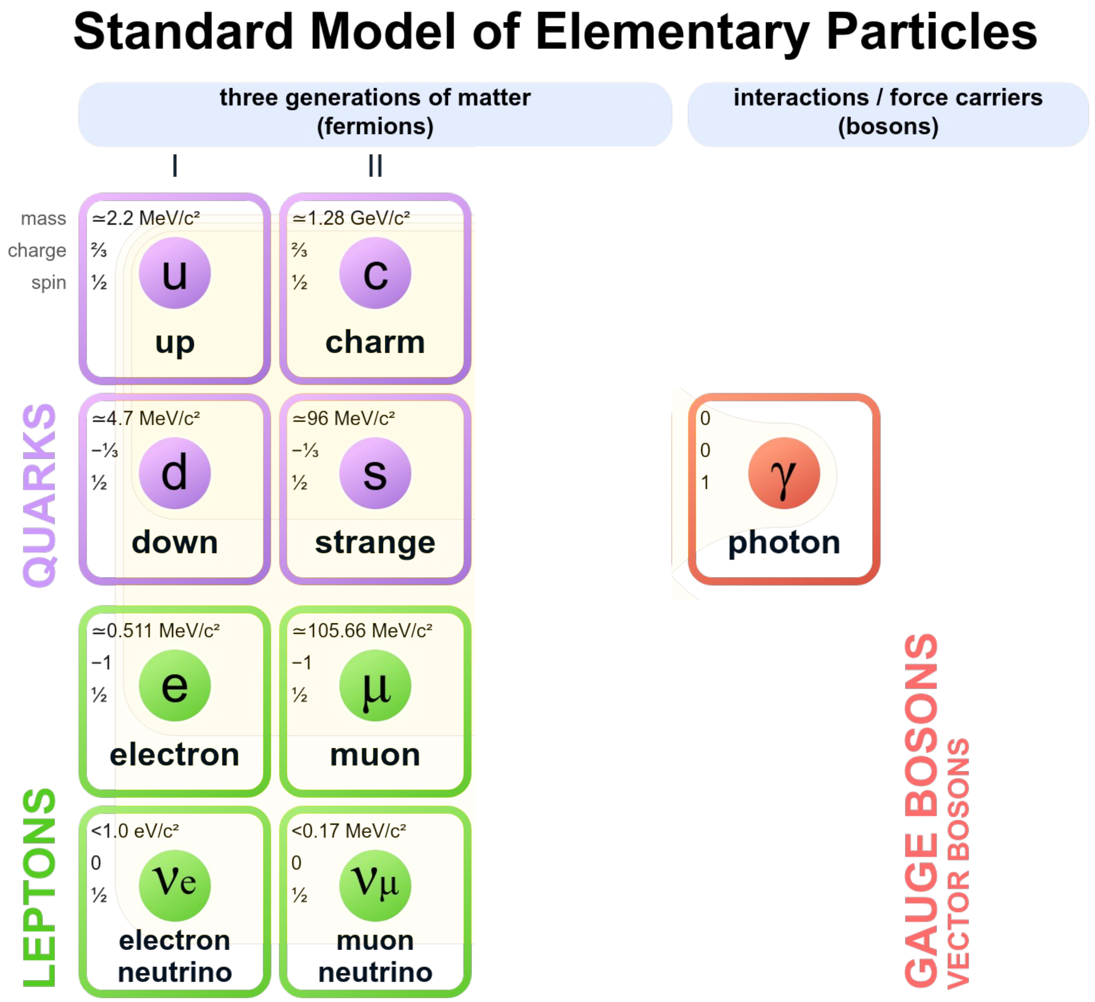






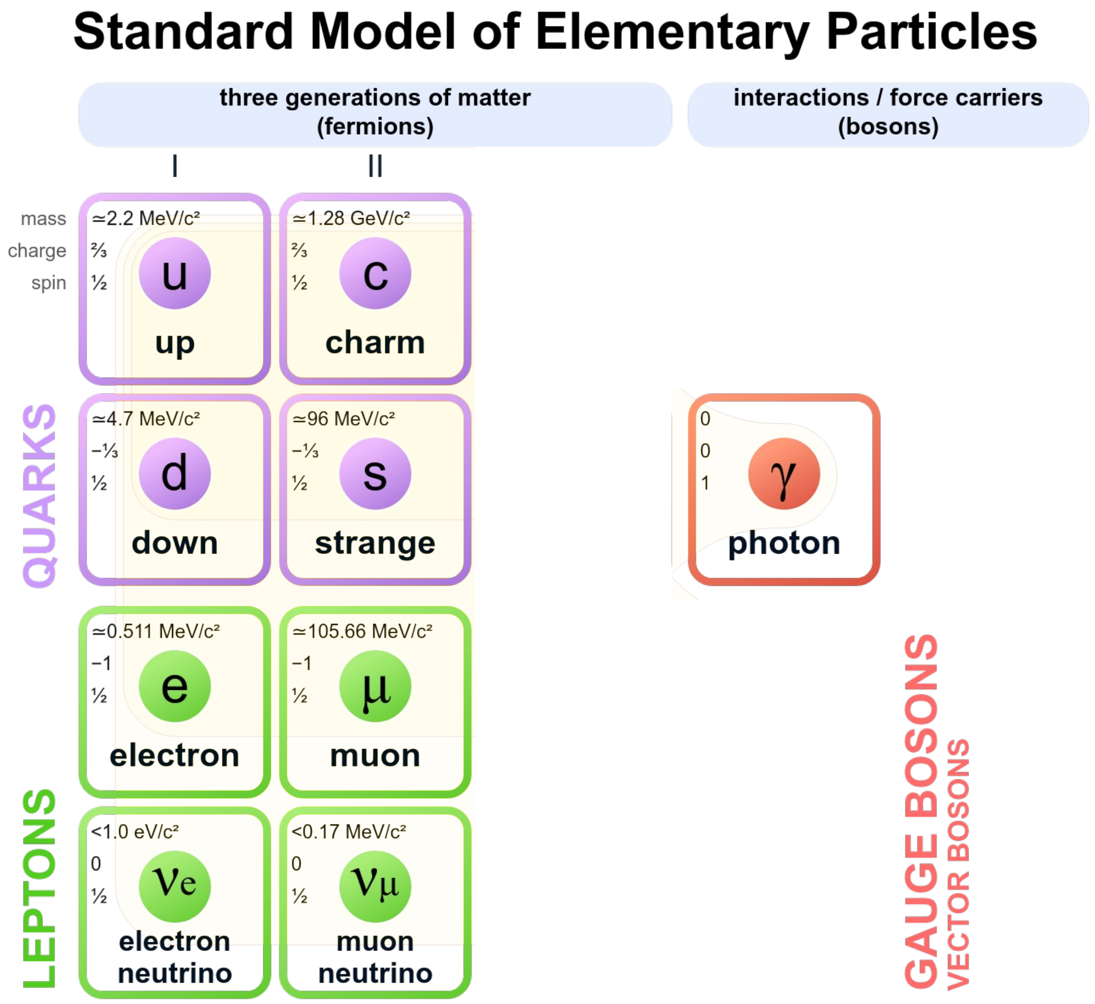
The birth of the Standard Model

- Going back to the story of why particle accelerators were built, the early results confused rather than enlightened physicists.
  - Instead of being able to categorise the new particles, more and more new particles were discovered!
- Our modern understanding of the elementary particles started taking form in the 1960s and 1970s:
  - Most new particles were made up of smaller particles: quarks!
- It was also realised that the forces in nature are mediated by particles.
  - For example, the electromagnetic force is mediated by the photon.
- The Standard Model was born.
- The fundamental quantities are the quantum fields, and the elementary particles are excitations of them.



The particles in nature

- Since the birth of the Standard Model, the missing pieces have gradually been found in particle accelerator experiments.



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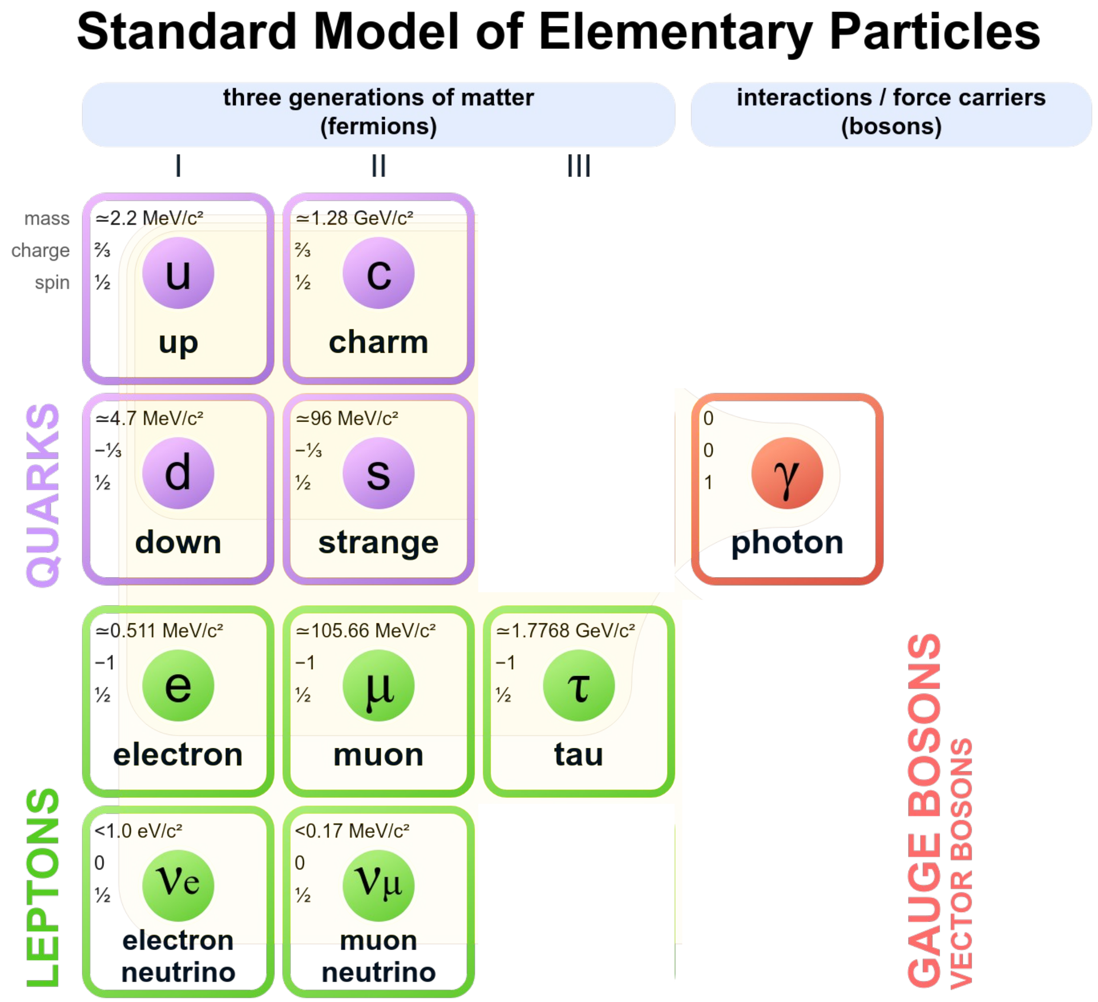

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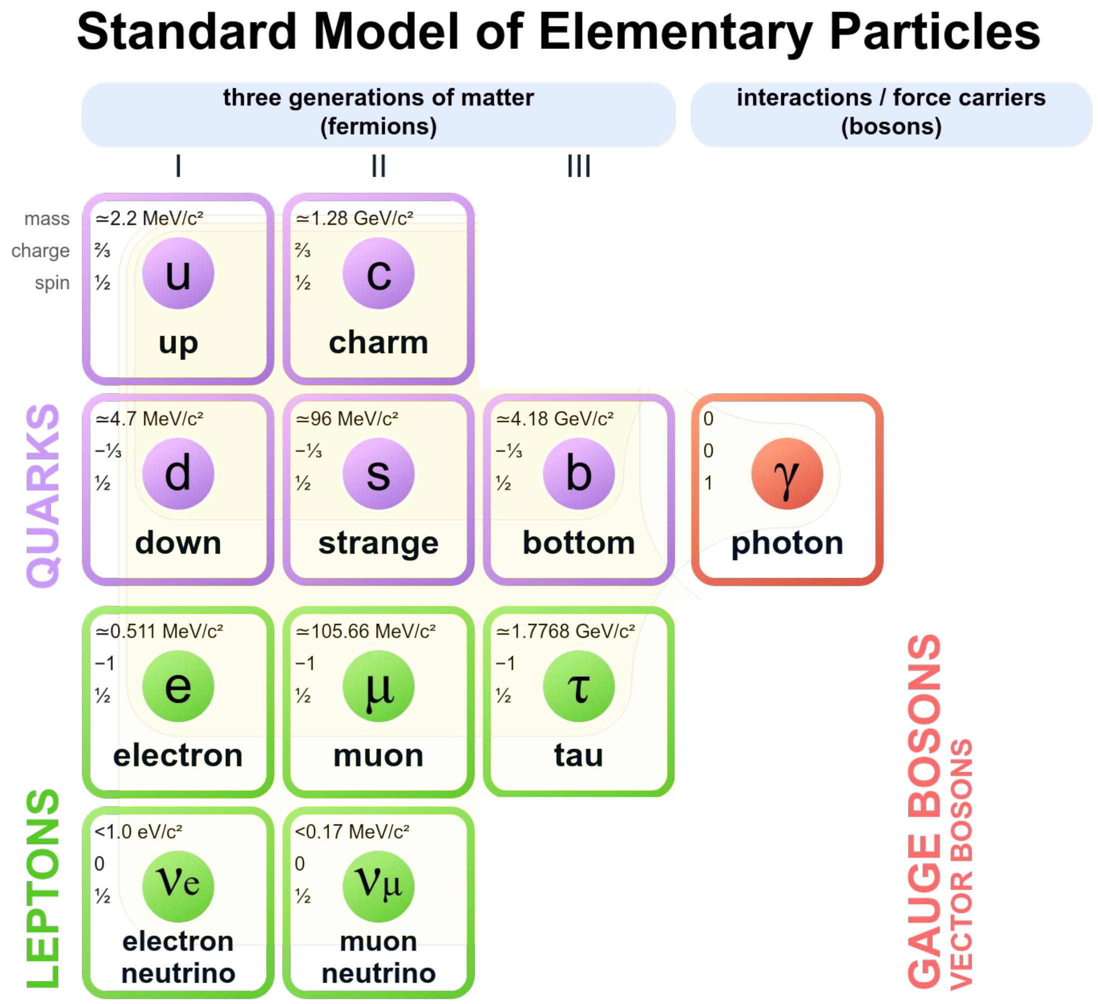

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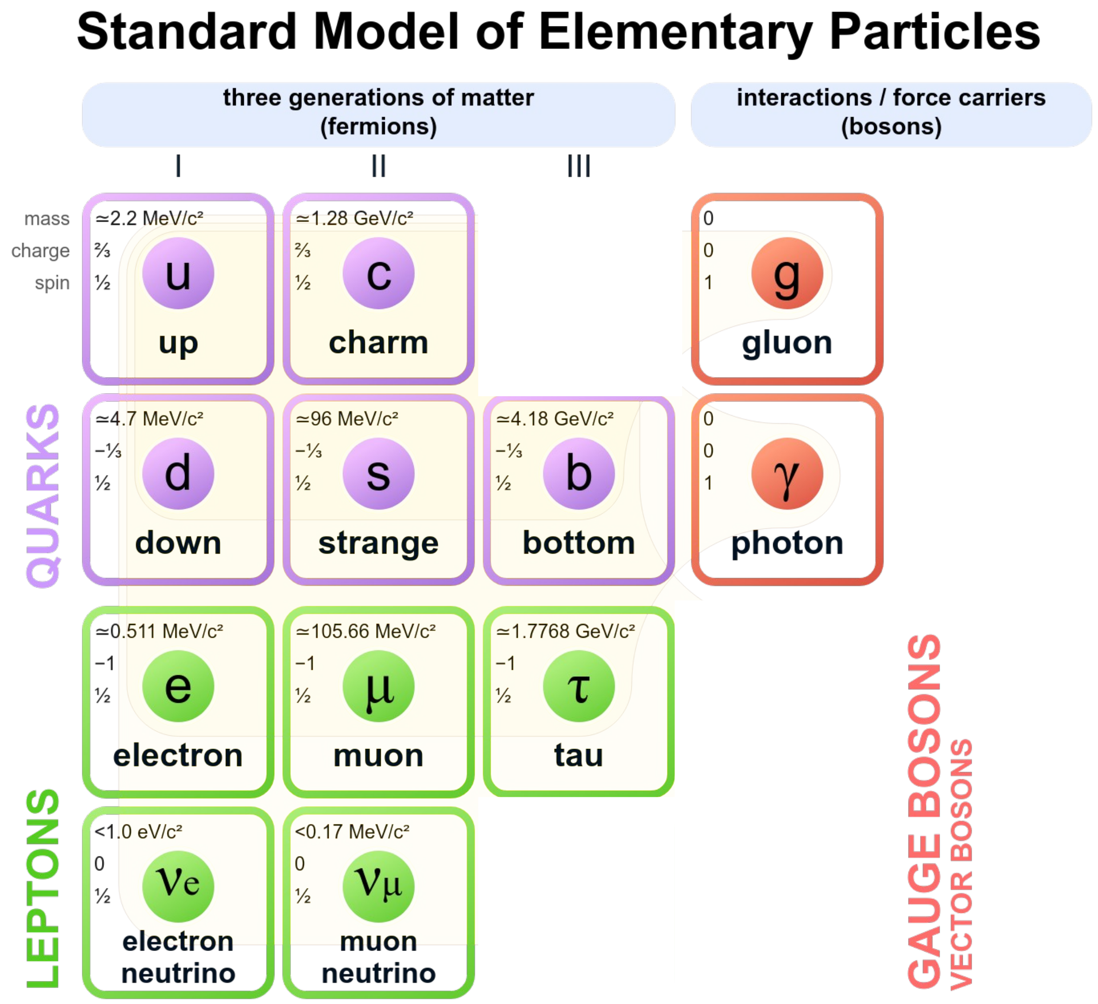

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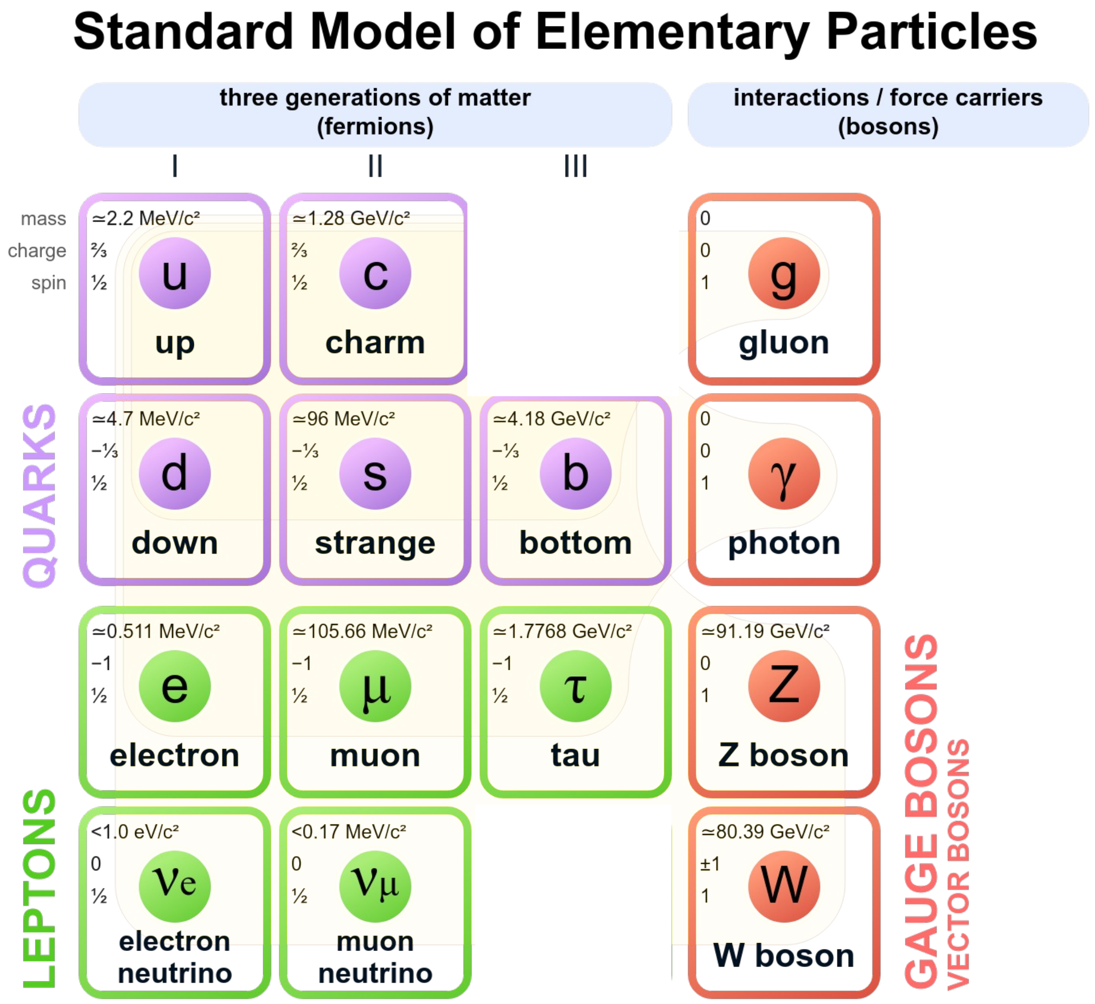

Standard Model of Elementary Particles

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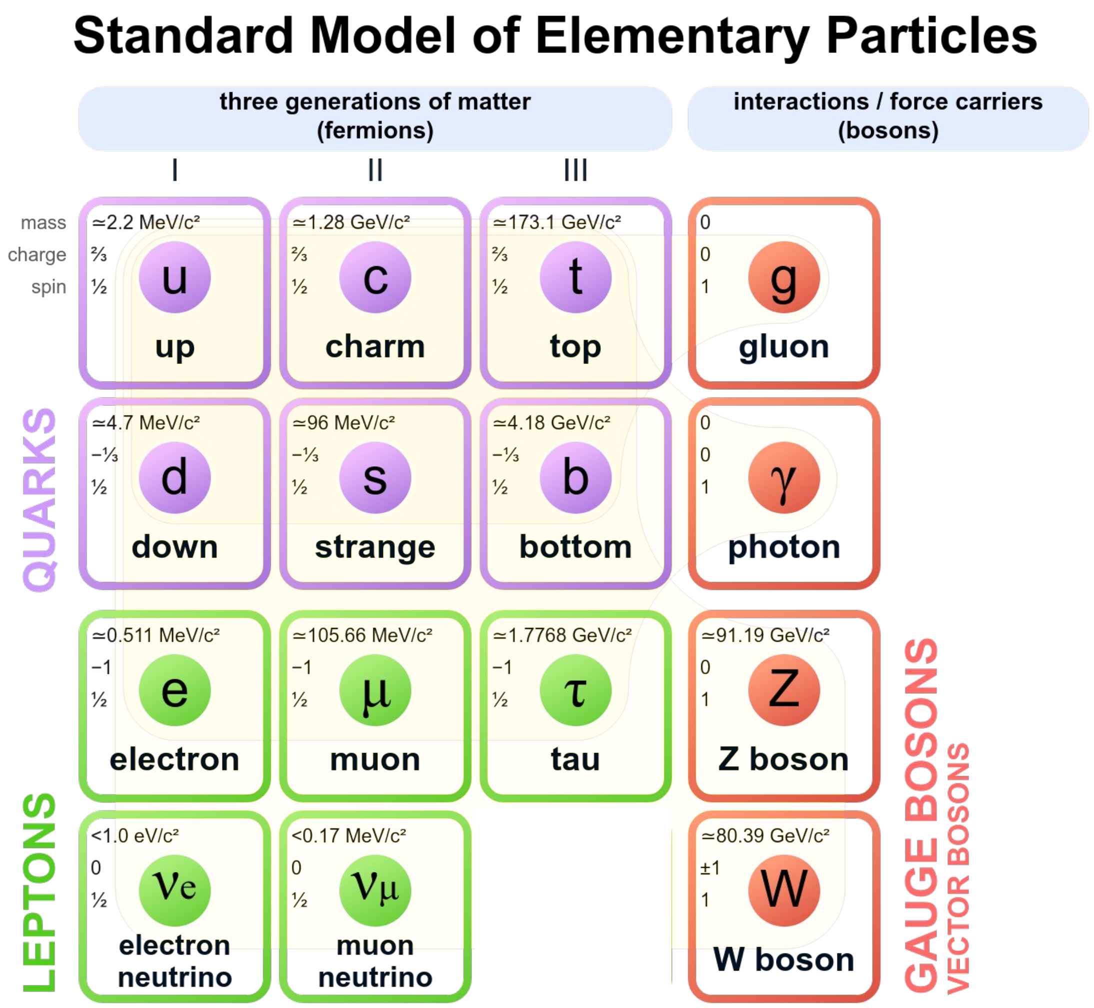
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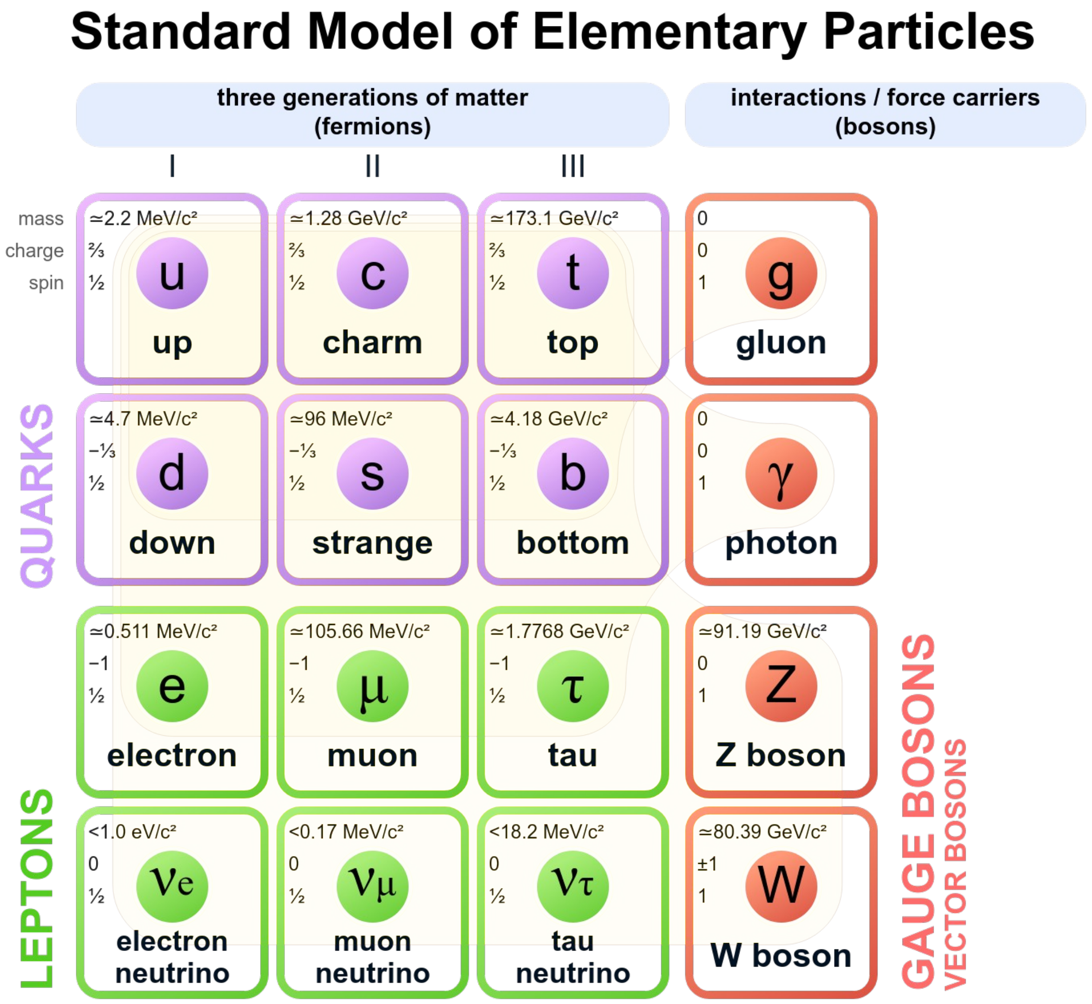
  - The tau neutrino in 2000.

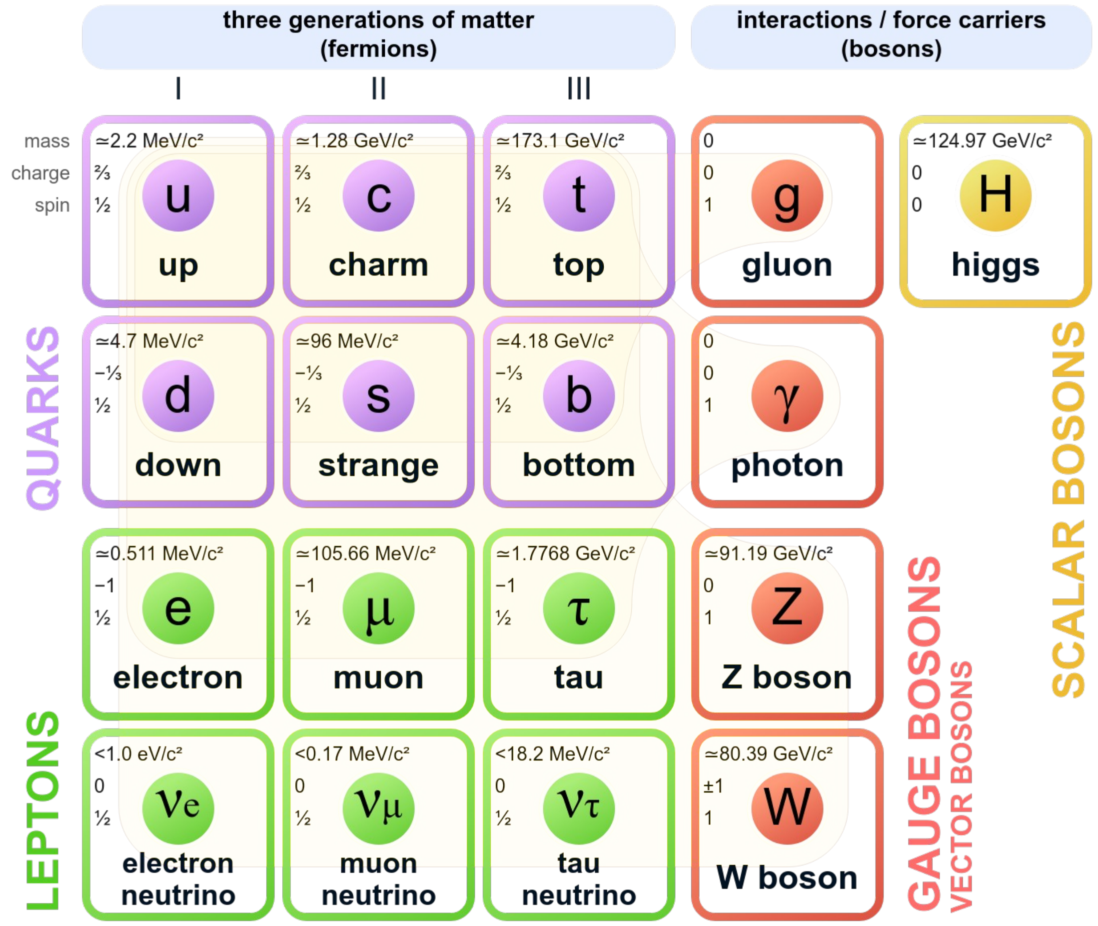


Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin QUARKS	$\simeq$2.2 MeV/c^2 ⅔ ½ u up	$\simeq$1.28 GeV/c^2 ⅔ ½ c charm	$\simeq$173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	
QUARKS	$\simeq$4.7 MeV/c^2 −⅓ ½ d down	$\simeq$96 MeV/c^2 −⅓ ½ s strange	$\simeq$4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	
LEPTONS	$\simeq$0.511 MeV/c^2 −1 ½ e electron	$\simeq$105.66 MeV/c^2 −1 ½ μ muon	$\simeq$1.7768 GeV/c^2 −1 ½ τ tau	$\simeq$91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
LEPTONS	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	$\simeq$80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

The particles in nature

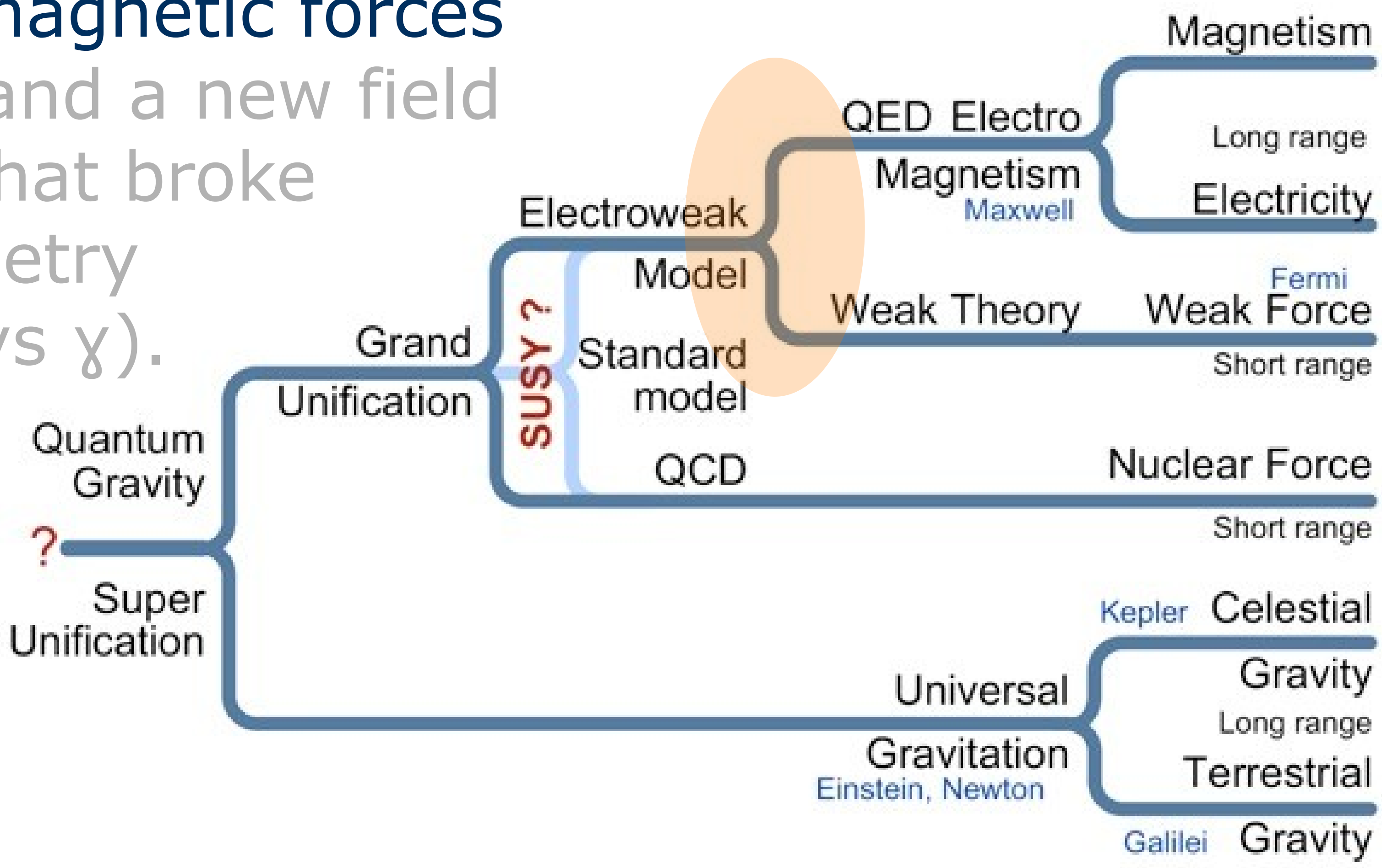
- Since the birth of the Standard Model, the missing pieces have gradually been found in particle accelerator experiments.
  - The tau lepton in 1975.
  - The bottom quark in 1977.
  - The gluon in 1978-1979.
  - The W and Z bosons in 1983.
  - The top quark in 1995.
  - The tau neutrino in 2000.
- But there was one missing piece, which had been predicted to exist already in the 60s - the Higgs boson.



Standard Model of Elementary Particles

Why do we need the Higgs?

- The Standard Model could successfully describe the observed particles, and the forces between them.
  - With one caveat - according to the theory all particles had to be massless. This is (clearly!) in contradiction with experiment.
- The problem was solved theoretically by three independent groups of theorists (one of them Peter Higgs) in 1964 and 1965:
  - The weak and electromagnetic forces needed to be unified, and a new field had to be introduced that broke the electroweak symmetry at low energies (W/Z vs ɣ).
  - The new field came with a new particle.
  - The missing particle became known as the Higgs boson.



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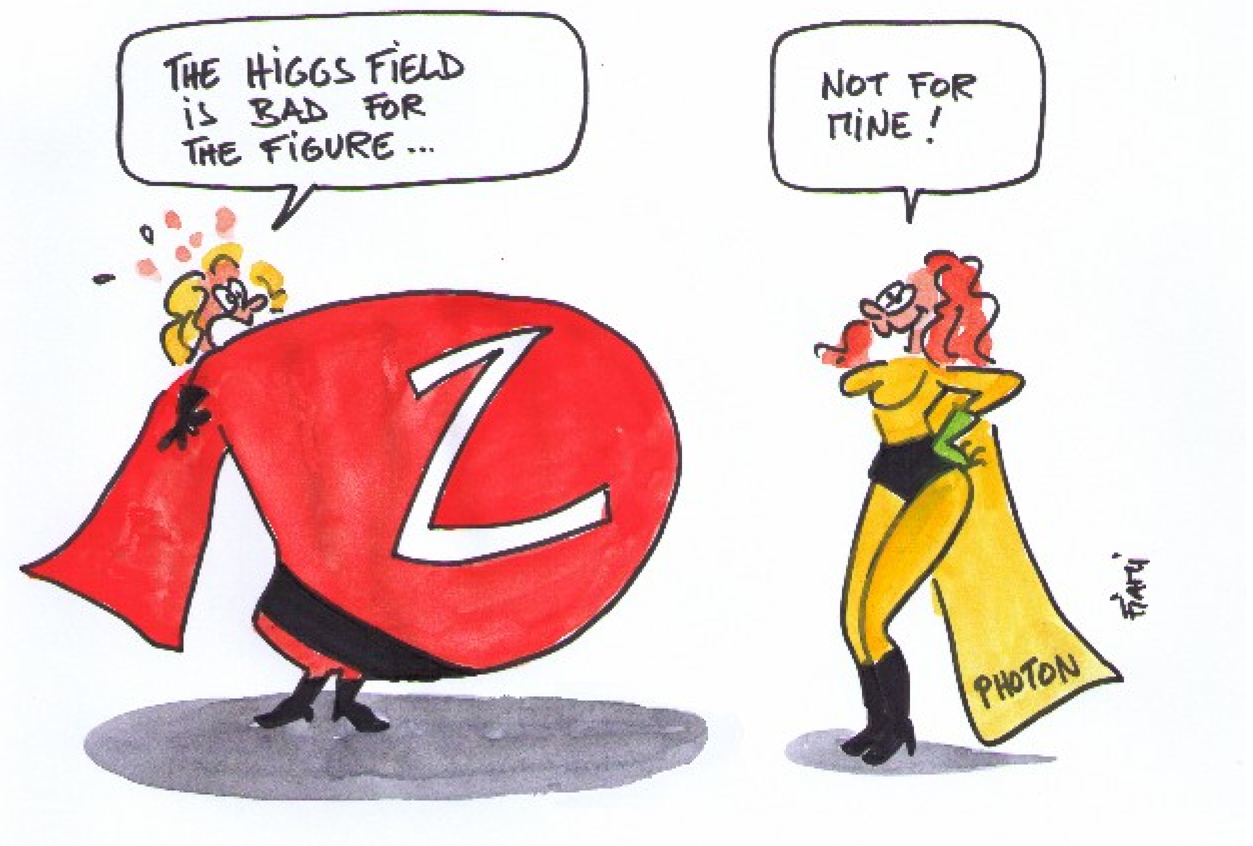
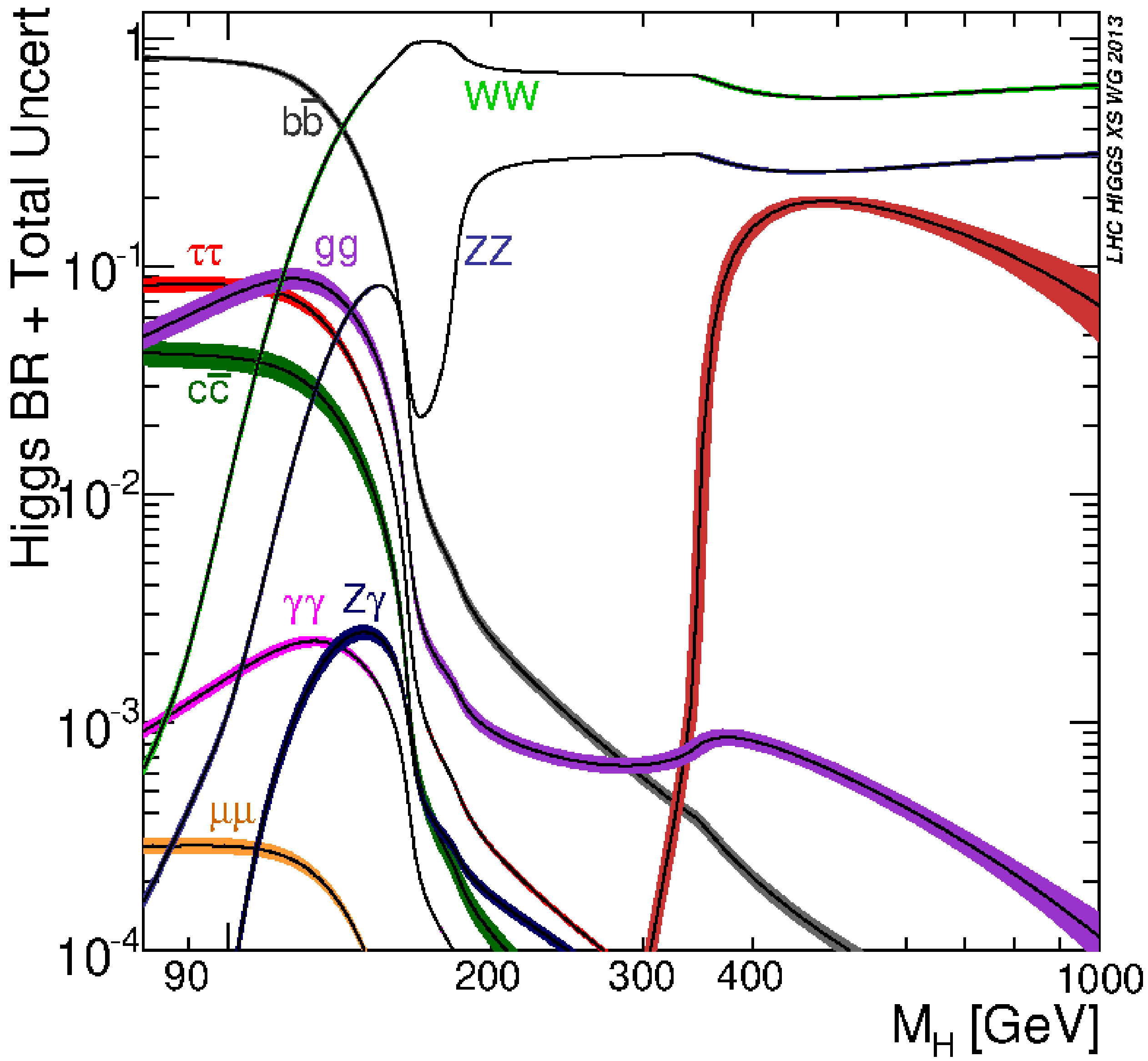


How did we find the Higgs?

- First we need the necessary energy to create it → LHC.
- How can one detect a particle that is only created in 1 out of 10^{10} collisions, and only exist for 10^{-24} s (enough to travel ~10^{-16} m)?
  - Need to know how it decays and look for that signature.
- Many different decay modes:
  - 4 electrons or muons (via ZZ).
  - 2 photons (ɣ).
- Same final states can also be created by other processes in the Standard Model.

  → Background processes.
  - Lots of data is needed to statistically verify the existence of the signal on top of the background.



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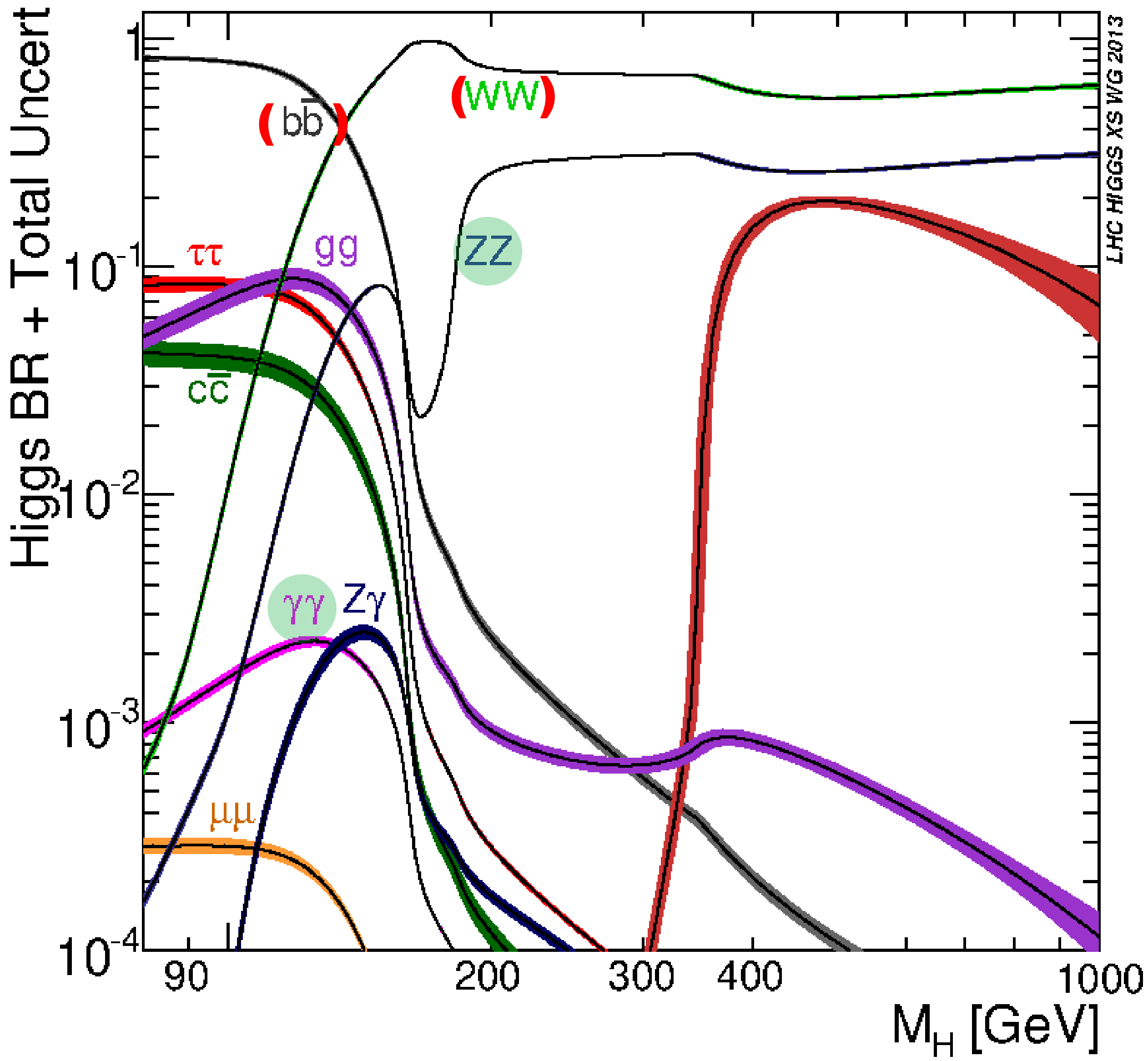

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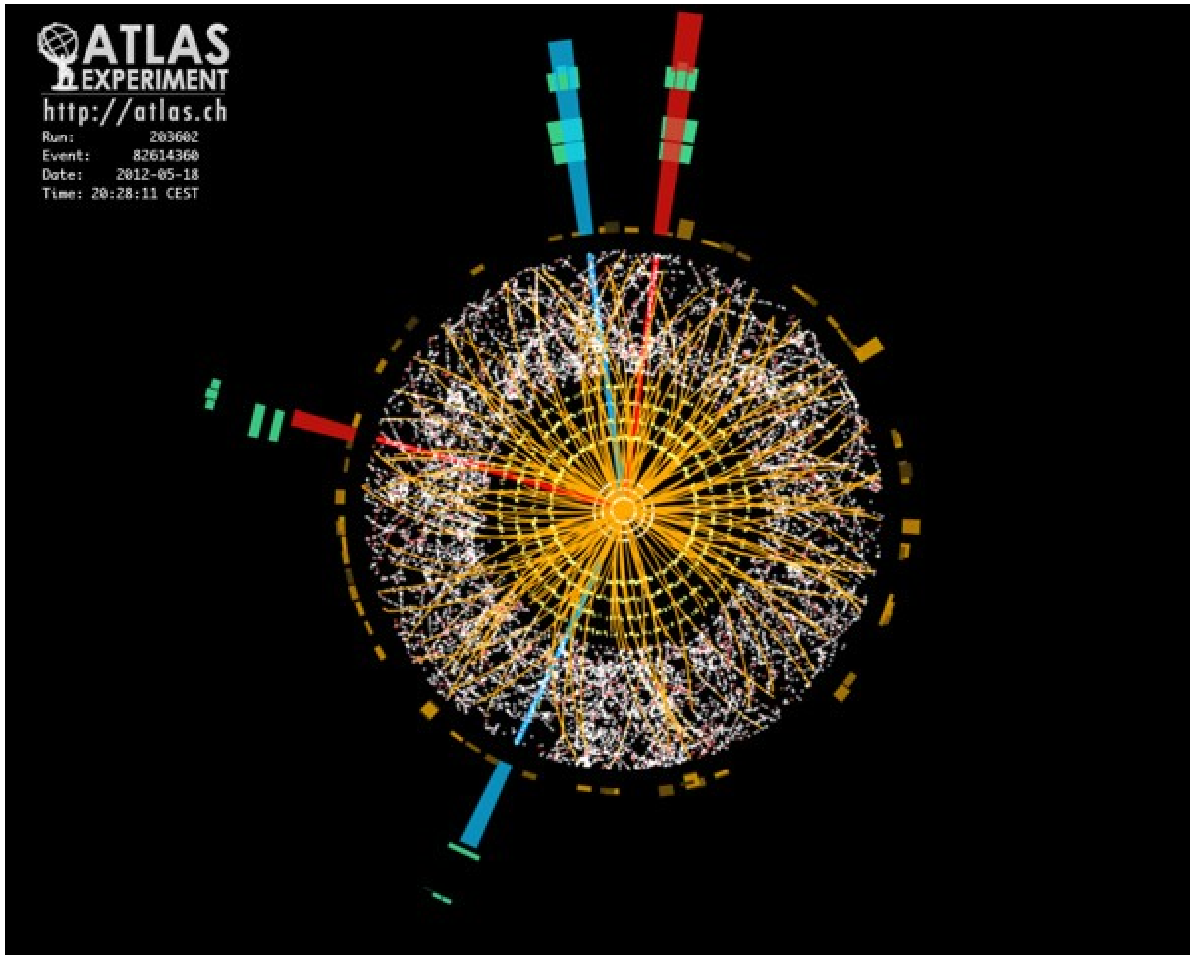
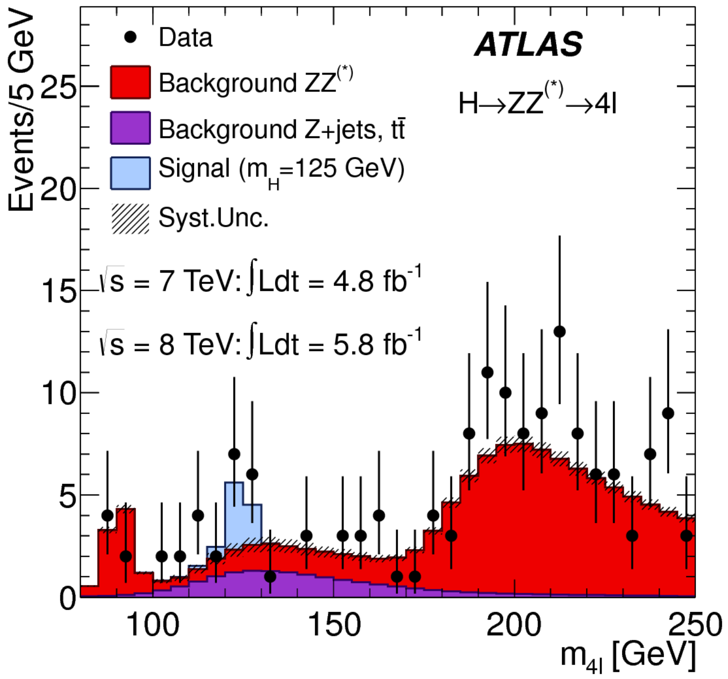


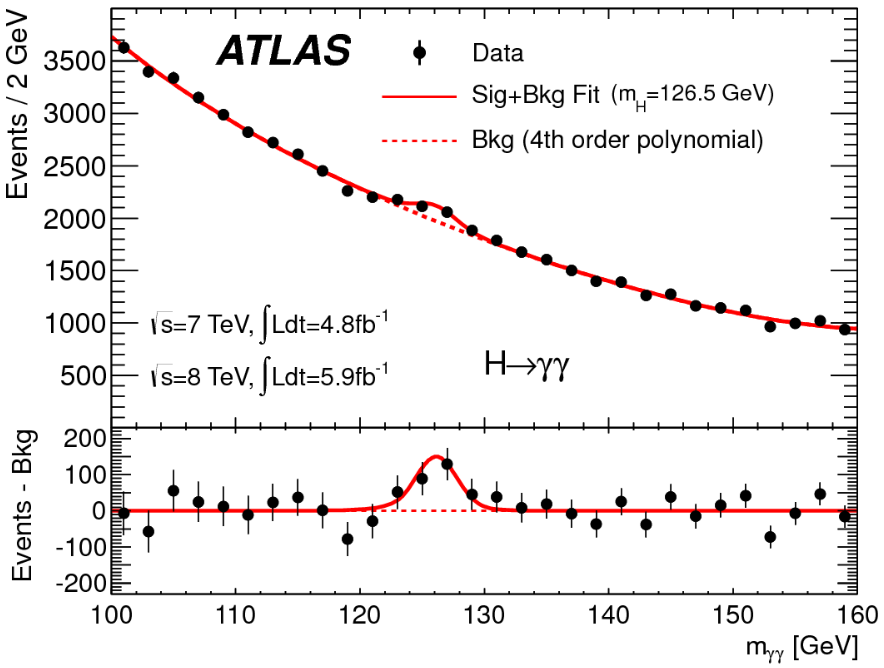
The Higgs discovery

- By July 4th 2012, enough data had been collected that there was no doubt anymore.
  - The Higgs boson existed!
  - The ATLAS and CMS experiments had made the same observation, independently of each other.

- 2013 Nobel prize awarded to Peter Higgs and Francois Englert.

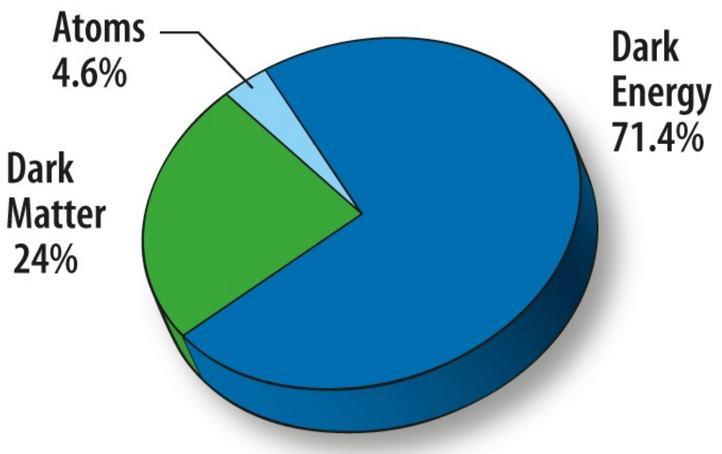
> ”for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s LHC”



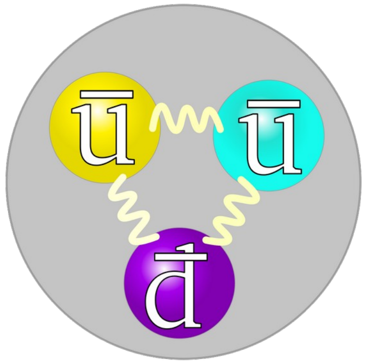


Are we done now?

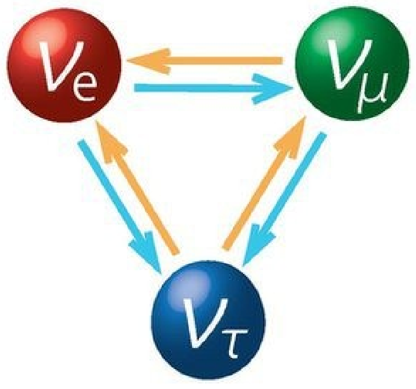
- The Higgs boson was the last missing piece needed to make the Standard Model a self-consistent theory.



- But we know it is not a complete description of the subatomic world.
  - It does not include gravitation.
  - It cannot explain the dark matter and the dark energy in the Universe.
  - It cannot explain the large asymmetry between matter and antimatter.



  - The neutrinos are massless in the Standard Model although we know from neutrino oscillations that they have a (small) mass.

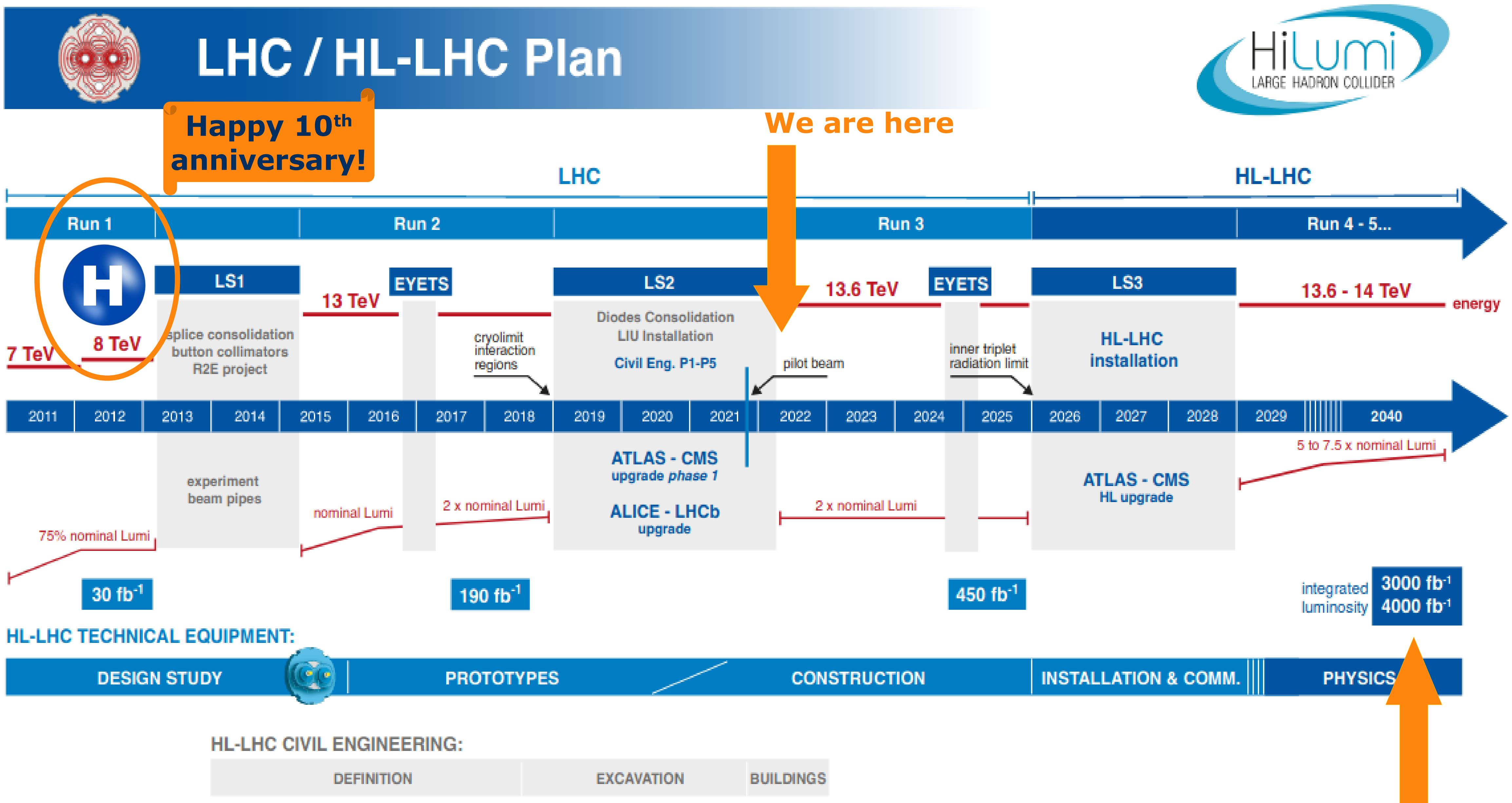


  - ...

How do we proceed?

- The overarching goal of particle physics today is to understand how the Standard Model should be extended.
- Evidence for physics beyond the Standard Model (BSM) can be
  - (a) direct: new particle discovered.
  - (b) indirect: measurements of known processes are not agreeing with Standard Model predictions.
- Historically both ways have been vital in pushing the frontier of knowledge forward.
- LHC will gradually shift from an emphasis on (a) to emphasis on (b) over the course of its lifetime.
  - Will be no more big increase in energy (7→8→13→13.8→14 TeV), but a large increase in the dataset size
    - → more precise measurements.
    - → sensitivity to rarer processes.

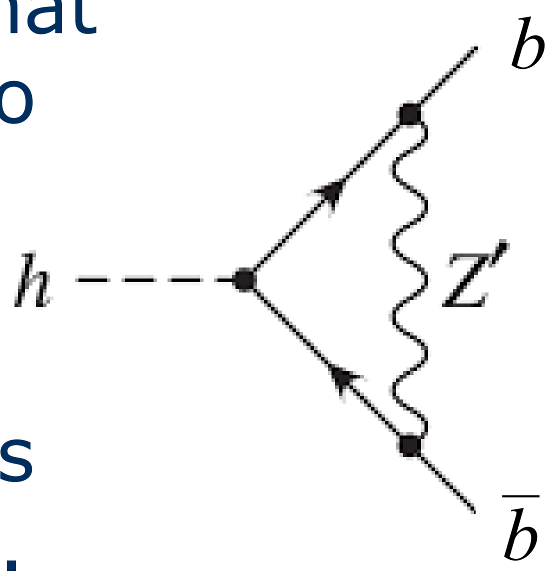
The next two decades

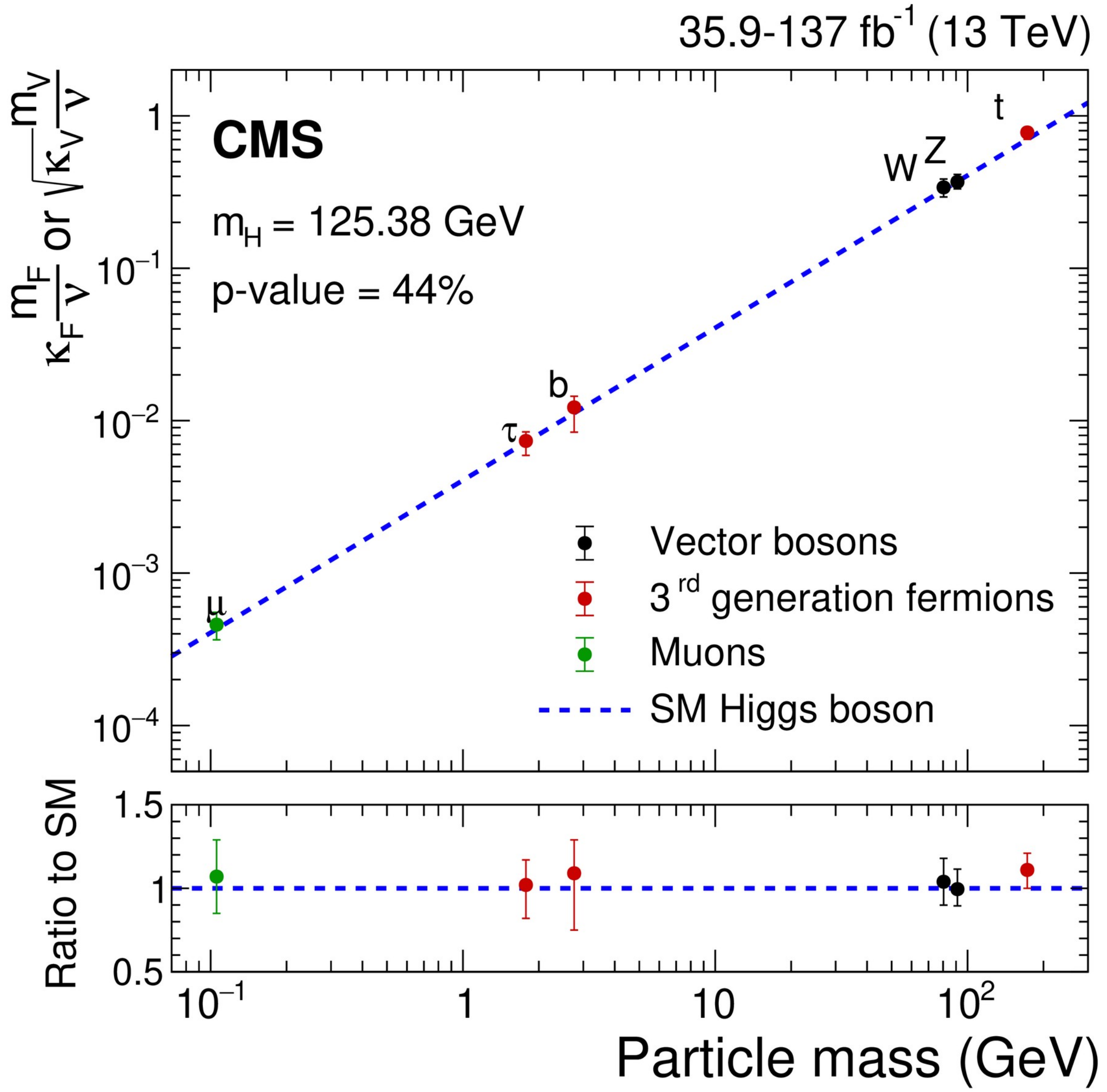


- LHC will continue to run until ~2040.
- More than 20 times the current amount of data expected.
- Can use this to learn a lot more about the Higgs boson.

Higgs precision

- The Higgs boson is the only spin-0 particle in the SM.
- Coupling strengths to the other particles in the Standard Model are proportional to their masses.
- If there is physics beyond the SM this can alter the couplings.
    - New particles that are too heavy to produce at the LHC can still contribute to SM processes as virtual particles.

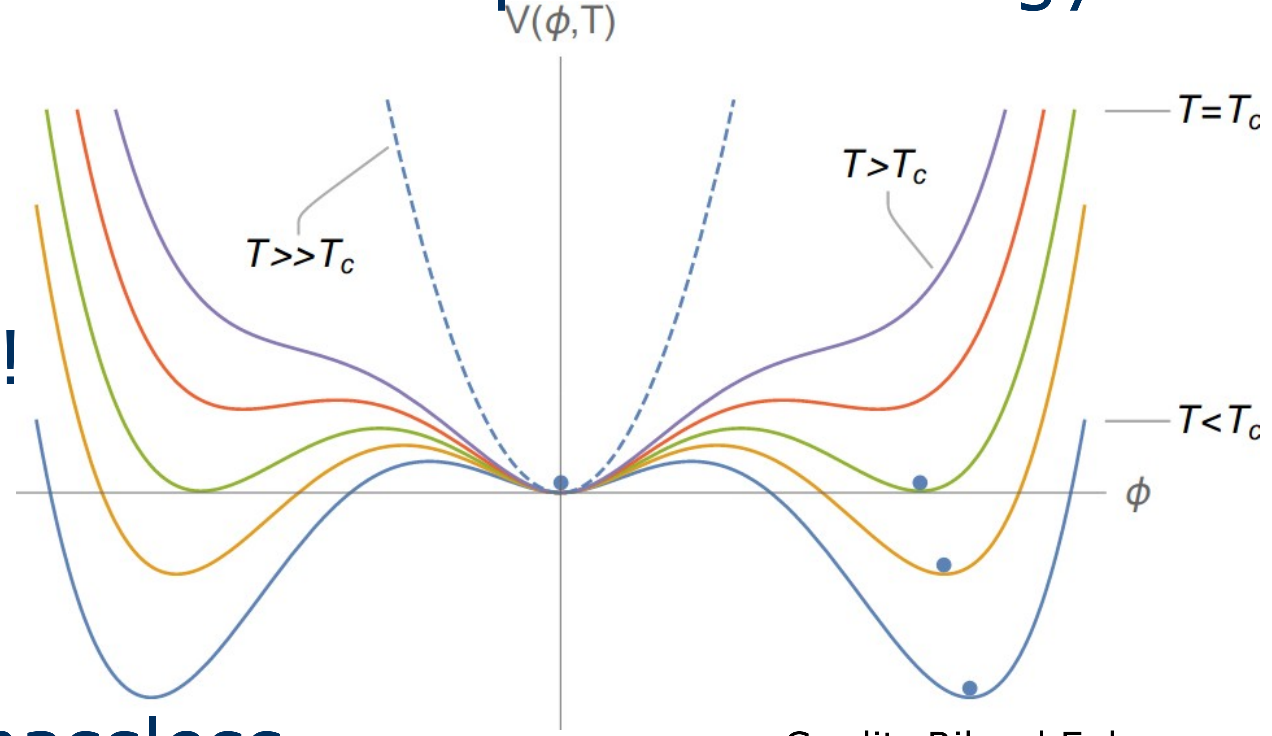




- Will use the large amount of LHC data to test if the properties of the Higgs boson agree with the Standard Model predictions.

The Higgs potential

- All quantum fields have an associated potential energy function.
- The ground state corresponds to the lowest potential energy (minimum of potential).
- Usually the value of the field is zero in the ground state.
- Not the case for the Higgs field!
- In the early Universe, the minimum of Higgs potential was at φ=0.

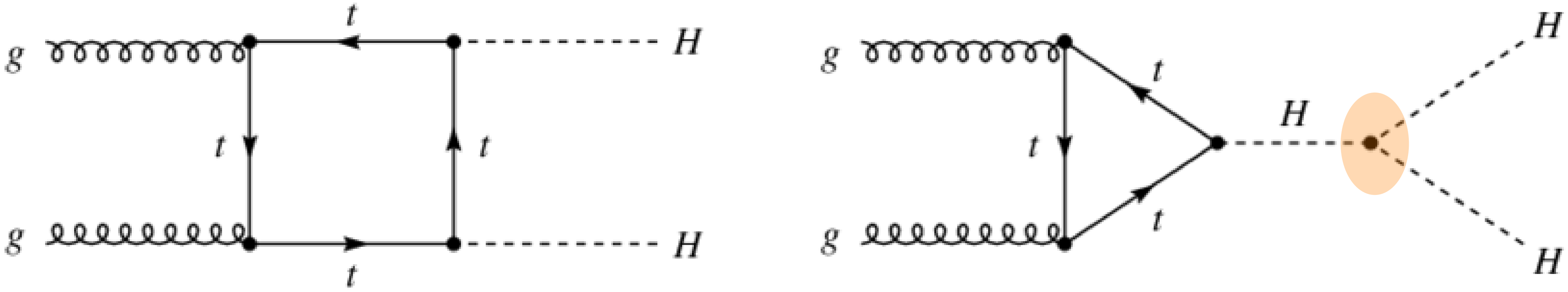


Credit: Rikard Enberg

- All elementary particles were massless.
- But O(ps) after the Big Bang a new minimum at φ≠0 developed.
  → Electroweak phase transition.
- Particles acquired mass by interacting with the ≠0 Higgs field.
- Matter-antimatter asymmetry can also have been created here.
- To better understand this phase transition we need to experimentally probe the shape of the Higgs potential.

The Higgs self-coupling

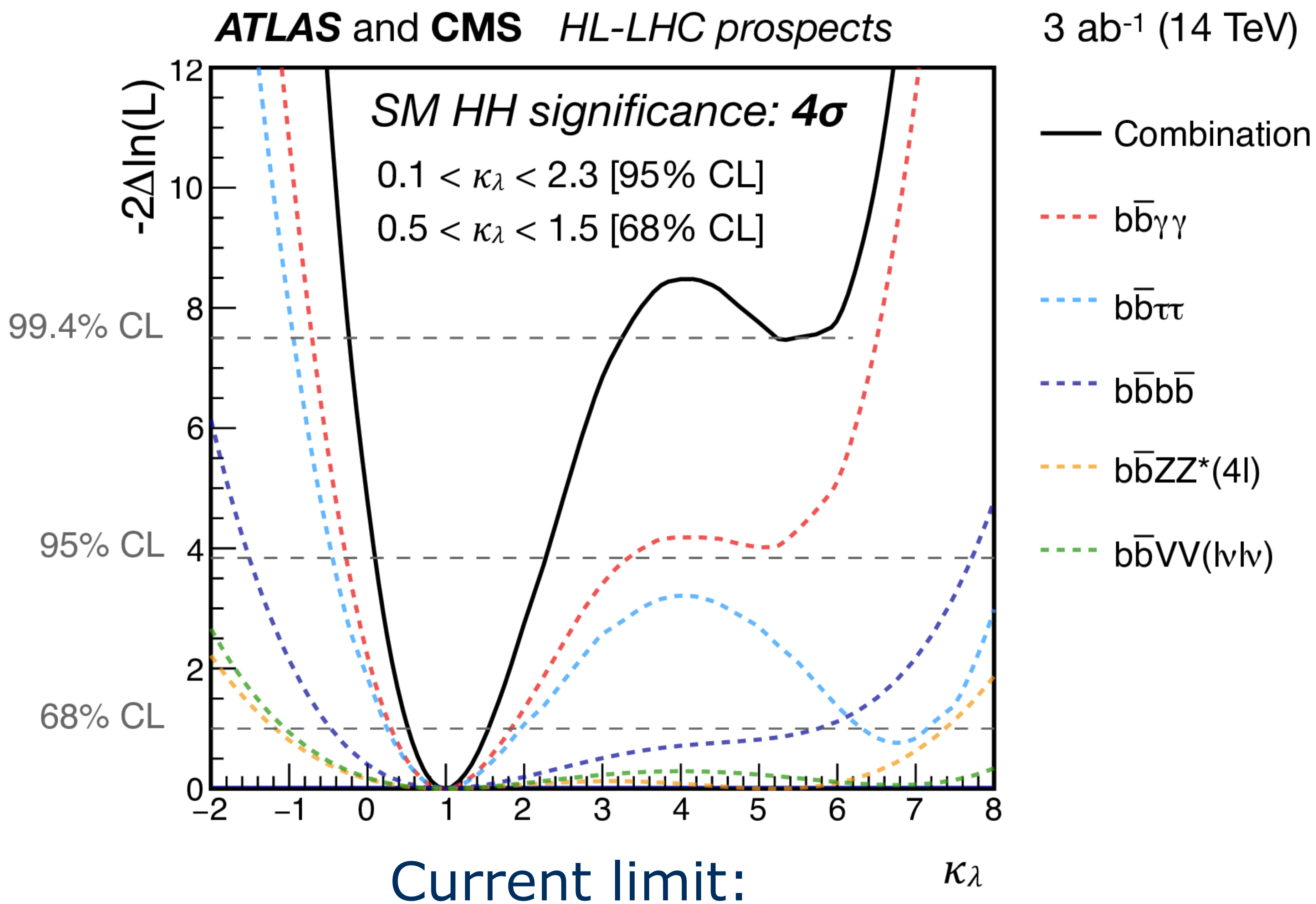
- One parameter affecting the shape of the Higgs potential is the Higgs self-coupling λ.
- Can be experimentally probed by measuring how often Higgs bosons are produced in pairs. → Flagship analysis at the HL-LHC.



- If the Higgs self-coupling has the strength predicted by the Standard Model, ATLAS and CMS together will be able to measure HH production with the full HL-LHC data (by 2040).
  - Will give us information about the ground state of the Universe.
- If the coupling is different from the Standard Model value, the process could be observed earlier.

The Higgs self-coupling

- 4σ discovery significance for SM-like HH production by the end of HL-LHC.
- $\kappa_\lambda = \lambda / \lambda_{SM}$



Current limit:
-1.1 < κ_λ < 6.6

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Beam is back!

- After a three year long shutdown, beam is back in the LHC since April 22nd.
- Currently beam and detector commissioning.
- 13.6 TeV collisions expected on July 5th.
- Extensive research program ahead!

LHC Page1 Fill: 7540 E: 450 GeV 22-04-22 10:09:51

BEAM SETUP: INJECTION PROBE BEAM

I TI2: 4.23e+09 I B1: 1.59e+09 I TI8: 1.50e+10 I B2: 2.29e+08

TED TI2: BEAM TDISA B1 gap/mm: up: 19.97 down: 19.98

TED TI8: DUMP TDISA B2 gap/mm: up: 1.47 down: 1.54

Updated: 10:09:51

Run 3 at last !

Comments (22-Apr-2022 10:08:58)

Beam 1 to IR1

CCC 77600 / Machine coordination 164367

AFS: MD_MKI_13inj_both

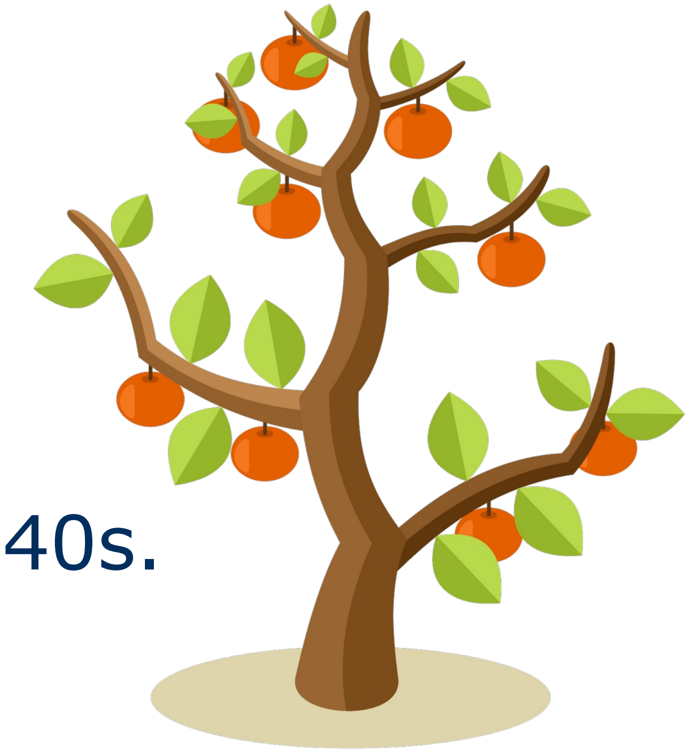
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

PM Status B1 DISABLED PM Status B2 DISABLED

Happy crowd in the ATLAS Control Room on 22 Apr 2022

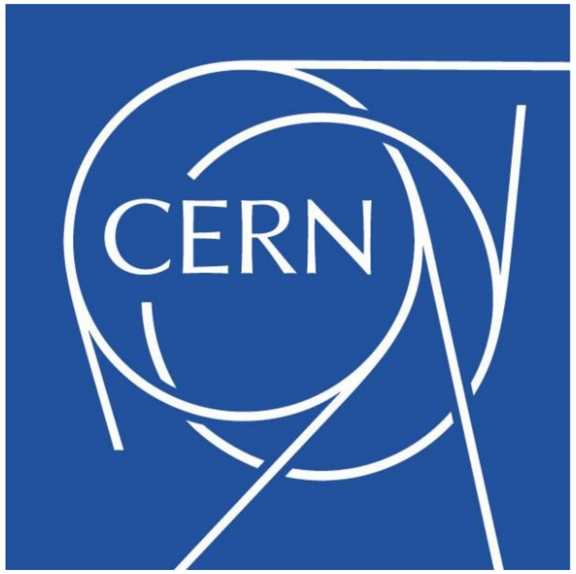
Summary and outlook

- Particle accelerators have given us the Standard Model.
  - Extremely successful theory, has been extensively tested for 50+ years and still stands.
  - With the Higgs discovery we have arrived at a self-contained theory describing all the data at the energy scales we can reach in our laboratories.
  - At the same time the Universe is telling us that the theory is not complete (dark matter, matter-antimatter asymmetry, neutrino masses, ...).
- The LHC has only delivered 5% of the expected dataset and will run until 2040.
  - Will give an extended reach for BSM physics, and allow measuring the Higgs self-coupling.
- Situation is remarkably similar to the 30s and 40s.
- Will the next 20 years of particle physics be as fruitful as the 50s and 60s?



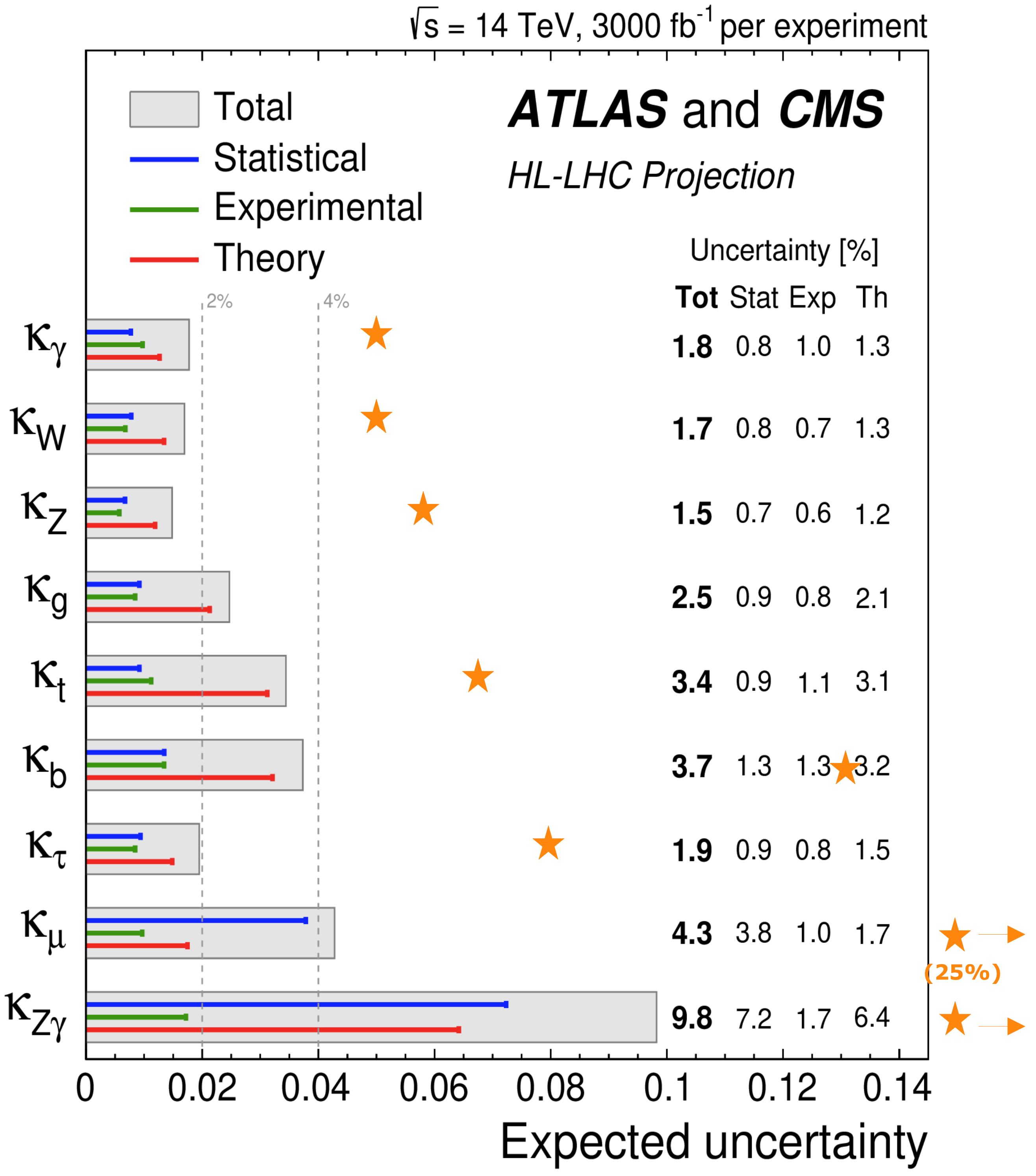
Credit: https://www.cppng.com

Backup



Higgs precision

- Currently our precision on the measurements on the coupling strengths between the Higgs boson and the other Standard Model particles is 5-10% (some cases even as bad as 25%).
- Percent-level precision is expected on these measurements by the end of HL-LHC.
  - Will give sensitivity to BSM particles with masses in the multi-TeV regime.
- We also use the data to search for additional spin-0 bosons.



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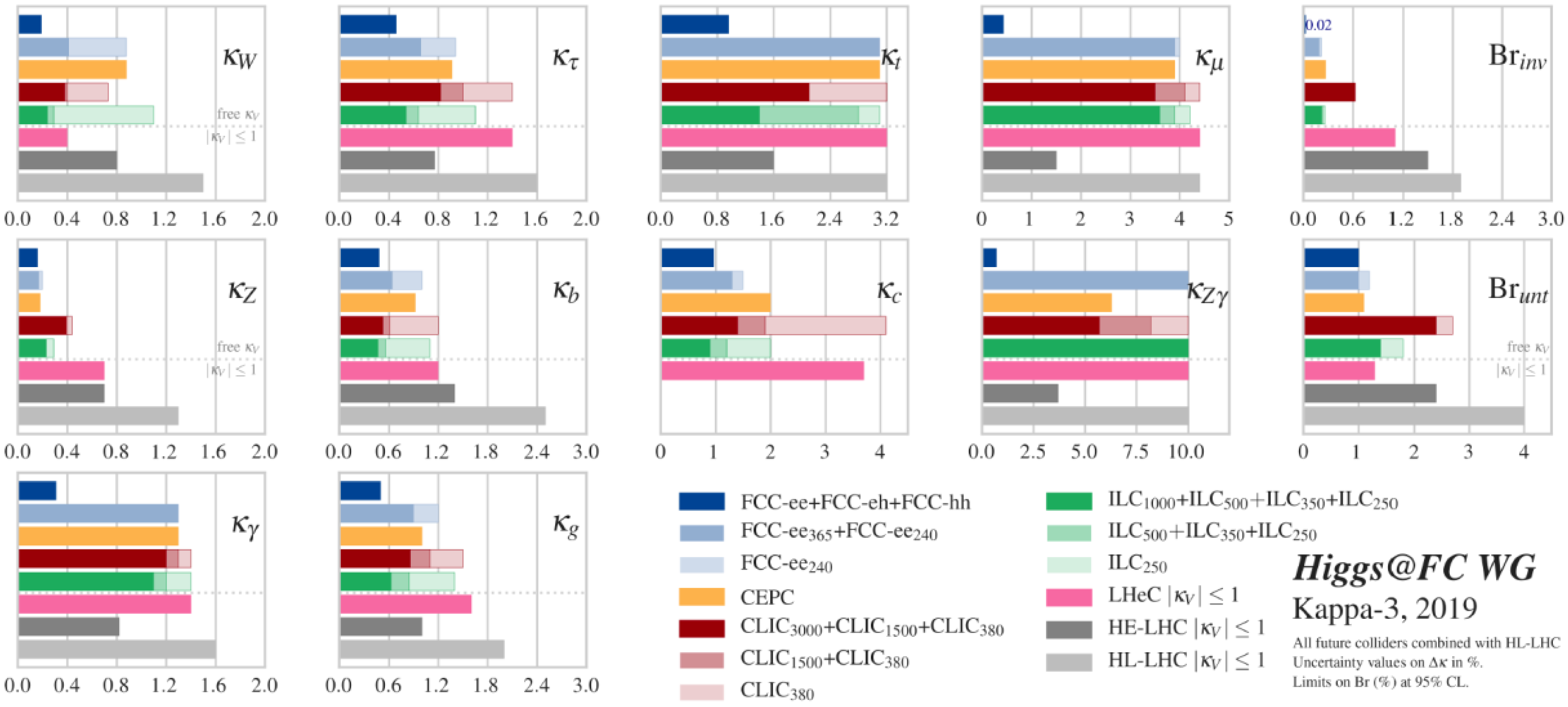
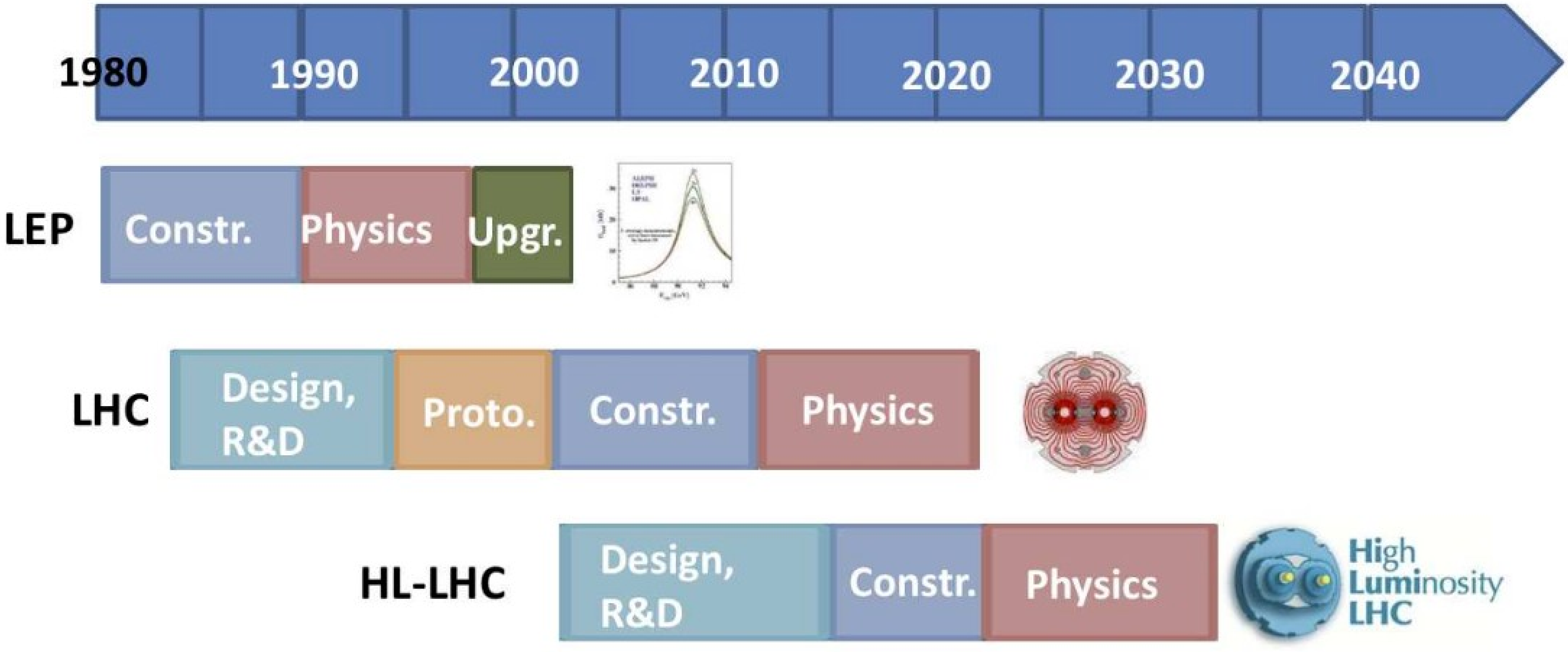
Higgs at future colliders



- CLIC at $\sqrt{s} = 3$ TeV and ILC at $\sqrt{s} = 1$ TeV can constrain trilinear self-coupling to $\mathcal{O}10\%$ while FCC-hh can reach 5% precision.
- 2σ sensitivity to the quartic self-coupling expected at FCC-hh.

Future colliders



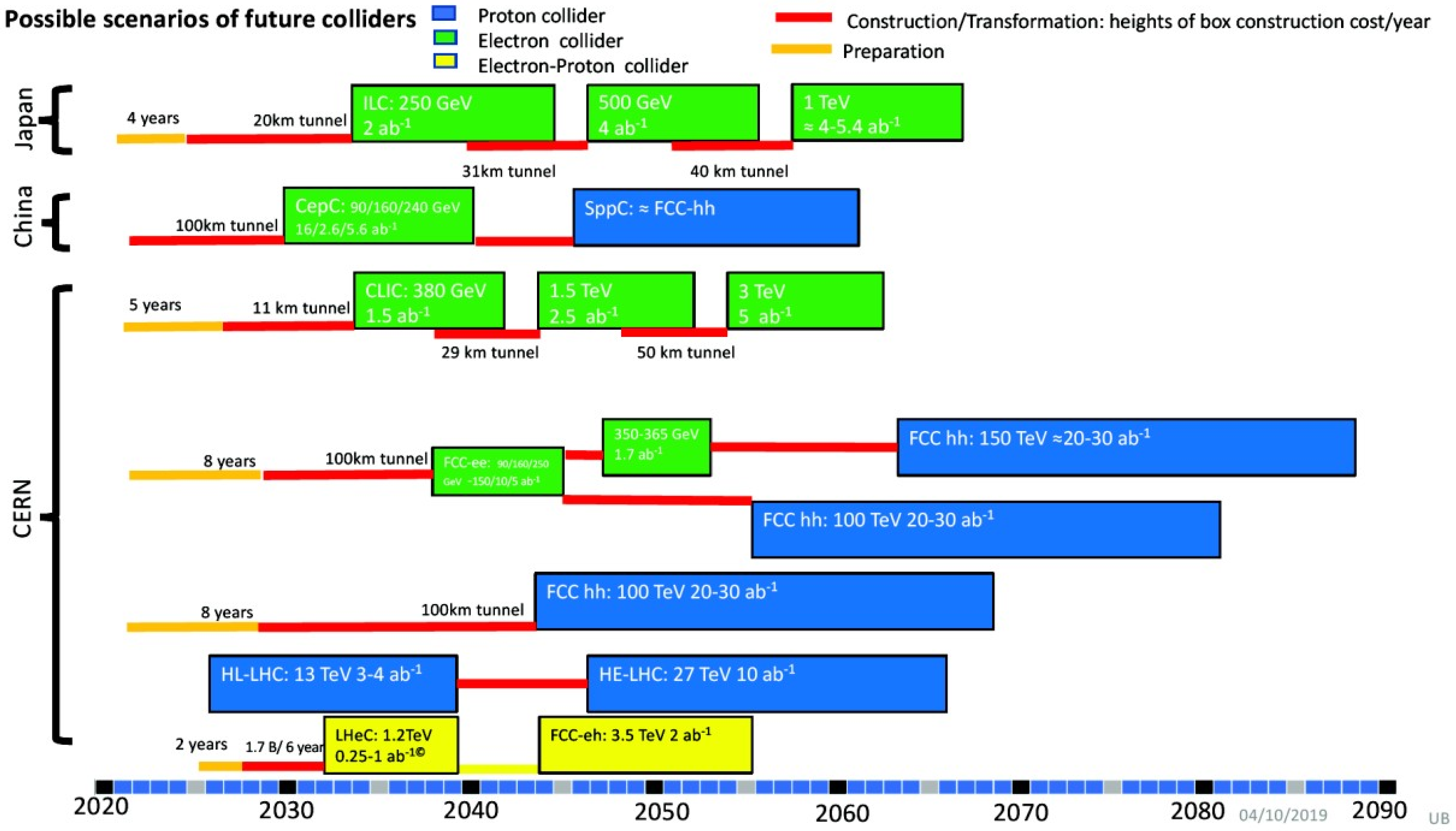
1980 1990 2000 2010 2020 2030 2040

LEP Constr. Physics Upgr.

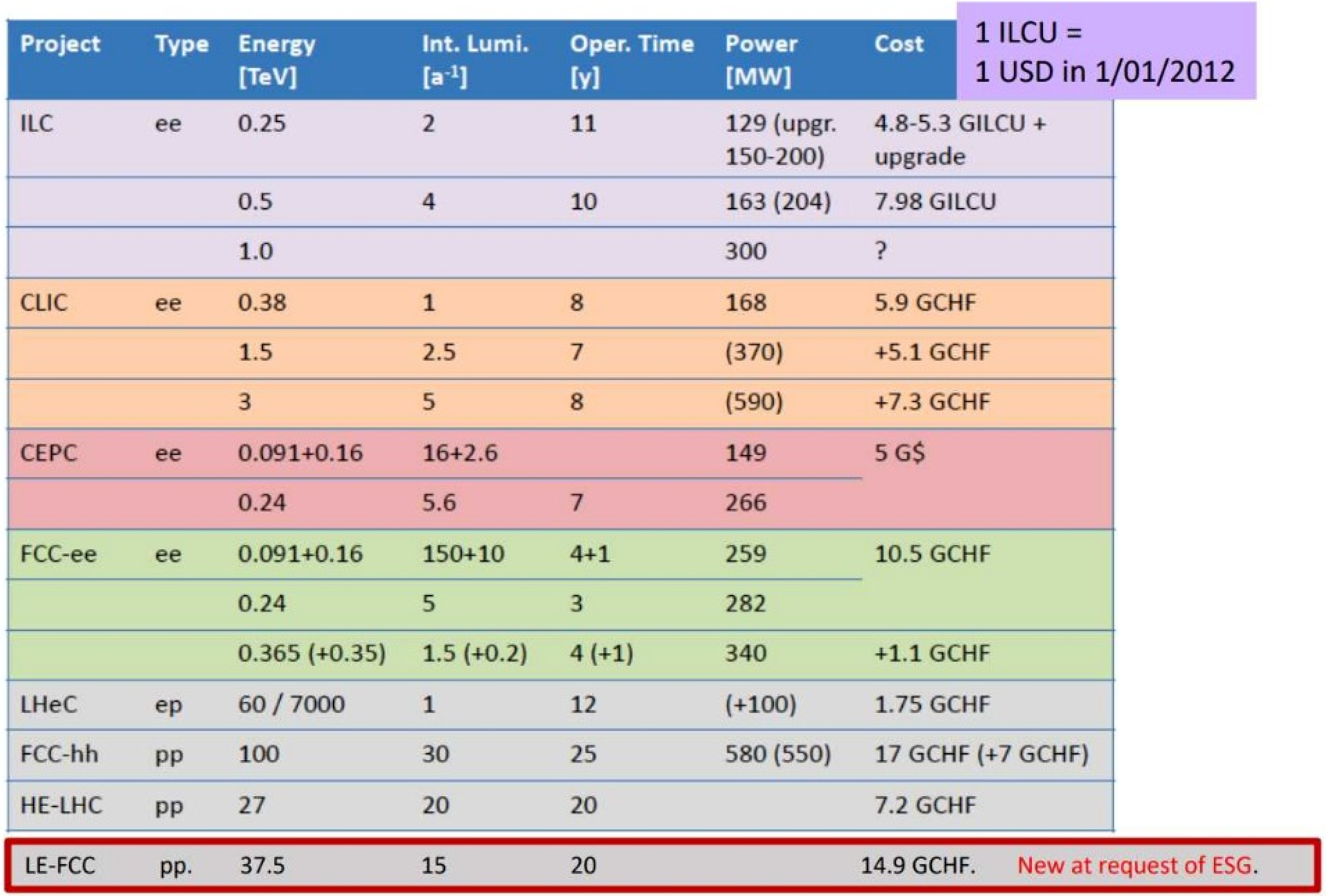
LHC Design, R&D Proto. Constr. Physics

HL-LHC Design, R&D Constr. Physics

The starting lineup



The starting lineup



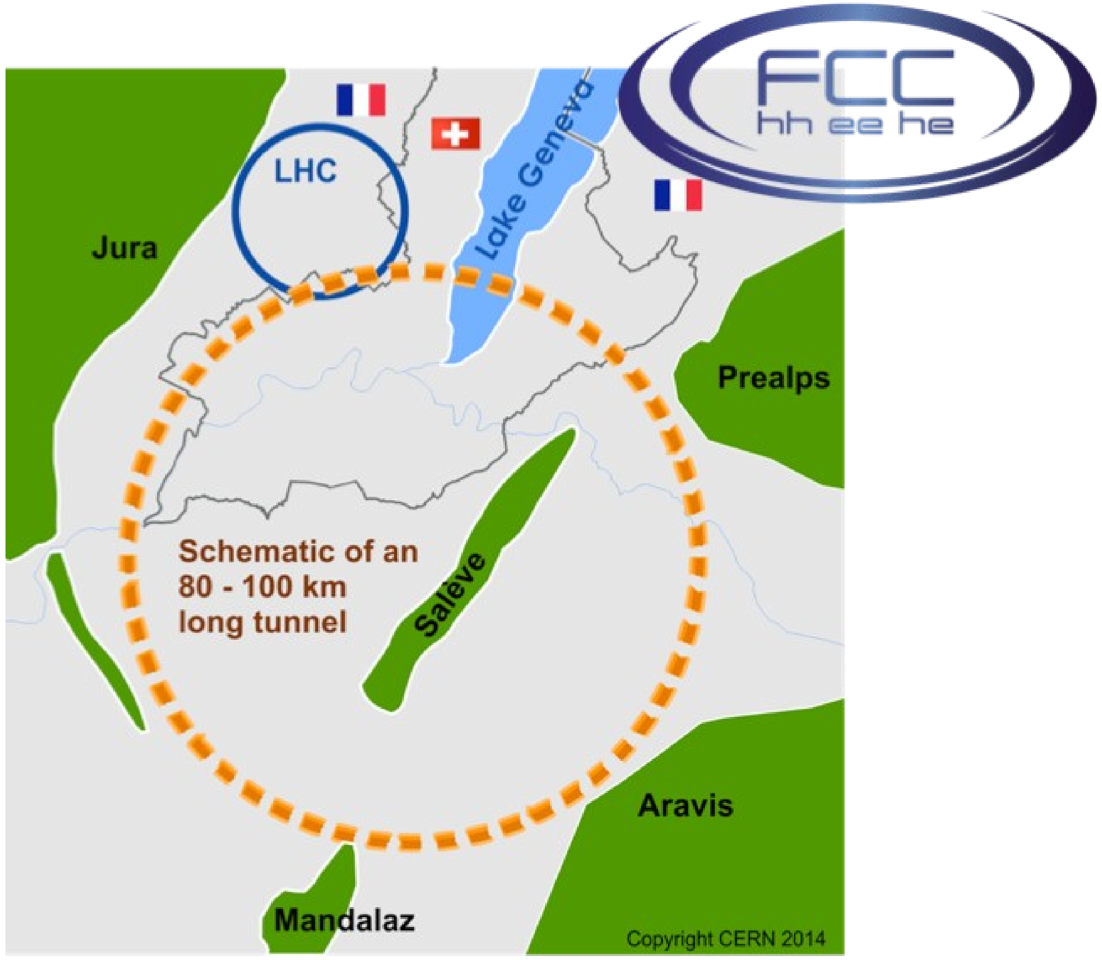
1 ILCU =
1 USD in 1/01/2012

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF
LE-FCC	pp.	37.5	15	20		14.9 GCHF. New at request of ESG.

(For reference - LHC construction cost ≈ 4 GCHF, annual CERN budget ≈ 1 GCHF.)

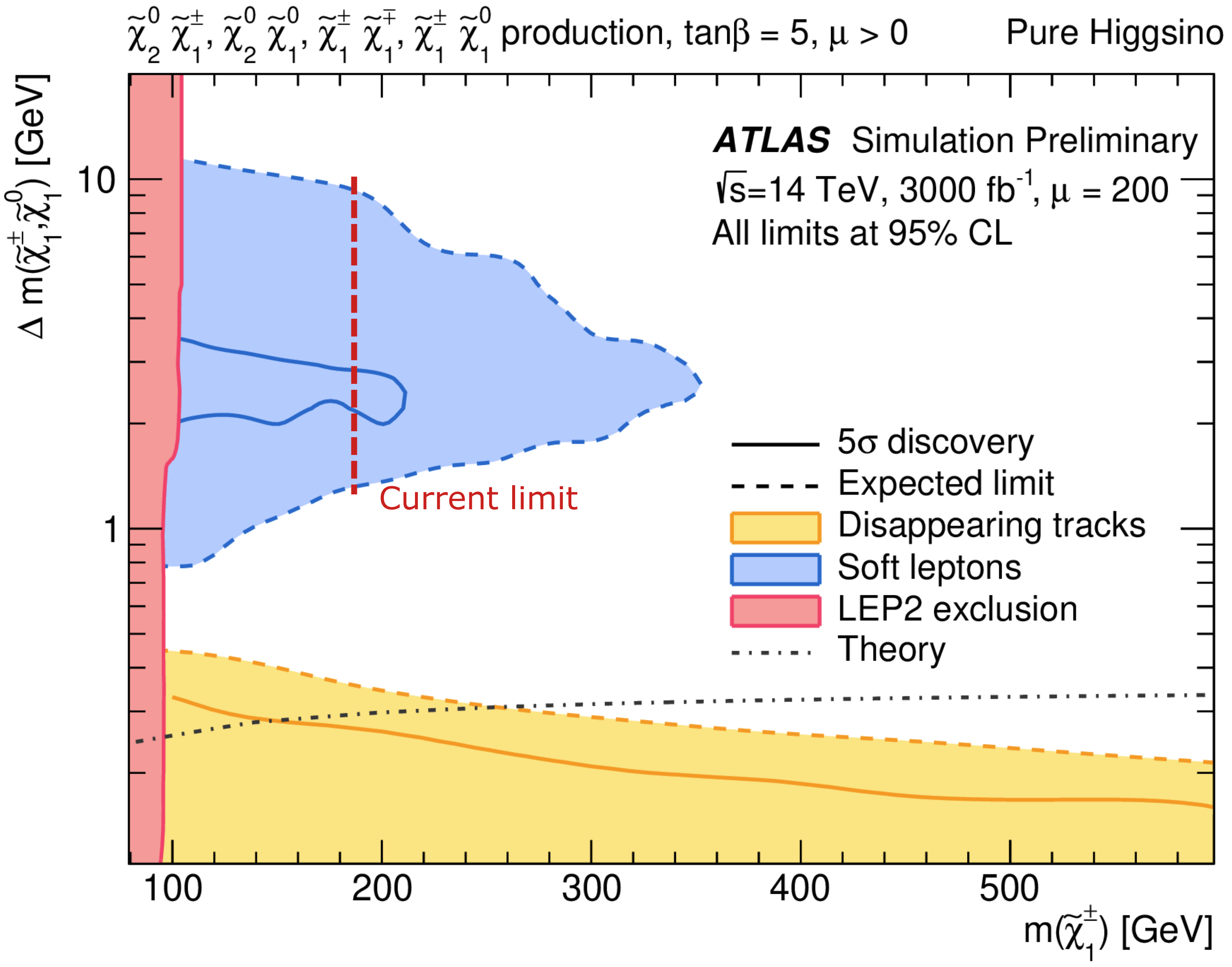
The FCC

	LHC	HL-LHC	FCC-hh	
			Initial	Nominal
Main parameters and geometrical aspects				
c.m. Energy (TeV)	14		100	
Circumference C (km)	26.7		97.75	
Dipole field (T)	8.33		<16	
Arc filling factor	0.79		0.8	
Straight sections	8 × 528 m		6 × 1400 m + 2 × 2800 m	
Number of IPs	2 + 2		2 + 2	
Injection energy (TeV)	0.45		3.3	



EW SUSY at HL-LHC

- Able to probe new regions of BSM parameter space with HL-LHC.
- Especially for signals with smaller cross sections (e.g. EW SUSY rather than strongly interacting particles like squarks and gluinos).



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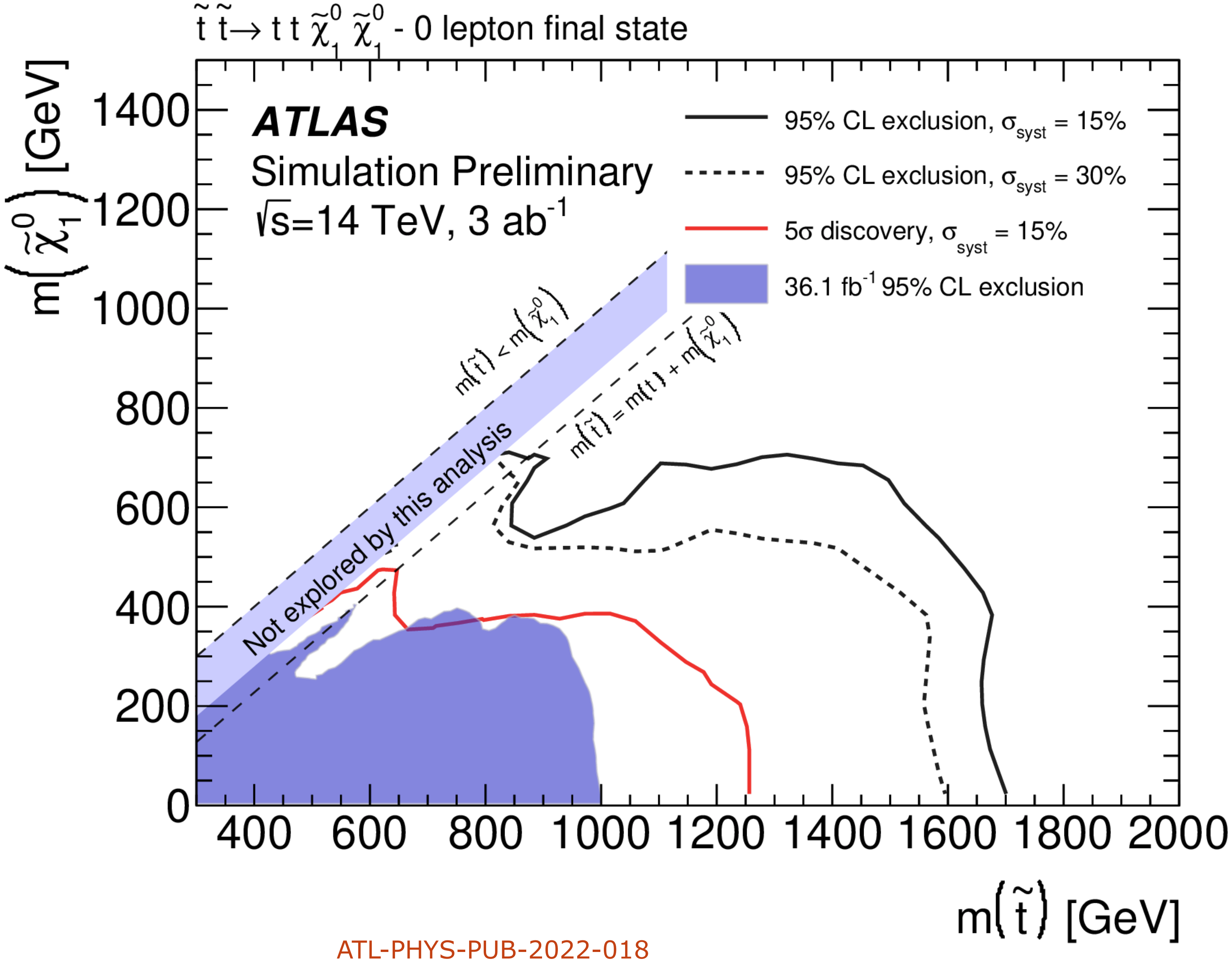
Strong SUSY at HL-LHC

- Limits on stop mass will only marginally improve with the HL-LHC dataset.



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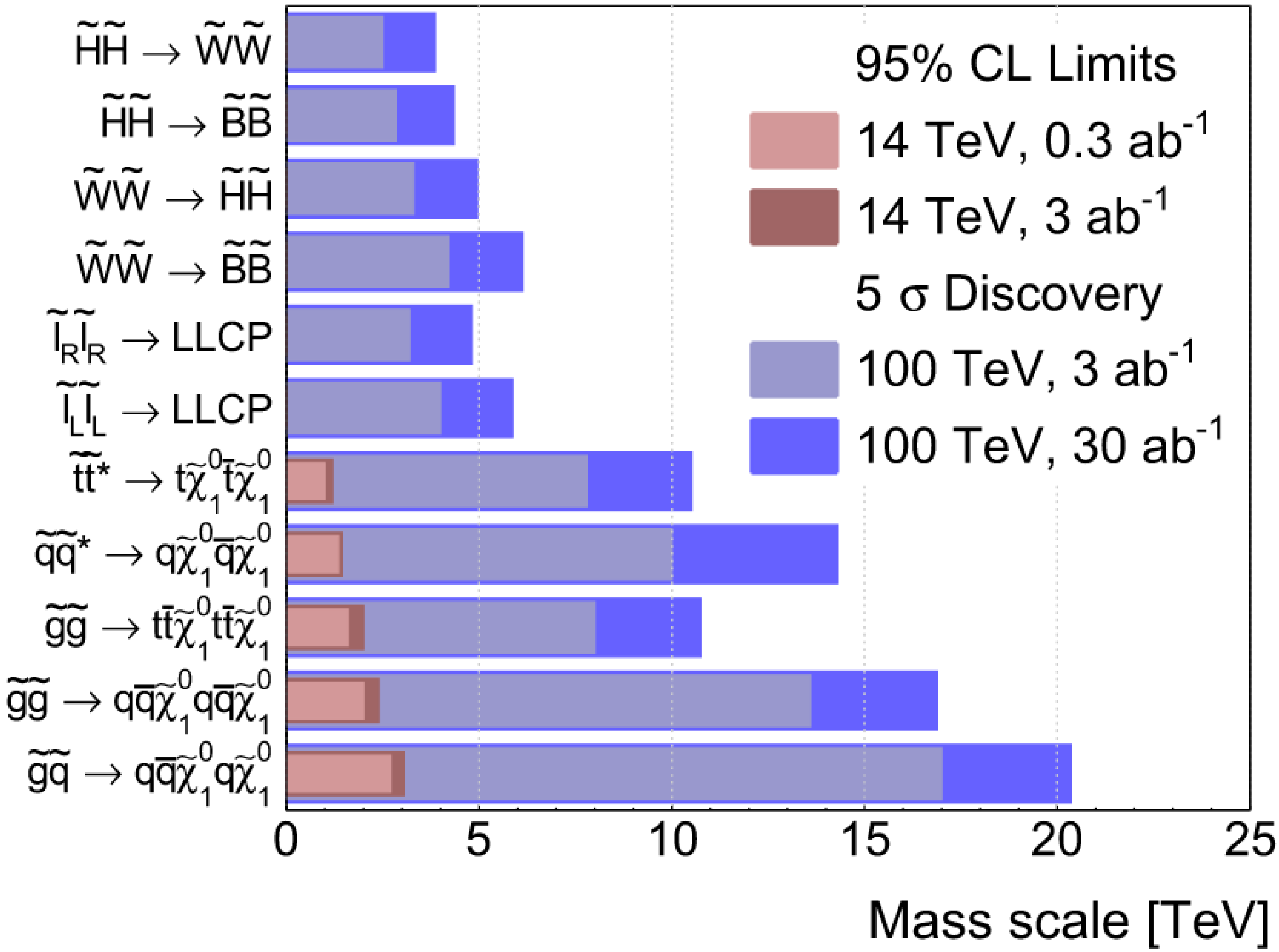
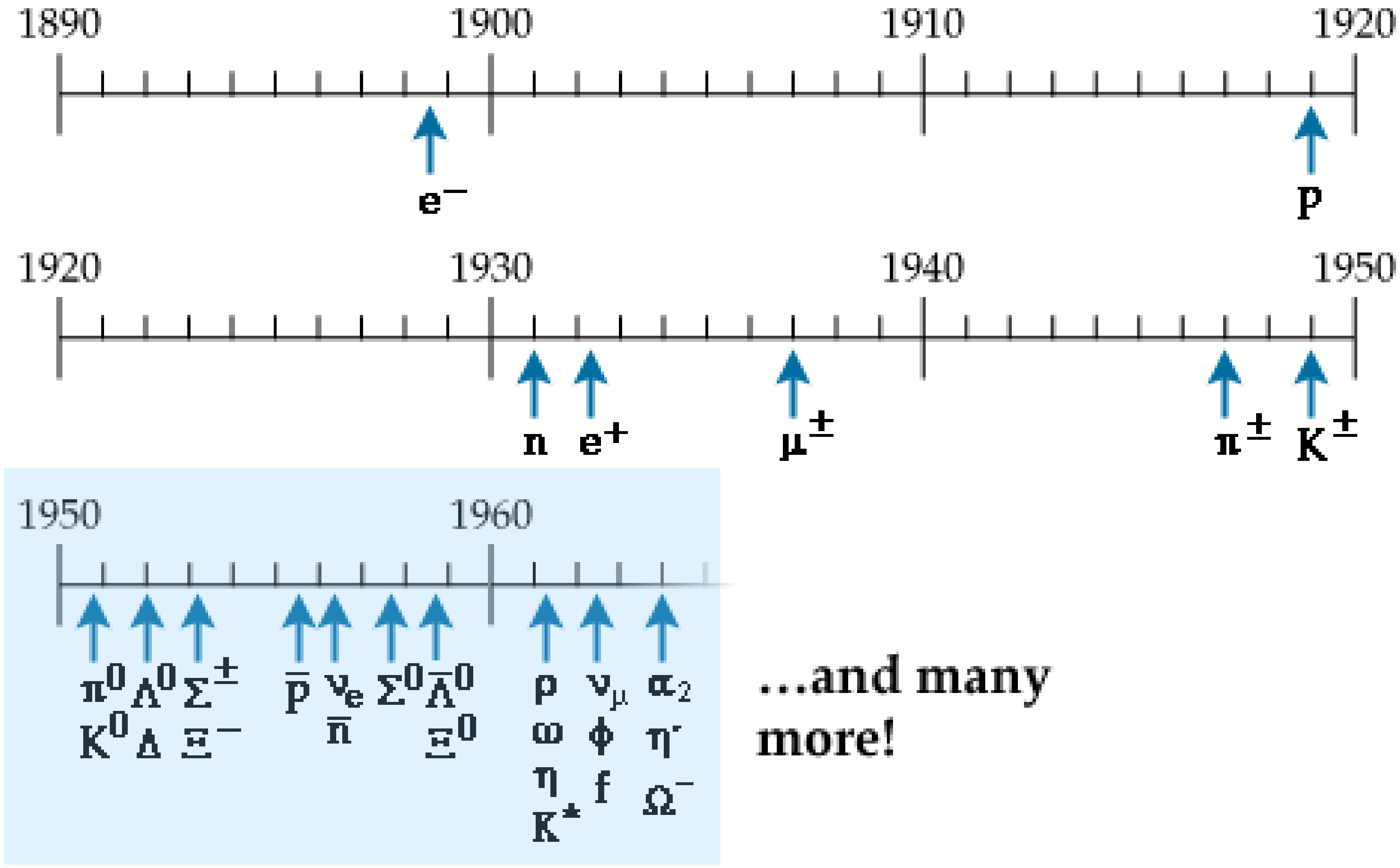
What the FCC can do

- FCC-hh would be sensitive to gluino masses up to 15 TeV stop masses up to 10 TeV slepton masses up to 6 TeV



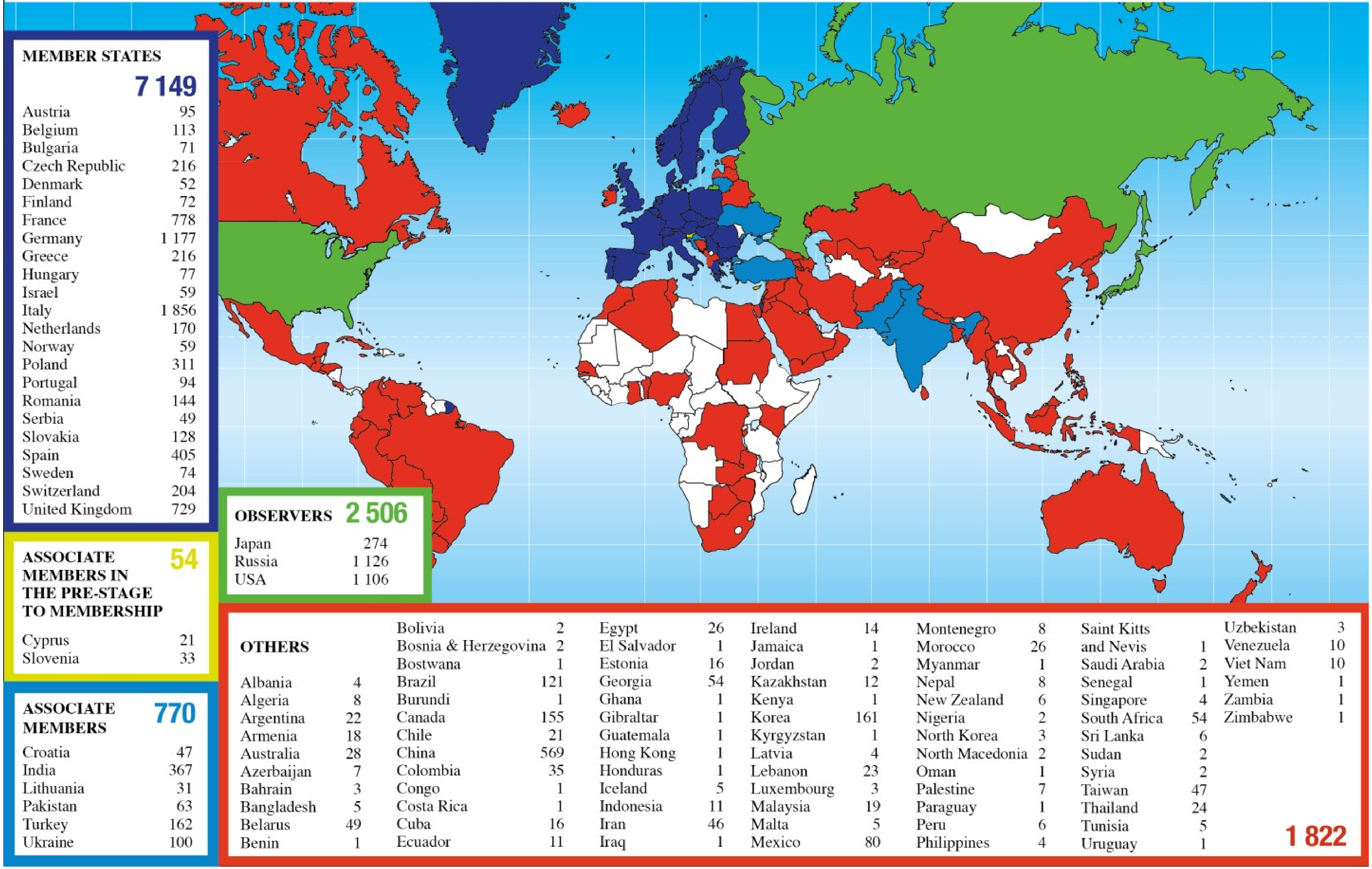
FCC physics opportunities

Particle zoo



…and many more!

Distribution of All CERN Users by Nationality on 27 January 2020



MEMBER STATES	7 149
Austria	95
Belgium	113
Bulgaria	71
Czech Republic	216
Denmark	52
Finland	72
France	778
Germany	1 177
Greece	216
Hungary	77
Israel	59
Italy	1 856
Netherlands	170
Norway	59
Poland	311
Portugal	94
Romania	144
Serbia	49
Slovakia	128
Spain	405
Sweden	74
Switzerland	204
United Kingdom	729

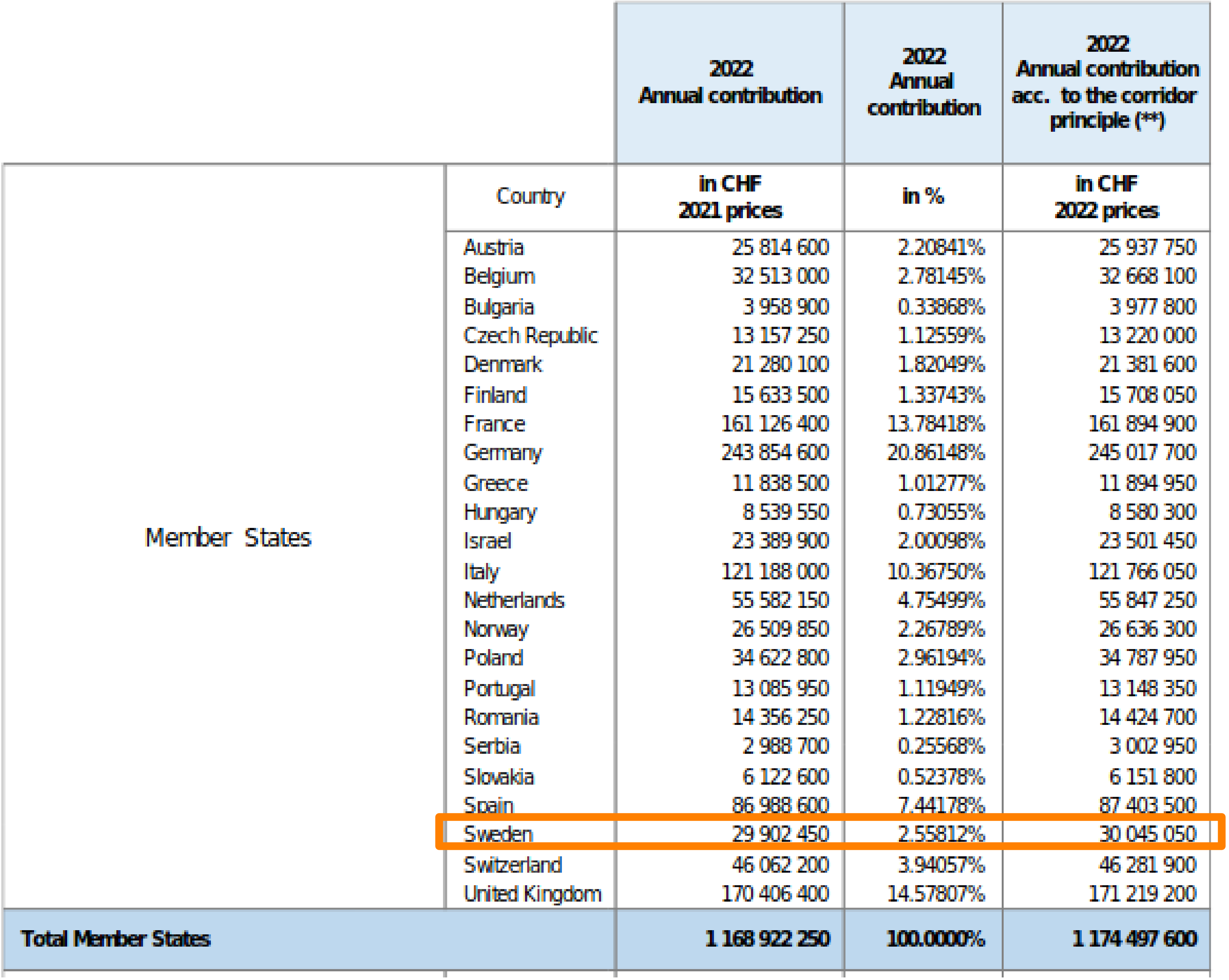
ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP	54
Cyprus	21
Slovenia	33

ASSOCIATE MEMBERS	770
Croatia	47
India	367
Lithuania	31
Pakistan	63
Turkey	162
Ukraine	100

OBSERVERS	2 506
Japan	274
Russia	1 126
USA	1 106

OTHERS	1 822
Albania	4
Algeria	8
Argentina	22
Armenia	18
Australia	28
Azerbaijan	7
Bahrain	3
Bangladesh	5
Belarus	49
Benin	1
Bolivia	2
Bosnia & Herzegovina	2
Bostwana	1
Brazil	121
Burundi	1
Canada	155
Chile	21
China	569
Colombia	35
Congo	1
Costa Rica	1
Cuba	16
Ecuador	11
Egypt	26
El Salvador	1
Estonia	16
Georgia	54
Ghana	1
Gibraltar	1
Guatemala	1
Hong Kong	1
Honduras	1
Iceland	5
Indonesia	11
Iran	46
Iraq	1
Ireland	14
Jamaica	1
Jordan	2
Kazakhstan	12
Kenya	1
Korea	161
Kyrgyzstan	1
Latvia	4
Lebanon	23
Luxembourg	3
Malaysia	19
Malta	5
Mexico	80
Montenegro	8
Morocco	26
Myanmar	1
Nepal	8
New Zealand	6
Nigeria	2
North Korea	3
North Macedonia	2
Oman	1
Palestine	7
Paraguay	1
Peru	6
Philippines	4
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	54
Sri Lanka	6
Sudan	2
Syria	2
Taiwan	47
Thailand	24
Tunisia	5
Uruguay	1
Uzbekistan	3
Venezuela	10
Viet Nam	10
Yemen	1
Zambia	1
Zimbabwe	1

CERN budget

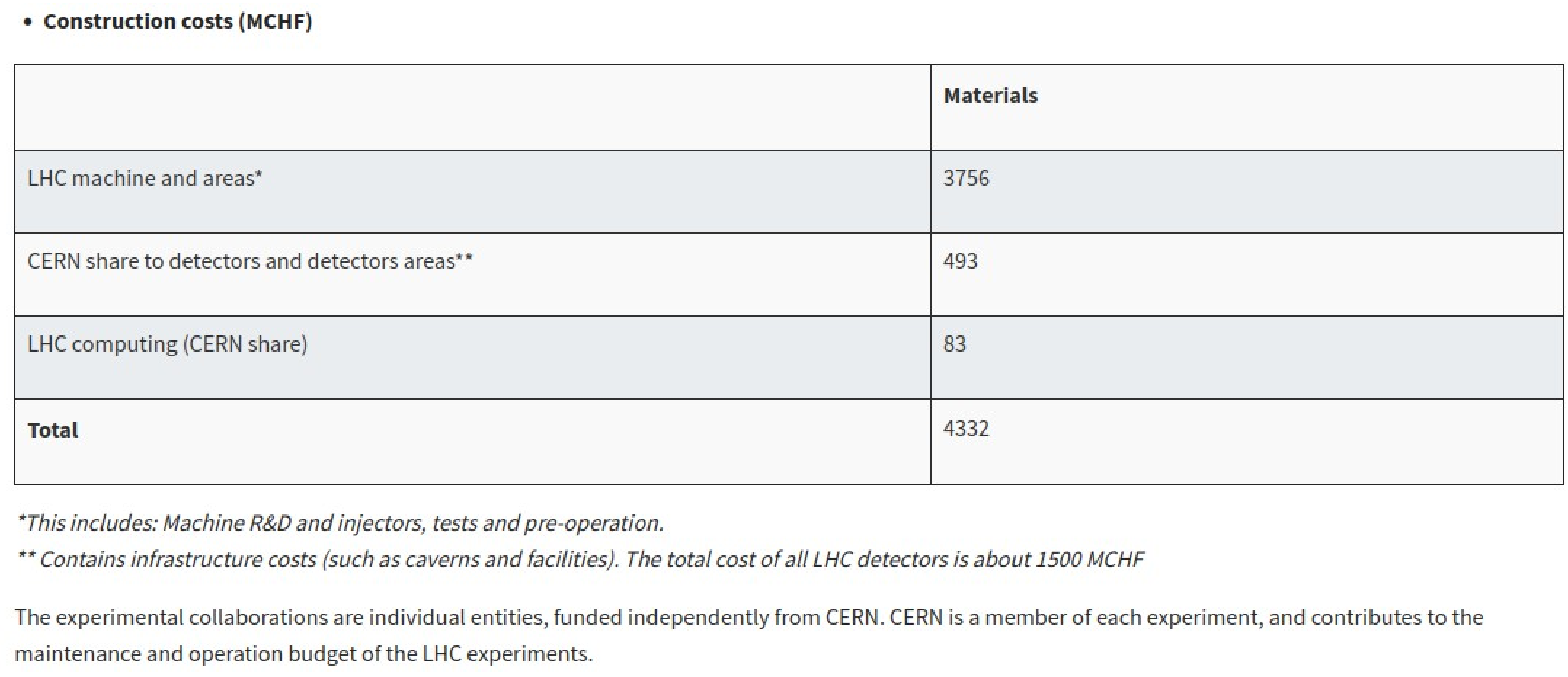


		2022 Annual contribution	2022 Annual contribution	2022 Annual contribution acc. to the corridor principle (**)
	Country	in CHF 2021 prices	in %	in CHF 2022 prices
Member States	Austria	25 814 600	2.20841%	25 937 750
	Belgium	32 513 000	2.78145%	32 668 100
	Bulgaria	3 958 900	0.33868%	3 977 800
	Czech Republic	13 157 250	1.12559%	13 220 000
	Denmark	21 280 100	1.82049%	21 381 600
	Finland	15 633 500	1.33743%	15 708 050
	France	161 126 400	13.78418%	161 894 900
	Germany	243 854 600	20.86148%	245 017 700
	Greece	11 838 500	1.01277%	11 894 950
	Hungary	8 539 550	0.73055%	8 580 300
	Israel	23 389 900	2.00098%	23 501 450
	Italy	121 188 000	10.36750%	121 766 050
	Netherlands	55 582 150	4.75499%	55 847 250
	Norway	26 509 850	2.26789%	26 636 300
	Poland	34 622 800	2.96194%	34 787 950
	Portugal	13 085 950	1.11949%	13 148 350
	Romania	14 356 250	1.22816%	14 424 700
	Serbia	2 988 700	0.25568%	3 002 950
	Slovakia	6 122 600	0.52378%	6 151 800
	Spain	86 988 600	7.44178%	87 403 500
	Sweden	29 902 450	2.55812%	30 045 050
	Switzerland	46 062 200	3.94057%	46 281 900
	United Kingdom	170 406 400	14.57807%	171 219 200
Total Member States		**1 168 922 250**	**100.0000%**	**1 174 497 600**

ca 300 MSEK

ca 12 GSEK

LHC construction cost



- **Construction costs (MCHF)**

	Materials
LHC machine and areas*	3756
CERN share to detectors and detectors areas**	493
LHC computing (CERN share)	83
Total	4332

**This includes: Machine R&D and injectors, tests and pre-operation.*

*** Contains infrastructure costs (such as caverns and facilities). The total cost of all LHC detectors is about 1500 MCHF*

The experimental collaborations are individual entities, funded independently from CERN. CERN is a member of each experiment, and contributes to the maintenance and operation budget of the LHC experiments.

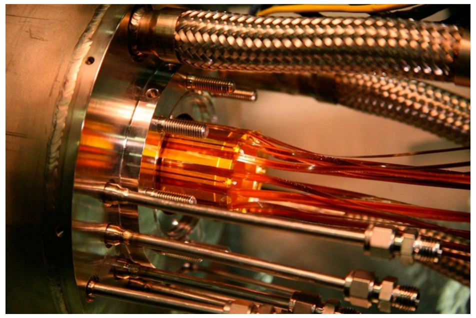
CERN’s location

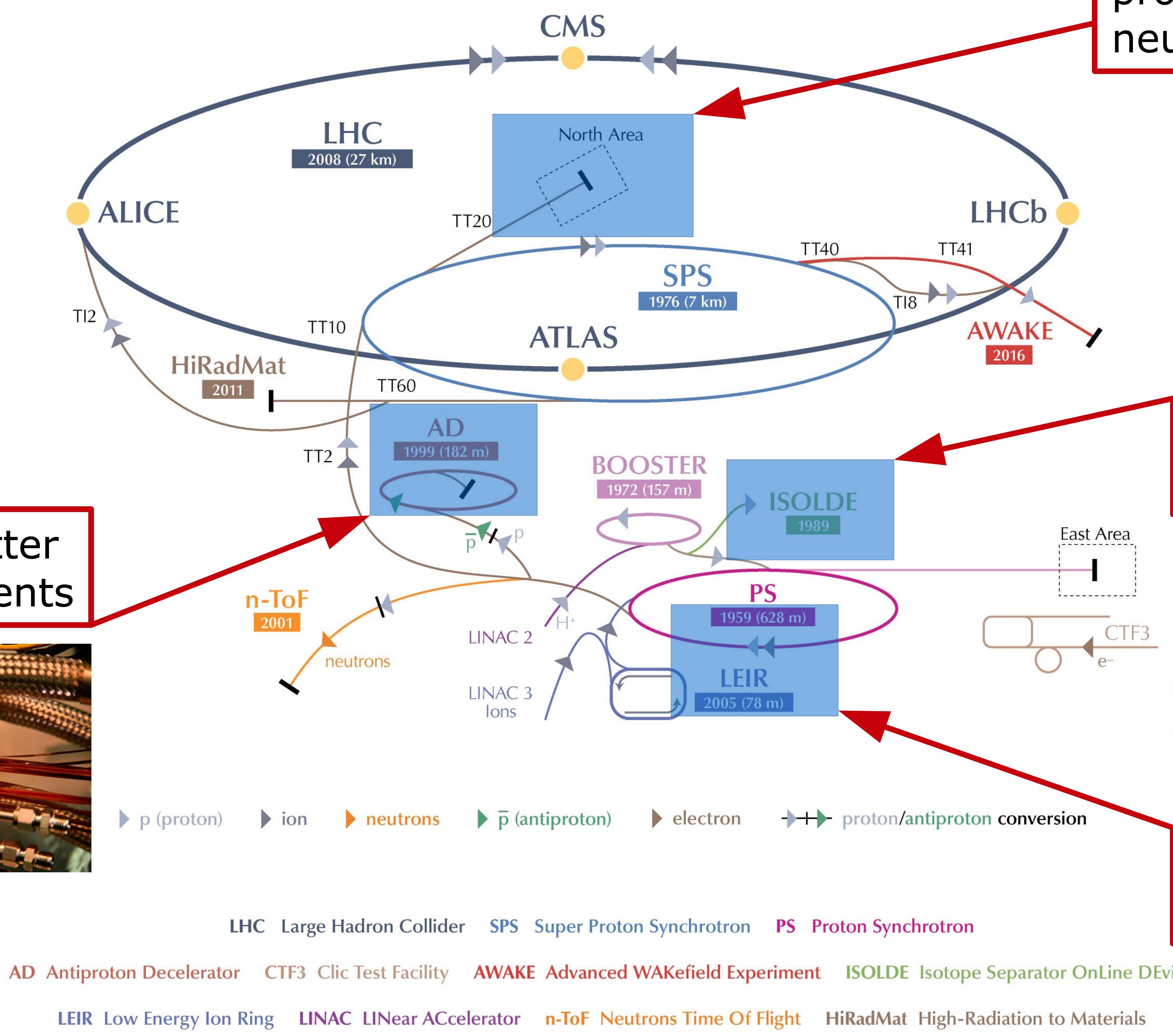
- Geneva was selected as the site for the CERN Laboratory at the third session of the provisional council in 1952.
- This selection successfully passed a referendum in the canton of Geneva in June 1953 by 16 539 votes to 7 332.
- On 17 May 1954, the first shovel of earth was dug on the Meyrin site in Switzerland.

CERN's Accelerator Complex

Non-accelerator experiments

Anti-matter experiments





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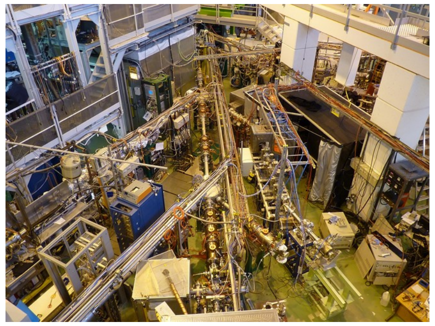
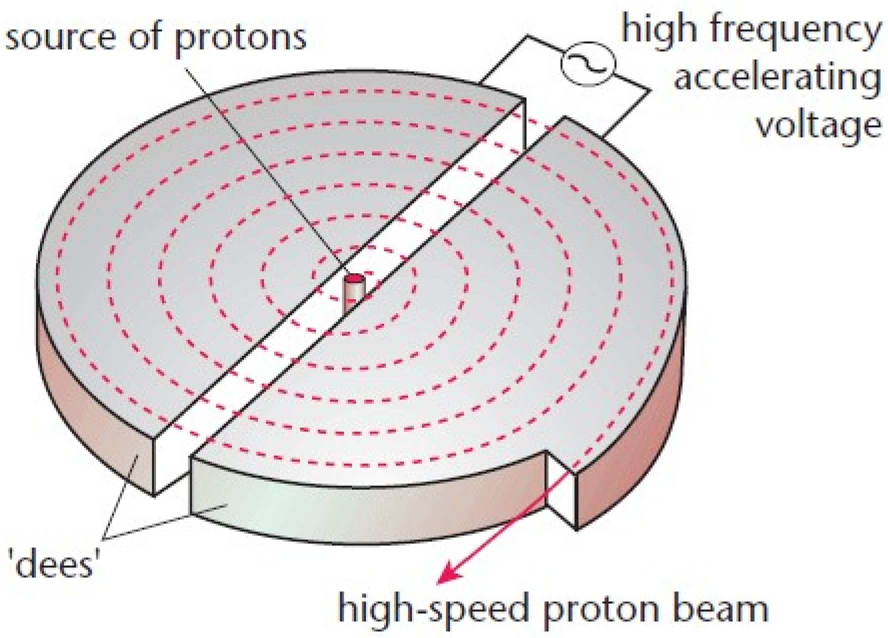
Fixed target program and neutrino physics



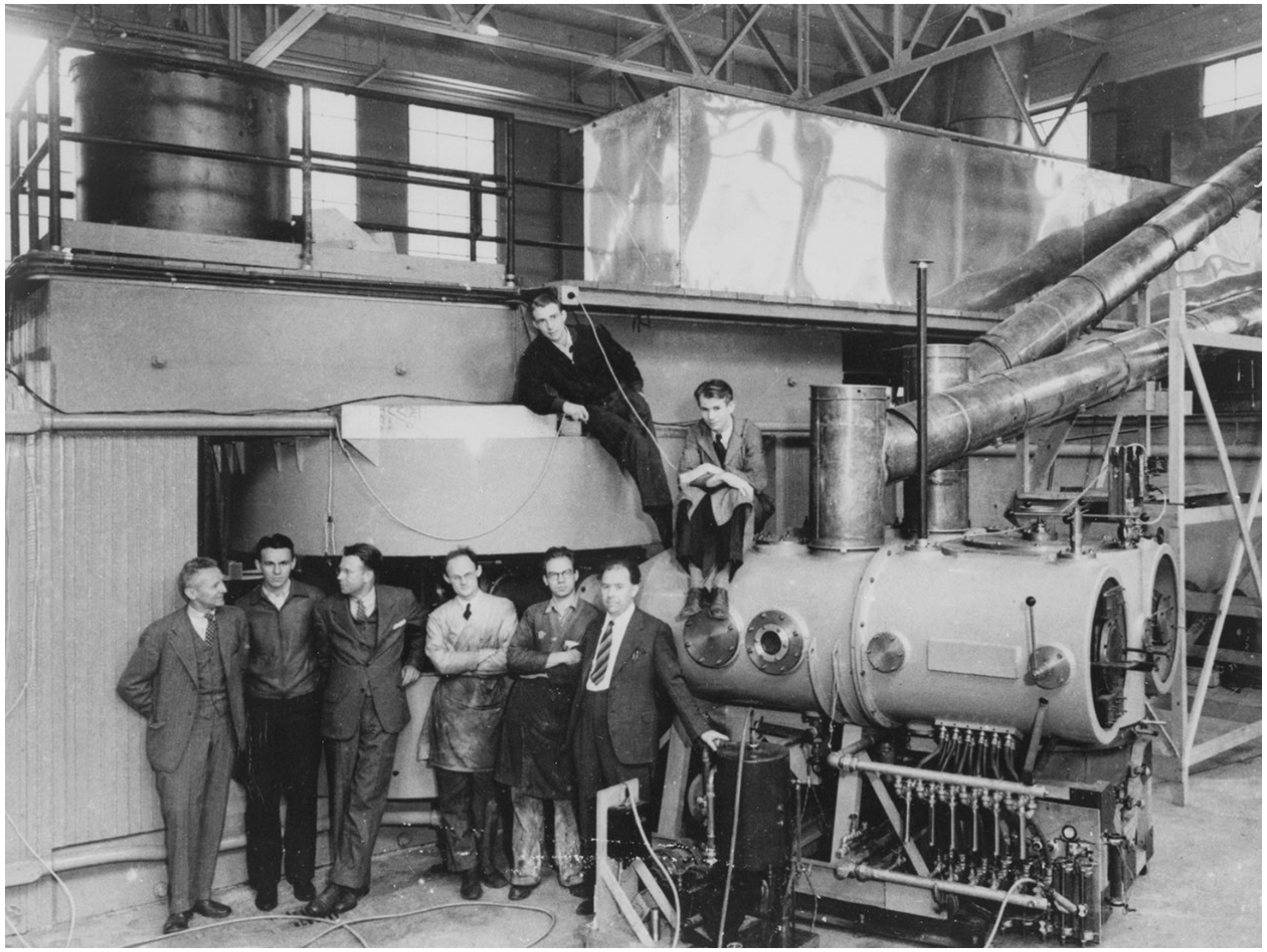
ISOLDE facility

Environmental physics

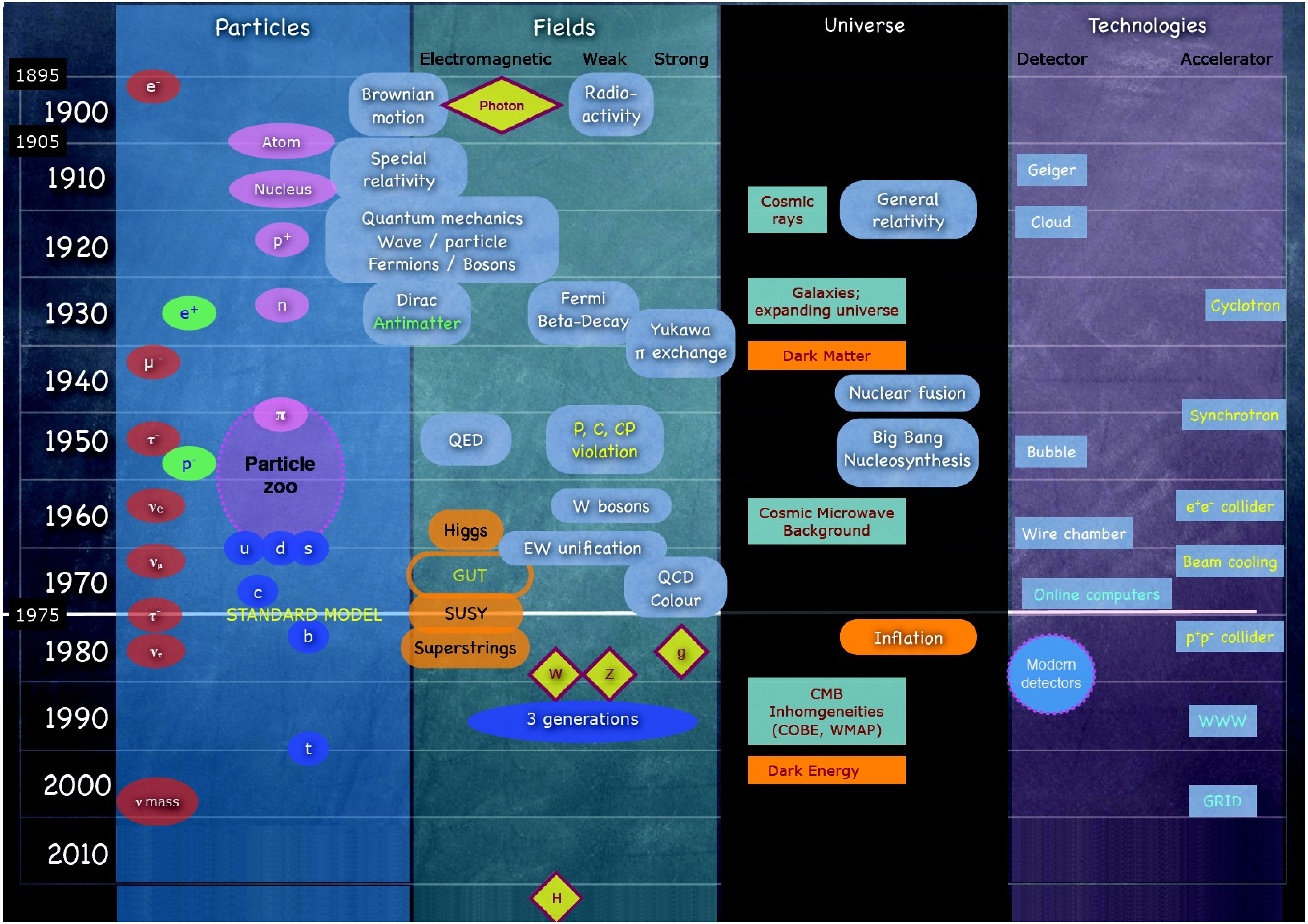
First cyclotrons



https://esim.ac.uk/project/cyclotron



60 inch cyclotron at Berkeley, 1939,



1895
1900
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1975
1980
1990
2000
2010

Particles

e^-
Atom
Nucleus
p^+
e^+
n
μ^-
π
τ^-
p^-
Particle zoo
ν_e
u d s
ν_μ
c
τ^-
STANDARD MODEL
b
ν_τ
t
ν mass

Fields

Electromagnetic Weak Strong

Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Fermi
Beta-Decay
Yukawa
π exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD
Colour
SUSY
Superstrings
g
W
Z
3 generations
H

Universe

Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
Nuclear fusion
Big Bang Nucleosynthesis
Cosmic Microwave Background
Inflation
CMB Inhomgeneities (COBE, WMAP)
Dark Energy

Technologies

Detector Accelerator

Geiger
Cloud
Cyclotron
Synchrotron
Bubble
e^+e^- collider
Wire chamber
Beam cooling
Online computers
p^+p^- collider
Modern detectors
WWW
GRID

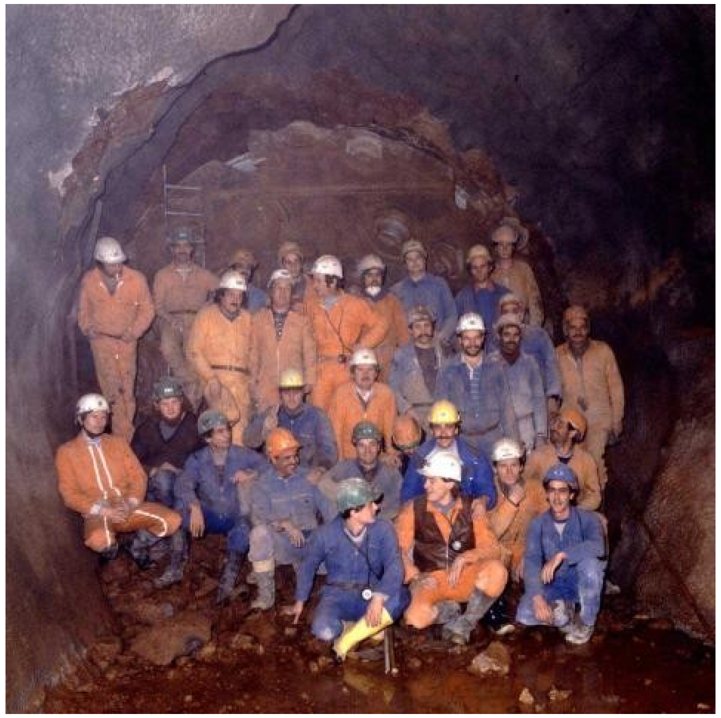
Scientific achievements at CERN

- 1973: The discovery of neutral currents in the Gargamelle bubble chamber
- 1983: The discovery of W and Z bosons in the UA1 and UA2 experiments
- 1989: The determination of the number of light neutrino families at the Large Electron–Positron Collider (LEP) operating on the Z boson peak
- 1995: The first creation of antihydrogen atoms in the PS210 experiment
- 1999: The discovery of direct CP violation in the NA48 experiment
- 2010: The isolation of 38 atoms of antihydrogen
- 2011: Maintaining antihydrogen for over 15 minutes
- 2012: Higgs boson discovery by the ATLAS and CMS experiments.

- The 1984 Nobel Prize in Physics to Carlo Rubbia and Simon van der Meer *”for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction”*
- The 1992 Nobel Prize in Physics to Georges Charpak *”for his invention and development of particle detectors, in particular the multiwire proportional chamber”*
- The 2013 Nobel Prize in Physics to François Englert and Peter W. Higgs *”for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”*

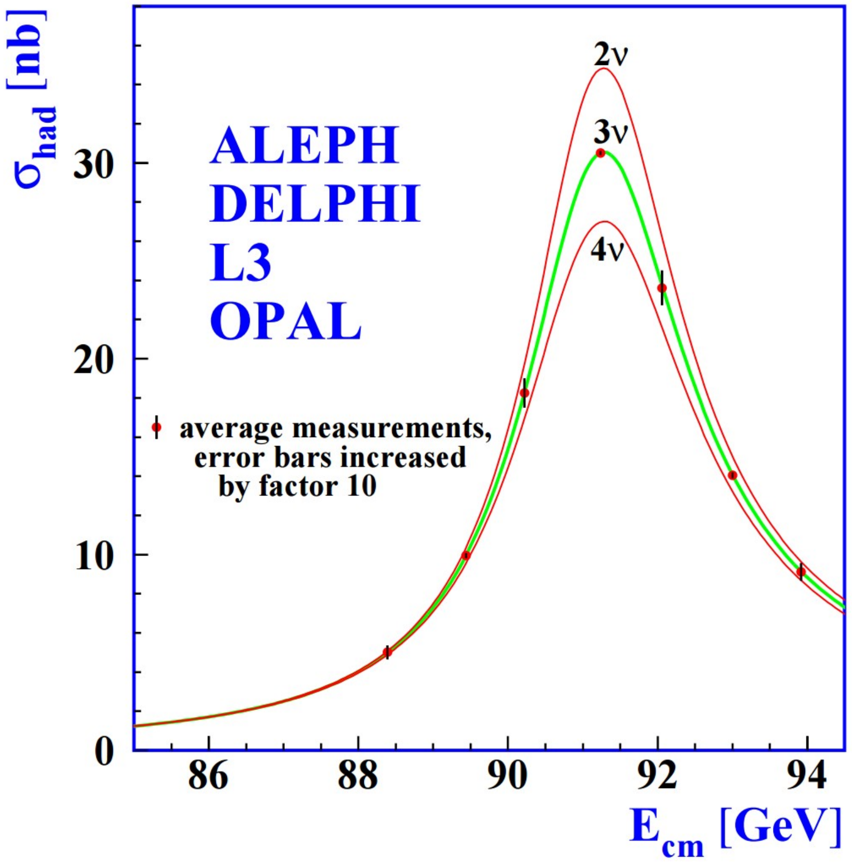
Large Electron Positron Collider

- Electron-positron collider in 27 km long tunnel.
- Tunneln ready 1988. The two ends met with only 1 cm displacement.
- Delivered collisions to ALEPH, DELPHI, L3 and OPAL experiments.
- Very precise measurements of the properties of W and Z bosons and electroweak interactions. Showed for instance that there are only three generations of light neutrinos.
- Closed in 2000 to give room for the LHC in the same tunnel.



Sector 2-3 completed

First beam 1989



Evolution of ATLAS

- Initial (conceptual) project planning started in the mid 1980's.
- Late 1980's:
  - Further R&D needed to prove feasibility of proposed technical concepts.
  - CERN initiated formal, generic detector R&D projects.
- Early 1990's:
  - Bottom-up detector proposals (EAGLE, ASCOT).
  - merging into ATLAS Letter of Intent (LoI, 1992.
- Mid 1990's:
  - ATLAS Technical Proposal (TP,1995).
  - Sub-detector prototyping and Technical Design Reviews.
- Late 1990/Early 2000's:
  - Approval of Cost Book.
  - Signing of MoU.
  - Start of detector modules manufacturing.
  - Start of installation at CERN (cavern handed over in 2003).
- Mid 2000's:
  - Installation, commissioning of ATLAS in the cavern.
  - ATLAS completed in 2008 for initial runs.

Sacharov conditions

- In 1967, Andrei Sakharov published three necessary conditions for baryogenesis:

1) Baryon number violation

2) CP violation

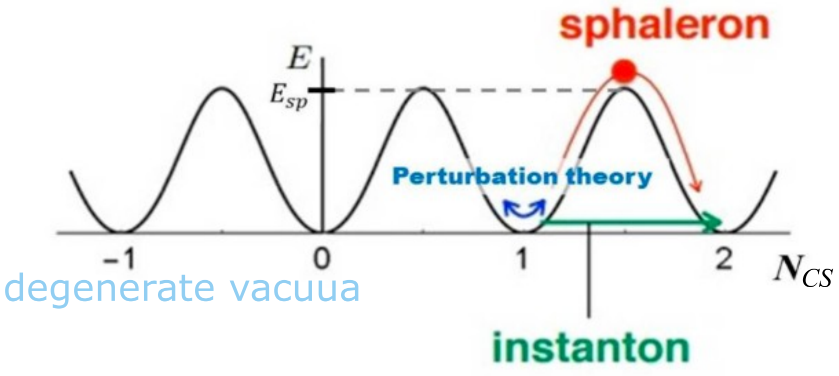
3) Departure from equilibrium

Baryon number violation

- Turns out there are quantum anomalies (instantons & sphalerons) that break B+L in the SM (t'Hooft 1976). They still conserve B-L.

$$\Delta B = \Delta L = \Delta N_{CS} = n_f[N_{CS}(t_1) - N_{CS}(t_0)]$$

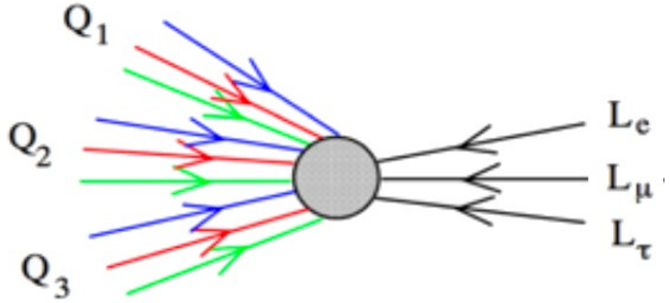
$$\Delta(B-L) = 0,\ \Delta(B+L) = 2\Delta N_{CS}$$



- Instanton processes extremely rare.
- Thermal rate of sphaleron production after EW symmetry breaking:

$$\Gamma_{sp}(T) \propto e^{-\frac{E_{sp}(T)}{T}}$$ (Boltzmann factor)

- where $E_{\rm sp} \approx 10\,$TeV for the EW potential, so highly suppressed by the exponential factor



$$^3\text{He}^{++} \to e^+ + \mu^+ + \bar{\nu}_\tau$$

$$\Delta B = -3,\ \Delta L = -3$$

$$\tau_0 = 10^{150}\,\text{y}$$

- Before EW symmetry breaking, there is no barrier and hence no exponential suppression:

$\Gamma_{sp}(T) \propto \alpha_W^5 T^4$ → much more common!

- Can create - but also destroy - a baryon asymmetry.

CP violation

- Consider the baryon-number violating process: $X \to Y + B$
- If charge conjugation (C) is a symmetry, then the rate of the charge conjugate process is identical:

$$\Gamma(X \to Y + B) = \Gamma(\bar{Y} + \bar{B} \to \bar{X})$$

- So C violation is necessary to generate a net baryon asymmetry. But it is not enough, we also need CP violation.
- Consider the decay of *X* into two left-handed or right-handed quarks:

$$X \to q_L q_L,\; X \to q_R q_R$$

- CP transformation: $q_L \to \bar{q}_R$, C conjugation: $q_L \to \bar{q}_L$
- C violation implies: $\Gamma(X \to q_L q_L) \neq \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$
- But CP conservation implies: $\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R)$

$$\Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

i.e. $\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$

Out of equilibrium

- Consider the baryon-number violating process:

  $$X \to Y + B$$

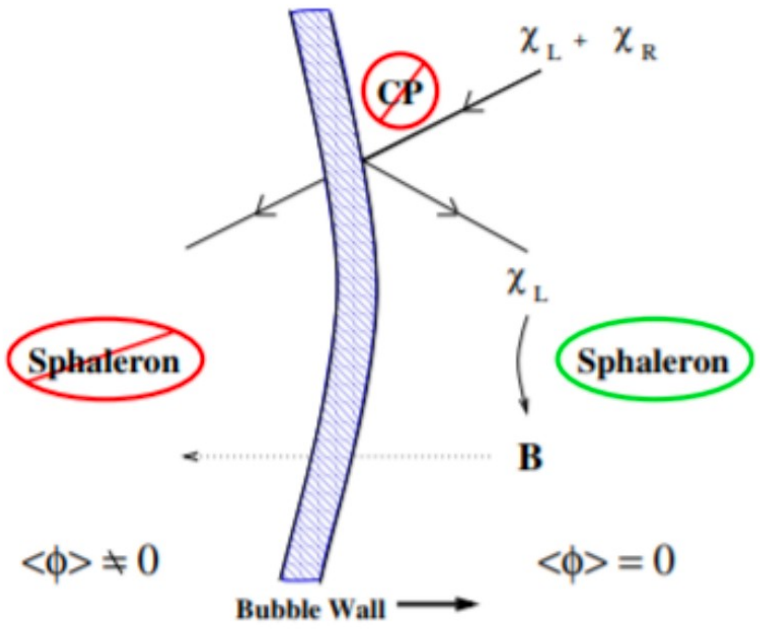
- If this process is in thermal equilibrium, then the rate of the inverse process is identical:

  $$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

- So baryons are created and destroyed at the same rate → no net baryon asymmetry can be produced.
- Two ways to get out of thermal equilibrium:
  - Long-lived particle decays out of equilibrium.
  - First order phase transition.

Electroweak baryogenesis

- Idea of electroweak baryogenesis is to let the SM sphalerons generate the baryon asymmetry during EW phase transition.
- Need BSM to get extra CP violation+1^{st} order phase transition.
- When particles bounce off the bubble walls, CP-violating processes give different R and T rates for left- and right-handed (anti)particles.
- Excess of left-handed particles outside bubbles (unbroken phase).
- The sphalerons, which couple to left-handed particles, generate a net baryon number from excess of left-handed fermions.
- Baryons pass into bubbles and survive since sphaleron process is highly suppressed there
- There are many ways to get a 2nd order phase transition in BSM models (additional Higgs fields, supersymmetry,...).



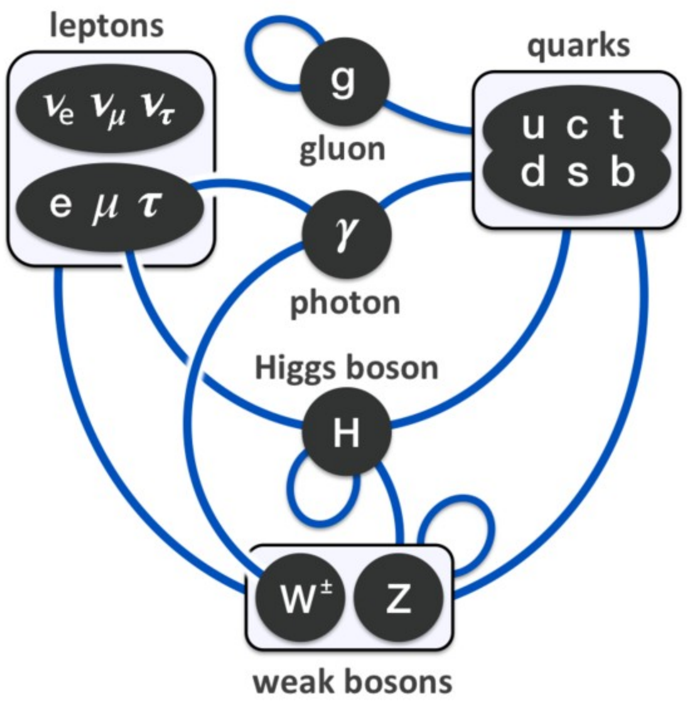
What is quantum field theory?

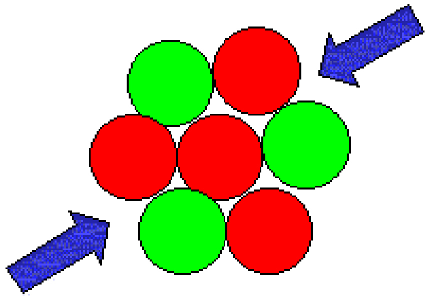
- Combines quantum mechanics and general relativity.
- Can describe the creation and decay of elementary particles.
- The fundamental quantities are the quantum fields, and the elementary particles are excitations of these fields.

Classical mechanics	**Quantum mechanics**
Relativistic mechanics	**Quantum field theory**

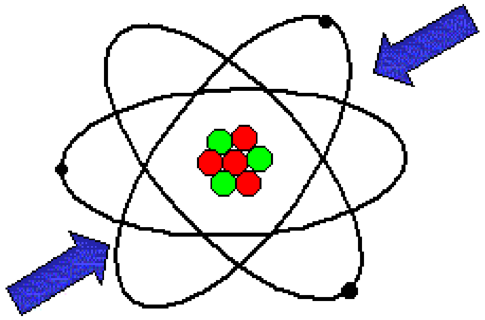
The forces in nature

- The forces determine how things move (gravitation for example), and what happens when particles meet.
  - The particles and the forces together describe nature.
- Four "fundamental" forces:
  - The electromagnetic force (ɣ).
  - The weak nuclear force (W, Z).
  - The strong nuclear force (g).
  - Gravitation (graviton?).
- The first three are described by the Standard Model.
  - Gravitation is too weak to be detected at the particle level.

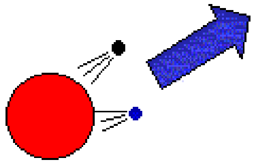




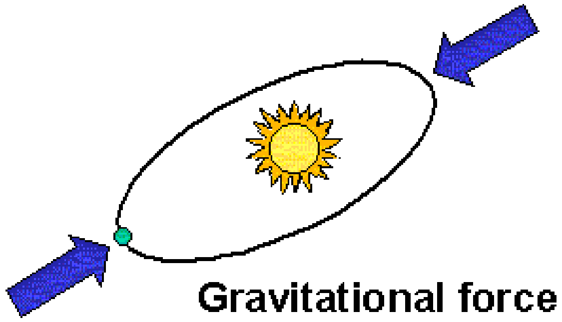
Strong force binds the nucleus



Electromagnetic force binds atoms



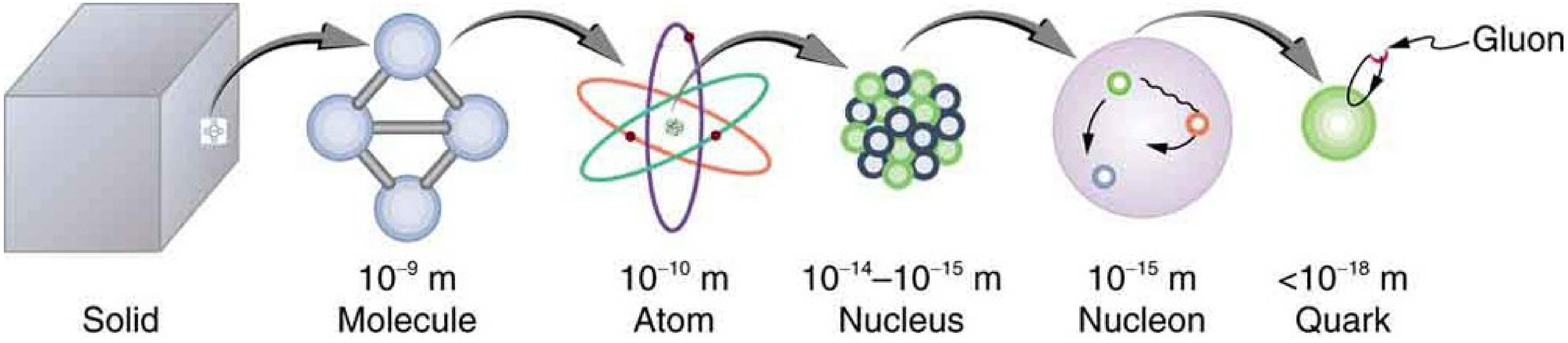
Weak force in radioactive decay



Gravitational force binds the solar system

What is particle physics?

- Particle physics try to identify the smallest building blocks of matter, and the forces that act between these particles.
- A so-called elementary particle has no smaller constituents.
  - But a heavy elementary particle can still be unstable, and decay to lighter particles as long as energy, charge etc. are conserved.



  - Particles we think are elementary are the quarks (that make up the proton and neutron) and the leptons (for example the electron).