Institut national de physique nucléaire
et de physique des particules

Particle Physics and the FCC

Ursula Bassler
Scientific Director IN2P3

Europeans Decide on Particl
Strategy
July 2, 2020 • Physics 13, 105
The CERN Council approved a strategy update that prioritizes a 100-km circul
while still developing other options for future particle physics projects.
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NEWS | 15 January 2019
Next-generation LHC: CERN lays out plans for €21-billion supercollider
The proposed facility would be the most powerful collider ever built.
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Мультимедійна платформа іномовлення України
N затвердила план будівництва нового
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Gigantic Particle Collid
It would cost many billions of dollars, the potent
be better spent researching
Washington Post
Democracy Dies in Darkness
scientists want to build an electron-
positron collider th
whopping 62
miles in circumfe
By Erin Blakemore
June 27, 2020 at 8:00 a.m. EDT
Try four weeks f
DER TAGESSPIEGEL
EXKLUSIV
20.06.2020
Die Maschine, die die Welt erklären soll
Das CERN will einen neuen, riesigen
Teilchenbeschleuniger
Kilometer langen Beschleuniger drängende Fragen der Te
VON RALF NESTLER
Le Cern veut faire construire un accélérateur de
particules de 100 km de long
Le Conseil européen pour la recherche nucléaire prévoit de construire un accélérateur de
particules géant à Genève. Le projet devrait coûter près de 20 milliards d'euros.
Klantendienst
Voor abo
REGIO
SLIMMER LEVEN
BILLIE
BINNENLAND
BUITENLAND
TV-GIDS
PUZZELS
tunnel van 100 km om
minuscule Higgsdeeltjes te
bestuderen
HEIDI.NEWS
LE MEDIA QUI EXPLIQUE & EXPLORE LE 21e SIÈCLE
GENEVA SOLUTIONS | CERN | NEWS
Publié le 26 juin 2020 16:00. Modifié le 26 juin 2020 18:45.
CERN unveils its new European strateg
does not rule out a new particle accelera
par Sarah Sermondadaz

2020 European Strategy for Particle Physics

est. **2005**: updated every 5-7 years by the CERN Council:

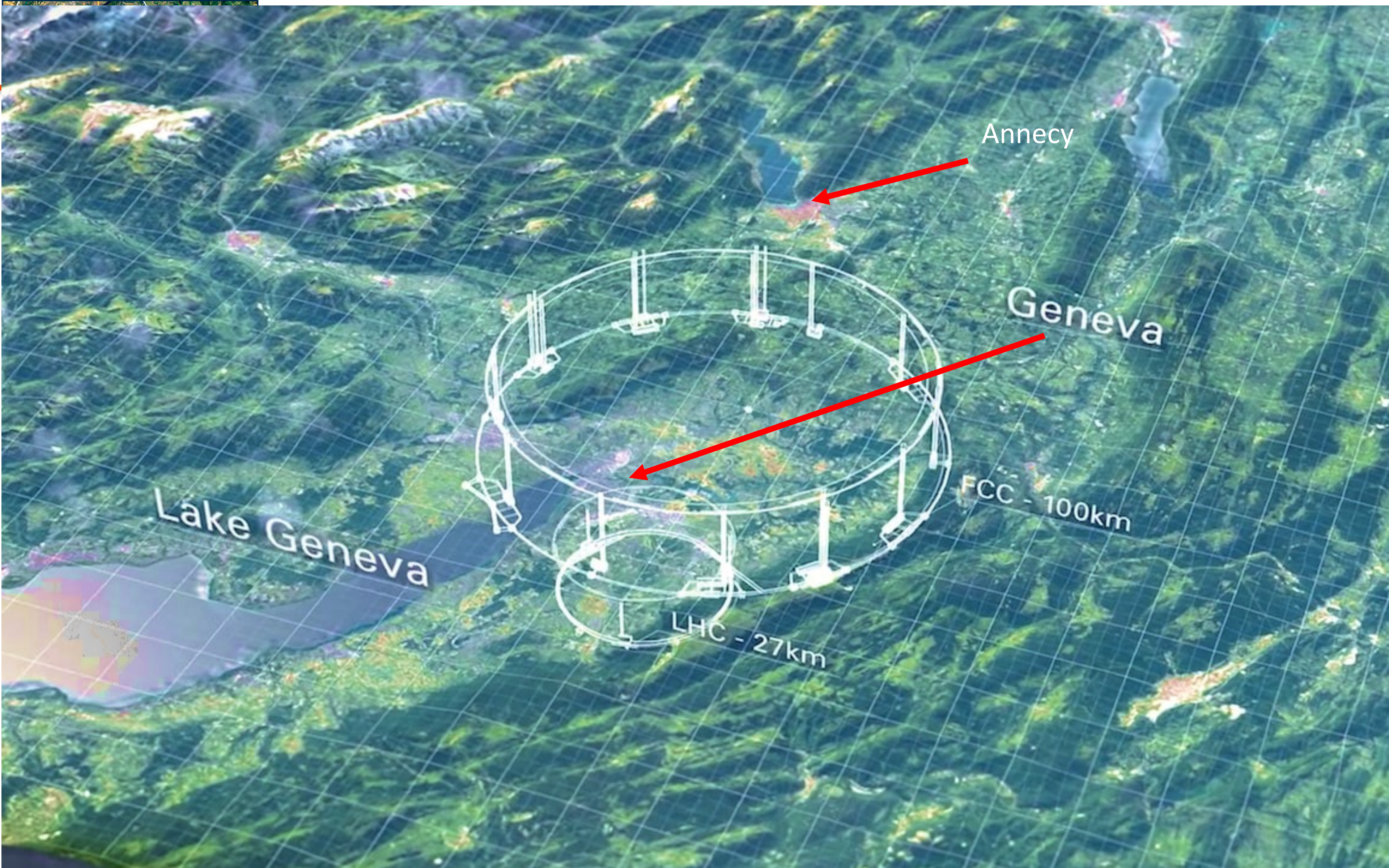
- **bottom-up** process with about 160 contributions received and discussed during an Open Symposium

→ Produced a 200 page briefing book

- "**topish-down**": delegates from all European Member States of CERN formulate the strategy

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. Accomplishing these compelling goals will require innovation and cutting-edge technology.

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.

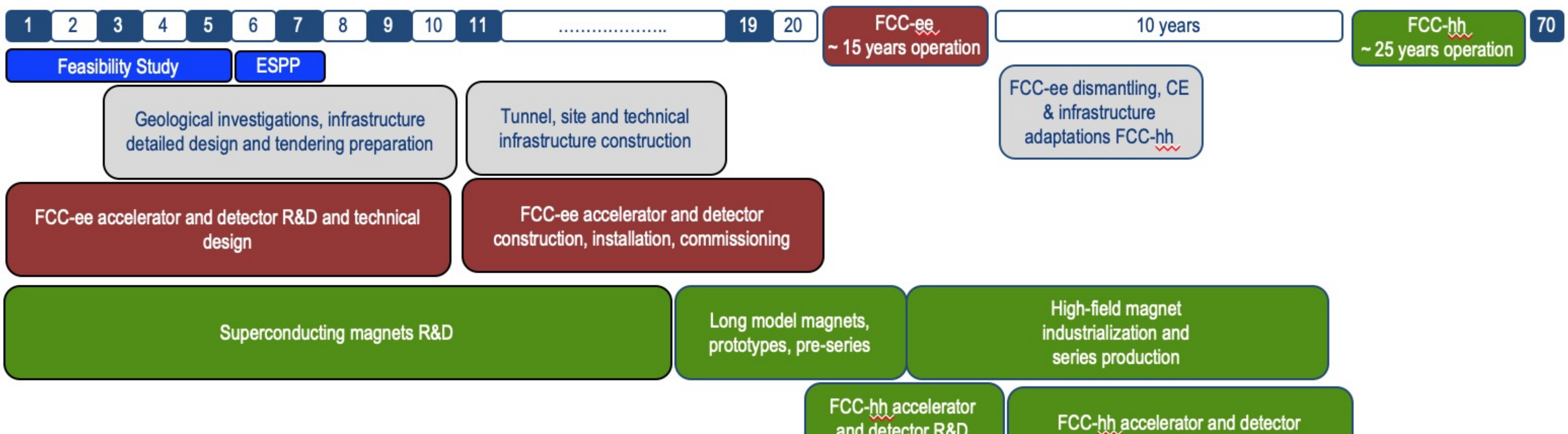

Annecy
Geneva
FCC - 100km
Lake Geneva
LHC - 27km

FCC studies

- **Design study started in 2014**
- **Feasibility study 2021-2025**
- Concept : 100km tunnel hosts successively different colliders (LEP/LHC)

→ optimal use of tunnel investment

- Location in Geneva area → 1/3 Swiss, 2/3 France
    - → cooperation with regional authorities
    - → assessment of geological conditions
    - → cost estimation



FCC project

LEP data accumulated in the first 3'!

FCC-ee		
Z peak	90 GeV	4 years
WW	160 GeV	2 years
H	240 GeV	3 years
Top	≈365 GeV	5 years

Increase in energy and luminosity similar to Tevatron to LHC

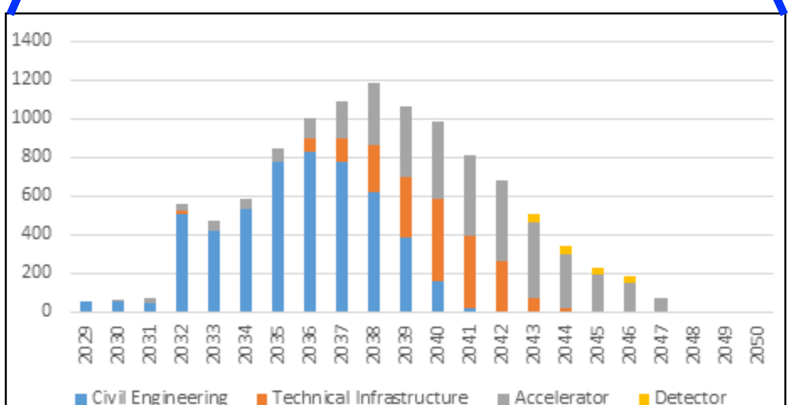
FCC-hh		
pp	100 TeV	25 years
PbPb	39 TeV	1 month/year

1 2 3 4 5 6 7 8 9 10 11 .... 19 20 | FCC-ee ~ 15 years operation | 10 years | FCC-hh ~ 25 years operation | 70

Feasibility Study | ESPP

Today — 2030 — 2040 — 2055 — 2065 — 2090

Preliminary cost estimation for FCC-ee:
≈ 11 Md CHF including
≈ 5 Md CHF civil engineering



FCC-hh: one of the cost-drivers:
4,700 16 T magnets →
high field magnets in development

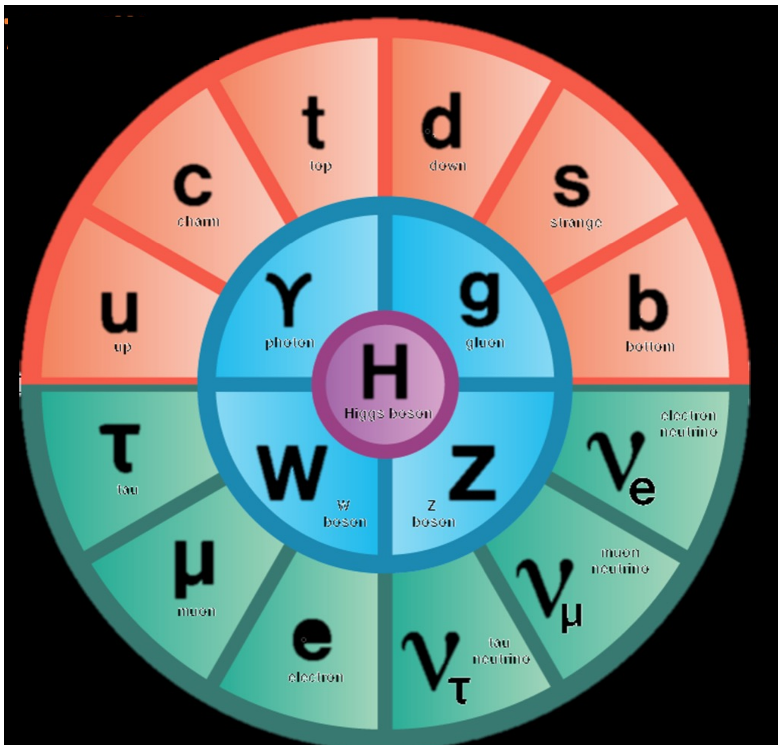
CNRS IN2P3 Les deux infinis

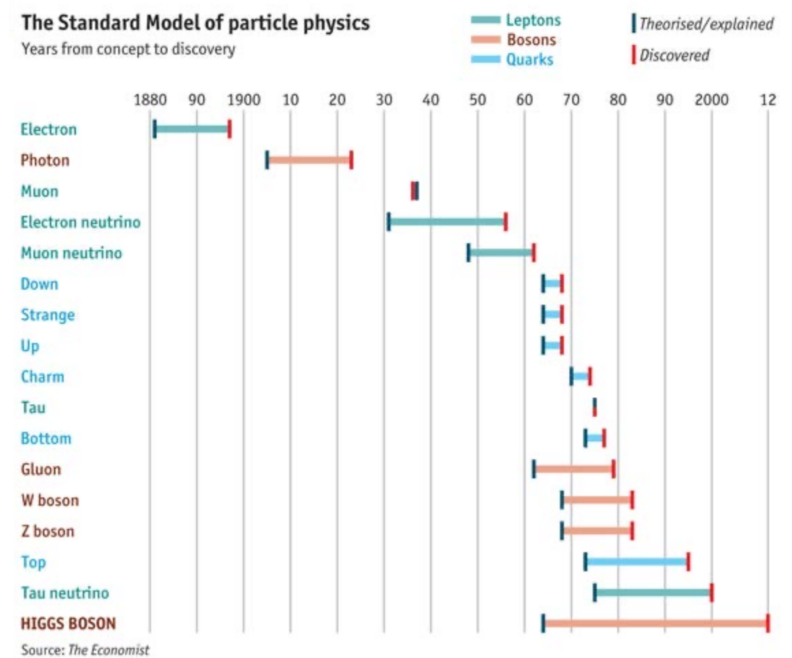
What is so interesting about the Higgs Boson?

and can FCC help answer “the big questions”?

The Standard Model of Particle Physics

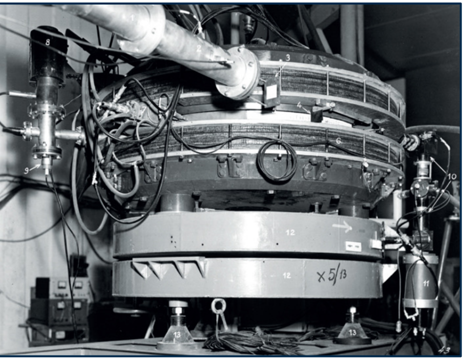
- Nearly 120 years ago, the first particle of the Standard Model was discovered: the electron
- About 50 years ago, the theory concepts behind the standard model have been established
- 10 years ago the Higgs boson was the last particle of the standard model to be discovered





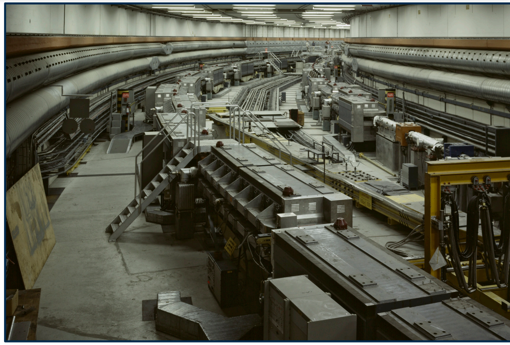
For comparison:
Gravitational waves

Workhorse of modern particle physics: Colliders



1963: The first electron-positron collider **AdA** was constructed in Frascati and the first collisions observed in Orsay

1971: First proton-proton collisions at the **ISR** at CERN



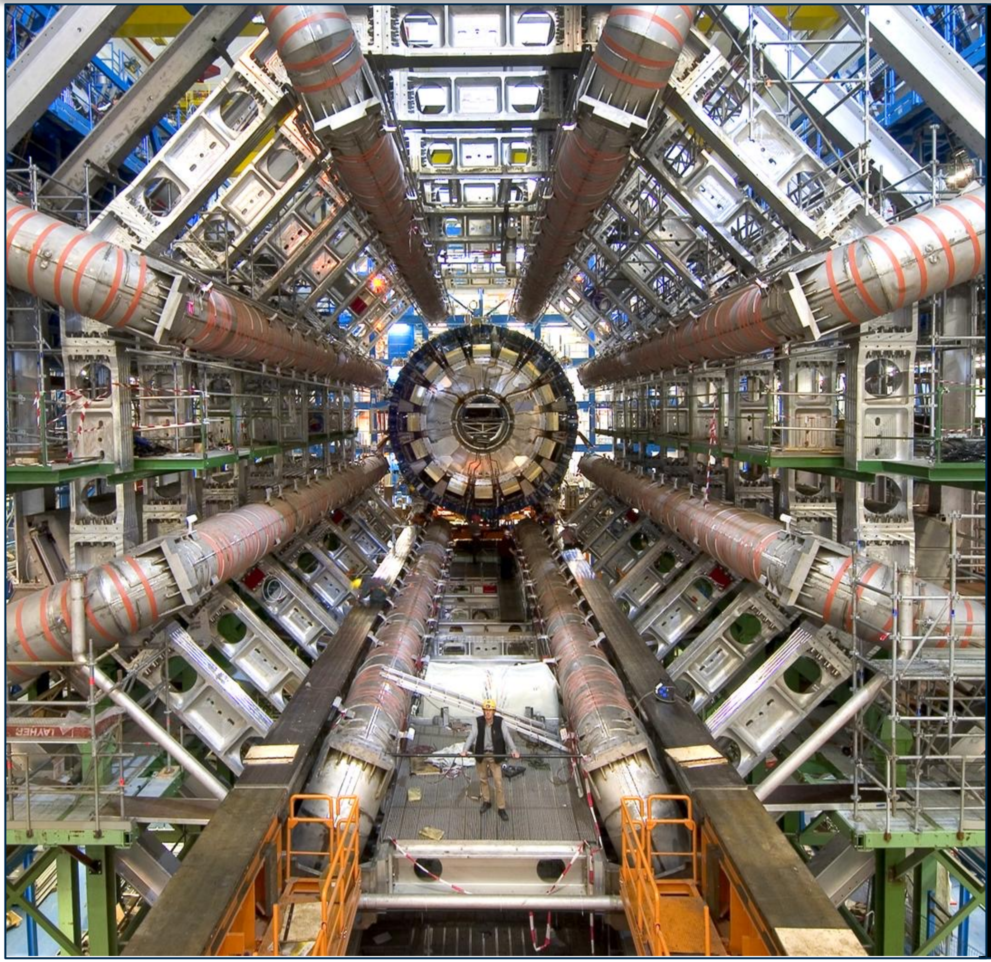
LEP/LHC at CERN:
electron-positron collider (1989-2000) and proton-proton collider (since 2009) using the same tunnel

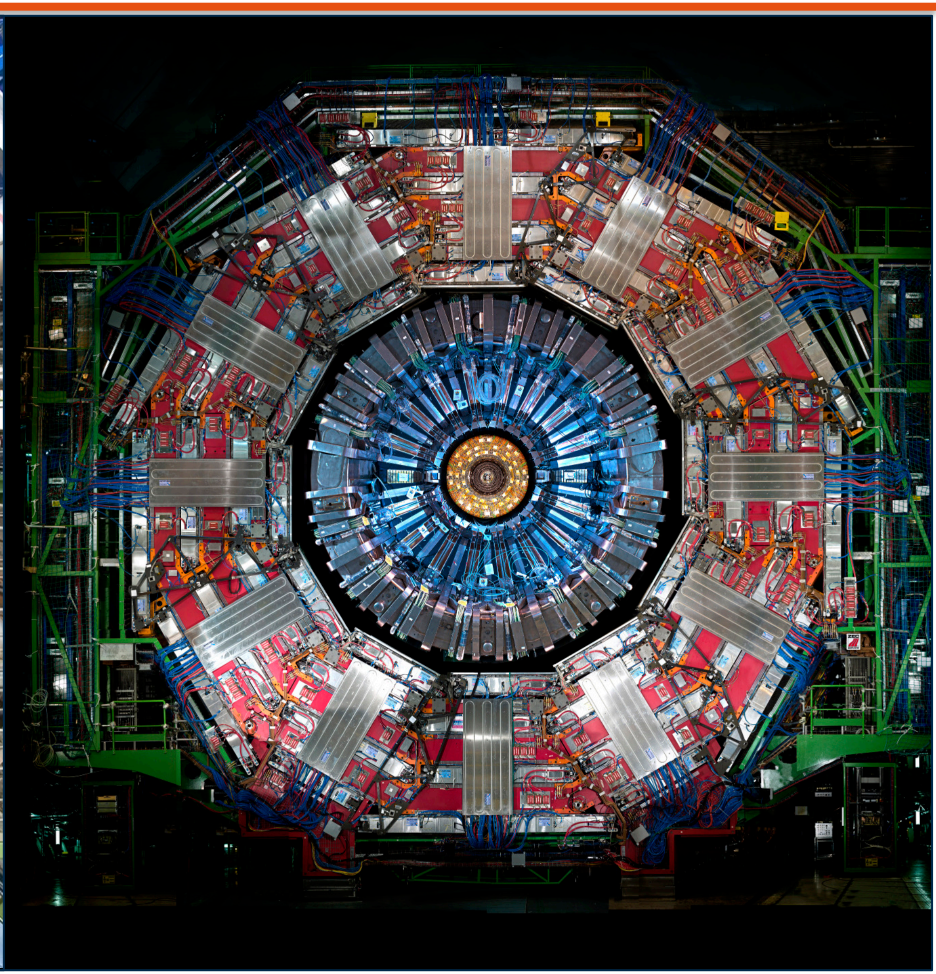
1981: First proton-antiproton collisions at the **SppS** at CERN

1991: First proton-electron collisions at **HERA** in DESY

→ **Talk by Pierre Vedrine**

…and marvellous detectors

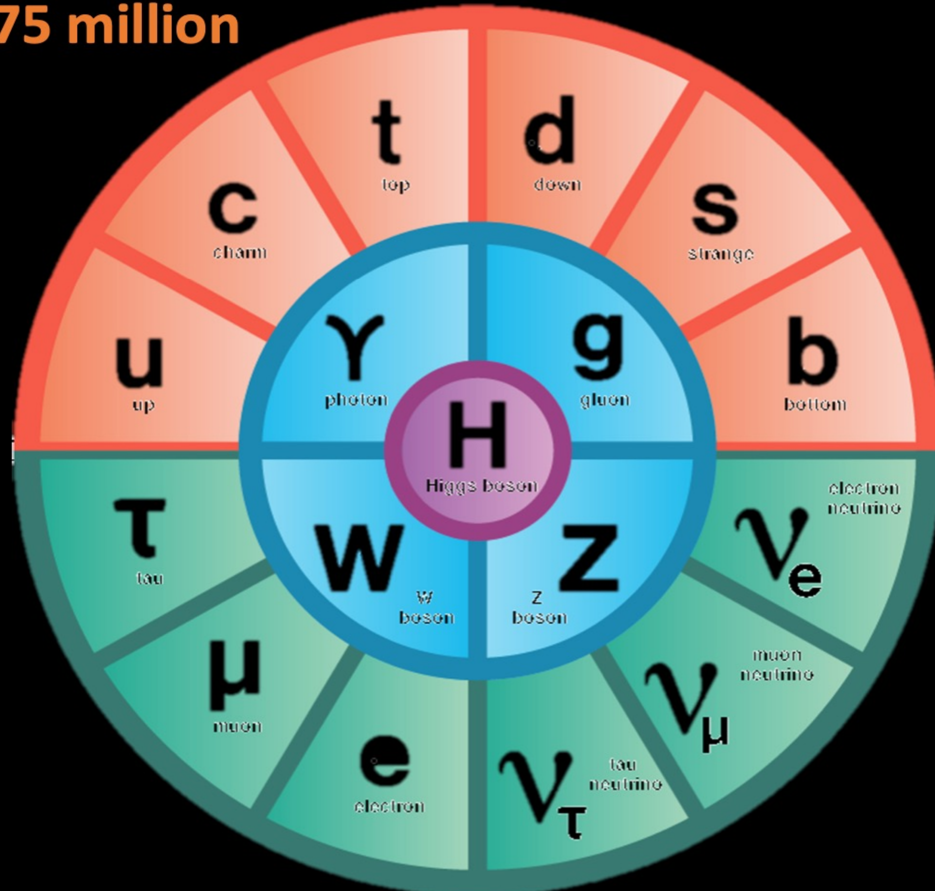




→ Talk by Didier Contardo

Run 2: 140 fb^{-1} proton-proton LHC data

t quark : 275 million



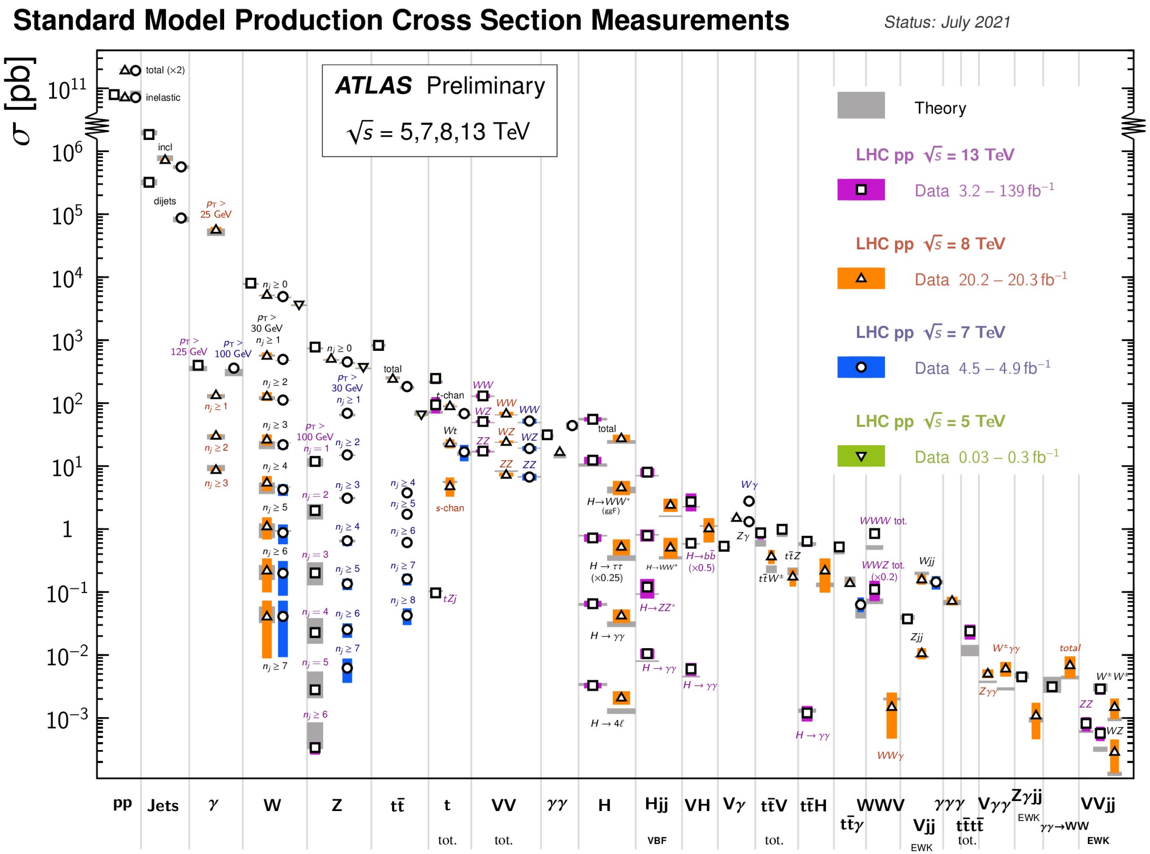
b quark: ~160 trillion

W boson: 26 billion

Z boson: 8 billion

Higgs boson: 8 million

LHC cross-section measurements



Measurement of production rates over 10 orders of magnitude:

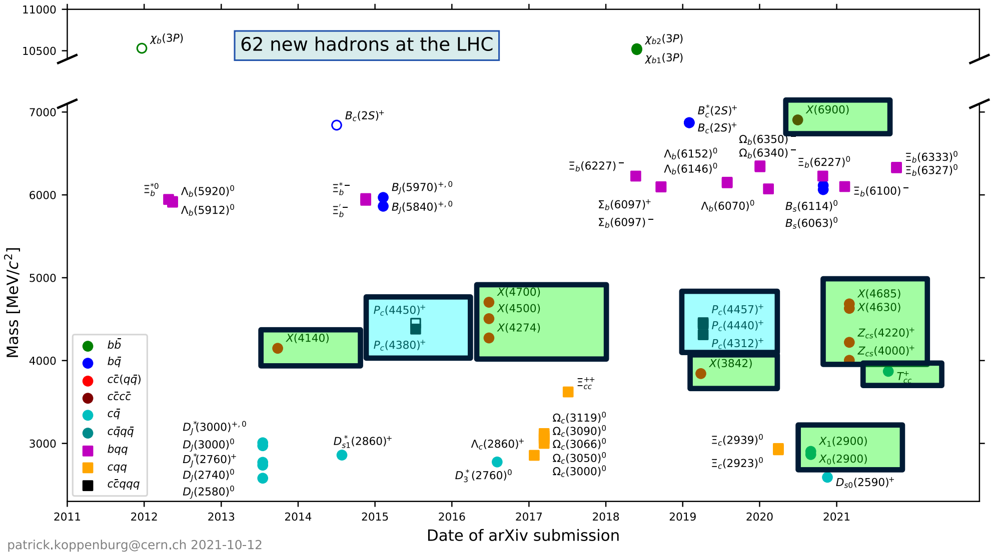
From jet-production to multi-boson processes

- *high precision measurements with inclusive production*
- *measurements of different production modes*
- *examine differential distributions*

➔ *Test high order QCD and EW calculations,*

➔ *check for deviations from SM*

Discoveries at the LHC: Exotic hadrons



LHC: More than 60 hadrons discovered !

Catching hadrons:

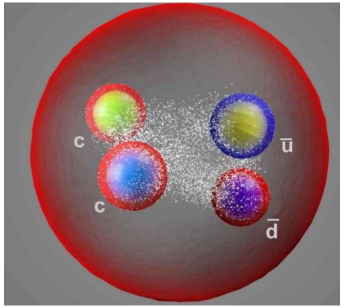
- 50 mesons possible : 1 undiscovered
- 75 baryons possible: ≈ 50 seen so far

→exotic hadrons @ LHC:

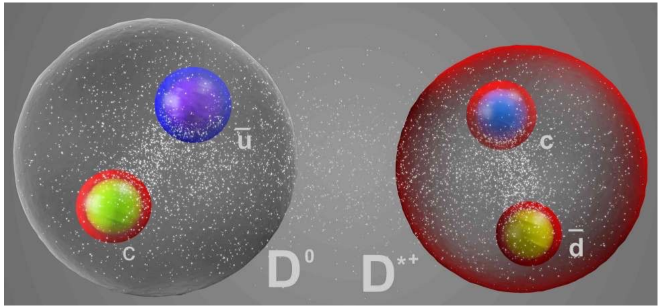
- 13 tetraquarks : 3 cqqq, 8 ccqq, 1 cccc
- 5 pentaquarks: ccqqq
- Do hexaquarks exist?

Structure of the tetraquarks?

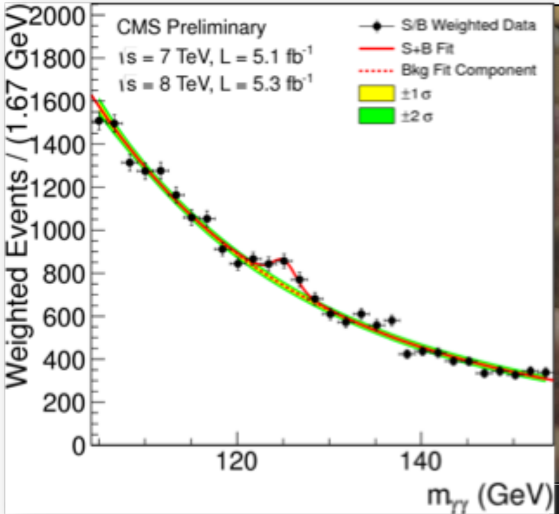
compact tetraquarks:
all 4 quarks see the colour of the others

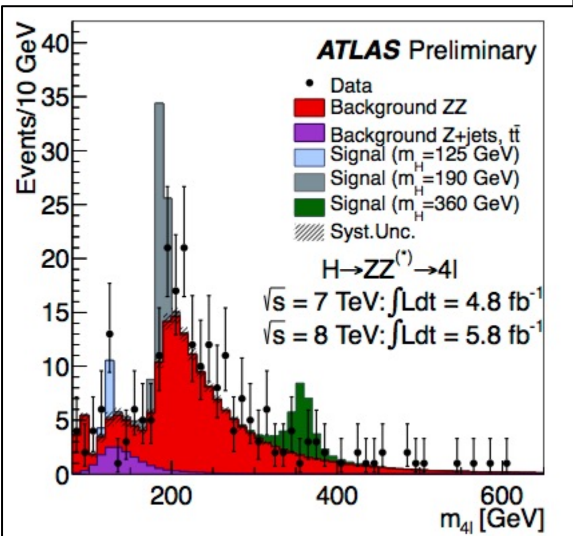


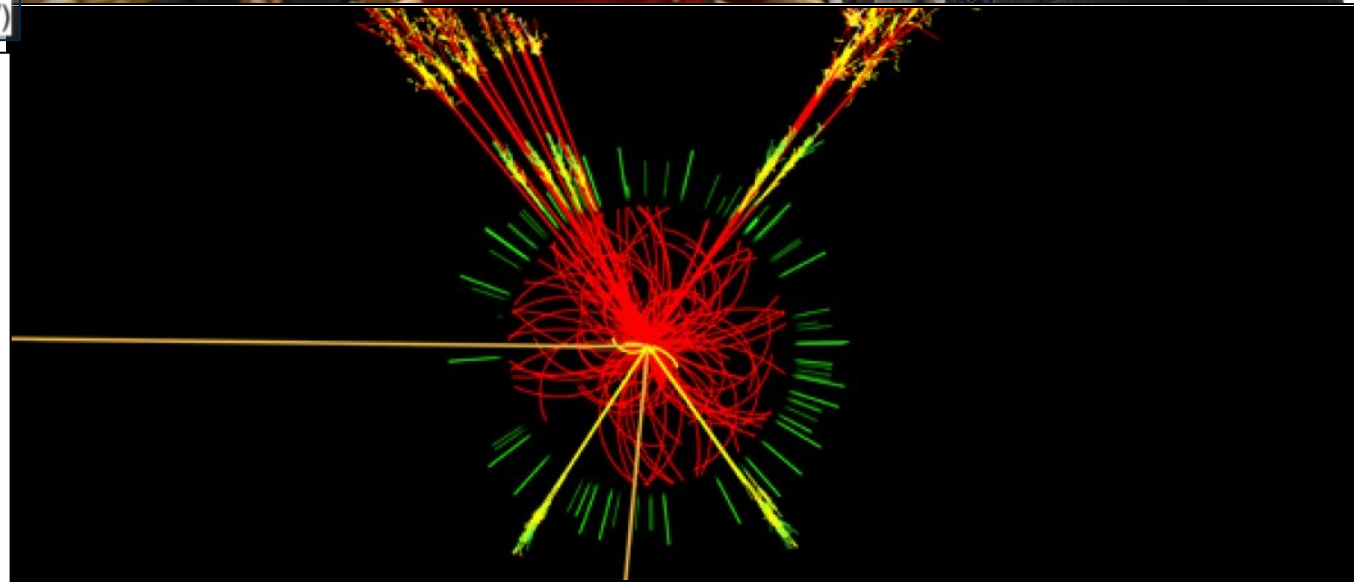
hadronic molecules:
2 colour-neutral di-quarks coupled through light meson-exchange



The "discovery" at the LHC: Higgs boson !







Higgs mass: coherence of the SM

Measurement of the Higgs mass at the 1 ‰ level !

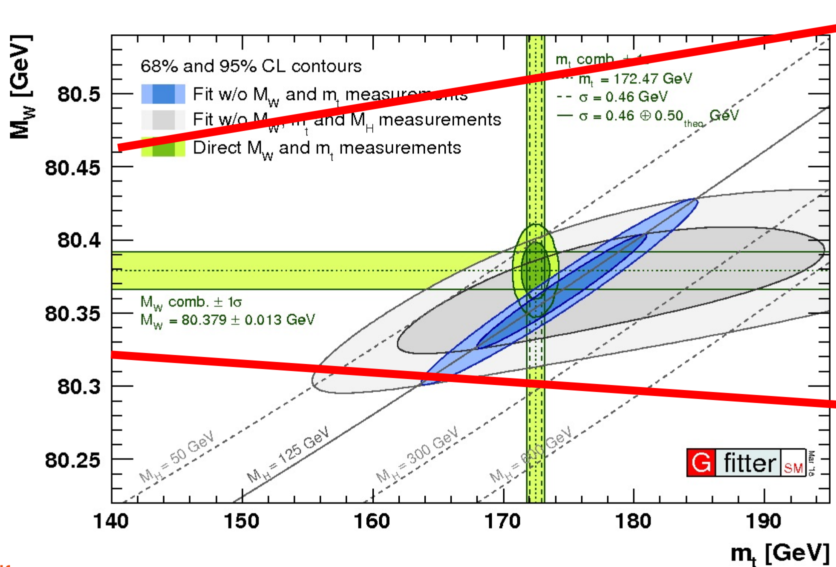
Top, W and Higgs mass → consistency check

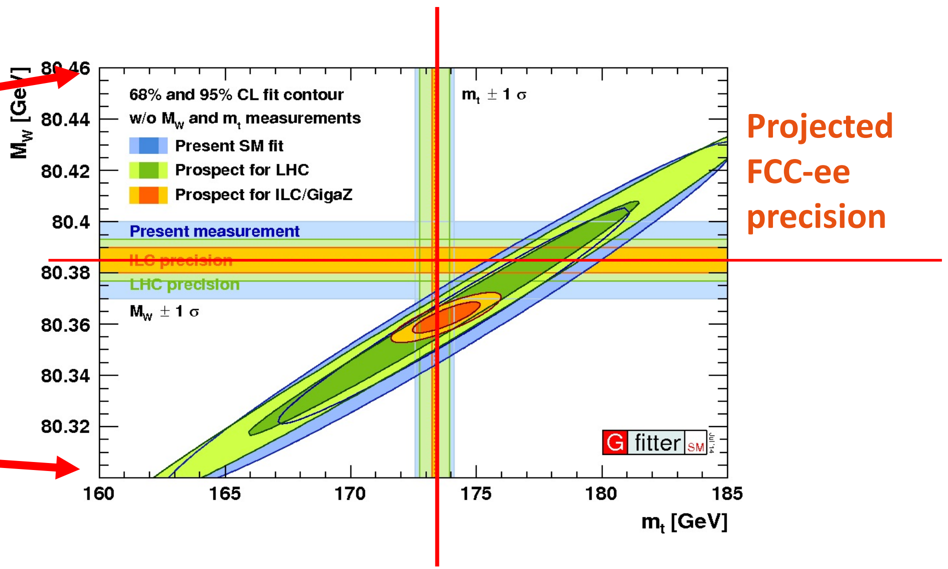
- **Increased precision from future colliders - FCC-ee should produce :**

→ 10 million WW events for precision W-mass measurements → precision 0.5 MeV

→ 1 million top anti-top events for the first model independent top-mass measurement

→ precision 16MeV





Projected FCC-ee precision

IN2P3
Les deux infinis

Higgs mass: coherence of the SM

Measurement of the Higgs mass at the 1 ‰ level !

Top, W and Higgs mass → consistency check

Recent mass measurement from CDF : 80,433.5 ± 6.4 (stat) ± 6.9 (syst) MeV **to be investigated!**

- **Increased precision from future colliders - FCC-ee should produce :**

→ 10 million WW events for precision W-mass measurements → precision 0.5 MeV

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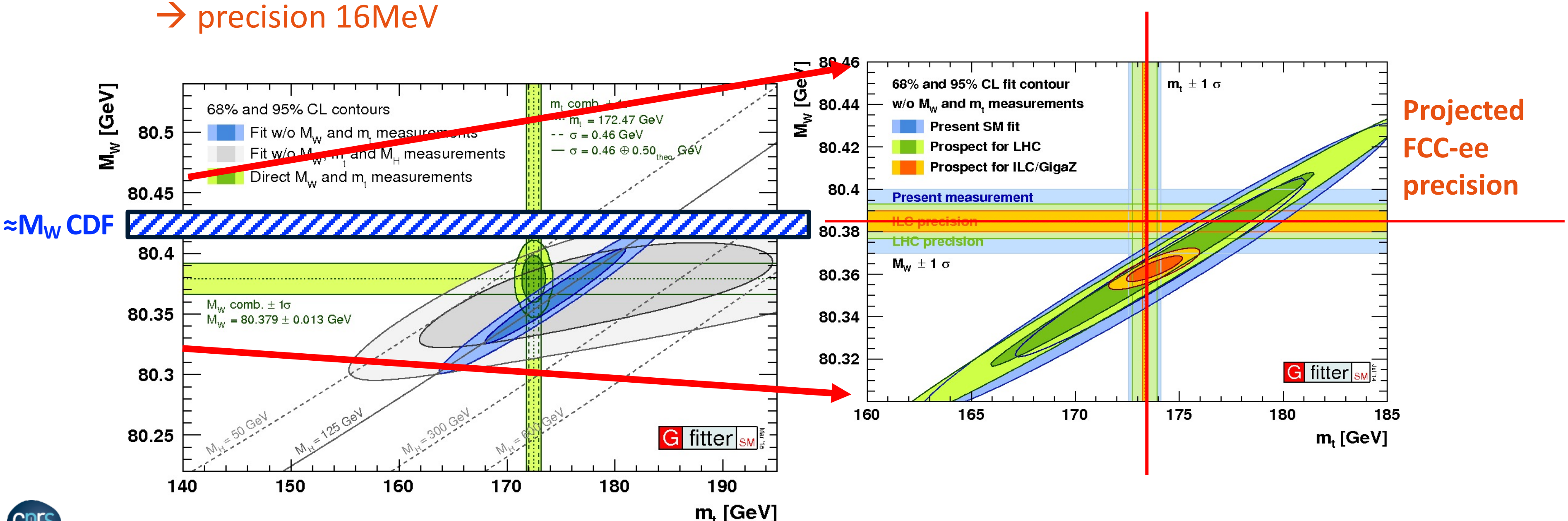
→ precision 16MeV



Higgs mass: stability of the Universe

Is the vacuum state of the Universe stable?

Evolution of the vacuum up to the Planck scale: Current analysis indicate meta stability at 1.3-2.8σ

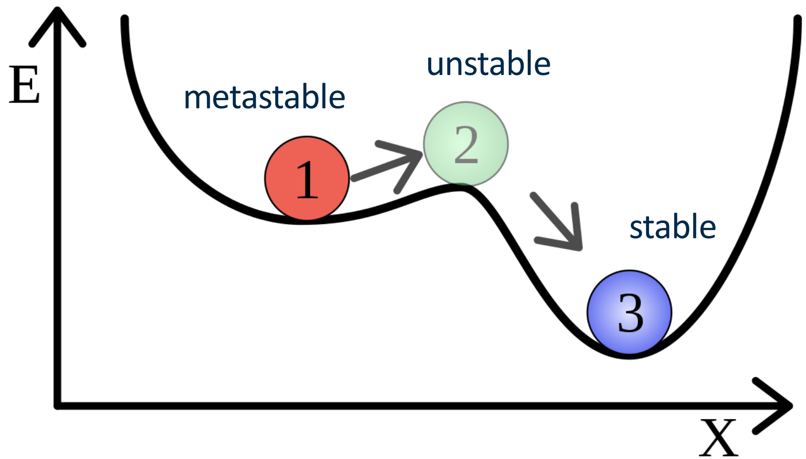
➔Or Universe may transit to another vacuum state sometime… *but maybe we have other problems before*

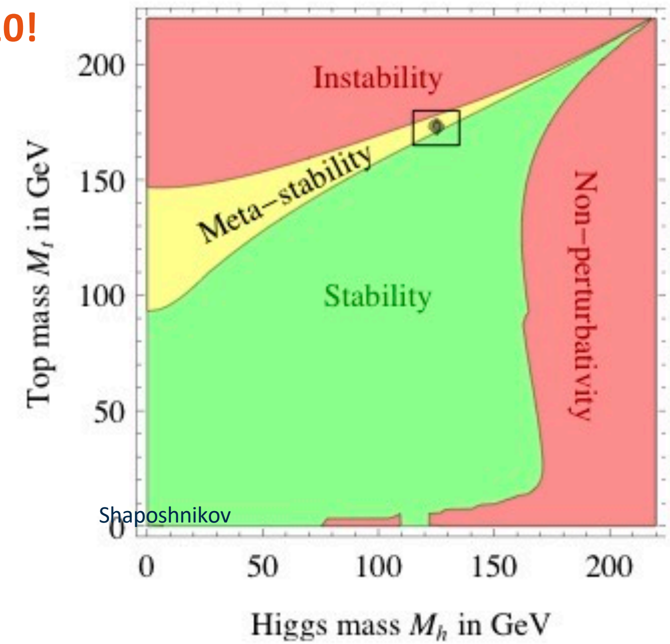
➔New physics?

Calculation based on the **Higgs mass** and the **top pole-mass**

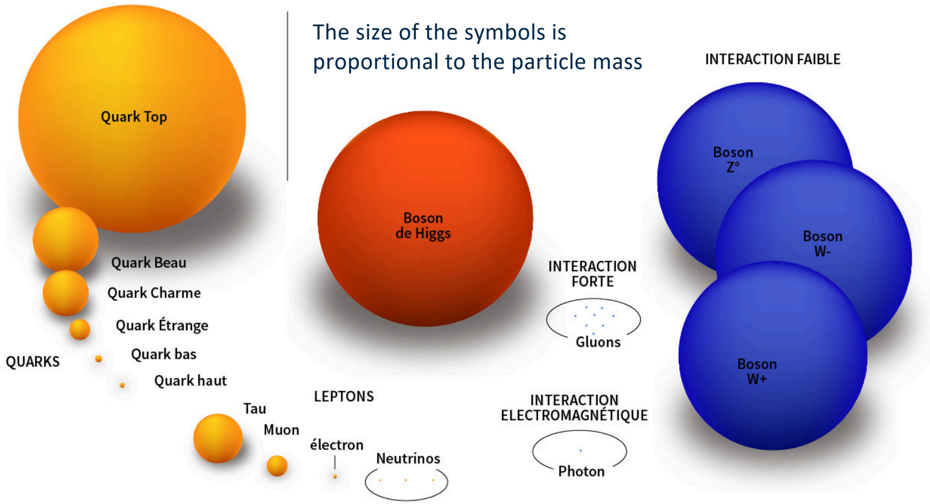
➔ee-collider at tt-bar threshold: **model independent top mass measurement!**

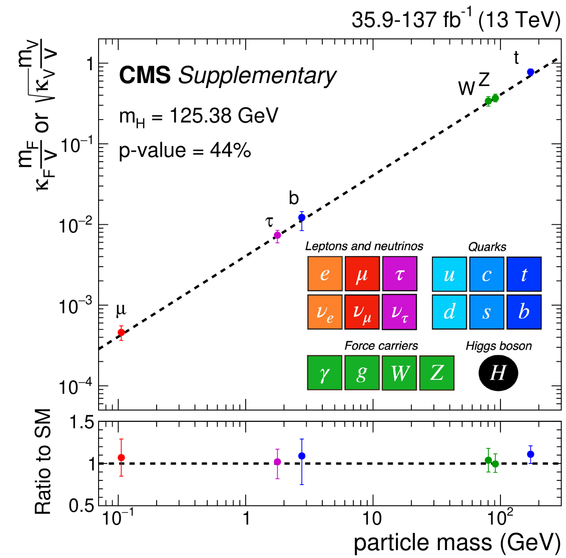
➔ **FCC-ee: improvement on top and Higgs mass by at least a factor 10!**





Higgs Couplings





-Couplings of the Higgs boson to elementary particles (quarks, leptons, bosons) proportional to their mass
- The interaction with the Higgs field is the only interaction that distinguishes fermion families !

→ **the higher the mass, the easier to verify !**

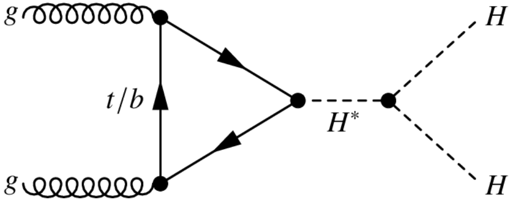
Verification down to the 2nd generation

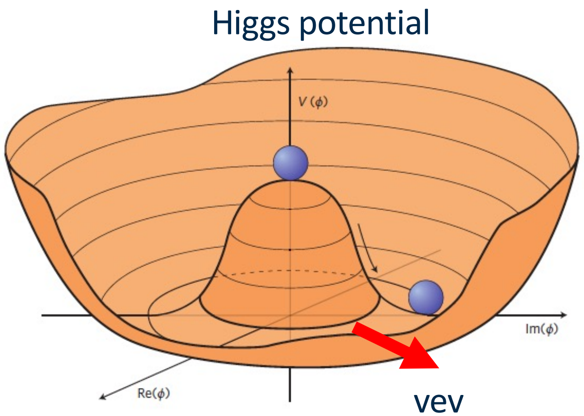
→ 1st generation: too small to be measured ~$O(10^{-9})$

except through Higgs production in monochromatic ee collisions **under study** !

Physics beyond the Standard Model : deviations at < 1% **can be reached at FCC-ee !**

Projections for HL-LHC: ≈ 5% range





Higgs boson has a mass → it couples to itself!

Potential of the Higgs boson "Mexican Hat" :

$$V=\frac{1}{2}m_H^2 H^2+\lambda\, v H^3+\frac{1}{4}\lambda\, H^4-\frac{\lambda}{4}v^4$$

Vacuum expectation value (vev) v=246 GeV

→ computed from M_W and the weak coupling g

λ= = $m_H^2/2v^2 \approx 0.13$ ➔ strong prediction

➔ HHH measurements give direct access to λ

But: small cross section: experimentally challenging

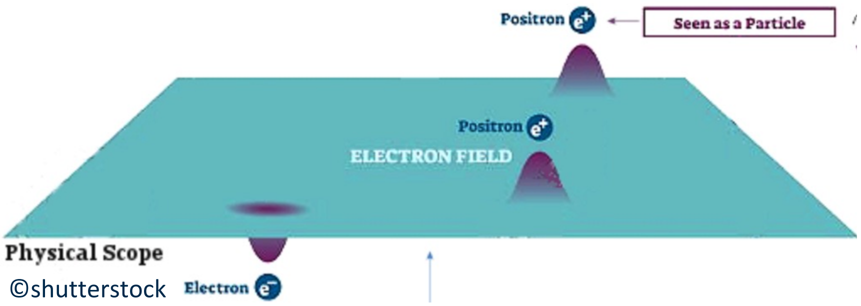
HL-LHC: about ~ 100k HH produced, but very difficult to identify

➔ determine if self-coupling exists

ee-colliders: directly measurement ZHH channel with √s ≳ 400 GeV

→ **FCC-ee indirect measurements :** NLO effects in single H production

Higgs Field



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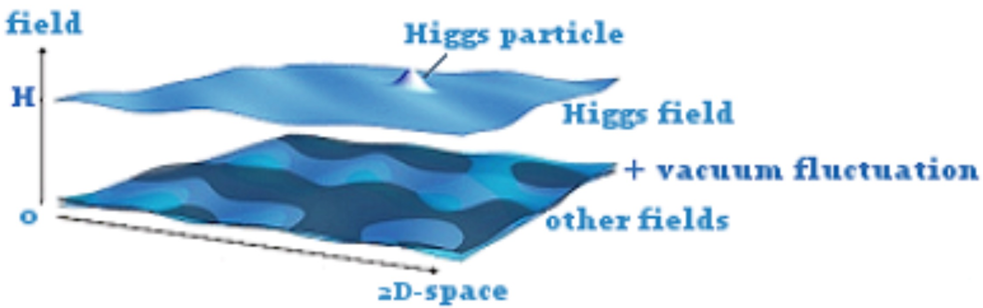
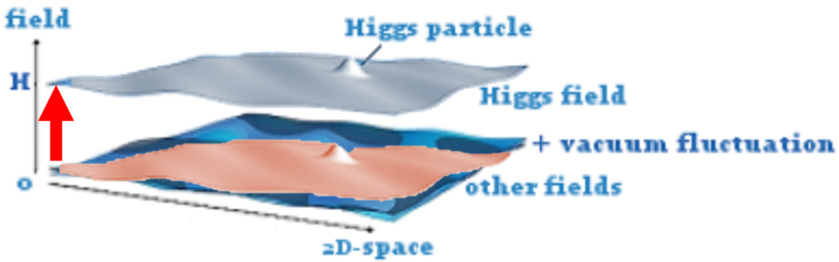
In Quantum Field Theory:
All particles are considered as excitations of the underlying field
→ Every electron is an excitation of the same electron-field filling up the whole Universe

→ allows to compute the probability, to find a given particle at a given time at a certain position
→ field contains all the quantum information associated to a type of particle
→ mean "ground state energy", the vacuum expectation value (vev) contained in a field is 0, except…



…for the Higgs field:
scaler field
→ symmetry can be broken
→ vacuum expectation value can be ≠ 0

Higgs boson in the primordial Univers

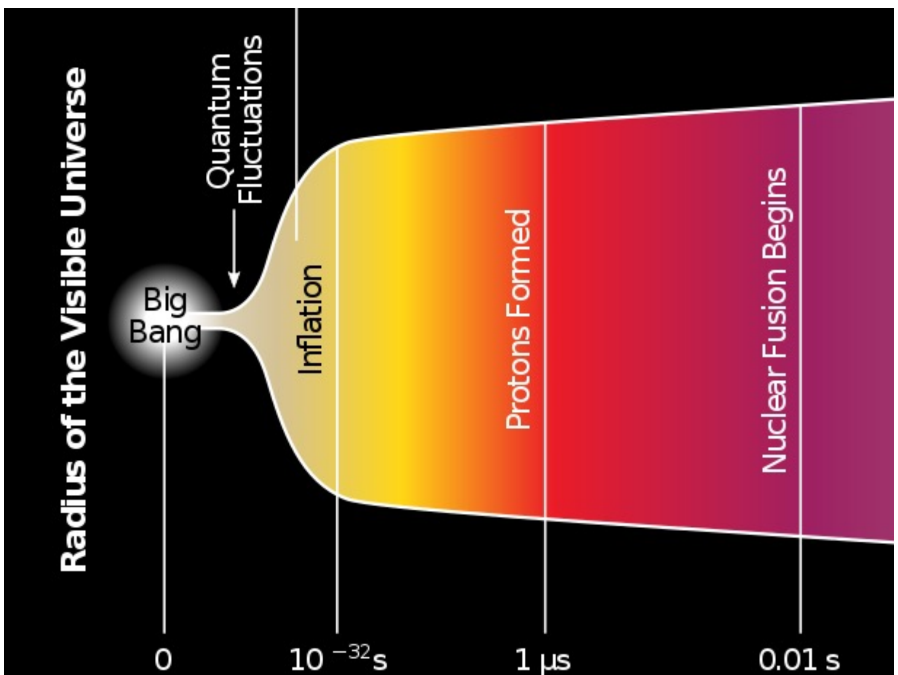


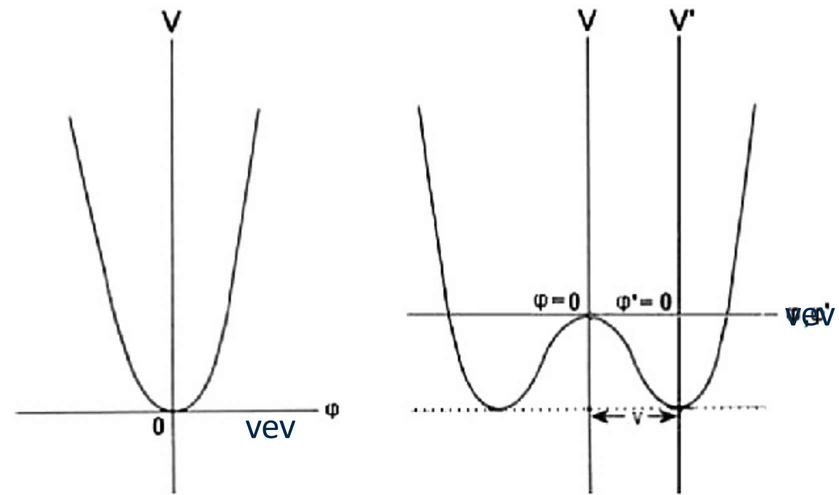
≈ 10^{-12} after the Big Bang, the Higgs boson underwent a phase transition:

- the potential energy of the Higgs field became minimal at a non-zero vacuum expectation value
- **symmetry breaking :**
  massive Z and W± + a H boson

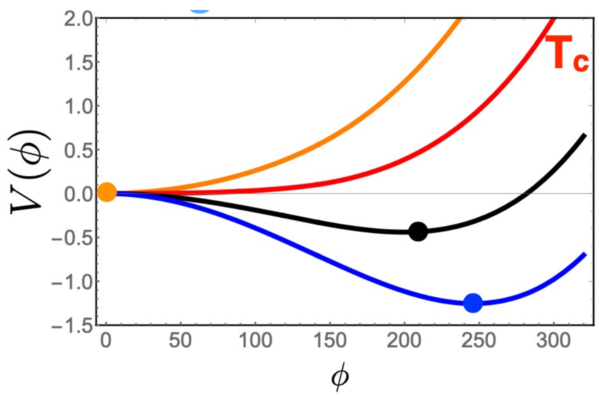
- matter particles interact with the Higgs field and appear massive

… the Universe as we know it!



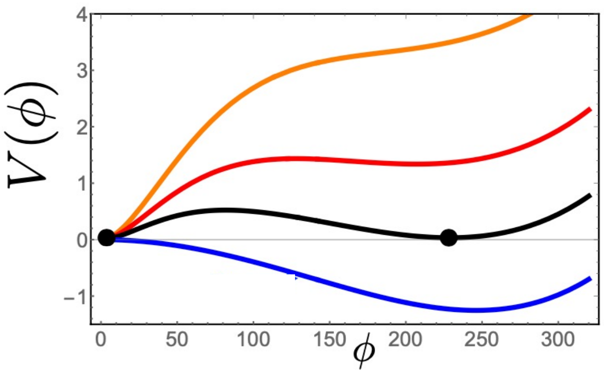


Higgs phase transition



Higgs potential must have evolved during the cool-down of the Universe : How?

2nd order phase transition: Universe stays in thermic equilibrium → favoured by the Higgs mass measurement (m_H>70 GeV): matter creation?

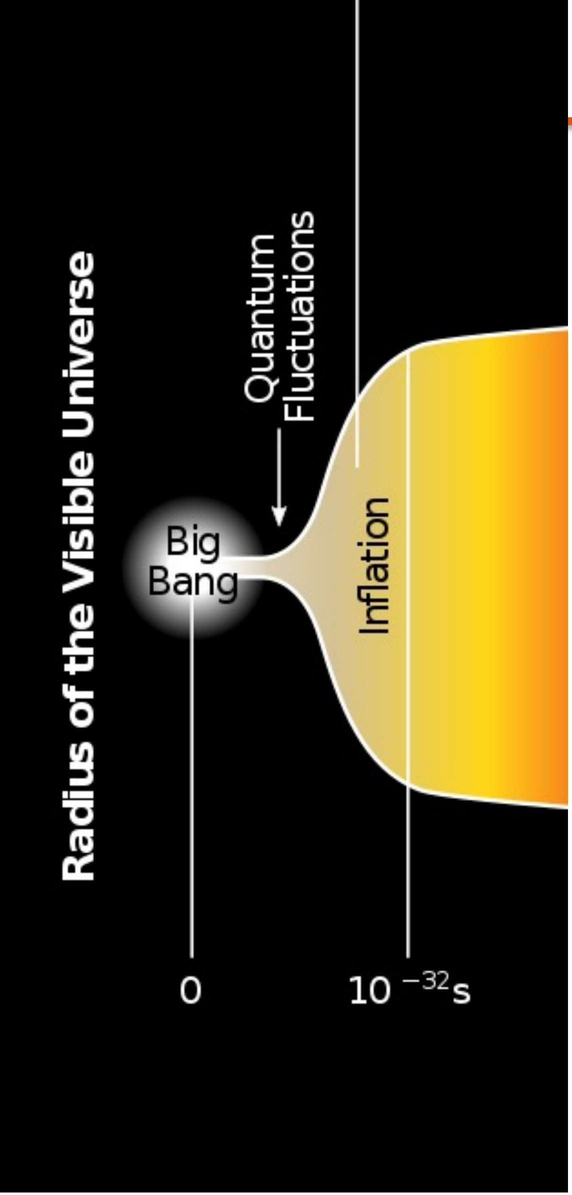


1st order phase transition:

No thermic equilibrium → formation of "bubbles" and tunnelling effects : required for baryogenesis, but physics beyond the Standard Model necessary i.e. additional scaler fields

→ Primordial gravitational waves may help understand!

→ LISA satellite ?



The Observation of a homogeneous Universe led to assumption that Cosmic Inflation could describe the very early expansion:

→ in the very first 10^{-34}s the Universe expanded by a factor 10^{26}

- Expansion would be due to the scaler inflaton-field

- the potential of the inflaton-field would decrease over time

→ generation of matter-antimatter particles creates negative pression

Good news: scaler fields exist !

Bad news: doesn't look to be the Higgs field : Higgs is to heavy and the expansion rate by a factor 10^{118}x too fast!

But: Search for Higgs-inflaton oscillations in B meson decays

→ not observation disfavours existence of light inflaton

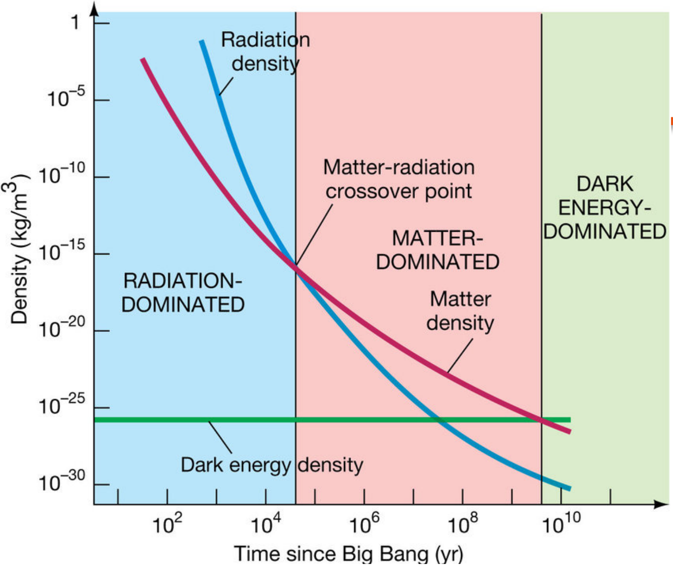
Future investigations on inflation:

- Inflation should have produced primordial gravitational wave

→ Polarised CMB, LISA satellite

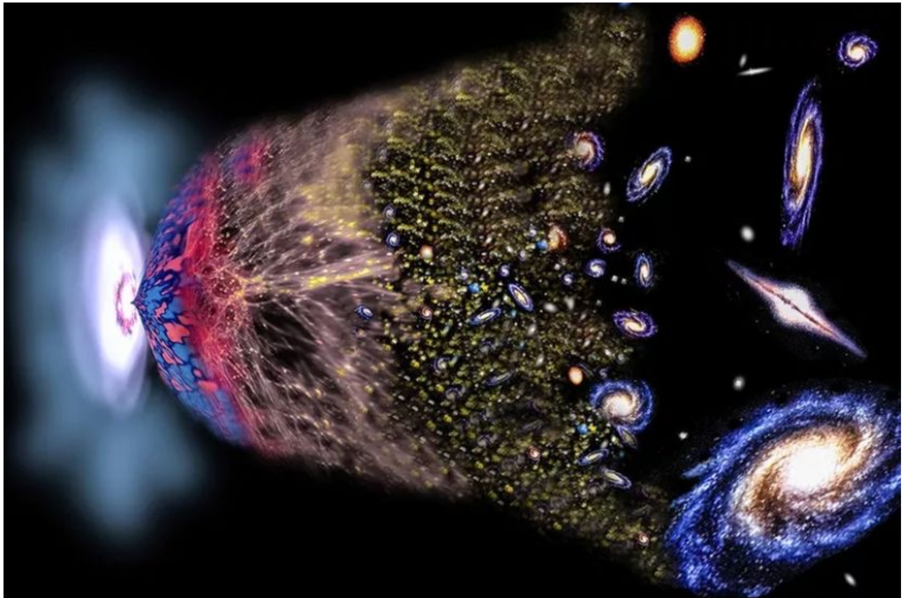
or observation of cosmic gravitational wave background

Higgs and dark energy?



The expansion of the Universe has different phases:

- Rapid expansion dominated by the negative pressure of photons and relativistic particles
- Slowed down by matter and its gravitational attraction
- Current acceleration due to a constant “dark energy“



Not much is know about Dark Energy:

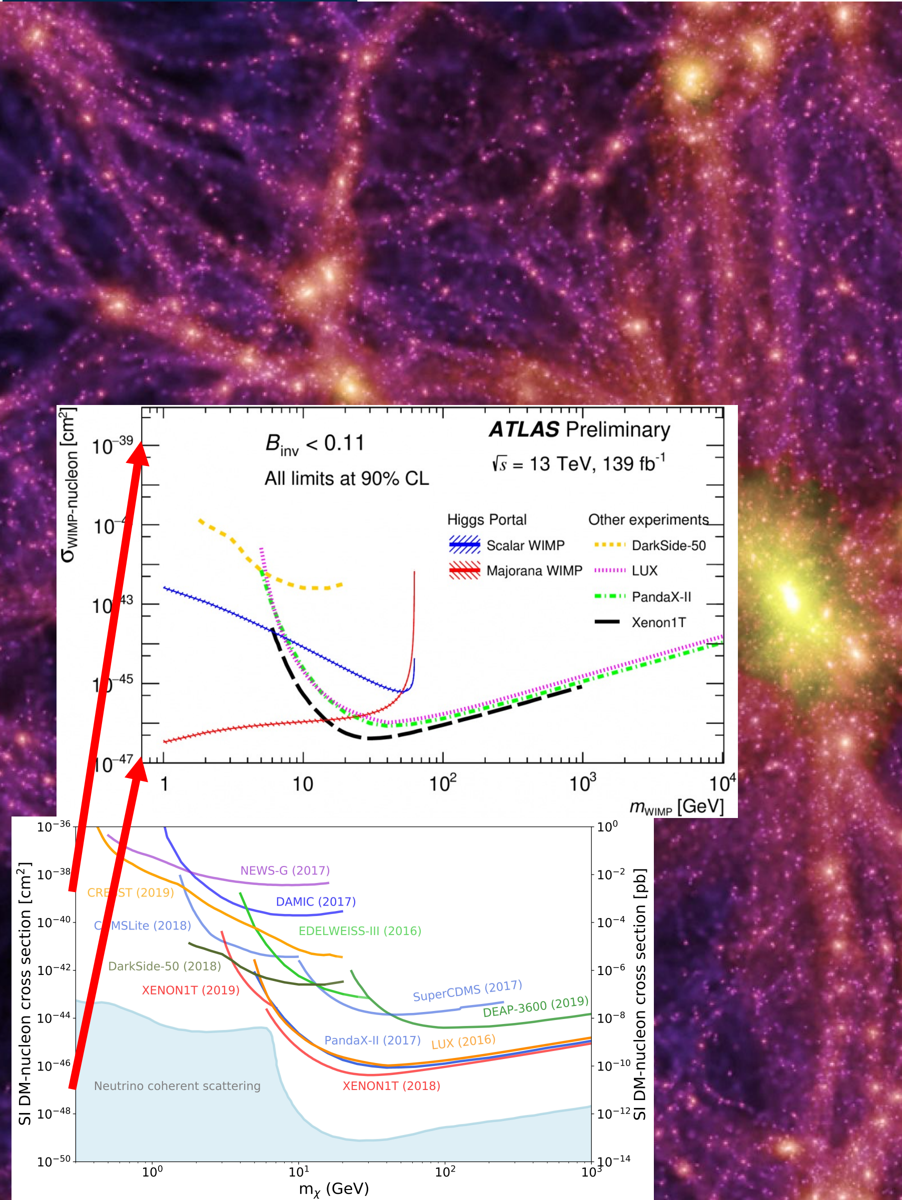
« could be a property of spacetime itself, or just a huge misunderstanding of how gravity works on a cosmic scale. »

at colliders?

Hmm « trying to determine the nature of a weak long range interaction through its interactions on the smallest possible length scales involving the highest possible terrestrial energies… »

➔models builders are looking for possible links to the Higgs boson and first searches at LHC started !

Higgs: portal to Dark Matter?



Since the 1930's astrophysical observations point to the existence of Dark Matter

- The Standard Model of Cosmology ΛCDM based on the existence of Dark Matter and Dark Energy
- Direct Dark Matter searches have reached an impressive sensitivity

→ in the high energy range through nucleon recoils

→ In the low energy range through electron recoil

All massive particles should couple to the Higgs boson:

Could we see Dark Matter particles through the Higgs boson?

Higgs as Dark Matter mediator:

Direct searches as for H → XX

Exclude $\mathcal{B}(H \rightarrow Z_d Z_d)$ as low as 2-8 x 10^{-5}

Higgs boson coupling to Dark Matter:

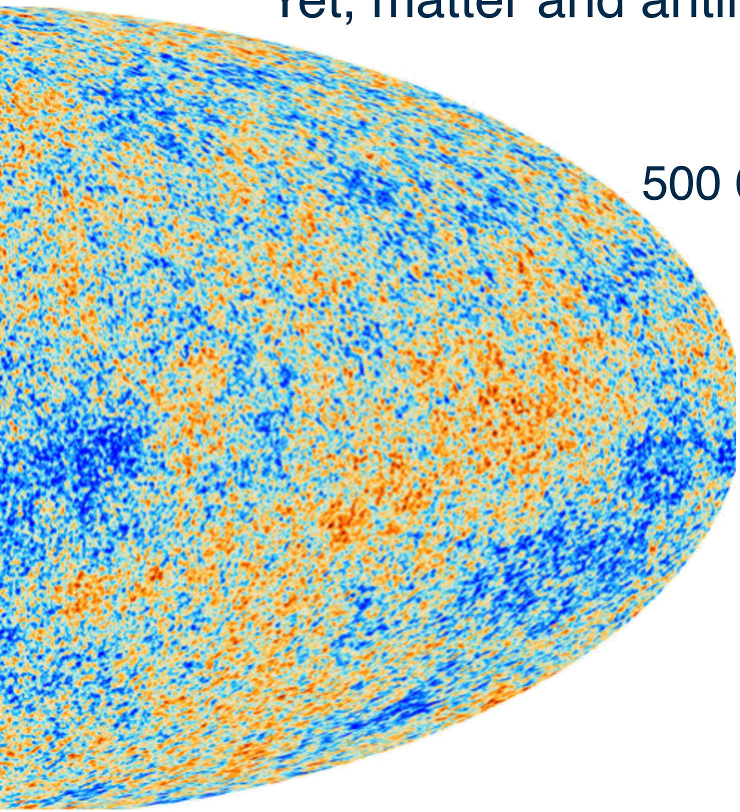
$\mathcal{B}$(H→inv) < 11% at 90% CL

➔ **FCC-ee: discovery potential to decays of 0.5%**


Dark Matter
Light bosons
Axion-like Particles
Fuzzy Dark Matter
QCD Axions
Neutrinos
Standard Model ν
Sterile neutrinos
Weak Scale
Super-symmetry
Extra-dimensions
Little Higgs
Simplified Models
Effective Field Theory
Modified Gravity
MOG
TeVeS
MoND
Emergent Gravity
Macroscopic
Macros
Primordial BHs
MaCHOs
Other Particle
WIMPzilla
Superfluid
Self-interacting

Where is the antimatter?

In the current Universe: 10^9 photons, 1 proton - 0 antiprotons
Yet, matter and antimatter should have been created in equal amounts



1 µs after the Big Bang:
500 000 001 quarks and 500 000 000 antiquarks annihilate!
Why does matter exist ?

3 Sakharov conditions for baryogenesis:

1) No thermal equilibrium:

reaction and backwards reaction not in equilibrium

→ 1st order phase transition

→ measurement of Higgs potential

2) Non-conservation of the baryon number:

stability of the proton measured to 10^{31}: limit to be reached 10^{39}

Sphaleron: non-perturbative process at high energy in the Standard Model → predicted by d'Hooft in 1976

- transformation of 3 baryons into 3 anti-leptons

→ first searches at the LHC: BaryoGen generator

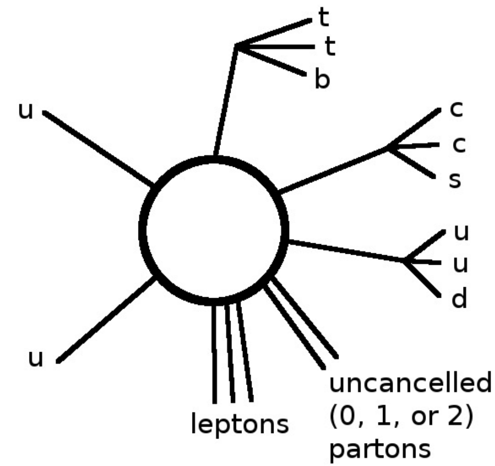
Production should occur above ≈9 TeV

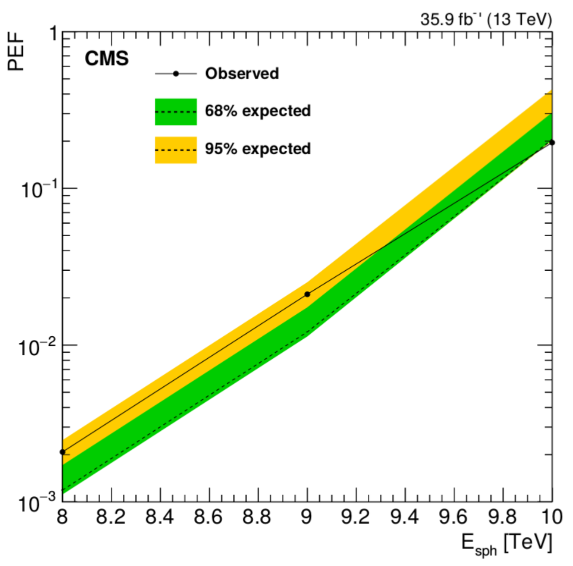
→Higgs mass last missing piece for prediction

Event signature:

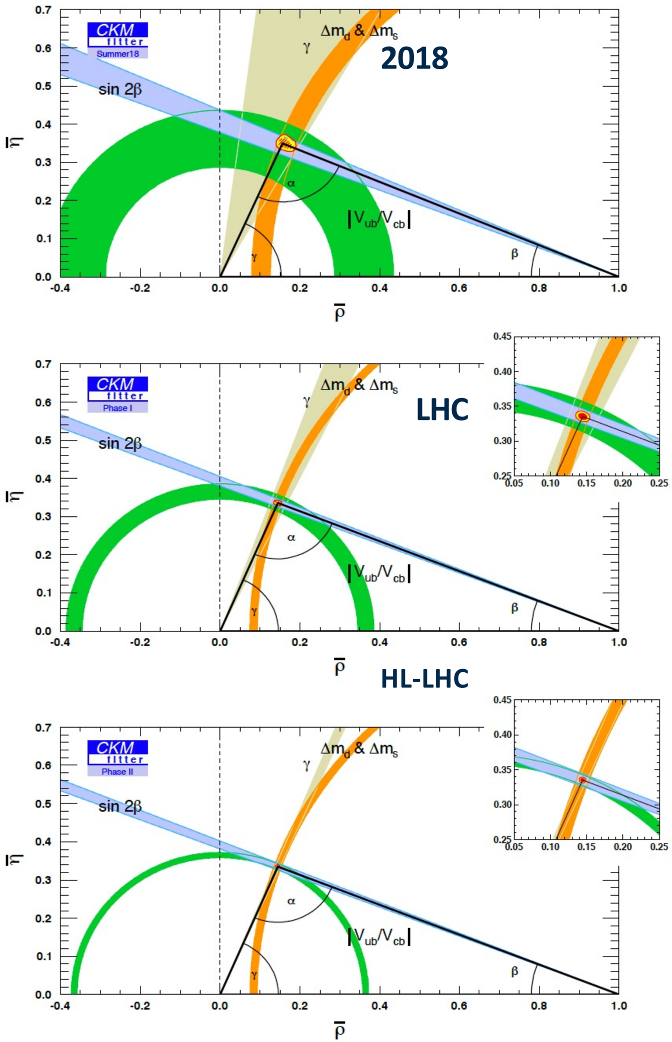
"Fireball" final states: around twelve 0.8 TeV particles

→ **High energy hadron collider ideal for searches**





CP-violation: Anti-matter in the mirror



3) CP violation:

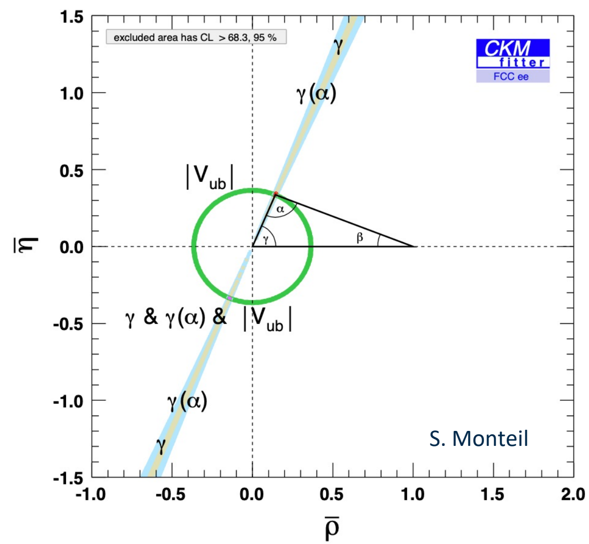
Charge-Parity symmetry is not conserved : matter and anti-matter behaves differently

Baryogenesis: CP violation from weak interactions in the quark sector too small x 10^9

→ Precision increase in the determination of the CKM parameters with HL-LHC statistics and upgraded detectors

→ Complementary measurements from Belle-2 in ee collisions

→ Coherence tests of SM



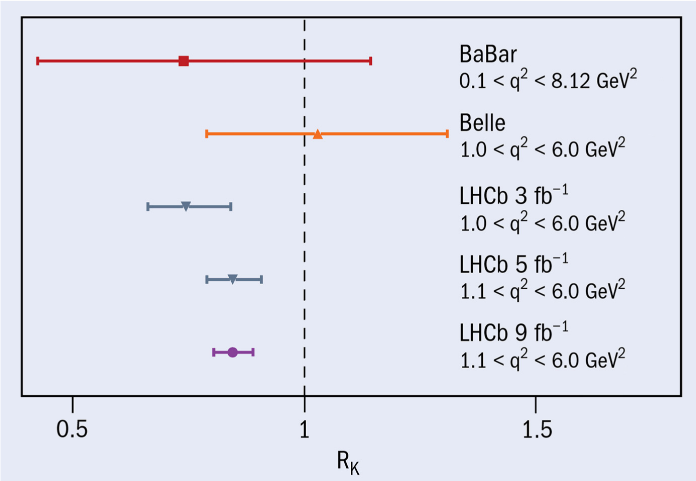
FCC-ee: boosted b-production at the Z-peak

→ at least 5 10^{12} Z decays needed ~15 times Belle II anticipated statistics

• All species of *b*-hadrons are produced

➔ **Constraints on limits on new Physics up to 20 TeV**

Lepton-Flavour Universality



- In the Standard Model all three lepton families should behave the same in electroweak decays, but…
Measurements from LHCb confirms deviations observed!

Lepton-flavour universality measurement through the ratio

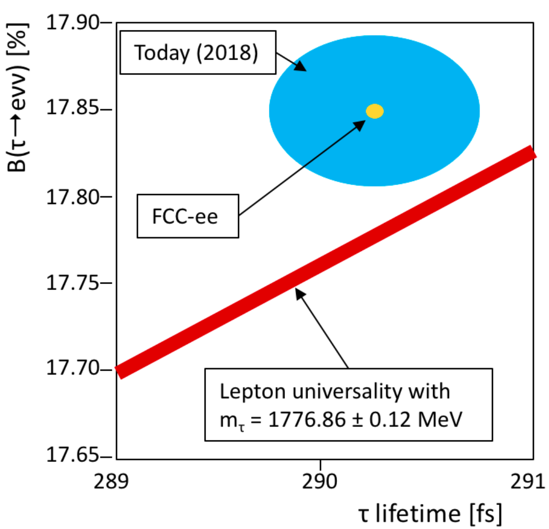
R_K = BR(B(ub)$^+ \rightarrow$K(us)$^+\mu^+\mu^-$)/BR($B^+ \rightarrow K^+e^+e^-$)

= $0.846^{+0.042}_{-0.039}$ (stat.) $^{+0.013}_{-0.012}$ (syst.)

SM prediction: R_K=1± O(10^{-4})[QCD] ± O(10^{-2})[QED]

➔ 3.1 σ evidence for LFV

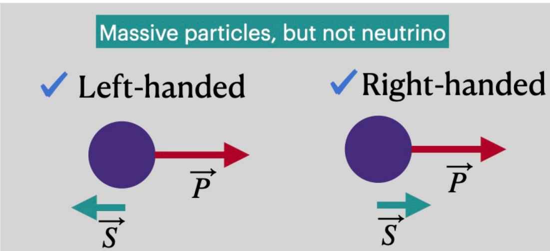
➔ Measurement with upgraded detector and higher statistics to come in new LHC Run and Belle-II

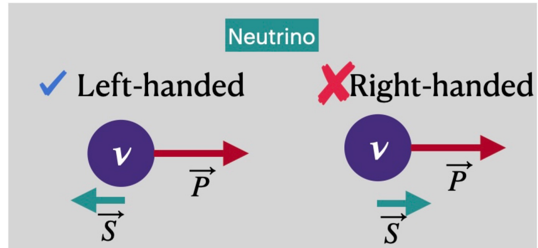


Lepton flavour Universality from τ decays:
Branching-faction into electrons depend on the τ-mass

Current measurement show tensions
→ FCC-ee increases precision by a factor 10

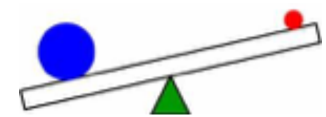
Lepton flavour violation in Z-decays typically < 10^{-50} in the Standard Model
→ Z-statistics at FCCee pushes sensitivity by 3 orders of magnitude

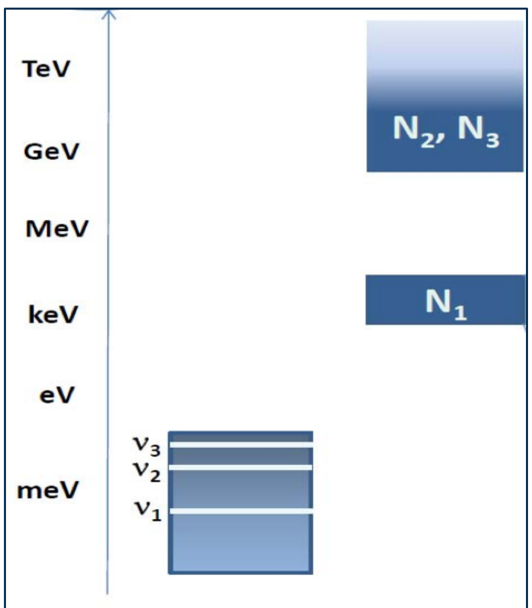




Standard Model:
no right handed neutrinos !
1998 discovery of Neutrino oscillations → neutrinos have a mass

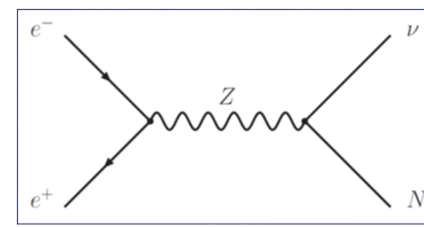
→ if neutrinos acquire mass through the Higgs mechanism, right handed neutrinos should exist
→ "See-saw'" mechanism: right-handed neutrinos could be very heavy
→ Could explain Matter-Antimatter Asymmetry through "leptogenesis"





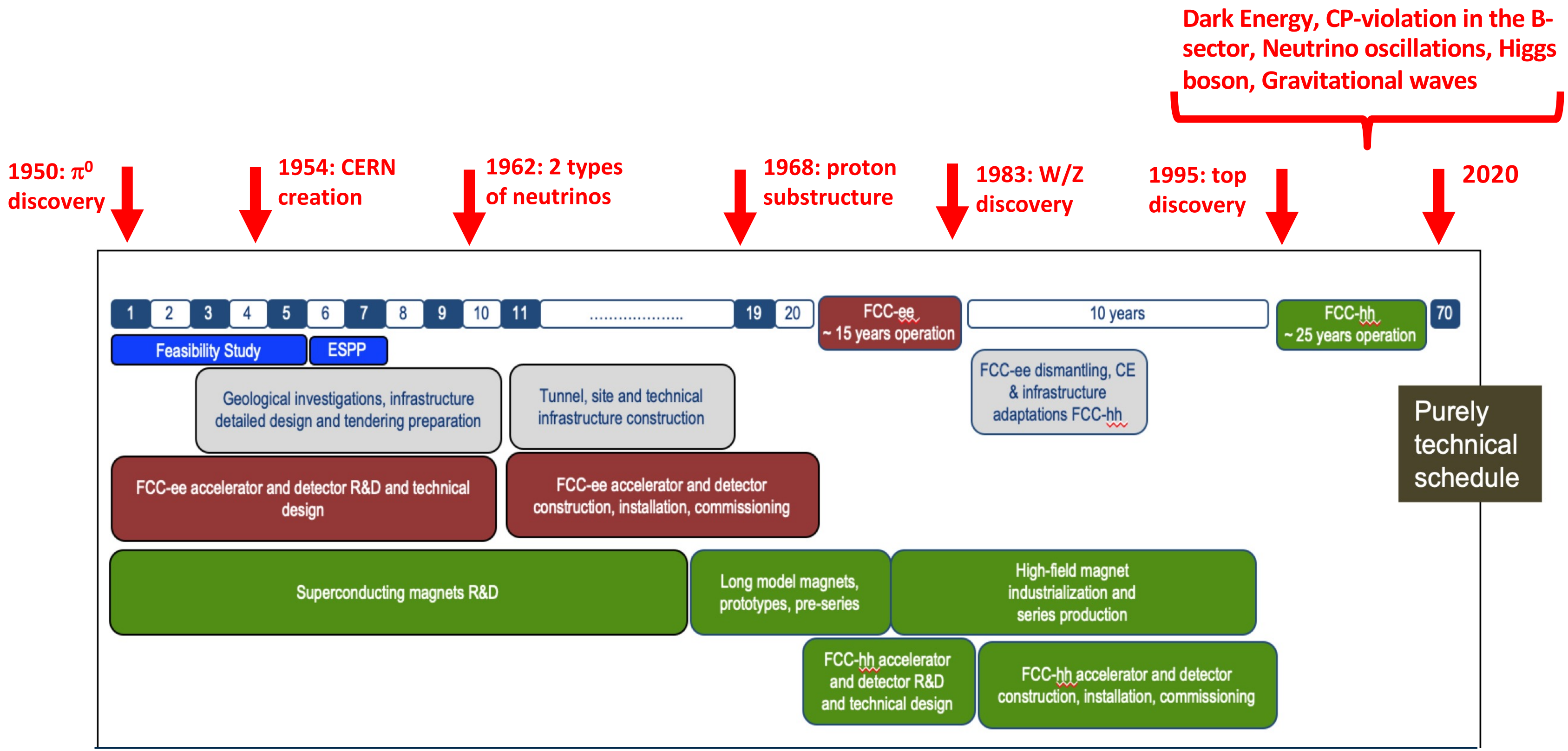
If mass > 140 MeV:
for matter anti-matter asymmetry

Constraint:
mass = 1-50 keV
Search through:
N → $\nu\gamma$ ongoing

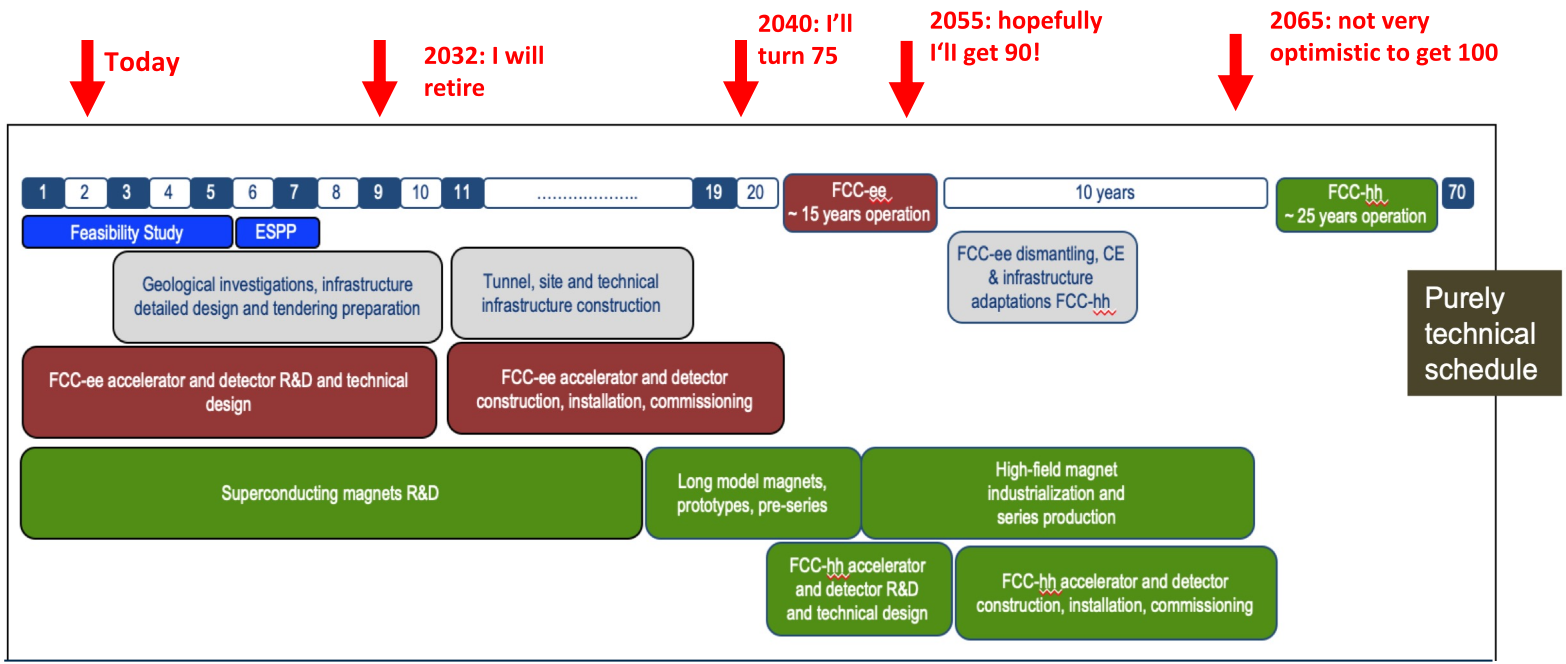


→Pairs of left- and right-handed neutrinos can be produced at FCC-ee!
Sensitivity FCC-ee :
8 orders of magnitude higher than LEP!

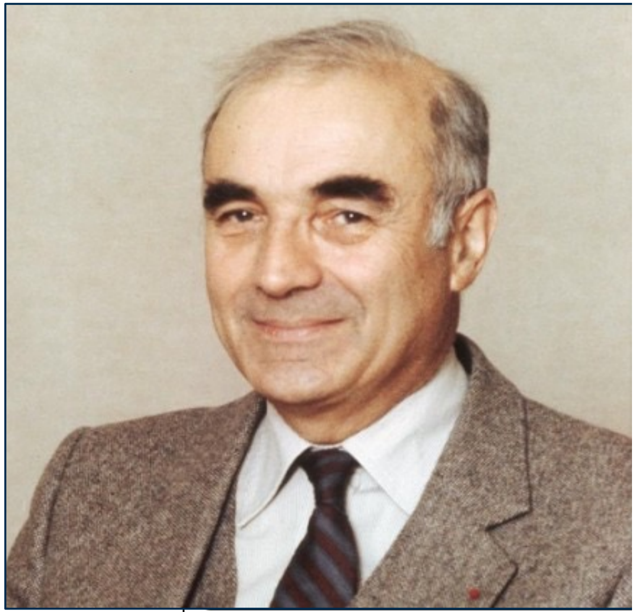
FCC : looking backwards



FCC : looking forwards



FCC : looking forwards



« Je voudrais revenir sur terre, un instant, dans mille ans, juste le temps de voir ce que trente générations de savants auront su découvrir, et entendre ce que les hommes (et femmes) de science seront alors en humeur de dire. »

Hubert Curien

Ministre délégué à la Recherche
DG CNRS
Président du CNES
Président de l'ESA
Président du conseil du CERN
…