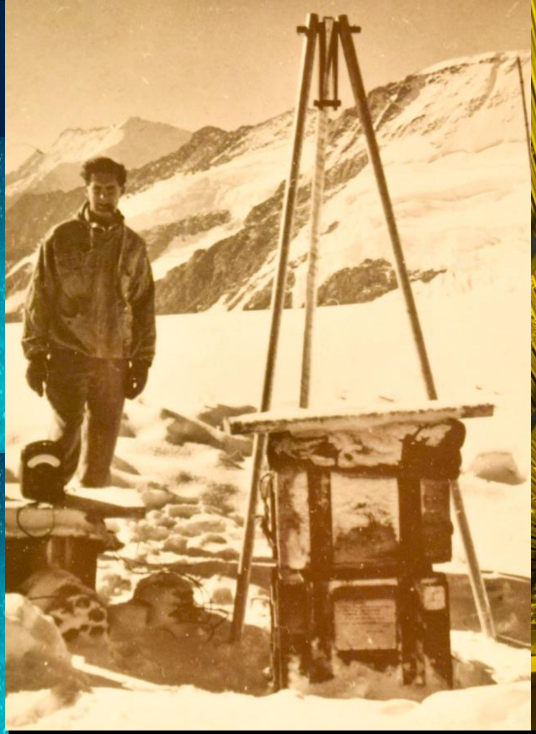

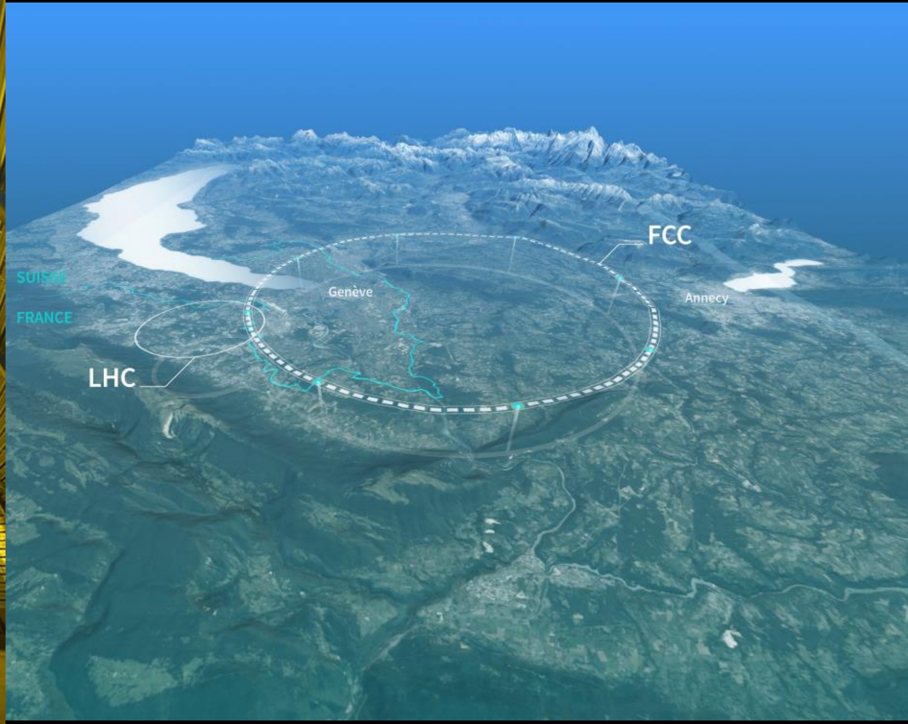

The Future of particle physics

The future


t
d
c
s
u
γ
g
b
H
τ
W
Z
ν_e
μ
ν_μ
e
ν_τ

Checking the progress

- Celebrating CERN's discoveries and looking into the future on 16 Sept 2003
- About 7 years before the start-up of LHC
- Now about 7 years before HL-LHC
- Common speakers and attendees with today's event
- Panel with Don

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THE EUROPEAN PHYSICAL JOURNAL C

Panel discussion on the future of particle physics chaired by Carlo Rubbia – (ENEA and formerly CERN)

Participants: R. Aymar, G. Charpak, P. Darriulat, L. Maiani, S. van der Meer, L. Okun, D. Perkins, C. Rubbia, M. Veltman, S. Weinberg

Statements from the floor: F. Gianotti, I. Antoniadis, S. Glashow, H. Schopper, C. Llewellyn Smith, V. Telegdi, G. Belletini, V. Soergel

C. Rubbia
Commissario Straordinario
Ente per le Nuove technologie, l'Energia e l'Ambiente (E.N.E.A.), Lungotevere Grande Ammiraglio Thaon di Revel, 76, 00196 Roma, Italy

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Introduction by Carlo Rubbia

I would like to open this panel discussion, which is almost a "Mission Impossible". Not only do we have something

Carlo Rubbia

like ten very distinguished people here around this table plus two young people who will speak from the floor, but we also have a subject which is not that simple. It is "The Future of Particle Physics", which is crystal ball reading as far as I am concerned. Maybe, I could suggest that we ask around this table who wants to speak first. We have been assigned 45 minutes, so I think that a time of 5 minutes per speaker should be enforced, and I suppose that's the only reason why I am here! The first statement is by Donald Perkins.

Donald Perkins

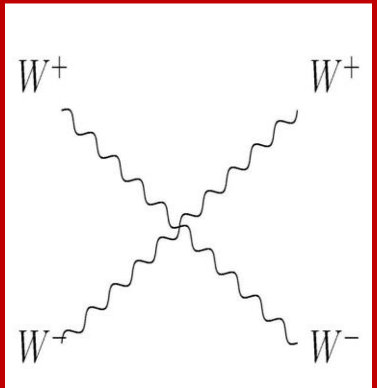
Statement

This meeting has recalled the discovery of neutral currents and the W and Z bosons, 20 or 30 years ago. My question is: what will be the programme of research at CERN in 20 or 30 years from now? Obviously it will depend on the results from experiments at LHC and possibly CLIC, and with luck these may spring some surprises, but perhaps we should think more widely.

I want to echo the words of Professor Maiani today, about the importance of astrophysics on the particle physics scene. During the last years, a trickle of experimental particle physicists has been moving over to research in astrophysics, for example in the study of atmospheric neutrinos and the search for very high-energy neutrino point sources; gravitational wave detection; very high-energy cosmic rays; gamma ray bursts, possibly the most violent events in the universe; high redshift supernovae, and

In 2003 the Higgs was missing

Either m_H < 800 GeV or perturbative unitarity violated around 3 TeV

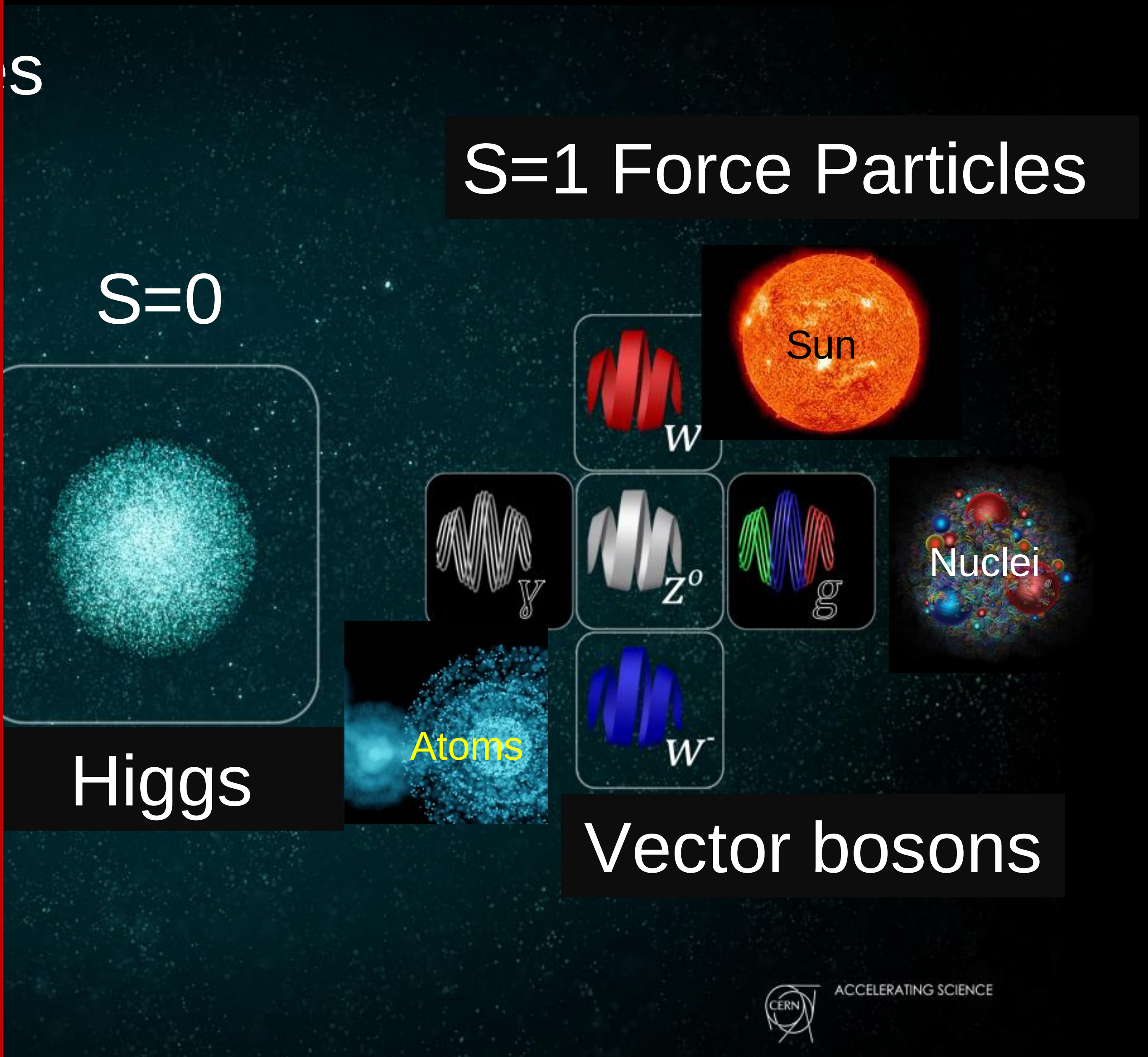


Cross sections grows with energy without Higgs

“NO-LOSE” theorem

The LHC had to find a Higgs or something else at an accessible scale

The standard model



The Large Hadron Collider @ CERN

- 1984: First studies
- 1994: LHC approved
- 1996: Construction starts
- 2003: Start Installation
- 2008: First Collisions

A discovery machine

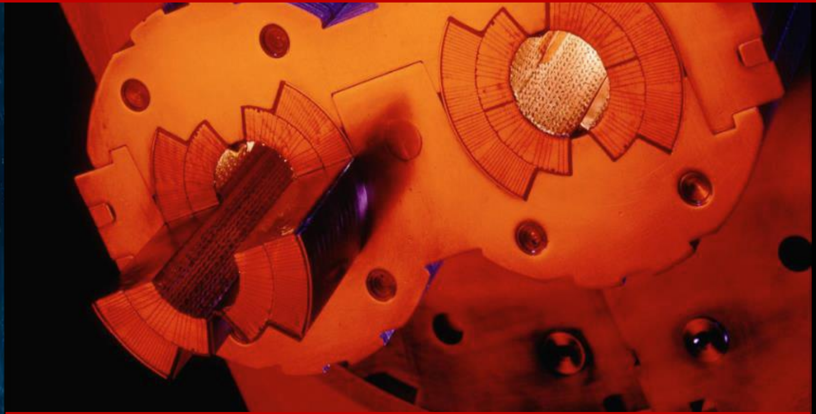
Covering all possible Higgs masses from 100 GeV to 1 TeV (100 – 1000 times the proton mass)

LHC is a machine of “extremes”

The largest and most sophisticated detectors ever built

Powerful magnets: 8.3 T

The fastest race track: protons travel at 0.999999990 c

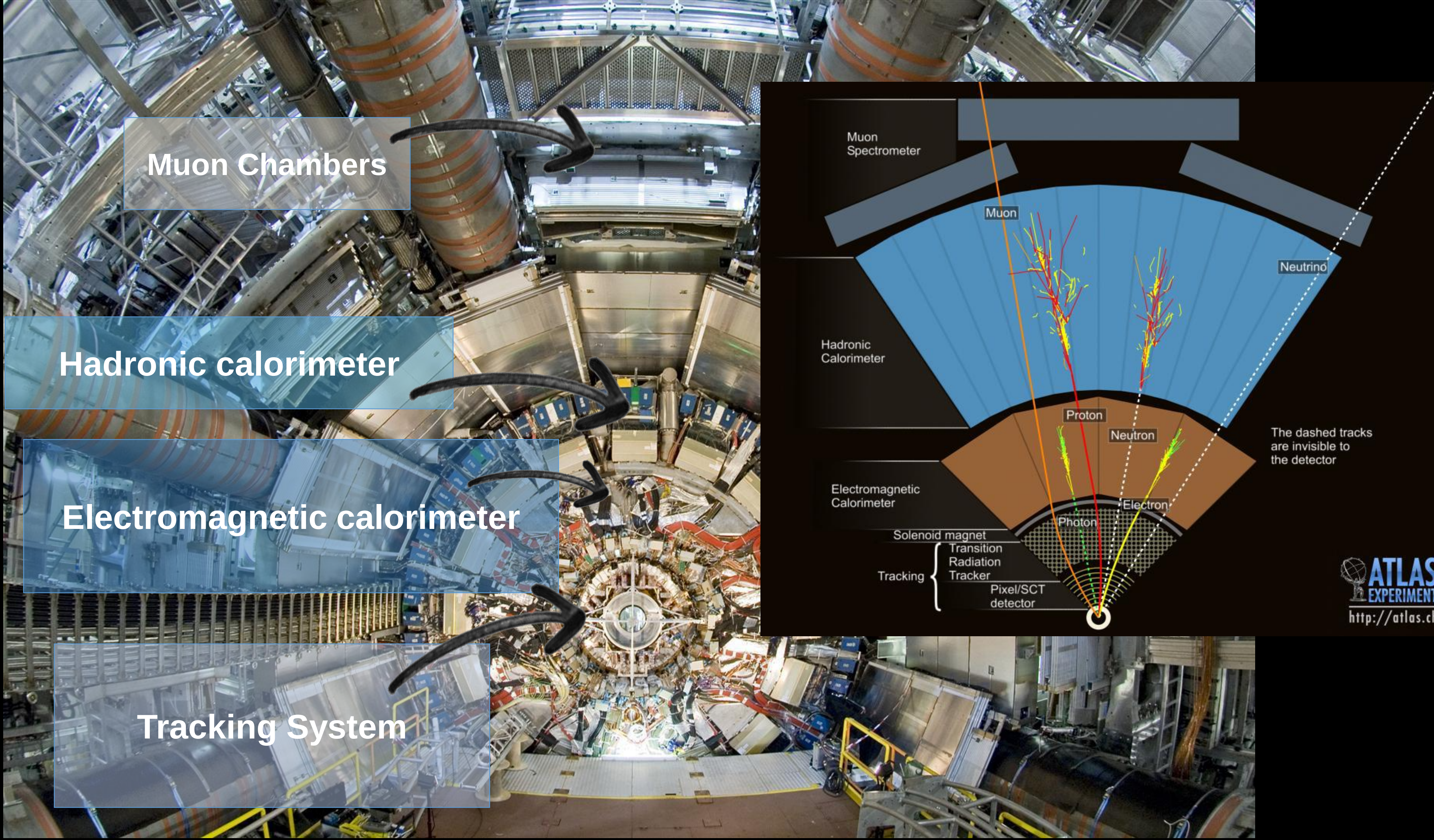


Highest vacuum: 10^{-13} bar comparable to the density of matter in outer space

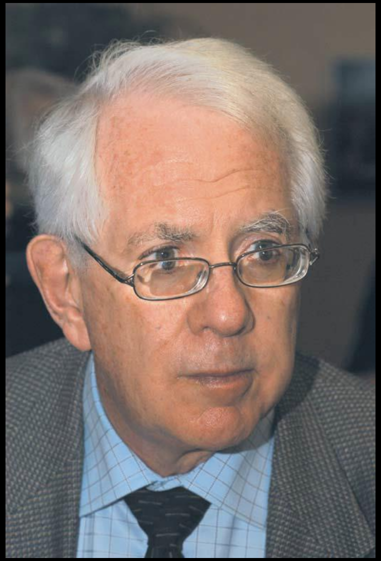
Highest energy 13.6 TeV ➠ T=1.15 x 10^{17} K Sun's surface is 5800 degrees Kelvin

Colder than outer space. Superconducting magnets operating a 1.9 K=-271.3 **°C**

particle Physics


Muon Chambers
Hadronic calorimeter
Electromagnetic calorimeter
Tracking System
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT

What was said in 2003 ?



Sheldon Glashow, Nobel 1979

I would like to make my own prediction and I would predict that the LHC will make astonishing discoveries which do not confirm the theories of anybody in this room.

Pierre Dariulat

Today's future is LHC where we all hope that Higgses and supersymmetric particles will soon be discovered, not to mention the unexpected.

Carlo Rubbia Nobel 1984

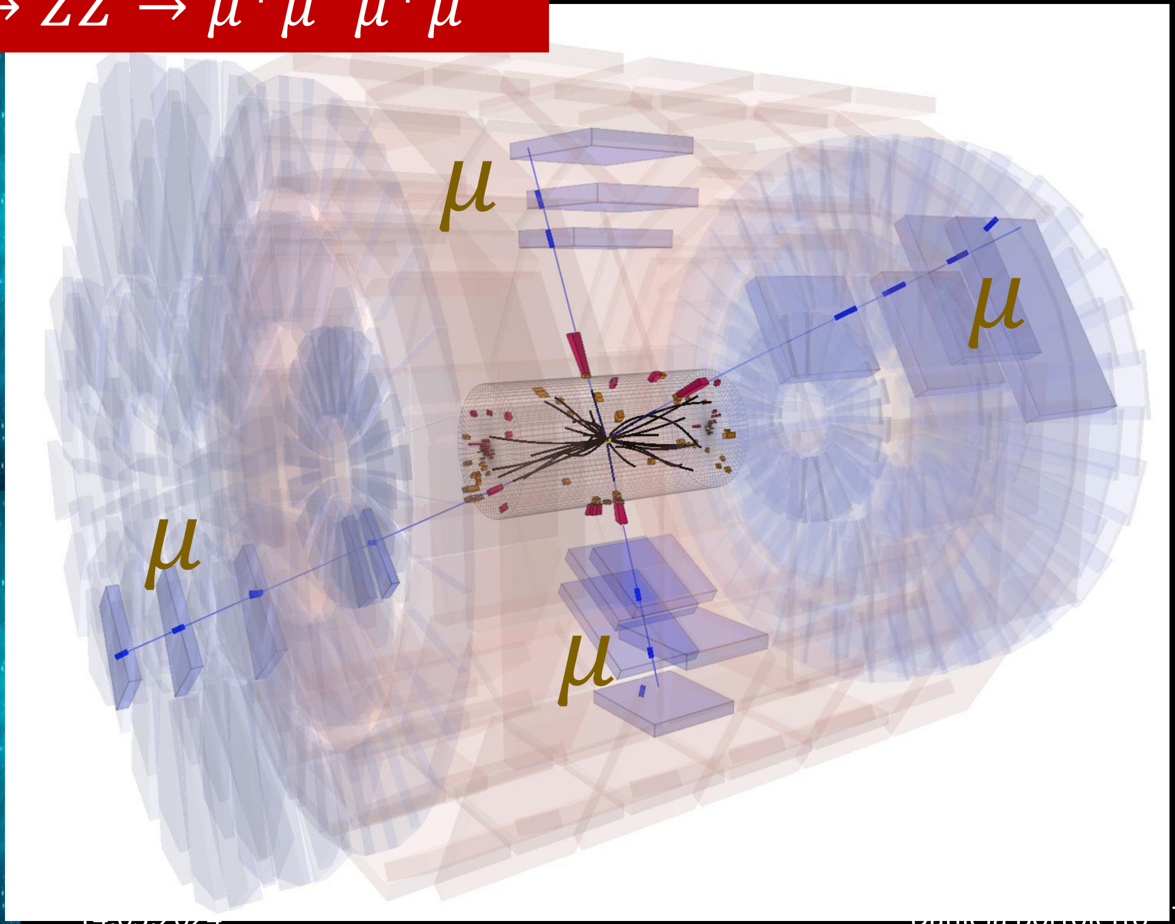
I think that what we should say is that we do need surprises in this particular field and I expect that the LHC will be capable of very substantial surprises. For instance, suppose we *don't find the Higgs, then* what*? It's not excluded that it wouldn't* come out. It has to be very low mass, it has to have well-known cross-sections; suppose you run and you *don't find it.* Then what do you do? What is next?

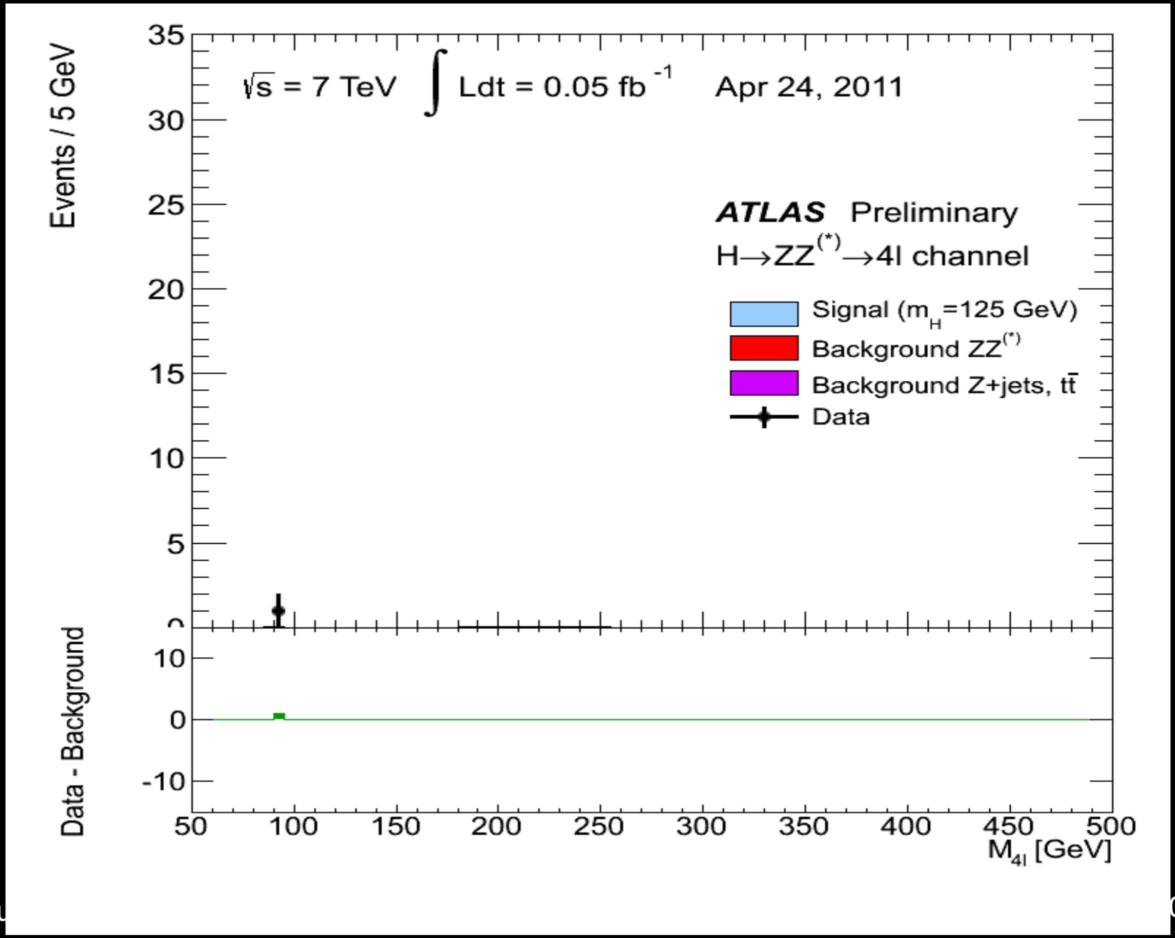
The ephemeral Higgs boson

- Once created the Higgs boson it **decays very rapidly (**1.6 x 10^{-22} s)
- Discovered by looking for very distinctive decays

Englert & Higgs

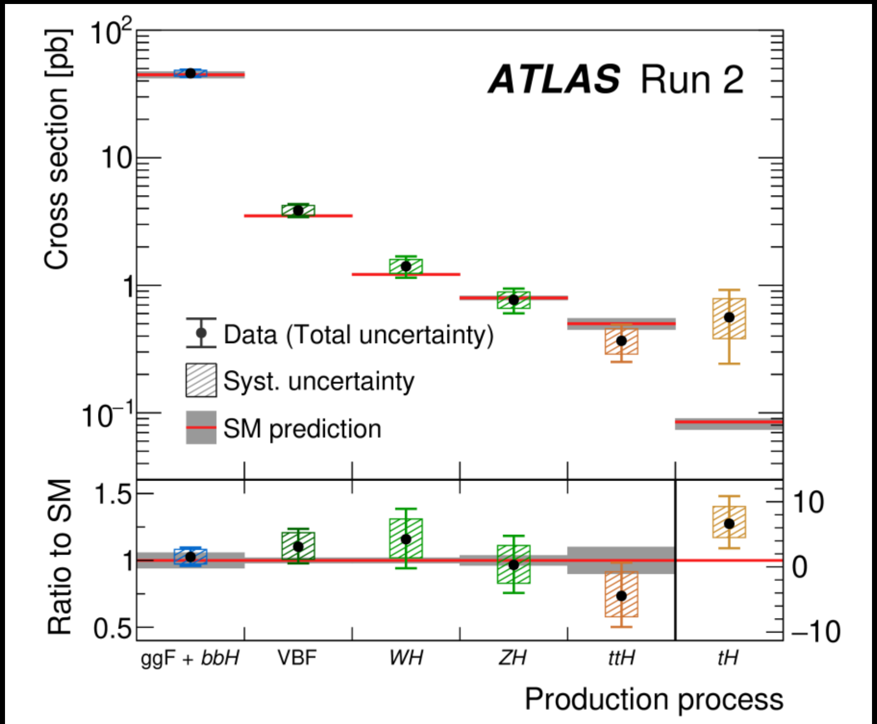
H→ $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$



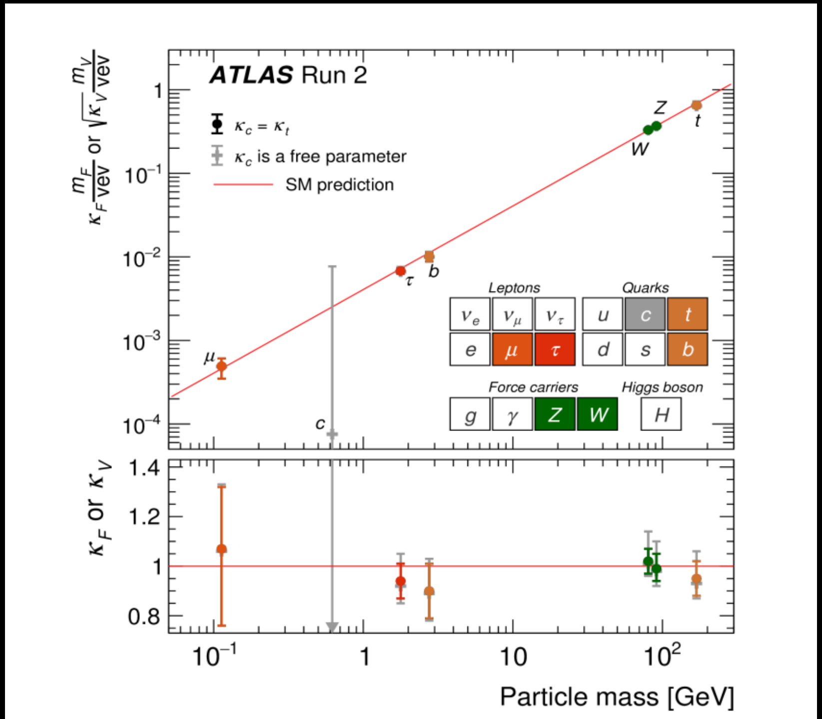


It is very Standard Model like !

Production



Decay

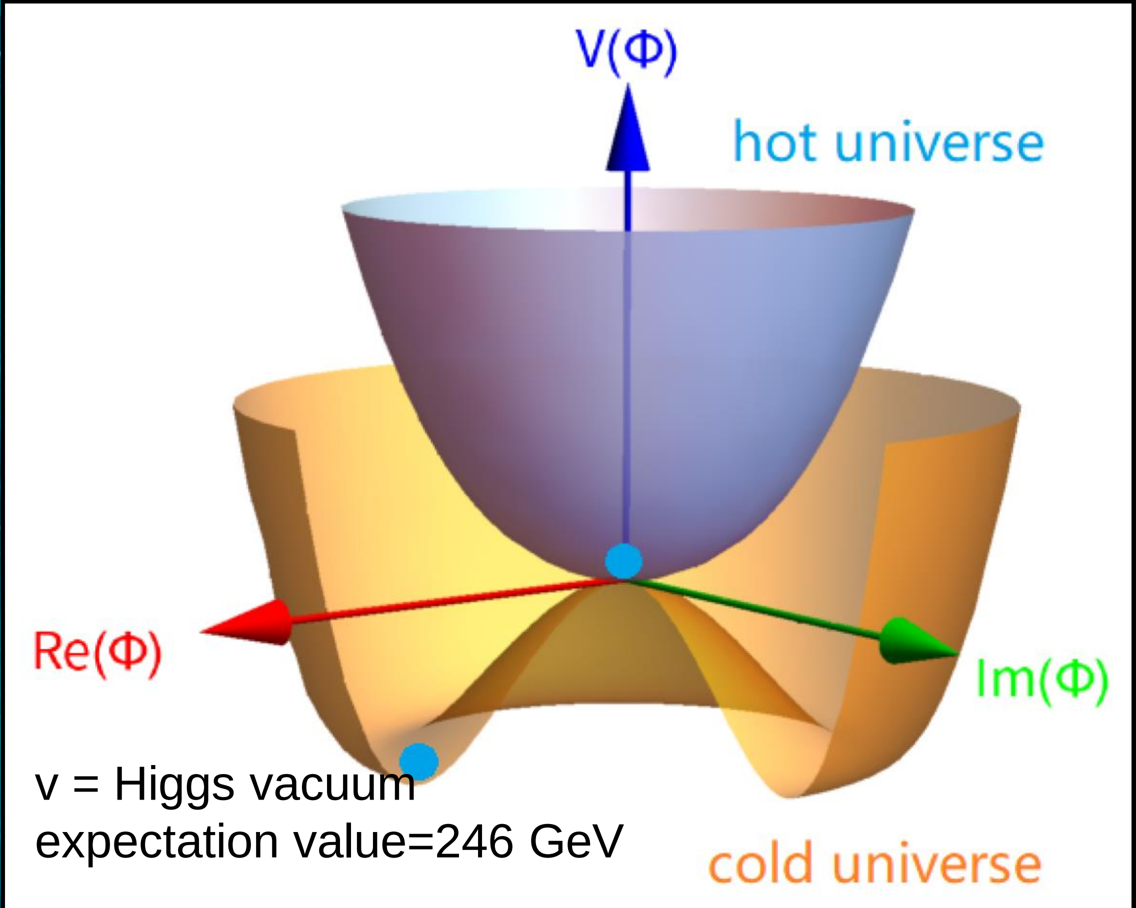


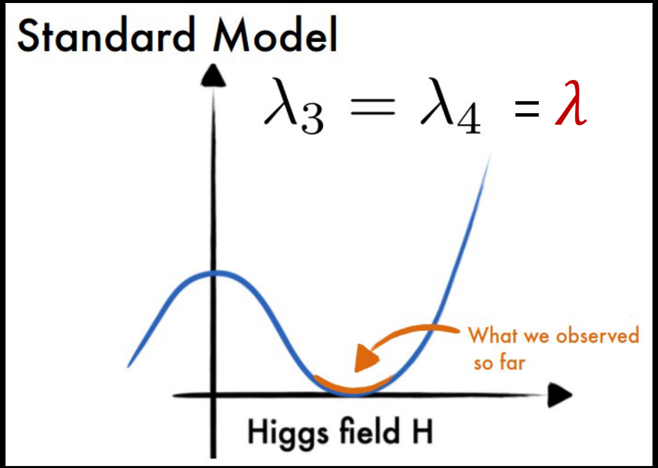
- We have only measured the couplings to the third-generation of quarks and leptons and to the W and Z bosons
- Immense theoretical progress but more work needed

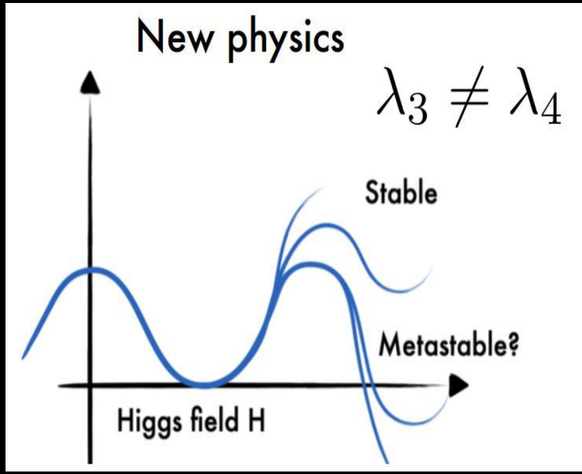
The Higgs potential

$$V_{SM}(H) = -m^2|H|^2 + \lambda|H|^4$$

- Our understanding of the SM rests on the assumption that electroweak symmetry breaking occurs through a scalar potential
- NO experimental evidence that this is the case!

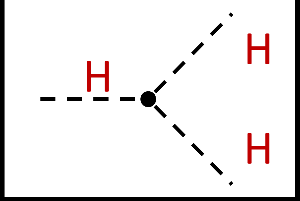




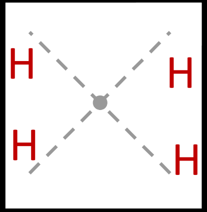


$$V(H) = \frac{1}{2} m_H^2 H^2 + \frac{1}{2}\lambda_3 H^3 + \frac{1}{4}\lambda_4 H^4$$

Trilinear coupling

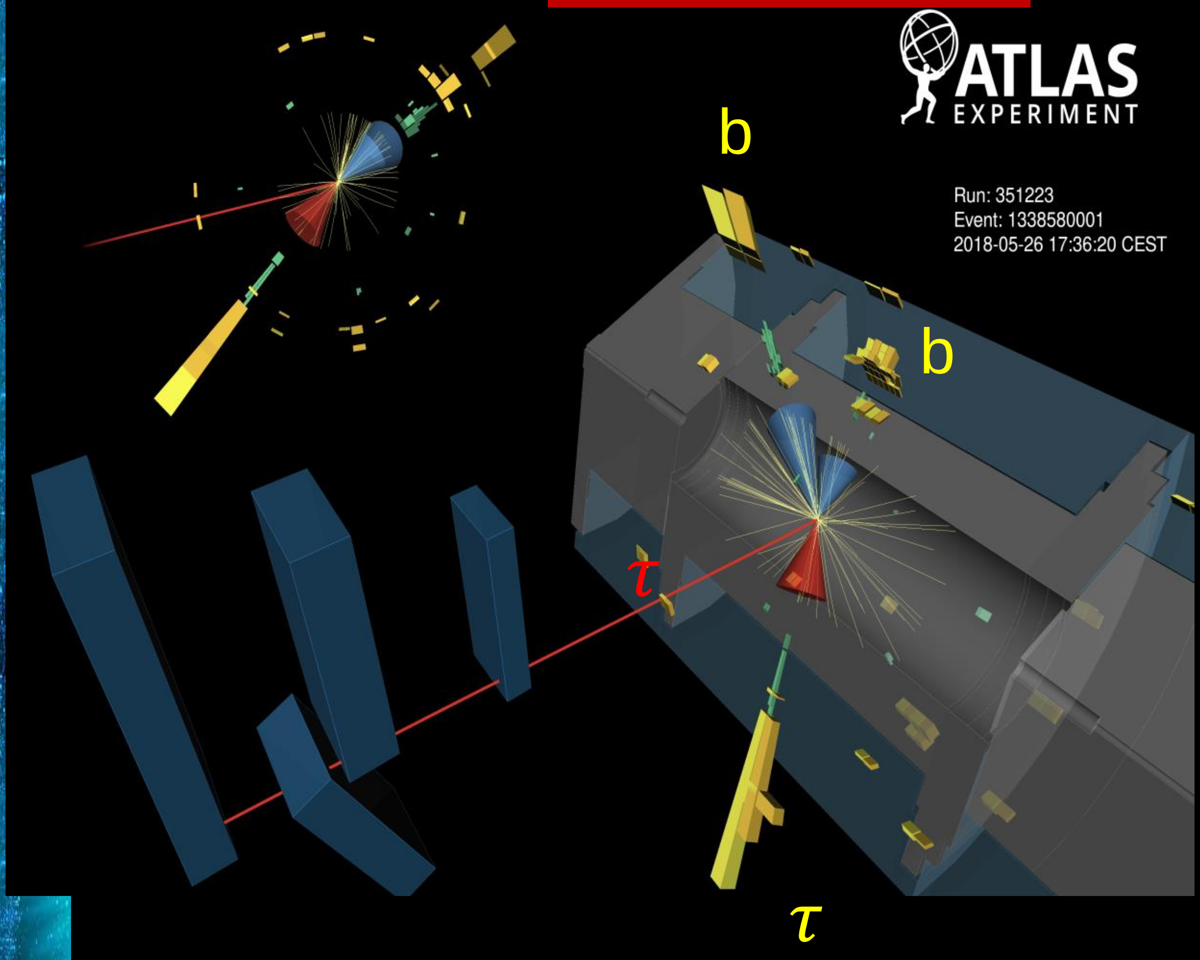


Quartic coupling

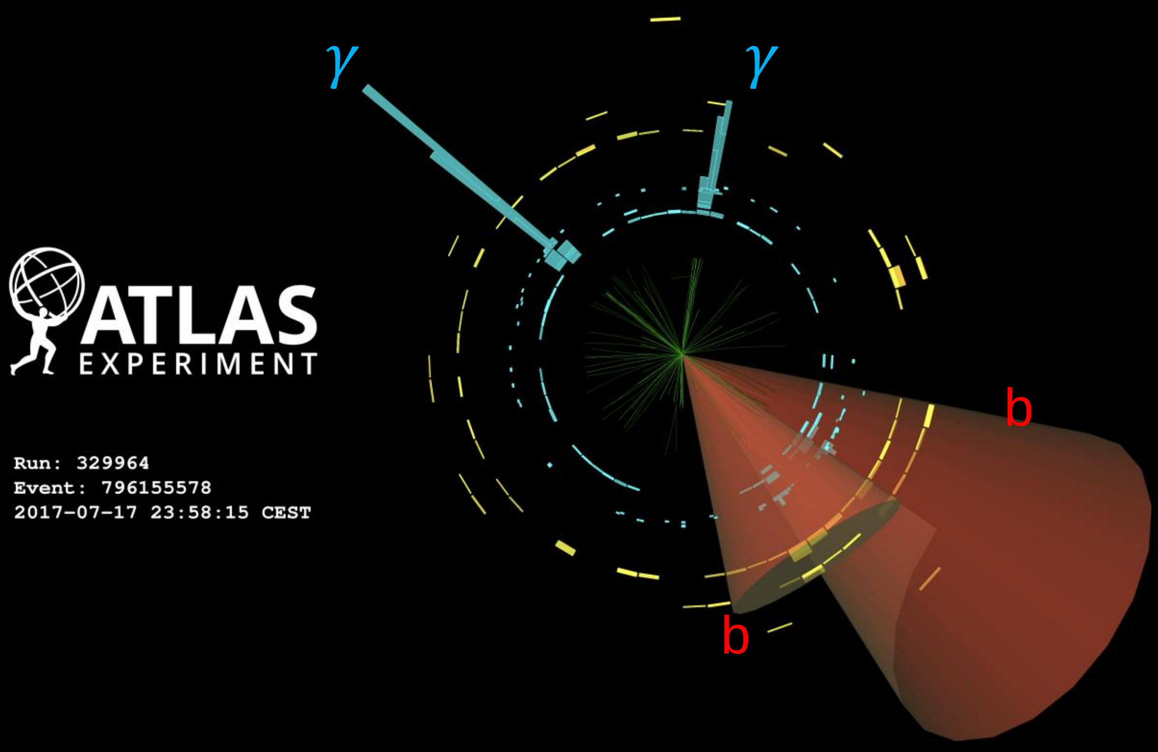


HH at the LHC

HH→ $bb\tau\tau$

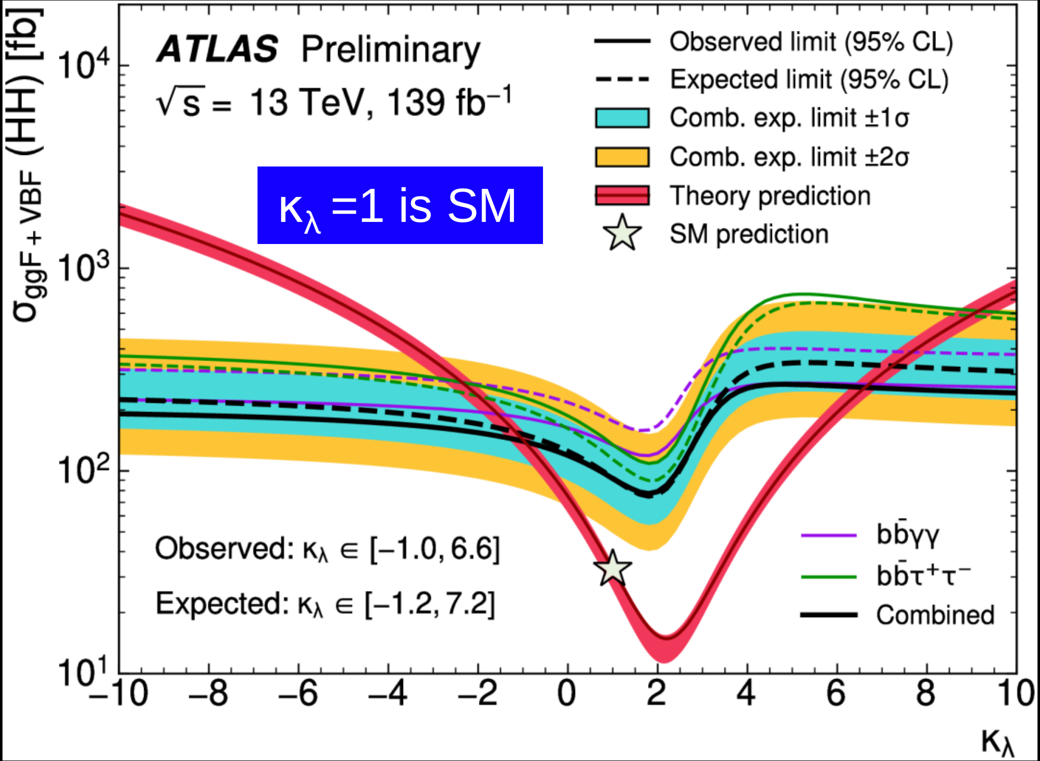


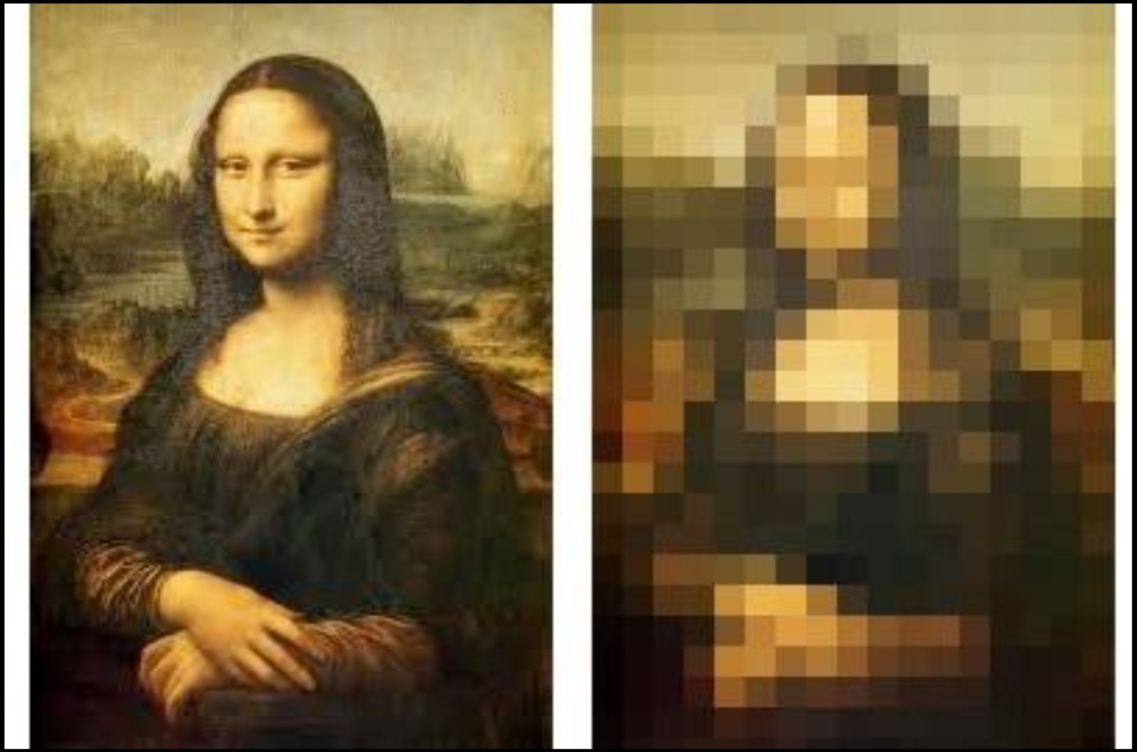
HH→ $bb\gamma\gamma$



HH in Run 2

- Maximal sensitivity obtained through statistical combinations

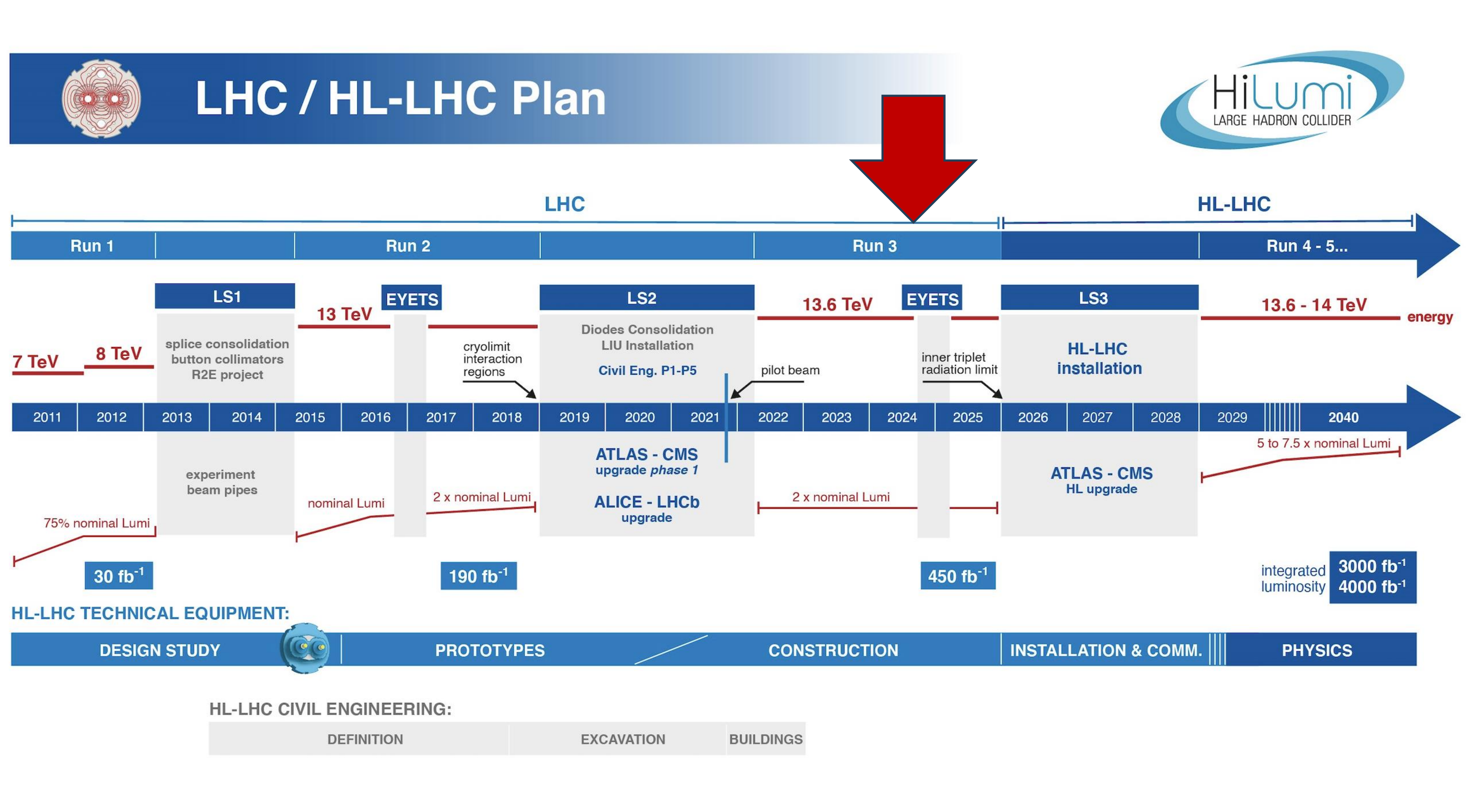




Observed (expected) allowed values of κ_λ
$-1.0 \leq \kappa_\lambda \leq 6.6$ ($-1.2 \leq \kappa_\lambda \leq 7.2$) at 95 % confidence level

- More improvements to be implemented
- Collecting data until the end of 2025 and then HL-LHC

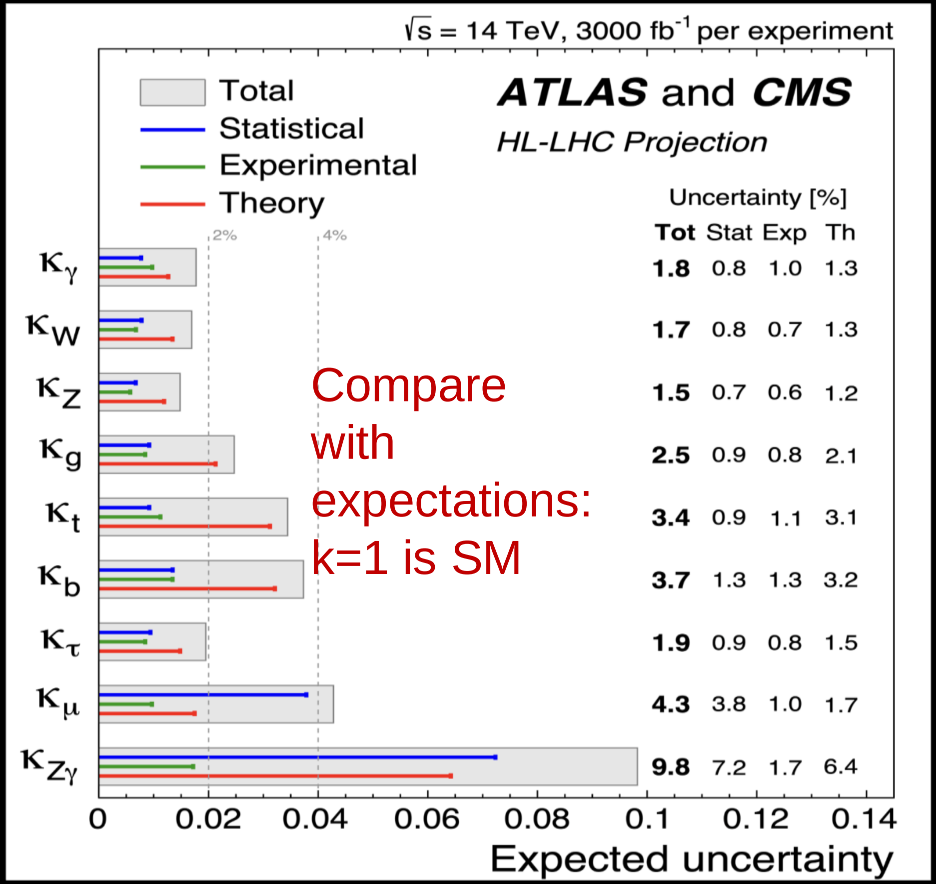
The near future



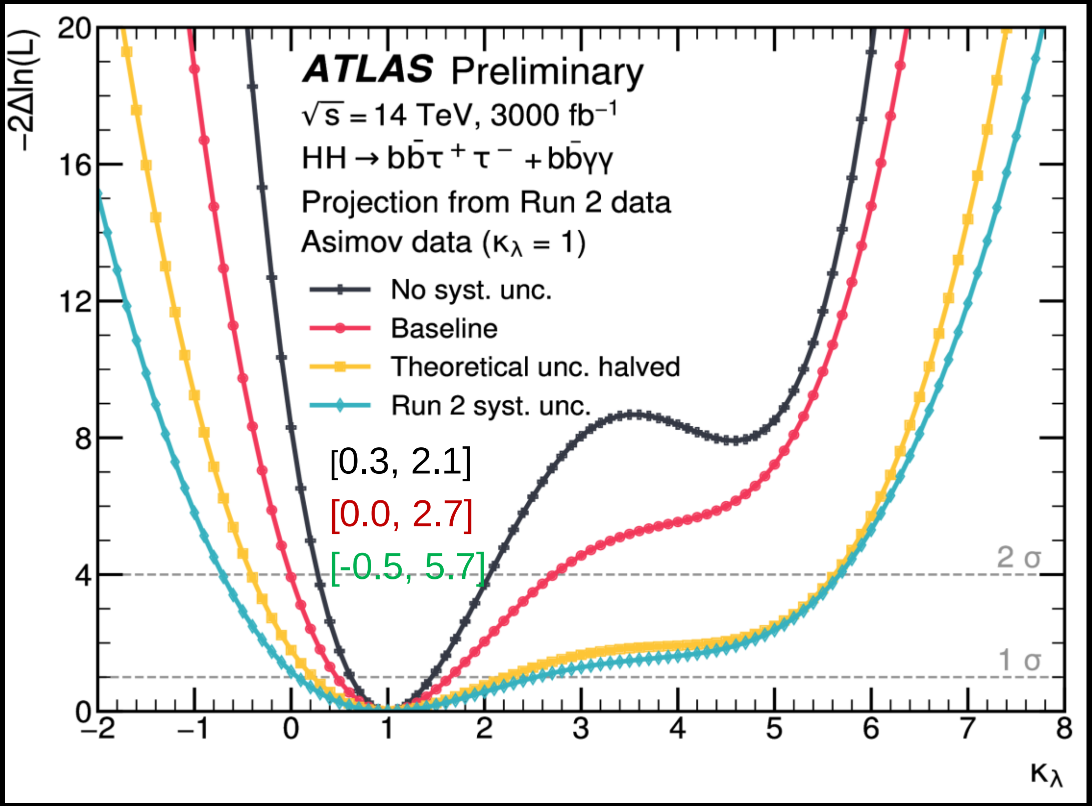
- 2-fold increase in statistics by the end of Run 3
- 20-fold increase in statistics by the end of HL-LHC!

UNIVERSITY OF OXFORD

The physics case of the HL-LHC



Compare with expectations: k=1 is SM

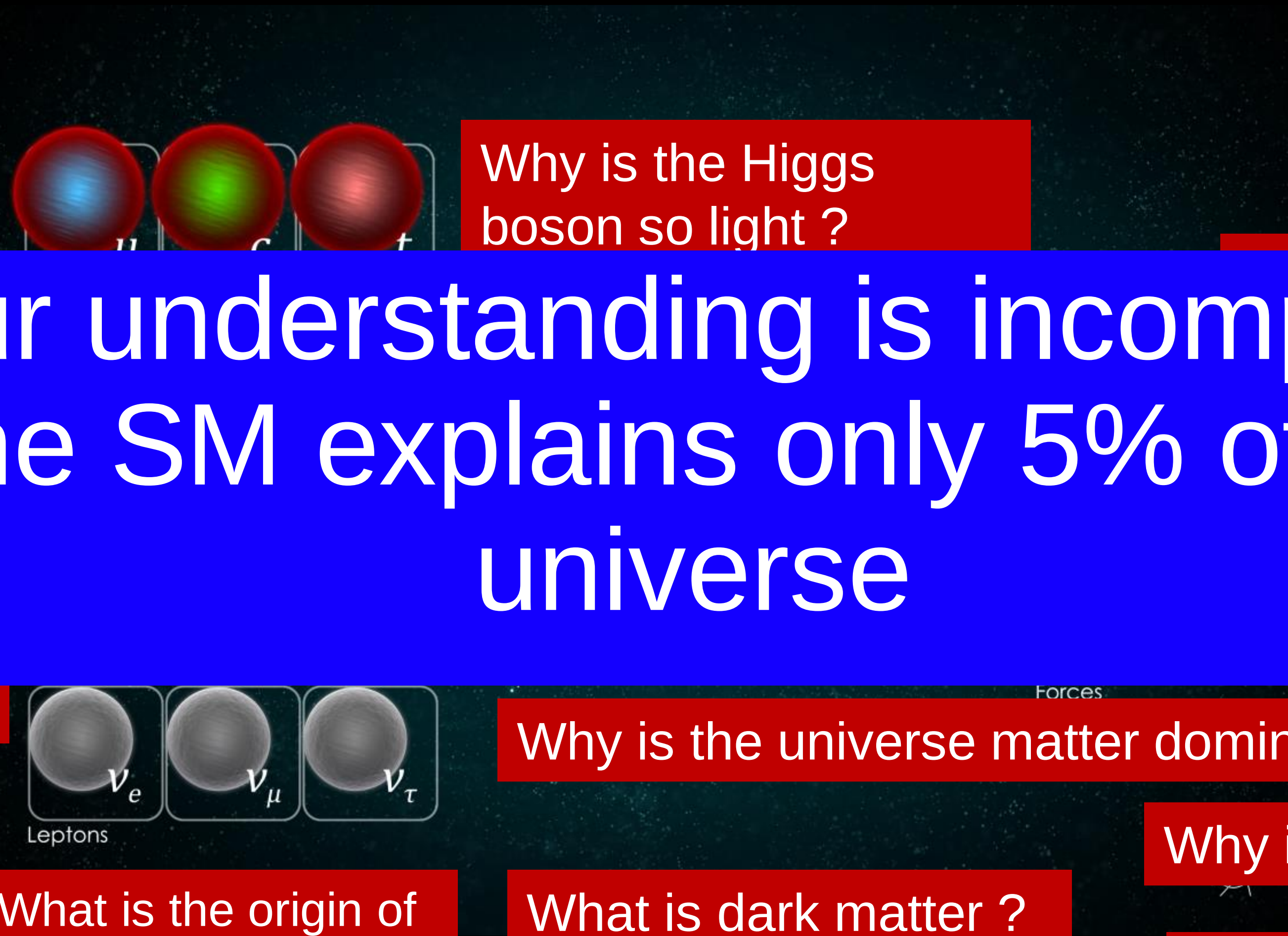


2-5 % on most couplings
More work is needed for theory uncertainties not to limit Higgs measurements.

Combination with other modes and CMS should yield a 50% measurement of λ

Very conservative expectations!

Many open questions remain



Why 3 fermion families ?

Why is the Higgs boson so light ?

...nism behind ...etry breaking?

Our understanding is incomplete
The SM explains only 5% of the universe

Why do... charge... and neu... leptons... differently ?

Why is the universe matter dominated?

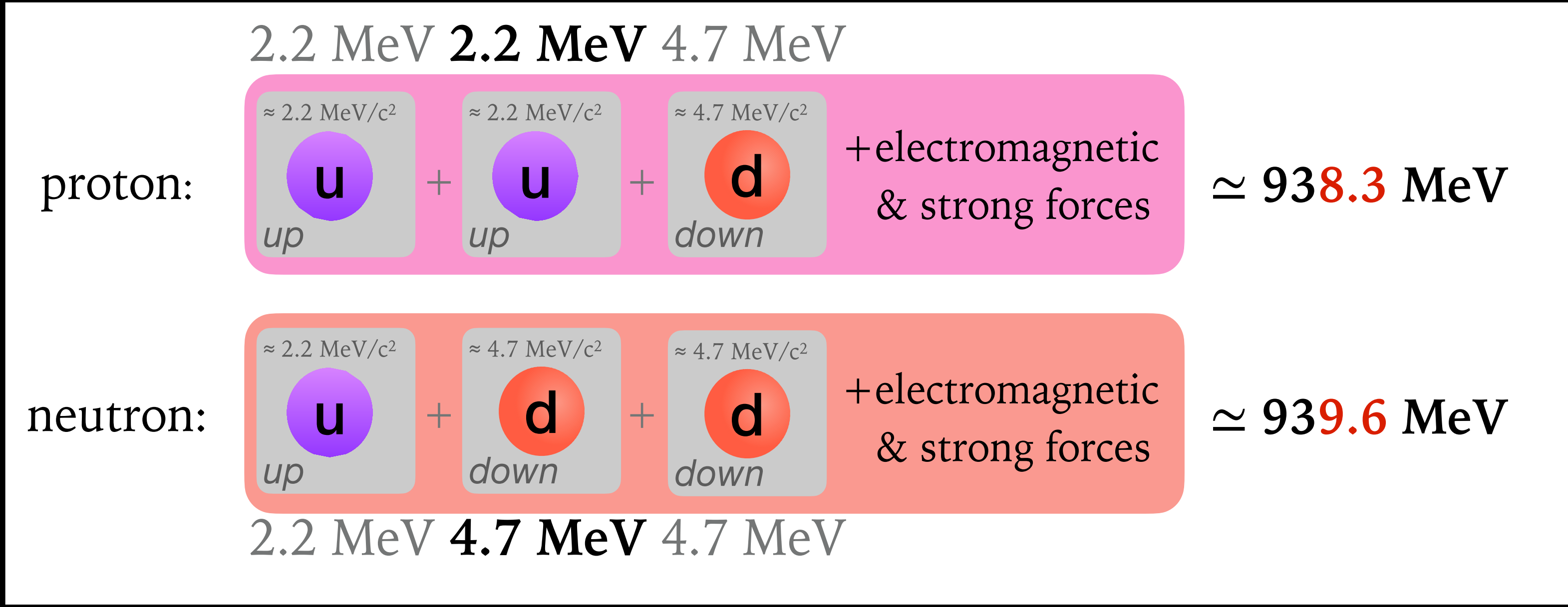
Why is gravity so weak ?

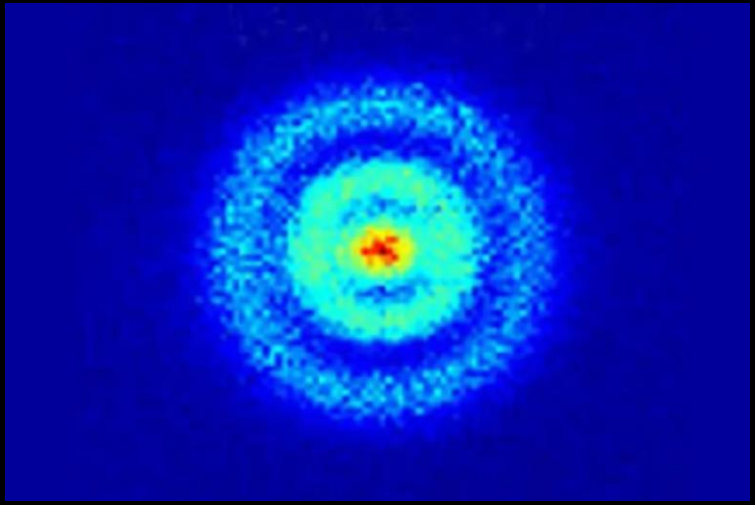
What is the origin of neutrino masses ?

What is dark matter ?

What is the dark energy causing the Universe's accelerated expansion ?

The importance of the Higgs





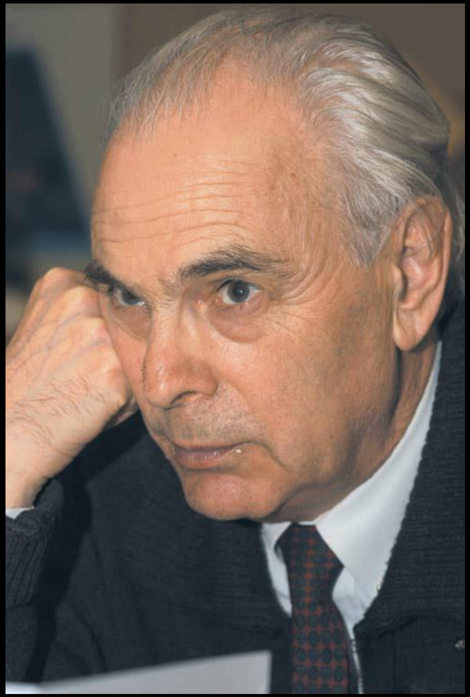
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

- Protons are **lighter** than neutrons protons are stable.
- **Because up quarks interact more weakly with the Higgs field than down quarks**

- The Bohr radius depends on the mass of the electron

But these couplings are very small and difficult to measure

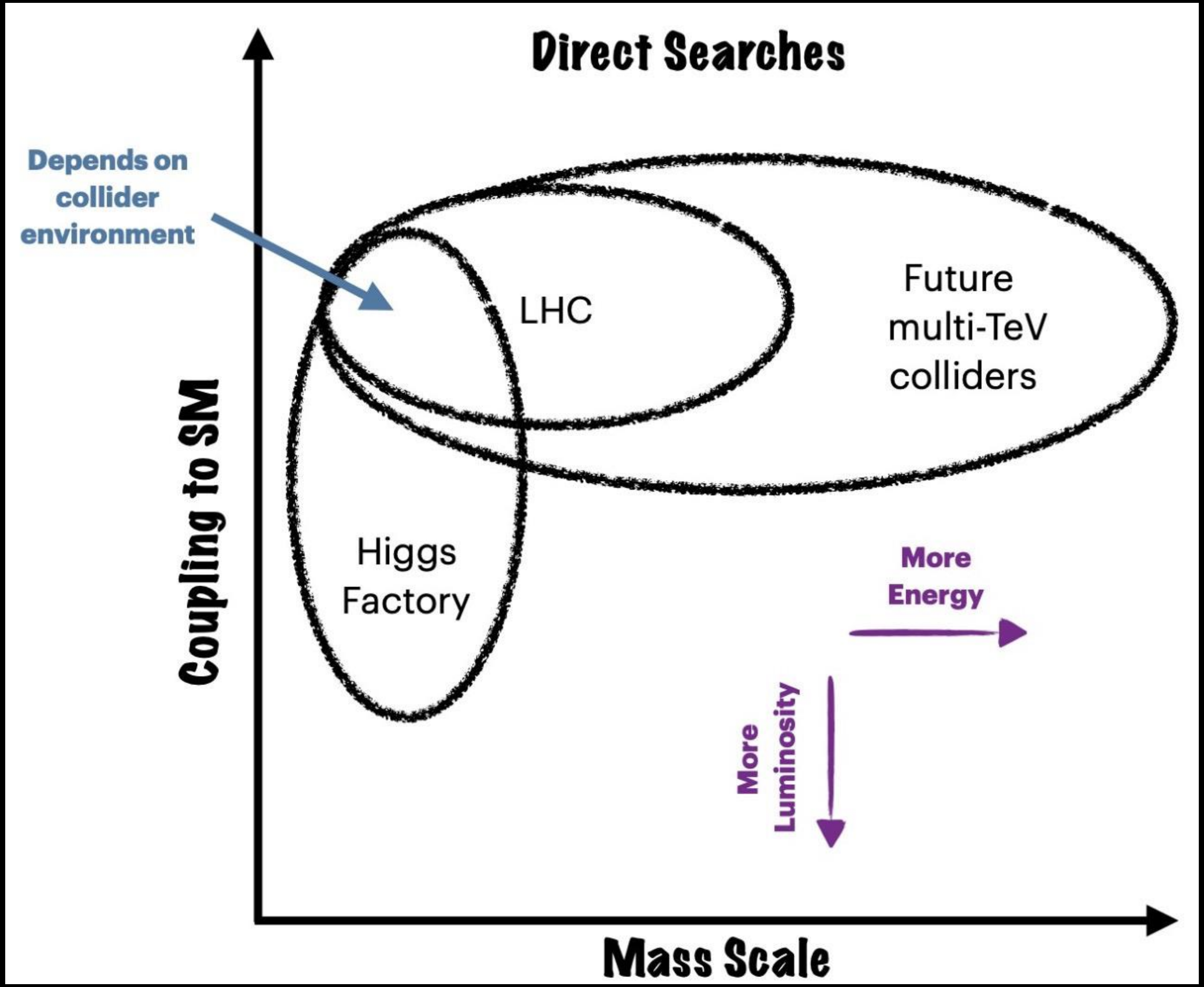
Again the 2003 meeting



Lev Okun

- I will stress only the importance of the discovery of the Higgs at LHC and R&D on CLIC.
- Higgs is a bridge to the vacuum. The breaking of the vacuum symmetry is responsible for the masses of all the elementary particles. This is closely related to the most unusual property of vacuum (“dark energy”) observed by astrophysicists.
- Luciano Maiani yesterday at the Scientific Policy Committee said that it would be impossible for CERN to start building CLIC immediately after getting LHC working. I fully agree with him. To build one collider after another is unreasonable: we need ample time for physics on LHC.
- But there is a difference between construction and R&D. It seems to me that R&D on CLIC should be intensified (and must be additionally funded) to get the decisive Robert Aymar answer on the feasibility of the machine as soon as possible.
- This would drastically change the landscape of the future of particle physics in the world.

Beyond the LHC



- We do not know the energy scale of the new physics
- Study known phenomena at high energies looking for indirect evidence of BSM physics
  - Need factories of Higgs bosons (and other SM particles) to probe the TeV scale via precision measurements
- Search for direct evidence of BSM physics at the energy frontier
  - Need multi-TeV colliders

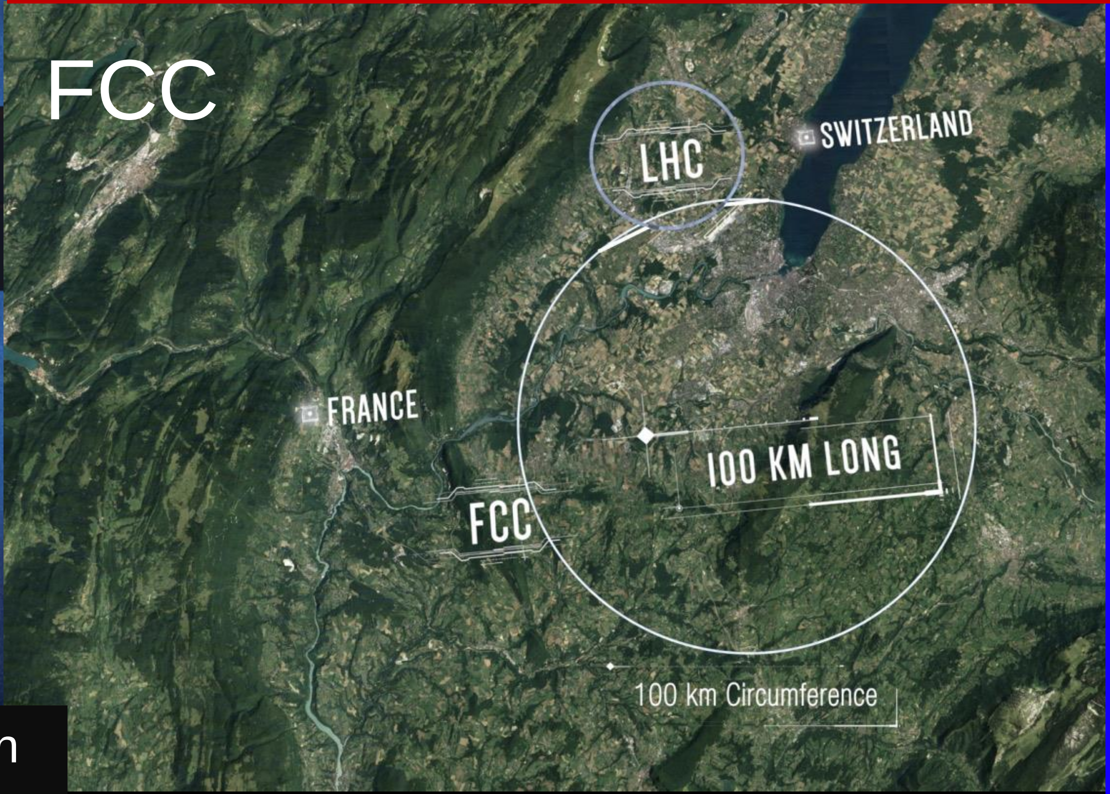
Future high-energy colliders

Every problem in the Standard Model originates from the Higgs interactions – G. Giudice

The Higgs is really New Physics. Put it under the microscope. Study it to death- N. Arkani--Hamed

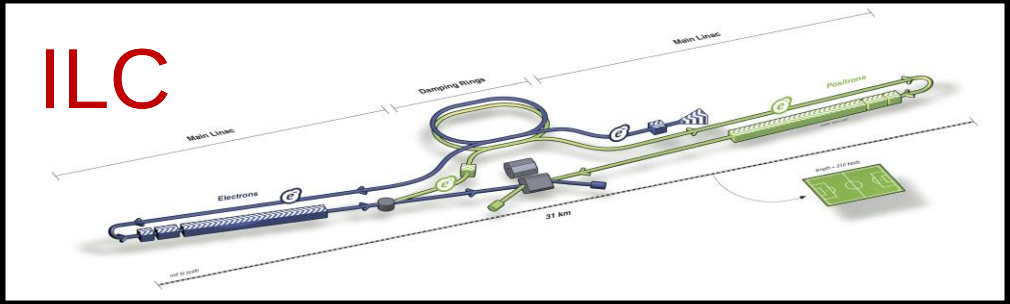
2020 Update of the European Particle Physics Strategy

An electron-positron Higgs factory is the highest-priority next collider.



- FCC-ee (90-350 GeV)
  - Precision Higgs, Z, top measurements
- FCC-hh (100 TeV)
  - Exploration at the energy frontier
- FCC-eh (3.5 TeV)
  - Understand the proton structure to empower FCC-hh

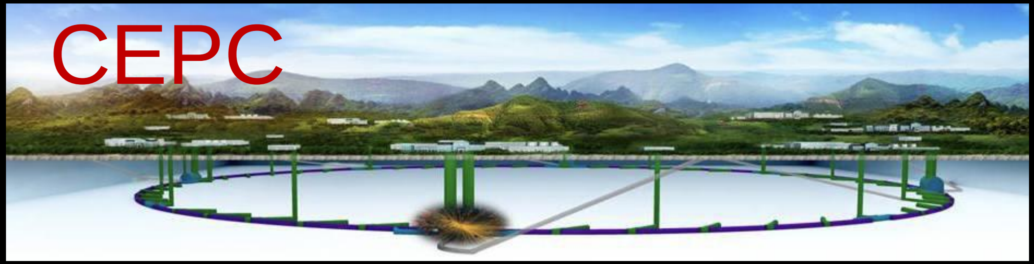
Other Future high-energy colliders



e^+e^- Linear collider
250 GeV Higgs factory
Upgrades: 91.2, 500, 1000 GeV

XFEL@DESY almost a prototype

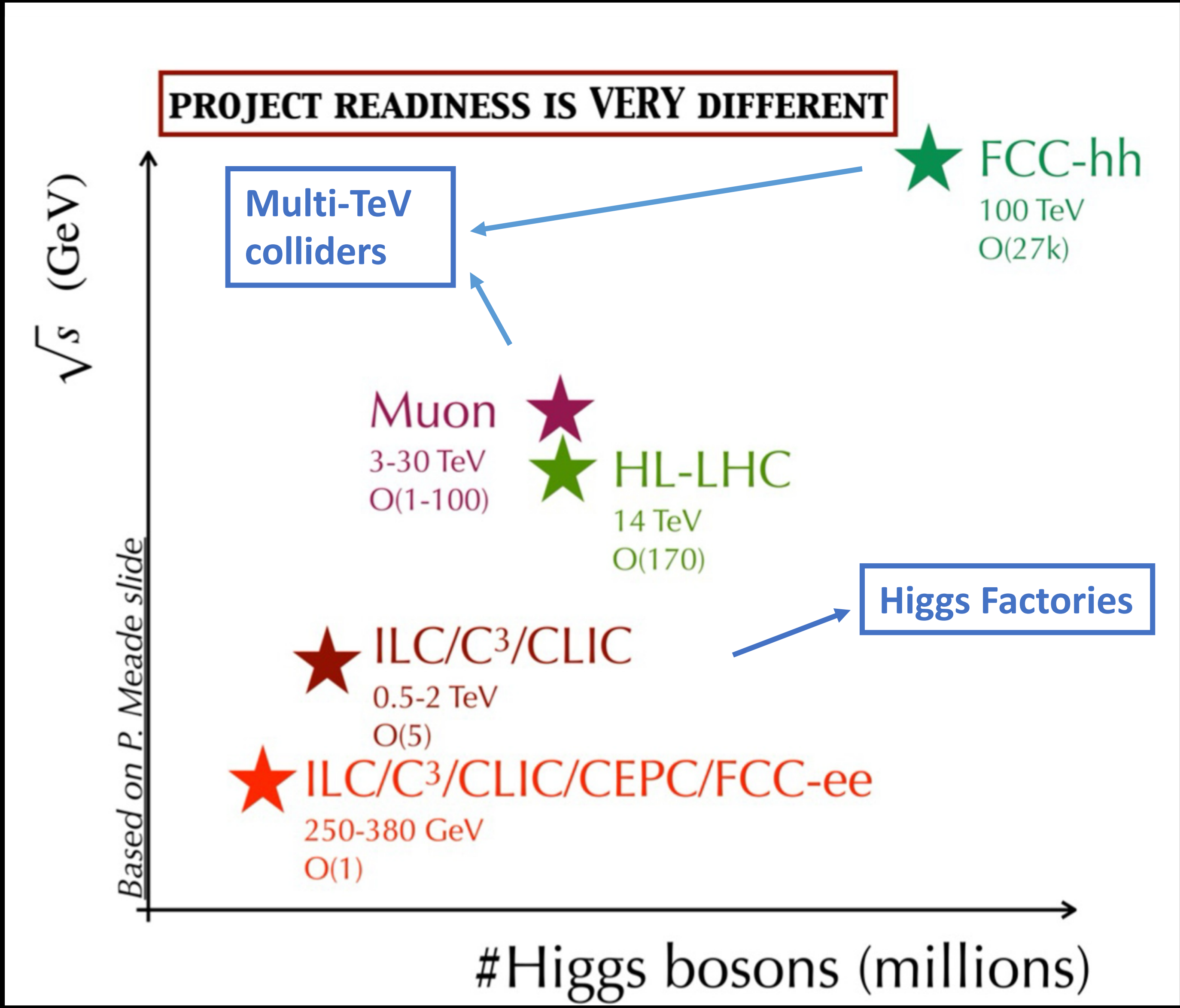
e^+e^- Linear collider:
novel accelerating technique based on high-gradient room temperature RF cavities: 380 GeV -3000 GeV



e^+e^-, hh:
Programme similar to FCC

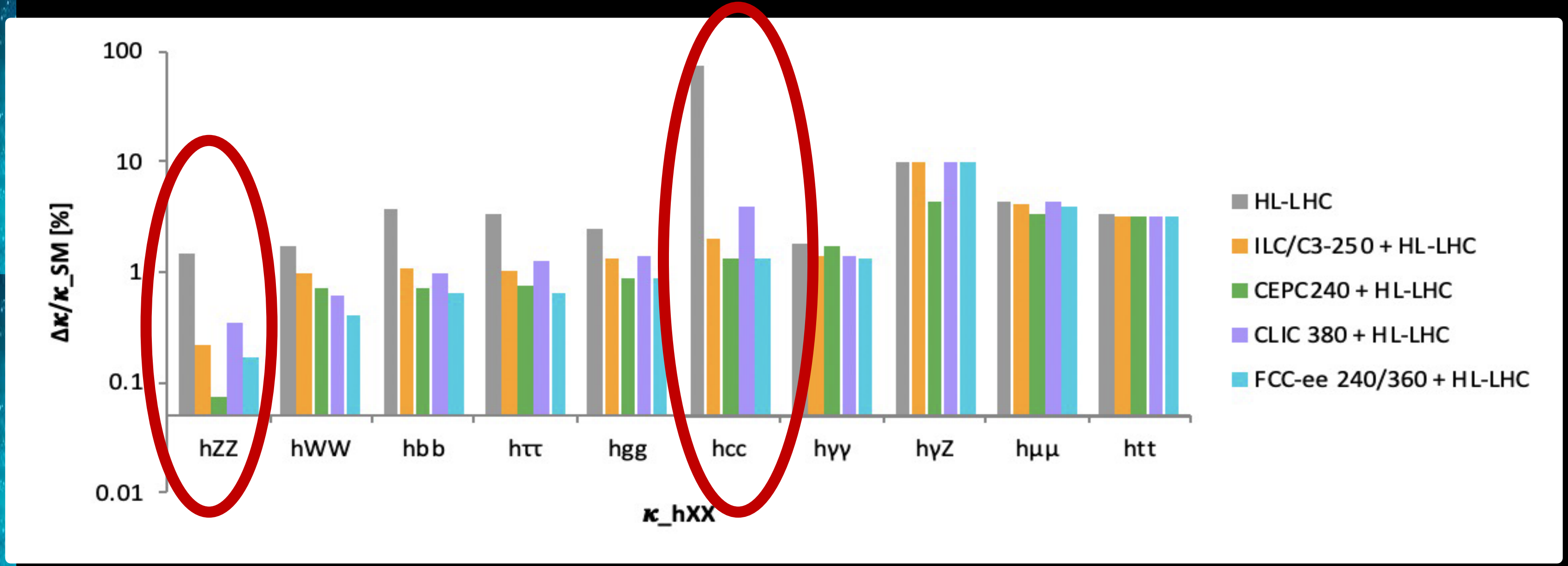
New ideas emerging: Cool Copper Collider, HALHF, ERL e^+e^- colliders

Older ideas regaining momentum: muon colliders

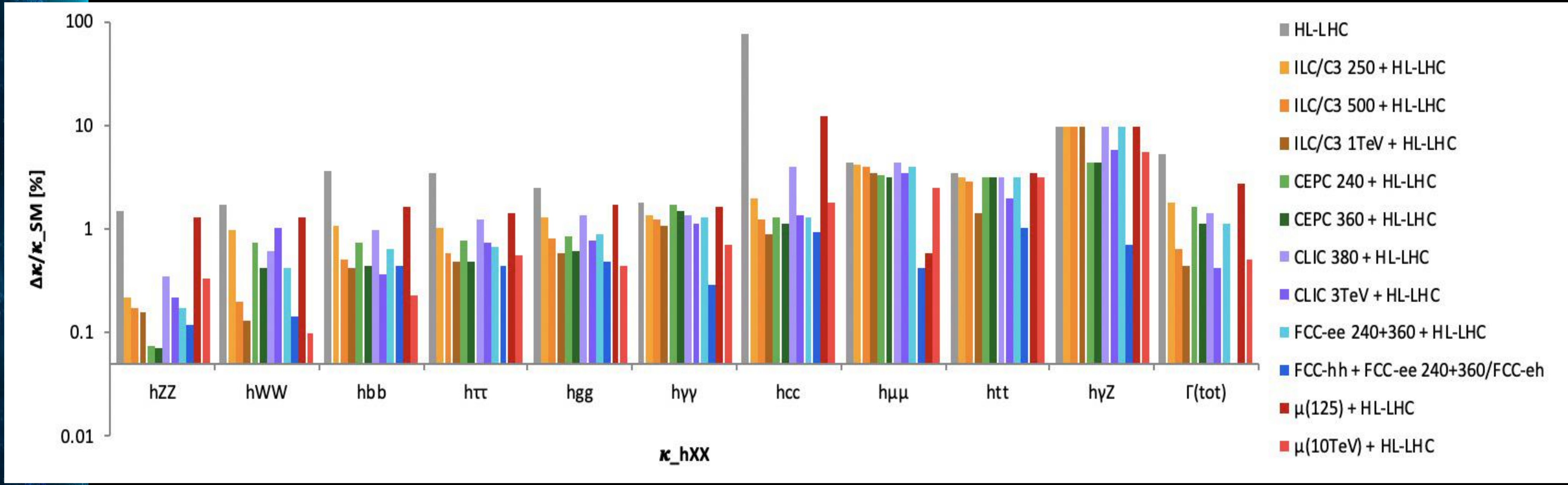


PROJECT READINESS IS VERY DIFFERENT
FCC-hh
100 TeV
O(27k)
Multi-TeV colliders
√s (GeV)
Muon
3-30 TeV
O(1-100)
HL-LHC
14 TeV
O(170)
Higgs Factories
ILC/C3/CLIC
0.5-2 TeV
O(5)
ILC/C3/CLIC/CEPC/FCC-ee
250-380 GeV
O(1)
Based on P. Meade slide
#Higgs bosons (millions)

Reach of future colliders



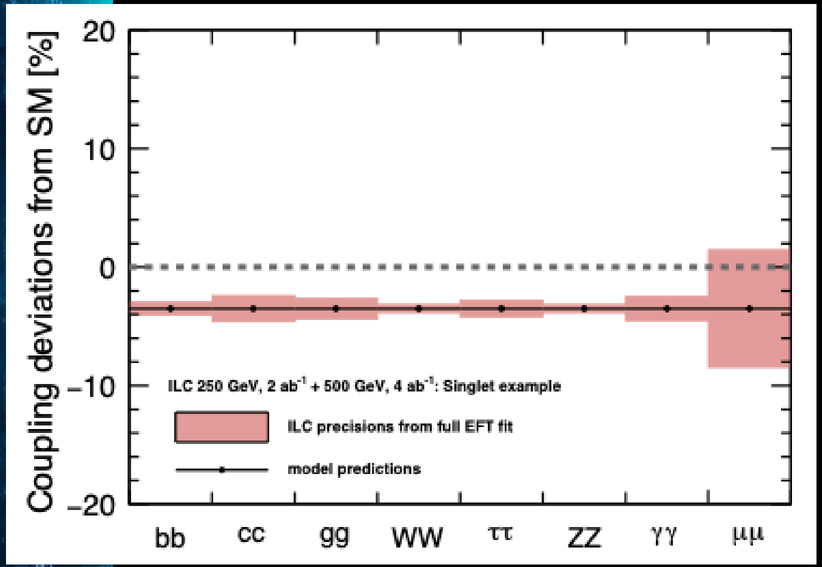
- Initial stage
  - Measurement of the Higgs coupling to charm (second-generation quarks)
  - Close reach for Hss and Hee with FCCee

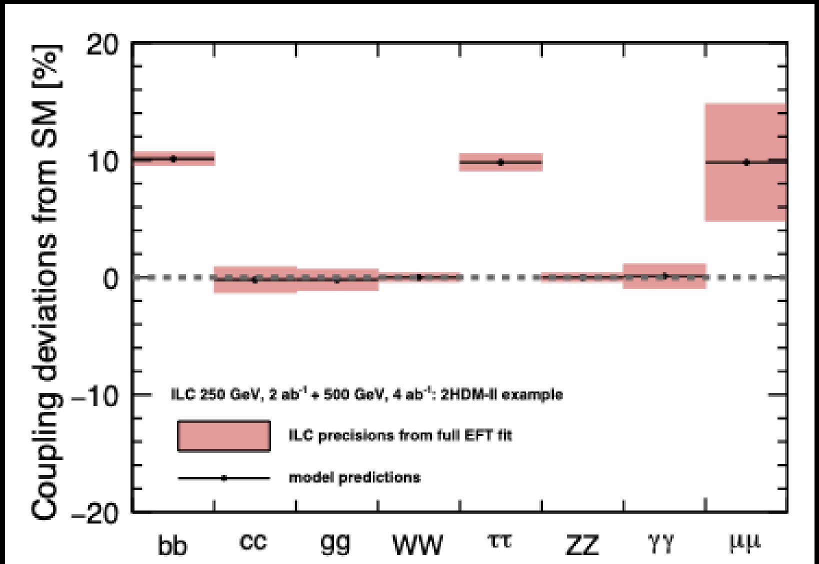


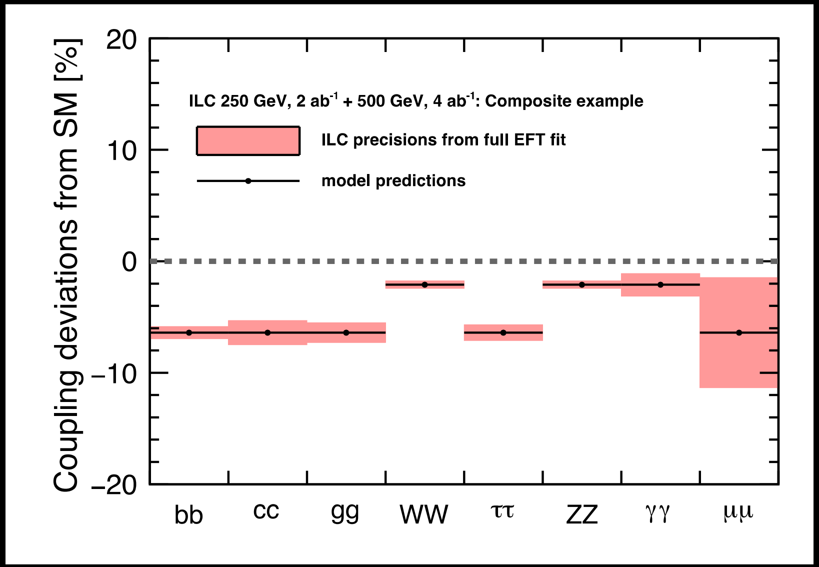
- Final stage
  - The full FCC programme offers the best performance.

Disentangling the BSM

- Higgs couplings allow finger-printing of new phenomena via their different patterns of deviations
- Need a precision of about 1% which can be achieved with future colliders







Additional scalar singlets

- (m_S=2.8 TeV, max mixing)

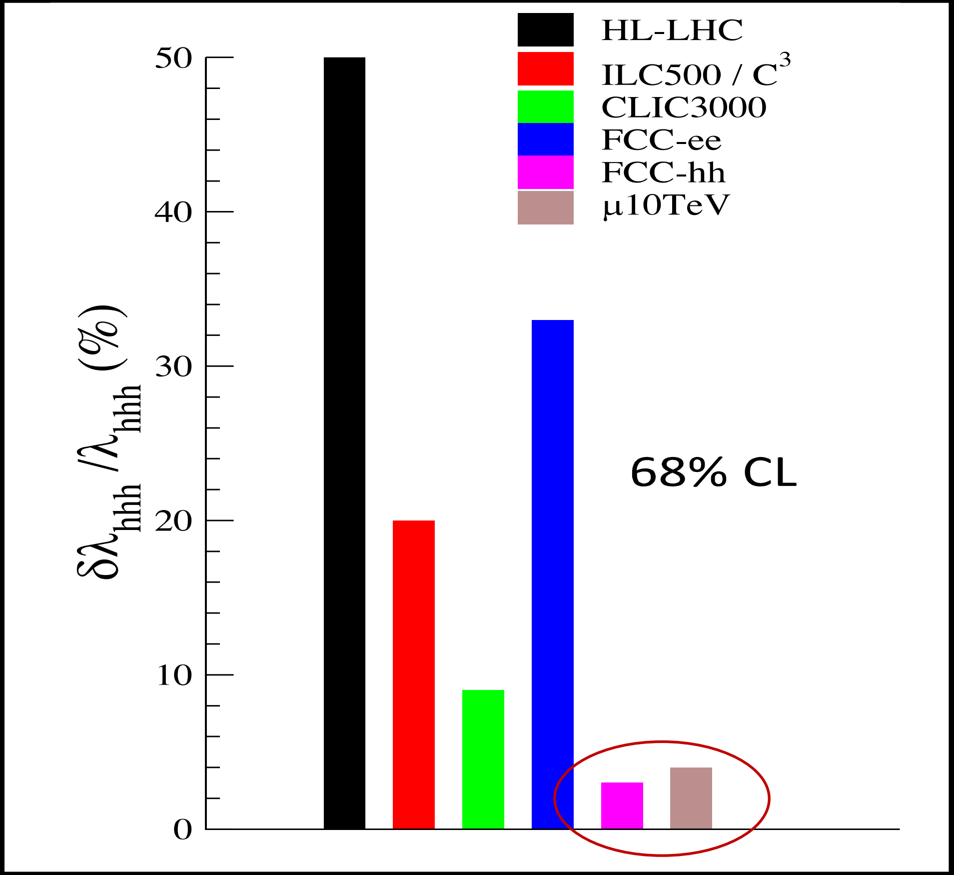
Two Higgs doublet

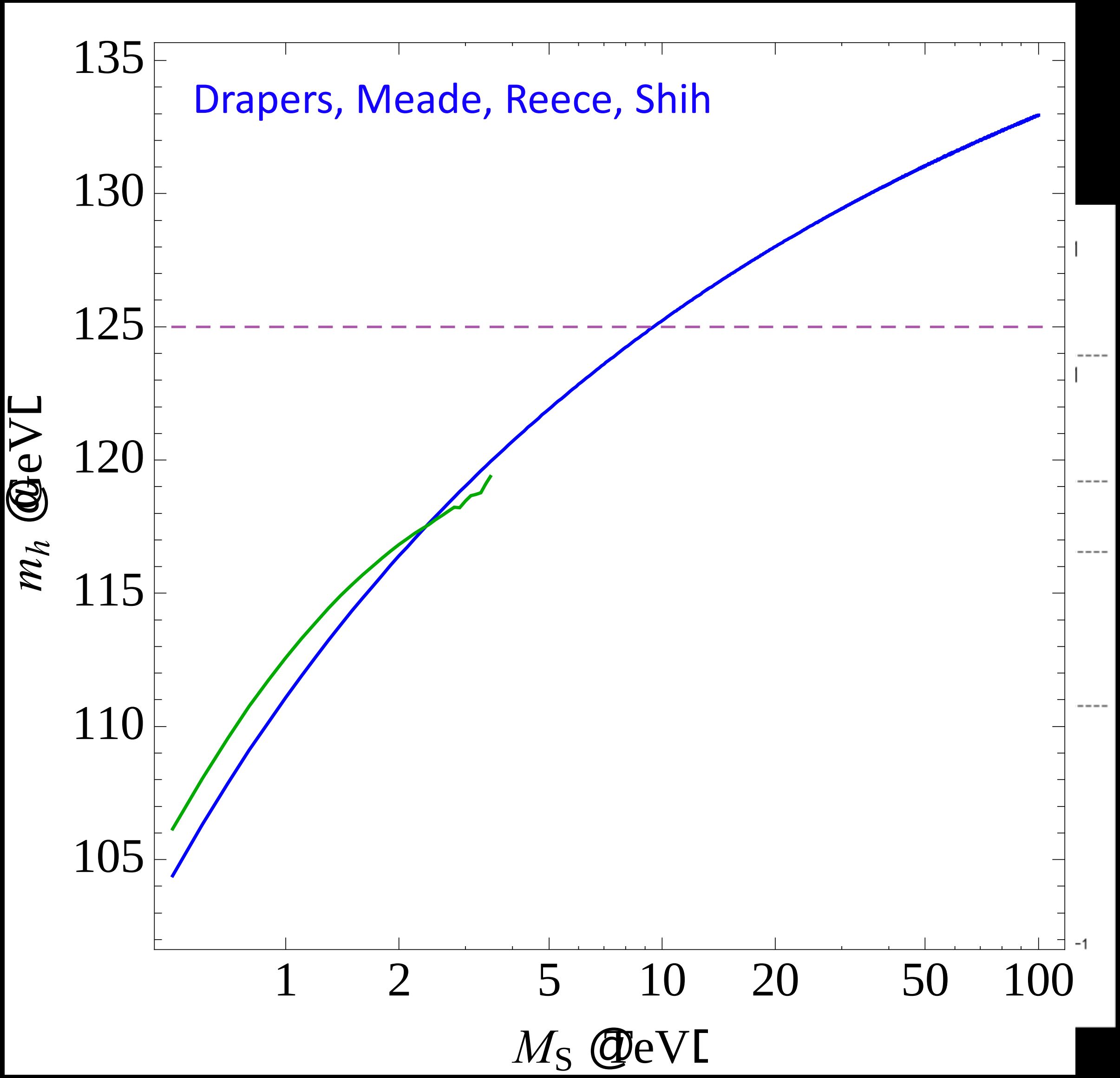
- (M_H=600 GeV, tan(beta)=7)

Composite Higgs

Reach of future colliders

self-coupling



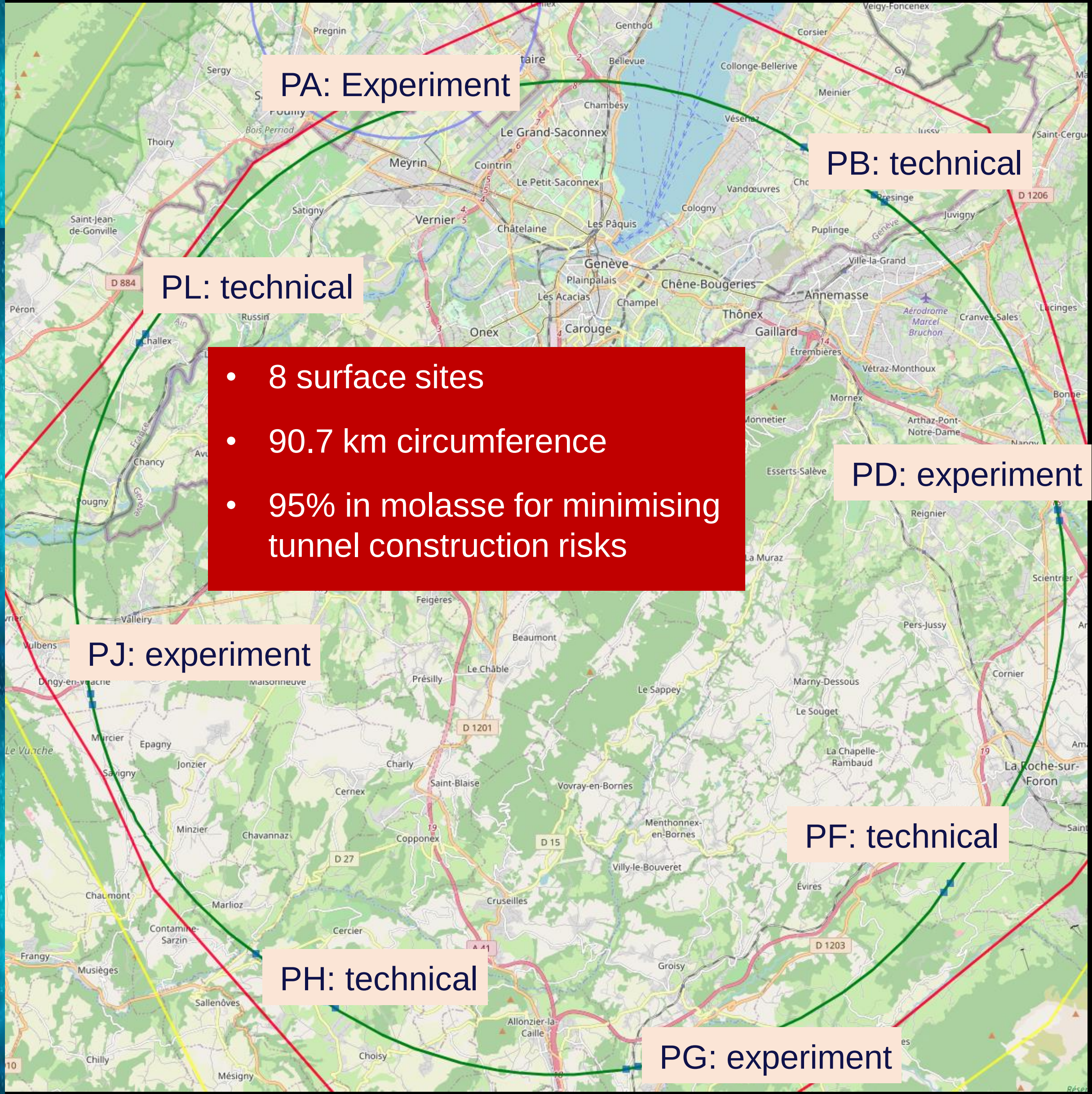


FCC Conceptual design & feasibility studies

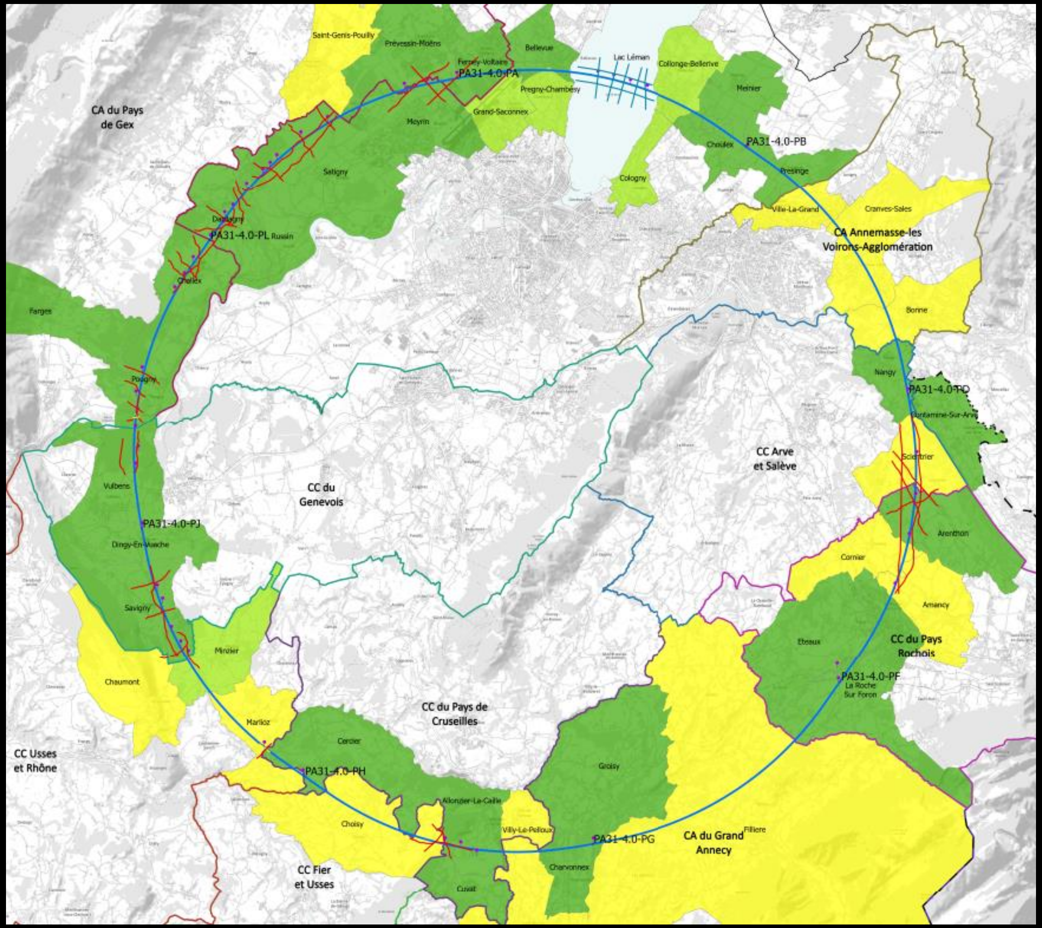
- FCC Conceptual Design Reports (2018/19)

- Followed by a feasibility study (2021-2025)
  - geological, technical, environmental and administrative feasibility of the tunnel and surface areas
  - optimisation of placement and layout of the ring and preparatory administrative processes
  - Design of the colliders and R&D to develop the needed vital technologies
  - Development of cost estimate, funding and organisational models
  - Identification of the resources
  - Sustainability
- Midterm review end of 2023 presented to CERN council on February 2024

Optimized placement and layout

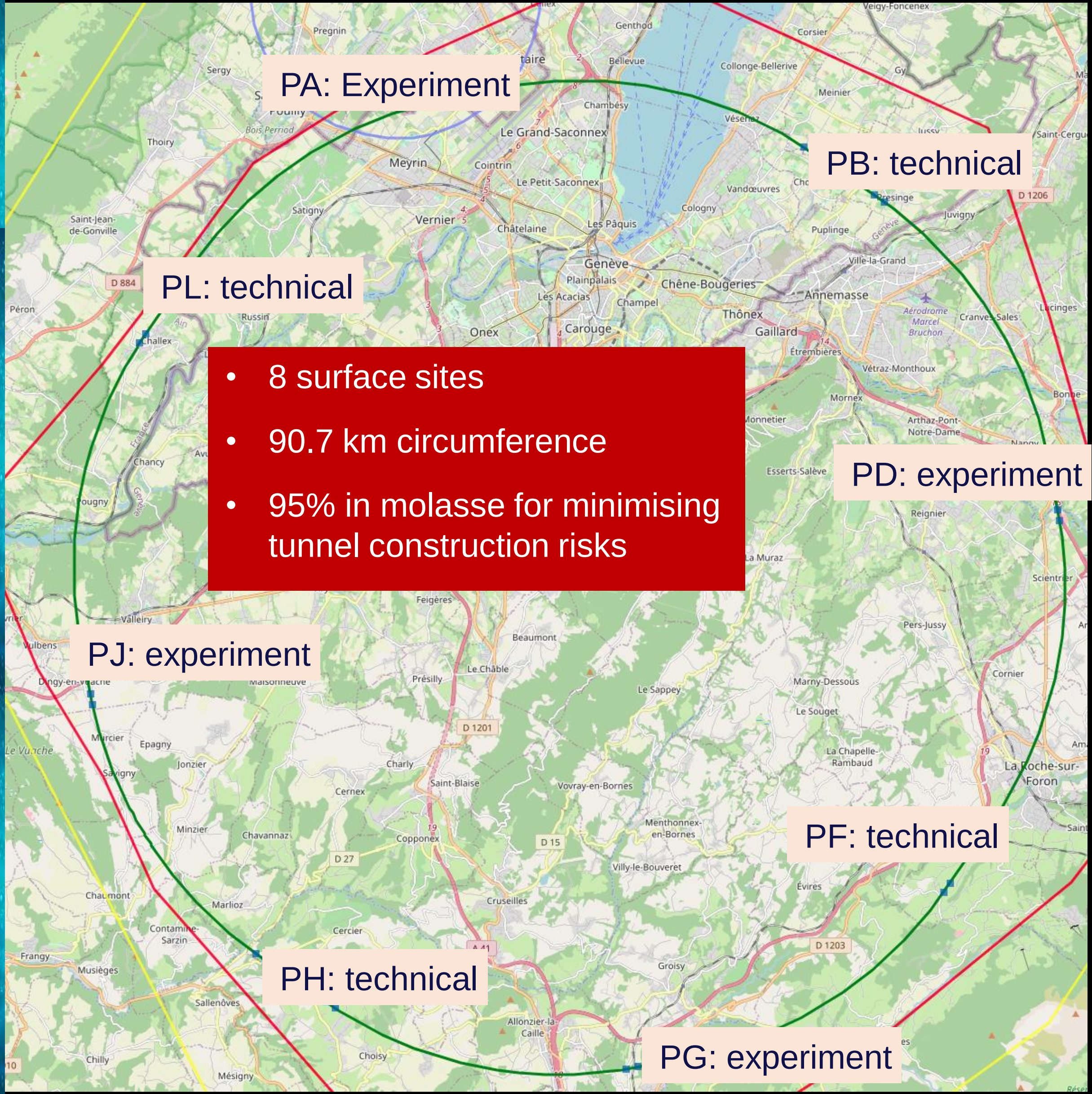


- 8 surface sites
- 90.7 km circumference
- 95% in molasse for minimising tunnel construction risks



- Individual meeting
- Individual meeting planned
- Collective meeting

Optimized placement and layout



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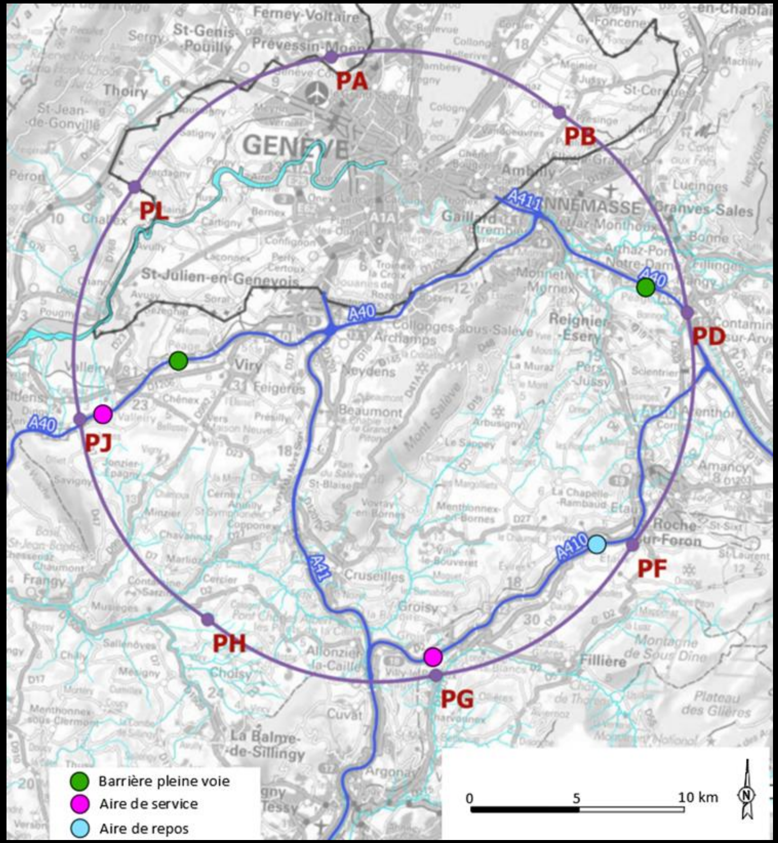
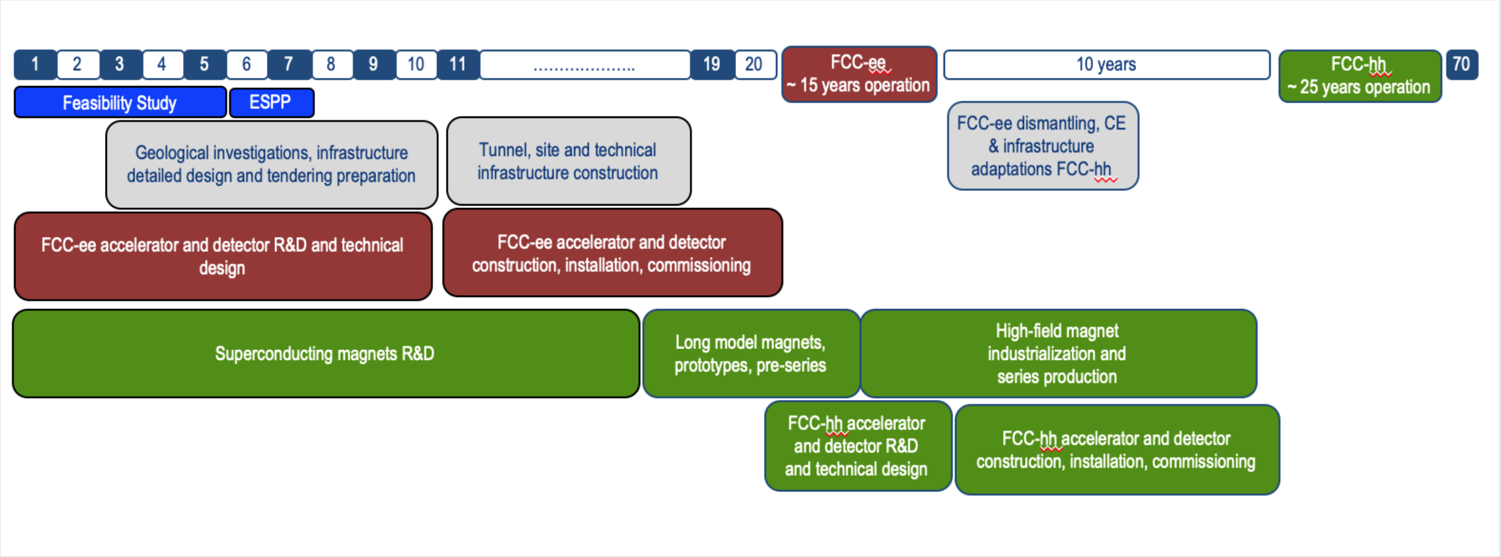
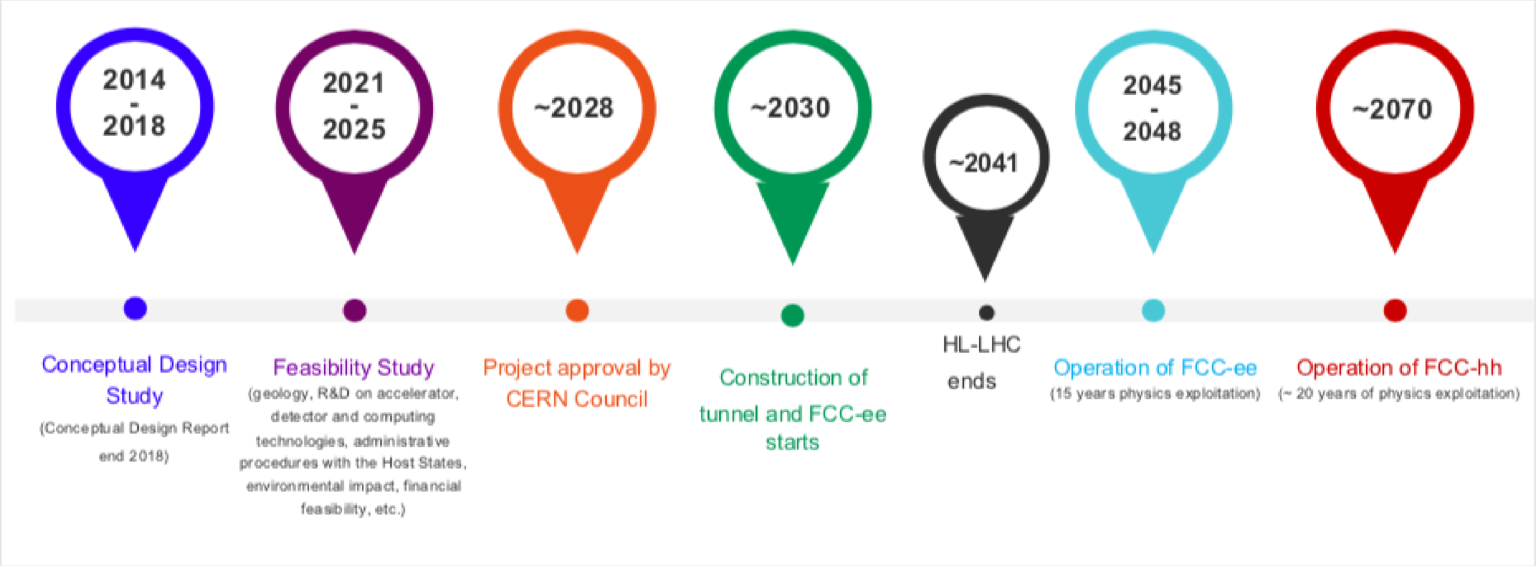


- Road accesses identified and documented for all 8 surface sites
- < 4 km of new roads required

Timeline





Technical schedule:
FCC-ee could start physics operation **in 2040 or earlier**

CERN resources are committed to HL-LHC running until 2041

1st stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2nd stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095

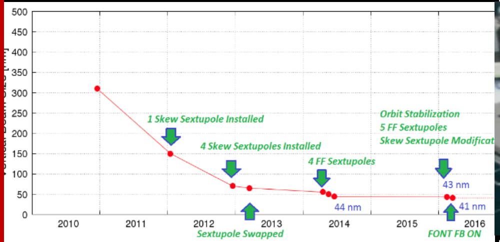
Innovation: accelerators

- All these complex programmes will require enormous innovation

Accelerators

ILC

Nanobeams
7.7 nm @250 GeV



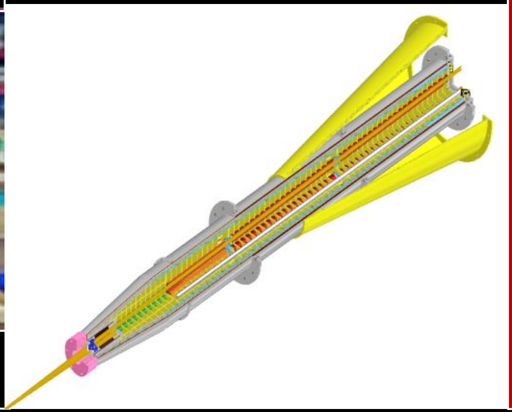
Superconducting RF technology

Nb & N-Infusion R &D

FCC-ee

Superconducting RF technology

Machine detector interface region



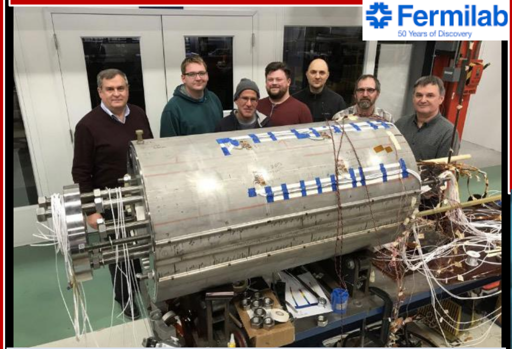
FCC-hh

High field magnets
16 T for 50

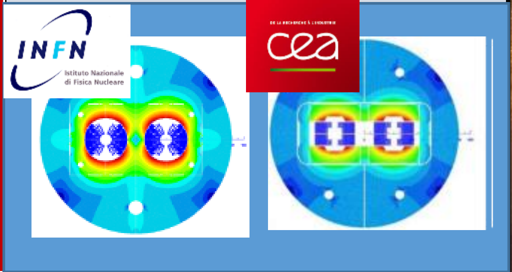
Key cost driver

- Improve cable performance
- Reduce cable cost
- Improve fabrication of magnet
- Minimize amount of cables
- Push lattice filling factor
- Field Quality

Move from NbTi (LHC technology) to Nb_3Sn



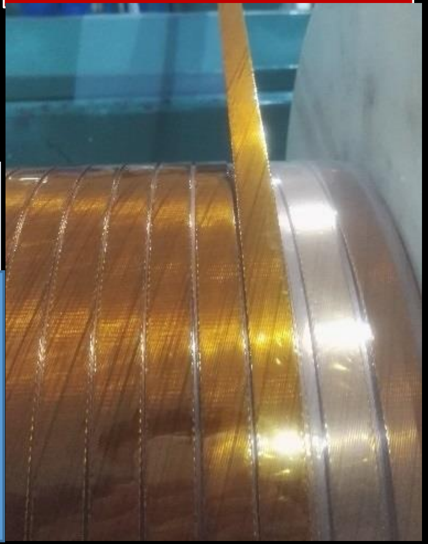
15 T dipole demonstrator (US)



SppC (China)

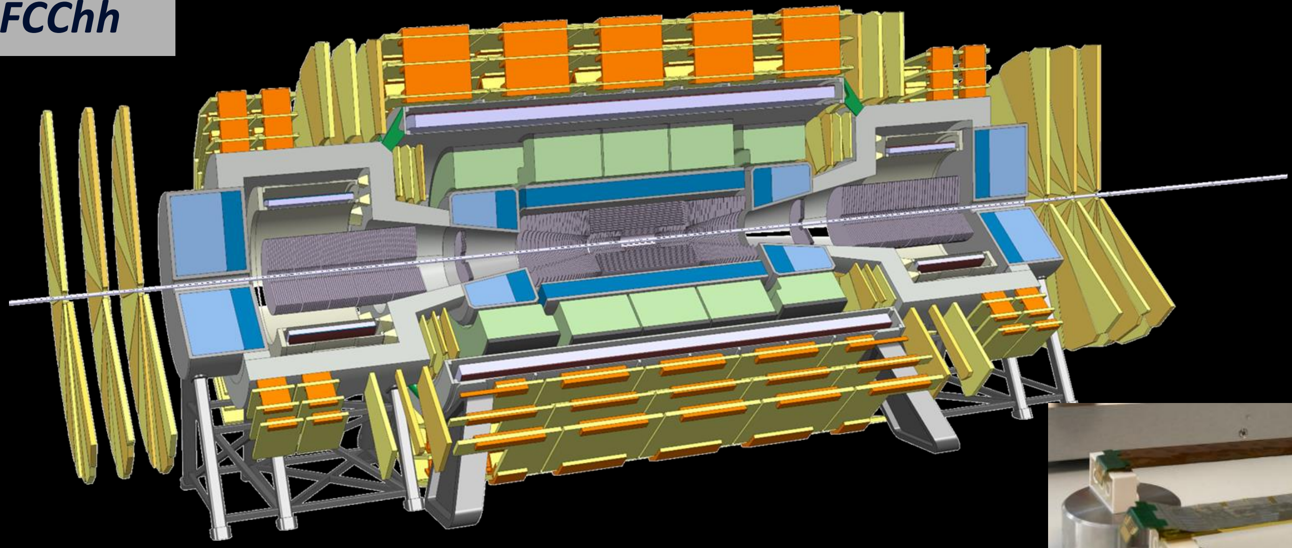
12 T

IBS –iron based
High T_c
Superconductor
much lower cost

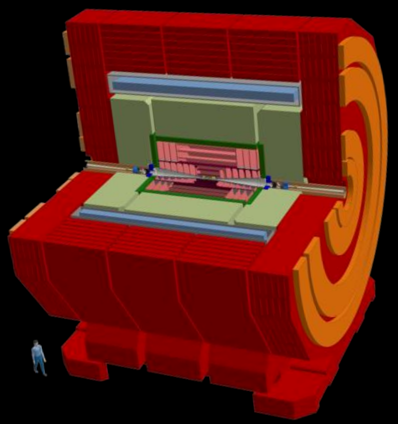


Innovation: Detectors

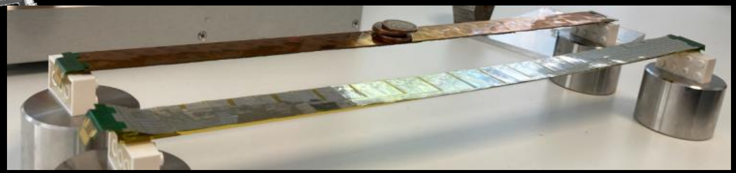
FCChh



CLIC, FCCee, ILC, CEPC,…

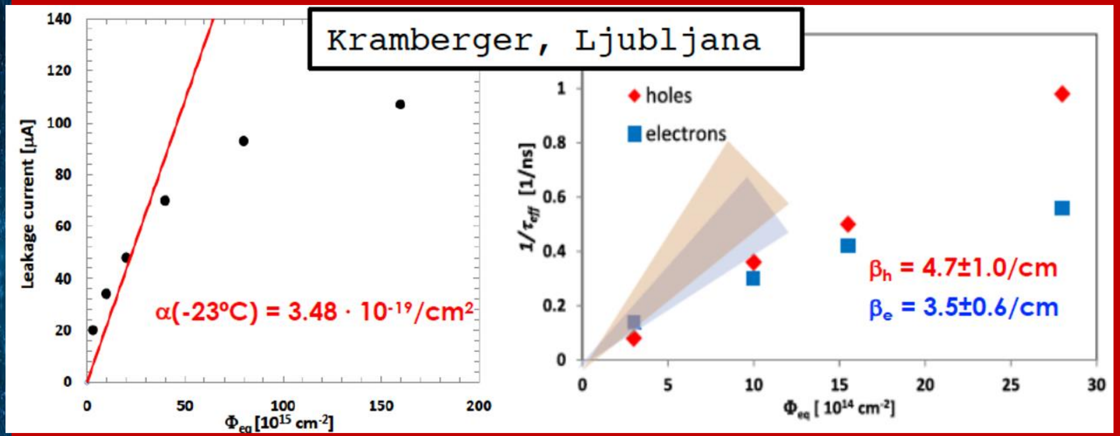


- Standard dimensions
- Trackers with superb spatial resolution (1-5 μm)
- Very low material (0.1X%)
- Vertex detector dissipated power (< 50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter



Oxford: carbon fiber support 25 μm or Kapton (MU3e)

Extremely challenging R&D-
Some good news about silicon

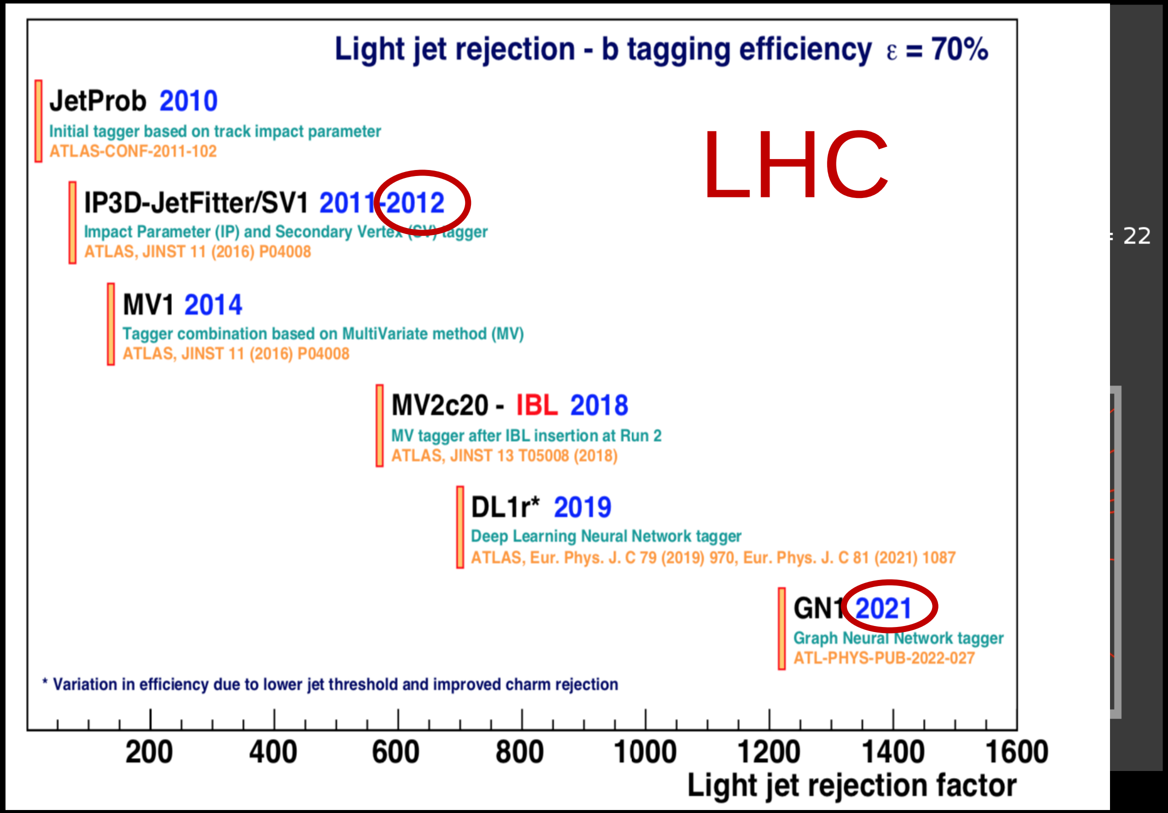


Technology advances already under study for the ALICE detector:

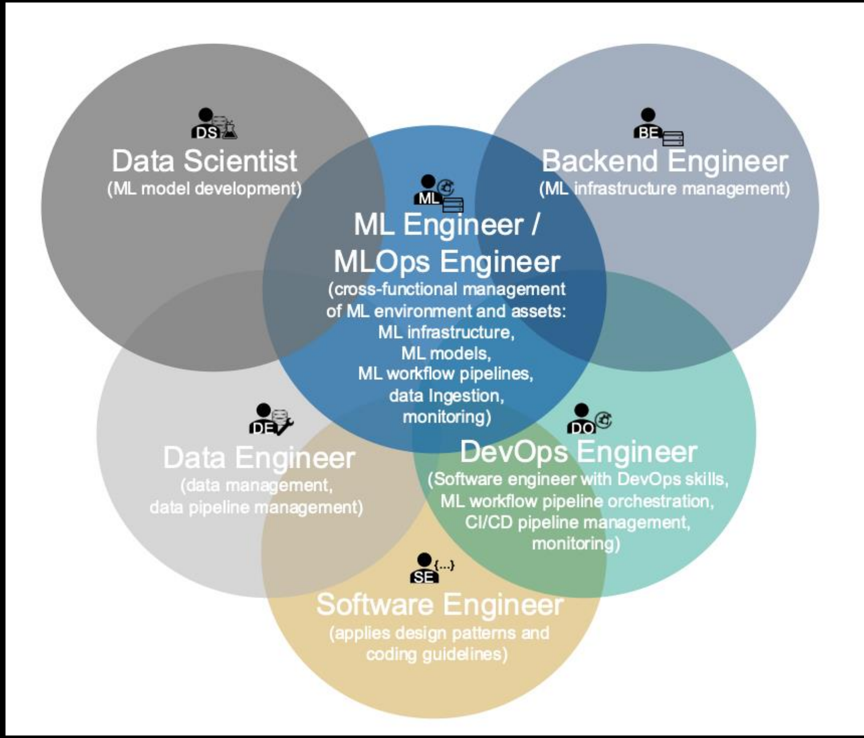
- thinned silicon down to 20-40 μm and bent it to the target radii

Innovation: Computing and analysis

- Machine learning is common thread through nearly everything we do



- Training: Valuable skill to develop for early career scientists



Conclusion

- Finding the Higgs boson has completed the standard model, but many questions remain unanswered.
- Precision studies of the Higgs and going beyond the SM require new accelerators.
  - The cost is significant, but the physics output superb
  - Timelines are very challenging for student training and careers
- We will have to be tremendously innovative to make the next steps.
  - Societal impact
- Progress in fundamental physics will be made by continuing the exploration with
  - Accelerators
  - Neutrinos
  - Broad searches for dark matter
  - Astrophysics experiments measuring dark energy and dark matter

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