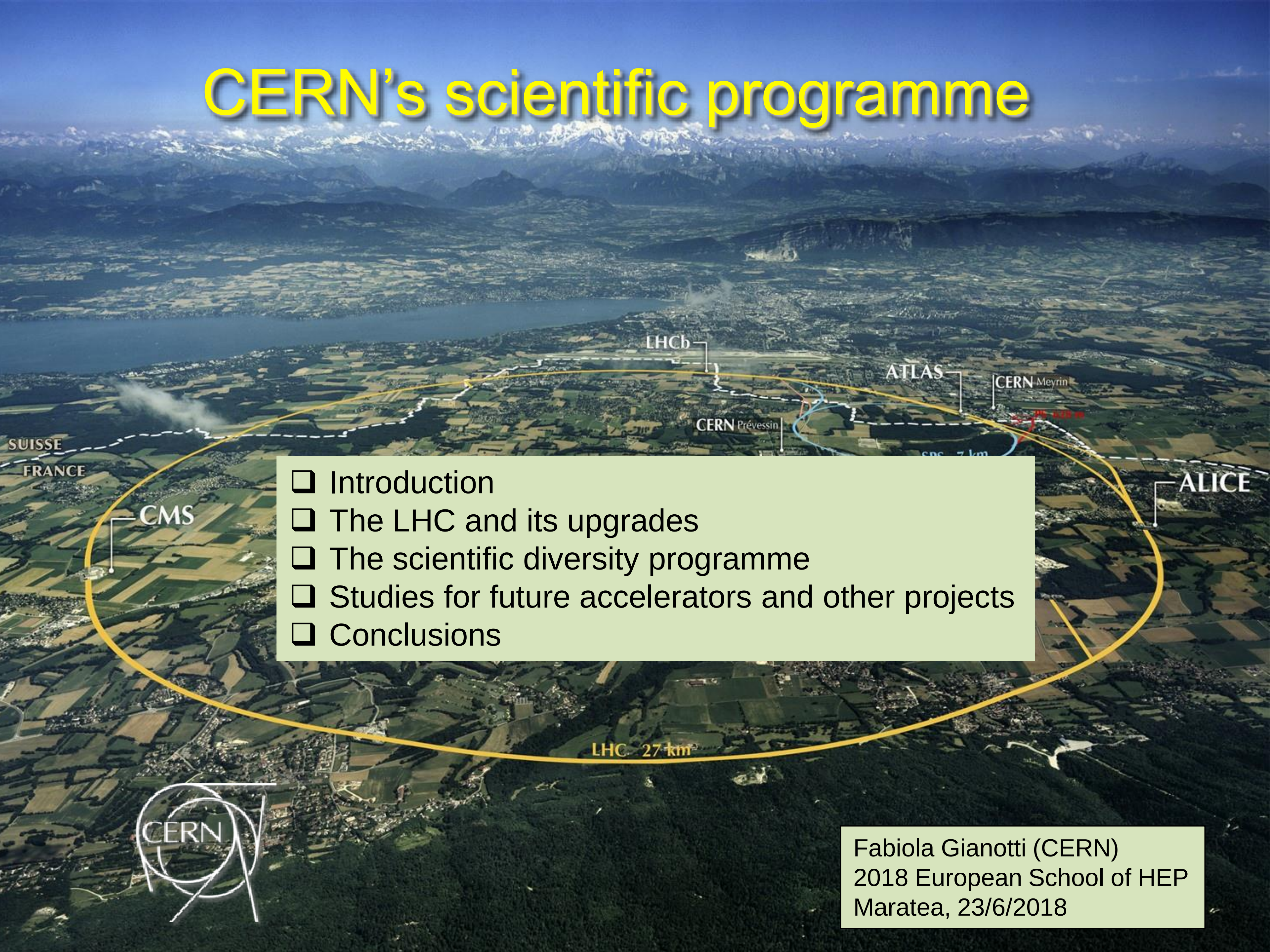
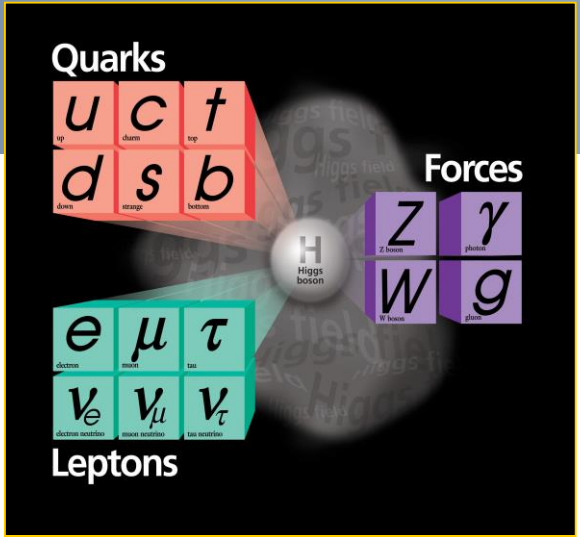
CERN's scientific programme



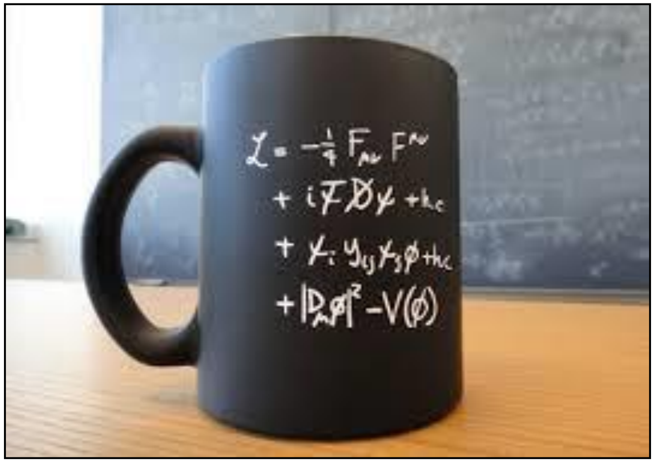
- ❑ Introduction
- ❑ The LHC and its upgrades
- ❑ The scientific diversity programme
- ❑ Studies for future accelerators and other projects
- ❑ Conclusions

Fabiola Gianotti (CERN)
2018 European School of HEP
Maratea, 23/6/2018

Introduction



With the discovery of the Higgs boson,
we have completed the Standard Model
(> 50 years of theoretical and experimental efforts !)



We have tested the Standard Model with very high precision (wealth of measurements since early '60s, in particular at accelerators)
→ it works BEAUTIFULLY (puzzling …)
→ no significant deviations observed (but difficult to accommodate non-zero neutrino masses)

However: the SM is not a complete theory of particle physics, as several outstanding questions remain (raised also by precise experimental observations) that cannot be explained within the SM.

These questions require NEW PHYSICS

Main questions in today's particle physics (a non-exhaustive list ..)

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?

What is the origin of neutrino masses and oscillations ?

What is the composition of dark matter (~25% of the Universe) ?

What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)

Why is Gravity so weak ?

However: there is NO direct evidence for new particles (yet…) from the LHC or other facilities

Where is New Physics sitting in terms of E-scale and couplings ???

Main open questions and main approaches to address them

The outstanding questions are compelling, difficult and interrelated → can only be successfully addressed through a variety of approaches (thanks also to strong advances in accelerator and detector technologies): particle colliders, neutrino experiments, cosmic surveys, dark matter direct and indirect searches, measurements of rare processes, dedicated searches (e.g. axions, dark-sector particles)

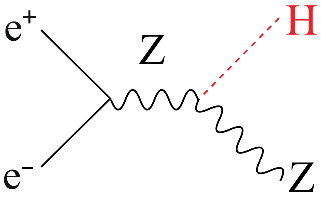
	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of E scales and couplings, and to properly interpret signs of new physics → with the goal to build a coherent picture of the underlying theory

3 main complementary ways to search for (and study) new physics at accelerators

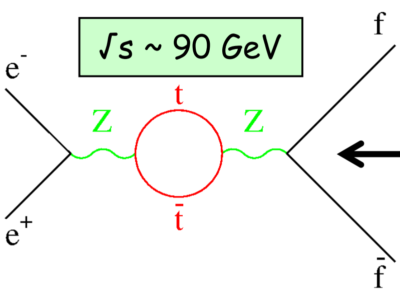
Direct — production of a given (new or known) particle

e.g.: Higgs production at future e^+e^- linear/circular colliders
at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ need high E and high L



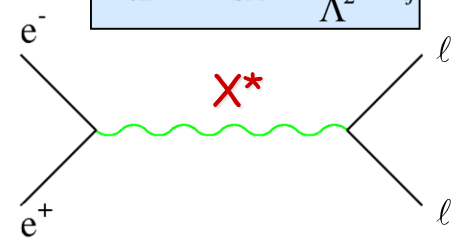
Indirect — precise measurements of known processes

→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales $\Lambda \gg \sqrt{s}$ → need high E and high L



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

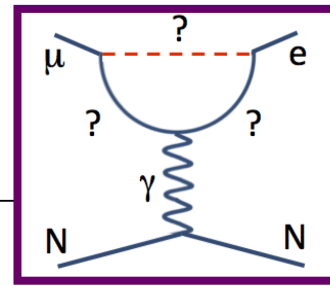
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}$$



Rare processes — suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → need intense beams, ultra-sensitive (massive) detectors ("intensity frontier")

E.g. transitions between charged leptons of different families with Lepton-Flavour-Violation: $\mu \to e\gamma$ (MEG@PSI), $\mu \to e$ (COMET@JPARC, Mu2e@FNAL).
Suppressed in SM, can occur if new physics
Note: flavour violation observed for ν (e.g. $\nu_\mu \to \nu_e$) and quarks (e.g. $t \to Wb$)



CERN scientific strategy: 3 main pillars

Full exploitation of the LHC:

- ❑ successful operation of the nominal LHC (Run 2, LS2, Run 3)
- ❑ construction and installation of LHC upgrades: LIU (LHC Injectors Upgrade) and HL-LHC

Note: expect to move to 14 TeV operation in Run 3. Currently also exploring the possibility to achieve “ultimate” energy of 15 TeV in Run4++

Scientific diversity programme serving a broad community:

- ❑ current experiments and facilities at Booster, PS, SPS and their upgrades (Antiproton Decelerator/ELENA, ISOLDE/HIE-ISOLDE, etc.)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

Preparation of CERN’s future:

- ❑ vibrant accelerator R&D programme exploiting CERN’s strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- ❑ design studies for future accelerators: CLIC, FCC (includes HE-LHC)
- ❑ future opportunities of scientific diversity programme (“Physics Beyond Colliders” Study Group)

Important milestone: update of the European Strategy for Particle Physics (ESPP), to be concluded in May 2020

LHC and its upgrades

→ See also lectures by N. Pastrone

Outstanding performance of the LHC since the beginning

- Run 1: 2010-2013: $\sqrt{s}$ = 7-8 TeV, ~ 30 fb^{-1} to ATLAS and CMS → **Higgs boson discovery**
- Run 2: 2015-2018: $\sqrt{s}$ = 13 TeV
  -- peak luminosity so far: ~2 x 10^{34} cm^{-2} s^{-1} → x 2 higher than nominal value
  -- integrated luminosity: ~115 fb^{-1} ATLAS and CMS ~5 fb^{-1} LHCb, ~47 pb^{-1} ALICE

n. of particles per bunch

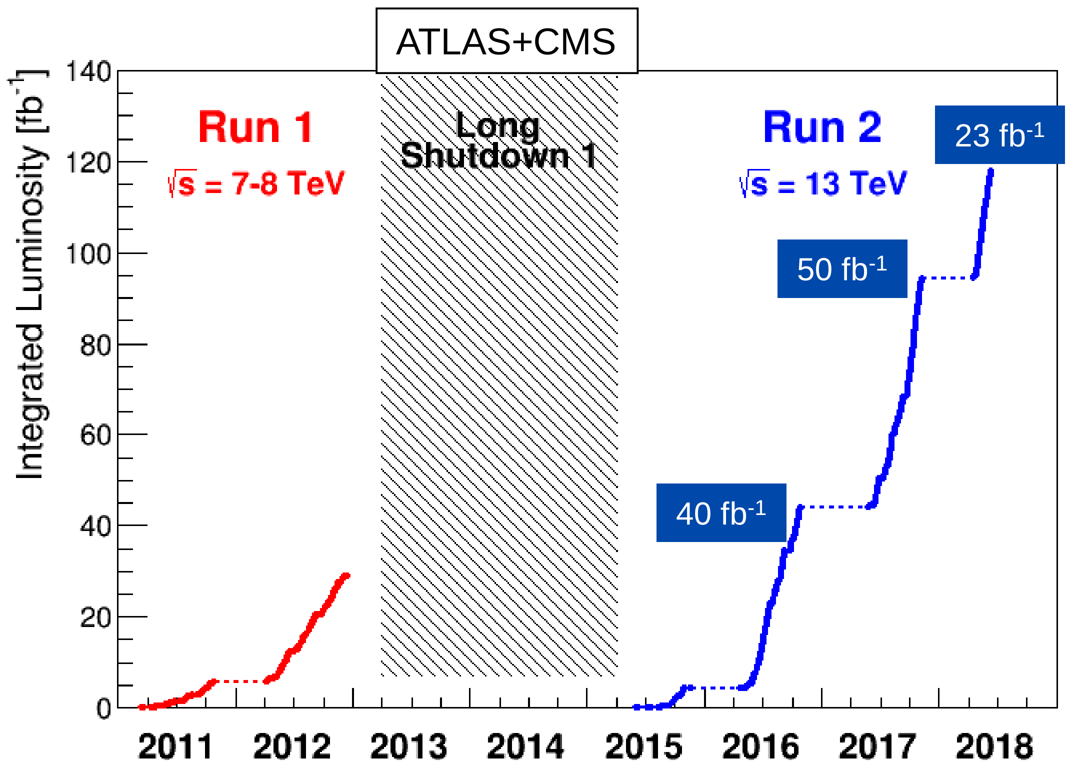
n. of bunches

n. of turns per second or repetition rate

$$\boxed{L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}}$$

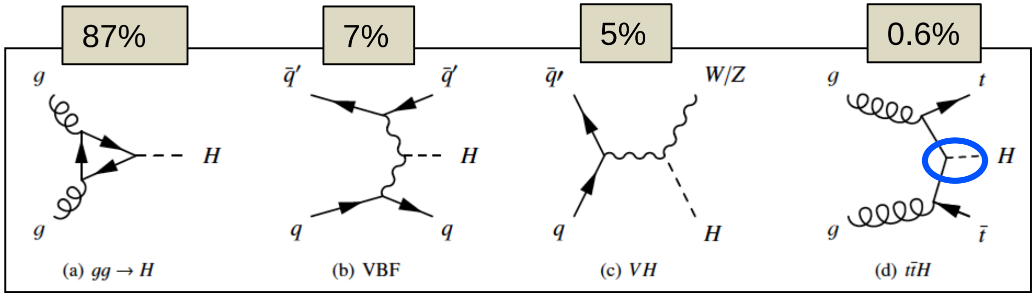
beam size at IP

N=∫Ldt x σ



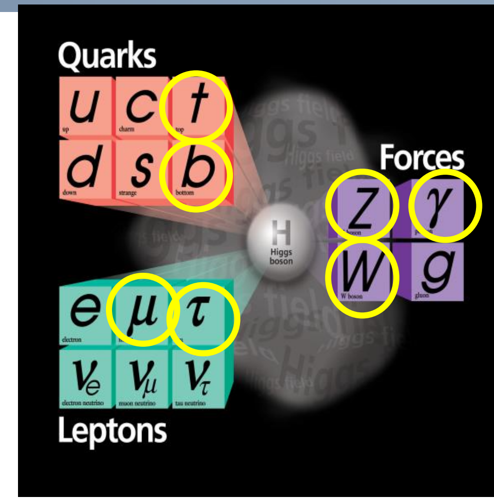
Detectors and computing also performing very well in spite of challenging conditions (pile-up up to ~ 60 events/x-ing, huge amount of data, etc.)

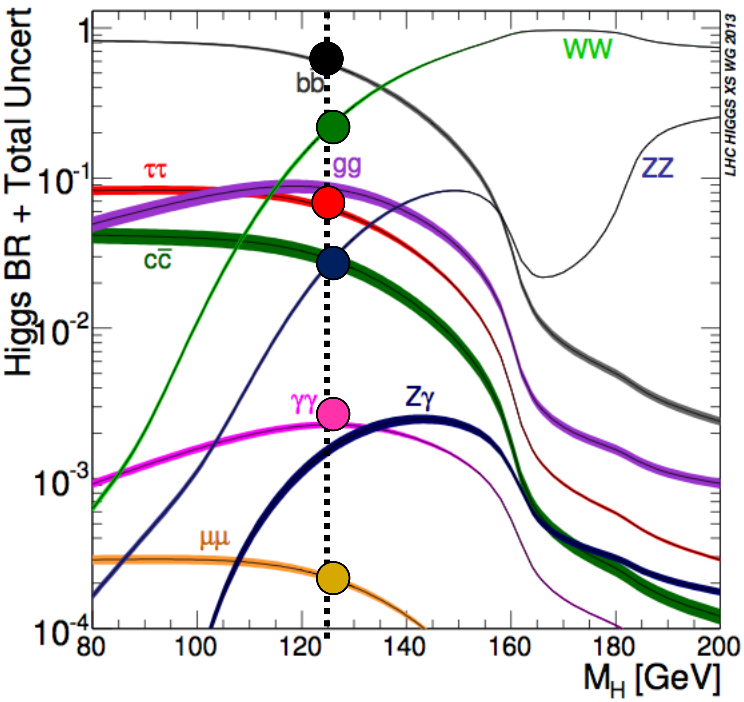
Excellent progress on Higgs boson studies



$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

$$g_{HVV} = \frac{2m_V^2}{v}$$





Higgs boson discovered and now well measured in H→ γγ, H→ZZ*→4l, H→ WW* → lνlν channels (small branching ratios but clean final states)

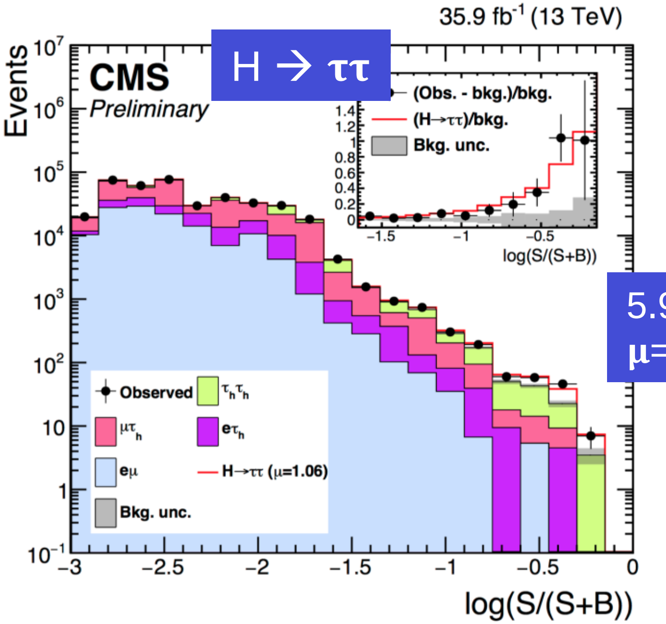
Decays and couplings to 3rd generation fermions (H→ bb, H → ττ, Htt production) experimentally more difficult as affected by huge backgrounds

Couplings to 2nd generation fermions (through rare H→ μμ decay) will only be accessible at HL-LHC

Higgs couplings to 3rd generation fermions well established recently

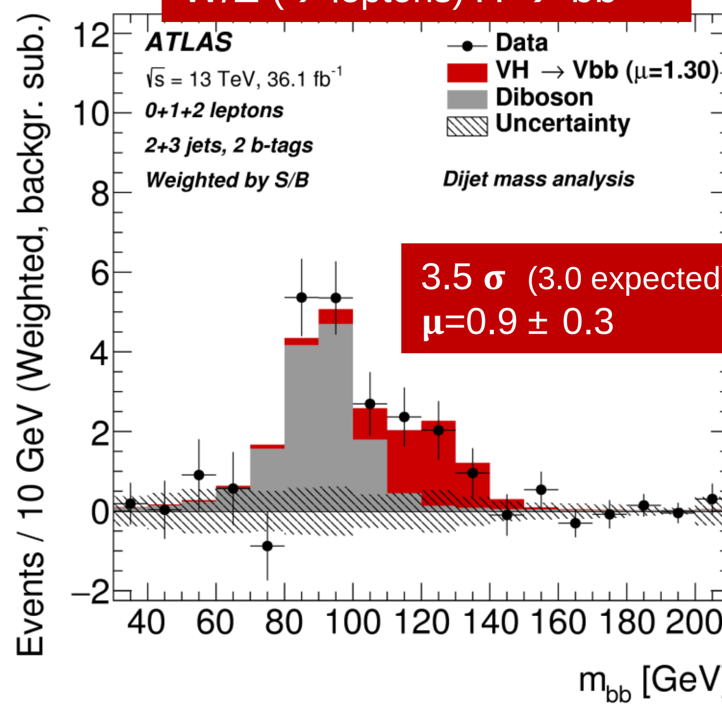
μ = (measured/SM-predicted) rate

H → ττ



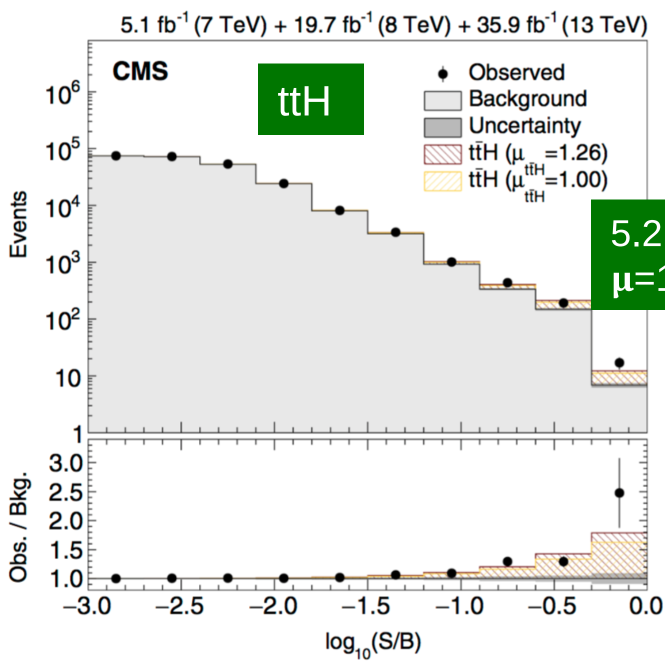
5.9 σ (5.9 expected)
μ=1.1 ± 0.3

W/Z (→ leptons) H → bb



3.5 σ (3.0 expected)
μ=0.9 ± 0.3

ttH



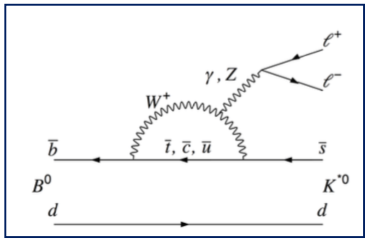
5.2 σ (4.2 expected)
μ=1.3 ± 0.3

Note: very complex final state topologies, huge backgrounds → excellent detector performance, exquisite control of the backgrounds and sophisticated analysis techniques required

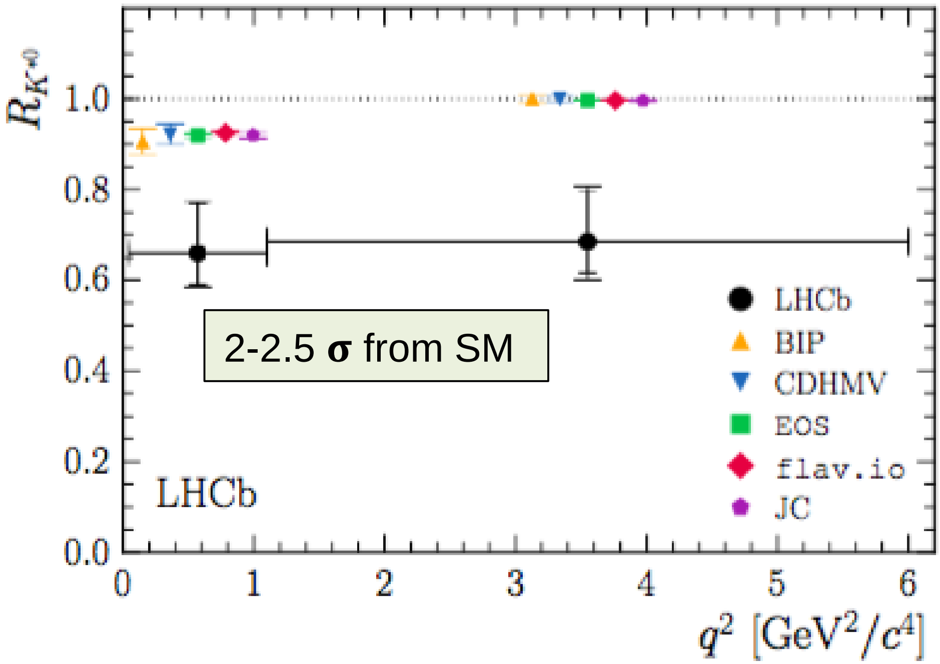
LHCb

Hints (so far inconclusive) for violation of lepton universality reported by BaBar, Belle and **LHCb (Run 1 data, ~ 3 fb^{-1}).**
Note: couplings of leptons (ℓ = e, μ, τ) should be identical apart from (calculable) mass effects

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

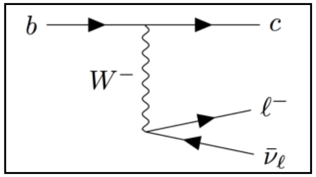


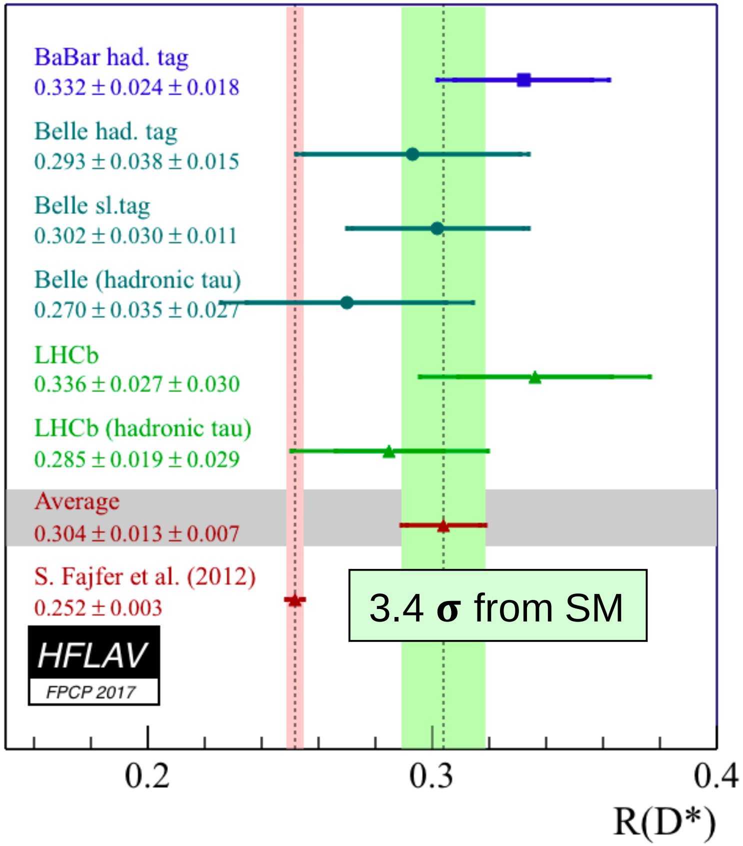
Deviations from SM decay rates may indicate new physics in the loop



2-2.5 σ from SM

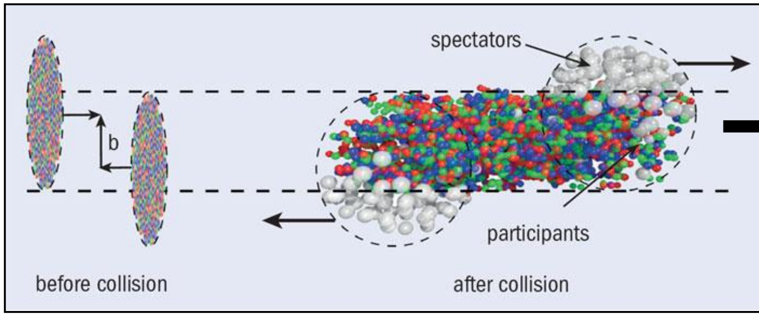
$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$$





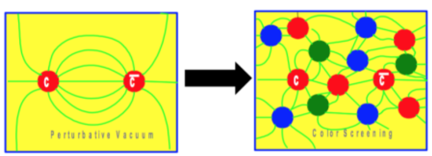
3.4 σ from SM

ALICE

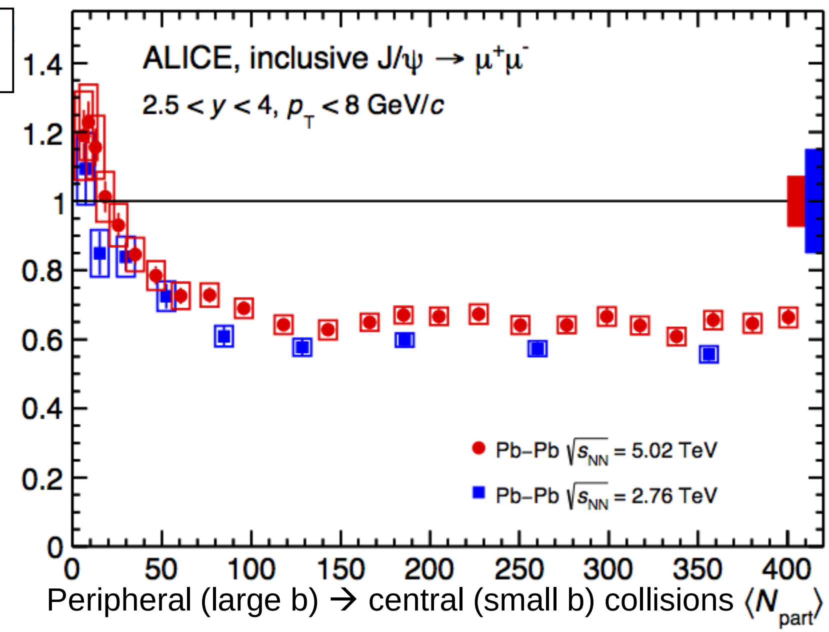


Heavy Ion collisions: conditions of high density and temperature of nuclear matter → formation of a plasma of deconfined quarks and gluons (QGP). Permeated early universe ~ 10 μs after Big Bang.

One of QGP manifestations is suppression of production of heavy-flavour resonances (J/ψ, ψ(2s), ϒ, etc.) due to screening by the dense medium



$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin}\rangle N(J/\psi)_{pp}}$$

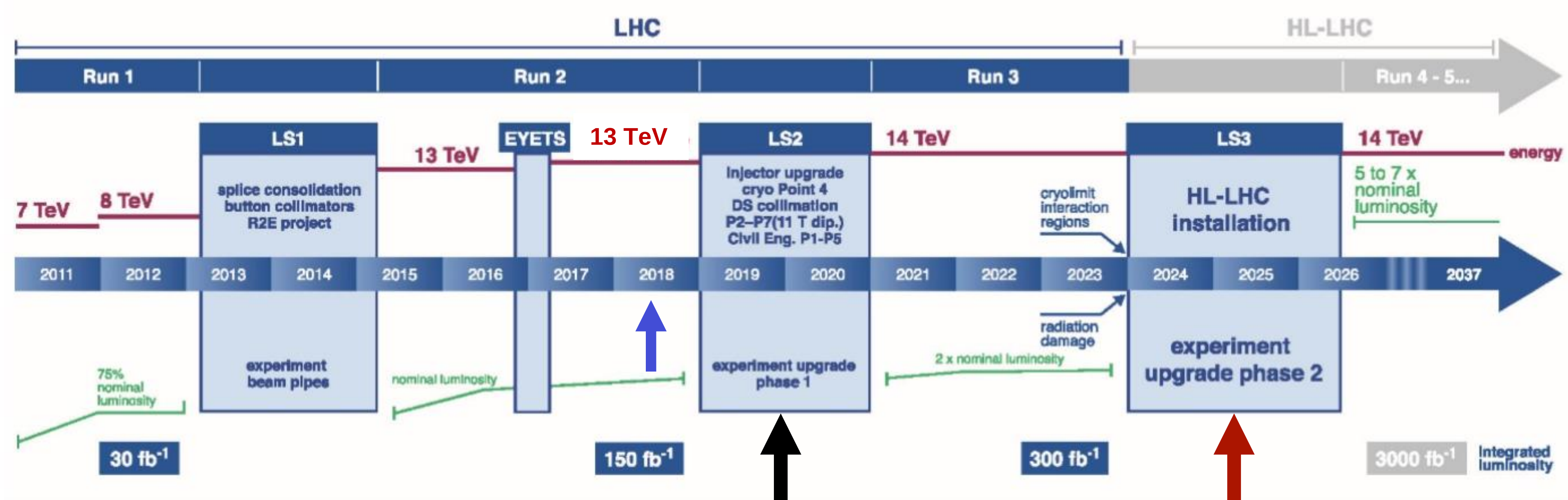


R_{AA} = quantifies departure from binary scaling
→ =1 if no nuclear effects in HI collisions
→ ≠ 1 if medium effects

HL-LHC parameters and timeline

Nominal LHC: $\sqrt{s}$ = 14 TeV, L= 1×10^{34} $cm^{-2} s^{-1}$ (Note: 2 $\times 10^{34}$ $cm^{-2} s^{-1}$ achieved already)
Integrated luminosity to ATLAS and CMS: 300 fb^{-1} by 2023 (end of Run 3)

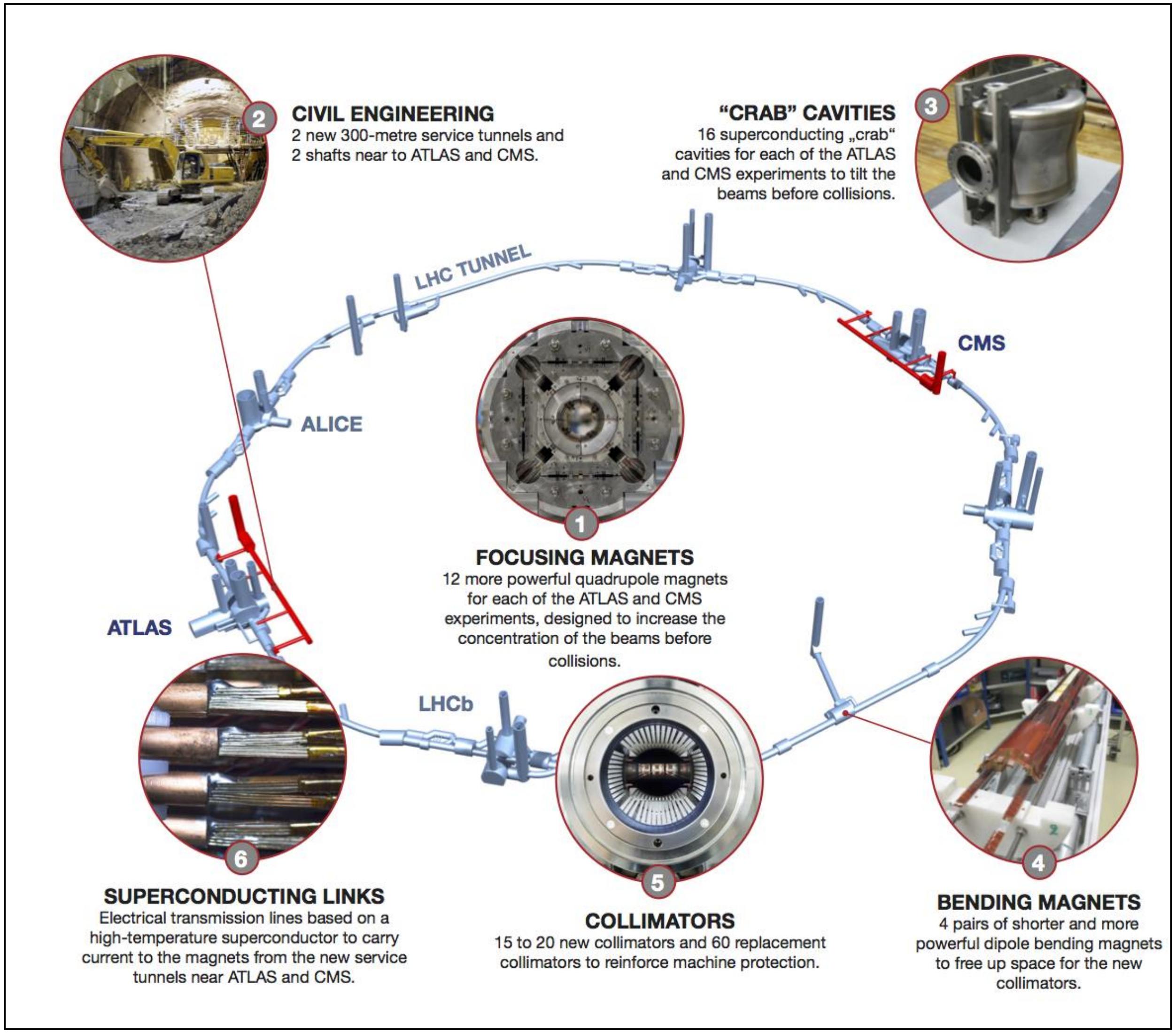
HL-LHC: $\sqrt{s}$ = 14 TeV, L= 5×10^{34} $cm^{-2} s^{-1}$
Integrated luminosity to ATLAS and CMS: 3000 fb^{-1} by ~ 2035



LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

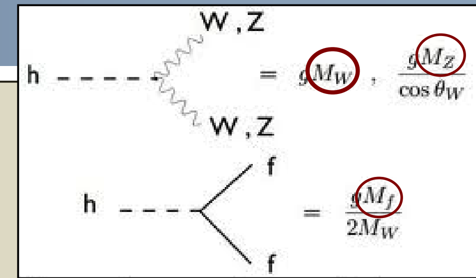
HL-LHC main upgrade components (and challenges …)



Nb_3Sn focusing magnet: full-size (4.2 m) prototype being tested in the US

One of most crucial challenges: new-generation superconducting magnets (Nb_3Sn)
→ fundamental milestone also for future, more powerful colliders (HE-LHC, FCC)

HL-LHC physics case



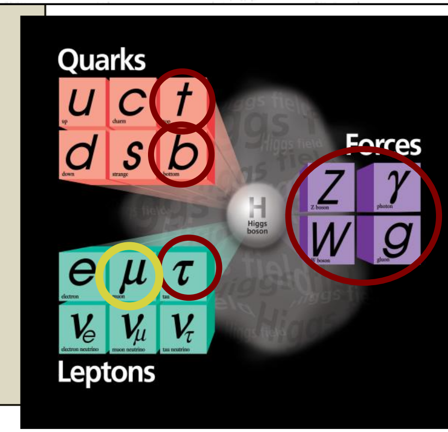
1 Precise measurements of the Higgs boson

Impact of New Physics on Higgs couplings to other particles:

$\Delta\kappa/\kappa \sim 5\%/\Lambda^2_{NP}$ (Λ_{NP} in TeV)

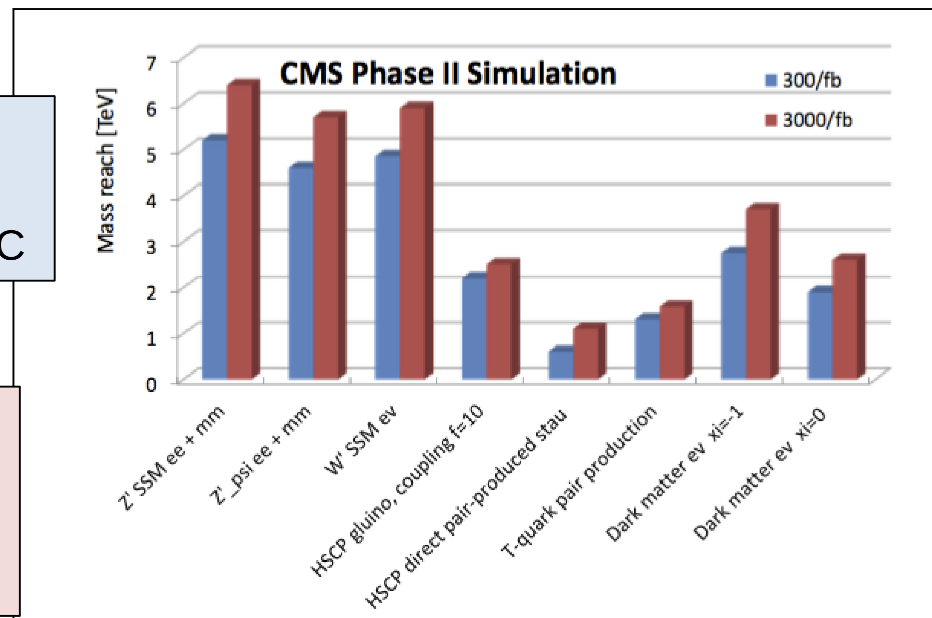
Precision ~2-5% at HL-LHC (~10% at nominal LHC)

In addition: measure H couplings to second-generation particles through rare **H→ μμ** decay. Nominal LHC: only couplings to (heavier) third-generation particles (top-quark, b-quark, τ-lepton) accessible



2 Discovery potential for new particles

~20-30% larger (up to m ~ 8 TeV) than nominal LHC



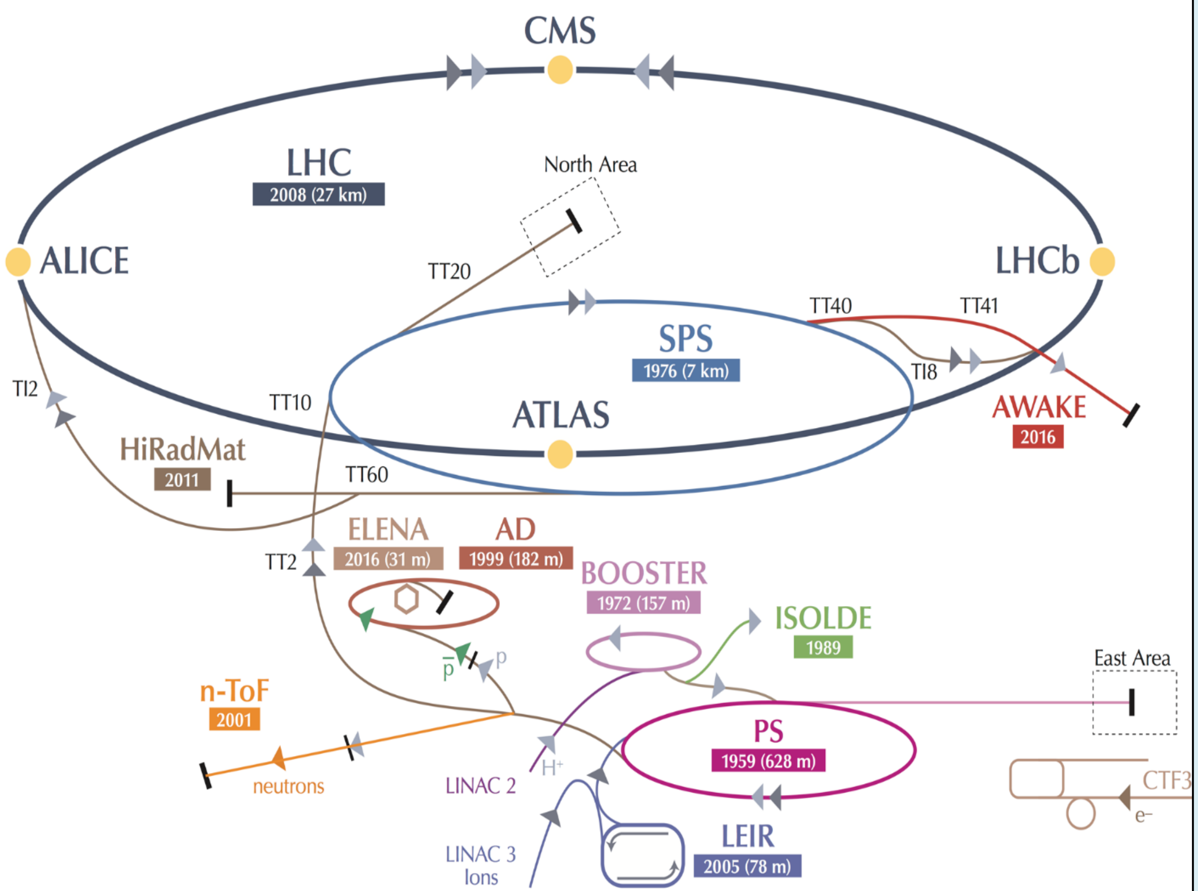
3 If new particles discovered in Run 2-3:

→ HL-LHC may find more and provide first detailed exploration of the new physics with well understood machine and experiments

Scientific diversity programme

Scientific diversity: a compelling programme beyond the LHC

~20 projects, > 1200 physicists



AD: Antiproton Decelerator for antimatter studies

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aeorosols and clouds → implications on climate

COMPASS: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

NA61/Shine: heavy ions and neutrino targets

NA62: rare kaon decays

NA63: interaction processes in strong EM fields in crystal targets

NA64: search for dark photons

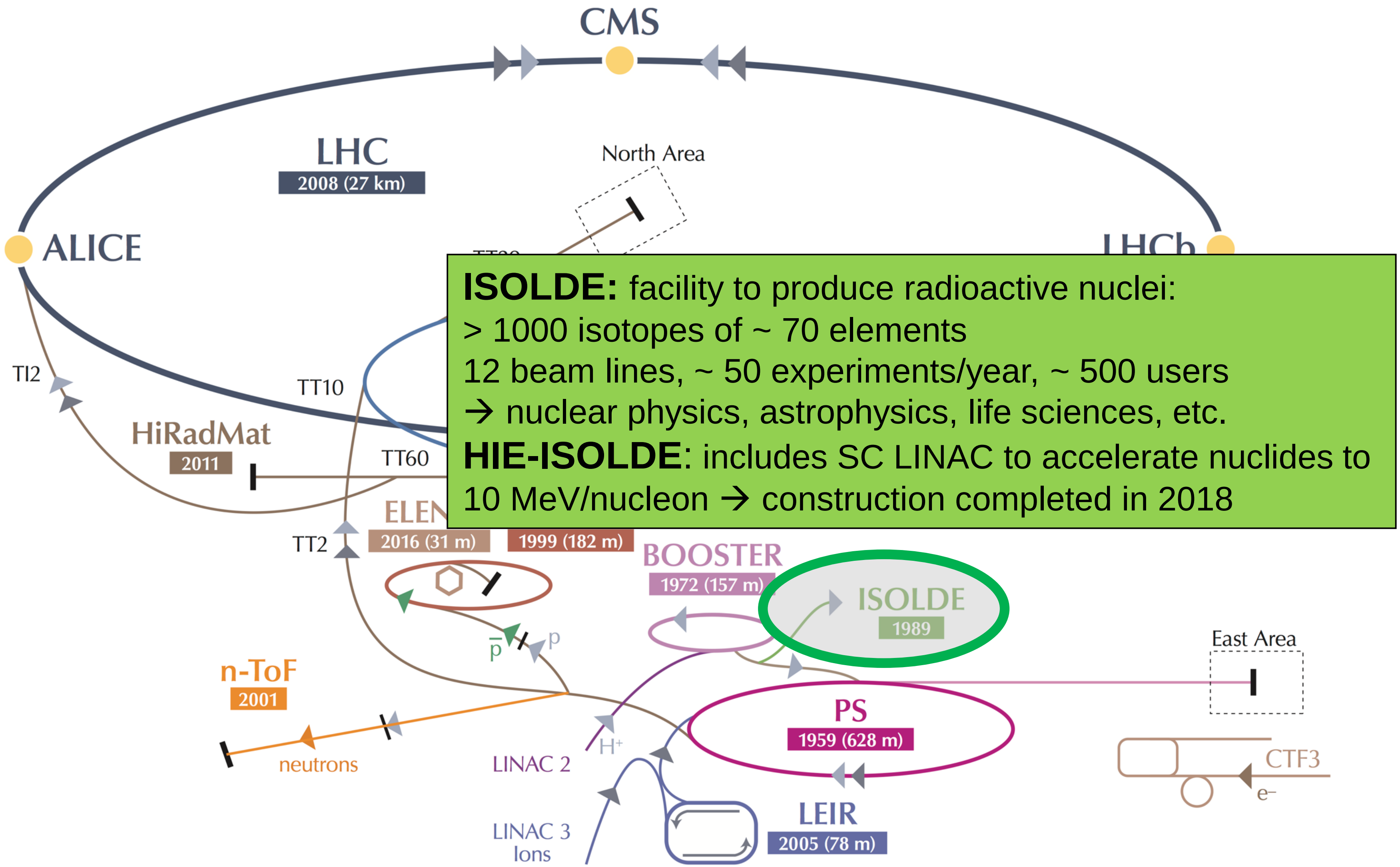
Neutrino Platform: ν detectors R&D for experiments in US, Japan

n-TOF: n-induced cross-sections

UA9: crystal collimation

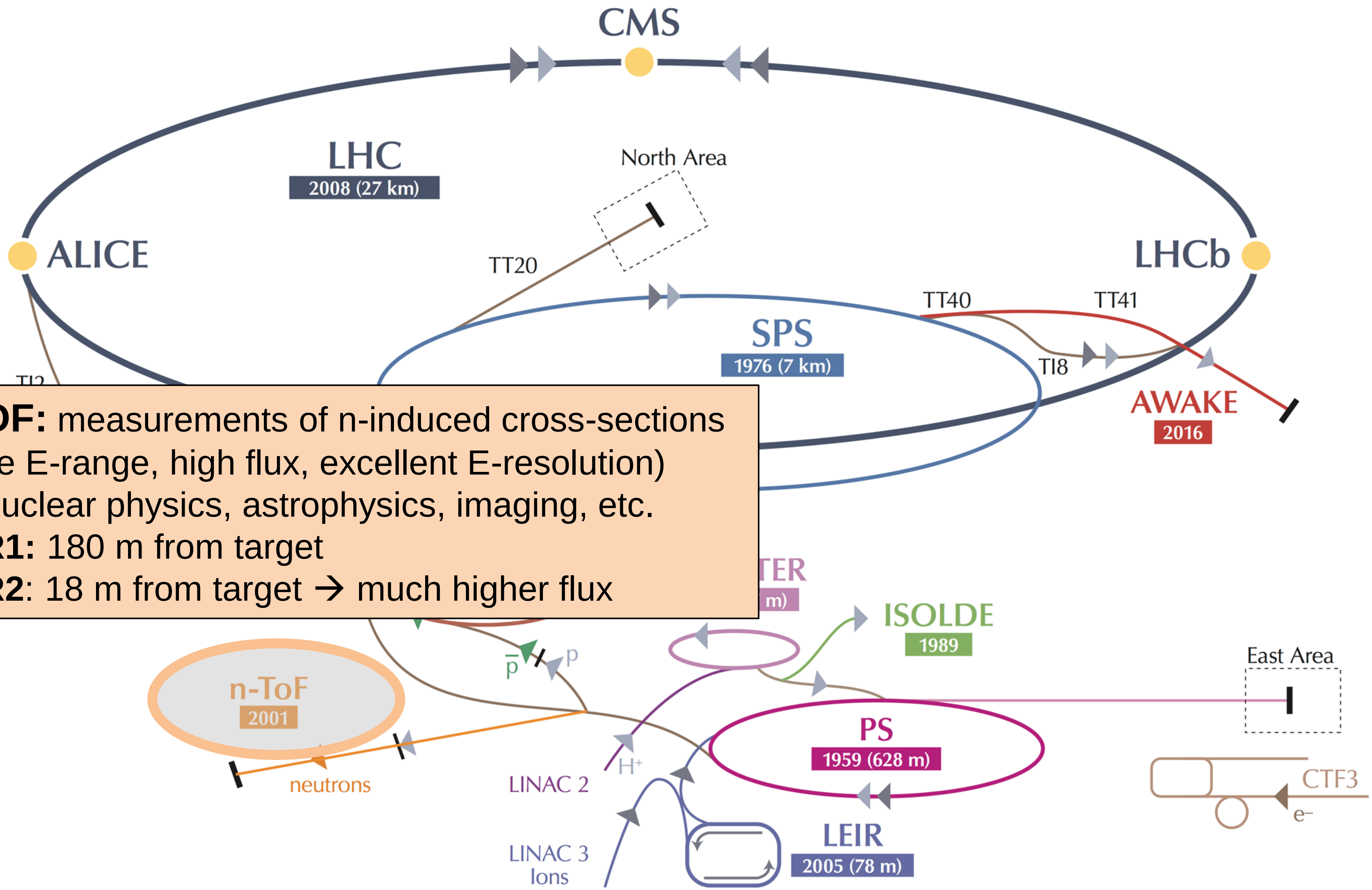
Exploits unique capabilities of CERN's accelerator complex; complementary to other efforts in the world → future opportunities being explored by "Physics Beyond Colliders" Study Group

Scientific diversity: a compelling programme beyond the LHC



ISOLDE: facility to produce radioactive nuclei:
> 1000 isotopes of ~ 70 elements
12 beam lines, ~ 50 experiments/year, ~ 500 users
→ nuclear physics, astrophysics, life sciences, etc.
HIE-ISOLDE: includes SC LINAC to accelerate nuclides to 10 MeV/nucleon → construction completed in 2018

Scientific diversity: a compelling programme beyond the LHC

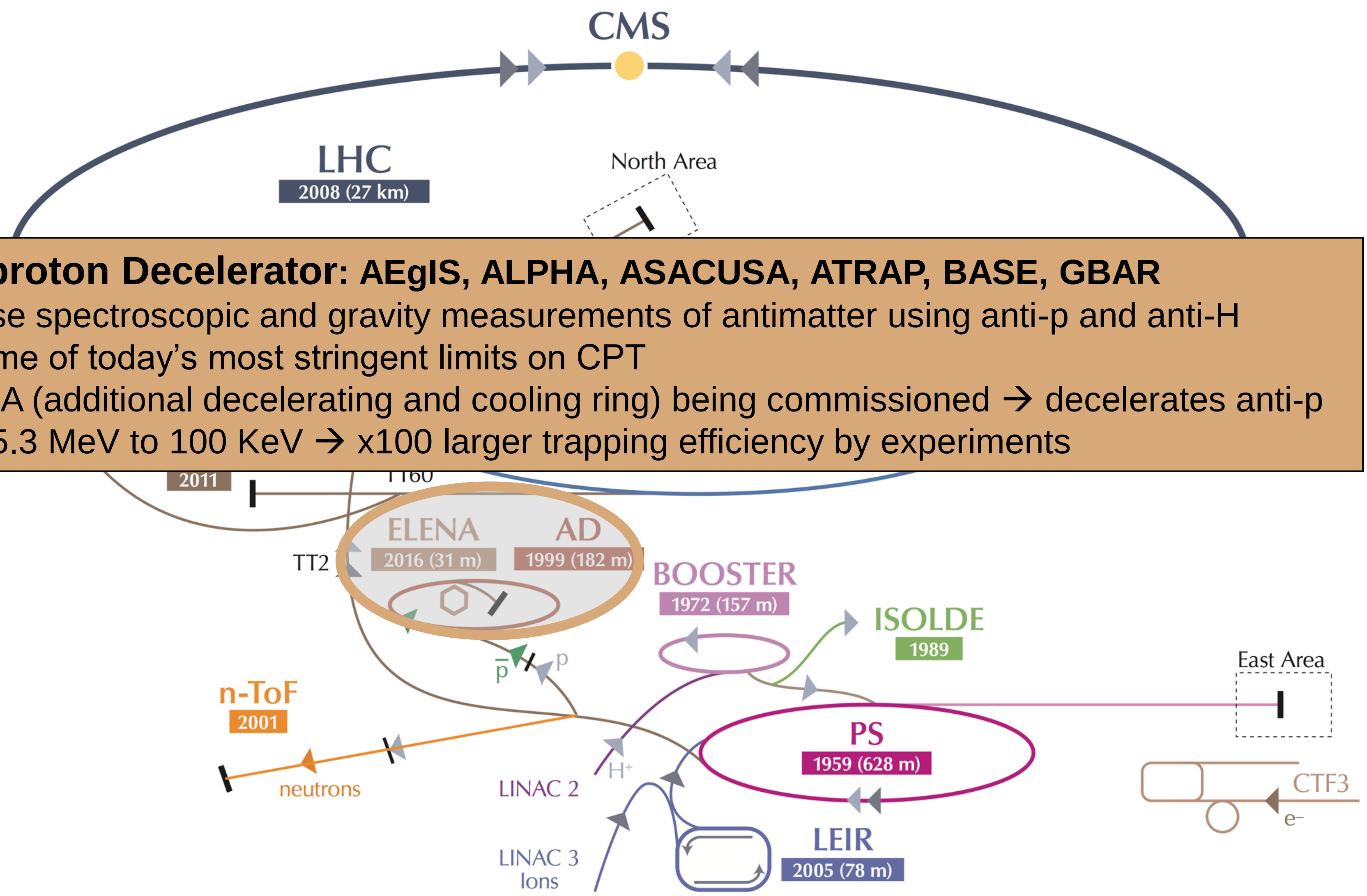


nTOF: measurements of n-induced cross-sections (wide E-range, high flux, excellent E-resolution)
→ nuclear physics, astrophysics, imaging, etc.

EAR1: 180 m from target

EAR2: 18 m from target → much higher flux

Scientific diversity: a compelling programme beyond the LHC



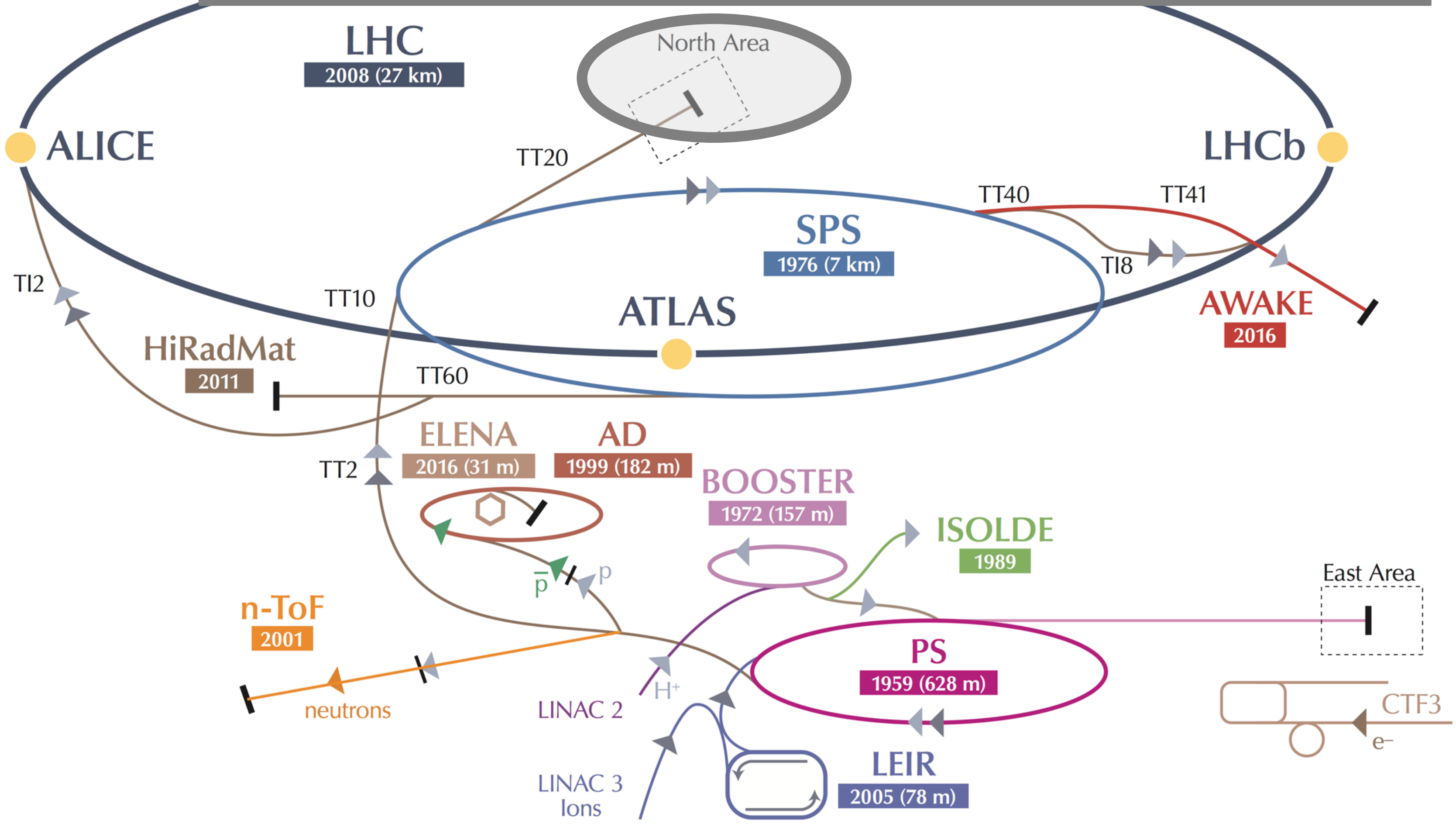
Antiproton Decelerator: AEgIS, ALPHA, ASACUSA, ATRAP, BASE, GBAR

Precise spectroscopic and gravity measurements of antimatter using anti-p and anti-H
→ some of today's most stringent limits on CPT

ELENA (additional decelerating and cooling ring) being commissioned → decelerates anti-p from 5.3 MeV to 100 KeV → x100 larger trapping efficiency by experiments

Scientific diversity: a compelling programme beyond the LHC

NA62: measure the rare, theoretically well known, $K^+ \rightarrow \pi^+ \nu\nu$ decay ($BR \sim 10^{-10}$ in SM) using high-intensity kaon beams
→ powerful test of the SM, indirect sensitivity to high-scale new physics



CERN Neutrino Platform

Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos → imply neutrinos have masses and mix
Since then: great progress in understanding ν properties at various facilities all over the world

Nevertheless, several open questions:

- Origin of ν masses (e.g. why so light compared to other fermions ?)
- Mass hierarchy: normal (ν_3 is heaviest) or inverted (ν_3 is lightest) ?
- Why mixing much larger than for quarks ?
- CP violation (observed in quark sector): do ν and anti-ν behave in the same way?
- Are there additional (sterile) ν (hints from observed anomalies)?

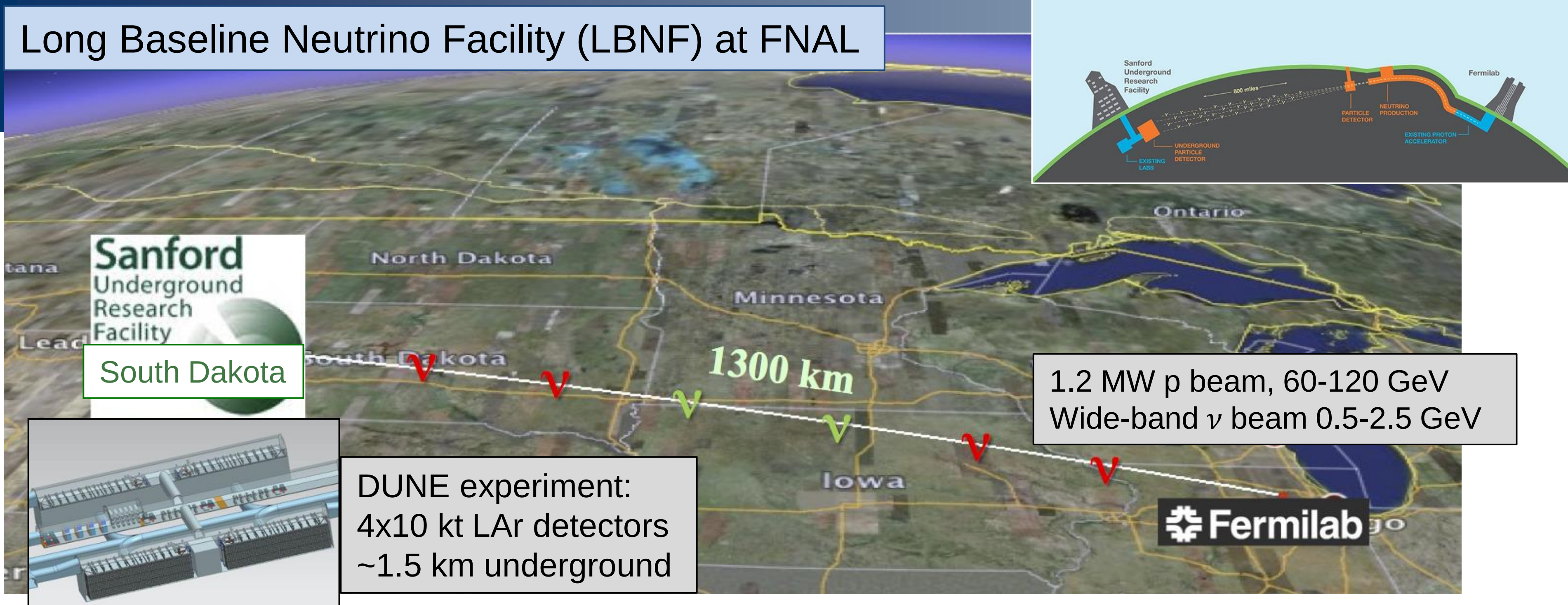
Accelerator experiments can address some of above questions studying $\nu_\mu \rightarrow \nu_e$ oscillations
Need high-intensity p sources (> 1 MW) and massive detectors, as ν are elusive particles and the searched-for effects tiny. Next-generation facilities planned in US and Japan.

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

European Strategy 2013

→ see lectures by S. Pascoli

Long Baseline Neutrino Facility (LBNF) at FNAL

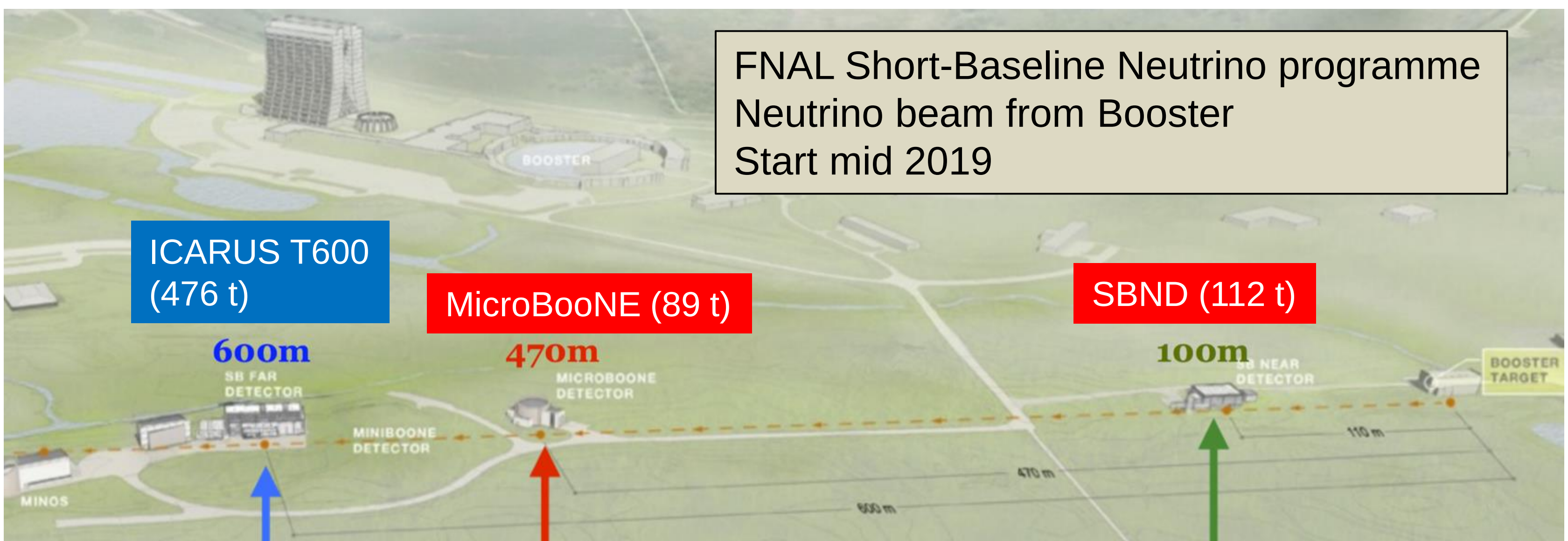


South Dakota

1.2 MW p beam, 60-120 GeV
Wide-band ν beam 0.5-2.5 GeV

DUNE experiment:
4x10 kt LAr detectors
~1.5 km underground

Far site construction started 2017, beam from FNAL ~ 2026



FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start mid 2019

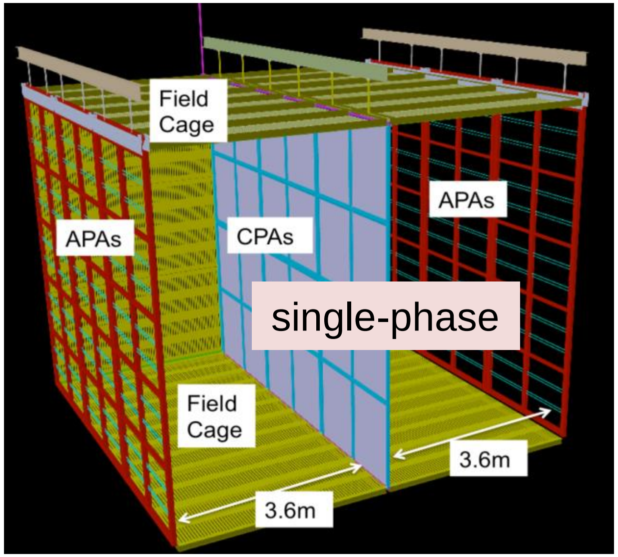
ICARUS T600 (476 t)

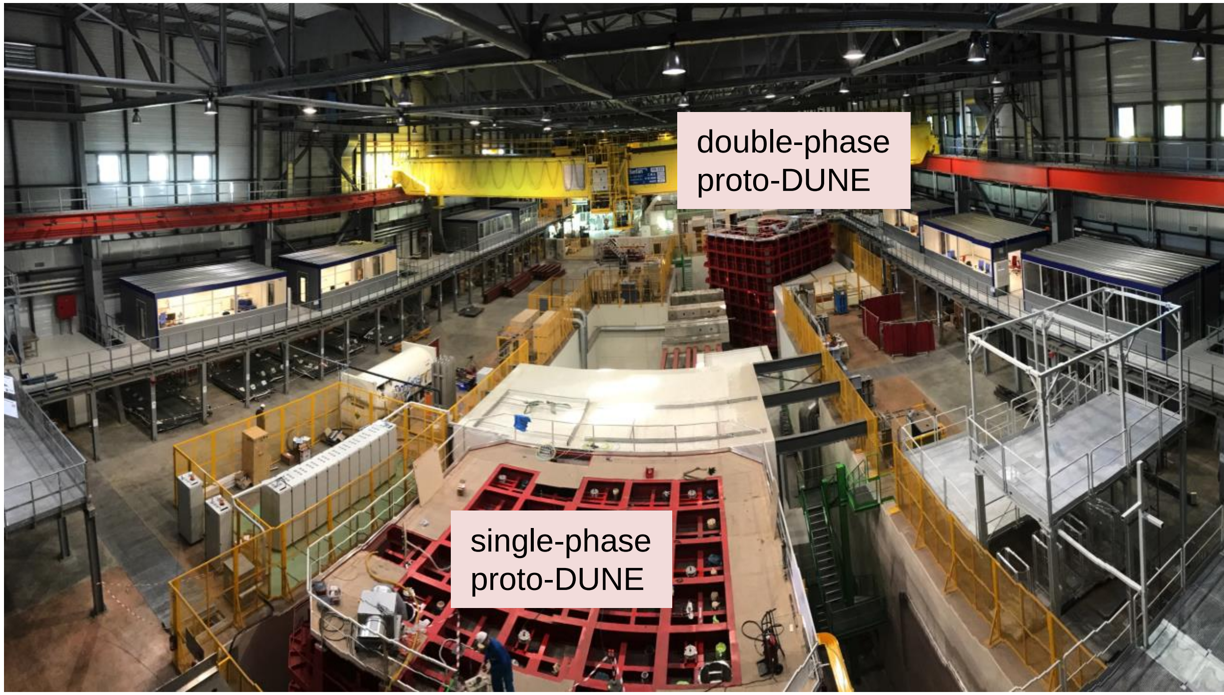
MicroBooNE (89 t)

SBND (112 t)

CERN Neutrino Platform

- ❑ supports European participation in accelerator-based neutrino projects in US and Japan
- ❑ North Area extension completed → provides charged beams and test space for neutrino detectors
- ❑ R&D to demonstrate large-scale LAr technology (cryostats, detectors, …); construction of cryostat for first DUNE module; participation in construction and test of two prototypes of DUNE detector: single and double-phase LAr TPC, ~ 6x6x6 m^3, ~ 700 tons





Preparation for the future

Higgs boson at future colliders

The H boson is not just … "another particle":
- ❑ Profoundly different from all elementary particles discovered previously
- ❑ Related to the most obscure sector of Standard Model
- ❑ Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

→ Its discovery opens new paths of exploration, provides a privileged door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \lambda H \psi \bar{\psi} + \cancel{\mu}^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour naturalness stability C.C.

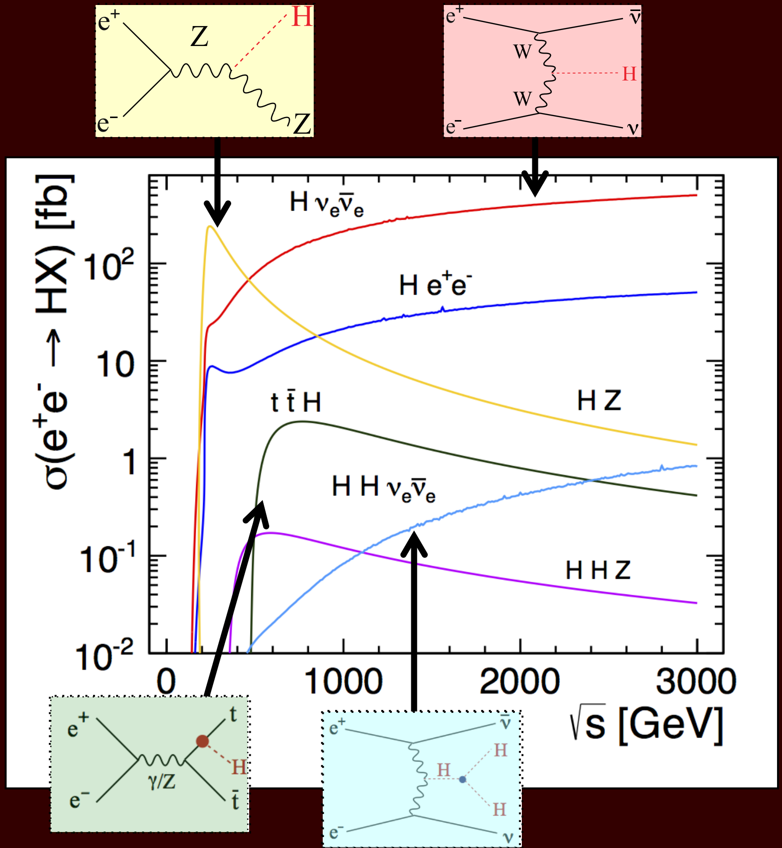
G.F. Giudice

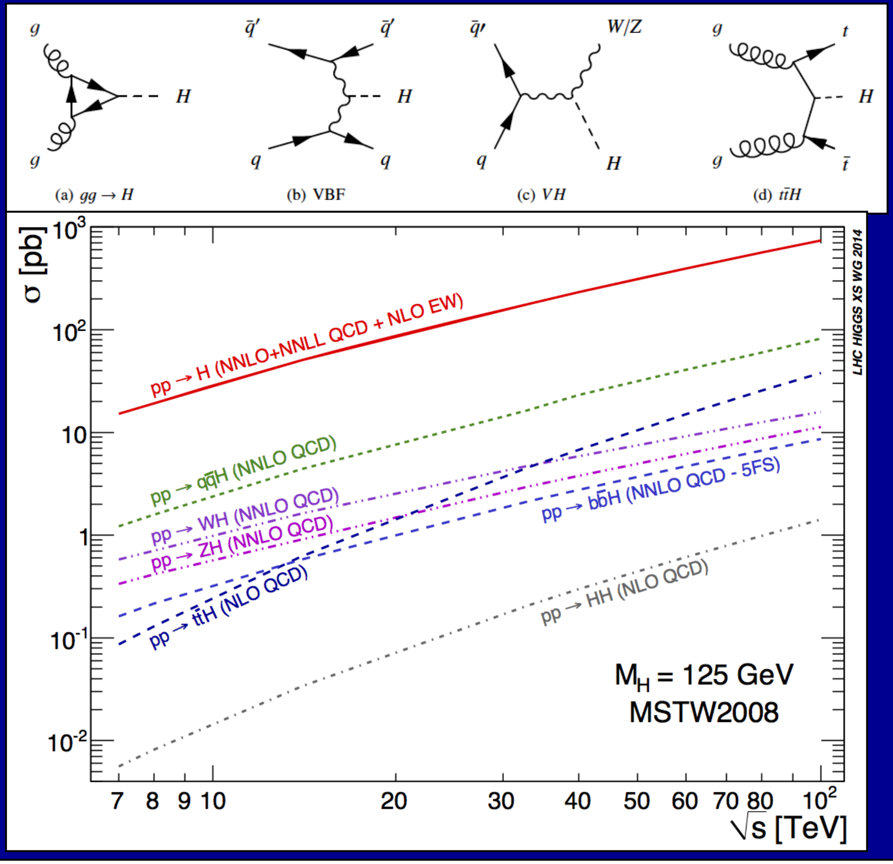
- ❑ Precision measurements of couplings (as many generations as possible, loops, …)
- ❑ Forbidden and rare decays (e.g. H→ τμ) → flavour structure and source of fermion masses
- ❑ H potential (HH production, self-couplings) → EWSB mechanism
- ❑ Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- ❑ Other H properties (width, CP, …)
- ❑ Searches for additional H bosons
- ❑ Etc.

→ See lectures by F. Maltoni

e⁺e⁻ colliders

pp colliders





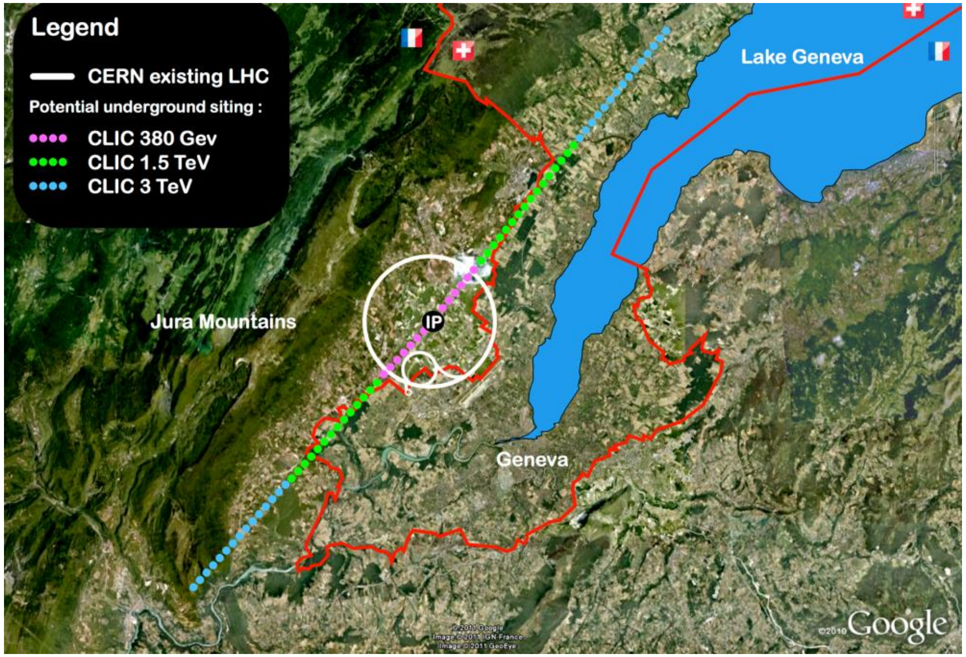
- ❑ Low backgrounds → all decay modes (hadronic, invisible, exotic) accessible
- ❑ Model-indep. coupling measurements: σ(HZ) and Γ_H from data
- ❑ ttH and HH require √s ≥ 500 GeV

- ❑ High energy, huge cross-sections
- → optimal for (clean) rare decays and heavy final states (ttH, HH)
- ❑ Huge backgrounds → not all channels accessible; only fraction of events usable
- ❑ Model-dep. coupling measurements: Γ_H and σ (H) from SM

Compact Linear Collider (CLIC)

Linear e^+e^- collider with $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine
→ based on normal-conducting accelerating structures and a two-beam acceleration scheme: power transfer from low-E high-intensity drive beam to (warm) accelerating structures of main beam



Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

Physics goals:
- ❑ Direct discovery potential and precise measurements of new particles (couplings to Z/γ*) up to m~ 1.5 TeV
- ❑ Indirect sensitivity to E scales Λ ~ O(100) TeV
- ❑ Measurements of “heavy” Higgs couplings: ttH to ~ 7%, HH ~ 20%

Future Circular Colliders (FCC)

Conceptual design study of a ~100 km ring:

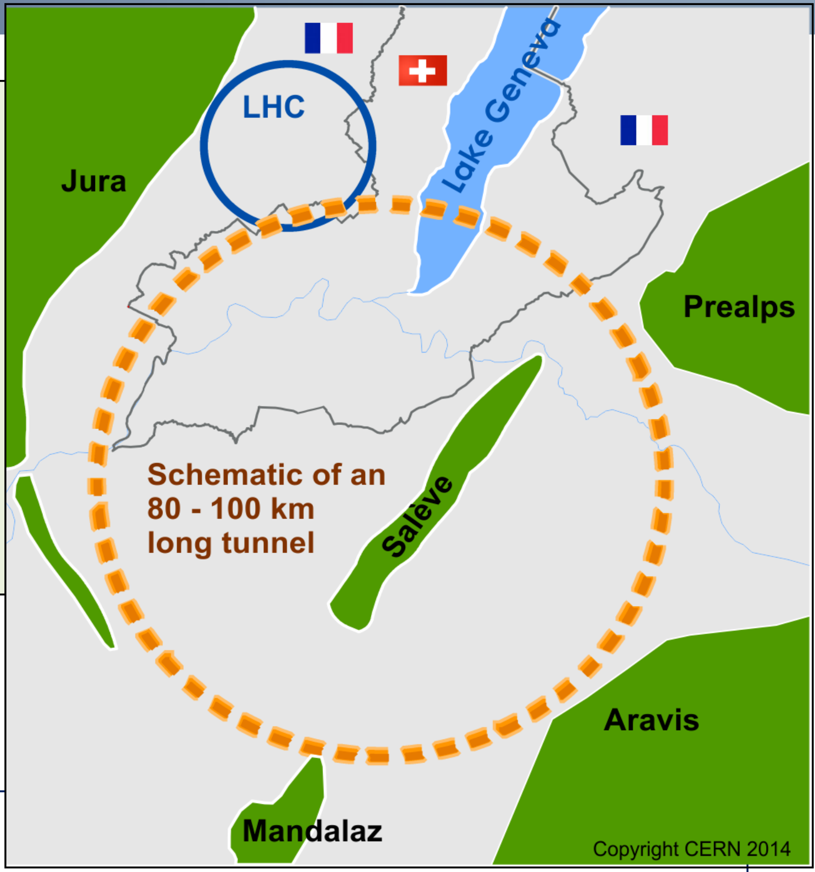
- **pp collider (FCC-hh):** ultimate goal

  $\sqrt{s}$ ~ 100 TeV, L~2x10^{35}; 4 IP, ~20 ab^{-1}/expt

- **e^+e^- collider (FCC-ee):** possible first step

  $\sqrt{s}$ = 90-350 GeV, L~200-2 x 10^{34}; 2 IP

- **pe collider (FCC-he):** option $\sqrt{s}$ ~ 3.5 TeV, L~10^{34}



Also part of the study: HE-LHC**:** FCC-hh dipole technology (~16 T) in LHC tunnel → $\sqrt{s}$ ~ 27 TeV

FCC-hh: a ~100 TeV pp collider is expected to:
- explore directly the 10-50 TeV E-scale
- conclusive exploration of EWSB dynamics
- say the final word about heavy WIMP dark matter

FCC-ee: 90-350 GeV
- measure many Higgs couplings to few permill
- indirect sensitivity to E-scale up to O(100 TeV) by improving by ~20-200 times the precision of EW parameters measurements, ΔM_W < 1 MeV, Δm_{top} ~ 10 MeV

Conclusions (I)

These are very exciting times in particle physics

The Standard Model is complete and works very well with no significant “cracks” as yet
→ we don’t understand why, as it is unable to address the outstanding questions

⬇

There must be new physics → BUT at which energy scale???
And with which strength does it couple to the SM particles?

Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of E scales and couplings, and to properly interpret signs of new physics.

Conclusions (II)

Historically, high-energy accelerators have been our most powerful tool for exploration in particle physics

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The full exploitation of the LHC, and more powerful future colliders, will be needed to advance our knowledge of fundamental physics.

No doubt that future high-E colliders are extremely challenging projects

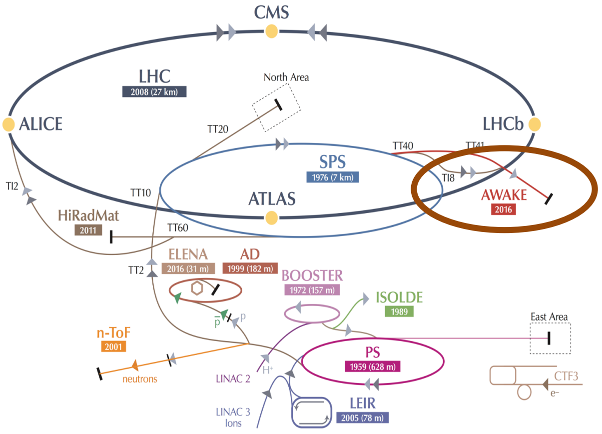
However: the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. Instead, we should use our creativity to develop the technologies needed to make future projects financially and technically affordable

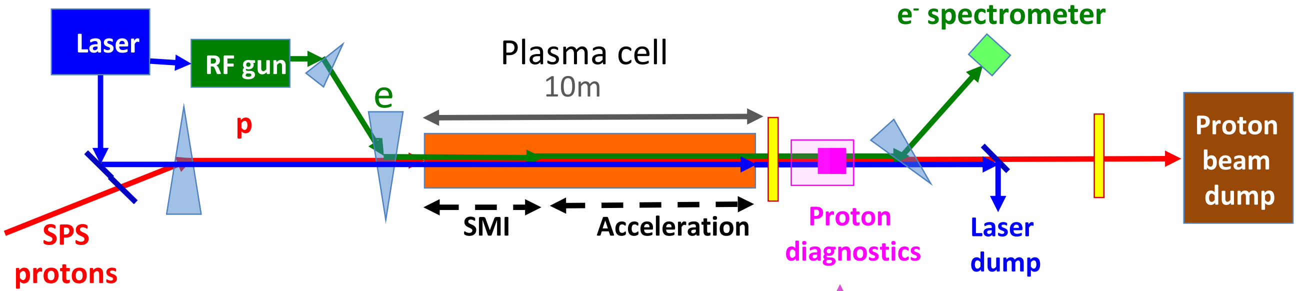
EXTRA

AWAKE

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

R&D experiment: proof-of-concept demonstration of a novel acceleration technique: use 400 GeV SPS protons to generate strong EM fields in a 10 m plasma cell → externally injected e^- beam accelerated in the wake of the p beam. Aim at e^- acceleration of ~GeV/m → compact accelerators. Started end 2016.





Measured with optical transition radiation + streak camera