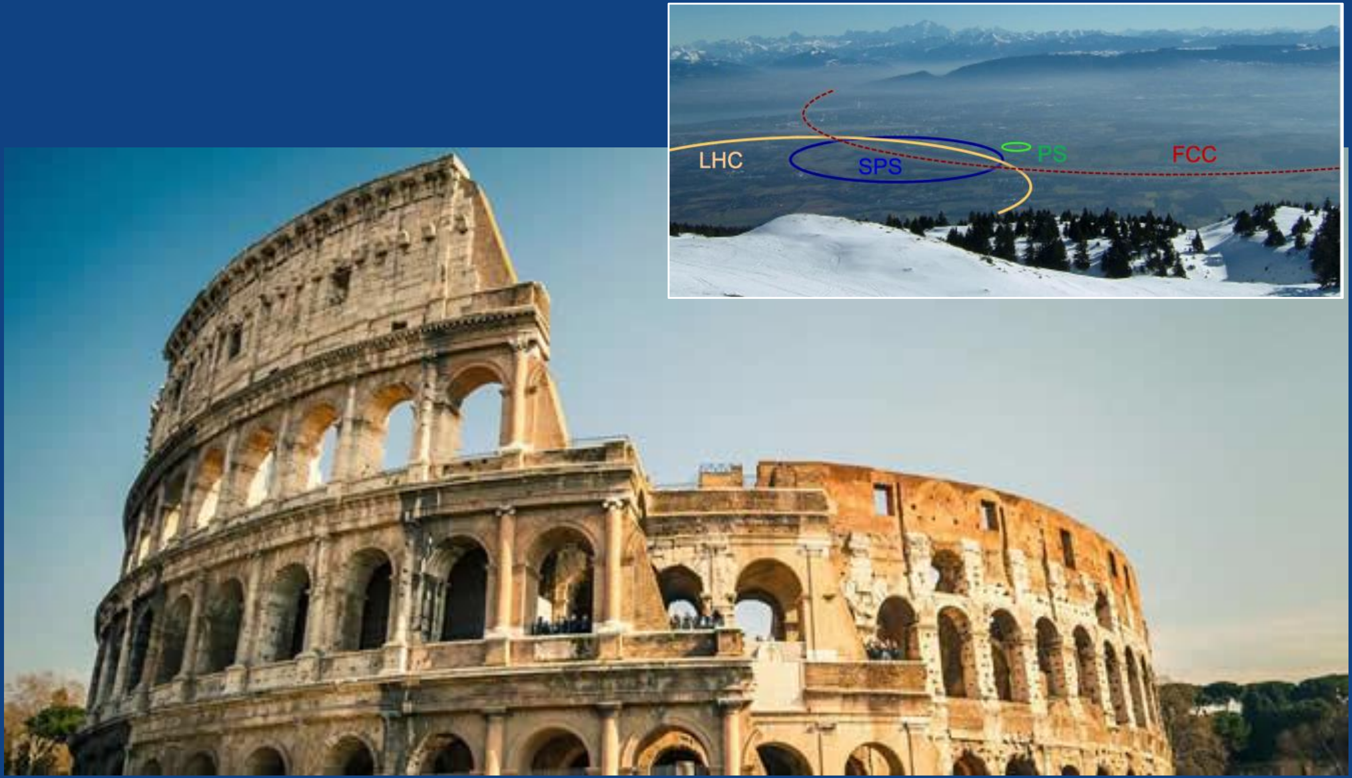
CERN roadmap and FCC



Fabiola Gianotti, FCC Workshop, Rome, 11 April 2016

CERN scientific roadmap

Full exploitation of the LHC:

- ❑ Run 2 started last year → goal this year is $L=10^{34}$ at $\sqrt{s}$ =13 TeV, ~25 fb^{-1}
- ❑ building upgrade of injectors (LIU), collider (HL-LHC) and detectors (Phase-1 and Phase-2)

Diversity programme serving a broad community:

- ❑ ongoing experiments and facilities at Booster, PS, SPS and their upgrades (ELENA, HIE-ISOLDE)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through the 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 for scientific diversity programme (new)

CERN roadmap

Full exploitation of the LHC:

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Preparatio

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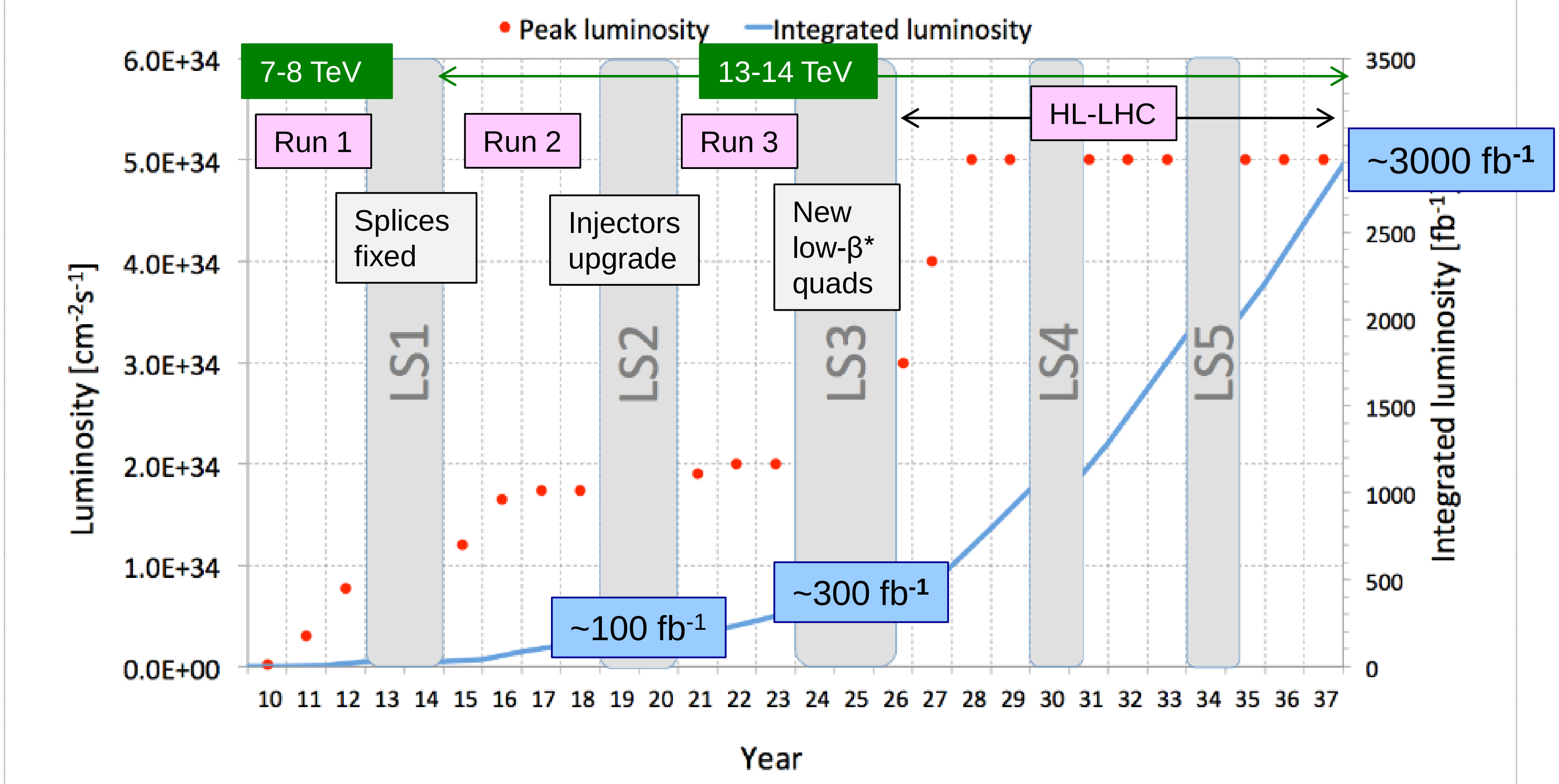
☐ future opp scientific diversity programme (new)

Important milestone: update of the European Strategy for Particle Physics (~ 2019-2020)

1) Full exploitation of the LHC

LHC and HL-LHC



LHC is today's most powerful collider → full exploitation ($\sqrt{s}$ ~ 14 TeV, 3000/fb) is mandatory:

❑ If new physics discovered in Run 2-3:

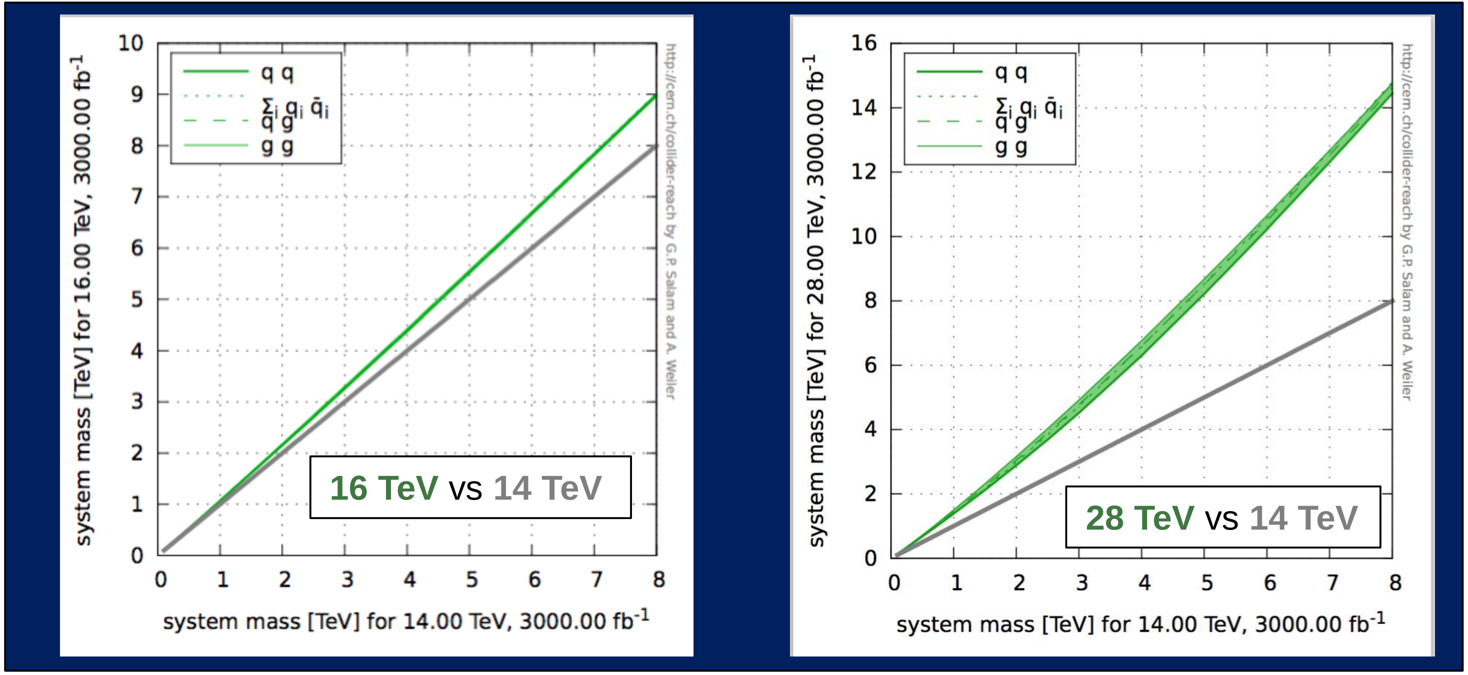
→ first detailed exploration of new physics with well understood machine and experiments while building next accelerator

❑ If no new physics in Run 2-3:

→ extend direct discovery potential by ~ 20-30% (up to m ~ 10 TeV)

In either case: measure H couplings to few percent (including 2nd generation: Hμμ)

Higher √s in the LHC tunnel ?



Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:

1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb$_3$Sn magnets)

→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability

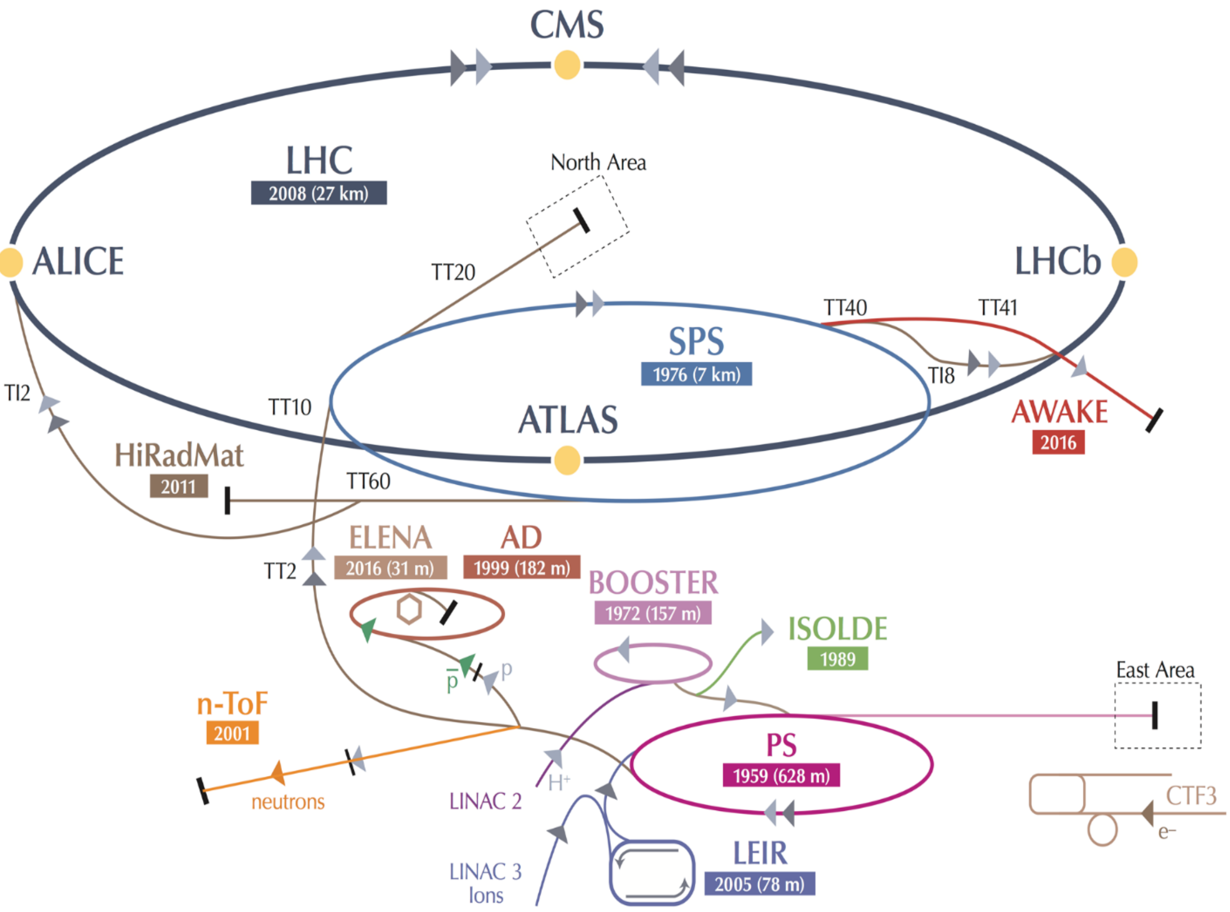
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ √s~ 30 TeV)

- ☐ uses existing tunnel and infrastructure; can be built at fixed budget
- ☐ strong physics case if new physics from LHC/HL-LHC
- ☐ powerful demonstration of the FCC-hh magnet technology

2) Scientific diversity programme

A compelling scientific programme beyond the LHC



~20 experiments > 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: ions and neutrino targets

NA62: rare kaon decays

NA63: radiation processes in strong EM fields

n-TOF: n-induced cross-sections

UA9: crystal collimation

Neutrino Platform: collaborating with experiments in US and Japan → see later

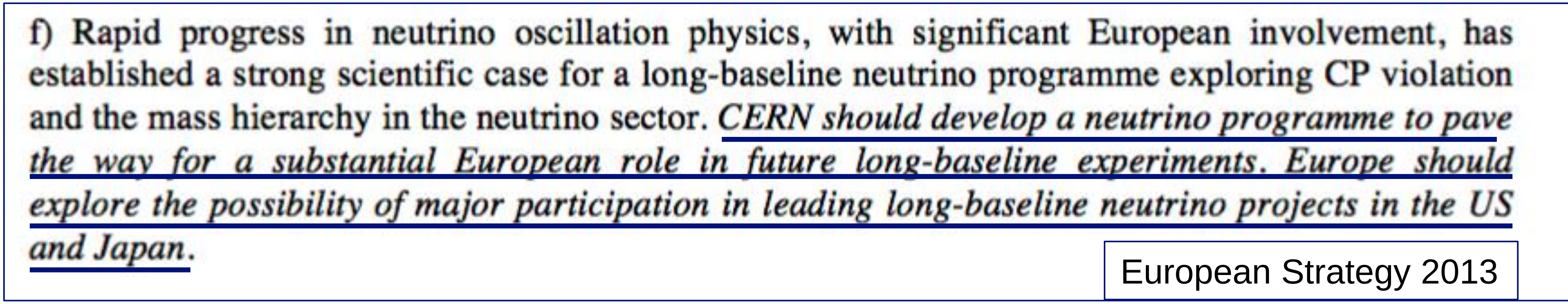
CERN neutrino activities

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)?

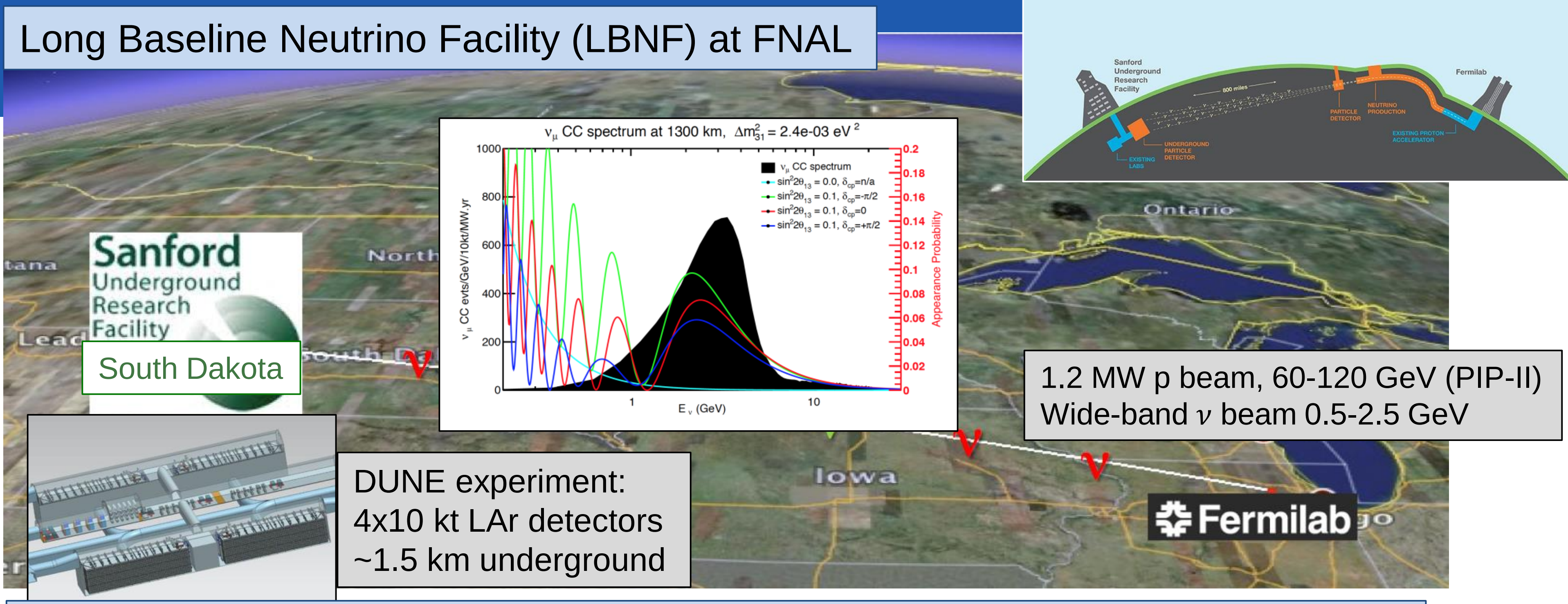
Accelerator experiments can address some of above questions studying $\nu_\mu \rightarrow \nu_e$ oscillations
Need high-intensity p sources (> 1MW) and massive detectors, as ν are elusive particles and the searched-for effects tiny → Next-generation facilities planned in US and Japan.



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

Long Baseline Neutrino Facility (LBNF) at FNAL

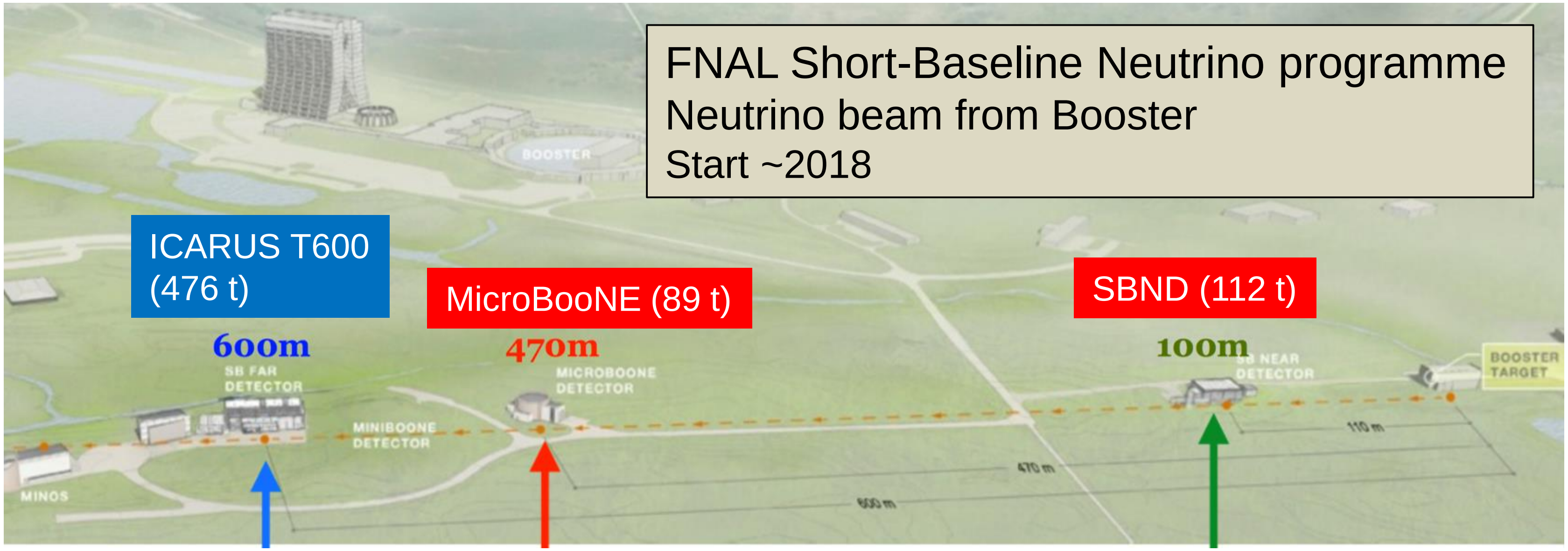


South Dakota

1.2 MW p beam, 60-120 GeV (PIP-II)
Wide-band ν beam 0.5-2.5 GeV

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

Far site construction starts ~2017, 1st detector installed ~2022, beam from FNAL ~ 2026



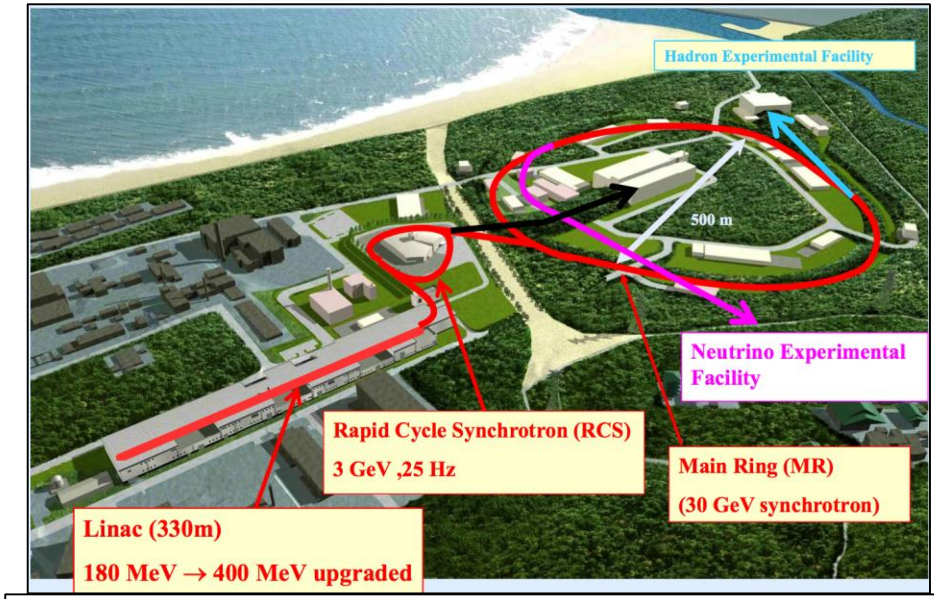
FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start ~2018

ICARUS T600
(476 t)

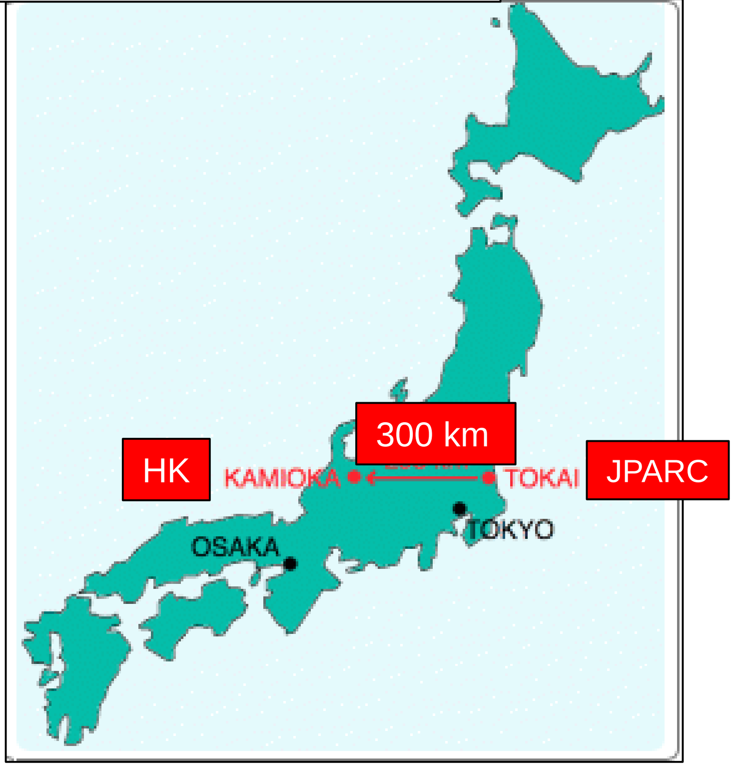
MicroBooNE (89 t)

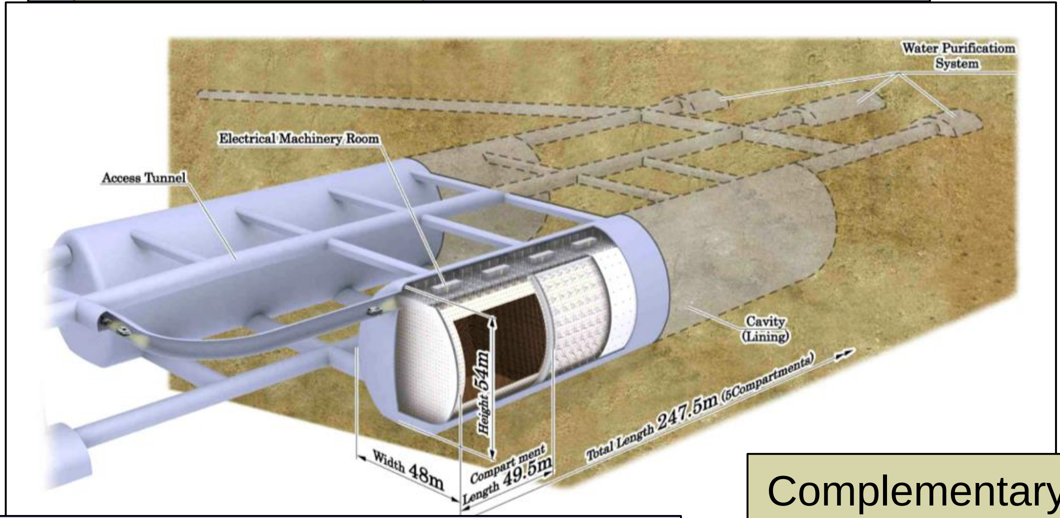
SBND (112 t)

Hyper-Kamiokande, JPARC: construction could start ~2018



0.38 → 0.75 → > 1 MW p source
E_p = 30 GeV → E_ν~ 0.6 GeV
Narrow-band ν beam
→ high intensity at oscillation peak

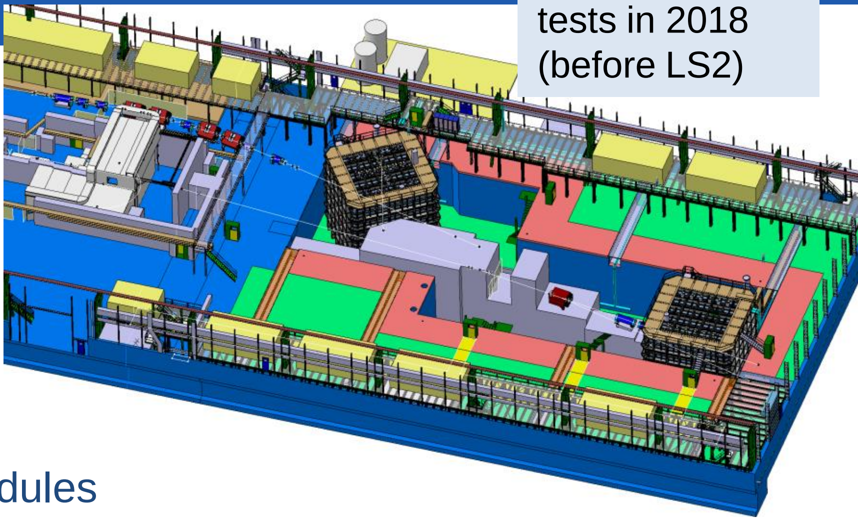




~0.5 Mton Water Cerenkov detector
(~20 x Super-K)
~ 1 km underground
~ 2.5^0 off-axis → narrow-band beam

Complementary to LBNE: different detector technology, shorter baseline (→ less sensitive to mass hierarchy), narrow-band beam (→ high statistics of ν/anti-ν at oscillation peak but limited measurement of oscillation spectrum)

CERN Neutrino Platform



ready for beam tests in 2018 (before LS2)

Mission:

- ☐ Provide charged beams and test space to neutrino community → North Area extension
- ☐ Support European participation in accelerator neutrino experiments in US and Japan:

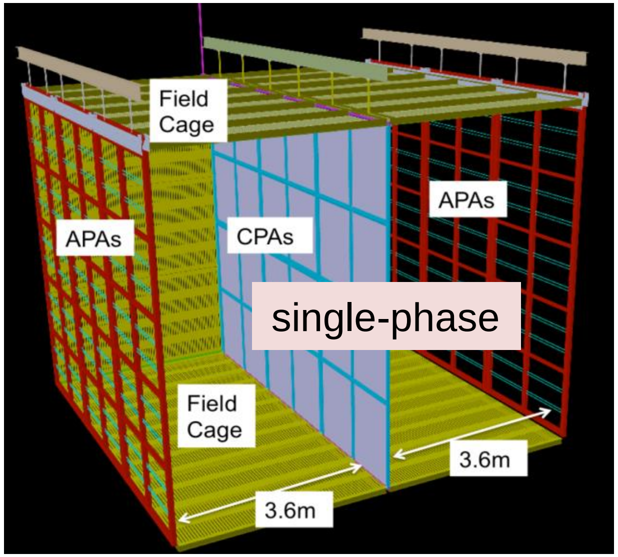
→ R&D to demonstrate large-scale LAr technology (cryostats, cryogenics, detectors)

→ Construction of one cryostat for DUNE detector modules

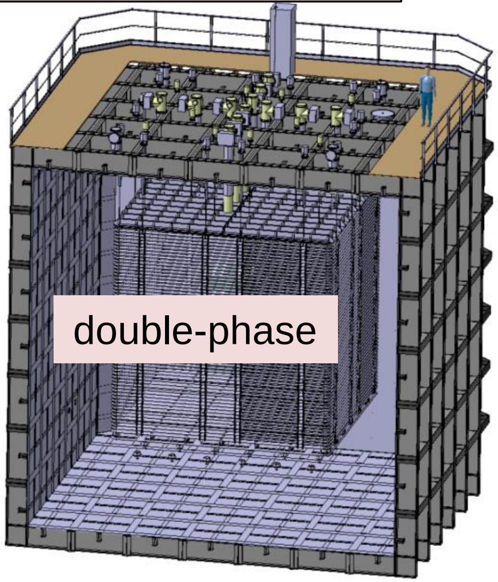
→ Construction of BabyMIND magnet: muon spectrometer for WAGASCI experiment at JPARC

Refurbishment of ICARUS T600 for short baseline programme
→ ship to FNAL beg 2017

Construction and test of “full-scale” prototypes of DUNE drift cells: ~ 6x6x6 m^3, ~ 700 tons



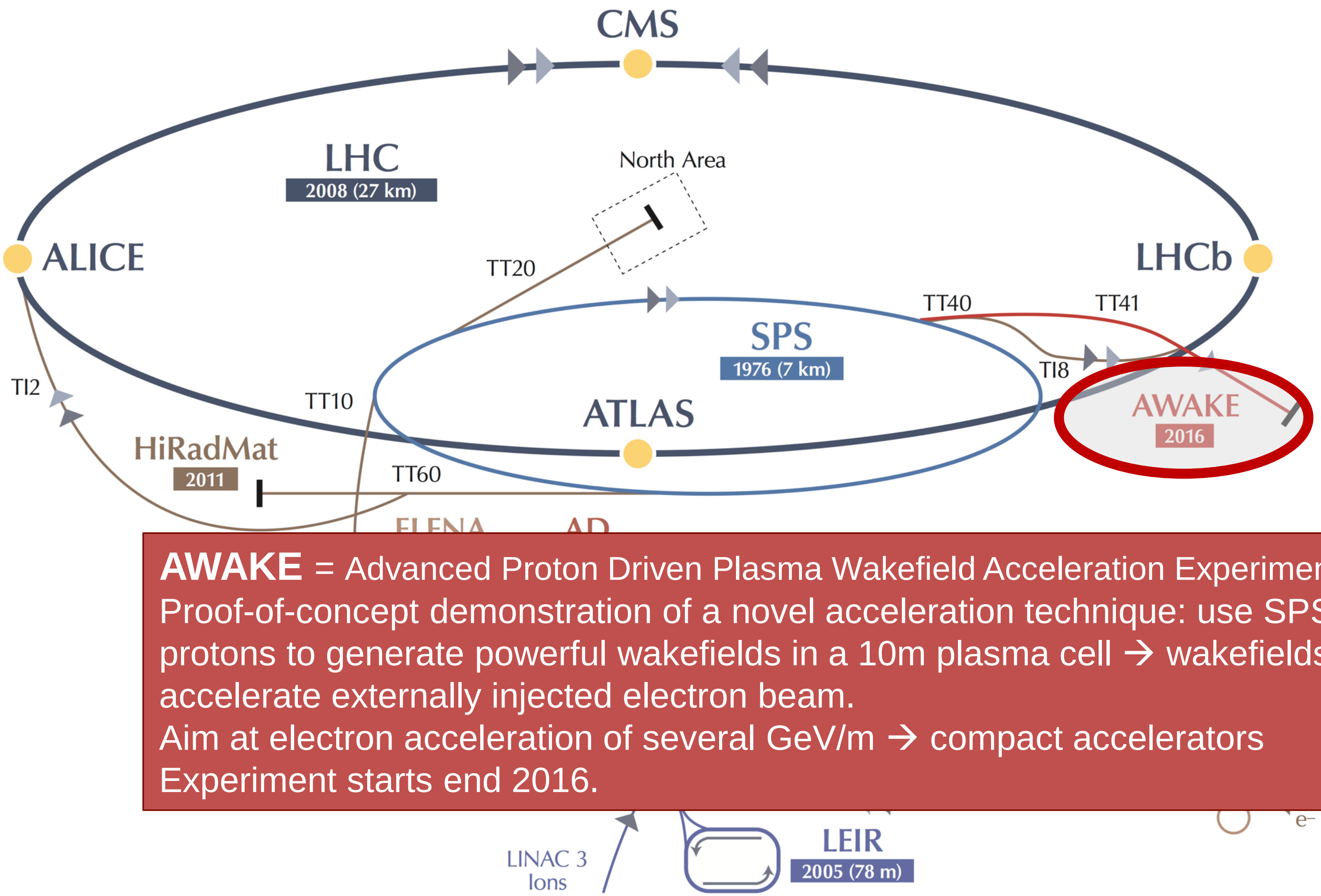
single-phase



double-phase

3) Preparation of CERN’s future

R&D on novel acceleration technologies



AWAKE = Advanced Proton Driven Plasma Wakefield Acceleration Experiment
Proof-of-concept demonstration of a novel acceleration technique: use SPS protons to generate powerful wakefields in a 10m plasma cell → wakefields accelerate externally injected electron beam.
Aim at electron acceleration of several GeV/m → compact accelerators
Experiment starts end 2016.

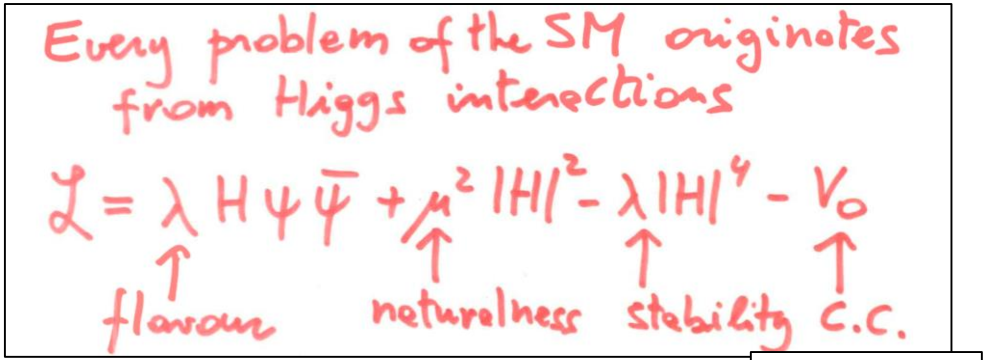
Two main goals of future high-energy/high-intensity colliders

1) Higgs boson studies

H boson is not just “yet another particle”:

- Profoundly different from all elementary particles discovered so far
- Related to the most obscure sector of SM
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

Its discovery opens new paths of exploration, and a very broad and challenging experimental programme: couplings, self-couplings, rare/exotic decays, searches for additional H, etc.



Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\underset{\text{flavour}}{\uparrow}}{\lambda} H \psi \bar{\psi} + \underset{\underset{\text{naturalness}}{\uparrow}}{\mu^2} |H|^2 - \underset{\underset{\text{stability}}{\uparrow}}{\lambda} |H|^4 - \underset{\underset{\text{c.c.}}{\uparrow}}{V_0}$$

G.F. Giudice

2) Searches for new physics

- the known unknown (e.g. dark matter)
- the unknown unknown → exploration for uncharted territory
- are we asking ourselves the right questions ?

Using direct observation (→ requires high energy) and indirect evidence through precision measurements (→ requires mainly high intensity)

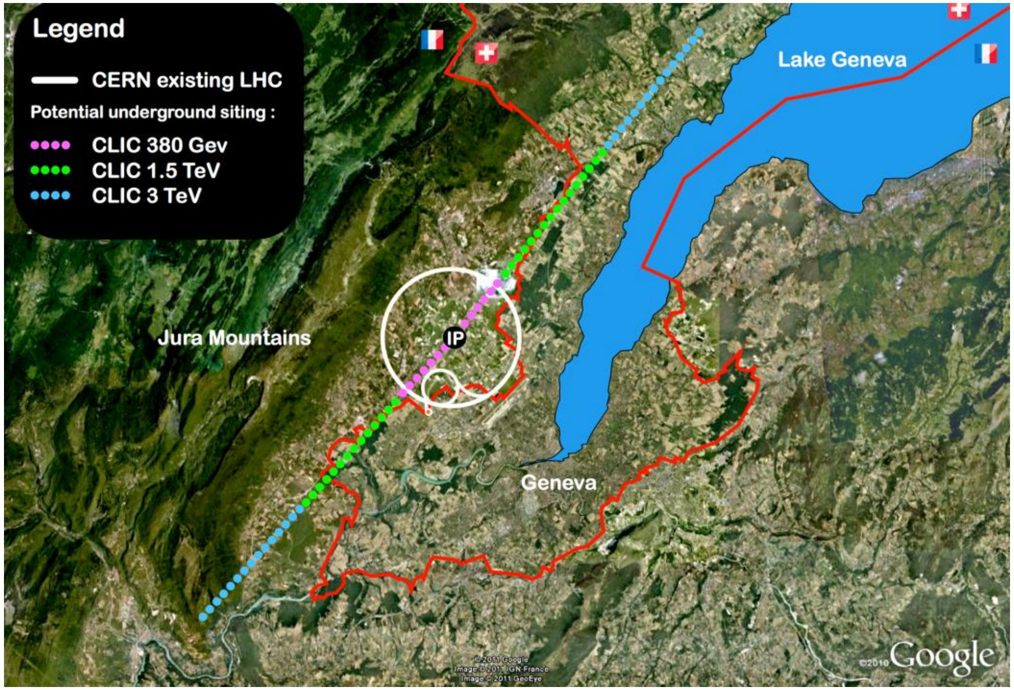
Compact Linear Collider (CLIC)

Linear e^+e^- collider $\sqrt{s}$ 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

- ☐ Direct discovery potential and precise measurements of new particles (couplings to Z/γ^*) up to m~ 1.5 TeV
- ☐ Indirect sensitivity to E scales $\Lambda \sim O(100)$ TeV
- ☐ Measurements of “heavy” Higgs couplings: ttH to ~ 4%, HH ~ 10%

Most recent operating scenario: start at $\sqrt{s}$=380 GeV for H and top physics



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

CLIC

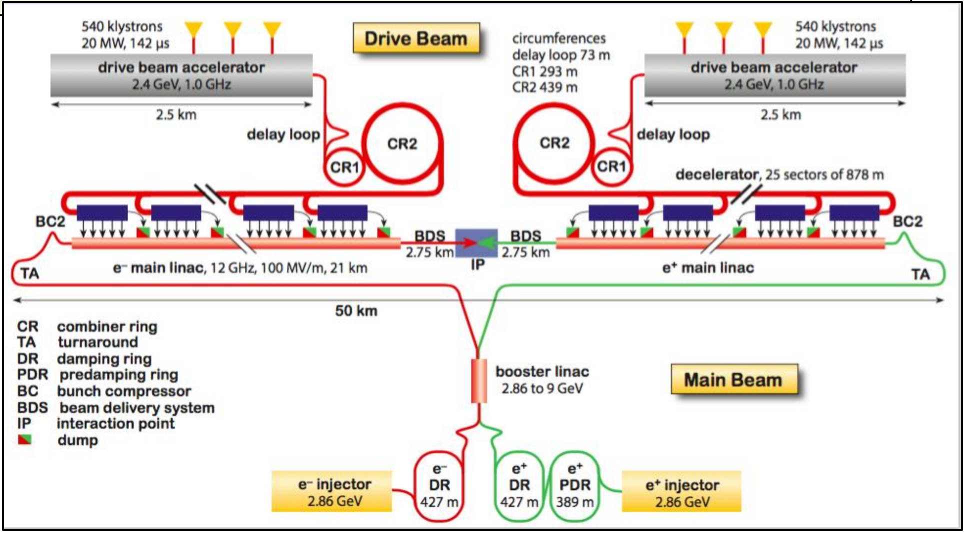
International Collaboration: ~80 Institutions
CDR completed end 2012
→ Until ES update:

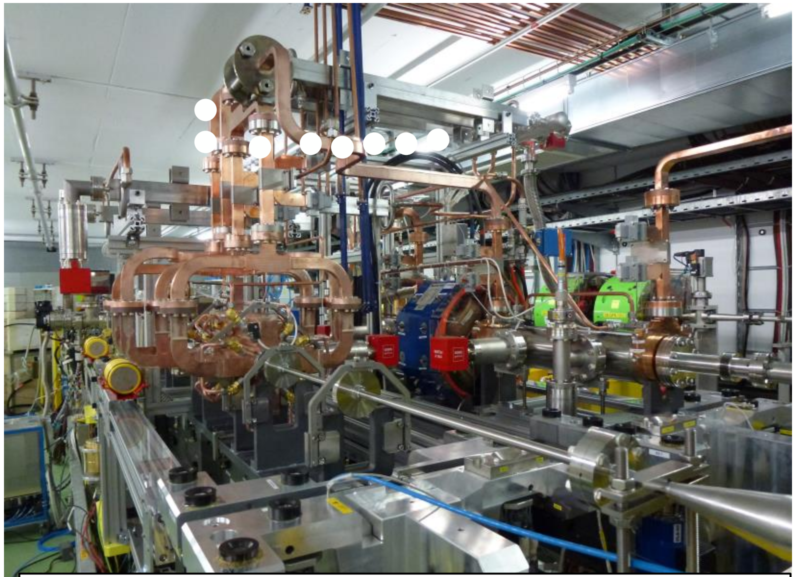
- ❑ develop plan for staged implementation
- ❑ complete key technical feasibility R&D
- ❑ cost and schedule review

Challenges:

- ❑ minimise RF breakdown rate in cavities
- ❑ efficient RF power transfer from drive beam to main beam
- ❑ reduction of power consumption (600 MW at 3 TeV)
- ❑ nm size beams, final focus
- ❑ huge beamstrahlung in detectors

CTF3 facility: testing two-beam acceleration concept: efficient power transfer from high-intensity low-E “drive” beam to the accelerating structure of the main (“probe”) beam.
→ to be completed in 2016





CLIC two-beam module under test in CTF3

CLIC construction could technically start ~2025, duration ~6 years for √s ~ 380 GeV (11 km Linac)
→ physics could start by ~2035

FCC: physics reach in a nutshell

FCC-hh: 100 TeV

- explore directly the 10-50 TeV E-scale
- provide conclusive exploration of EWSB dynamics
- study nature the Higgs potential and EW phase transition
- say final word about heavy WIMP dark matter
- etc.

FCC-ee: 90-350 GeV

- indirect sensitivity to E scales up to O(100 TeV) by measuring most Higgs couplings to O(0.1%), improving the precision of EW parameters measurements by ~20-200, $\Delta M_W < 1$ MeV, $\Delta m_{top} \sim 10$ MeV, etc.
- sensitivity to very-weakly coupled physics (e.g. light, weakly-coupled dark matter)
- etc.

FCC-ep: ~ 3.5 TeV

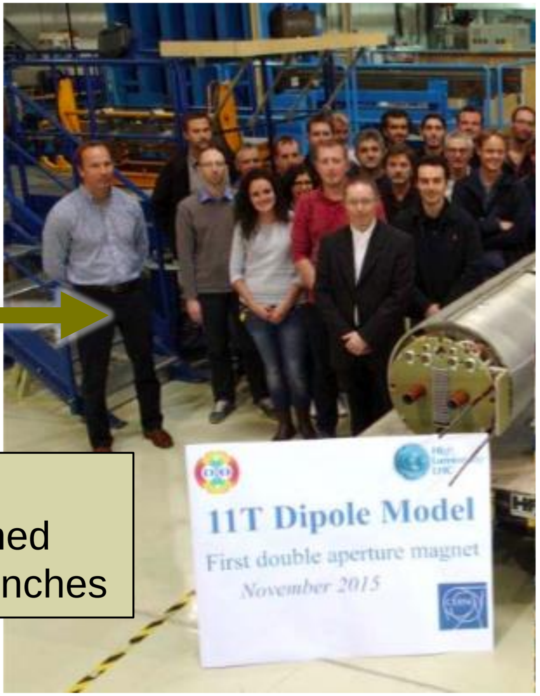
- unprecedented measurements of PDF and α_s
- new physics: leptoquarks, eeqq contact interactions, etc.
- Higgs couplings (e.g. Hbb to ~ 1%)
- etc.

Machines are complementary and synergetic, e.g. from measurement of ttH/ttZ ratio, and using ttZ coupling and H branching ratio from FCC-ee, FCC-hh can measure ttH to ~ 1%

FCC magnet technology: learning from LHC/HL-LHC

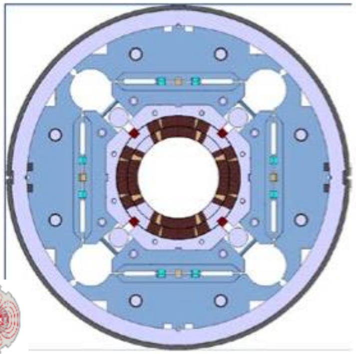
“Natural” continuation of LHC and HL-LHC programmes.
Step-wise approach → each step deployed and operated in a (big) accelerator:

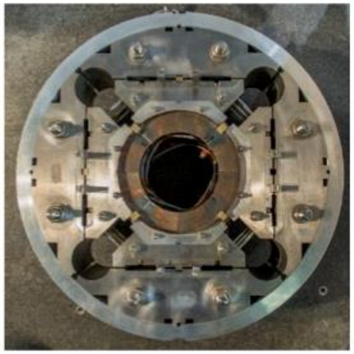
- LHC: 8.3 T → push to ultimate field of 9 T ?
- HL-LHC: Nb_3Sn technology:
  - -- 11 T dipoles in dispersion suppression collimators
  - -- 12-13 T peak field low-β quads for ATLAS and CMS IR’s



December 2015: short (1.8 m) Nb_3Sn two-in-one dipole reached 11.3 T (> nominal) without quenches

March 2016: short (1.5 m) Nb_3Sn quadrupole model (final aperture =150 mm) reached current 18 kA (nominal: 16.5 kA). CERN-US LARP Collaboration (2 coils from CERN + 2 coils from US)





LARP

Future opportunities other than high-energy colliders

A “Physics Beyond Colliders" Study Group has been put in place

Mandate
Explore opportunities offered by CERN accelerator complex and infrastructure to address outstanding questions in particle physics through projects:

❑ complementary to future high-energy colliders (HE-LHC, CLIC, FCC)
❑ exploiting unique capabilities of CERN accelerator complex and infrastructure
❑ complementary to other efforts in the world → optimise resources of the discipline globally
Examples: searches for rare processes and very-weakly interacting particles, electric dipole moments, etc.

→ Enrich and diversify CERN’s future scientific programme

❑ Will bring together accelerator scientists, experimental and theoretical physicists
❑ Kick-off meeting in Summer 2016
❑ Final report end 2018 → in time for European Strategy

One of the goals is to involve interested worldwide community, and to create synergies with other laboratories and institutions in Europe (and beyond)

Conclusions

Today's outstanding questions in fundamental physics can only be successfully addressed through the variety of approaches the field has developed (thanks also to strong advances in accelerator and detector technologies): particle colliders, neutrino experiments, dark matter direct and indirect detection, precision measurements of rare processes, dedicated searches (e.g. axions, dark-sector particles), cosmic surveys, …

The full exploitation of the LHC, and more powerful future accelerators, are an essential component of any future programme aiming at improving our knowledge of fundamental physics. N.B. historically, accelerators have been our most powerful tool for exploration in particle physics

New ideas, vigorous technological developments, perseverance, as well as worldwide collaboration, will be needed to reach the highest energies and intensities and make future accelerators financially and technically affordable.

The extraordinary success of the LHC demonstrates the strength of the community (accelerators, experiments, computing, theory) → a crucial asset in view of future, even more ambitious, projects.

EXTRAS

Projected integrated luminosities of proposed future colliders for current operating scenarios

Integrated luminosities (ab^{-1})

√s	90	~240	350-380	500	1.4	3	70	100	Total $\int L\,dt$ at √s>240 GeV	# of years	# H events at production
	←		GeV	→	←	TeV		→			
FCC-ee	90	10	3						13	~ 15	2 M
CepC		5							5	~10	1 M
ILC		2	0.2	4					6.2	~20	1.6 M
CLIC			0.5		1.5	2			4	~20	1.5 M
SppC							30		30	~10	30 B
FCC-hh								40	40	~25	40 B

2 experiments assumed for CepC, SppC and FCC-hh, 2 for FCC-ee
L upgrade assumed for ILC and crab waist option for FCC-ee

Note:
- ❑ Different definitions of "year" across projects: assumed physics data-taking time varies over 0.5-1.6x10^7 s/year. Note: LHC 2012: 0.6x10^7 s machine operation in physics with stable beams
- ❑ pp colliders: usable H events are ~ 10% of total cross-section due to large backgrounds
- ❑ H studies are only one of several physics goals

Higgs couplings measurements:
- ❑ Couplings to W, Z, g, c, b, τ: best measurements: 0.2-0.8% at FCC-ee (luminosity)
- ❑ Couplings to top: best measurements: few % ILC, CLIC, FCC-hh (heavy final state → energy)
- ❑ Self-couplings HH: best measurements: ~10 % at CLIC, FCC-hh (heavy final state → energy)