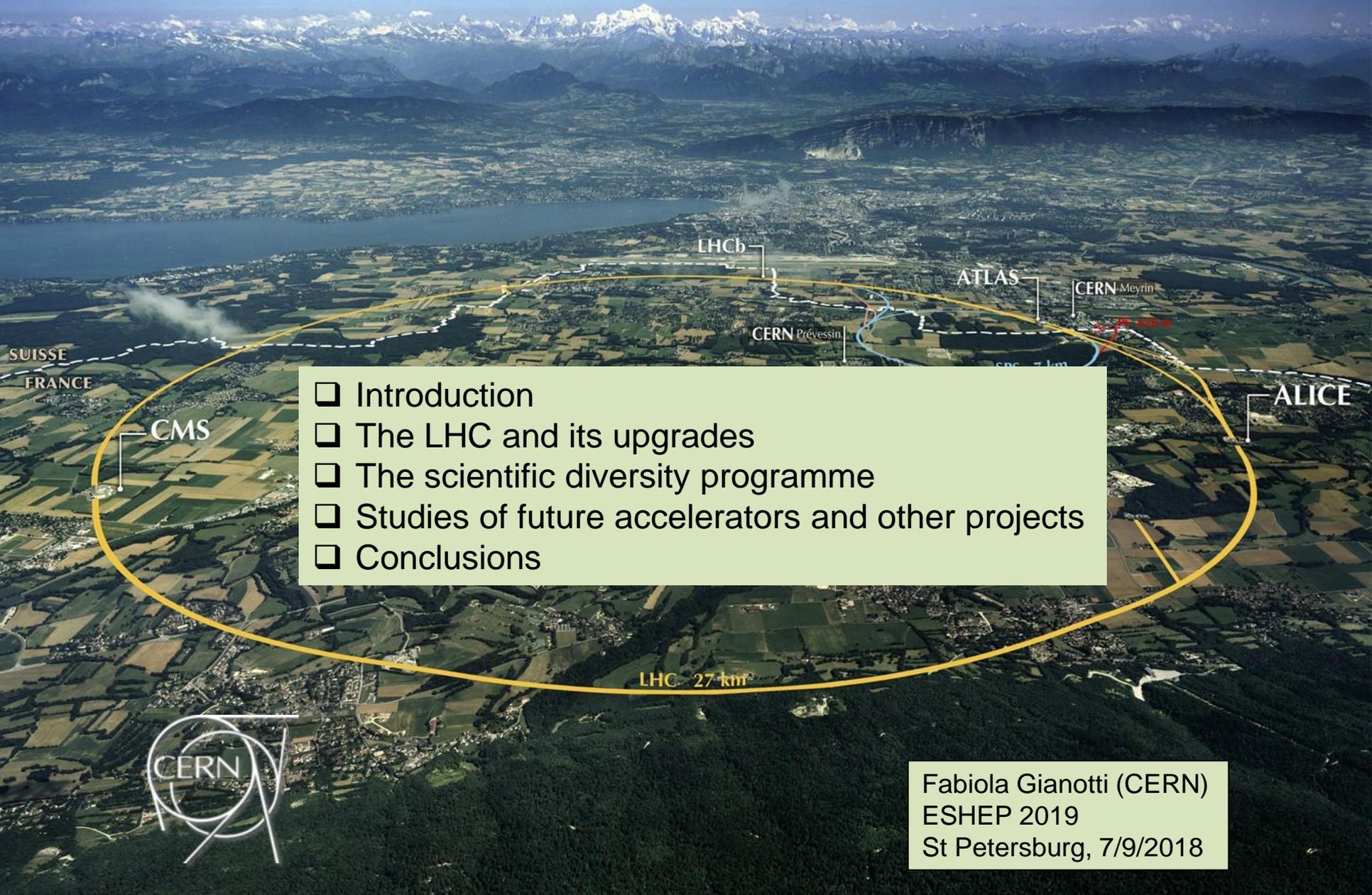


CERN's scientific programme



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

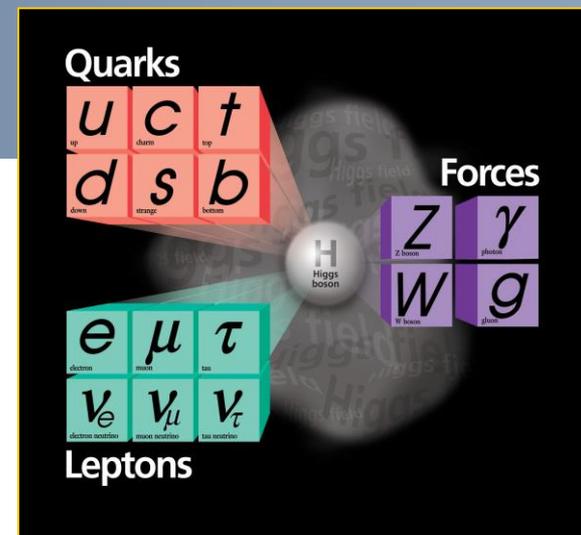


Fabiola Gianotti (CERN)
ESHEP 2019
St Petersburg, 7/9/2018



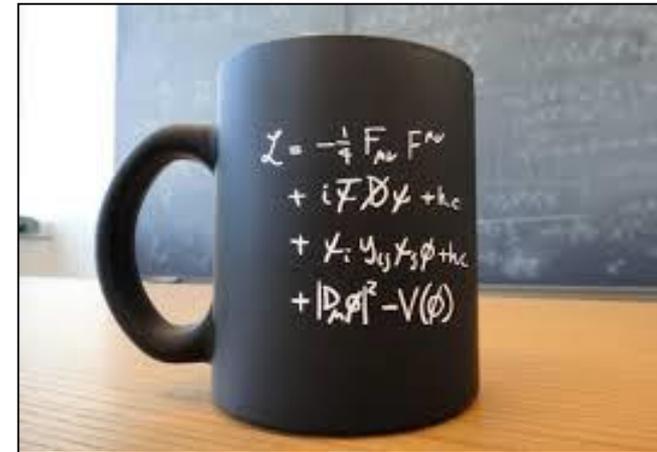
Introduction

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 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

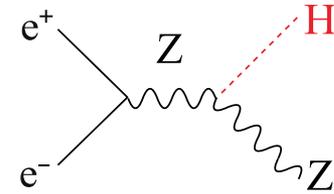
Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of E scales and couplings, and to properly interpret signs of new physics → with the goal to build a coherent picture of the underlying theory

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

Direct

production of a given (new or known) particle

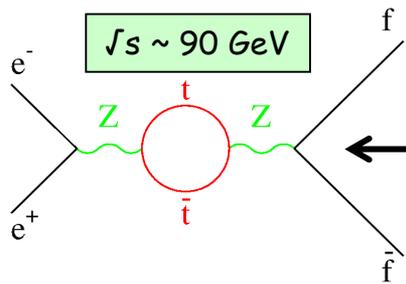
e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s} \sim 250 \text{ GeV}$ through the HZ process
 → need high E and high L



Indirect

precise measurements of known processes

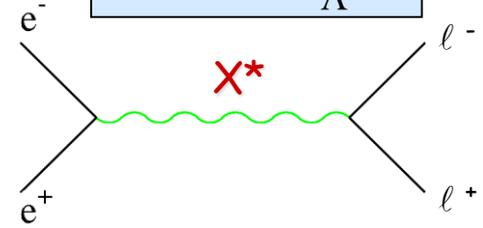
→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
 → sensitivities to E-scales $\Lambda \gg \sqrt{s}$ → need high E and high L



$\sqrt{s} \sim 90 \text{ GeV}$

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

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

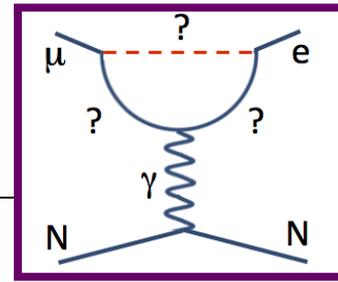


Rare processes

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: $\mu \rightarrow e \gamma$ (MEG@PSI), $\mu \rightarrow e$ (COMET@JPARC, Mu2e@FNAL). Suppressed in SM, can occur if new physics
 Note: flavour violation observed for ν (e.g. $\nu_\mu \rightarrow \nu_e$) and quarks (e.g. $t \rightarrow Wb$)





CERN scientific programme: 3 main pillars

Full exploitation of the LHC:

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

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
- ❑ future opportunities of scientific diversity programme ("Physics Beyond Colliders" Study Group)

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

LHC and its upgrades

→ See also lectures by J. Boyd



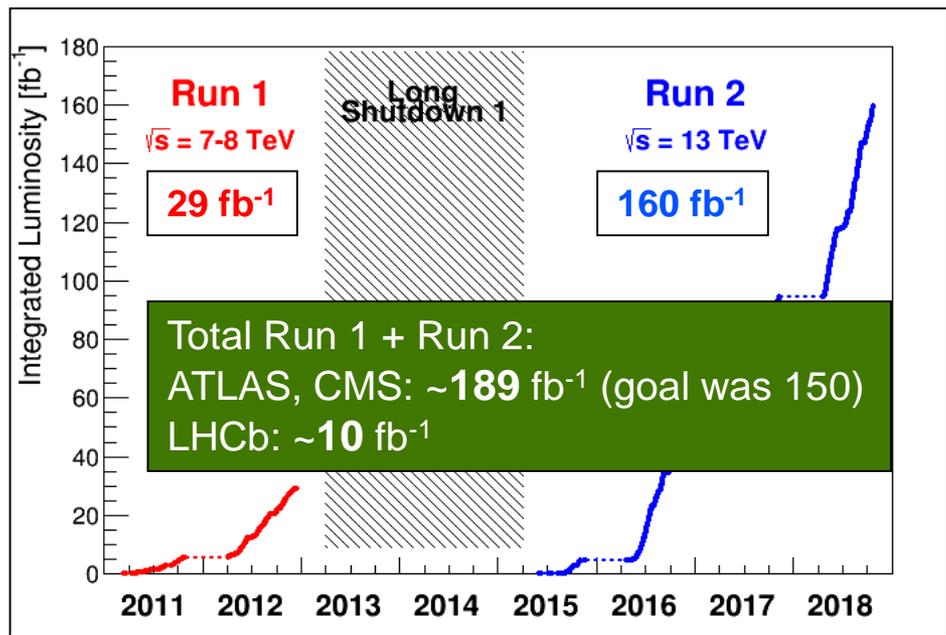
Outstanding performance of the LHC since the beginning

n. of particles per bunch n. of bunches n. of turns per second or repetition rate

$$L = \frac{N^2 k_b f}{4 \rho S_x S_y}$$

beam size at IP

$$N = \int L dt \times \sigma$$

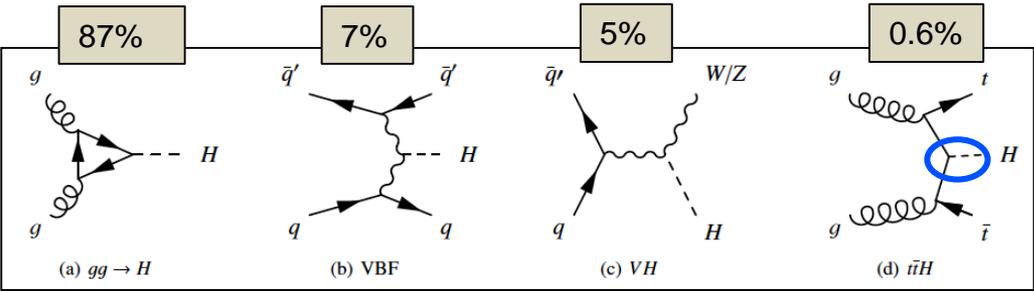


- ❑ Run 1: 2010-2013: $\sqrt{s} = 7-8 \text{ TeV}$, $\sim 30 \text{ fb}^{-1}$ to ATLAS and CMS → **Higgs boson discovery**
- ❑ Run 2: 2015-2018: $\sqrt{s} = 13 \text{ TeV}$
 - peak luminosity: $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ → x 2 higher than nominal value
 - int. luminosity: $\sim 160 \text{ fb}^{-1}$ ATLAS and CMS; $\sim 6.5 \text{ fb}^{-1}$ LHCb; $\sim 65 \text{ pb}^{-1}$ pp ALICE (1.3 nb^{-1} Pb-Pb)

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.)

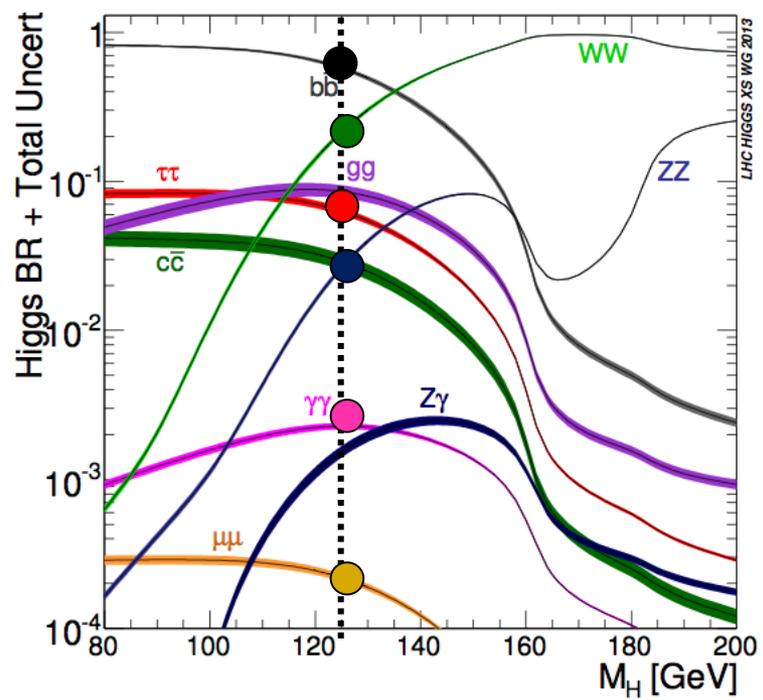
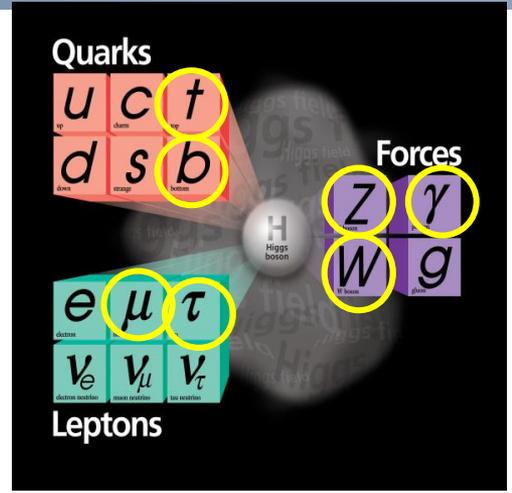


Excellent progress on Higgs boson studies



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

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



Higgs boson discovered and now well measured in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\nu l\nu$ channels (small branching ratios but clean final states)

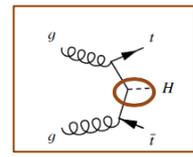
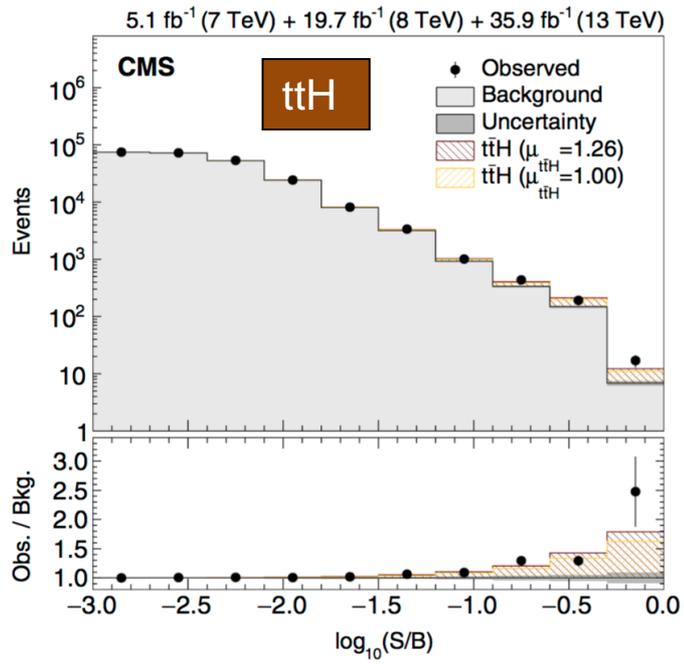
Decays and couplings to 3rd generation fermions ($H \rightarrow bb$, $H \rightarrow \tau\tau$, Htt production) experimentally more difficult as affected by huge backgrounds. Recently observed at $> 5\sigma$ level

Couplings to 2nd generation fermions (through rare $H \rightarrow \mu\mu$ decay) will only be accessible at HL-LHC

→ See lectures by J. Ellis



Higgs couplings to 3rd generation quarks well established in 2018



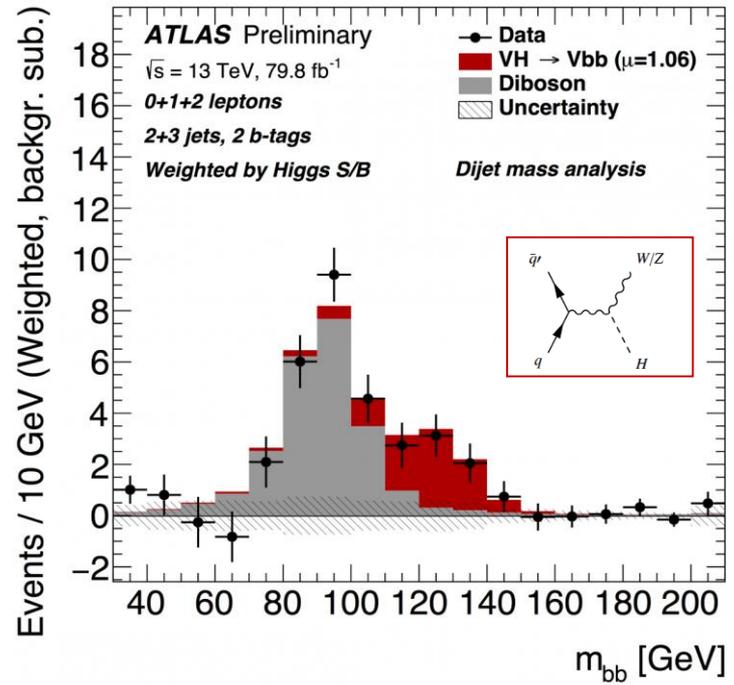
5.2 σ (4.2 expected)
 $\mu = 1.3 \pm 0.3$

$\mu = (\text{measured}/\text{SM-predicted}) \text{ rate}$

Combining with ttH and VBF production:
5.4 σ (5.5 expected)
 $\mu = 1.0 \pm 0.2$

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

W/Z (\rightarrow leptons) H \rightarrow bb

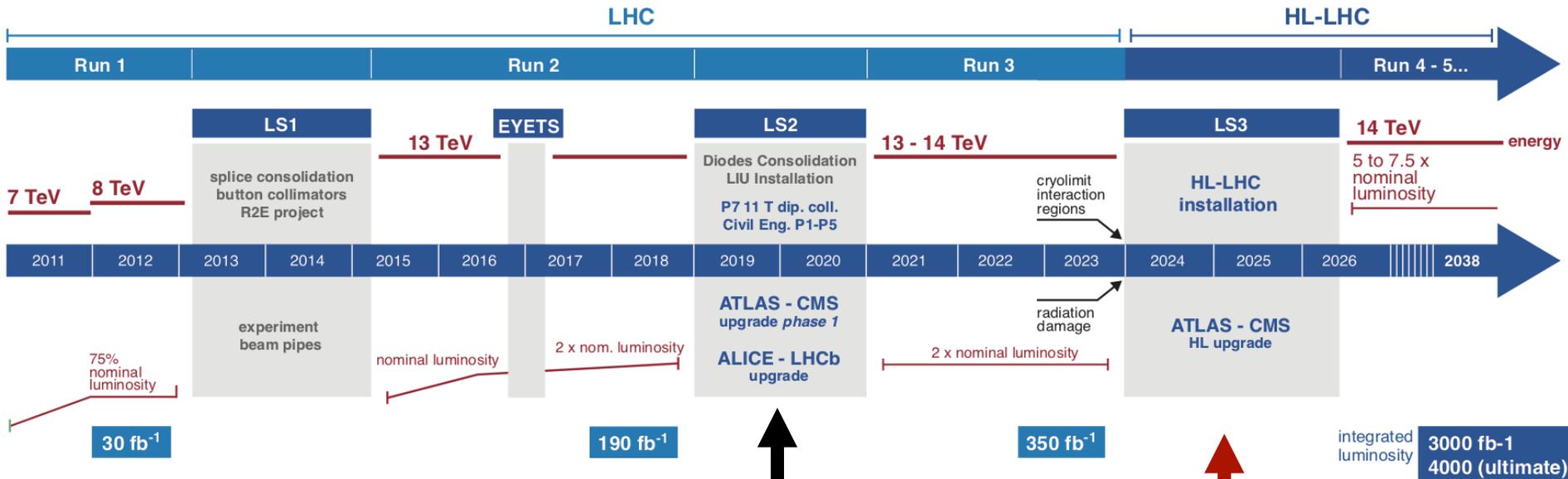




HL-LHC parameters and timeline

Nominal LHC: $\sqrt{s} = 14 \text{ TeV}$, $L = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (Note: $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ achieved already, but "only" 13 TeV)
 Integrated luminosity to ATLAS and CMS: 300 fb^{-1} by 2023 (end of Run 3)
 New target: $\sim 350 \text{ fb}^{-1}$

HL-LHC: $\sqrt{s} = 14 \text{ TeV}$, $L = 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 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

LS2 (Long Shutdown 2) activities

LIU will provide beams of intensity and brightness needed by HL-LHC:

e.g. 2.3×10^{11} p/bunch (today 1.2×10^{11})

Linac 4: 160 MeV H^-

Booster: 1.4 \rightarrow 2 GeV

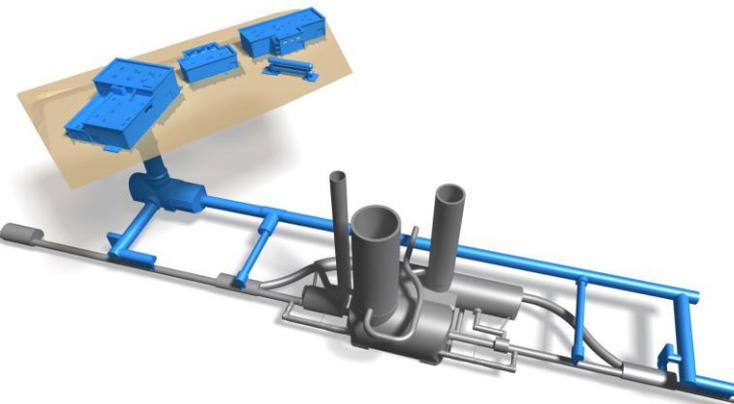
PS: new injection and feedback systems

SPS: new 200 MHz RF system



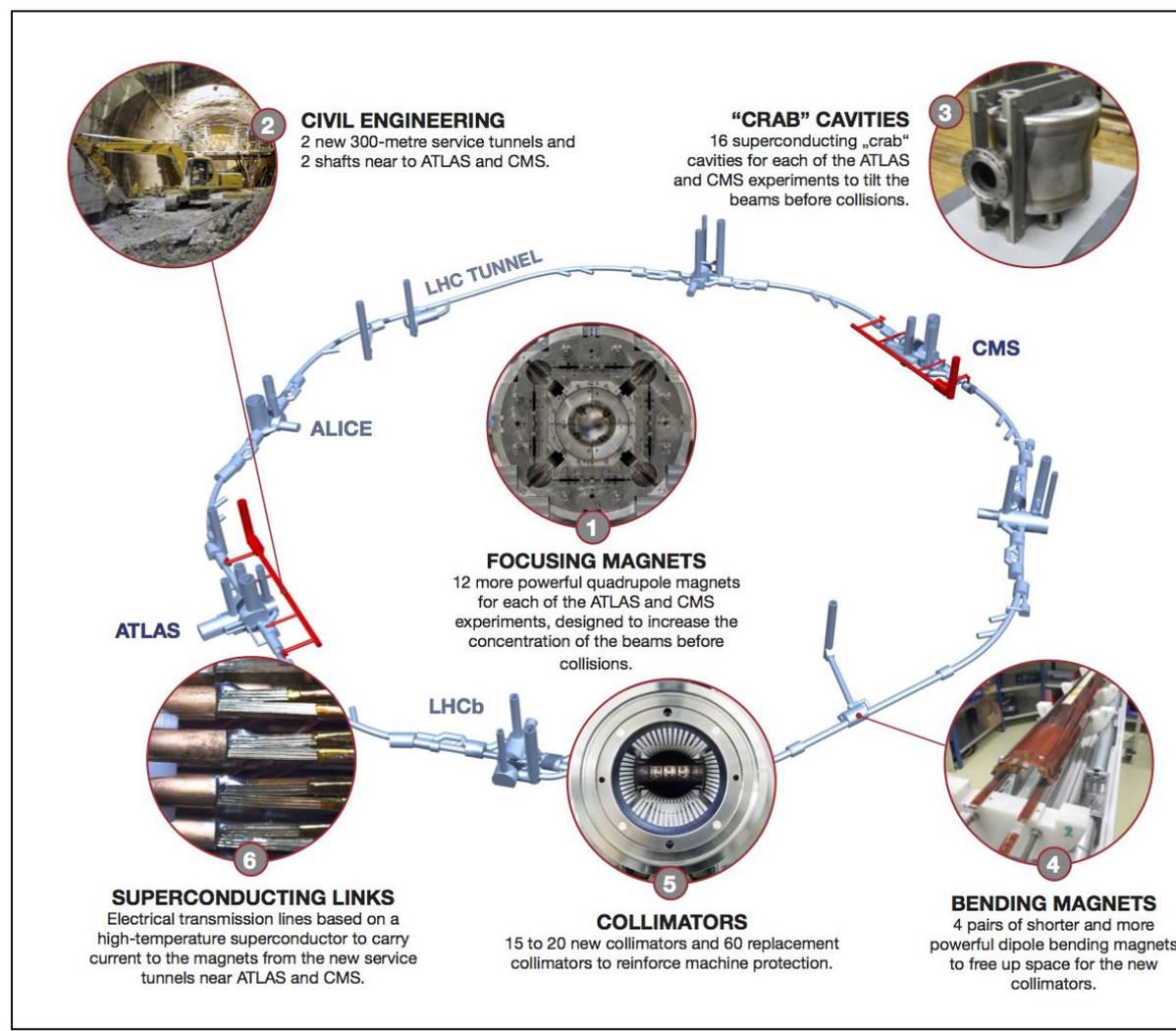
Linac4 (replacing Linac2) will become first step of CERN accelerator chain in 2021

Civil Engineering work: > 1 km of new underground galleries, 10 new buildings to house HL-LHC equipment. Excavation must be done in LS2 not to affect LHC operation.



Point 5

HL-LHC main upgrade components (and challenges ...)



Greatest challenge: new-generation superconducting magnets (Nb_3Sn)
→ fundamental milestone also for future, more powerful colliders (FCC)

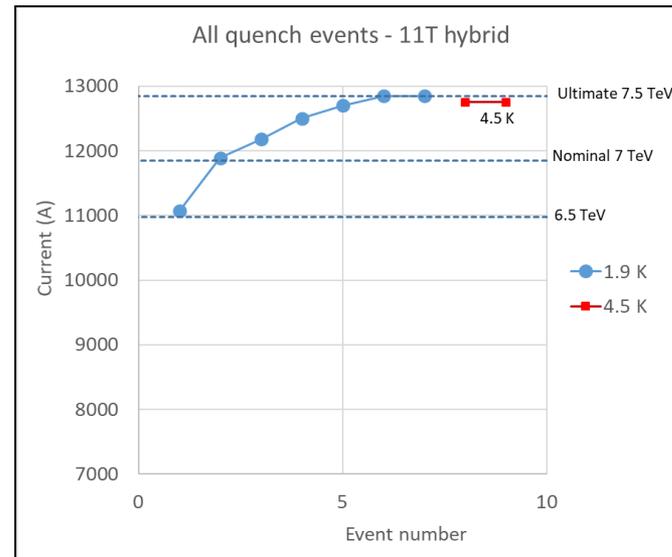
HL-LHC construction: magnets



Cryo-assembly replacing one 15 m NbTi 8 T dipole with two 5.5 m Nb₃Sn 11 T dipoles and a collimator. Difficult R&D. Now the first dipole tested successfully



Test of long (5.5 m) Nb₃Sn dipole prototype

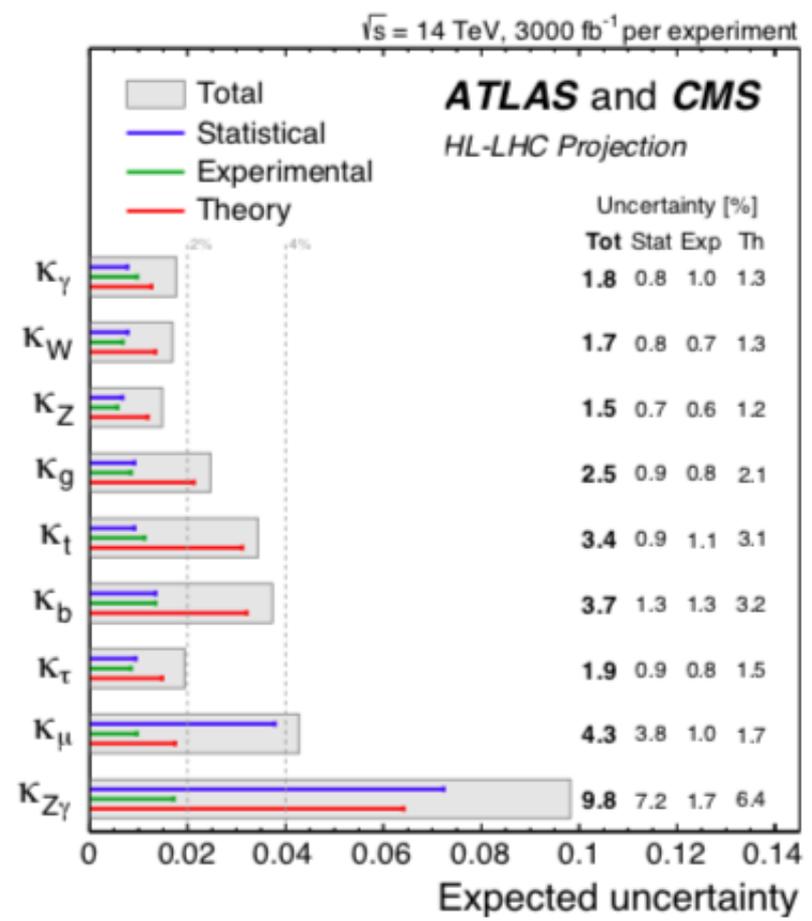
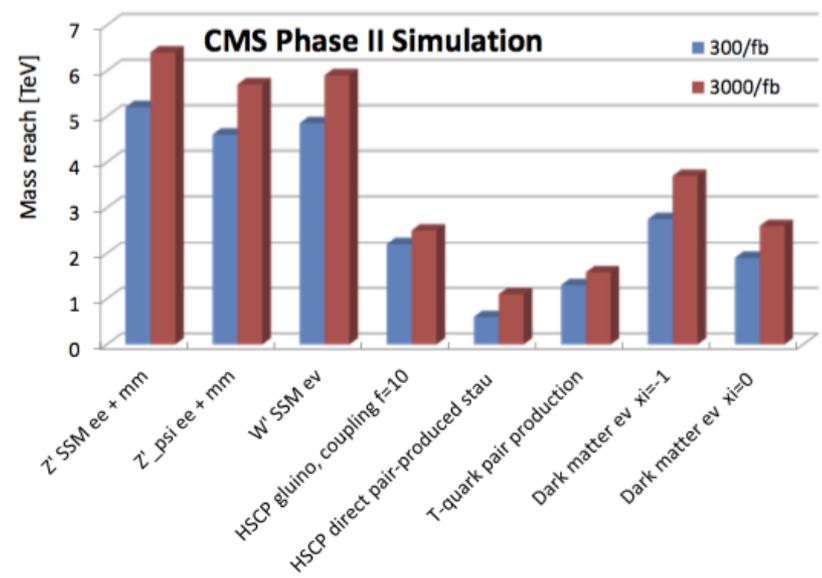




HL-LHC physics case

1 Precise measurements of the Higgs boson
 Precision 1.5-4% at HL-LHC (~10% at nominal LHC)

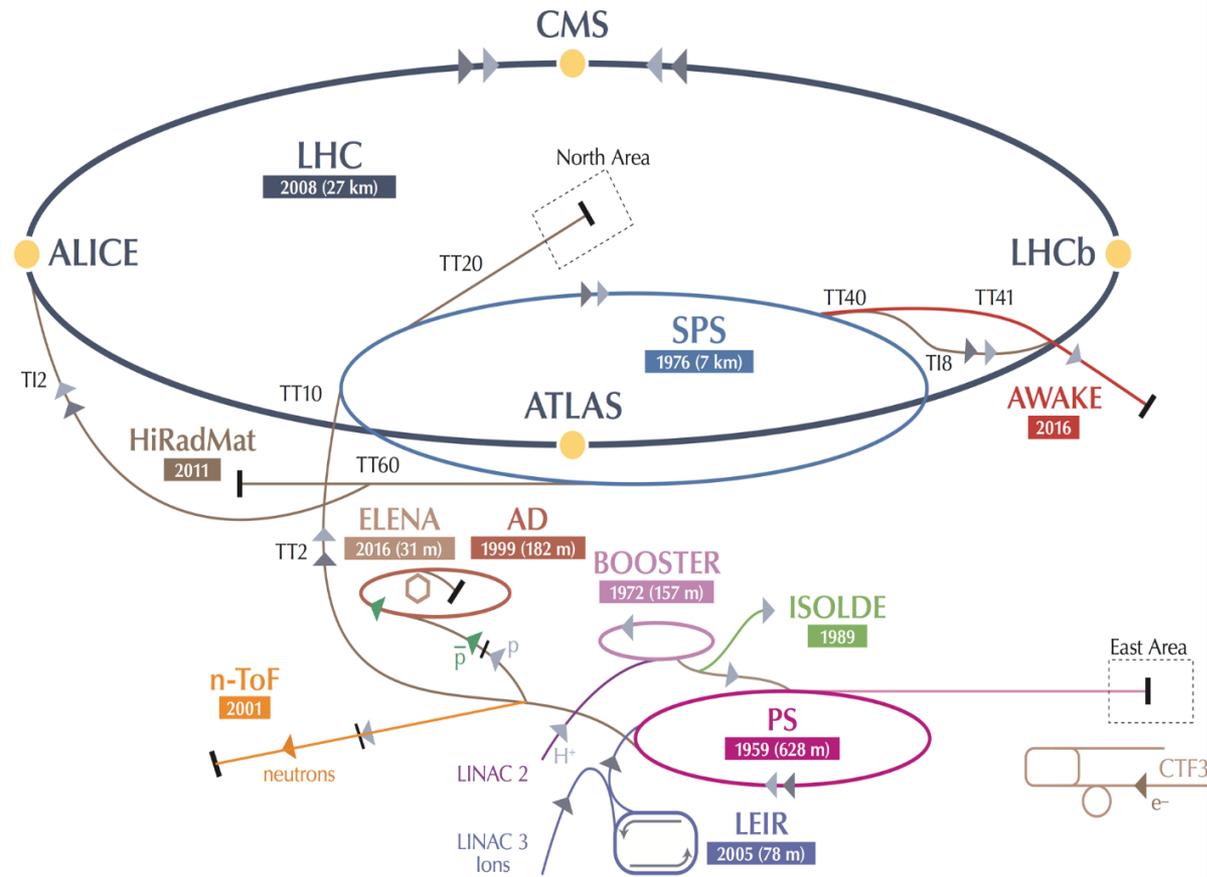
2 Discovery potential for new particles
 ~20-30% larger (up to $m \sim 8$ TeV) than nominal LHC



3 If new particles discovered in Run 3:
 → HL-LHC may find more and provide first detailed exploration of the new physics with well understood machine and experiments

Scientific diversity programme

~20 projects, ~ 2000 physicists



AD: Antiproton Decelerator for antimatter studies

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aerosols 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

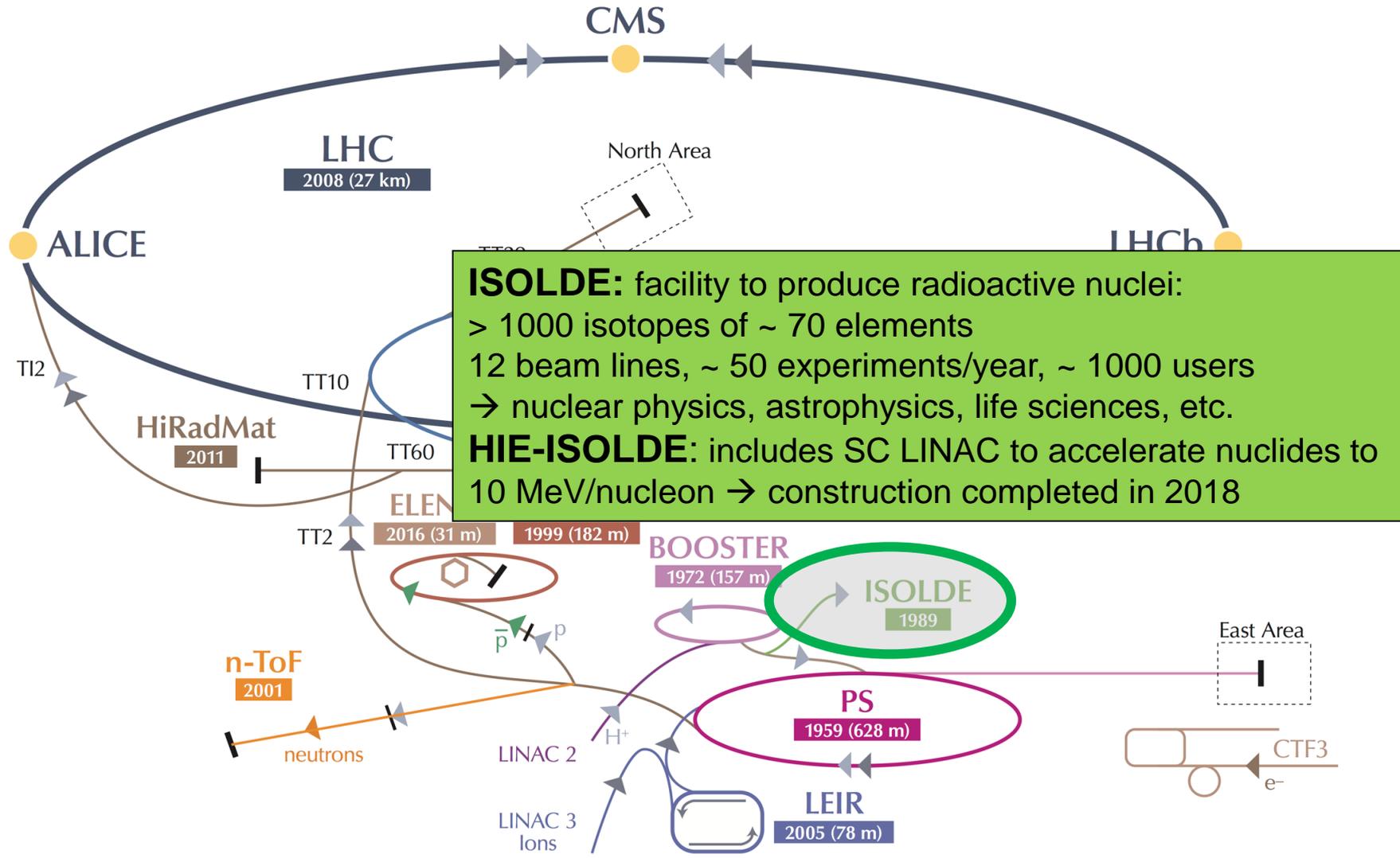
n-TOF: n-induced cross-sections

UA9: crystal collimation

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

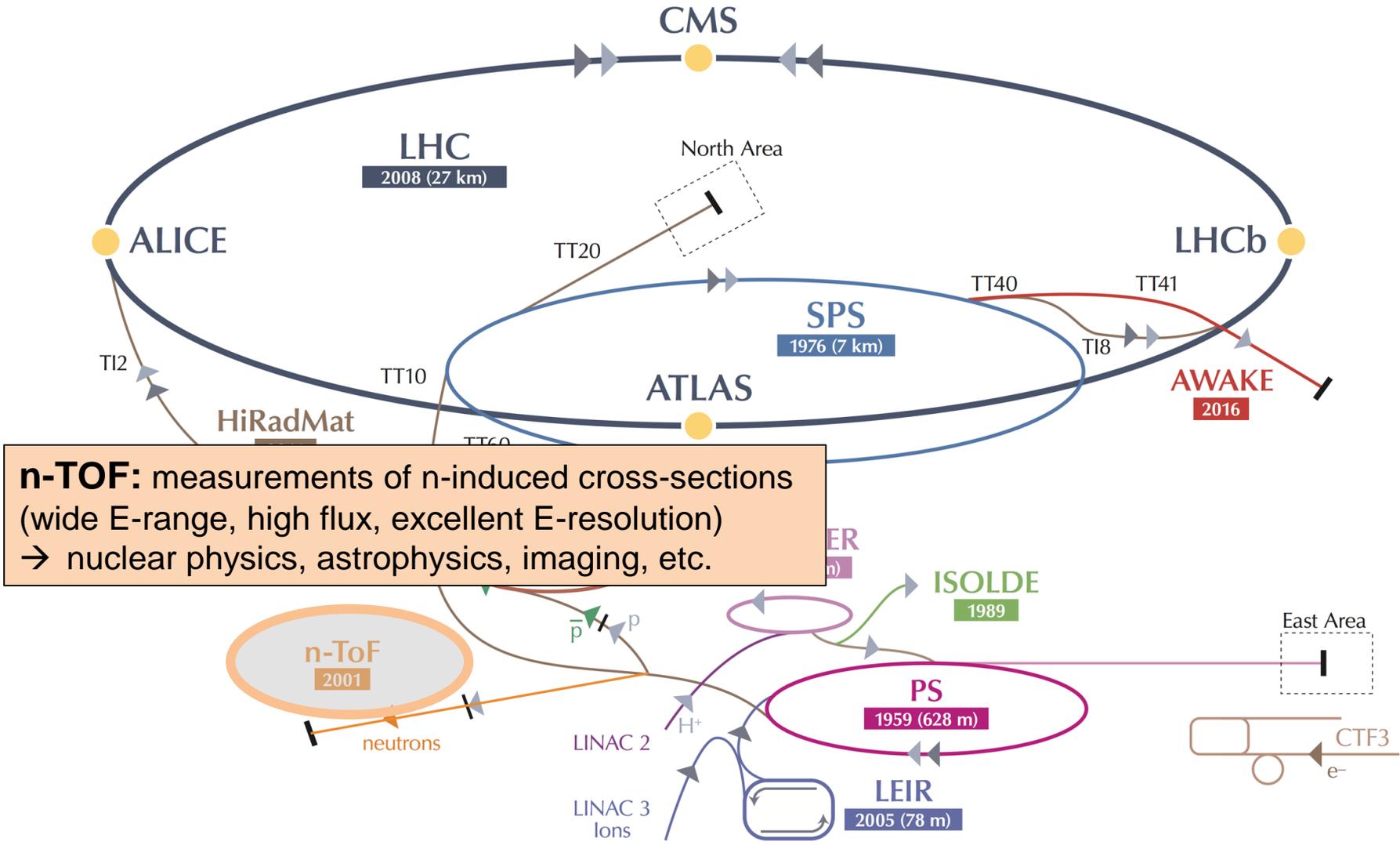


Scientific diversity: a compelling programme beyond the LHC





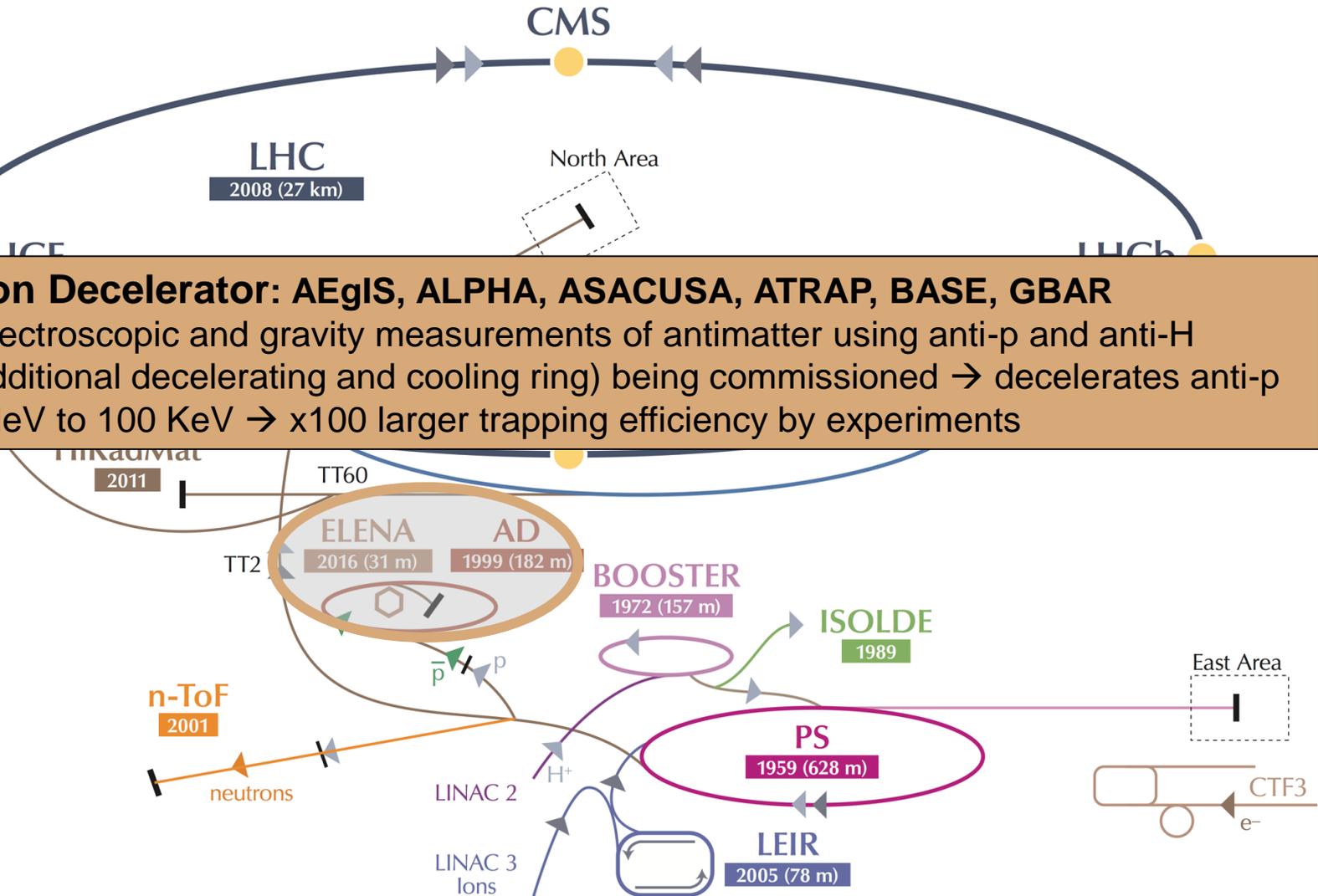
Scientific diversity: a compelling programme beyond the LHC



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



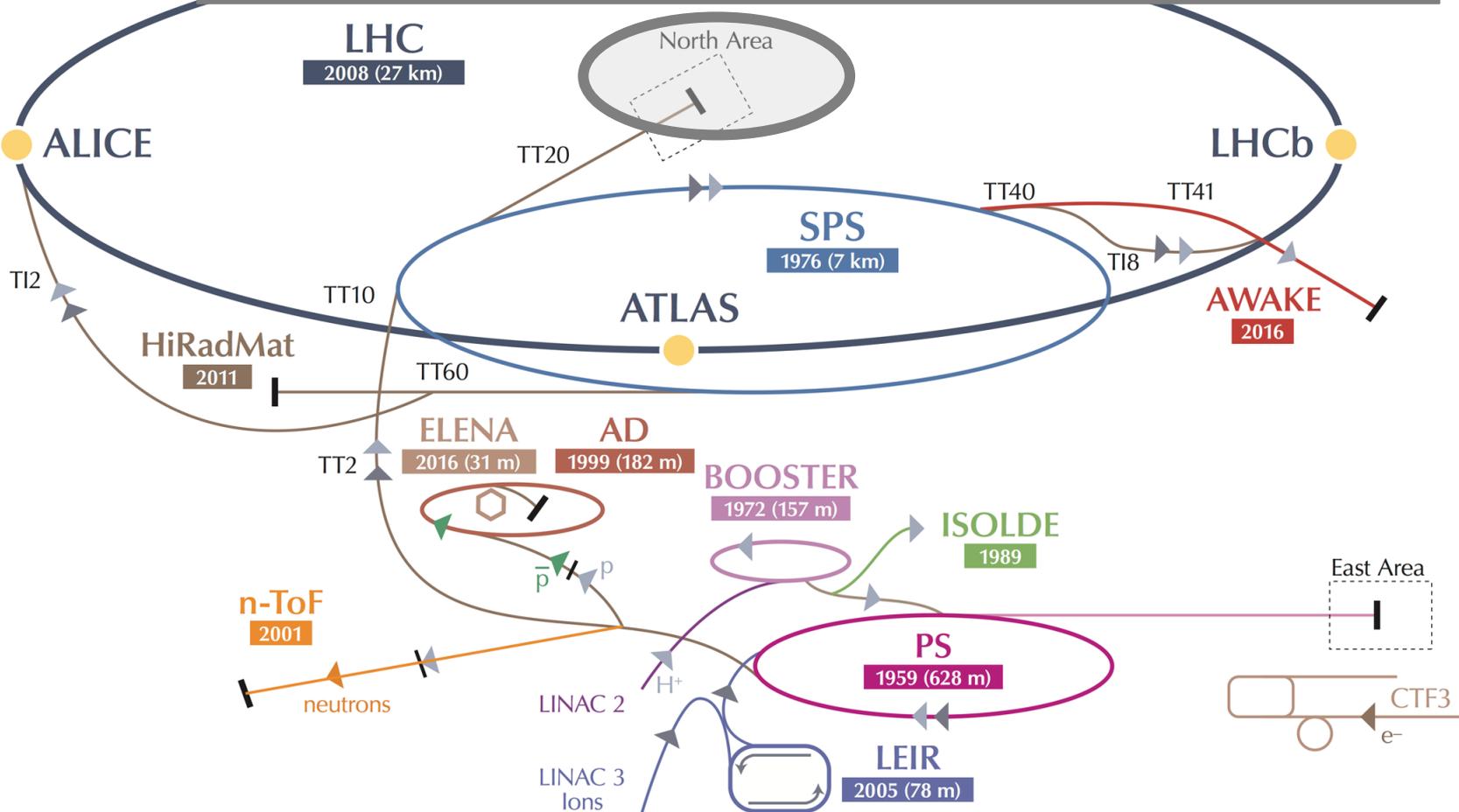
Scientific diversity: a compelling programme beyond the LHC





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





Scientific diversity: CERN Neutrino Platform

Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos \rightarrow 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.

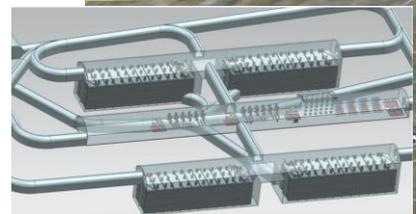
European Strategy 2013



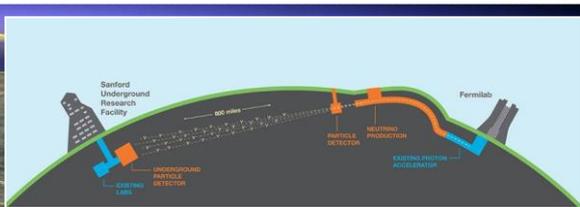
Scientific diversity: CERN Neutrino Platform

Long Baseline Neutrino Facility (LBNF, US)

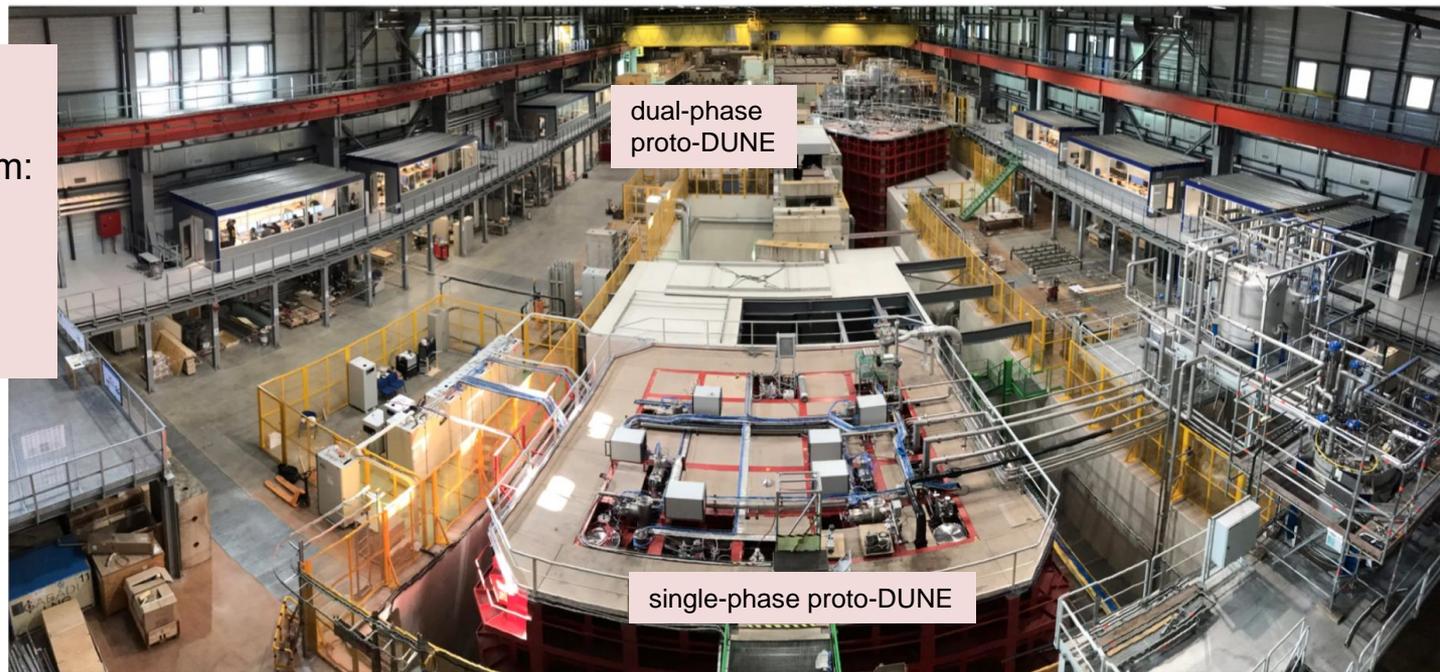
Sanford (South Dakota)



DUNE detector: ~ 1.5 km underground
4 x 17.5 kt liquid-argon modules



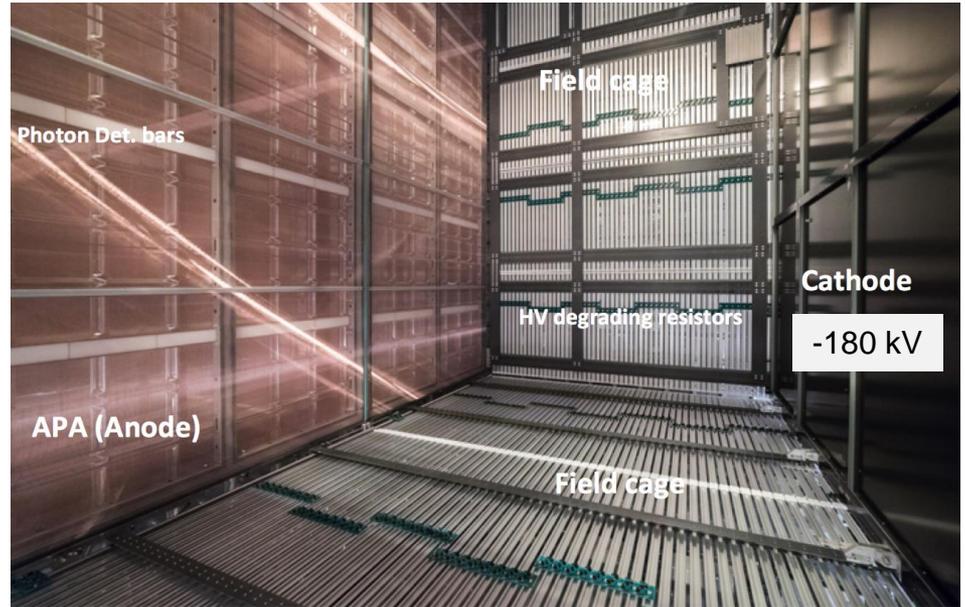
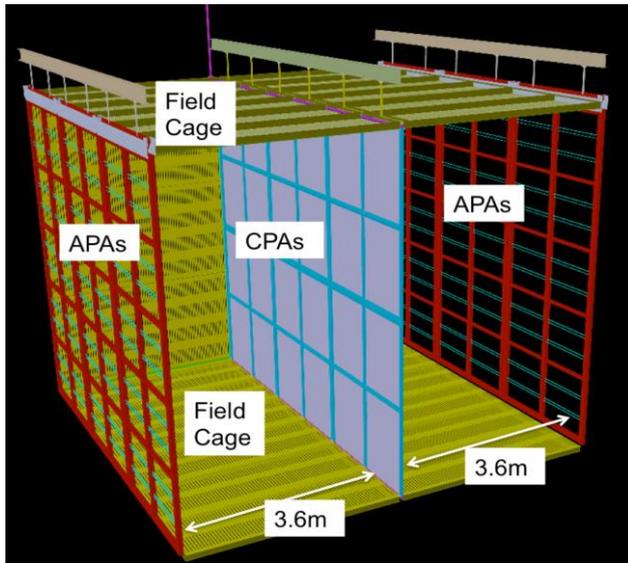
Construction and tests of DUNE detector prototypes at CERN's Neutrino Platform:
11x11x11 m³ cryostat
~750 tons LAr each
1 DUNE module:
x 20-25 proto-DUNE



dual-phase proto-DUNE

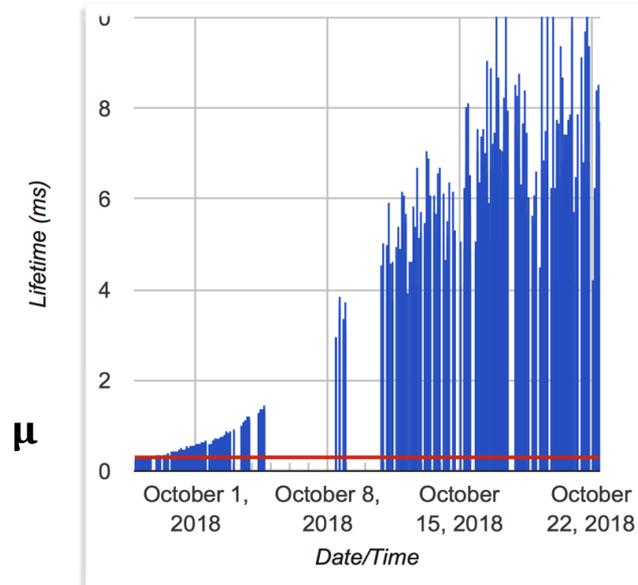
single-phase proto-DUNE

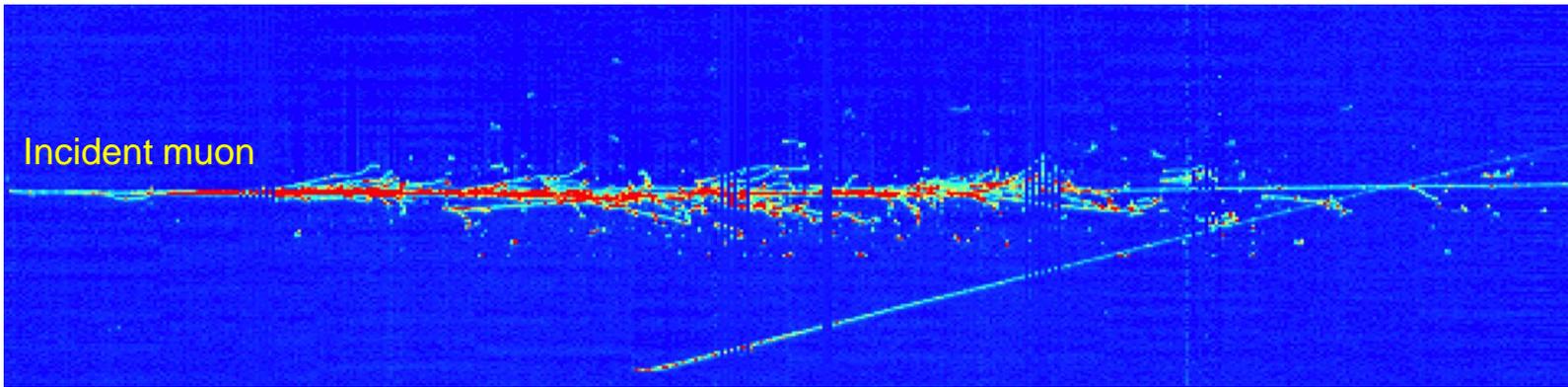
Test of single-phase DUNE prototype at the Neutrino Platform



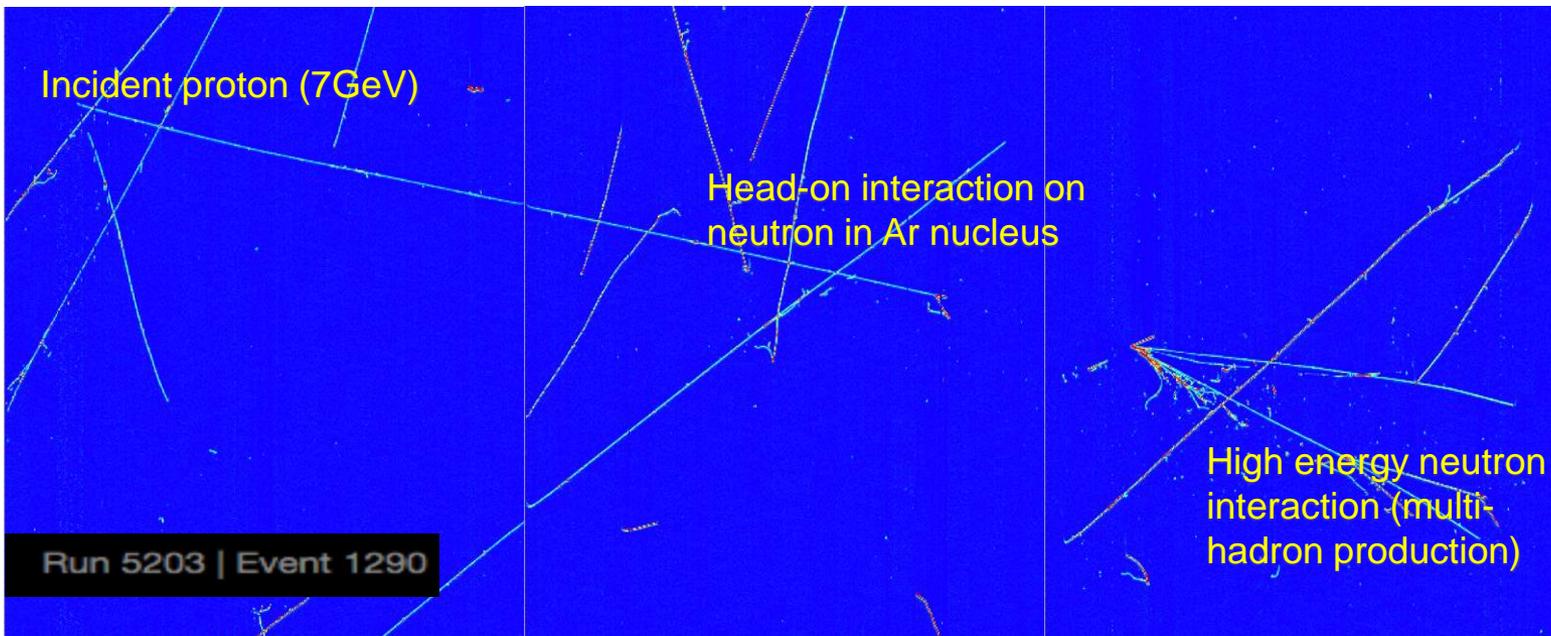
- ❑ 2 LAr TPC sharing same cathode → 3.6 m drift
- ❑ Cathode at **-180 kV** → 500 V/cm
- ❑ Anode Plane Assembly: 2.3 m x 6 m; 3 planes/APA ($0^\circ, \pm 35.7^\circ$), 5 mm wire pitch
- ❑ FE electronics (amplifier, shaper, ADC) inside cryostat
- ❑ Light collecting bars read out by SiPM

- ❑ Test beam 2018: > 4M events recorded, ~0.3-7 GeV e^+, p, K, π, μ
- ❑ Achieved **e^- lifetime of 6-8 ms** (~40 ppt O_2 eq.): nominal is 3 ms
- ❑ S/N (tracks): 40-60





Online event displays



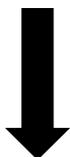
Preparation for the future



Higgs boson is a guaranteed deliverable of future colliders

The H boson is not just ... “another particle”:

- ❑ Profoundly different from all elementary particles discovered previously
 - ❑ It got almost no properties; brings a different type of “force”
 - ❑ 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 unique 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

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

↑ flavour
 ↑ naturalness
 ↑ stability
 ↑ C.C.

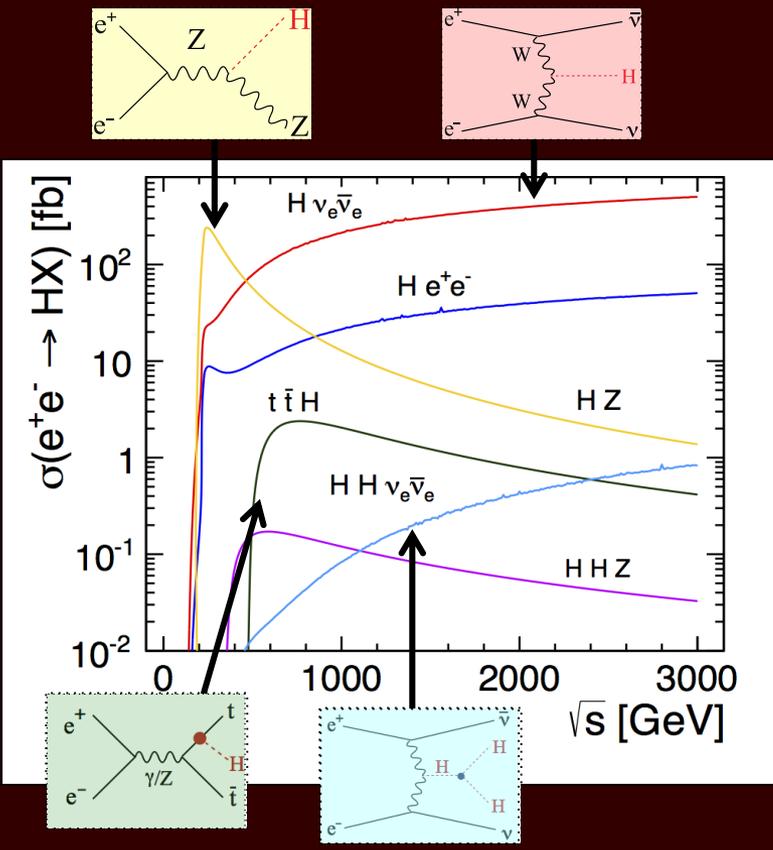
G.F. Giudice

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

→ See lectures by J. Ellis

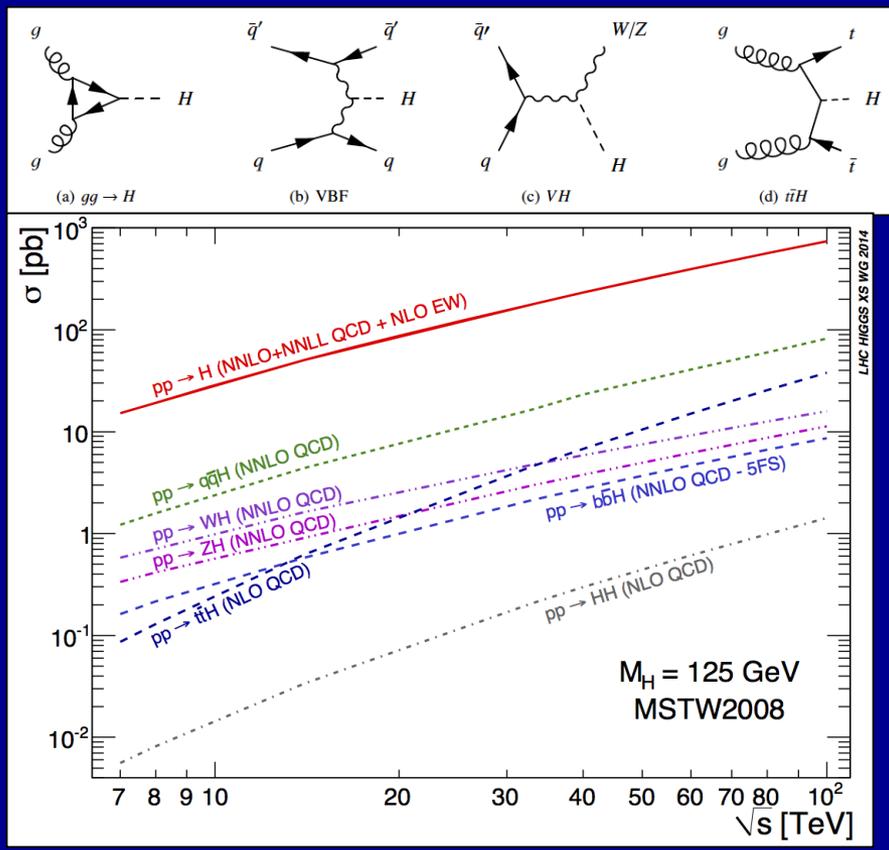


e⁺e⁻ colliders



- Low backgrounds \rightarrow all decay modes (hadronic, invisible, exotic) accessible
- Model-indep. coupling measurements: $\sigma(HZ)$ and Γ_H from data
- $t\bar{t}H$ and HH require $\sqrt{s} \geq 500$ GeV

pp colliders



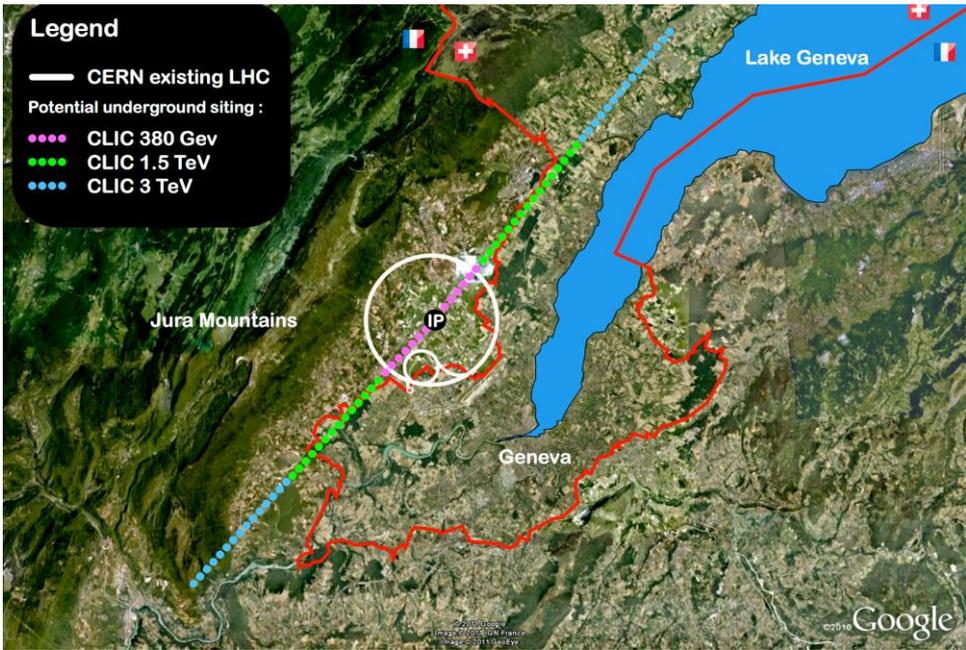
- High energy, huge cross-sections \rightarrow optimal for (clean) rare decays and heavy final states ($t\bar{t}H$, HH)
- Huge backgrounds \rightarrow not all channels accessible; only fraction of events usable
- Model-dep. coupling measurements: Γ_H and $\sigma(H)$ from SM



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

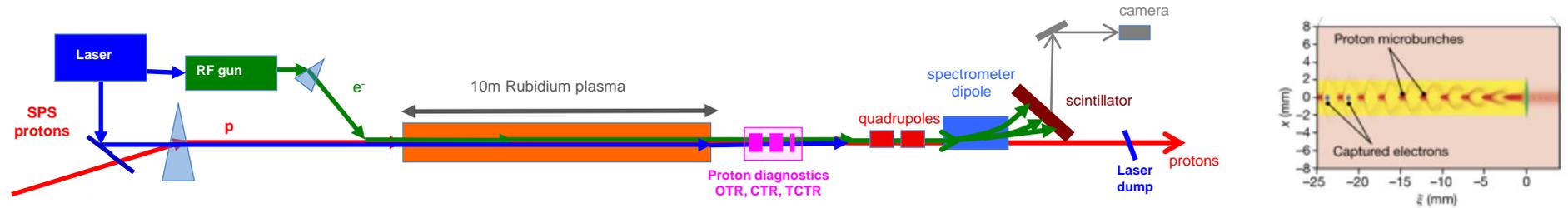


Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	1.5	5.9
Luminosity above 99% of \sqrt{s}	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5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

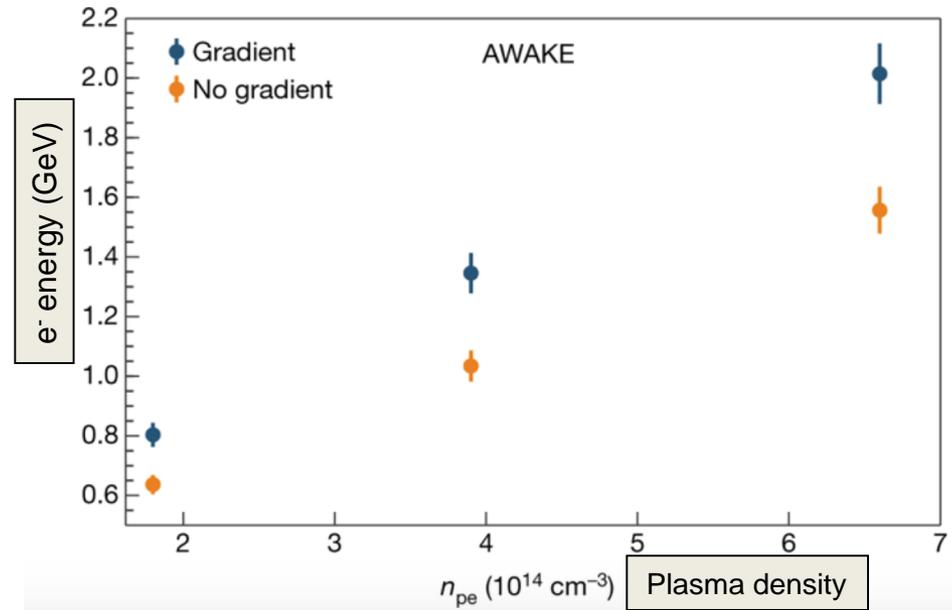
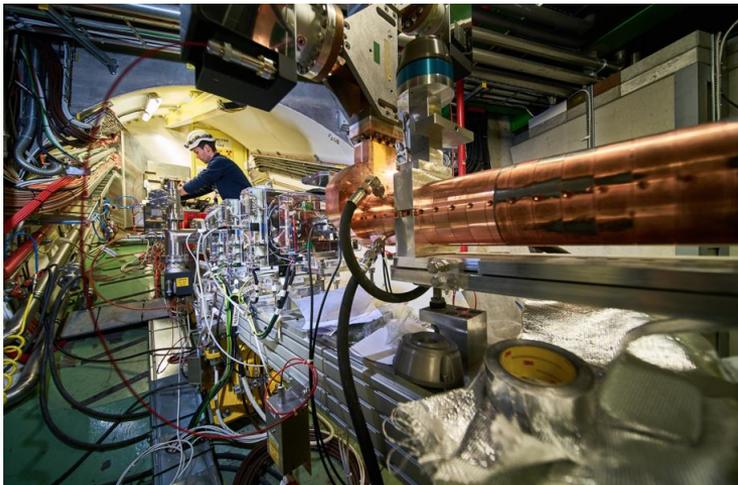
Physics goals:

- Direct discovery potential and precise measurements of new particles (couplings to Z/γ^*) up to $m \sim 1.5 - 3 \text{ TeV}$
- Indirect sensitivity to E scales $\Lambda \sim O(100) \text{ TeV}$
- Measurements of “heavy” Higgs couplings: $t\bar{t}H$ to $\sim 3\%$, HH $\sim 10\%$

Proof-of-concept demonstrated: 400 GeV protons from SPS generate strong EM fields in a 10 m plasma cell → injected e^- beam accelerated in the wake of the p beam
 $\sim 3 \times 10^{11}$ p/bunch at 400 GeV → 20 kJ (cfr ~ 40 J for laser/ e^- driving pulses)



2018: first demonstration of p-driven e^- acceleration (paper published in *Nature*):
20 MeV → 2 GeV over 10 m: corresponds to **gradient of 200 MV/m**





Future Circular Colliders (FCC)

Conceptual design study of a ~100 km ring:

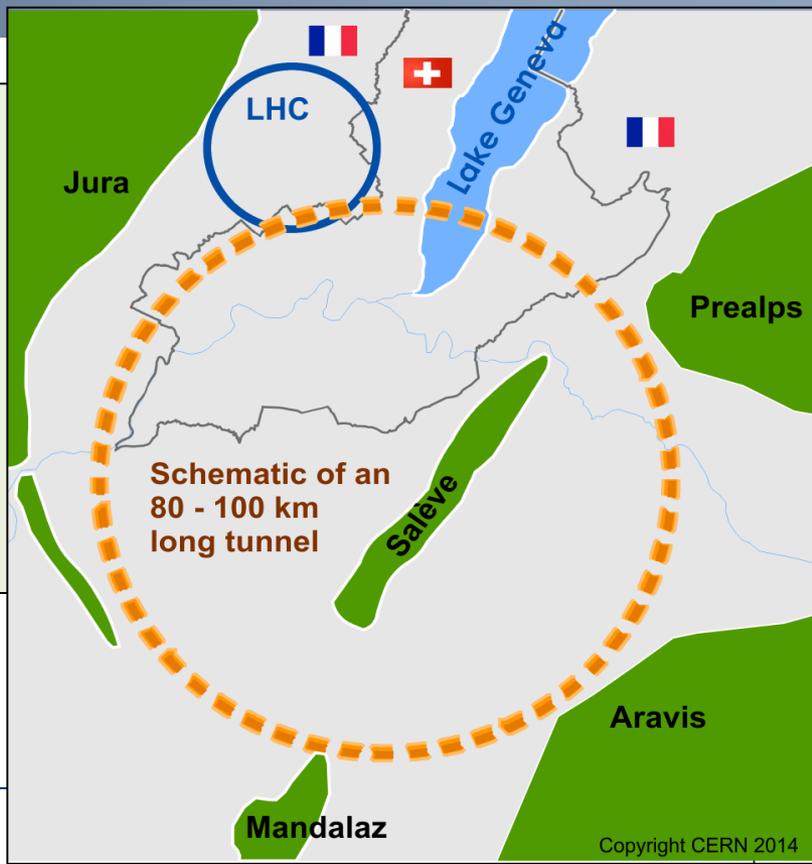
- pp collider (FCC-hh):** ultimate goal
 $\sqrt{s} \sim 100 \text{ TeV}$, $L \sim 2 \times 10^{35}$; 4 IP, $\sim 20 \text{ ab}^{-1}/\text{expt}$
- e⁺e⁻ collider (FCC-ee):** possible first step
 $\sqrt{s} = 90\text{-}350 \text{ GeV}$, $L \sim 200\text{-}2 \times 10^{34}$; 2 IP
- pe collider (FCC-he):** option $\sqrt{s} \sim 3.5 \text{ TeV}$, $L \sim 10^{34}$

Main technology challenge: ~ 16 T magnets

- 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, $\Delta M_W < 1 \text{ MeV}$, $\Delta m_{\text{top}} \sim 10 \text{ MeV}$



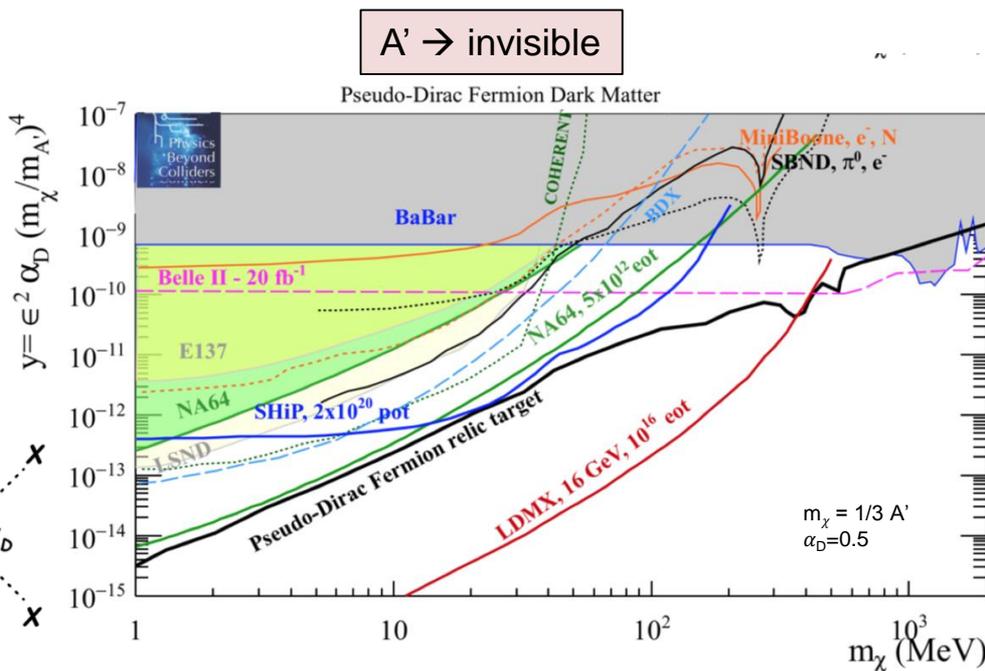
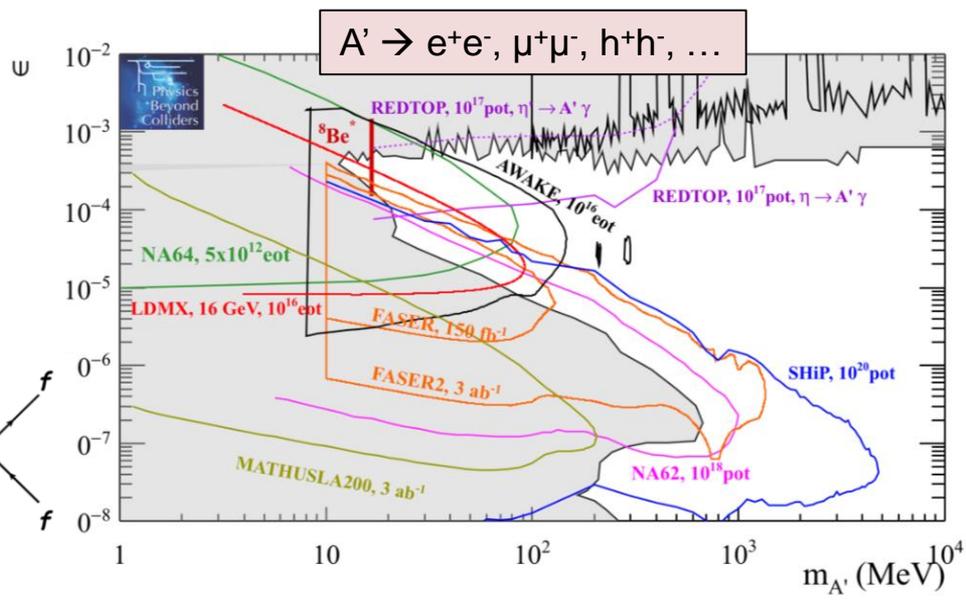
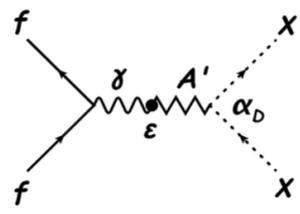
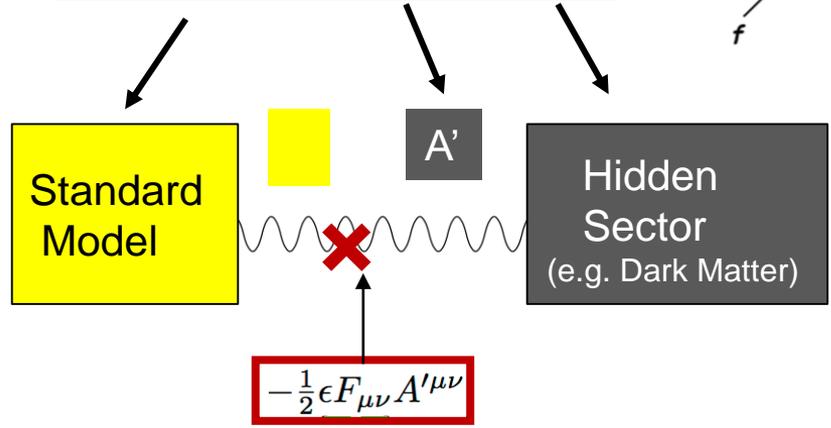


Future of scientific diversity programme: Physics Beyond Colliders

Several projects propose exploration of Hidden Sector particles in the MeV-GeV energy range. Very-weakly coupled to SM via "portals".

Present in several BSM scenarios addressing dark matter, neutrino masses, baryogenesis problems

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{PORTAL}} + \mathcal{L}_{\text{HS}}$$



Figures show 10-15 years outlook

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



The full exploitation of the LHC, and more powerful colliders, will be needed in the future 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