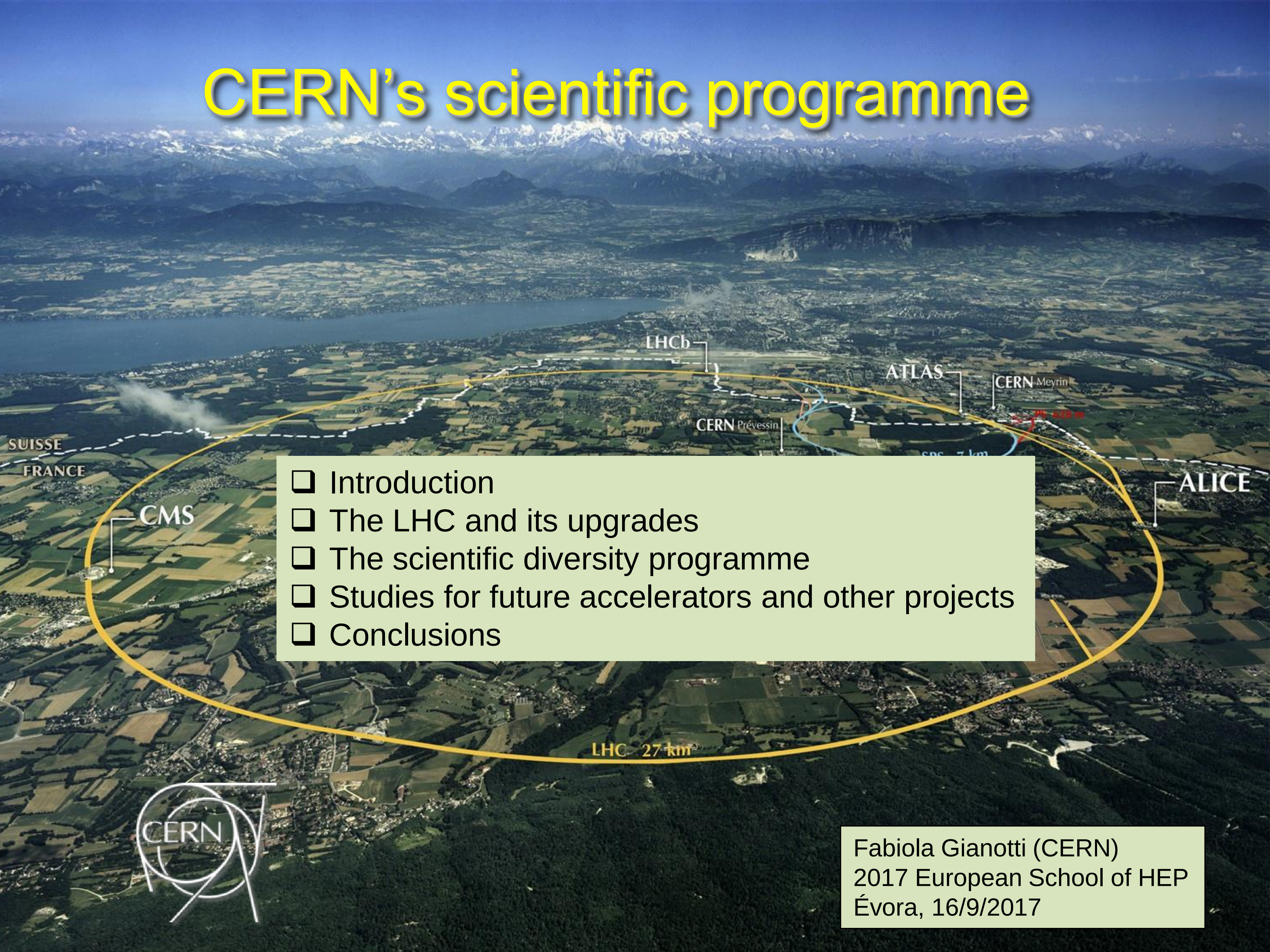
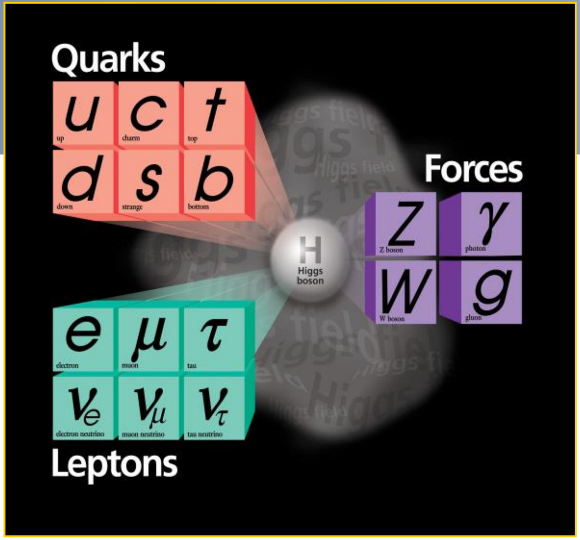
CERN's scientific programme



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

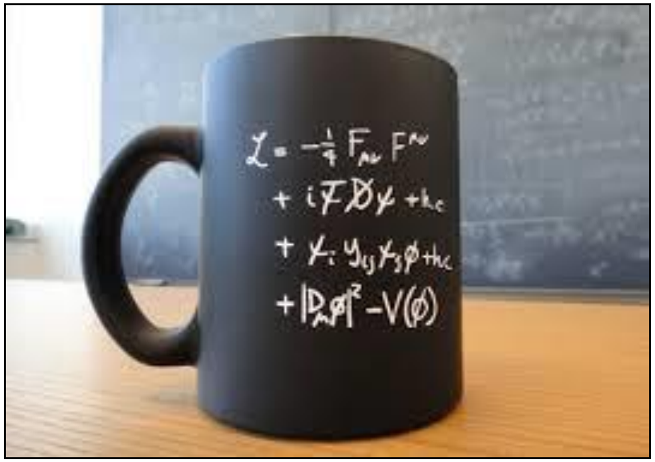
Fabiola Gianotti (CERN)
2017 European School of HEP
Évora, 16/9/2017

Introduction



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

Note: fermions (c, b, t, τ) discovered at accelerators in the US, bosons (g, W, Z, H) in Europe !



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 (23% 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

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

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

A few examples here → see lectures by P. Silva

Outstanding performance of the LHC since the beginning

- Run 1: 2010-2013: √s = 7-8 TeV, ~ 30 fb^{-1} to ATLAS and CMS → **Higgs boson discovery**
- Run 2: 2015-2018:
  - -- peak luminosity so far: ~1.7 x 10^{34} cm^{-2} s^{-1} → 70% higher than nominal value
  - -- integrated luminosity 2016: ~ 40 fb^{-1} ATLAS, CMS (> total before), 1.9 fb^{-1} LHCb, 10 pb^{-1} ALICE
  - -- 2017: ~ 24 fb^{-1} so far to ATLAS and CMS

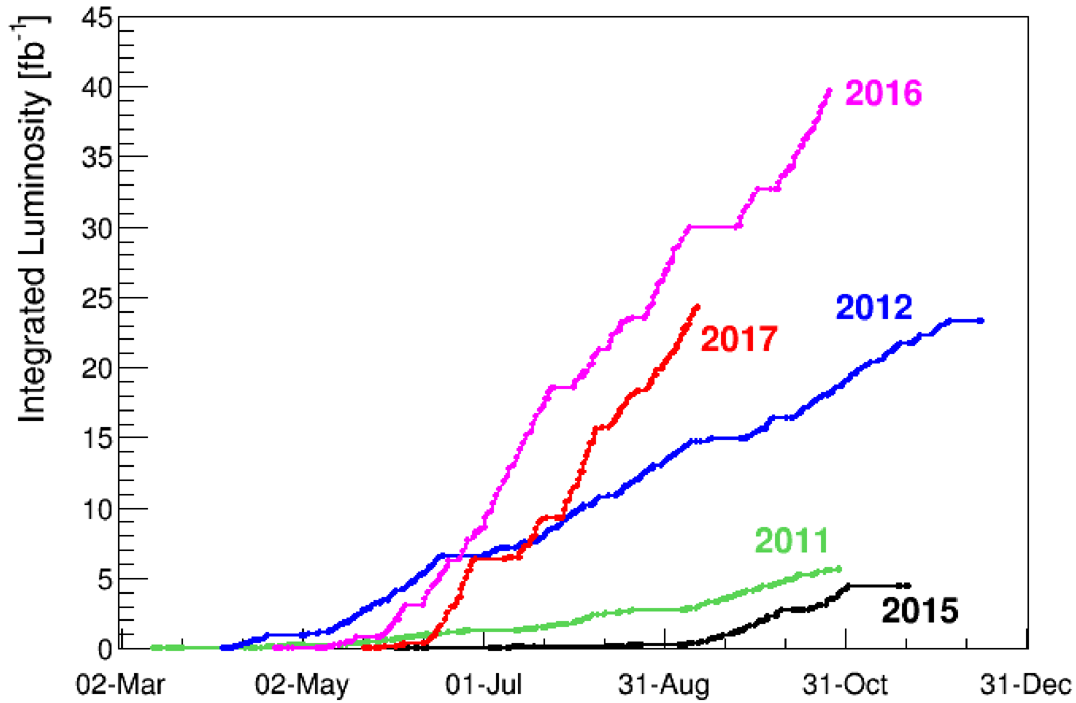
n. of particles per bunch

n. of bunches

n. of turns per second or repetition rate

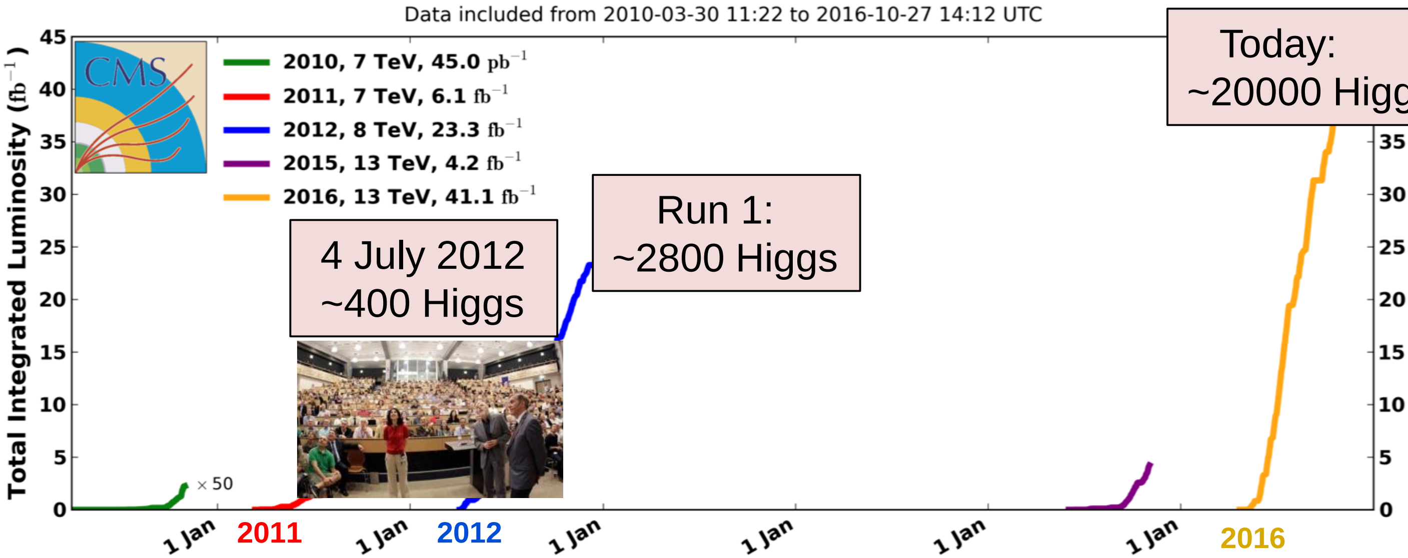
$$\boxed{L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}}$$

beam size at IP



Detectors and computing also performing very well in spite of challenging conditions (average pile-up up to ~ 30 events/x-ing, huge amount of data, etc.)

ATLAS and CMS



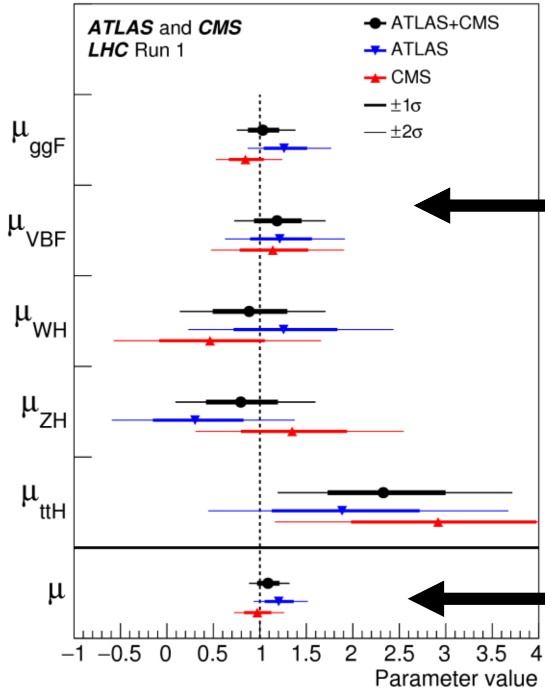
4 July 2012
~400 Higgs

Run 1:
~2800 Higgs

Today:
~20000 Higgs

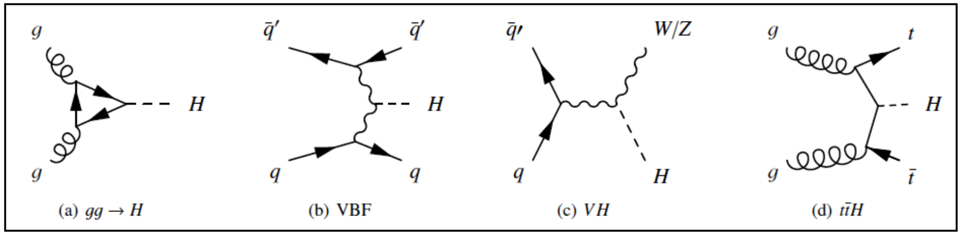
End of Run 2: expect
~40000 Higgs

Here (approximate) number of Higgs boson events is given after the analyses selection cuts

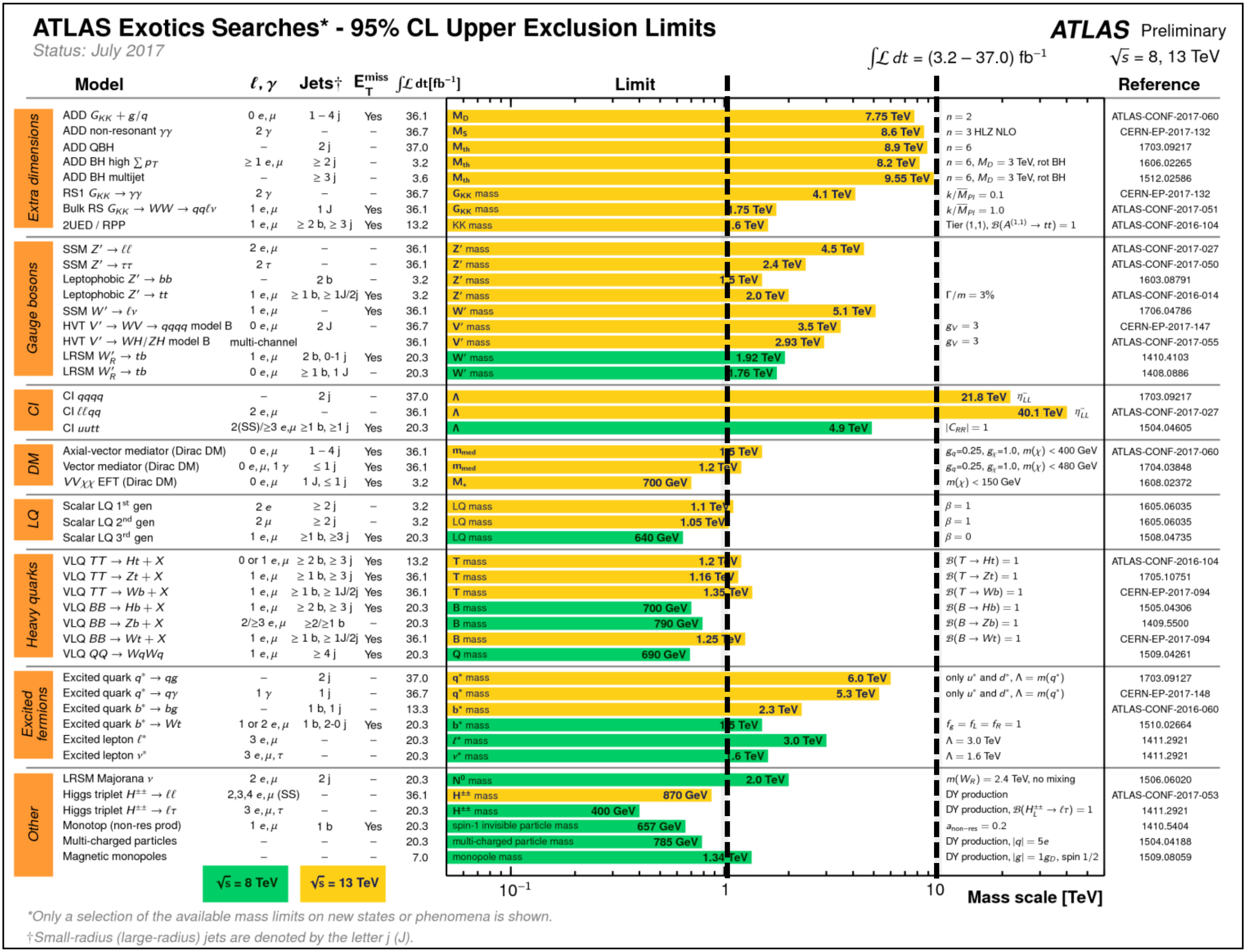


Measured production rates in various channels divided by SM expectation

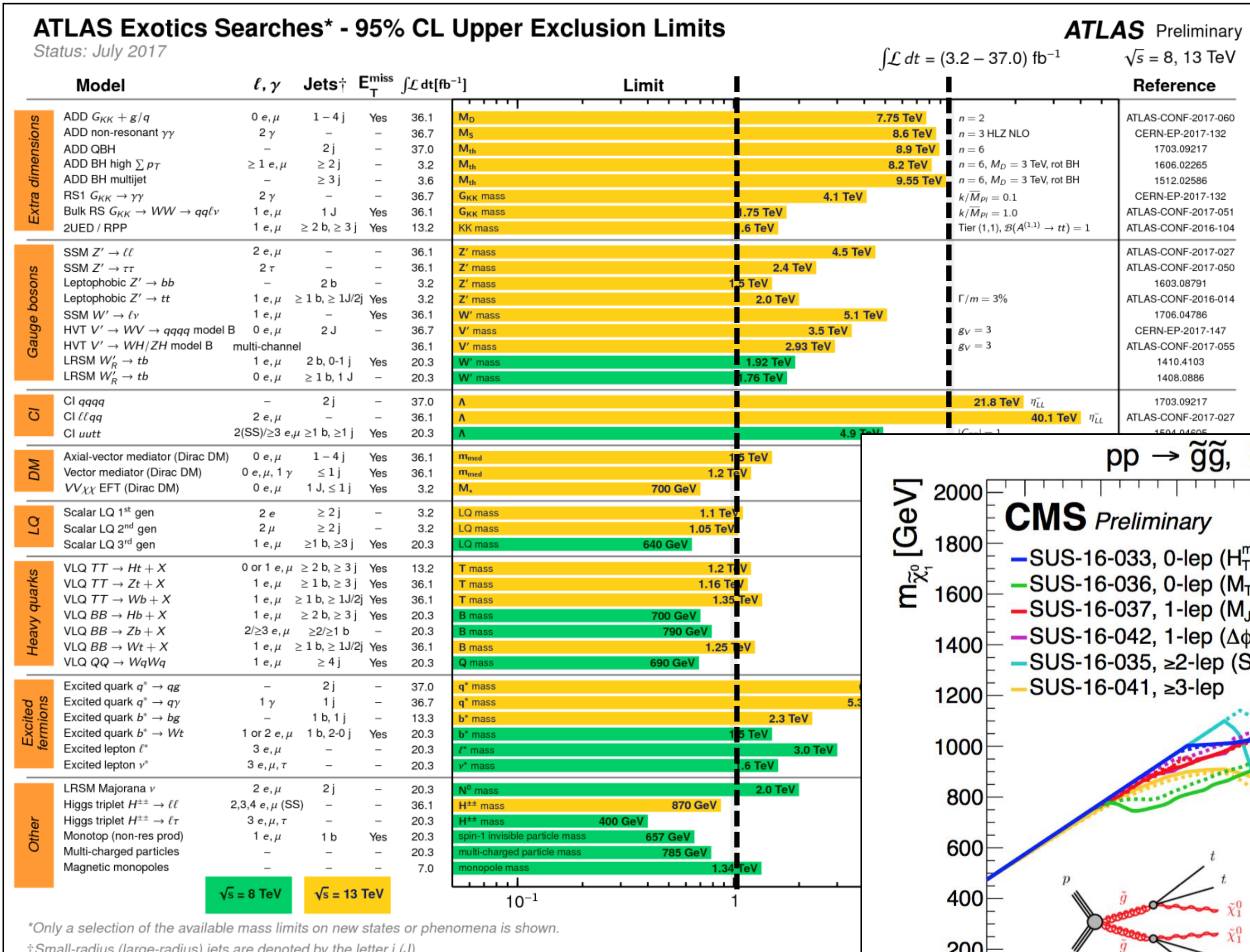
Combined:
1.09 ± 0.11

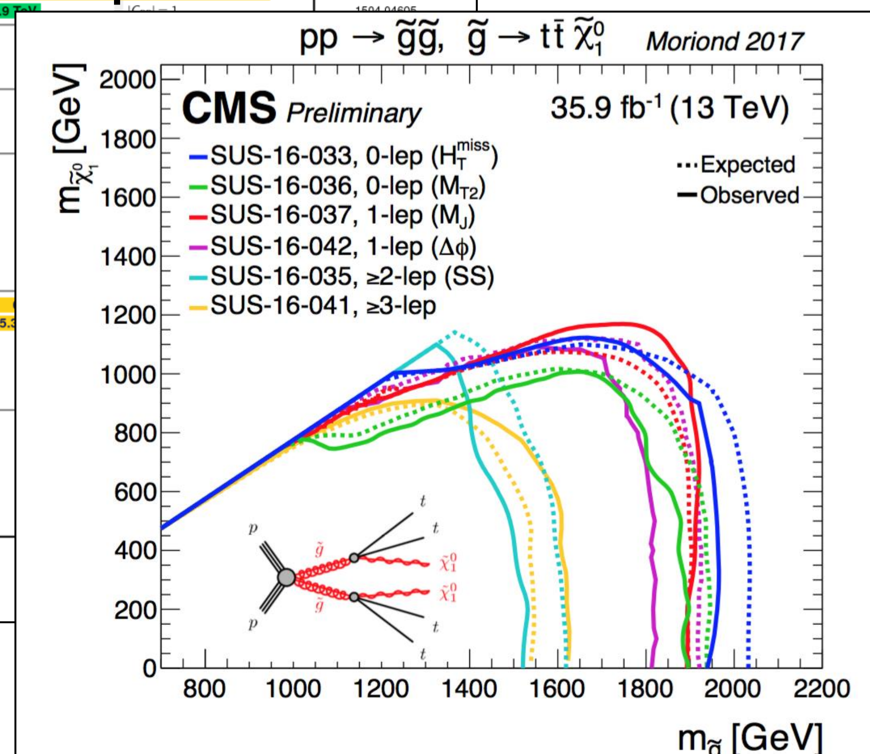


ATLAS and CMS



ATLAS and CMS

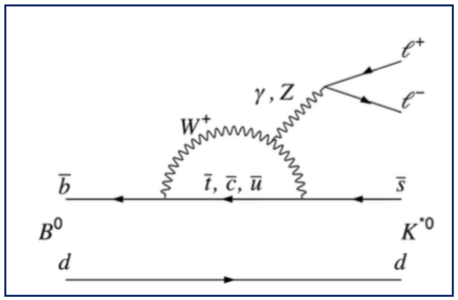




LHCb

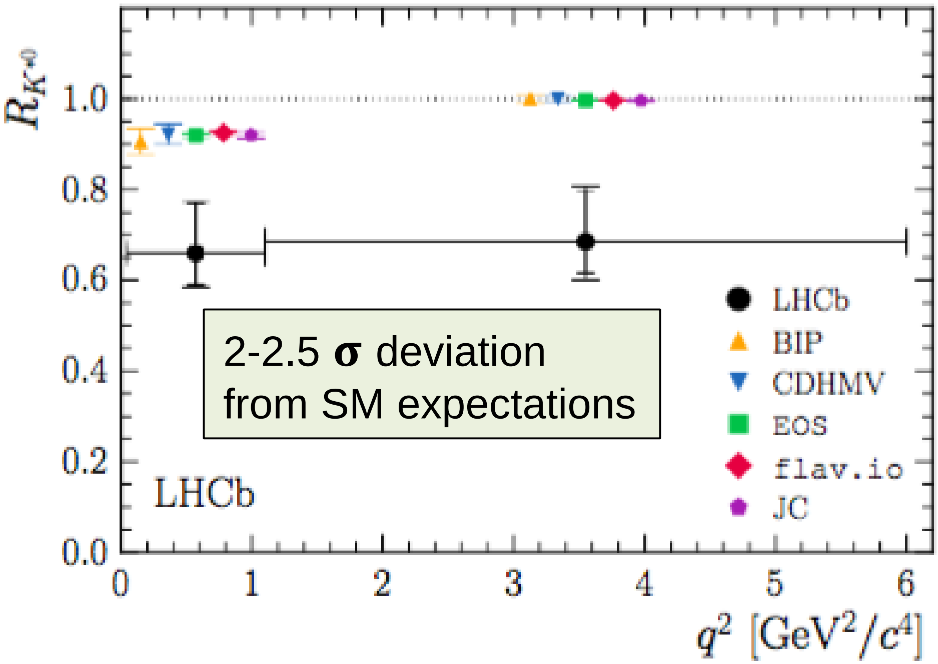
Hints (so far inconclusive) for deviations from lepton universality?
Couplings of leptons (ℓ = e, μ, τ) should be identical apart from (calculable) mass effects

$B^0 \rightarrow K^{0*} \ell^+ \ell^-$ with $K^{0*} \rightarrow K^\pm \pi^\mp$ and ℓ = e, μ

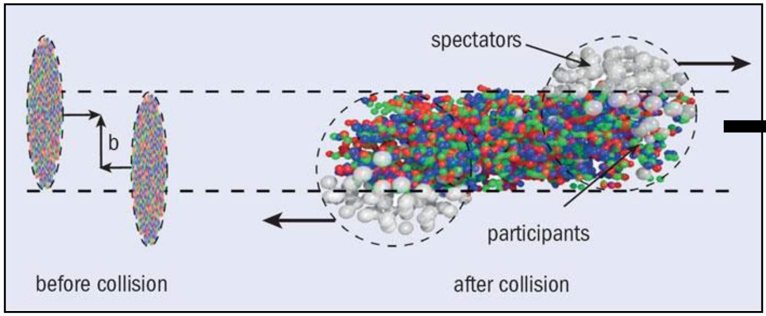


$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

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

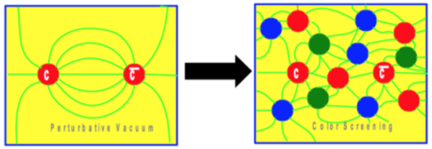


2-2.5 **σ** deviation from SM expectations

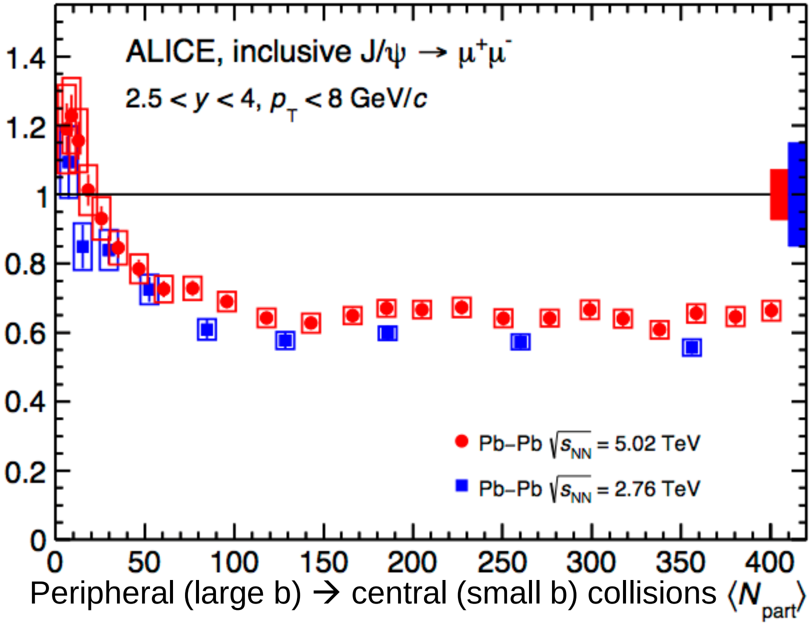


Heavy Ion collisions: conditions of high density and temperature of nuclear matter → formation of a plasma of deconfined quarks and gluons (QGP). Permeated early universe ~ 10 μs after Big Bang.

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



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

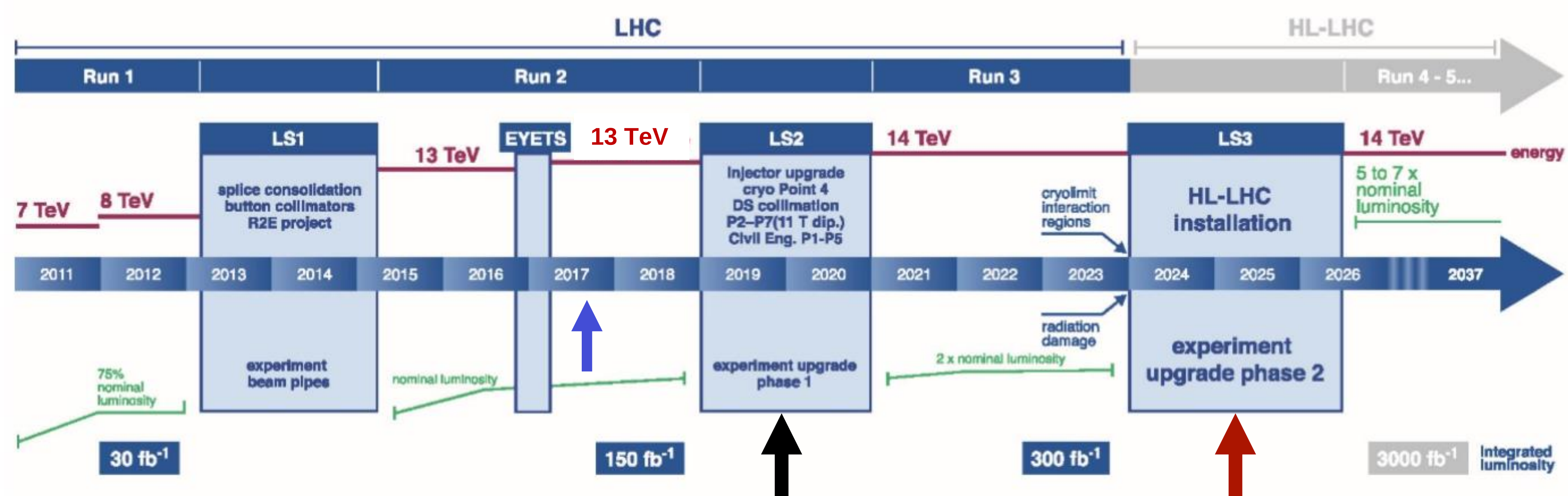


R_{AA} = quantifies departure from binary scaling
→=1 if no nuclear effects in HI collisions
→≠ 1 if medium effects

HL-LHC parameters and timeline

Nominal LHC: $\sqrt{s}$ = 14 TeV, L= 1×10^{34} cm^{-2} s^{-1} (Note: 1.7 $\times10^{34}$ cm^{-2} s^{-1} achieved already)
Integrated luminosity to ATLAS and CMS: 300 fb^{-1} by 2023 (end of Run-3)

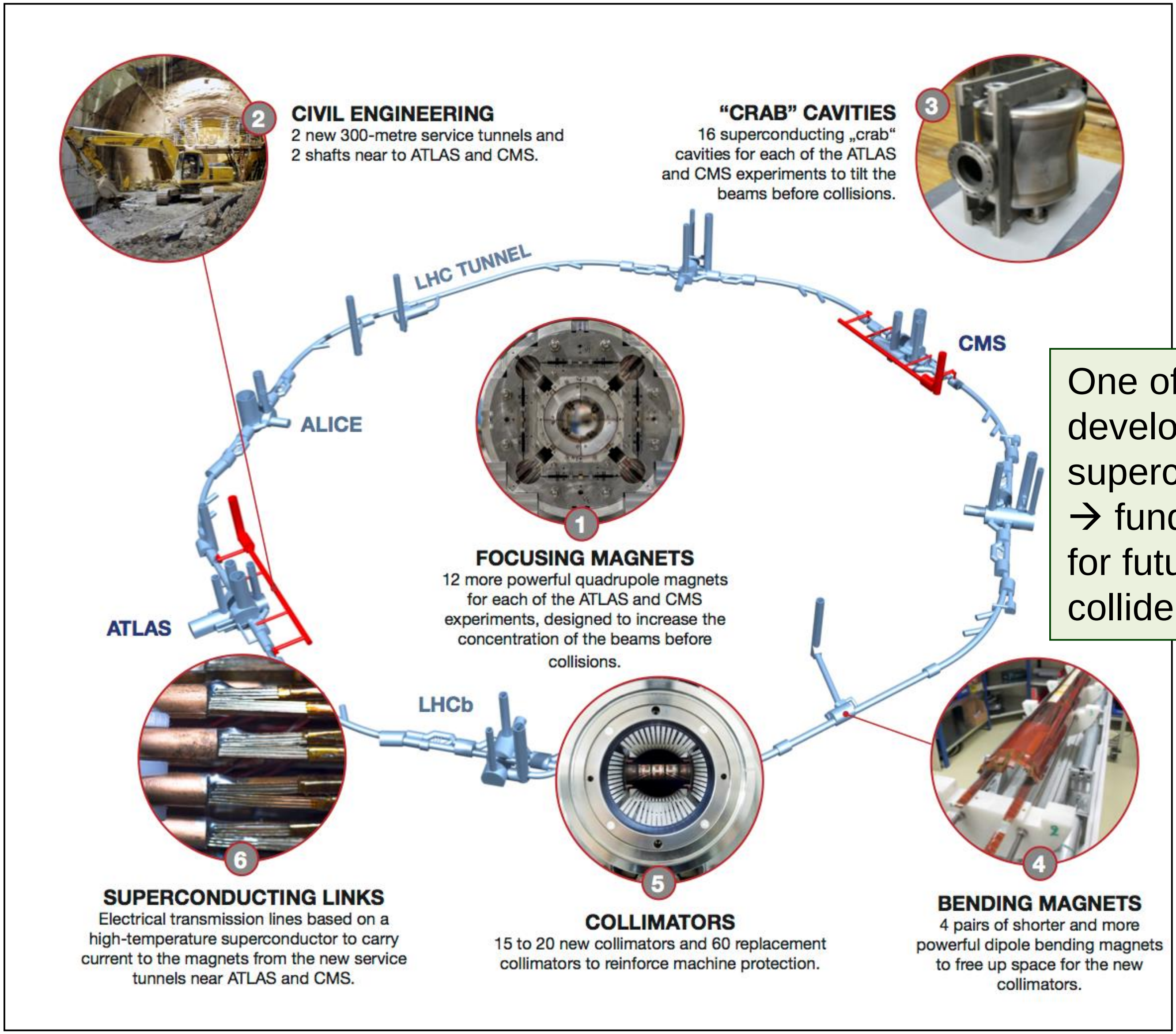
HL-LHC: $\sqrt{s}$ = 14 TeV, L= 5×10^{34} cm^{-2} s^{-1} (levelled)
Integrated luminosity to ATLAS and CMS: 3000 fb^{-1} by ~ 2035



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

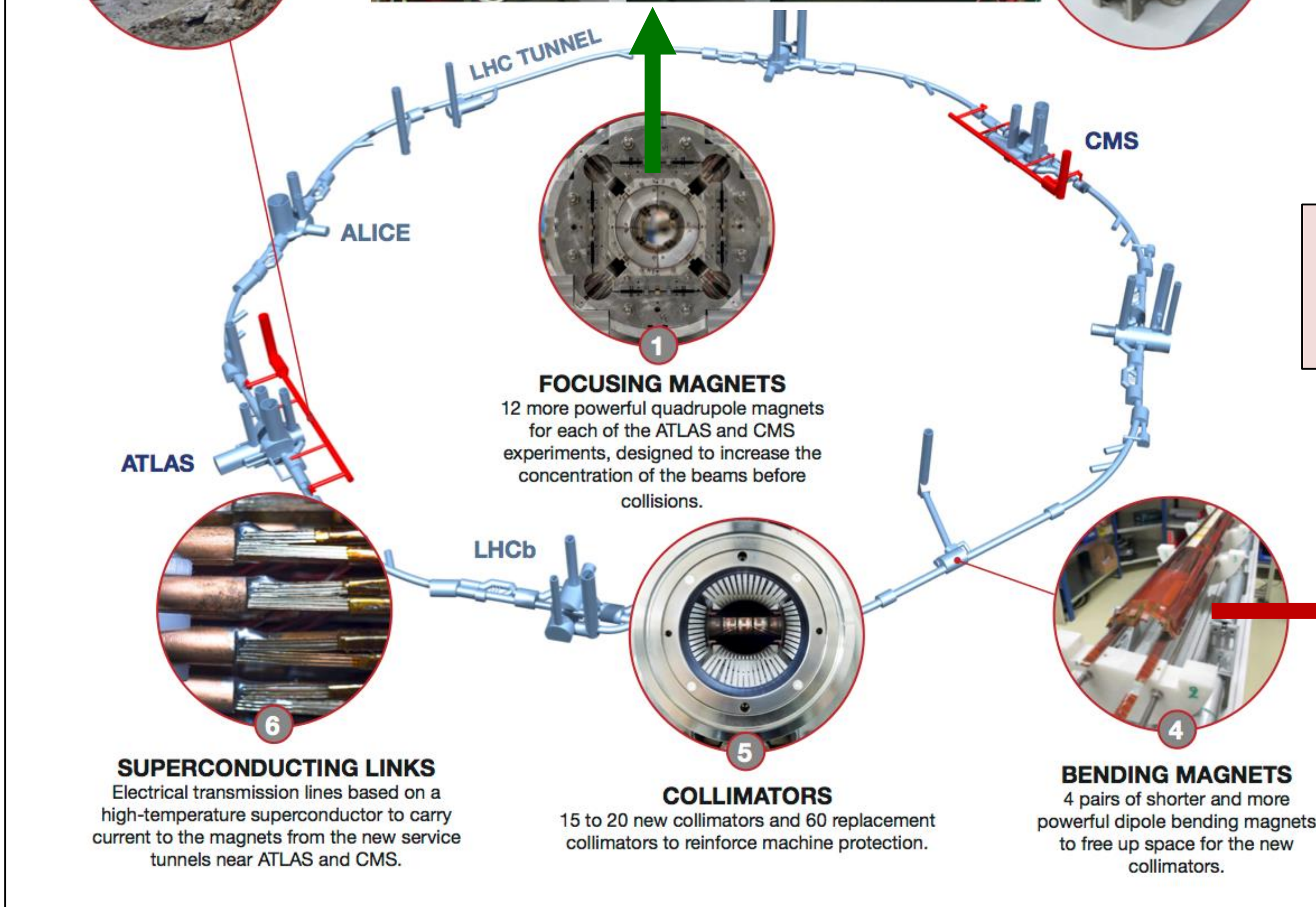
HL-LHC main upgrade components (and challenges …)



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

HL-LHC main upgrade components (and challenges …)

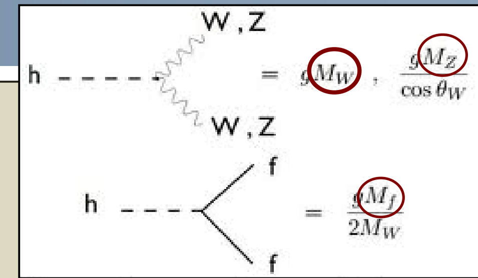
March 2016: Nb_3Sn quadrupole model (1.5 m long, aperture =150 mm) reached current of 18 kA (nominal: 16.5 kA) at FNAL. 2 coils from CERN + 2 coils from US.



End 2015: Nb_3Sn dipole (1.8 m) reached 11.3 T (> nominal) without quenches.

HL-LHC physics case

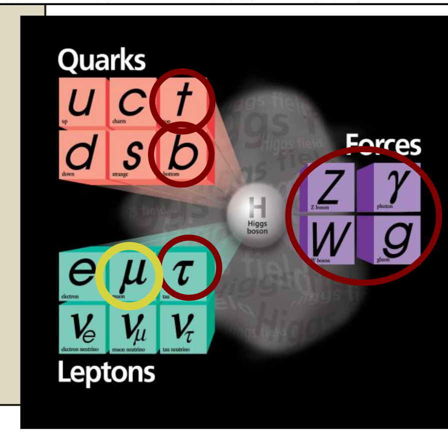
1 Precise measurements of the Higgs boson



Impact of New Physics on Higgs couplings to other particles:

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

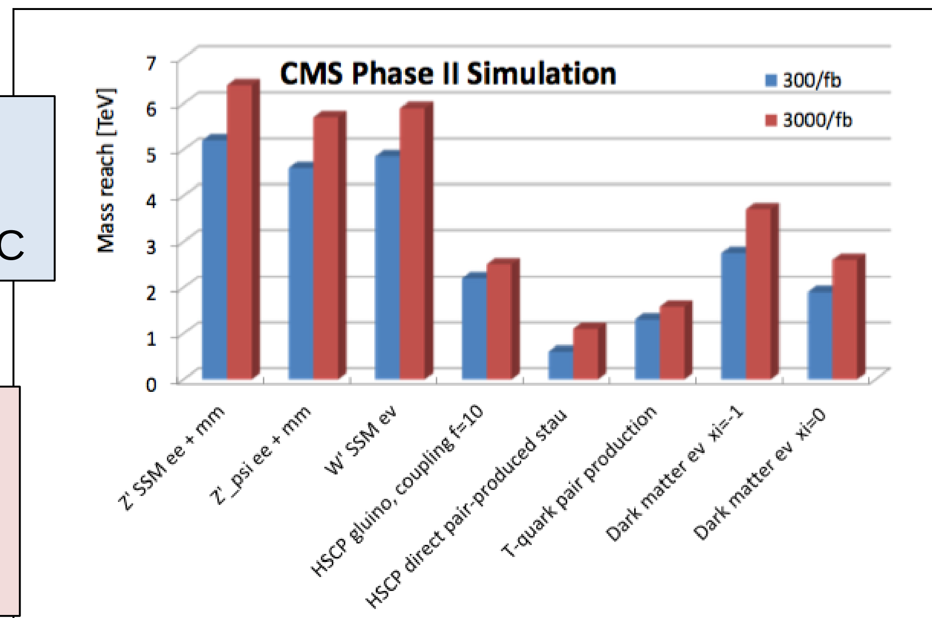
Precision ~2-5% at HL-LHC (~10% at nominal LHC)



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

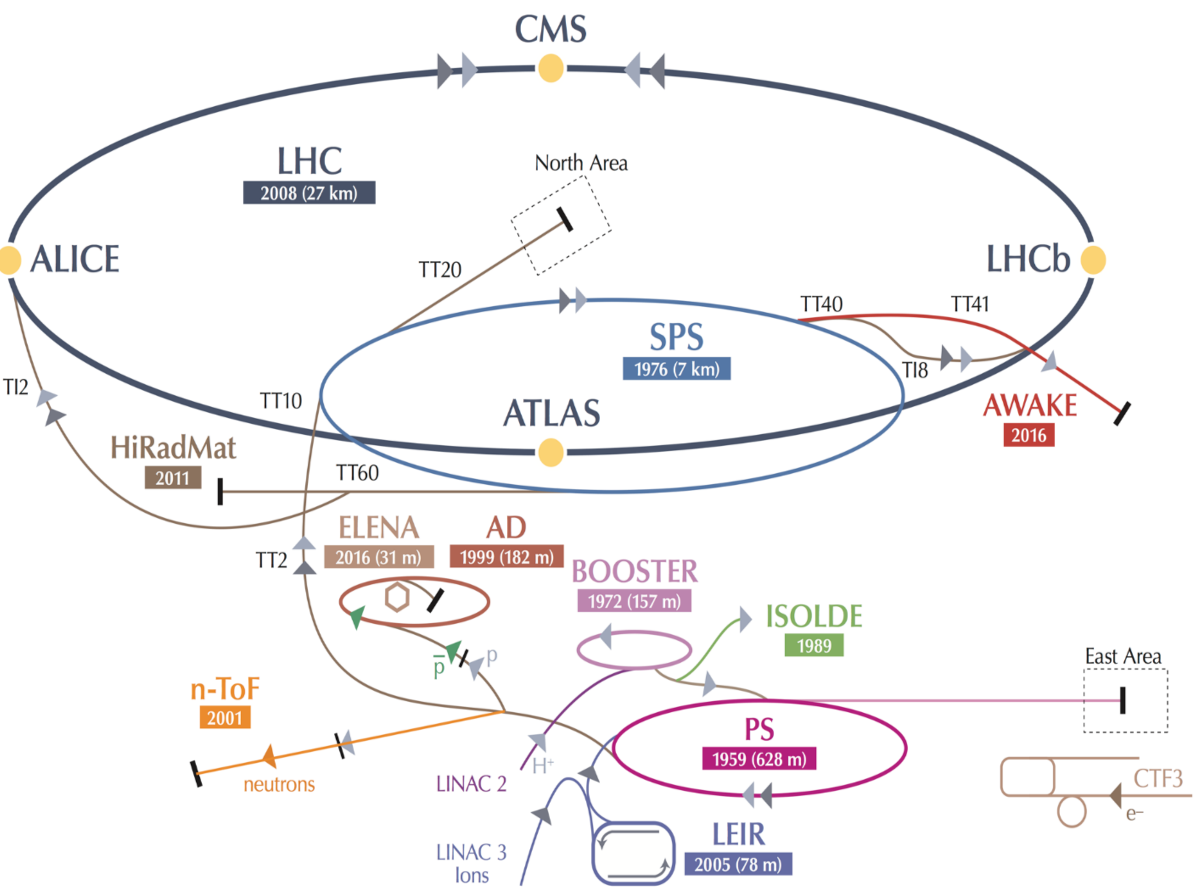


3 If new particles discovered in Run 2-3:

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

Scientific diversity programme

CERN's scientific diversity programme



AD: Antiproton Decelerator for antimatter studies

AWAKE: proton-induced plasma wakefield acceleration

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aerososls 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

~20 experiments > 1200 physicists

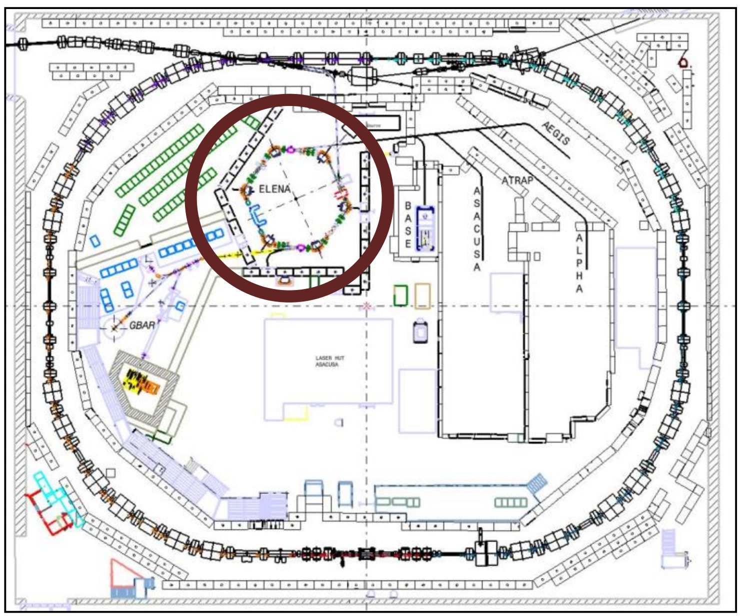
Antiproton Decelerator (AD)

CPT invariance of physics law is the most fundamental symmetry in relativistic quantum field theory
→ matter and anti-matter must have same properties (mass, charge, atomic spectra, etc.)

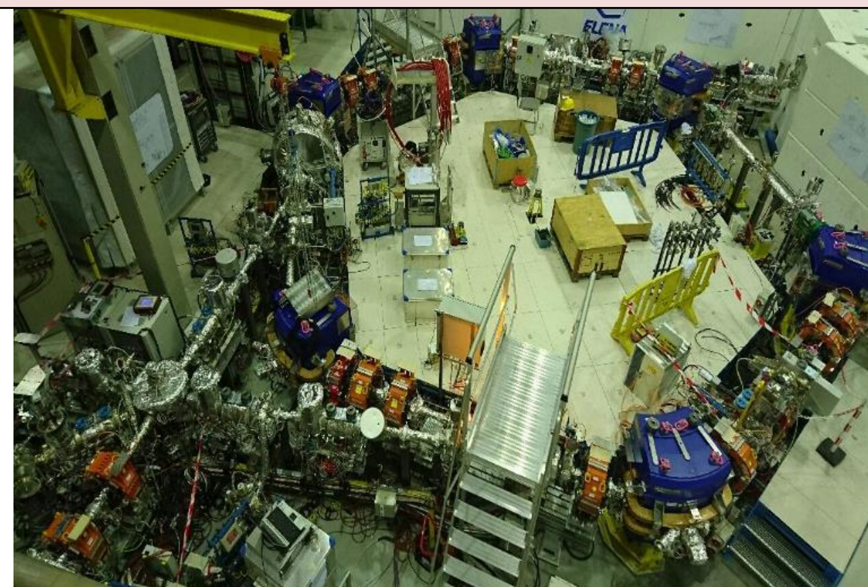
5 running experiments (AEgIS, ALPHA, ASACUSA, ATRAP, BASE), 1 in preparation (GBAR)

Precise spectroscopic and gravity measurements of antimatter using anti-p and anti-H atoms

Exquisite, ingenious experimental techniques developed over ~20 years to capture, cool down, trap, manipulate and measure anti-p, and to produce, manipulate and measure anti-H atoms.



ELENA commissioning with beams started Nov 2016

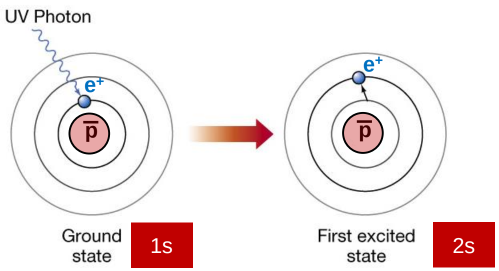


Upgrade: ELENA (additional decelerating and cooling ring) → anti-p decelerated to 100 keV (AD today: ~5 MeV) → x 10-100 larger trapping efficiency

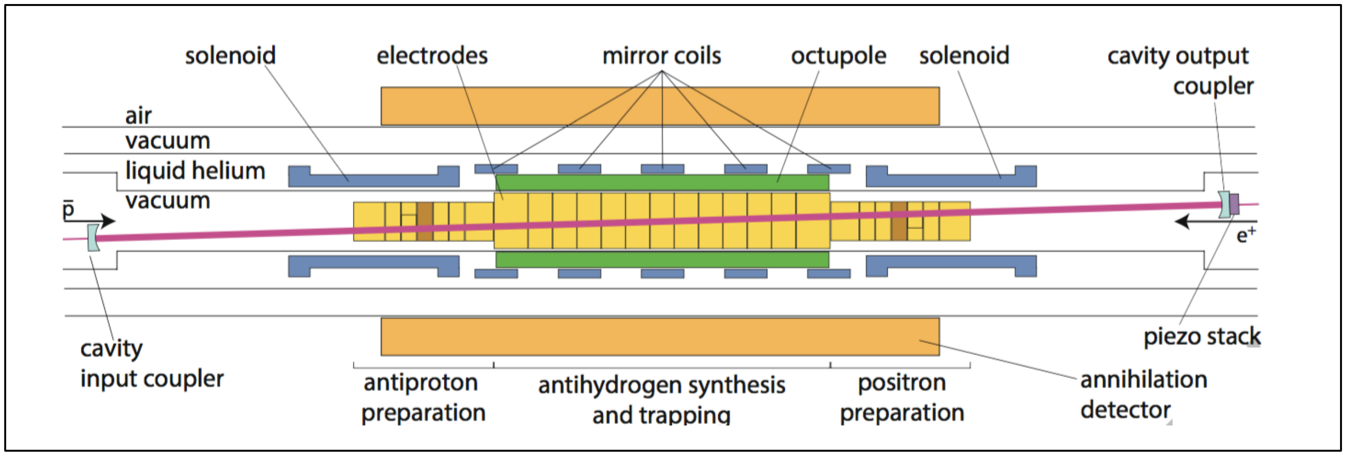
ALPHA: first measurement of anti-H spectrum

Based on laser-induced 1s → 2s transition of ~ 150 magnetically trapped anti-H atoms
→ opens the door to precise antimatter spectroscopy

Simplified sketch for illustration



Light wavelength at which transition occurs measured to be the same as for H atom within **2×10^{-10}**



Anti-H atoms detected from annihilation on electrode walls when magnetic trap is shut down

In each measurement cycle:

- ❑ 9×10^4 anti-p from AD mixed with 1.6×10^6 e^+ to produce ~ 25000 anti-H atoms
- ❑ ~14 atoms with E < 500 mK captured in magnetic trap
- ❑ vacuum chamber illuminated with laser at precisely tuned wavelength
- ❑ occurrence of 1s → 2s transition detected from sharp decrease in number of anti-H atoms remaining in the trap as a consequence of ionization or e^+ spin flip in excited atoms

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)?

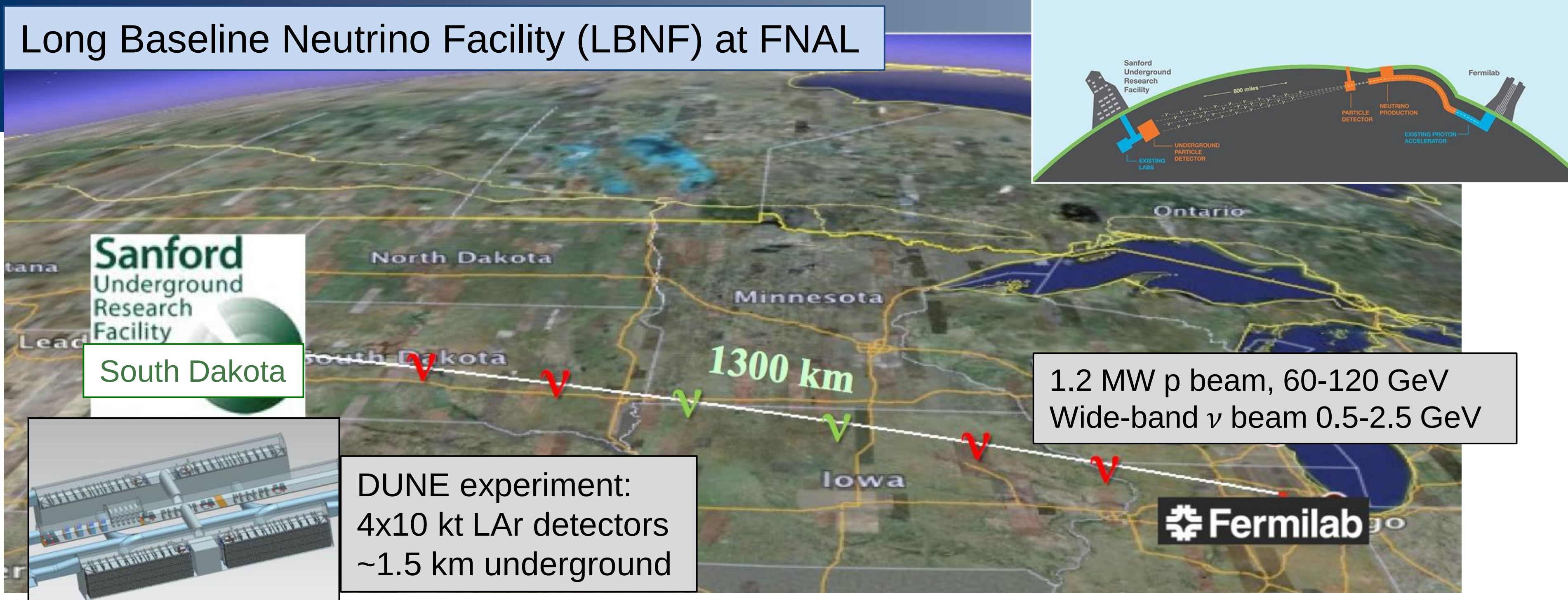
Accelerator experiments can address some of above questions studying $\nu_\mu \rightarrow \nu_e$ oscillations
Need high-intensity p sources (> 1 MW) and massive detectors, as ν are elusive particles and the searched-for effects tiny. Next-generation facilities planned in US and Japan.

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. Davidson

Long Baseline Neutrino Facility (LBNF) at FNAL

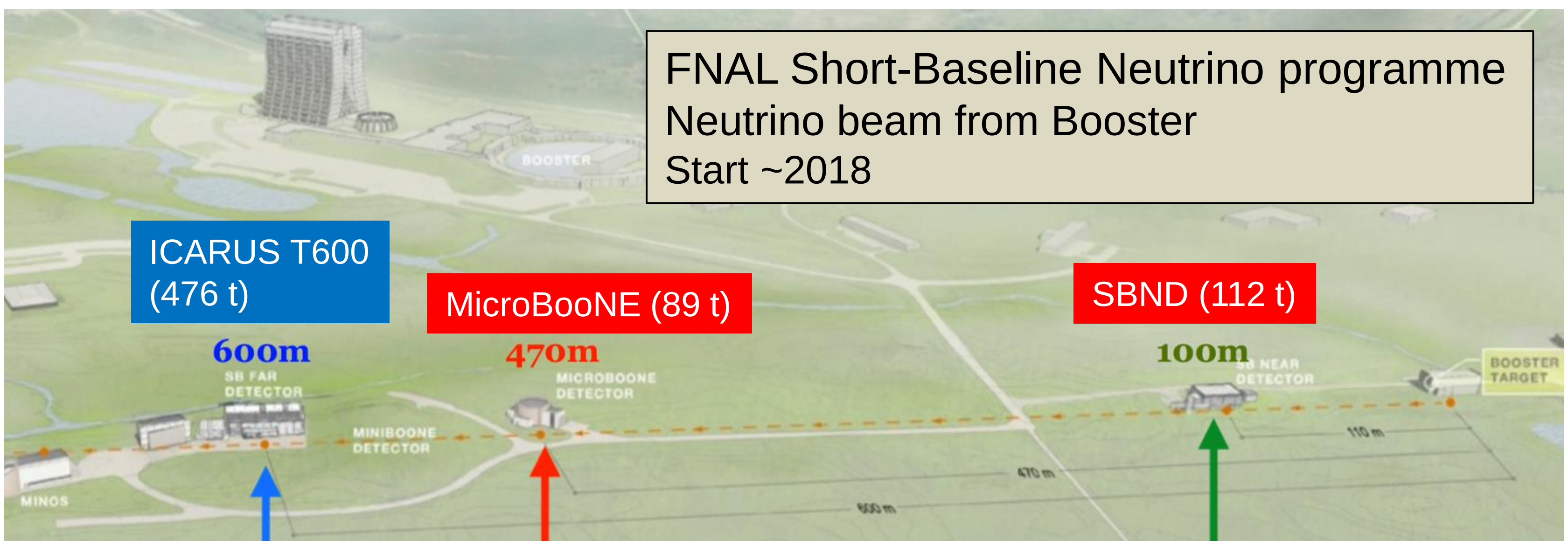


1.2 MW p beam, 60-120 GeV
Wide-band ν beam 0.5-2.5 GeV

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

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

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

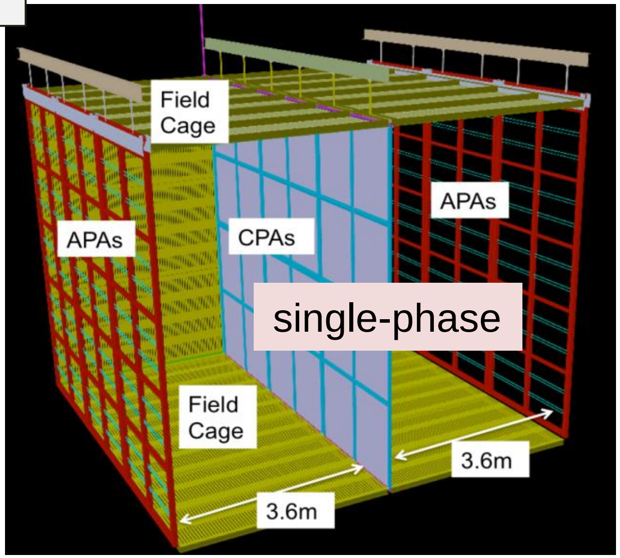


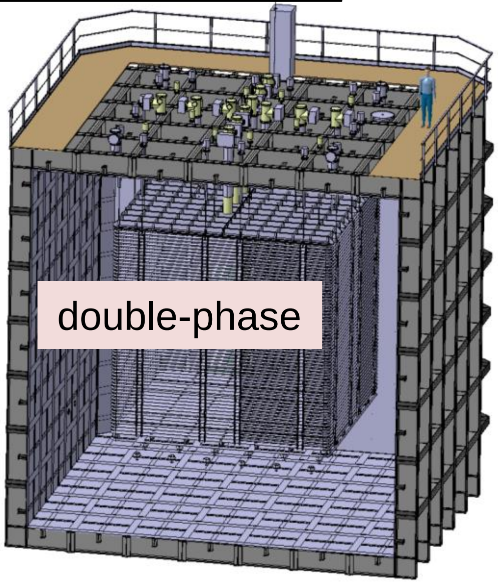
CERN Neutrino Platform

Scope:
- ❑ Provide charged beams and test space to neutrino community → NA extension
- ❑ R&D to demonstrate large-scale LAr technology (cryostats, detectors, …)
- ❑ Construction of cryostat for first module of DUNE
- ❑ Support neutrino experiments in US, Japan

ICARUS 600 t detector (two modules) now at FNAL, after refurbishment at CERN, to take part in short baseline neutrino programme.

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



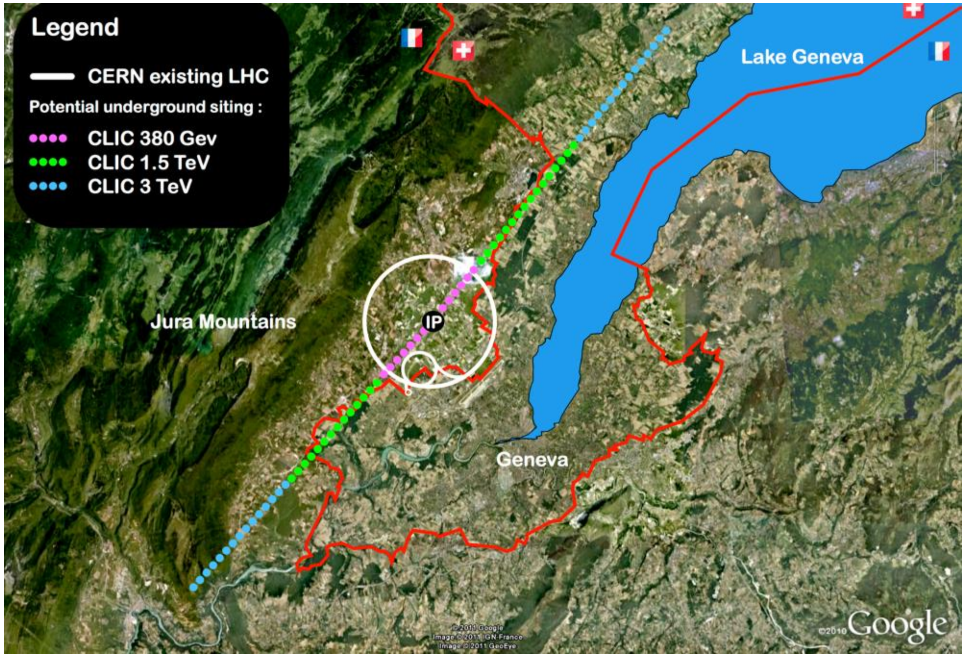


Preparation for the future

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



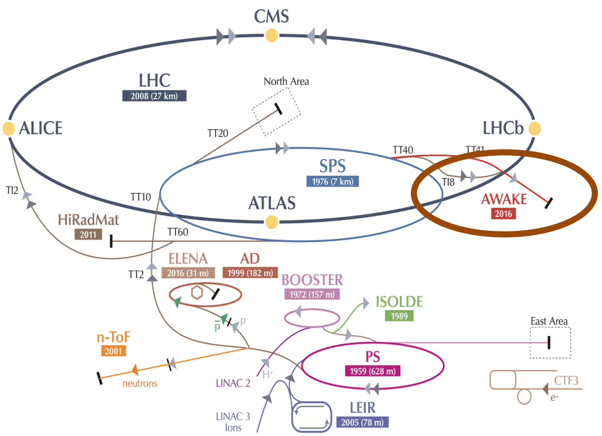
Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72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

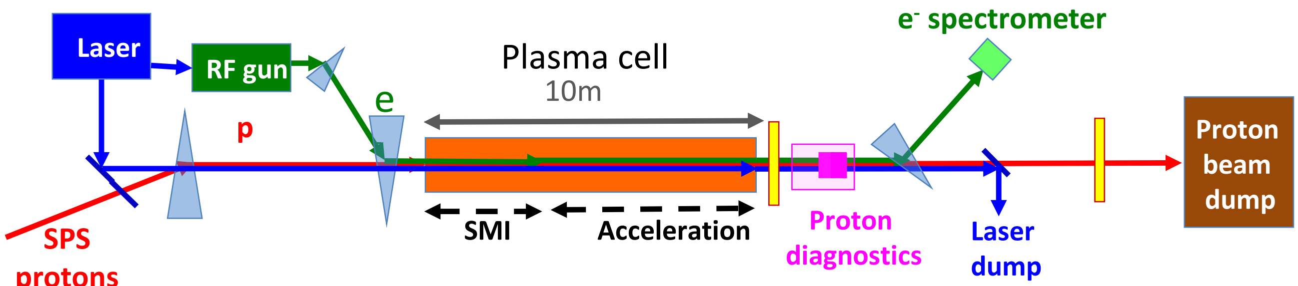
Physics goals:
- ❑ Direct discovery potential and precise measurements of new particles (couplings to Z/γ*) up to m~ 1.5 TeV
- ❑ Indirect sensitivity to E scales Λ ~ O(100) TeV
- ❑ Measurements of "heavy" Higgs couplings: ttH to ~ 4%, HH ~ 10%

AWAKE

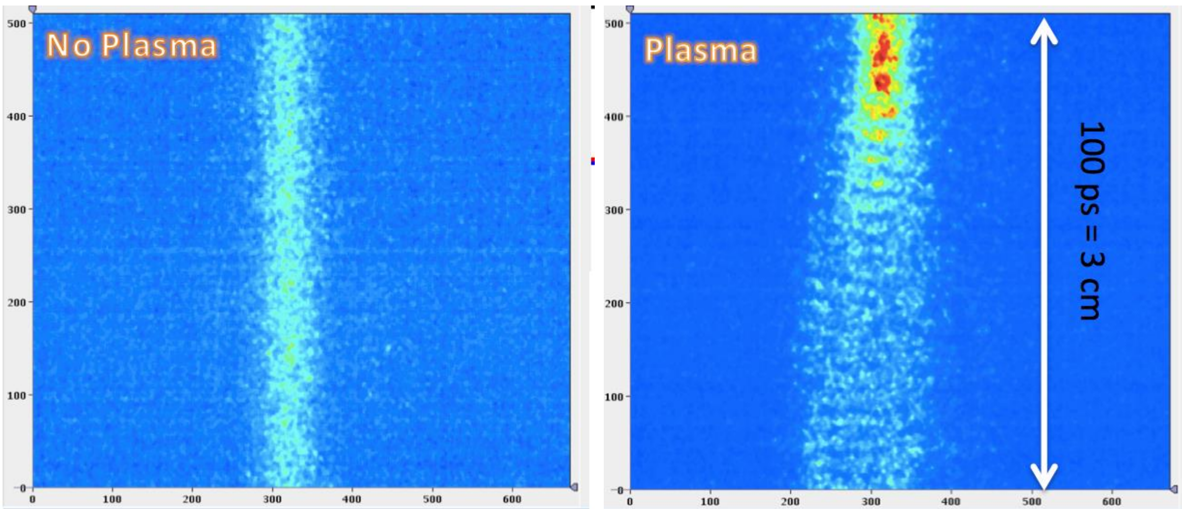
Advanced Proton Driven Plasma Wakefield Acceleration Experiment

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

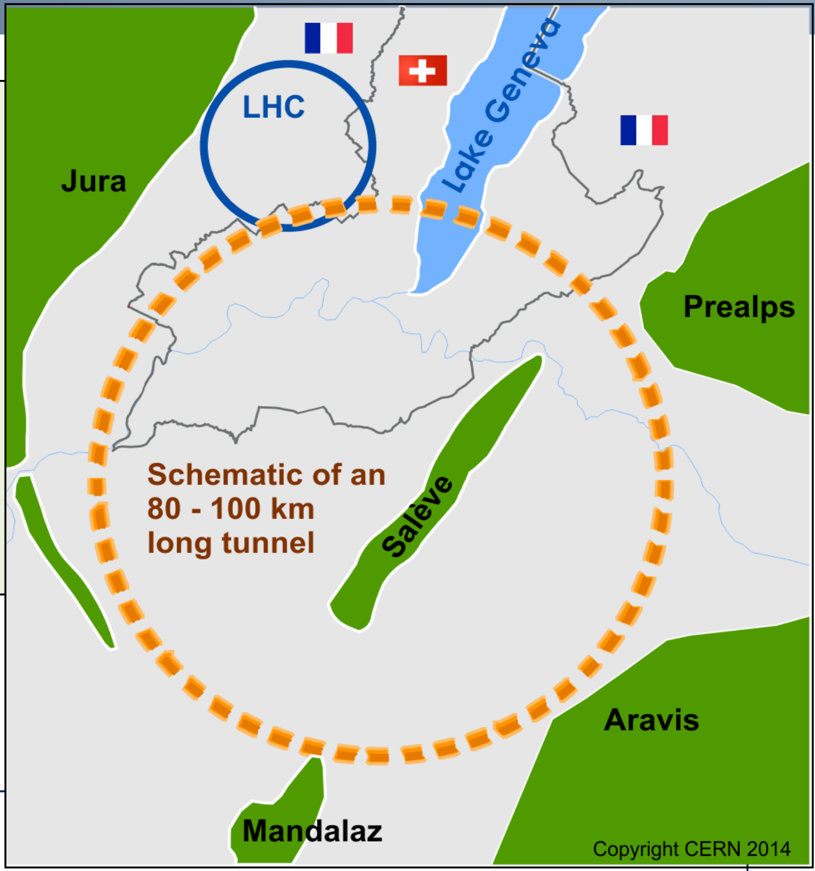


Future Circular Colliders (FCC)

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 → $\sqrt{s}$ ~ 30 TeV



FCC-hh: a ~100 TeV pp collider is expected to:

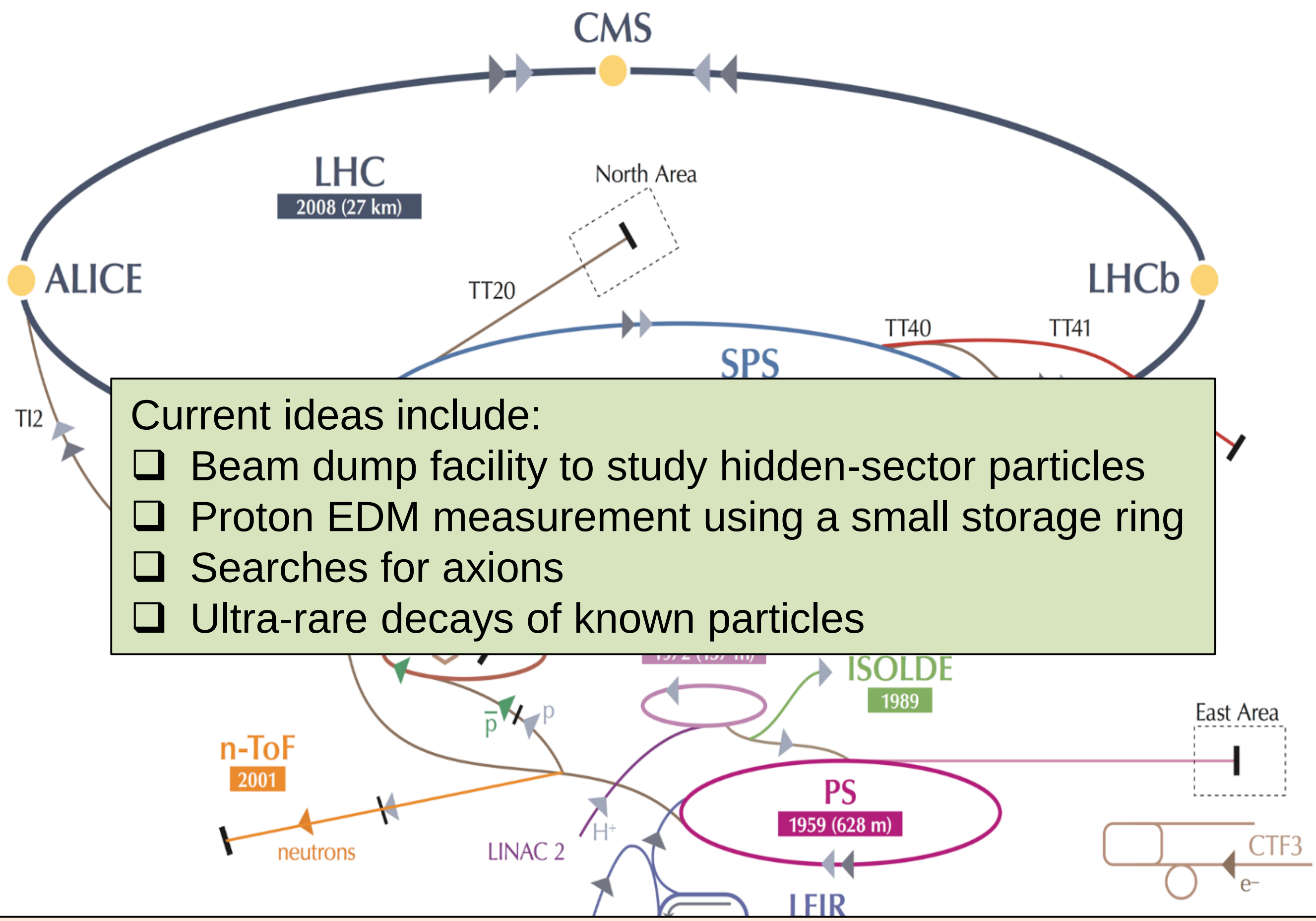
- ❑ explore directly the 10-50 TeV E-scale
- ❑ conclusive exploration of EWSB dynamics
- ❑ say the final word about heavy WIMP dark matter

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

Future scientific opportunities other than high-E colliders

We are also exploring opportunities to address the outstanding questions in particle physics through projects complementary to high-energy colliders, exploiting the unique capabilities of the (very rich) CERN's accelerator complex and infrastructure



Current ideas include:

- ❑ Beam dump facility to study hidden-sector particles
- ❑ Proton EDM measurement using a small storage ring
- ❑ Searches for axions
- ❑ Ultra-rare decays of known particles

Emphasis on light, extremely-weakly-coupled particles and indirect exploration of very high E scales through precise measurements

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 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