



Accelerating Science and Innovation

Particle Physics at CERN
Introduction
Science
A Forward Look



Accelerating Science and Innovation

Introduction

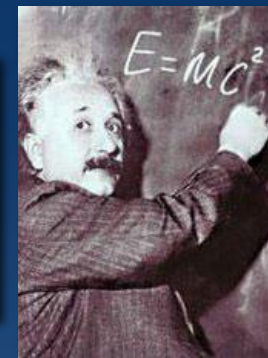
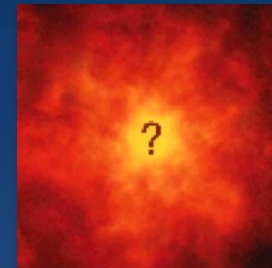
CERN



The Mission of CERN

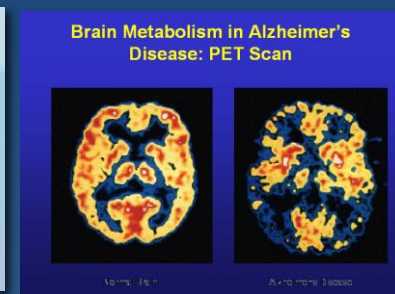
- **Push back** the frontiers of knowledge

E.g. the secrets of the Big Bang ...what was the matter like within the first moments of the Universe's existence?

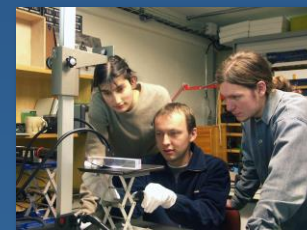


- **Develop** new technologies for accelerators and detectors

Information technology - the Web and the GRID
Medicine - diagnosis and therapy



- **Train** scientists and engineers of tomorrow



- **Unite** people from different countries and cultures



CERN was founded 1954: 12 European States

“Science for Peace”

Today: 21 Member States

- ~ 2300 staff
- ~ 1600 other paid personnel
- ~ 10500 scientific users

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

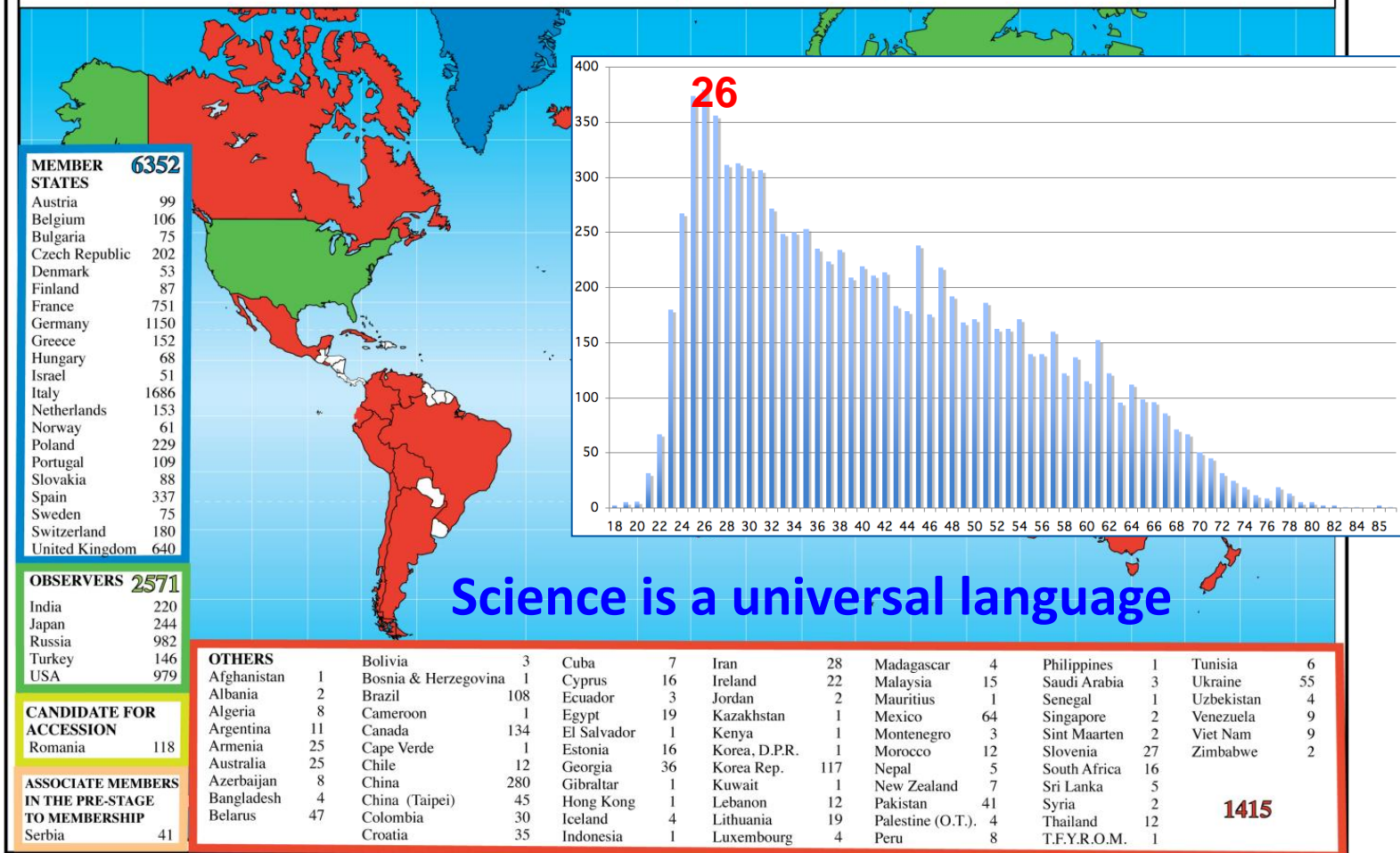
States in accession to Membership: Romania, Serbia

Applicant States for Membership or Associate Membership: Brazil, Croatia, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

Observers to Council: India, Japan, Russia, Turkey, United States of America; European Commission and UNESCO

Breaking the Walls between Cultures and Nations since 1954

Distribution of All CERN Users by Nationality on 14 January 2014





Accelerating Science and Innovation

Science

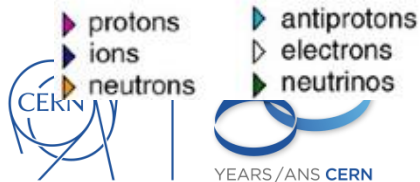
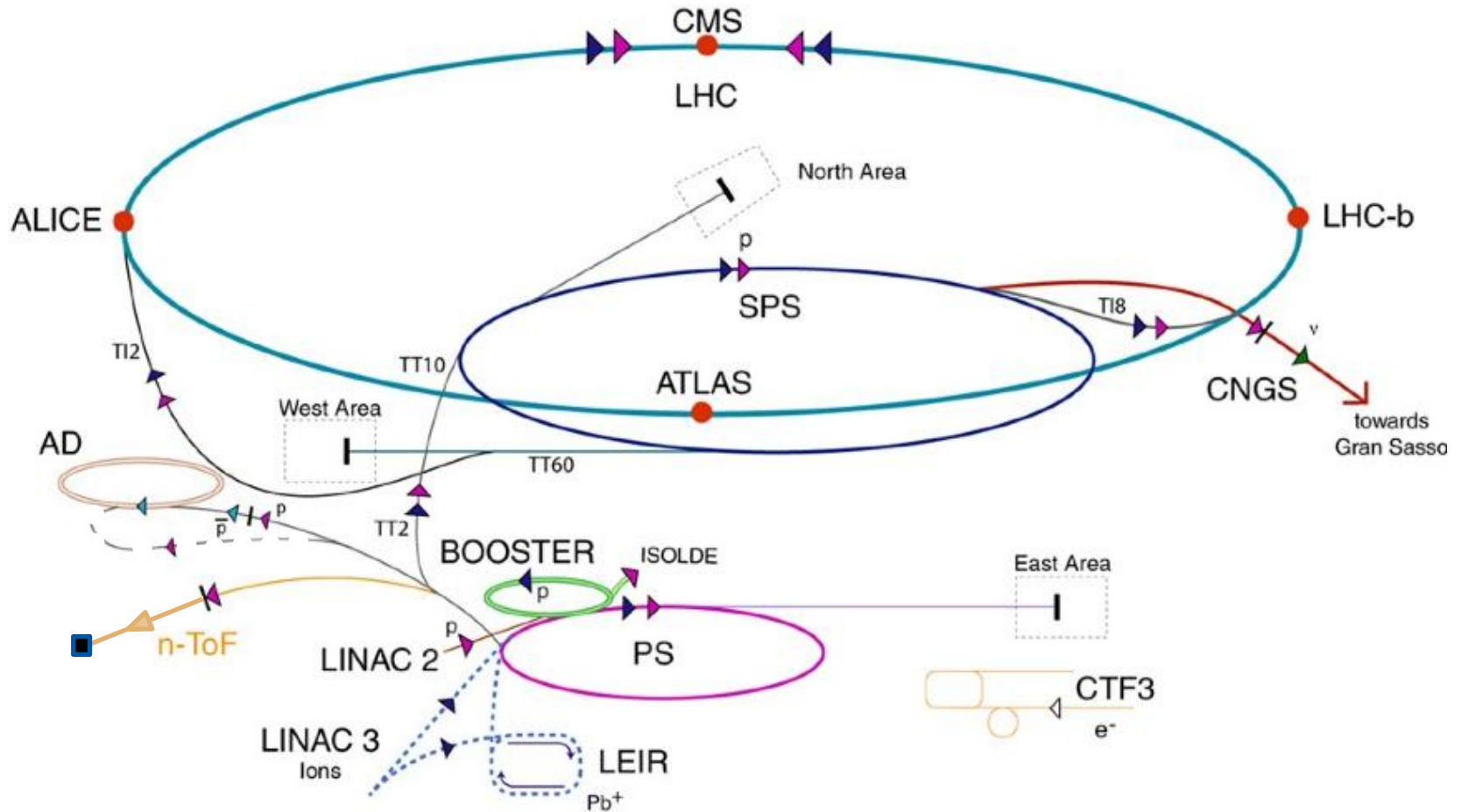
Particle Physics at CERN Experiments and Theory

Starting 1954

**Mid 1950's the first accelerator
(the synchrocyclotron) arrives . . .**



CERN Accelerator Complex today



AD Antiproton Decelerator
 PS Proton Synchrotron
 SPS Super Proton Synchrotron

LHC Large Hadron Collider
 n-ToF Neutron Time of Flight
 CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

The Particle Physics Landscape at CERN

High Energy Frontier

LHC

Low Energy

*heavy flavours / rare decays
neutrino oscillations*

anti-matter

Multidisciplinary

climate, medicine

Non-accelerator

*dark matter
astroparticles*

Hadronic Matter

*deconfinement
non-perturbative QCD
hadron structure*

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

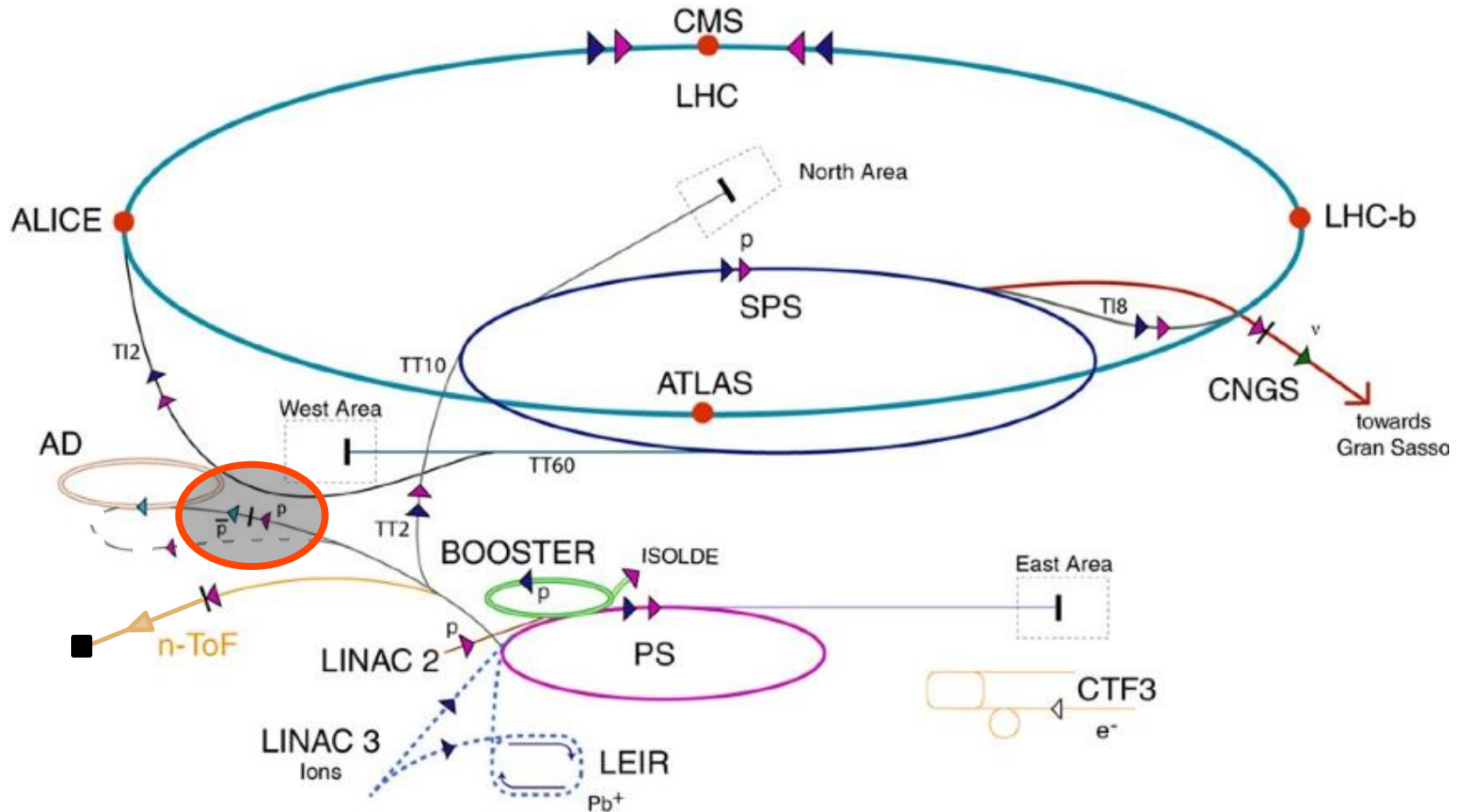
In the past few years

Several breakthroughs !

Steady progress of other programs

New mid-term and long-term projects started or in discussion

CERN Accelerator Complex



- ▶ protons
- ▶ ions
- ▶ neutrons

- ▶ antiprotons
- ▶ electrons
- ▶ neutrons

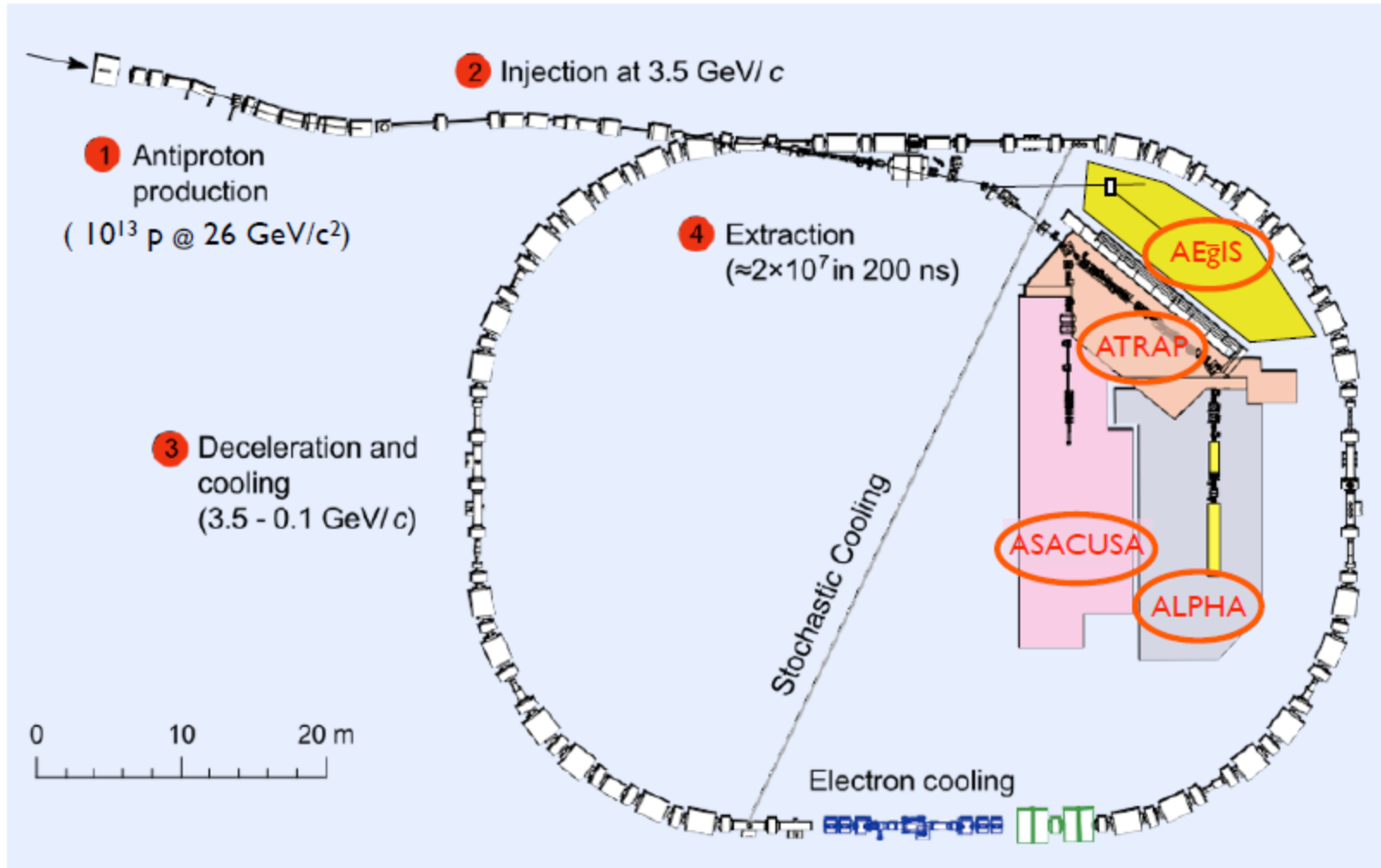
- AD Antiproton Decelerator
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CTF3 CLIC Test Facility 3

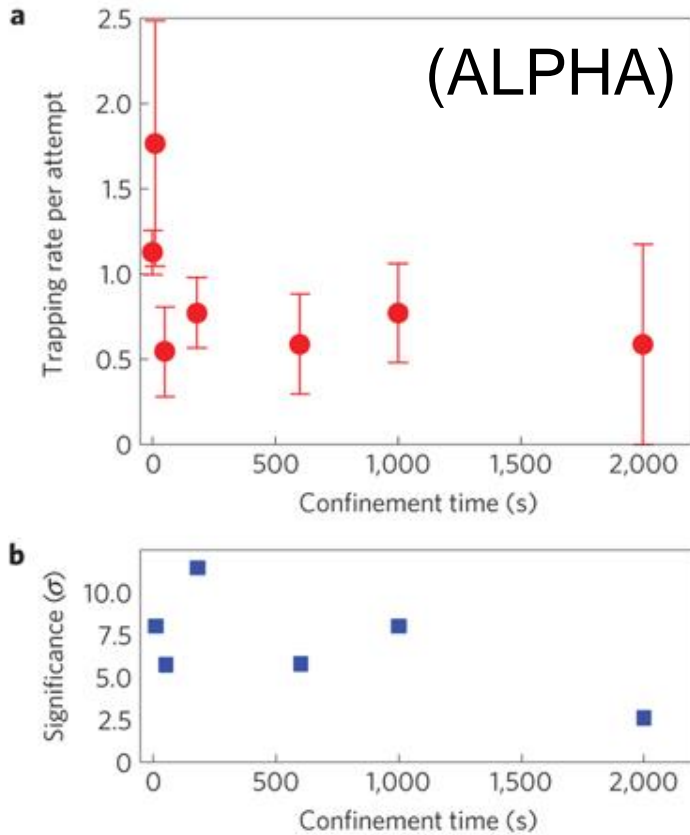
AD (current situation)

Antiproton decelerator

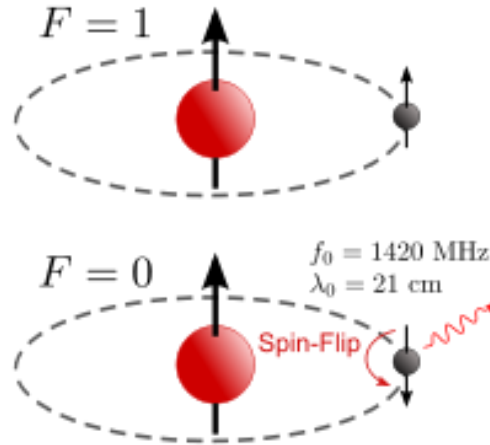


Spectroscopy with trapped antihydrogen?

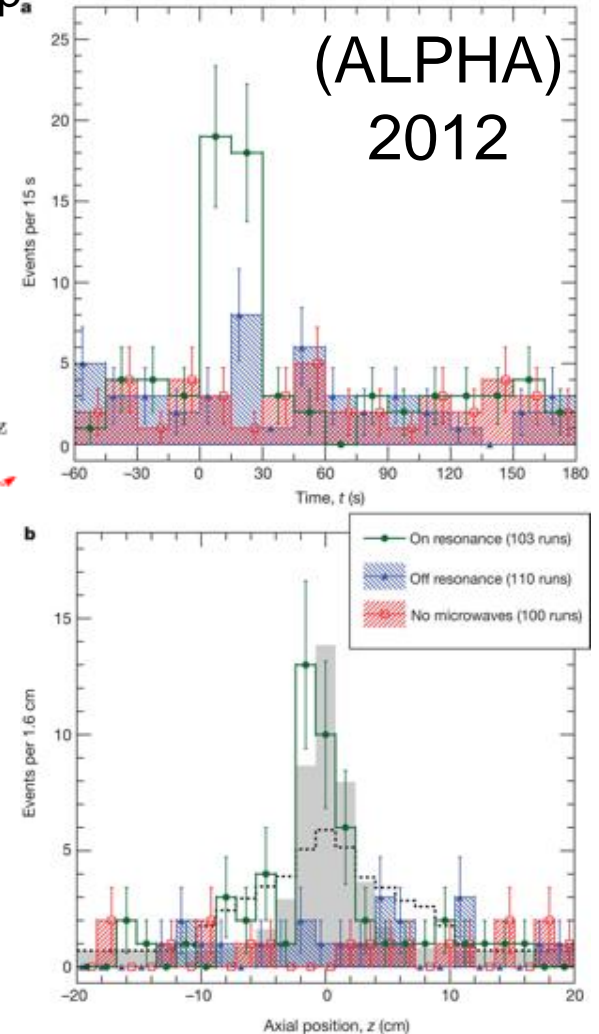
Antihydrogen atom trapping time



Spectroscopy:
HFS
via microwave



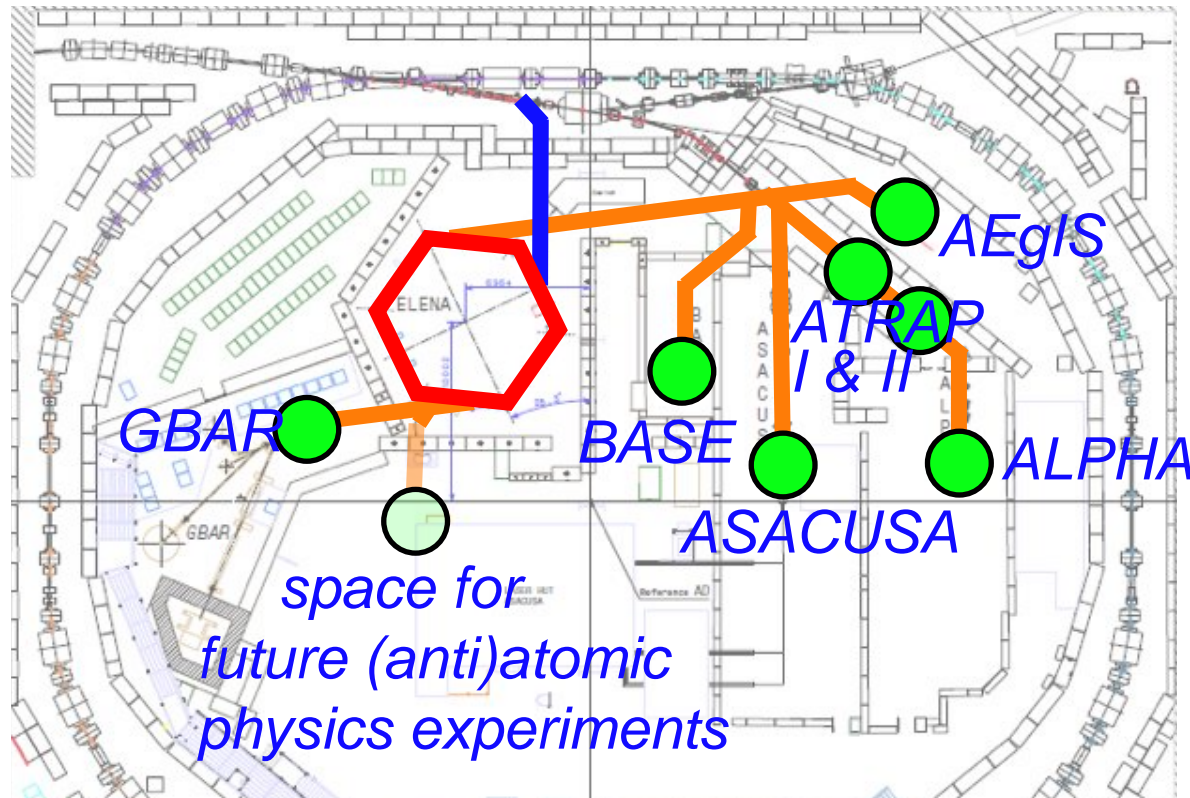
but: B-field varies strongly over trap.



Next steps: better cooling, more atoms,
laser spectroscopy

increasing & continuous demand for antiprotons,
current methods for trapping them are very inefficient

→ ELENA (will start 2017)



- dramatically slows down the antiprotons from the AD
- increases the trapping efficiency x 100
- allows 4 experiments to run in parallel

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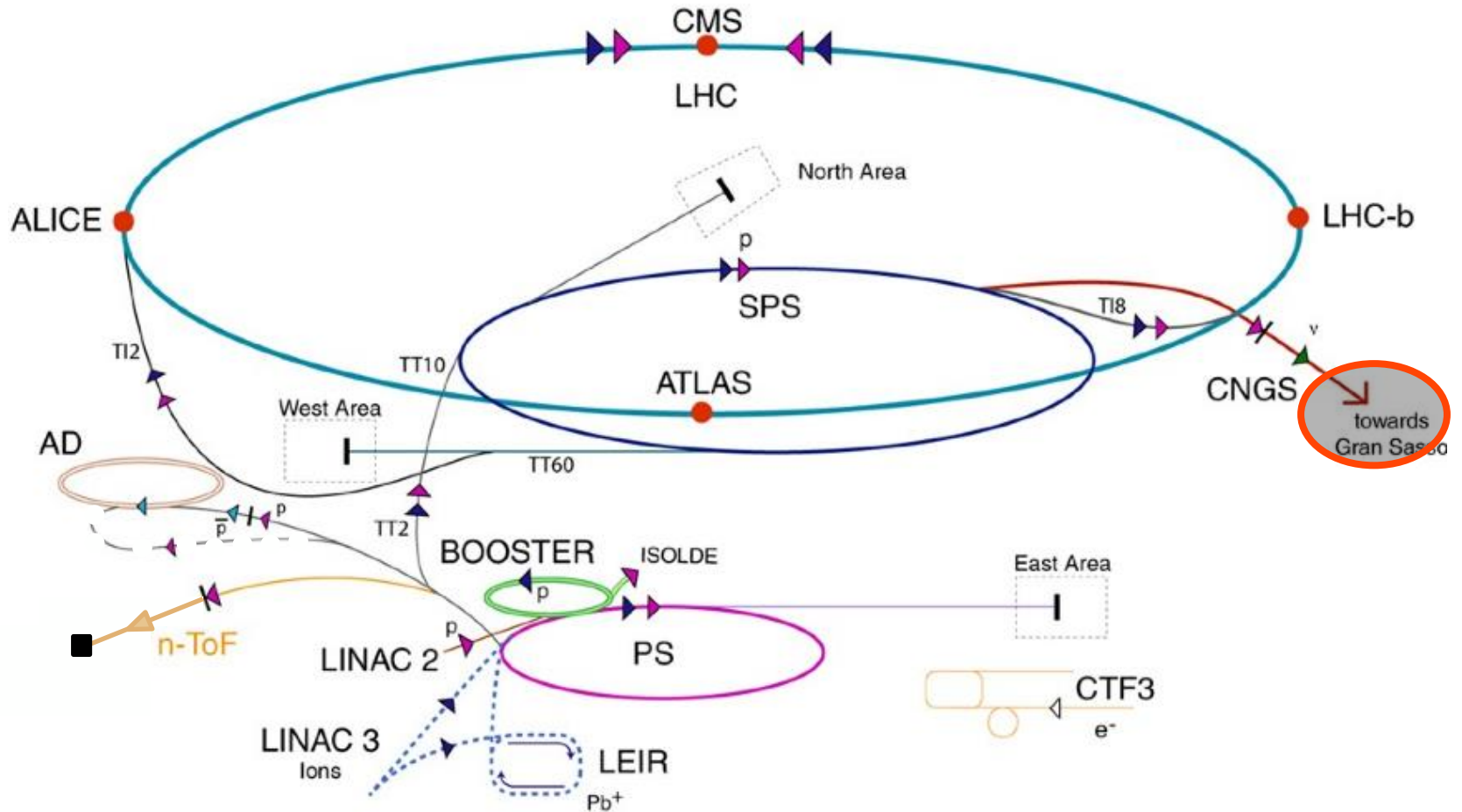
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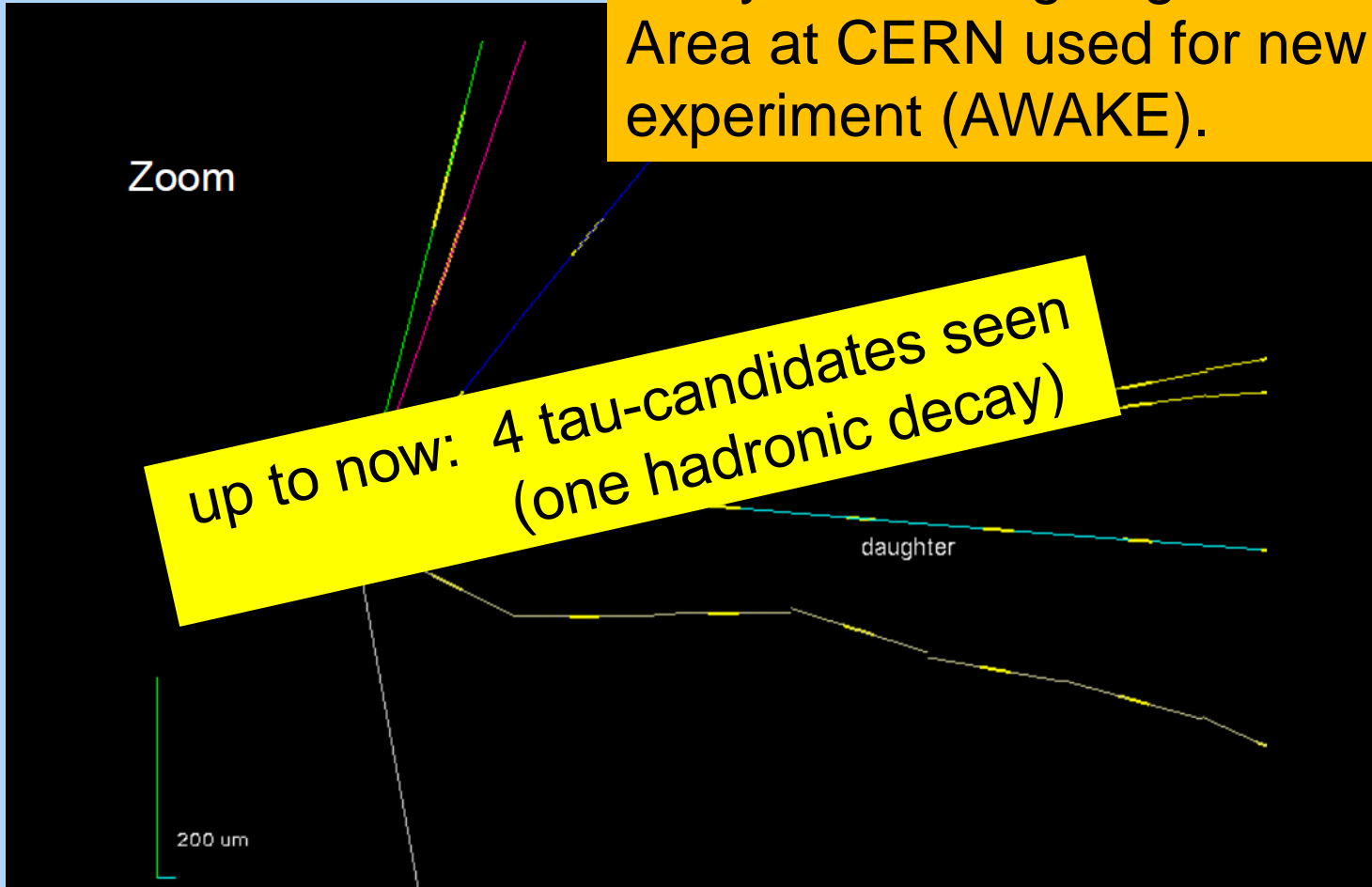
- LHC Large Hadron Collider
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CTF3 CLIC Test Facility 3

CNGS - OPERA

First ν_τ Candidate

Data taking now terminated,
analysis still ongoing.
Area at CERN used for new
experiment (AWAKE).



Muonless event 9234119599, taken on 22 August 2009, 19:27 (UTC)
(as seen by the electronic detectors)

The Particle Physics Landscape at CERN

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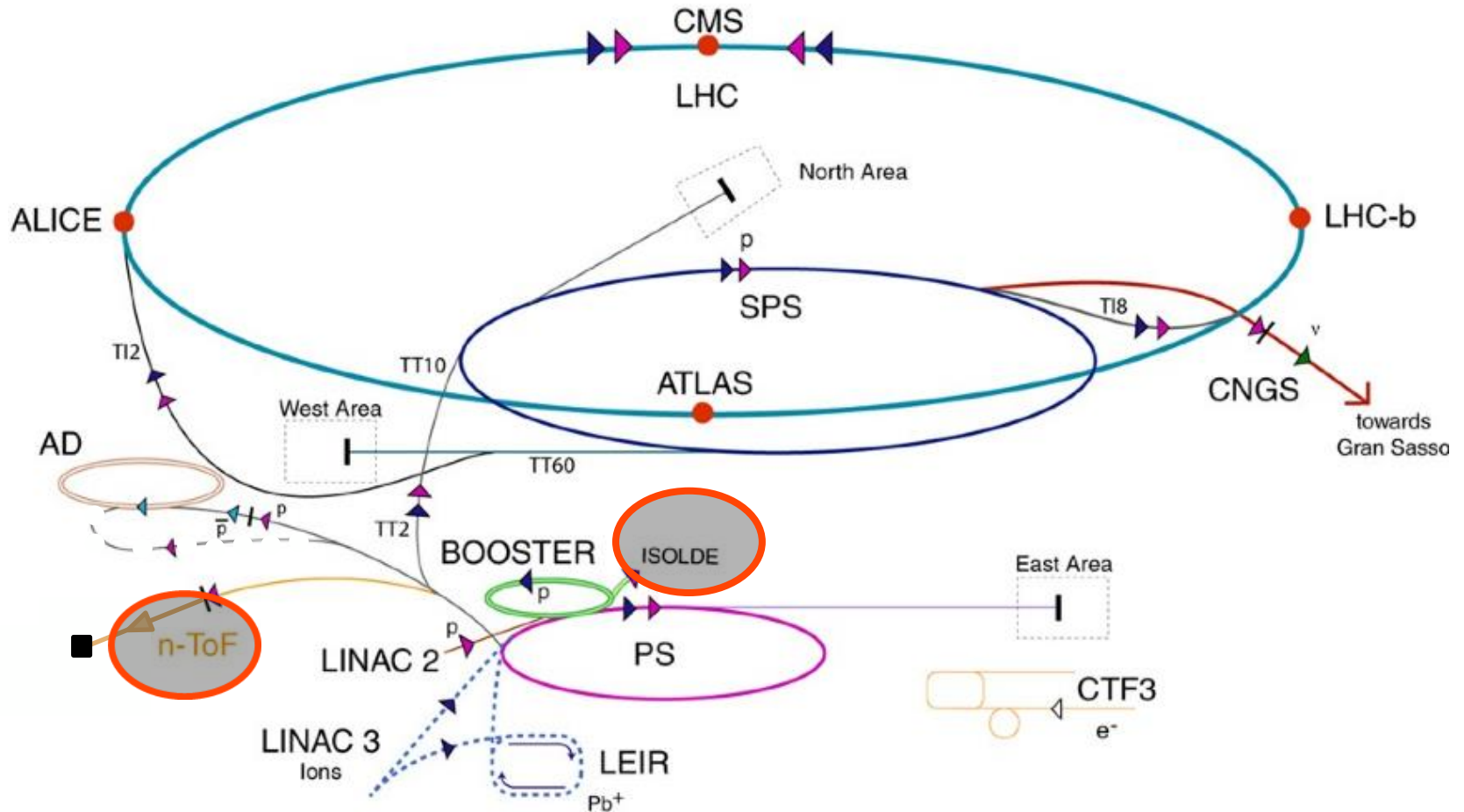
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CERN Accelerator Complex



- | | | | |
|------------|---------------|------------------------------|--------------------------------|
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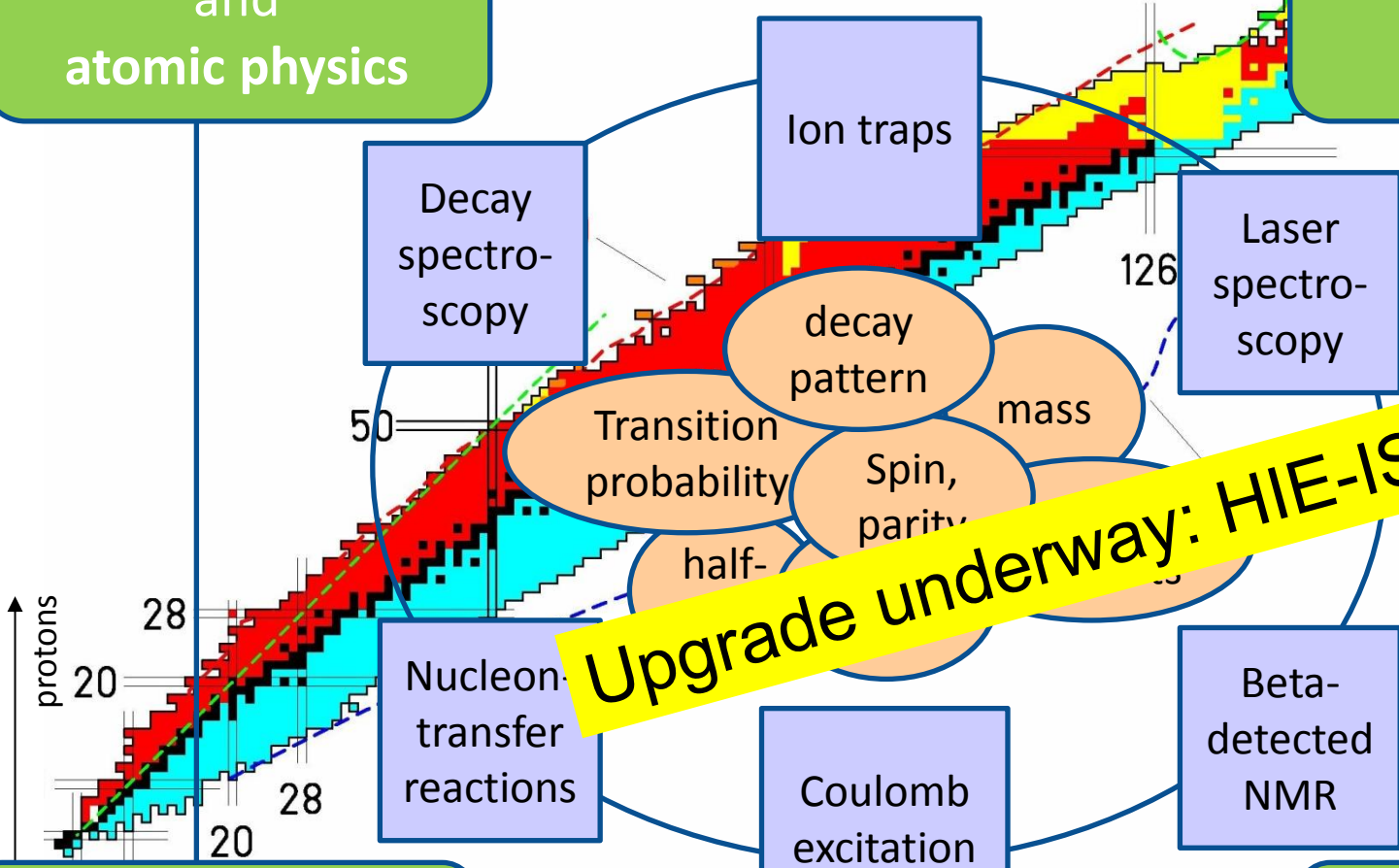


Research with radioactive nuclides

More than 700 nuclides of over 70 chemical elements delivered

Nuclear physics and atomic physics

Material science and life sciences



Fundamental interactions

Nuclear astrophysics

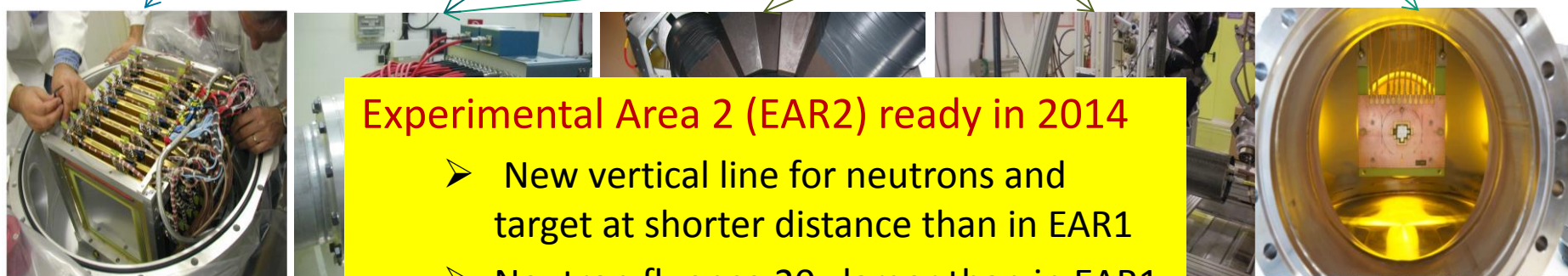
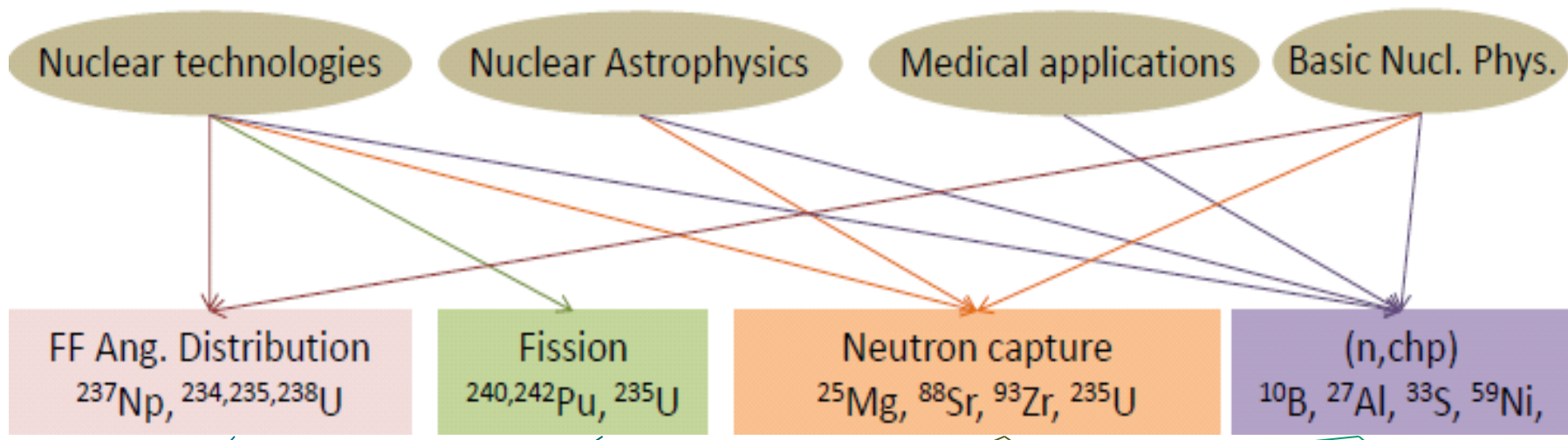
Techniques: all available at ISOLDE



n_TOF physics



100 members, 32 institutions



Experimental Area 2 (EAR2) ready in 2014

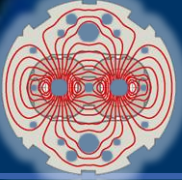
- New vertical line for neutrons and target at shorter distance than in EAR1
- Neutron fluence 20x larger than in EAR1 but lower resolution due to shorter TOF



Accelerating Science and Innovation

Energy Frontier

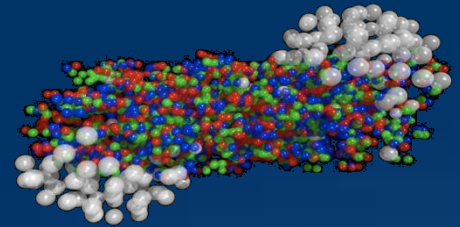
LHC



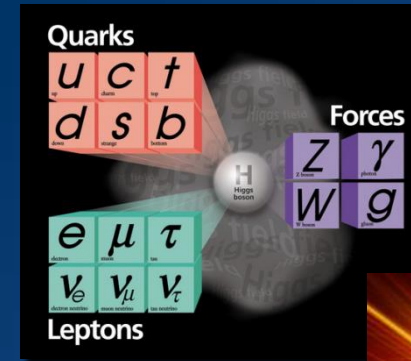
The study of LHC data will allow us to answer some of the key questions ...



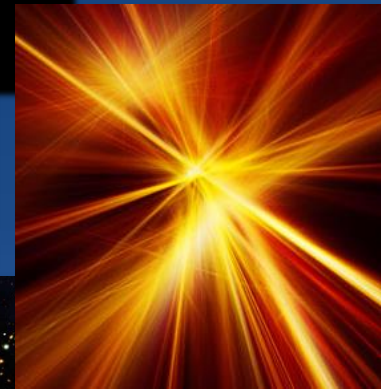
Will we understand the **primordial state of matter** after the Big Bang before protons and neutrons formed?



Have we found the **Higgs particle** that is 'responsible for **giving mass**' to all particles?



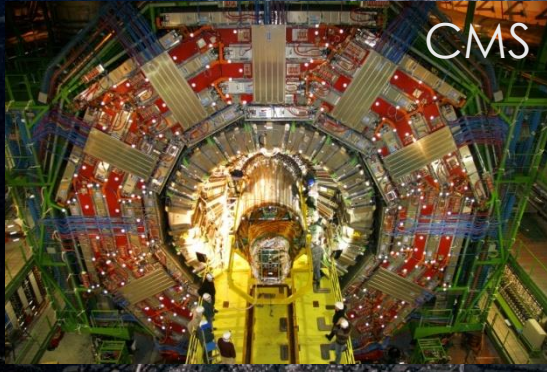
Will we find the reason why **antimatter and matter did not completely destroy each other**?



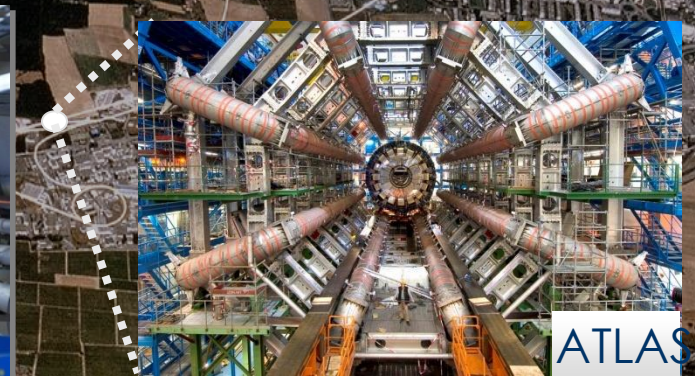
Will we find the **particle(s)** that make up the **mysterious 'dark matter'** in our Universe? And what's **'dark energy'**?

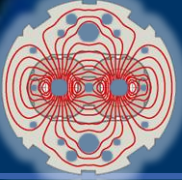


2010: a New Era in Fundamental Science



Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at E_{CM} up to 14 TeV

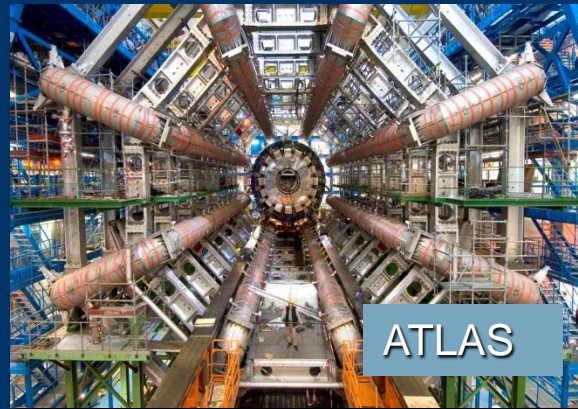
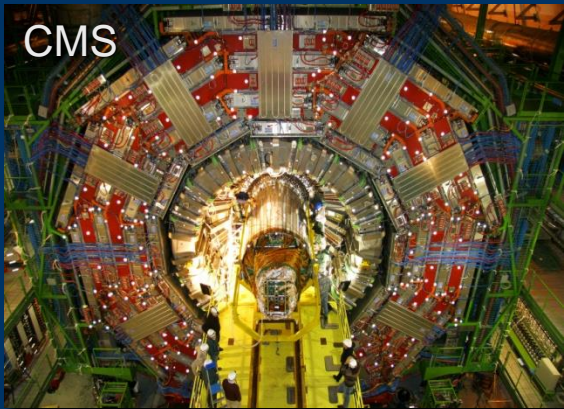




LHC Experiments → complementary



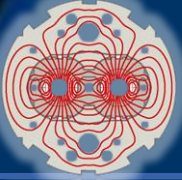
Specialised detector to study b-quarks → CPV



General purpose detectors



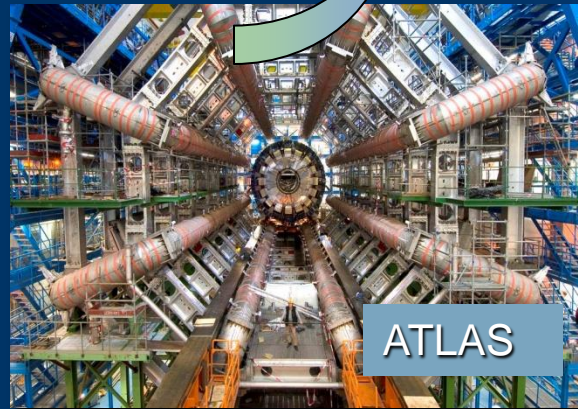
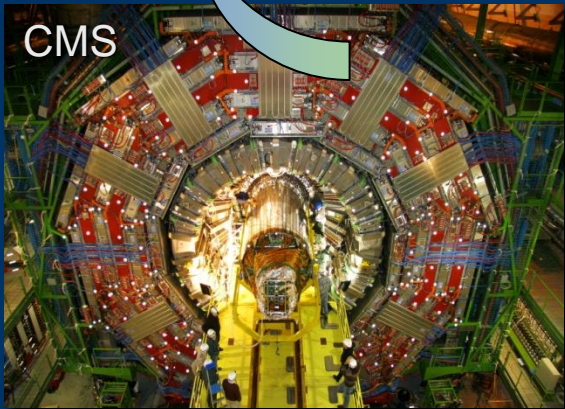
Specialised detector to study heavy ion collisions



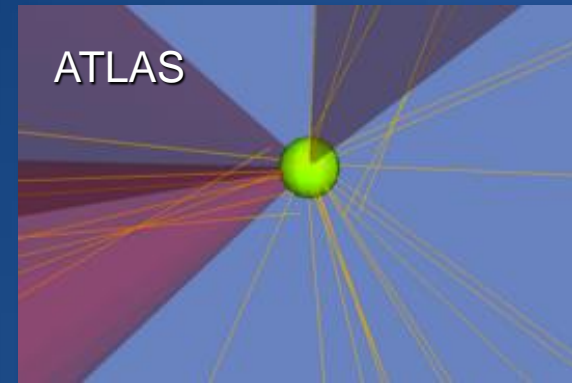
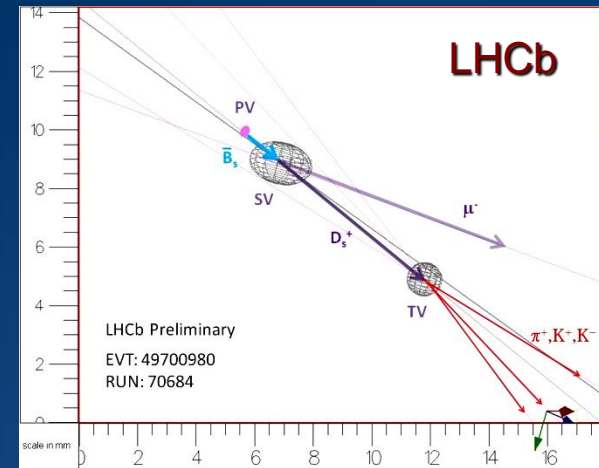
LHC Experiments → complementary

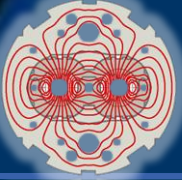


Overlap
in
physics
reach



Key feature: reconstruct
secondary vertex





LHC Experiments → complementary

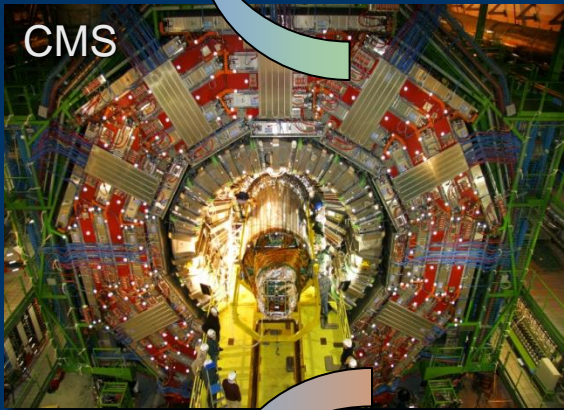


Overlap
in
physics
reach

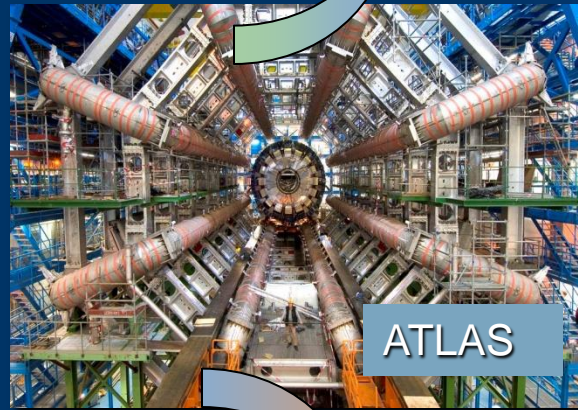


LHCb

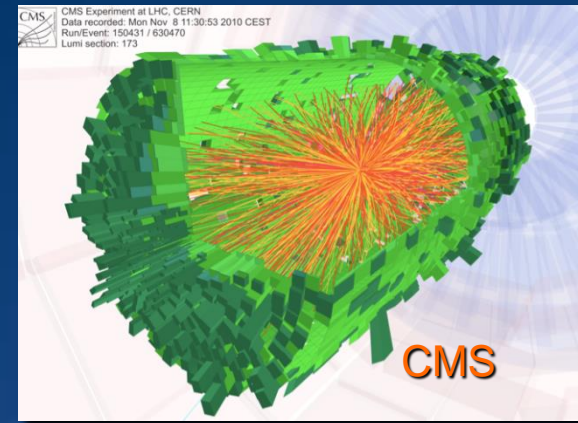
Key feature: reconstruct
> 20'000 charged tracks
in one event



CMS

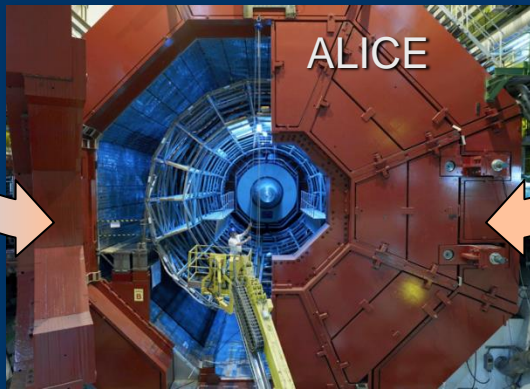


ATLAS

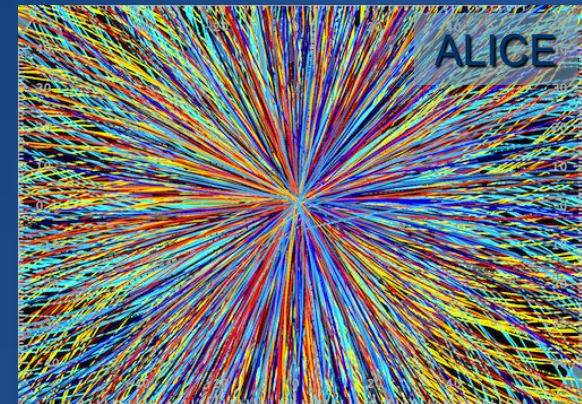


CMS

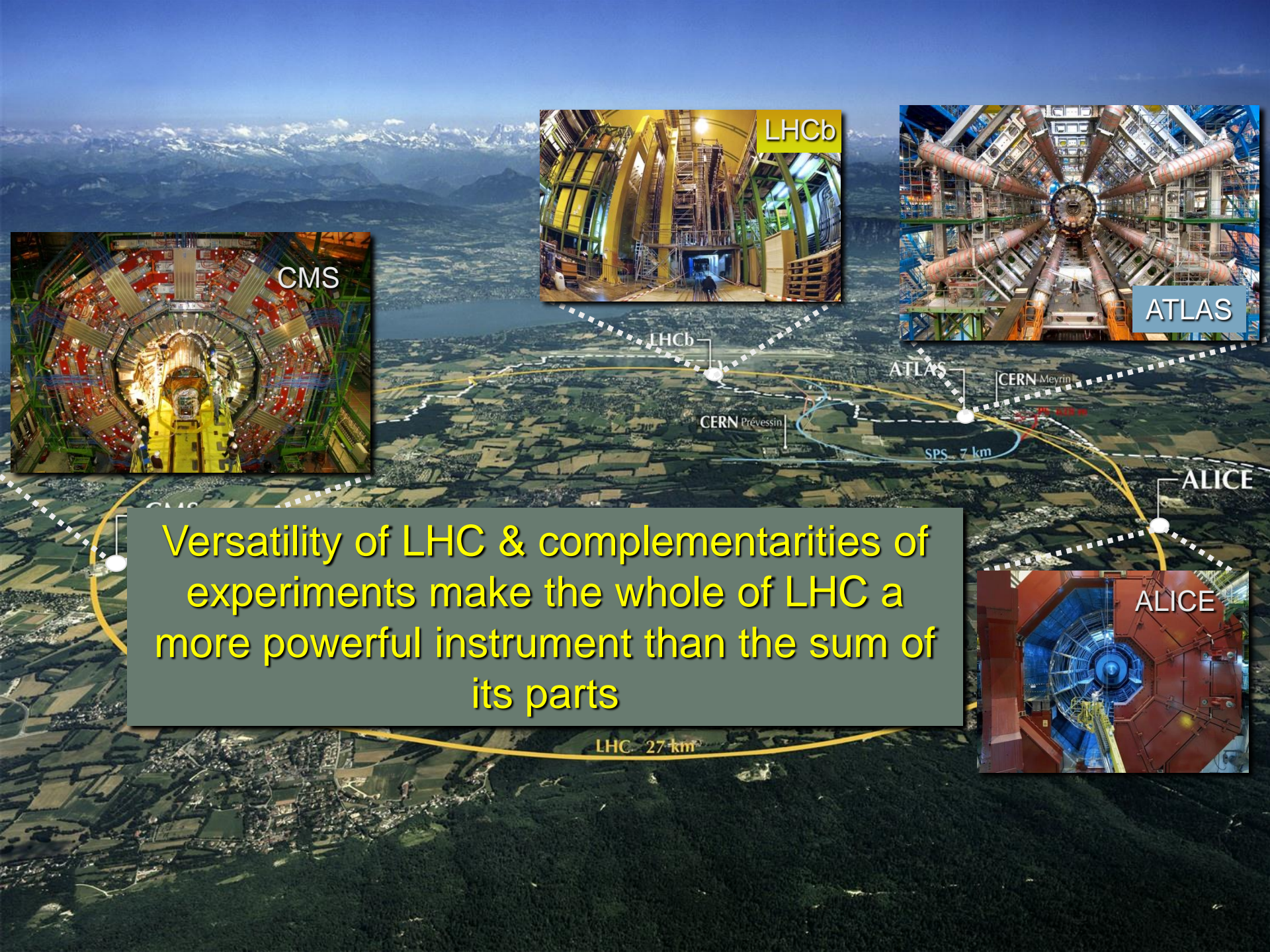
Overlap
in
physics
reach



ALICE



ALICE



Versatility of LHC & complementarities of experiments make the whole of LHC a more powerful instrument than the sum of its parts

LHC 27 km

SPS 7 km

CERN Prévessin

CERN Meyrin

LHCb

ATLAS

ALICE

CMS

LHCb

ATLAS

ALICE

LHC run 1 at 7 and 8 TeV

a great success

p-p / Pb-Pb / p-Pb

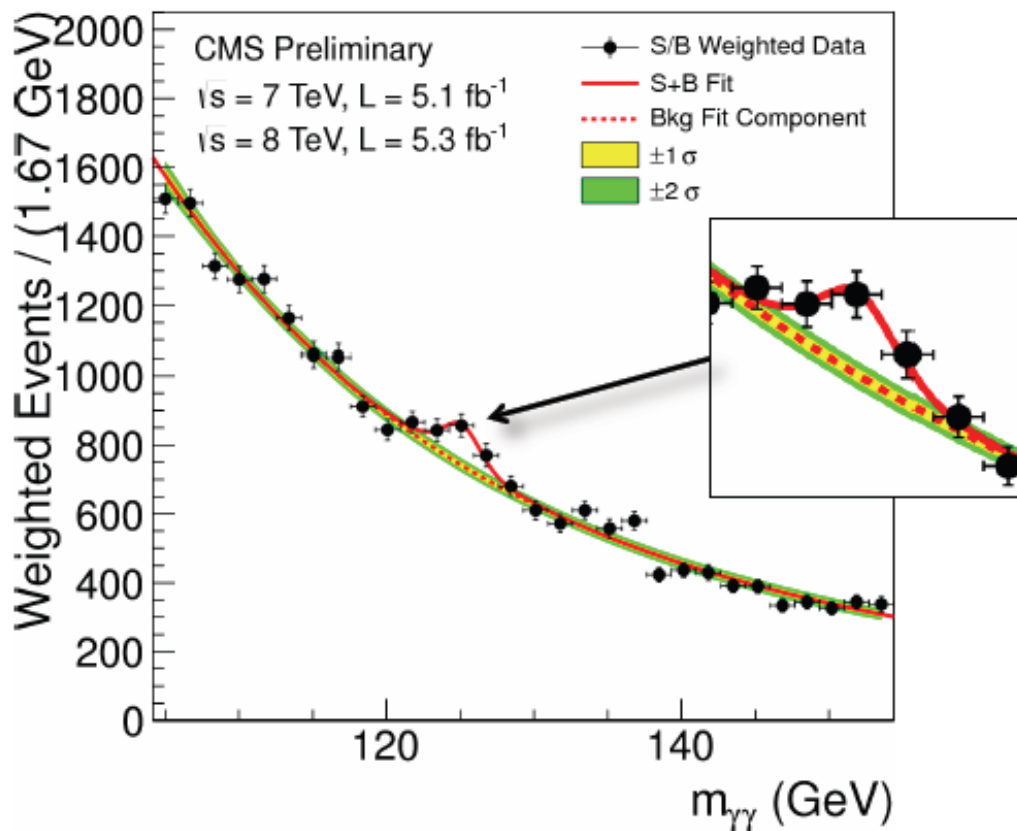
**Discovery of a Higgs-boson,
messenger of the BEH mechanism**





S/B Weighted Mass Distribution

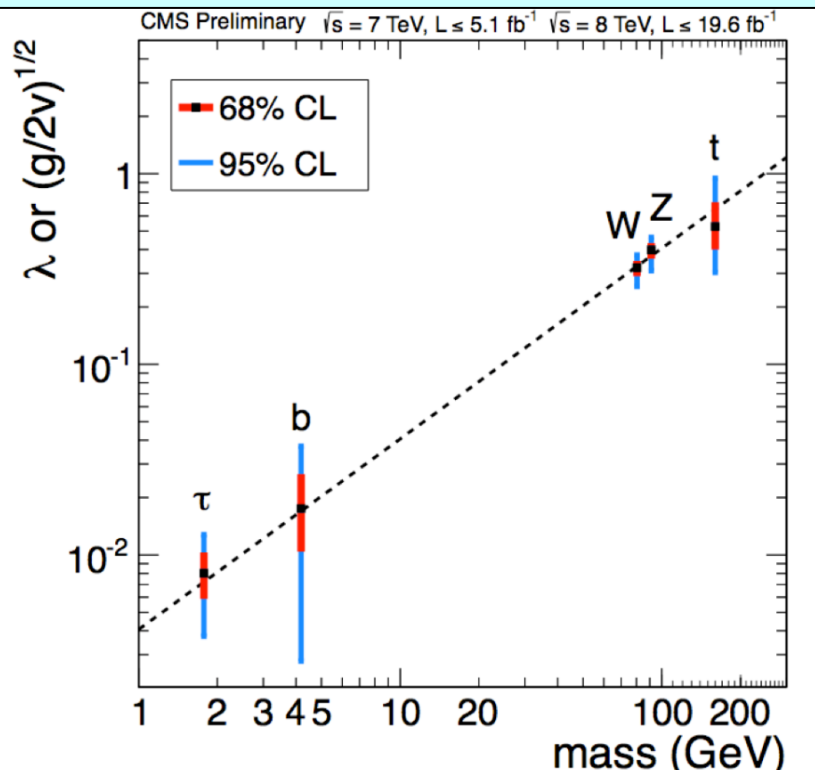
- Sum of mass distributions for each event class, weighted by S/B
 - B is integral of background model over a constant signal fraction interval



The new particle is a Higgs boson

ATLAS and CMS have verified the two “fingerprints”

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses



2) It has spin 0, it is representing a scalar field

It completes the Standard Model, thus describing ~5% of the Universe

What about the “Dark Universe” ?

The detailed study of the properties of this Higgs Boson could give

... information on Dark Matter
... first hints on Dark Energy

Four main results from LHC Run-1

- 1) We have **consolidated** the Standard Model
(wealth of measurements at 7-8 TeV, including the rare $B_s \rightarrow \mu\mu$ decay, very sensitive to New Physics)
→ it works BEAUTIFULLY ...
- 2) We have **completed** the Standard Model: Discovery of the messenger of the BEH-field, the Higgs boson discovery
(over 50 years of theoretical and experimental efforts !)
- 3) We found interesting properties of the hot dense matter
- 4) We have no evidence of new physics (YET)

What's next ?

post- H(126)-discovery

- Good reasons to expect more
 - We have really just begun the searches
 - Much space has yet to be accessed
 - And there are important new physics models yet-to-be invented
- Precision and rare physics
 - Beyond our direct production reach
 - LHC is a superb intensity frontier machine
- Invest in the LHC as a Higgs, (top, Z, W...) factory on the planet for many years to come!
 - Power computing
 - A sustained period of important results
 - And practical applications



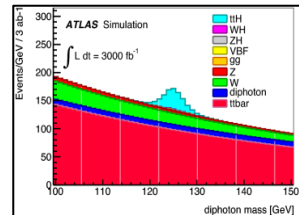
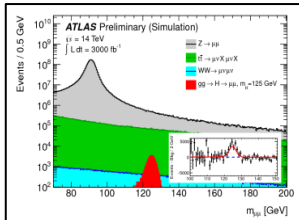
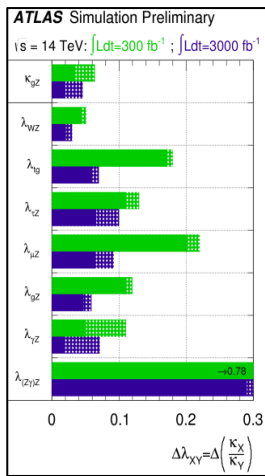


LHC --> HL-LHC: *THE* Higgs factory

today : ATLAS+CMS have 1400 Higgs events
 HL-LHC: (3000fb-1) > 3M/170M useful for precise measurement

- ❑ Measure as many Higgs couplings to fermions and bosons as precisely as possible
- ❑ Measure Higgs self-couplings (give access to λ)
- ❑ Verify that the Higgs boson fixes the SM problems with W and Z scattering at high E

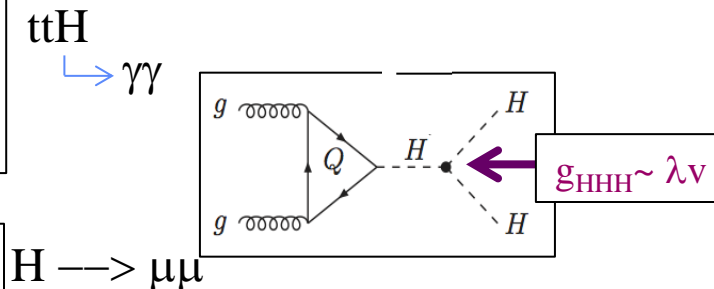
Couplings



x 1.5 to 2 for
 300 --> 3000fb⁻¹

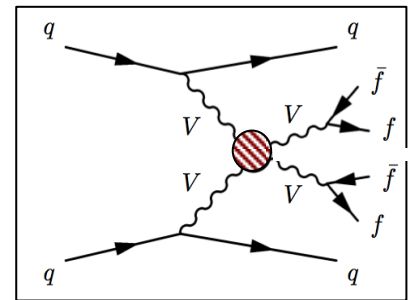
Access to rare
 processes

Self-coupling



Difficult measurement
 precision 30%(?) for 3000fb-1

Vector boson fusion



Check if Higgs does the
 (whole) job of
 cancelling divergences

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

Particle Physics Projects Prioritisation Panel (P5)

Strategic Plan for U.S. Particle Physics

- Charge: A strategic plan, executable over 10 years, in the context of a 20-year global vision
- US community has come together to make a plan

- Driven by the science

- Meets field's needs

Recommendations in line with the European Strategy

...in the global context

- Resolves key issues for the field

- Provides a continuous flow of results while making essential investments for the future



From the P5 report

Recommendation 10:

Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). **The LHC upgrades constitute our highest-priority near-term large project.**

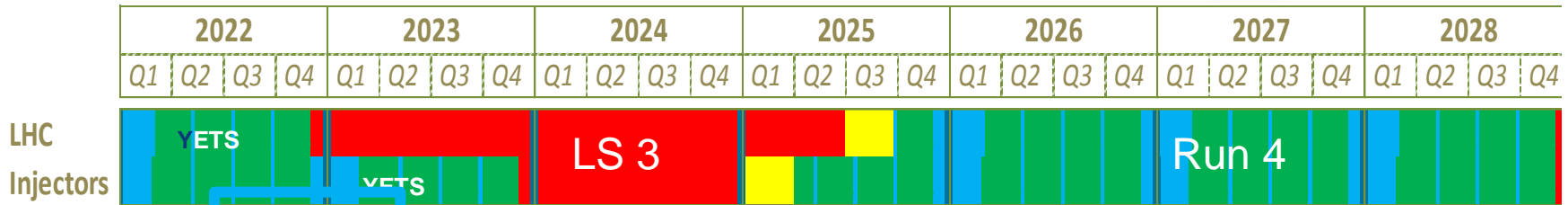
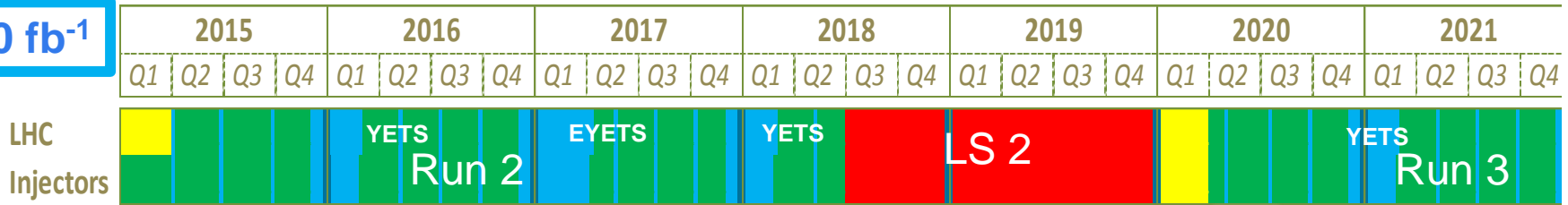


LHC schedule beyond LS1

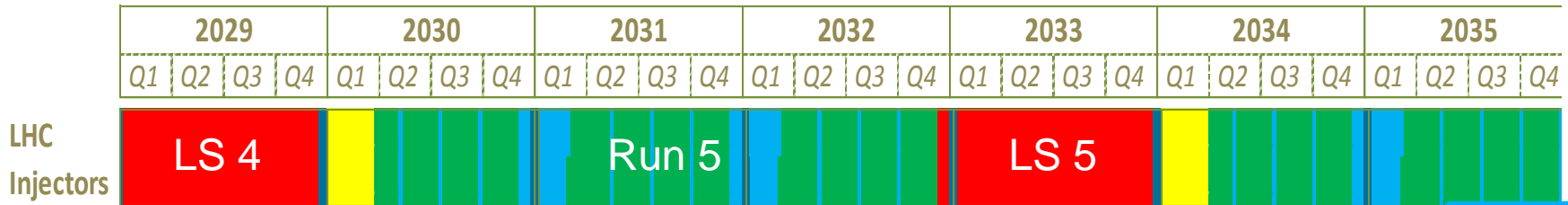
LS2 starting in 2018 (July) => 18 months + 3 months BC
 LS3 LHC: starting in 2023 => 30 months + 3 months BC
 Injectors: in 2024 => 13 months + 3 months BC



30 fb⁻¹



300 fb⁻¹



3'000 fb⁻¹

(Extended) Year End Technical Stop: (E)YETS



Key message

There is a...
vital to fully exploit the physics potential of LHC

Upgrades to accelerator complex, detectors, and computing Grid are

14 TeV (essentially done)

14 TeV design luminosity

14 TeV high luminosity (HL-LHC)



Accelerating Science and Innovation

Energy Frontier

Beyond LHC

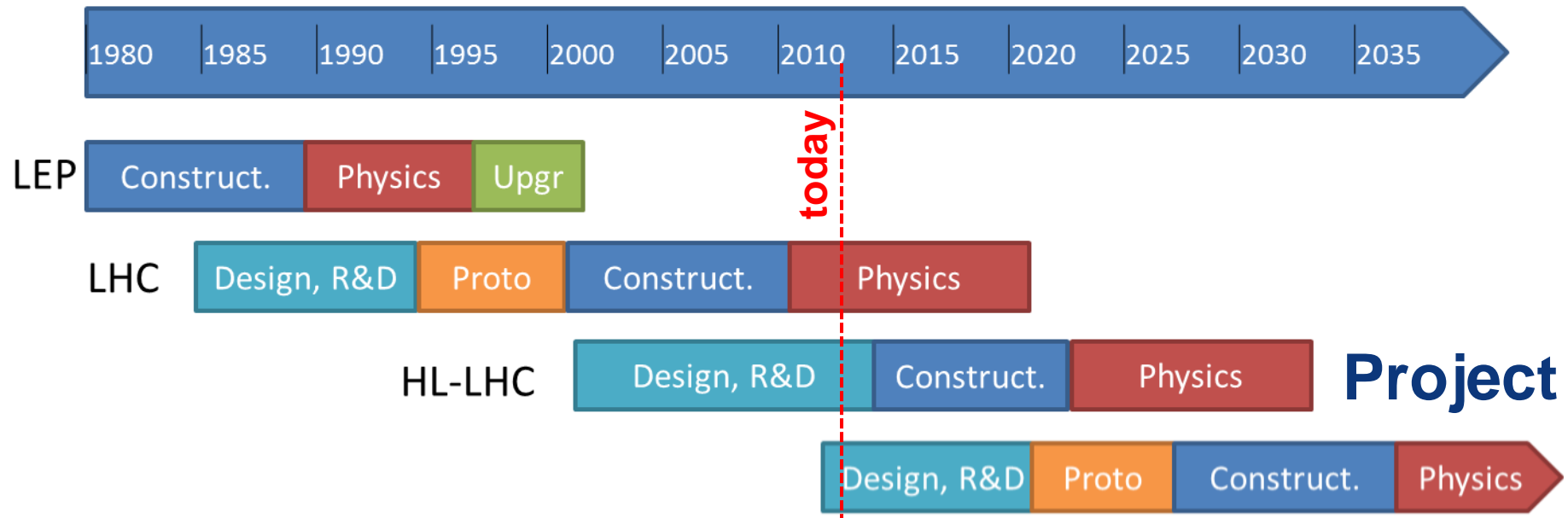
European Strategy for Particle Physics

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After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. ***CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.***

*European Strategy: “CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton** and electron- positron **high-energy frontier machines.**”*



FCC Study : p-p towards 100 TeV

**Kick-off meeting: February 2014
(Univ. Geneva)**

FCC: Future Circular Colliders



Future Circular Collider Study - SCOPE

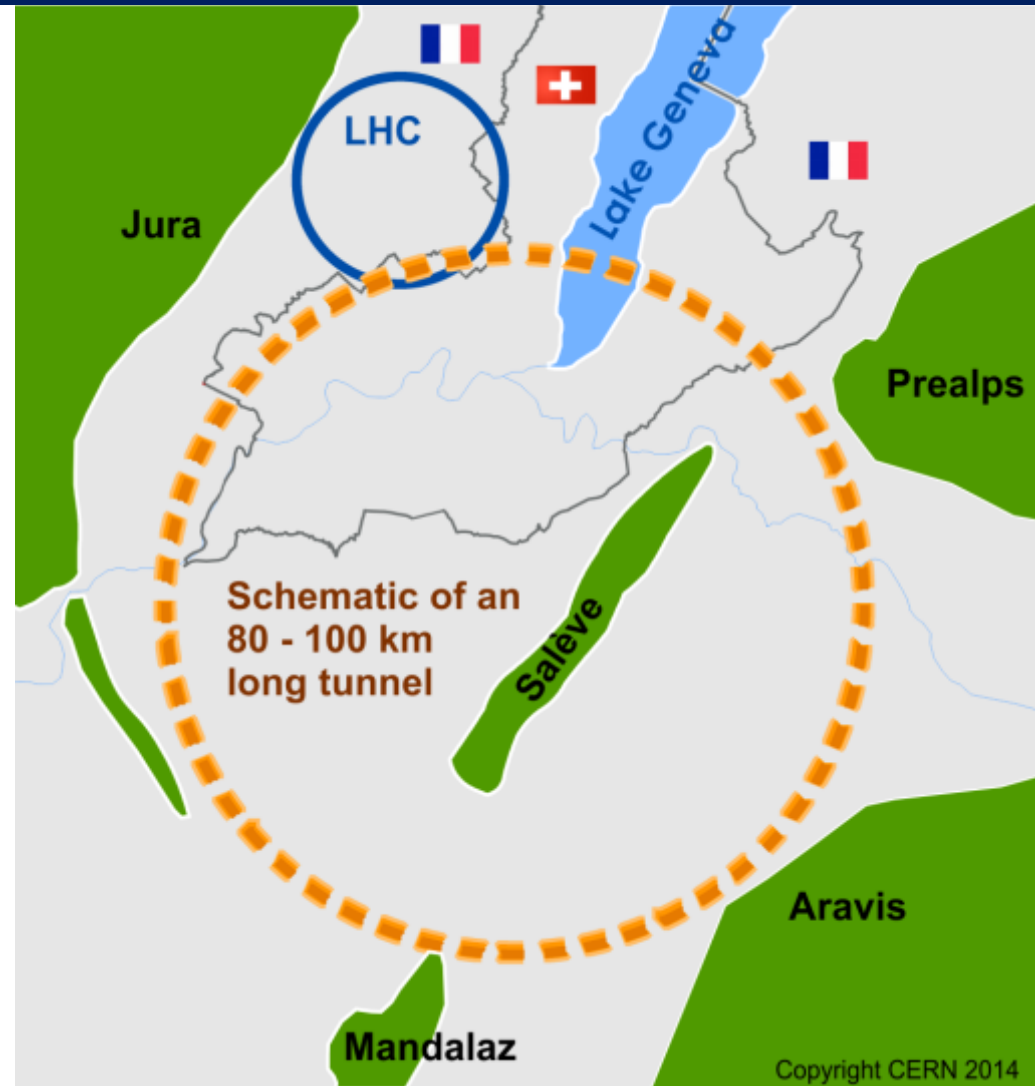
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
→ defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- *p-e* (*FCC-he*) option
- **80-100 km infrastructure** in Geneva area



CLIC near CERN

Legend

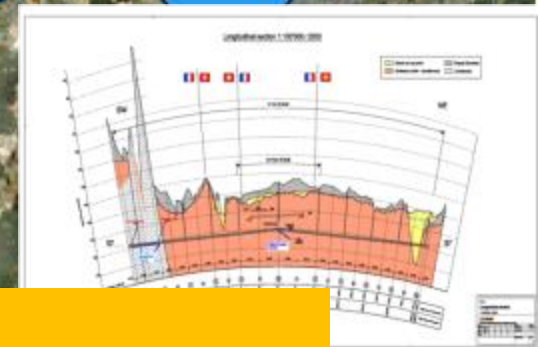
— CERN existing LHC

Potential underground siting :

●●●● CLIC 500 GeV

●●●● CLIC 1.5 TeV

●●●● CLIC 3 TeV



Conceptual Design Report published

R&D continues (accelerator and detector)
in the framework of the LC effort and the
CLIC collaboration
(e.g. high gradient accelerating structures)

Central MDI & Interaction Region

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable effort and long-term commitment, the following four activities have been identified as high priority.

e) There is a strong scientific case for a high-energy electron-positron collider, complementary to the LHC, to study the properties of the Higgs boson and other particles produced in the LHC. Such a collider would be upgraded to a high-energy linear collider, providing high luminosity and whose energy can be upgraded to 3 TeV. The **Design Report of the International Linear Collider (ILC) has been completed**, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. ***Europe looks forward to a proposal from Japan to discuss a possible participation.***



Linear Collider(s)

Continue working on the technical design report for CLIC and common research on ILC (machine and detectors)

P5 Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should **engage in modest and appropriate levels of ILC accelerator and detector design** in areas where the U.S. can contribute critical expertise. **Consider higher levels of collaboration if ILC proceeds.**

This parallel research (CLIC and ILC) aims to be ready to decide on the way forward at the time of the next European Strategy update (around 2018)



Accelerating Science and Innovation

Intensity Frontier



European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

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.

Neutrino Platform

Create a platform to pave the way for a European contribution in a neutrino facility in the US or Asia

Financial scenario with an allocation to allow for

- Extension of the experimental area of the SPS complex (North Area)
- (liquid argon) detector R&D for neutrino experiments
- Preparing detectors at CERN for transport to US

P 5 Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text.

LBNF is the highest-priority large project in its timeframe.



Final Remark on Science

With the European Strategy, approved by Council May 2013,
with the P5 recommendations, approved by HEPAP in the US,
with the Japanese roadmap

we have (for the first time) a global vision for our field
going beyond regional boundaries

CERN is playing a major role
in this global endeavour



Accelerating Science and Innovation

Beyond Science

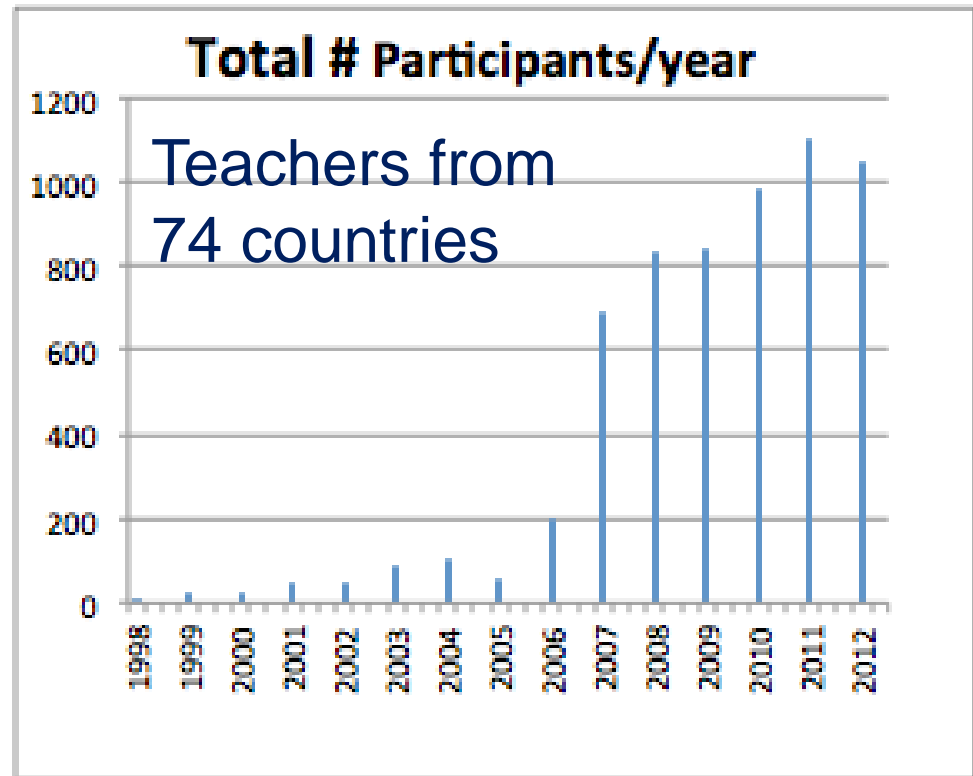


Education and Capacity Building at CERN

➤ Teachers Programs

- international and 'national' programs at CERN and remotely

Education and Capacity Building



Teachers Programme: courses of one week duration in the mother language of the teachers

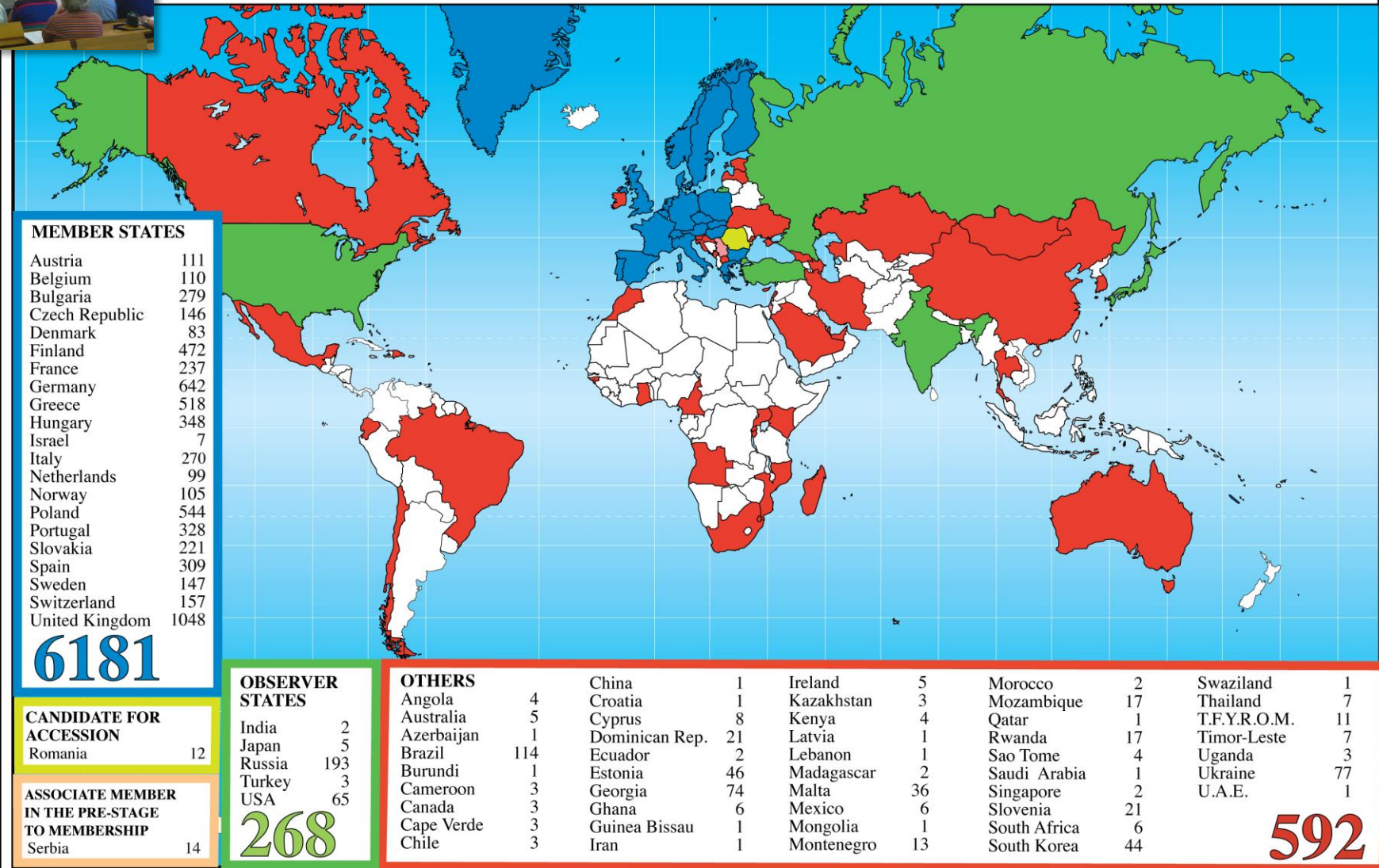


Today: ~1000 teachers per year

CERN Teacher Programme



Teacher Programme Participants 1998 - 2013 (Total: 7067)



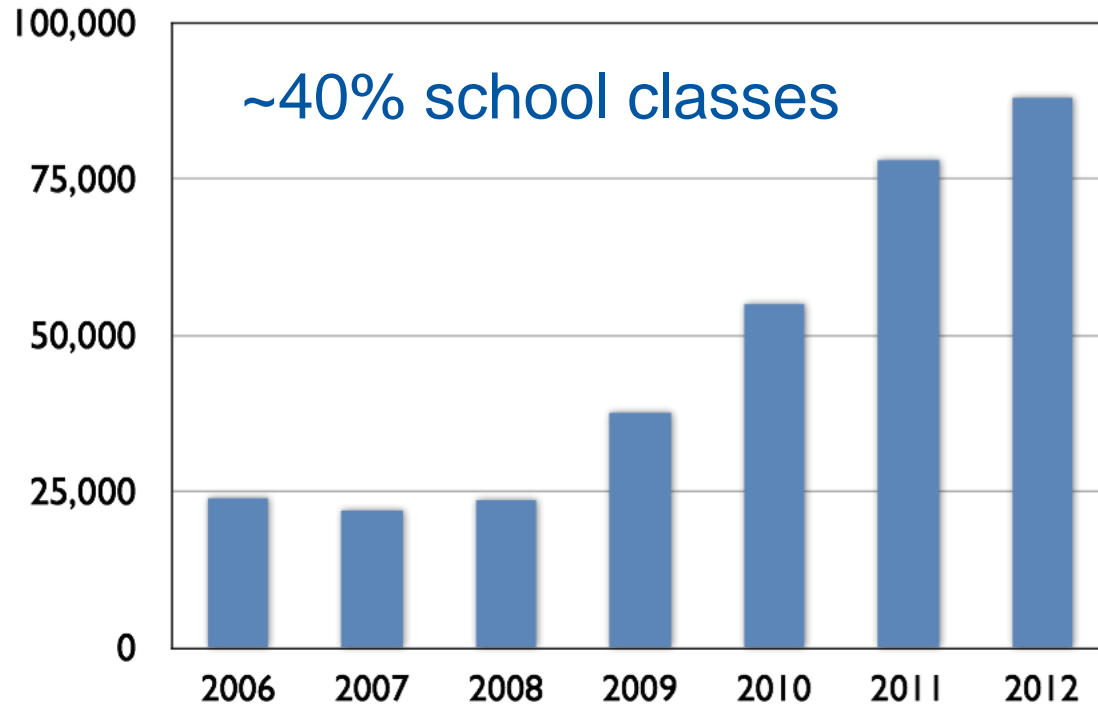
Education and Capacity Building at CERN

- Teachers Programs
 - international and ‘national’ programs at CERN and remotely
- School Students Programs
 - “slip into the skin of a researcher”
 - special competitions (e.g. in Spain)
- High School Students Programs
 - S’Cool Lab
 - Beamline for Schools
 - Masterclasses
- Summer Students Program



Education and Capacity Building at CERN

CERN guided tours: Participants



2013:
~95,000 participants
per year

Over 200,000 requests

Bridge the Gap between Science and Society



CERN

– innovate, discover, publish, share



... and bring the world together