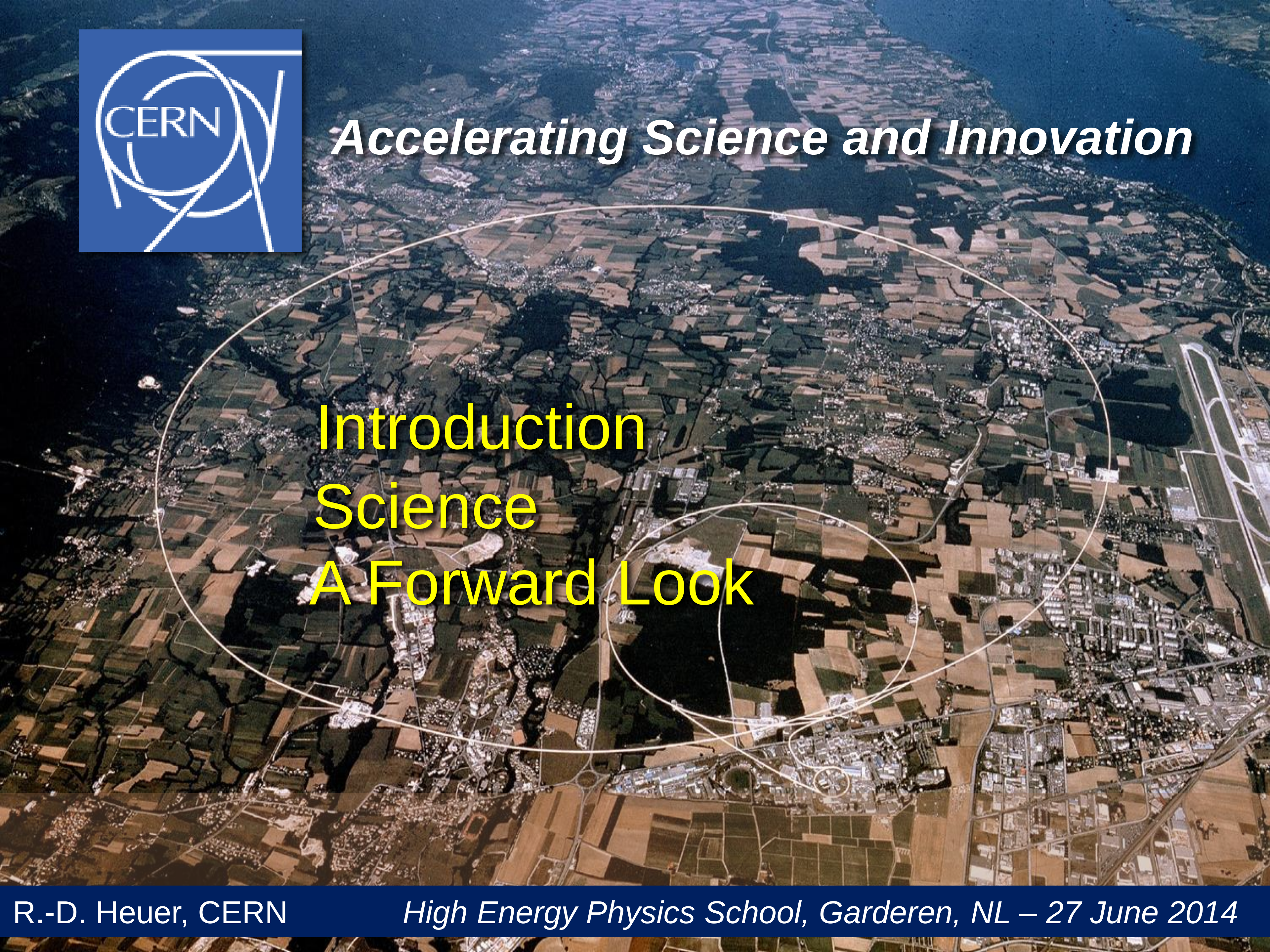


Accelerating Science and Innovation

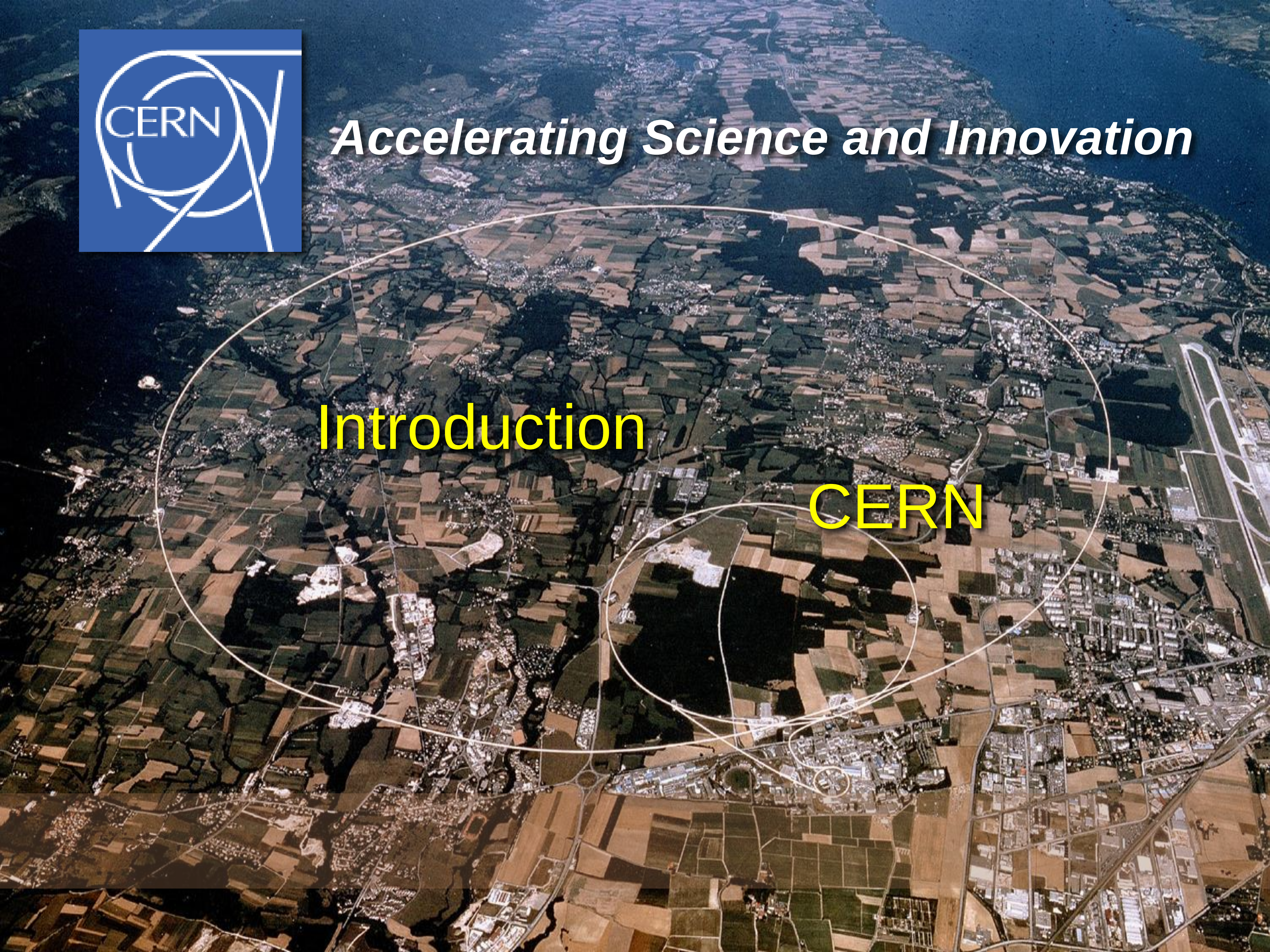
Introduction
Science
A Forward Look

R.-D. Heuer, CERN

High Energy Physics School, Garderen, NL – 27 June 2014

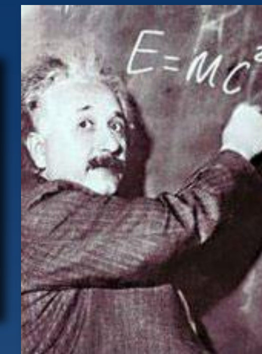
Accelerating Science and Innovation

Introduction
CERN



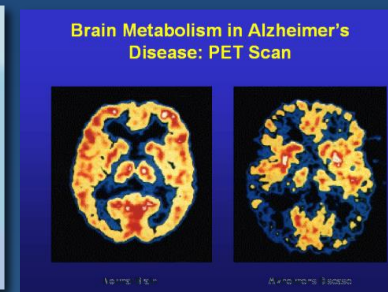
Innovation
Education
CERN
uniting people
Research

The Mission of CERN



- Push back the frontiers of knowledge

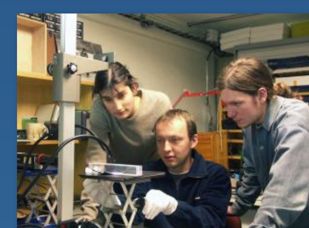
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



- 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

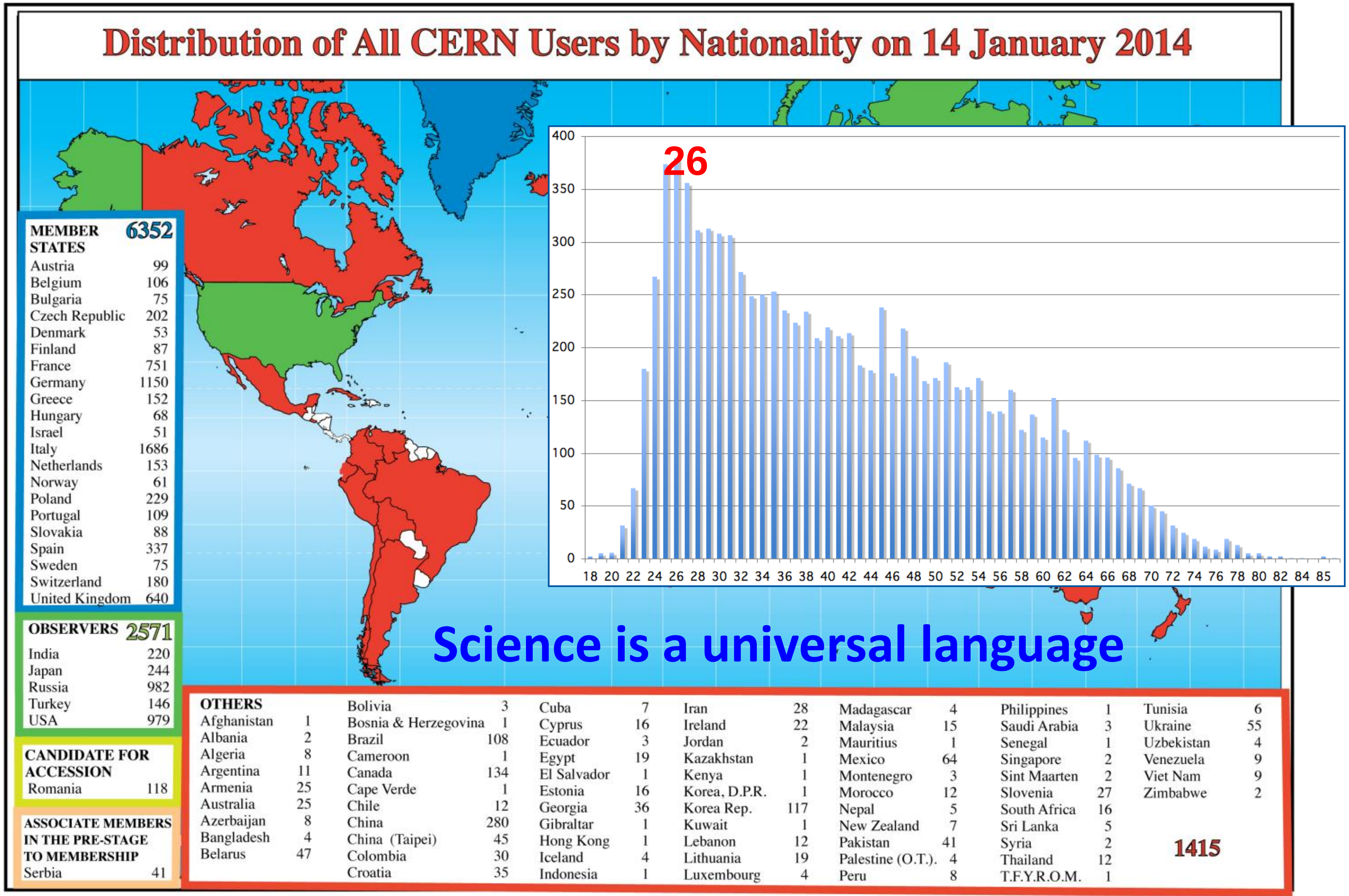
Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

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



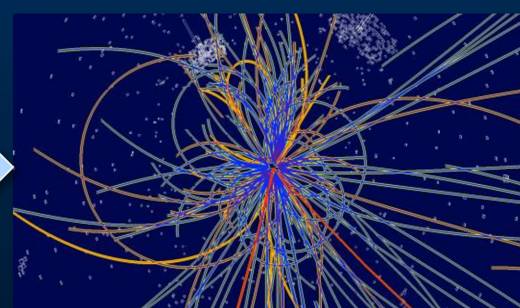
Innovation Education
CERN
uniting people
Research

CERN: Particle Physics and Innovation

- **Interfacing** between fundamental science and key technological developments

- **CERN Technologies and Innovation**

Accelerating particle beams



Detecting particles

Large-scale computing (Grid)

Innovation
Education
CERN
uniting people
Research

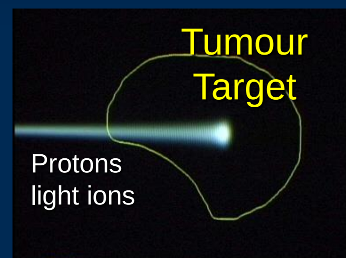
CERN Technologies and Innovation

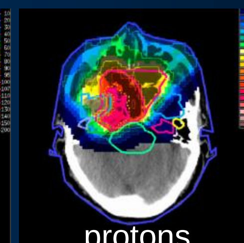
Example: Medical applications

Combining Physics, ICT, Biology and Medicine to fight cancer

Accelerating particle beams
~30’000 accelerators worldwide
~17’000 used for medicine

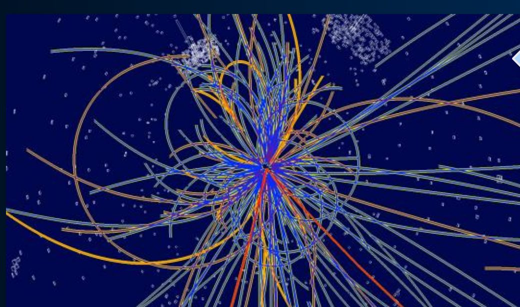
Hadron Therapy





Leadership in Ion Beam Therapy now in Europe and Japan

>70’000 patients treated worldwide (30 facilities)
>21’000 patients treated in Europe (9 facilities)

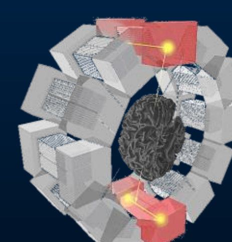


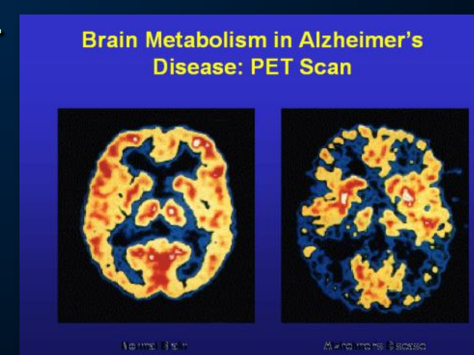
Detecting particles

Imaging

PET Scanner

Clinical trial in Portugal for new breast imaging system (ClearPEM)

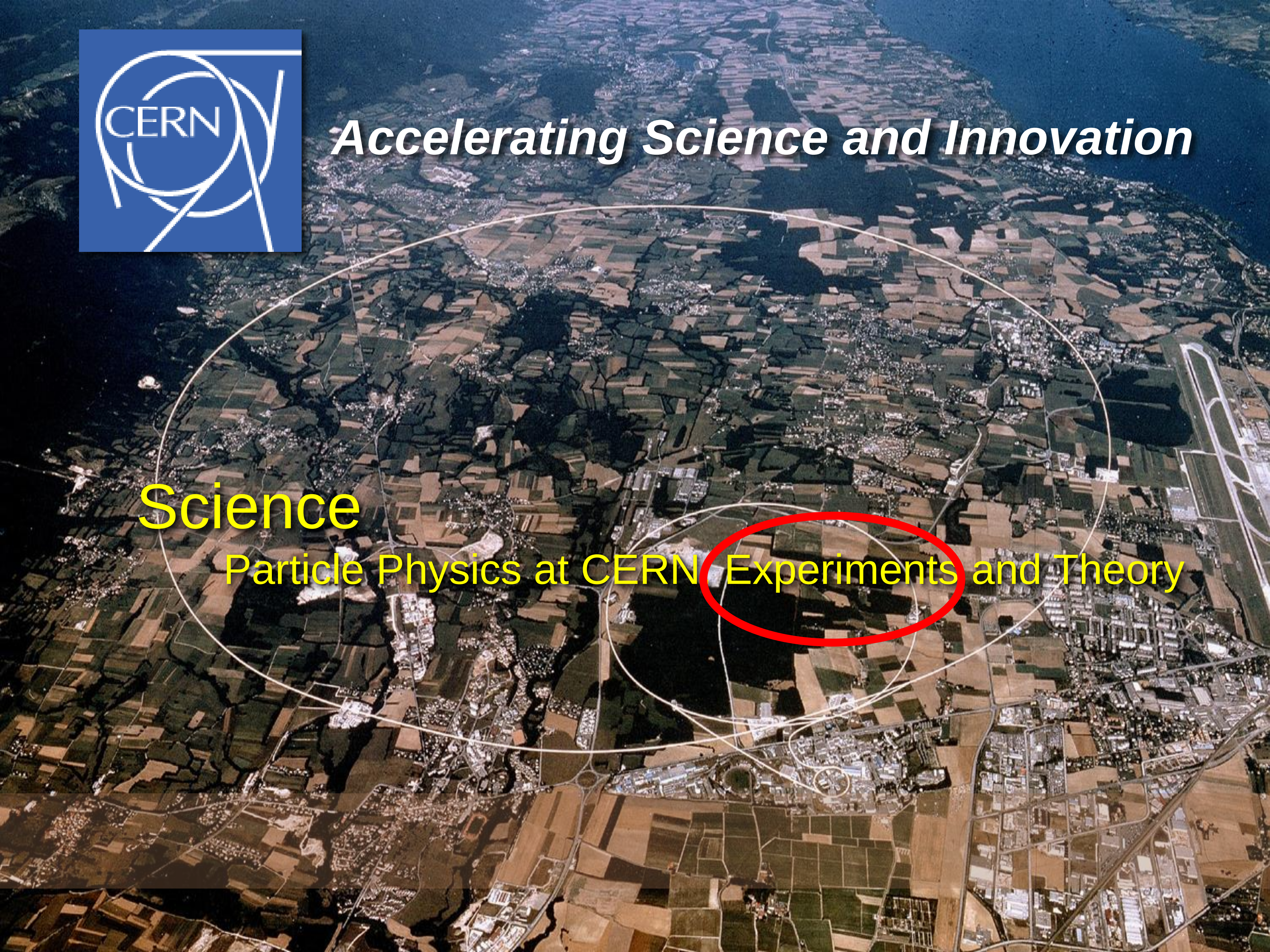




Accelerating Science and Innovation

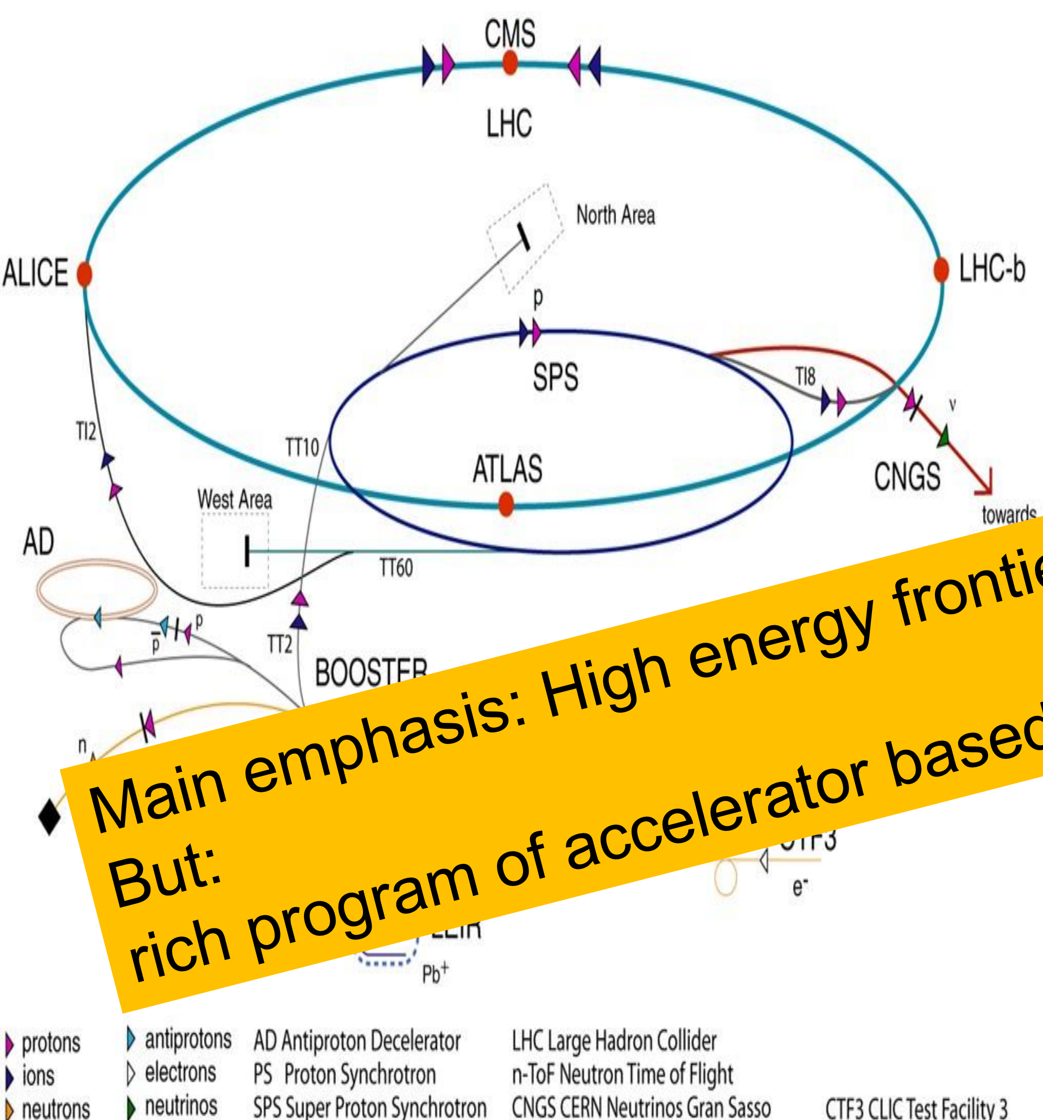
Science

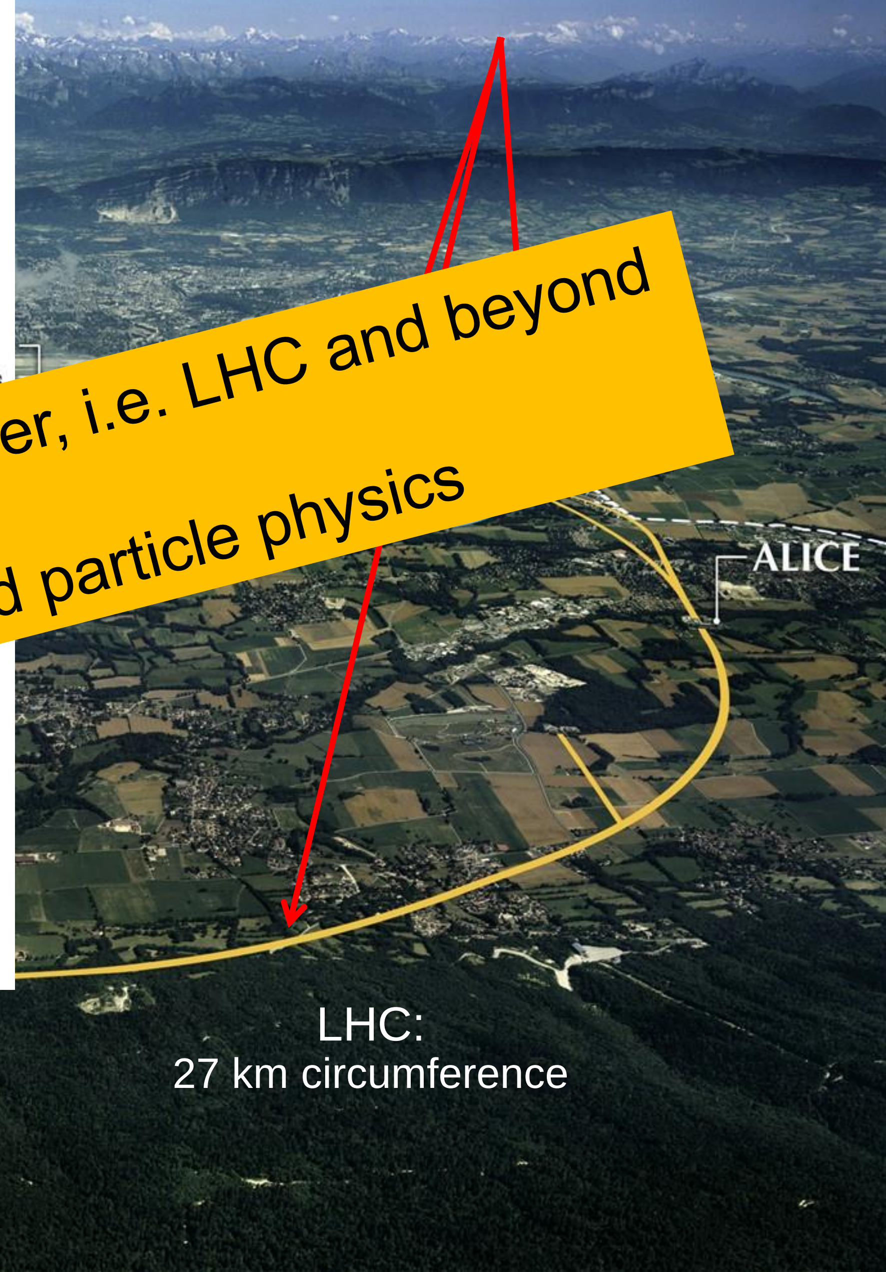
Particle Physics at CERN: Experiments and Theory



The accelerators

Main emphasis: High energy frontier, i.e. LHC and beyond
But:
rich program of accelerator based particle physics





LHC:
27 km circumference

The Particle Physics Landscape at CERN

High Energy Frontier
LHC

Hadronic Matter
deconfinement
non-perturbative QCD
hadron structure

Low Energy
heavy flavours / rare decays
neutrino oscillations
anti-matter

Non-accelerator
dark matter
astroparticles

Multidisciplinary
climate, medicine

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

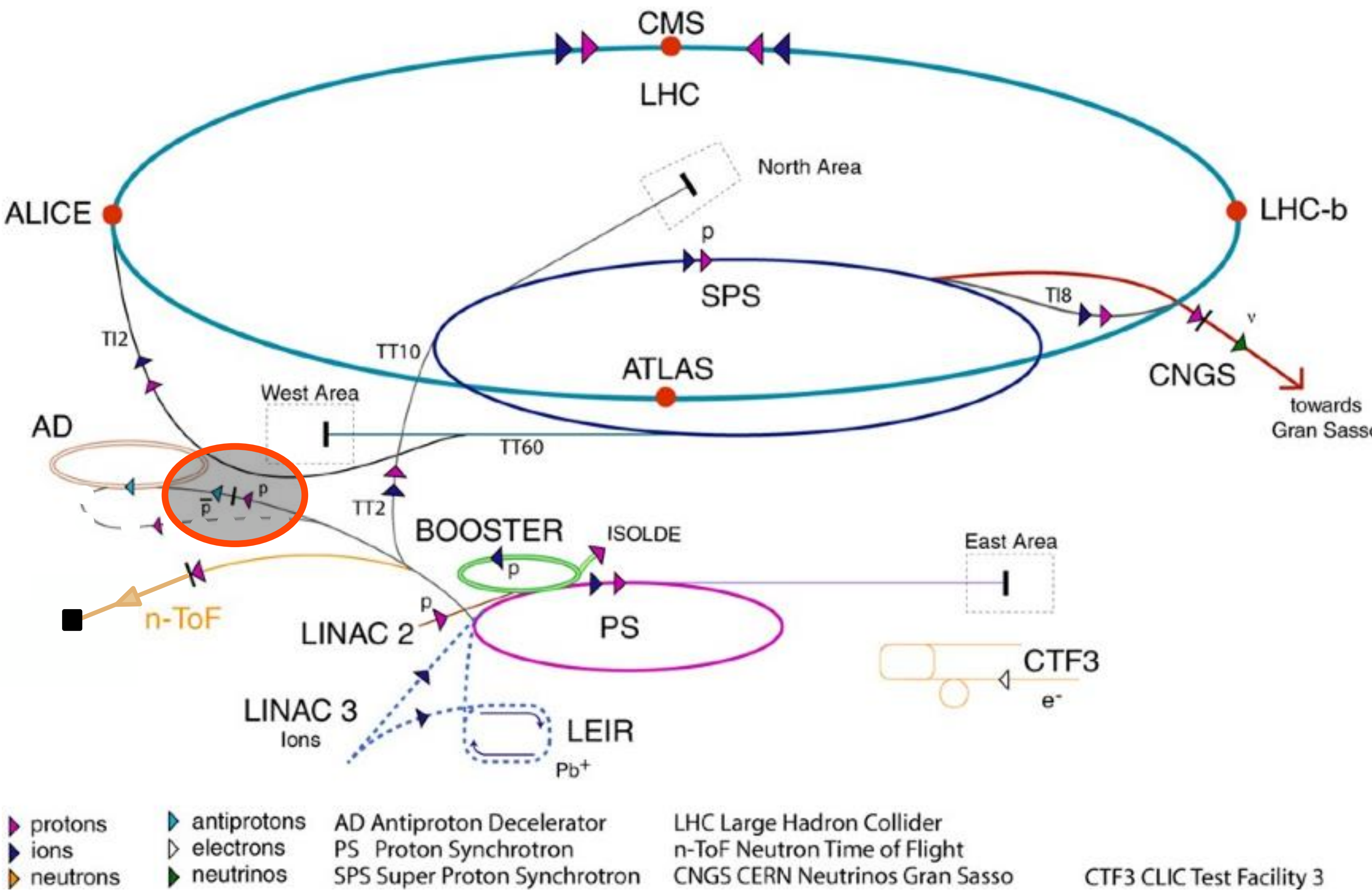
In the past few years

Several breakthroughs !

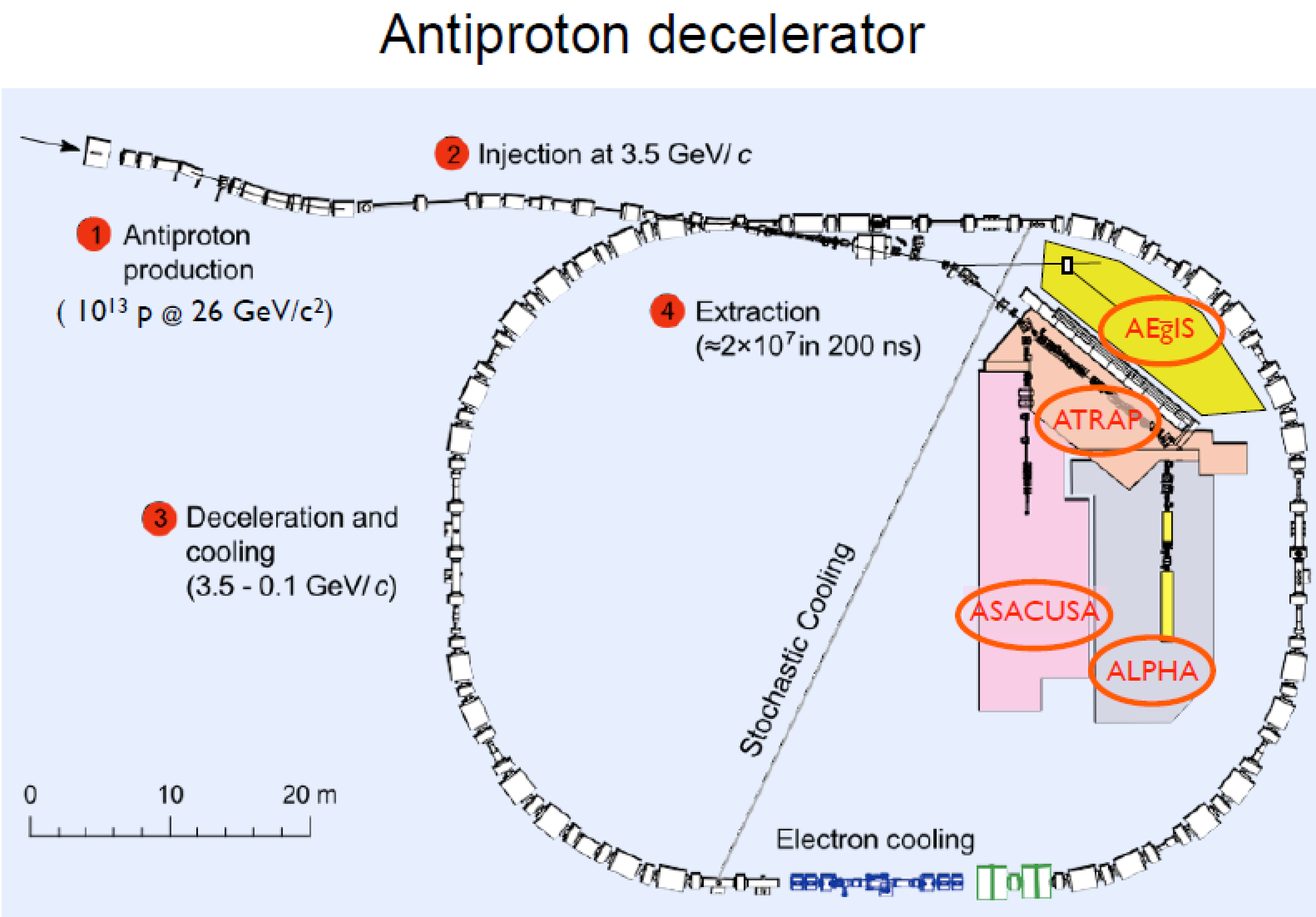
Steady progress of other programs

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

CERN Accelerator Complex

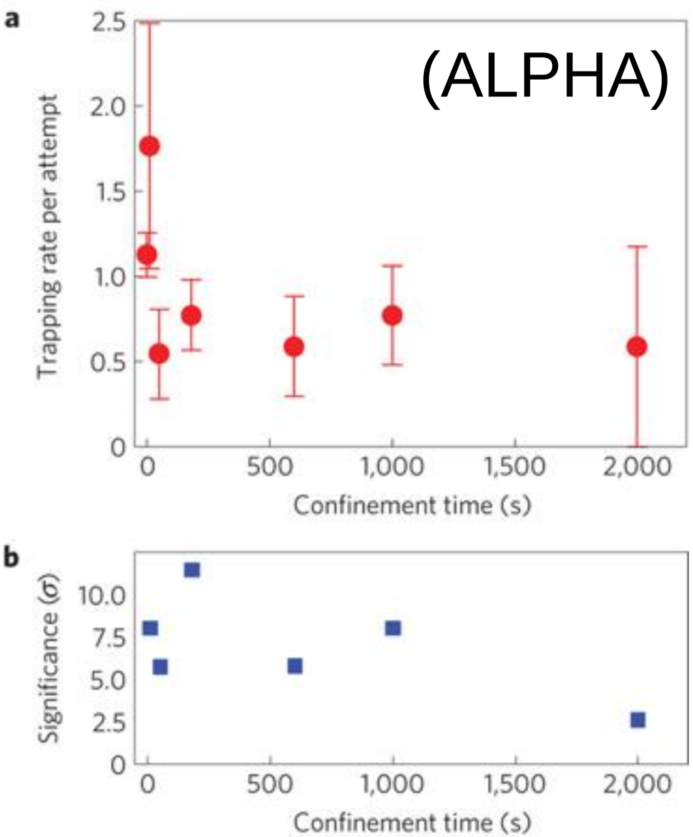


AD (current situation)

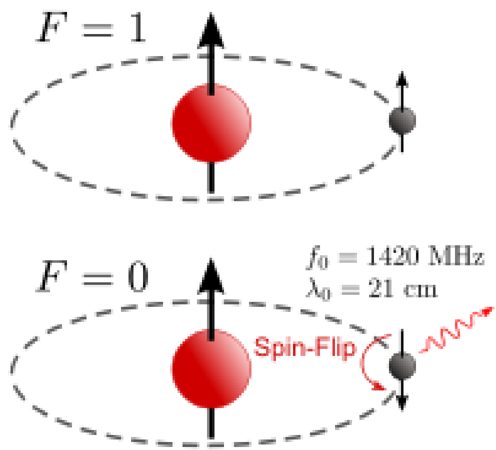


Spectroscopy with trapped antihydrogen?

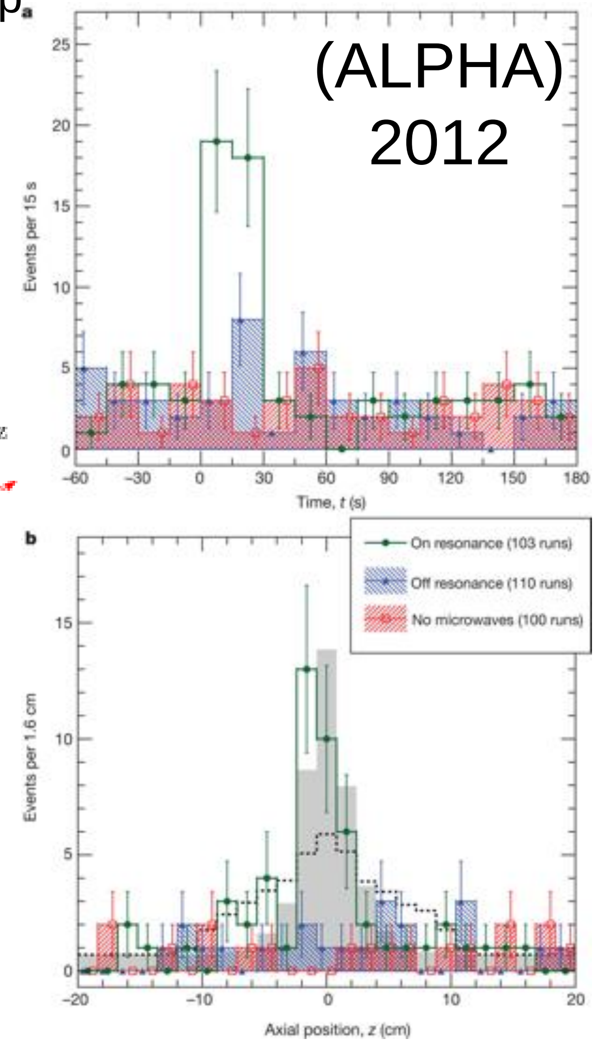
Antihydrogen atom trapping time



Spectroscopy:
HFS
via microwave



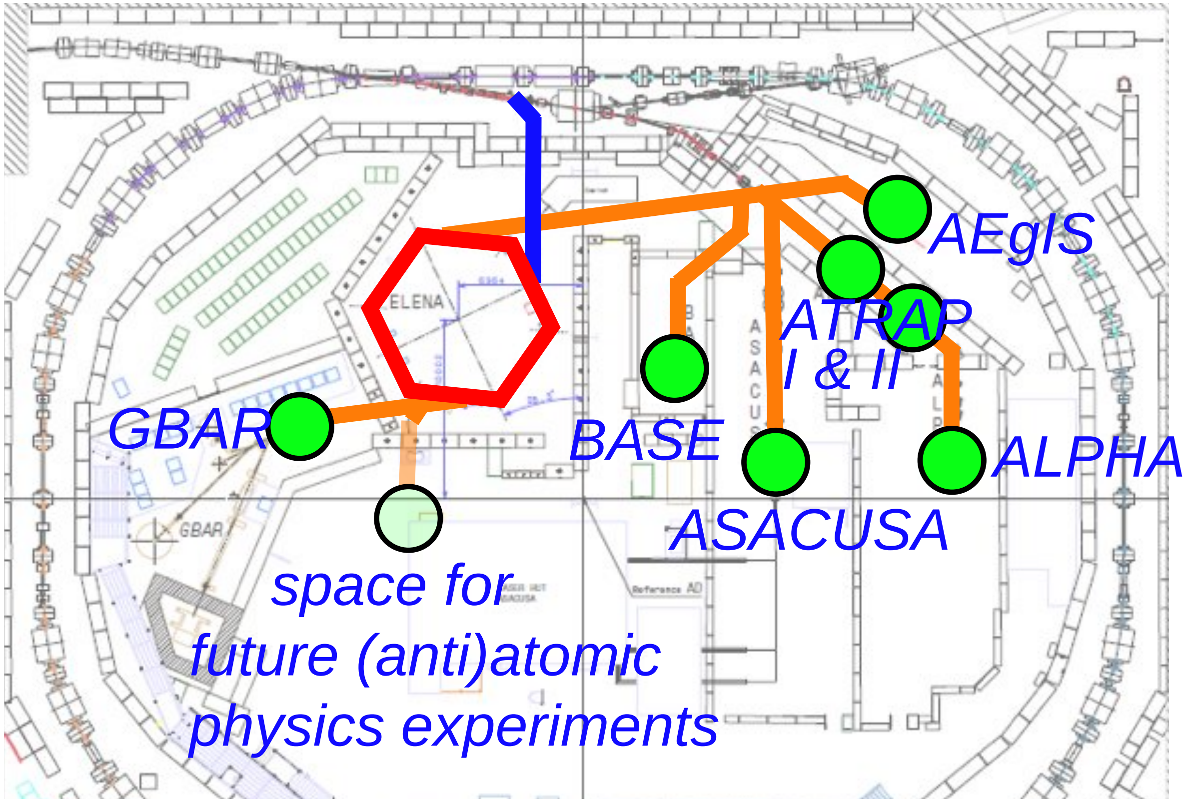
but: B-field varies strongly over trap



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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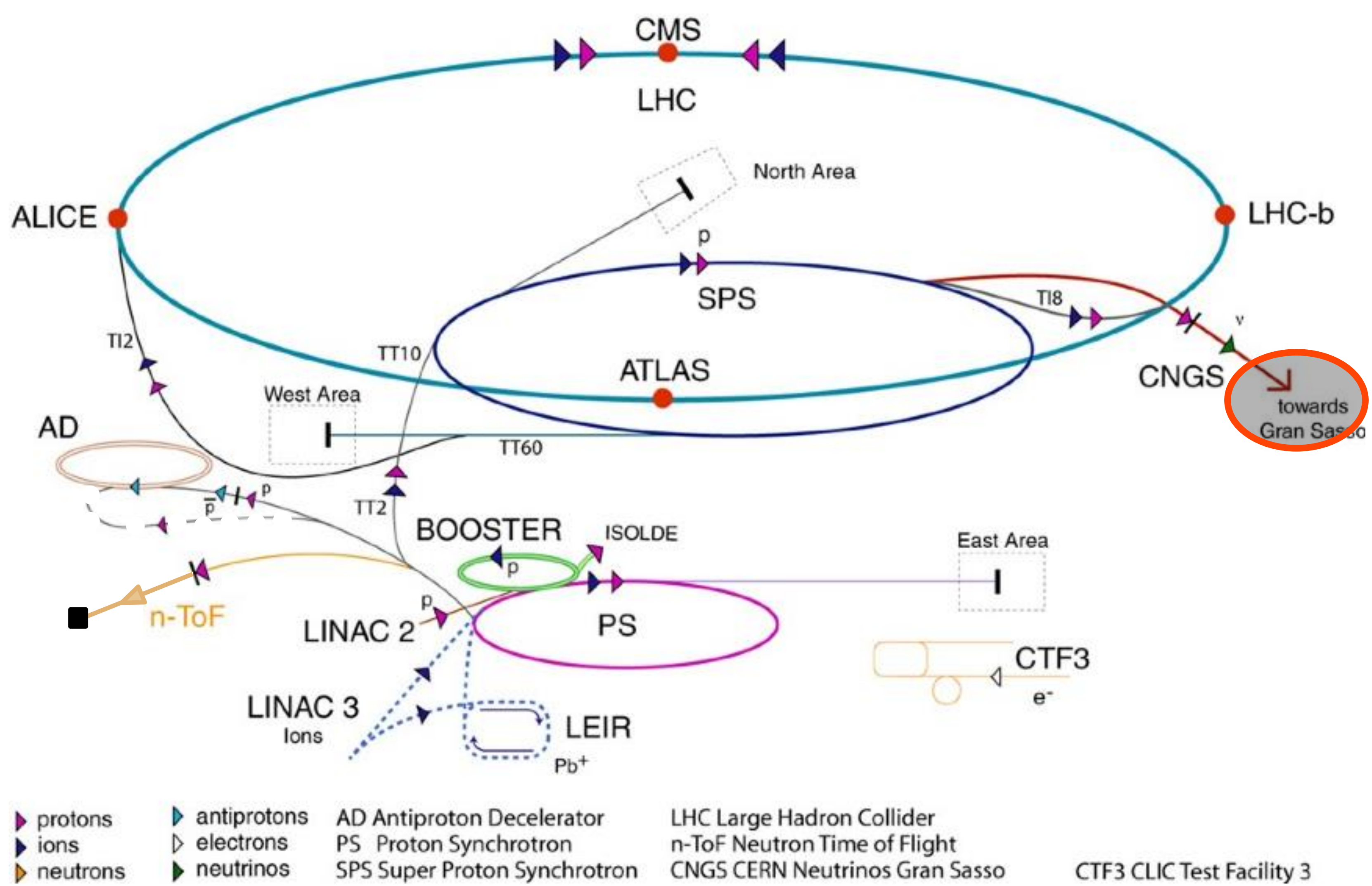
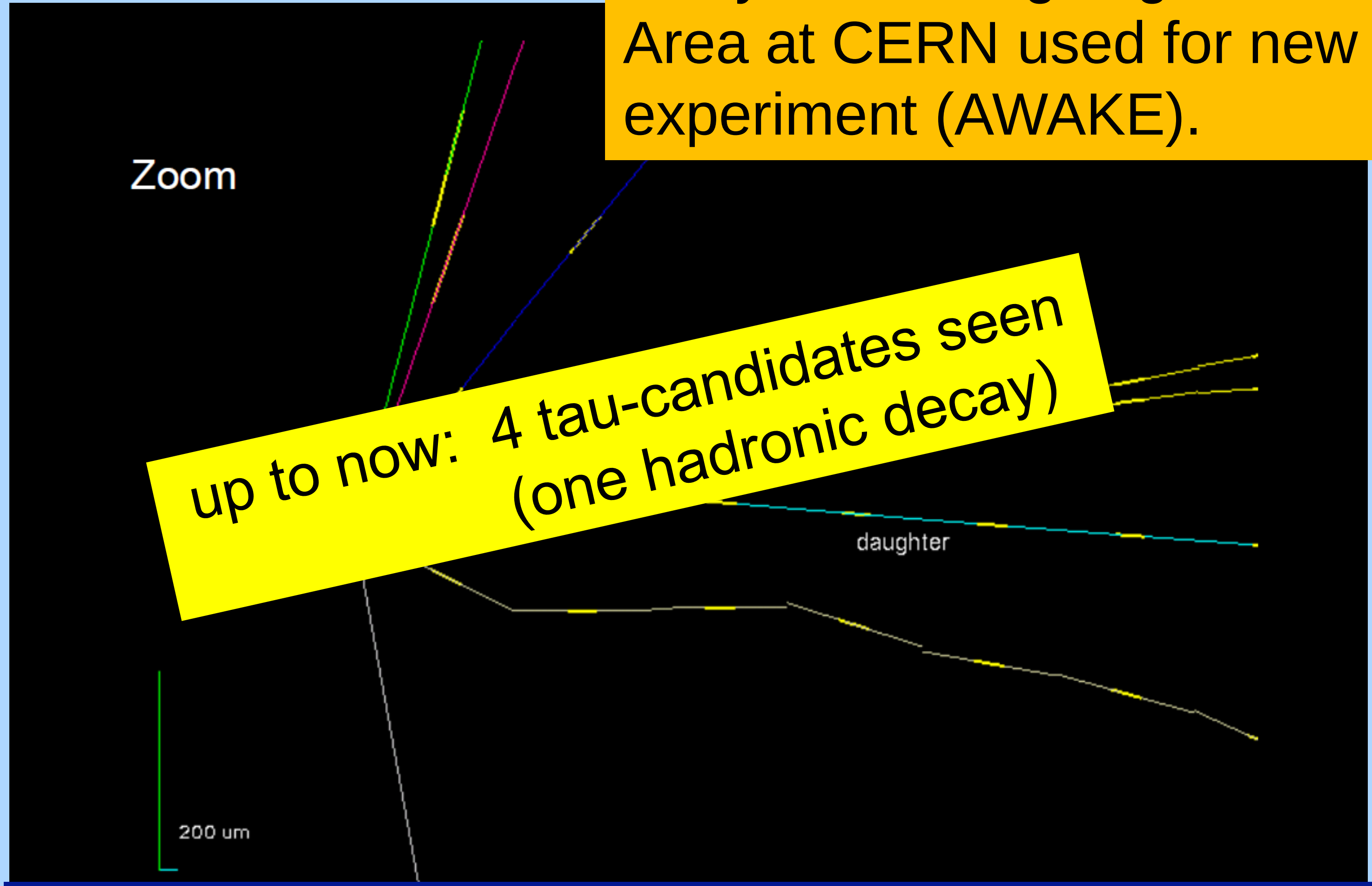


CNGS - OPERA

First υ_τ Candidate

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



up to now: 4 tau-candidates seen (one hadronic decay)

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

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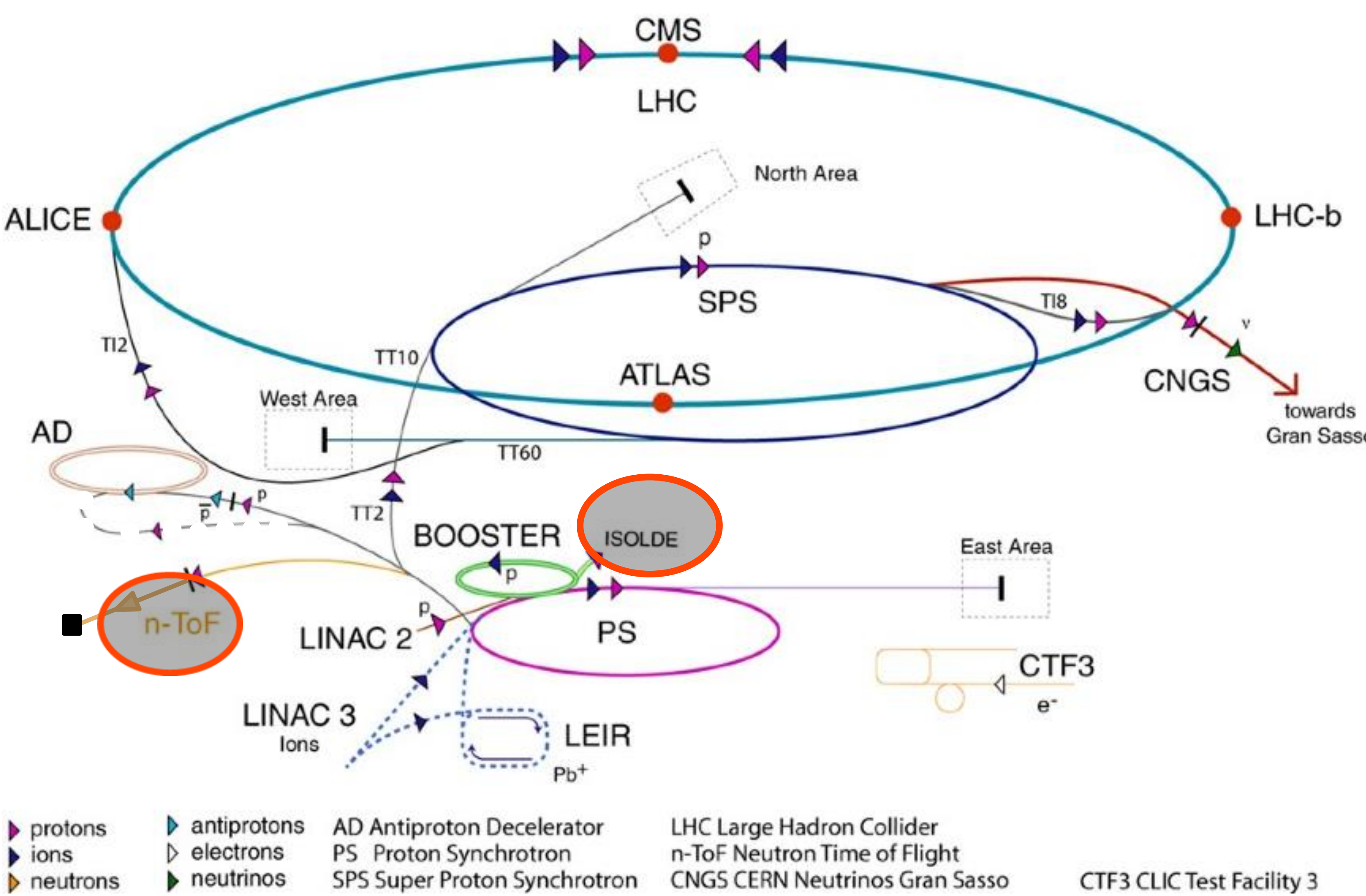
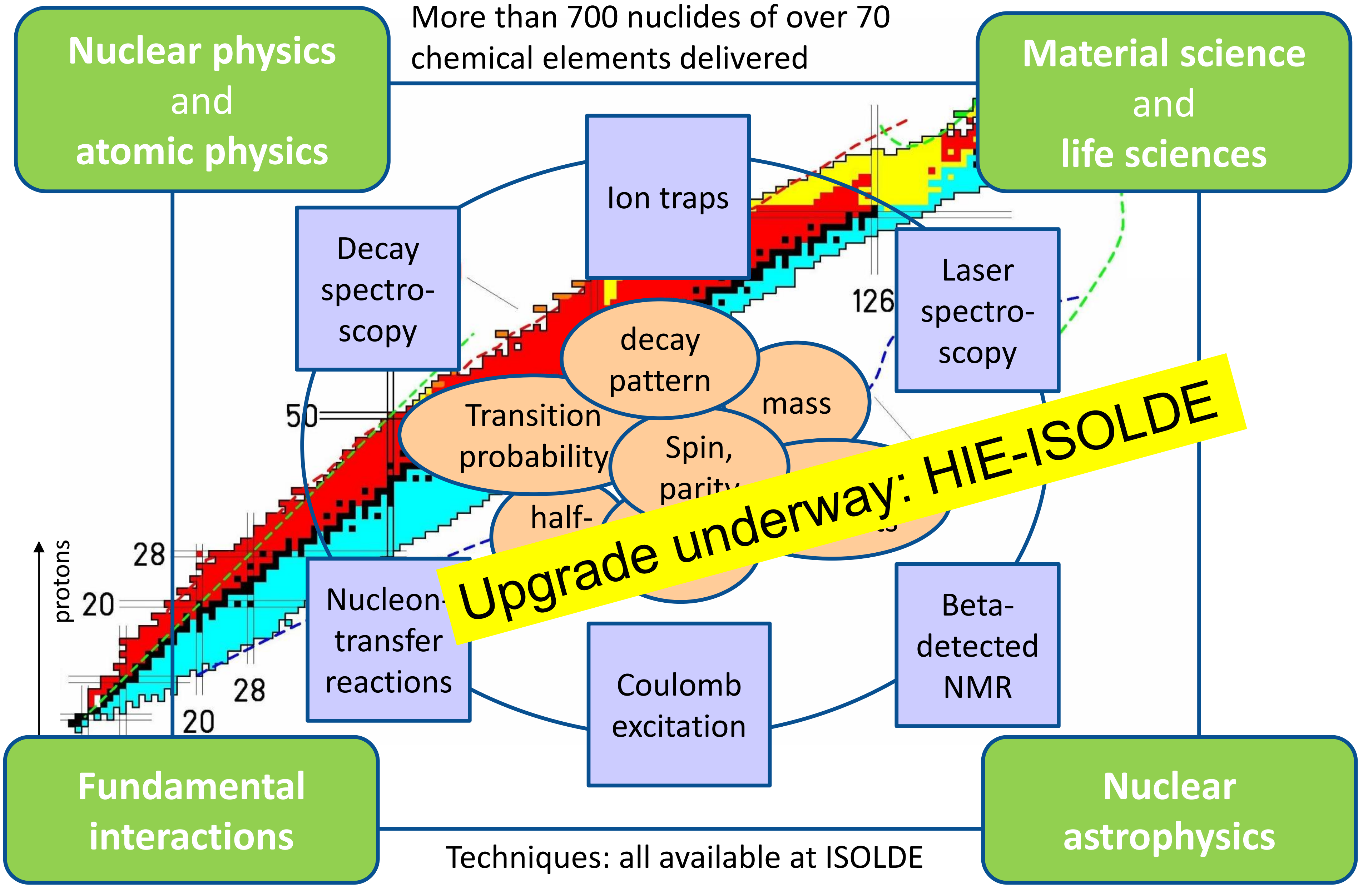


Research with radioactive nuclides



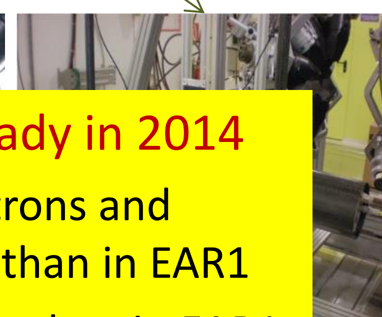
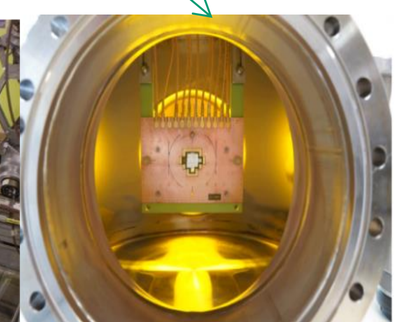
n_TOF physics

100 members, 32 institutions

- Nuclear technologies
- Nuclear Astrophysics
- Medical applications
- Basic Nucl. Phys.

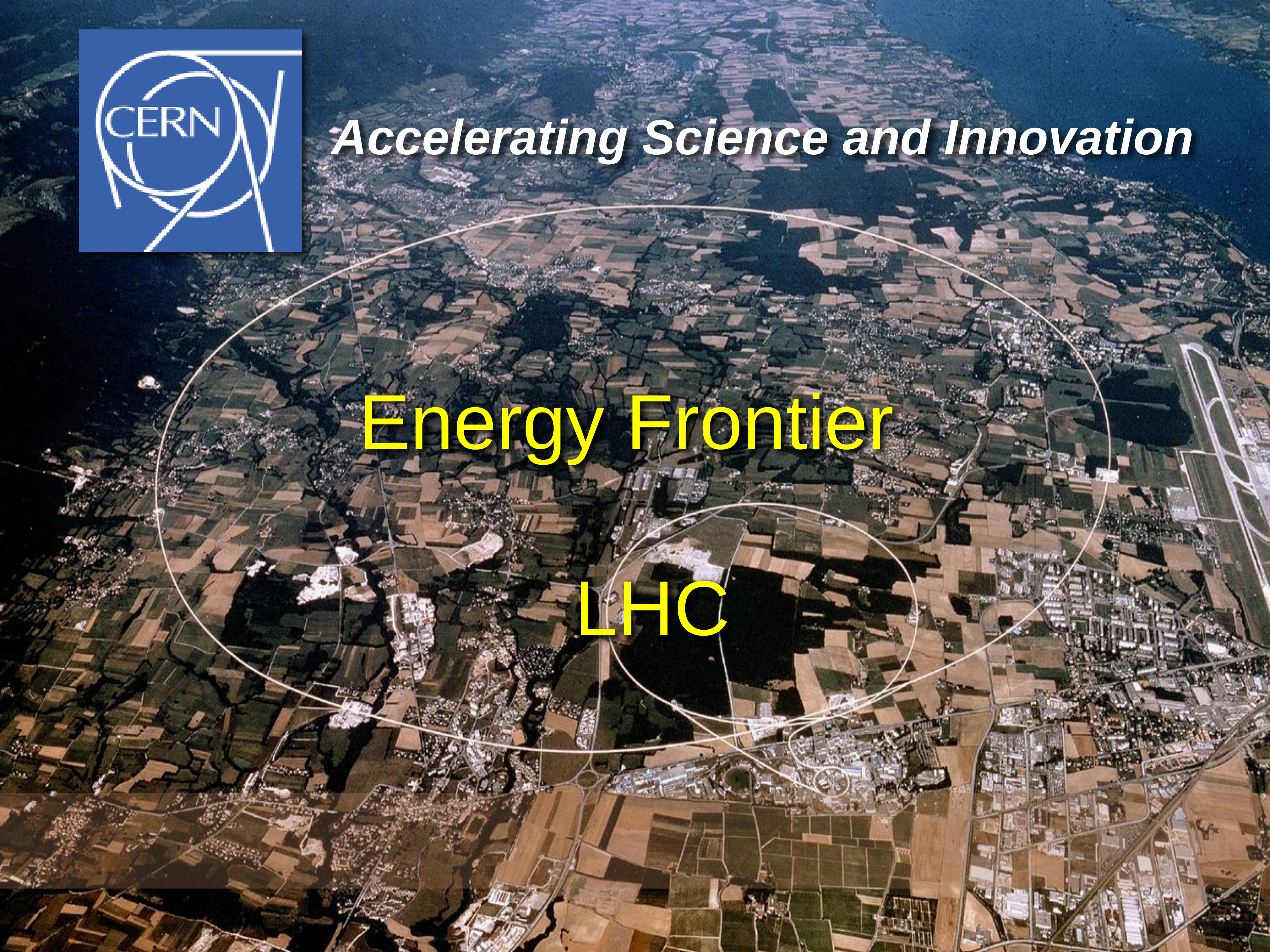
FF Ang. Distribution	Fission	Neutron capture	(n,chp)
^{237}Np, $^{234,235,238}U$	$^{240,242}Pu$, ^{235}U	^{25}Mg, ^{88}Sr, ^{93}Zr, ^{235}U	^{10}B, ^{27}Al, ^{33}S, ^{59}Ni,



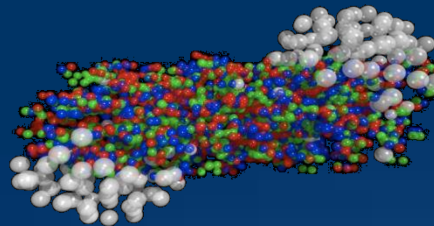




Experimental Area 2 (EAR2) ready in 2014

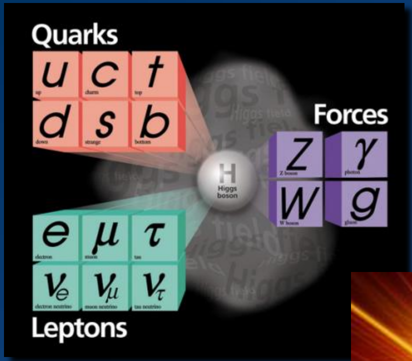
- New vertical line for neutrons and target at shorter distance than in EAR1
- Neutron fluence 20x larger than in EAR1 but lower resolution due to shorter TOF


CERN
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?

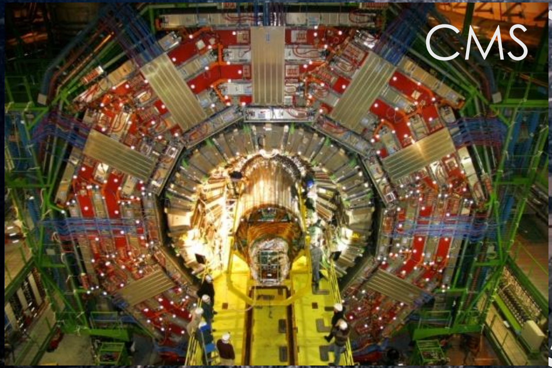


Have we found the Higgs particle that is 'responsible for giving mass' to all particles?

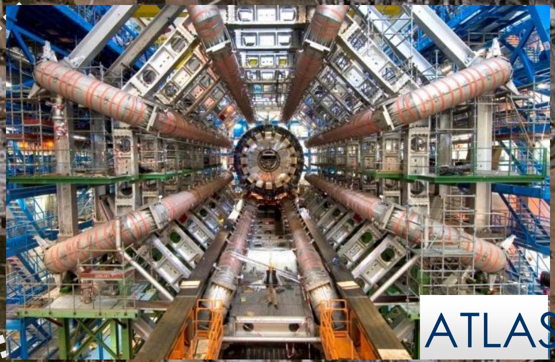
Will we find the reason why antimatter and matter did not completely destroy each other?

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

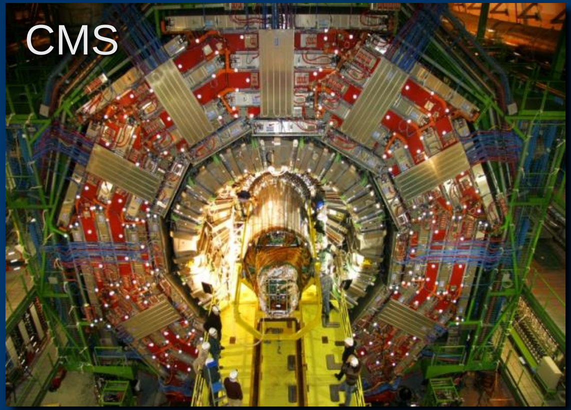


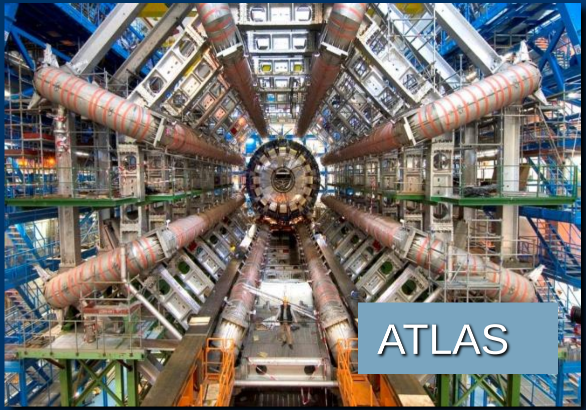
Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at E_{CM} up to 14 TeV



LHC Experiments → complementary

Specialised detector to study b-quarks → CPV



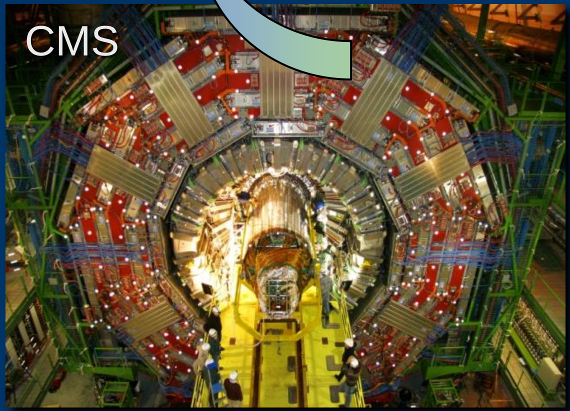


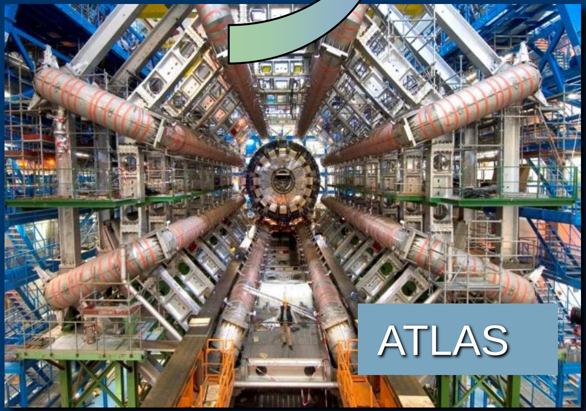
General purpose detectors

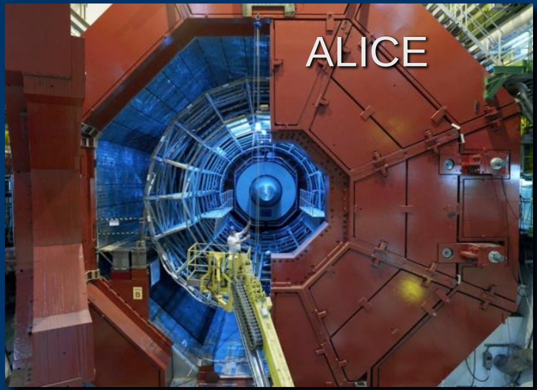
Specialised detector to study heavy ion collisions

LHC Experiments → complementary

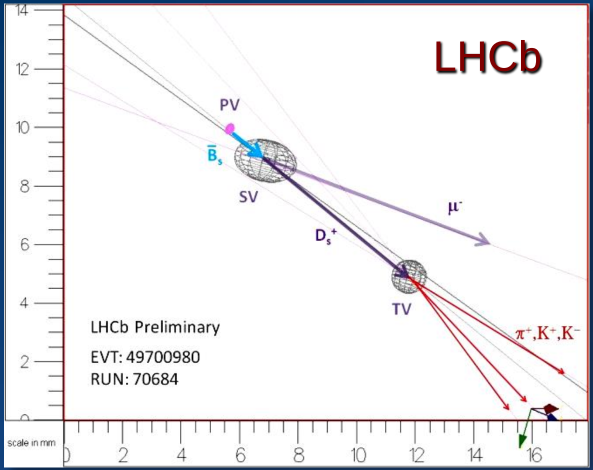
Overlap in physics reach

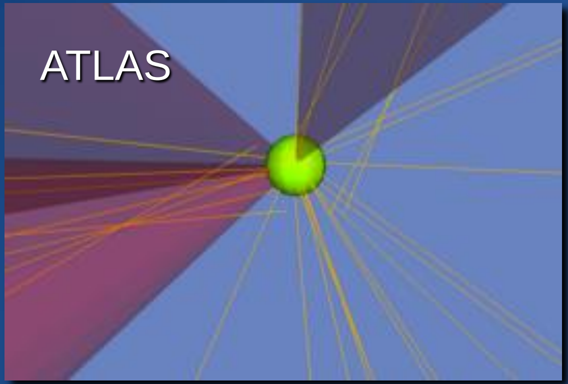






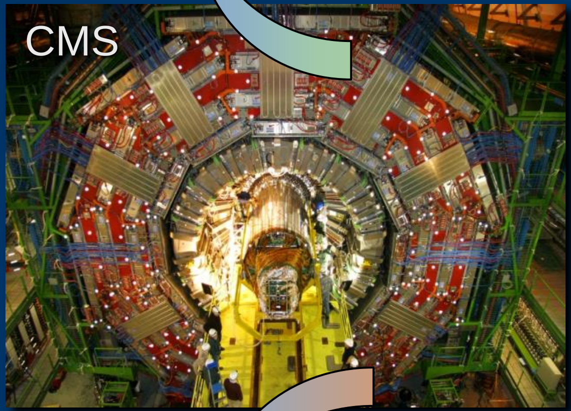
Key feature: reconstruct secondary vertex

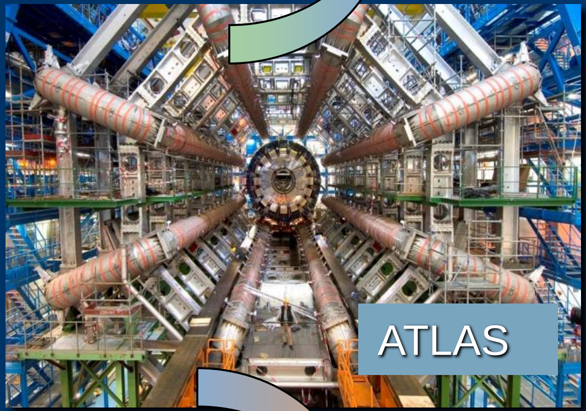




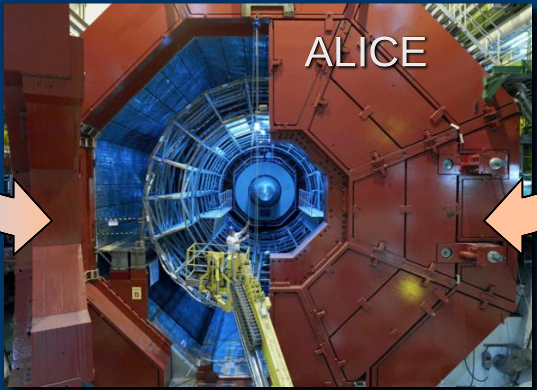
LHC Experiments → complementary

Overlap in physics reach

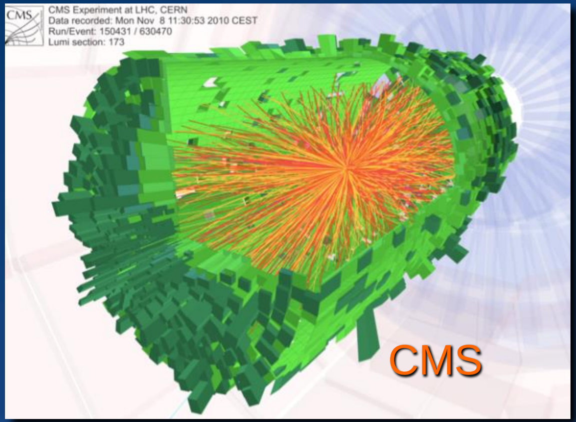


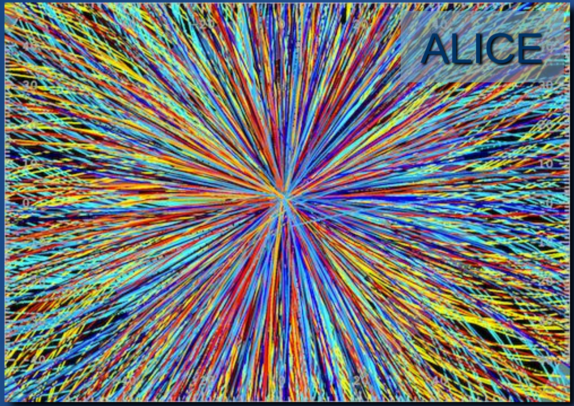


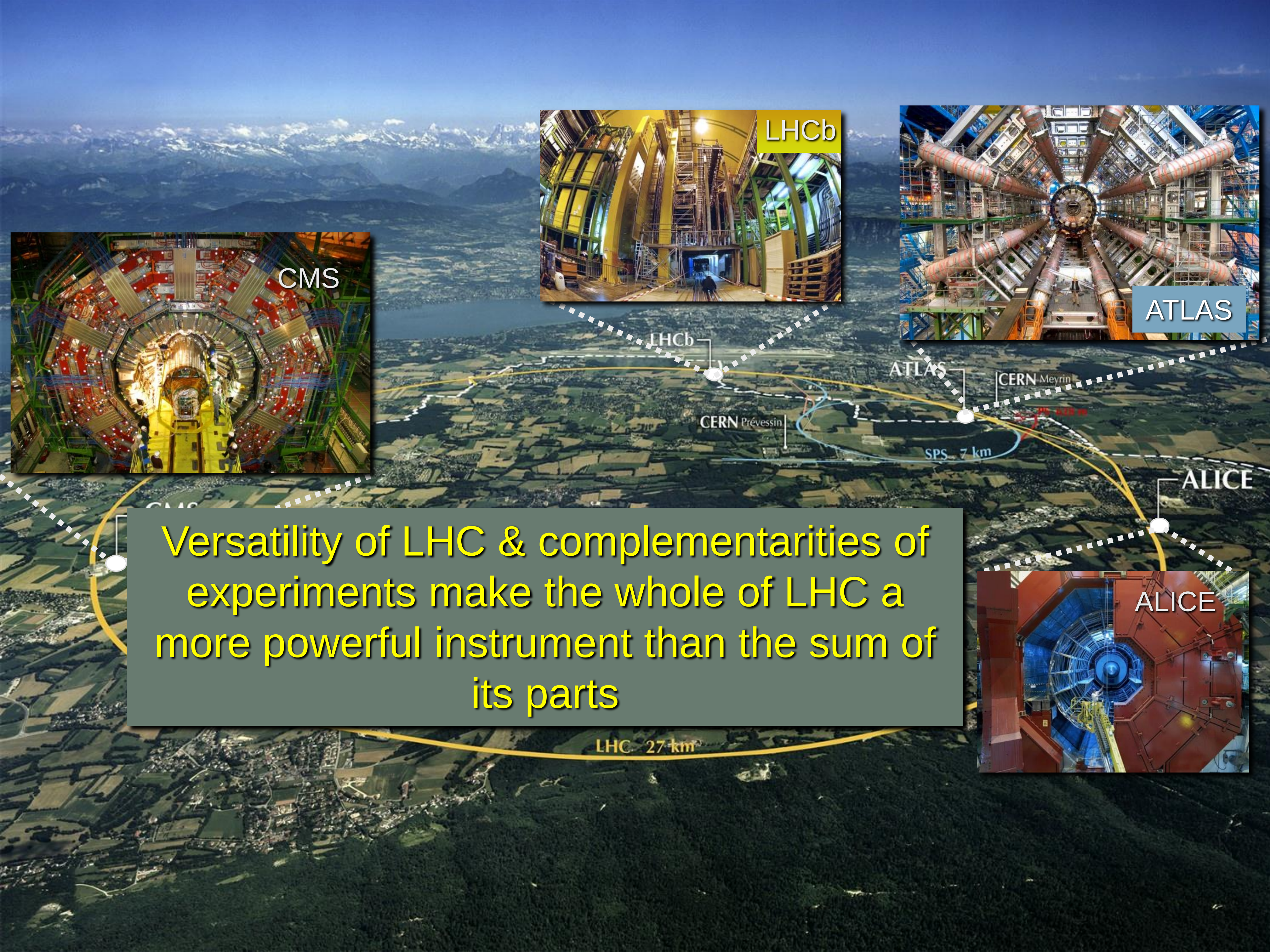
Overlap in physics reach



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







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

LHC run 1
at 7 and 8 TeV

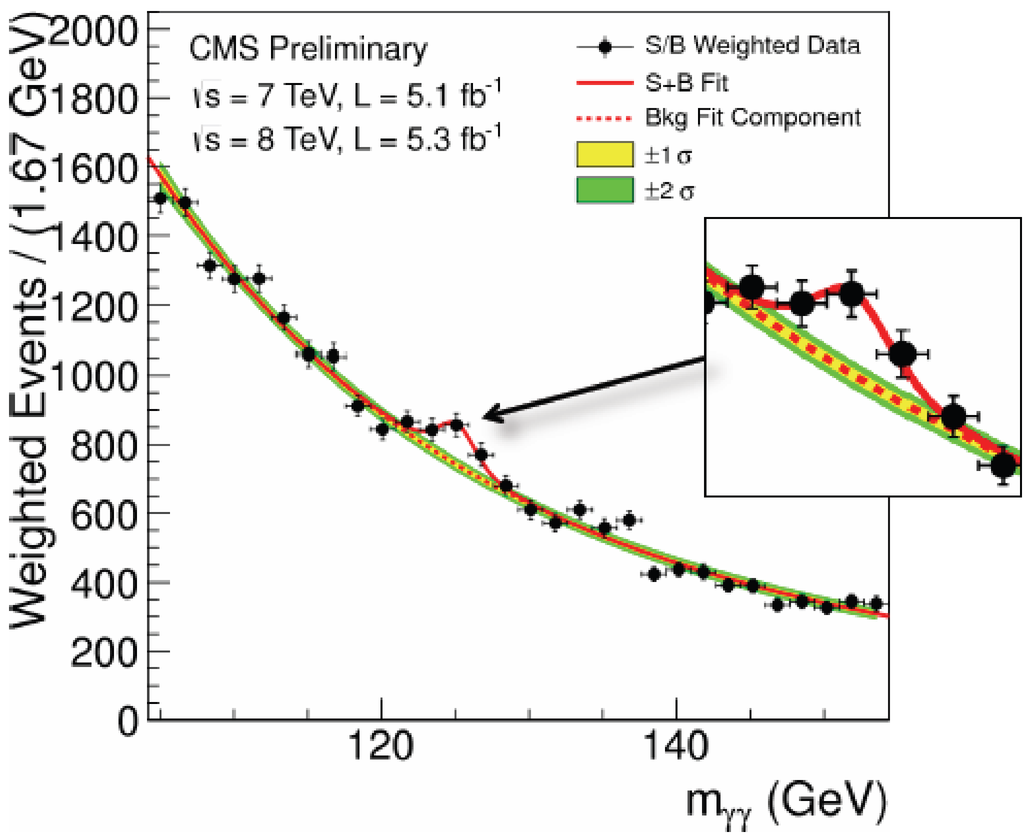
a great success

p-p / Pb-Pb / p-Pb

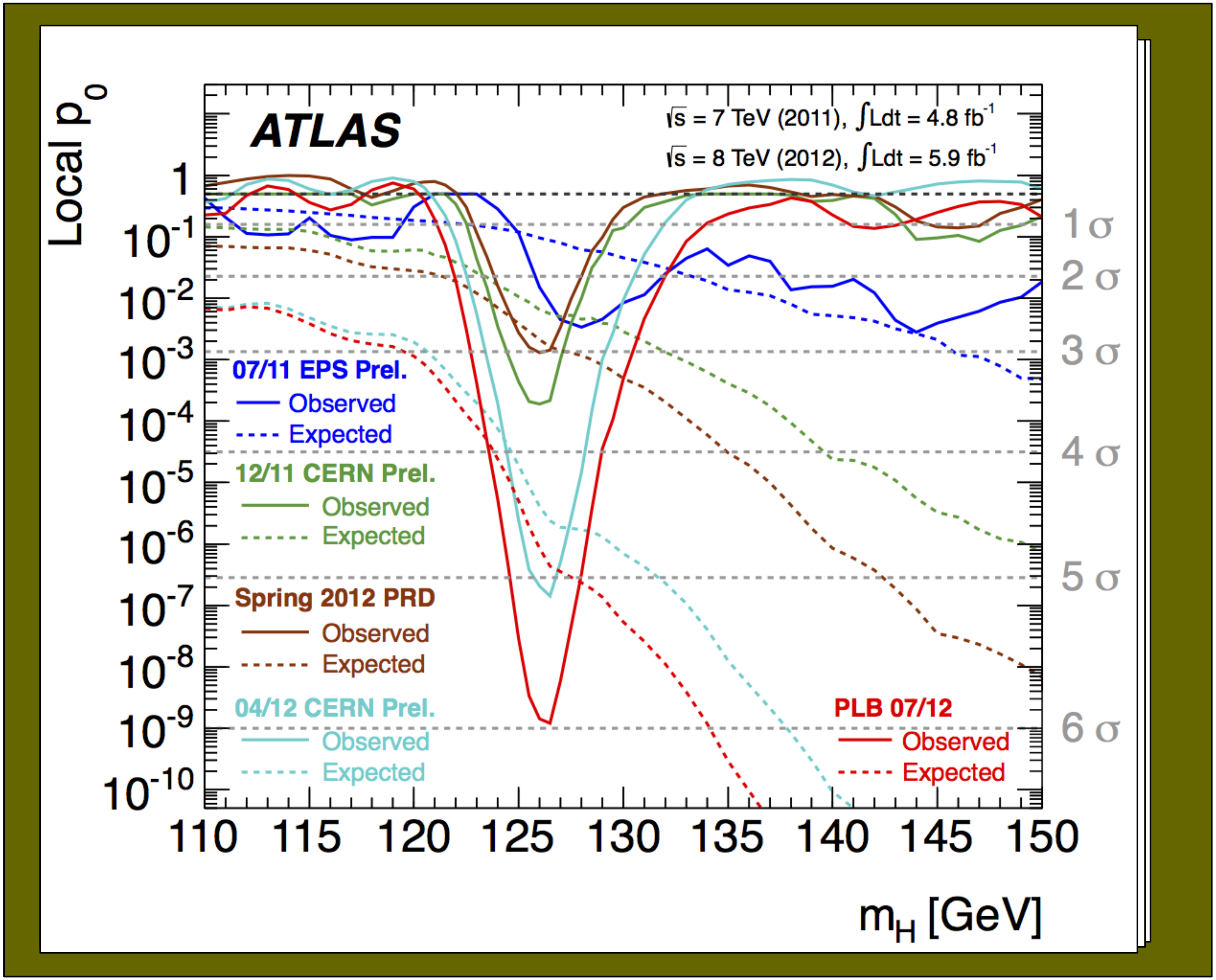
Discovery of a Higgs-boson, messenger of the BEH mechanism

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



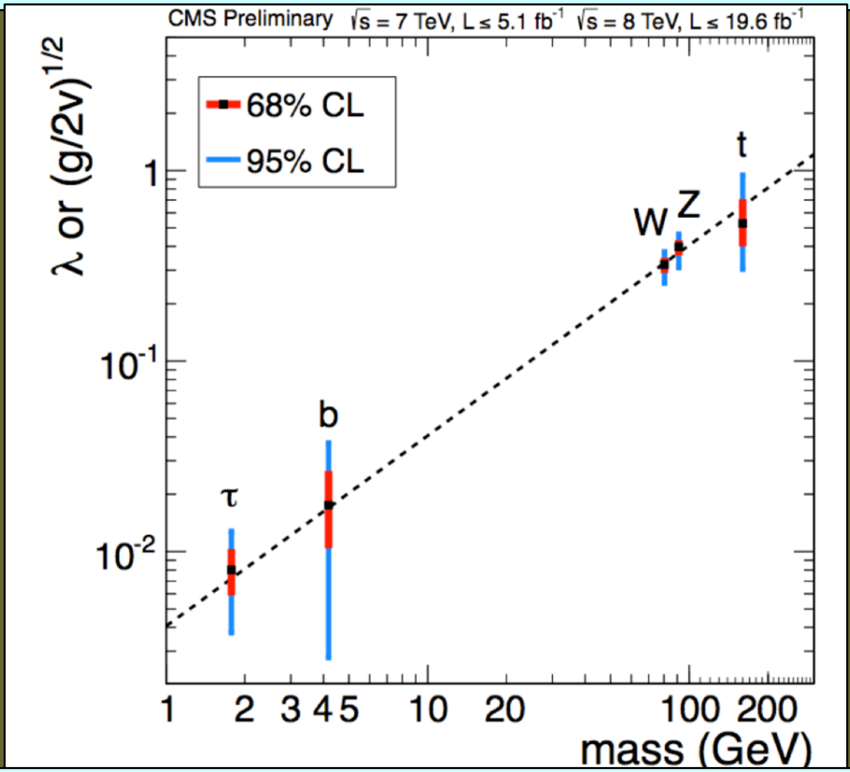
Evolution of the excess with time



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

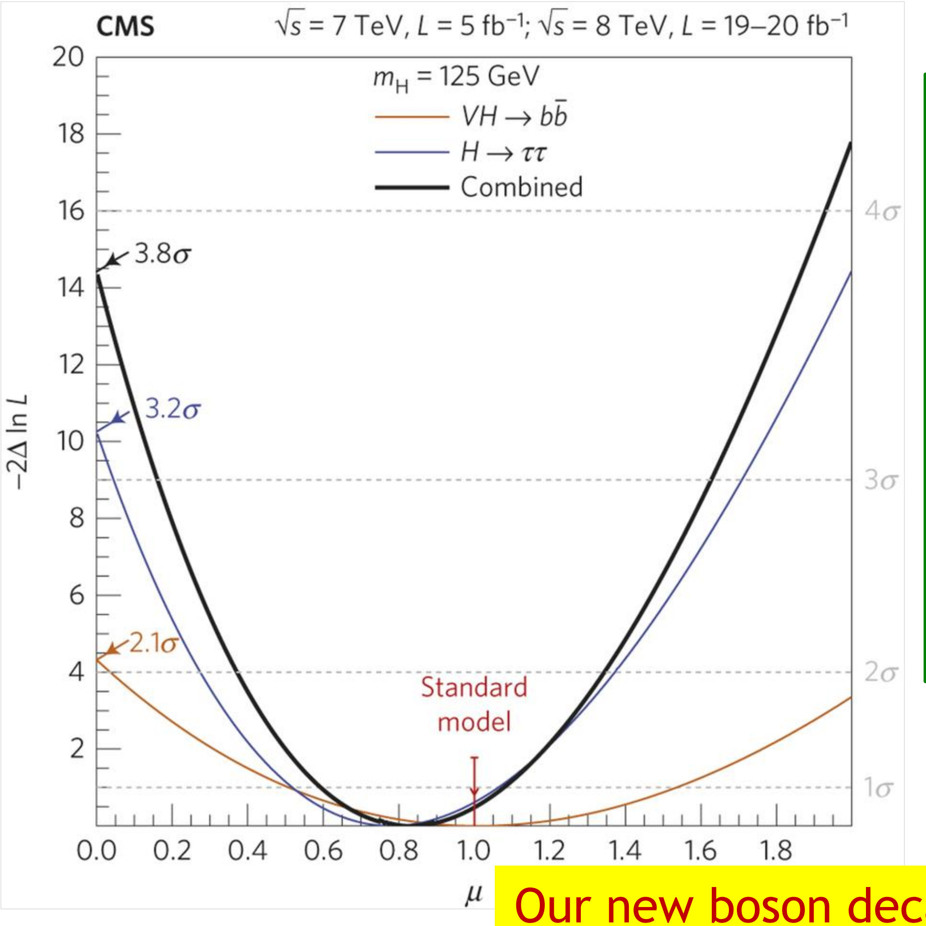
What about the “Dark Universe” ?

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

… information on Dark Matter
… first hints on Dark Energy

H → bb, ττ

H → ττ



Strong evidence for fermionic (tau) decays of the Higgs boson, at the 4.1σ level

Confirms and strengthens previous evidence from CMS (3.4σ excess at 125 GeV combining bb and ττ), now updated to combined 4.0σ excess

Our new boson decays to fermions as well as to bosons!

published (Nature)

preliminary

LHCb 2012:

The search for $B_{s\,(d)} \to \mu\,\mu$

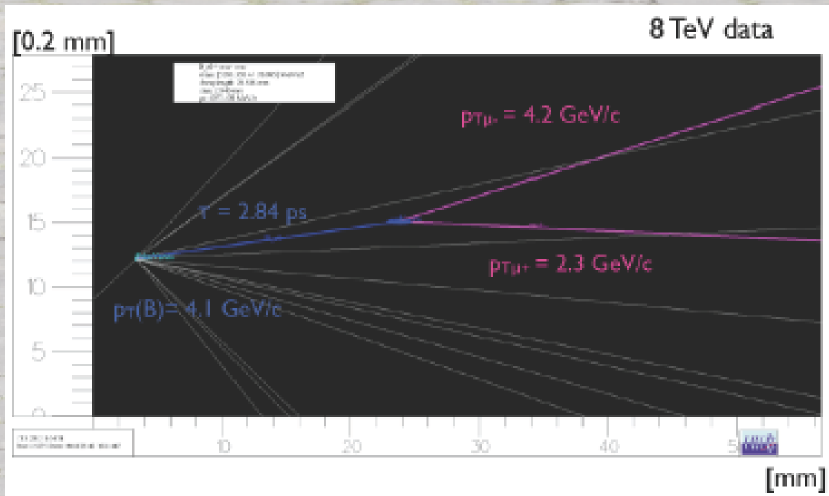
Predicted to be very rare in SM due to GIM & helicity suppression:

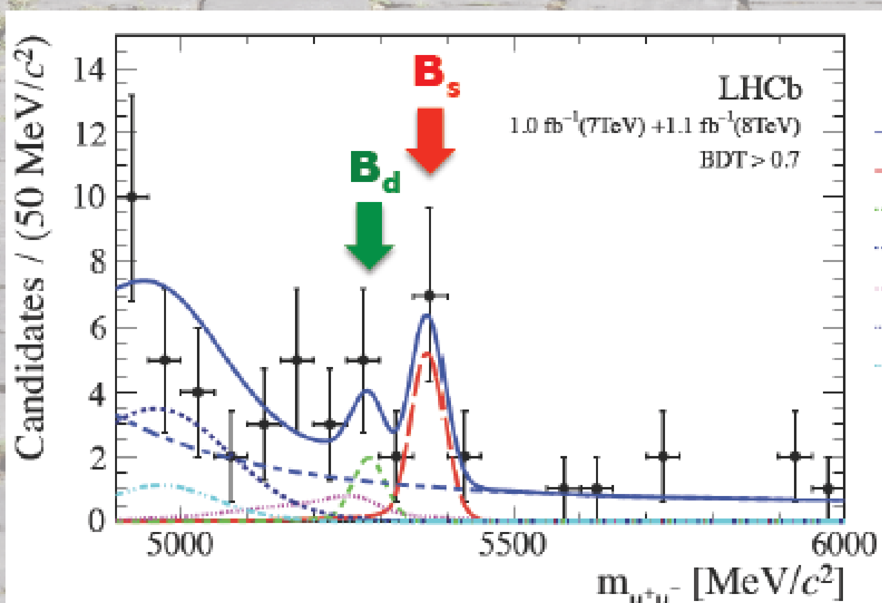
Precise predictions in SM:

- $BR(B_s \to \mu\,\mu) = 3.5 \pm 0.2\ 10^{-9}$
- $BR(B_d \to \mu\,\mu) = 1.1 \pm 0.2\ 10^{-10}$

"Golden channel" for New Physics effects

$$\mathrm{Br}_{\mathrm{MSSM}}(B_q \to \ell^+\ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6\beta}{M_A^4}$$





With 2011+2012 data (2.1/fb) LHCb has got the first evidence of $B_s \to \mu\,\mu$ decay at ~ 3.5 σ

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

in agreement with SM.

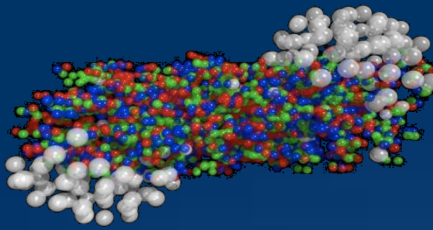
"Background only" p value ~ $5\ 10^{-4}$

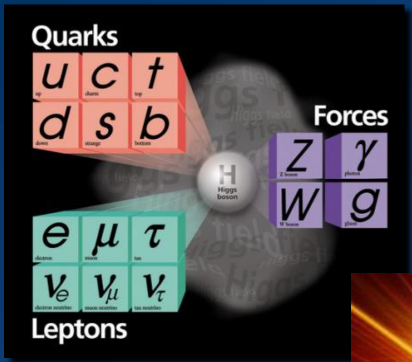
Also best limit on $B_d \to \mu\,\mu$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at 95\% CL}$$

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?





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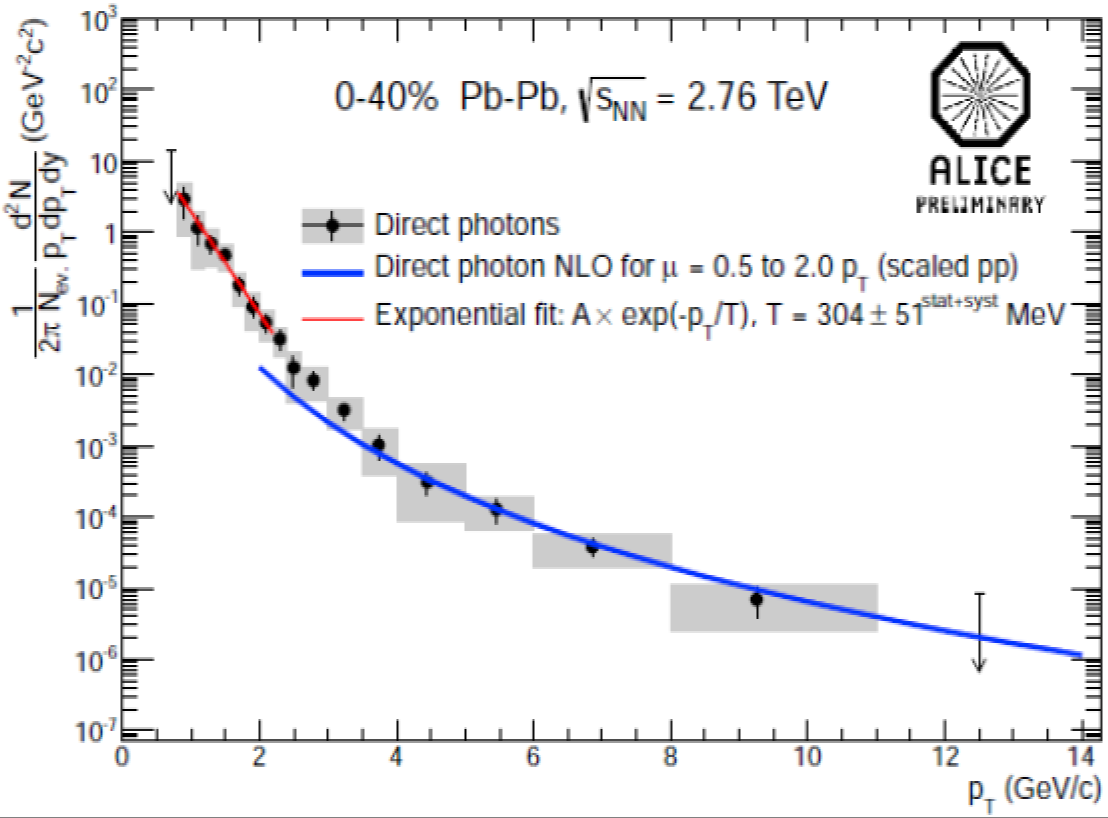
Will we find the particle(s) that make up the mysterious 'dark matter' in our Universe? And what's 'dark energy'?

Low p_T direct photons → a direct thermometer for the temperature of the fireball



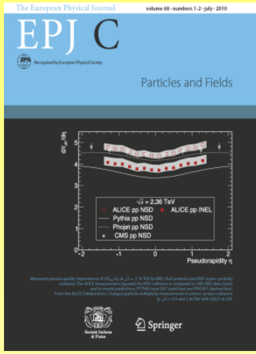
Integrated over fireball history: T = 304 MeV
initial temperature > 450 MeV
highest temperature ever measured in the laboratory

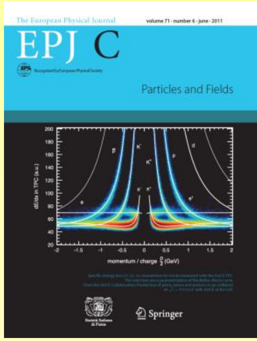
around 3.5×10^{12} K

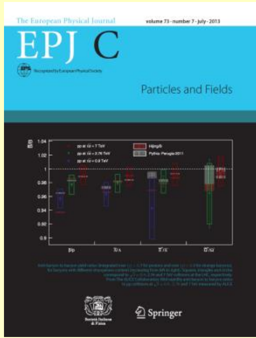
Results keep flowing

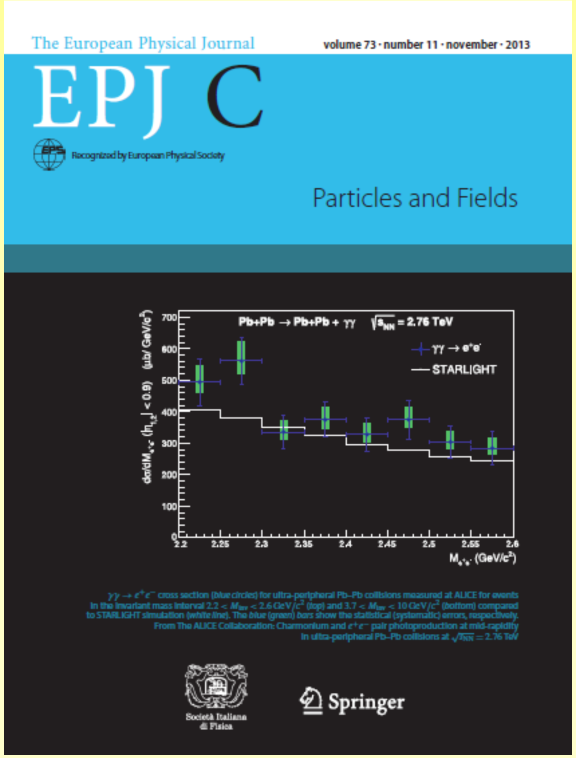
- A huge scientific output
  - **77 ALICE papers on arXiv**

  - **High impact papers:** the top cited paper at the LHC after the Higgs discovery ones is the ALICE paper on flow in HI collisions, and out of the 10 top cited physics papers at the LHC 3 are from ALICE and one from ATLAS-Heavy Ion program (source: ISI)
  - **Several hundred** presentations at international conferences *each year*









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 !)

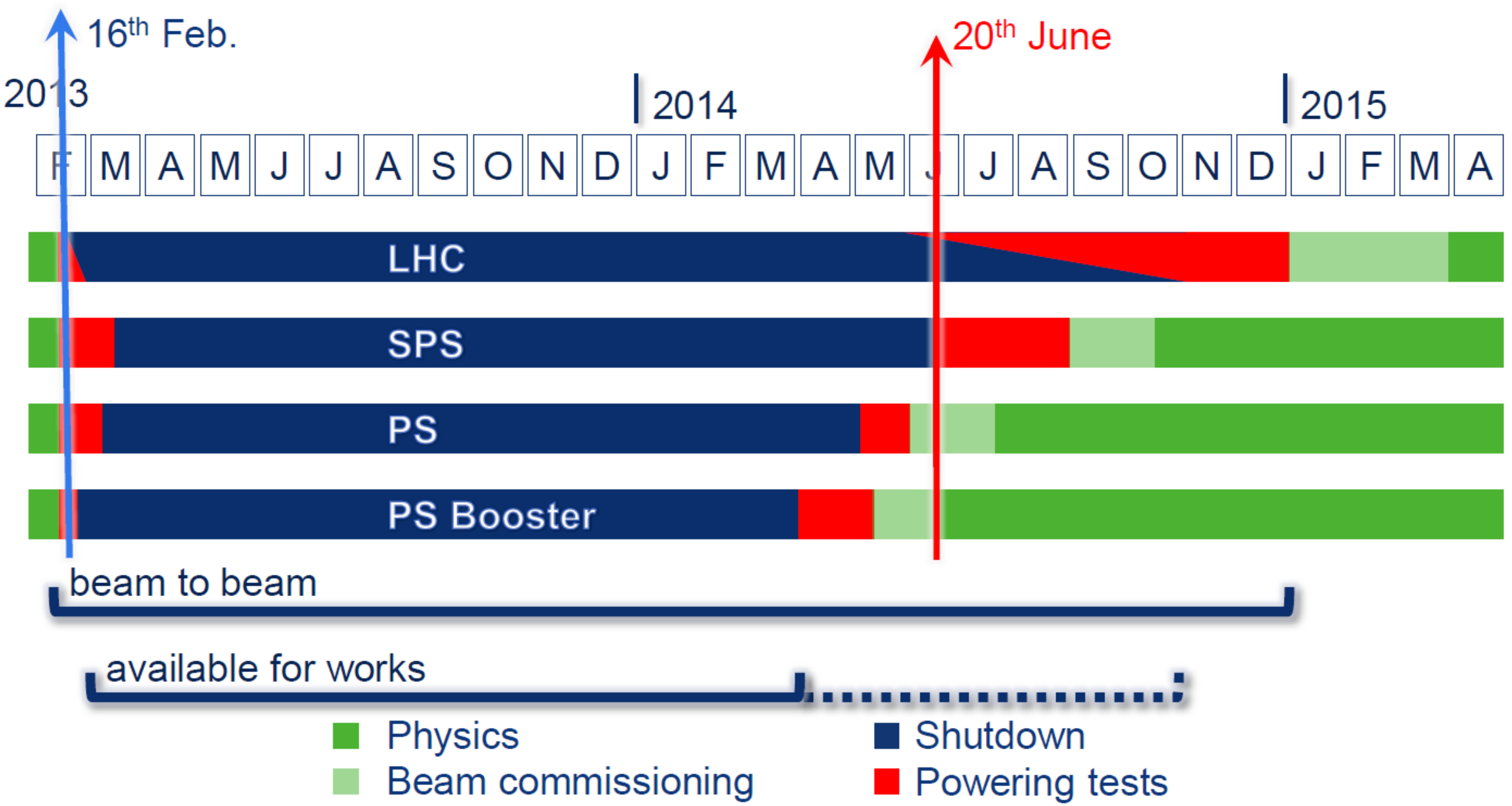
3) We found interesting properties of the hot dense matter

4) We have no evidence of new physics (YET)

What's next ?

CERN | 60 YEARS/ANS CERN

LS 1 from 16th Feb. 2013 to Dec. 2014



The main 2013-14 LHC consolidations

Opening:100%
1695 Openings and final reclosures of the interconnections
Closure: 100% 18th June

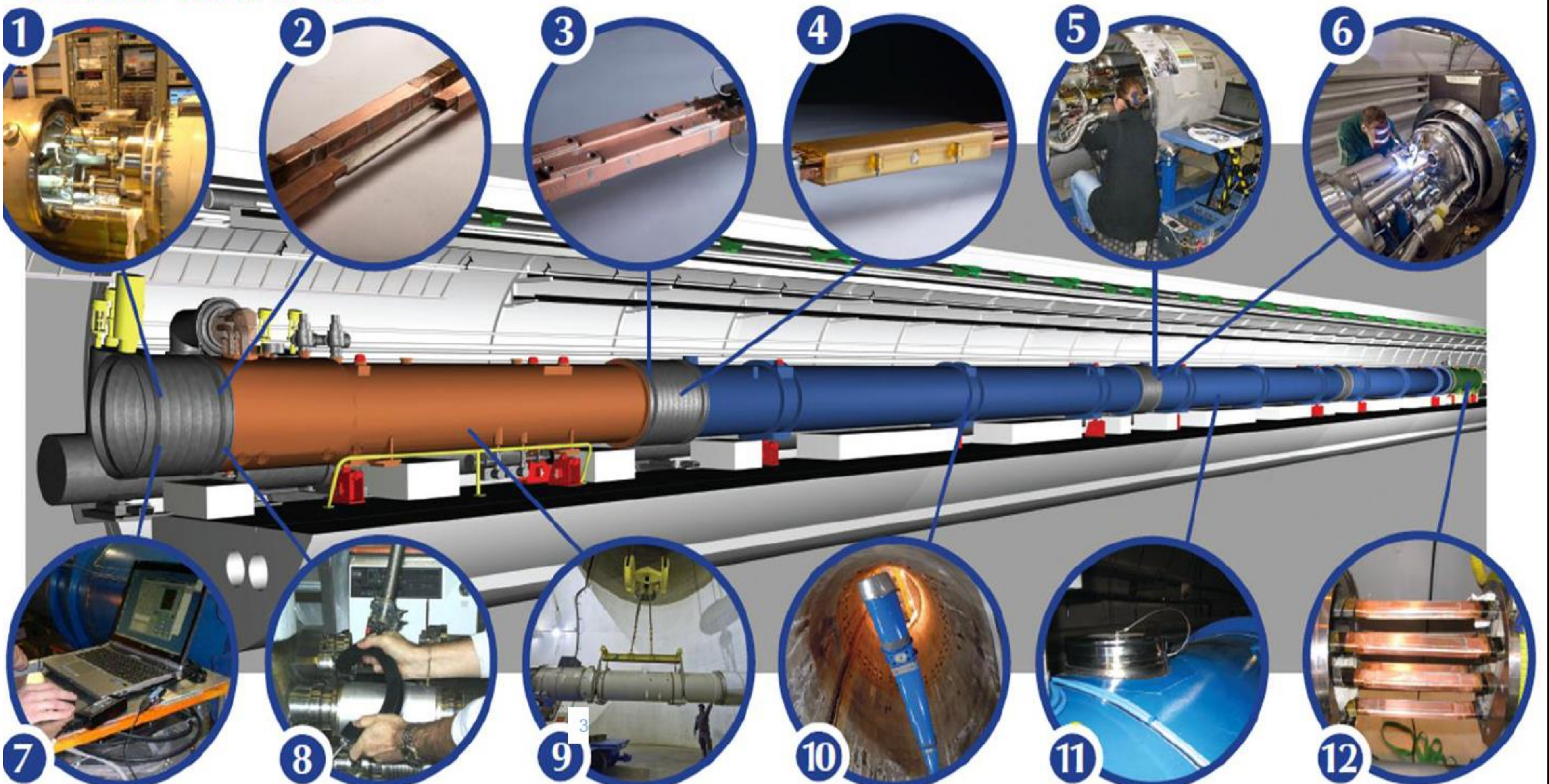
100 % done
Complete reconstruction of 3000 of these splices

100 % done
Consolidation of the 10170 13kA splices, installing 27 000 shunts

100 % done
Installation of 5000 consolidated electrical insulation systems

100 % done
300 000 electrical resistance measurements

100 % done
10170 orbital welding of stainless steel lines



90 % done
18 000 electrical Quality Assurance tests

80 % done
10170 leak tightness tests

3 quadrupole magnets to be replaced
Done

15 dipole magnets to be replaced
Done

100 % done
Installation of 612 pressure relief devices to bring the total to 1344

98 % done
Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

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 frontie… machine
- Invest…
  - Powe… triggers, compu…
    - A sustained period of important results
    - And practical applications

The LHC is the only Higgs, (top, Z, W…) factory on the planet for many years to come!

Fabiola:

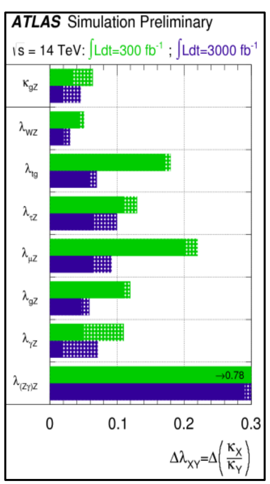
LHC --> HL-LHC: *THE* Higgs factory

today : ATLAS+CMS have 1400 Higgs events

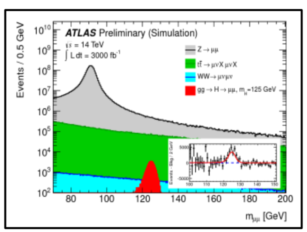
HL-LHC: (3000fb-1) > 3M/170M useful for precise measurement

- ❑ 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

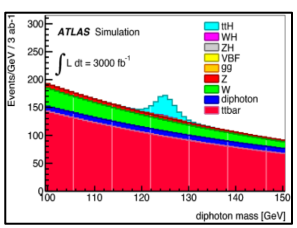


x 1.5 to 2 for 300 --> 3000fb^{-1}



ttH

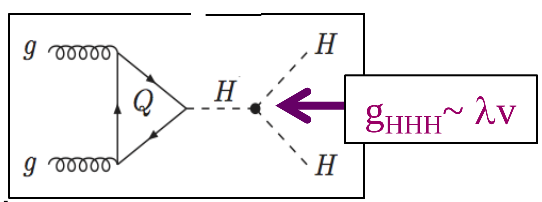
→ γγ



H --> μμ

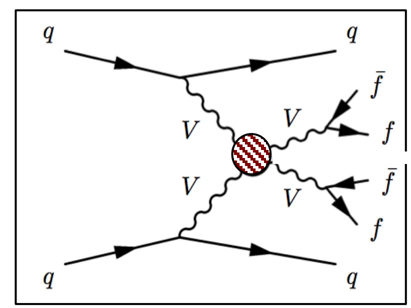
Access to rare processes

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 fiscal
  - …siders the global context
  - Resolves key issues for the field
  - Provides a continuous flow of results while making essential investments for the future

Recommendations in line with the European Strategy

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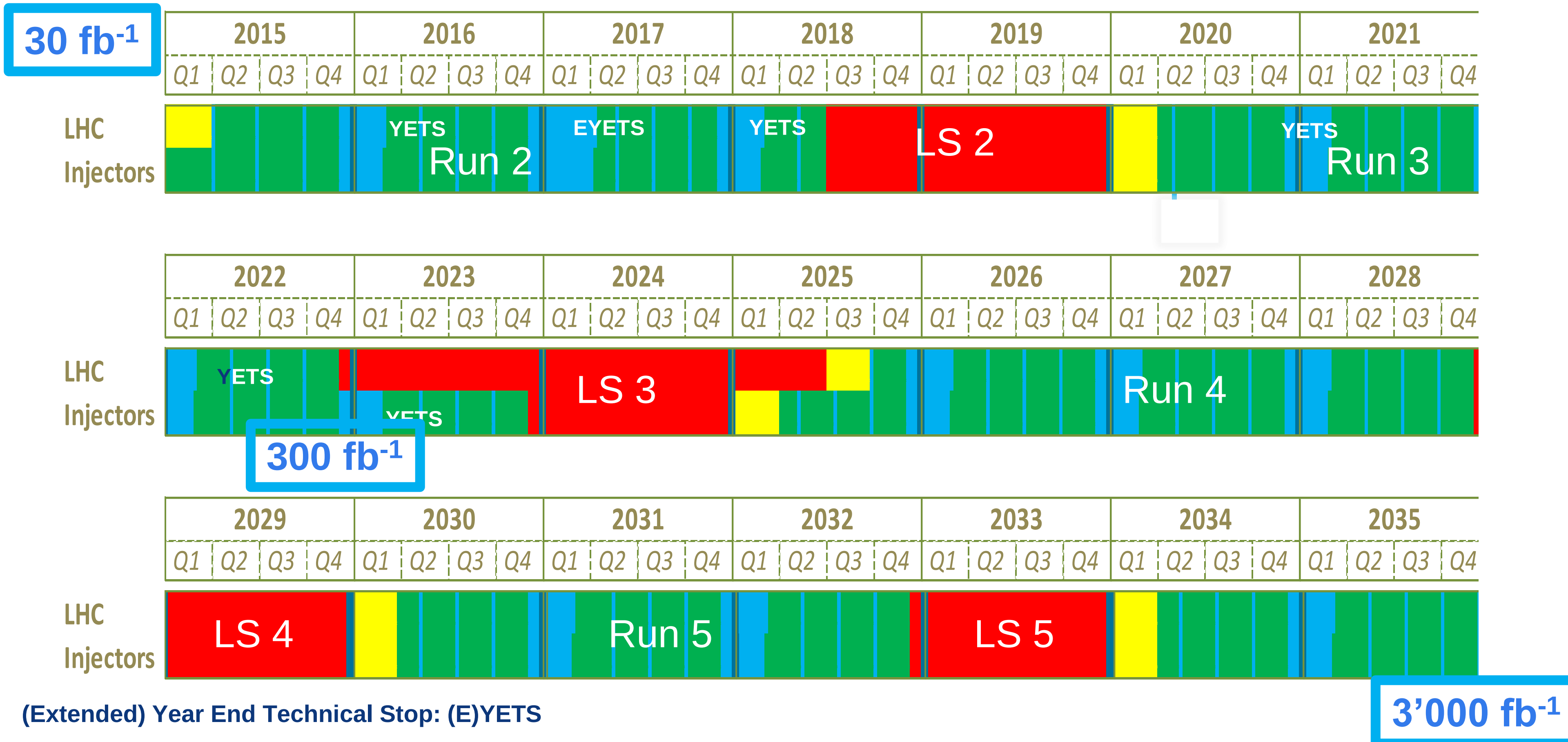
From the P5 report

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

Physics
Shutdown
Beam commissioning
Technical stop



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

Key message

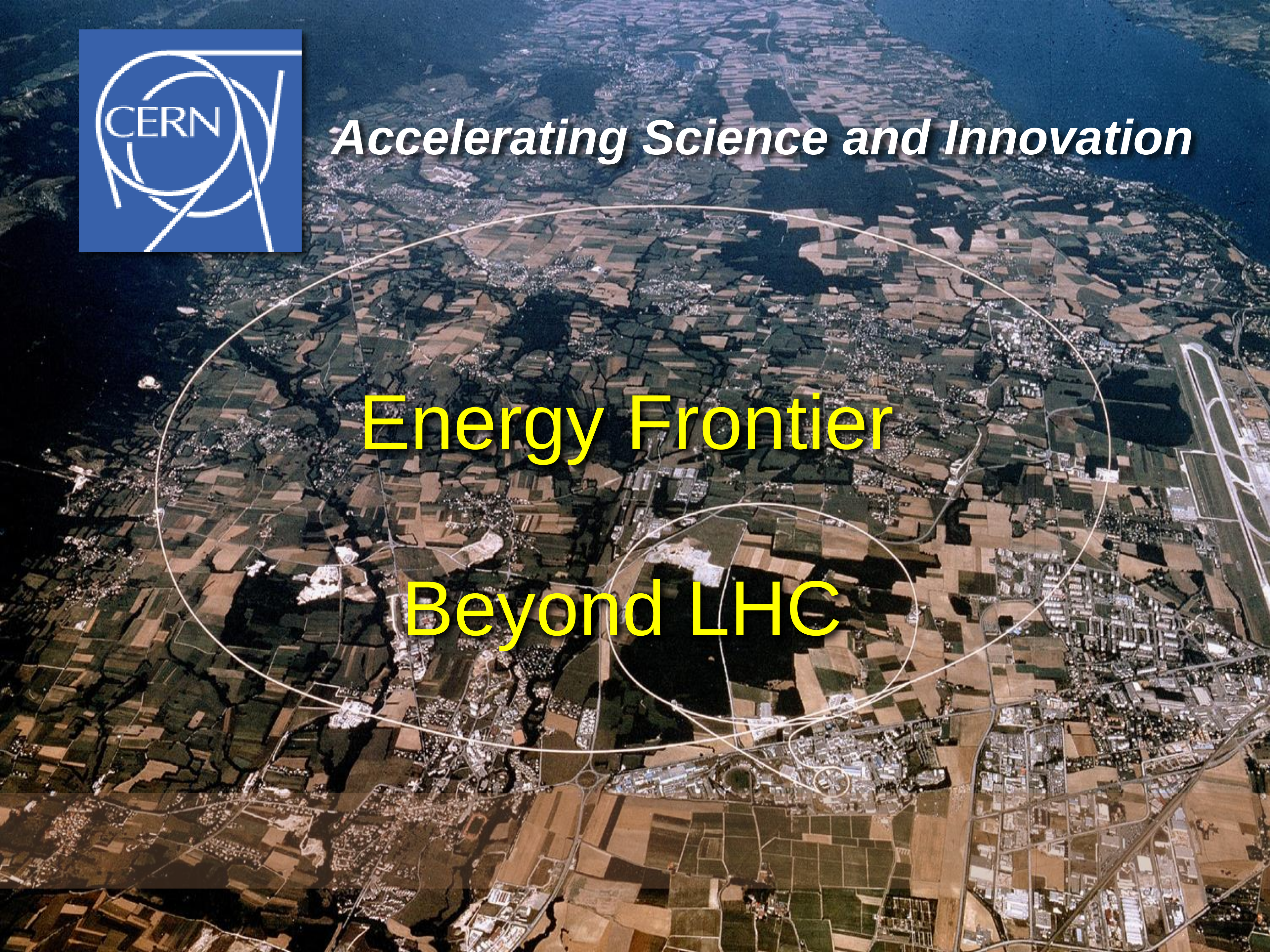
There is a … …ntier

… TeV (essentially done)

14 TeV design luminosity

14 TeV high luminosity (HL-LHC)

Upgrades to accelerator complex, detectors, and computing Grid are vital to fully exploit the physics potential of LHC


CERN
Accelerating Science and Innovation
Energy Frontier
Beyond LHC

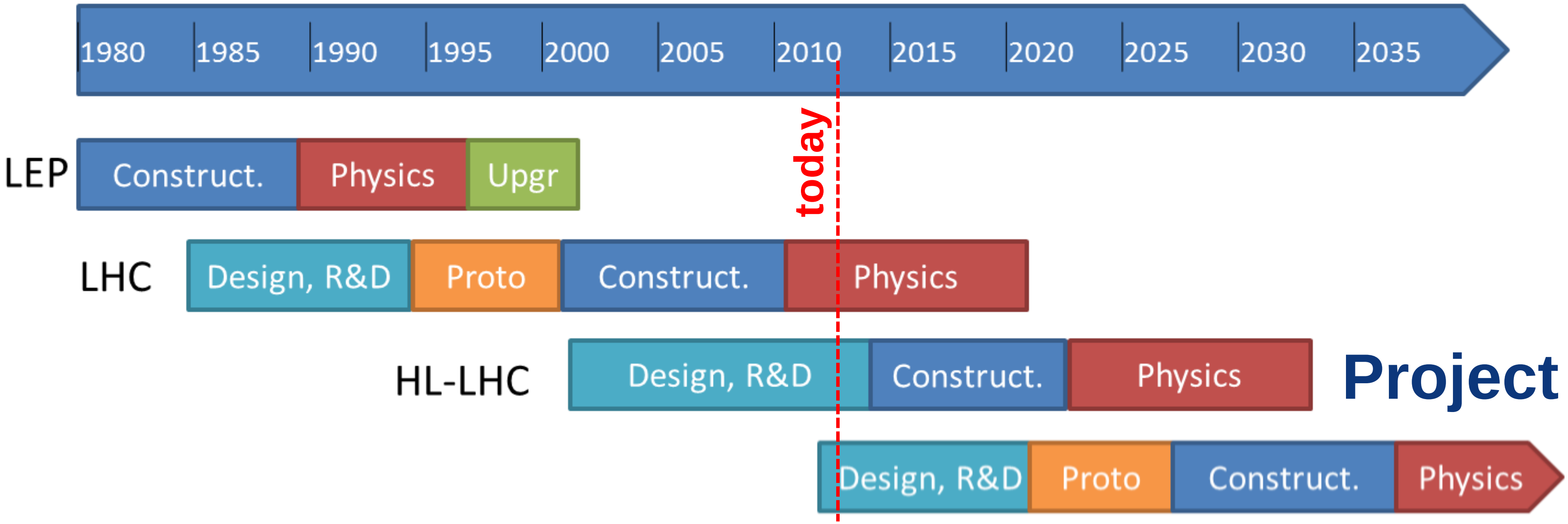
European Strategy for Particle Physics

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.

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 <u>design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines</u>. 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

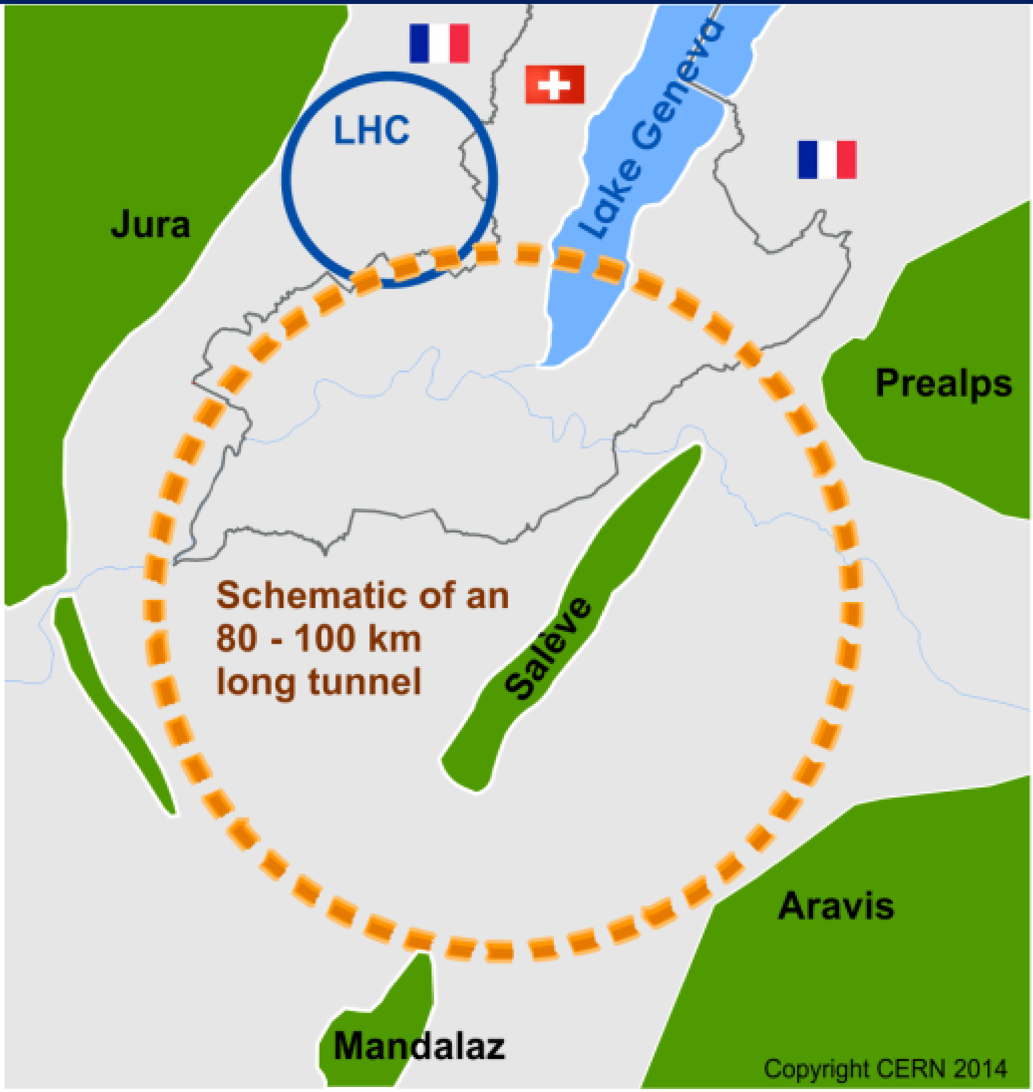
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

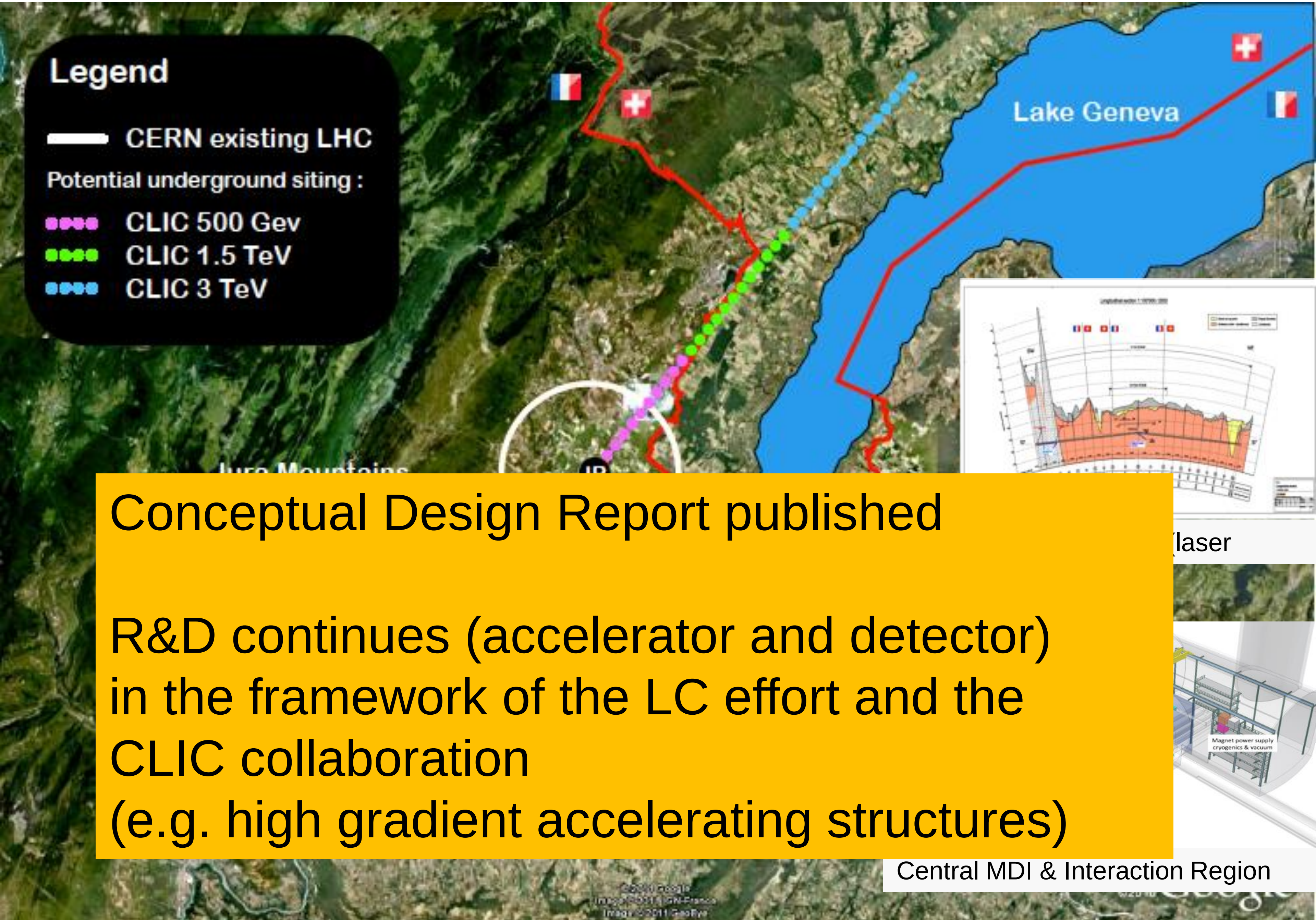
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~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



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)

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible la[illegible]ities requiring significant resources, sizeable co[illegible]itment, the following four activities h[illegible] priority.

e) There [illegible] positron collider, comple[illegible] the properties of the Higgs boson and othe[illegible]nted precision and whose energy can be upgraded[illegible] Design Report of the International Linear Collider (ILC) has [illegible]ompleted, 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.***

At CERN ILC efforts continue in the framework of the LC efforts. Hosting LCC Director(ate) at CERN

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 <u>develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments</u>. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

Neutrino Platform

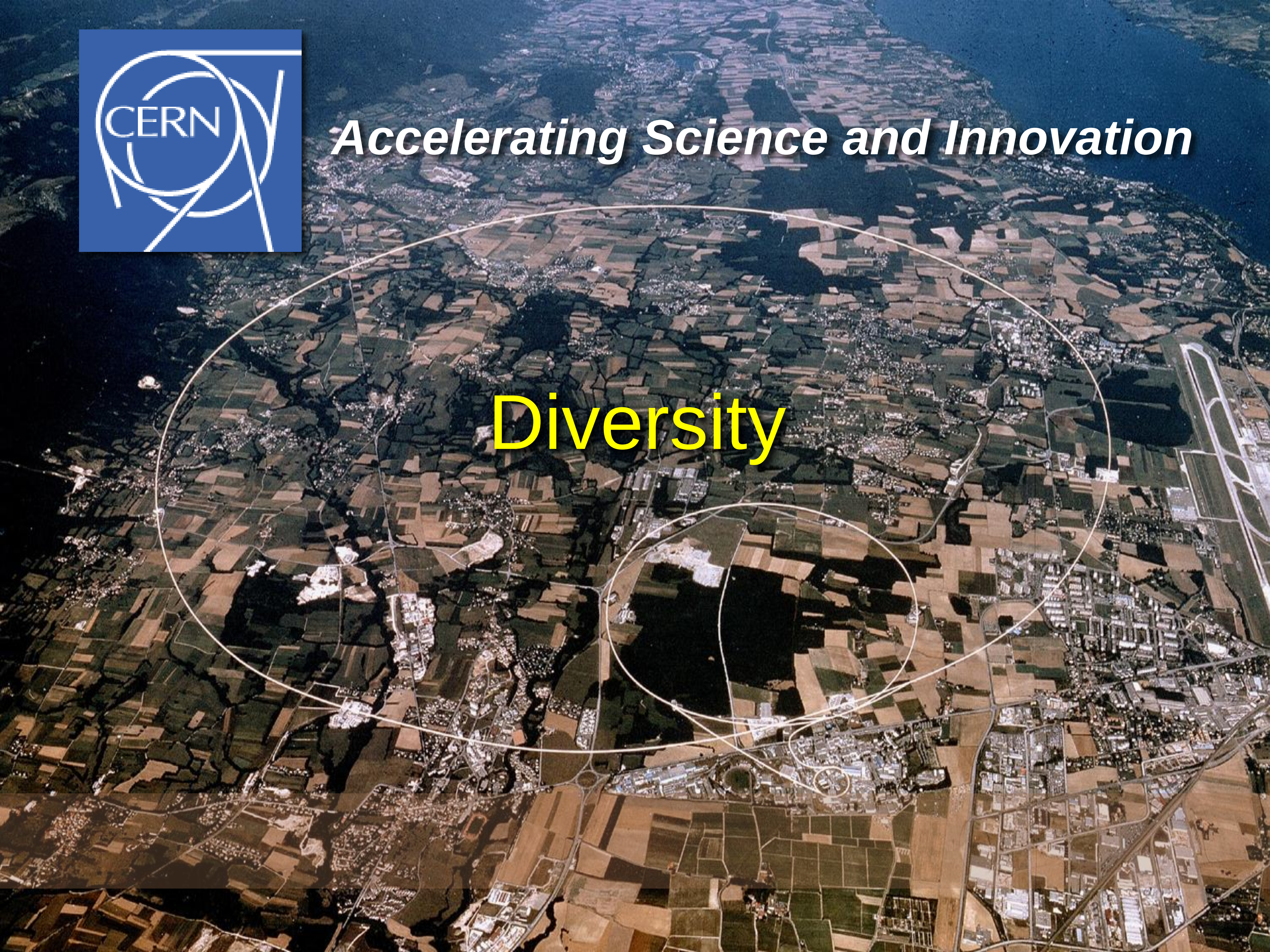
Create a platform to pave the way for a European contribution in a neutrino facility in the US or Asia

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.**

Accelerating Science and Innovation



Diversity

European Strategy for Particle Physics

A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments.
The CERN Laboratory should maintain its capability to perform unique experiments.
CERN should continue to work with NuPECC on topics of mutual interest.

- Honor ongoing obligations at **unique facilities**
  - Na61, Na62
  - N_Tof area 2
  - HIE-ISOLDE construction
  - ELENA construction including consolidation of the AD facility
  - Maintain experimental areas for fixed-target experiments

Conclusion

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