

# Le LHC, une aventure scientifique, technologique et humaine



[www.cern.ch](http://www.cern.ch)

Frédéric Bordry

40 ans LAPP - Annecy  
14 Octobre 2016



# LHC (Large Hadron Collider)

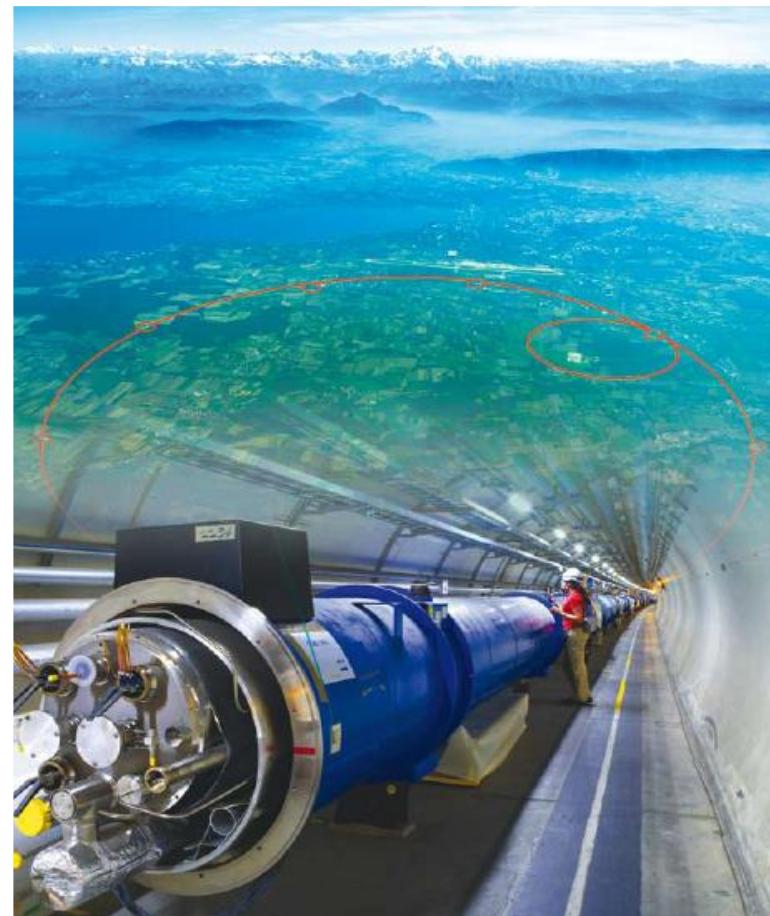
**14 TeV proton-proton  
accelerator-collider built in the  
LEP tunnel**

Lead-Lead (Lead-proton) collisions

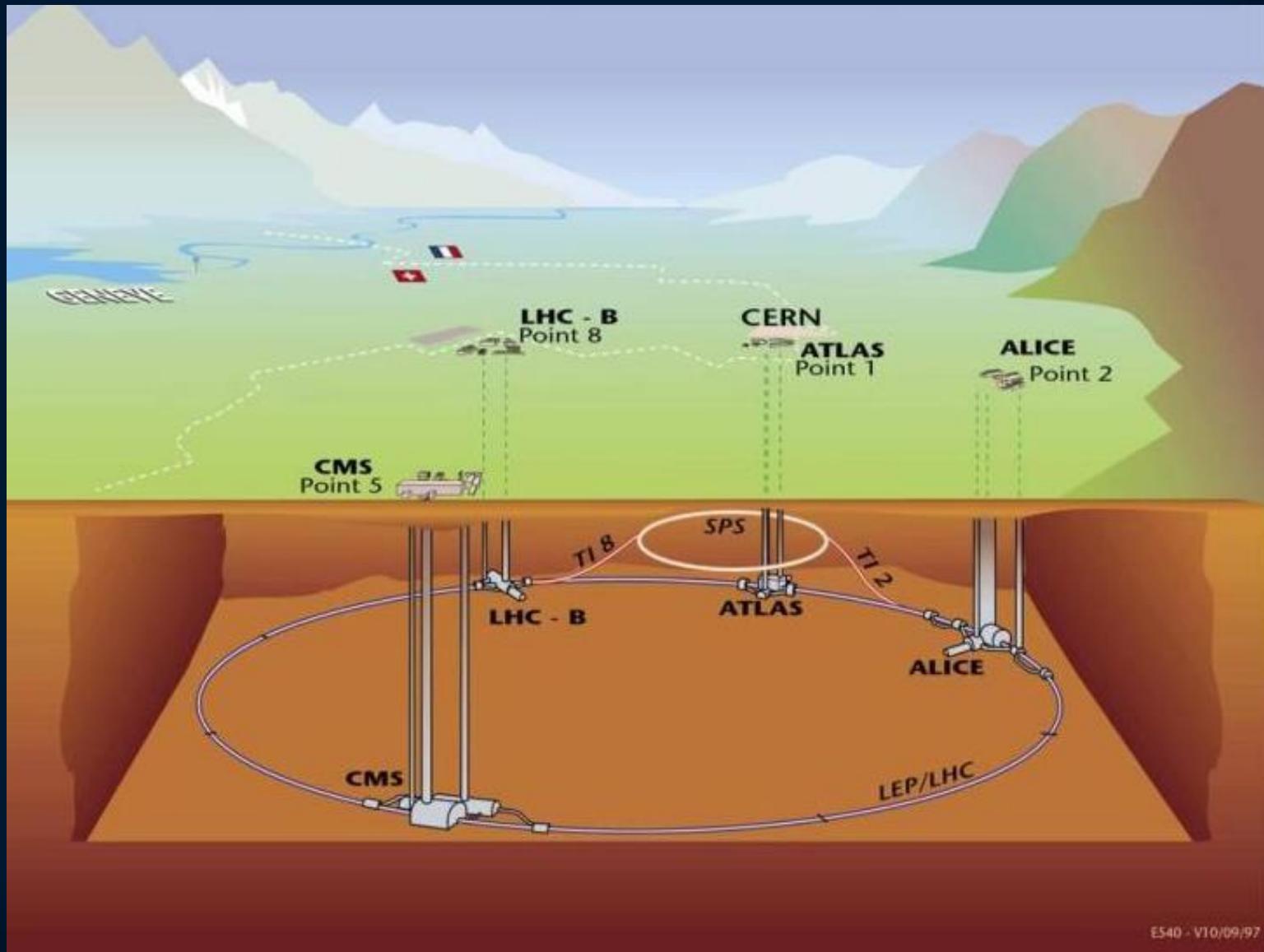
- 1983 : First studies for the LHC project
- 1988 : First magnet model (feasibility)
- 1994 : Approval of the LHC by the CERN Council
- 1996-1999 : Series production industrialisation
- 1998 : Declaration of Public Utility & Start of civil engineering
- 1998-2000 : Placement of the main production contracts
- 2004 : Start of the LHC installation
- 2005-2007 : Magnets Installation in the tunnel
- 2006-2008 : Hardware commissioning
- 2008-2009 : Beam commissioning and repair

## 2010-2035: Physics exploitation

- 2010 – 2012 : Run 1 ; 7 and 8 TeV
- 2015 – 2018 : Run 2 ; 13 TeV
- 2021 – 2023 : Run 3
- 2024 – 2025 : HL-LHC installation
- 2026 – 2035... : HL-LHC operation



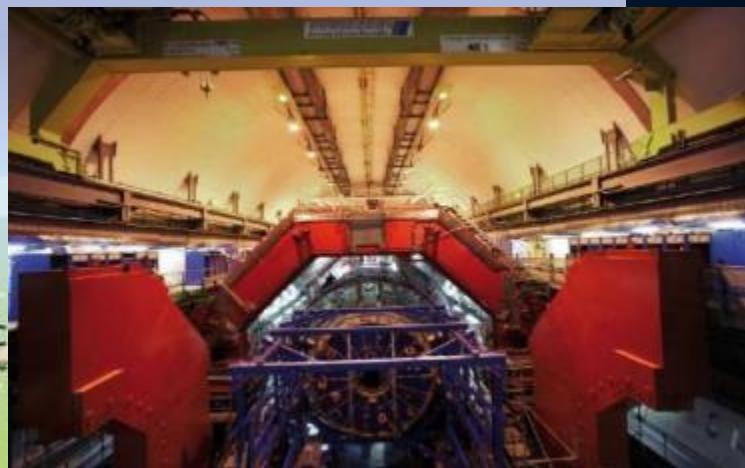
# LHC: an accelerator of 27 km



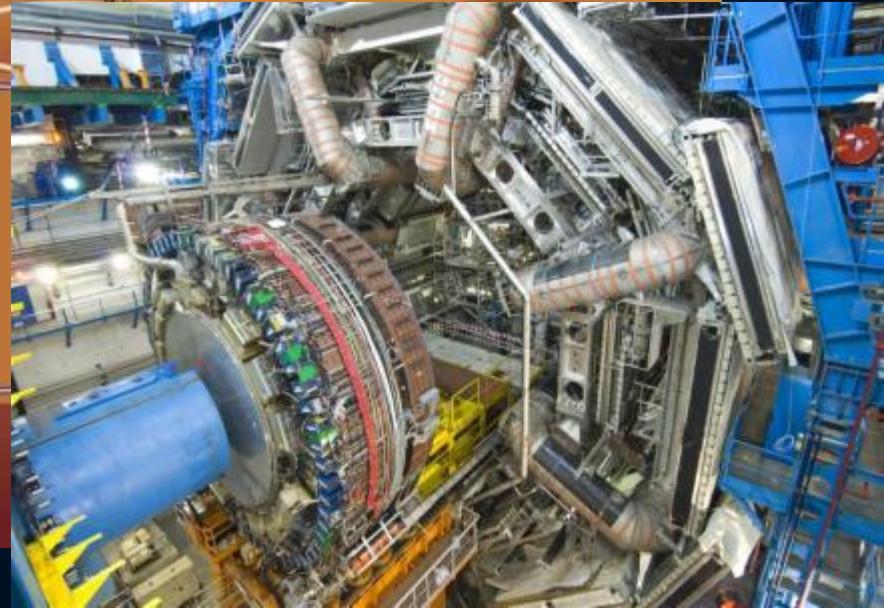
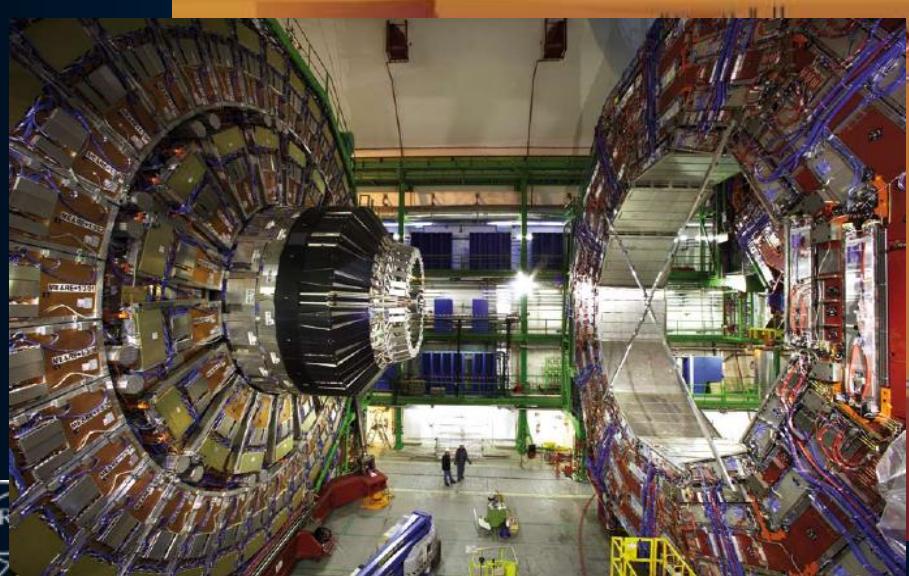
# Four experiments :



LHC - B  
Point 8



CMS  
Point 5



# Four experiments : the coopetition



# LHC: technological challenges

The specifications of many systems were over the state of the art.

Long R&D programs with many institutes and industries worldwide.



- The highest field accelerator magnets: 8.3 T (1232 dipole magnets of 15 m)
- The largest superconducting magnet system (~10'000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium, 150 tons of LHe to cool down 37'000 tons)
- Ultra-high cryogenic vacuum for the particle beams ( $10^{-13}$  atm, ten times lower than on the Moon)
- The highest currents controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters (ppm level)
- A sophisticated and ultra-reliable magnet quench protection system  
(Energy stored in the magnet system: ~10 Gjoule, in the beams > 700 MJ)

# La France s'engage dans la construction du LHC: *les décisions politiques de 1994-1995*

Septembre 1994: lettre du ministre F. Fillon au DG du CERN au sujet d'une  
**contribution exceptionnelle de la France au LHC**

**Octobre 1994: lettre du président Ch. Millon aux collectivités locales**

*Annonce d'une participation à hauteur de 52 MFRF ventilée en 50 % pour la région Rhône-Alpes, 30 % pour le département de l'Ain, 20 % pour le département de la Haute Savoie*

Décembre 1994: lettre du ministre F. Fillon au DG du CERN

*Confirmation d'un effort exceptionnel de 64,5 MCHF (54.5 MCHF + 10 MCHF additionnels)*

Décembre 1994: approbation du LHC par le Conseil du CERN

*Contributions volontaires de la France et de la Suisse pour aider et accélérer la réalisation*

**Avril 1995: lettre du ministre F. Fillon au DG du CERN**

*Proposition d'un effort du CEA et du CNRS évalué à 160 MFRF (valeur 1994) avec l'implication dans les organismes français d'environ 200 hommes-an*



# 1994 : contribution exceptionnelle de la France au LHC

## Répartition:

- 50 % Région (Programme PRAC),
- 30 % Ain (Hall SMA18),
- 20 % Haute-Savoie (Transfert de technologie et formation)



30 avril 1999, Jean Pépin, Sénateur de l'Ain et Président du Conseil général, et le Professeur Luciano Maiani CERN DG

Première pierre de SMA 18 : hall de montage des aimants du LHC (3600 m<sup>2</sup>)



13 novembre 2001 le Directeur général Luciano Maiani, Ernest Nycollin, Anne-Marie Comparini, et Jean Pépin entourés par les jeunes ingénieurs et techniciens de PRAC



Masse froide du LHC dans le HALL SMA18

# Le Programme Rhône-Alpes/CERN (PRAC)

Le Programme PRAC constitue la partie régionale (Rhône-Alpes) de la contribution exceptionnelle de la France au financement du Projet LHC, soit **26 MFRF** (environ ~ 4M €).

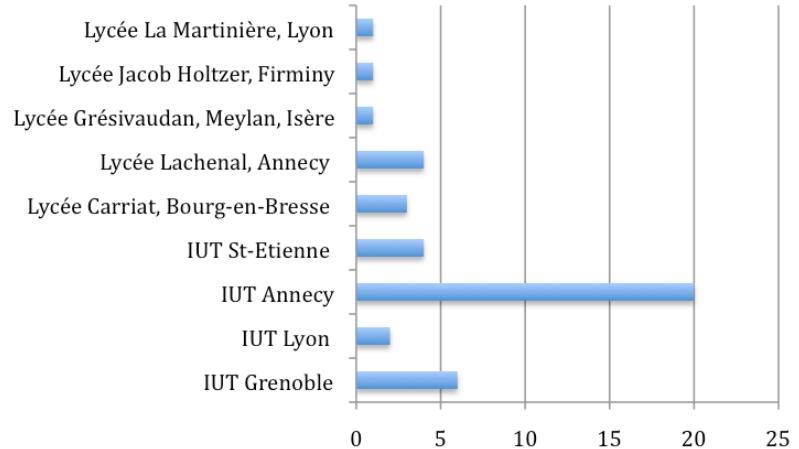
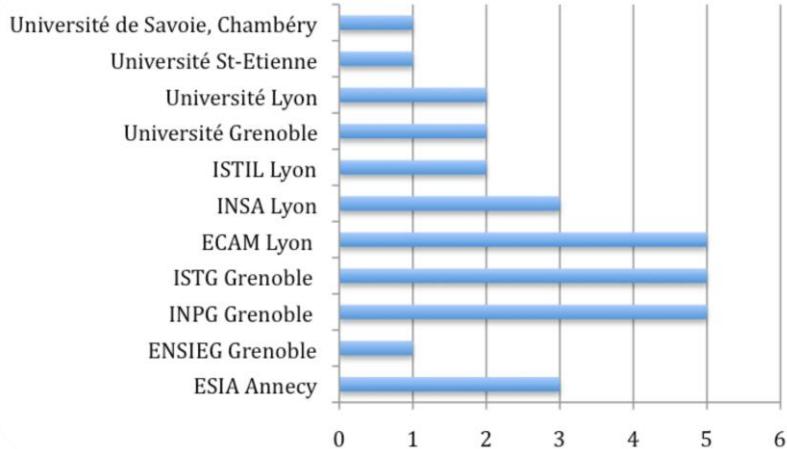
Contribution sous la forme d'un **programme d'insertion professionnelle** pour de jeunes **ingénieurs** ou équivalents (bac + 5/6: DESS ou DEA) et **techniciens supérieurs** (bac + 2/3: BTS, DUT) fraîchement diplômés d'un établissement d'enseignement supérieur de Rhône-Alpes et sans expérience professionnelle.

Ce programme repose sur deux conventions (une convention-cadre tripartite CERN/Région Rhône-Alpes/Fondation scientifique de Lyon et du Sud-Est signée le 2 mars 1998 et une convention d'application CERN-Fondation scientifique signée le 24 juin 1998)

Le programme PRAC a duré 8 ans (1998 à 2006).

Promotion	Ingénieurs	Techniciens	Total
1998-2000	7	5	12
1999-2001	7	8	15
2000-2002	4	6	10
2001-2003	4	7	11
2002-2004	4	7	11
2003-2005	2	9	11
<b>Total</b>	<b>28</b>	<b>42</b>	<b>70</b>

# Le Programme Rhône-Alpes/CERN (PRAC)



- **19** ont obtenu un poste au CERN (dont 15 techniciens supérieurs)
- **16** ont trouvé un emploi dans l'industrie en Rhône-Alpes (Alcatel, Air liquide, EDF, Alsthom, Total, Peugeot, ST Microélectronique, SNR, Volvo, ...)
- **8** dans une autre région de France
- **12** à l'étranger (10 en Suisse – essentiellement intérim ou prestation de service, 2 dans l'Union européenne)
- 4 étaient sans emploi à leur départ du CERN
- 10 : reprise des études, séjours à l'étranger, mission humanitaire, ...

# Collaboration CERN - Haute Savoie

**1<sup>ère</sup> convention-cadre 1996-2000 + Avenant 2001-2003**, dans le cadre de la contribution exceptionnelle de la France au Projet LHC = (~ 1,6 M€)

**C4I** (Centre de Compétence en Conception de Circuits Intégrés), **Archamps**:  
Conception et tests de circuits intégrés (ASIC) (cryostats LHC)

**LAPP-CNRS-IN2P3**:

Développement techniques de soudure par ultrasons en partenariat avec l'industrie locale (Mécasonic) pour soudure des câbles supraconducteurs (interconnexions des aimants du LHC).

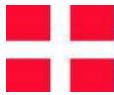
**2<sup>ème</sup> convention-cadre 2004-2009** – 5 ans (~ 1,7 M€)

**3<sup>ème</sup> convention-cadre 2010-2013** – 4 ans (~ 1,2 M€)

**4<sup>ème</sup> convention-cadre 2014-~~2017~~  
2016** – 4 ans (à fin 2016 = 802 K€).

Avec la réforme des régions de 2015, un grand nombre de compétences sont passées des départements aux régions.

# Développement d'un procédé de soudure par ultrasons LHC 74 N°3



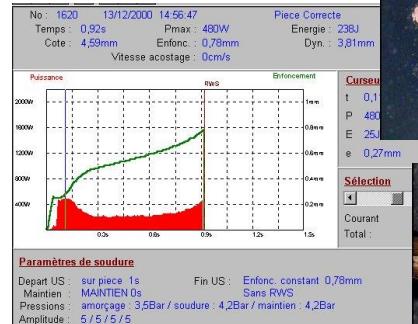
Le Conseil Général de Haute-Savoie



## Études d'outillages spécifiques



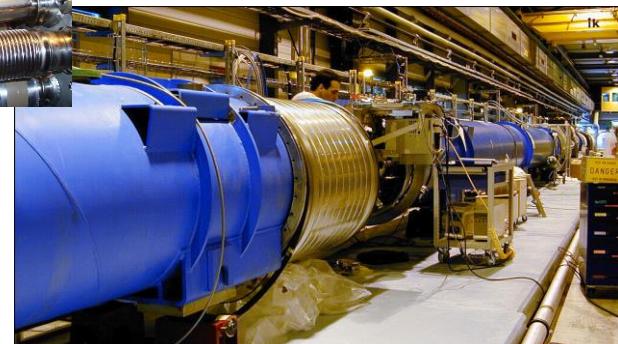
## Maîtrise du procédé Optimisation des paramètres Contrôle Qualité



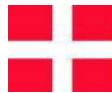
## Intégration machine standard (MECASONIC) dans le contexte LHC



## Réalisation des premières interconnexions du prototype du LHC (STRING 2)



# Etude corps de pompe ionique (LHC 74 N°4)

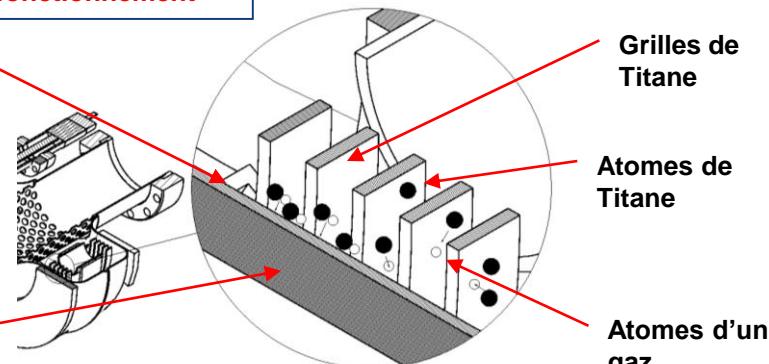


Le Conseil Général de Haute-Savoie



## Principe de fonctionnement

Parois de la pompe

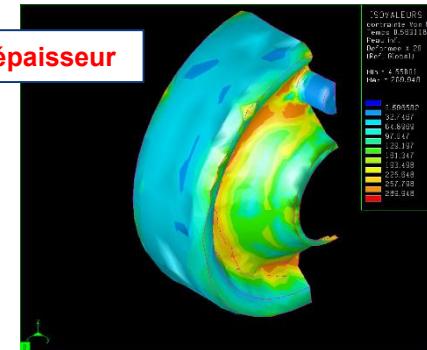


Grilles de Titane

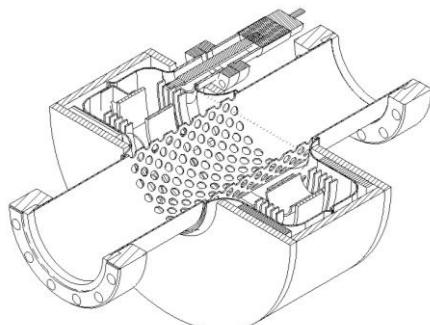
Atomes de Titane

Atomes d'un gaz

## Optimisation de l'épaisseur



Aimants permanents



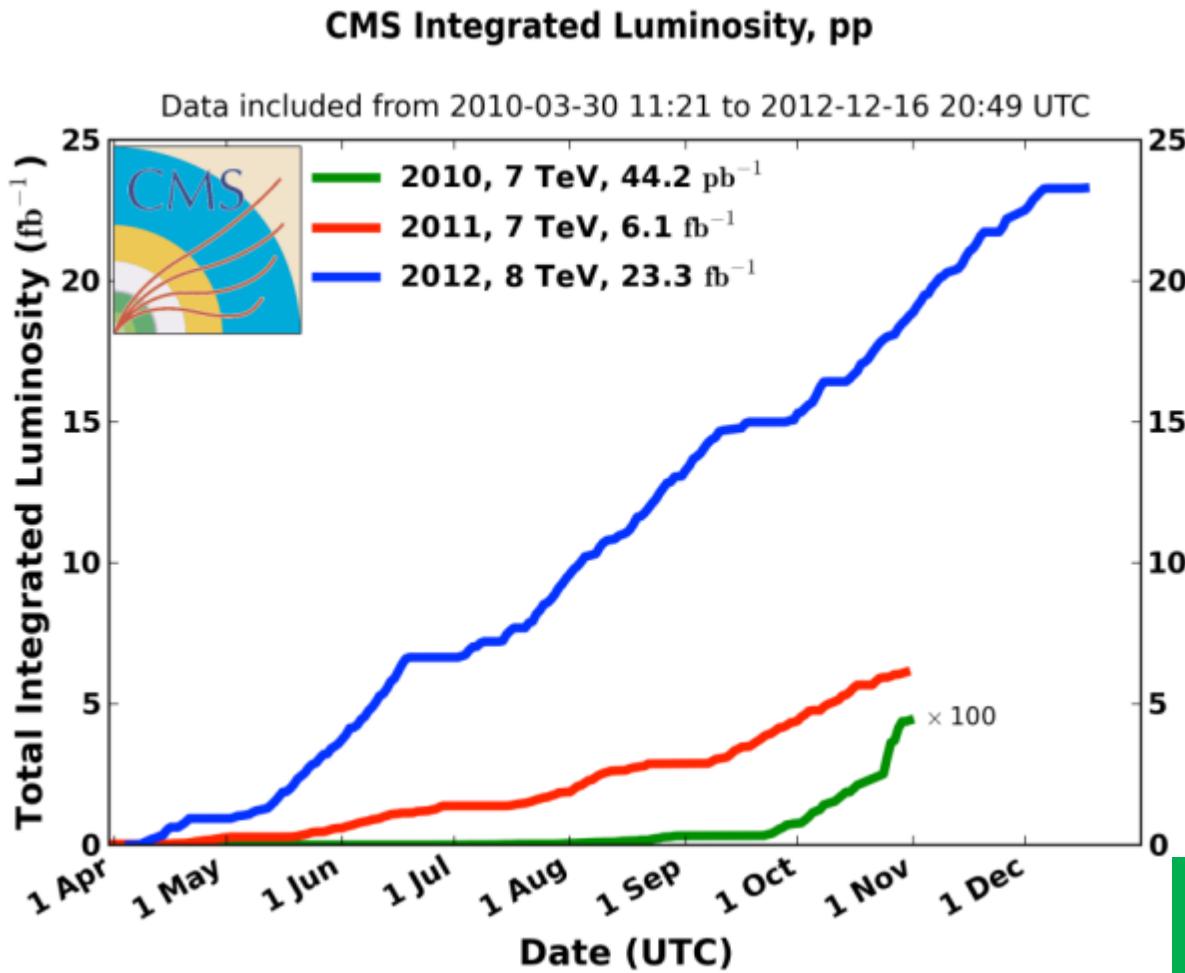
## Coupe de la pompe complète

## Pompe Ionique (premier prototype)

## Tests de qualification



# LHC 2010-2012: a rich harvest of collisions



$\Sigma \sim 30 \text{ fb}^{-1}$   
 $\sim 2 \cdot 10^{15}$  collisions

2010: **0.04 fb<sup>-1</sup>**  
7 TeV CoM  
Commissioning

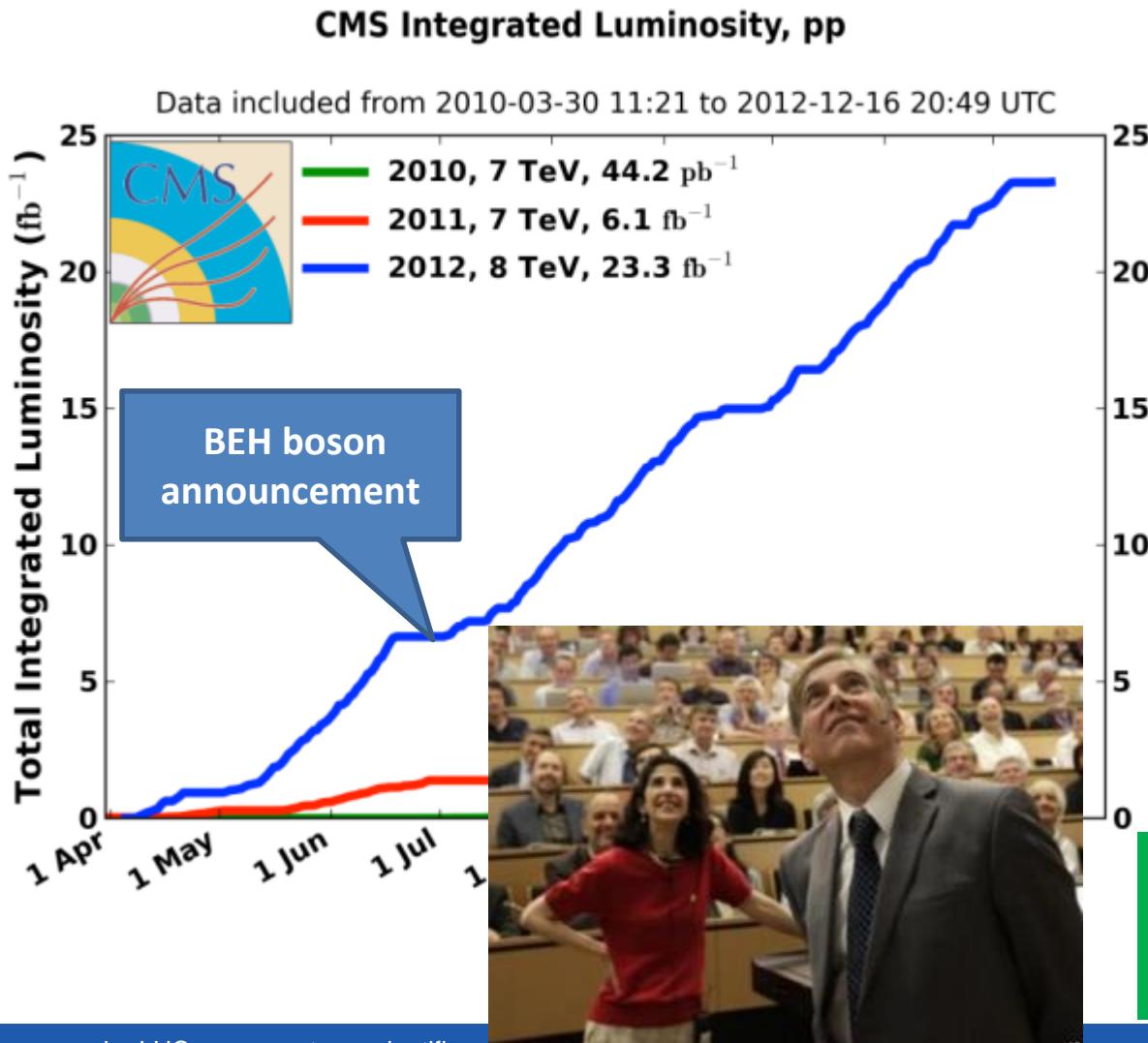
2011: **6.1 fb<sup>-1</sup>**  
7 TeV CoM  
... exploring limits

2012: **23.3 fb<sup>-1</sup>**  
8 TeV CoM  
... production

7 TeV and 8 TeV in 2012  
Up to 1380 bunches  
with  $1.5 \cdot 10^{11}$  protons



# LHC 2010-2012: a rich harvest of collisions



# Discovery 2012, Nobel Prize in Physics 2013



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*.

# From individual theoretical physicist idea....

# ...to collective innovation !

VOLUME 13, NUMBER 16

PHYSICAL REVIEW LETTERS

19 OCTOBER 1964

## BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland  
(Received 31 August 1964)

In a recent note<sup>1</sup> it was shown that the Goldstone theorem,<sup>2</sup>

about the "vacuum" solution  $\varphi_1(x) = 0, \varphi_2(x) = \varphi_0;$

theories in which symmetry under a conserved current group are purpose of the particle as a consequence quantum mechanics of the longitudinal particles (which were zero) go over in coupling tends to the relativistic, which An that the scalar  $\varphi$  conducting neutral plasmon mode is charged.

The simplest theory is a gauge theory used by Goldstone fields  $\varphi_1, \varphi_2$  and through the Lag.

$$L = -\frac{1}{2}(\nabla^\mu \varphi_i)^2$$

where

$$\nabla_\mu$$

$$\nabla_\mu$$

$$F$$

$e$  is a dimension metric is taken simultaneously on  $\varphi_1 \pm i\varphi_2$ . Let us suppose spontaneous breaking. Consider the equations of motion for  $\Delta\varphi_1, \Delta\varphi_2$  governing the pa-

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## BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS\*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction<sup>1</sup>; by a gauge vector meson we mean a Yang-Mills field<sup>2</sup> associated with the extension of a Lie group from global to local symmetry.

The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.<sup>3</sup> In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.<sup>4,5</sup> A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.<sup>6,8</sup> We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons  $\varphi_A$  which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local  $\gamma_5$ -phase transformations. In this model the gauge fields themselves may break the  $\gamma_5$  invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

(1) Let the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

The interaction between the  $\varphi$  and the  $A_\mu$  fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \partial_\mu \varphi - e^2 \varphi^* \varphi A_\mu A^\mu \quad (1)$$

where  $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$ . We shall break the symmetry by fixing  $\langle\varphi\rangle \neq 0$  in the vacuum, with the phase chosen for convenience such that  $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi\rangle/\sqrt{2}$ .

We shall assume that the application of the



1964

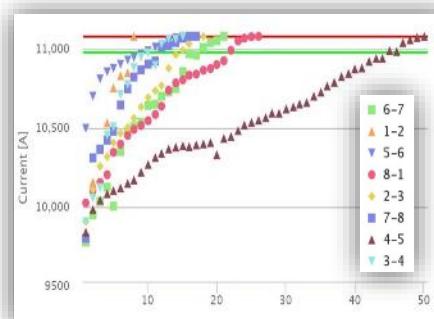
1964-2012

# 2013 - 2015

April '13 to Sep. '14



13-14 | Aug 14-Apr | 2015



Dipole training campaign

10<sup>th</sup> April  
Beam at 6.5 TeV



28<sup>th</sup> October  
Physics with record number of bunches  
Peak luminosity  $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

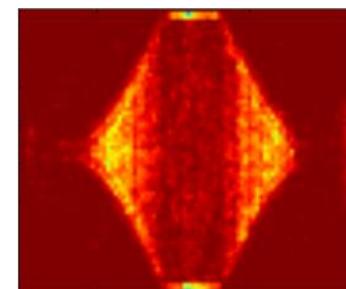
3<sup>rd</sup> June  
First Stable Beams



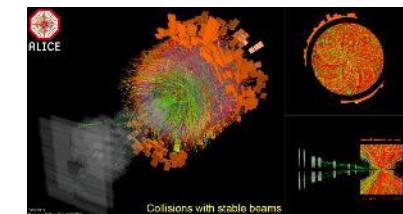
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2244

Struggle



IONS



Pb-Pb at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

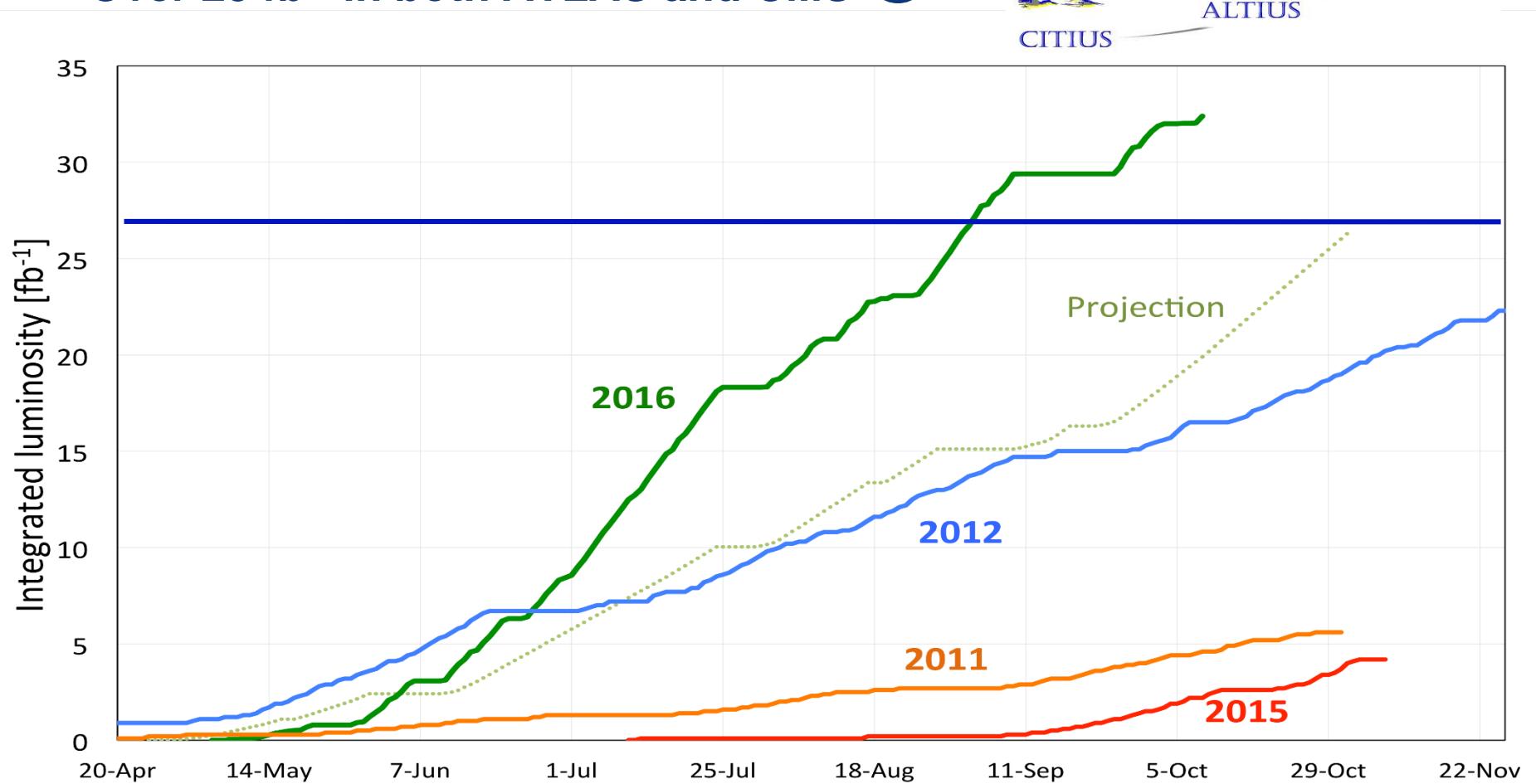
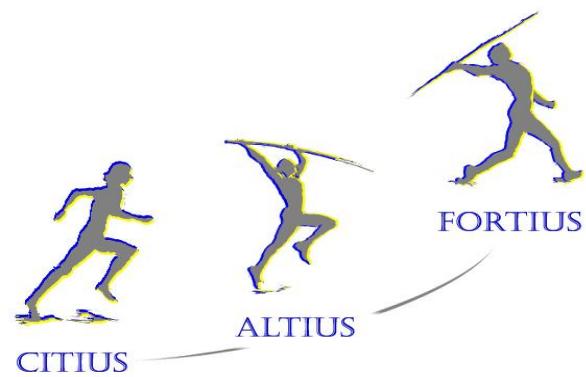


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# Conclusion: 2016 goals

Peak luminosity  $> 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Over 25  $\text{fb}^{-1}$  in both ATLAS and CMS 😊





# The European Strategy for Particle Physics

## Update 2013

*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.*

**HL-LHC from a study to a PROJECT**  
 **$300 \text{ fb}^{-1} \rightarrow 3000 \text{ fb}^{-1}$**

**including LHC injectors upgrade LIU**  
**(Linac 4, Booster 2GeV, PS and SPS upgrade)**



# Strategic Plan for U.S. Particle Physics

Particle Physics Project Prioritization Panel (P5) – May 2014



## Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle  
Physics Project  
Prioritization Panel (P5)



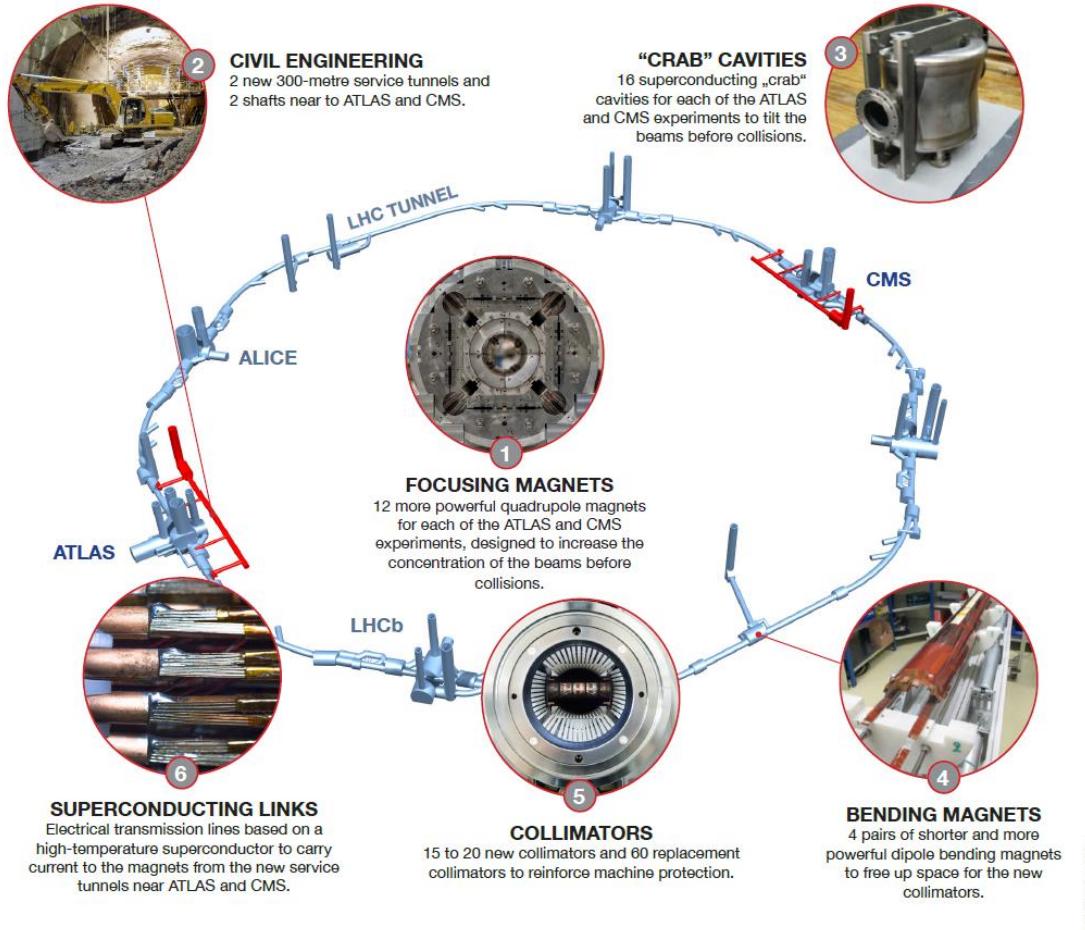
### Near-term & Mid-term High-energy Colliders

#### LARGE HADRON COLLIDER

- The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.
- *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.*



# The HL-LHC Project



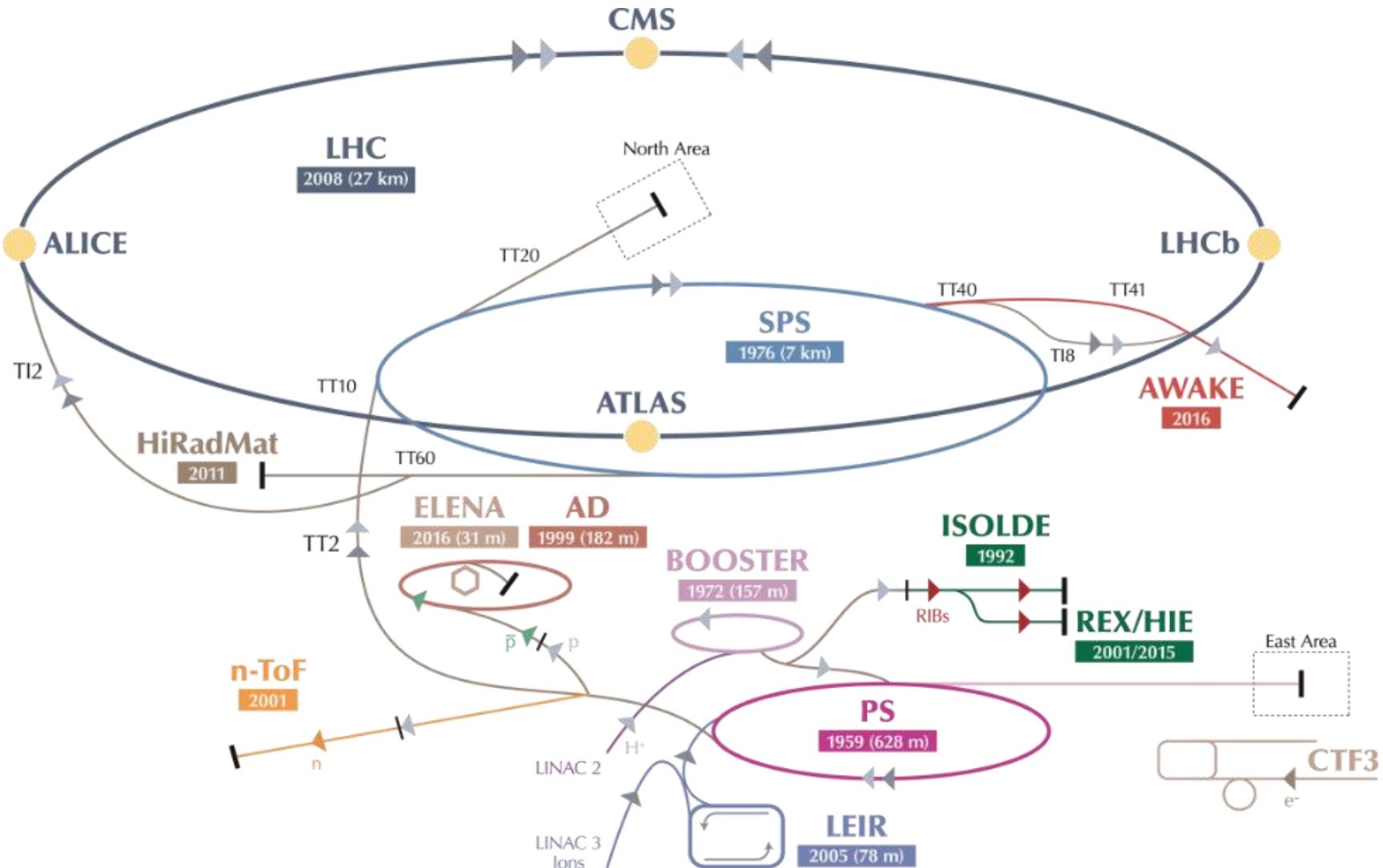
- **New IR-quads  $\text{Nb}_3\text{Sn}$  (inner triplets)**
- **New 11 T  $\text{Nb}_3\text{Sn}$  (short) dipoles**
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

CERN November 2015

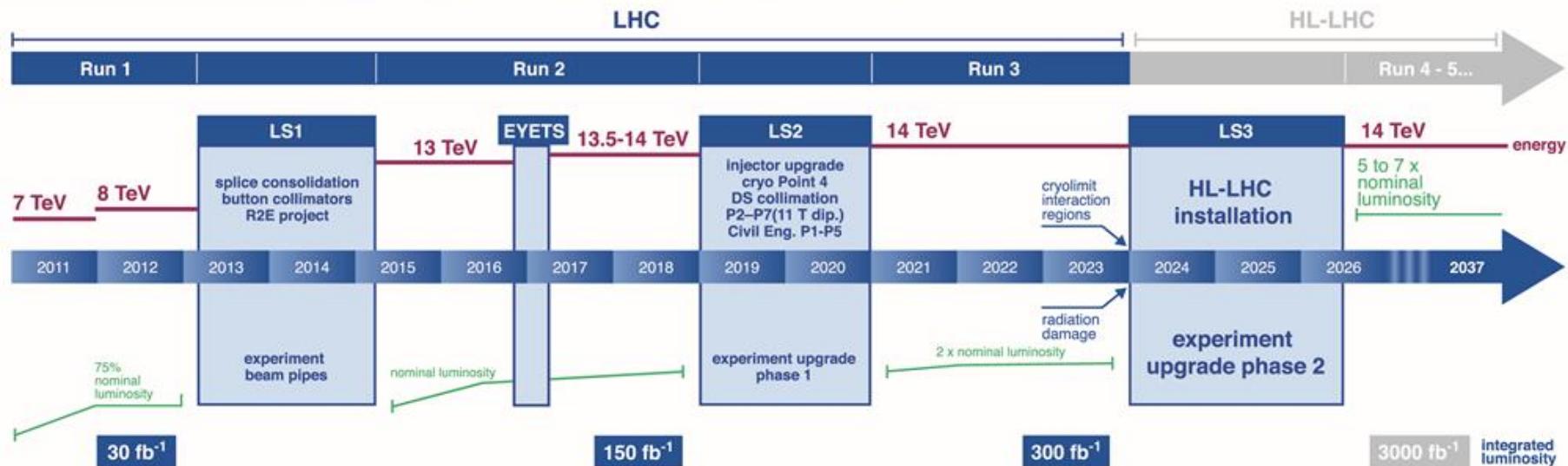
## Major intervention on more than 1.2 km of the LHC



# The CERN accelerator complex



# LHC / HL-LHC Plan



## HL-LHC Plan



High  
Luminosity  
LHC



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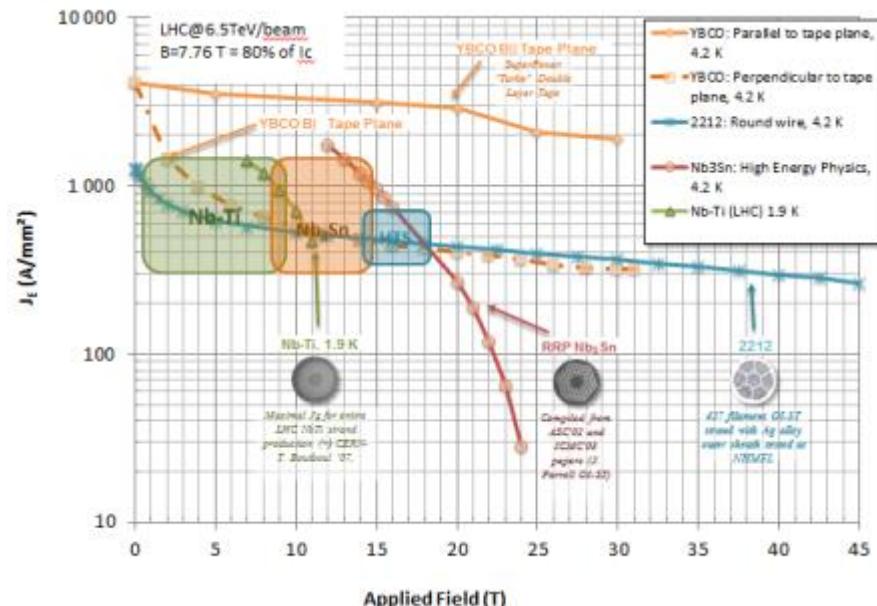


“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”

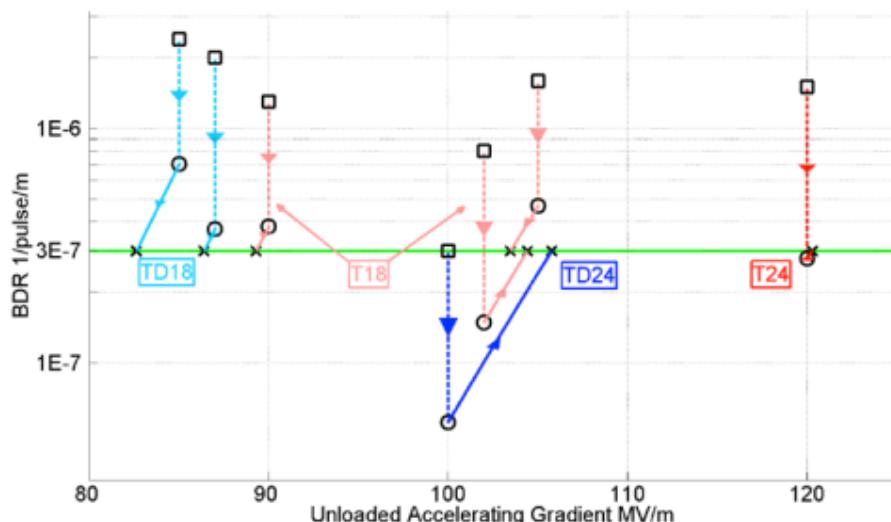
**d) CERN should undertake design studies for accelerator projects in a global context,**

*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.*

## HFM – FCC-hh



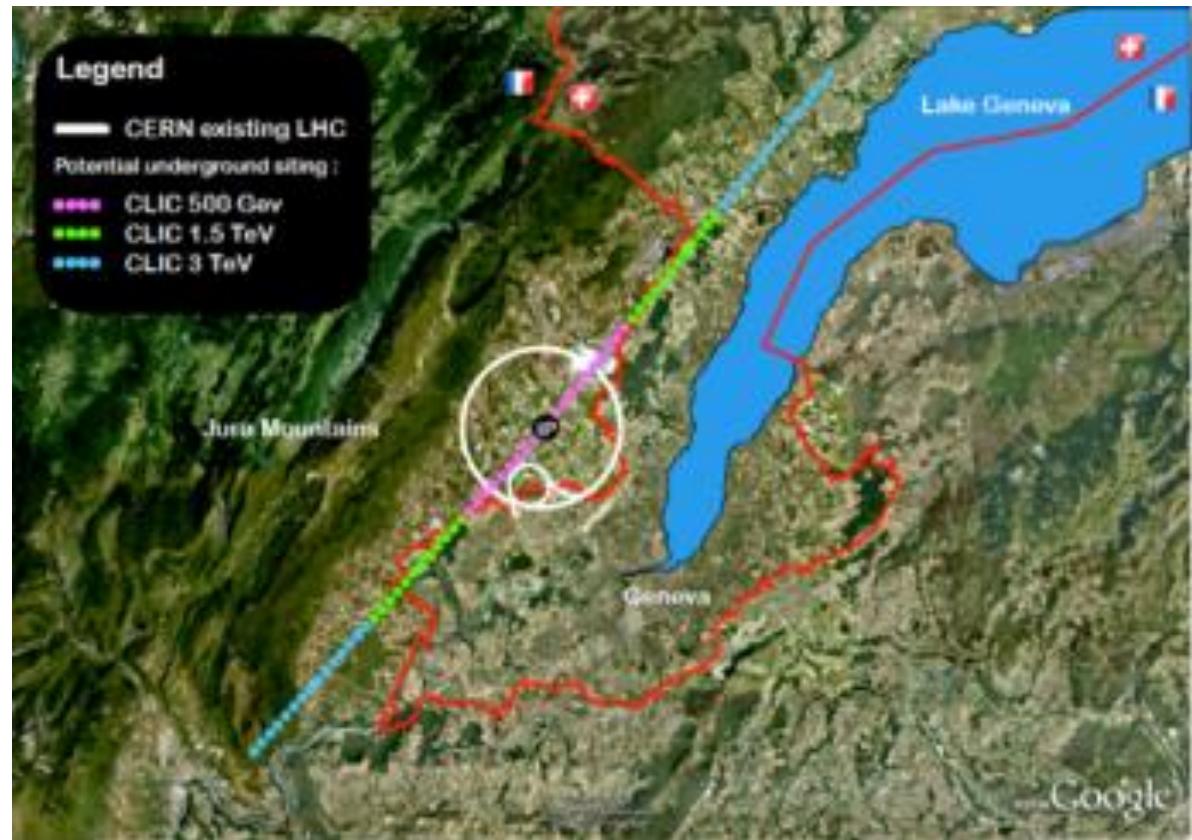
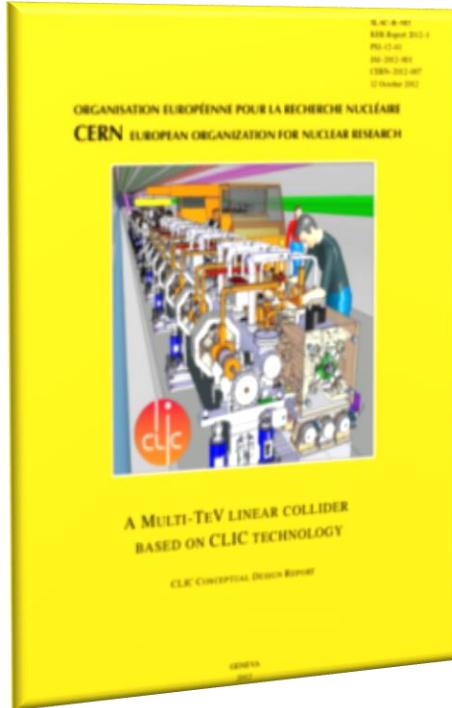
## HGA



And also R&D on Proton-Driven Plasma Wakefield Acceleration (AWAKE Expt at CERN)



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



Highest possible energy  $e^+e^-$   
with CLIC (CDR 2012)  
Multi-lateral collaboration

## Chassis d'acquisition local, préamplification BPMs.

► **Première version: 2006-2009,**

Acquisition des **50 BPMs** inductifs de CTF3.  
12 châssis, budget total ~**150K€**.

**Lecture des faisceaux de 2008 et 2009,**



► **Deuxième version: 2010-2014.** Collaboration avec CERN-CO.

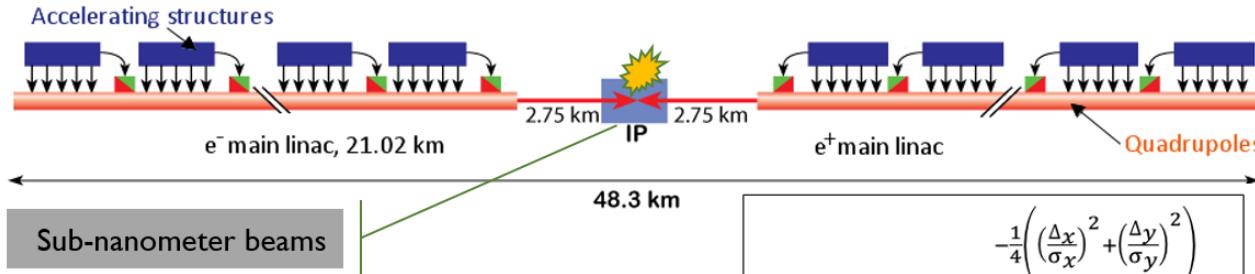
Acquisition BPM stripline & lien optique unique synchrone et déterministe.  
Budget ~**10k€/an.**

**Actuellement en acquisition du faisceau.  
Système intégré au framework du CERN.**



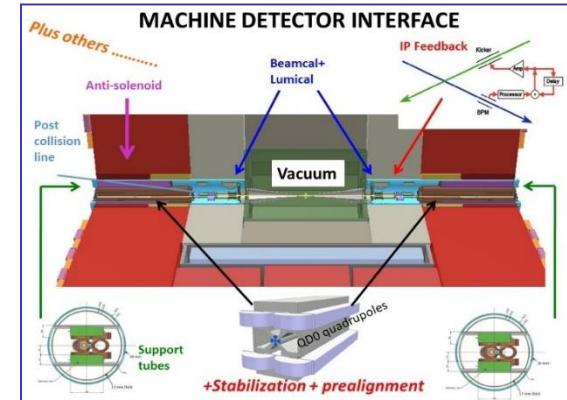
→ **Moyenne de 2,2 FTE.**

→ **R&D électronique valorisée sur ATLAS ITK. Gain ~1 an.**



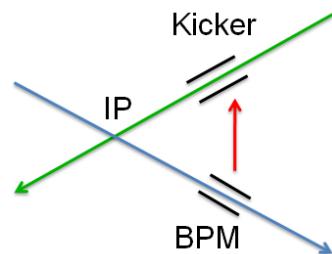
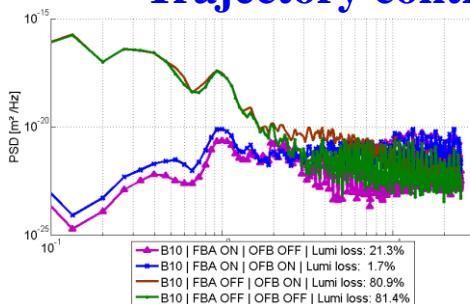
**Spéc. : 0,2 nm RMS @ 0,1Hz**

$$L(\sigma_{x,y}, \Delta_{x,y}) \sim \frac{e^{-\frac{1}{4} \left( \left( \frac{\Delta_x}{\sigma_x} \right)^2 + \left( \frac{\Delta_y}{\sigma_y} \right)^2 \right)}}{\sigma_x \sigma_y}$$



- Collaboration with many CERN teams in various fields : Linac stabilization (K. Artoos), Beam physics (D. Schulte), Magnet (M. Modena), integration (L. Gatignon), alignment (H. Mainaud Durand)...
- Academic partner of a thesis in the Innovative Doctoral Program Network named **PACMAN** (Particle Accelerator Components' Metrology and Alignment to the Nanometre scale), WP3.2, Marie Curie program at **CERN** (2014 – 2017)

## • Trajectory control of the beam:



## ➤ Simulation results (PLACET - CERN) 0,1 nm RMS @ 0,1Hz

- G. Balik (LAPP) et al, Integrated simulation of ground motion mitigation, techniques for the future compact linear collider (CLIC), Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 700 (2013) 163-170.
- B. Caron, G. Balik, L. Brunetti, A. Jérémie, "Vibration control of the beam of the future linear collider", Control Engineering Practice 20 (2012) 236



# Future Circular Collider Study

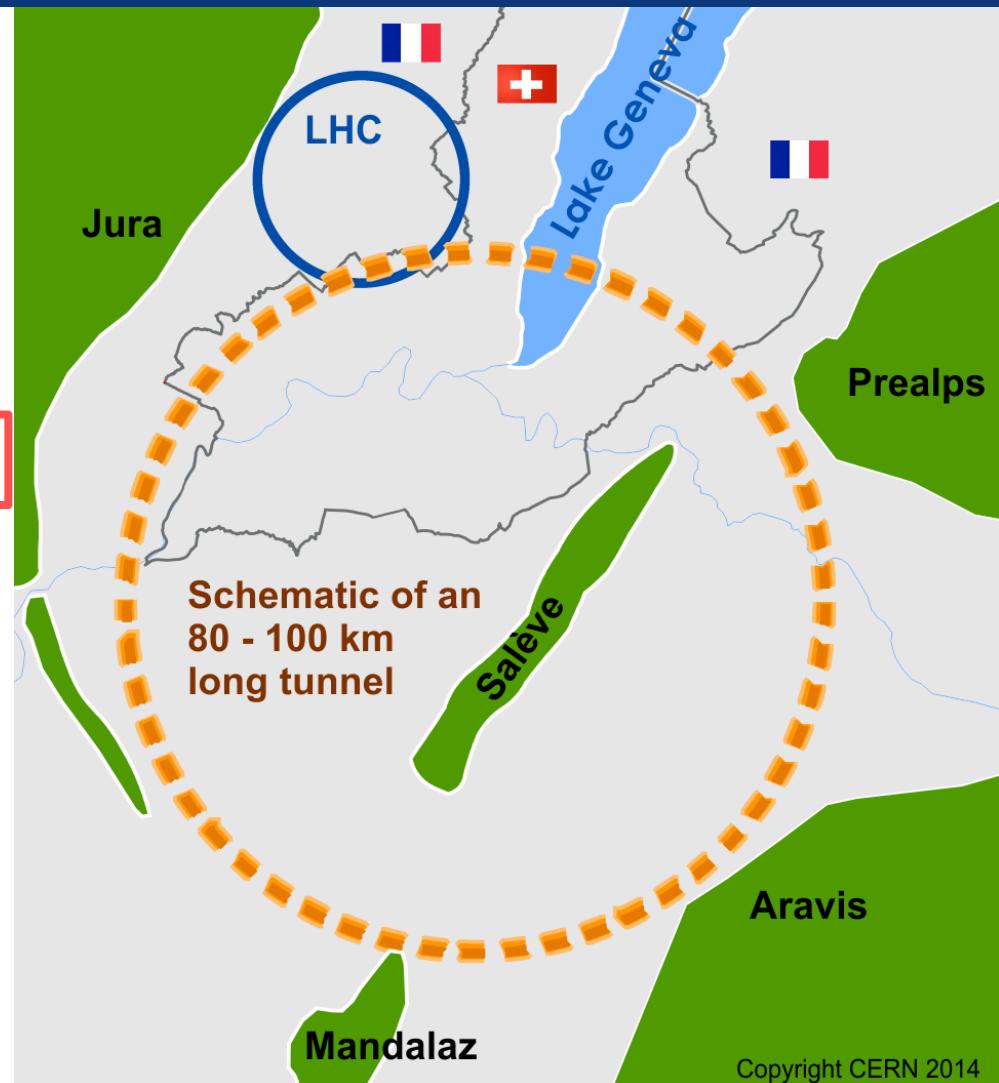
**GOAL: CDR and cost review for the next ESU (2019)**

**International FCC collaboration  
(CERN as host lab) to study:**

- **$p\bar{p}$ -collider (*FCC-hh*)**  
→ main emphasis, defining infrastructure requirements

**$\sim 16 \text{ T} \Rightarrow 100 \text{ TeV } p\bar{p} \text{ in } 100 \text{ km}$**

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **$e^+e^-$  collider (*FCC-ee*),** as potential first step
- **$p-e$  (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC with *FCC-hh* technology**



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# Collaboration Status (Sept. 2016)

- 88 Institutes (research centers & universities)
- European Commission
- 28 countries

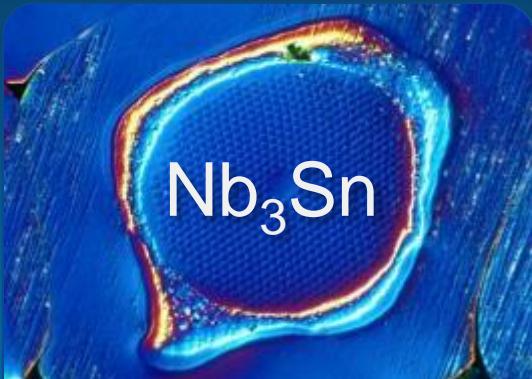




# Push Technologies



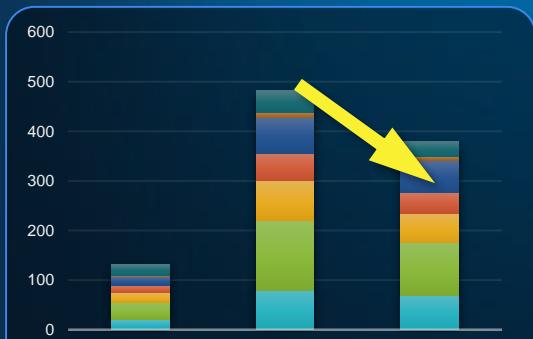
High-field  
Magnets



Nb<sub>3</sub>Sn  
Novel Materials  
and Processes



Large-scale  
Cryogenics



Power Efficiency



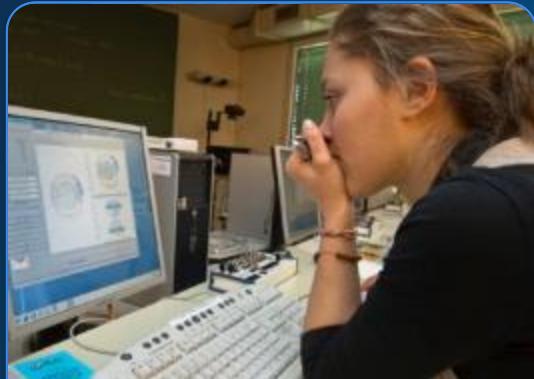
Repair  
&  
Maintenance  
Reliability &  
Availability



Global Scale  
Computing



# Strengthen Europe and the region



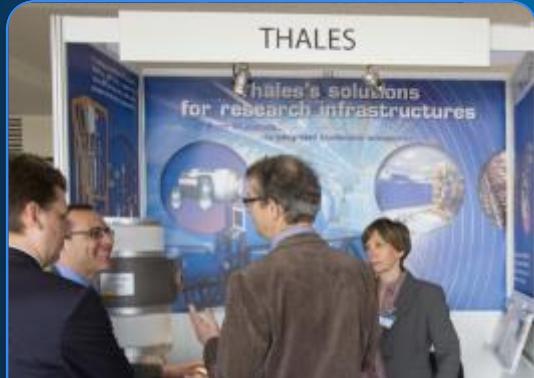
In-field training



Higher Education



Visibility for  
National Institutes



Showcases for  
leading industries



Opportunities for  
SMEs



Focus of world-  
wide research



1976 - 2016



Happy birthday  
Long life to LAPP

"La fonction la plus élémentaire de l'être humain,  
c'est de créer de l'avenir"

*Paul Valéry*

