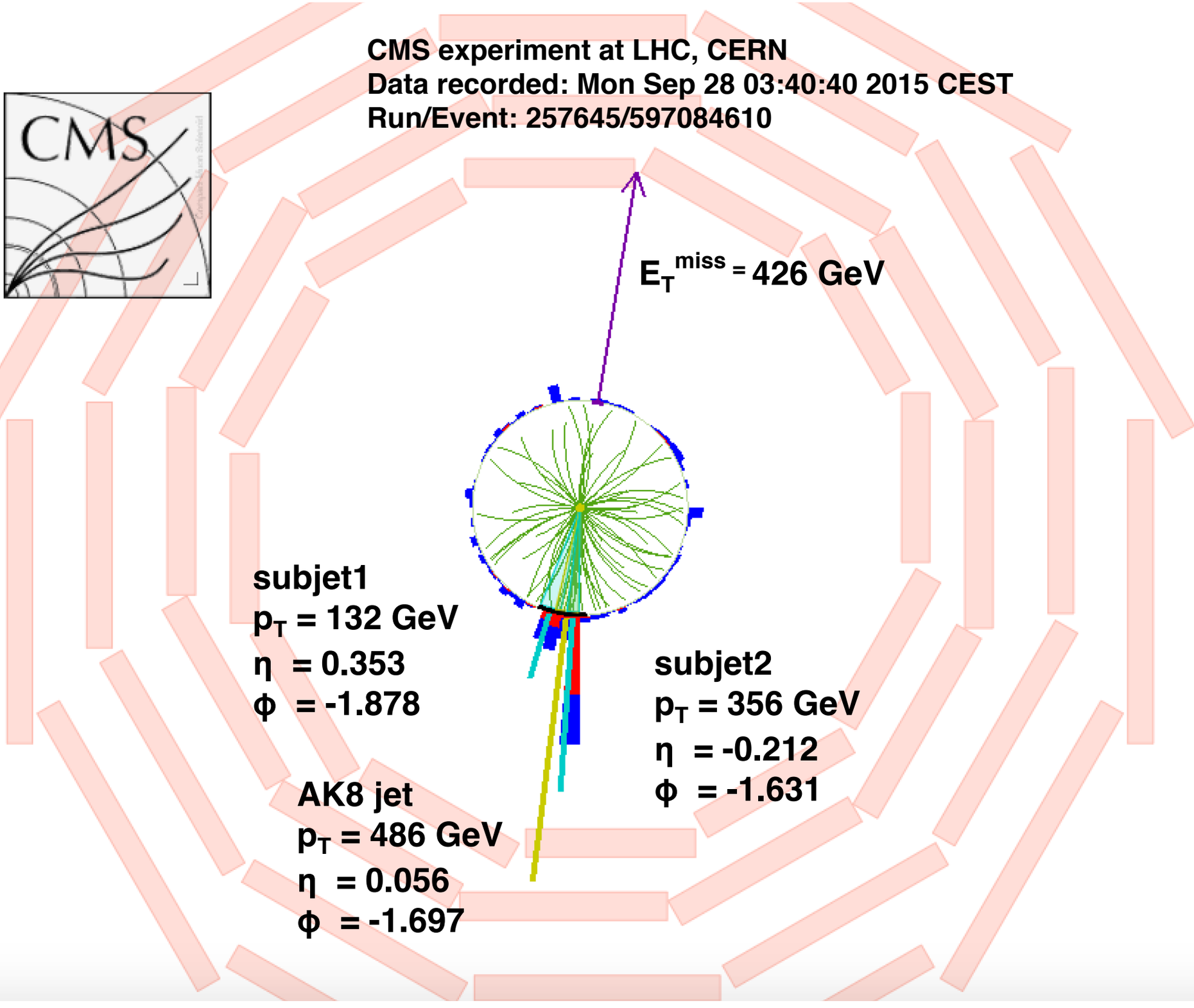
Experimental Methods and Physics at the LHC

Shin-Shan Eiko Yu

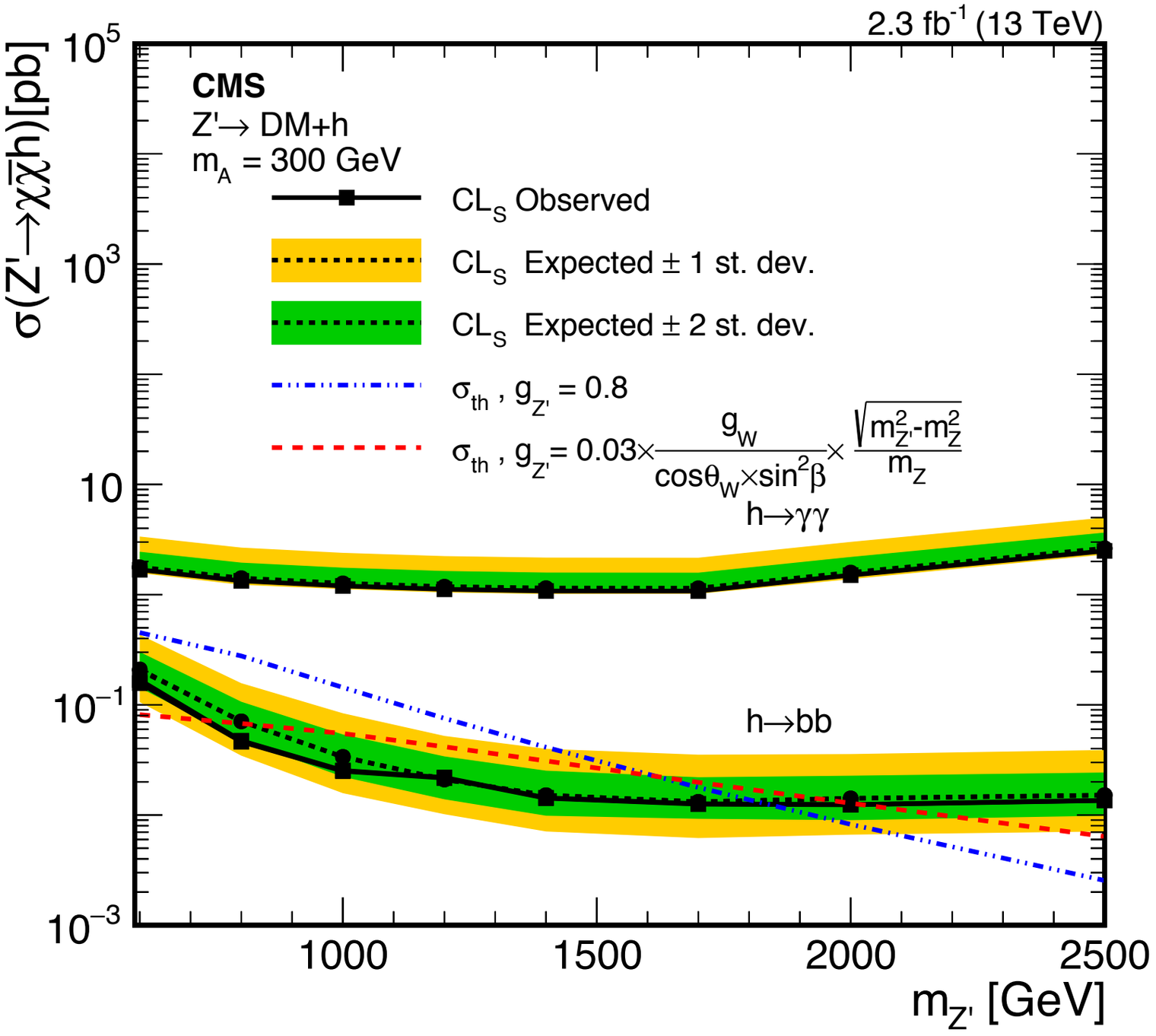
Department of Physics, National Central University, Taiwan

24th Vietnam School of Physics: Particles and Cosmology

Namely, How You Transform



Into the Following Figure



From the Beginning to the End

Collider
pp or NN collisions

Detector and Trigger

Reconstruction of basic objects:
track, γ, e, μ, τ, jet, b-jet, missing E_T

Combining objects and perform physics analysis

Outline of the Experimental Lectures

- Introduction to CERN and LHC experiments
- Detectors
- First measurements with run 1 data
- Jet and jet-related measurements
- Jet substructures and related searches
- LHC dark matter searches

Disclaimers

- Experimental techniques is a huge topic and I will not cover everything
- 50% pictures are taken from other talks (either mine or others')
  - Biased towards CMS
  - Please forgive repetition of things you may have seen before

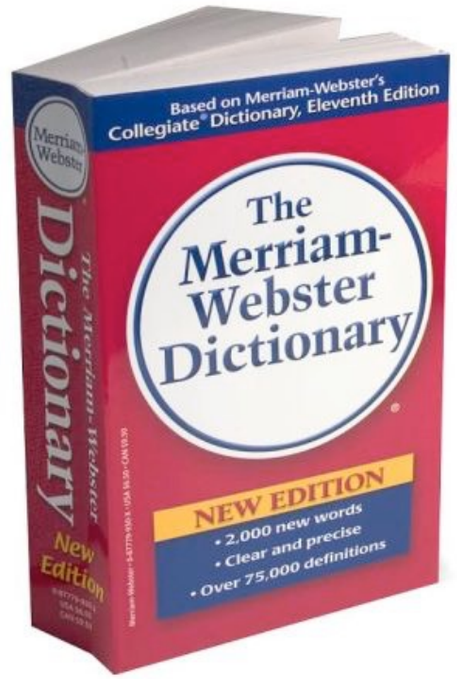
Useful Links for Your Own Study

- Lectures for CERN summer students
  - https://indico.cern.ch/category/345/
- CERN/Fermilab hadron collider summer schools
  - http://hcpss.web.cern.ch/hcpss/
- SLAC summer institute
  - https://www-conf.slac.stanford.edu/ssi/
- TASI
  - https://physicslearning.colorado.edu/tasi/

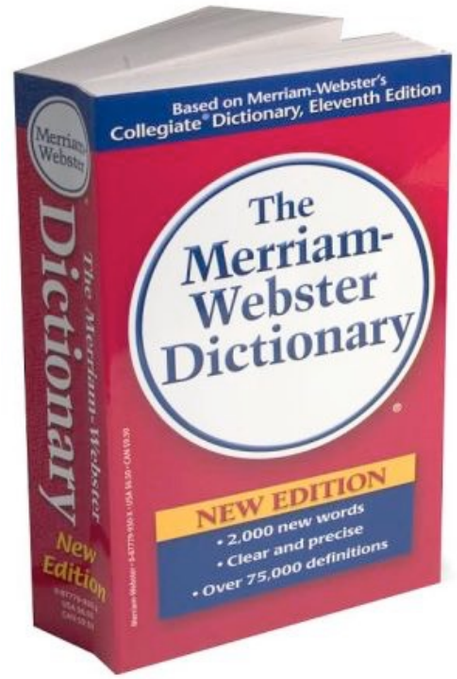
Outline of Lecture Part I

- Introduction to CERN and LHC
- Brief story of the four experiments
- Introduction to sub-detectors
  - Trackers
  - Muon system
  - Calorimeters
- Brief story of the trigger

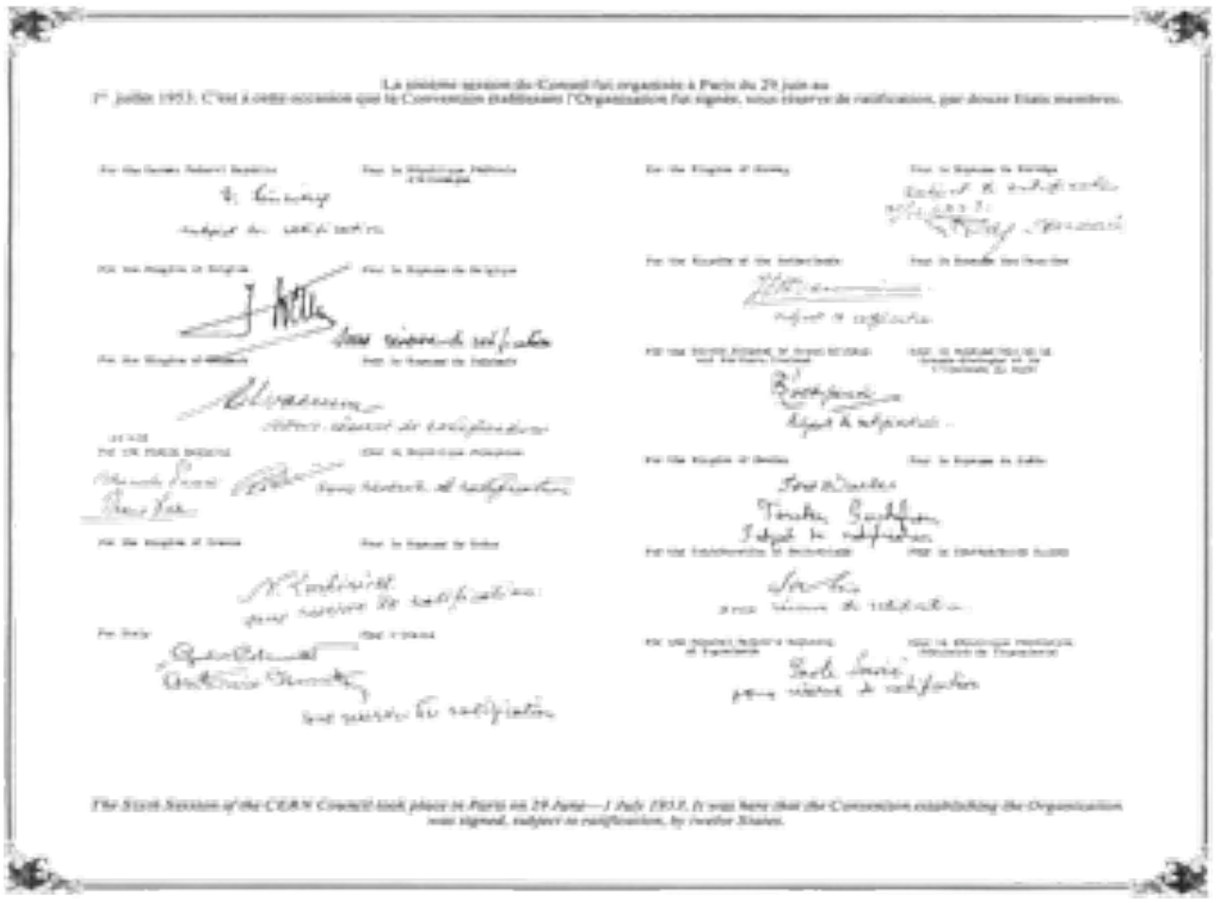
Introduction to CERN and LHC


Based on Merriam-Webster's
Collegiate® Dictionary, Eleventh Edition
The Merriam-Webster Dictionary
NEW EDITION
• 2,000 new words
• Clear and precise
• Over 75,000 definitions
The Merriam-Webster Dictionary
New Edition

- **CERN**
  - Conseil Européen pour la Recherche Nucléaire
  - European Council for Nuclear Research
  - Location of LHC and the experiments



CERN

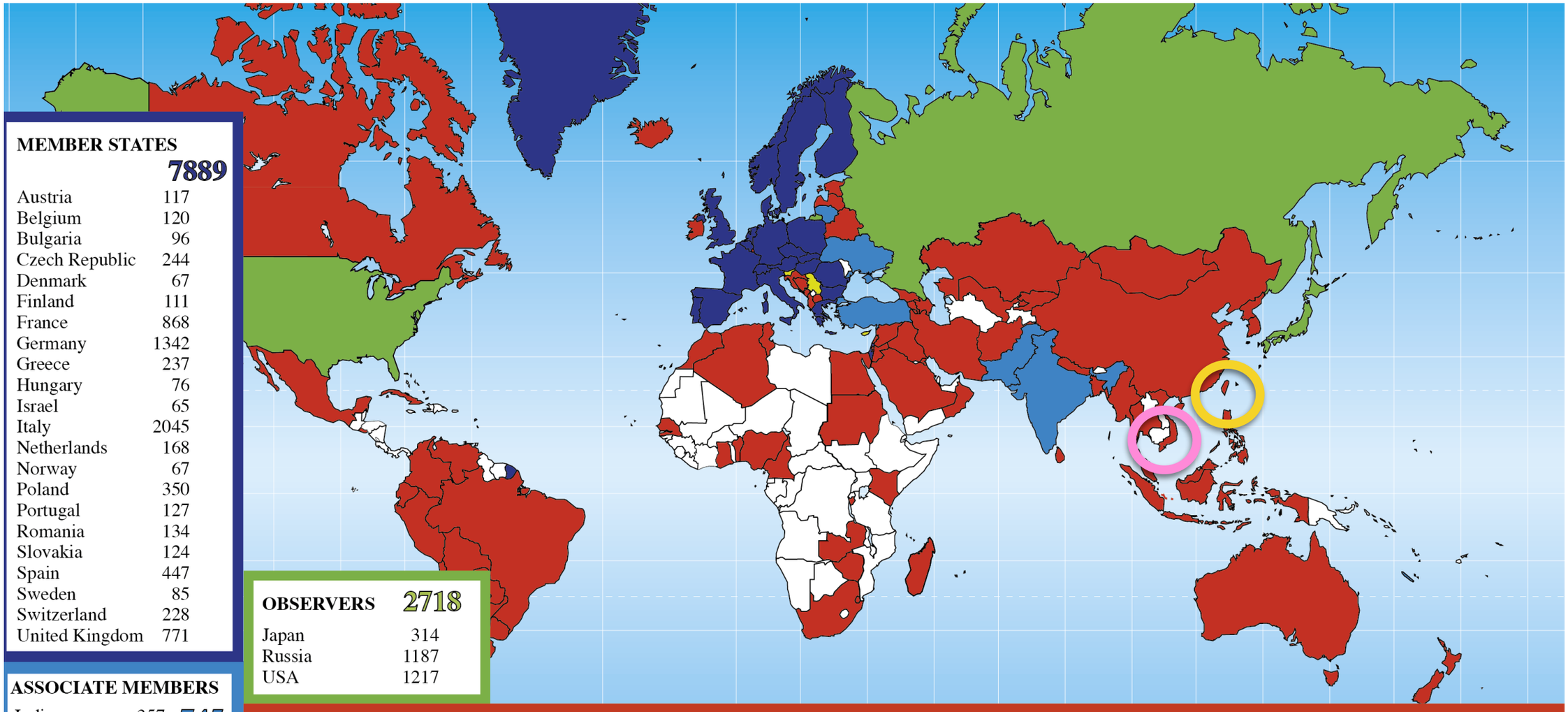


- Established by 12 European countries on 1954/09/29
- Origin of WWW
  - Tim Berners-Lee in 1989
- Director
  - Fabiola Gianotti

- 22 member states
- Yearly budget $\sim 10^9$ CHF (= 2.4×10^{13} VND)
  - Germany、UK、France、Italy
  - LHC cost ~ 4.3×10^9 CHF

Users Around the World

Distribution of All CERN Users by Nationality on 24 January 2018



MEMBER STATES **7889**

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

OBSERVERS **2718**

Japan	314
Russia	1187
USA	1217

ASSOCIATE MEMBERS **745**

India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP **118**

Cyprus	26
Serbia	57
Slovenia	35

OTHERS **1872**

Afghanistan	1	Bolivia	4	Egypt	31	Kazakhstan	5	Mongolia	2
Albania	3	Bosnia & Herzegovina	2	El Salvador	1	Kenya	3	Montenegro	11
Algeria	14	Brazil	135	Estonia	15	Korea Rep.	185	Morocco	20
Argentina	27	Burundi	1	Georgia	46	Kyrgyzstan	1	Myanmar	1
Armenia	19	Cameroon	1	Ghana	1	Latvia	2	Nepal	10
Australia	31	Canada	161	Hong Kong	1	Lebanon	23	New Zealand	5
Azerbaijan	10	Chile	20	Iceland	3	Luxembourg	2	Nigeria	3
Bangladesh	11	China	510	Indonesia	11	Madagascar	4	North Korea	1
Belarus	48	Colombia	45	Iran	51	Malaysia	15	Oman	3
Benin	1	Croatia	41	Iraq	1	Malta	9	Palestine (O.T.).	7
		Cuba	12	Ireland	16	Mauritius	1	Paraguay	2
		Ecuador	6	Jordan	1	Mexico	82	Peru	7
								Philippines	3
								Saint Kitts and Nevis	1
								Saudi Arabia	2
								Senegal	1
								Singapore	4
								South Africa	56
								Sri Lanka	6
								Sudan	1
								Swaziland	1
								Syria	1
								Taiwan	51
								Thailand	22
								T.F.Y.R.O.M.	2
								Tunisia	5
								Uruguay	1
								Uzbekistan	4
								Venezuela	10
								Viet Nam	13
								Zambia	1
								Zimbabwe	2

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  - Conseil Européen pour la Recherche Nucléaire
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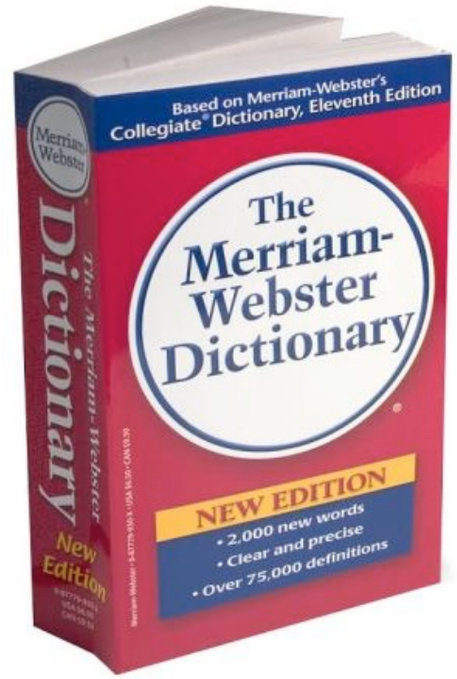
  - Location of LHC and the experiments



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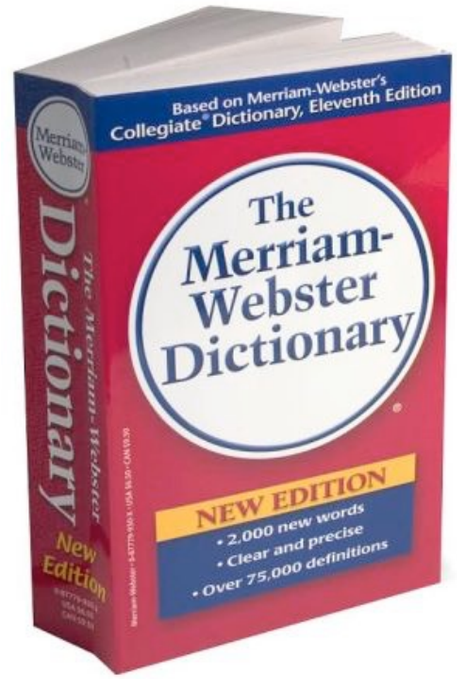

- **LHC**
  - Large Hadron Collider
  - CERN LHC guide

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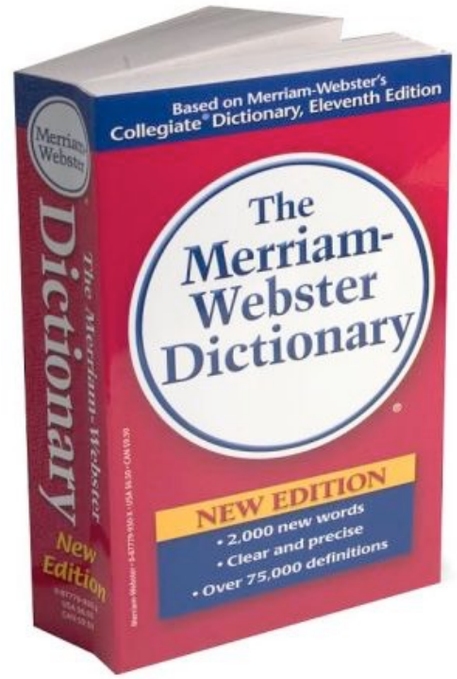

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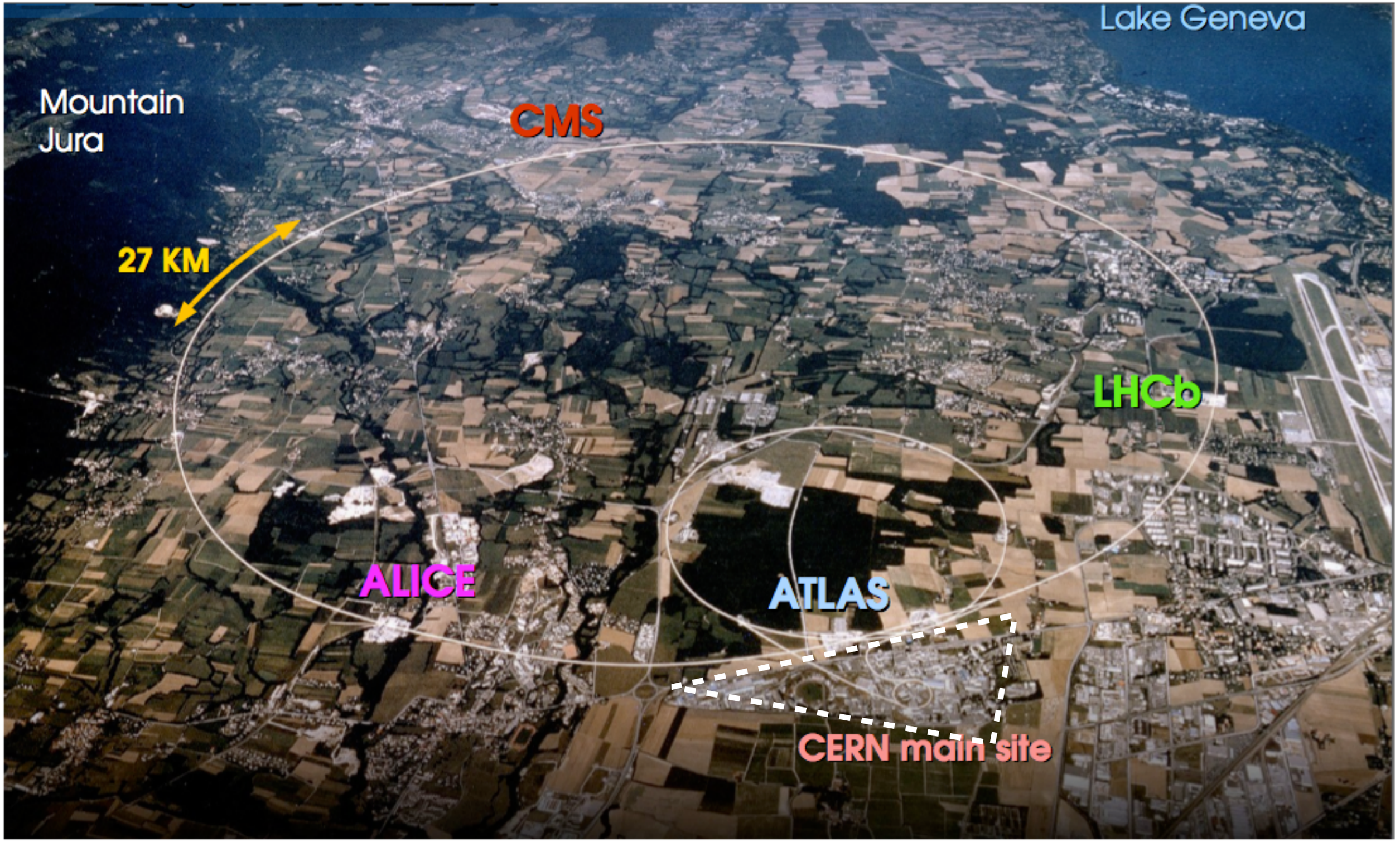
- **Hadron**
  - Bound-state of quarks (anti-quarks), such as: proton, neutron, π meson



LHC Birdview

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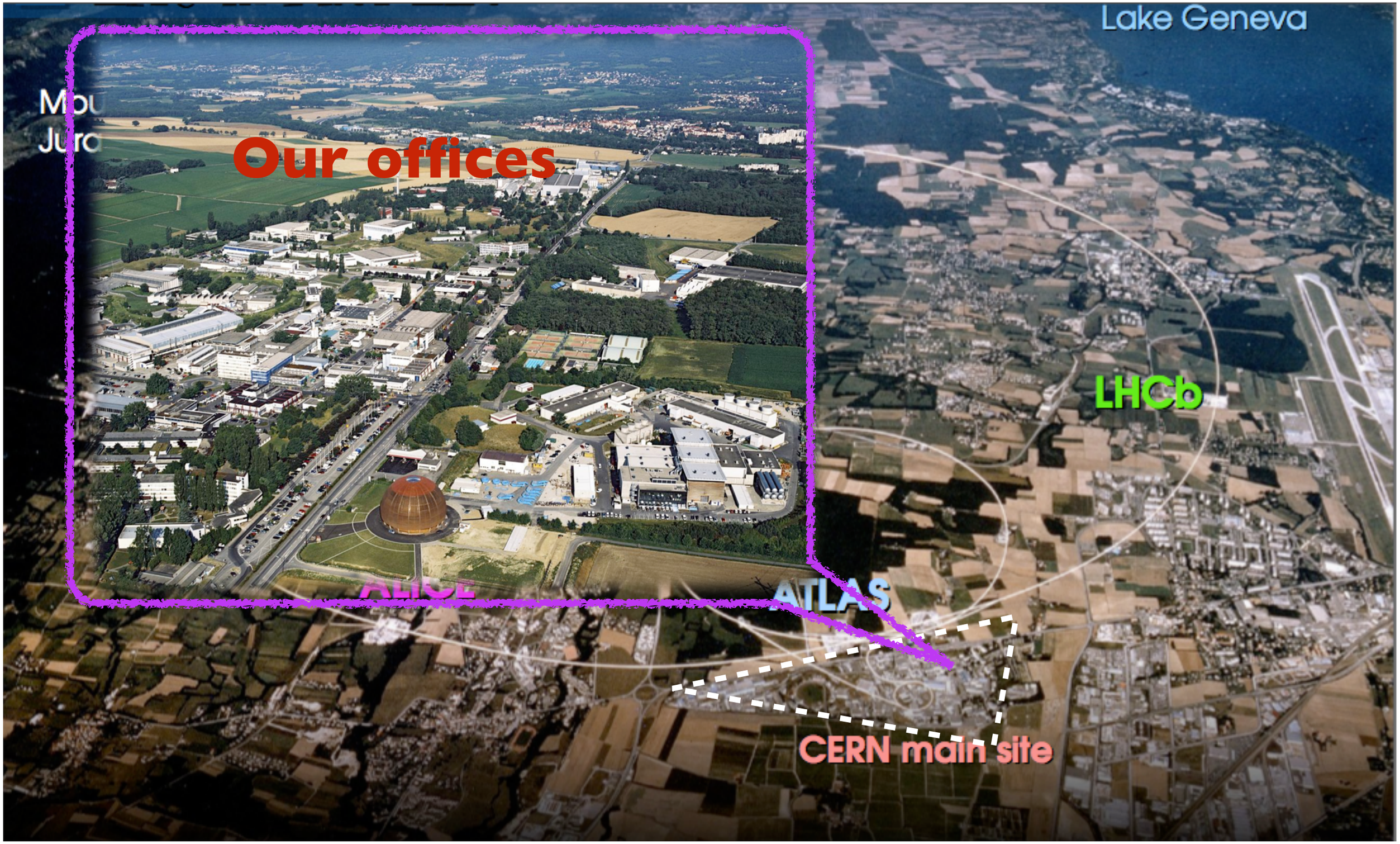
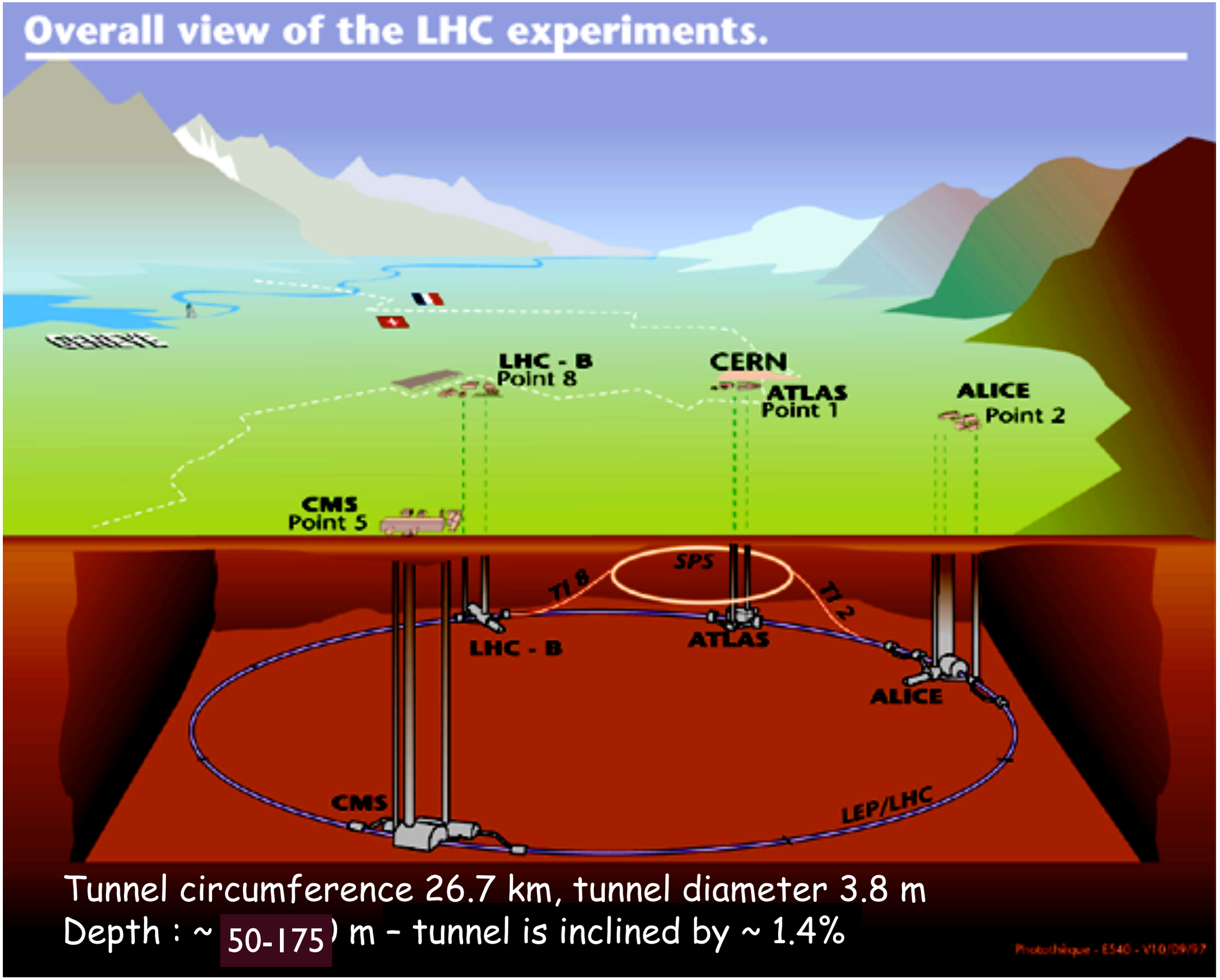


LHC Birdview


搜尋 Google 地圖
查看交通時間、路況和附近地點
Queen Beach
KHU VỰC 3
Vịnh Quy Nhơn
Đường 1D
Bãi biển Quy Hòa
GHỀNH RÁNG
QL1D
KHU VỰC 8
QL1A
Đường 1D
QL1D
Đường 1D
BÃI XÉP
KHU VỰC 1
平定
富安
衛星
Google
地圖資料 ©2018 Google
法國
使用條款
提供意見
500 公尺

Overall view of the LHC experiments.



Tunnel circumference 26.7 km, tunnel diameter 3.8 m

Depth : ~ 50-175 m – tunnel is inclined by ~ 1.4%

LHC Tunnel

Magnetic dipole field: 8.3 Tesla

Beam-pipe pressure: 10^{-13} atm

1232 superconducting dipoles

Operating temperature: 1.9 K

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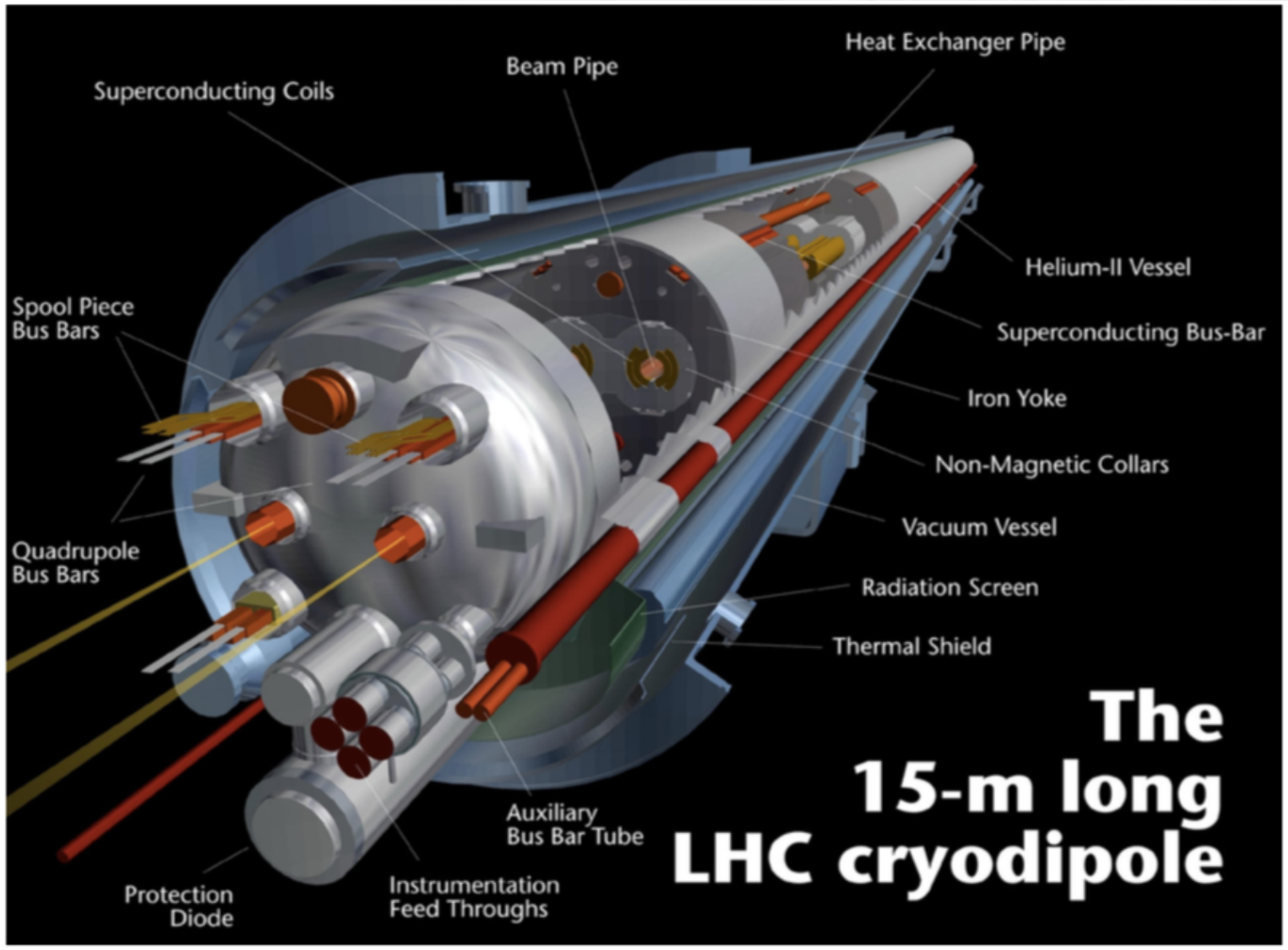

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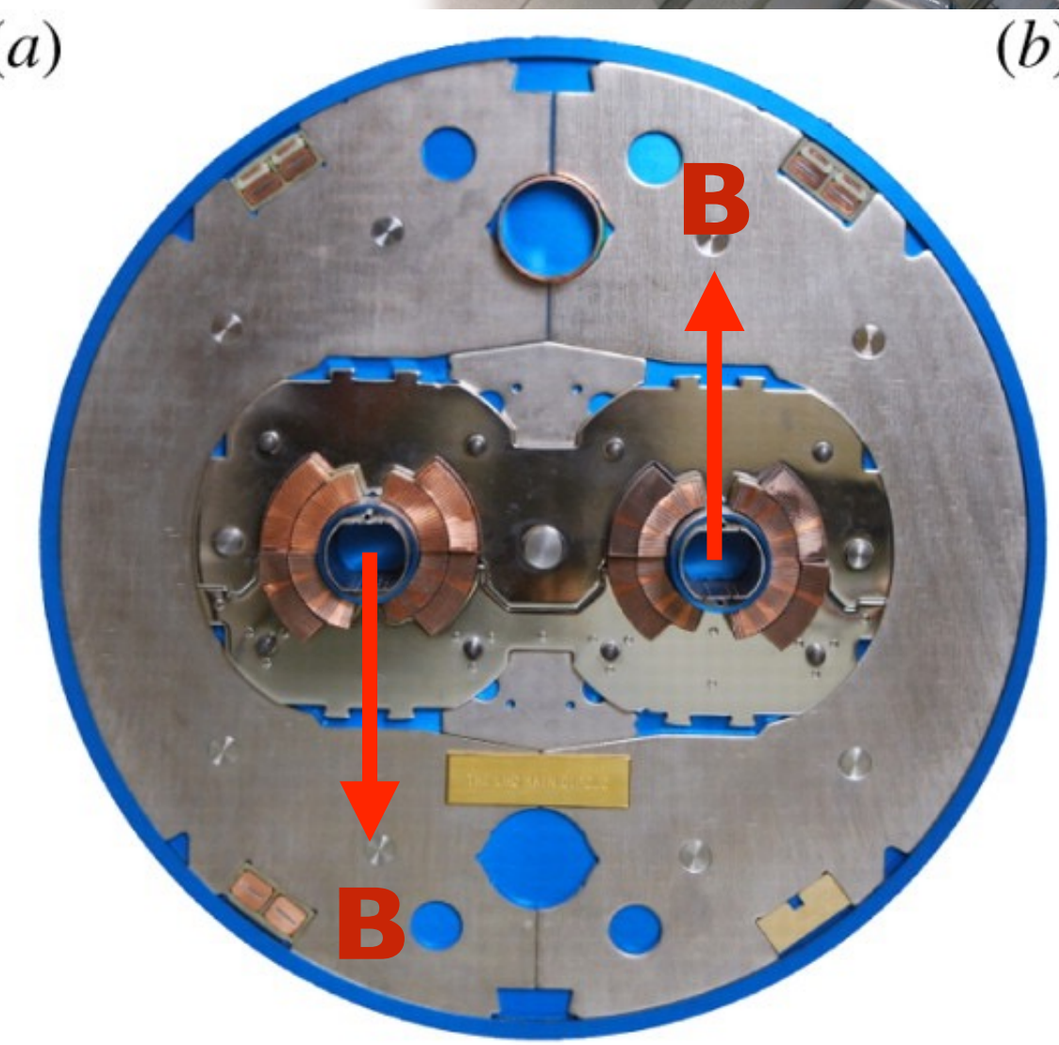

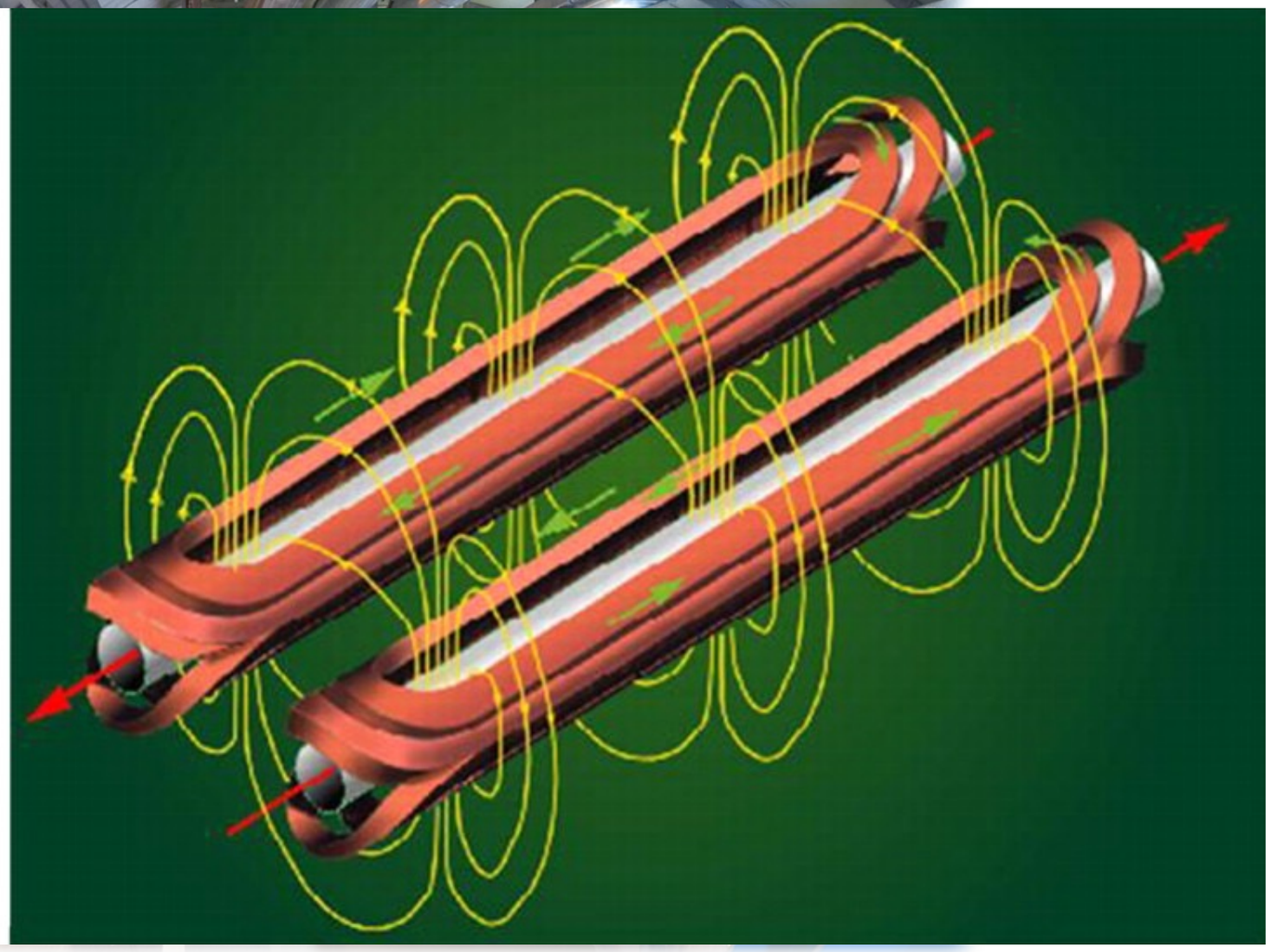

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Large Hadron Collider

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- Circular high-energy hadron collider

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- Why high energy?

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Wavelength of probe radiation needs to be smaller than object to be resolved

$$\lambda = \frac{h}{p} = \frac{h \cdot c}{E}$$

Object	size	Radiation energy
Atom	10^{-10} m	0.00001 GeV
Nucleus	10^{-14} m	0.01 GeV
Nucleon	10^{-15} m	0.1 GeV
Quarks	-	> 1 GeV

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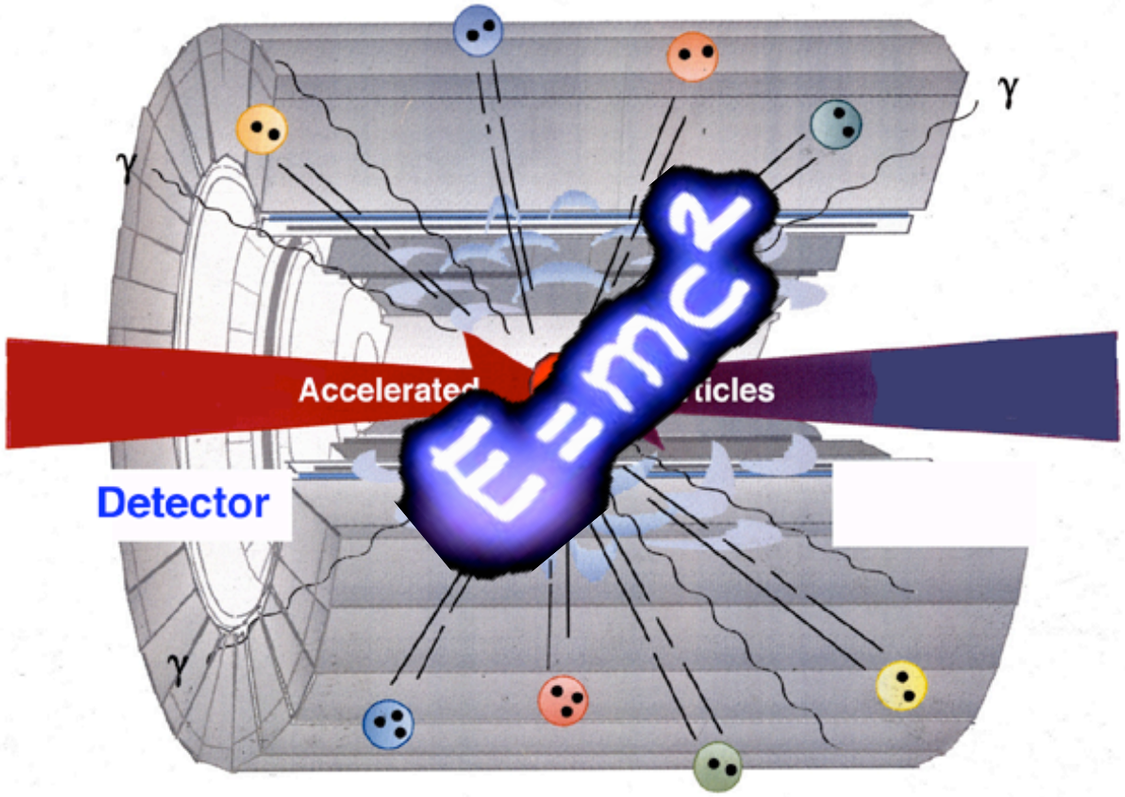

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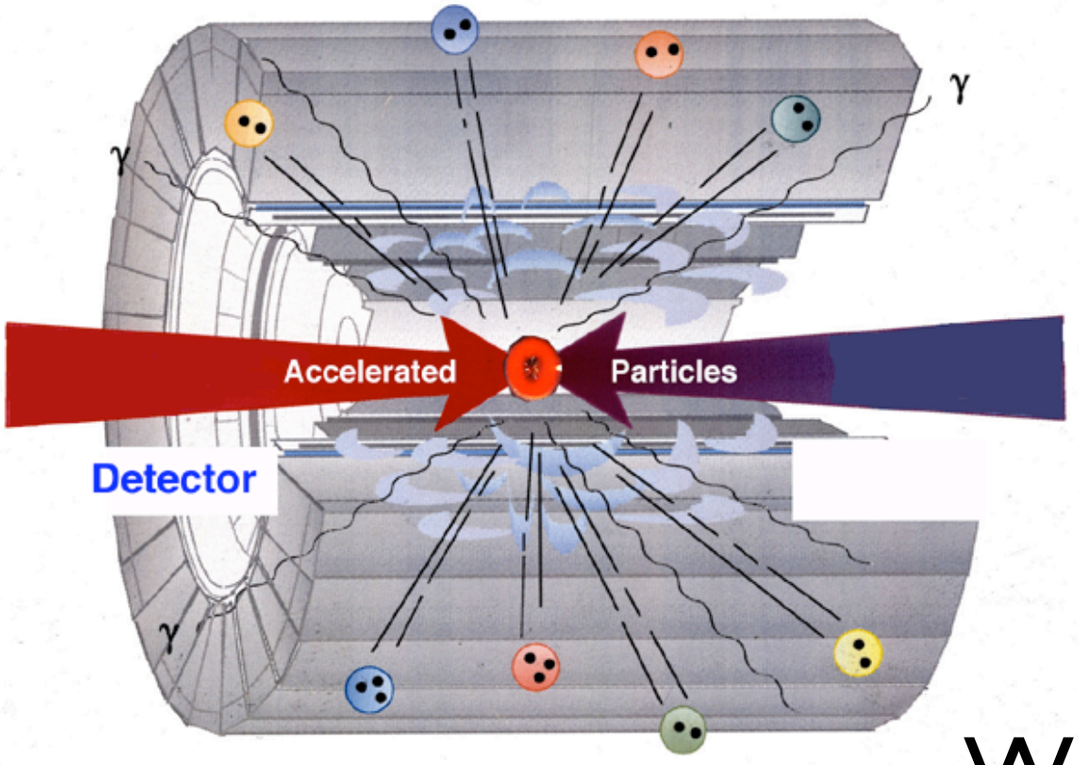
Fixed Target and Collider Experiments

- Pros: higher interaction rate
- Cons: lower available energy for producing new particles



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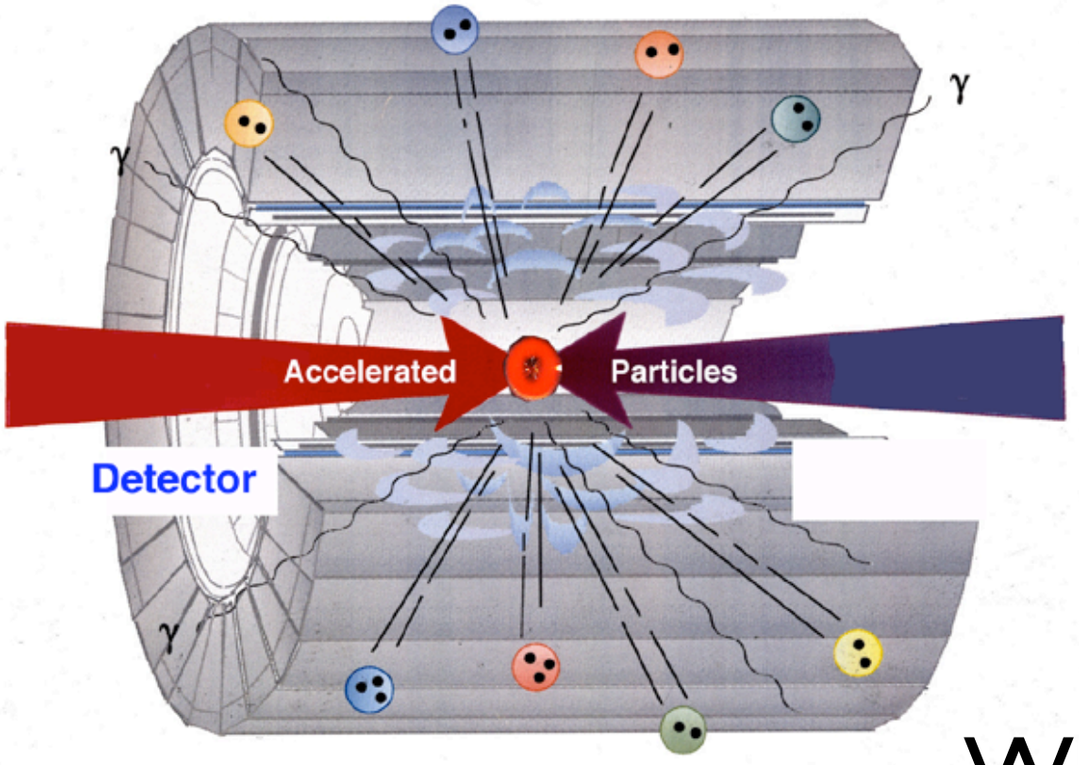
<u>Why?</u>

Fixed Target and Collider Experiments

$$E_{CM} \sim \sqrt{2 m_t E_b}$$

Assuming $E_b \gg m_t, m_b$



$$E_{CM} \sim \sqrt{4 E_1 E_2}$$

Assuming $E_1, E_2 \gg m_1, m_2$

Why?

Several Important Colliders

Large Hadron Collider (LHC)

- Circular high-energy hadron collider
- Why high energy?
- Why large?

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$$p = qBR$$

$$\frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} = qBR$$

$$\Rightarrow R = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} \times \frac{1}{qB}$$

Large Hadron Collider (LHC)

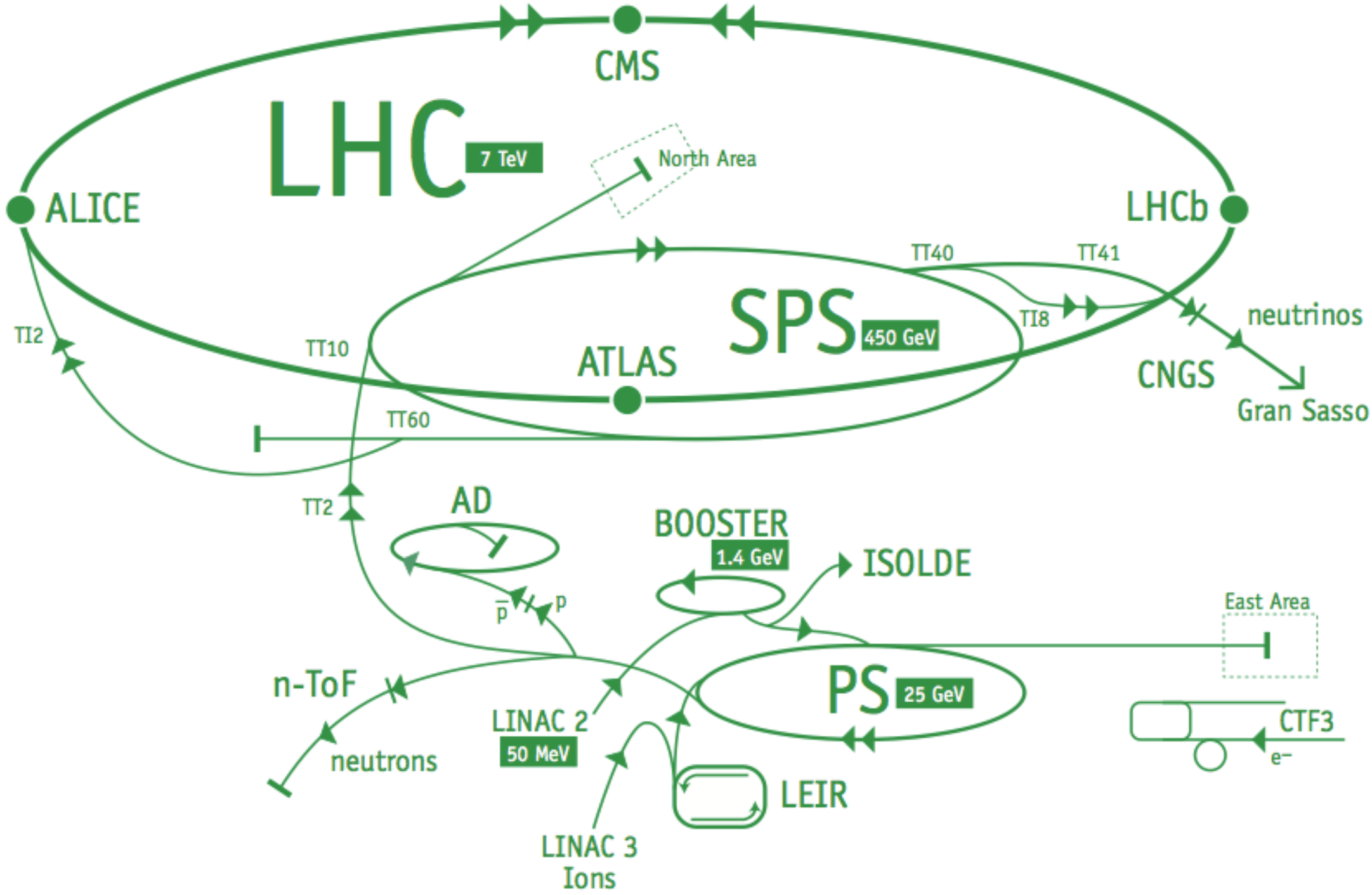
- Circular high-energy hadron collider
- Why high energy?
- Why large?

$$p = qBR$$

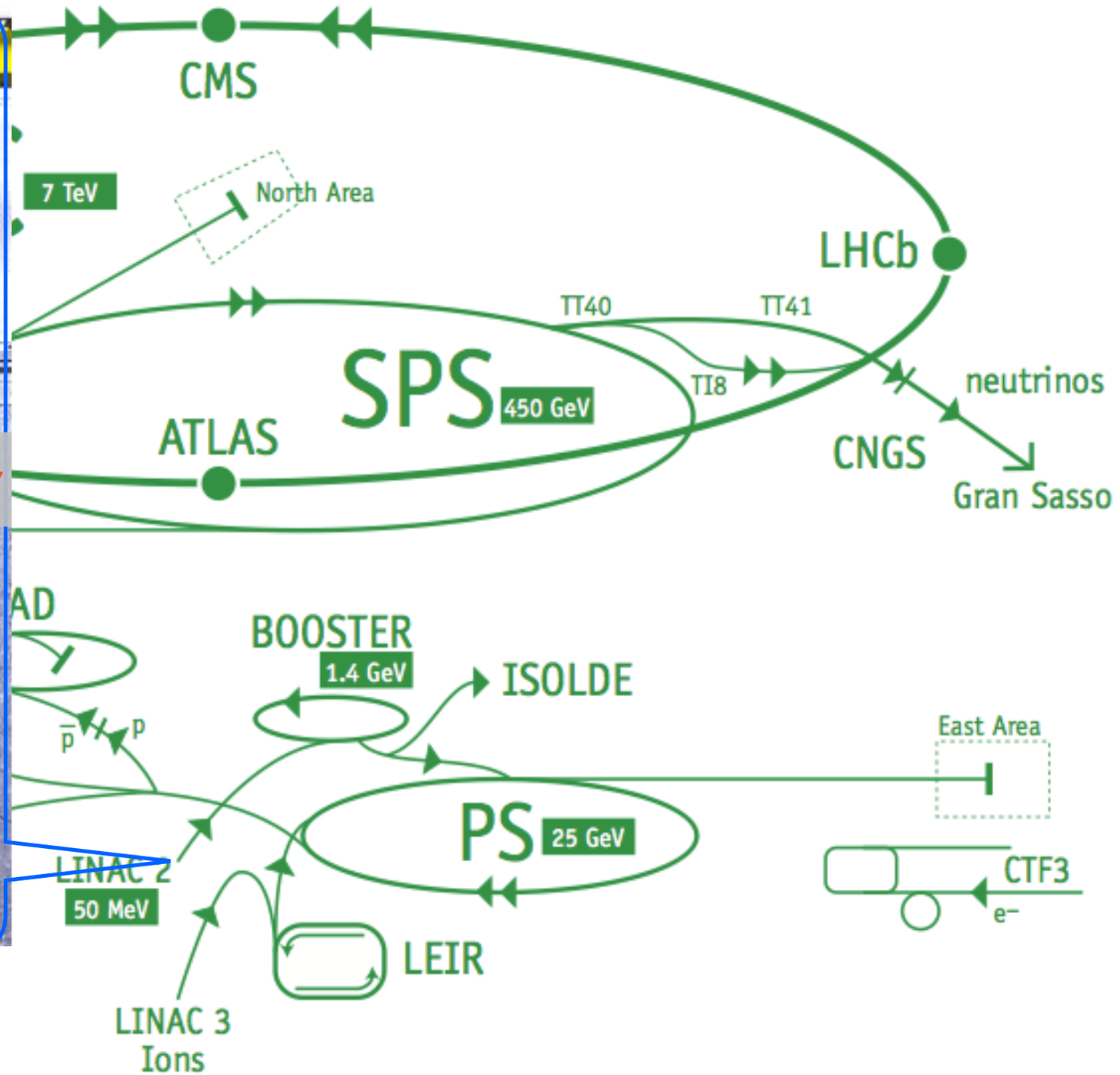
$$\frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} = qBR$$

- Physics Goals
  - Discover Higgs boson(s)
  - Test standard model
  - Find new physics

$$\Rightarrow R = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} \times \frac{1}{qB}$$


CMS
LHC
7 TeV
North Area
ALICE
LHCb
TT40
TT41
SPS
450 GeV
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
Gran Sasso
TT60
TT2
AD
BOOSTER
1.4 GeV
ISOLDE
East Area
p̄
p
n-ToF
PS
25 GeV
CTF3
LINAC 2
50 MeV
e⁻
neutrons
LEIR
LINAC 3
Ions


PREINJECTEUR
LINAC 2
ATTEN
HAUTE
HIGH
100 KV
H2
A PROTON SOURCE
Flammable gas - Gaz inflammable
2×10-9 g/day
Starting point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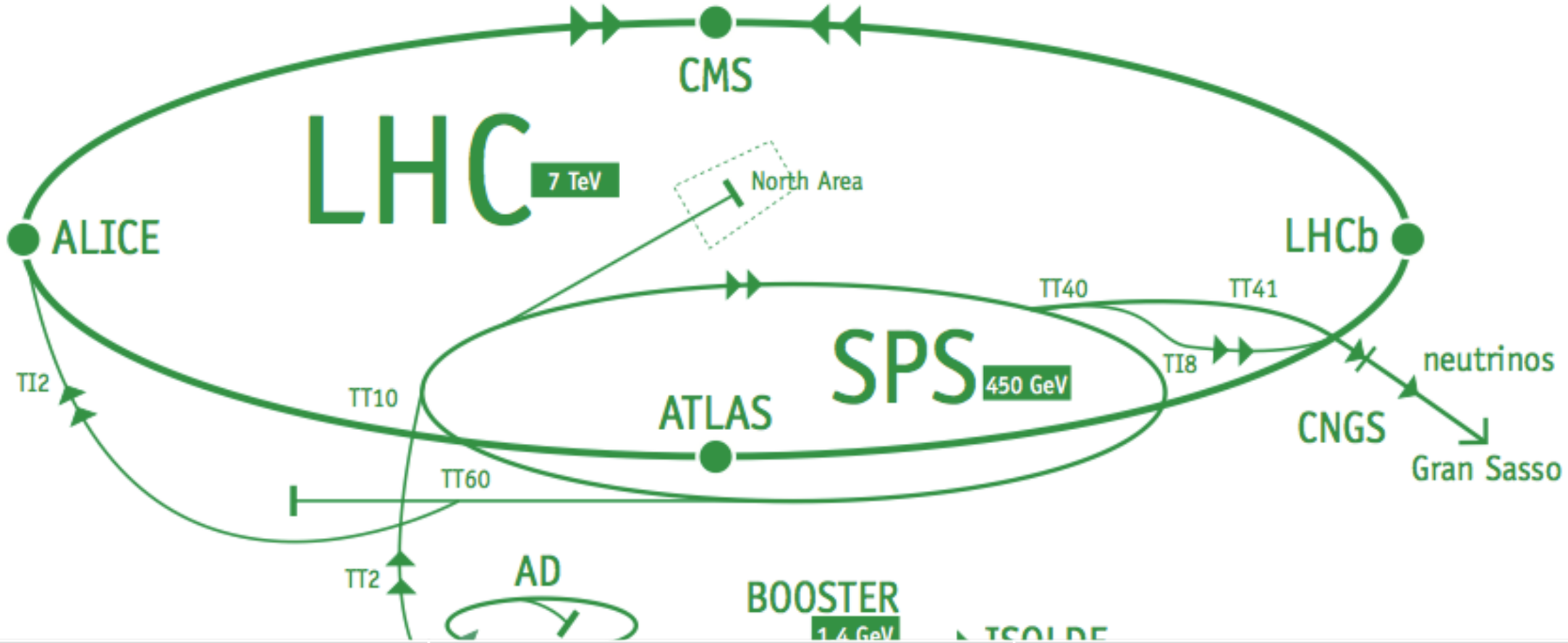
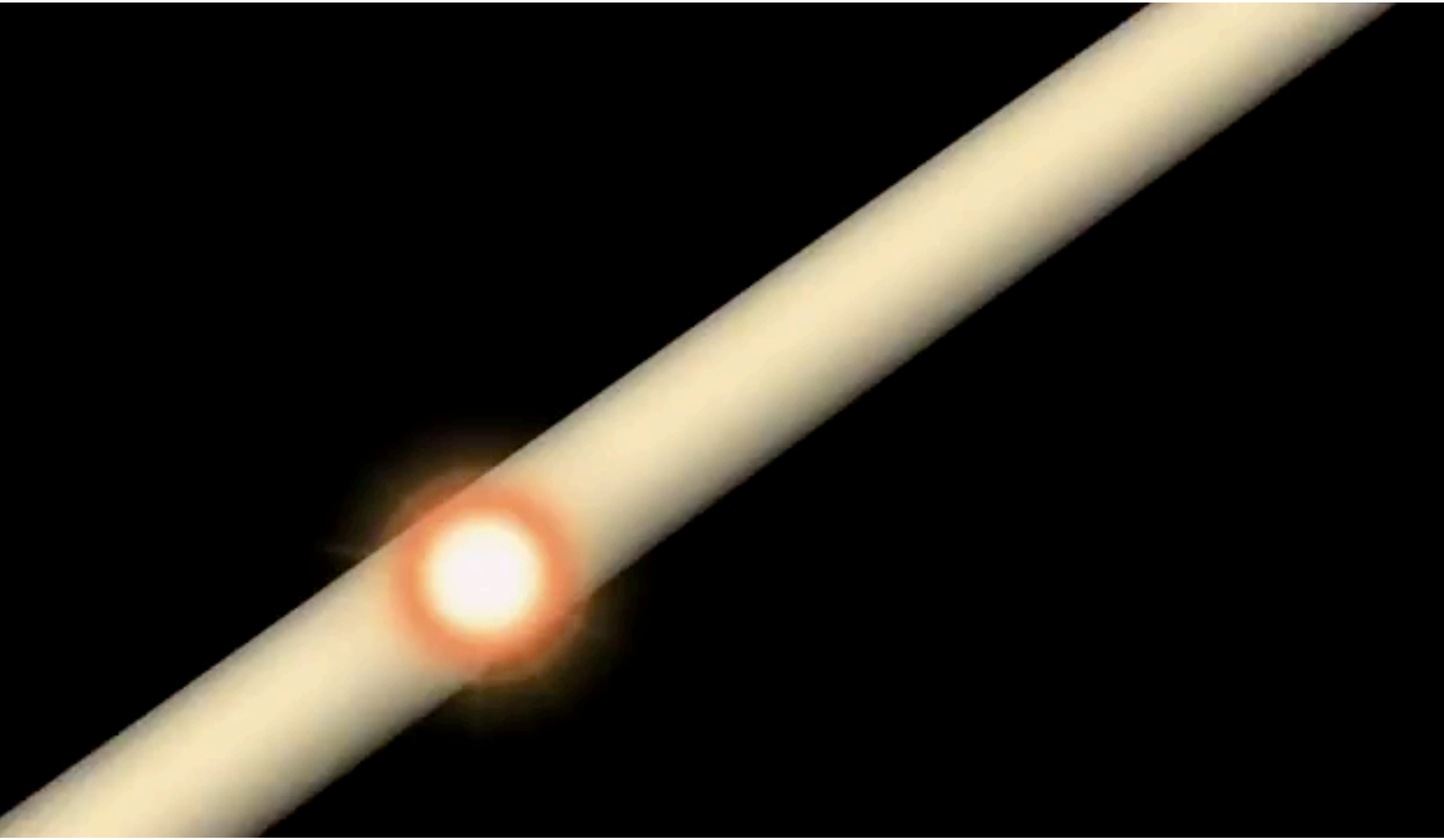


加速器名稱	質子動能	質子速度(%光速)
Linac 2	5000 萬電子伏特 (50 MeV)	31.4
PS Booster	14 億電子伏特 (1.4 GeV)	91.6
PS	250 億電子伏特 (25 GeV)	99.93
SPS	4500 億電子伏特 (450 GeV)	99.9998
LHC	7 兆電子伏特 (7 TeV)	99.9999991

Final goal

https://www.seeker.com/videos/inside-the-worlds-largest-particle-accelerator



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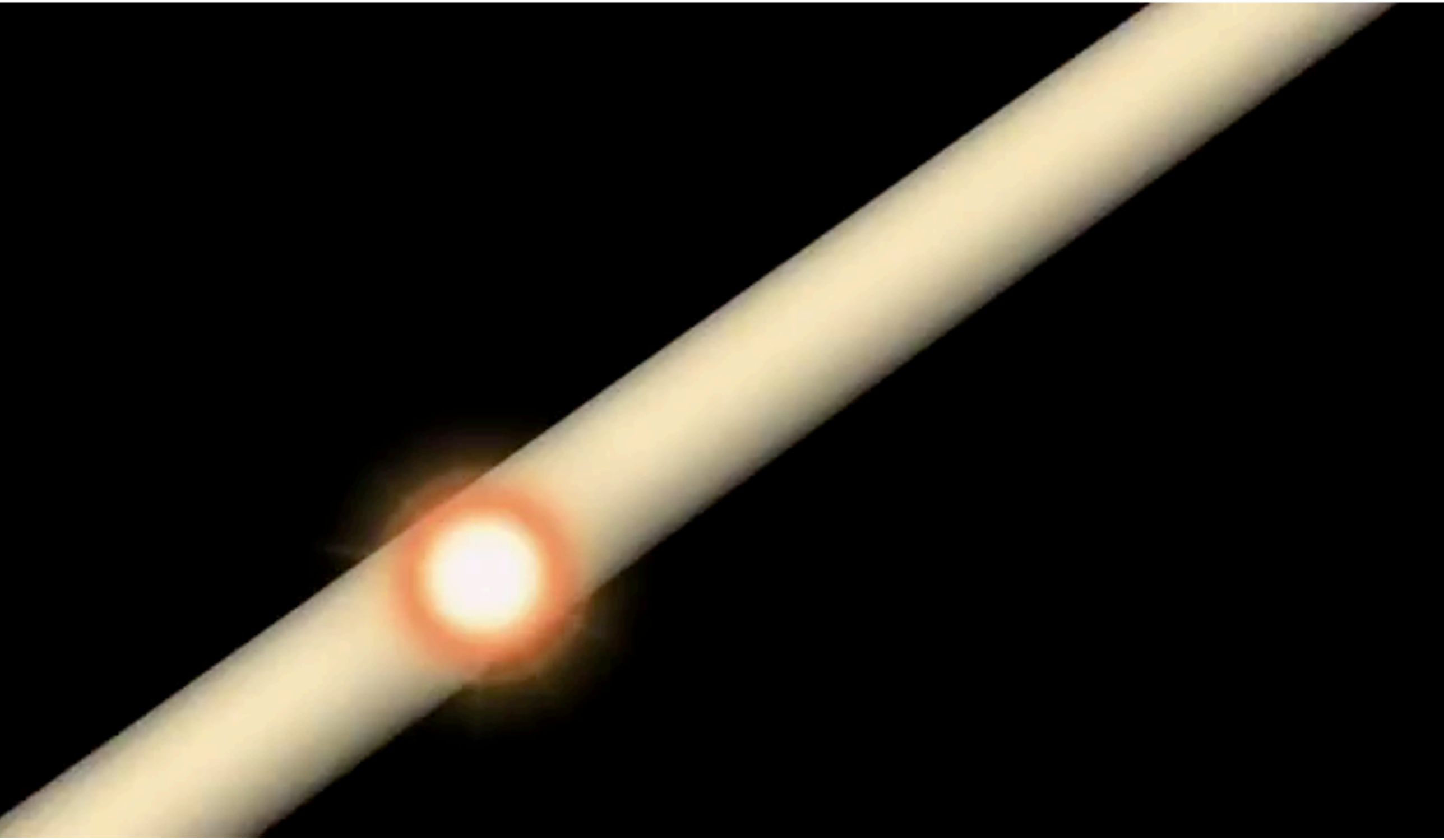


LHC Numbers

Parameter	Current Value
Center of mass energy (pp)	13 TeV (14 TeV*)
Center of mass energy (NN)	5.02 TeV
# of bunches	2808
Bunch Spacing (ns)	25
Bunch Spacing (m)	~7.5
# of protons per bunch	1.2E+11
Peak Instantaneous Luminosity (/cm*cm/sec)	2E+34
Average # of interactions per bunch crossing	50
Interaction Rate (Hz)	2E+09

Tevatron luminosity record: 4.04E+32 $cm^{-2}sec^{-1}$

- **Event rates [N/s]**

$$\frac{dR}{dt} = \sigma \times \mathcal{L}$$

- **Cross section [barn]**
  - The likelihood to have a certain interaction between a pair of particles
  - Determined by physics processes, beam particle type, and beam energy

1 barn= 10^{-28} m^2

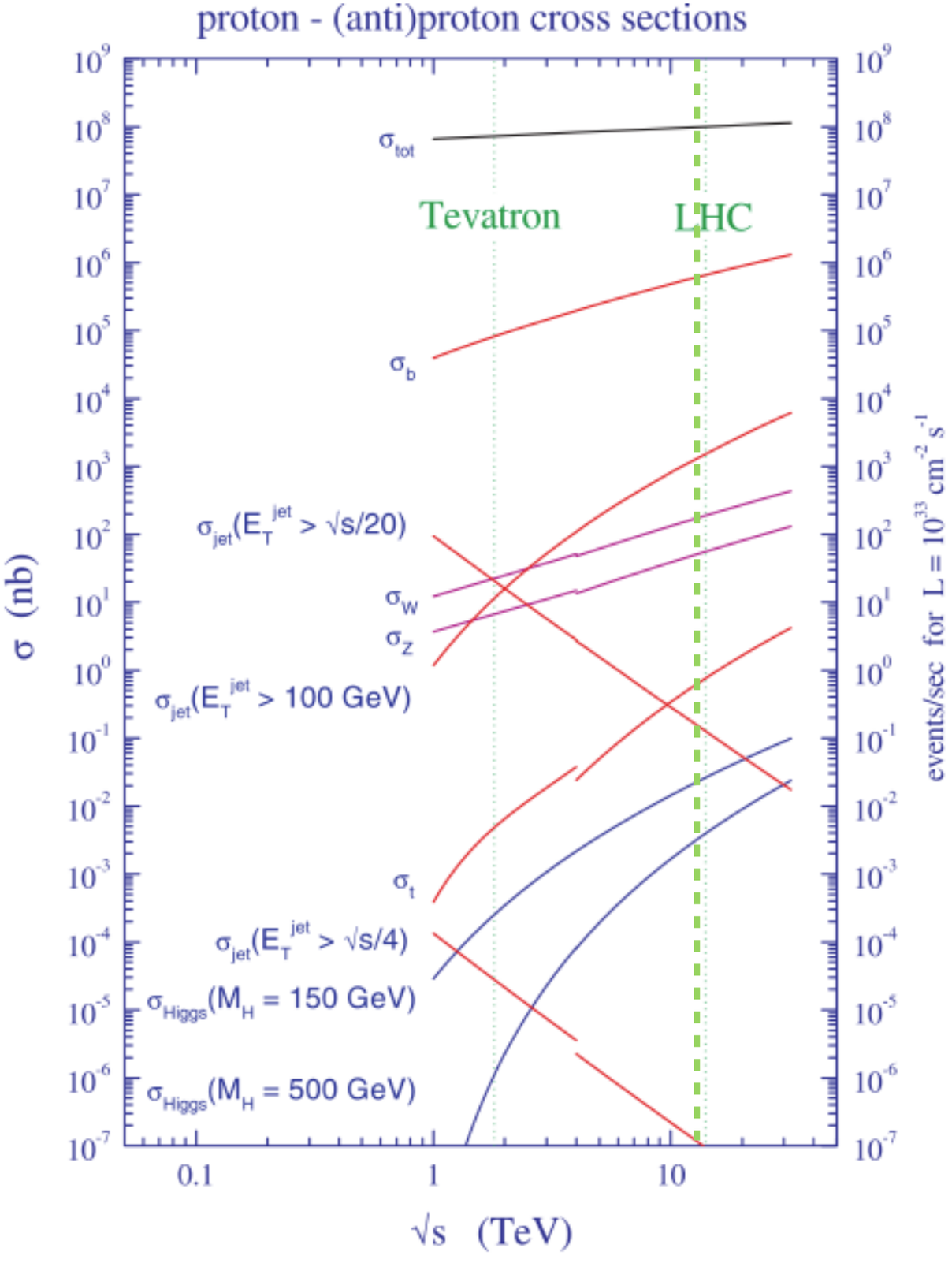
- **Instantaneous Luminosity [cm^{-2} s^{-1}]**
  - Driven by the accelerator performance: number of particles in each bunch, collision frequency, beam profile

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

- **Integrated Luminosity [barn^{-1}]**
  - How we quote the amount of data collected

$$L_{\text{int}} = \int \mathcal{L}\, dt$$

Number of Produced Events per Second



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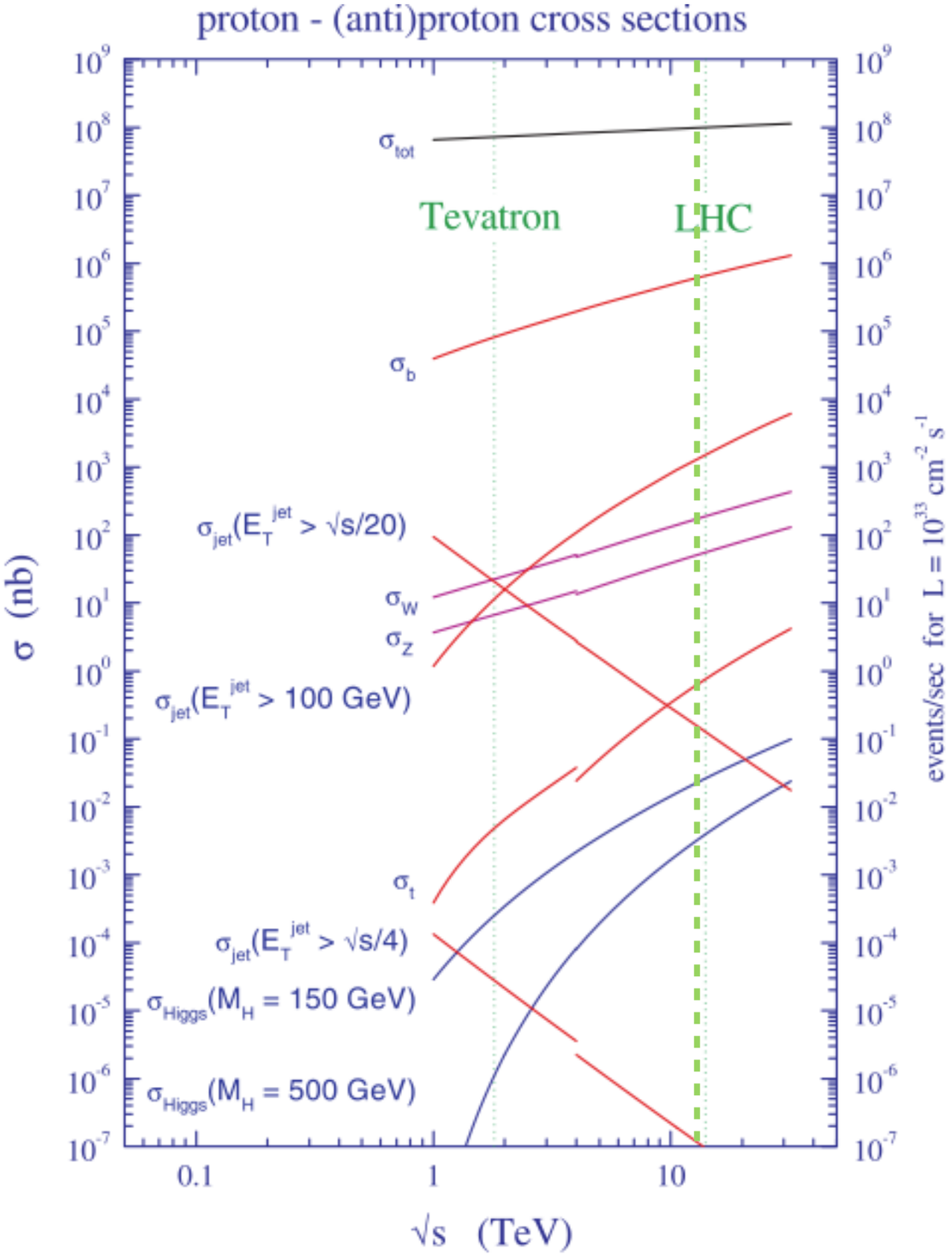


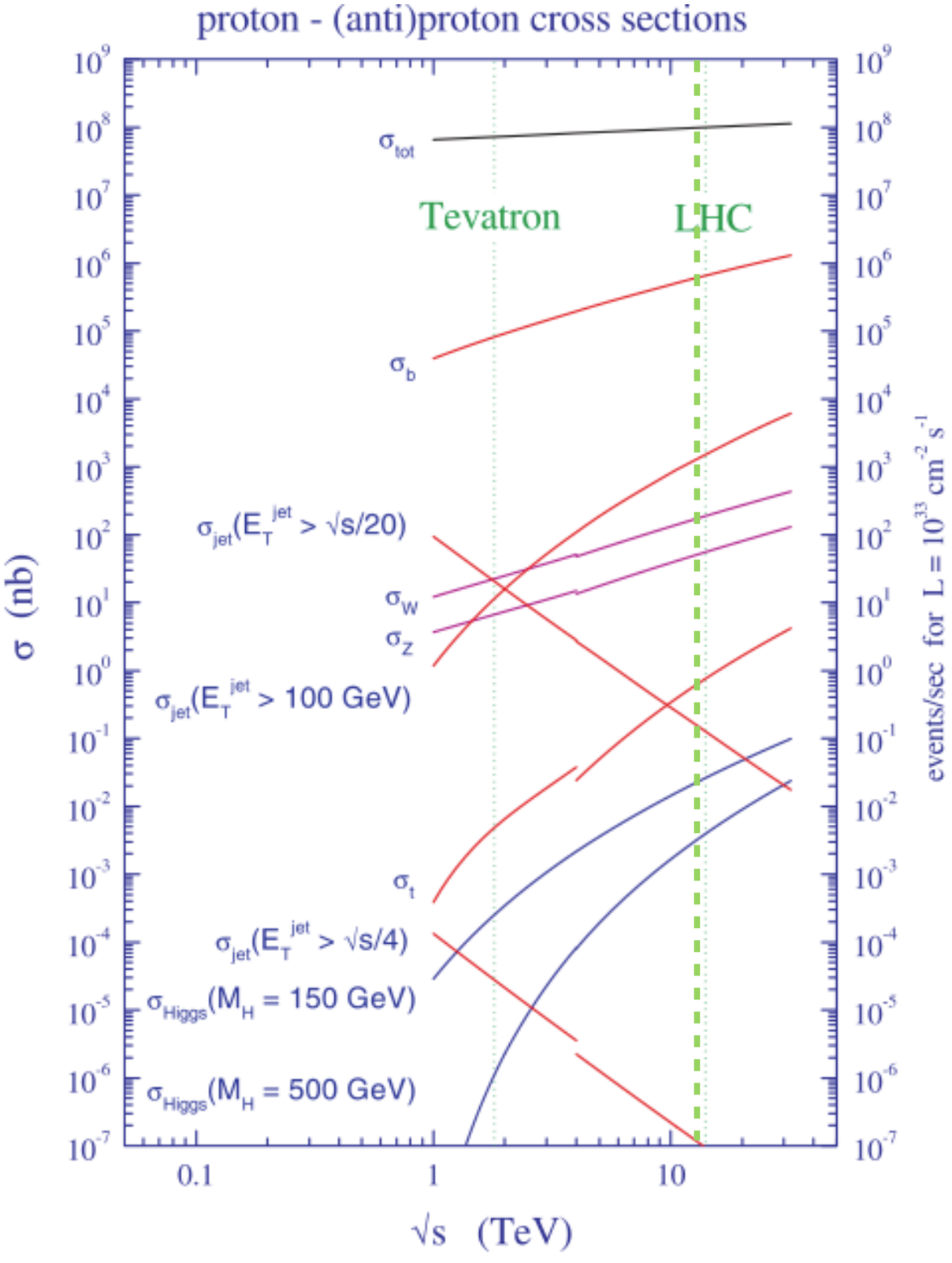
- 10^8/sec Total number of pp interactions, ~60% inelastic

- 200/sec W boson
- 60/sec Z boson

- 0.8/sec top quark

- 0.045/sec Higgs

Number of Produced Events per Second



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Current instantaneous luminosity is 20 times higher!

LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider (SppbarS)

1989 : Start of LEP operation (Z/W boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of LHC installation

2005 : Start of LHC hardware commissioning

2008 : Start of (short) beam commissioning

Powering incident on 19th Sept.

2009 : Repair, re-commissioning and beam commissioning

2009.11.23: First pp collisions at 900 GeV

2009.11.30: Proton beam energy reaches 1.18 TeV each

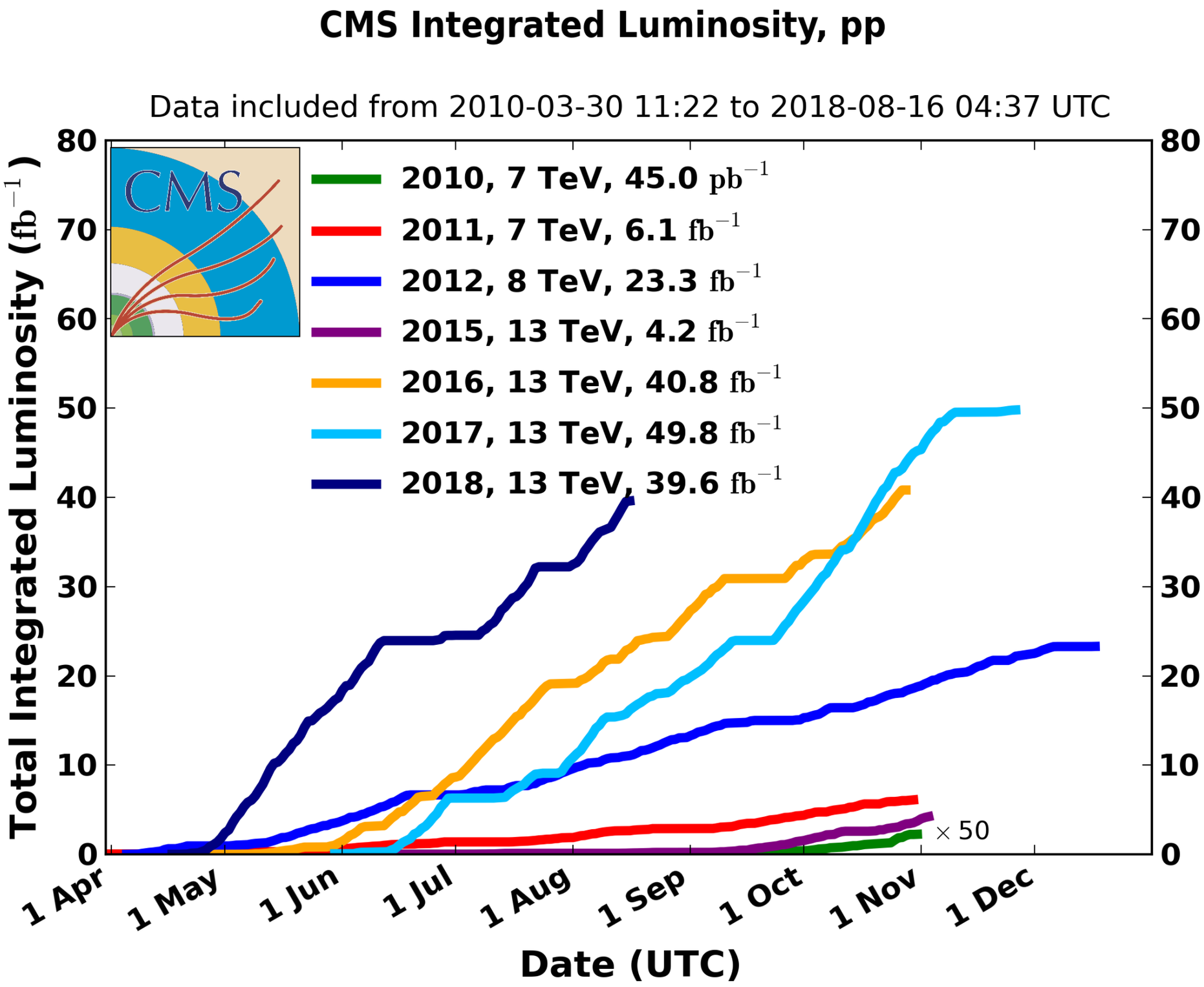
2010.03.30: First pp collisions at 7 TeV

2012.04.05: First pp collisions at 8 TeV

2013.02.14: First 3-year running period finished

2015.06.03: First 13 TeV collisions

Data Delivered to CMS



- But what is the use of producing a lot of data/collisions, if no one is there to observe and study them?

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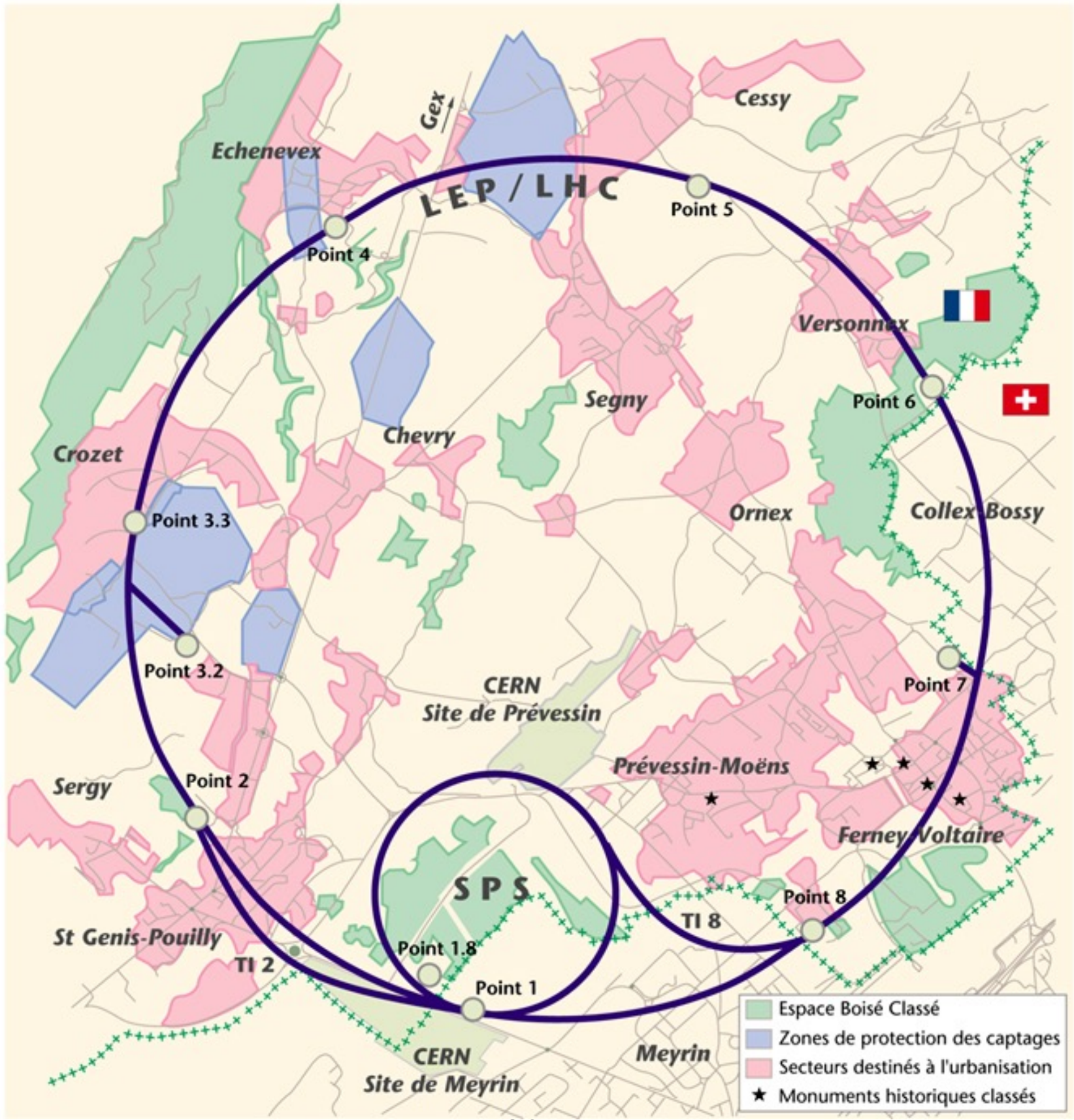
  - Detectors

Brief Story of the Four Experiments

The LHC Experiments

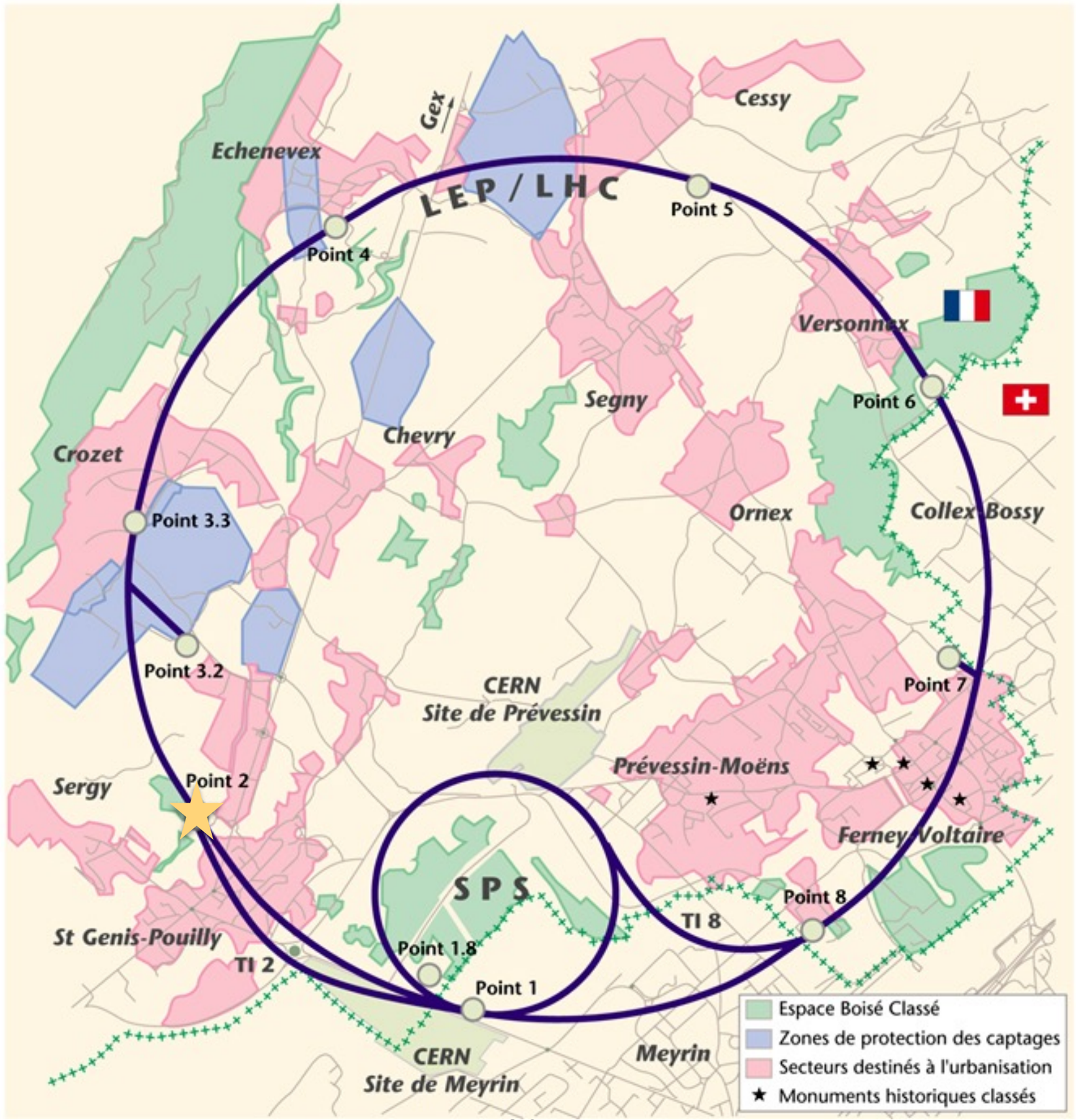
- ALICE
  - A Large Ion Collider Experiment
- ATLAS
  - A Toroidal LHC ApparatuS
- CMS
  - Compact Muon Solenoid
- LHCb
  - the Large Hadron Collider beauty experiment

Principales zones d'occupation des sols à proximité du LEP



CERN AC - EI6-35 - 03 1997

Principales zones d'occupation des sols à proximité du LEP



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ALICE Introduction

- Designed to study lead-ion collisions
- Study properties of quark-gluon plasma, a state of matter likely existed just after the Big Bang
  - a state of matter where quarks and gluons are not confined inside hadrons due to very high temperature and densities
- 37 Countries, 154 Institutes and over 1500 members

History of the Universe

Accelerators: CERN-LHC, FNAL-Tevatron, BNL-RHIC, CERN-LEP, SLAC-SLC

high-energy cosmic rays

Inflation

BIG BANG

?

possible dark matter relicts

cosmic microwave radiation visible

t 10 -44 10 -37 s
T 10 32 10 28
E 10 19 10 15

10 -10 s
10 15
10 2

10 -5 s
10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
3x10 -10

10 9 y
15
10 -12

12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)

Today

Key:

q quark
g gluon
e electron
m muon t tau
n neutrino

W, Z bosons
qq meson
qqq baryon
ion
atom

photon
star
galaxy
black hole

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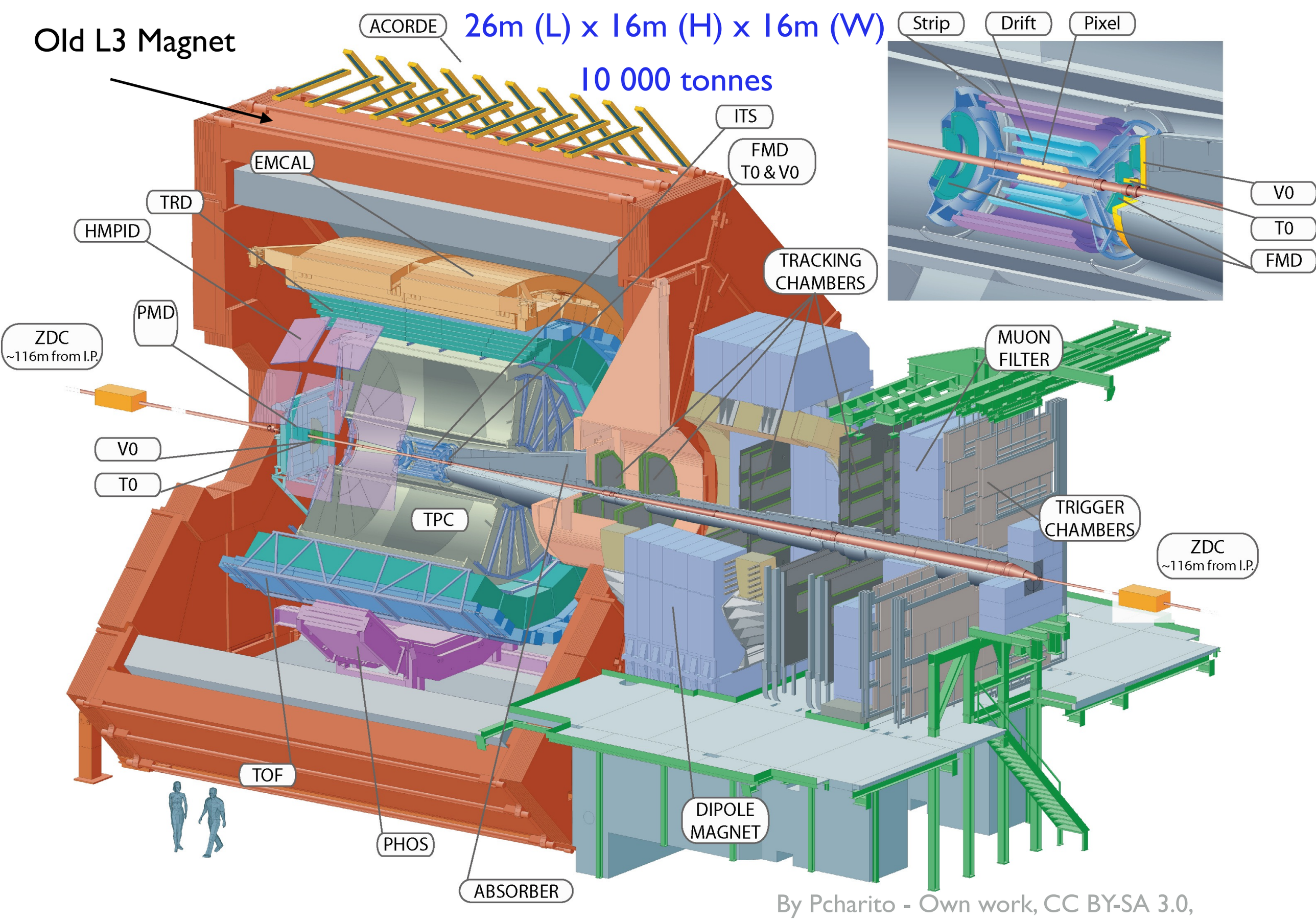

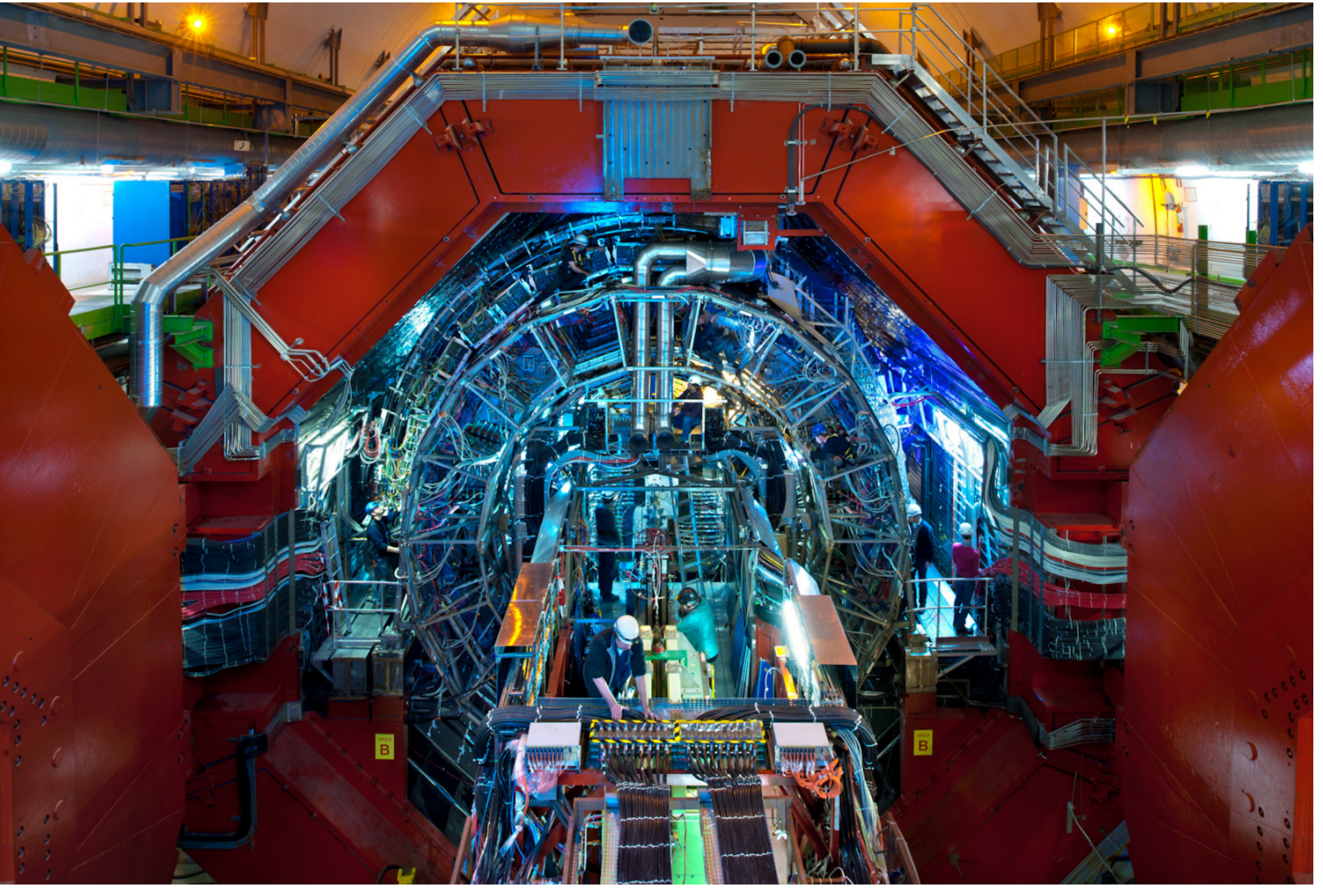

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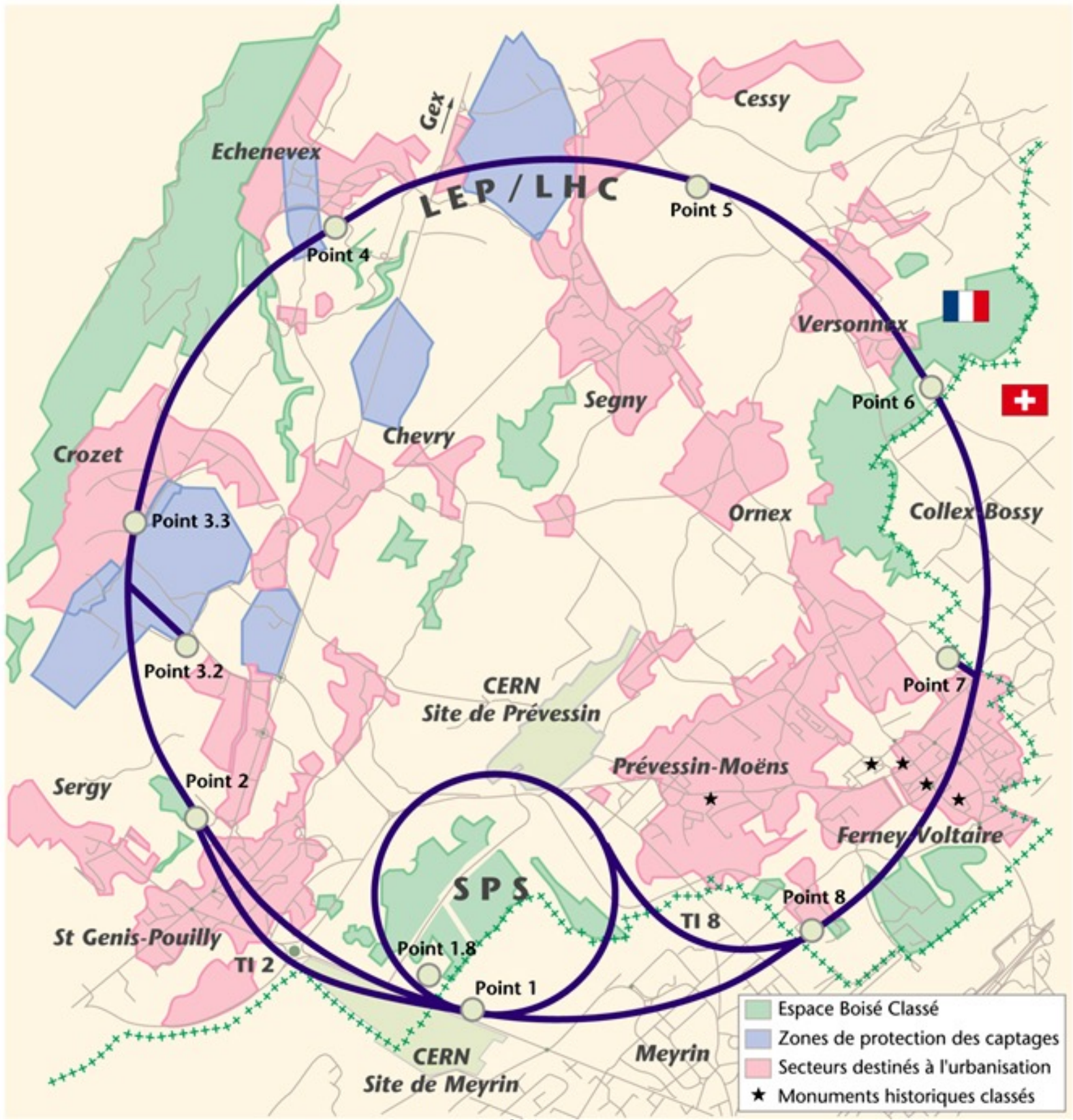

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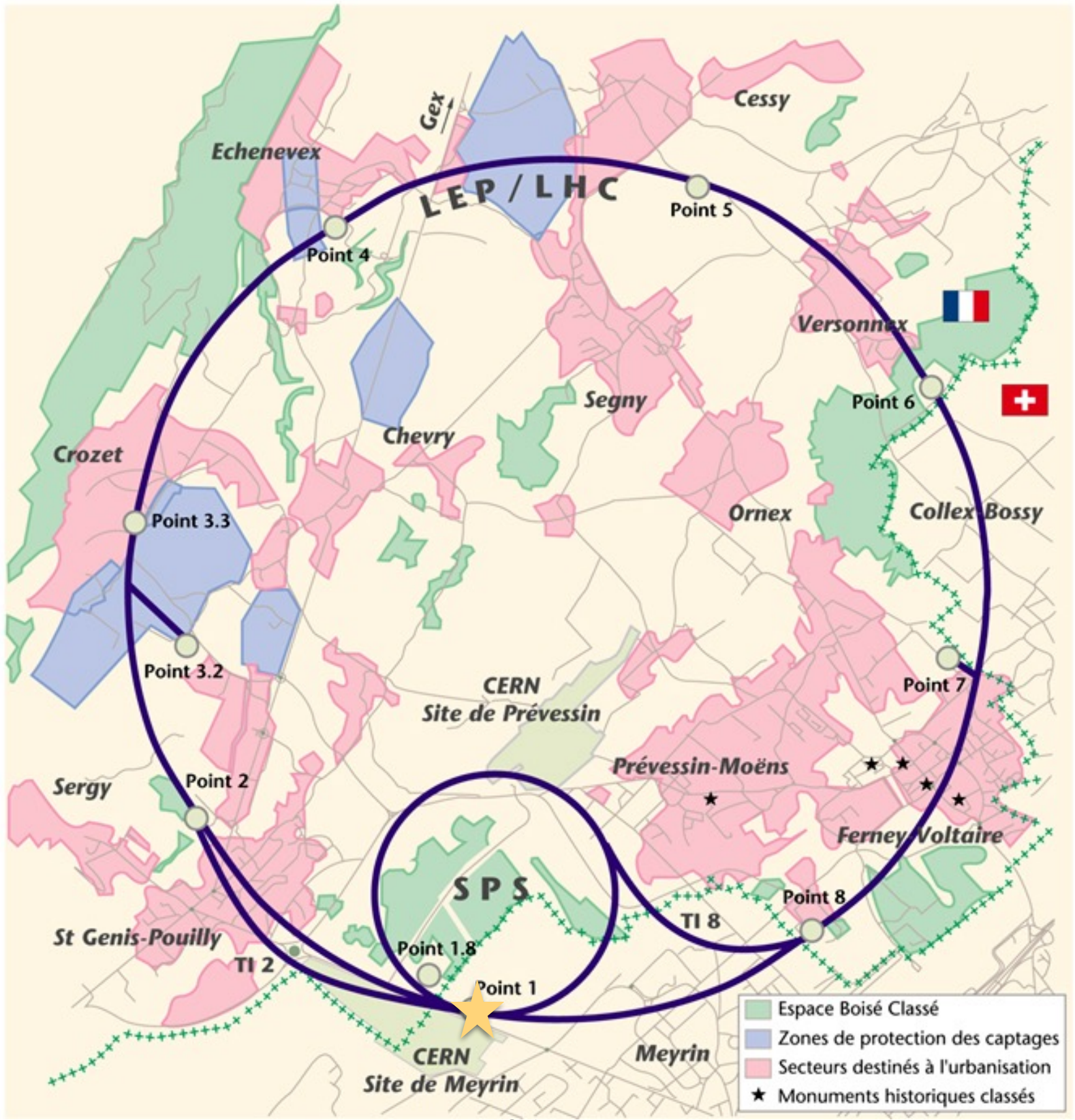

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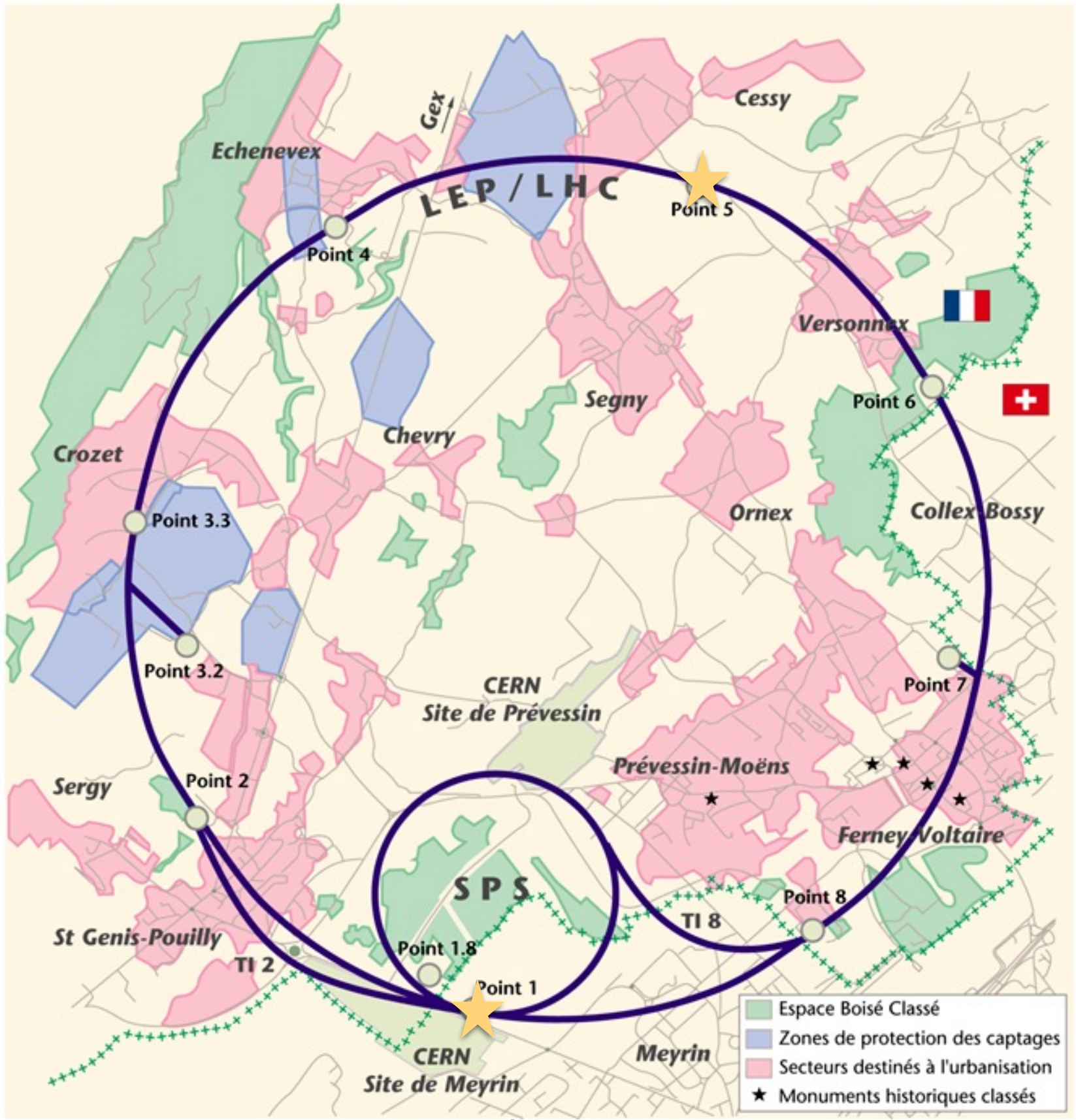

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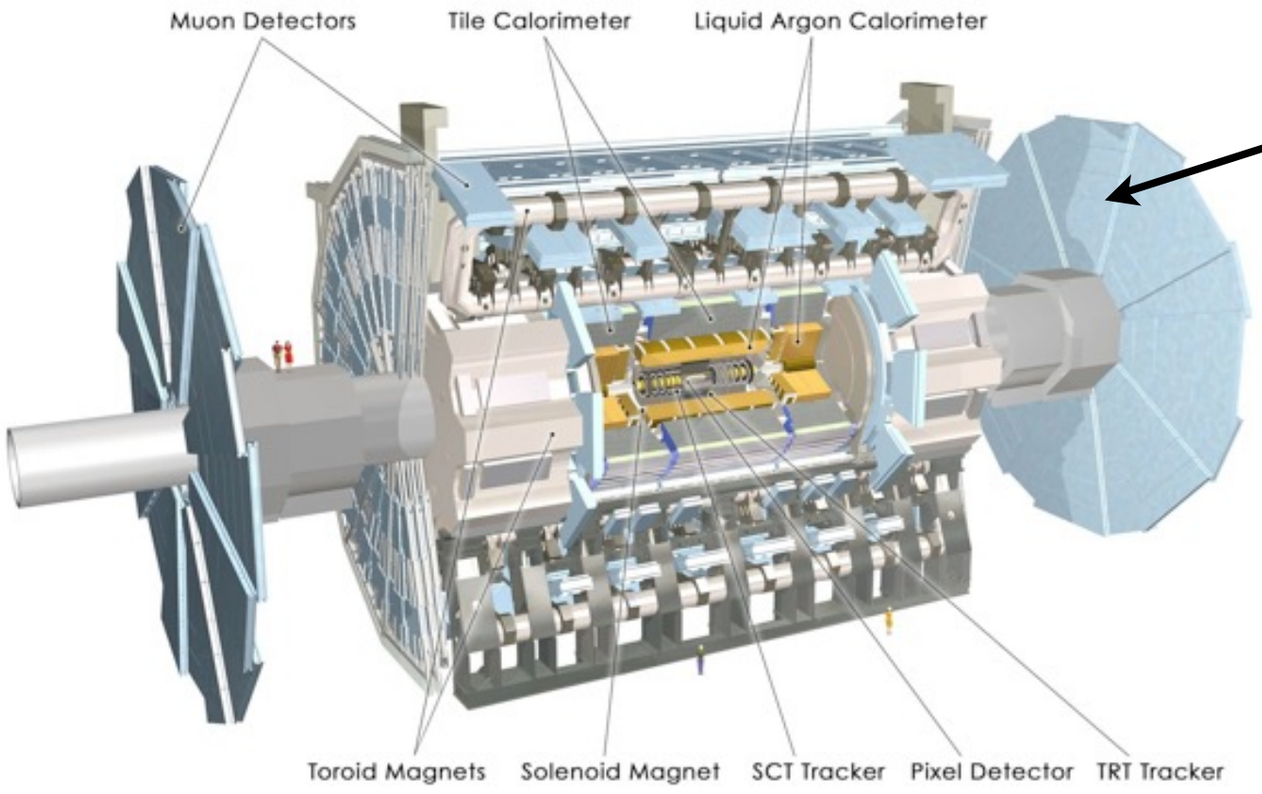
ATLAS/CMS Mission

- General purpose detectors
- Search for Higgs boson and measure its properties
- Search for physics beyond the standard model, e.g. supersymmetry, extra dimension, or something totally unexpected
- 38/40 Countries, 182/200 Institutes and over 3000/4000 members

One Floats and One Sinks in the Water

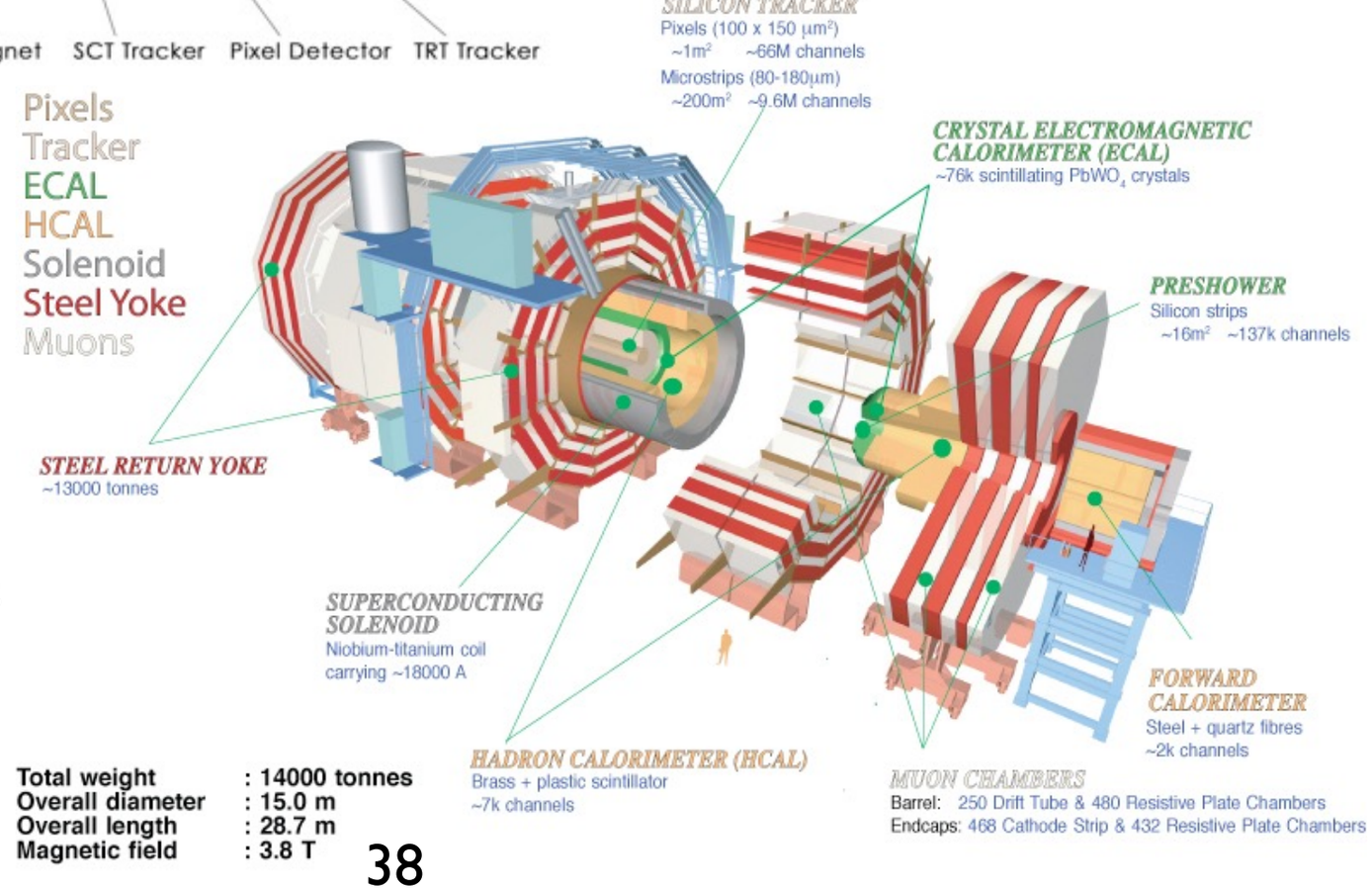


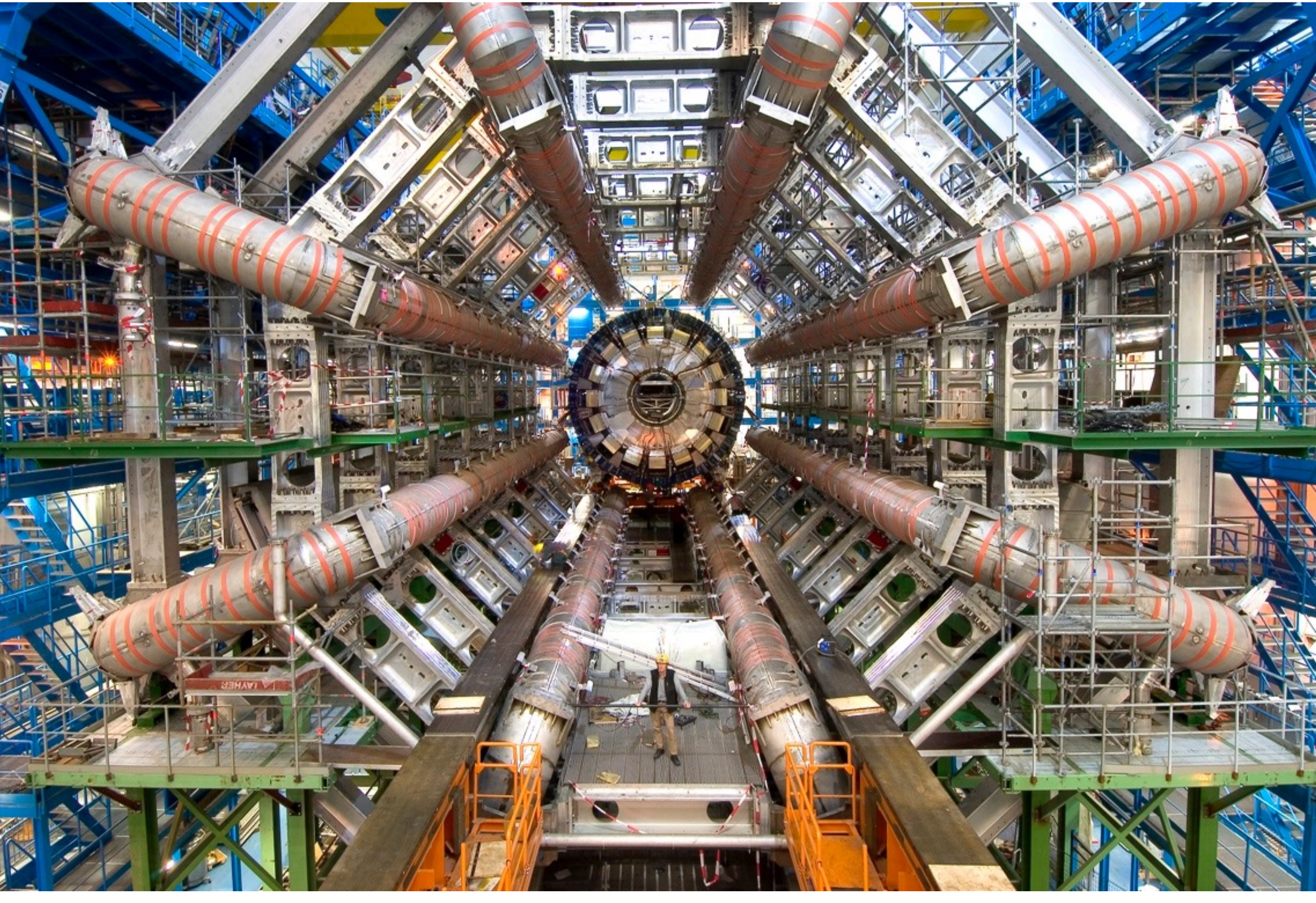
ATLAS

Height: 26m
Width: 26m
Length: 46m
Weight: 7000 tonnes

CMS

Diameter: 15m
Length: 21m
Weight: 14000 tonnes





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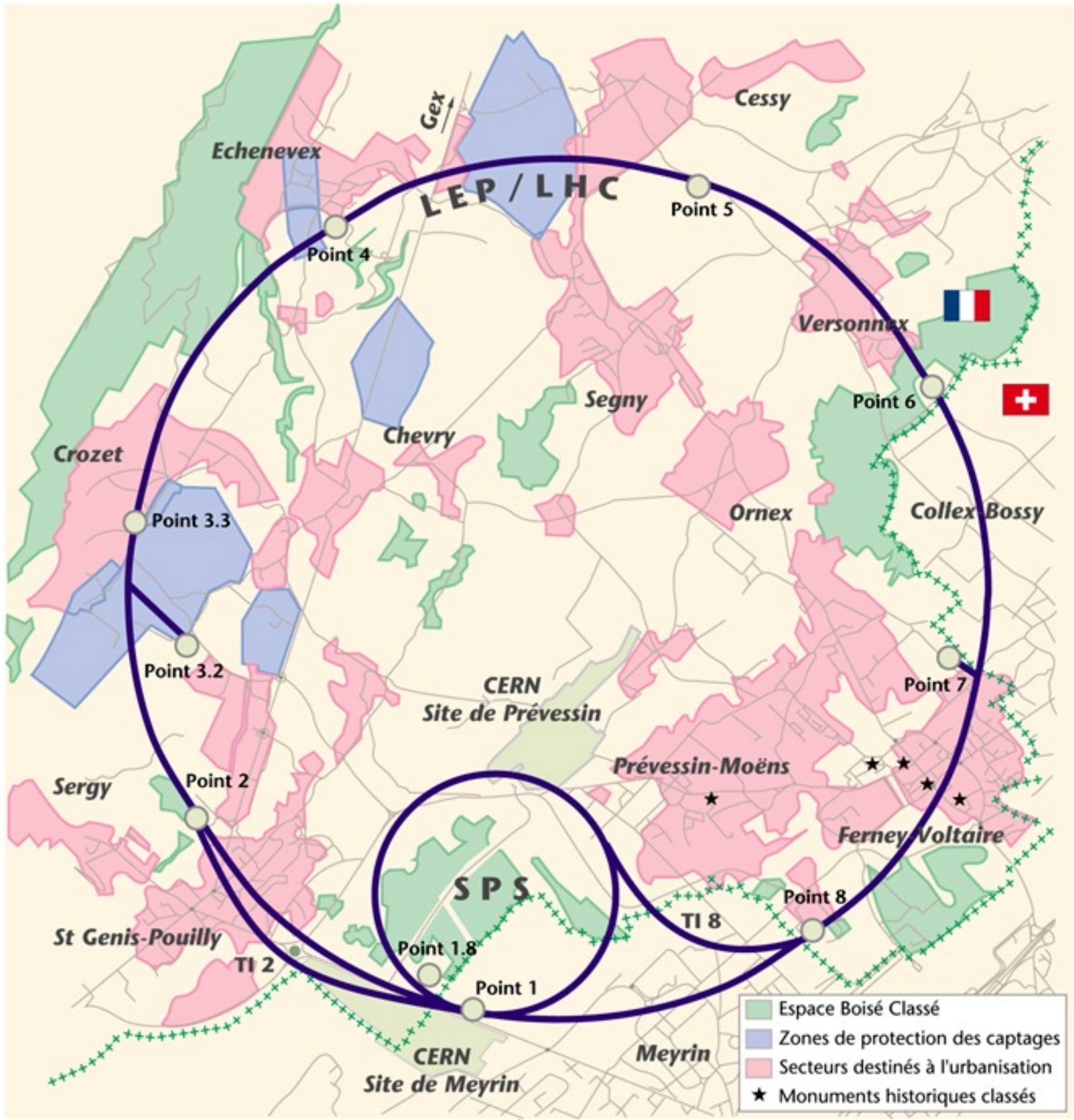

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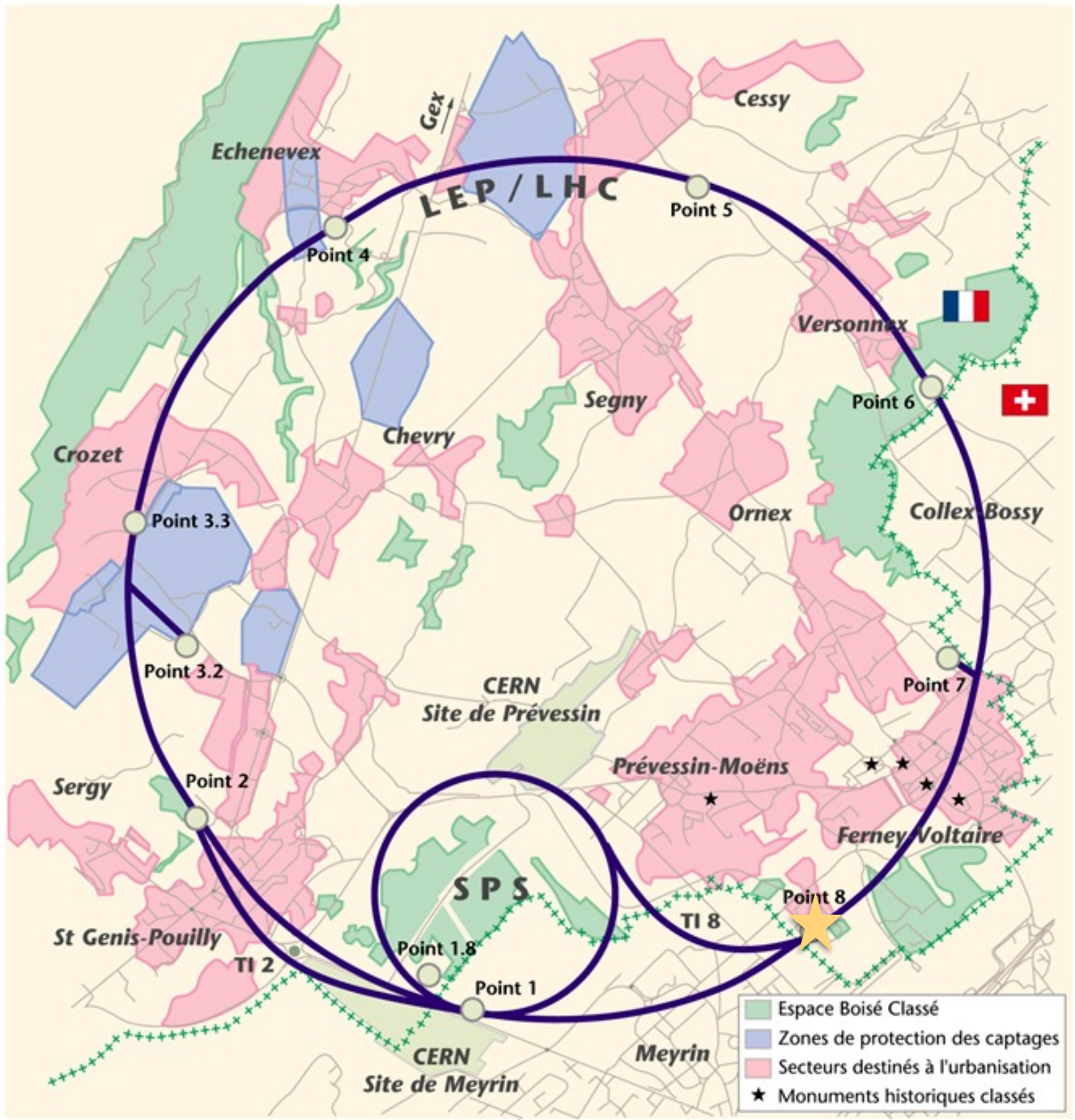

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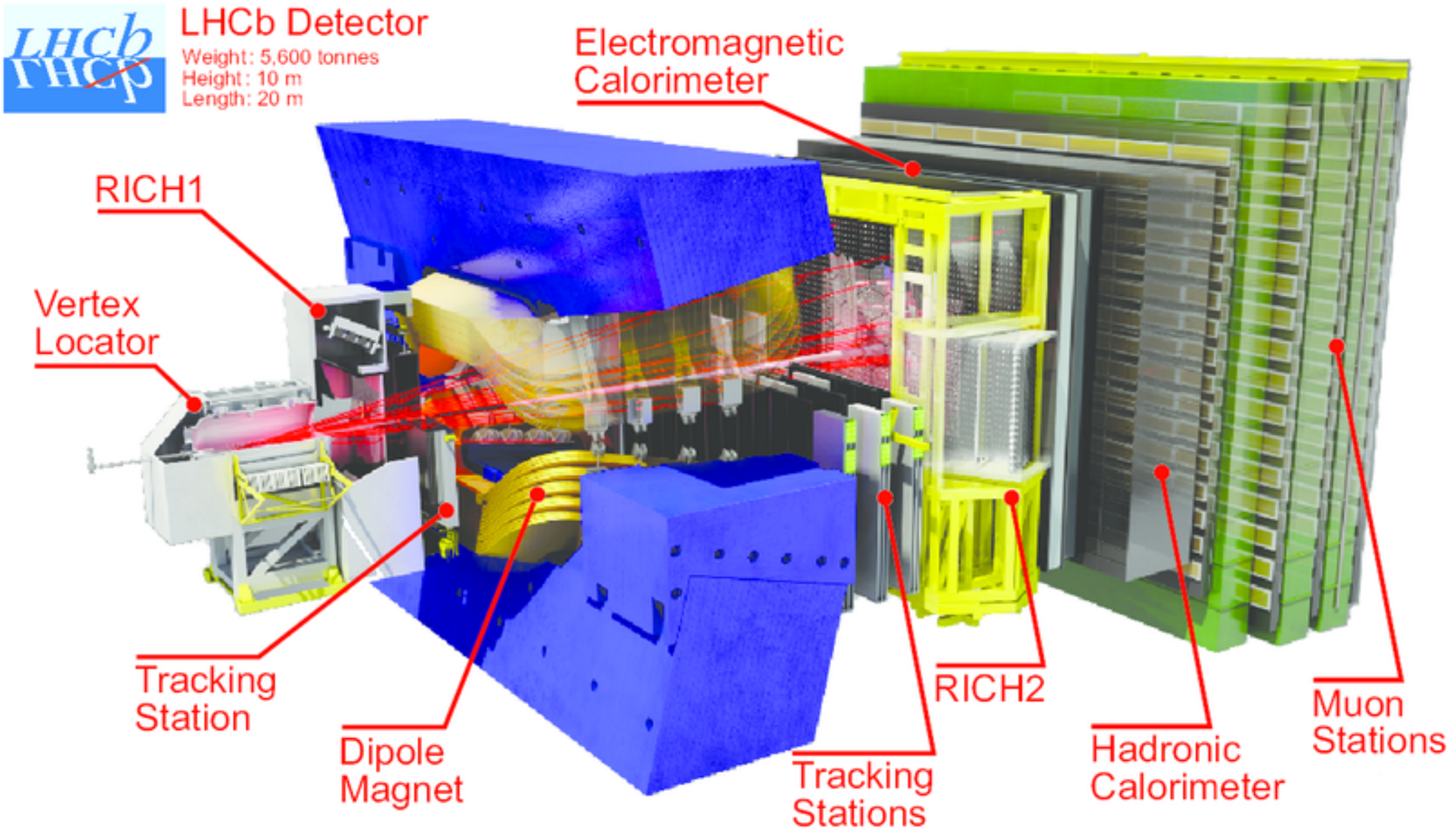
LHCb Mission

- Precision measurement of CP violation and rare b/c hadron decays
- 16 Countries, 71 Institutes and over 1200 members

LHCb Detector Sketch




LHCb
YCMM01
UX85


LHCb
LHCb


LHCb
YCMM01
UX85