Introduction to the LHC

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CMSDAS @ NTU, Taipei, Taiwan

Inkyu Park on behalf of Korea CMS

University of Seoul

Disclaimer

- I am not an accelerator expert.
  - Rather an enthusiast.
- Source materials
  - Many of pictures, plots and ideas were from
    - ✓ Mike Lamont @ Rencontres de Moriond 2015
    - ✓ Frank Zimmermann @ CERN Summer School 2015
    - ✓ Chandra Bhat @ CMSDAS 2015
    - ✓ Daniel Brant @ CAS 2010, Varna
    - ✓ CERN courier 2005, 2009

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What is Particle Physics? How?

What is Particle Physics?

1922-
1988
Leon Lederman

"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

<u>Leon Lederman's definition:</u>

"Particle physics is a search for the most primitive, primordial, unchanging and indestructible forms of matter and the rules by which they combine to compose all the things of the physical world. It deals with matter, energy, space, and time.

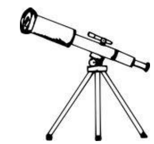
The objectives of particle physics are to identify the most simple objects out of which all matter is composed and to understand the forces which cause them to interact and combine to make more complex things."

What are the elementary building blocks?
How do they interact with each others?

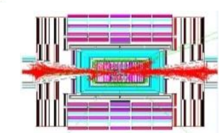
Particle Physics, How to do?

- **Method of observation**
  - Probes + Camera
    - ✓ EM wave, γ, e, p → visible
  - De Broglie wave: $\lambda = \frac{h}{p}$
    - ✓ Just look inside it
      - – Low energy, non-destructive
    - ✓ if not possible, smash it
      - – High energy, destructive

	26	universe
	21	galaxy
(Ly)	16	light year
(AU)	11	solar system
	6	earth
(km)	3	
(m)	0	human
(mm)	-3	
(um)	-6	micro, cell
(nm)	-9	nano
(A)	-10	atom
(fm)	-15	nuclear
	-20	



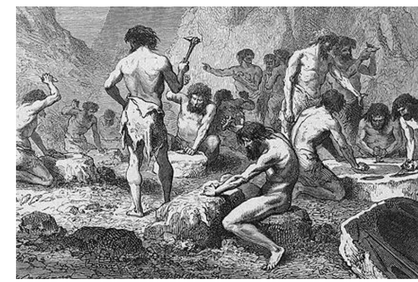


- **Particle Physics era**
  - According to the method of smashing, one can define the era of Particle Physics!
    - ✓ From the radio active source to the accelerator

A brief history of Particle Physics

- Using chemistry (~1900)
  - discovery of atoms
    - ✓ Discovery of Fire

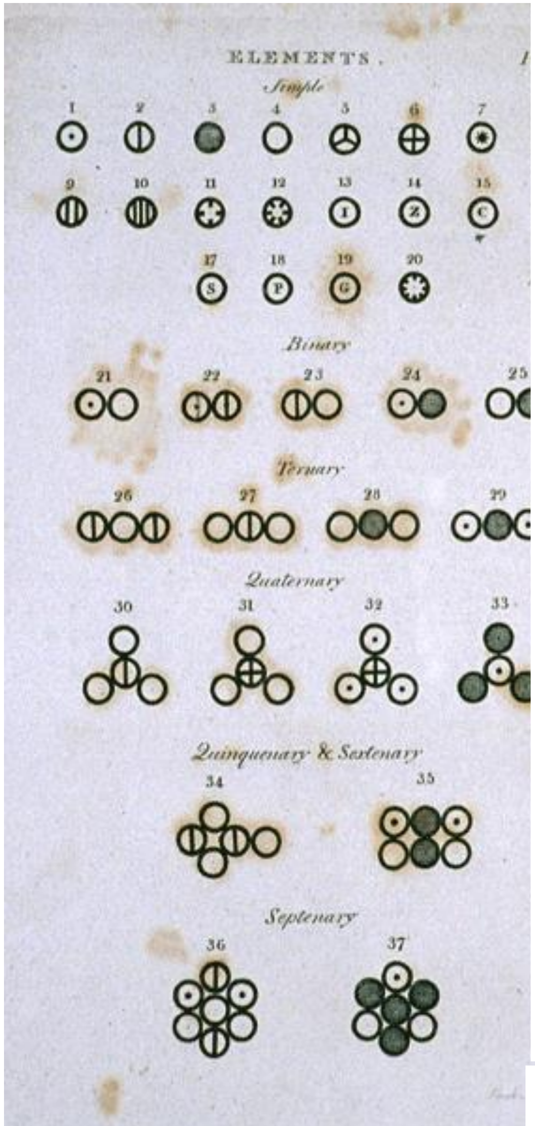
- Using radioactive rays (~1920)
  - discovery of nuclear
    - ✓ Stone age

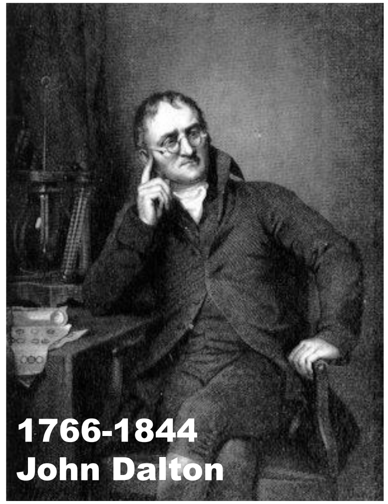


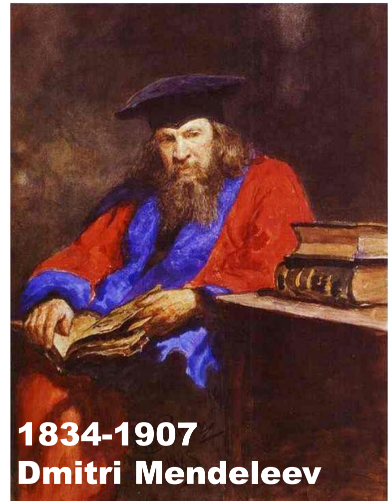
- Using cosmic rays (~1950)
  - discovery of many new particles
    - ✓ Hunter-gatherer's era

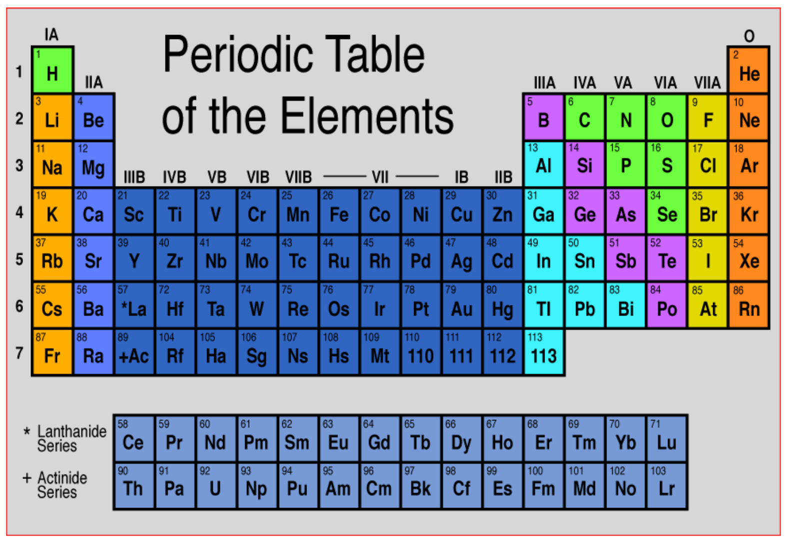
- Using accelerators (~present)
  - creation of elementary particles
    - ✓ Agrarian era

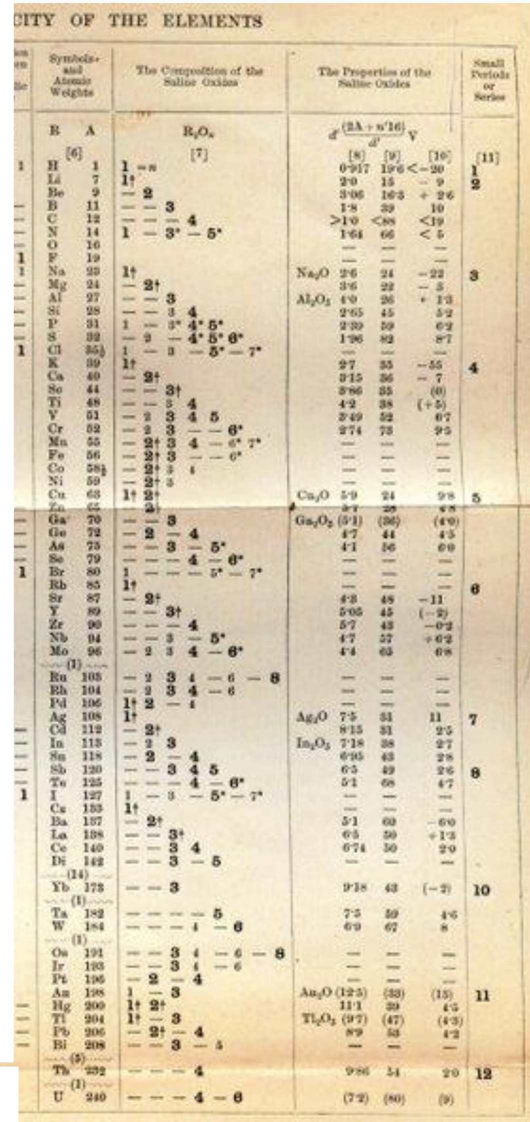
Discovery of Atom





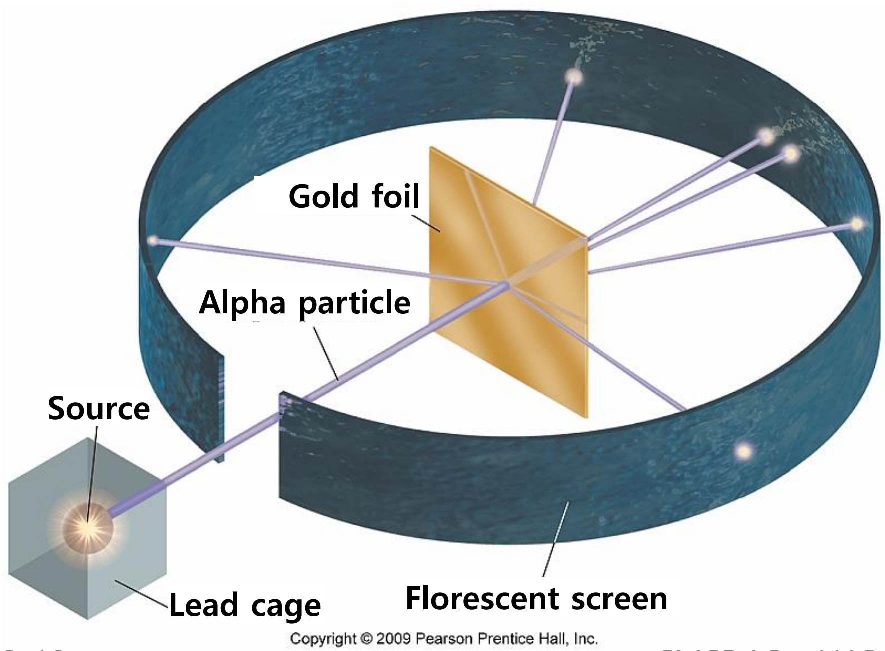


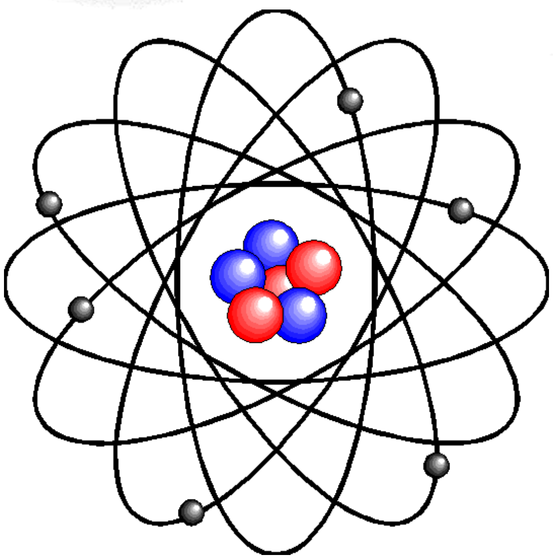




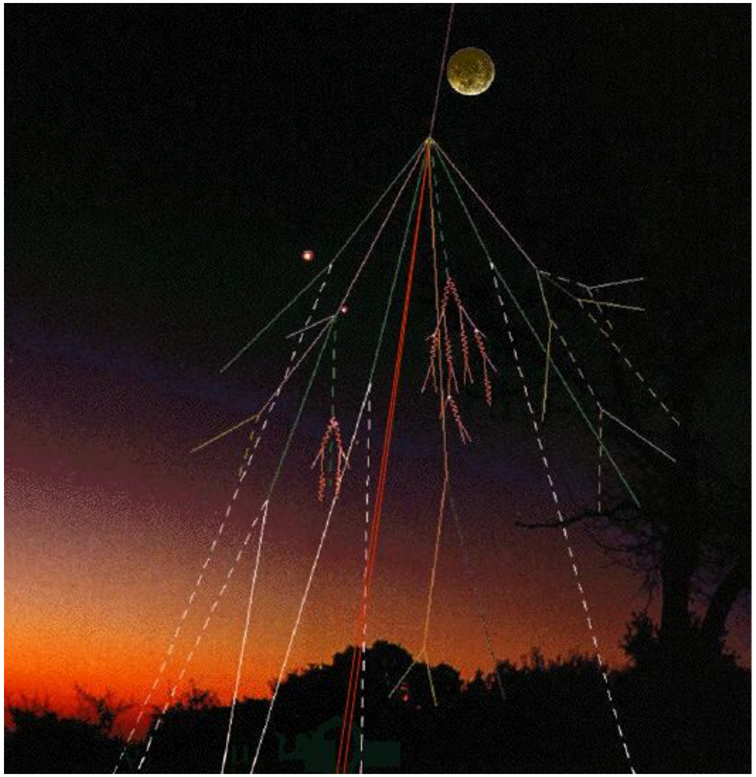
Atoms are periodic → Inner structure

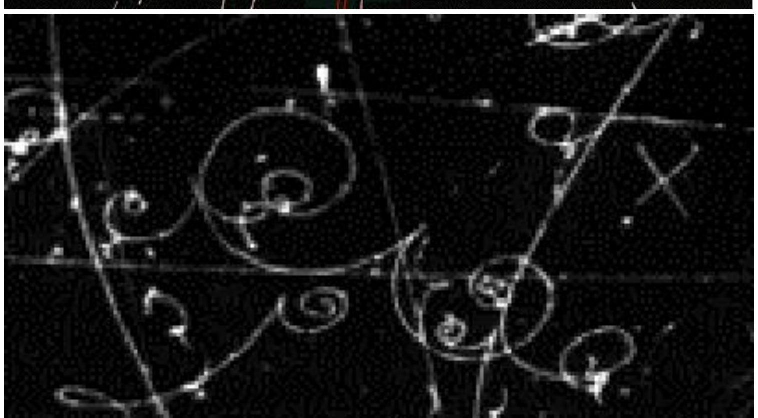
Discovery of nuclear

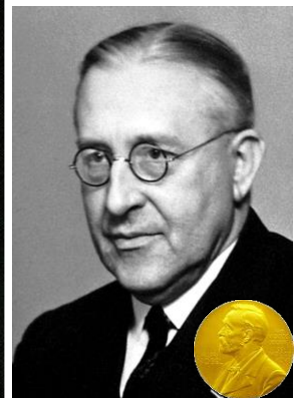




Discoveries from cosmic rays: e^+, μ, π

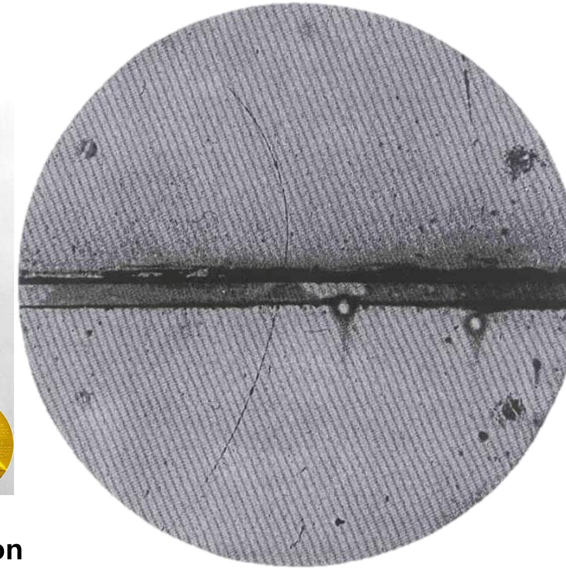






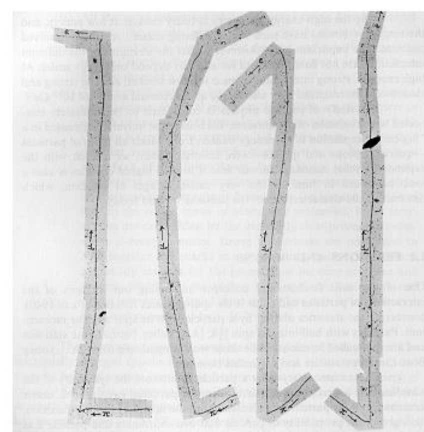
1883-1964 **1936**
Victor Hess

1905-1991 **1936**
Carl David Anderson



1932: Discovery of Positron

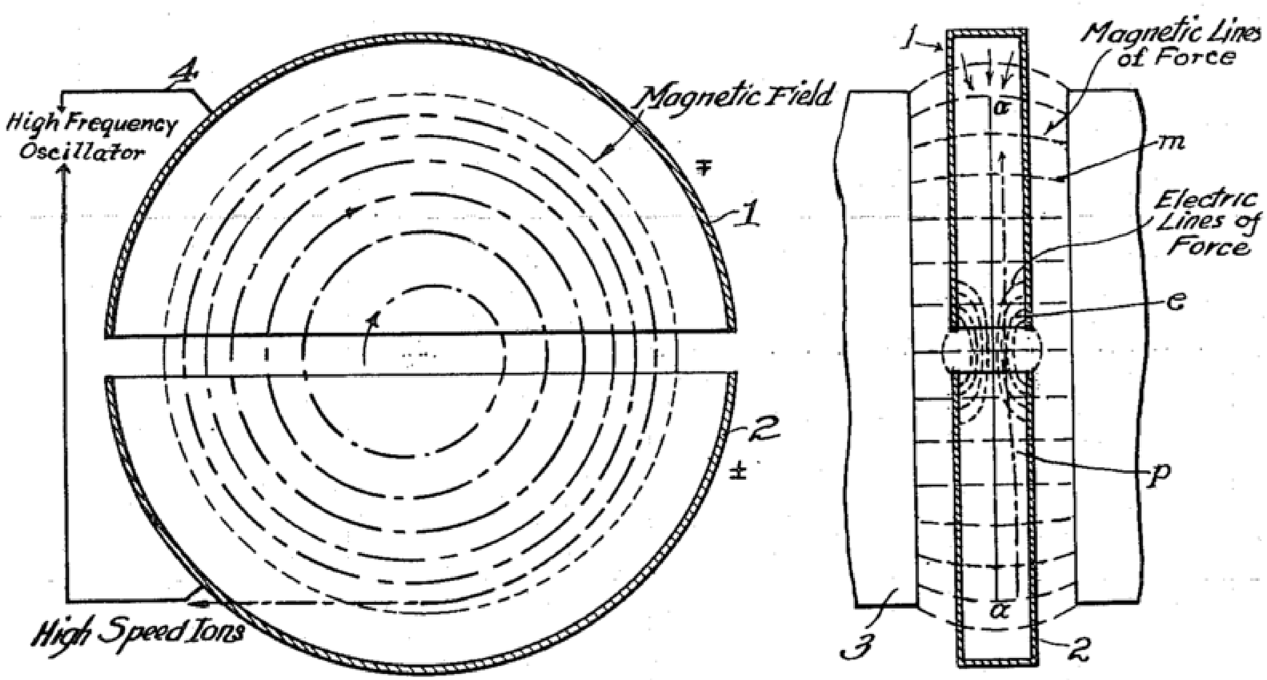
1936: Discovery of Muon

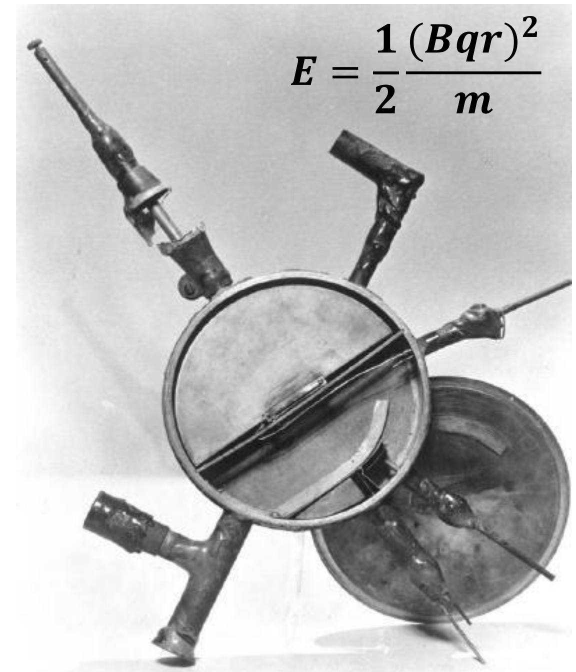


1947: Discovery of Pi meson

1903-1969 **1950**
Cecil Powell

Creation of elementary particles





$$E = \frac{1}{2}\frac{(Bqr)^2}{m}$$

1929년 Ernest Lawrence

1900	1910	1920	1930	1940	1950	1960	1970

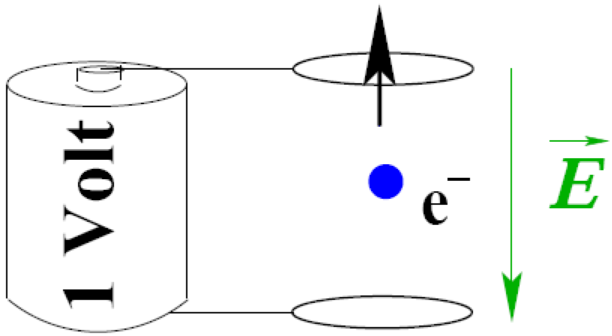
e p ne^+ μ πK $\Lambda\Sigma\Xi$ $\bar{p}$ ν_e $\rho\omega\eta\phi\Omega\cdots$

cyclotron synchrotron

Many new particles were created & discovered

Accelerator basics

Basic physics

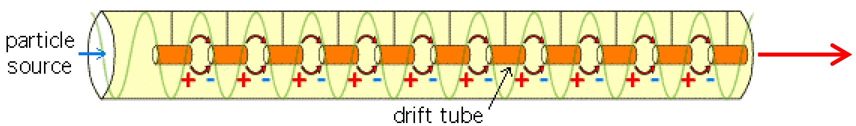


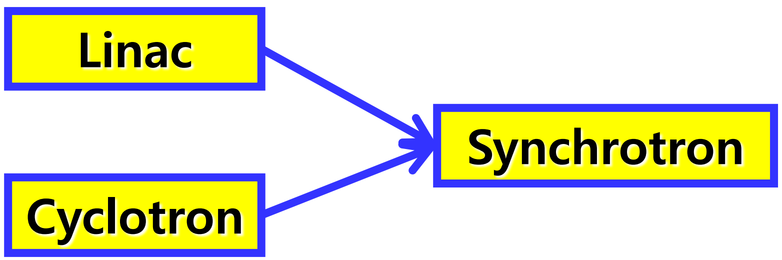
- Energy: eV
  - 1eV=1.6x10^{-19}J
    - ✓ MeV, GeV, TeV, …
      - – Mass and momentum are often written in GeV too. But it really means GeV/c^2 for mass and GeV/c for momentum.

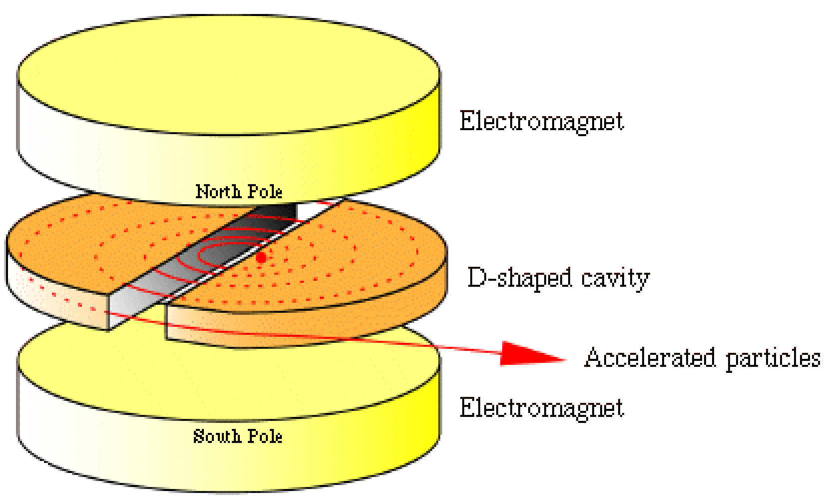
- Electromagnetism
  - $F = qE$ to accelerate particles
  - $F = qvB$ to bend particles
    - ✓ But in reality, much more complicate → Beam dynamics.

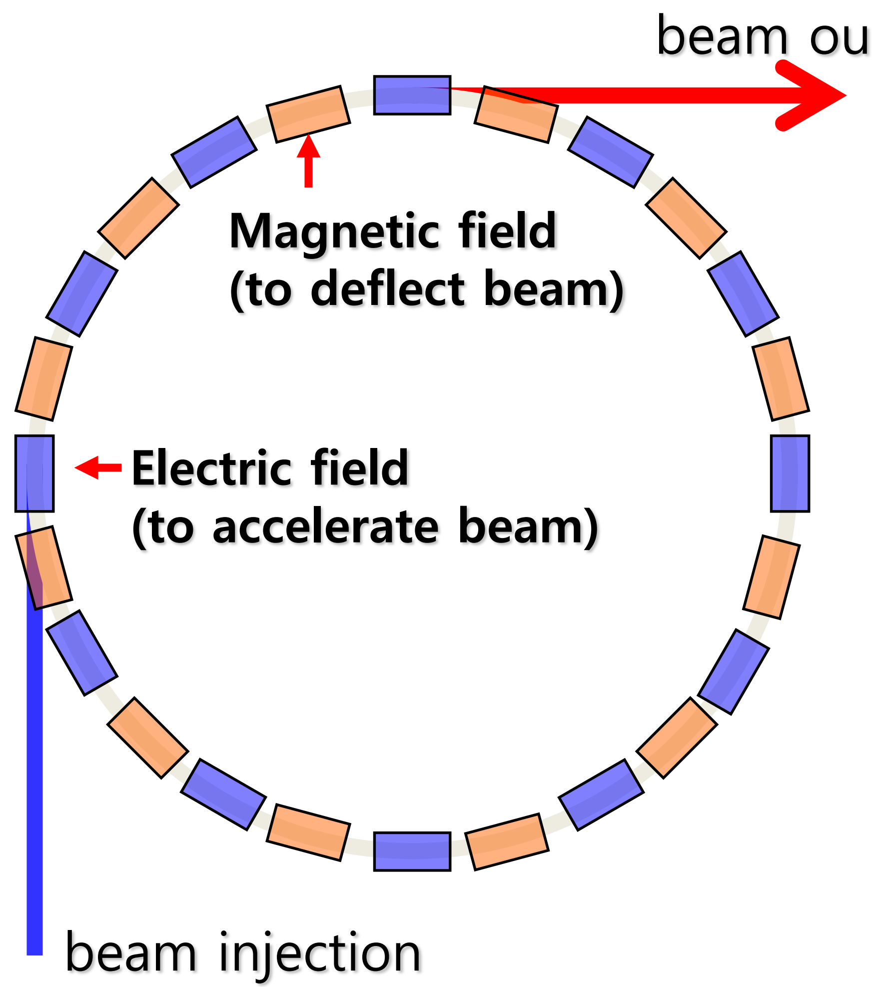
3 types of accelerators

- **All about size and Bremsstrahlung!**



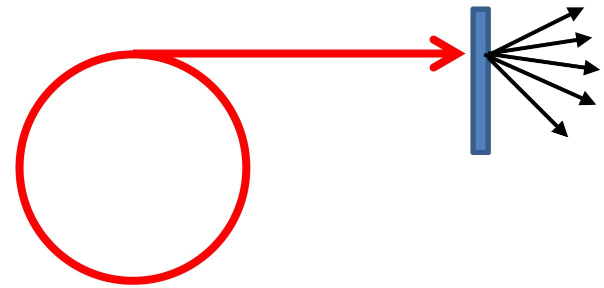






To look at elementary particles

- Order of magnitude
- Nucleons ~ GeV
- Quarks ~ 10GeV
- W/Z0 ~100 GeV
- Higgs, SUSY ~TeV
- …



Need more energetic beams!

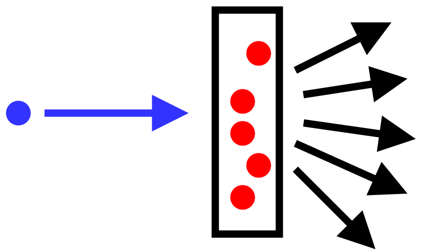
But, how?

Modern way of smashing

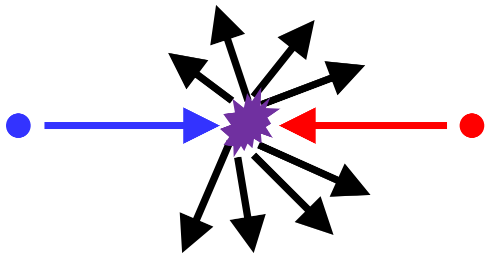
Today's main topic → Collider

Why use collider?

- Fixed target
  - $E_{CM} \sim \sqrt{2 m_T E_{beam}}$
    - ✓ 7TeV beam will make $E_{CM} \sim 1.2$TeV



- Collider
  - $E_{CM} = 2E_{beam}$
    - ✓ 7TeV beam will make $E_{CM} \sim 14$TeV



Q) What will be the beam energy to get $E_{CM} = 14$TeV in Target experiment?
A) ?

From the beginning to now

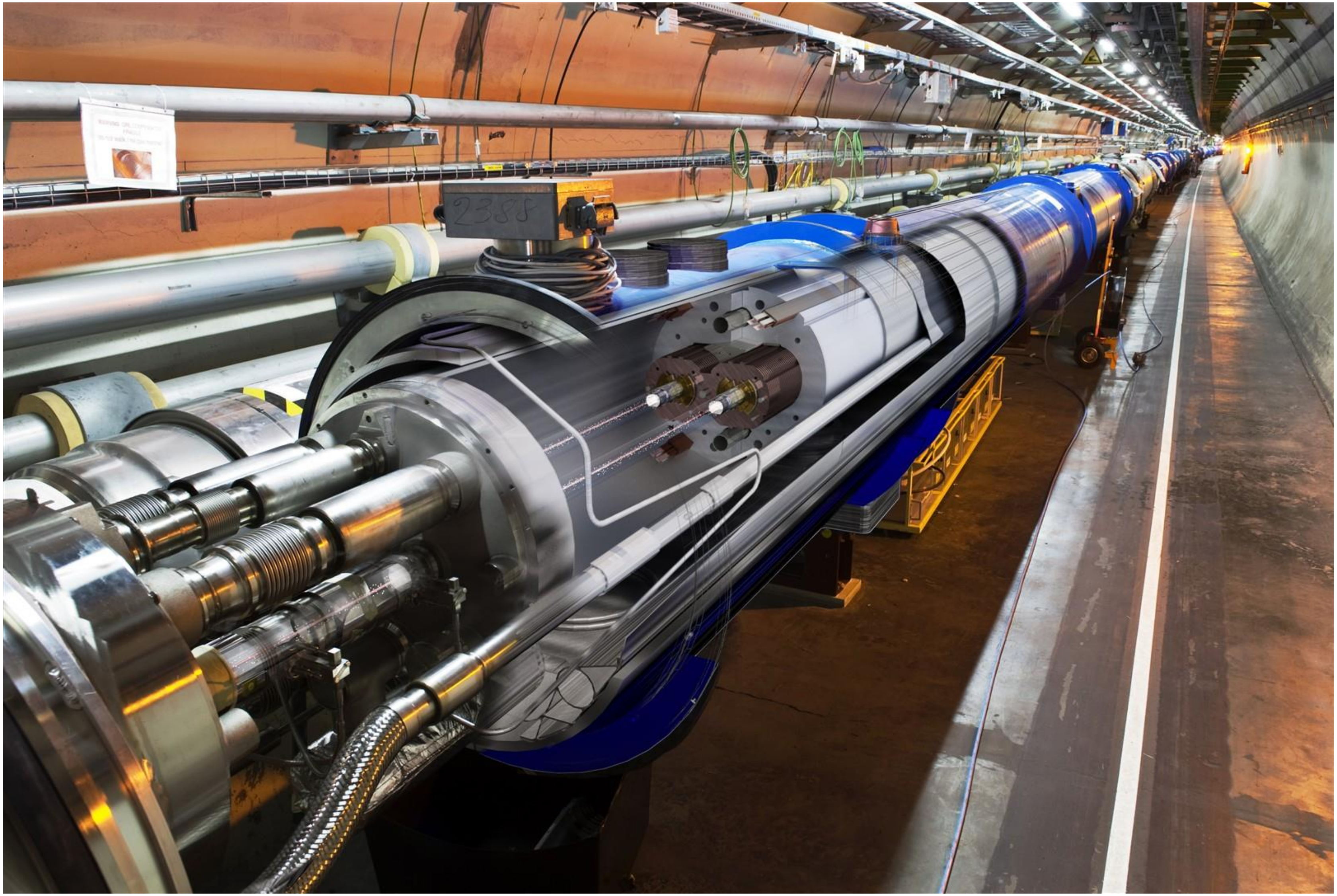
The first cyclotron (1930)
D~11cm, E~1.1 MeV

The latest synchrotron (2010)
D~9km, E~7TeV

after 80 years, 10^5 x larger and ~10^7 x more energetic

Introduction to LHC

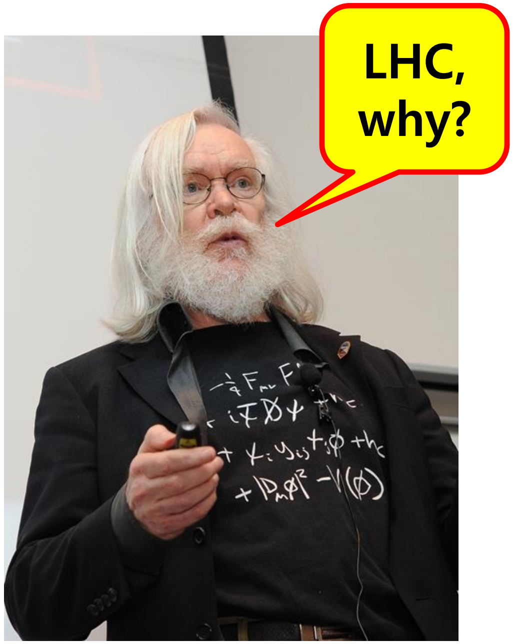
LHC



LHC, why? by John Ellis

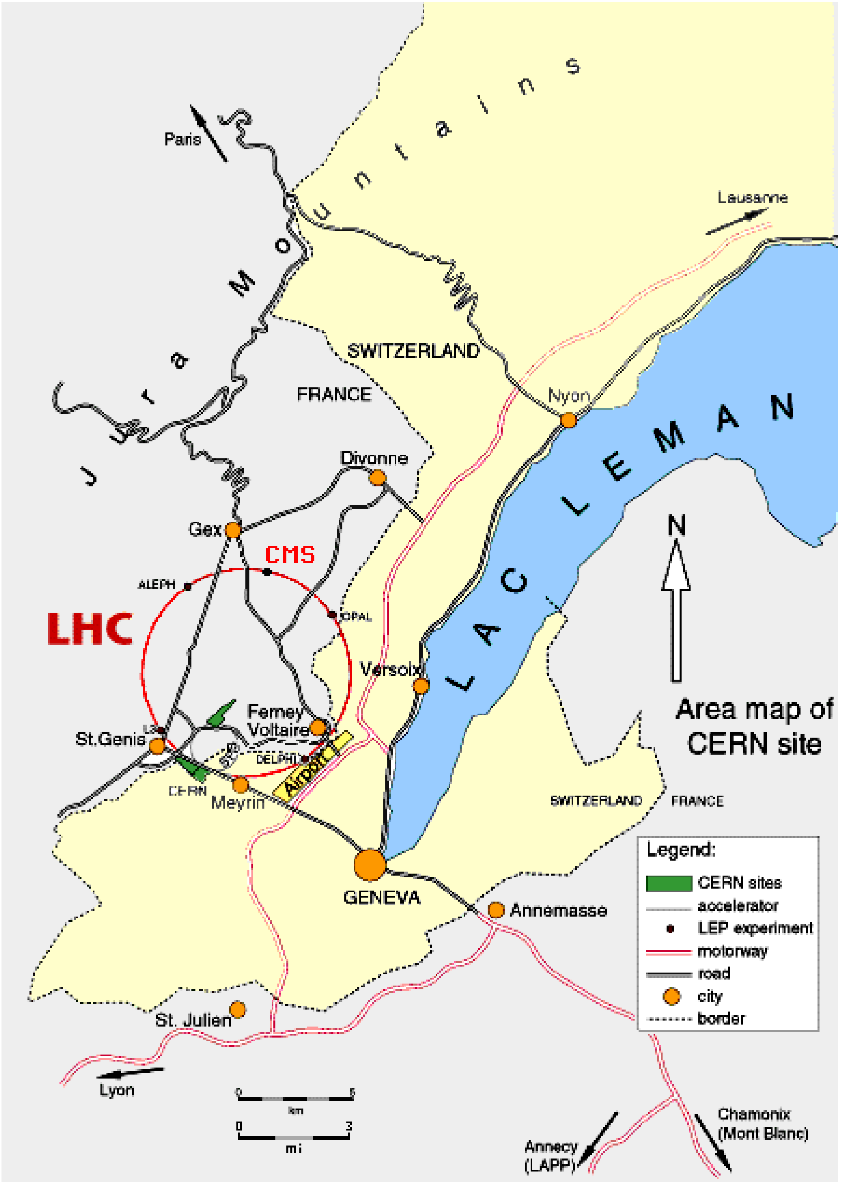
- Principal goal
  - Exploration of a completely new region of energies and distances
    - ✓ to the tera-electron-volt scale and beyond

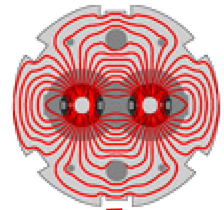
- Main objectives
  - Search for the Higgs boson
    - ✓ Confirm Standard Model
  - Explore new physics
    - ✓ Supersymmetry, Extra-Dimensions
  - Perhaps above all + to find something that the theorists have not predicted



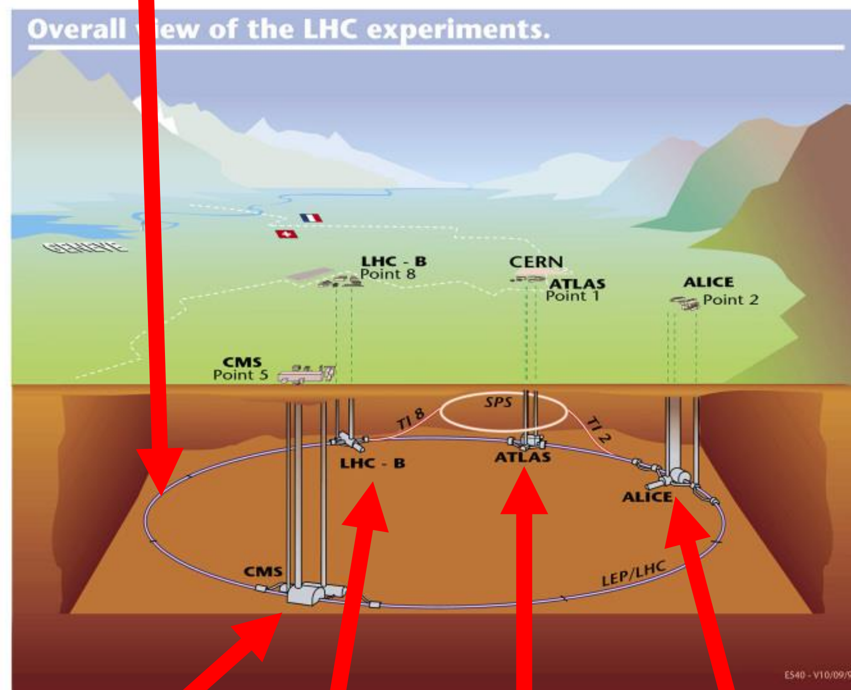
John Ellis
CERN Courier, May 2007

LHC, where?

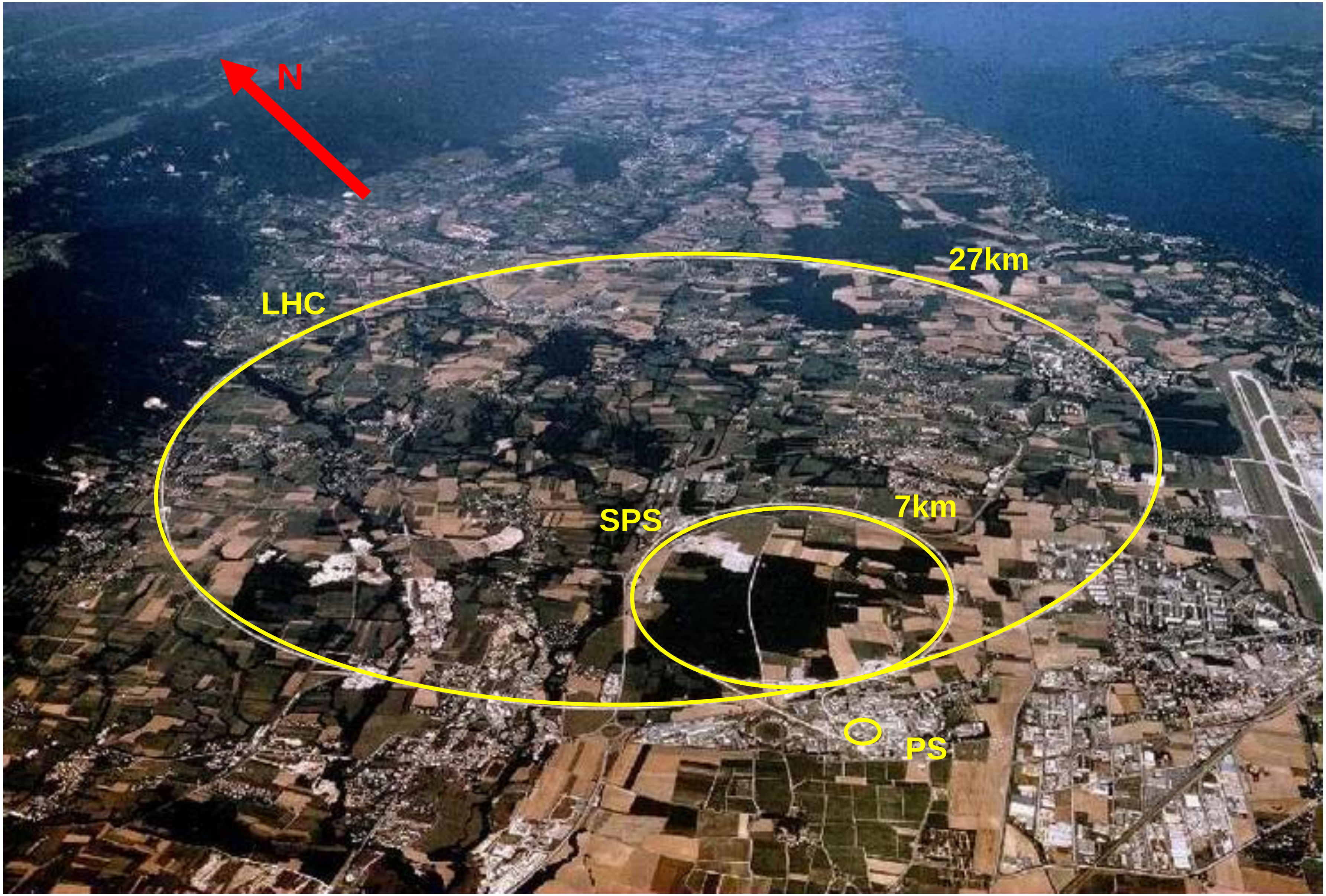




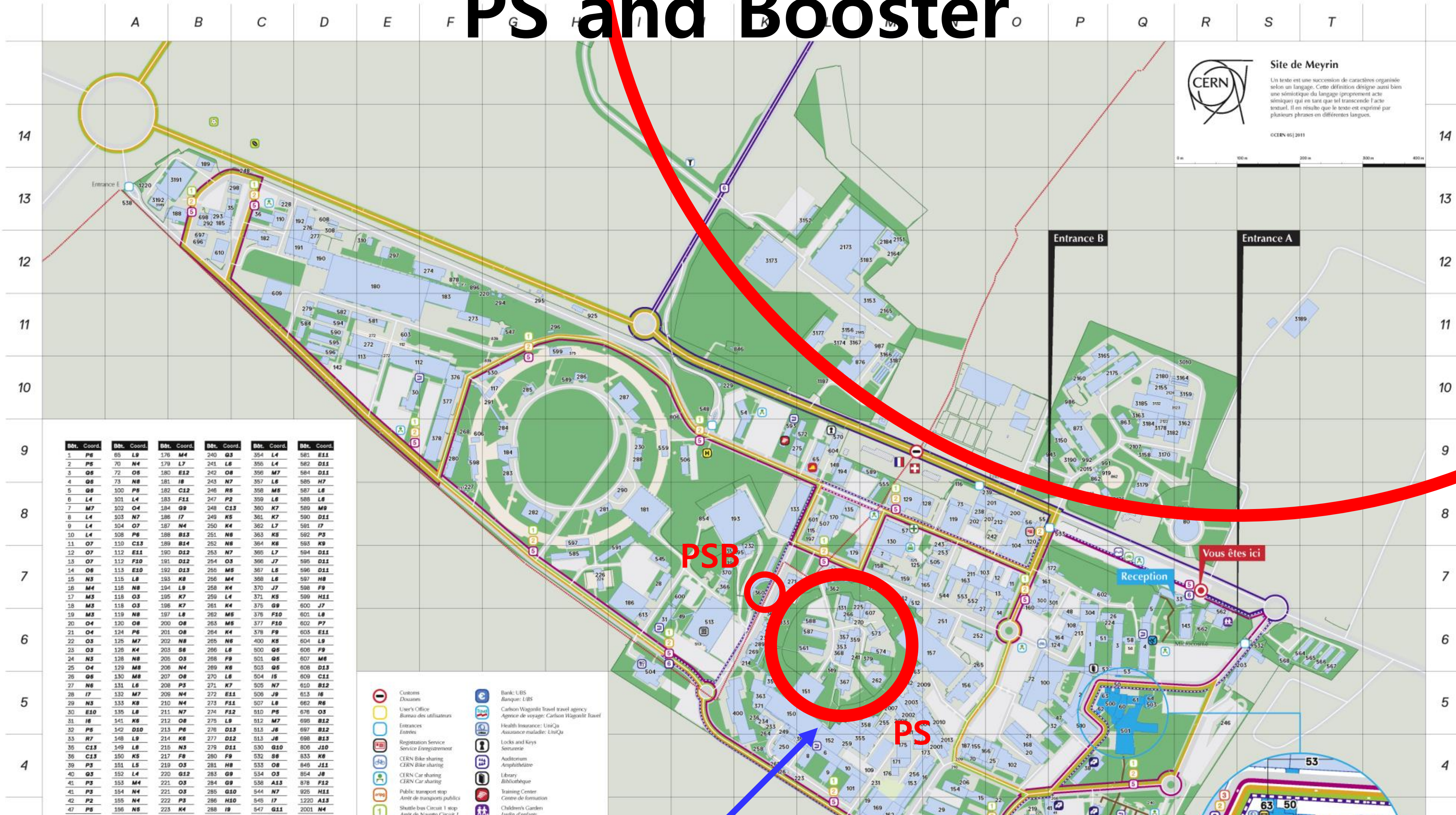
50-175m underground



Aerial view



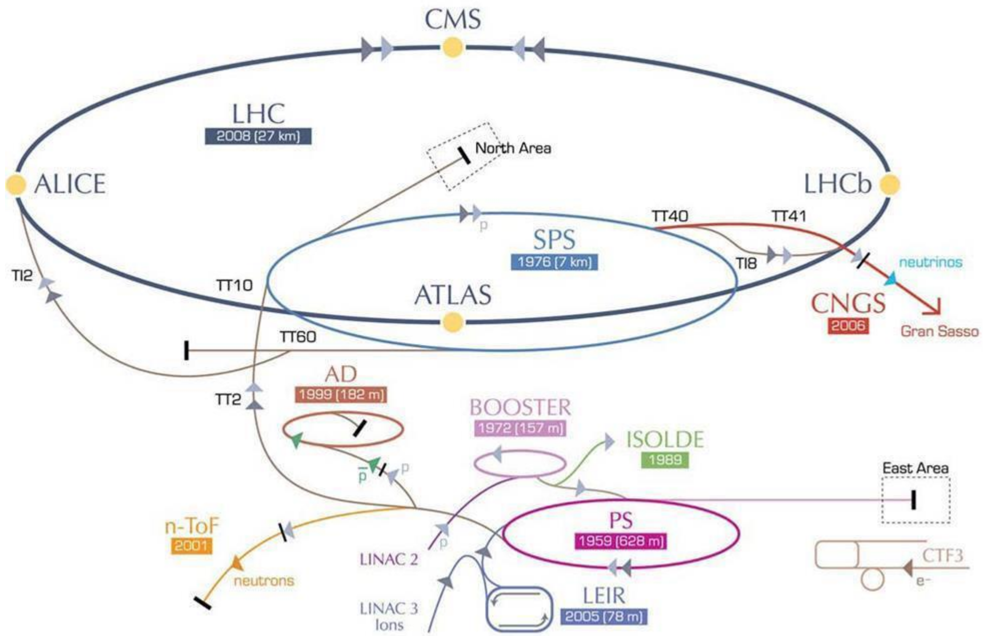
PS and Booster



LINAC to LHC

LINAC2: Proton starting point

LINAC3: Ion starting point



Large Hadron Collider, 7TeV

Super Proton Synchrotron 7km 450GeV

Proton booster 1.4GeV

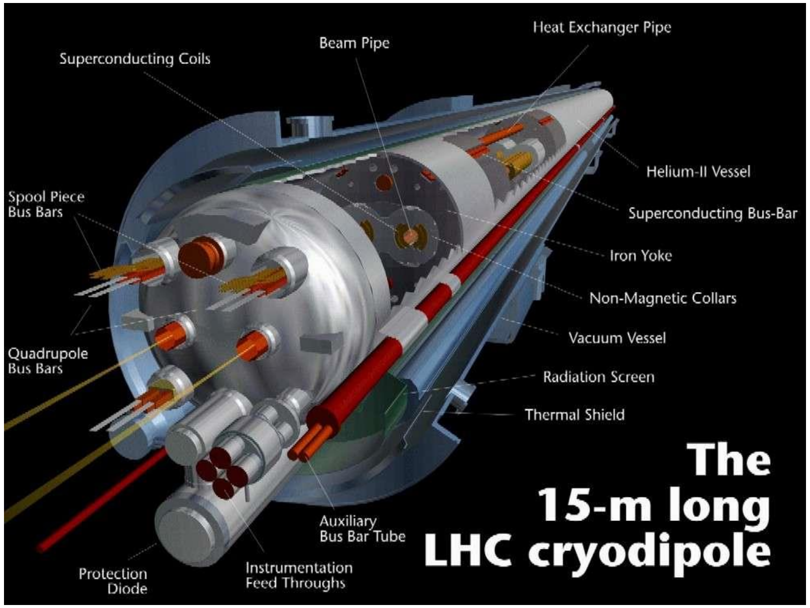
Low-Energy Ion Ring

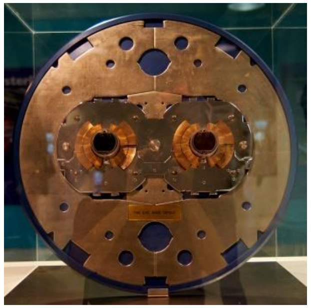
Proton Synchrotron 628m, 25GeV

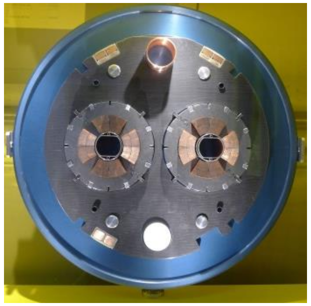
LHC Primer

Synchrotron components

- RF cavities
  - to accelerate
- Magnets
  - Dipole → to bend
  - Quadrupole → to focus
    - ✓Sextupole, Octupole, etc.
- Cryogenics
  - For superconducting
  - For cooling the machines
- Beam diagnostics
  - to monitor the beam movement







Facts and Figures, CERN 2007

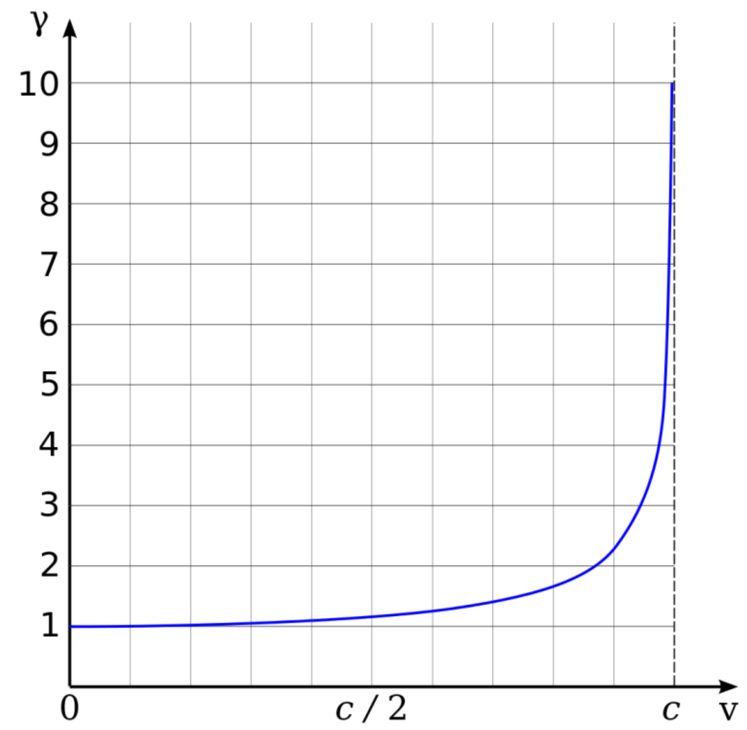
- **The largest machine in the world...**
  - The precise circumference = 26 659 m, with 9300 magnets.
  - pre-cooled to -193.2°C (80 K) with 10,080 tonnes of liquid N, then down to -271.3°C (1.9 K) with 60 tonnes of liquid He.
- **The fastest racetrack on the planet...**
  - Trillions of protons rotate the ring 11,245 times a second at "c".
  - Beam energy of 7 TeV, making head-to-head collisions of 14 TeV.
- **The emptiest space in the Solar System...**
  - Pressure is ~ 10^{-13} atm, ten times less than the pressure on the Moon!
- **The most powerful supercomputer system in the world...**
  - Each experiment will record ~100 000 DVDs data / every year.
  - ~10,000 computers will be networked as a Grid system.

Important parameters for us

- Beam properties
  - Beam type
    - ✓ Protons, electrons, heavy ions…
  - Beam energy
    - ✓ $\sqrt{s}$: MeV, GeV, TeV, …
  - Beam parameters
    - ✓ Number of bunches
    - ✓ Bunch intensity (#of particles in a bunch)
    - ✓ Beam crossing angle, emittance, beta
- Luminosity
  - $\mathcal{L}$: $cm^{-2}s^{-1}$
  - Integrated luminosity: pb^{-1}, fb^{-1}

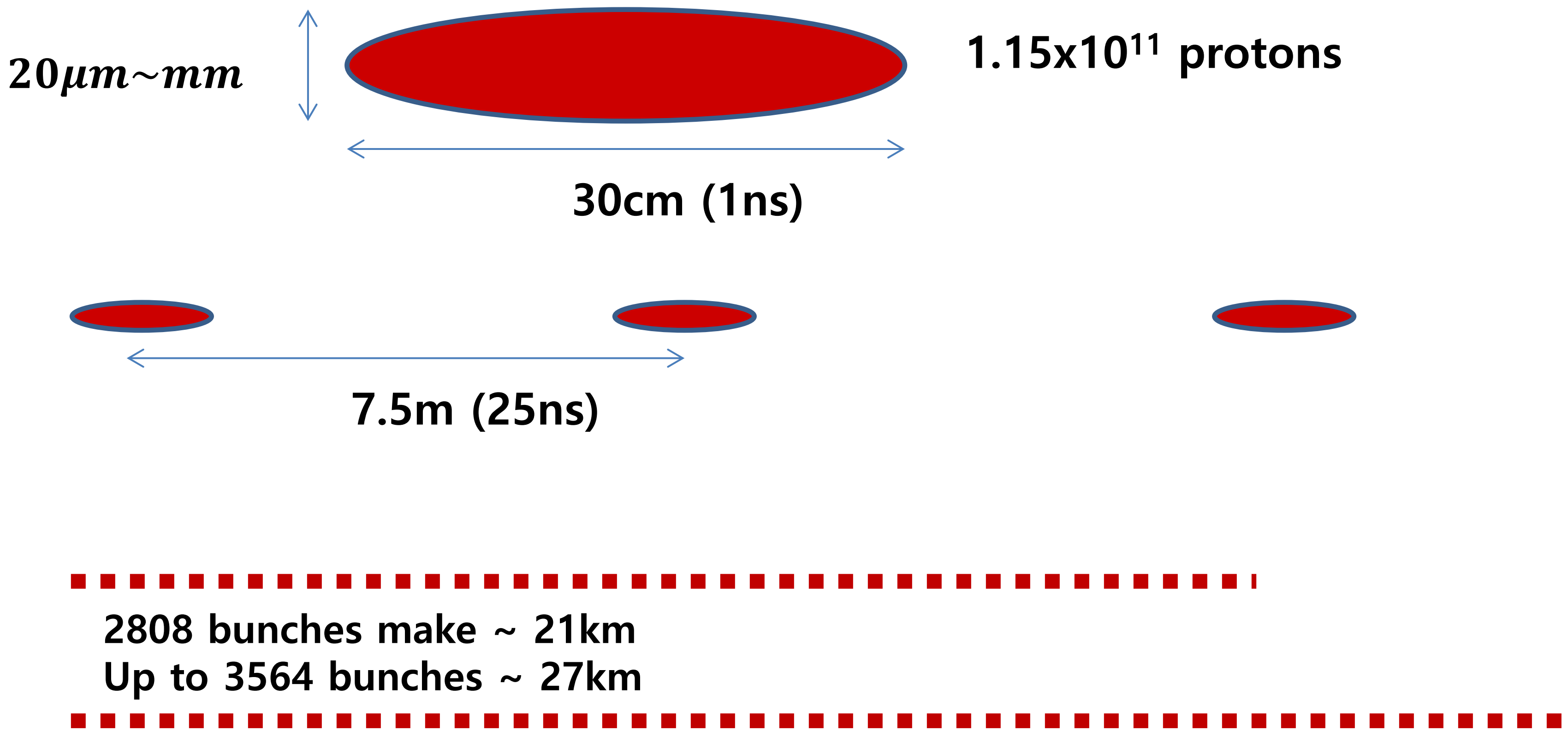
Beam energy

- 7 TeV beam! What does it really mean?
  - Proton mass ~ 1GeV/c² → negligible
    - ✓ Kinetic energy dominant → $E = \gamma mc^2$
  - $\gamma_{LHC} = \frac{7TeV}{1GeV} = 7000$
    - ✓ $\beta_{LHC} = 0.99999999$
  - $\gamma_{SPS} = 450$
    - ✓ $\beta_{SPS} = 0.99999753$



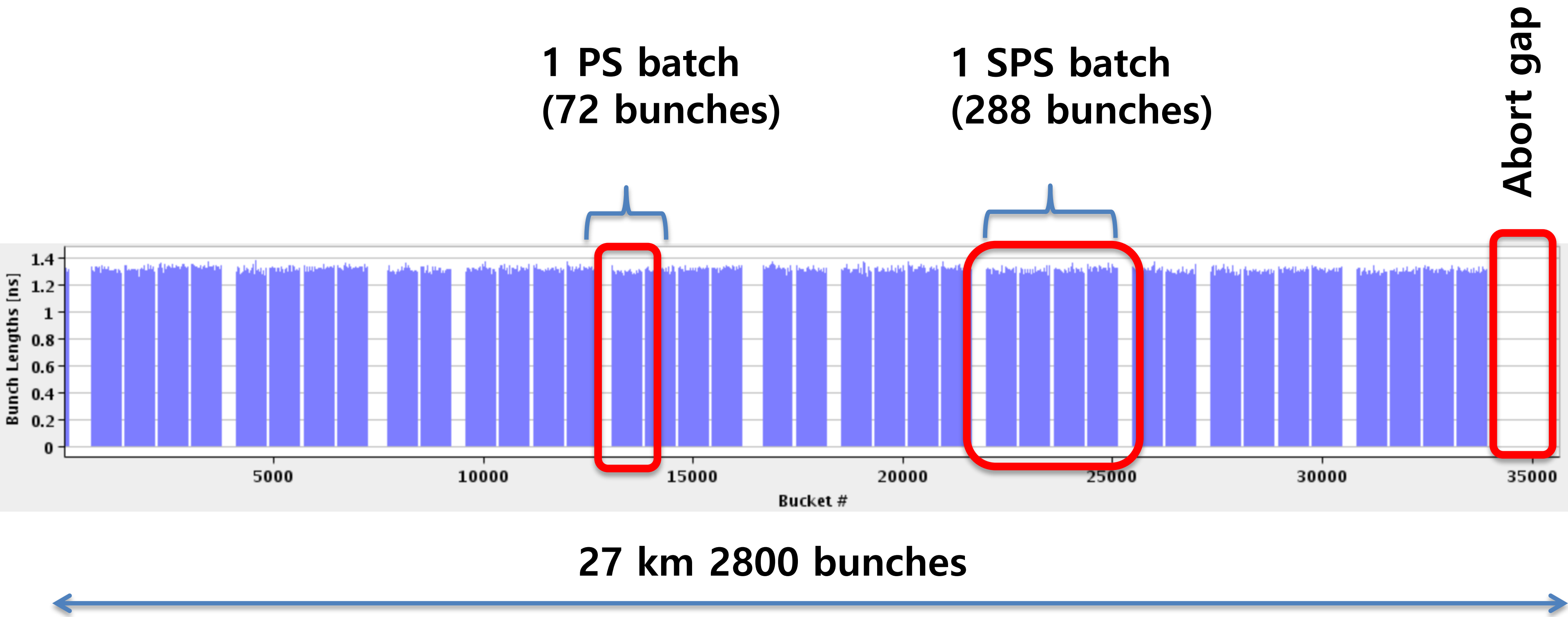
Beam parameters

- **Understanding beam bunch**



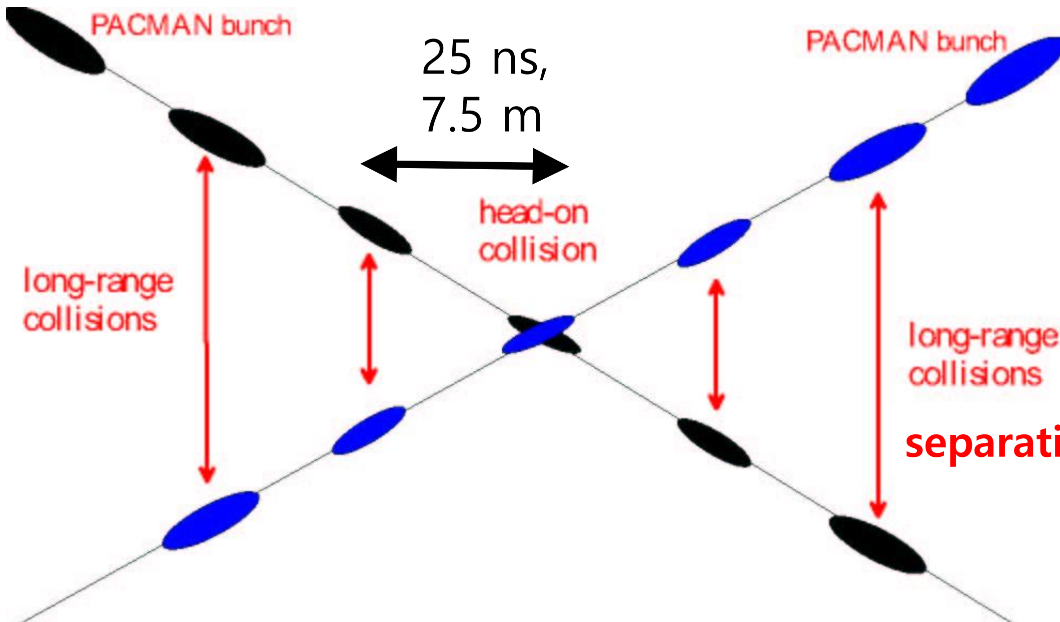
Bunch structure

- 25 ns bunch spacing
- ~2800 bunches
- nominal bunch intensity 1.15 x 10^{11} protons per bunch

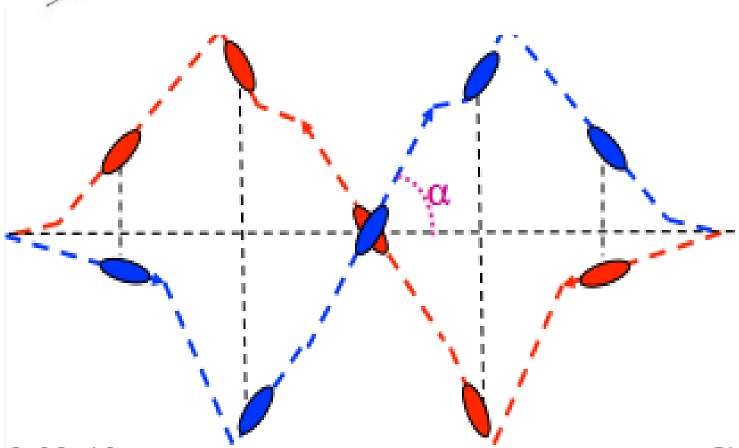


Bunch crossing angle

work with a crossing angle to avoid parasitic collisions.



separation: 10 -12 σ



at 25ns ≈ 30 long-range collisions per IP
at 50ns ≈ 15

geometric luminosity reduction factor

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Understanding Luminosity

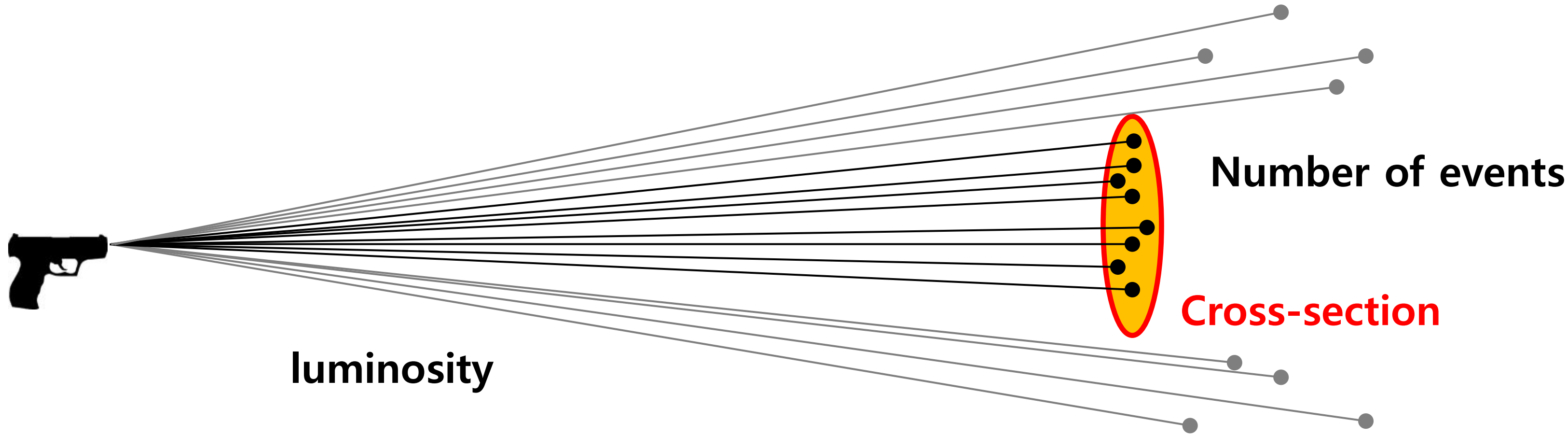
- Event rate: how frequently events happens? (# of events per second)
  - $R = \mathcal{L} \times \sigma$

    *some refer as $\frac{dR}{dt}$ instead of R

    ✓ Number of incident particles / $cm^2 s$ → $\mathcal{L}$ (luminosity)

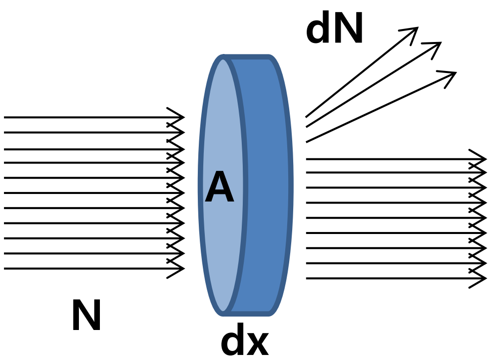
    ✓ Effective area for interaction → σ (cross-section)

    – the dimension is "cm^{-2}"

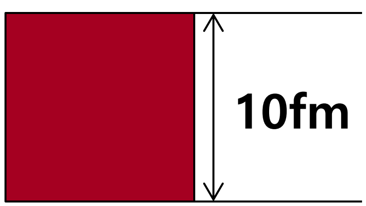


Cross-section

- Target
  - area=A, thickness=dx, n atoms/m^3
    - ✓ Total atoms in the target = n A dx
  - cross-section of each atom = σ
    - ✓ Total cross-section of the target = $n\sigma Adx$



- Beam
  - N particles enter in A and dN interact
    - ✓ $dN/N = n\sigma Adx/A = n\sigma dx$
  - $-\frac{dN}{N} = n\sigma dx \rightarrow N = N_0 e^{-n\sigma x}$
- Dimension of cross-section = [L]^2
  - Unit: 1 barn = 1b = $10^{-24}cm^2$=$10^{-28}m^2$
    - ✓ $r = r_0 A^{1/3}$ → 1barn is A~100 nuclei (Z~45)



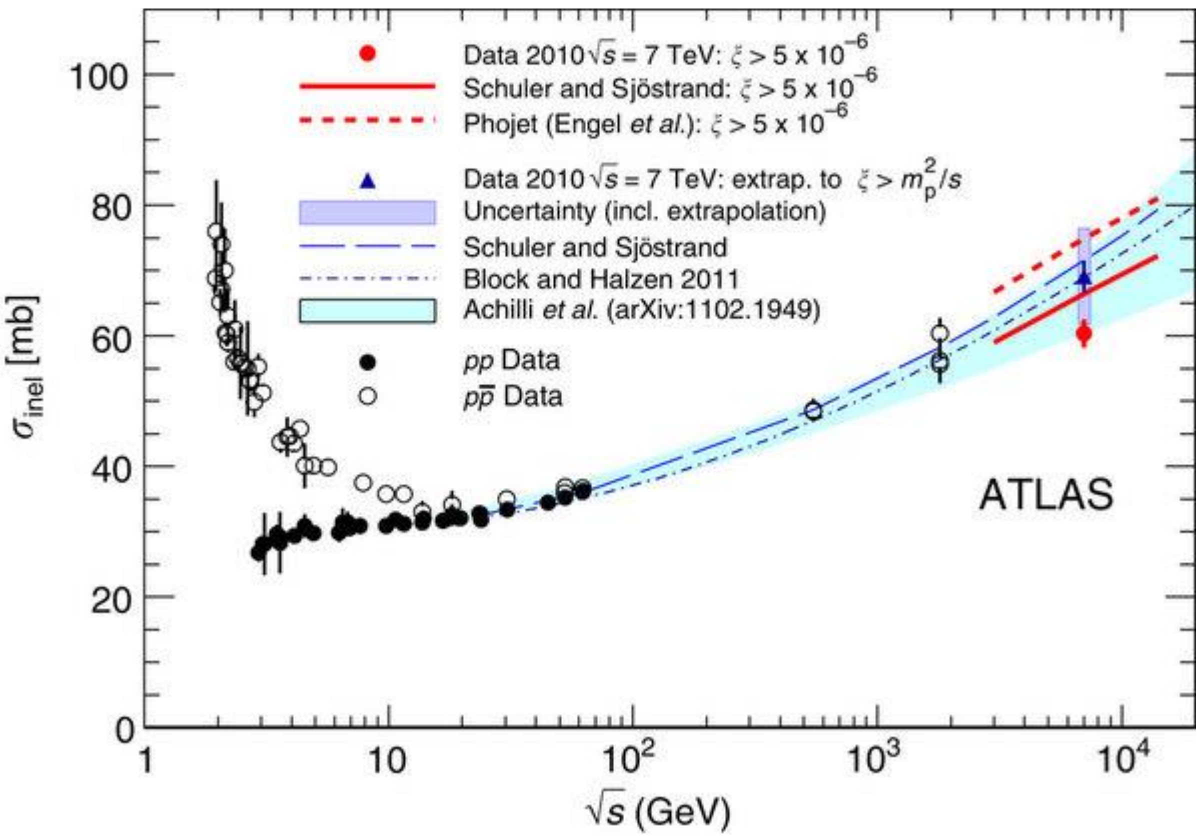
r_0=1.2fm

$10^{-12}cm = 10^{-14}m = 10fm$

Barn?

proton cross-section

- **Event rate,** $\frac{dN}{dt} = R = \mathcal{L} \times \sigma$
  - $\mathcal{L}$: **luminosity**



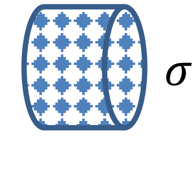
0.1barn

70mb

Only 1 collision happens when 10^{25} beam particles incident

Calculation of luminosity

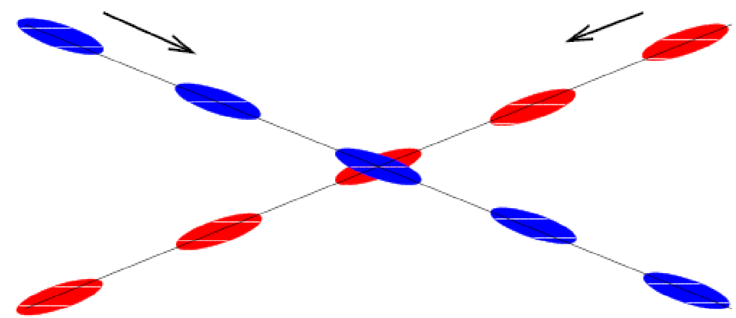
- In fixed target experiment → easy
  - $\mathcal{L} = \Phi \rho_T l \; [T^{-1} L^{-3} L^{1}]$



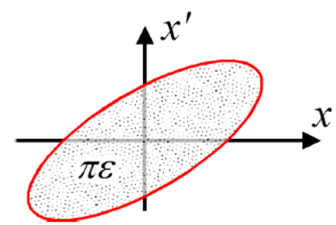
- For collider → complicate

Target is also moving!

  - $\mathcal{L} = \frac{N_1 N_2 n_b f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{N^2 n_b f \gamma}{4\pi \varepsilon_n \beta^*} F$



N	number of particles per bunch
n_b	number of bunches / beam
f	revolution frequency
σ*	beam size at interaction point
F	reduction factor due to crossing angle
ε	emittance
ε_n	normalized emittance = $\varepsilon\gamma\beta$
β*	Lattice beta function at IP

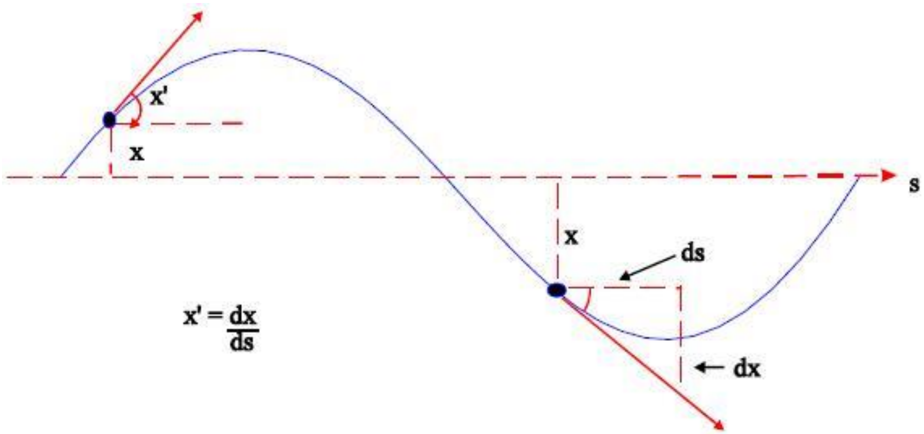


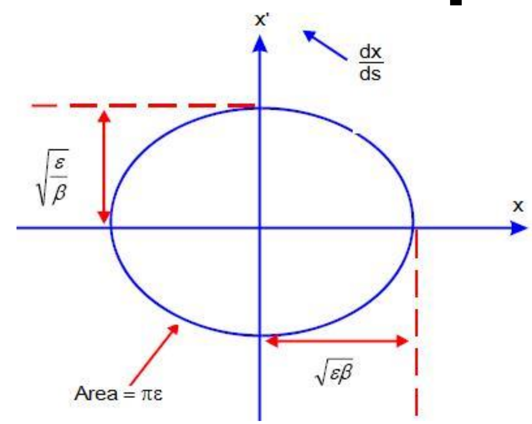
$\sigma^* = \sqrt{\beta^* \varepsilon}$

$\varepsilon_n = \varepsilon \beta \gamma$

Emittance & beta

- **Beam movement along its central path**

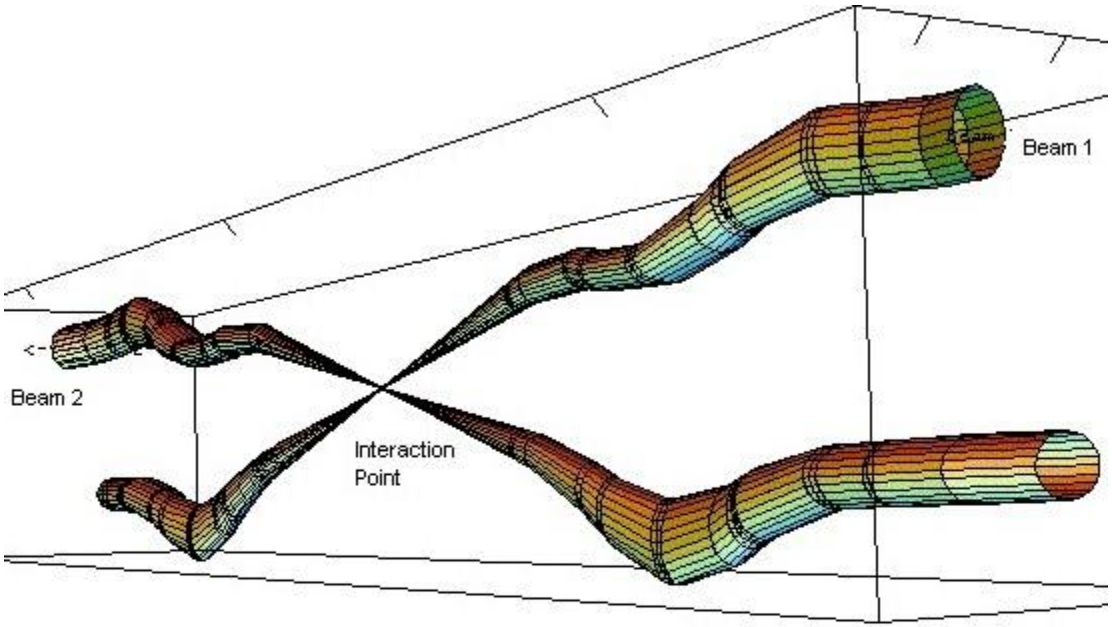


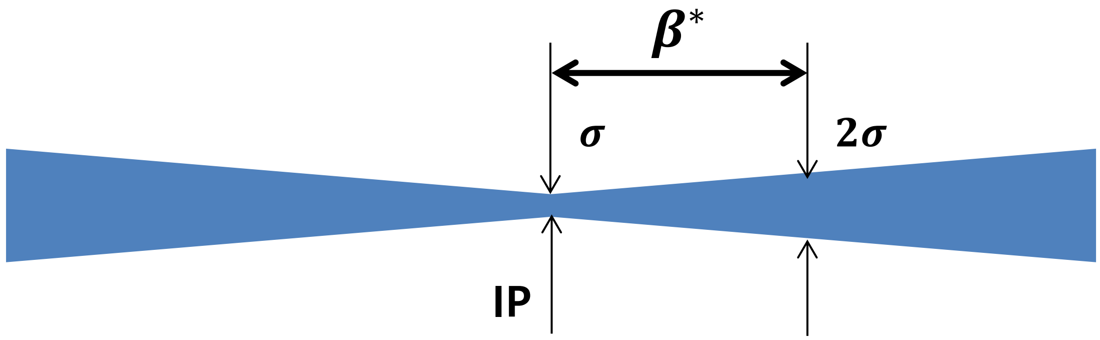


  - **Emittance: transverse & longitudinal**
    - ✓ **"low" emittance → small beam size, small momentum spread**
  - **Beta: transverse beam size^2/emittance**
    - ✓ **Small beta → beam is squeezed**

Beta*

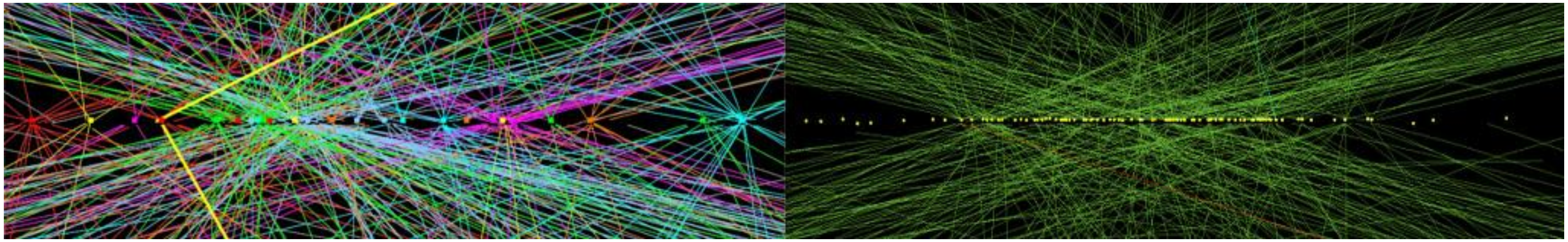
- **Beta* means beta at IP**





Pile-up!

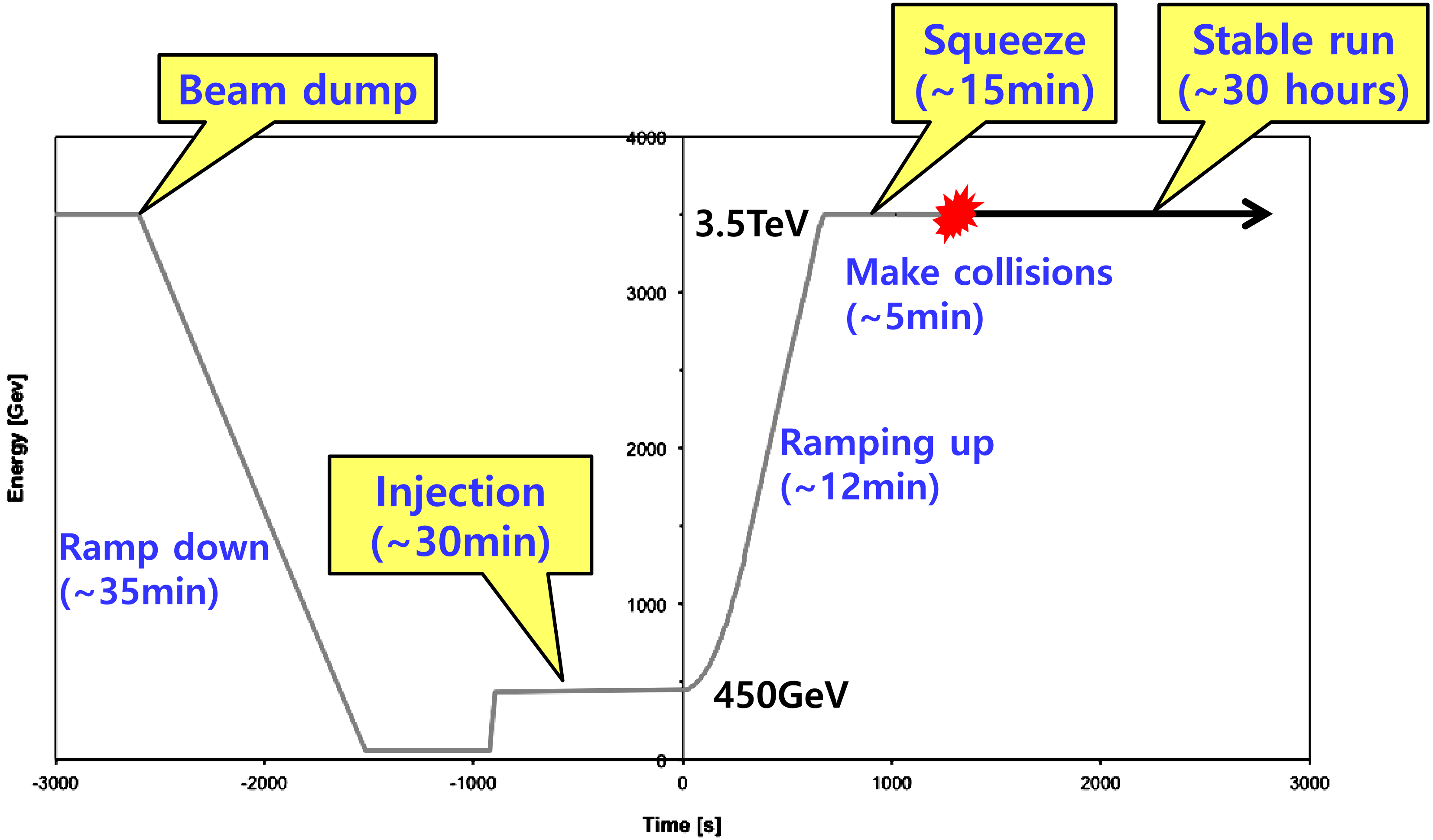
- **Multiple events in a photo**
  - Pileup in Firework
    - ✓ How many explosions can you identify?
  - Pileup in LHC
    - ✓ How many vertices can you reconstruct?



Pile-up estimation

- **Pileup: average number of collisions produced per bunch crossing**
  - Bunch crossing rate, R_{BC}
    - ✓ $R_{BC} = \frac{c}{27km} \times n_b = 11253Hz \times n_b$
  - For the nominal LHC
    - ✓ $R = \mathcal{L} \times \sigma_{inel} = 10^{34}cm^{-2}s^{-1} \times 70mb \sim 7 \times 10^8 Hz$
      - $Pileup = R/R_{BC} = 7 \times 10^8/(11253 \times 2808) \sim 22$
  - For example, LHC 2012 run
    - ✓ $R = \mathcal{L} \times \sigma_{inel} = 7.7 \times 10^{33}cm^{-2}s^{-1} \times 70mb \sim 5.4 \times 10^8$
      - $Pileup = 5.4 \times 10^8/(11253 \times 1380) \sim 35$

Typical LHC operational cycle



LHC Run history so far

Pre-LHC history

2010

2009: Repair, re-commissioning and beam commissioning →

Sep.19 incident

2008: Start of beam commissioning →

2005: Start of LHC Hardware commissioning →

2003: Start of LHC installation →

← 2002 : LEP removed

2000

← 2000: LEP II operation end

← 1996: Final approval for LHC construction

← 1994: Approval of the LHC by CERN Council

1990

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

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

← 1982: First studies for the LHC project

1980

2008 accident

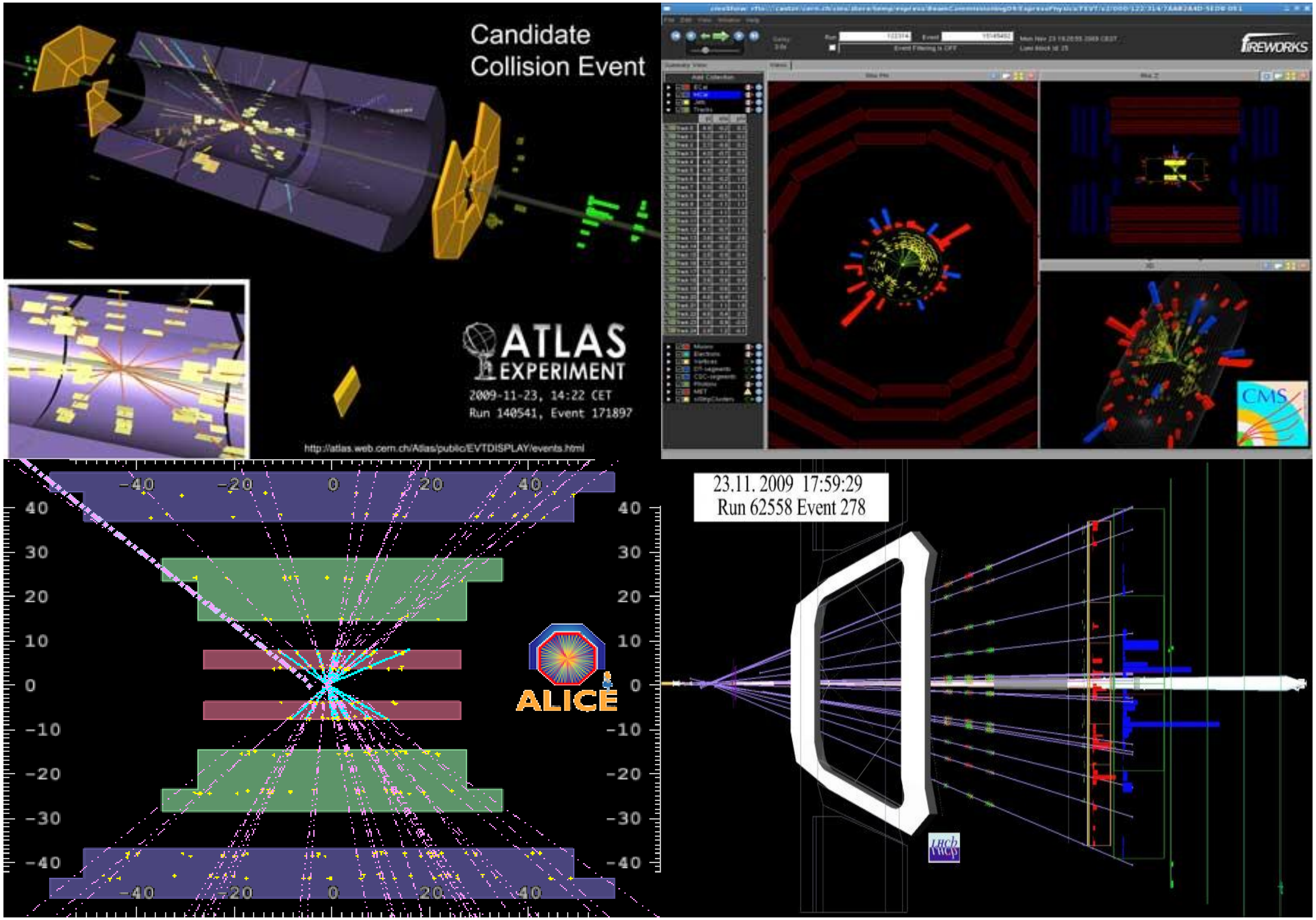
The accident happened during test runs without beam. (Sep.19, 2008)

A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressur e wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.

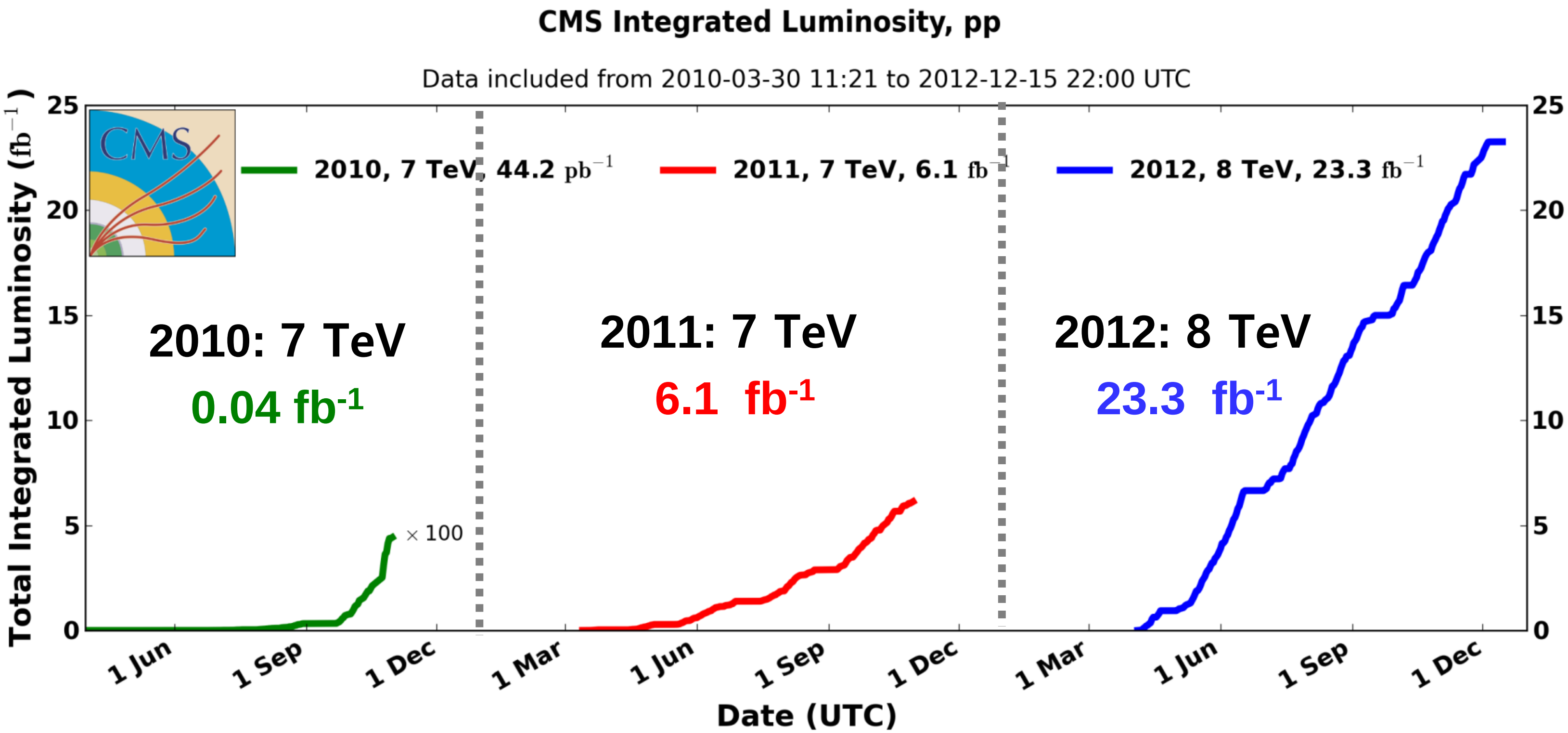
53 magnets to repair,
14 months downtime

J. Wenninger for LHC, PAC09

First collision, Nov. 23, 2009



LHC run 1



Total integrated luminosity ~ $30fb^{-1}$

Run 1 Performance

	Design	2010	2011	2012
Energy [TeV]	7	3.5	3.5	4.0
Bunch spacing [ns]	25	150	50	50
No. of bunches	2808	368	1380	1380
# protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
β^* [m]	0.55	3.5	1.0	0.6
Normalized emittance	3.75	~2.0	~2.4	~2.5
Crossing angle [μrad]	285		100	145
Peak luminosity[$cm^{-2}s^{-1}$]	1.0×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Ave. Pileup	26	8	17	38

7 TeV	7 TeV	8 TeV
0.04 fb^{-1}	6.1 fb^{-1}	23.3 fb^{-1}

Discovery of Higgs, 2012

LHC Run2 and future

LS1 (2013-2014)

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

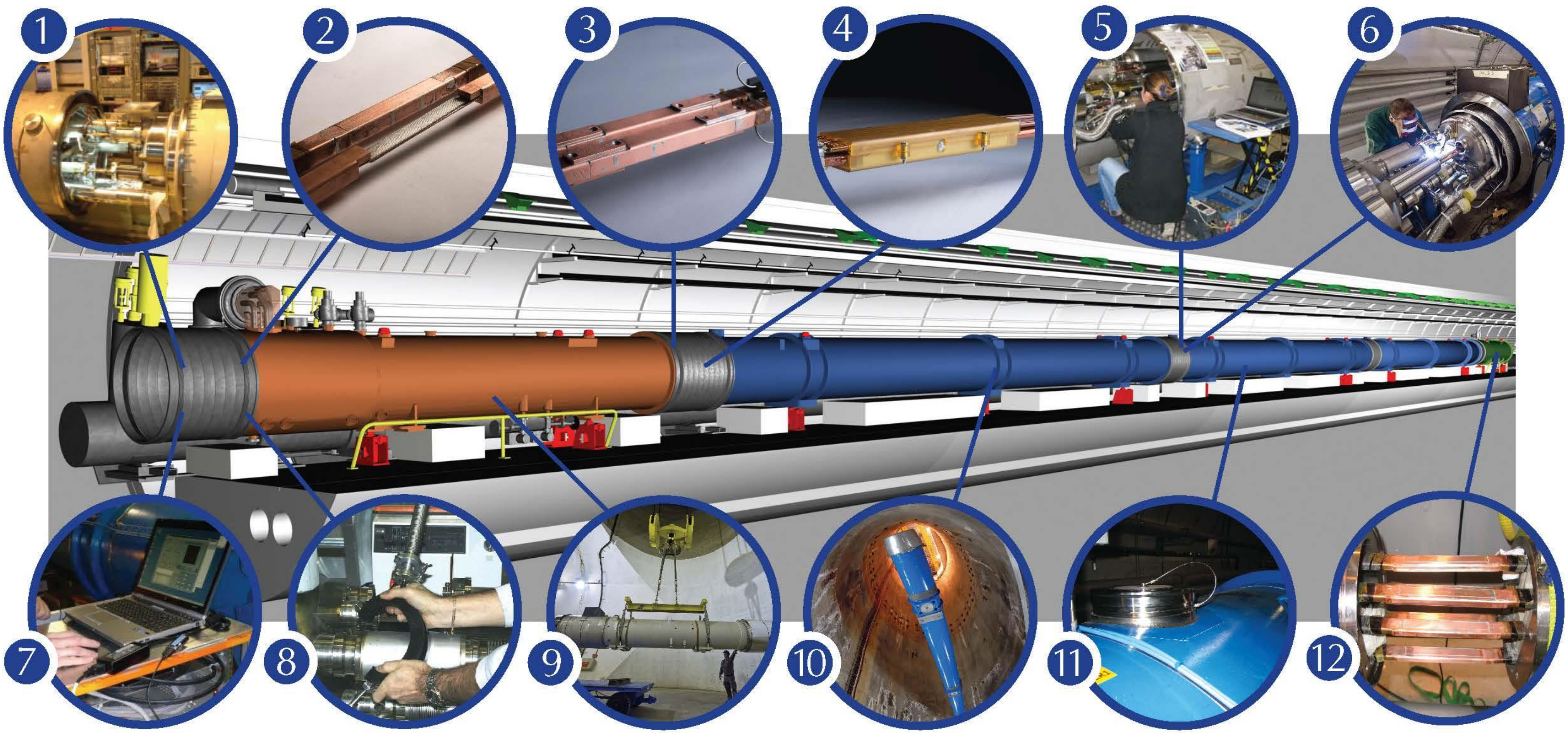
Complete reconstruction of 3000 of these splices

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

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

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

Superconducting Magnets and Circuits Consolidation (SMACC)

Monumental effort

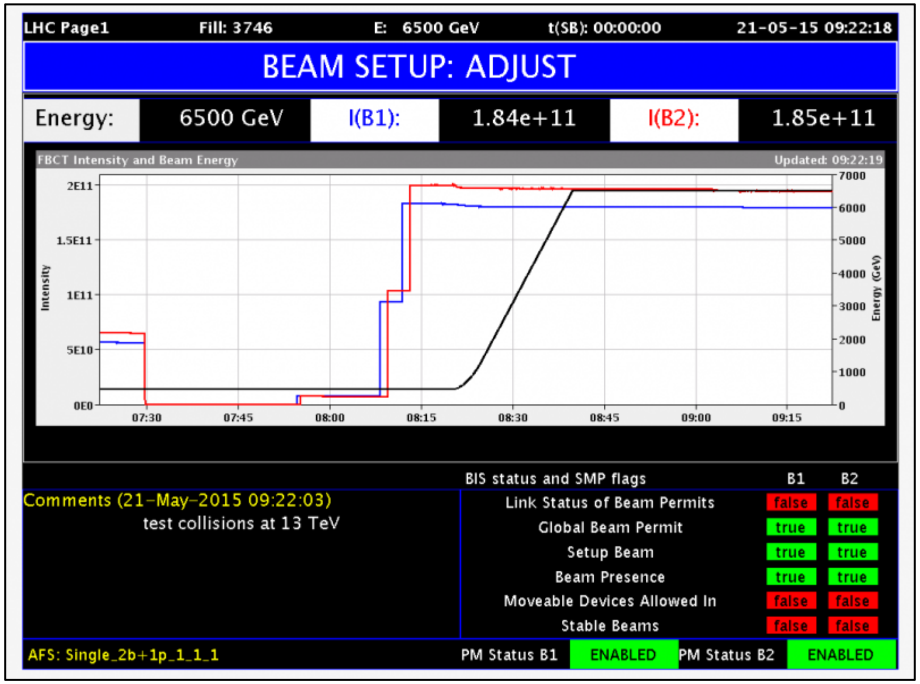
- Over 350 persons involved
- Including preparation: ~1,000,000 working hours
- No serious accidents!

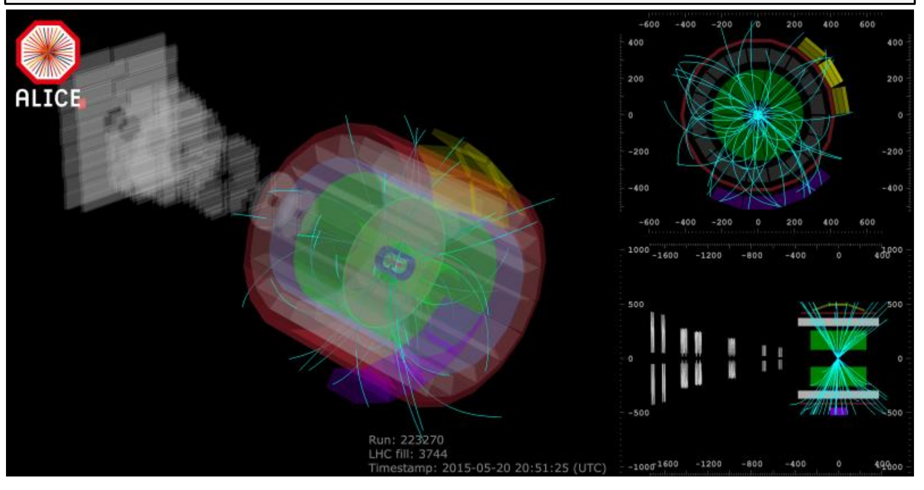
Jean-Philippe Tock

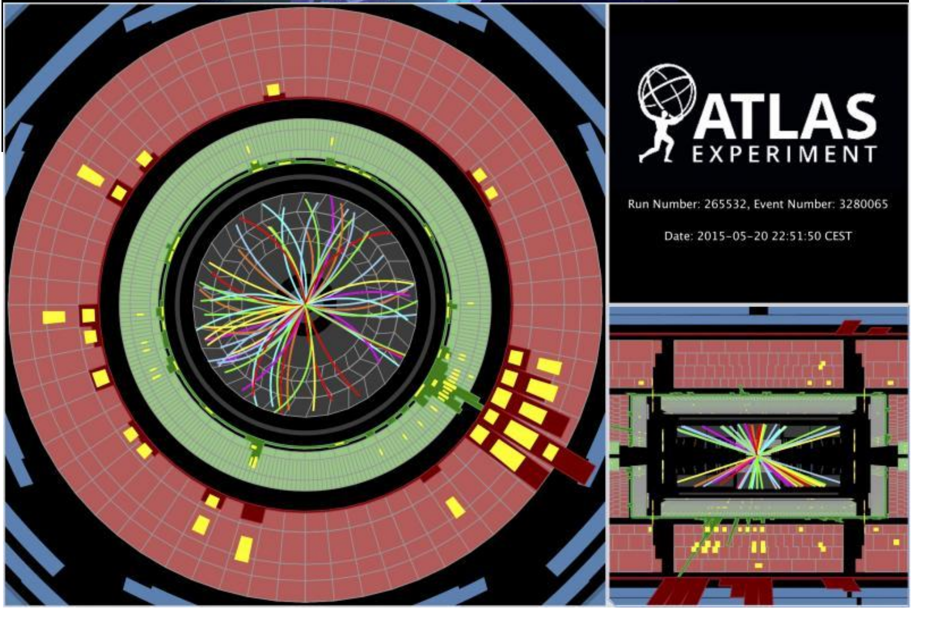
Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)

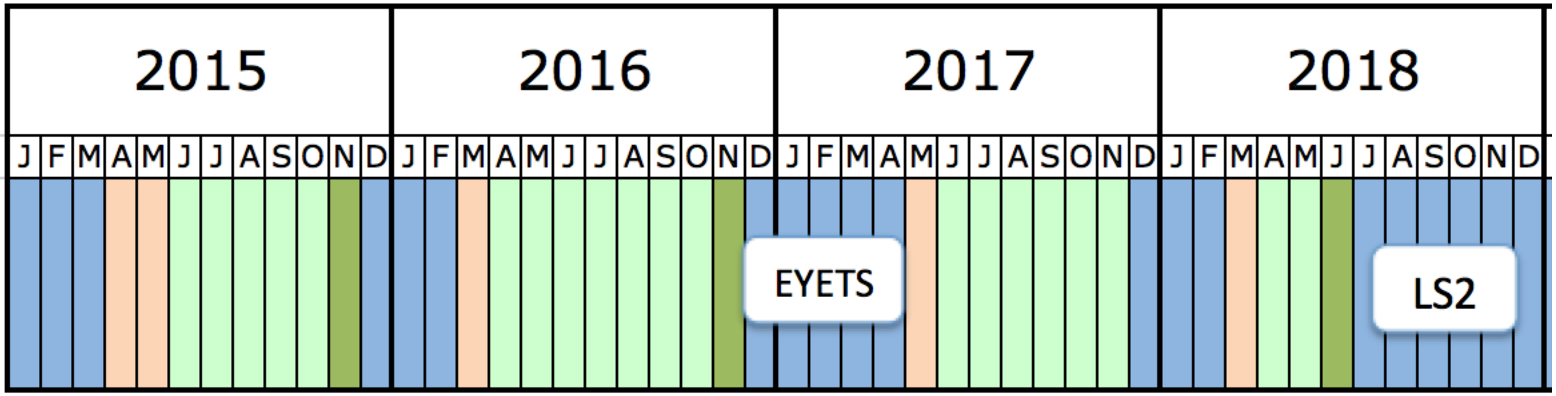
13TeV Collisions (May 20, 2015)

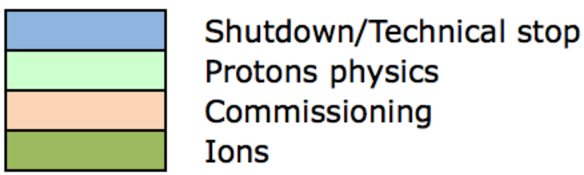






Run 2

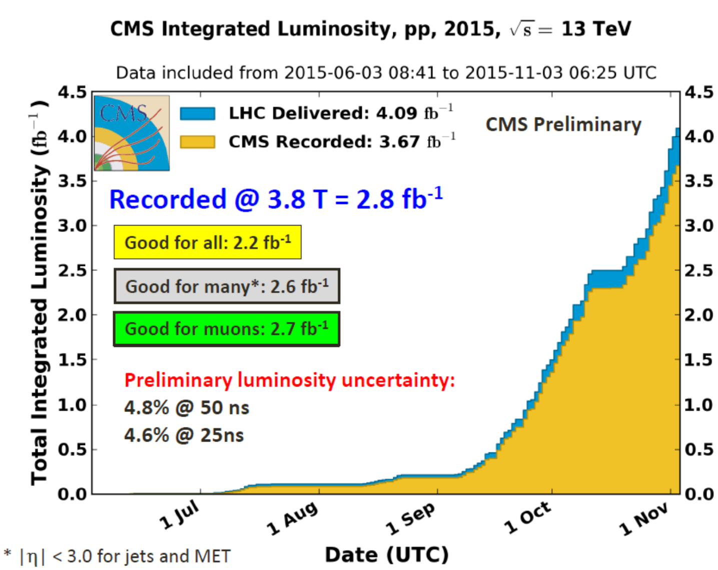


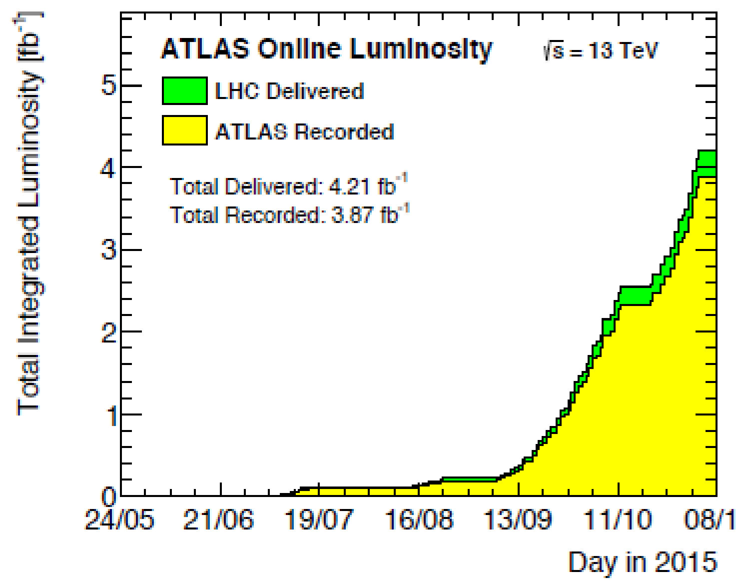


Cryogenic system to supply Liquid He was impaired

→ collected only ~¾ of the delivered luminosity

Cryo system will be repaired during the 2016 YETS





Performance plan for 2015

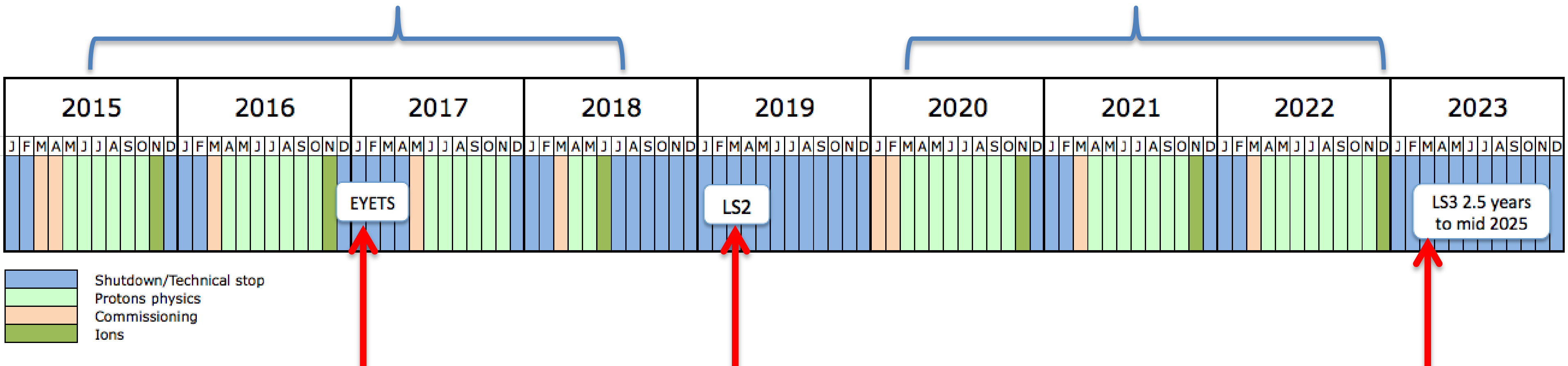
	Design	2012	2015
Energy [TeV]	7	4.0	6.5
Bunch spacing [ns]	25	50	25
No. of bunches	2808	1380	2748
# protons/bunch	1.15×10^{11}	1.7×10^{11}	1.2×10^{11}
β^* [m]	0.55	0.6	0.8→0.4
Normalized emittance	3.75	~2.5	3.1
Crossing angle [μrad]	285	145	290
Peak luminosity[$cm^{-2}s^{-1}$]	1.0×10^{34}	7.7×10^{33}	8.5×10^{33}
Ave. Pileup	26	38	22

50 ns data: 100 pb^{-1}
25 ns data: 4.2 fb^{-1} delivered, 3.8 recoded (ATLAS),
4.1 fb^{-1} delivered, 3.7 recoded (CMS) [2.8 with 3.8T]
Peak Luminosity: 5.1×10^{33} $cm^{-2}s^{-1}$ (Run1: 7~$8 \times 10^{33} cm^2 s^{-1}$)

Run2, Run3 and HL-LHC

Run 2: 13~14 TeV with peak luminosity of ~1.7×10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV with peak luminosity of ~2×10^{34} cm^{-2} s^{-1}

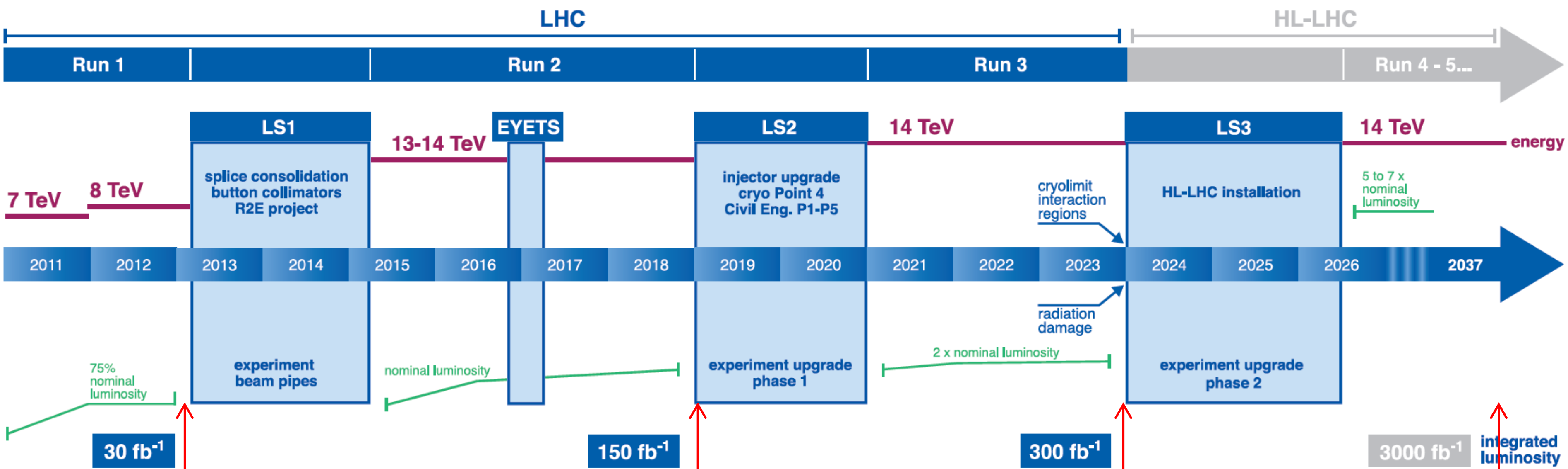


EYETS (19 weeks)
Extended year end technical stop (CMS)

LS2 (18 months)
Connection of LINAC4
LHC Injectors Upgrade

LS3 (30 months)
High Luminosity LHC

Long range plan



peak =7.7nb-1/s, total ~30fb-1
Pileup(Max)~35,Bunch spacing=50ns

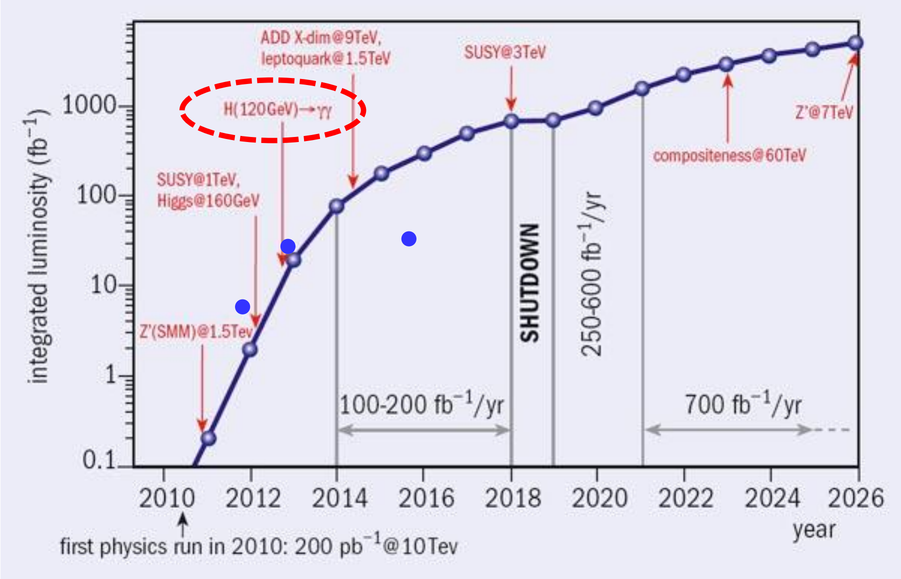
peak =17nb-1/s, total ~150fb-1
Pileup(Max)~42, Bunch spacing=25ns

peak =20nb-1/s, total ~300fb-1
Pileup(Max)~42, Bunch spacing=25ns

peak =50nb-1/s, total ~3000fb-1
Pileup(Max)~140, Bunch spacing=25ns

Final remarks

- **Dec.7, 2009 CERN Courier**
  - **Albert De Roeck, John Ellis and Sven Heinemeyer**



- **2015 was another record breaking year**
  - **13TeV with ~ design luminosity**
- **Let's explore a new land together!**