

Introduction to the LHC

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CMSDAS @ NTU, Taipei, Taiwan

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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**

Contents

1. What is Particle Physics? How?
2. Accelerator basics
3. Introduction to LHC
4. LHC primer
5. LHC Run history so far
6. LHC Run2 and future

What is Particle Physics? How?

What is Particle Physics?



1922-
Leon Lederman

1988

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

Leon Lederman's definition:

"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, $\gamma, e, p \rightarrow$ visible

- De Broglie wave: $\lambda = \frac{h}{p}$

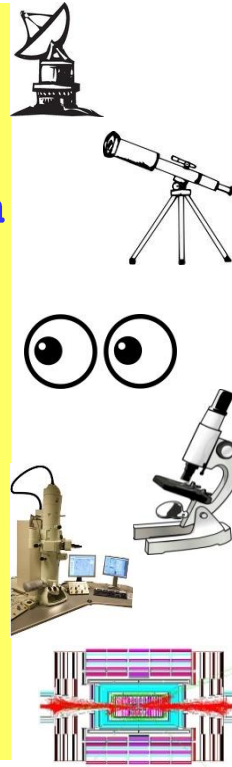
- ✓ Just look inside it

- 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	
(μ m)	-6	micro, cell
(nm)	-9	nano
(\AA)	-10	atom
(fm)	-15	nuclear
	-20	



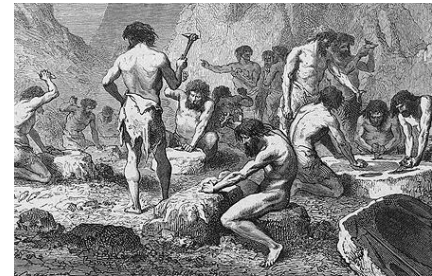
- Particle Physics era

- According to the method of smashing, one can define the era of Particle Physics!

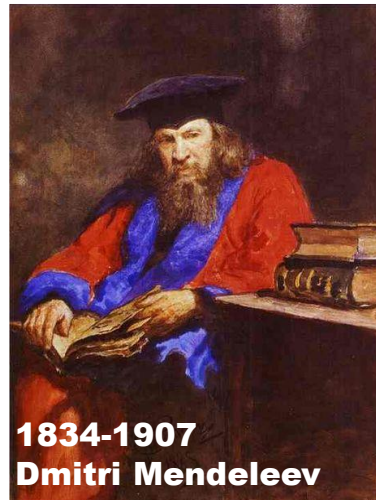
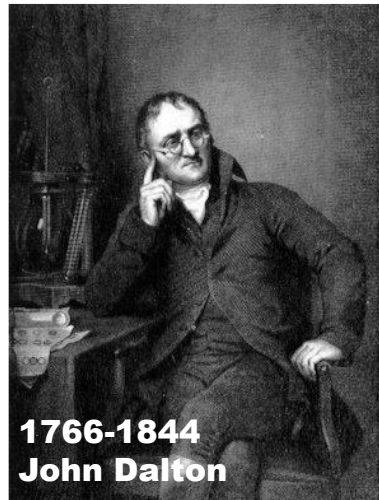
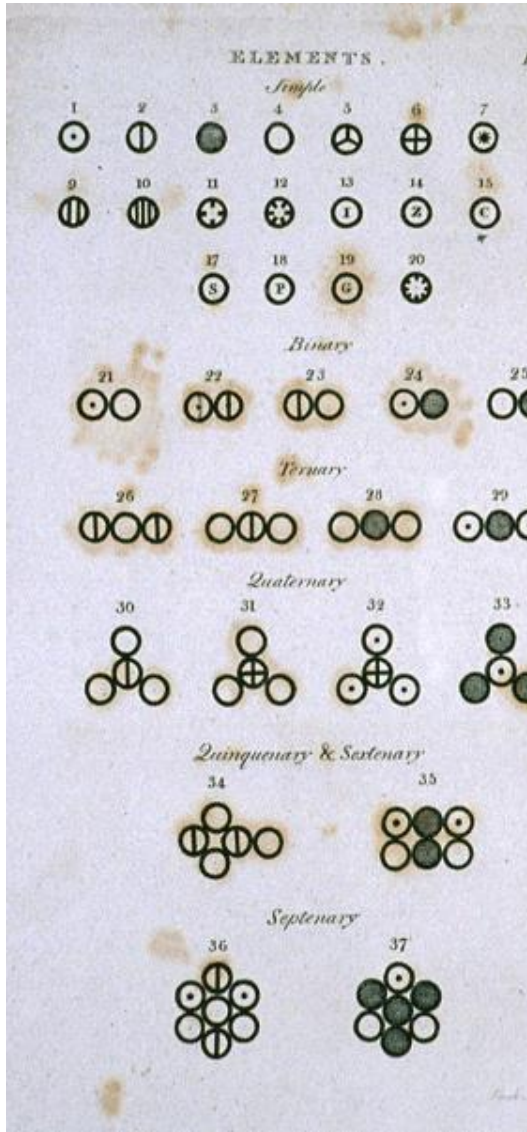
- ✓ From the radio active source to the accelerator

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



Periodic Table of the Elements

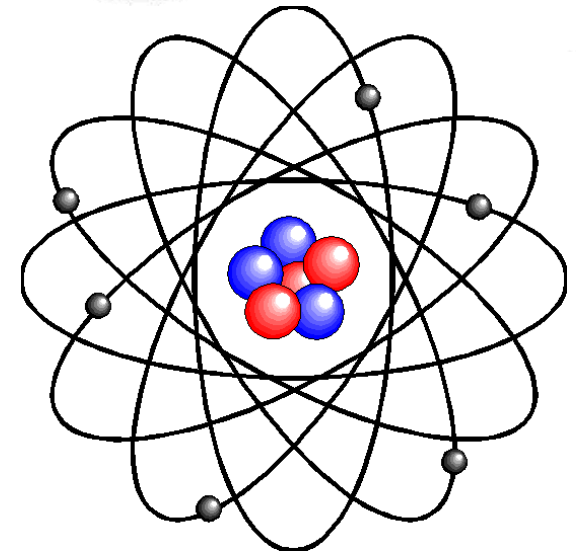
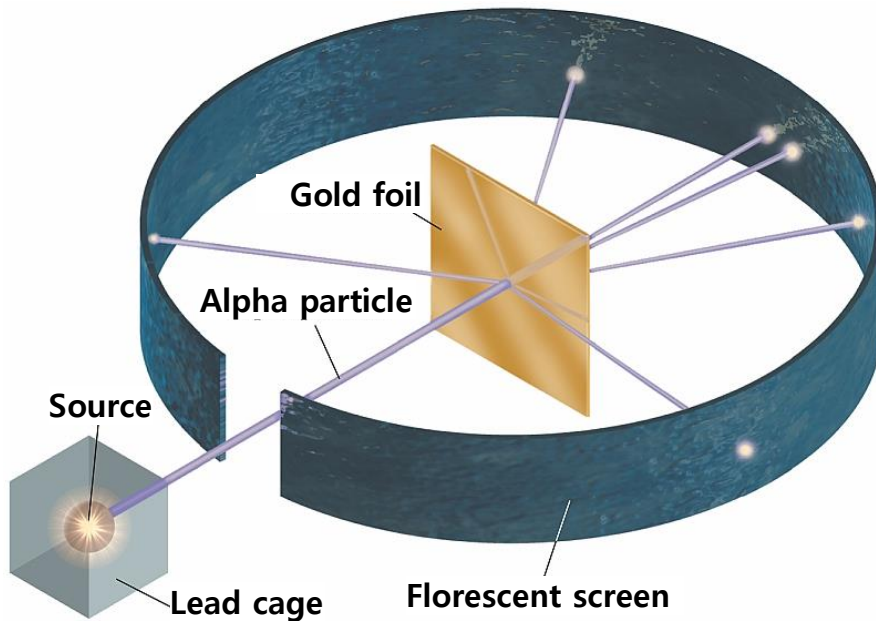
1	IA																2	O				
1	H	IIA																He				
2	Li	Be															B	C	N	O	F	Ne
3	Na	Mg	III B	IV B	VB	VIB	VII B	VIII B	VII	IB	II B	Al	Si	P	S	Cl	Ar					
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
7	Fr	Ra	+Ac	Rf	Ha	Sg	Ns	Hs	Mt	110	111	112	113									
* Lanthanide Series			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu						
+ Actinide Series			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr						

CITY OF THE ELEMENTS

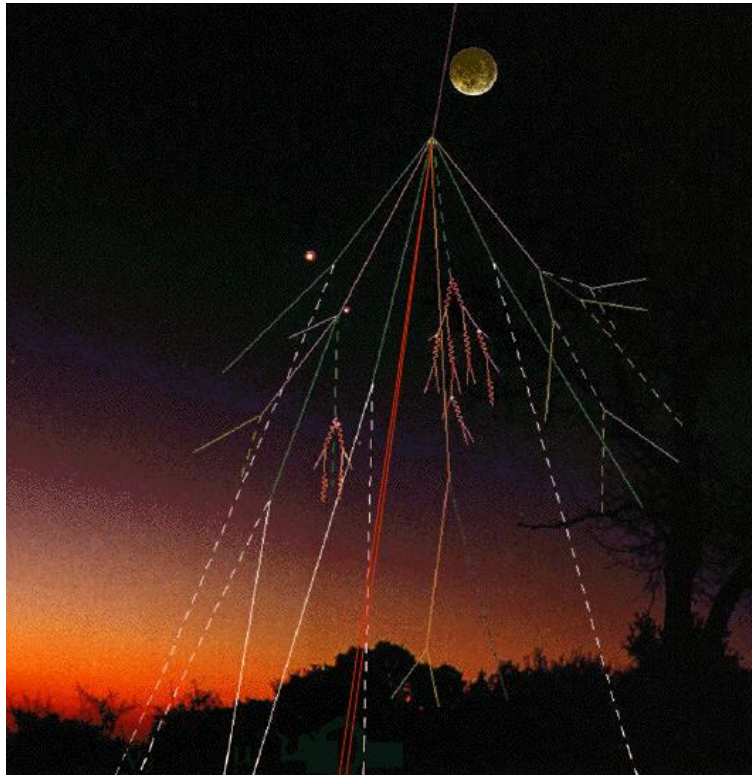
Symbol and Atomic Weights	The Composition of the Saline Oxides	The Properties of the Saline Oxides	Small Periods or Series
B A	R ₂ O ₃	d (2A + n/16) v	
H [6] 1	1 - n [7]	[8] [9] [10]	[11]
Li 7	1 1	0.977 19.6 < -30	1
Be 9	2	3.06 16.5 + 3.6	2
B 11	3	1.8 39 10	
C 12	4	> 1.0 < 80 < 19	
N 14	3* 5*	1.64 66 < 5	
O 16	5*		
F 19			
Na 23	1*	Na ₂ O 2.6 24 -22	3
Mg 24	2*	3.6 22 - 5	
Al 27	3*	Al ₂ O ₃ 4.0 36 + 13	
Si 28	4*	2.65 45 5.2	
P 31	3* 4* 5*	3.29 59 6.3	
S 32	2* 4* 5* 6* 7*	1.96 42 8.7	
Cl 35.5	3* 5* 7*		
K 39	1*	2.7 35 -55	4
Ca 40	2*	3.15 36 - 7	
Sc 44	3*	3.86 35 (0)	
Ti 48	4*	4.2 38 (+ 5)	
V 51	2* 3* 4* 5*	3.49 52 6.7	
Cr 52	2* 3* 4* 6* 7*	2.74 73 9.5	
Mn 55	2* 3* 4* 6* 7*		
Fe 56	2* 3* 4* 6* 7*		
Co 58.5	2* 3* 4* 6* 7*		
Ni 59	2* 3* 4* 6* 7*		
Cu 63	1* 2*	Cu ₂ O 5.9 24 9.8	5
Zn 65	2*		
Ga 70	3*	Ga ₂ O ₃ (5.1) (26) (4.9)	
Ge 72	4*		
As 75	3* 4* 5*	4.1 36 6.0	
Se 79	4* 5* 6*		
Br 80	1* 2* 3* 4* 5* 6* 7*		
Rb 85	1*		6
Kr 84	2*	4.8 35 -11	
Y 89	3*	5.05 45 (- 2)	
Zr 90	4*	5.7 45 -0.2	
Nb 94	3* 4* 5* 6*	4.7 57 +0.2	
Mo 96	2* 3* 4* 6* 7*	4.4 53 6.8	
Ru 101	2* 3* 4* 6* 7*		
Rh 104	2* 3* 4* 6* 7*		
Pd 106	1* 2* 3* 4* 6* 7*		
Ag 108	1*	Ag ₂ O 7.5 31 11	7
Cd 112	2*	8.15 31 2.5	
In 113	3*	7.18 34 4.3	
Sn 118	2* 3* 4* 5* 6*	6.95 43 2.8	
Sb 120	3* 4* 5* 6* 7*	6.5 49 3.6	
Te 125	2* 3* 4* 6* 7*	5.1 68 4.7	
I 127	1* 2* 3* 4* 5* 6* 7*		
Cs 133	1*		
Ba 137	2*	5.1 33 -6.0	
La 138	3*	6.5 50 +1.3	
Ce 140	2* 3* 4*	6.74 50 2.0	
Pr 142	3* 4* 5*		
Yb 173	3*	9.38 48 (- 2)	10
Ta 182	5*	7.5 59 4.6	
W 184	4* 6*	6.9 67 8	
Os 191	3* 4* 6* 7*		
Ir 193	3* 4* 6* 7*		
Pt 195	2* 3* 4* 6* 7*		
Au 198	1* 2*	Au ₂ O (12.5) (38) (15)	11
Hg 200	1* 2*	11.1 39 4.5	
Tl 204	1* 2* 3*	Tl ₂ O ₂ (27) (47) (4.3)	
Pb 206	2* 3* 4*	8.9 54 4.2	
Bi 208	3* 4* 5*		
Th 232	4*	9.86 54 2.0	12
U 240	4* 6*	(7.2) (80) (6)	

Atoms are periodic → Inner structure

Discovery of nuclear



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

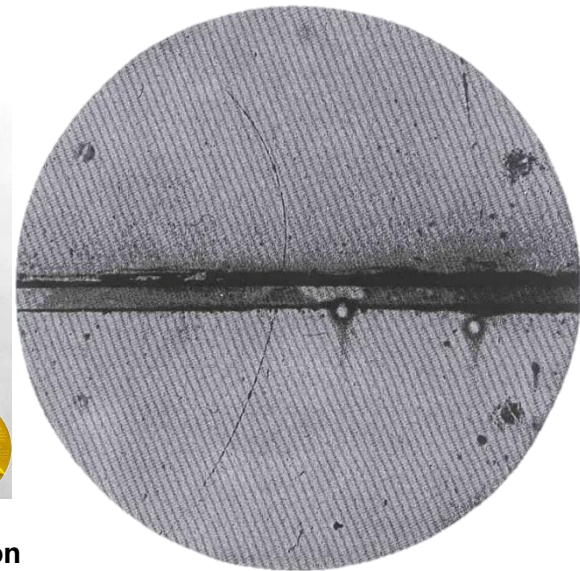


1883-1964
Victor Hess

1936

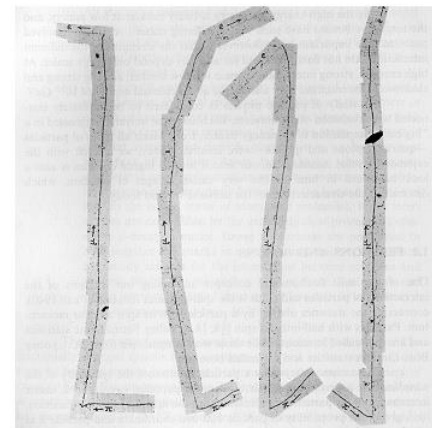
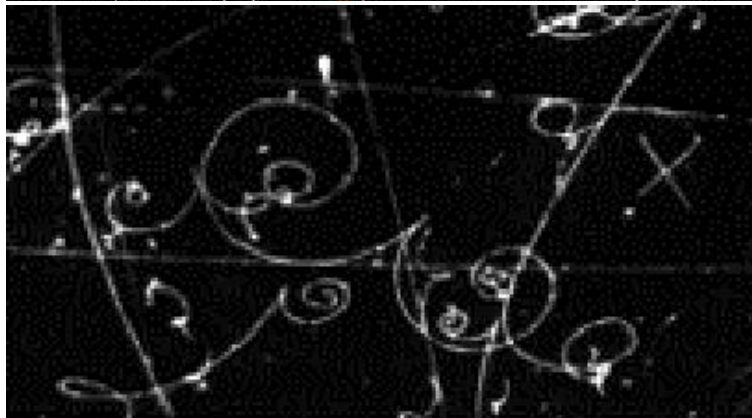


1905-1991
Carl David Anderson

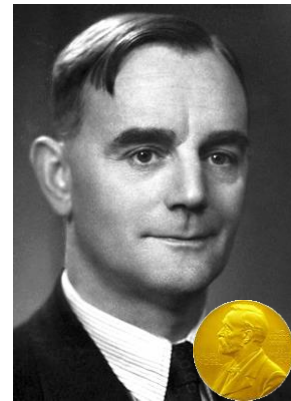


1932: Discovery of Positron

1936: Discovery of Muon



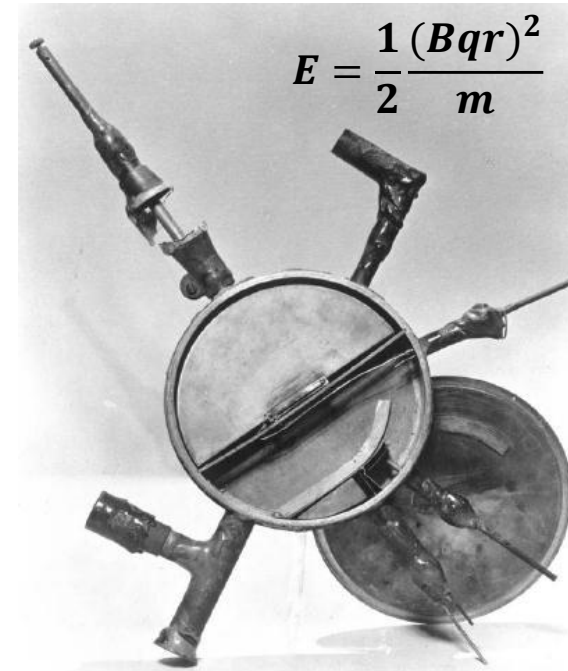
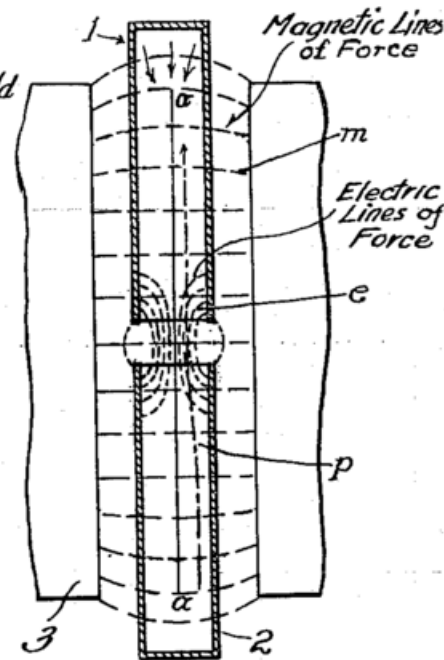
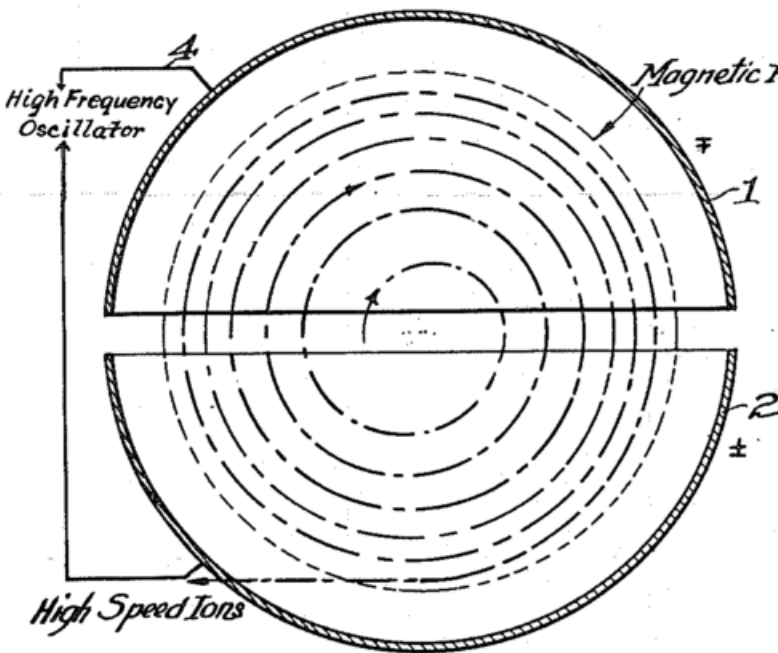
1947: Discovery of Pi meson



1903-1969
Cecil Powell

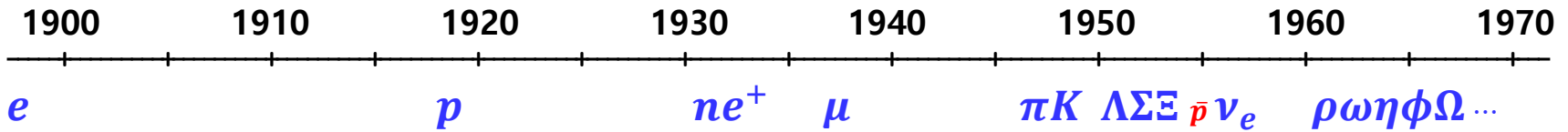
1950

Creation of elementary particles



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

1929년 Ernest Lawrence



Many new particles were created & discovered

cyclotron

synchrotron

Accelerator basics

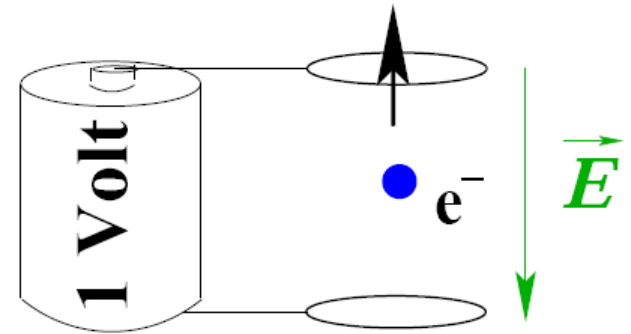
Basic physics

- Energy: eV

- $1\text{eV} = 1.6 \times 10^{-19}\text{J}$

- ✓ 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

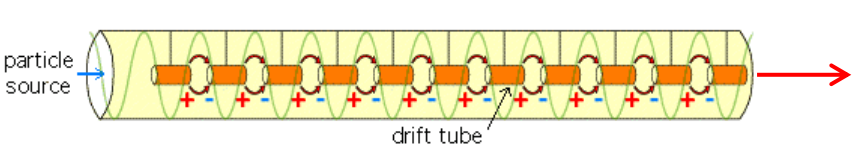
- $F = qE$ to accelerate particles

- $F = qvB$ to bend particles

- ✓ But in reality, much more complicate → Beam dynamics.

3 types of accelerators

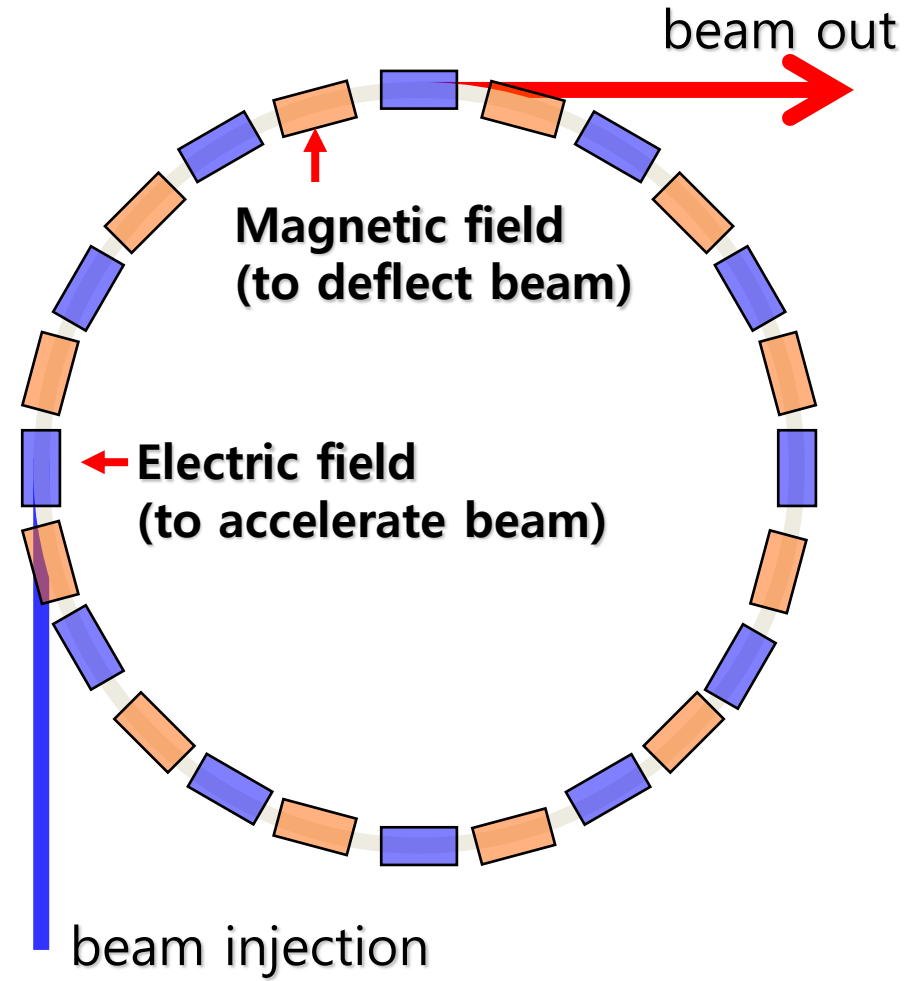
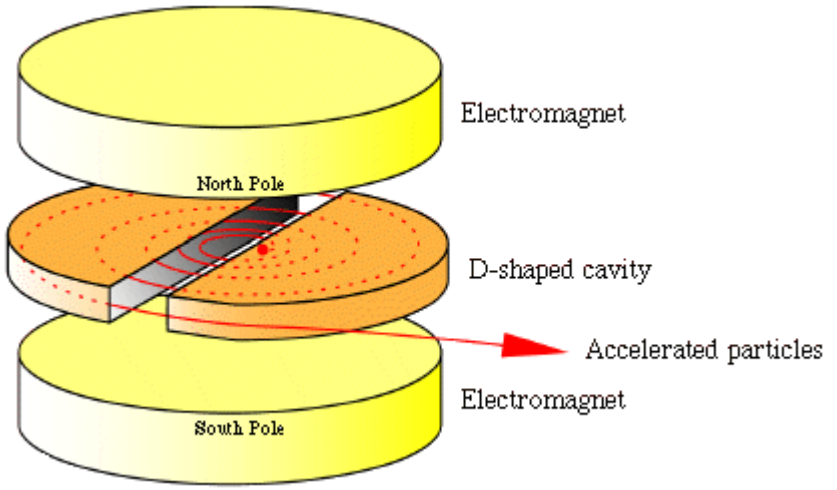
- All about size and Bremsstrahlung!



Linac

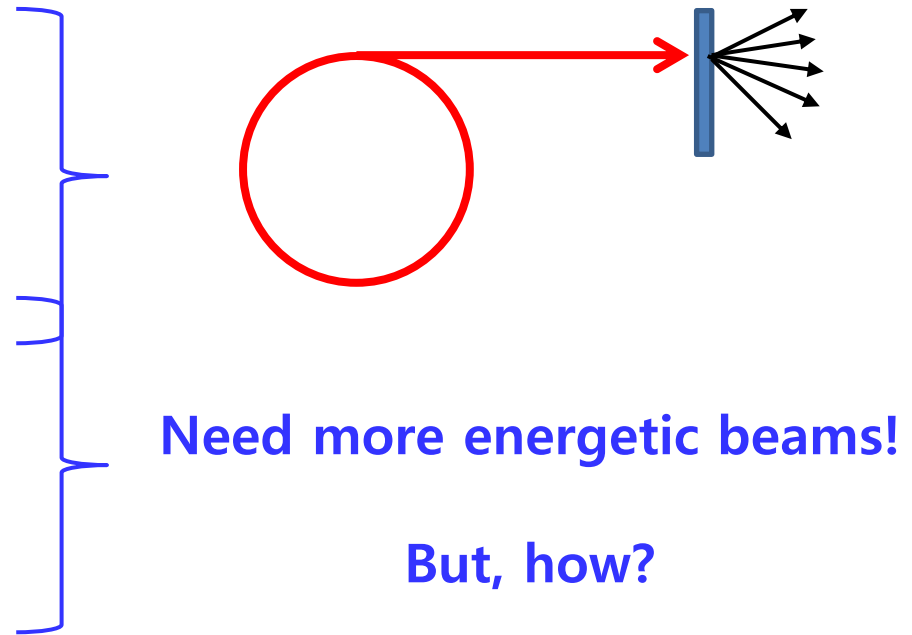
Cyclotron

Synchrotron



To look at elementary particles

- Order of magnitude
- Nucleons \sim GeV
- Quarks \sim 10GeV
- W/Z0 \sim 100 GeV
- Higgs, SUSY \sim TeV
- ...



Modern way of smashing



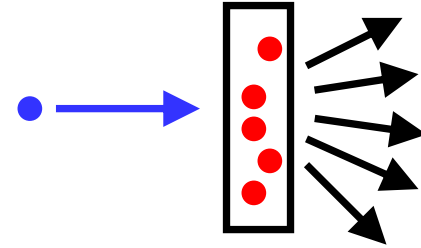
Today's main topic → Collider

Why use collider?

- Fixed target

- $E_{CM} \sim \sqrt{2m_T E_{beam}}$

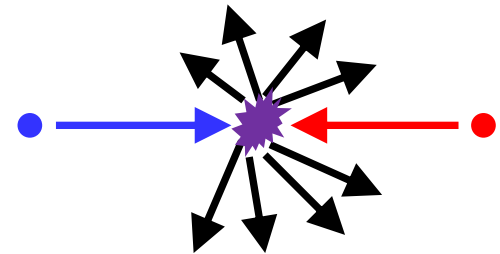
- ✓ 7TeV beam will make $E_{CM} \sim 1.2\text{TeV}$



- Collider

- $E_{CM} = 2E_{beam}$

- ✓ 7TeV beam will make $E_{CM} \sim 14\text{TeV}$



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

A) ?

From the beginning to now



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

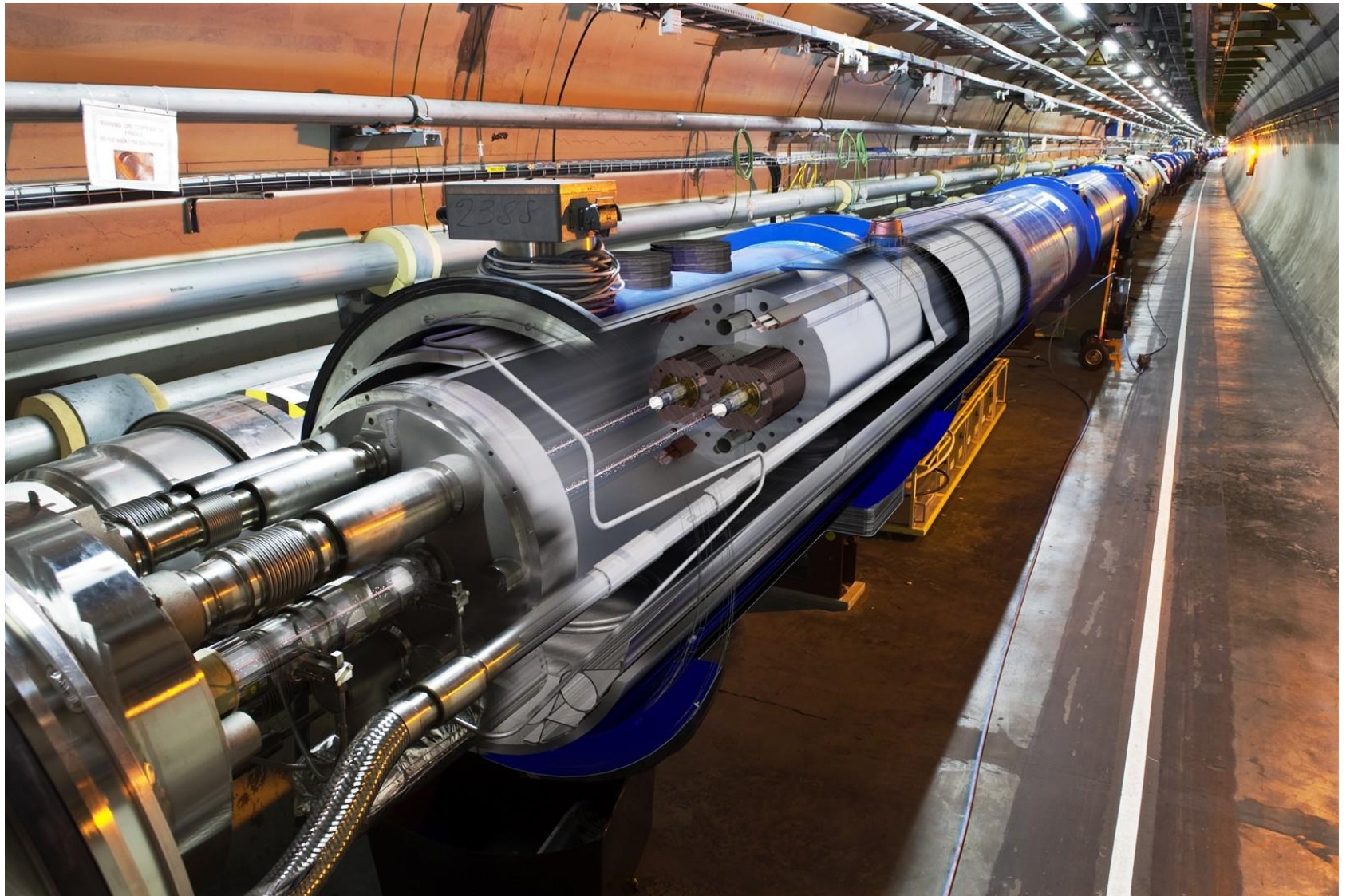


The latest synchrotron (2010)
D~9km, E~7TeV

after 80 years, 10^5 x larger and $\sim 10^7$ x more energetic

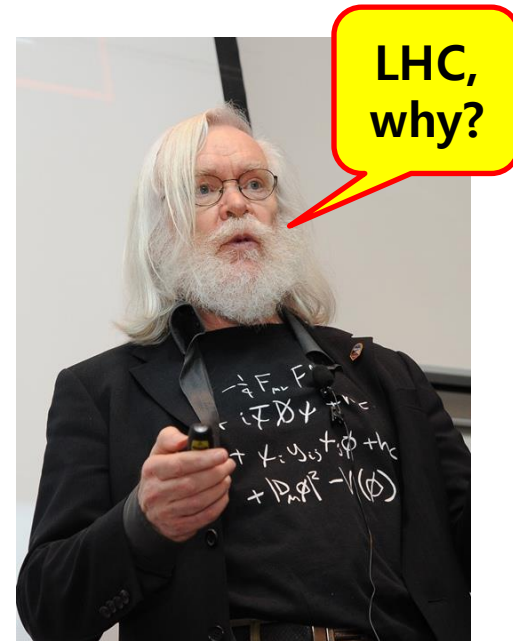
Introduction to LHC

LHC



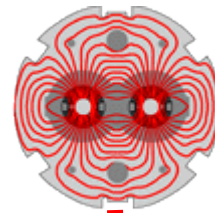
LHC, why? by John Ellis

- **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**

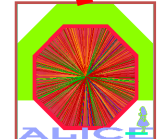
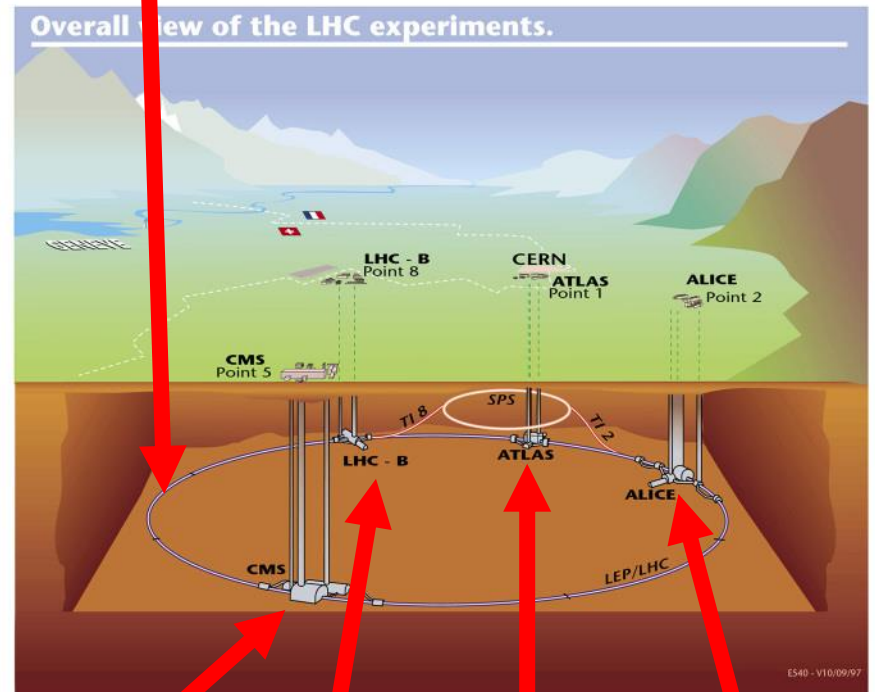


John Ellis
CERN Courier, May 2007

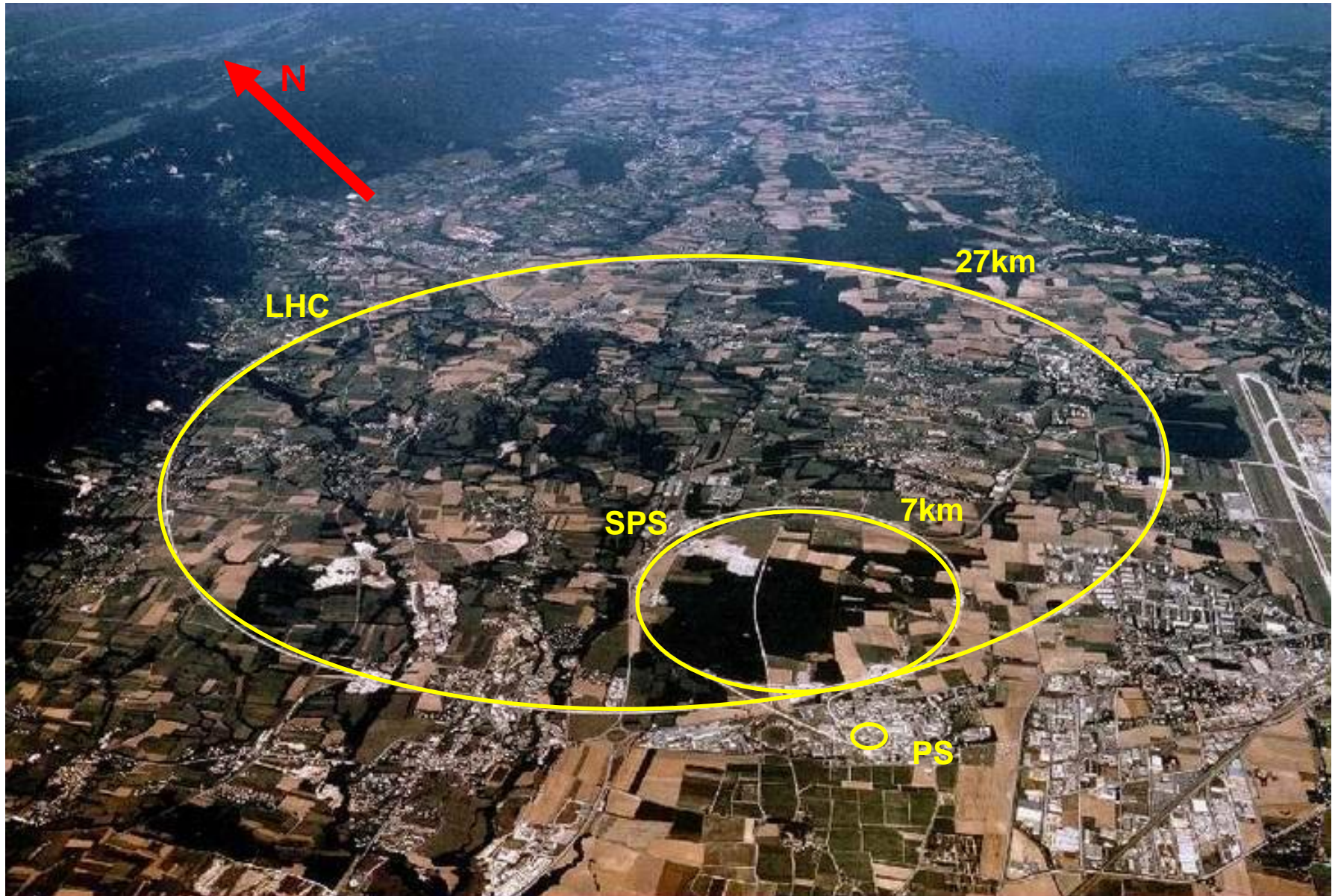
LHC, where?



50-175m underground



Aerial view

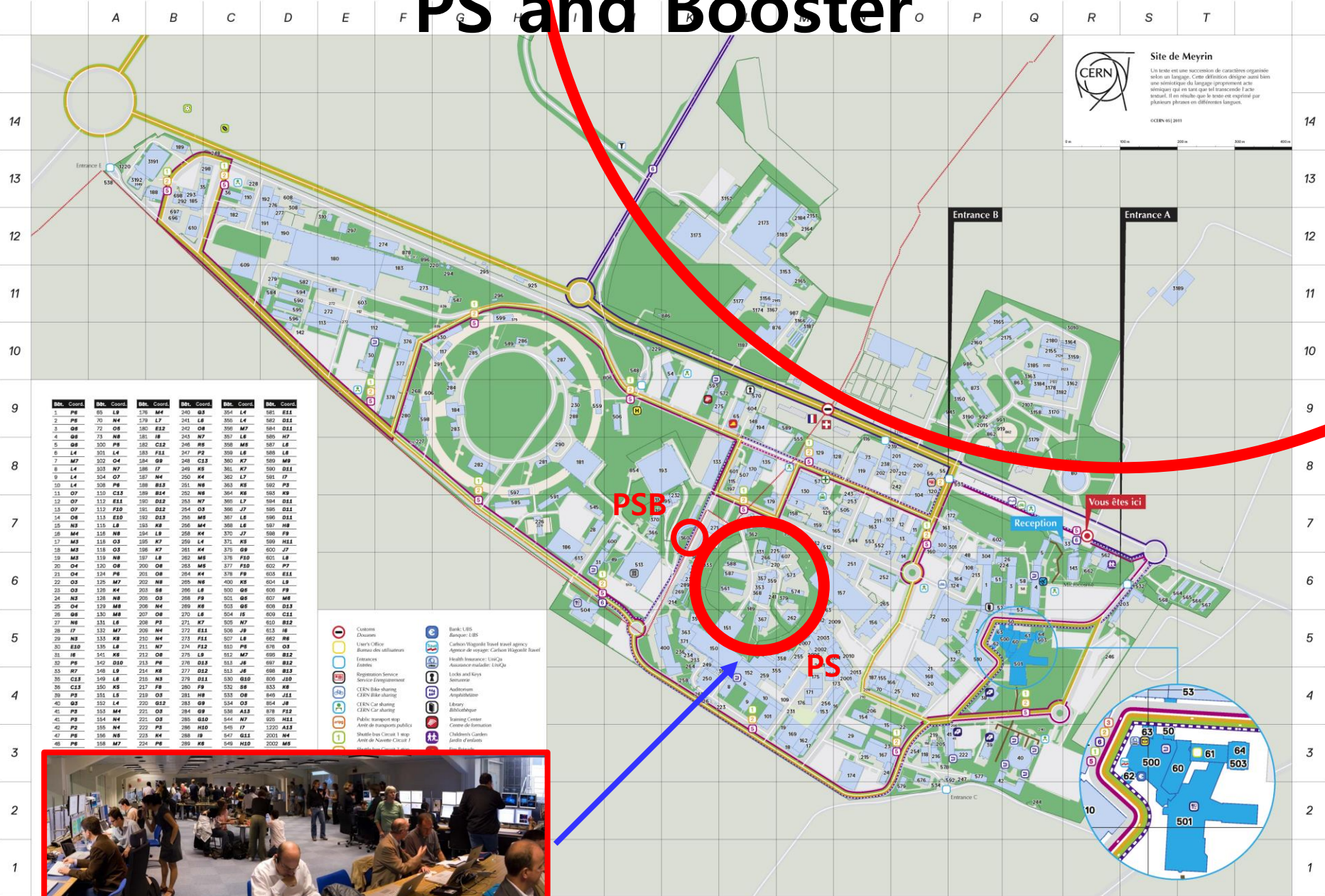


PS and Booster



Site de Meyrin
 Un texte est une succession de caractères organisés selon un langage. Cette définition désigne aussi bien une séquence de lettres (généralement une syllabe) qu'un mot qui lui transcende l'acte initial. Il en résulte que le texte est enregistré par plusieurs phrases en différents langages.

CCERN 001 0011

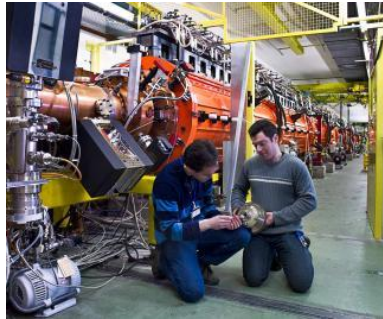


Mat. Coord.	Mat. Coord.	Mat. Coord.	Mat. Coord.	Mat. Coord.	Mat. Coord.
1 PS	01 L3	136 M4	243 O3	354 L4	561 E11
2 PS	70 N4	179 L7	241 L6	355 L4	562 O11
3 O8	72 O8	180 E12	242 O8	356 M7	564 O11
4 O8	73 N8	181 N6	243 M7	357 L6	565 M9
5 O8	100 PS	182 C12	246 N8	358 M8	567 L4
6 L4	101 L4	183 F11	247 P2	359 L6	568 L6
7 M7	102 O4	184 O9	248 C13	360 M7	569 M9
8 L4	103 M7	185 L7	249 N8	361 E7	570 O11
9 L4	104 O7	187 N4	250 K4	362 L7	581 F7
10 L4	108 PS	188 E13	251 N8	363 K8	582 P8
11 O7	110 C13	189 E14	252 N8	364 K8	583 N8
12 O7	112 E11	190 D12	253 M7	365 L7	584 O11
13 O7	112 F10	191 D12	254 O3	366 J7	585 O11
14 O8	113 E10	192 D13	255 M8	367 L6	586 O11
15 N3	115 L8	193 K8	256 M4	368 L6	587 M8
16 M4	116 N8	194 L8	258 K4	370 J7	588 F8
17 M3	118 O3	195 K7	259 L4	371 K8	589 H11
18 M3	118 O3	196 K7	261 K4	373 O8	600 J7
19 M3	118 O3	197 L8	262 M8	374 F10	601 L8
20 O4	120 O8	200 O8	263 M8	377 F10	602 P7
21 O4	124 PS	201 O8	264 K4	378 F8	603 E11
22 O3	125 M7	202 N8	265 N8	400 K5	604 L8
23 O3	126 K4	203 S8	266 L6	600 O8	607 M8
24 N3	128 N8	205 O3	268 F8	601 O8	607 M8
25 O4	129 M8	206 M4	269 N8	601 O8	608 D13
26 O8	130 M8	207 O8	270 L6	604 K5	609 C11
27 N8	131 L6	208 P3	271 K7	605 M7	610 E12
28 F7	132 M7	209 M4	272 E11	606 J8	613 L8
29 M3	133 K5	210 M4	273 F14	607 L8	662 P8
30 E10	135 L8	211 M7	274 F12	610 PS	678 O3
31 E6	141 M6	212 O8	275 L9	612 M7	689 E12
32 PS	142 D10	213 PS	276 D12	613 L8	687 E12
33 M7	143 L8	214 K8	277 D12	613 J6	688 E13
36 C13	149 L8	215 N3	279 D11	630 E10	806 J10
38 C13	150 K5	217 PS	280 F8	632 S8	833 M8
39 M3	151 L8	218 O3	281 N8	633 O8	848 E11
40 O3	152 L4	220 E12	283 O9	634 O3	854 J8
41 PS	153 M4	221 O3	284 O9	635 A13	878 F12
42 PS	154 M4	221 O3	285 O10	641 M7	902 H11
42 P2	155 N4	222 P2	286 H10	645 J7	1220 A13
47 PS	156 N8	223 K4	288 J8	647 E11	2001 N4
48 PS	158 M7	224 PS	289 N8	649 E10	2002 M8

- Customs / Douanes
- User's Office / Bureau des utilisateurs
- Entrances / Entrées
- Registration Service / Service d'enregistrement
- Bank: LBS / Banque: LBS
- Cartoon Village / Cartoon Village travel agency
- CERN Bike sharing / CERN Bike sharing
- CERN Car sharing / CERN Car sharing
- Public transport stop / Arrêt de transport public
- Shuttle Bus / Shuttle Bus
- Children's Garden / Jardin d'enfants
- Health Insurance: LBS/Qu / Assurance-maladie: LBS/Qu
- Lock and Keys / Serrurerie
- Auditorium / Amphithéâtre
- Library / Bibliothèque
- Training Center / Centre de formation



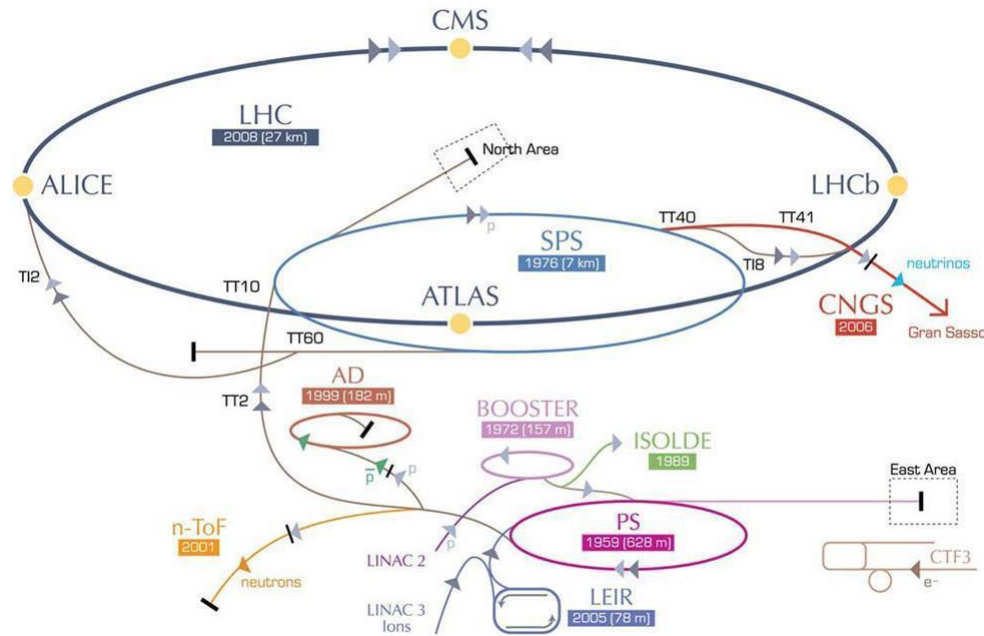
LINAC to LHC



LINAC2: Proton starting point



LINAC3: Ion starting point



Large Hadron Collider, 7TeV



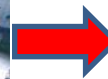
Super Proton Synchrotron
7km 450GeV



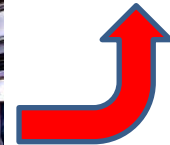
Proton booster
1.4GeV



Low-Energy Ion
Ring



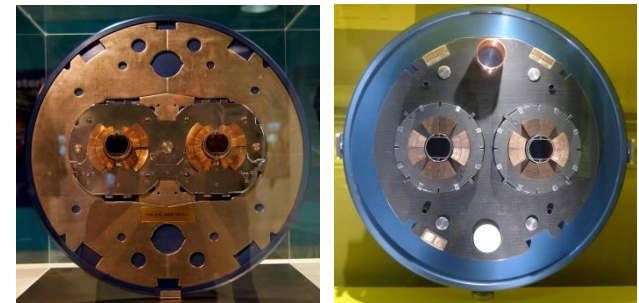
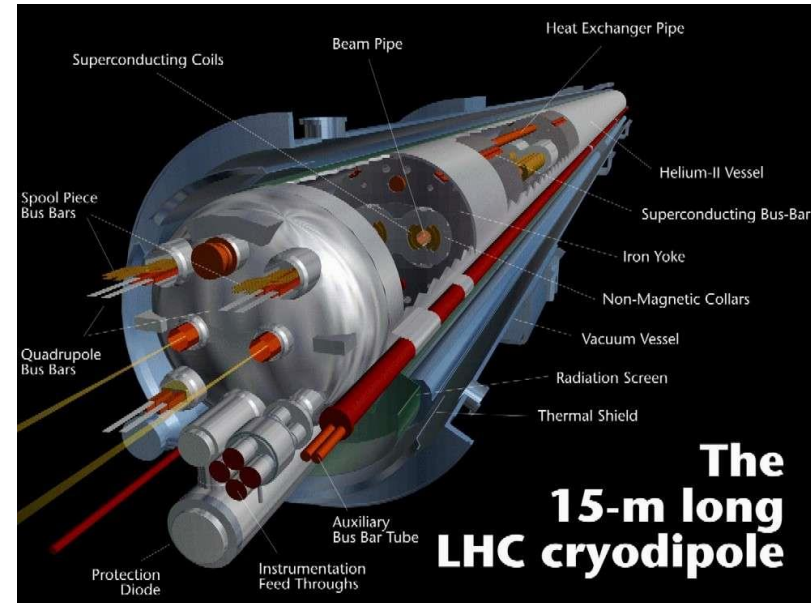
Proton Synchrotron
628m, 25GeV



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 $\sim 10^{-13}$ atm, ten times less than the pressure on the Moon!
- The most powerful supercomputer system in the world...
 - Each experiment will record $\sim 100\,000$ DVDs data / every year.
 - $\sim 10,000$ 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 $\sim 1\text{GeV}/c^2 \rightarrow$ negligible

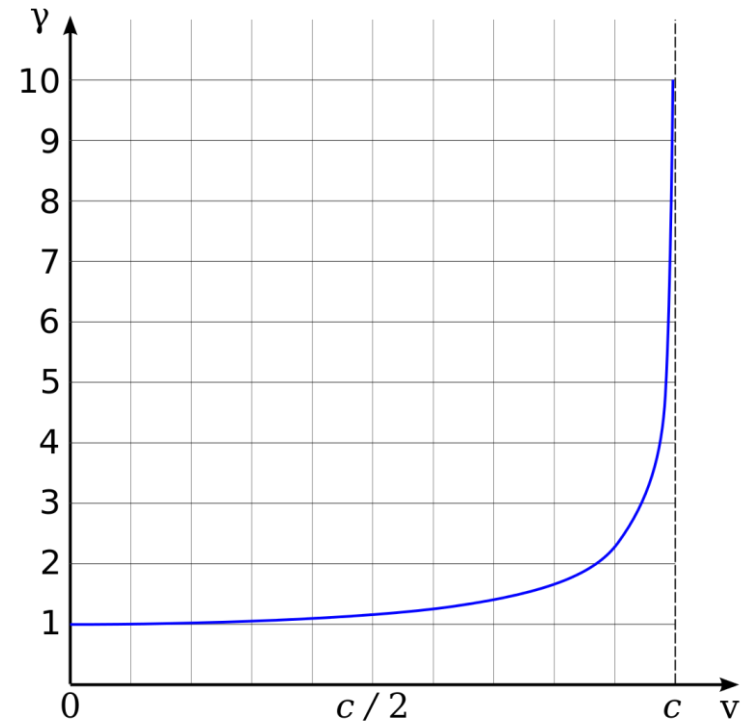
- ✓ Kinetic energy dominant $\rightarrow E = \gamma mc^2$

- $\gamma_{LHC} = \frac{7\text{TeV}}{1\text{GeV}} = 7000$

- ✓ $\beta_{LHC} = 0.999999999$

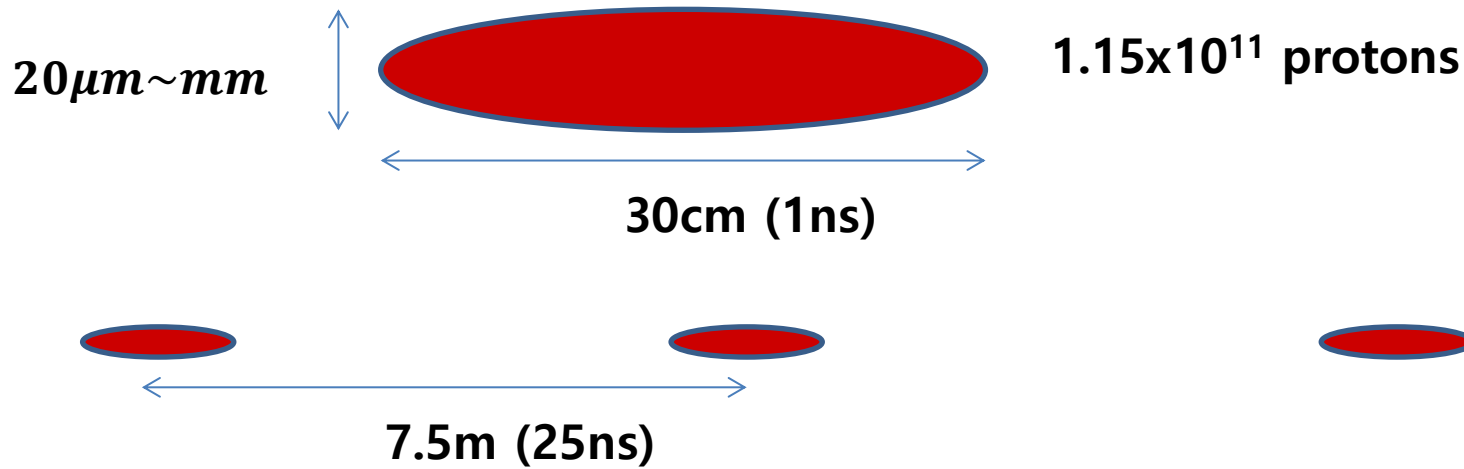
- $\gamma_{SPS} = 450$

- ✓ $\beta_{SPS} = 0.99999753$



Beam parameters

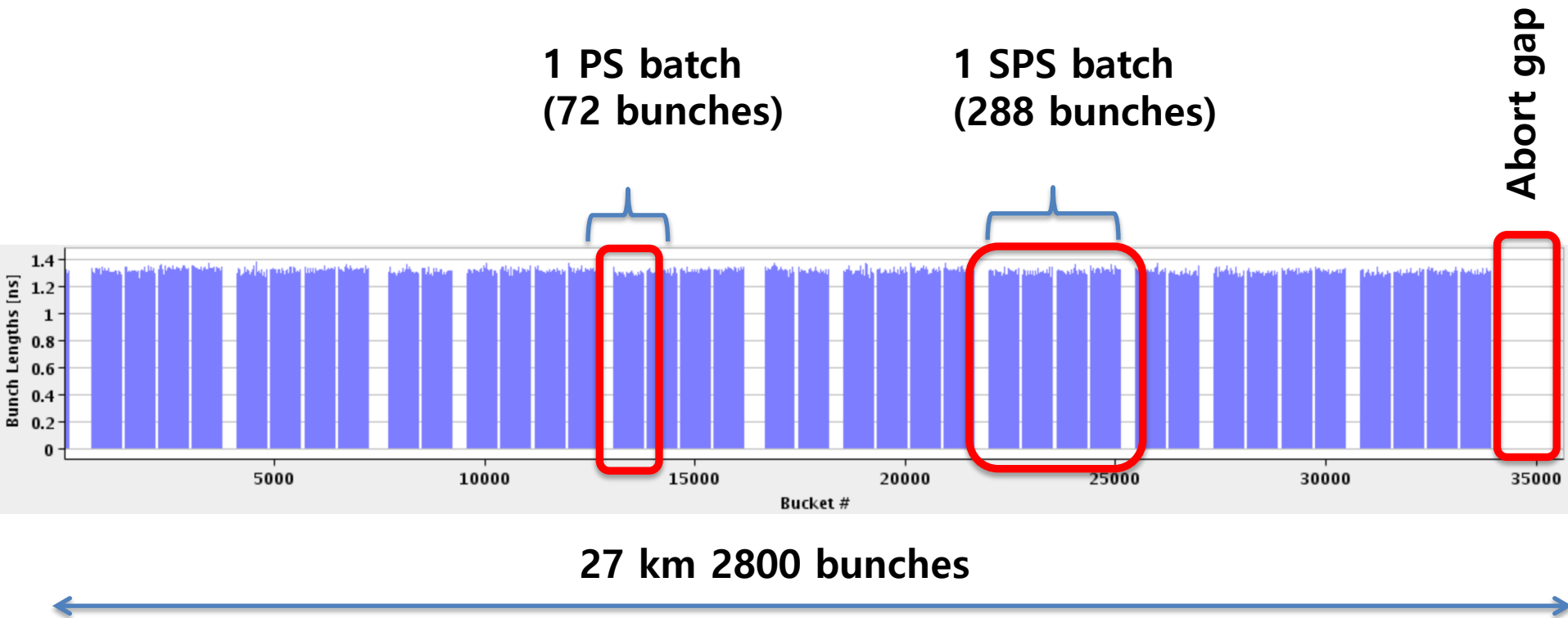
- Understanding beam bunch



2808 bunches make $\sim 21km$
Up to 3564 bunches $\sim 27km$

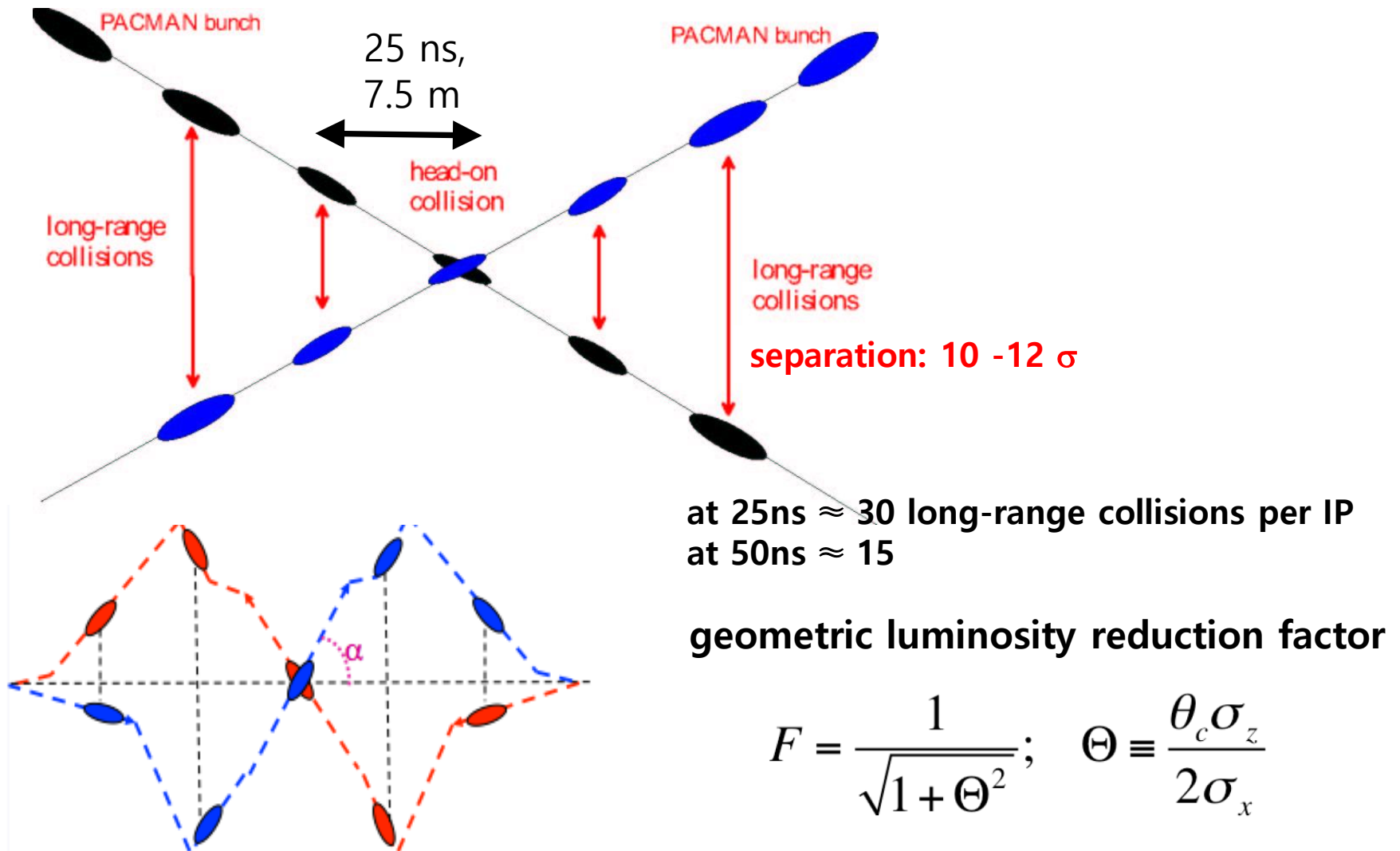
Bunch structure

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



Bunch crossing angle

work with a crossing angle to avoid parasitic collisions.



Understanding Luminosity

- Event rate: how frequently events happens? (# of events per second)

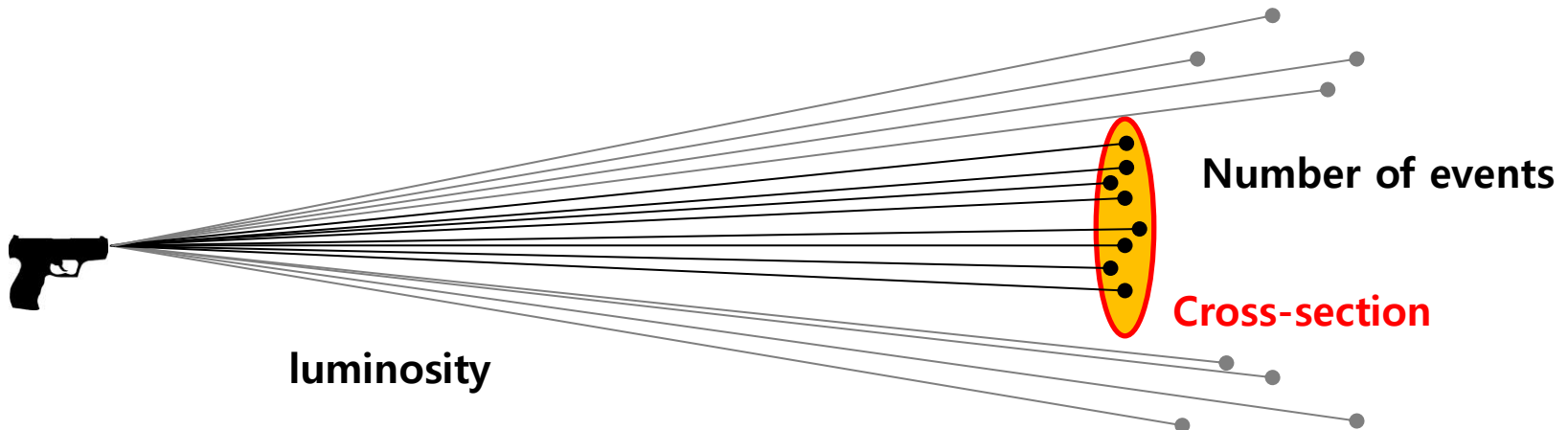
- $R = \mathcal{L} \times \sigma$

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

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

- ✓ Effective area for interaction $\rightarrow \sigma$ (cross-section)

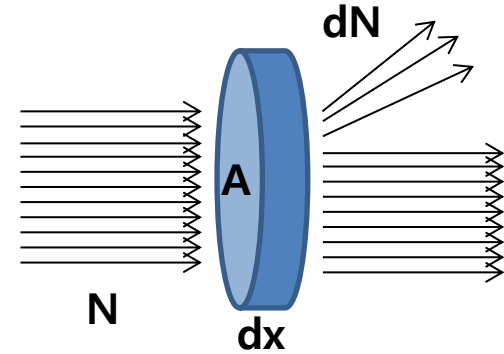
- the dimension is " cm^{-2} "



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 = $n\sigma A dx$

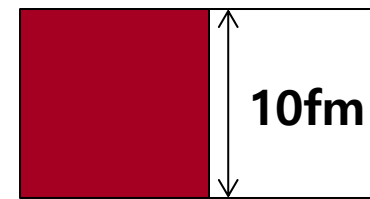


- Beam

- N particles enter in A and dN interact
 - ✓ $dN/N = n\sigma A dx/A = n\sigma dx$
- $-\frac{dN}{N} = n\sigma dx \rightarrow N = N_0 e^{-n\sigma x}$

- Dimension of cross-section = $[L]^2$

- Unit: 1 barn = $1b = 10^{-24} cm^2 = 10^{-28} m^2$
 - ✓ $r = r_0 A^{1/3} \rightarrow 1barn$ is $A \sim 100$ nuclei ($Z \sim 45$)



$$r_0 = 1.2 \text{ fm}$$

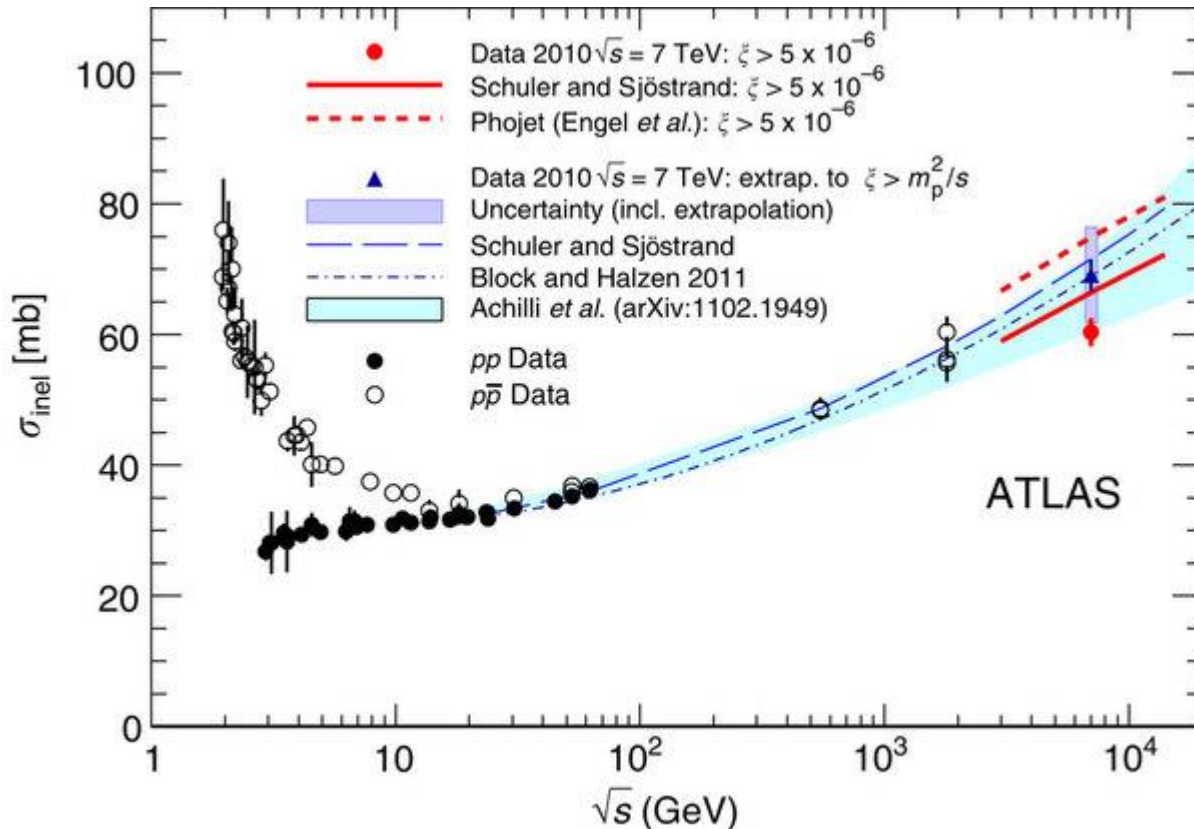
$$10^{-12} \text{ cm} = 10^{-14} \text{ m} = 10 \text{ fm}$$

Barn?



proton cross-section

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



0.1barn

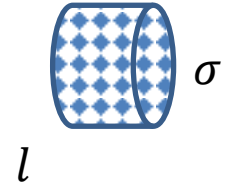
70mb

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

Calculation of luminosity

- In fixed target experiment → easy

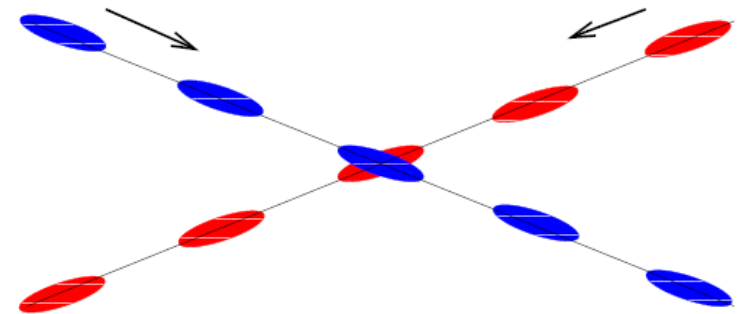
- $\mathcal{L} = \Phi \rho_T l [T^{-1} L^{-3} L^1]$



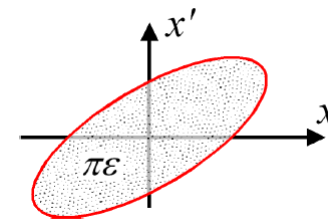
- For collider → complicate

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

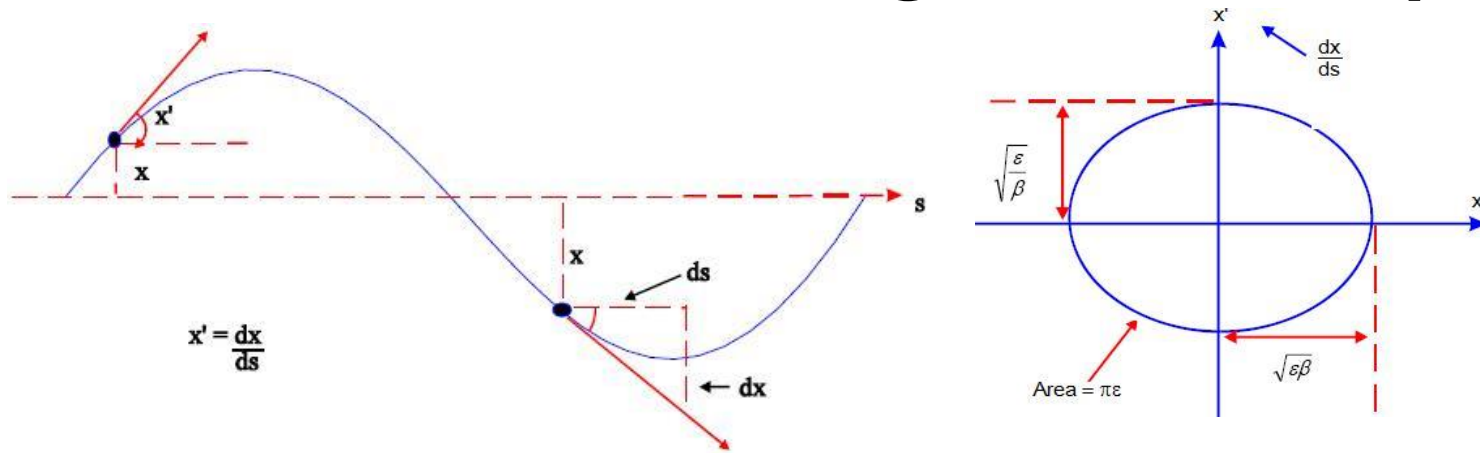


$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

$$\varepsilon_n = \varepsilon \beta \gamma$$

Emittance & beta

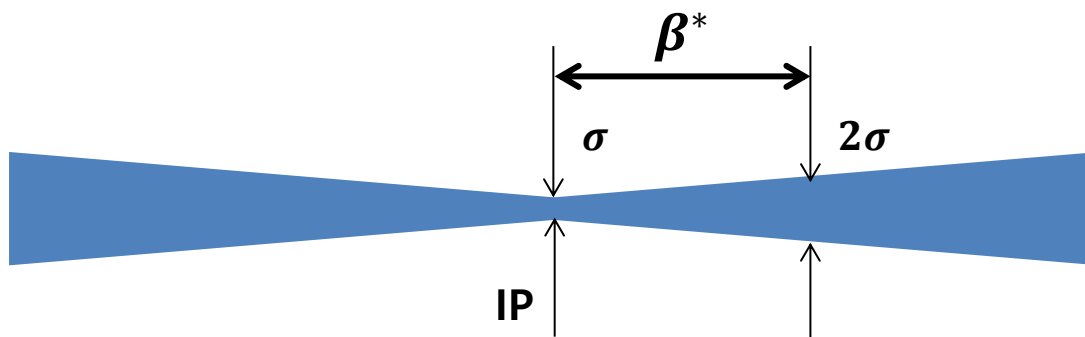
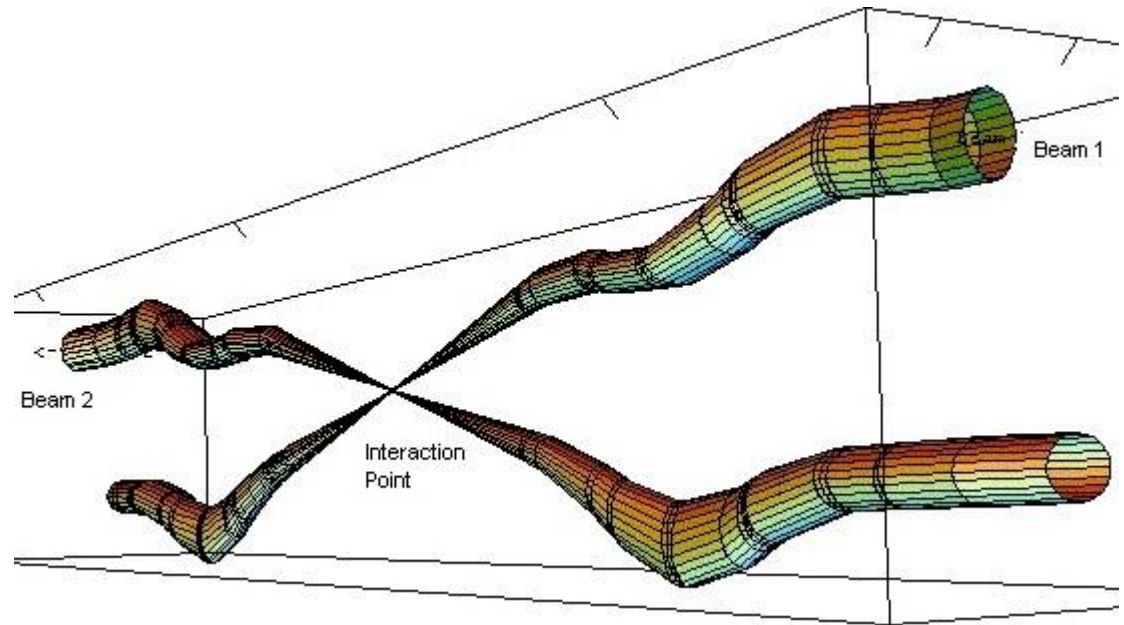
- Beam movement along its central path



- **Emittance: transverse & longitudinal**
 - ✓ “low” emittance \rightarrow small beam size, small momentum spread
- **Beta: transverse beam size²/emittance**
 - ✓ Small beta \rightarrow beam is squeezed

Beta*

- Beta* means beta at IP



Pile-up!

- **Multiple events in a photo**

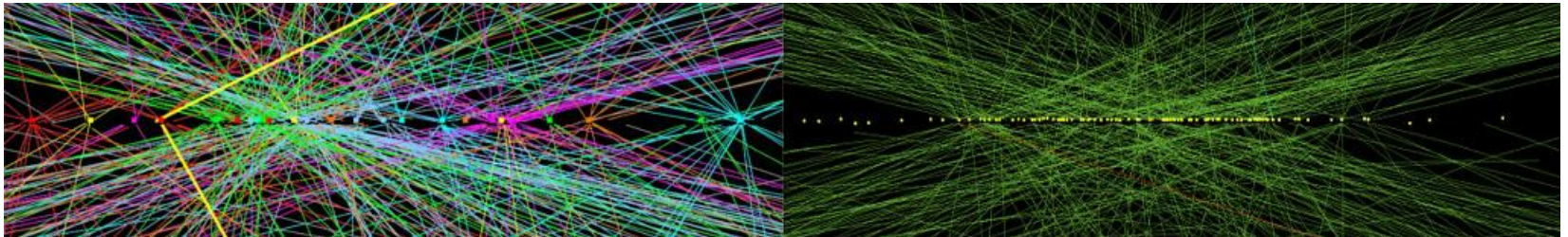
- **Pileup in Firework**

- ✓ 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}

$$\checkmark R_{BC} = \frac{c}{27km} \times n_b = 11253Hz \times n_b$$

- For the nominal LHC

$$\checkmark R = \mathcal{L} \times \sigma_{inel} = 10^{34} cm^{-2} s^{-1} \times 70mb \sim 7 \times 10^8 Hz$$

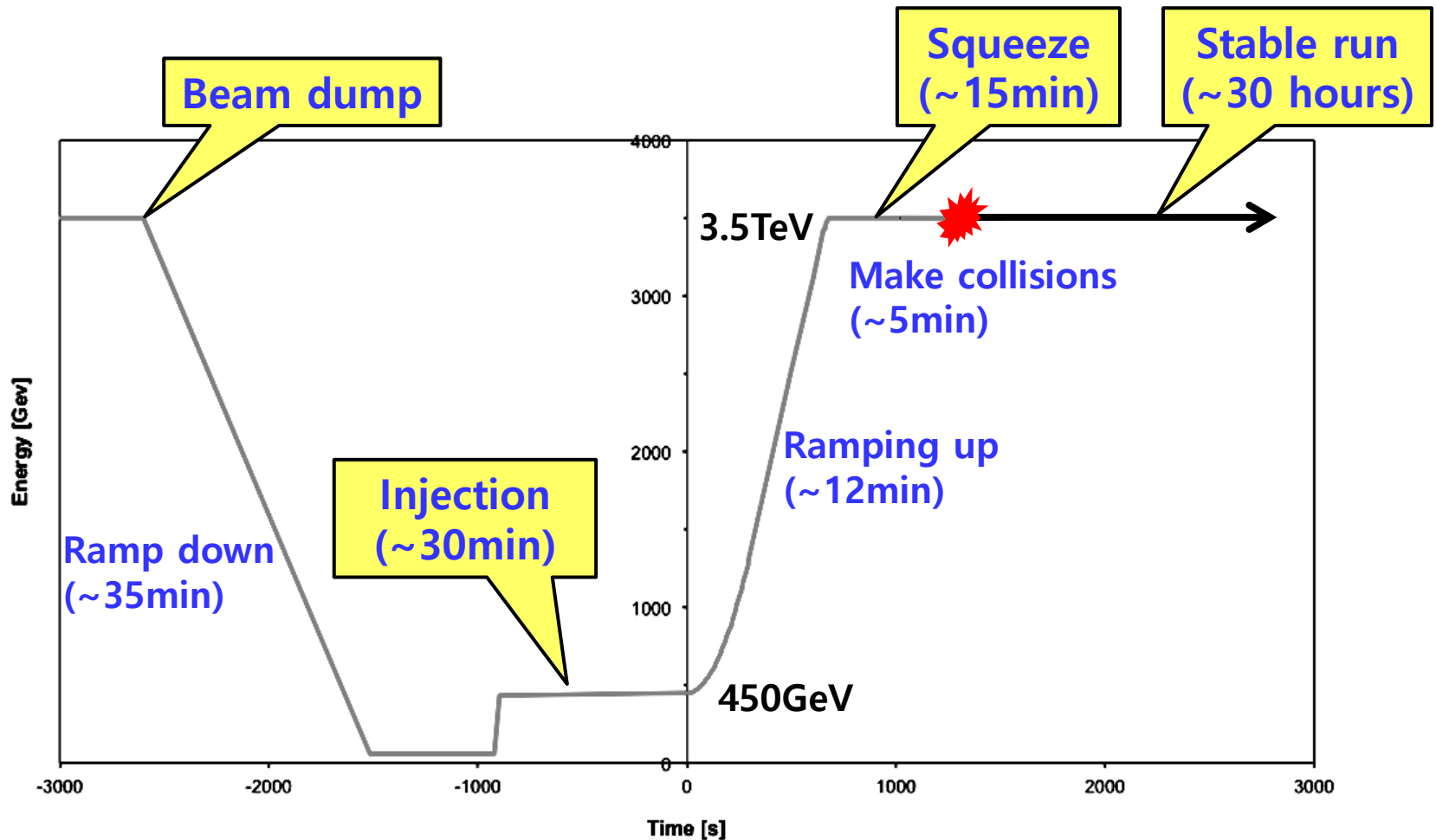
$$- Pileup = R/R_{BC} = 7 \times 10^8 / (11253 \times 2808) \sim 22$$

- For example, LHC 2012 run

$$\checkmark R = \mathcal{L} \times \sigma_{inel} = 7.7 \times 10^{33} cm^{-2} s^{-1} \times 70mb \sim 5.4 \times 10^8$$

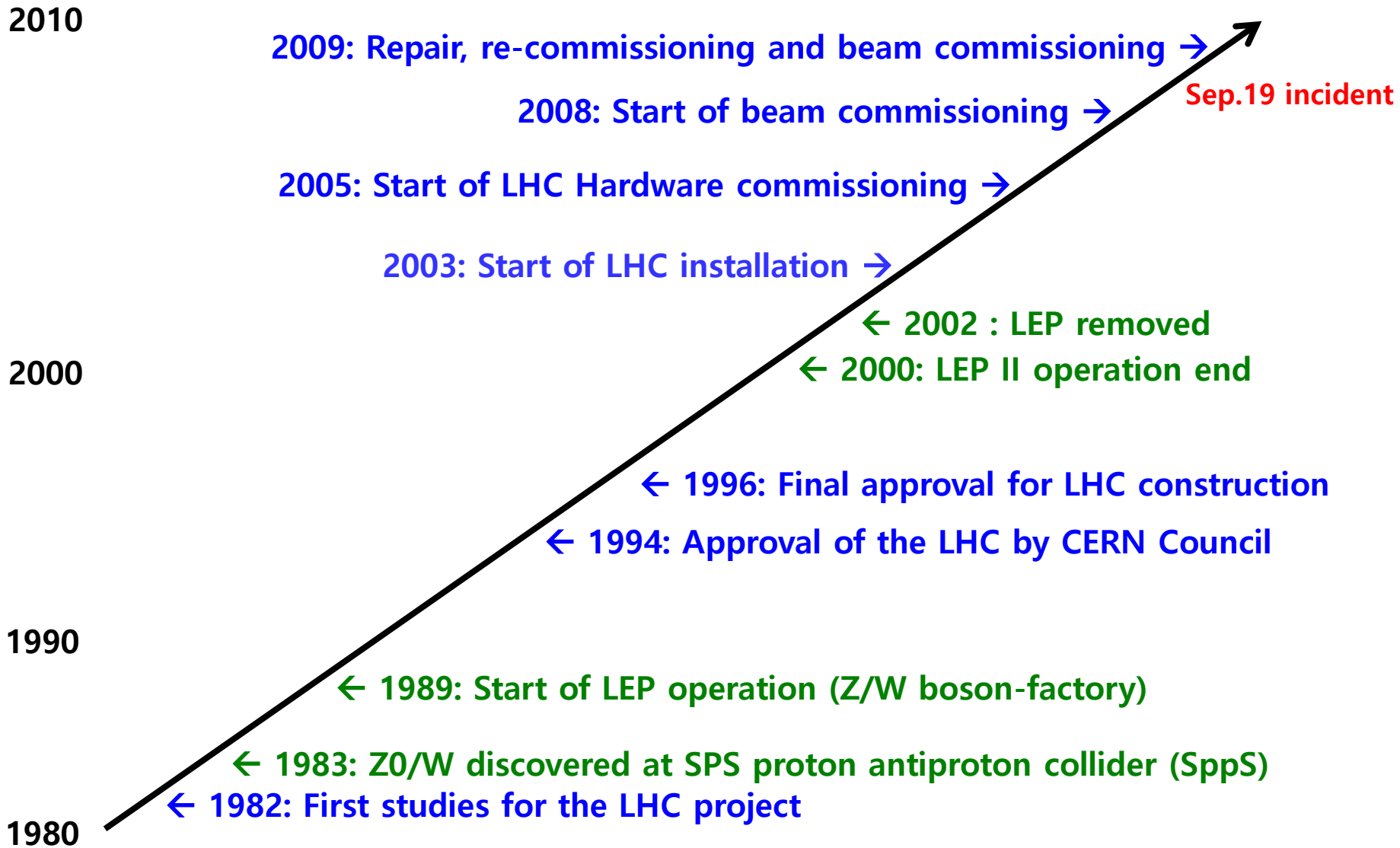
$$- Pileup = 5.4 \times 10^8 / (11253 \times 1380) \sim 35$$

Typical LHC operational cycle



LHC Run history so far

Pre-LHC history



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 pressure wave **damaging ~600 m** of LHC, **polluting** the beam vacuum over **more than 2 km**.

Arcing in the interconnection



Magnet displacement



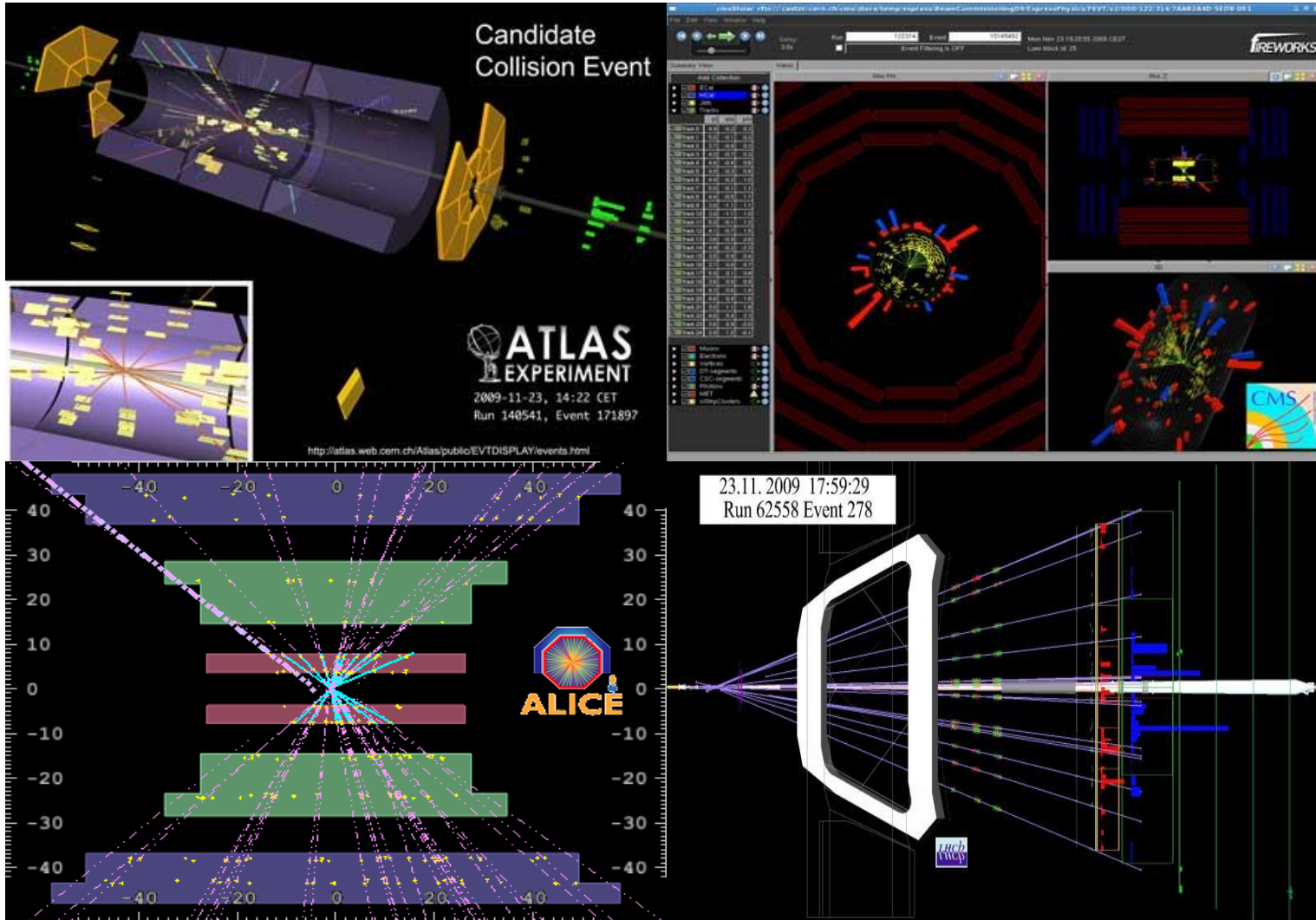
Over-pressure



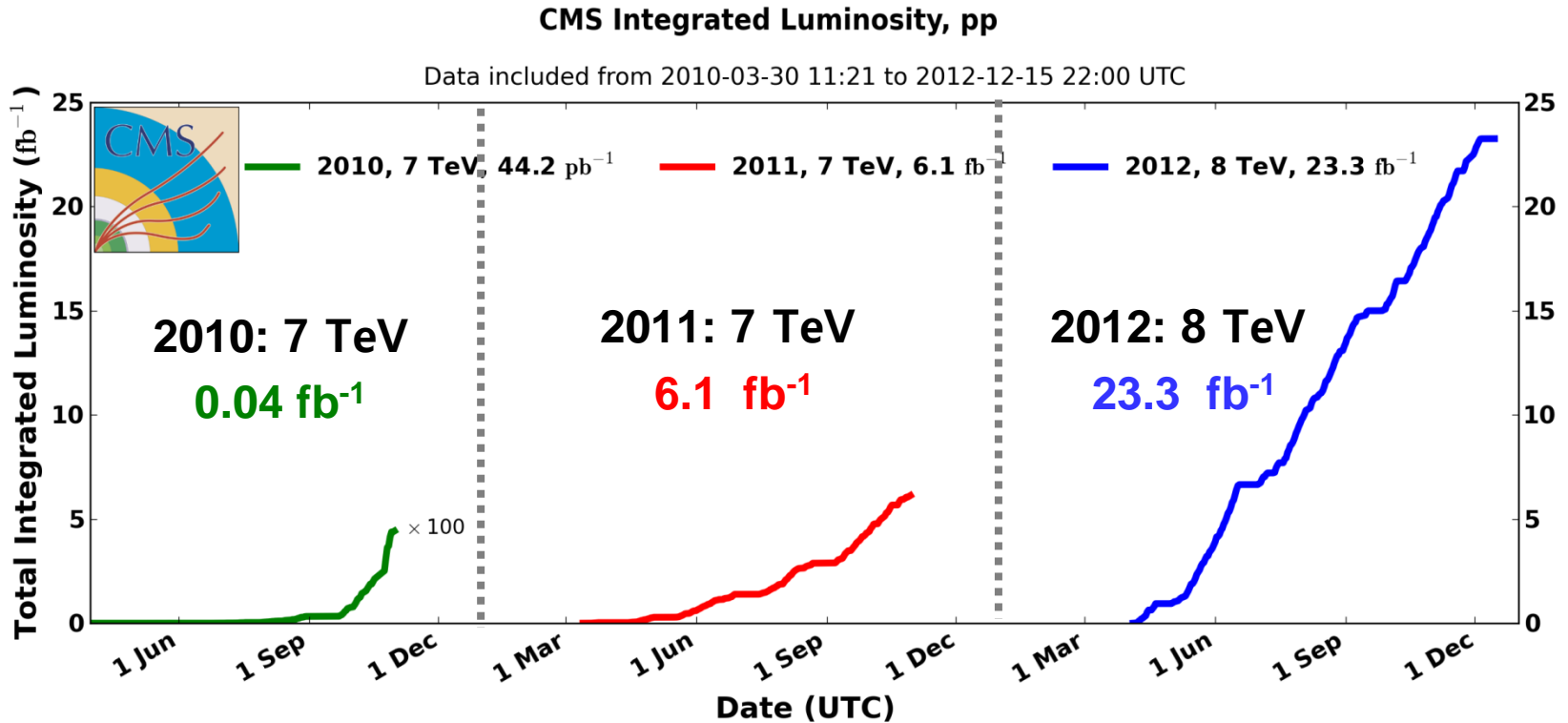
**53 magnets to repair,
14 months downtime**

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 [μ rad]	285		100	145
Peak luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	1.0×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Ave. Pileup	26	8	17	38

7 TeV
0.04 fb⁻¹

7 TeV
6.1 fb⁻¹

8 TeV
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

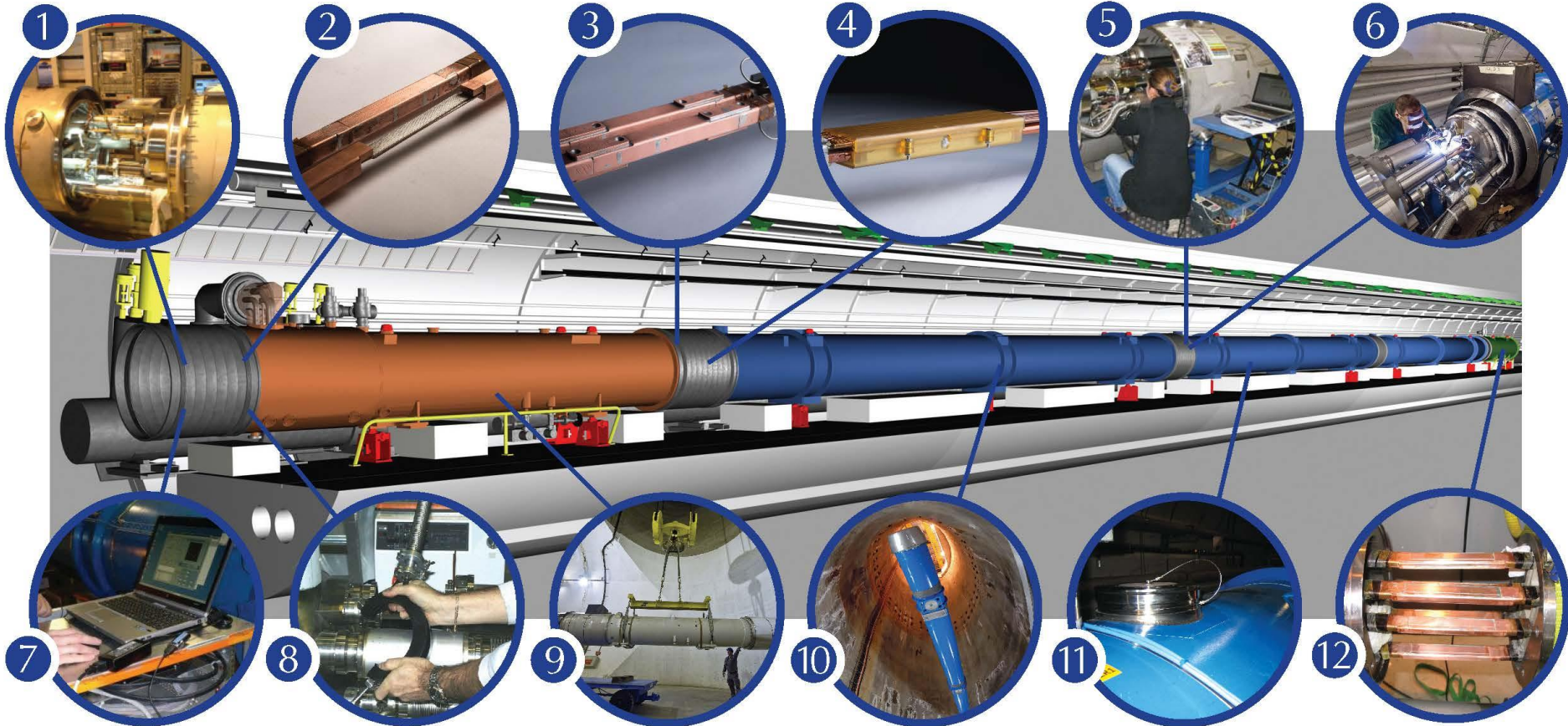
Complete reconstruction of **3000** of these splices

Consolidation of the 10170 13 kA 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

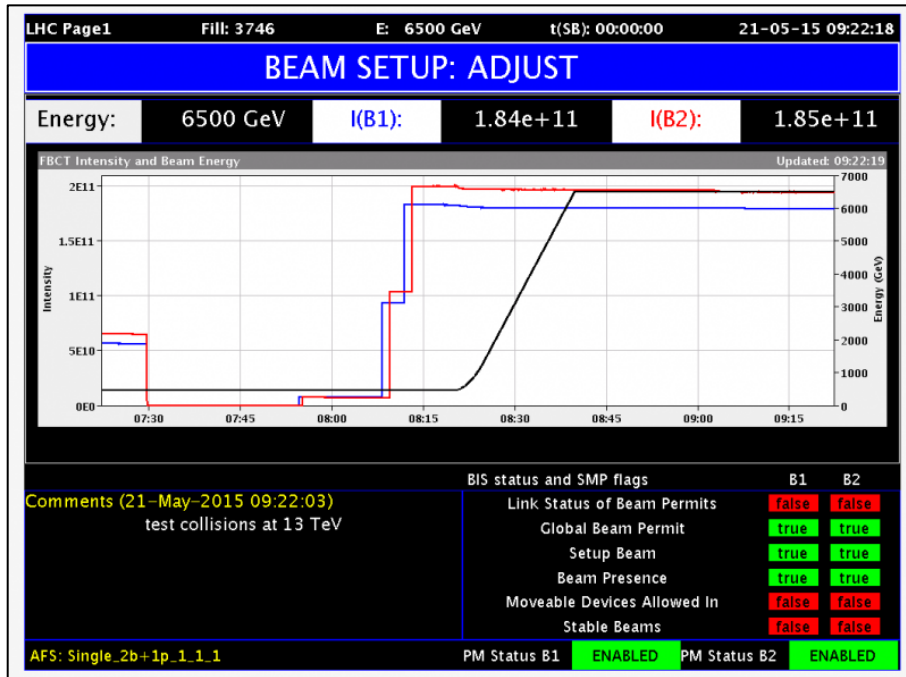


Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

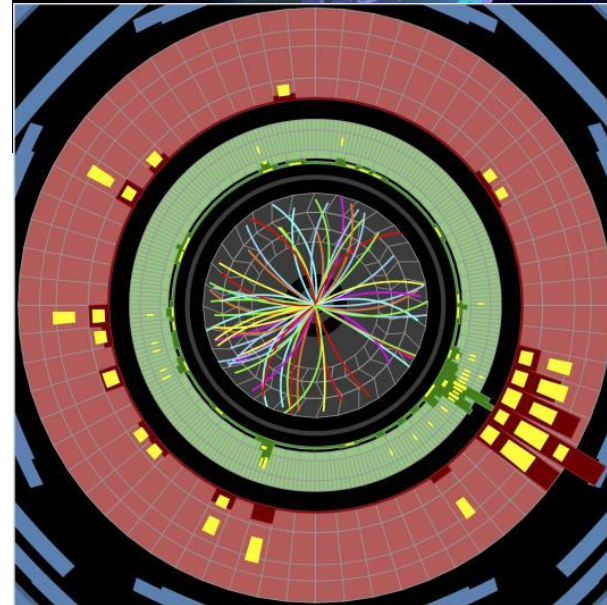
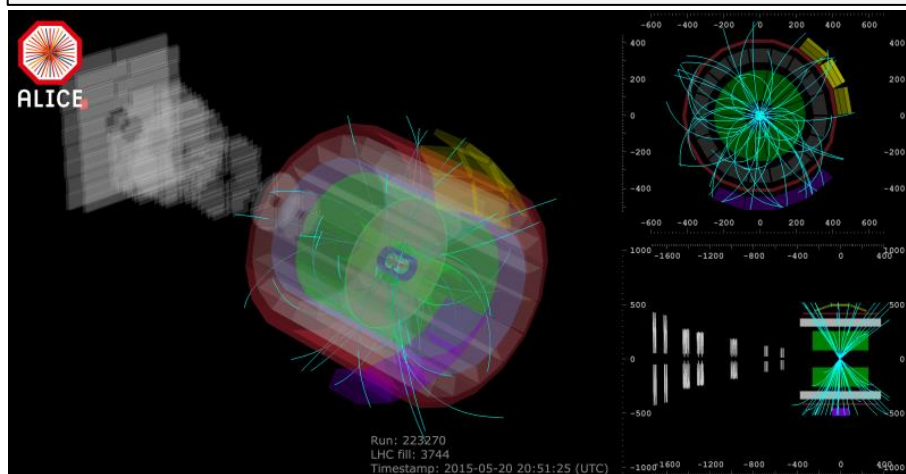
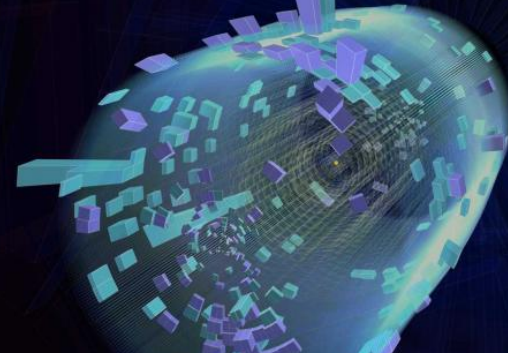


SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MS)

13TeV Collisions (May 20, 2015)



CMS Experiment at LHC, CERN
 Data recorded: Wed May 20 22:51:10 2015 CEST
 Run/Event: 245155 / 123300843
 Lumi section: 363
 Orbit/Crossing: 94976371 / 208



Run Number: 265532, Event Number: 3280065
 Date: 2015-05-20 22:51:50 CEST

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 [μ rad]	285	145	290
Peak luminosity[$\text{cm}^{-2}\text{s}^{-1}$]	1.0×10^{34}	7.7×10^{33}	8.5×10^{33}
Ave. Pileup	26	38	22

50 ns data: 100 pb^{-1}

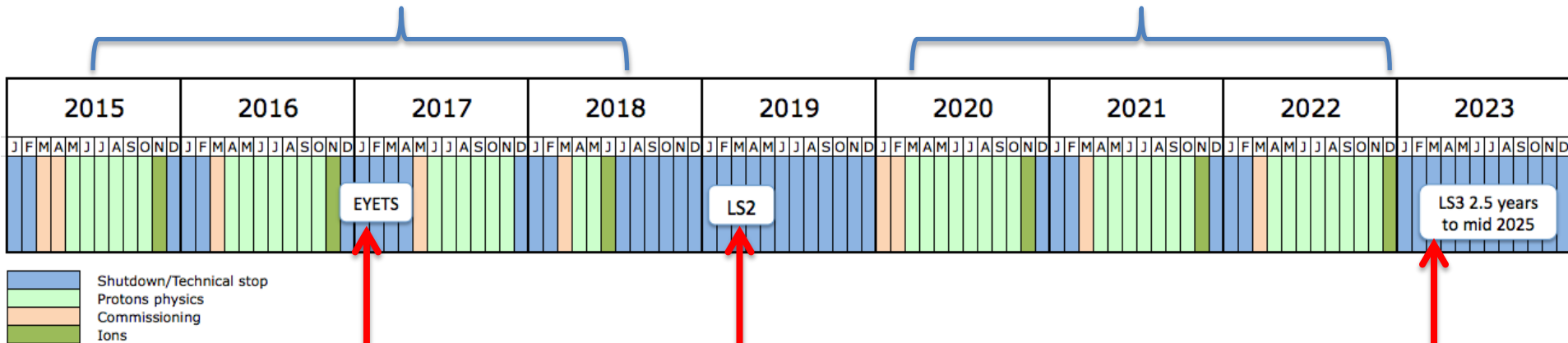
25 ns data: 4.2 fb^{-1} delivered, 3.8 recoded (ATLAS),
 4.1 fb^{-1} delivered, 3.7 recoded (CMS) [2.8 with 3.8T]

Peak Luminosity: $5.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (Run1: $7 \sim 8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$)

Run2, Run3 and HL-LHC

Run 2: 13~14 TeV with peak luminosity of $\sim 1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Run 3: 14 TeV with peak luminosity of $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



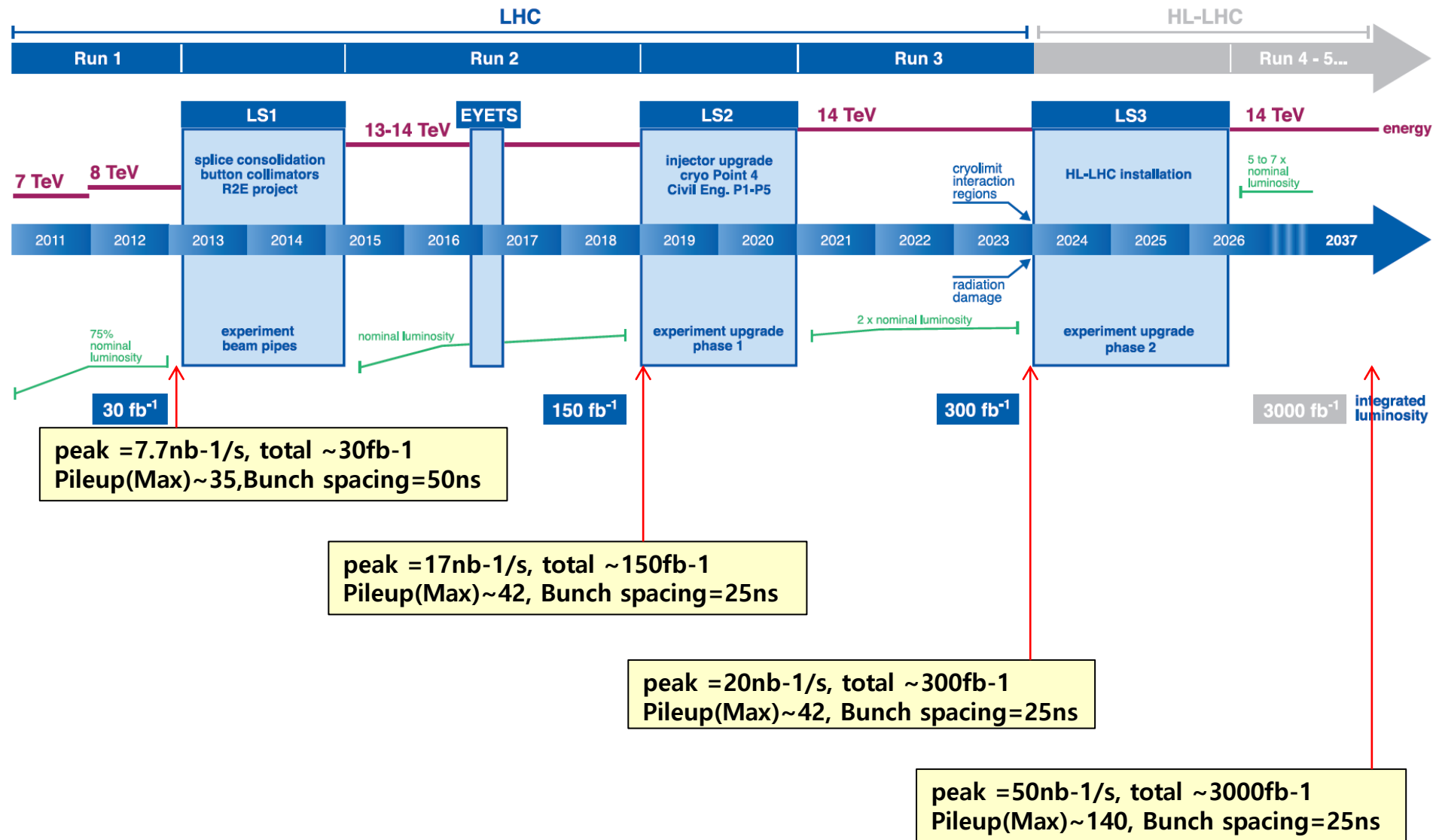
- Shutdown/Technical stop
- Protons physics
- Commissioning
- Ions

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

LS2 (18 months)
Connection of LINAC4
LHC Injectors Upgrade

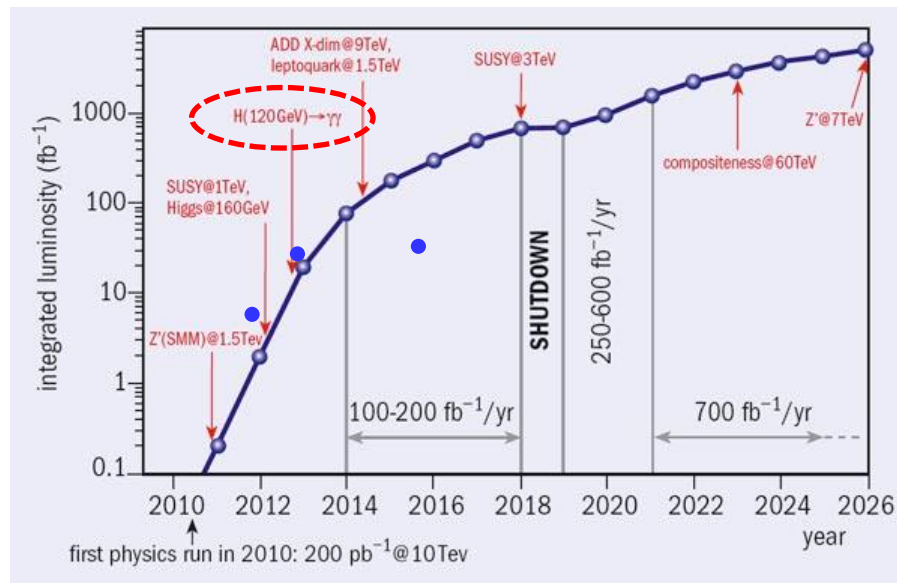
LS3 (30 months)
High Luminosity LHC

Long range plan



Final remarks

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



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