Elementary Particle Physics: theory and experiments

Experiment:

Accelerators for high energy physics

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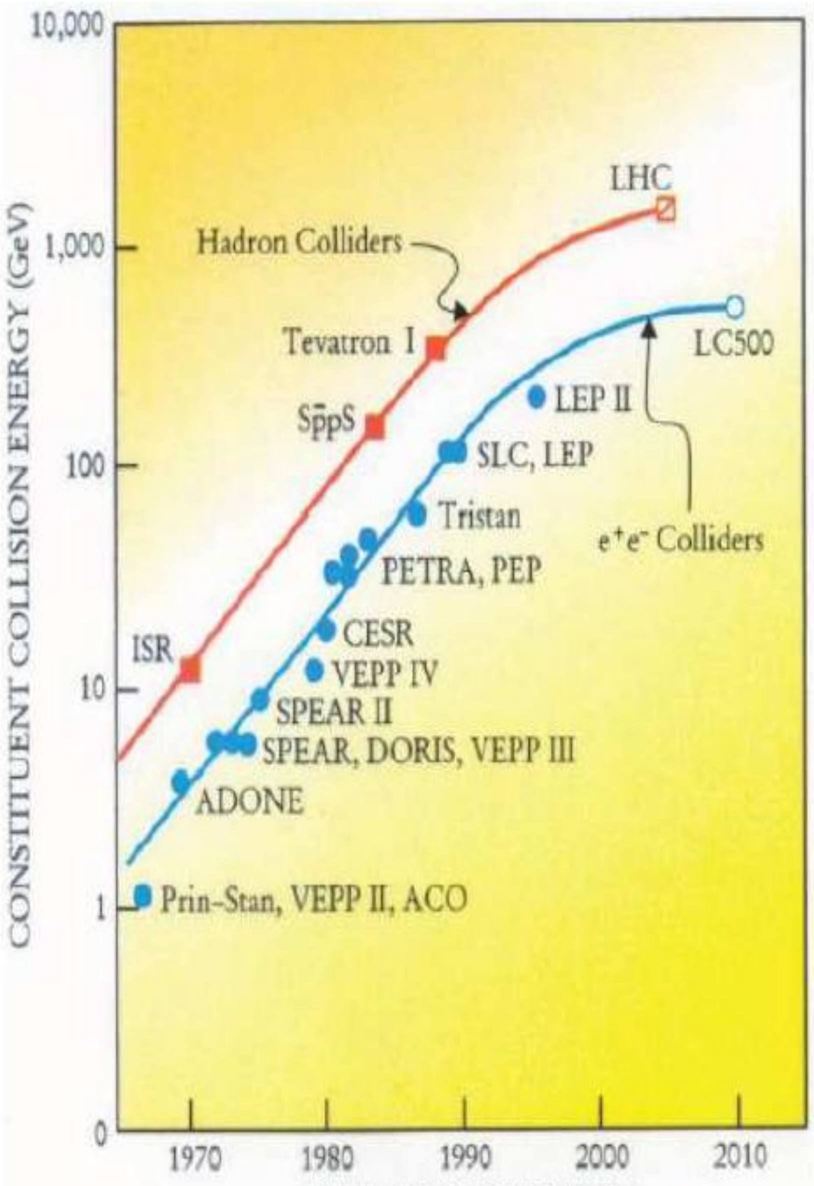
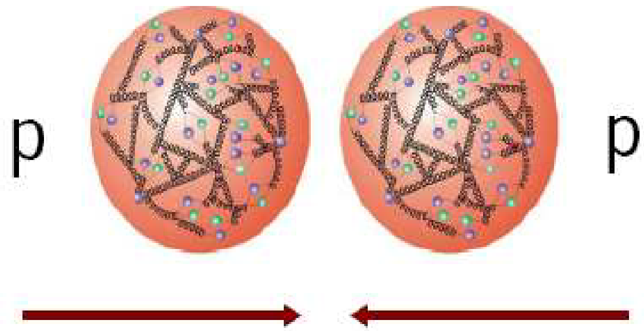
Accelerators for high energy physics experiments

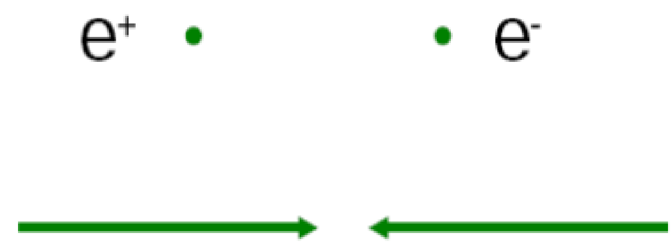
Energy frontier



- The interplay between electron and hadron machines has a long and fruitful tradition
  - J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
  - Υ discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
  - ...
  - top quark at LEP and Tevatron
- To be continued in the form of LHC and ILC

Complementarity between pp and ee machines

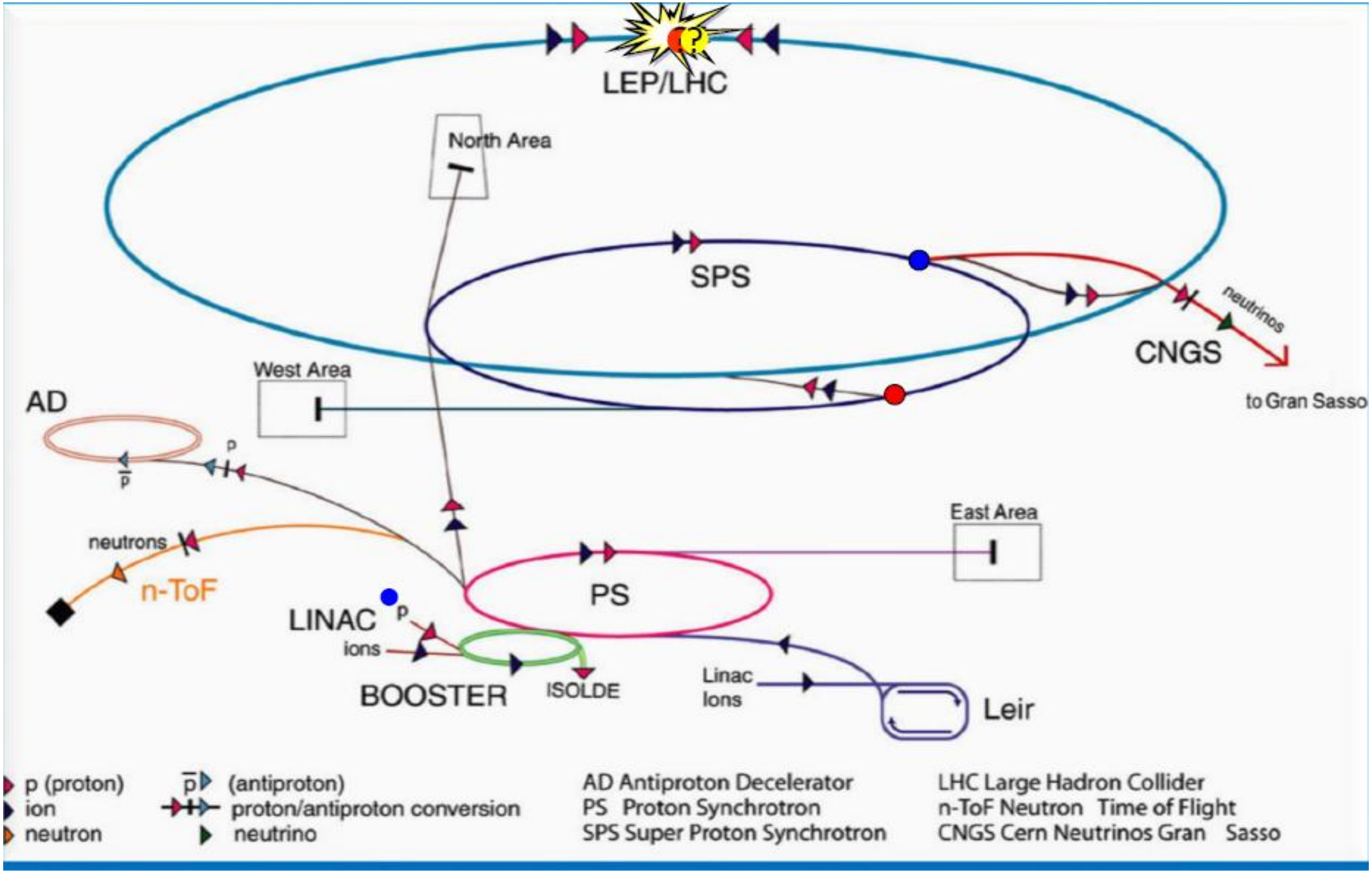




- Proton-(Anti-)Proton Colliders
  - Higher energy reach (limited by magnets)
  - Composite particles: unknown and different colliding constituents, energies in each collision
  - Confusing final states
- Discovery machines (W, Z, t)
- In some cases: precision measurements possible (W mass at the Tevatron)

- Electron-Positron-Colliders
  - Energy reach limited by RF
  - Point like particles, exactly definded initial system, quantum numbers, energy, spin polarisation possible
  - Hadronic final states with clear signatures
- Precision machines
- Discovery potential, but not at the energy frontier

CERN accelerator complex



Luminosity frontier

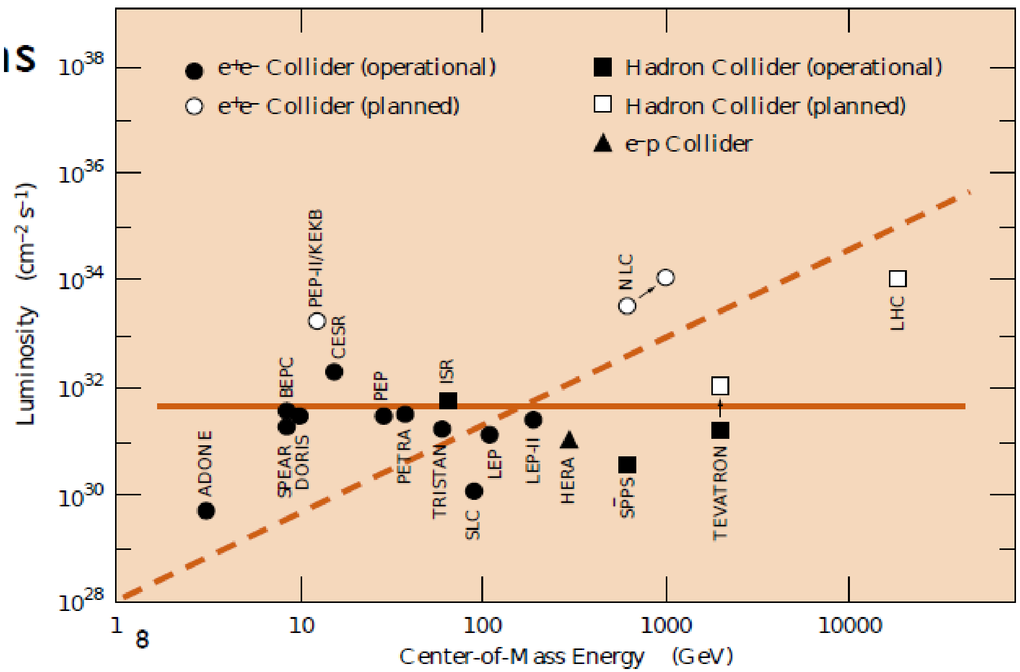
- Need corresponding rise in luminosity (beam intensity)

Number of events — Instantaneous luminosity

$$N = \sigma L = \sigma \int \mathcal{L}\, dt$$

Cross section — Integrated luminosity

- High luminosity brings all the challenges for the detectors:
  - High event rates
  - Pile up
  - Beam –beam interactions
  - Beamstrahlung



Designing a machine

- Particle species
  - Electron/positrons
  - Protons/antiprotons
  - Muons/antimuons
- Beam energy
- Spin
- Luminosity

- How do you produce antiparticles?
- Ones produced how ones keep them (muon collider)?
- Ones collided what ones does with spent beams?
- Accelerator and detector protection

Accelerator is much more than just….

- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc.)
- Diagnostics and controls
- Machine (and detector protection)
- Beam delivery and luminosity production
- Technology spin off
  - Lower energy machines, medical applications, applied physics, materials, …..

Acceleration

Lorentz force law

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

Electric field Velocity Magnetic field

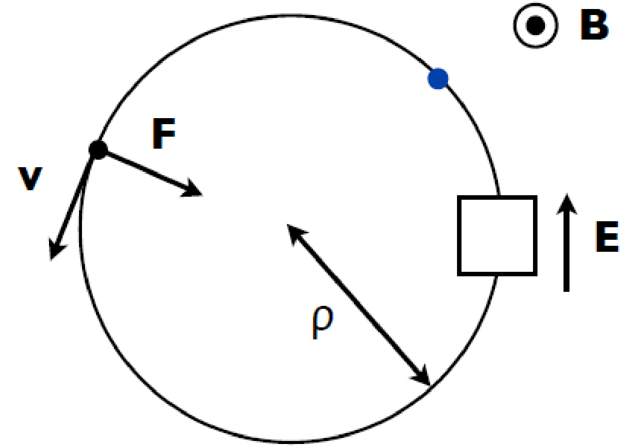
Energy change

$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- Electric field (either static or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
- Magnetic part of Lorentz force used to guide and focus
  - Dipole magnets: to bend
  - Quadrupole: to focus or defocus

Synchrotron

- Workhorse of modern particle physics
  - Huge legacy of discovery
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum



Velocity

$$qBv = \frac{m_0 v^2}{\rho}$$

Magnetic field

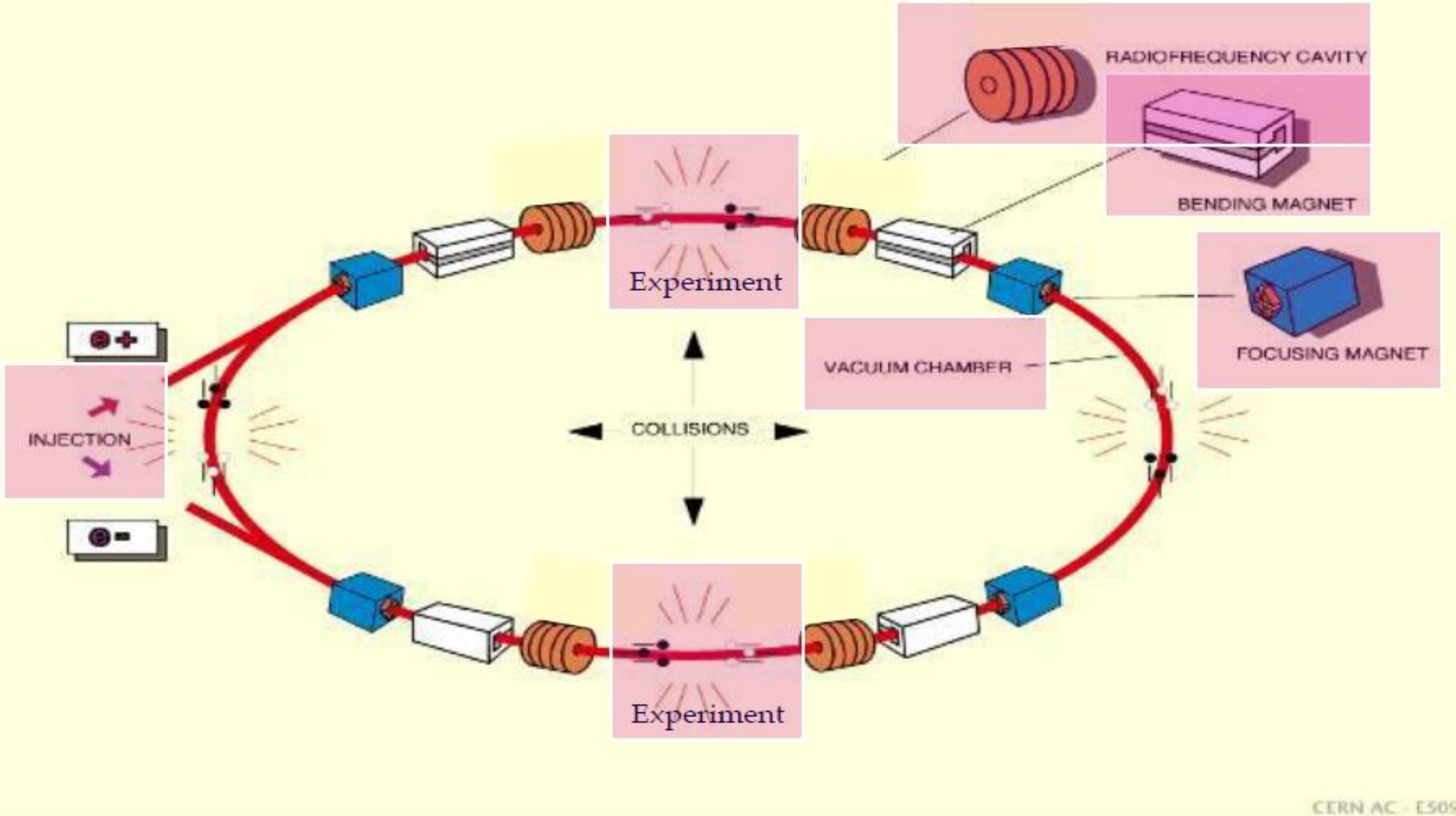
Bending radius

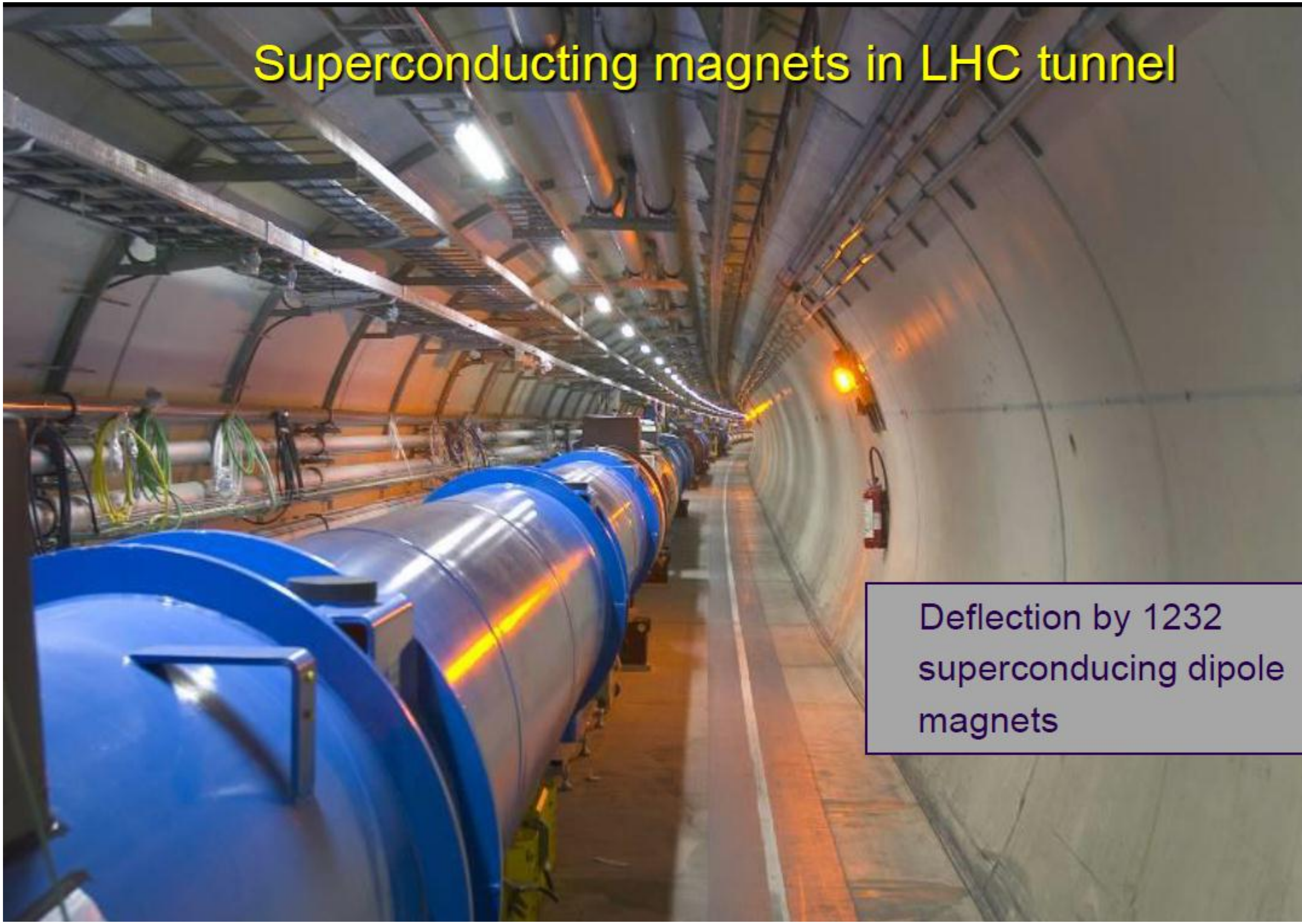
$$B\rho = p/q$$

Momentum

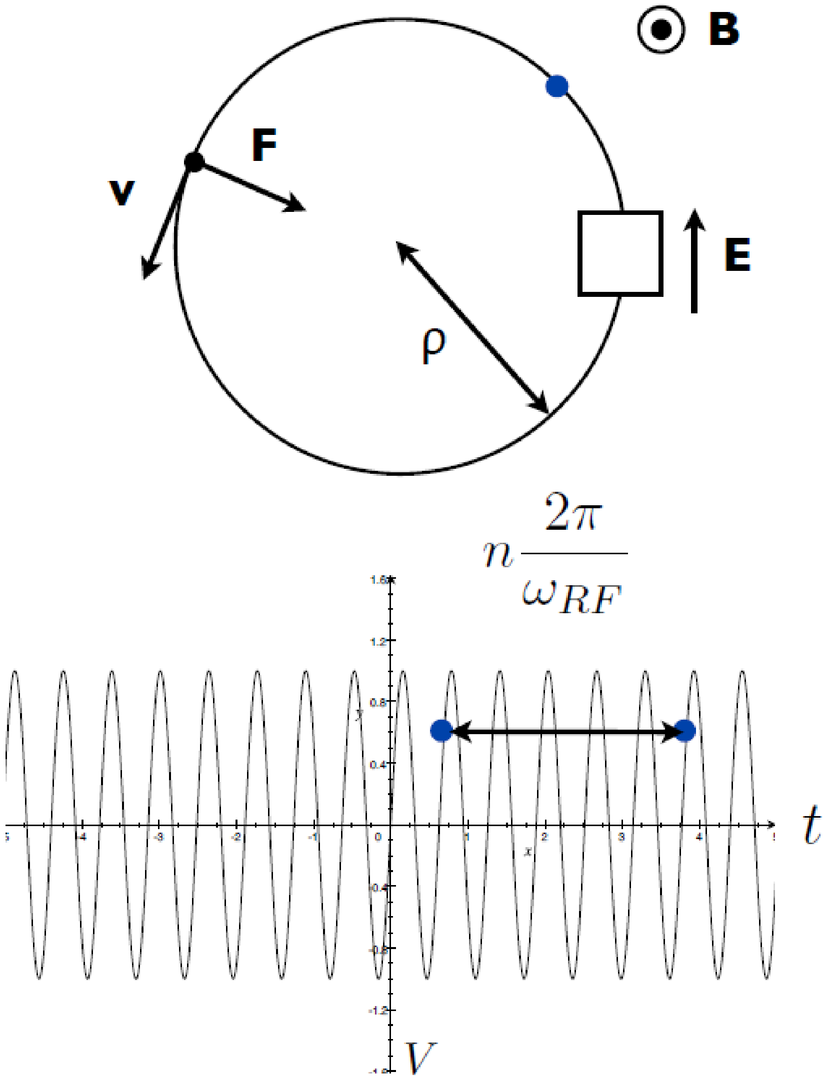
Synchrotron + many passages in RF cavities

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes




Superconducting magnets in LHC tunnel
Deflection by 1232 superconducing dipole magnets

Synchrotron



- Time varying electric field:

$$V(t) = V_0 \sin(\omega_{RF} t + \phi)$$

Angular frequency of accelerating field

- Particle gets a kick every revolution

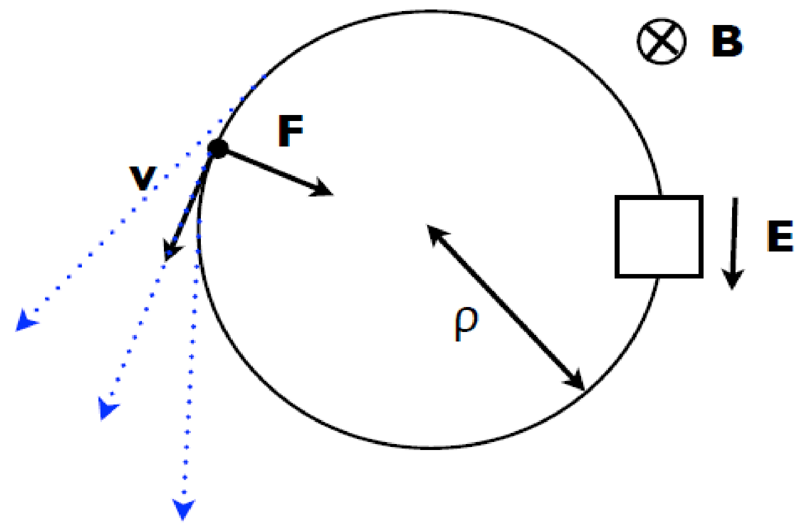
$$\frac{1}{f_{\mathrm{ref}}} = n\frac{2\pi}{\omega_{\mathrm{RF}}}$$

Revolution frequency

Integer

Synchrotron Radiation Limits

- Why not just build bigger LEP?
  - Reuse accelerating section every revolution of particle bunch
  - Power loss due to synchrotron radiation
  - LEP2 was practical limit for electron-positron synchrotron



Power

$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3\rho^2}\gamma^4$$

Energy loss per turn

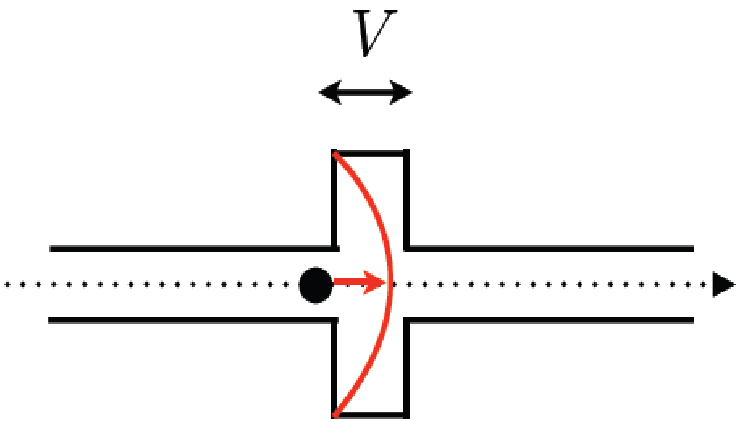
Beam energy

$$W = 8.85 \times 10^{-5} E^4/\rho$$

Magnetic radius

Absolute Limits on Acceleration

- Need to create large on axis electric fields
  - Accelerating structures:
    - Superconducting (~35 MV/m)
    - Normal conducting (~100 MV/m)
- Beyond these values there is high voltage breakdown



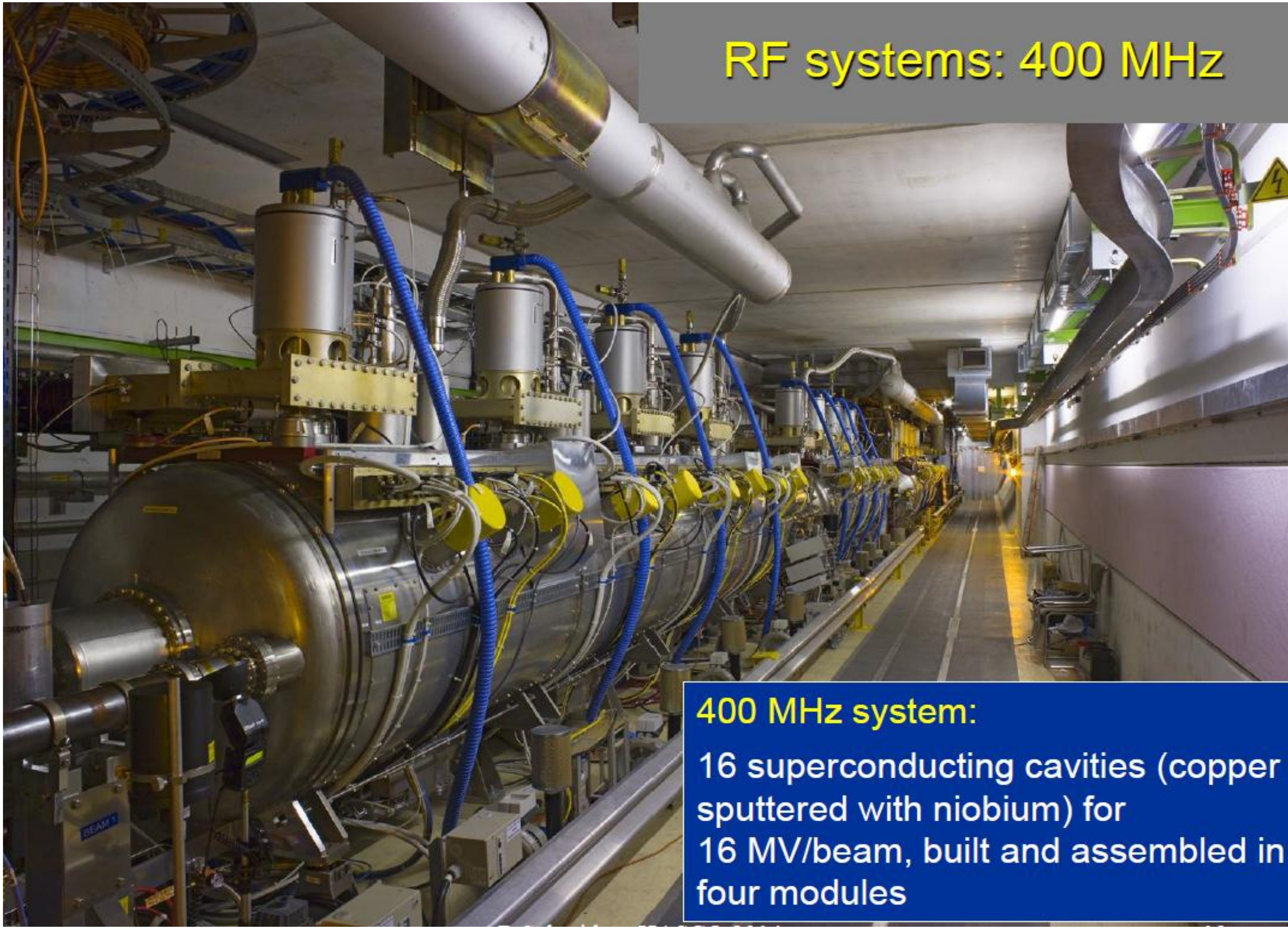
Machine length [m]

Beam energy [MeV]

$$S = \frac{E}{q\, dV/ds}$$

Accelerating gradient [MV/m]

RF systems: 400 MHz

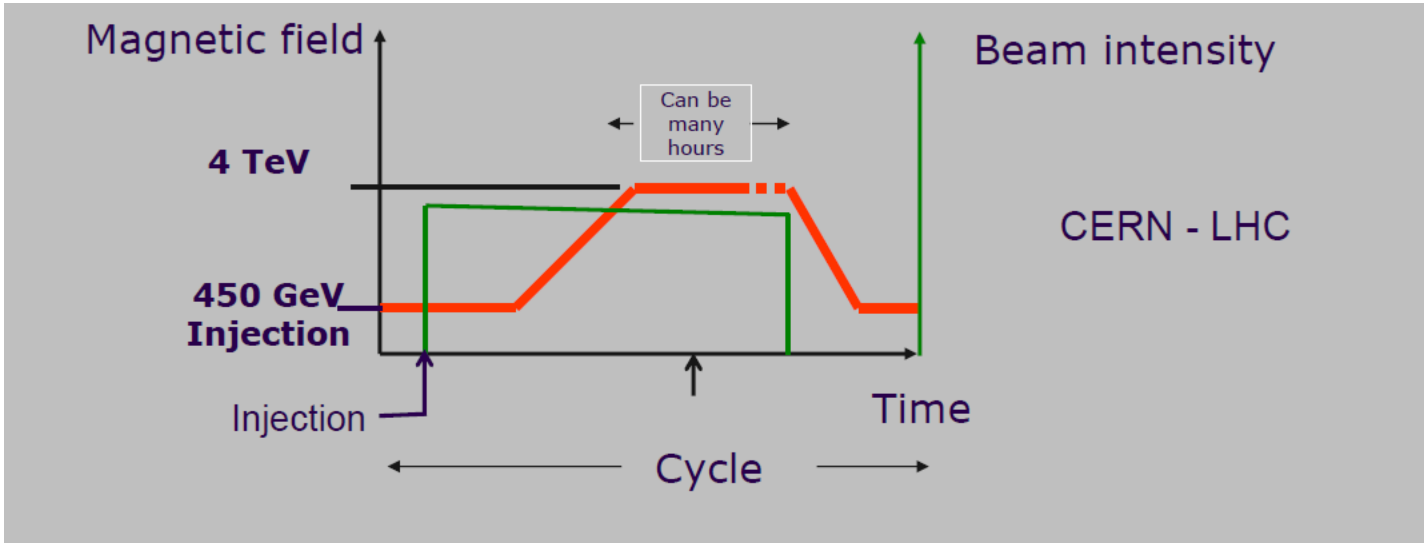


400 MHz system:

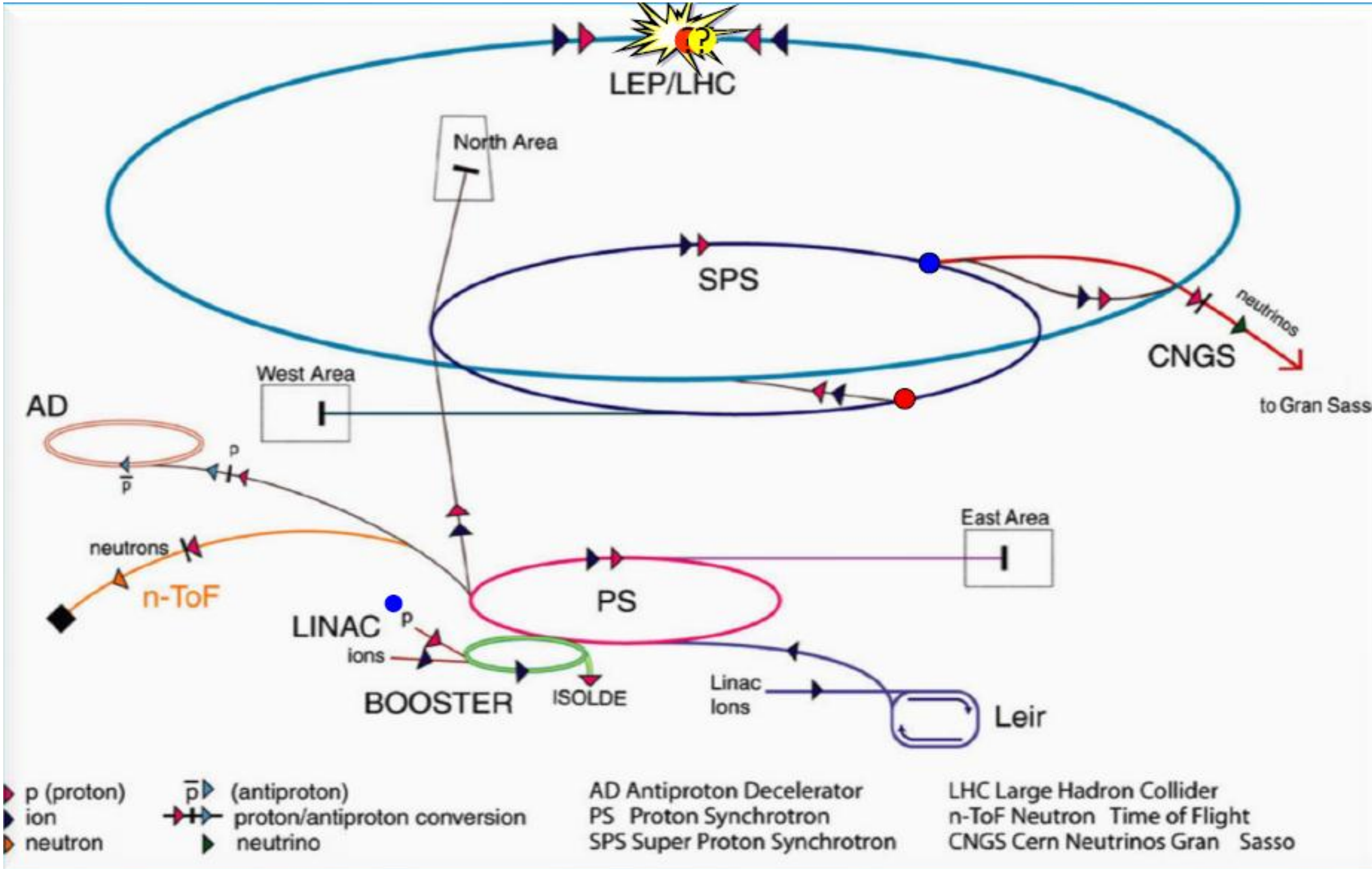
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

Principle of a synchrotron

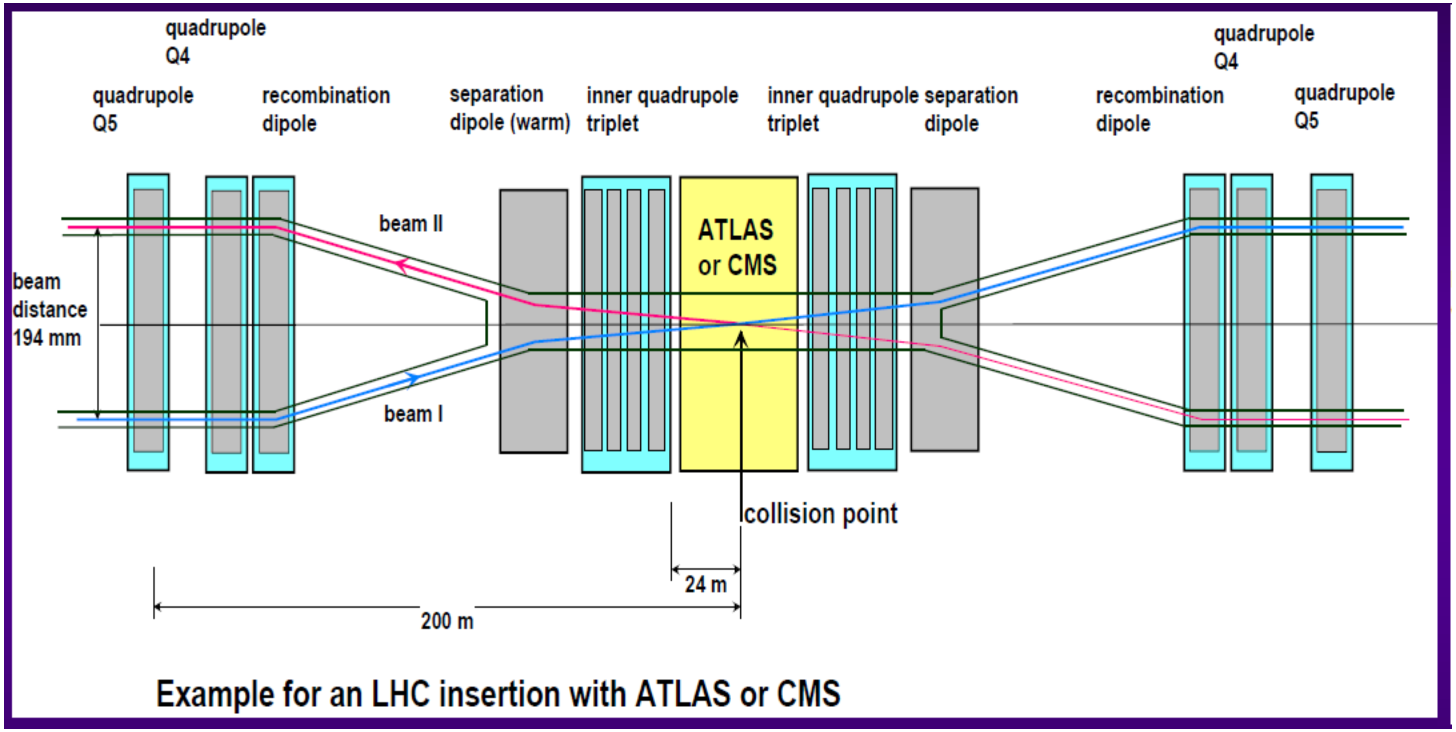
- Injection at low energy
- Ramping of magnetic field and acceleration by RF field. Beams are accelerated in bunches
- Operation (collisions) at top energy



CERN accelerator complex



Experimental long straight section



The 2 LHC beams are brought together to collide in common region. Over ~260m the beams circulate in one vacum chamber with „parasitic" encounters.

The crossing angle of about 300μrad

Luminosity

- What luminosity is required for measurement?
  - Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes

Luminosity [s^{-1} m^{-2}]

Bunch populations

$$\mathcal{L} = f\,\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Frequency of collisions [Hz]

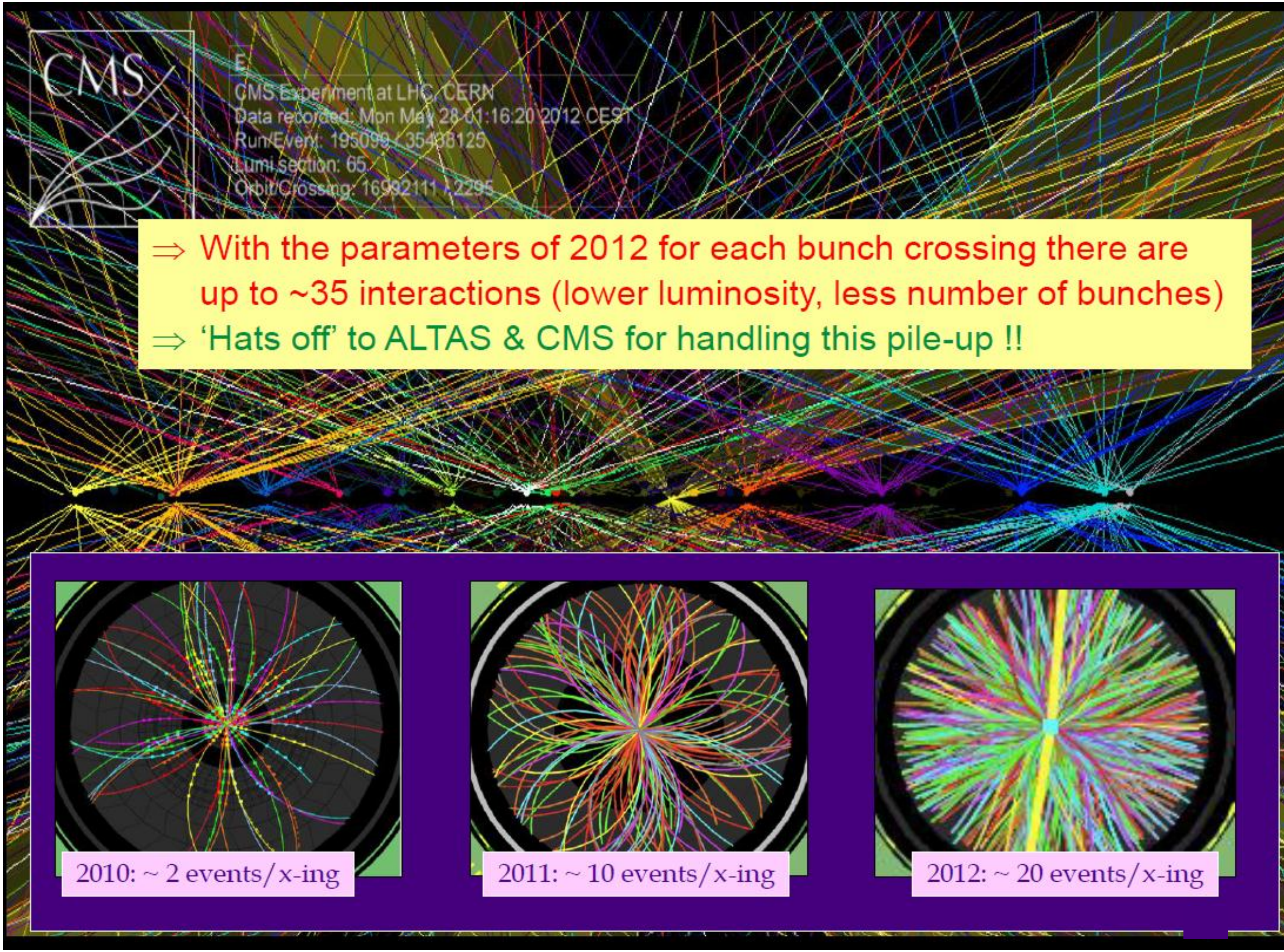
Beam r.m.s. sizes [m]

$$\sigma = \sqrt{\epsilon\beta}$$

Emittance [m]

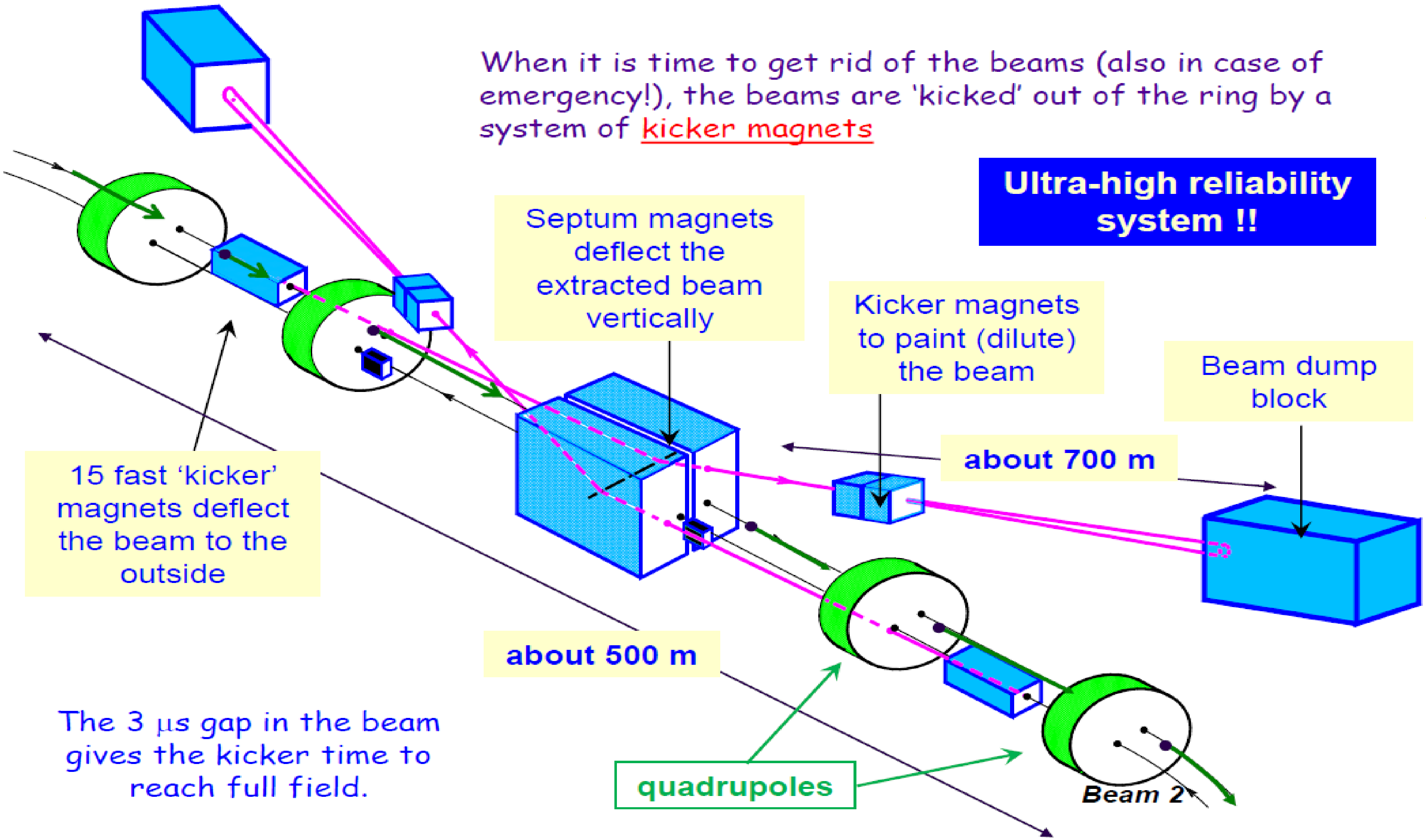
Beta function [m]

$$\mathcal{L} = f\,\frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)
⇒ 'Hats off' to ALTAS & CMS for handling this pile-up !!
2010: ~ 2 events/x-ing
2011: ~ 10 events/x-ing
2012: ~ 20 events/x-ing

Layout of beam system dump

When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets



The 3 µs gap in the beam gives the kicker time to reach full field.

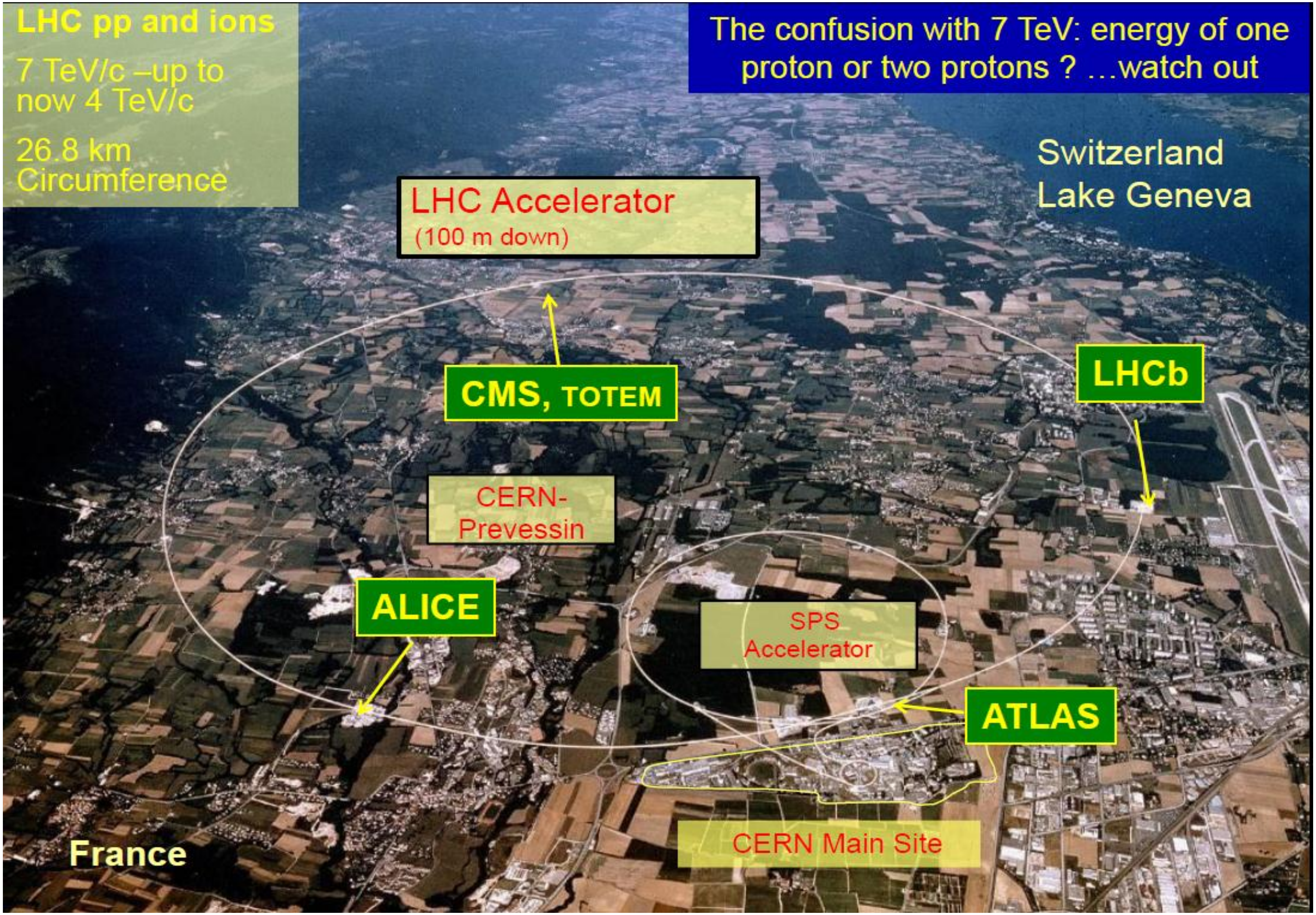
Dump line

Beam Loss Monitors

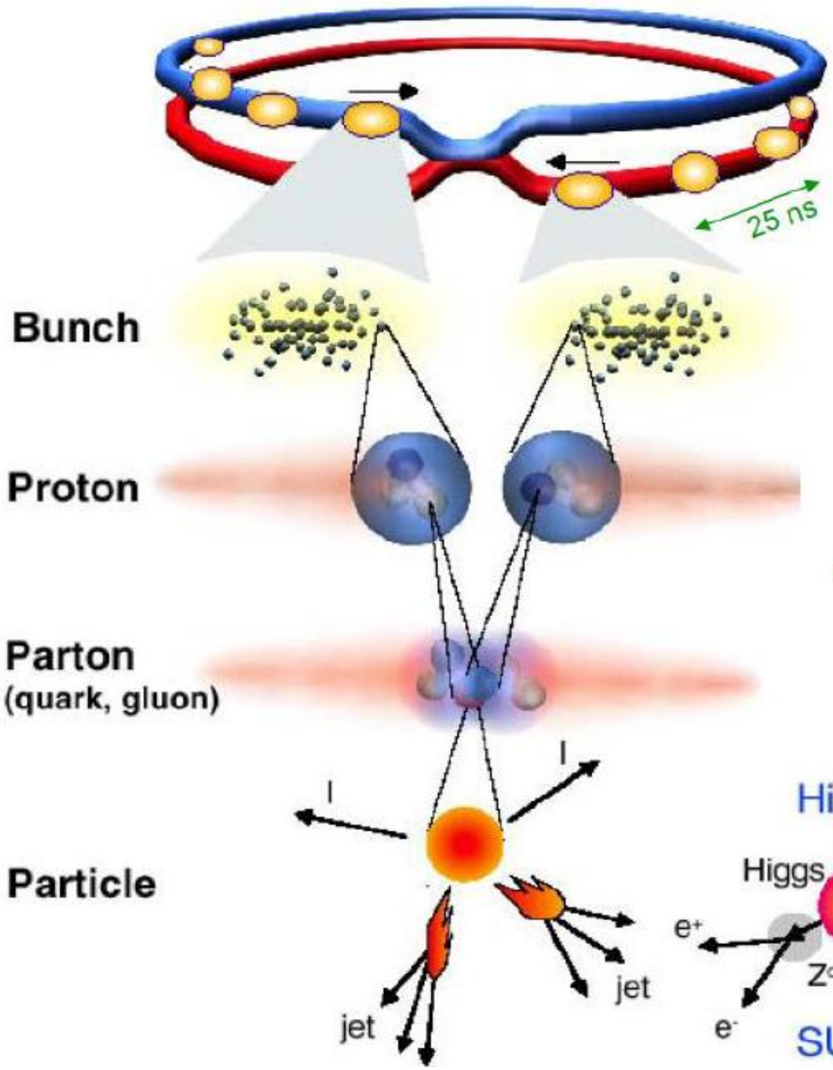
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

The LHC: just another collider?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi [$cm^{-2}s^{-1}$]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	4.3 10^{32}	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	5.1 10^{31}	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	1.5 10^{32}	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 4000	26800	8.3	10^{34} Now 7.7× 10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**

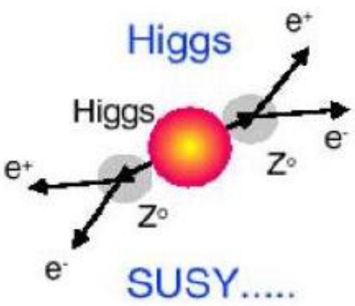

LHC pp and ions
7 TeV/c –up to now 4 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

In the experiments:
10^9 pp interactions per second
~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing



Selection of 1 in 10,000,000,000,000

Summary: 2010 - 2012

$$L = \frac{kN_b^{\;2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

Parameter	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	**4.0**	7.0
N_b [10^{11} p/bunch]	1.2	1.45	**1.6**	1.15
k (no. bunches)	368	1380	**1380**	2808
Bunch spacing [ns]	150	75 / 50	**50**	25
Stored energy [MJ]	25	112	**140**	362
ε^* [μm]	2.4	2.4	**2.5**	3.75
β^* [m]	3.5	1.5 → 1	**0.6**	0.55
Crossing angle [μrad]	200	240	**290**	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	**0.76**	1.0
Beam-beam parameter/IP (ΔQ_{bb})	-0.0054	-0.0065	**-0.0069**	-0.0033
Average Pile-up @ beg. of fill	8	17	**38**	26

The next years