# Introduction to particle physics: experimental part

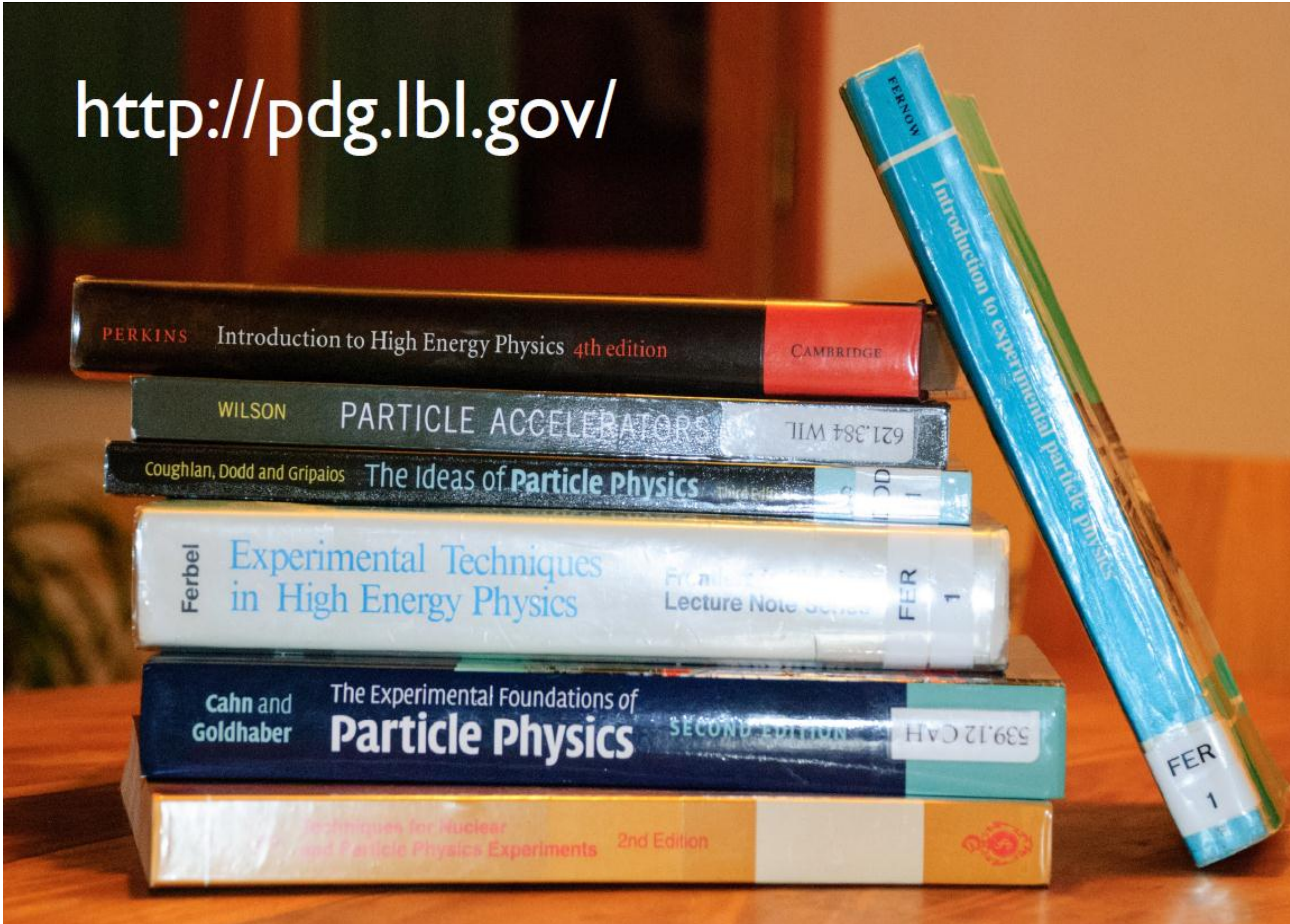
**Few words about Standard Model**

**Accelerators**

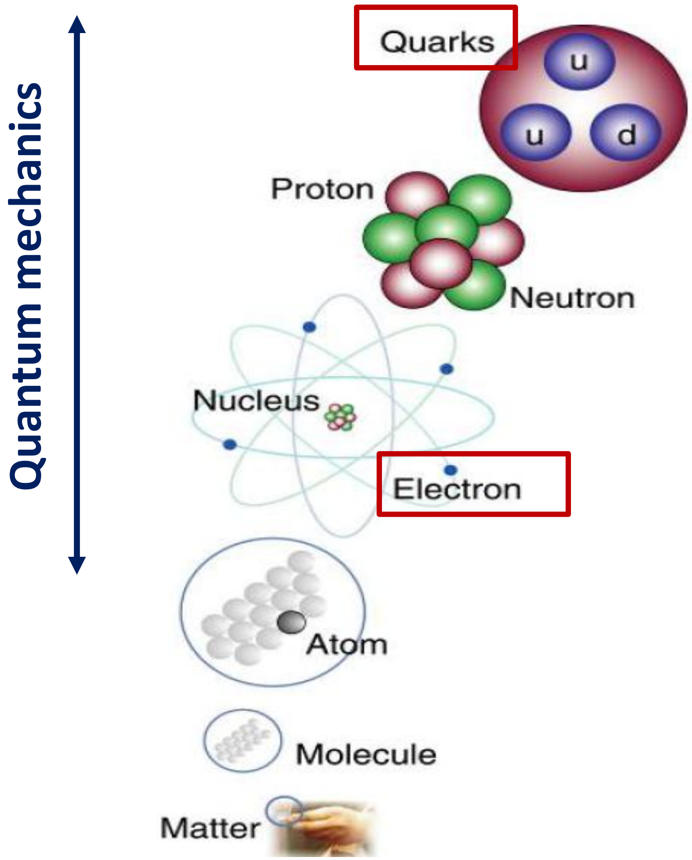
**CERN and LHC**

**Credits:**
**a lot of material in this lecture is from lectures by R.Schmidth at HASCO2017 school.**

Prof. dr hab. Elżbieta Richter-Wąs

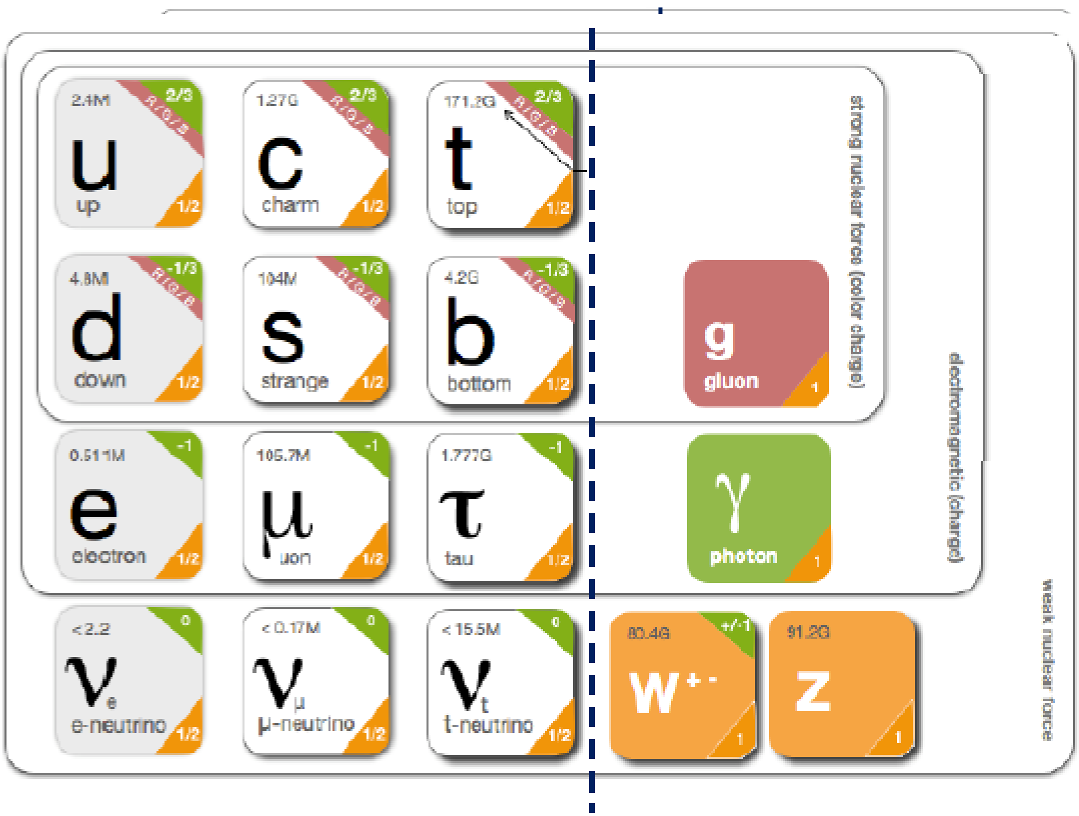

http://pdg.lbl.gov/
PERKINS Introduction to High Energy Physics 4th edition
CAMBRIDGE
WILSON PARTICLE ACCELERATORS
621.384 WIL
Coughlan, Dodd and Gripaios The Ideas of Particle Physics
Ferbel
Experimental Techniques in High Energy Physics
FER 1
Cahn and Goldhaber
The Experimental Foundations of Particle Physics
539.12 CAH
FERNOW
Introduction to experimental particle physics
FER 1

# Particles of the Standard Model




**Matter particles**
**(< $10^{-16}$ cm)**

**Interaction particles**





**Higgs particle**
**Is not a matter particle and not an interaction particle**

# Nobel Prizes in Elementary Particle Physics


Sin-Itiro Tomonaga


Julian Schwinger


Richard P. Feynman


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg

GREEN - theoretical
BLUE - experimental

1964: „Higgs mechanism" was born


Leon M. Lederman


Melvin Schwartz


Jack Steinberger


Carlo Rubbia


Simon van der Meer


Georges Charpak


Gerardus 't Hooft

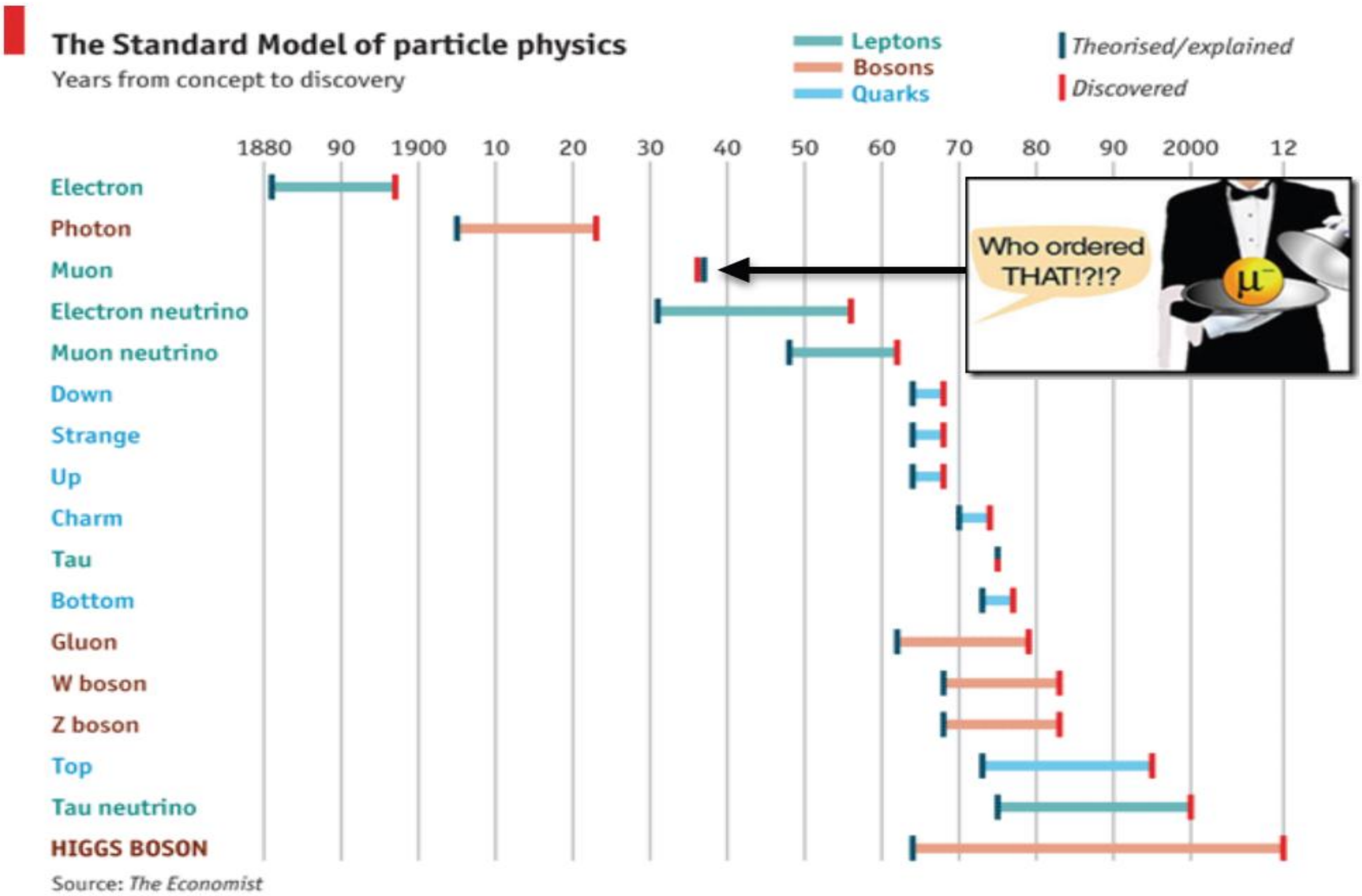

Martinus J.G. Veltman


M. Gell-Mann

- 1957 – C. N. Yang, T. Lee
- 1965 – S. I. Tomonaga, J. Schwinger, R.P Feynman
- 1969 – M. Gell-Mann
- 1976 – B. Richter and S. Ting
- 1979 – S.L. Glashow, A. Salam, S. Weinberg
- 1980 – J. Cronin, V. Fitch
- 1984 – C. Rubbia, S. van der Meer
- 1988 – L. M. Lederman, M. Schwartz, J. Steinberger
- 1990 – J. Friedman, J. Kendall, R. Taylor
- 1992 - G. Charpak
- 1995 – M. Perl, F. Reines
- 1999 - G. tHooft, M. J. Veltman
- 2004 - D. J. Gross, H. D. Politzer, F. Wilczek
- 2008 – Y. Nambu, M. Kobayashi, T. Masakawa
- 2013 – F. Englert and P. Higgs
- 2015 - T. Kajita and A. B. McDonald

2012: „Higgs particle" was discovered

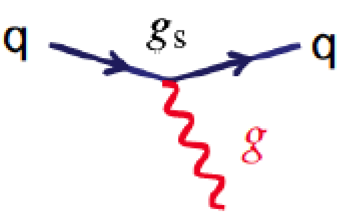
# Uncharted discoveries?



# Interactions

The interaction of gauge bosons with fermions is described by the Standard Model

**STRONG**




Only quarks

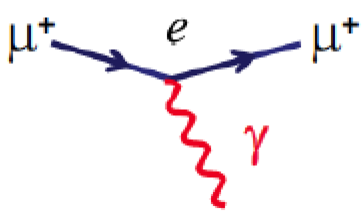
Never changes flavour

$\alpha_S \sim$ **1/10**

**Gluons**

massless

**EM**




All charged fermions

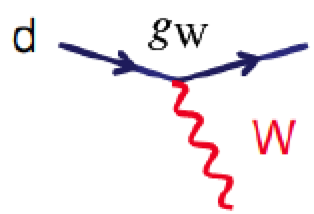
Never changes flavour

$\alpha \simeq 1/137$

**Photon**

massless

**WEAK CC**



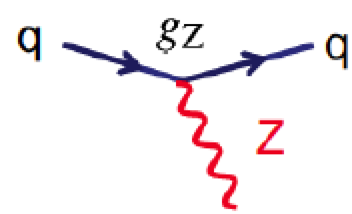

All fermions

<u>Always</u> changes flavour

**W+, W-**

very massive

**WEAK NC**




All fermions

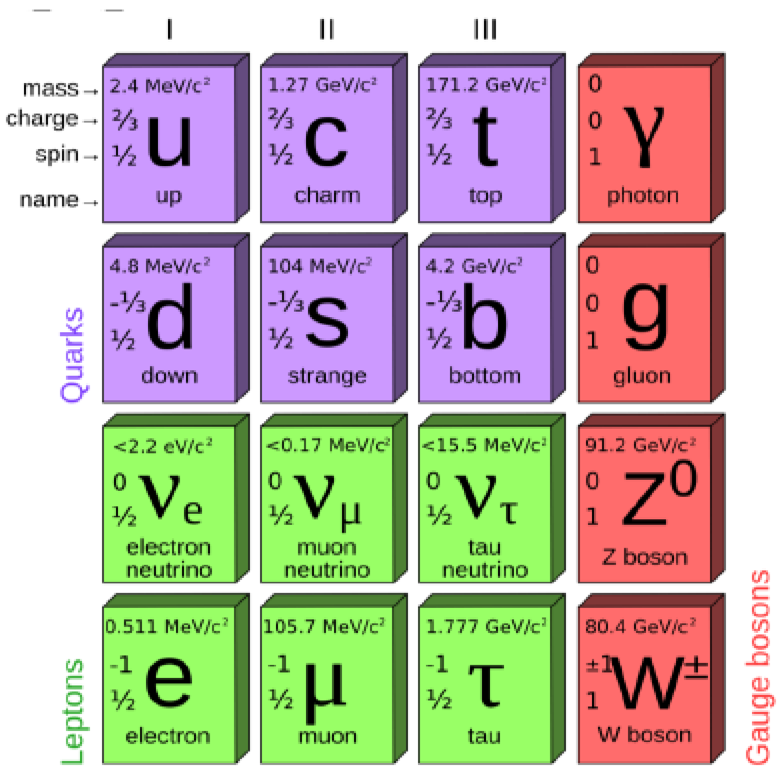
Never changes flavour

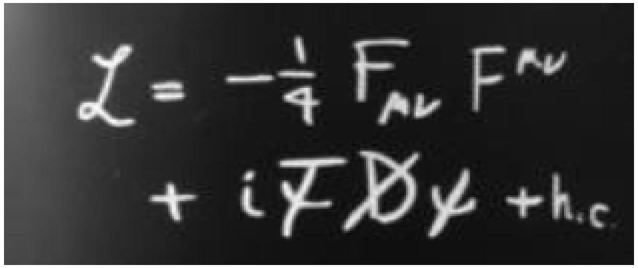
$\alpha_{W/Z} \sim 1/40$

**$Z^0$**

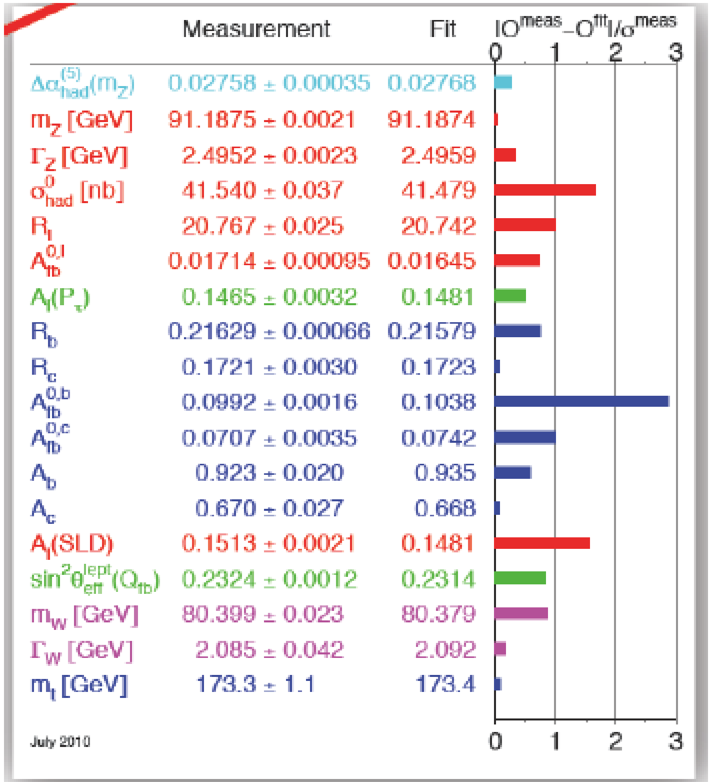
very massive

# Standard Model confirmed by the data




## STANDARD MODEL OF ELEMENTARY PARTICLES

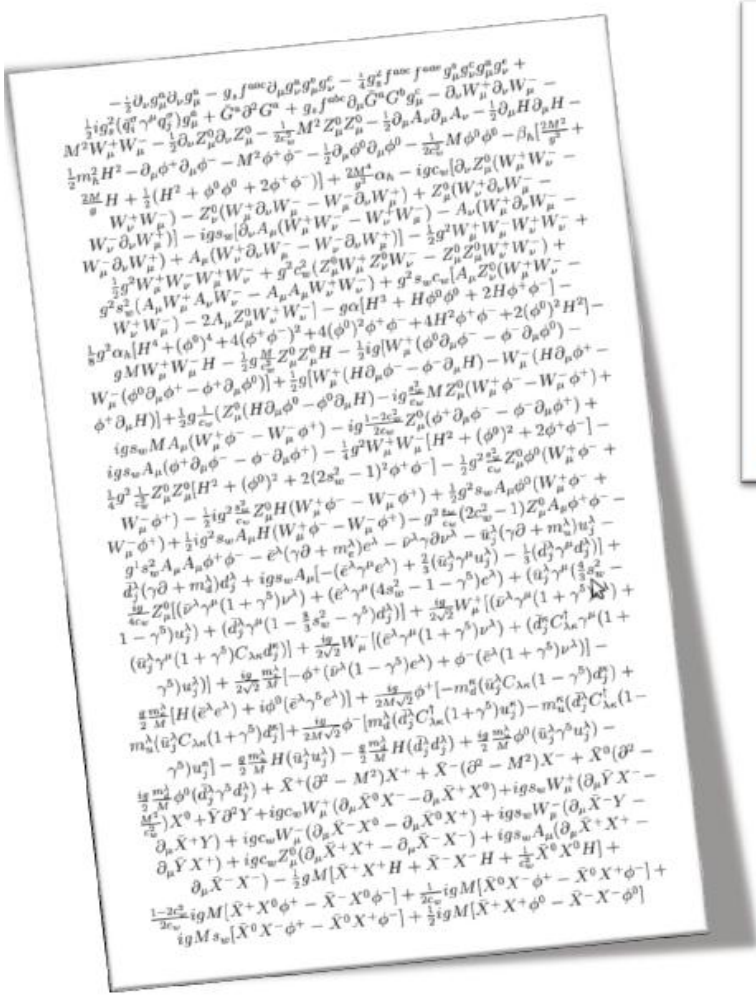


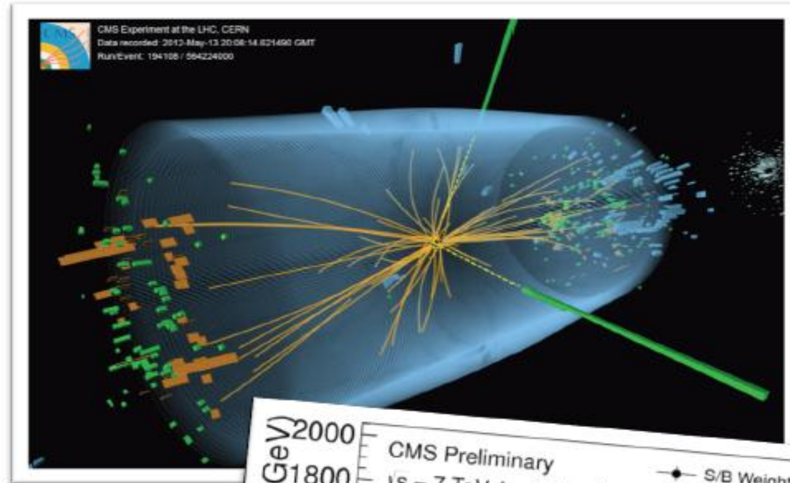
| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^{0}$ [nb] | 41.540 ± 0.037 | 41.479 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01645 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1481 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1481 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.399 ± 0.023 | 80.379 |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 |
| $m_t$ [GeV] | 173.3 ± 1.1 | 173.4 |

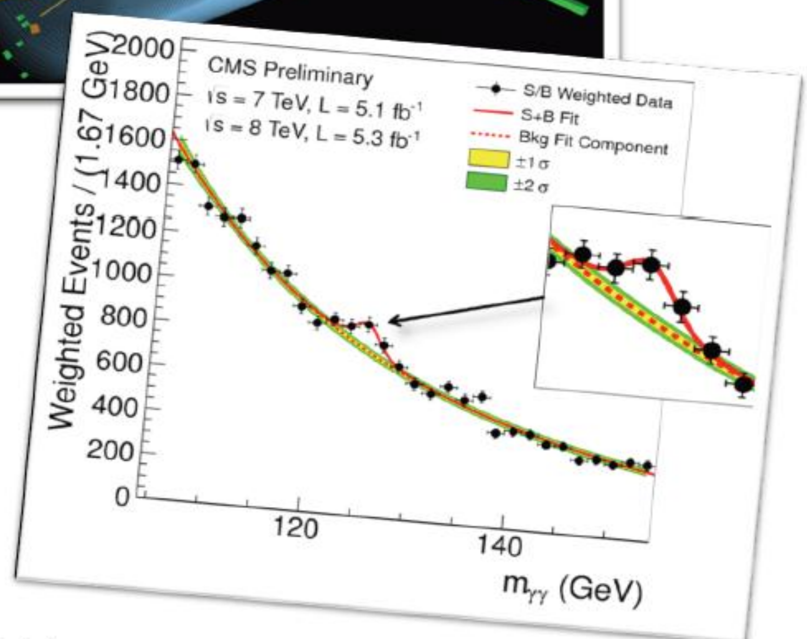


Confirmed at sub 1% level!

# Experiment = probing theories with data

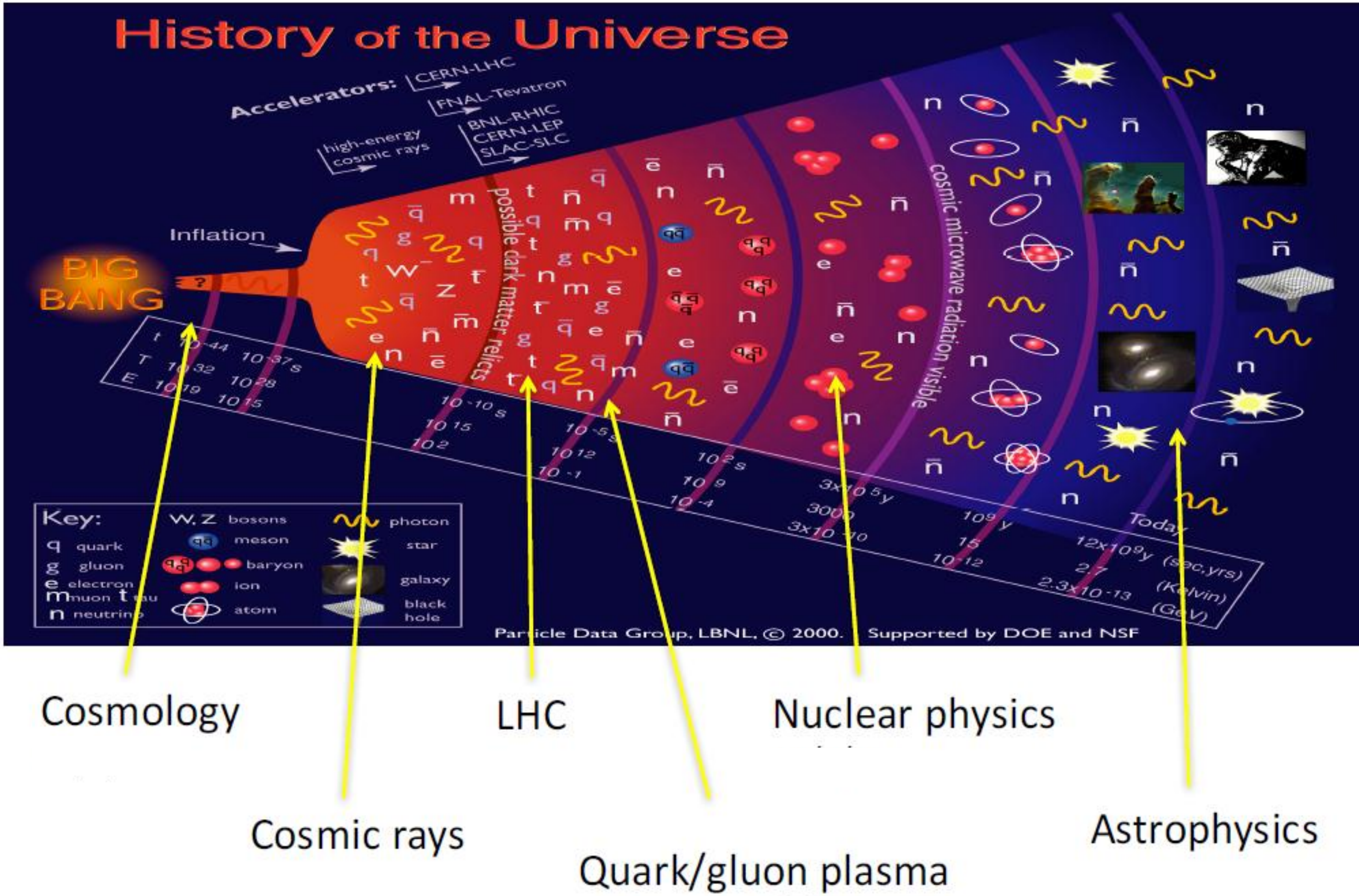




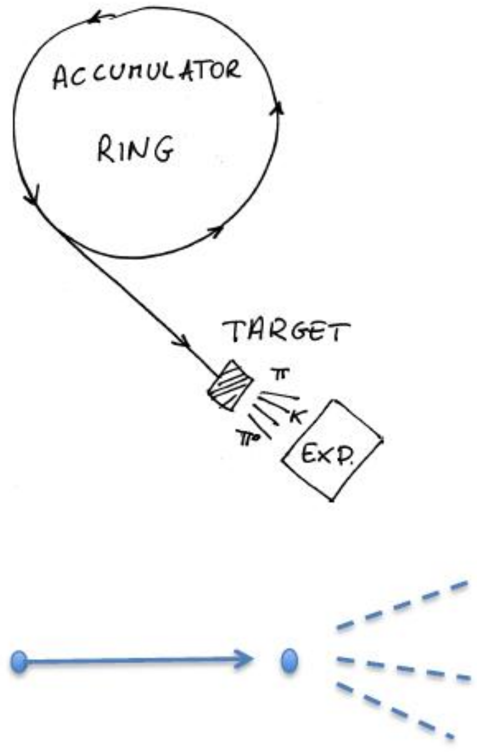
# Accelerators for high energy physics experiments

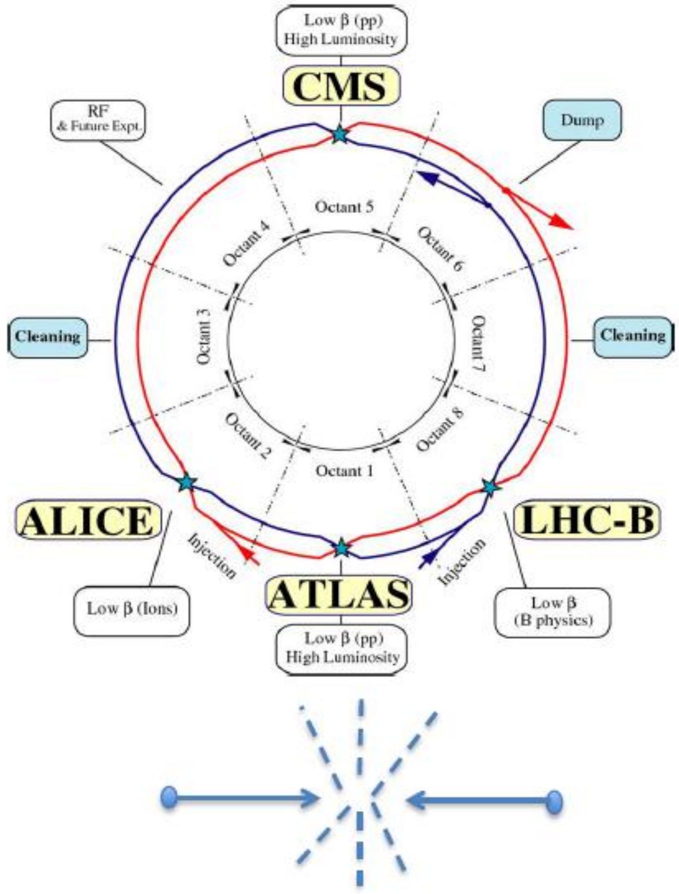
# History of the Universe



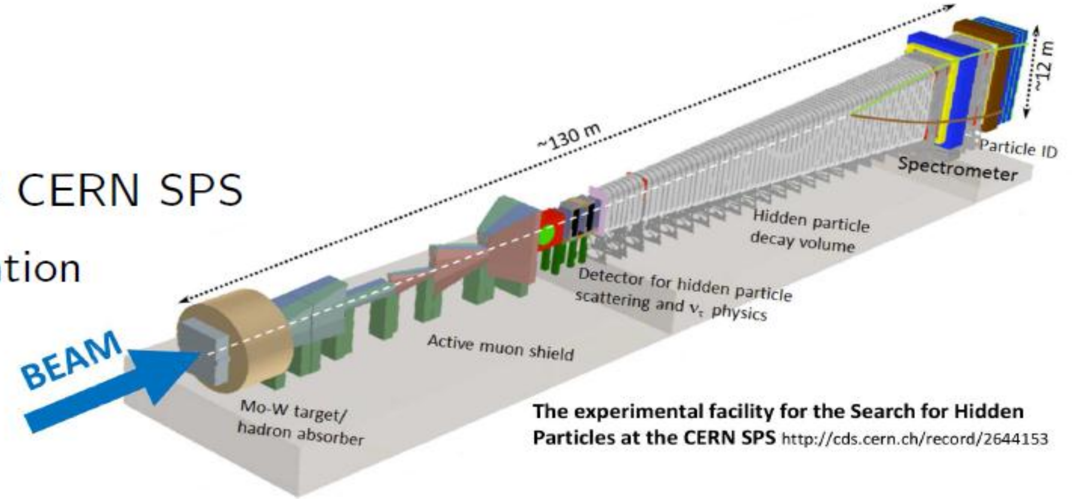

Plus ....

# Fixed target vs Colliders



# Fixed target vs Colliders

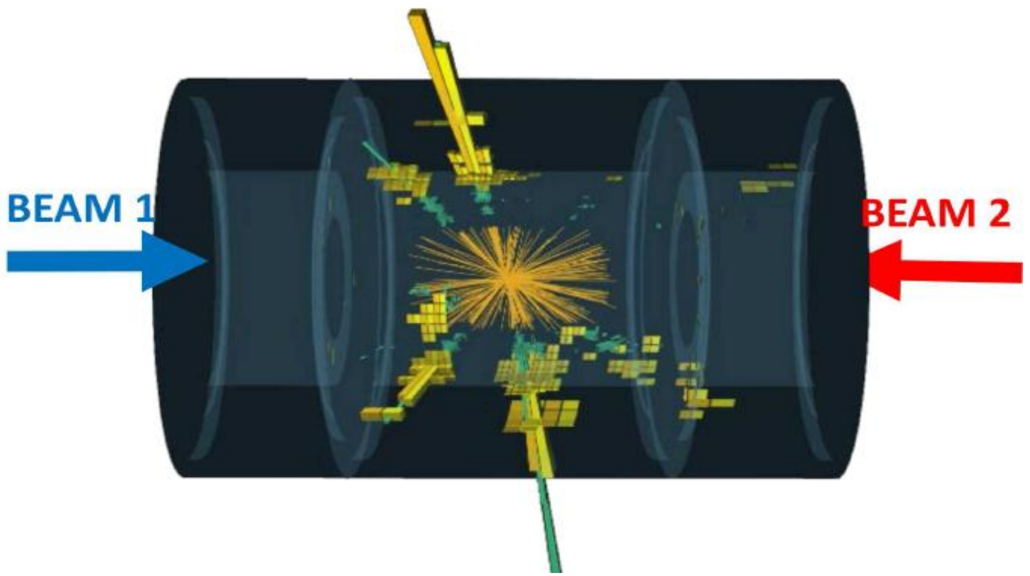



**Fixed target** e.g. SHIP @ CERN SPS

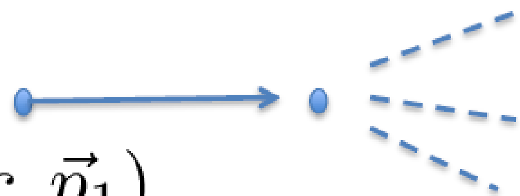
- Simpler design/implementation
  → **cost!**
- Potential for very high intensity beams & large numbers of collissions

**Collider** e.g. LHC @ CERN

- More complex design
  + many extra challenges
- **LAB frame = CM frame**
  → maximum energy available
  for new particle creation



# $E_{CM}$ in Fixed Target Experiment



$$p_2 = (m_2 c, \vec{0})$$

$$p_1 = (E_1/c, \vec{p}_1)$$

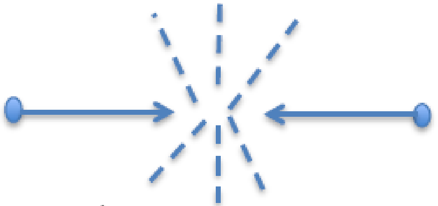
$$p_{tot} = (E_1/c + m_2 c, \vec{p}_1)$$

$$E_{CM}^2 = (m_1^2 + m_2^2)c^4 + 2E_1 m_2 c^2$$

$$E_{CM} \propto \sqrt{E_1}$$

# $E_{CM}$ in Collider Experiment

Laboratory Frame = CM Frame



$$p_1 = (E_1/c, \vec{p}_1) \qquad p_2 = (E_2/c, -\vec{p}_1)$$

$$E_{CM} = E_1 + E_2$$

➔ Collider more energy efficient;
But also more complex: two beams to be accelerated and to be brought into collision

# Acceleration

Lorentz force law

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

Electric field Velocity Magnetic field

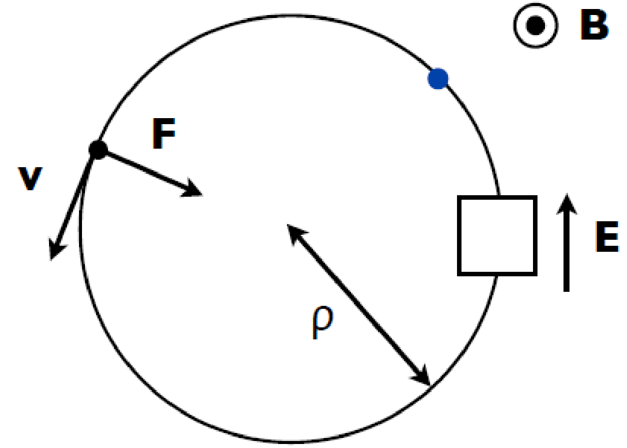
Energy change

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

- 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

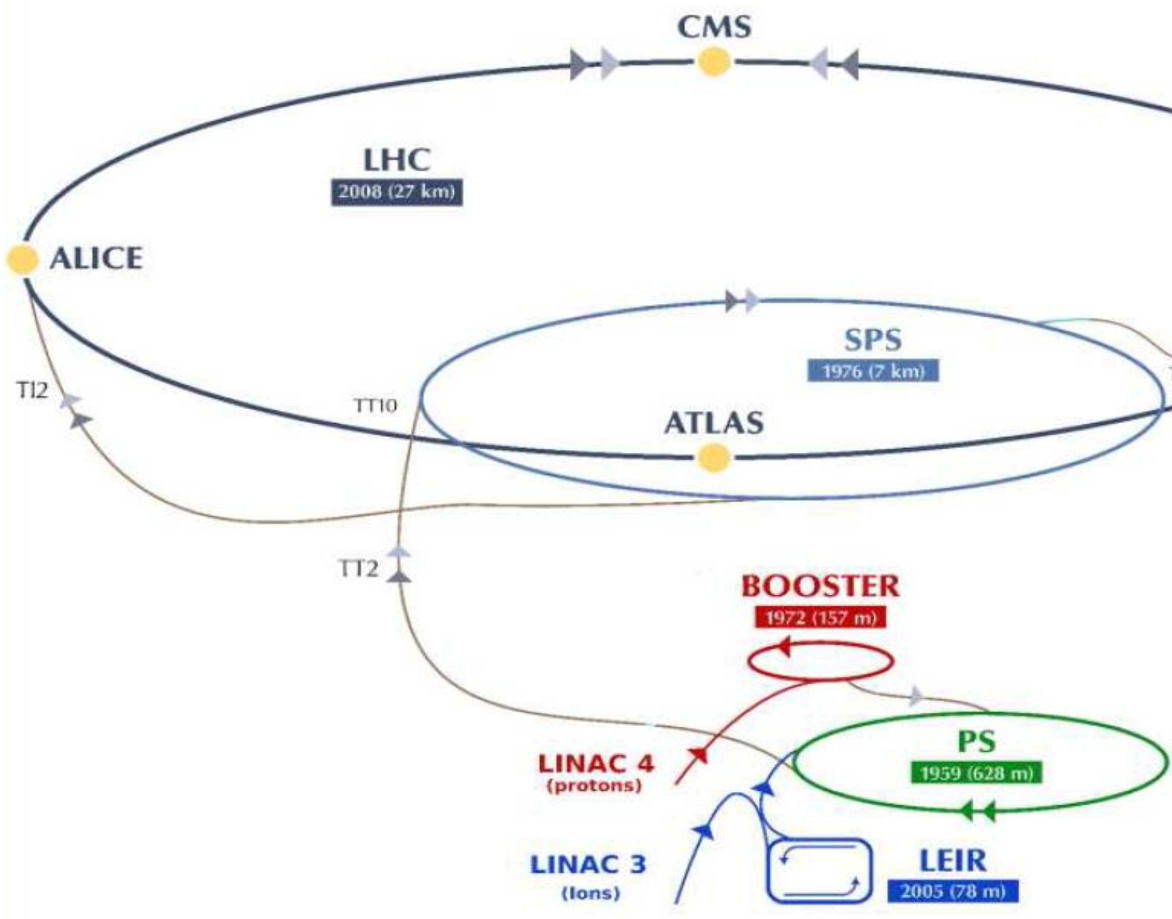
Bending radius

$$B\rho = p/q$$

Momentum

# CERN accelerator complex

## LHC injector chain




| $E_k$ (extraction) | post-LIU ($\geq$ 2020) |
|---|---|
| Linac 4 ($H^-$) | 160 MeV |
| PSB ($H^+$) | 2.0 GeV |
| PS | 25 GeV |
| SPS | 449 GeV |
| LHC | $\geq$ 6.8 TeV |

# Linac

## Linear Accelerator→'Linac'

*Colloquially 'Linac' can refer both to a general Linear*

*Accelerator facility or to a specific accelerating structure*

- **Single pass accelerator**

→ beam goes through once

→ facility not always straight, e.g. SLC

- **Energy depends on length**

## For HEP 2 main applications:

- **Low energy hadrons**
- **High energy $e^-$ or $e^+$ collider**

e.g. Stanford Linear Collider (1987-98, 3 km/0.09TeV)

e.g. next-gen lepton colliders: ILC (50 km / 1TeV)

e.g. next-gen lepton colliders: CLIC (50 km / 3TeV)

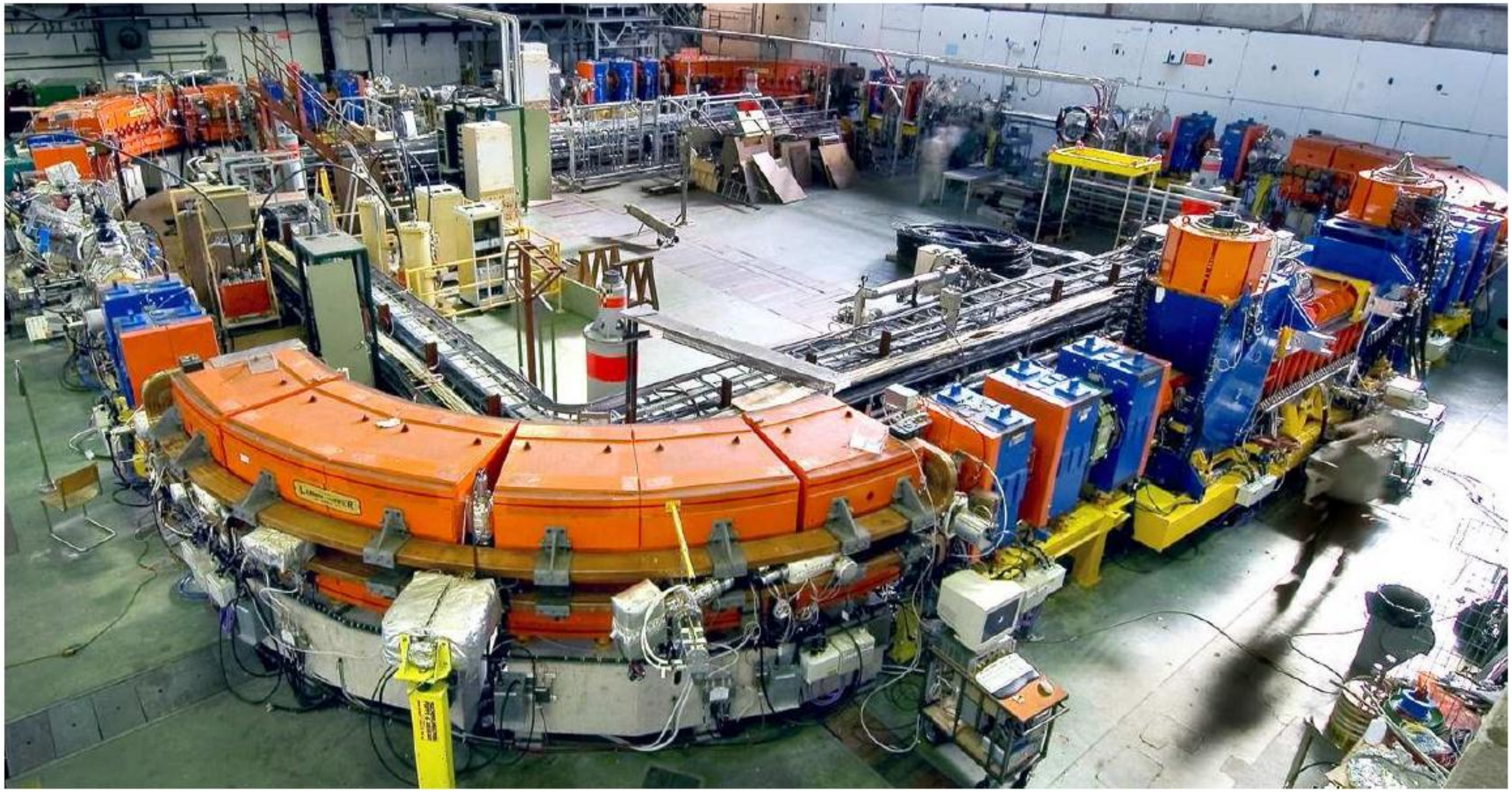
# Synchrotron

## Synchrotron

→ e.g. **LHC**, LEP, Tevatron, RHIC, HERA, SPS, PS...

→ *'circular accelerator'*, *'collider ring'* (doesn't actually need to be a circle)

- **Repeated passage around the accelerator ring → great for HEP!**
  → re-use accelerating structures & repeatedly collide same beam:
- **During acceleration guiding fields increase to keep the beam on (∼) same orbit**



# Storage ring Colliders

Make use of all the particles' energy. 2-beam synchrotrons.

The first one: AdA (Frascatti), 1961-64, e+,e-, 250 MeV, 3m circumference

Many examples to come at DESY, SLAC, KEK, Fermilab with the Tevatron (980 GeV), BNL with RHIC

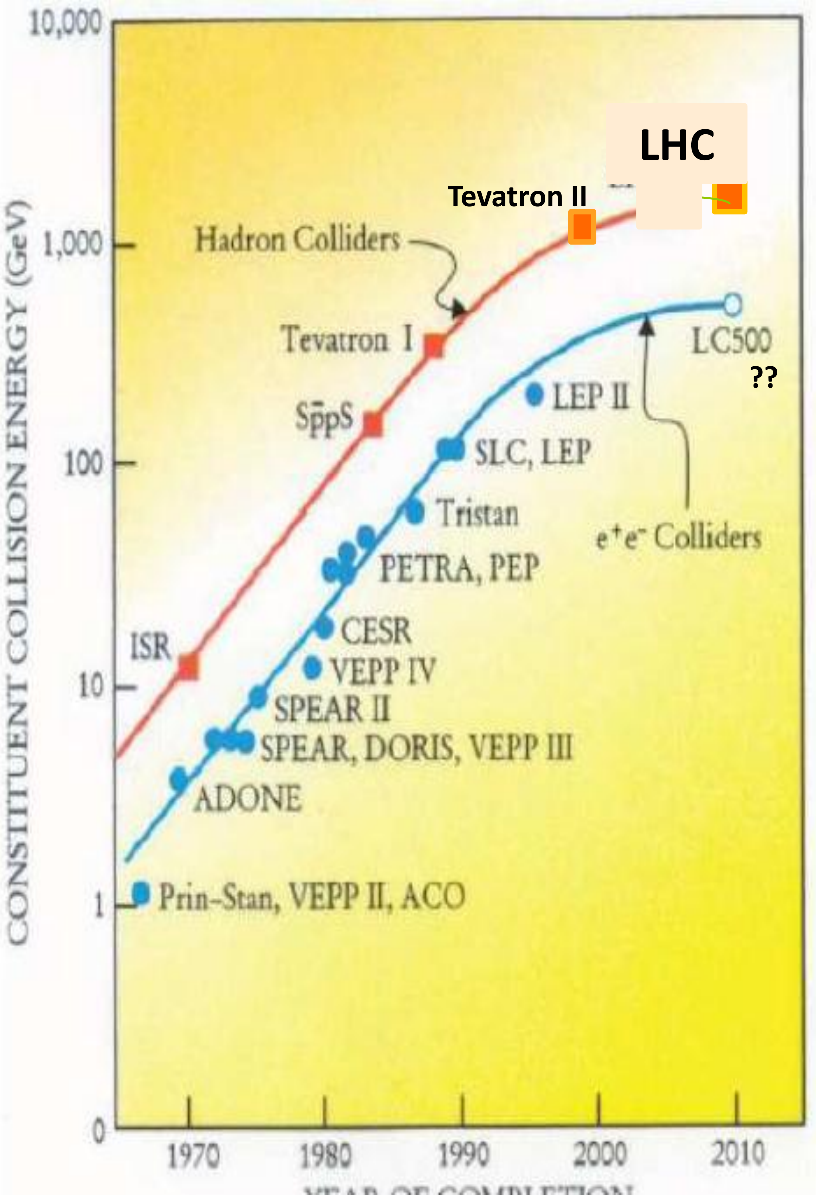
1971-1984: ISR (CERN), p+,p+, 31.5 GeV, 948 m circumference

1981-1991: SPS running as $Sp\bar{p}S$, p+, p-, 270 – 315 GeV, 6.9 km circumference; discovery of W and Z Bosons

1989-2000: LEP highest energy electron synchrotron, e+,e-, 104 GeV, 27 km circumference; three generations of quarks, gluons and leptons

2008 - : LHC highest energy proton synchrotron, p+,p+, heavy ions, 6.5 TeV (2.76 TeV per nucleon for $^{208}Pb^{82+}$); Discovery of Higgs

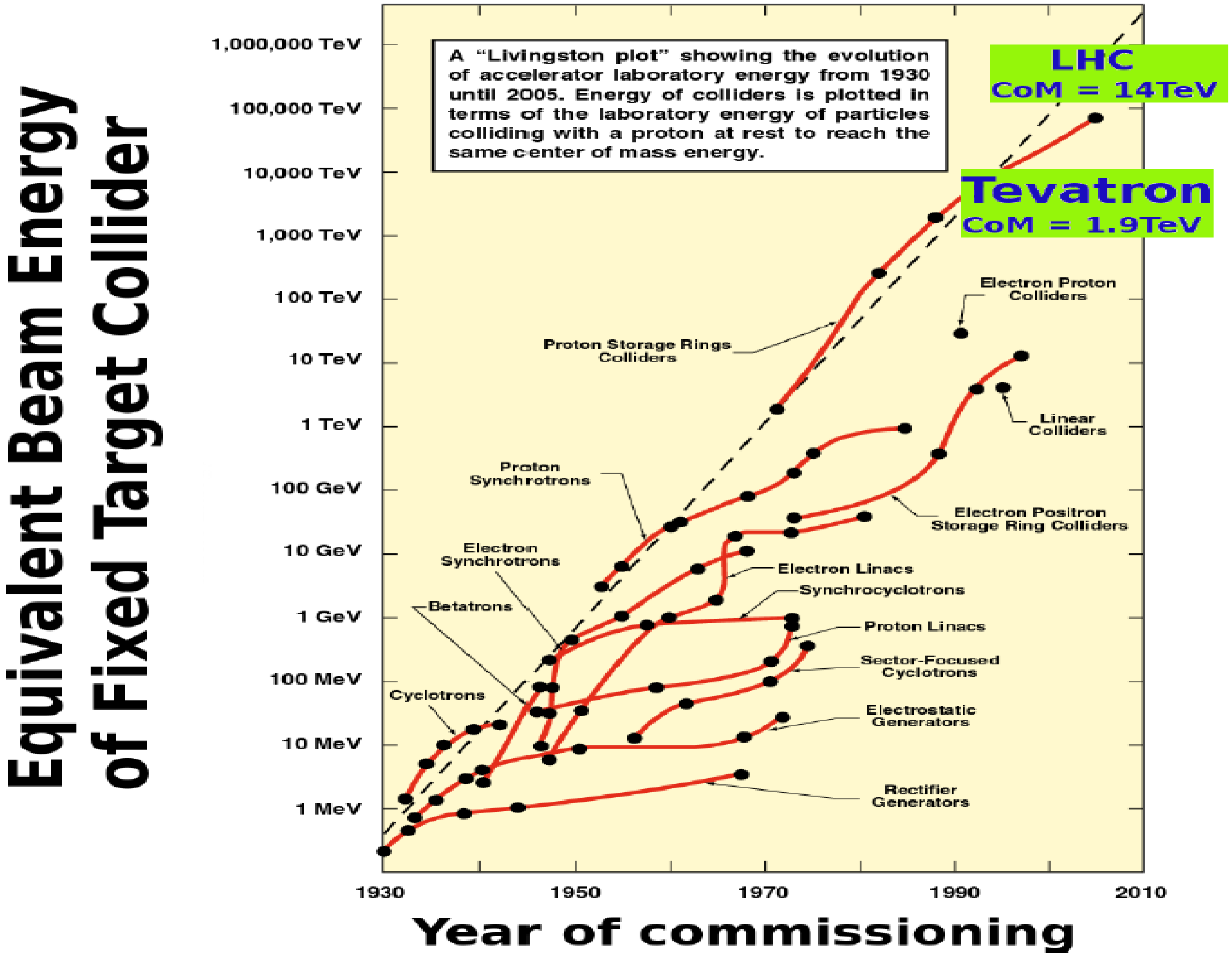
# Energy frontier




- The interplay between electron and hadron machines has a long and fruitful tradition
  - $J/\psi$ at SPEAR ($e^+e^-$) and AGS (proton fixed target)
  - $\Upsilon$ discovery at E288 (p fixed target), precision $B$ studies at the $e^+e^-$ B factories
  - ...
  - top quark at LEP and Tevatron
  - **Higgs boson at the LHC**

# Energy frontier

From 2001 Snowmass AQccelerator R&D report,
Part I : Executive Summaries, eConf C010630, SLAC-R-599
http://www.slac.stanford.edu/econf/C010630/papers/MT1001.PDF

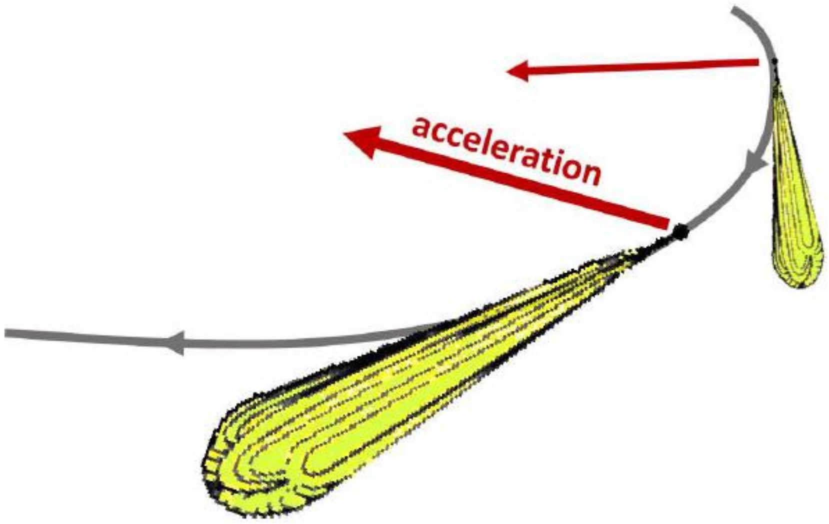


# Energy frontier

**Limiting factor for circular $e^+$ / $e^-$ accelerators:**

$\rightarrow$ particles emit **synchrotron radiation** as they are bent around ring

$$\Delta E/\text{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$




- **LEP** (e) **energy loss:** $\sim 3\,\text{GeV}/\text{turn}$ (@ $101\,\text{GeV}$)
- **LHC** (p) **energy loss:** $\sim 5\,\text{keV}/\text{turn}$ (@ $6.5\,\text{TeV}$)

# Energy frontier

**Limiting factor for circular hadron collider:**

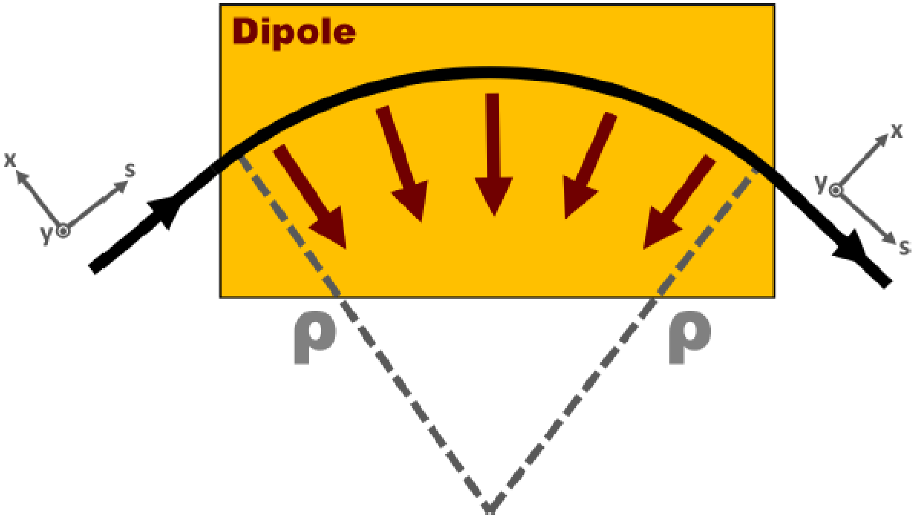
→ need sufficient dipole field strength to bend beams around the ring

→ **High Energy = high magnetic rigidity**

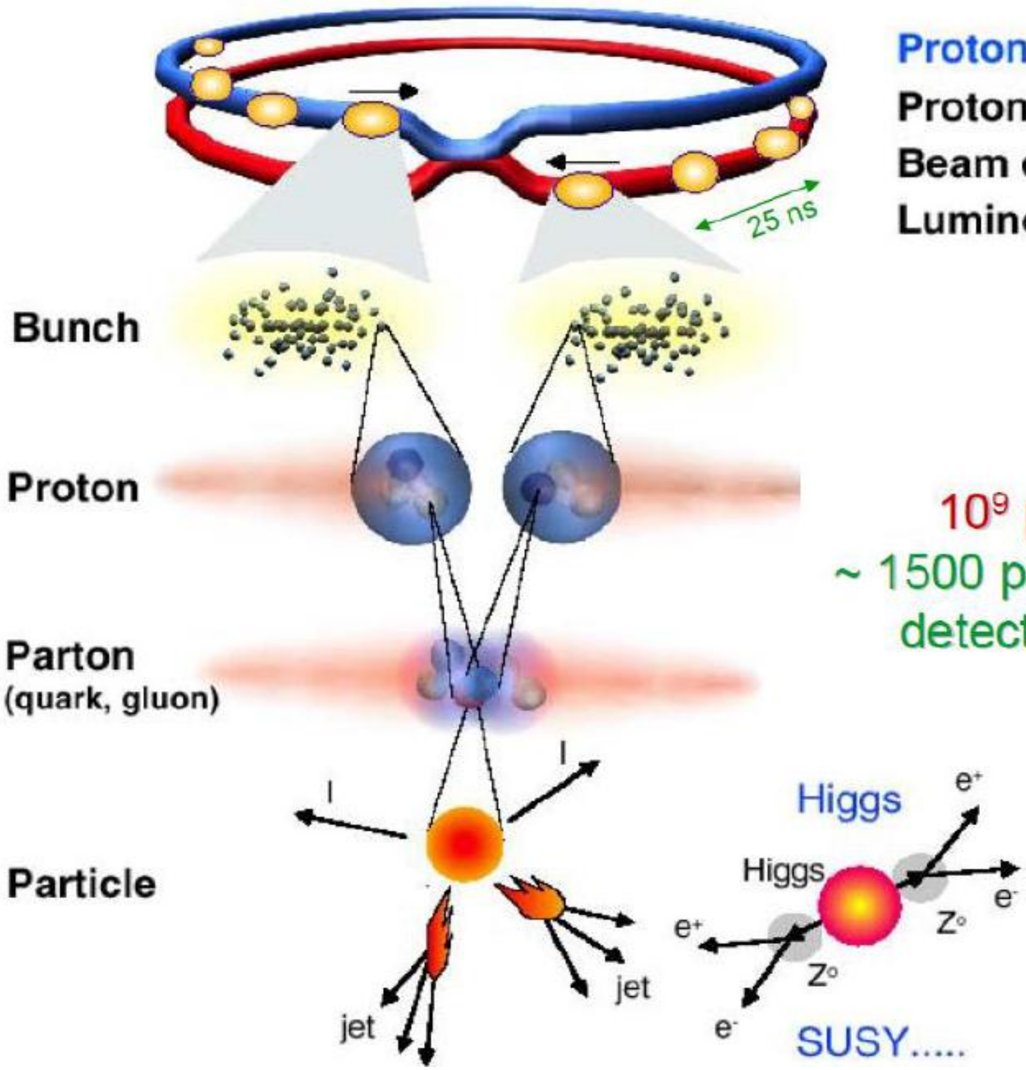
$$F_{Lorentz} = F_{centrip}$$

$$qvB = \frac{\gamma m_{rest} v^2}{\rho} = \frac{pv}{\rho}$$

$$B\rho = \frac{p}{q}$$



# Collisions at LHC




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

In the experiments:

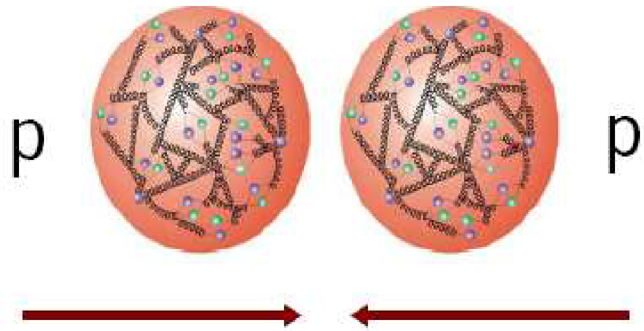
$10^9$ pp interactions per second

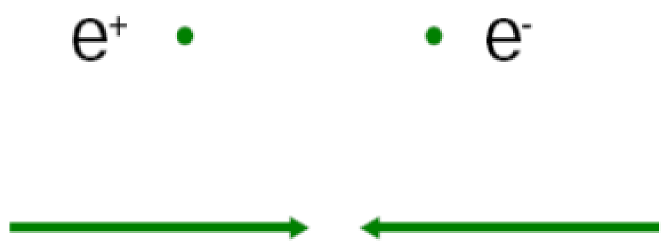
~ 1500 particles (p,n, $\pi$) produced in the detectors at each bunch-crossing

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

**$E = m c^2$**

# 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

# 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]

**Beamsize:**

$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

- $\beta(s)$: *'beta-function'* [m]
  - → Property of the magnetic lattice
  - → varies around the ring
- $\epsilon$: *'emittance'* [$\mu$m]
  - → Property of the particle bunch
  - → Invariant around the ring

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

# Luminosity frontier

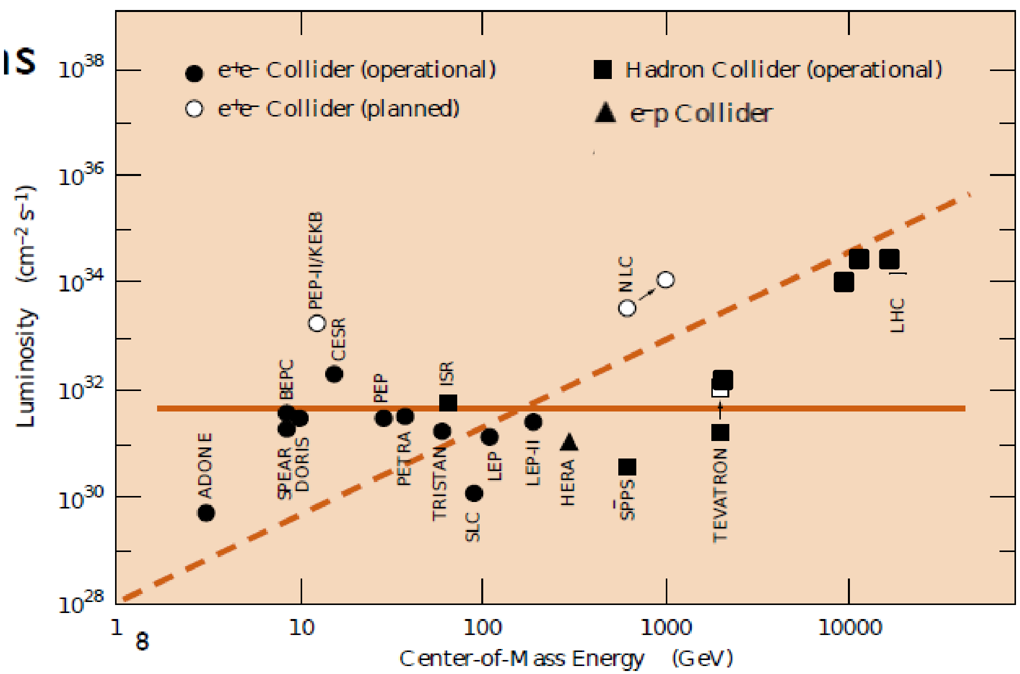
- Need corresponding rise in luminosity (beam intensity)

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/anti-protons**
  - **Muons/anti-muons**
- **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**

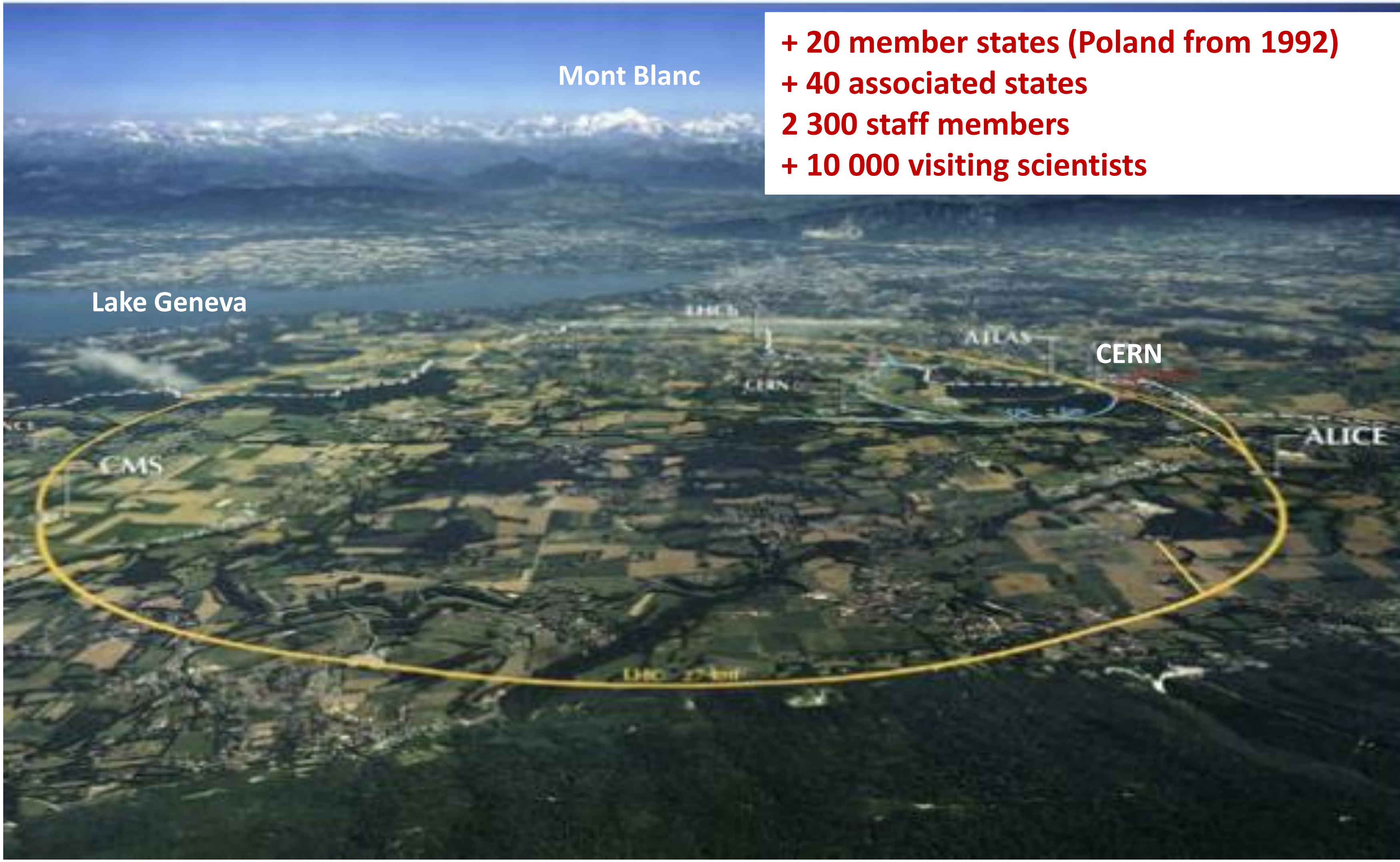
# Accelerator is much more ….

- 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, …..

# Particle Physics Labs

- There are many thousands of accelerators in operation today, mostly for medical or industrial applications
  But few *colliders* – they are used only for particle physics research
- Major particle physics laboratories around the world:

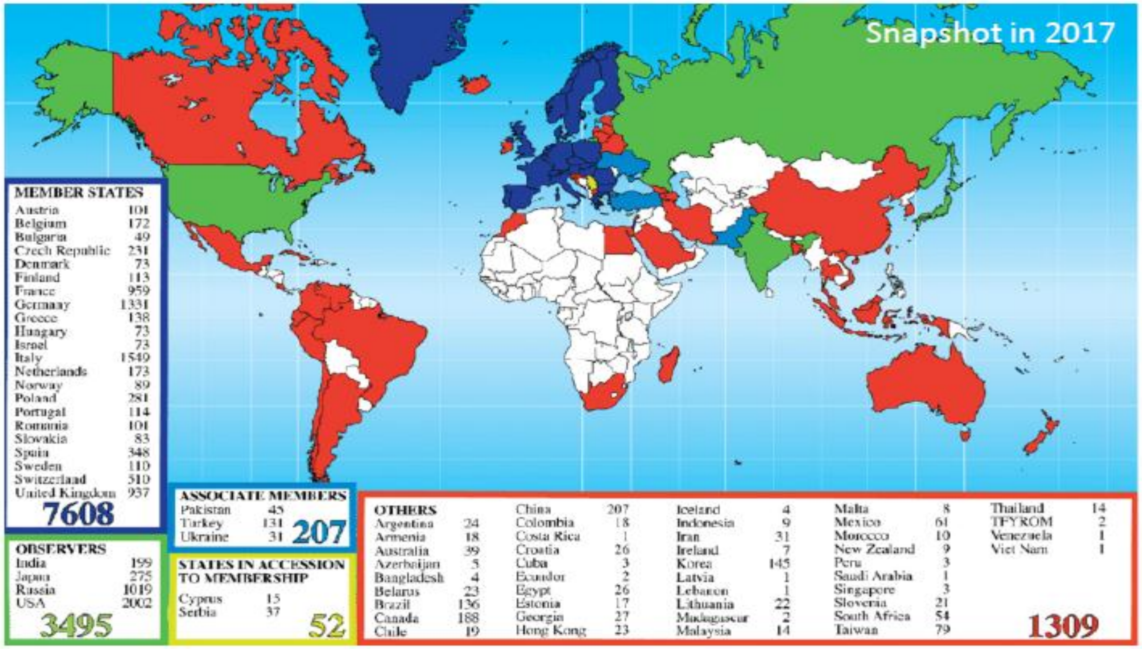
# CERN laboratory (founded in 1954)



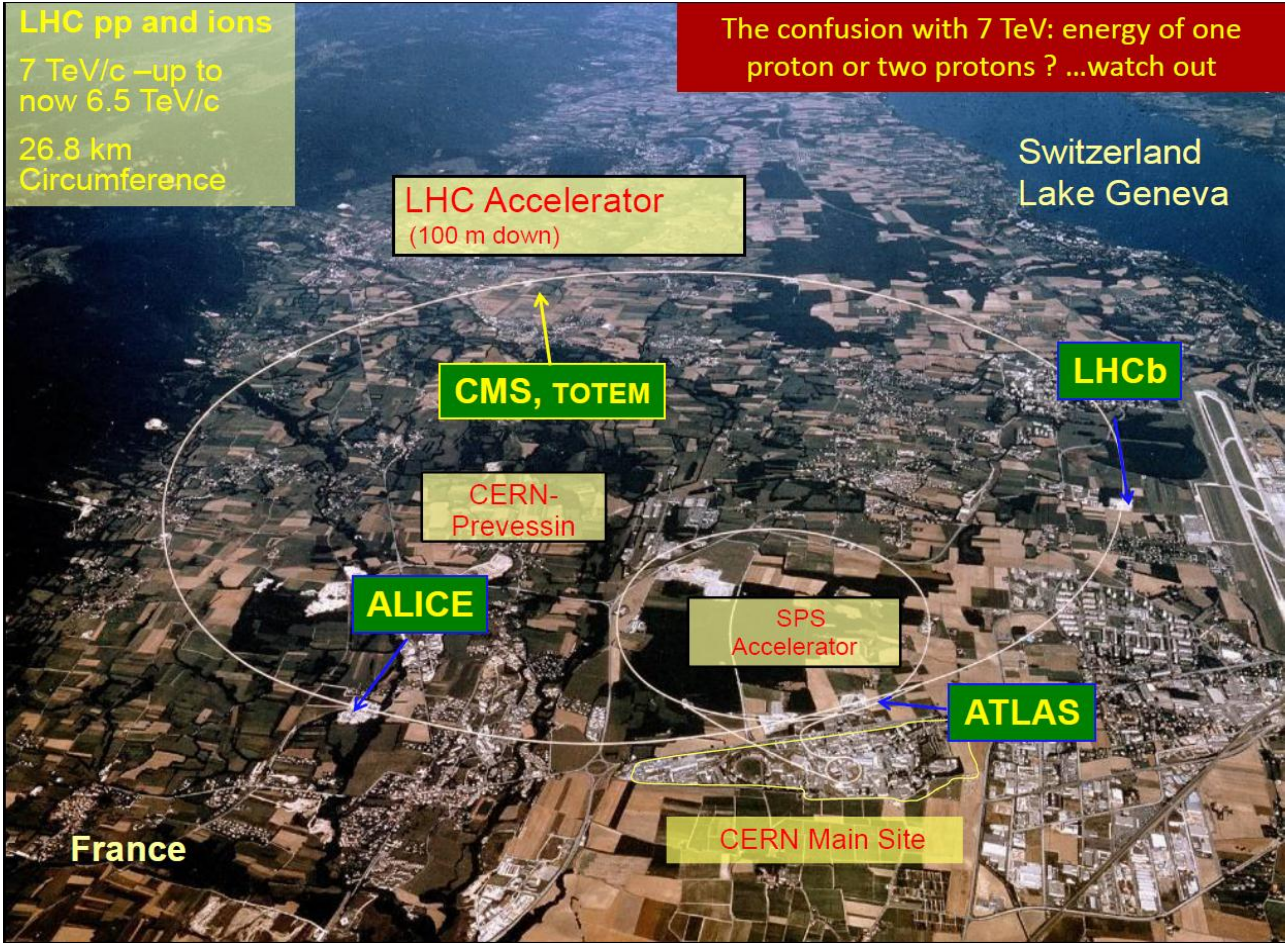

+ 20 member states (Poland from 1992)
+ 40 associated states
2 300 staff members
+ 10 000 visiting scientists

# CERN laboratory: users

## CERN users

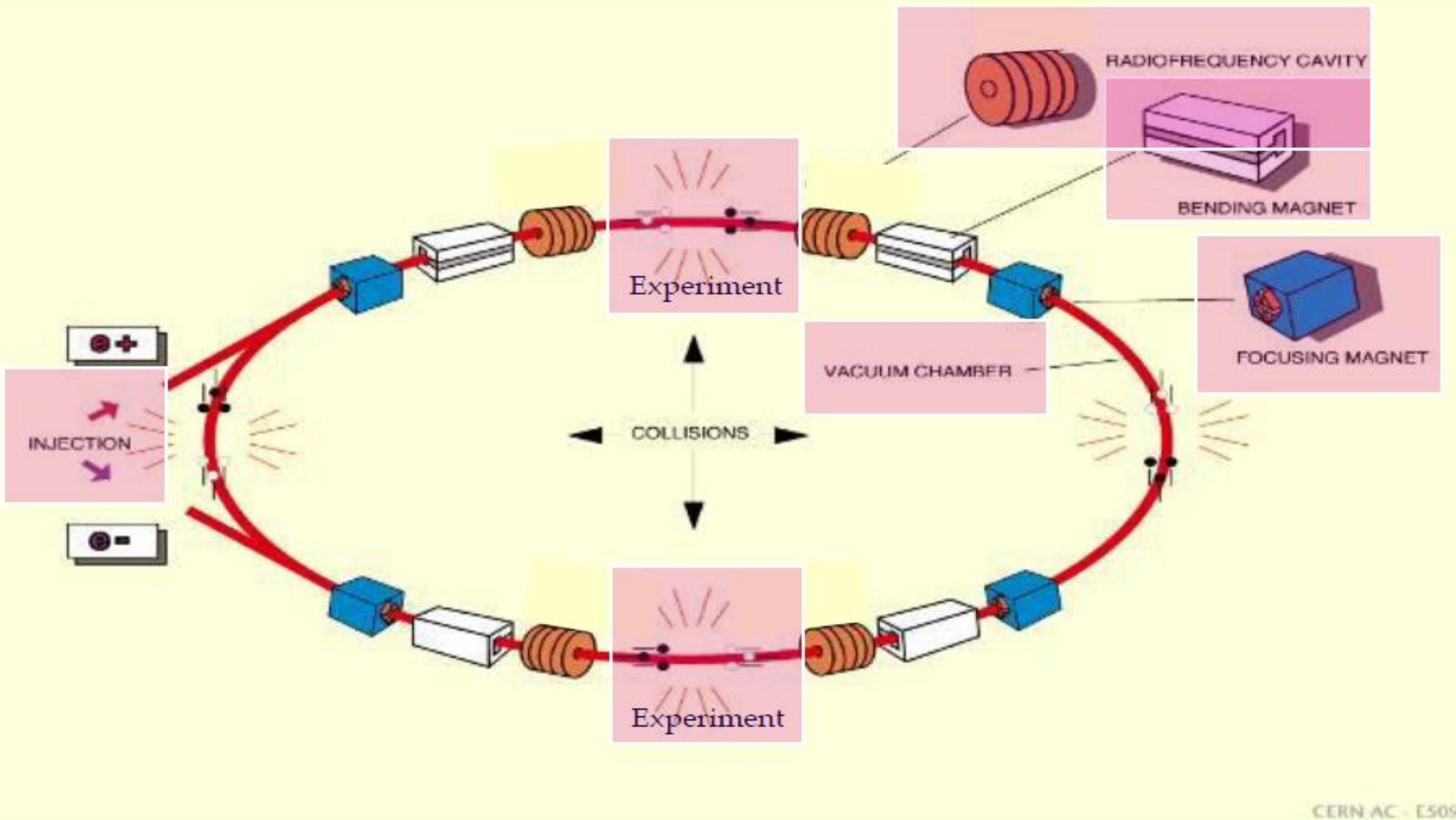



- CERN takes care of running the accelerators on its site (such as the LHC) while the experiments are built and run by collaborations of users from institutes around the world (ATLAS and CMS each have about 3000 authors)
- Specific programmes to encourage CERN-Latin America collaboration
  - **HELEN:** High-Energy physics Latin-American European Network (2005-9)
  - **EPLANET:** European Particle physics Latin-American NETwork (2011-15)

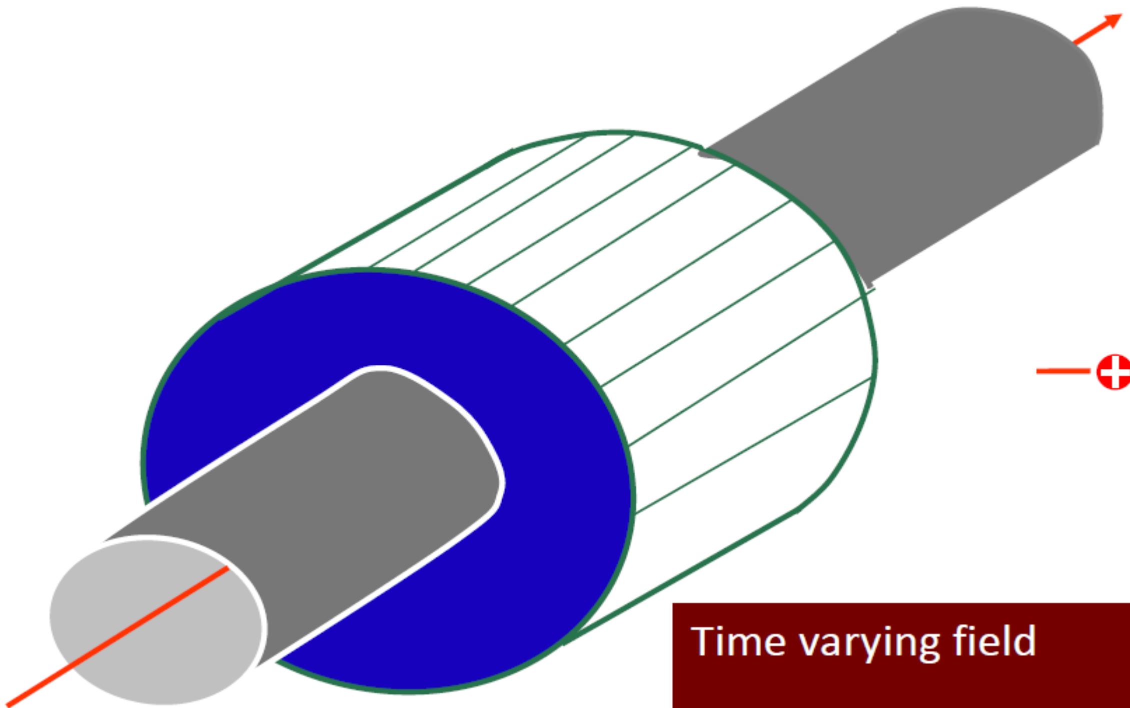

LHC pp and ions
7 TeV/c –up to now 6.5 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? ...watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
France
CERN Main Site

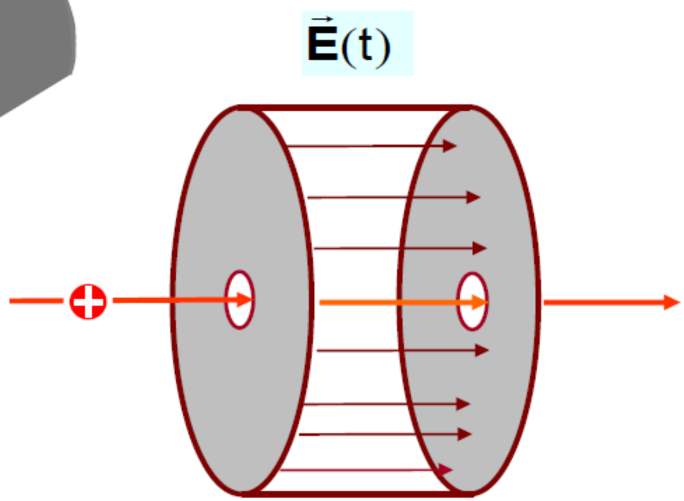
# Synchrotron + many passages in RF cavities

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



# Particle acceleration in RF cavity






LHC RF frequency
400 MHz

Revolution frequency
11246 Hz

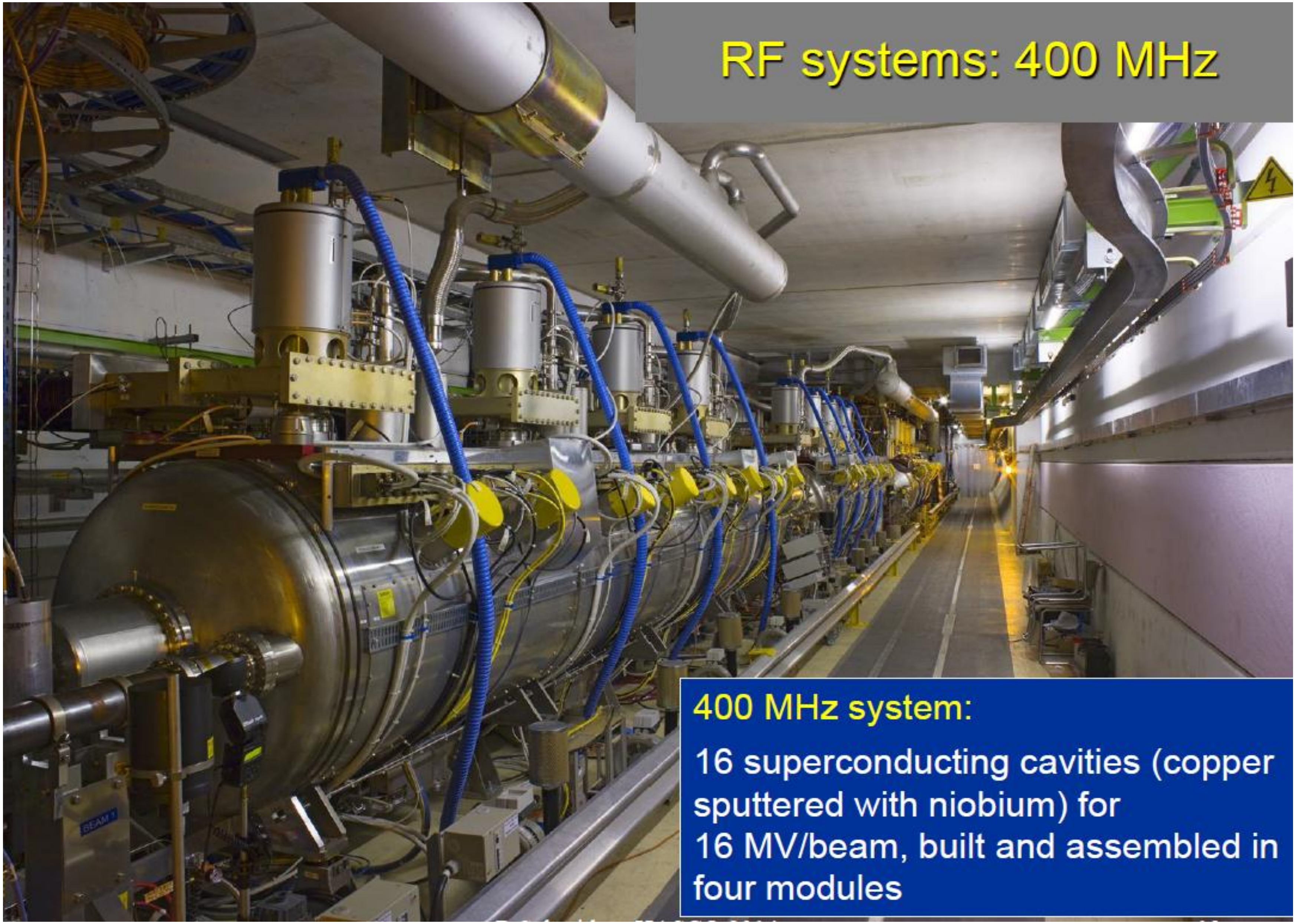
Time varying field

$$E_z(t) = E_0 \times \cos(\omega t + \phi)$$

Maximum field about 20 MV/m

Beams are accelerated in bunches (no continuous beam)

# RF systems: 400 MHz



400 MHz system:

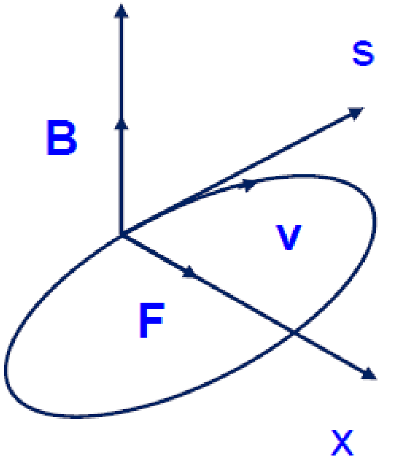
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

# Particle deflection: superconducting magnets

The force on a charged particle is proportional to the charge, the electric field, and the vector product of velocity and magnetic field given by Lorentz Force:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$



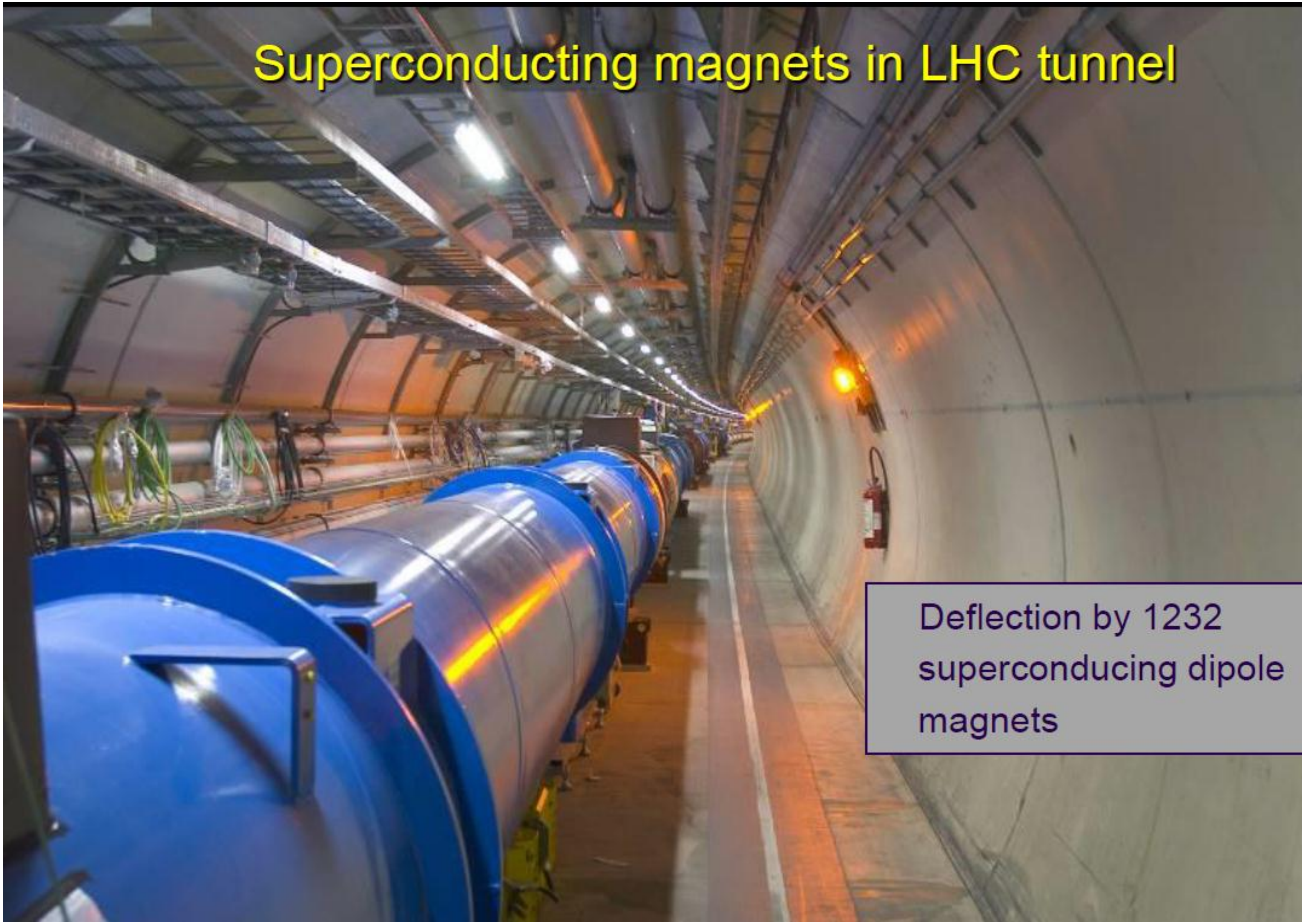

Maximum momentum 7000 GeV/c

Radius 2805 m fixed by LEP tunnel

**Magnetic field B = 8.33 Tesla**

Iron magnets limited to 2 Tesla, therefore superconducting magnets are required

Deflecting magnetic fields for two beams in opposite directions

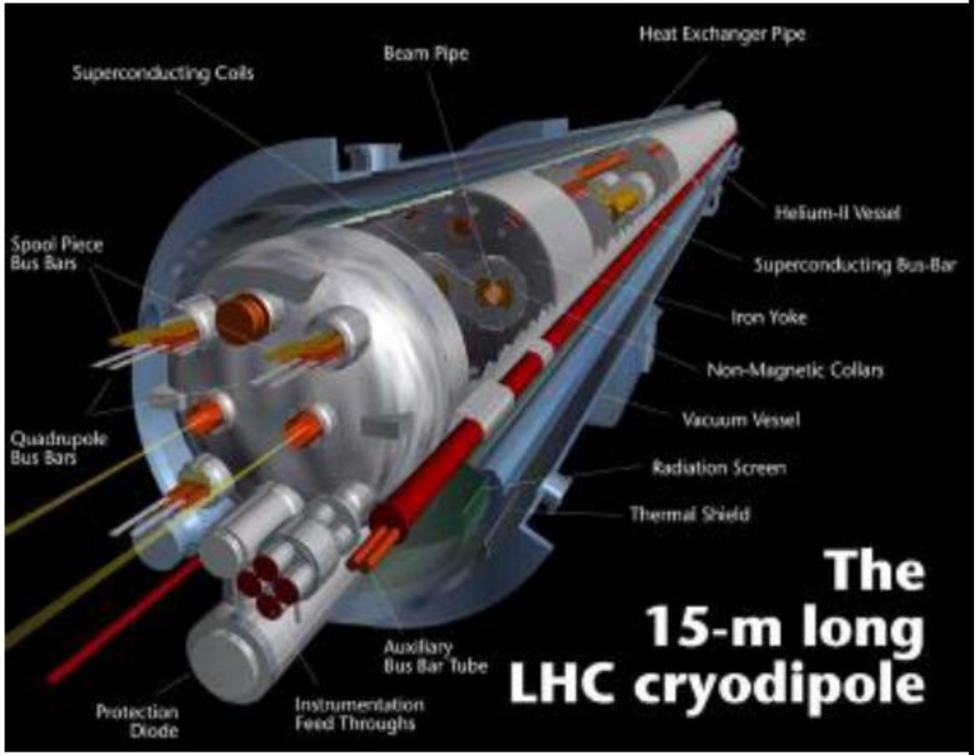

Superconducting magnets in LHC tunnel
Deflection by 1232 superconducing dipole magnets

# Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

Magnetic Field 8.3 T for 7 TeV

Two beam tubes with an opening of 56 mm



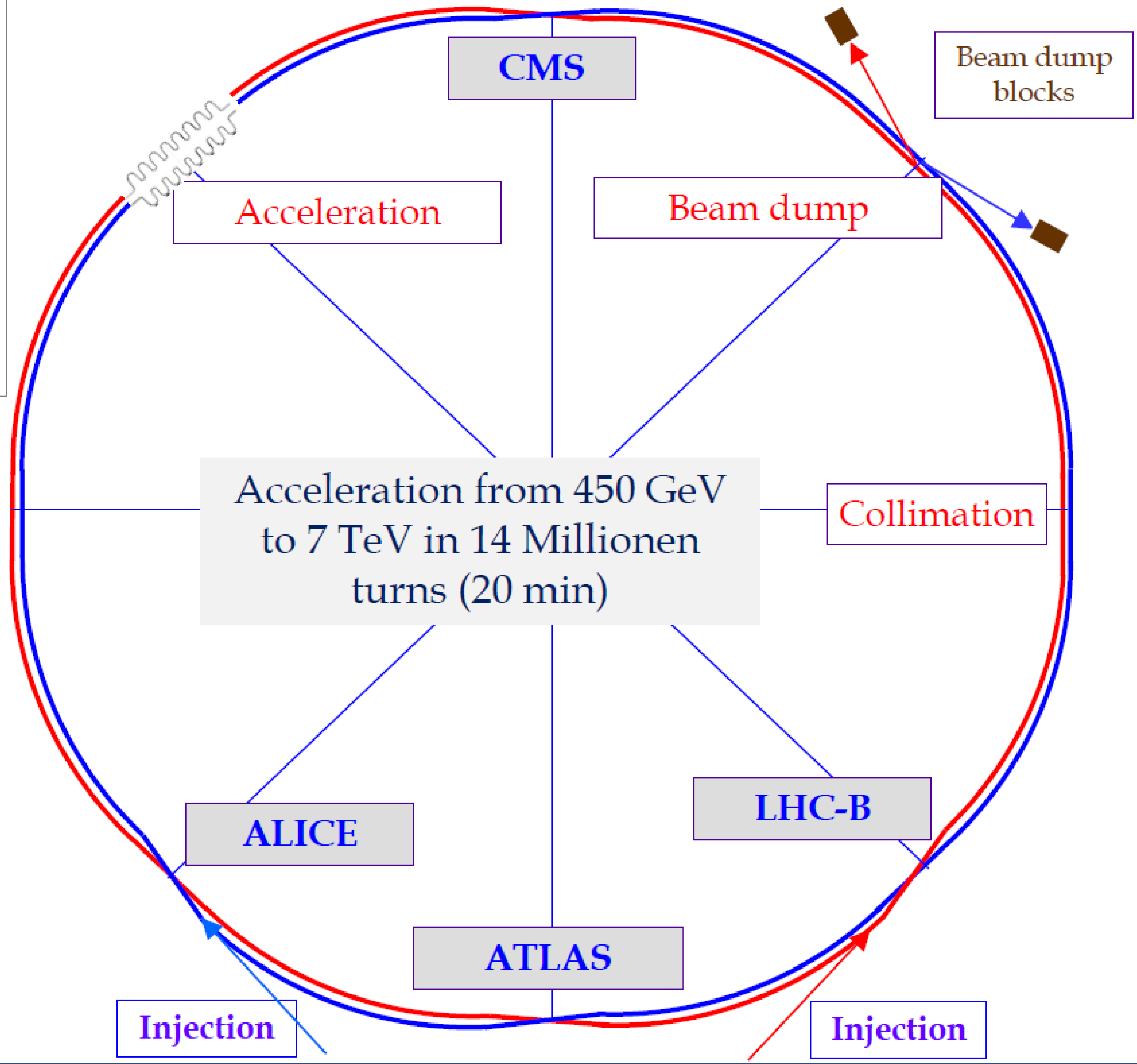

plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

# LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)

1232 deflecting dipole magnets




- 27 km
- 2 beams
- 11246 turns/ second

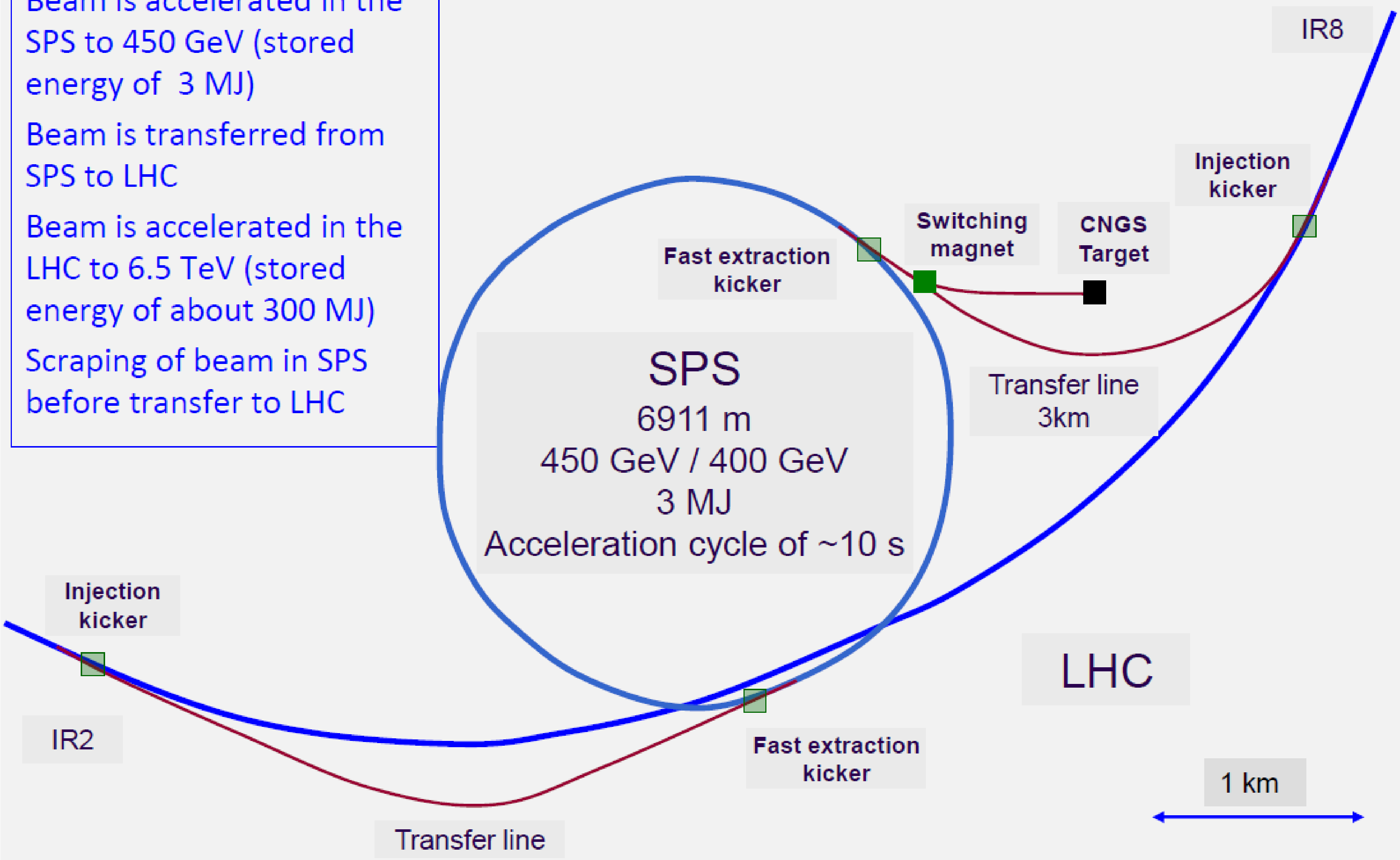
# SPS, transfer line and the LHC

Beam is accelerated in the SPS to 450 GeV (stored energy of 3 MJ)

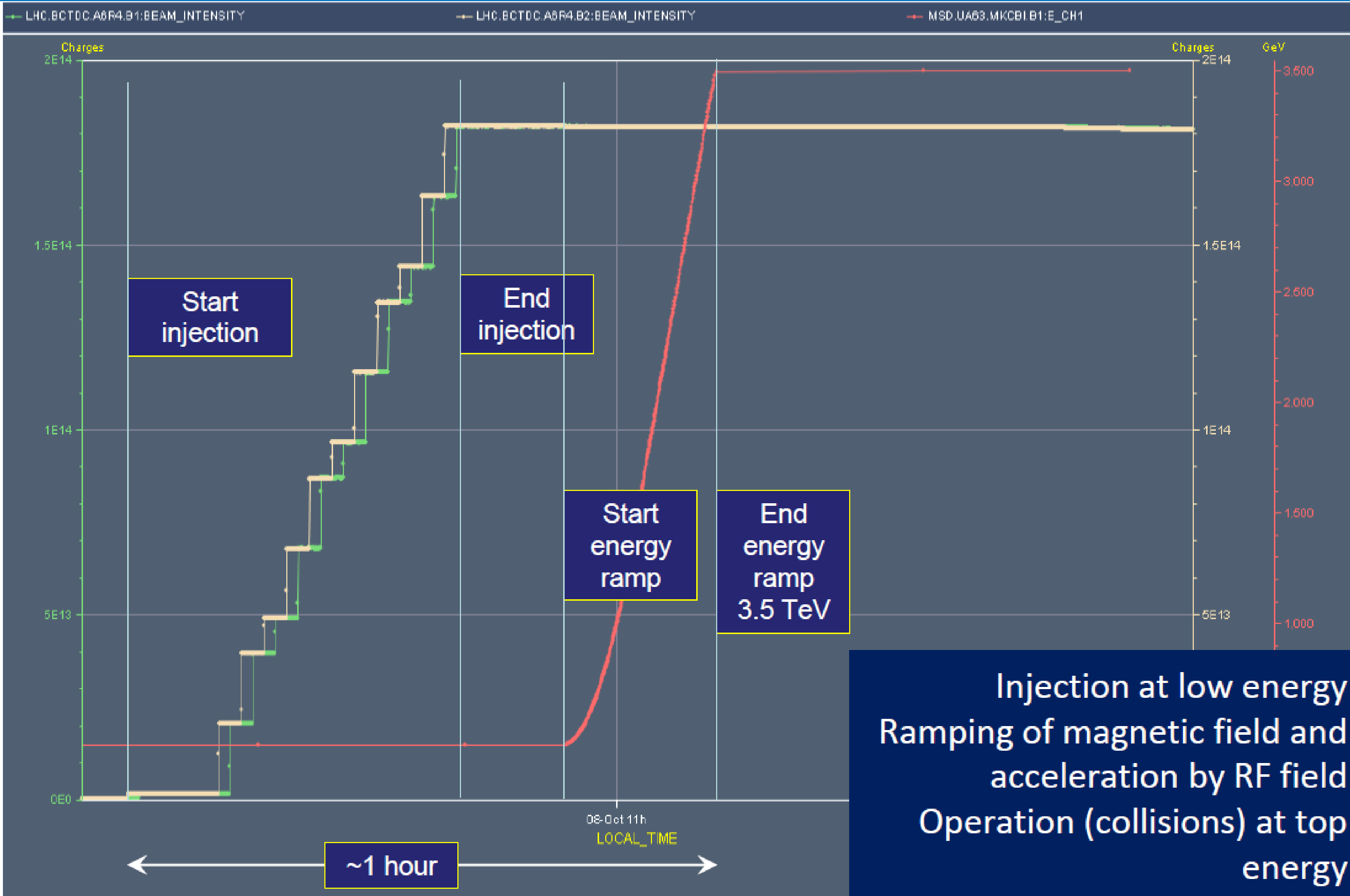
Beam is transferred from SPS to LHC

Beam is accelerated in the LHC to 6.5 TeV (stored energy of about 300 MJ)

Scraping of beam in SPS before transfer to LHC



# Synchrotron principle: LHC fill (2011)

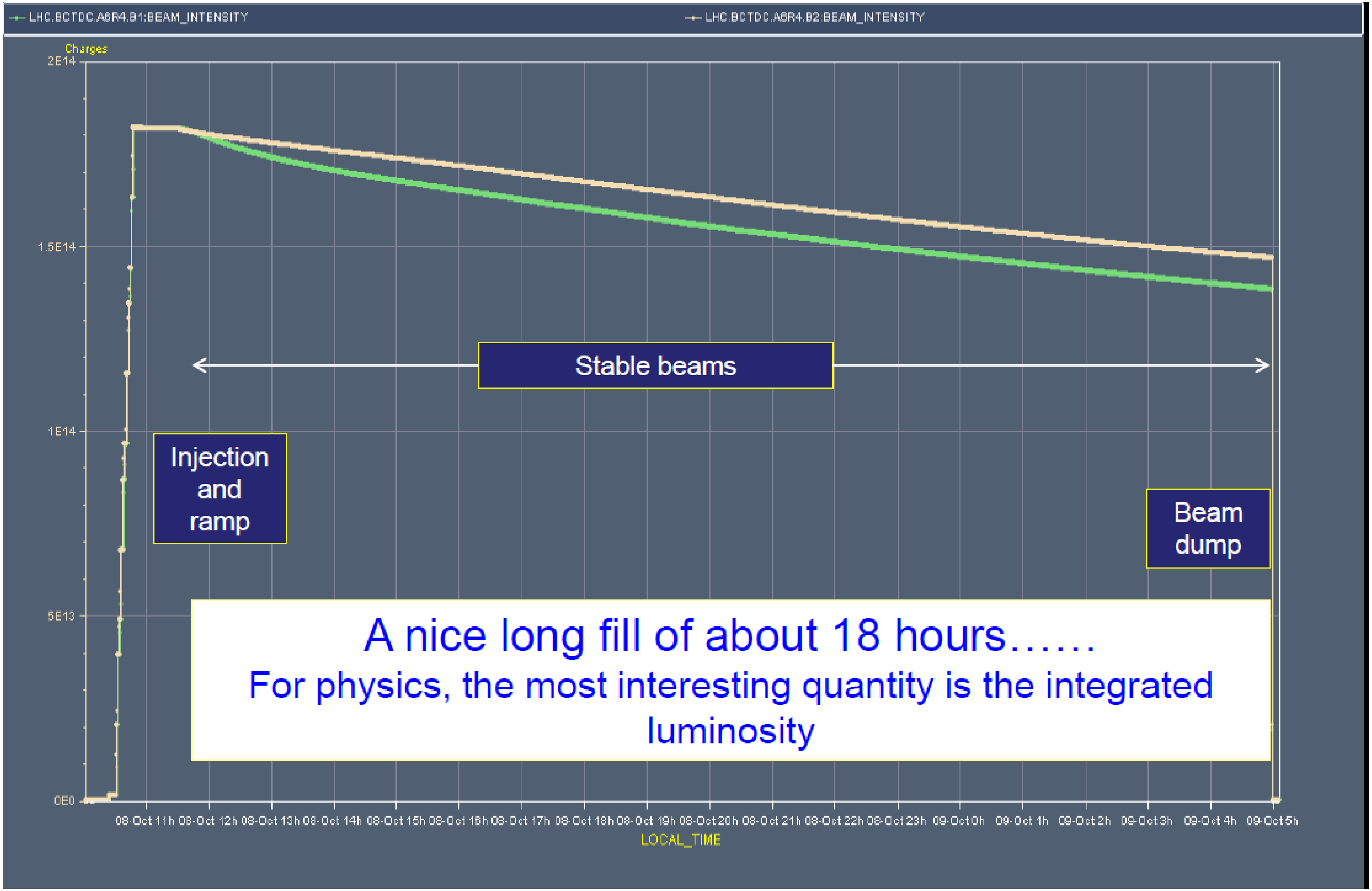



Injection at low energy

Ramping of magnetic field and acceleration by RF field

Operation (collisions) at top energy

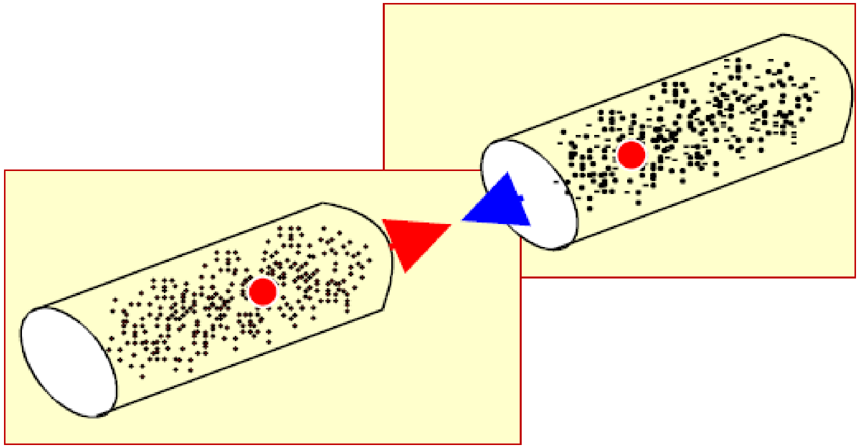
# Excelent fill (2011)



# Luminosity parameters

$$L = \frac{N^2 \times f \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

| | |
|---|---|
| $N$ … | number of protons per bunch |
| $f$ … | revolution frequency |
| $n_b$ … | number of bunches per beam |
| $\sigma_x \times \sigma_y$ … | beam dimensions at interaction point |



# Luminosity parameters

Number of protons per bunch limited to about **1-3×10$^{11}$** due to the beam-beam interaction and beam instabilities

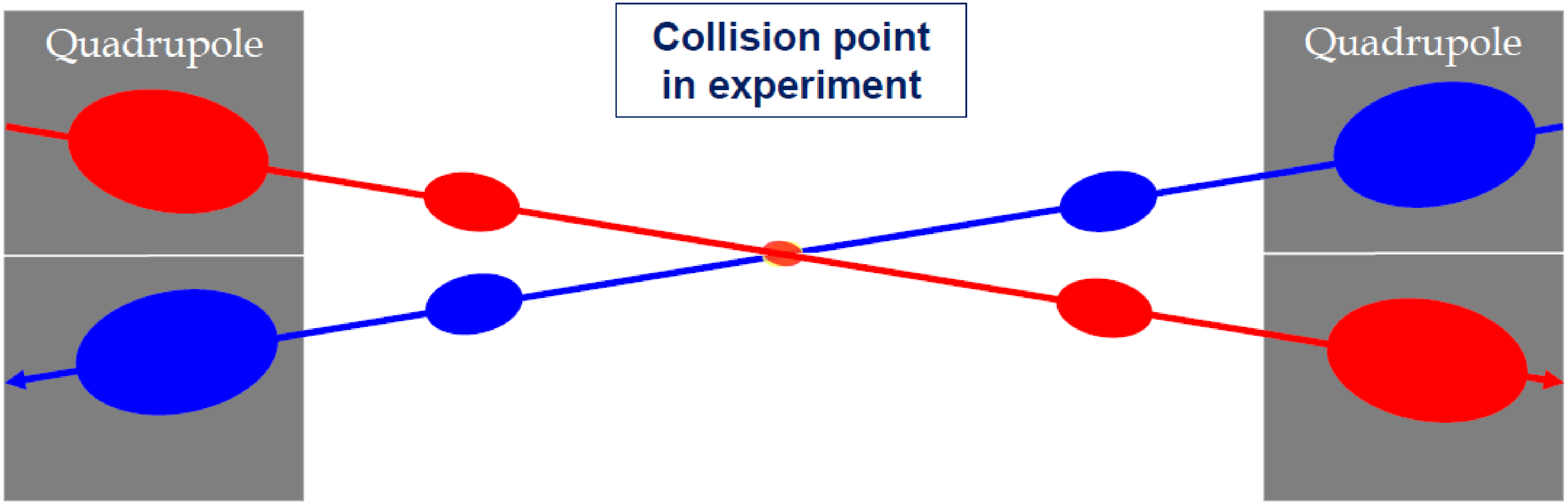
Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

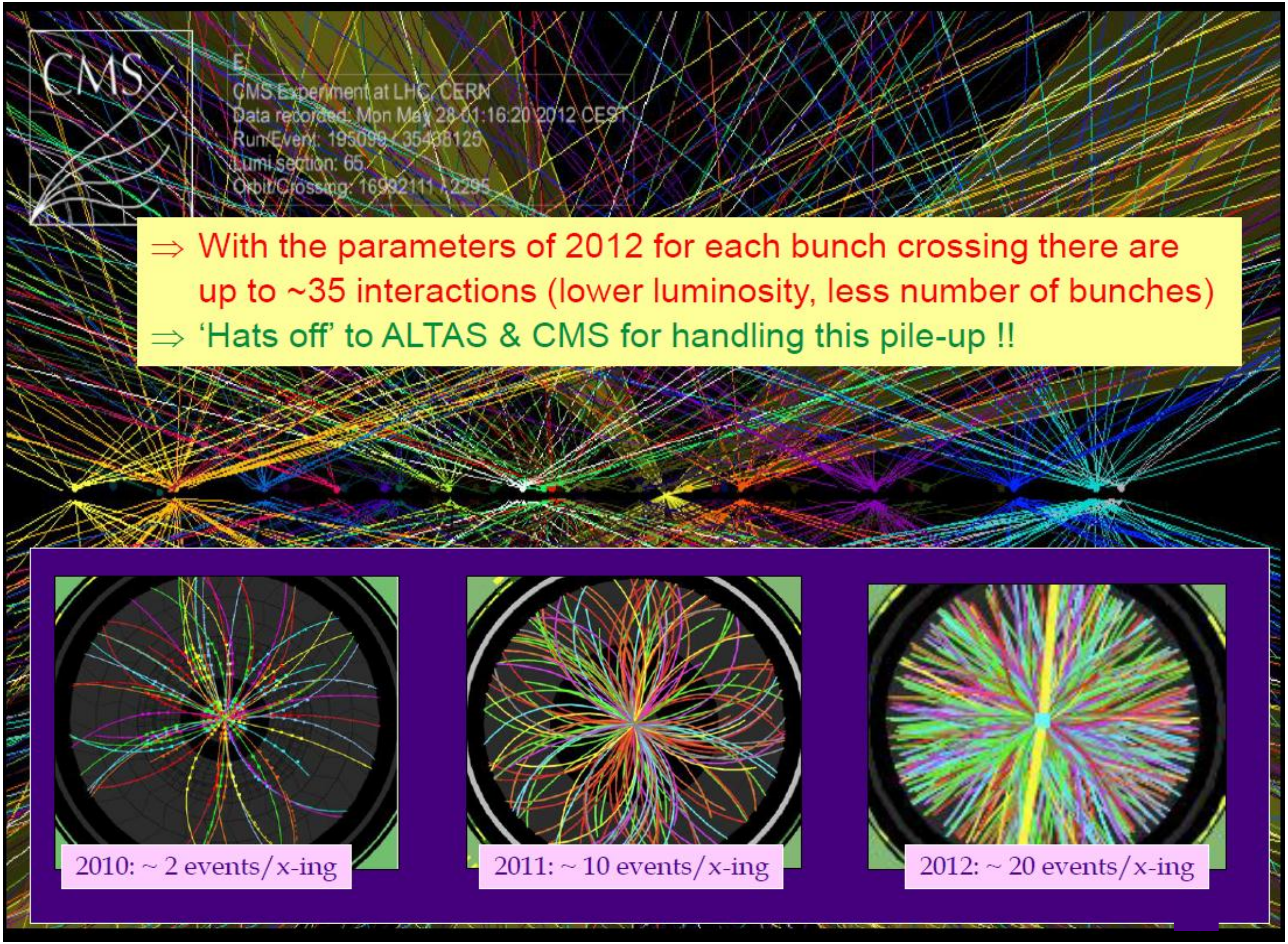
Beam size **16 μm**,
for β = 0.5 m (β is a function of the lattice)

$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y} = 10^{34}\ [cm^{-2}s^{-1}]$$ for 2808 bunches

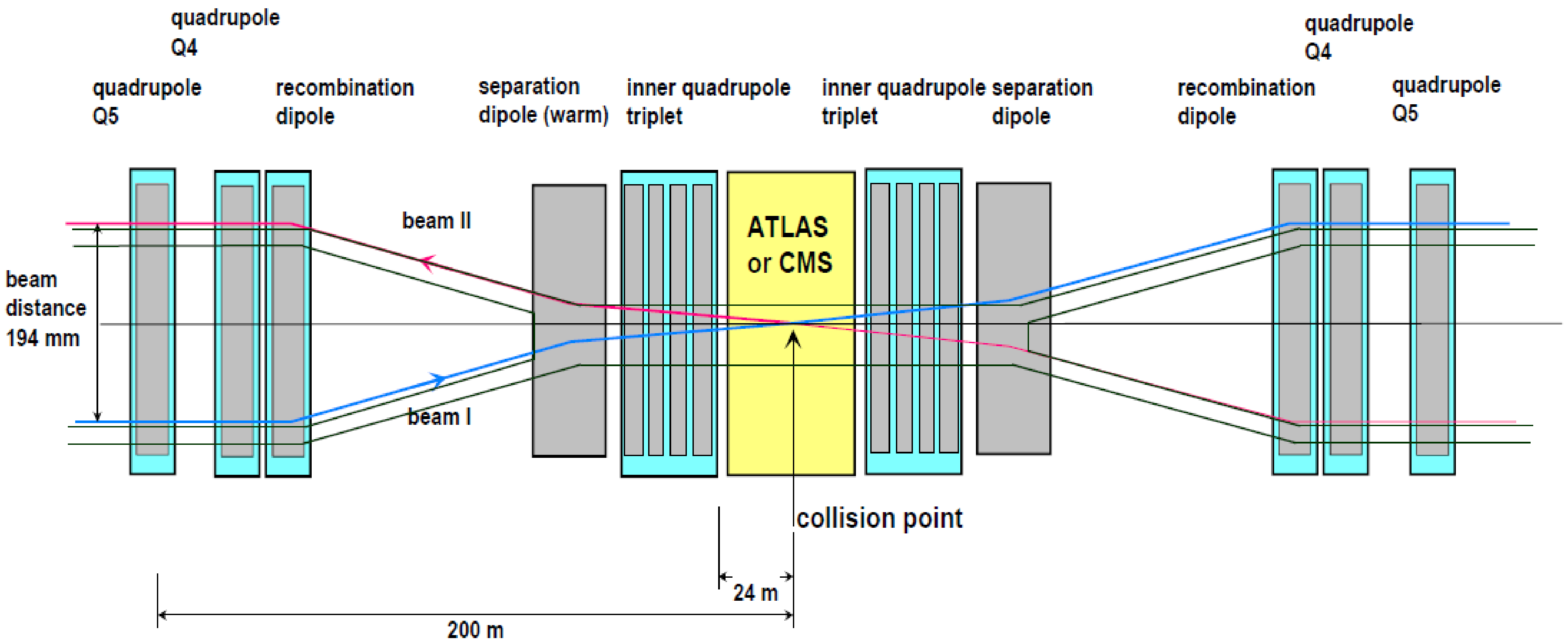
# Beam size




- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10 $\sigma$
- Limitation is the aperture in quadrupoles
- Limitation of $\beta$ function at IP to 0.4 m (2017)


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

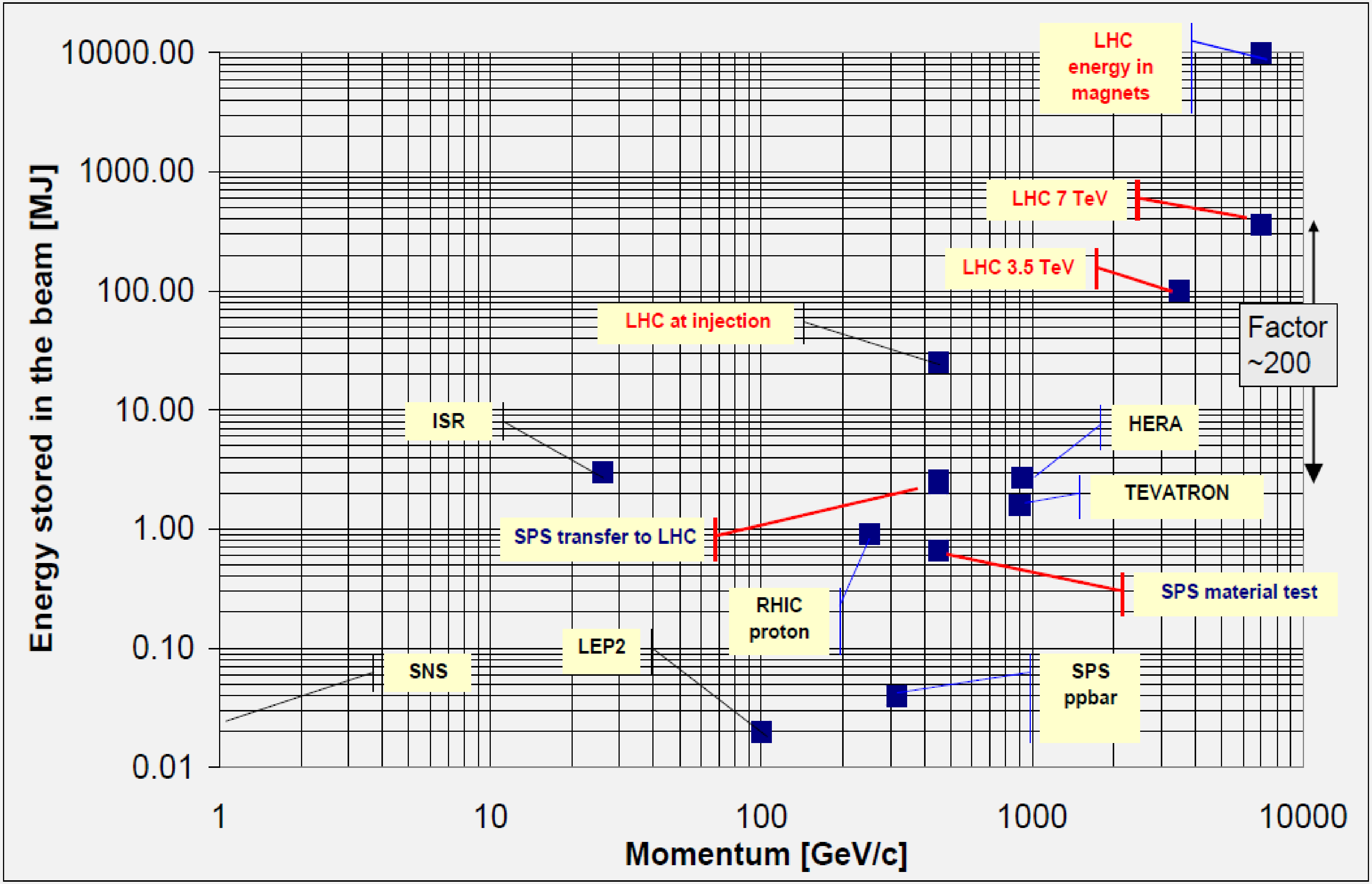
# Experimental long straight section




**Example for an LHC insertion with ATLAS or CMS**

- The 2 LHC beams are brought together to collide in a ‘common’ region
- Over ~260 m the beams circulate in one vacuum chamber with ‘parasitic’ encounters (when the spacing between bunches is small enough)
- Total crossing angle of about 250 μrad

# Energy stored in the beam



# What does it mean?

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

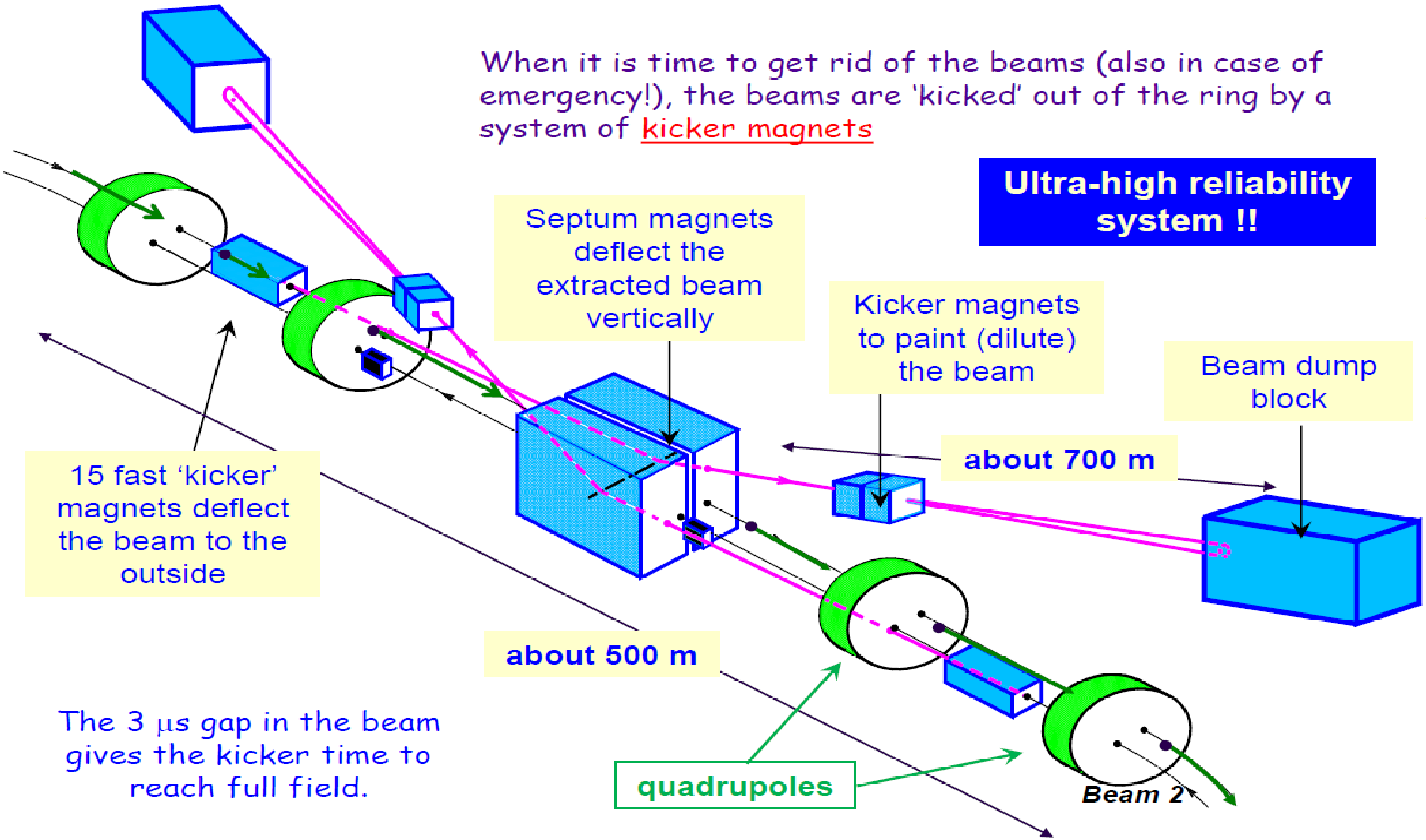
**360 MJoule:** the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

It's how ease the energy is released that matters most !!

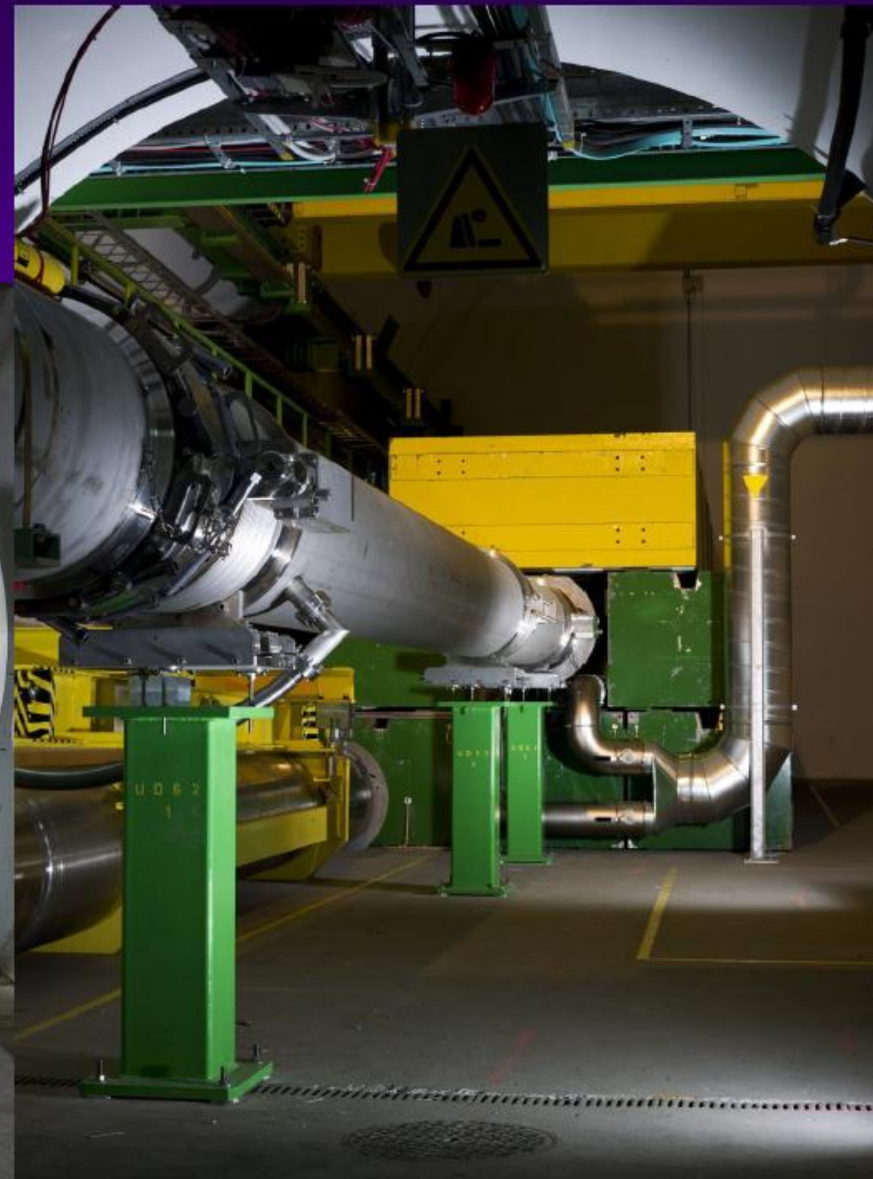
# Layout of beam system dump

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

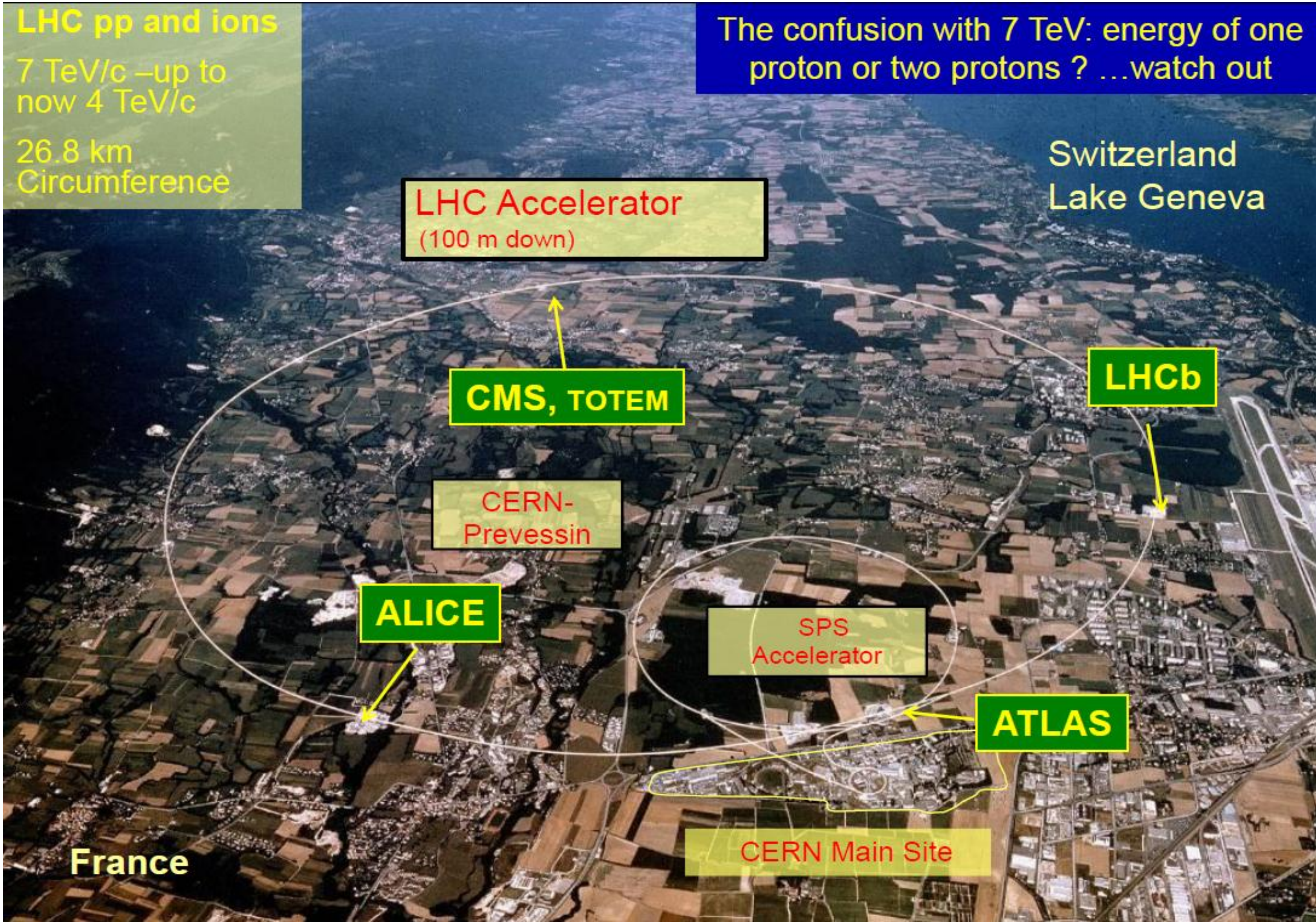


# Beam Loss Monitors

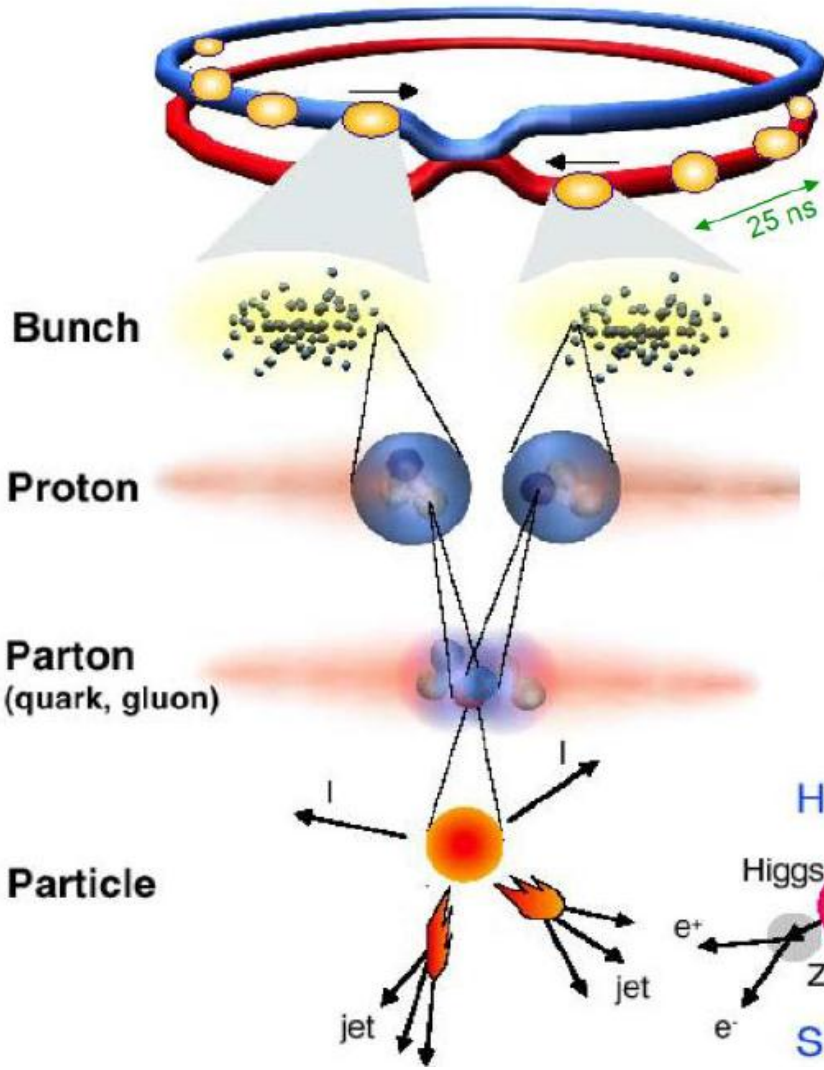
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 $\mu$s)
  - Very large dynamic range (> $10^6$)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

# 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 [redacted] | 26800 | 8.3 | $10^{34}$ Now $7.7\times 10^{33}$ | **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

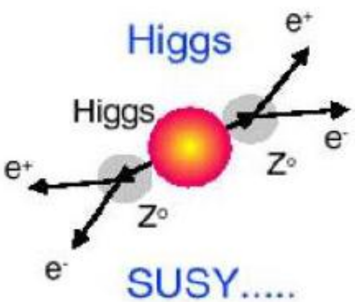



| | |
|---|---|
| Proton-Proton | 2835 bunch/beam |
| Protons/bunch | $10^{11}$ |
| Beam energy | 7 TeV ($7\times10^{12}$ eV) |
| Luminosity | $10^{34}$ cm$^{-2}$ s$^{-1}$ |

In the experiments:

$10^9$ pp interactions per second

~ 1500 particles (p,n, $\pi$) produced in the detectors at each bunch-crossing

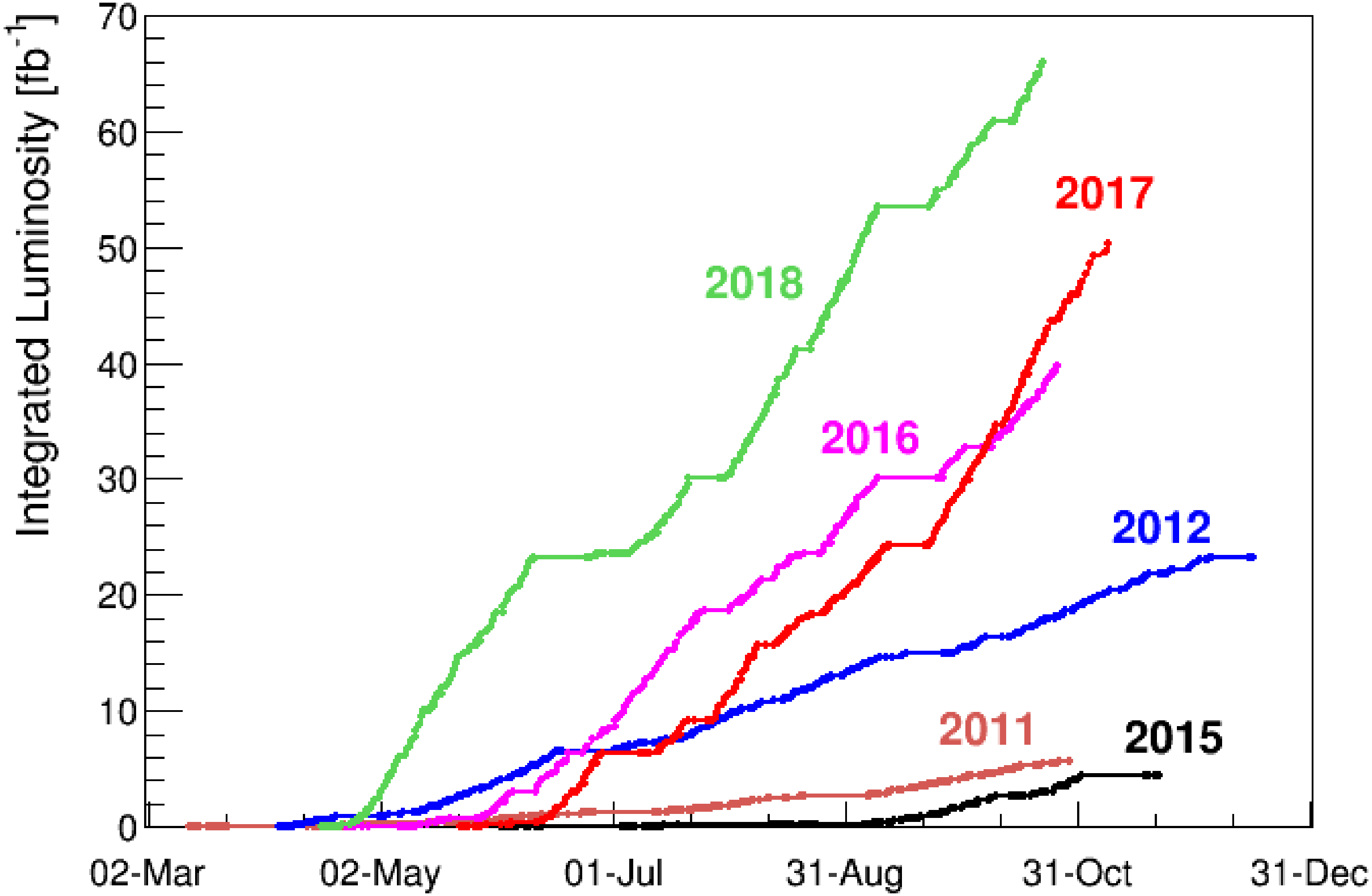



**Selection of 1 in 10,000,000,000,000**

$$E = m c^2$$

# LHC: Run 1 and Run 2

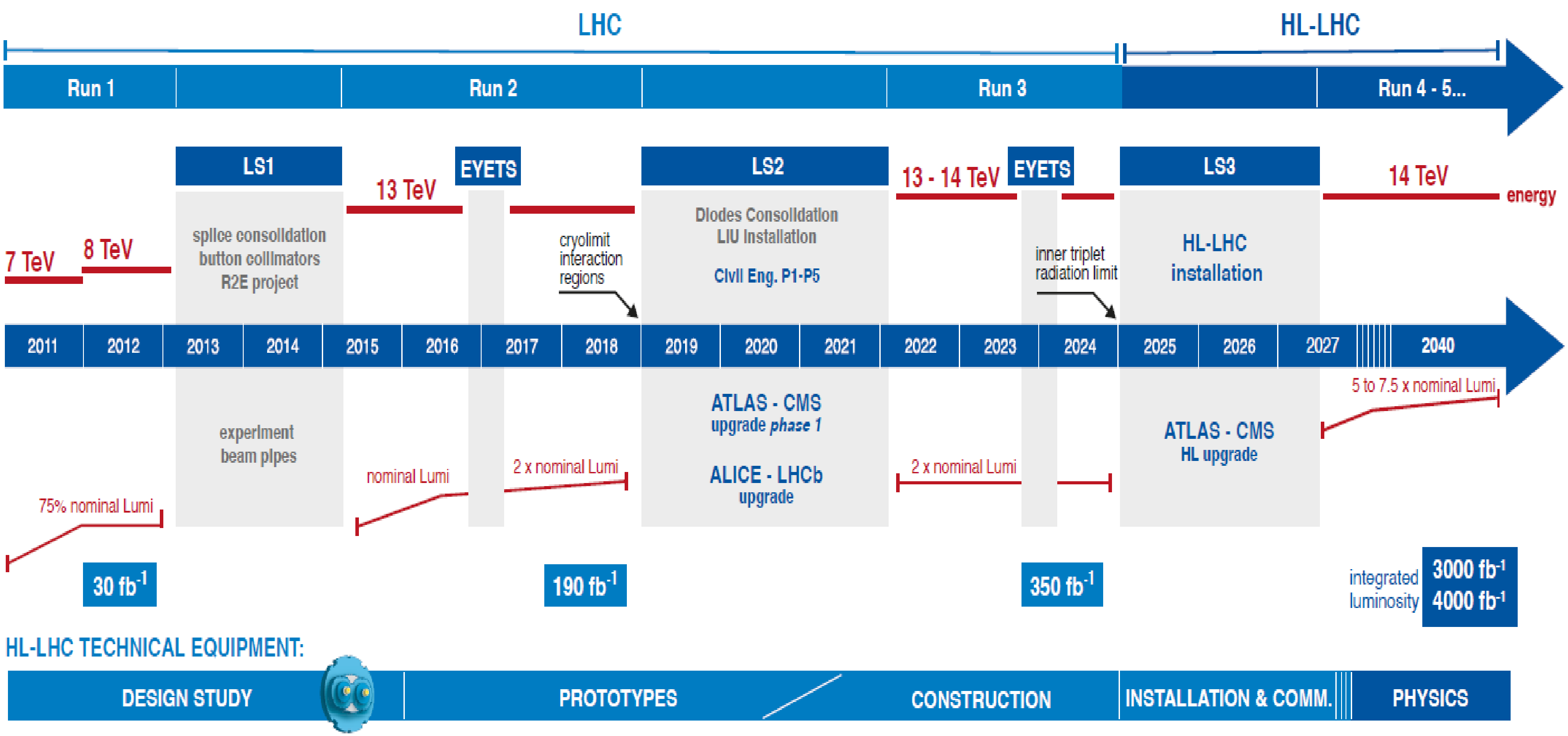
**Run 2 at 13 TeV:**
**2015, 2016, 2017, 2018**



# LHC Beam parameters achieved

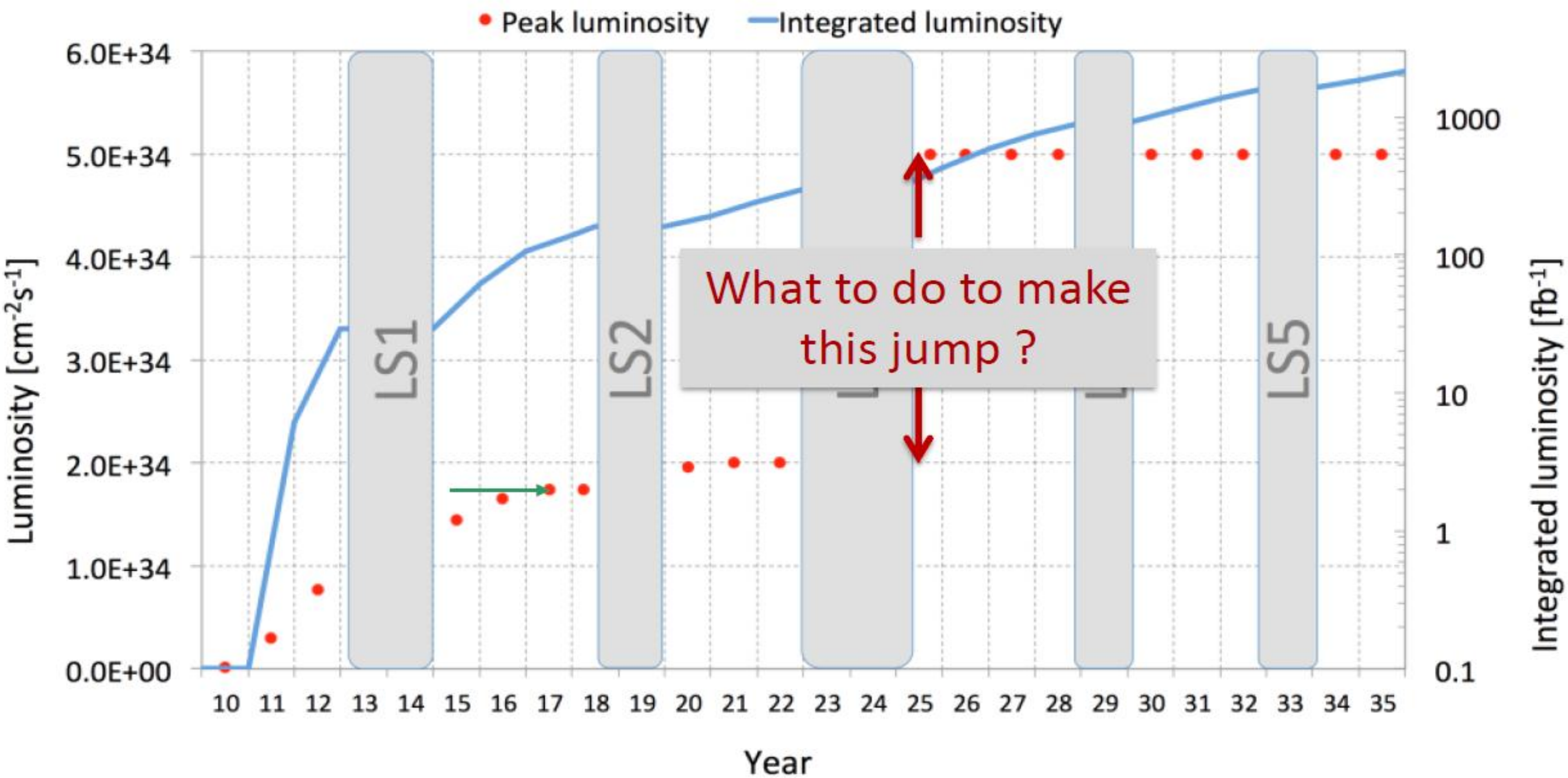
| Parameter | 2018 | Design |
|---|---|---|
| **Energy** [TeV] | **6.5** | 7.0 |
| **No. of bunches** | **2556** | 2808 |
| **Max. stored energy** per beam (MJ) | **312** | 362 |
| **β*** [cm] | **30→25** | 55 |
| **p/bunch** (typical value) [$10^{11}$] | **1.1** | 1.15 |
| Typical normalized **emittance** [μm] | **~1.8** | 3.75 |
| Peak **luminosity** [$10^{34}$ $cm^{-2}s^{-1}$] | **2.1** | 1.0 |

# Plans for next (two) decades




**For next 3 years, starting June this year, we will be taking data.**
**Great opportunity and timing to start analysing them in fall for your master thesis and then continue with PhD for full set of Run3 data.**

# LHC high luminosity upgrade



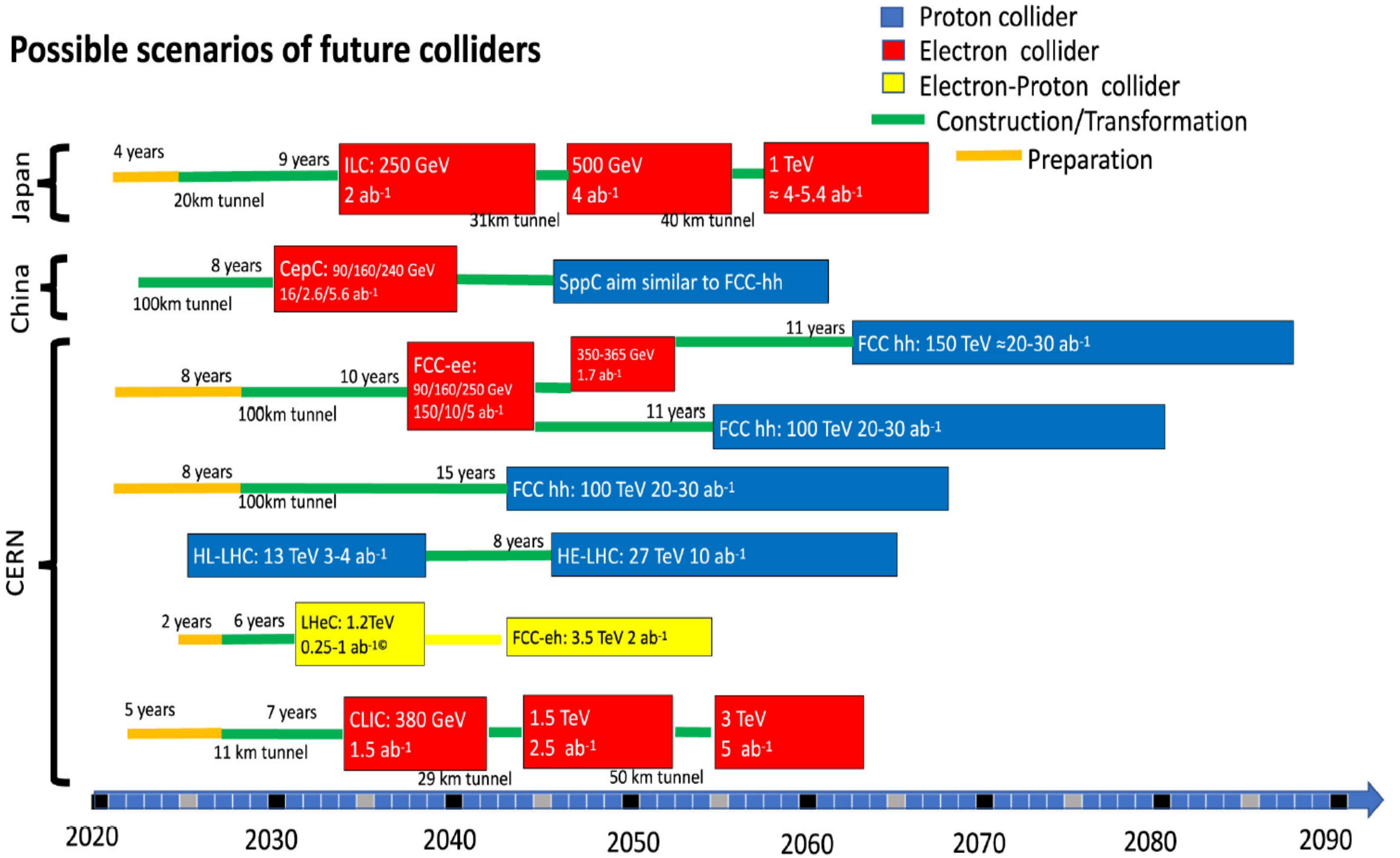
# High luminosity LHC perfomance estimates

| Parameter | Nominal | 25ns – HL-LHC |
|---|---|---|
| Bunch population $N_b$ [$10^{11}$] | 1.15 | 2.2 |
| Number of bunches | 2808 | 2748 |
| Beam current [A] | 0.58 | 1.12 |
| Crossing angle [μrad] | 300 | 590 |
| Beam separation [σ] | 9.9 | 12.5 |
| $\beta^*$ [m] | 0.55 | 0.15 |
| Normalized emittance $\varepsilon_n$ [μm] | 3.75 | 2.5 |
| $\varepsilon_L$ [eVs] | 2.51 | 2.51 |
| Relative energy spread [$10^{-4}$] | 1.20 | 1.20 |
| r.m.s. bunch length [m] | 0.075 | 0.075 |
| Virtual Luminosity (w/o CC) [$10^{34}$ cm$^{-2}$s$^{-1}$] | 1.2 (1.2) | 21.3 (7.2) |
| Max. Luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$] | 1 | 5.1 |
| Levelled Pile-up/Pile-up density [evt. / evt./mm] | 26/0.2 | 140/1.25 |

**Aim for ~250 fb$^{-1}$/y**

**$\Delta Q_{bb}$ ~ -0.01**

# Scenarios for future colliders



# Plans for FCC

**international FCC collaboration (CERN as host lab) to design:**

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL