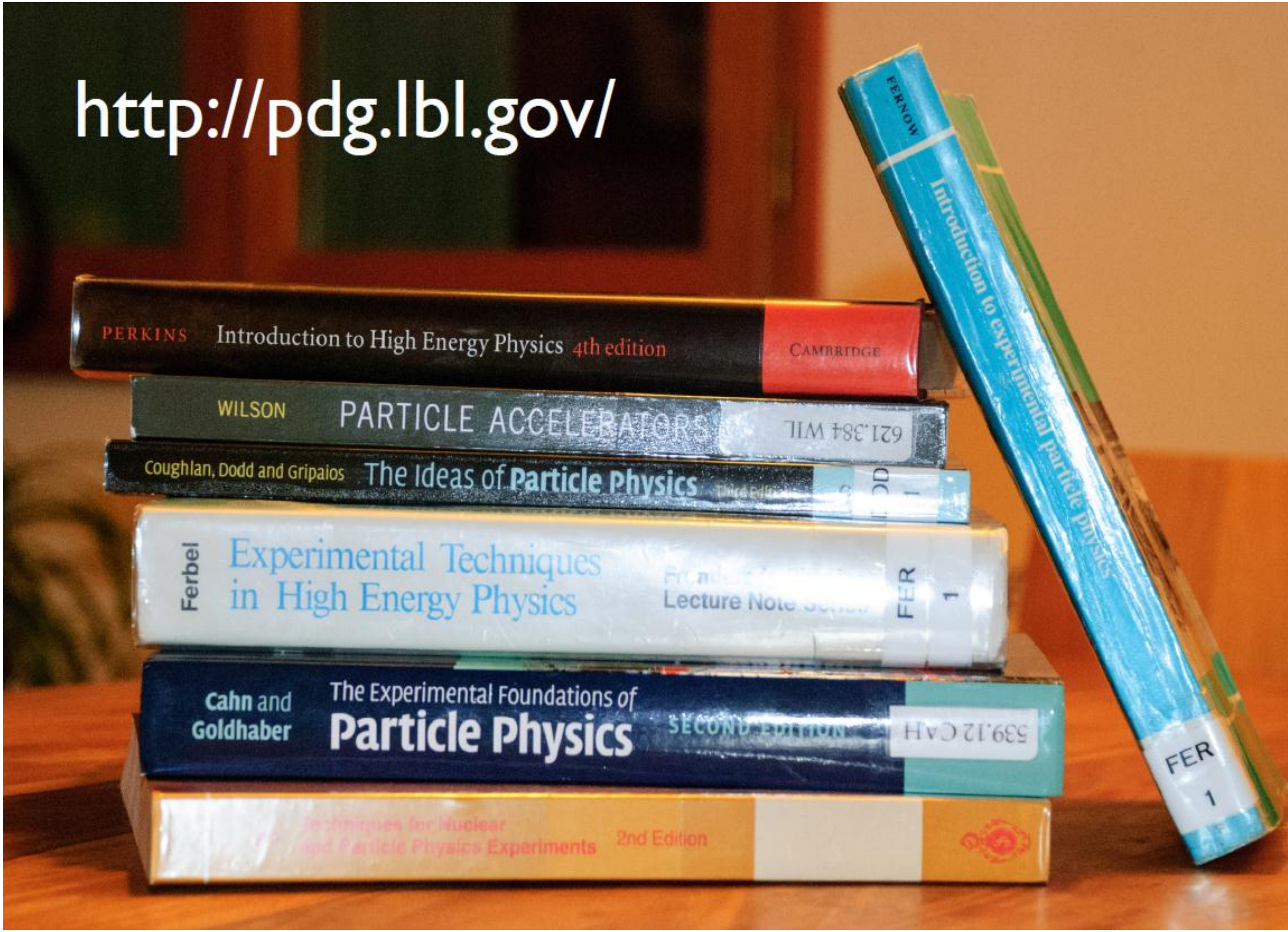
# Introduction to particle physics: experimental part

**Introduction (ones more) to Standard Model**

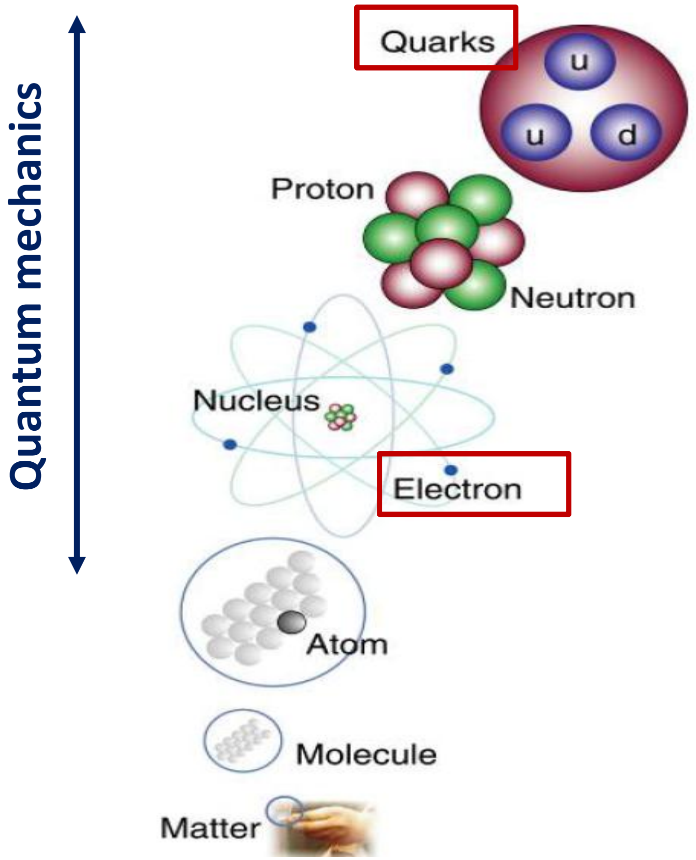
**Accelerators**

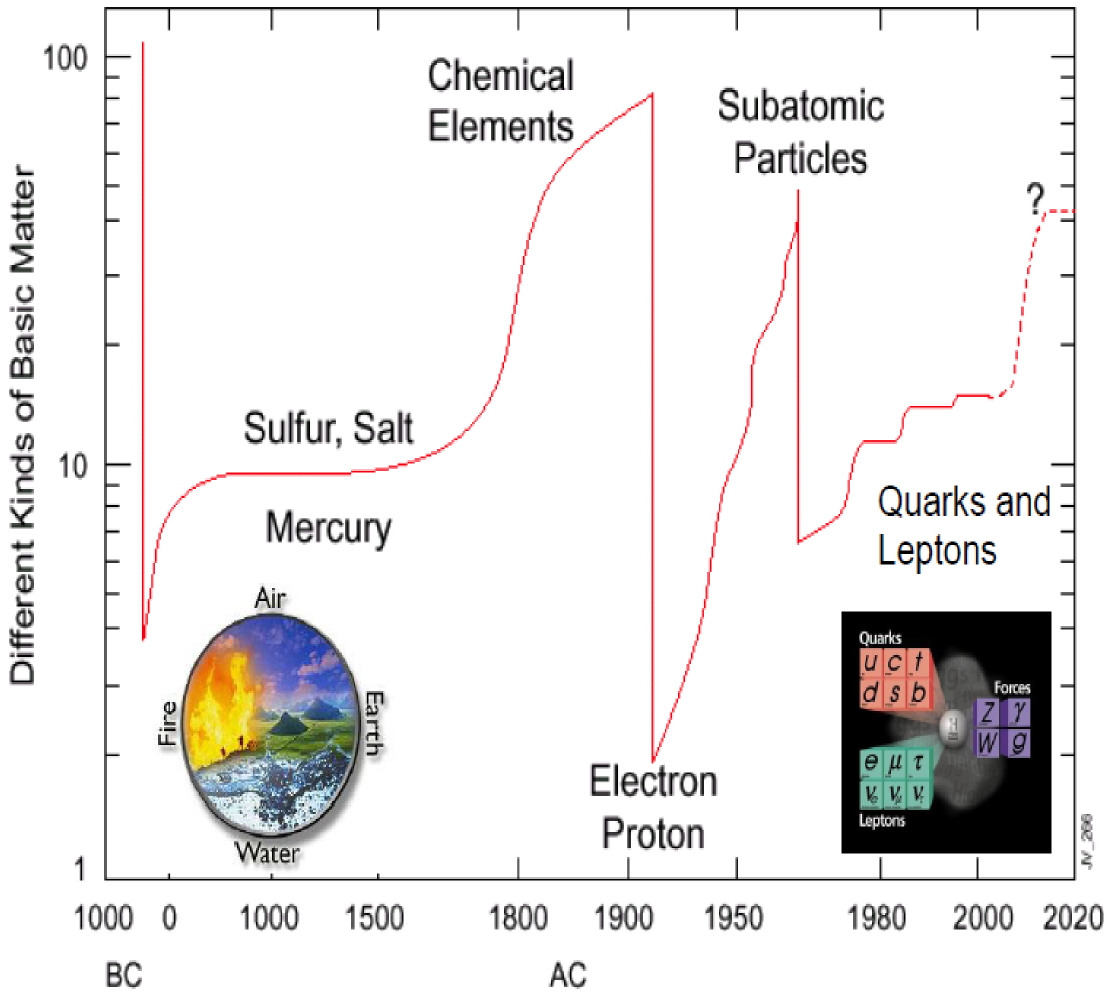
**CERN and LHC**

Prof. dr hab. Elżbieta Richter-Wąs

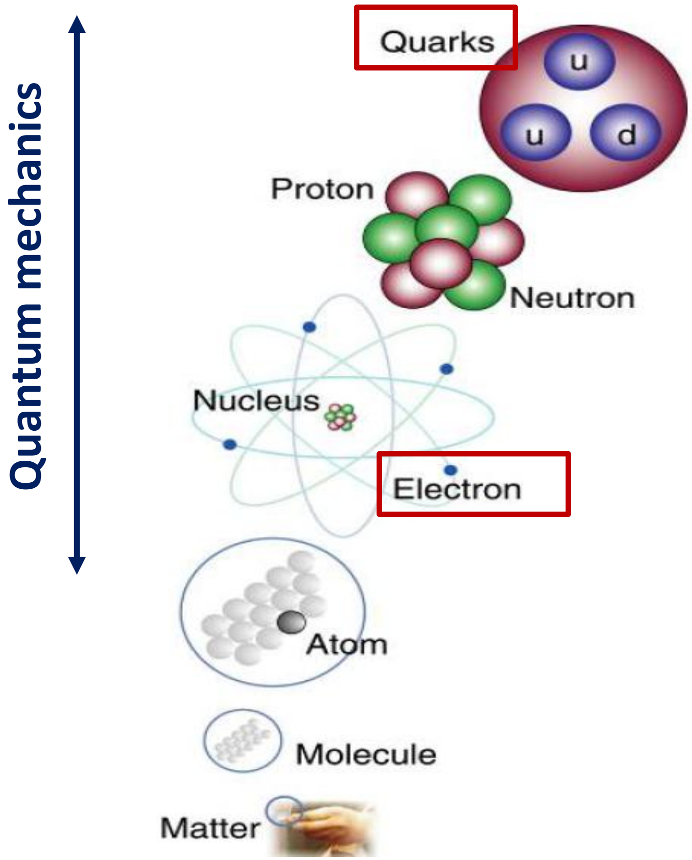

http://pdg.lbl.gov/
PERKINS Introduction to High Energy Physics 4th edition
CAMBRIDGE
WILSON PARTICLE ACCELERATORS
621.384 WIL
Coughlan, Dodd and Gripaios The Ideas of Particle Physics
Ferbel Experimental Techniques in High Energy Physics
Lecture Note
FER 1
Cahn and Goldhaber The Experimental Foundations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

# Constituents of matter along History



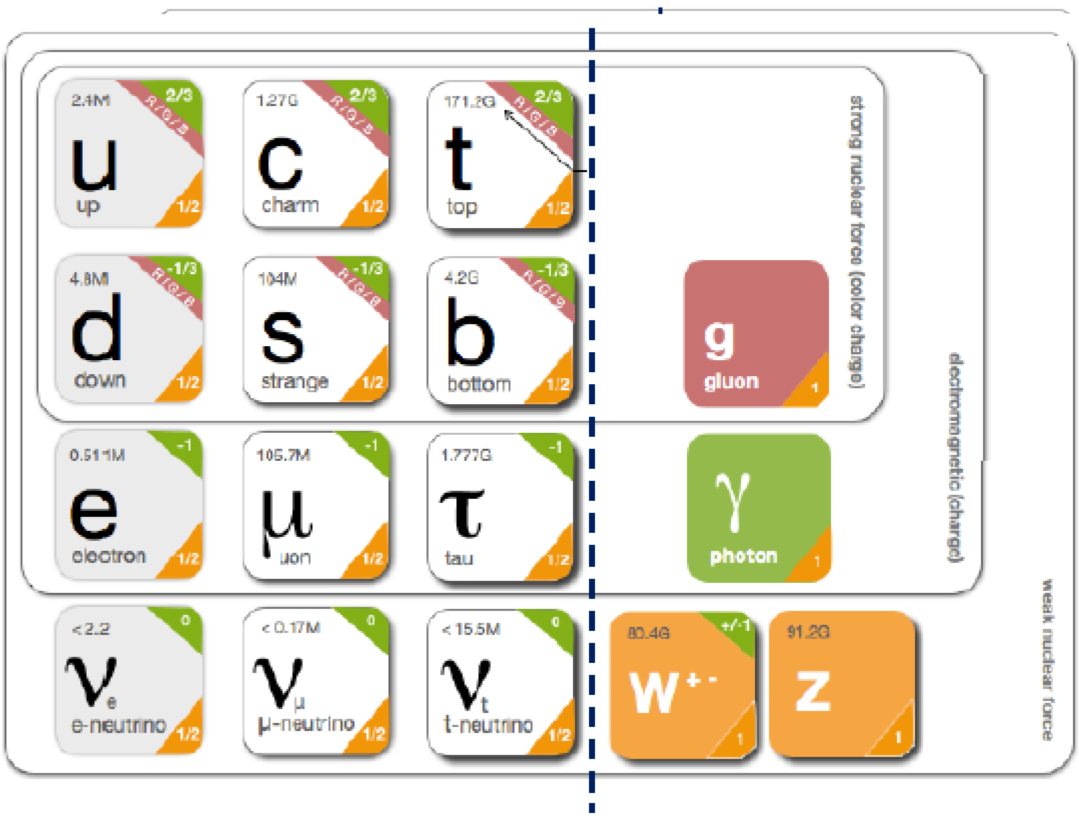



# Particles of the Standard Model




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

**Interaction particles**





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

# Nobel Prizes in Elementary Particle Physics


Sin-Itiro Tomonaga


Julian Schwinger


Richard P. Feynman


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg


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

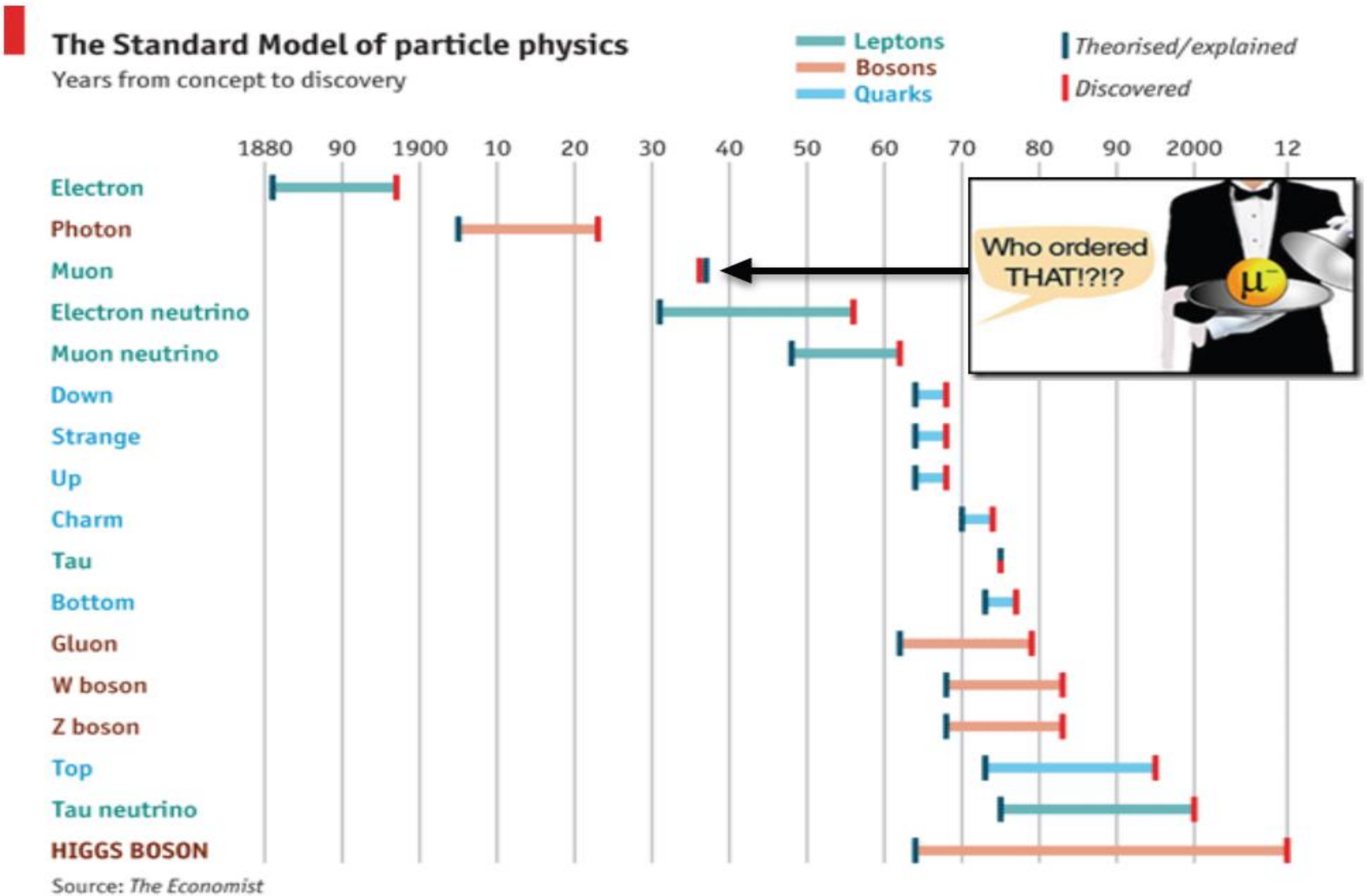
GREEN - theoretical
BLUE - experimental

1964: „Higgs mechanism" was born

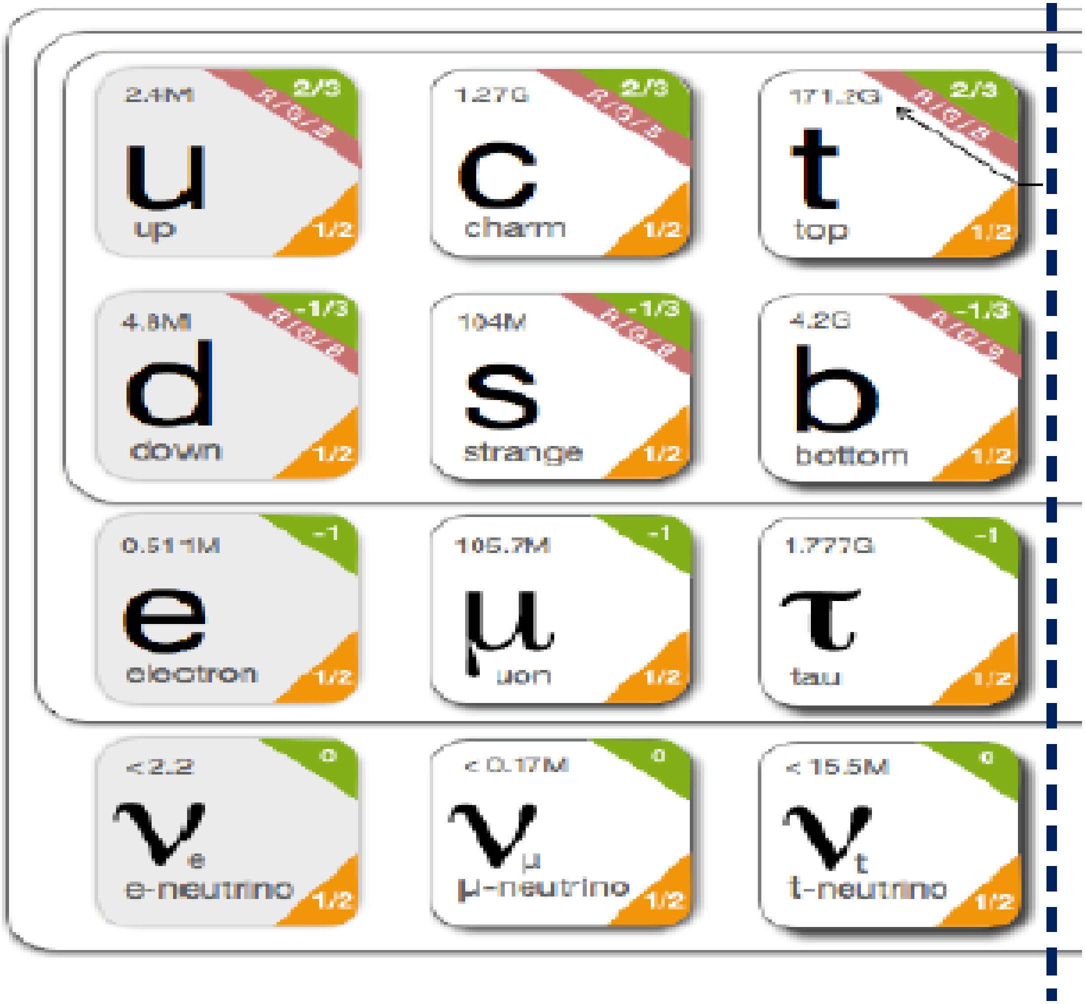
- 1957 – C. N. Yang, T. Lee
- 1965 – S. I. Tomonaga, J. Schwinger, R.P Feynman
- 1969 – M. Gell-Mann
- 1976 – B. Richter and S. Ting
- 1979 – S.L. Glashow, A. Salam, S. Weinberg
- 1980 – J. Cronin, V. Fitch
- 1984 – C. Rubbia, S. van der Meer
- 1988 – L. M. Lederman, M. Schwartz, J. Steinberger
- 1990 – 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?



# Matter particles




- **u, d, e**

**ordinary matter**

- **s, μ**

**cosmic rays**

- **c, b, t, τ**

**accelerators**

# Matter particles

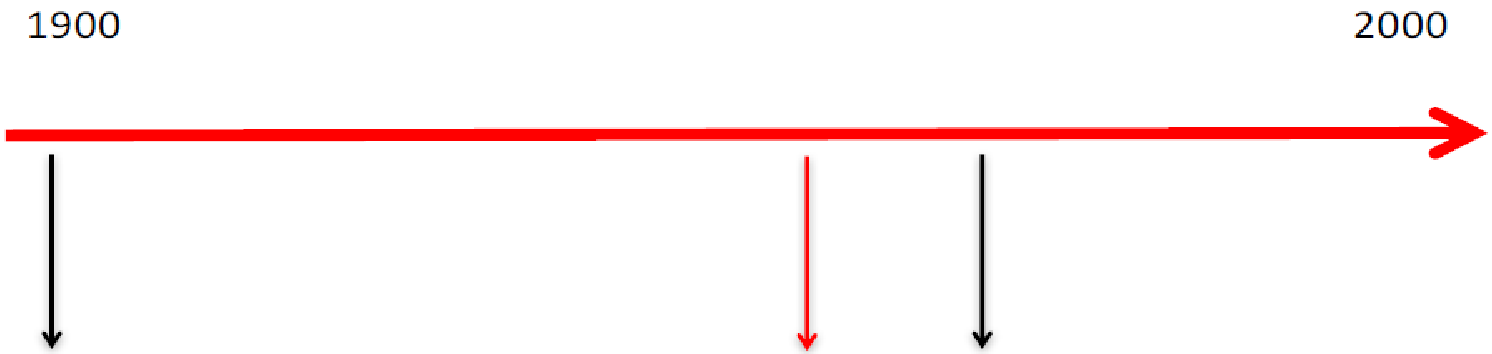

1897
Electron
J.J. Thomson, *Philosophical magazine* **44**:293

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
**J.** M. Breidenbach *et al. Physical Review Letters* **23** (16): 235

u,d proposed 1960s, discovered ~1968

e discovered 1897

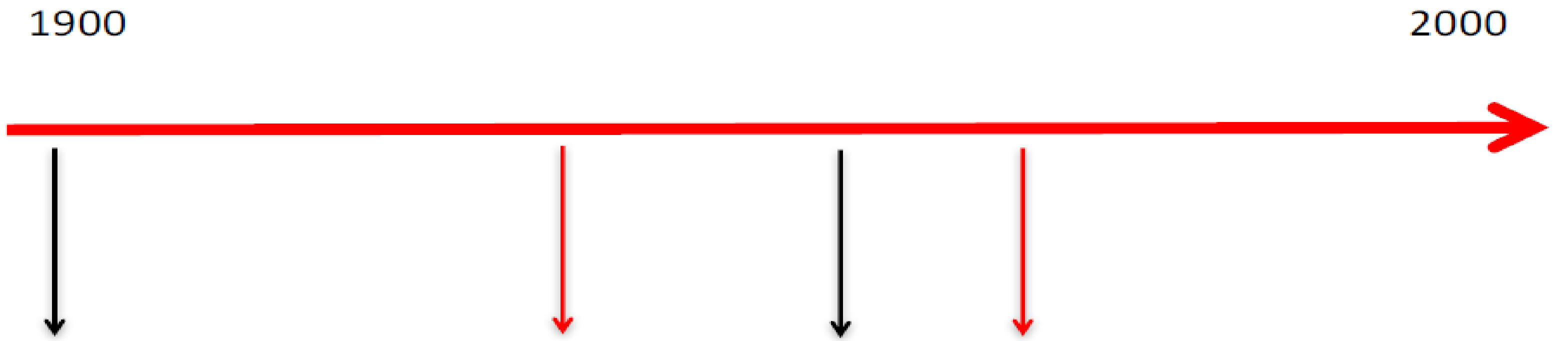
# Matter particles




1956
Electron neutrino
F. Reines, C.L. Cowan, *Nature* **178** (4531): 446

Radioactive decay (inferred 1930s, seen 1956)

# Matter particles

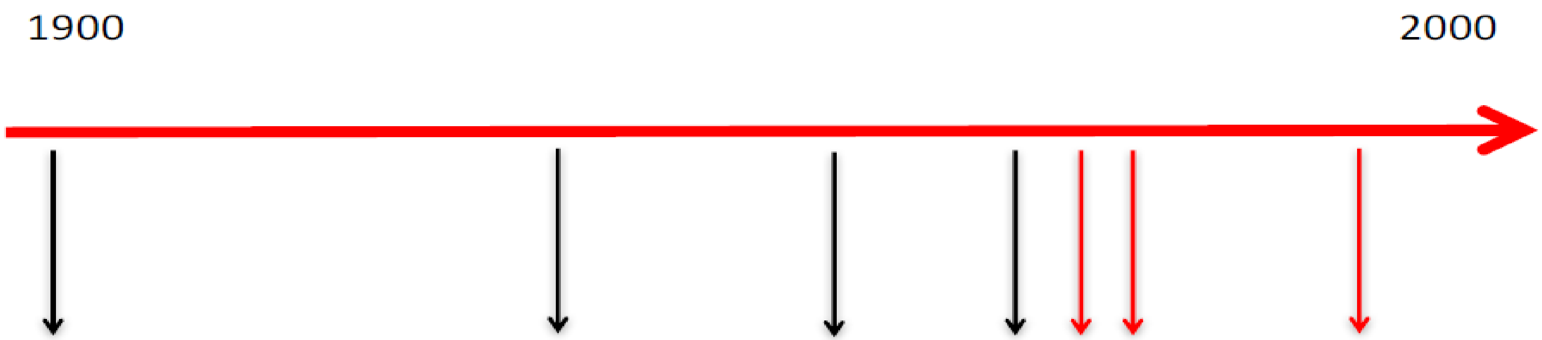



1937
Muon
S.H. Neddermeyer, C.D. Anderson,
*Physical Review* **51** (10): 884

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
**J.** M. Breidenbach *et al. Physical Review Letters* **23** (16): 235

Cosmic ray experiments (1930s, 1940s)

# Matter particles




1974
Charm quarks
J.J. Aubert *et al.* *Physical Review Letters* **33** (23): 1404
J.-E. Augustin *et al.* *Physical Review Letters* **33** (23): 1406

1977
Bottom quarks
S.W. Herb *et al.* *Physical Review Letters* **39** (5): 252.

1995
Top quarks
F. Abe *et al.* (CDF collaboration) *Physical Review Letters* **74** (14): 2626–2631.
S. Arabuchi *et al.* (D0 collaboration) *Physical Review Letters* **74** (14): 2632–2637.

## Collider experiments (1960s -)

# And … antimatter

Einstein's equation of motion*: $$E^2 = p^2c^2 + m^2c^4$$

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.

Same mass, opposite charge

eg. antiquark $\bar{q}$, antimuon $\mu^+$, antineutrino $\bar{\nu}$

*(and others, more famously Dirac)

# Forces in particle physics

**Electromagnetic**

0 eV/$c^2$
0
1
$\gamma$
photon

U(1)

**Strong (QCD)**

8 x
0 eV/$c^2$
0
1
g
gluon

SU(3)

**Weak**

2 x
80.4 GeV/$c^2$
±1
1
W
W boson
,
91.2 GeV/$c^2$
0
1
Z
Z boson

SU(2)

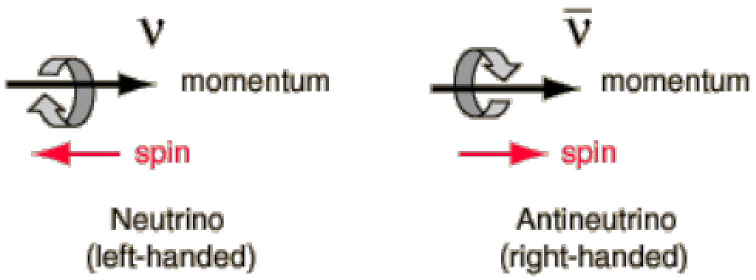
Note:
No gravity!!

# Forces in particle physics

| EM force | Weak force | Strong force |
|---|---|---|
| Electric charge (1) | Weak charge (2) | Colour charge (3) |
| Massless photon | Massive $W^{\pm}$,Z | 8 massless gluons |
| Coupling g | Coupling $g_W$ | Coupling $g_s$ |

Value unknown/
not predicted

# Forces in particle physics




**EM force**

Abelian

Only charged particles couple

**Weak force**

Non-abelian

Only left handed particles couple

quark mixing (3 generations, CP)

Neutrino mixing (3 generations, CP)

**Strong force**

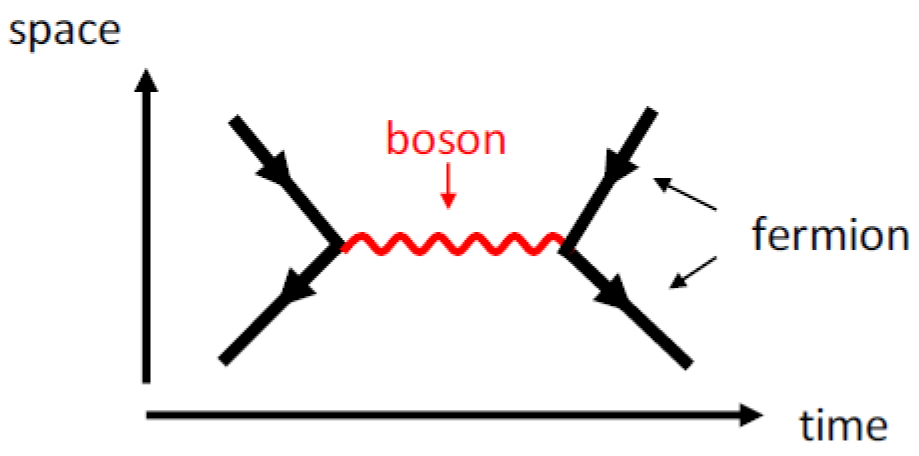
Non-abelian

Only quarks couple

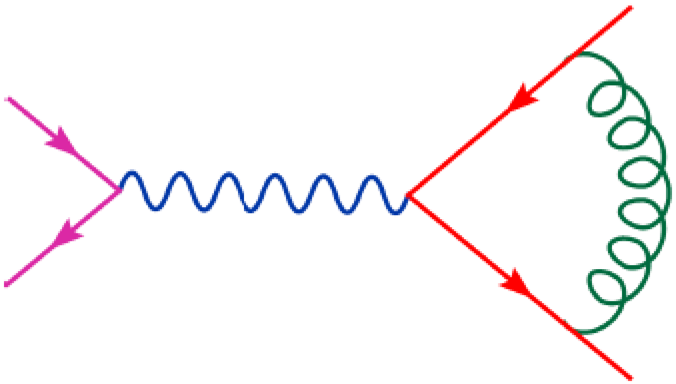
Value unknown/ not predicted

# Aside: Feynman diagrams

“tree” level
**Lowest order**



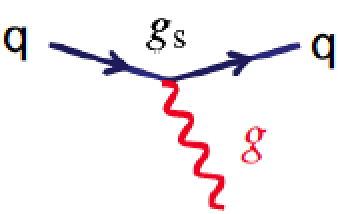

**Higher orders** possible
Loops



# Interactions

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

**STRONG**




Only quarks

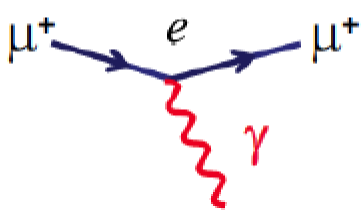
Never changes flavour

$\alpha_S \sim 1$

**Gluons**

massless

**EM**




All charged fermions

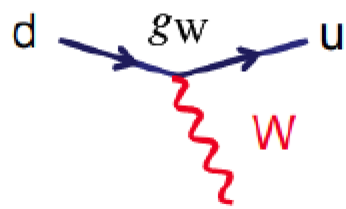
Never changes flavour

$\alpha \simeq 1/137$

**Photon**

massless

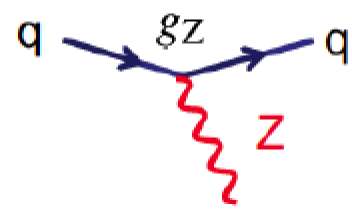
**WEAK CC**




All fermions

<u>Always</u> changes flavour

**WEAK NC**




All fermions

Never changes flavour

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

**W+, W-**

very massive

**$Z^0$**

very massive

# The Higgs boson

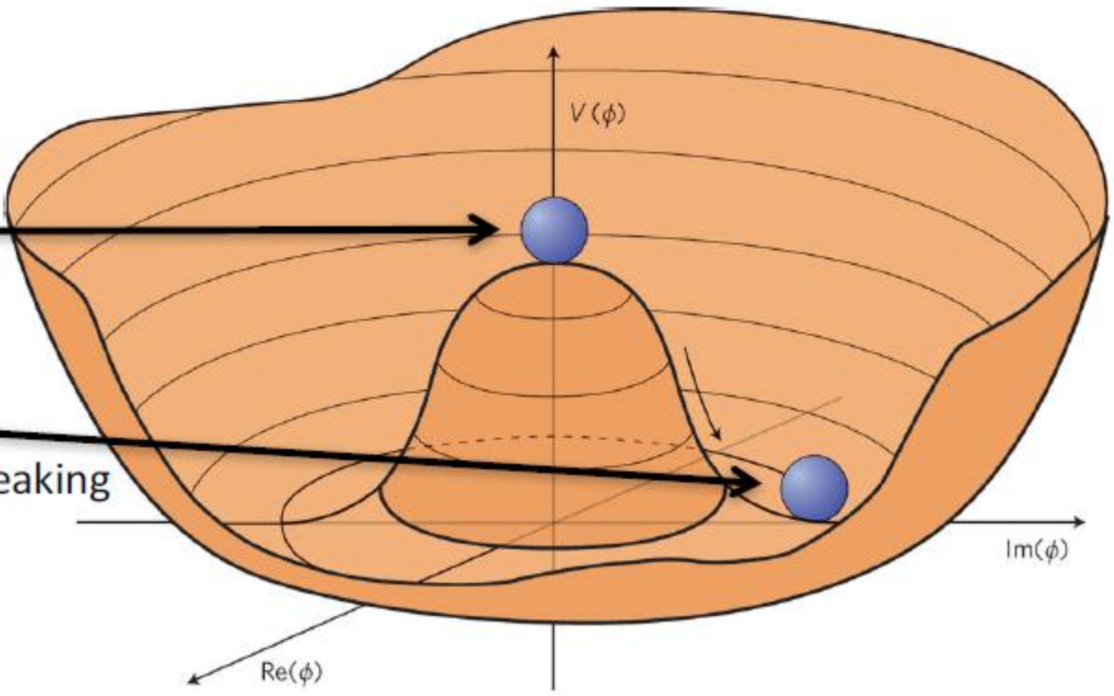
Introduce Higgs field:

Complex doublet (but 1d case shown here to get idea)

$V(\phi) = -0.5\mu^2|\phi|^2 + \lambda|\phi|^4$

Big Bang
Massless bosons

Shortly (~$10^{-12}$ s) after
Spontaneous symmetry breaking
Bosons acquire mass
(nb. fermions too)



# The Higgs boson

Introduce Higgs field :

**Couples to particles to give mass (amount ~ coupling strength)**

Complex doublet has **4 free parameters**

3 absorbed into W+, W-, Z boson mass

W+, W-, Z, $\gamma$ admixtures of original weak, em massless bosons.

1 manifested as a massive Higgs boson ($m_H$)

**Connection between weak and electromagnetic forces**

(note: Higgs field gives mass to fermions by a different mechanism)

Yukawa coupling; yet to be fully tested.

- No deep explanation; motivated by simplicity.

# The Higgs boson

Introduce Higgs field :

After symmetry breaking, Higgs sector properties are:

- spinless Higgs boson ($m_H$)
- vacuum expectation value (mean field value) ($v$)

**Consequences:**

Weak and electromagnetic forces connected

**Massive** Z is mixture of massless em + weak bosons

Relates Mw, Mz and weak, electromagnetic couplings:

$\tan \theta_W = g_W / g$

$M_W = M_Z \cos \theta_W$

# QED and QCD

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Interaction of electric charges and photons

Quantum Chromodynamics: QCD

Colour charge → Baryons → Nucleus

Interaction of colour charges and gluons

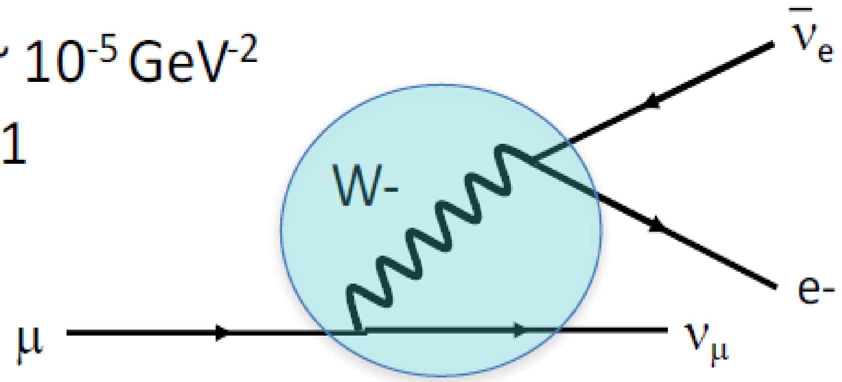
Different forces, but **similar** (mathematical) structure/behaviour

# Weak force vs QED and QCD

Muon decay:

Strength of weak force ~ $G_F$ ~ $10^{-5}$ $GeV^{-2}$

cf. strength of em force ~ 0.01



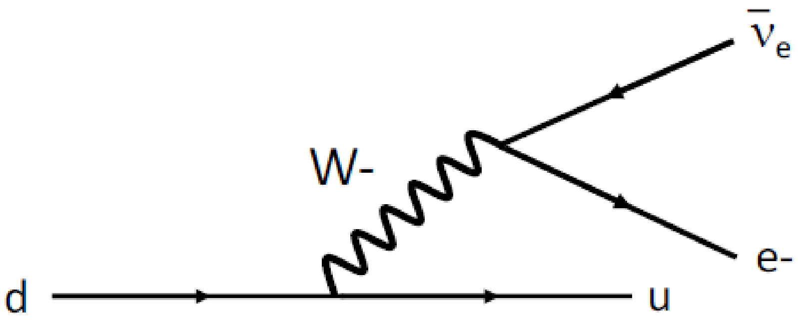

W boson **massive**

Factor involved in boson exchange ~ $1/(E^2+M^2)$ (hence units)

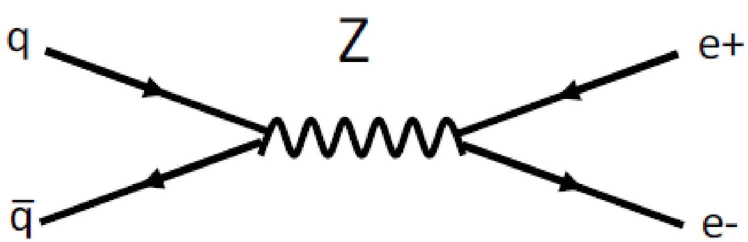
Strength of weak force = em force if M~ 30 GeV (M$_W$~80 GeV)

# Weak force vs QED and QCD

**W** couples to:
Upper and lower members of a fermion generation.
L- (R-) handed (anti)particles



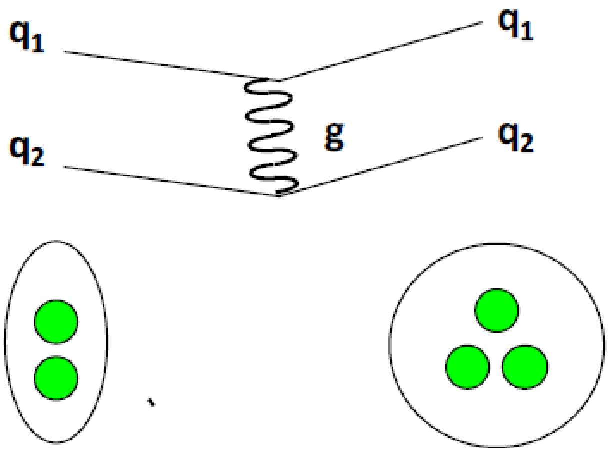

**Z** couples to:
Matter and antimatter versions of a fermion.
Complicated mix of L-, R- particles.




"vector, axial couplings"; Higgs mechanism.

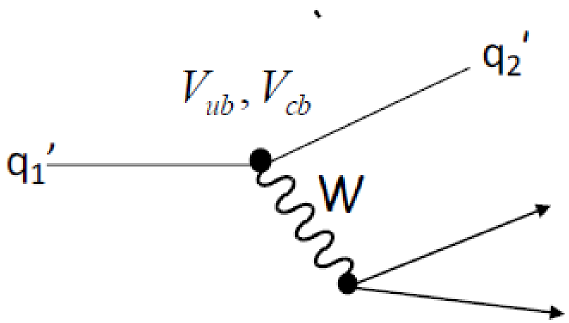
# Weak vs. mass quark eigenstates

Mass eigenstates of quarks form hadrons




W couples to weak quark eigenstates q’

q’ admixture of q and vice versa



# Quark mixing

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak, mass eigenstates related by mixing matrix in SM (3x3 matrix)

Mixing matrix is unitary (inverse = complex conjugate)

# CKM matrix

CKM matrix (1973 – before charm! Predicted 3rd generation)

Elements describe every weak quark transition

SM does not predict existence of or values for matrix elements (couplings of W to quarks).

**Input by experimental data**

$$V_{CKM} = \begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix}$$

# CKM matrix

- Need 3 generations of quarks to introduce CP violation into theory

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mixing matrix is 3x3.

Unitarity constraints $\Rightarrow$ 4 independent parameters

**3 angles** quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

# CP violation

**C = charge operator**

**P = parity operator**

CP operation changes particle q to antiparticle $\bar{q}$ (and vice versa)

CP **violation** if q→q' rate different to q'→q   ie. $V_{qq'} \neq V^{*}_{qq'}$

**CP violation observed** in weak decays.

**Note:**

- **SM does not predict** CP violation.
- **SM does not explain** CP violation.
- CP violation **must be added** to SM.

# Aside: neutrino CP violation, mixing

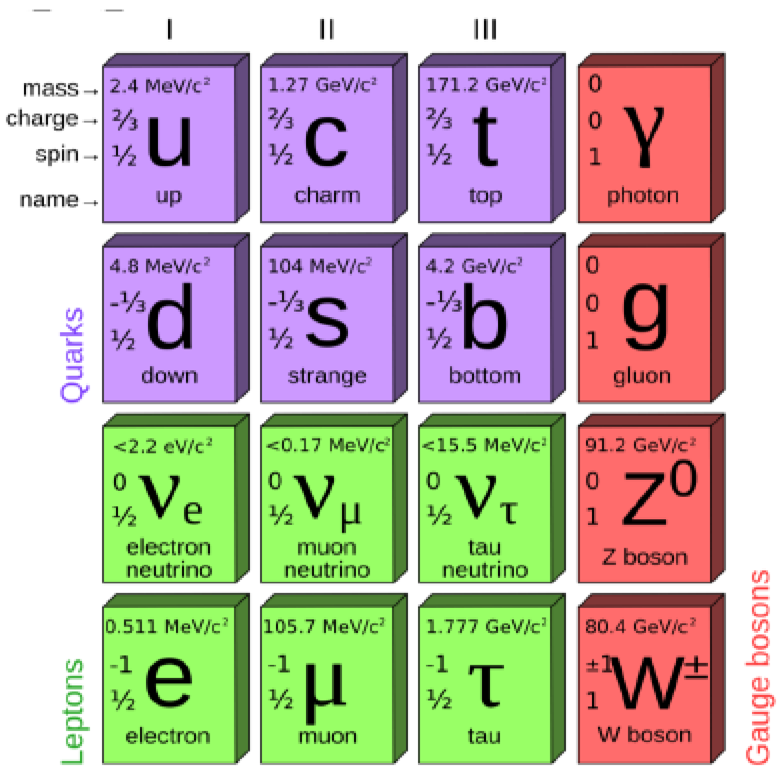
- Similar framework adopted for neutrinos (PMNS matrix). Weak ($\nu_e$, $\nu_\mu$, $\nu_\tau$) related to mass eigenstates ($\nu_1$ etc):

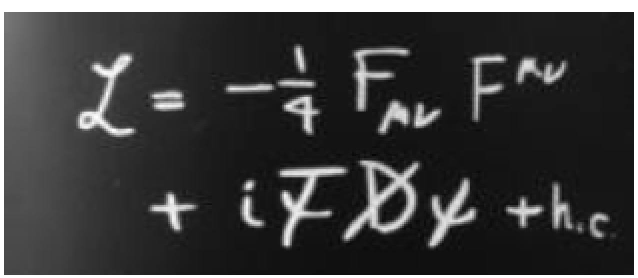
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

**3 angles** quantify mixing between (1,3) (2,3) (1,2) generations, **1 complex phase** (mechanism for introducing CP)

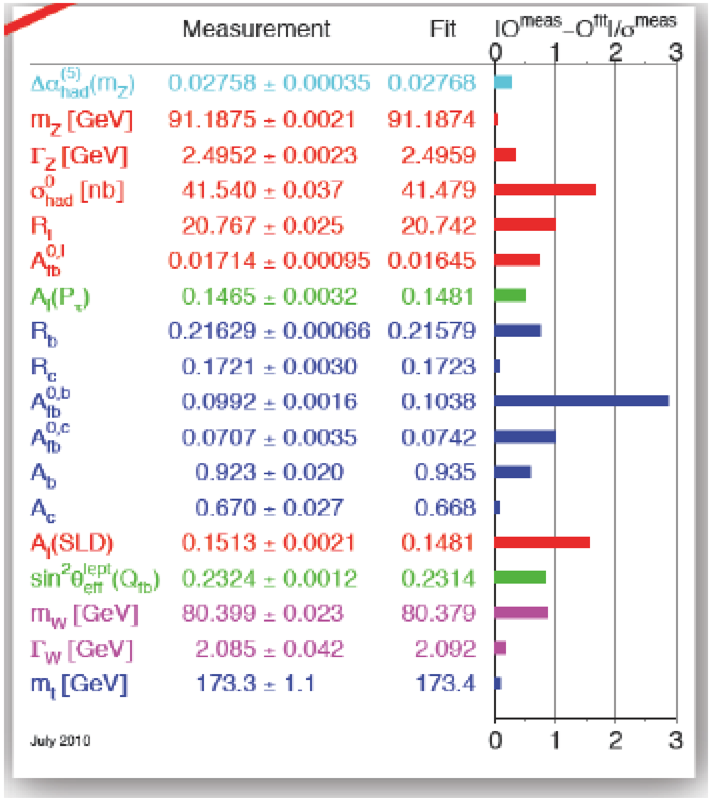
Note: parameters investigated in dedicated neutrino experiments

# Standard Model confirmed by the data




## STANDARD MODEL OF ELEMENTARY PARTICLES

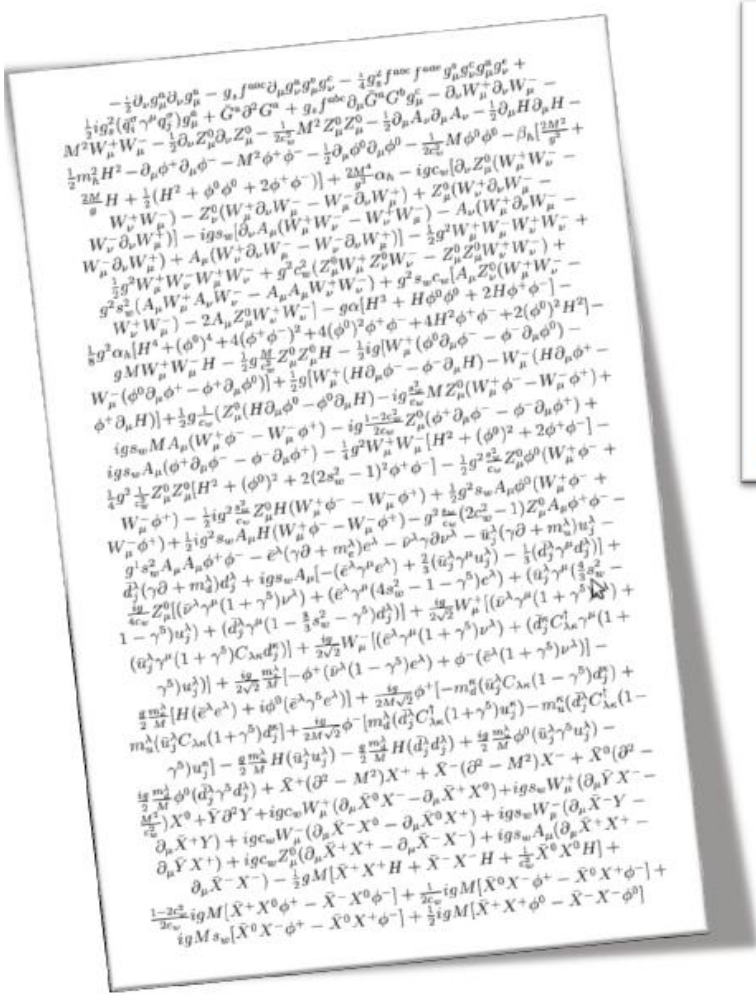


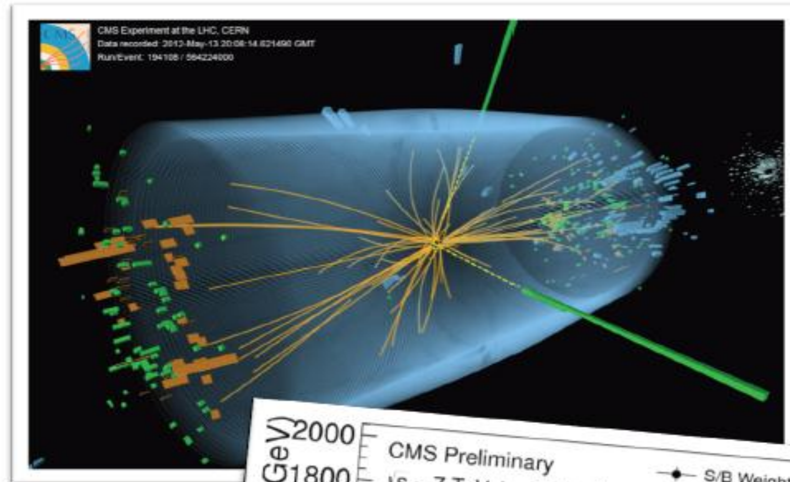
| | Measurement | Fit | $\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 | |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 | |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 | |
| $\sigma^0_{had}$ [nb] | 41.540 ± 0.037 | 41.479 | |
| $R_l$ | 20.767 ± 0.025 | 20.742 | |
| $A^{0,l}_{fb}$ | 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 | |
| $A^{0,b}_{fb}$ | 0.0992 ± 0.0016 | 0.1038 | |
| $A^{0,c}_{fb}$ | 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 | |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | 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 | |

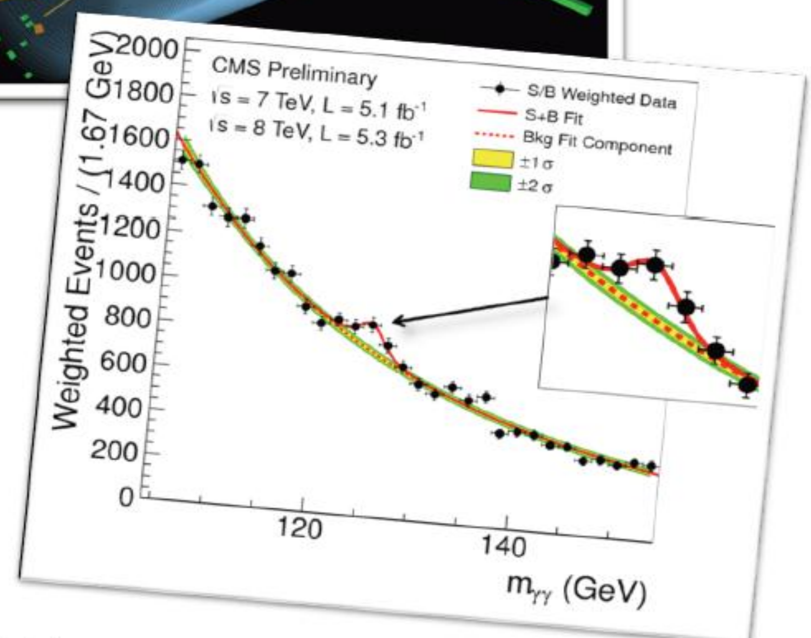


Confirmed at sub 1% level!

# Experiment = probing theories with data

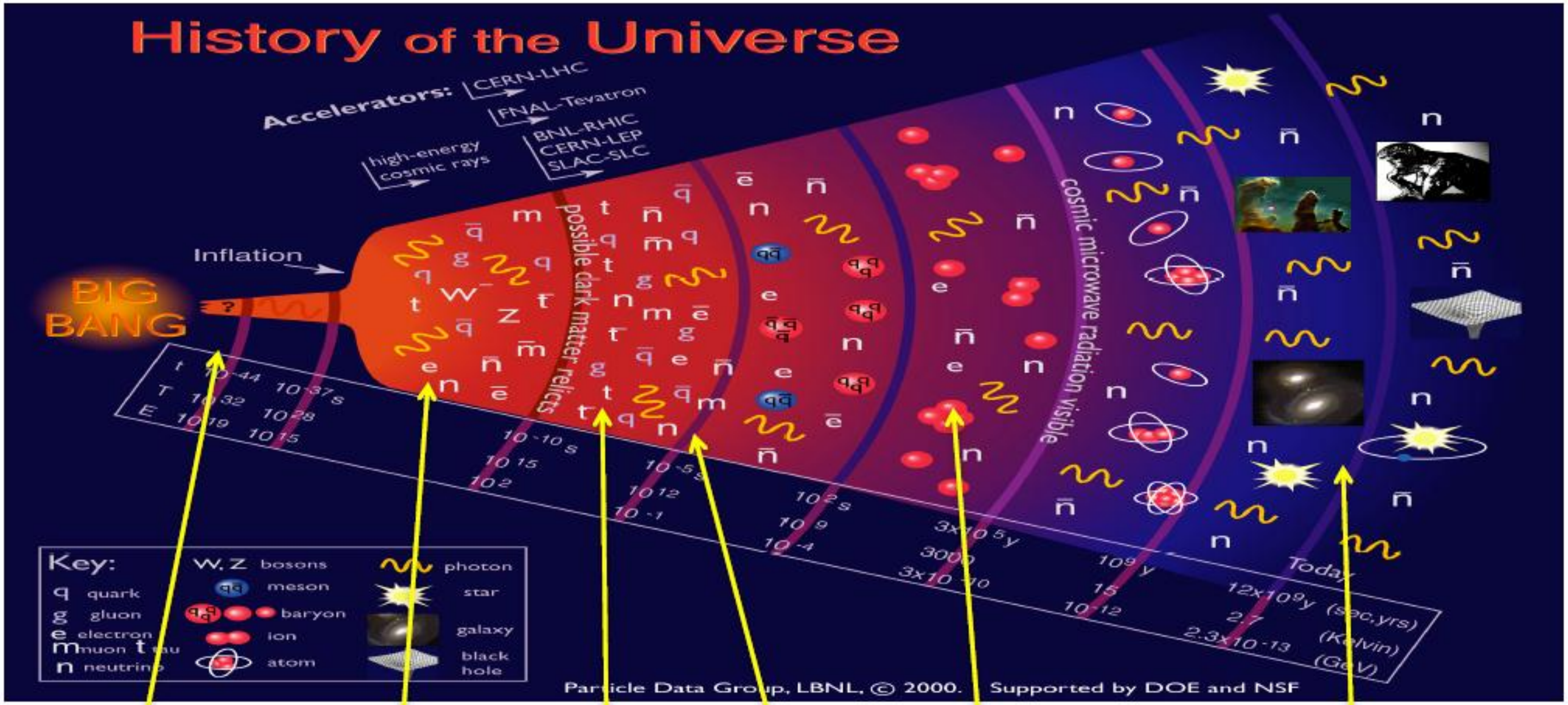




# Accelerators for high energy physics experiments

# History of the Universe




Cosmology

LHC

Nuclear physics

Cosmic rays

Quark/gluon plasma

Astrophysics

# Why accelerators?

Accelerators are instruments that increase the energy of particles to study smaller and smaller structures and create heavy short-lived objects in collision with

$$E = m \cdot c^2$$

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

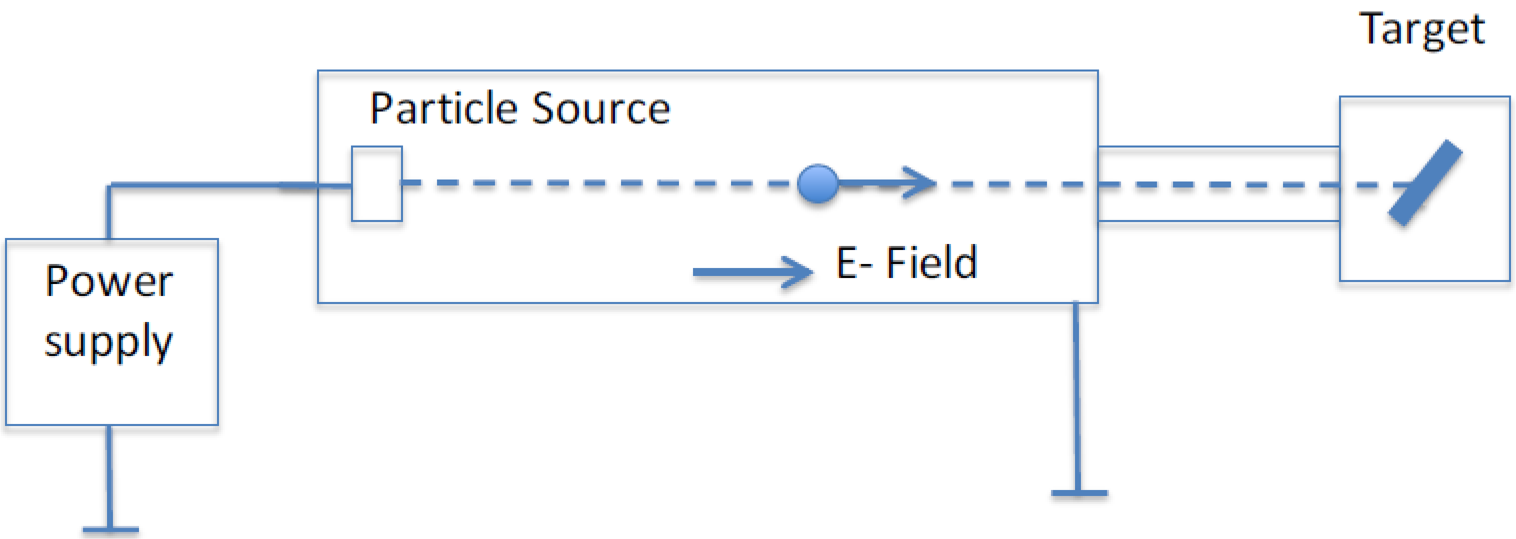
$$\lambda = \frac{h}{p} = \frac{h \cdot c}{E}$$

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

# The basic accelerator

Electrostatic accelerator:

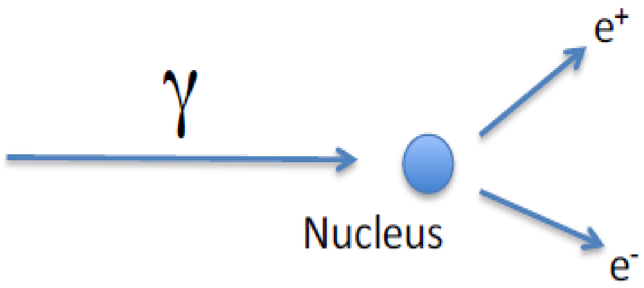
Charged particles go through the accelerating voltage gap <u>once</u> and then hit the target.




Limited by the maximum reachable voltage: ~ 10 MV

# Why collisions

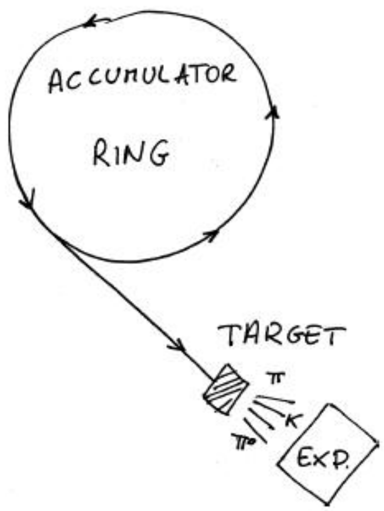
- Conservation laws: e.g. momentum and energy conservation

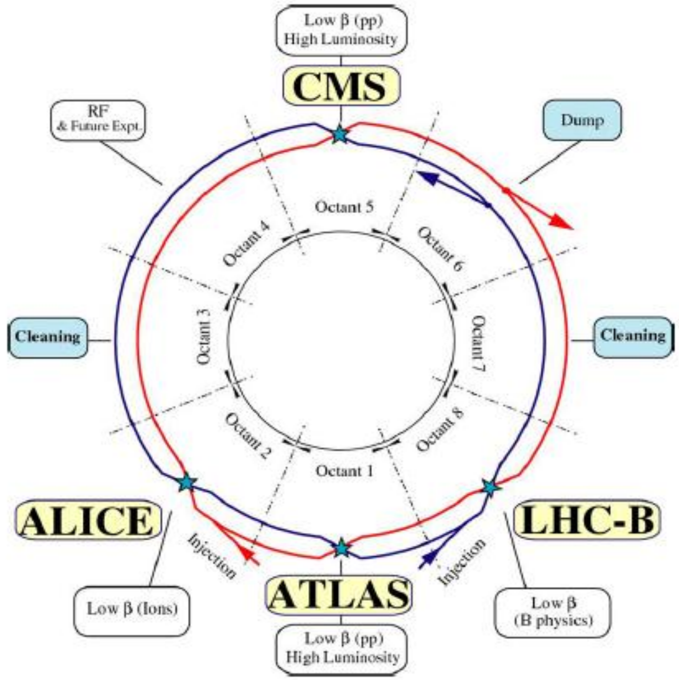


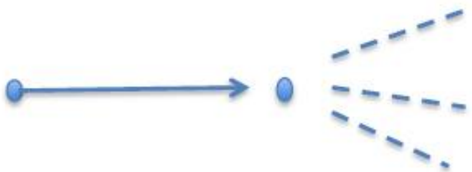

Photon into $e^+,e^-$ only in proximity of nucleus. Nucleus takes part of momentum (and part of available energy…)

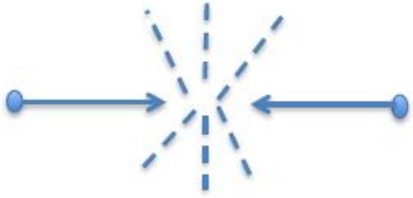
- Center-of-mass Frame and Center-of-mass Energy ($E_{CM}$)
  - Center-of-mass frame defined where: $$\sum \vec{p}_i = \vec{0}$$
  - The energy available for creation of particles corresponds to $E_{CM}$

# Fixed target vs Colliders

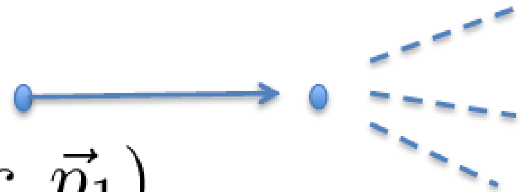




# $E_{CM}$ in Fixed Target Experiment



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

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

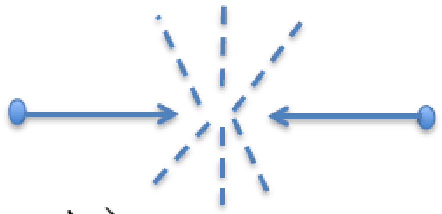
$$p_{tot} = (E_1/c + m_2 c, \vec{p}_1)$$

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

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

# $E_{CM}$ 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

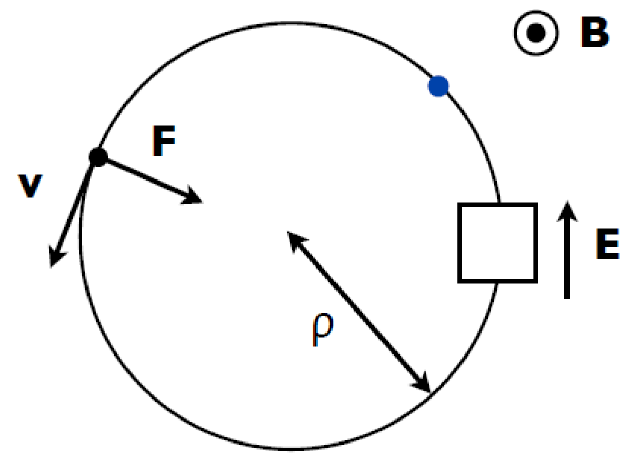
Energy change

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

- 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

# 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

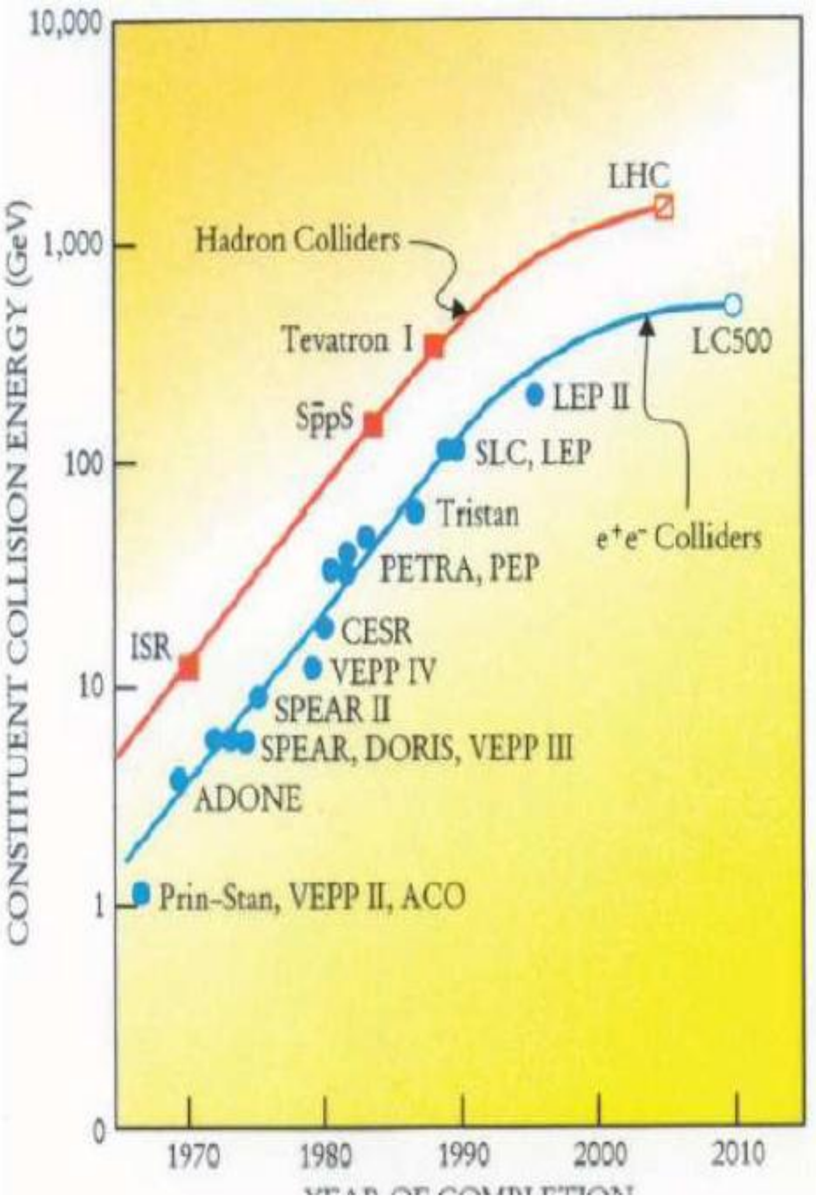
1971-1984: ISR (CERN), p+,p+, 31.5 GeV, 948 m circumference

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

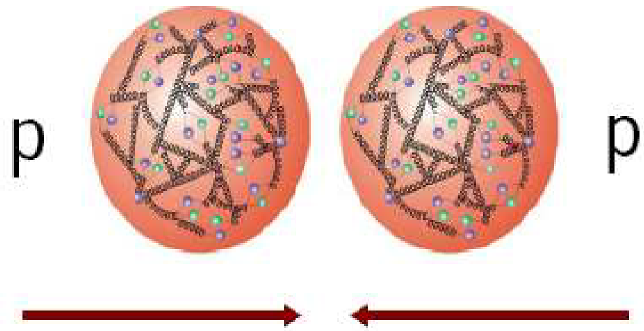
2008 - : LHC highest energy proton synchrotron, p+,p+, heavy ions, 6.5 TeV (2.76 TeV per nucleon for $^{208}Pb^{82+}$); Discovery of Higgs

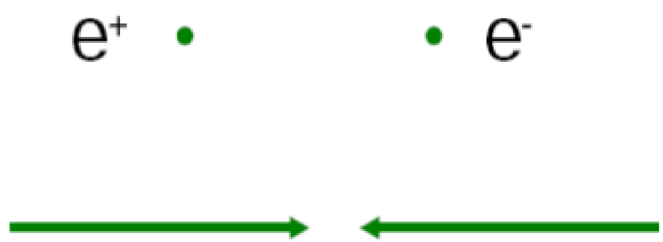
# Energy frontier




- 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
- 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

# 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]

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

# Luminosity frontier

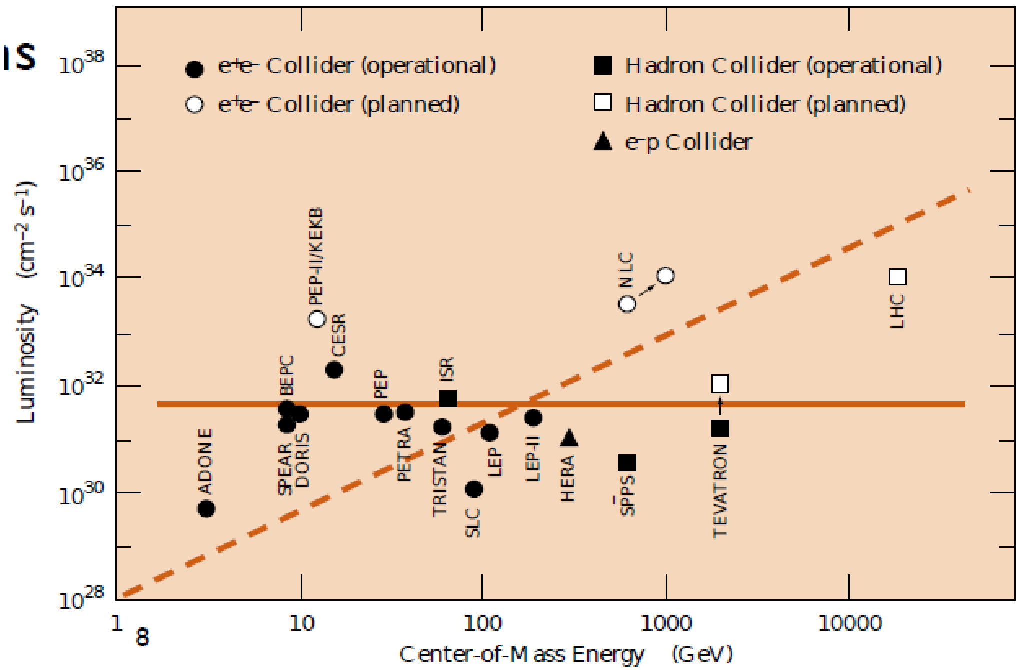
- Need corresponding rise in luminosity (beam intensity)

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

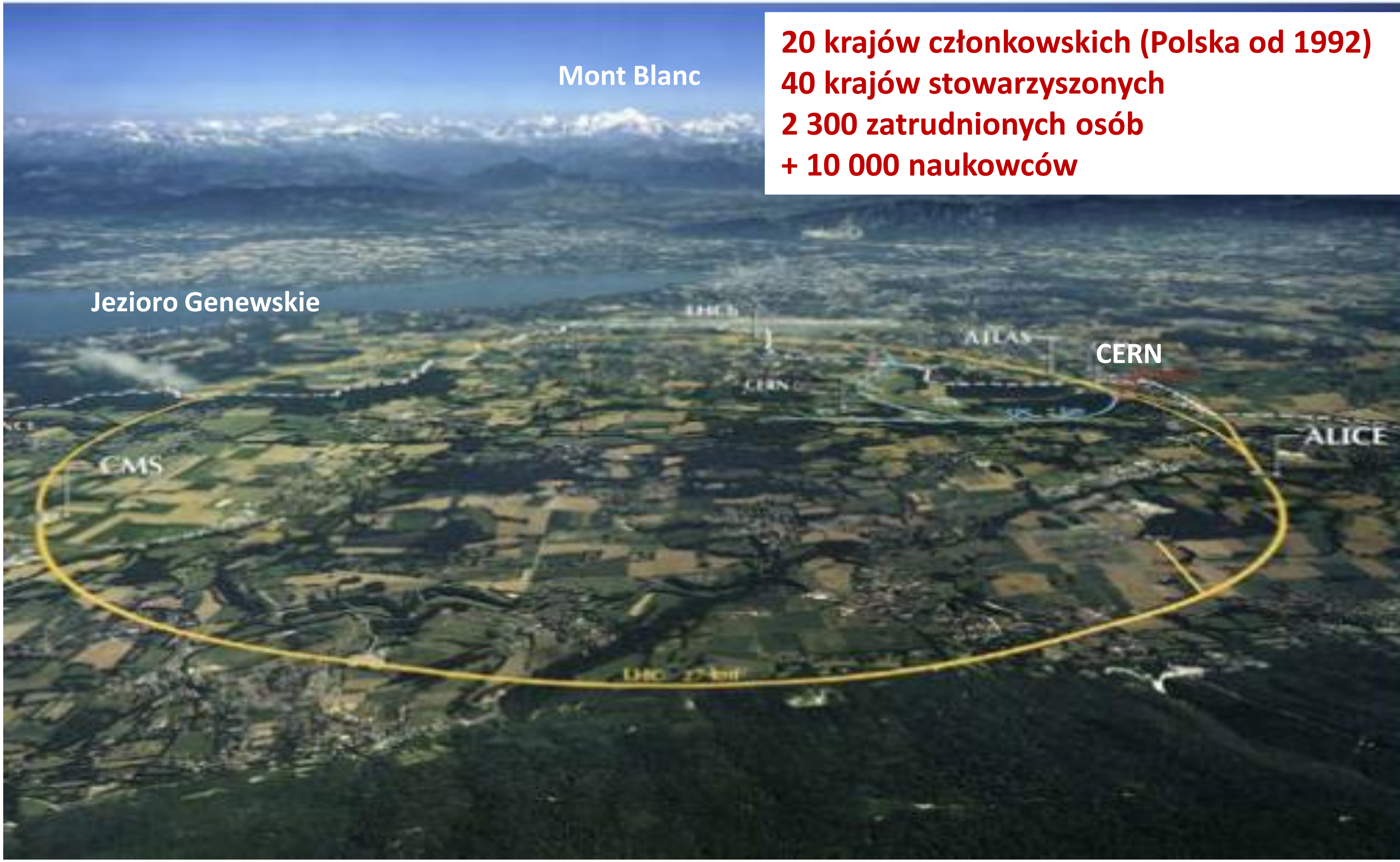
- Particle species
  - Electron/positrons
  - Protons/antiprotons
  - Muons/antimuons
- Beam energy
- Spin
- Luminosity

- 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….

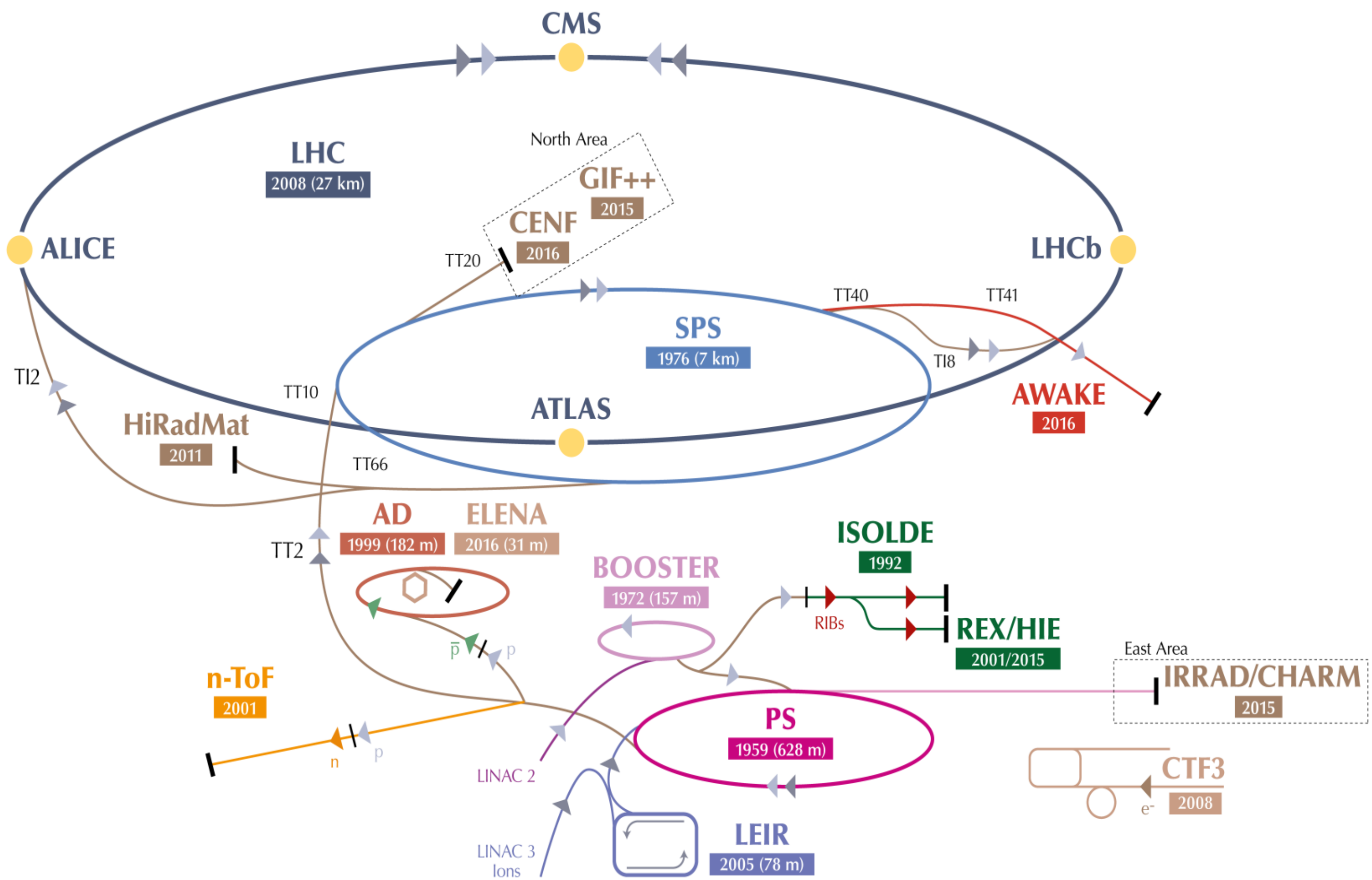
- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc.)
- Diagnostics and controls
- Machine (and detector protection)
- Beam delivery and luminosity production
- Technology spin off
  - Lower energy machines, medical applications,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

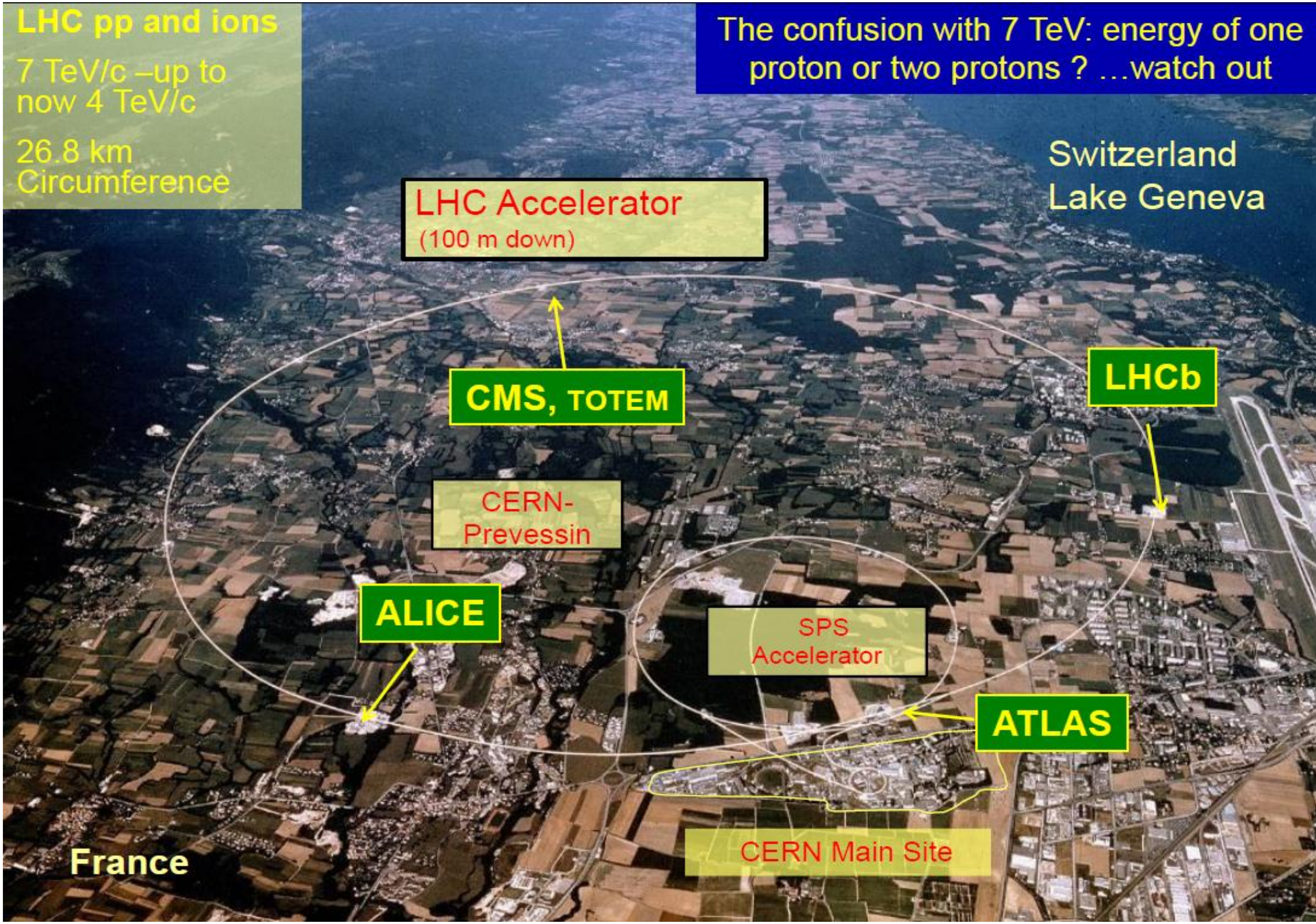
# CERN laboratory (founded in 1954)




20 krajów członkowskich (Polska od 1992)
40 krajów stowarzyszonych
2 300 zatrudnionych osób
+ 10 000 naukowców

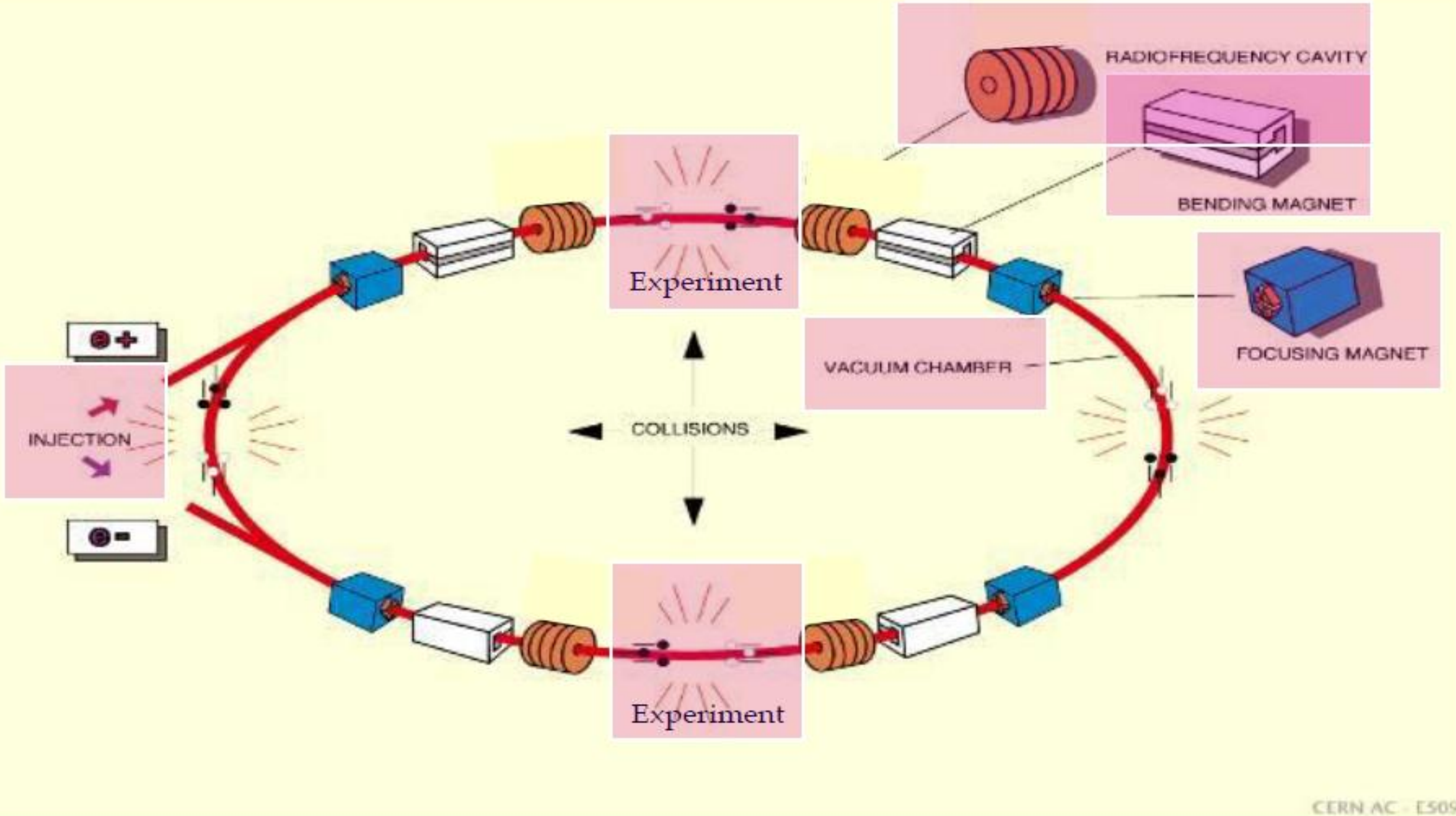
# CERN accelerator complex



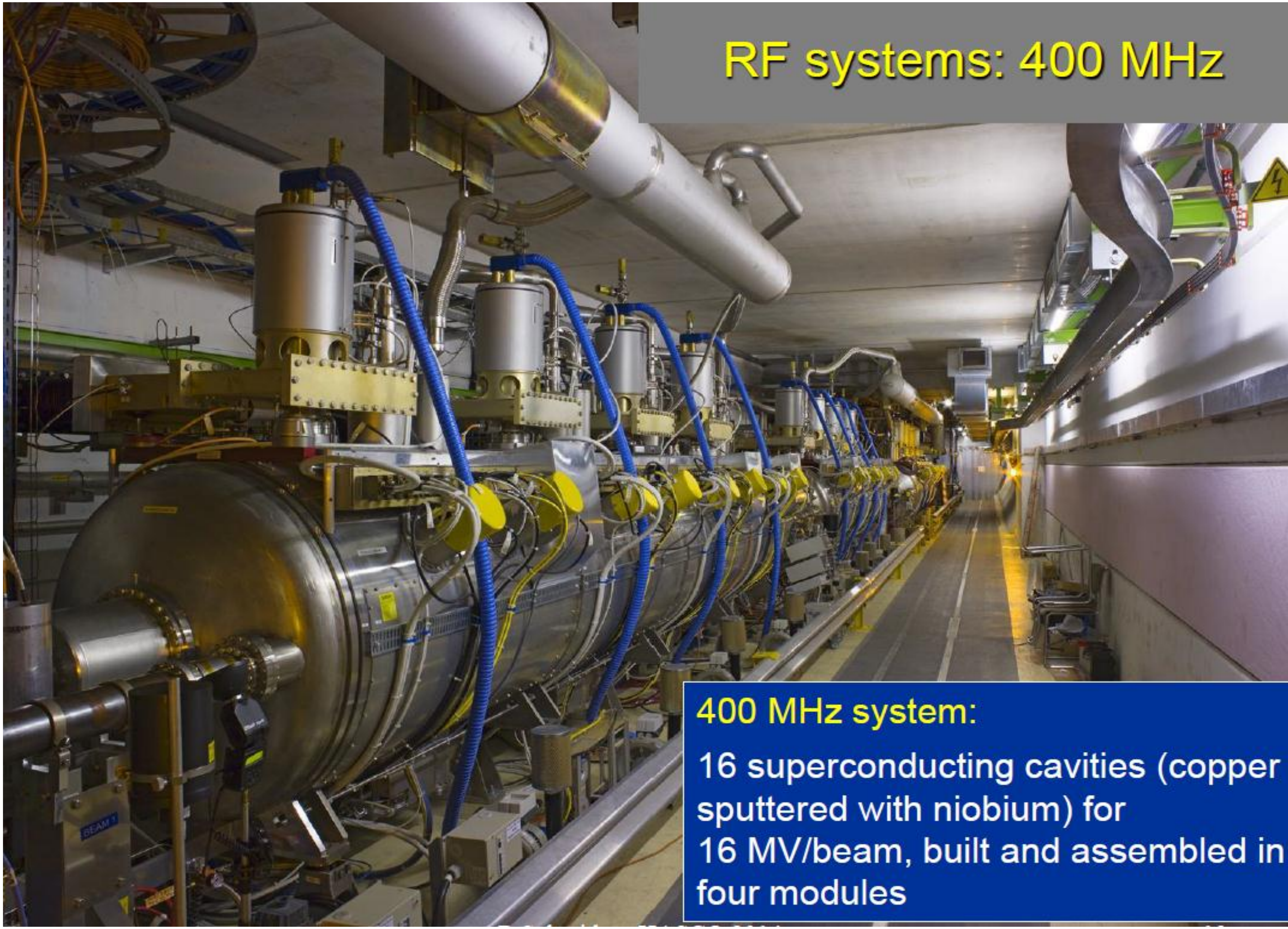

LHC pp and ions
7 TeV/c –up to now 4 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
France
CERN Main Site

# 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



# RF systems: 400 MHz



**400 MHz system:**

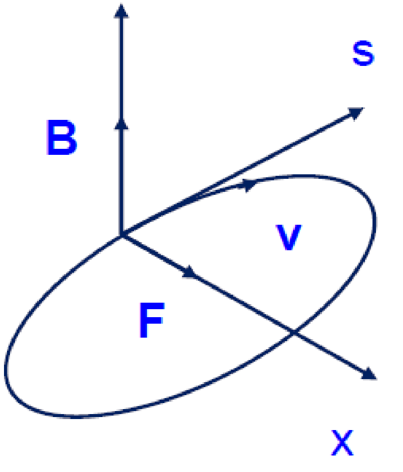
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

# 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:

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

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



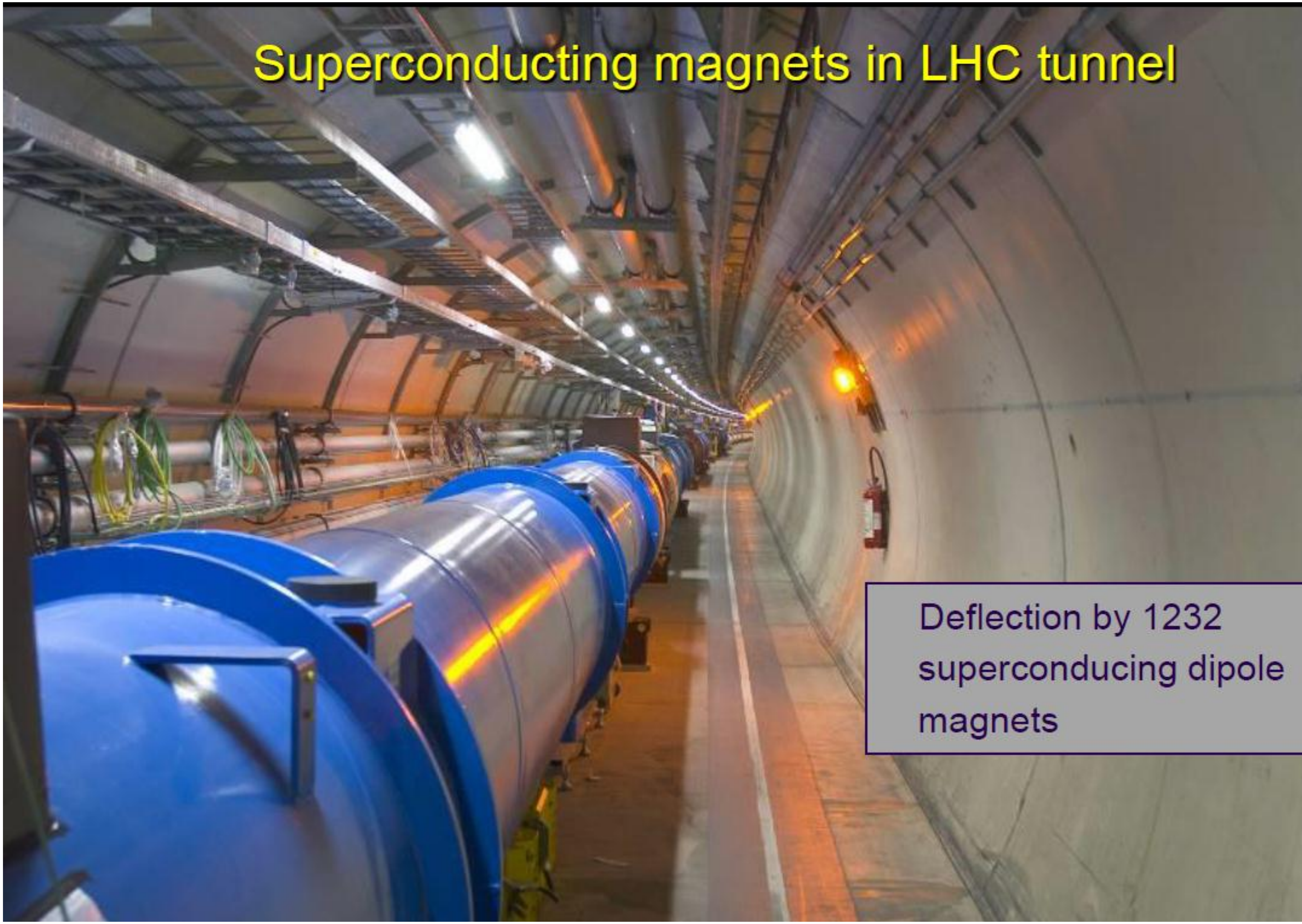

Maximum momentum 7000 GeV/c

Radius 2805 m fixed by LEP tunnel

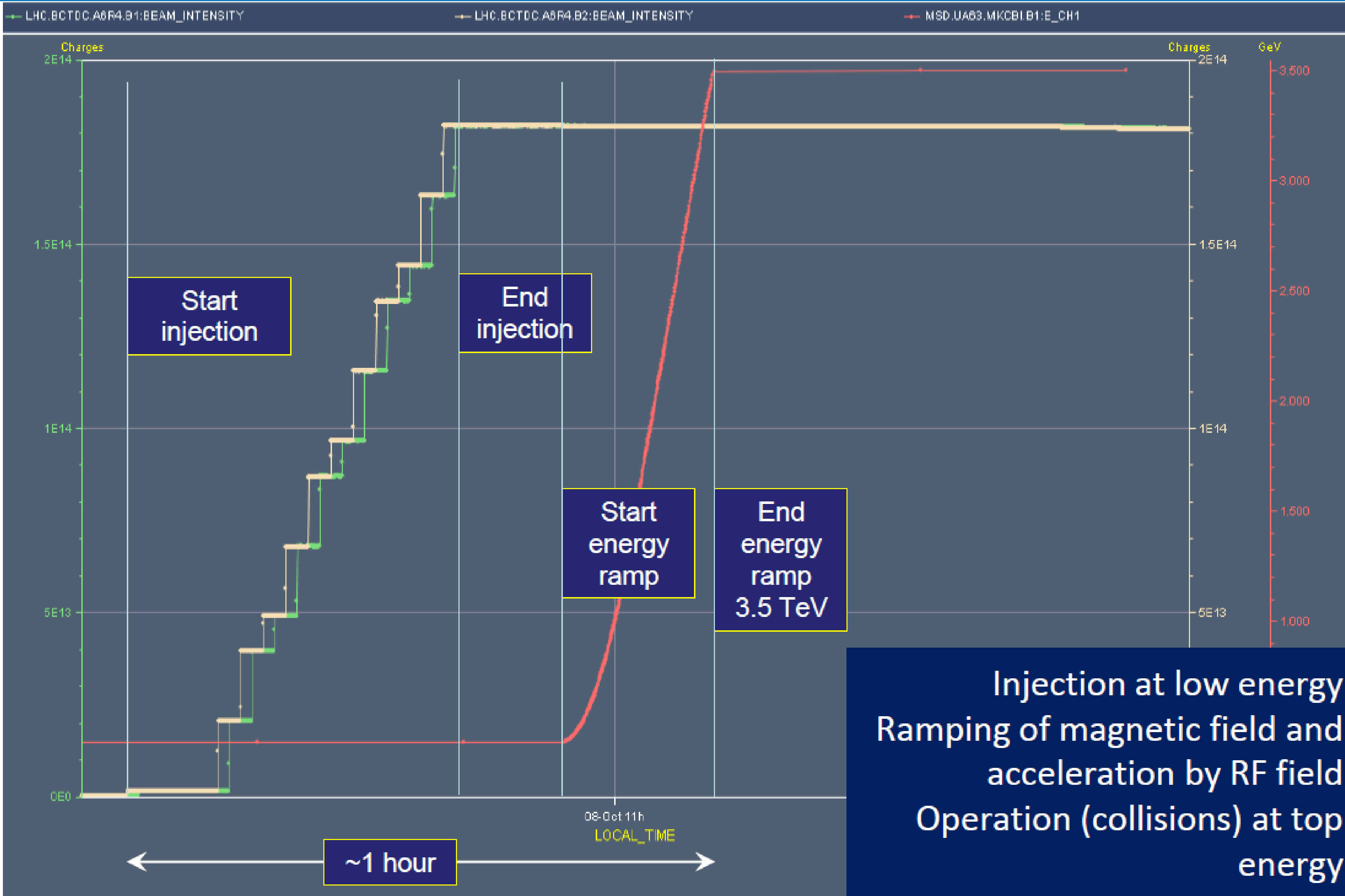
**Magnetic field B = 8.33 Tesla**

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

# Synchrotron principle: LHC fill (2011)

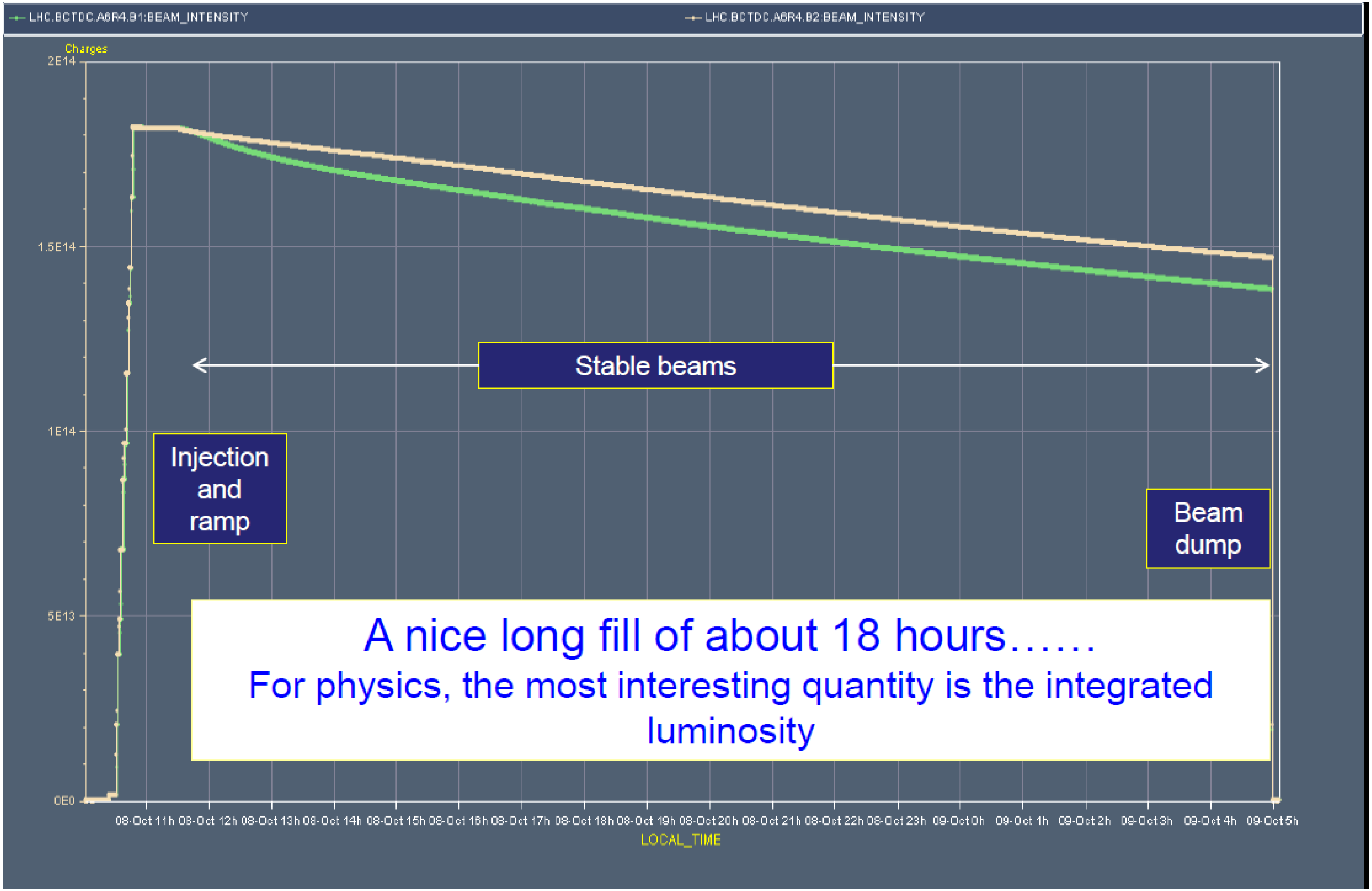



Injection at low energy

Ramping of magnetic field and acceleration by RF field

Operation (collisions) at top energy

# Excelent fill (2011)




A nice long fill of about 18 hours……

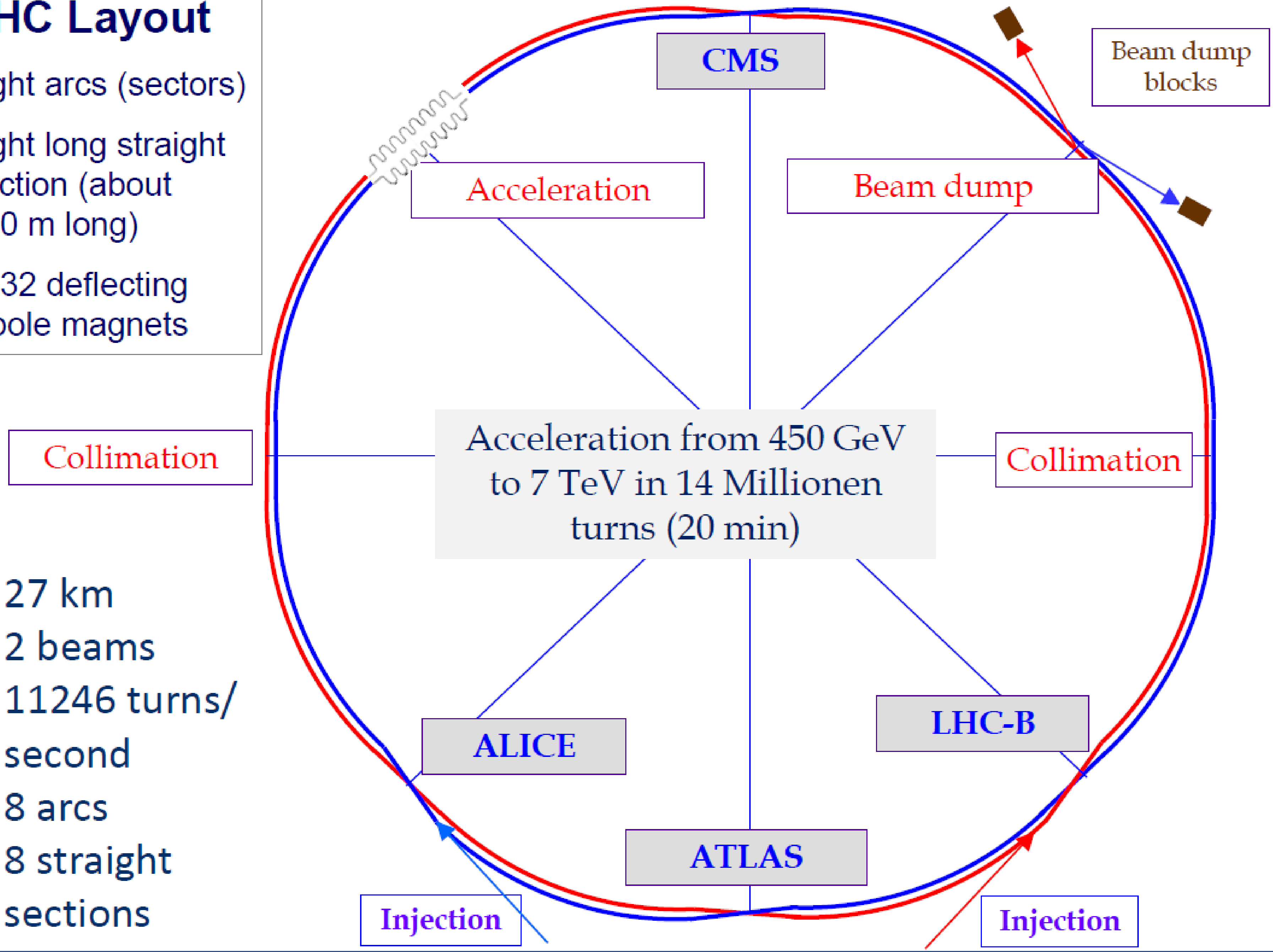
For physics, the most interesting quantity is the integrated luminosity

# LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)

1232 deflecting dipole magnets




- 27 km
- 2 beams
- 11246 turns/ second
- 8 arcs
- 8 straight sections

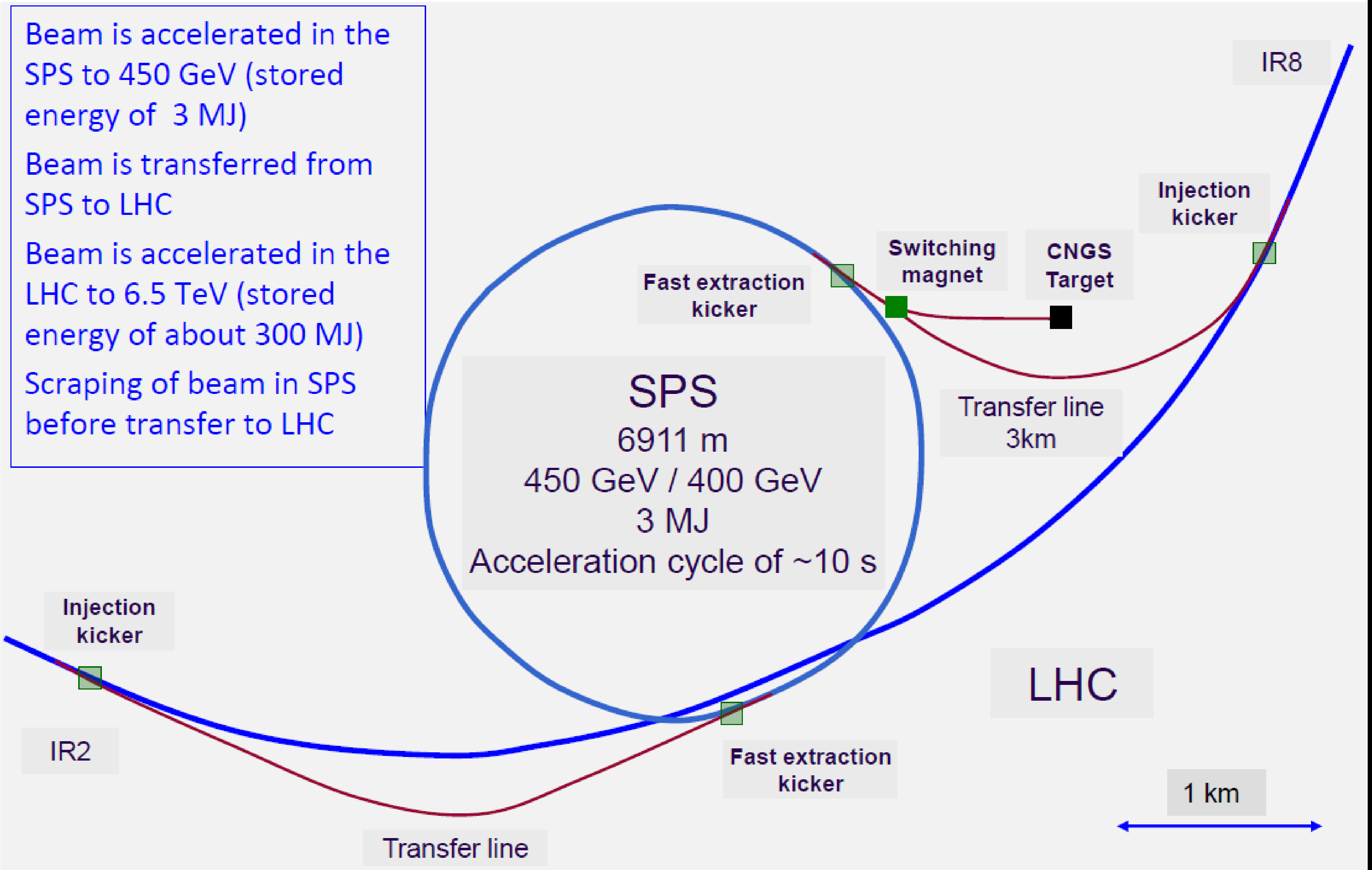
# SPS, transfer line and the LHC

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

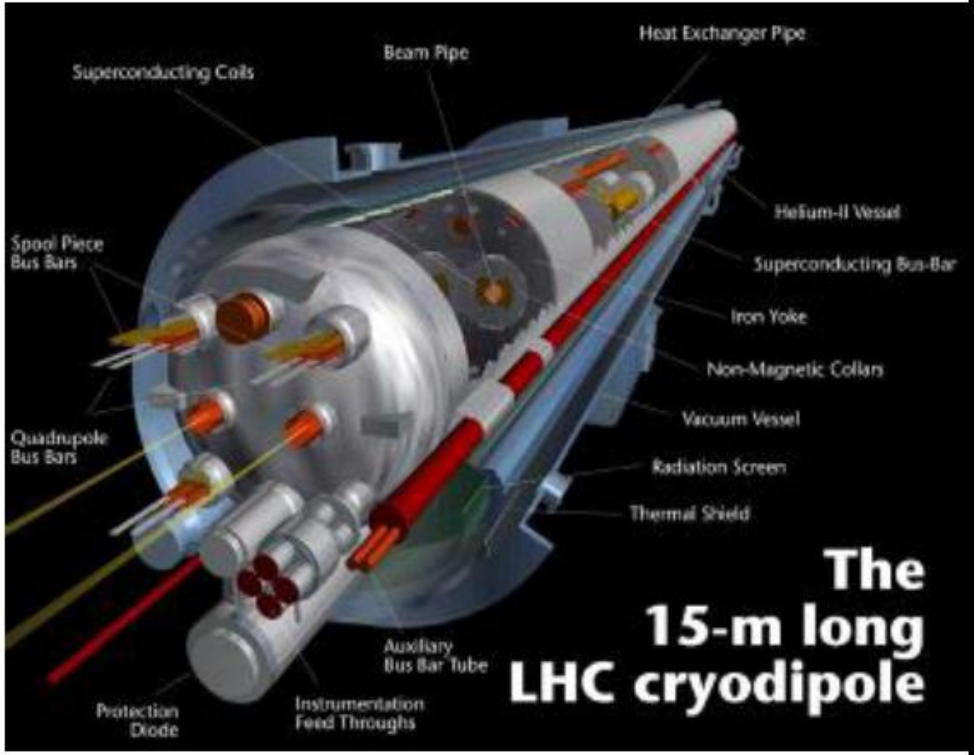


# Dipole magnets for the LHC

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)

# Colliding trains of bunches

Number of „New Particles“ per unit of time:

$$\frac{N}{\Delta T} = L\left[cm^{-2} \cdot s^{-1}\right] \cdot \sigma\left[cm^{2}\right]$$

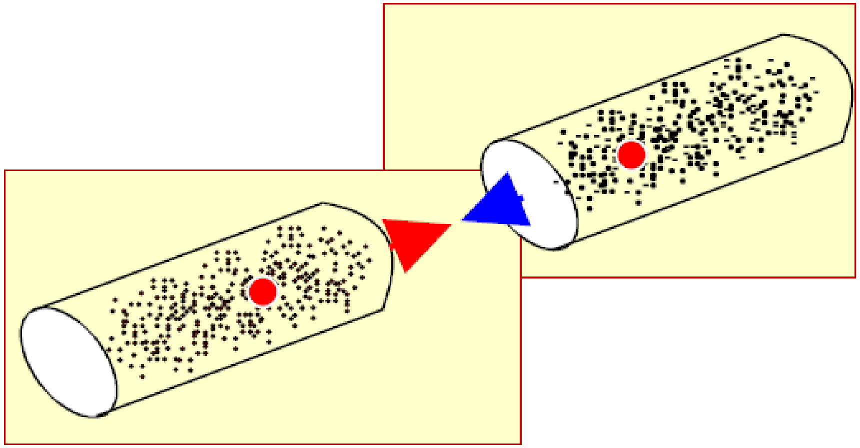
The objective for the LHC as proton – proton collider is a luminosity of about $10^{34}$ [$cm^{-2}s^{-1}$]

| | | |
|---|---|---|
| LEP (e+e-) | : | 3-4 $10^{31}$ [$cm^{-2}s^{-1}$] |
| Tevatron (p-pbar) | : | some $10^{32}$ [$cm^{-2}s^{-1}$] |
| B-Factories | : | > $10^{34}$ [$cm^{-2}s^{-1}$] |

# 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 **1-3×10¹¹** due to the beam-beam interaction and beam instabilities

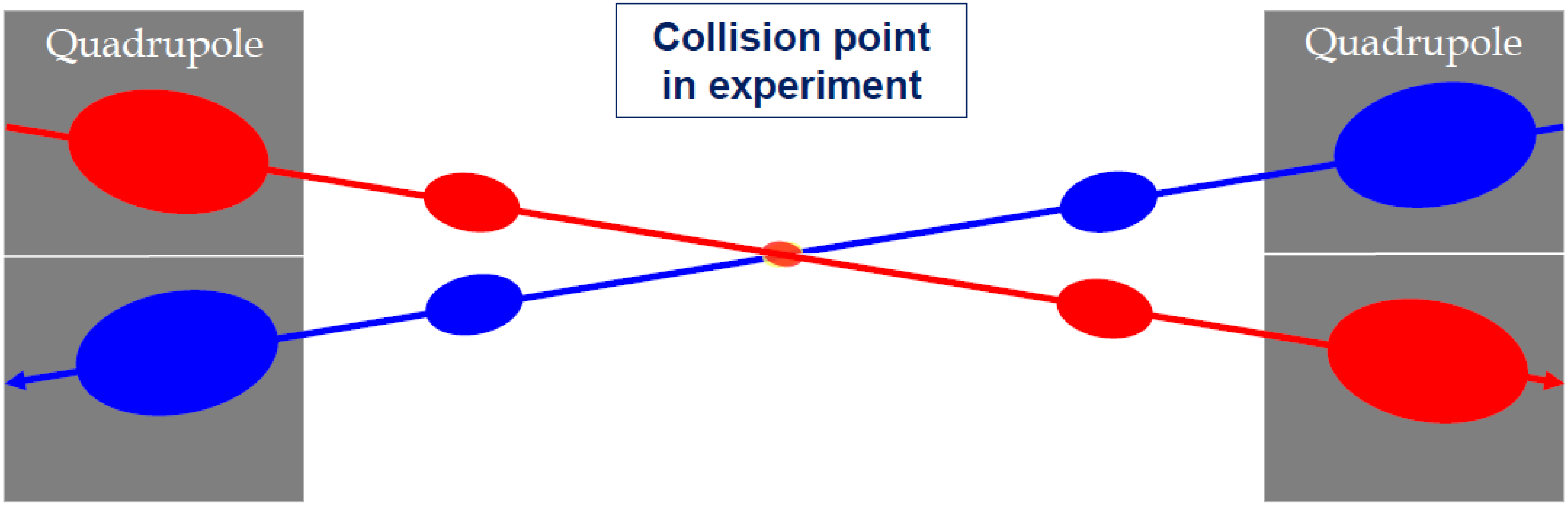
f = **11246 Hz**

Beam size given by injectors and by space in vacuum chamber

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

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

# Event pileup in LHC experiments

Assuming nominal parameters, for one bunch crossing, the number of colliding proton pairs (events) is given by:

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

**Event pile up for one bunch crossing:**

Total cross section: $\sigma_{tot} := 100\text{mBarn}$

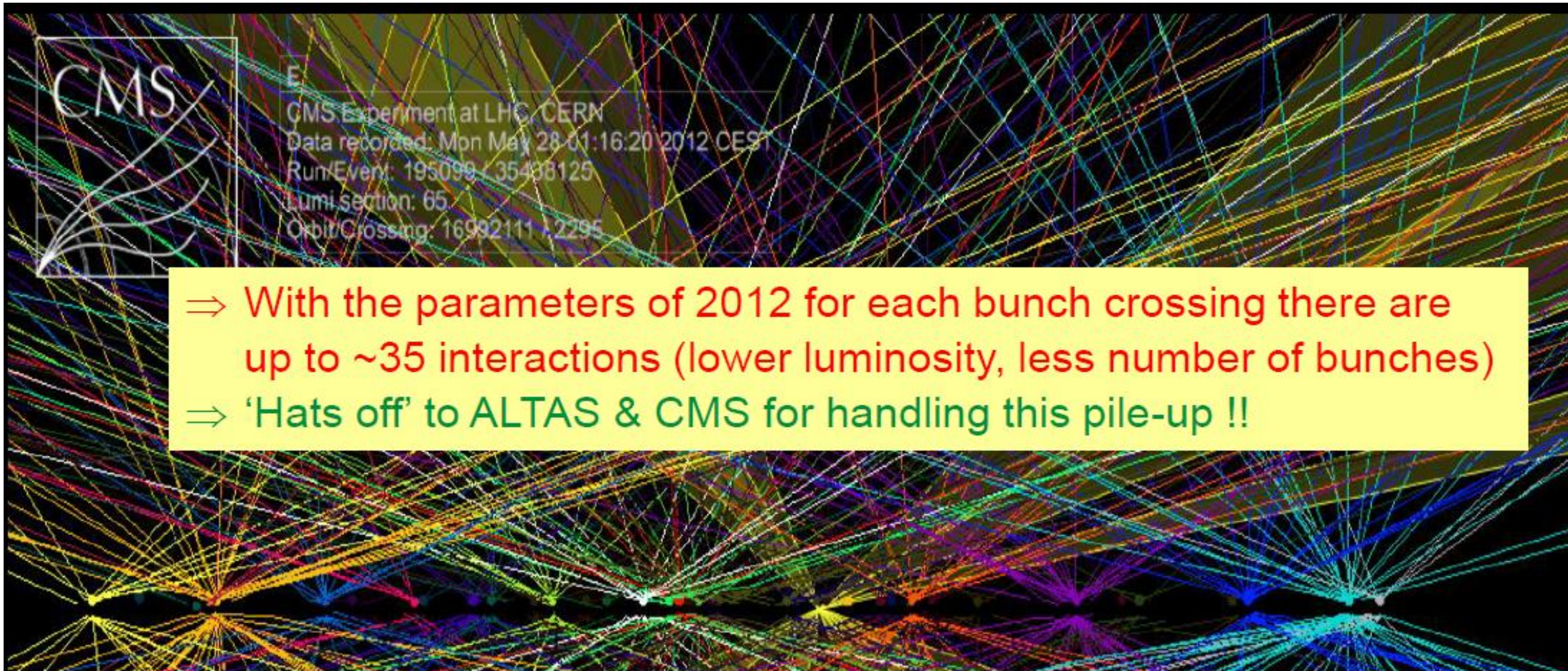
$\sigma_{tot} = 1 \times 10^{-25}\,\text{cm}^2$

Luminosity: $L = 1 \times 10^{34}\,\text{s}^{-1}\,\text{cm}^{-2}$

Number of events per second $L \cdot \sigma_{tot} = 1 \times 10^{9}\,\frac{1}{\text{s}}$

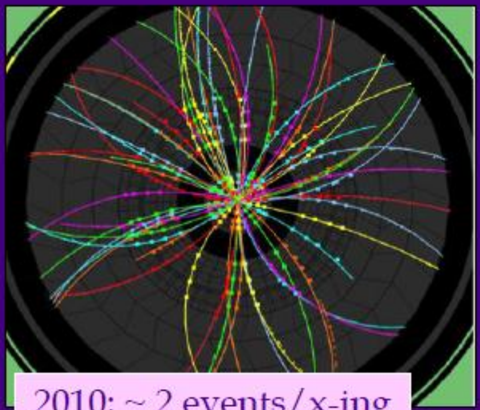
$frev_{lhc} = 1.1246 \times 10^{4}\,\frac{1}{\text{s}}$ and $N_{bunches\_1beam} = 2808$

Number of events per bunch crossing: $L \cdot \frac{\sigma_{tot}}{frev_{lhc} \cdot N_{bunches\_1beam}} = 31.7$




⇒ 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 !!

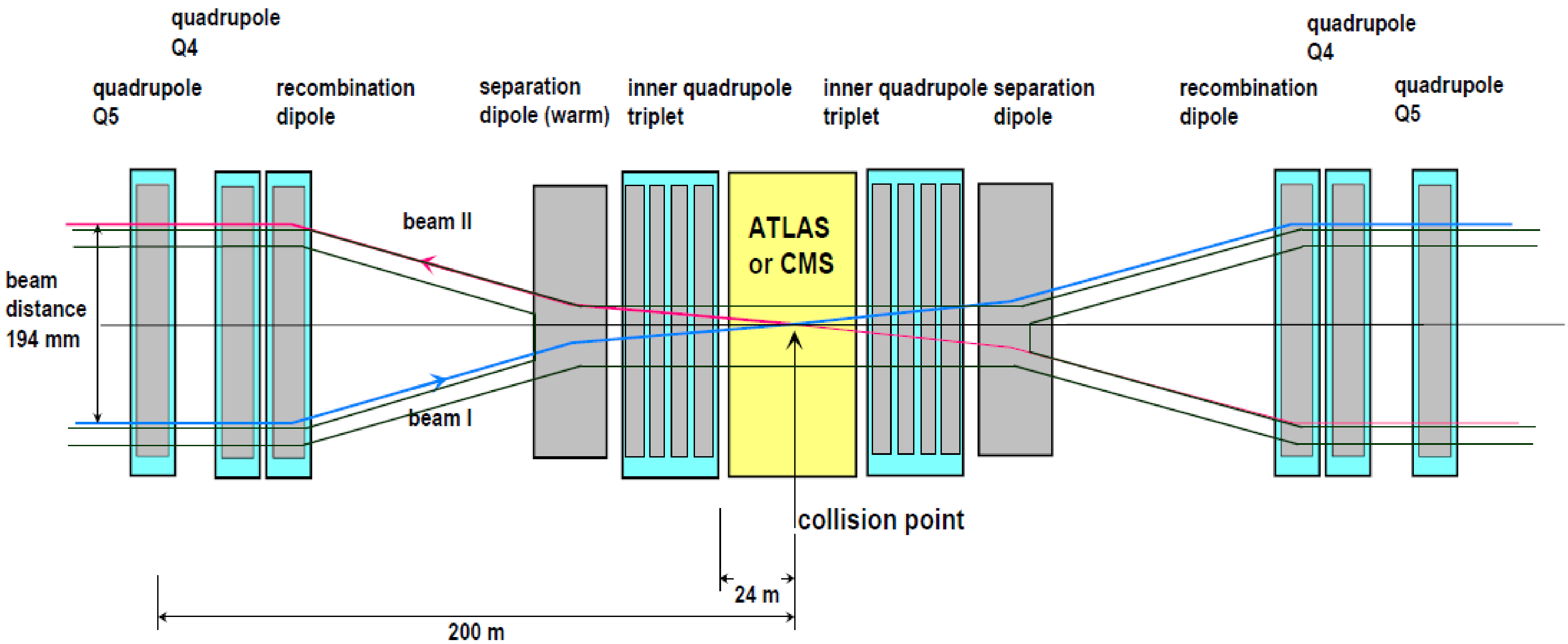


2010: ~ 2 events/x-ing

2011: ~ 10 events/x-ing

2012: ~ 20 events/x-ing

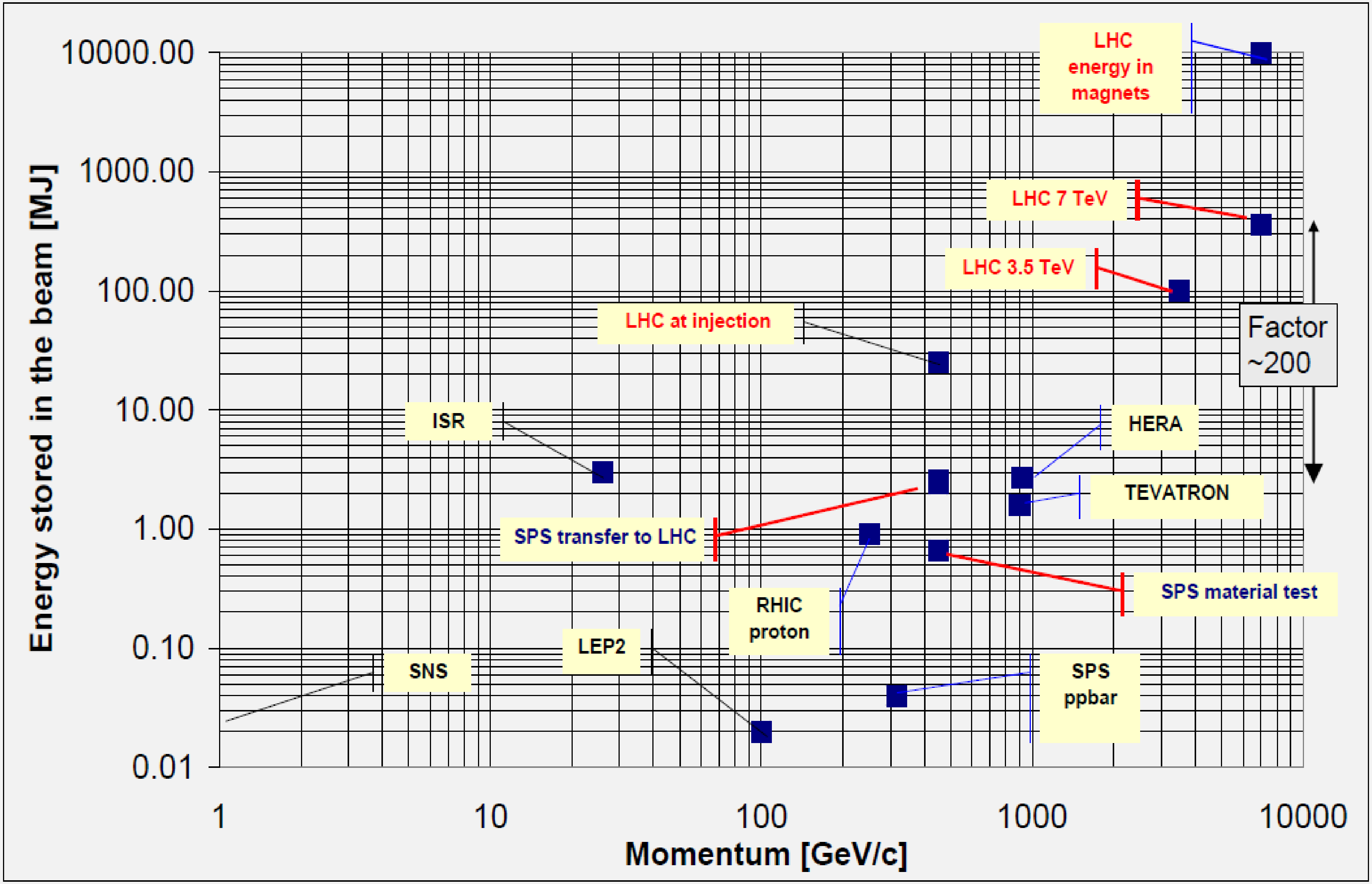
# Experimental long straight section




**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?

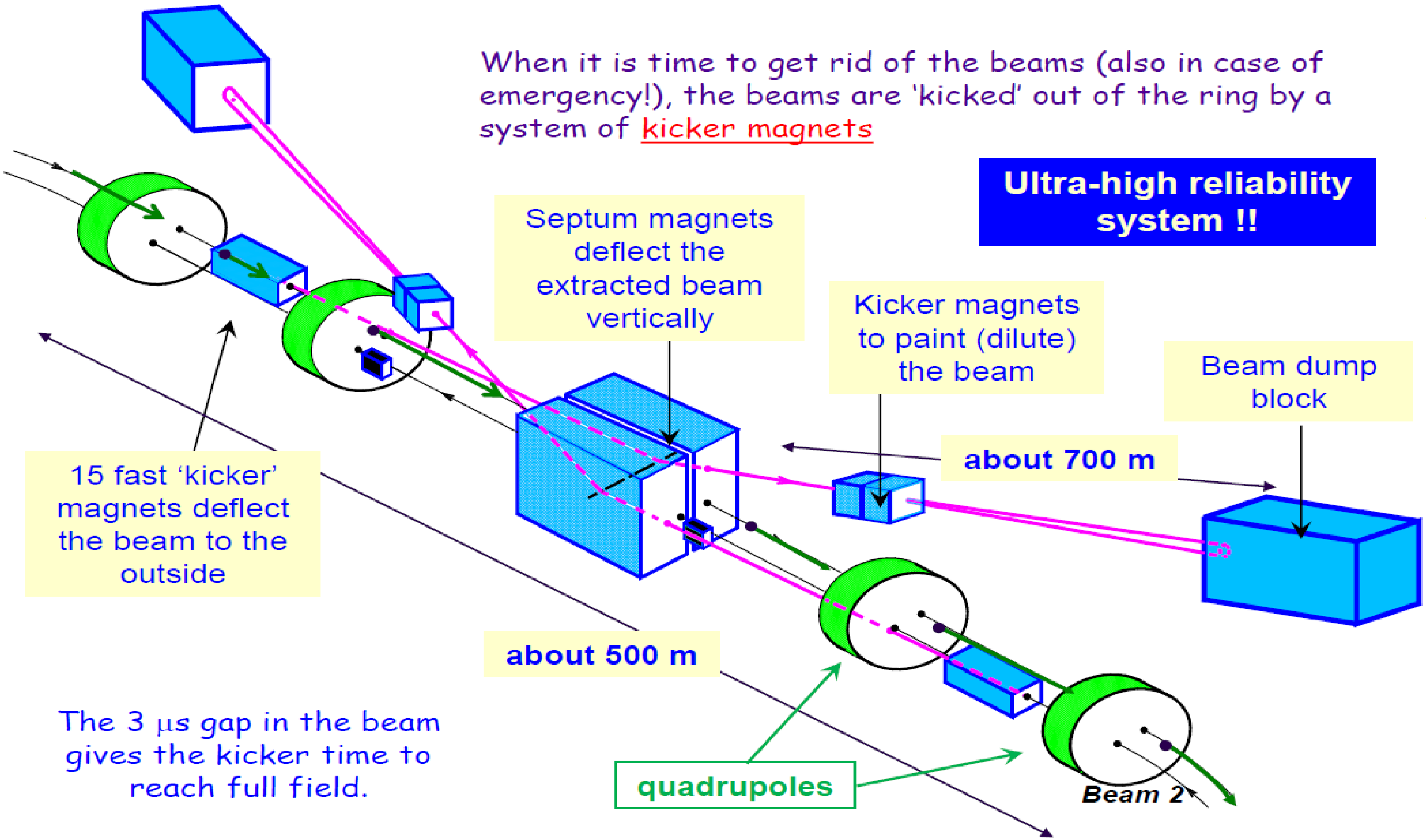
The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

**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

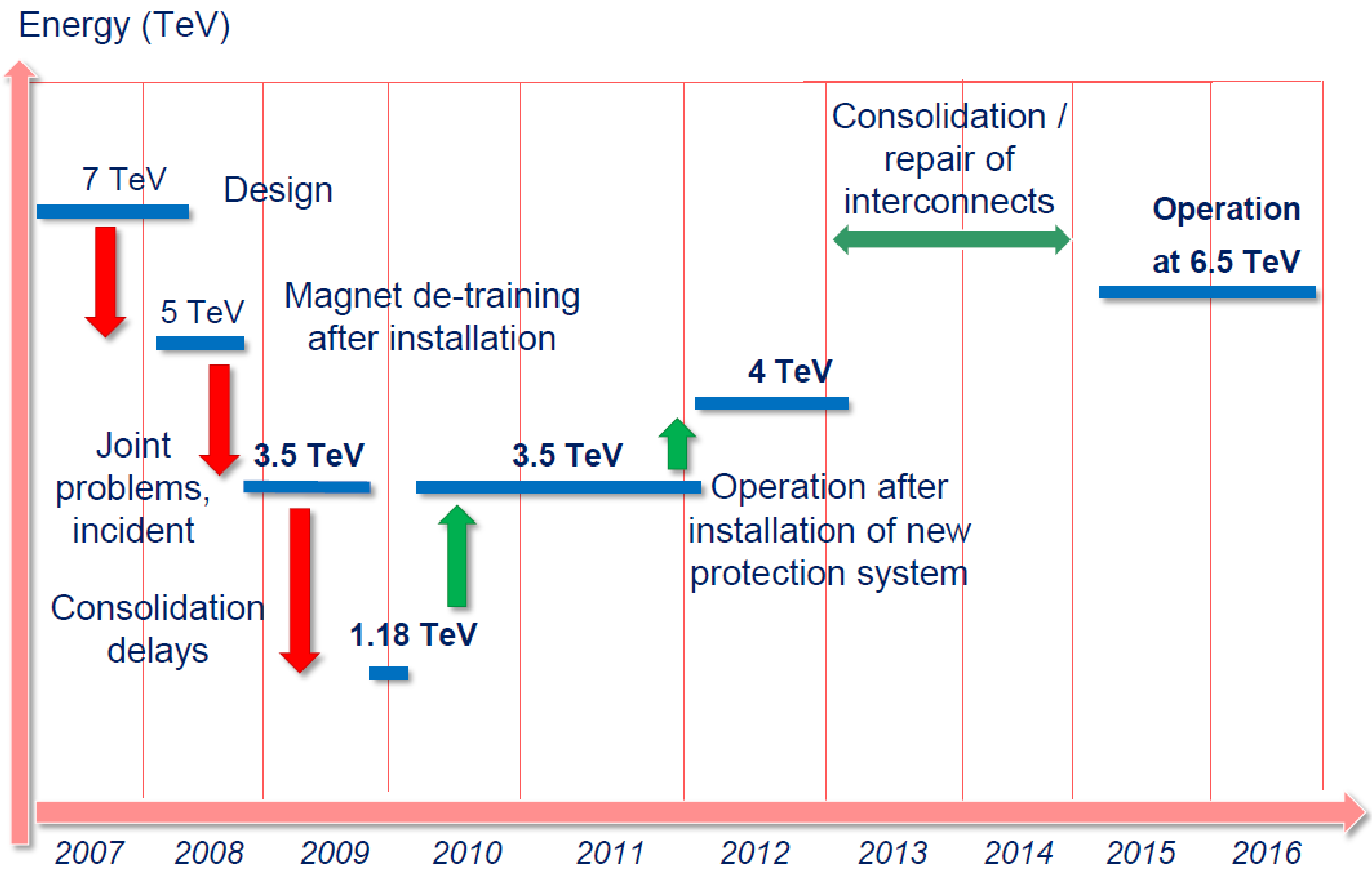


# Dump line

# Beam Loss Monitors

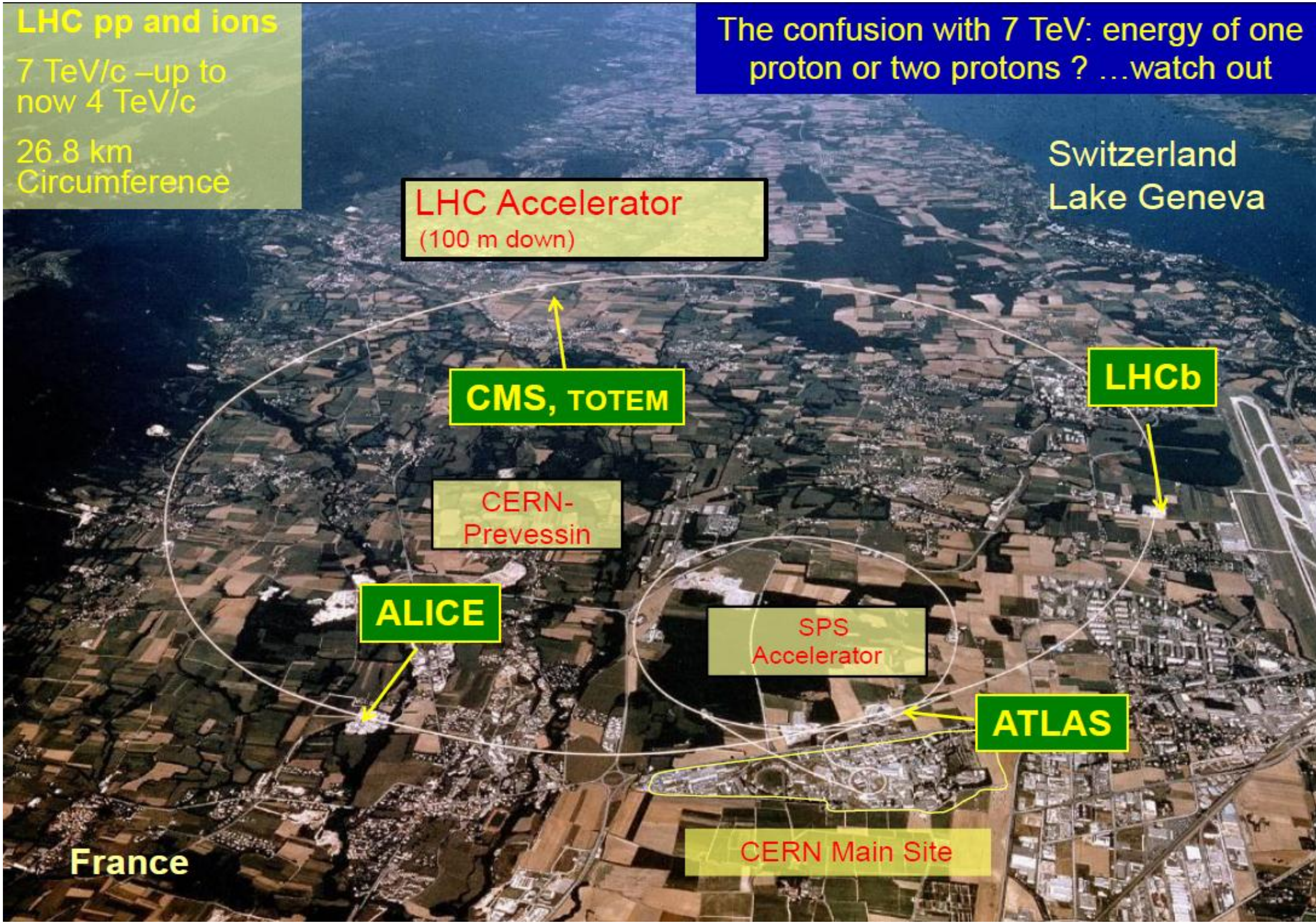
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 $\mu$s)
  - Very large dynamic range (> $10^6$)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

# LHC energy evolution

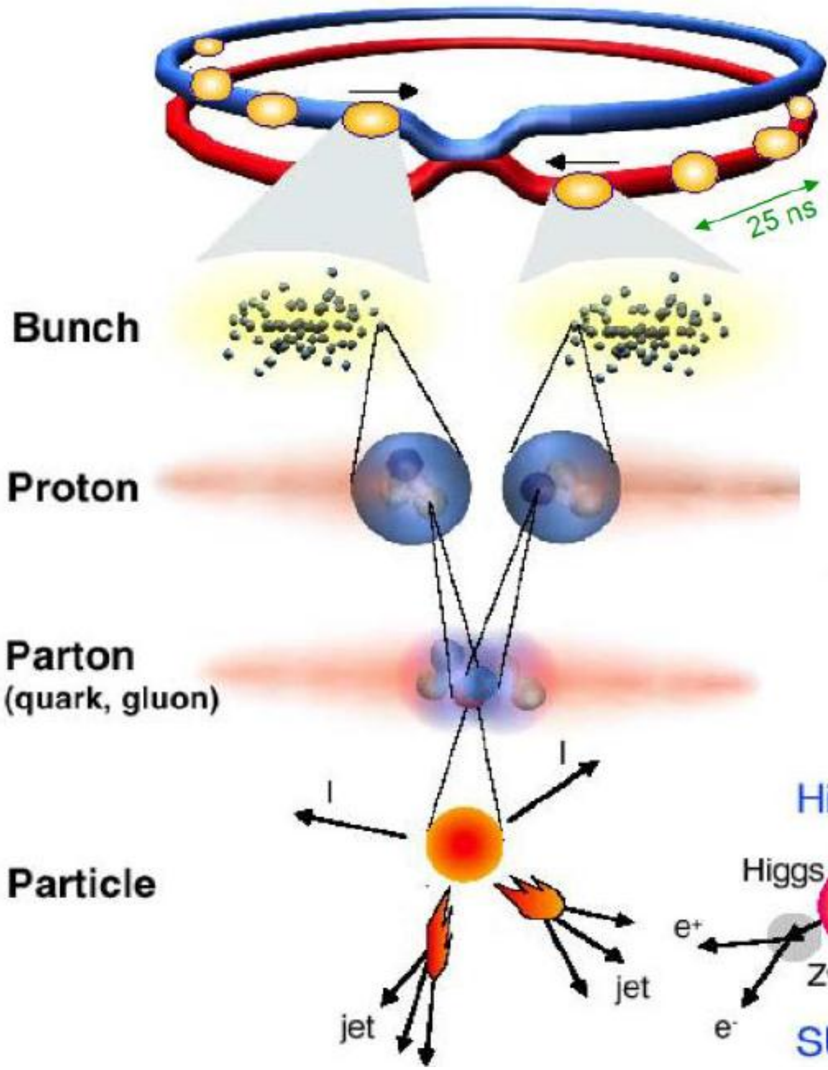


# The LHC: just another collider?

| | 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+<br>p – e- | 920 | 6300 | 5.5 | 5.1 $10^{31}$ | 2.7 for protons |
| RHIC Brookhaven Long Island | 2000 | Ion-Ion<br>p-p | 250 | 3834 | 4.3 | 1.5 $10^{32}$ | 0.9 per proton beam |
| LHC CERN | 2008 | Ion-Ion<br>p-p | 7000<br>Now 4000 | 26800 | 8.3 | $10^{34}$<br>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

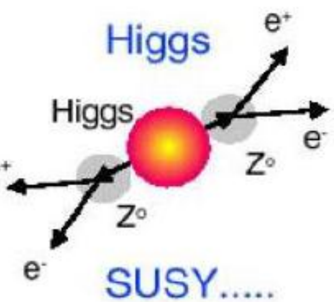



| | |
|---|---|
| Proton-Proton | 2835 bunch/beam |
| Protons/bunch | $10^{11}$ |
| Beam energy | 7 TeV ($7\times10^{12}$ eV) |
| Luminosity | $10^{34}$ $cm^{-2}$ $s^{-1}$ |

In the experiments:

$10^9$ pp interactions per second

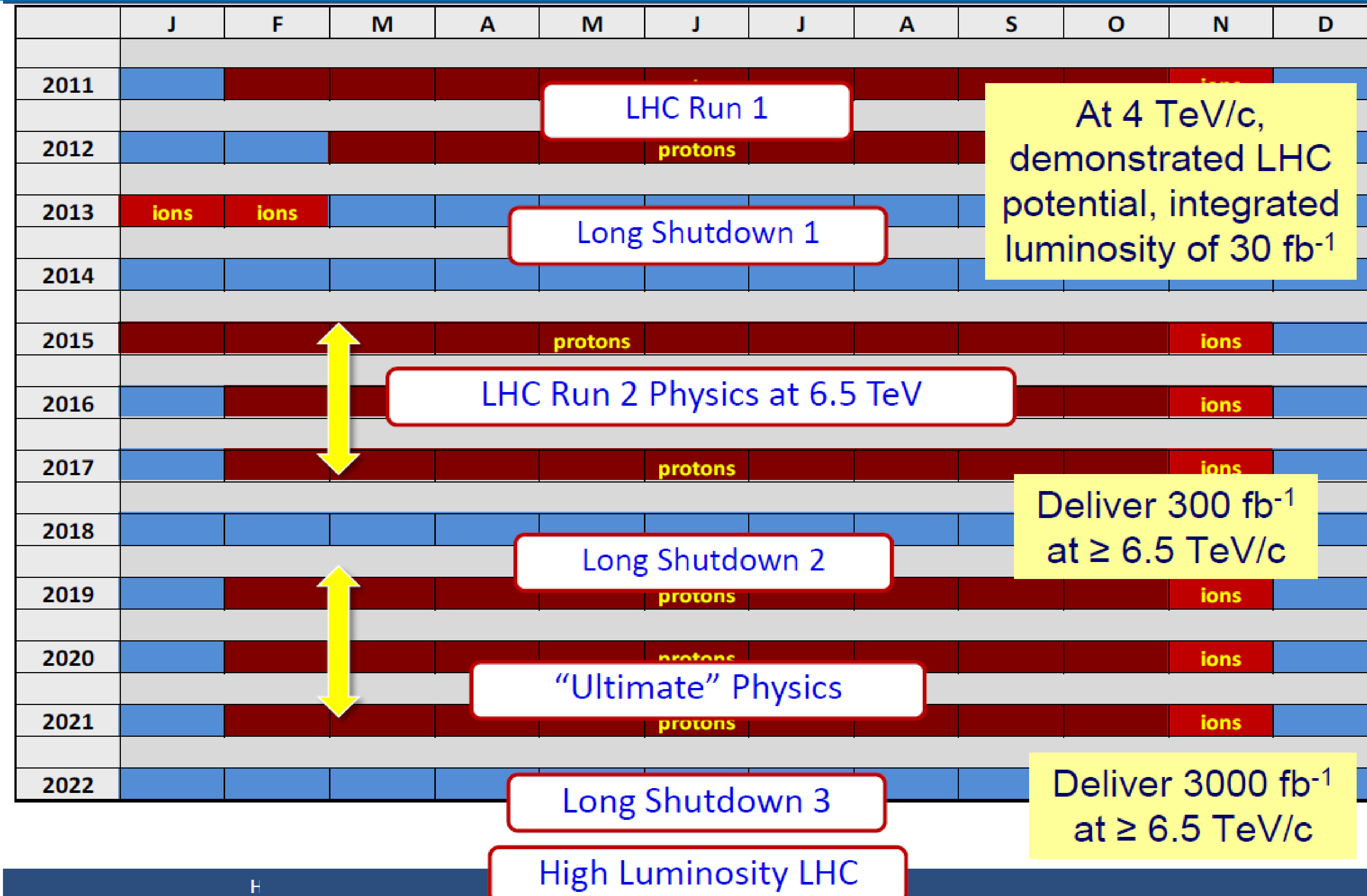
~ 1500 particles (p,n, $\pi$) produced in the detectors at each bunch-crossing




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

$E = m c^2$

# The next years



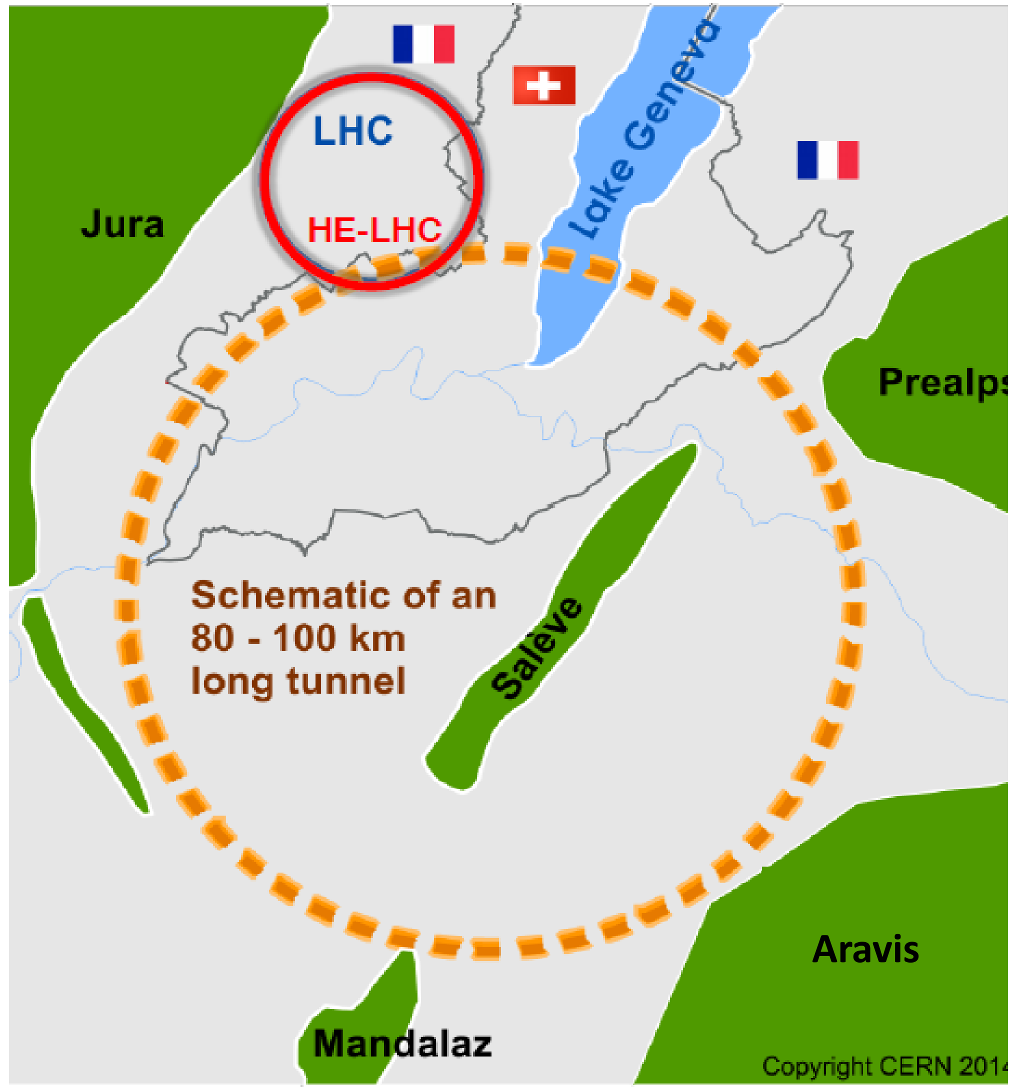
# Future plans

**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
- **HE-LHC** w *FCC-hh* technology



# SPARES

# Aside: units

| Our scale | |
|---|---|
| Length | m |
| Mass | kg |
| Time | s |
| Energy | kg $m^2$ $s^{-2}$ |

| Particle Physics | |
|---|---|
| Length | fm |
| Mass | $eV/c^2$ |
| Time | s |
| Energy | eV |

| Convert |
|---|
| 1 eV = $1.6 \times 10^{-19}$ J |
| 1 GeV = $10^9$ eV |
| 1 TeV = $10^3$ GeV |
| 1 fm = $10^{-15}$ m |

Note: often set $\hbar = c = 1$