

Introduction to particle physics: experimental part

Few words about Standard Model

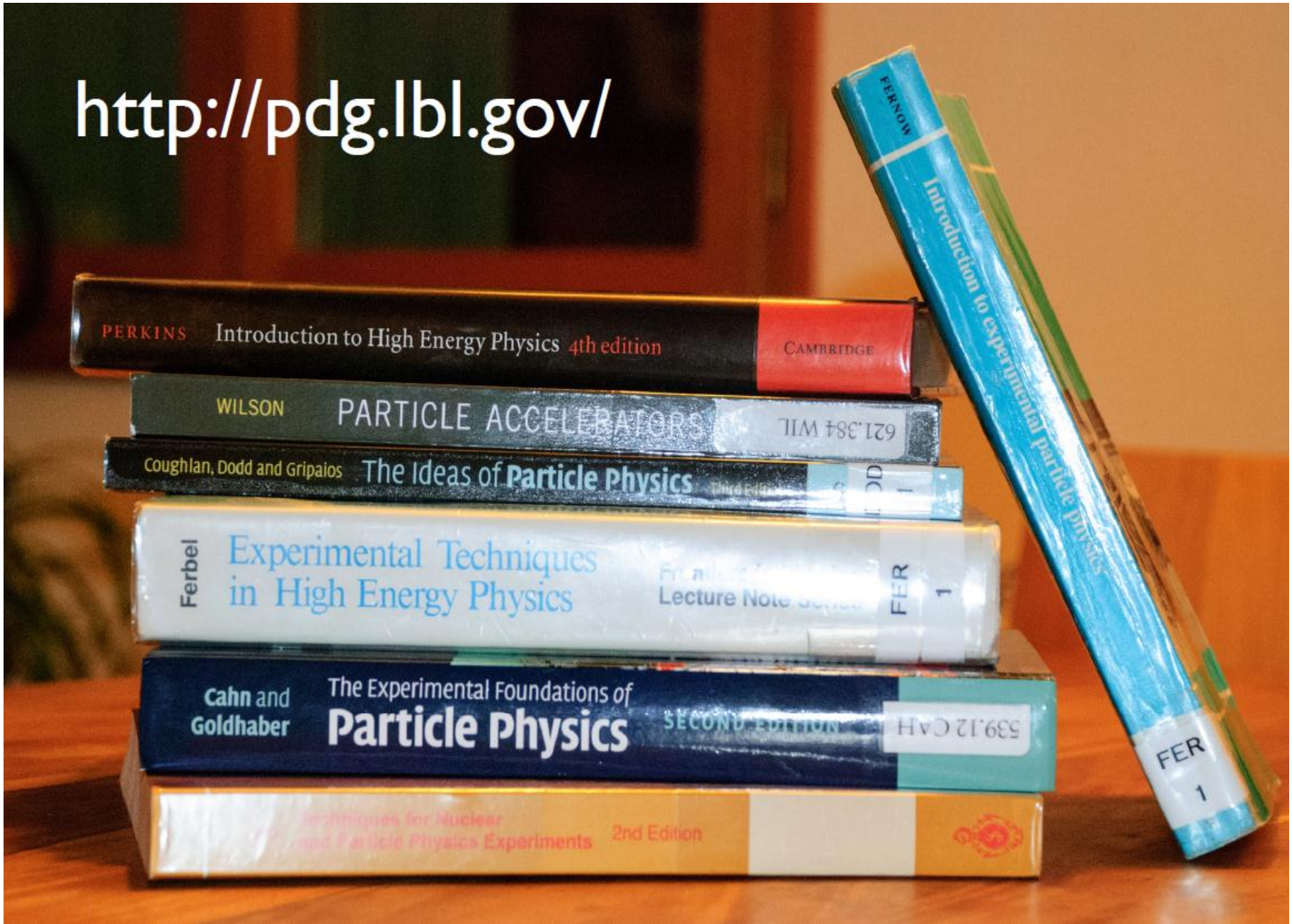
Accelerators

CERN and LHC

Credits:

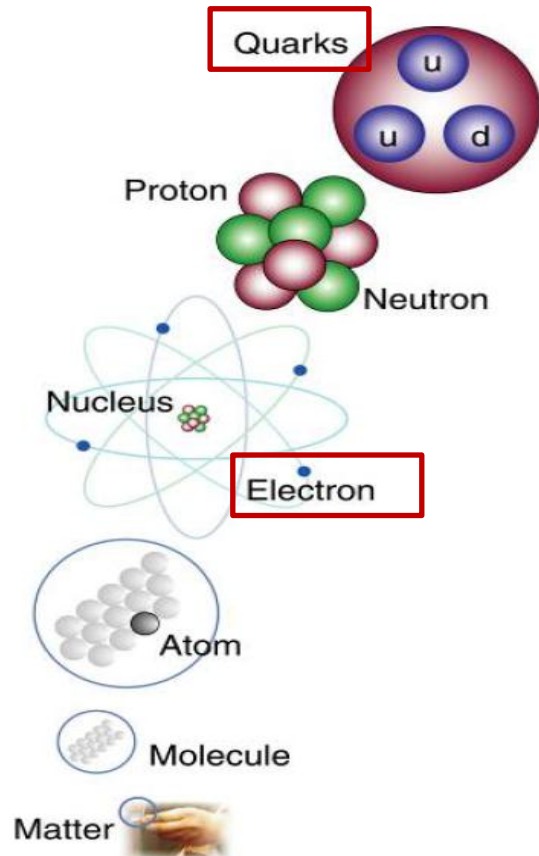
a lot of material in this lecture are from lectures by R.Schmidth at HASCO2017 school.

<http://pdg.lbl.gov/>



Particles of the Standard Model

Quantum mechanics



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

Interaction particles

| | | | | |
|-------------------------------------------------------------|-------------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------|--------------------|
| 2.1M $\frac{2}{3}$ u up $\frac{1}{2}$ | 1.27G $\frac{2}{3}$ c charm $\frac{1}{2}$ | 171.2G $\frac{2}{3}$ t top $\frac{1}{2}$ | strong nuclear force (color charge) | |
| 4.8M $-\frac{1}{3}$ d down $\frac{1}{2}$ | 104M $-\frac{1}{3}$ s strange $\frac{1}{2}$ | 4.2G $-\frac{1}{3}$ b bottom $\frac{1}{2}$ | | gluon 1 |
| 0.511M -1 e electron $\frac{1}{2}$ | 105.7M -1 μ muon $\frac{1}{2}$ | 1.777G -1 τ tau $\frac{1}{2}$ | photon 1 | |
| < 2.2 0 ν_e e-neutrino $\frac{1}{2}$ | $< 0.17M$ 0 ν_μ μ -neutrino $\frac{1}{2}$ | $< 15.5M$ 0 ν_t t-neutrino $\frac{1}{2}$ | | weak nuclear force |
| | | | W ⁺ 1 | |



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

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

2012: „Higgs particle”
was discovered

2015 - T. Kajita and A. B. McDonald



Carlo Rubbia



Simon van der Meer



Georges Charpak



Gerardus 't Hooft



Martinus J.G. Veltman



M. Gell-Mann

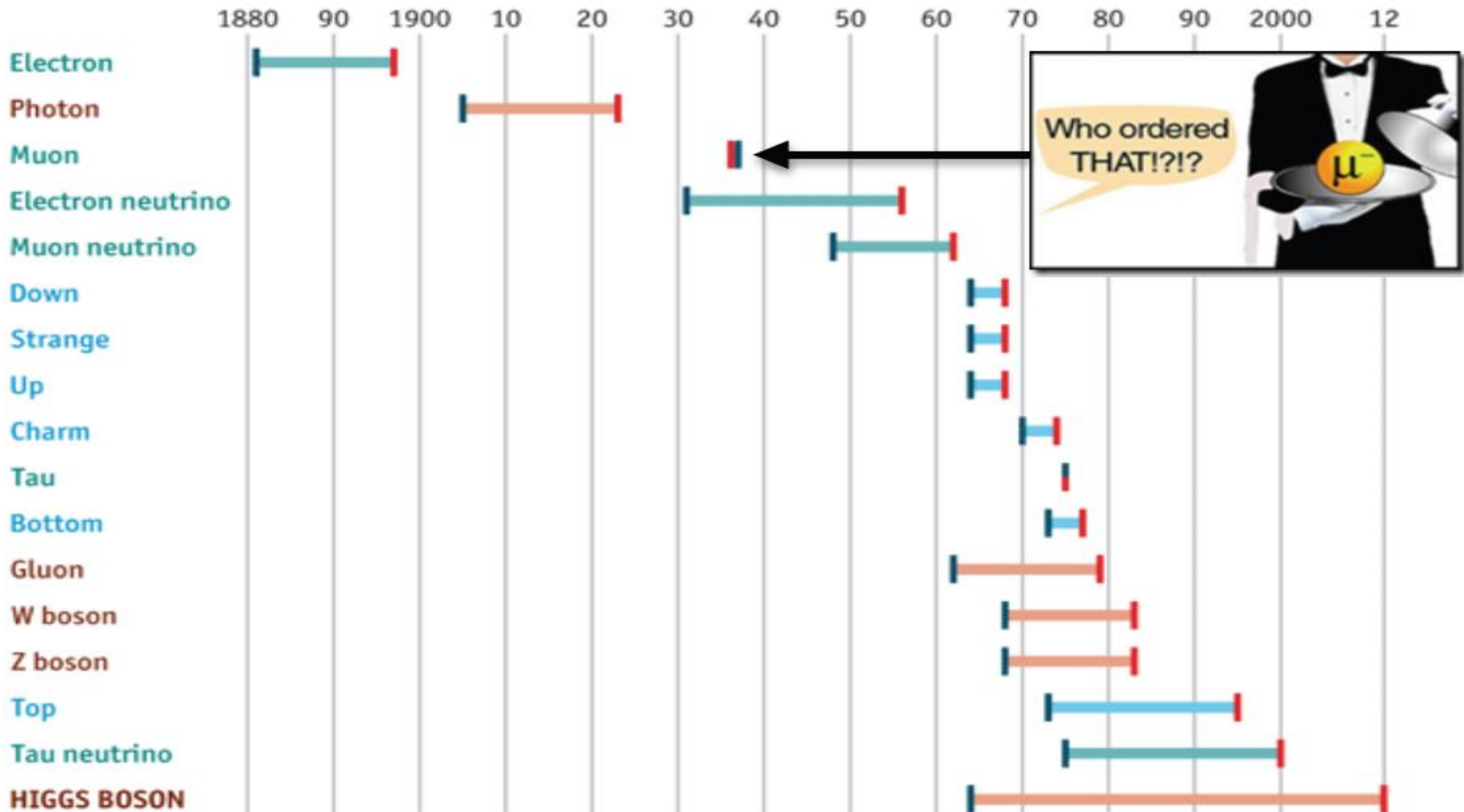
Uncharted discoveries?

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

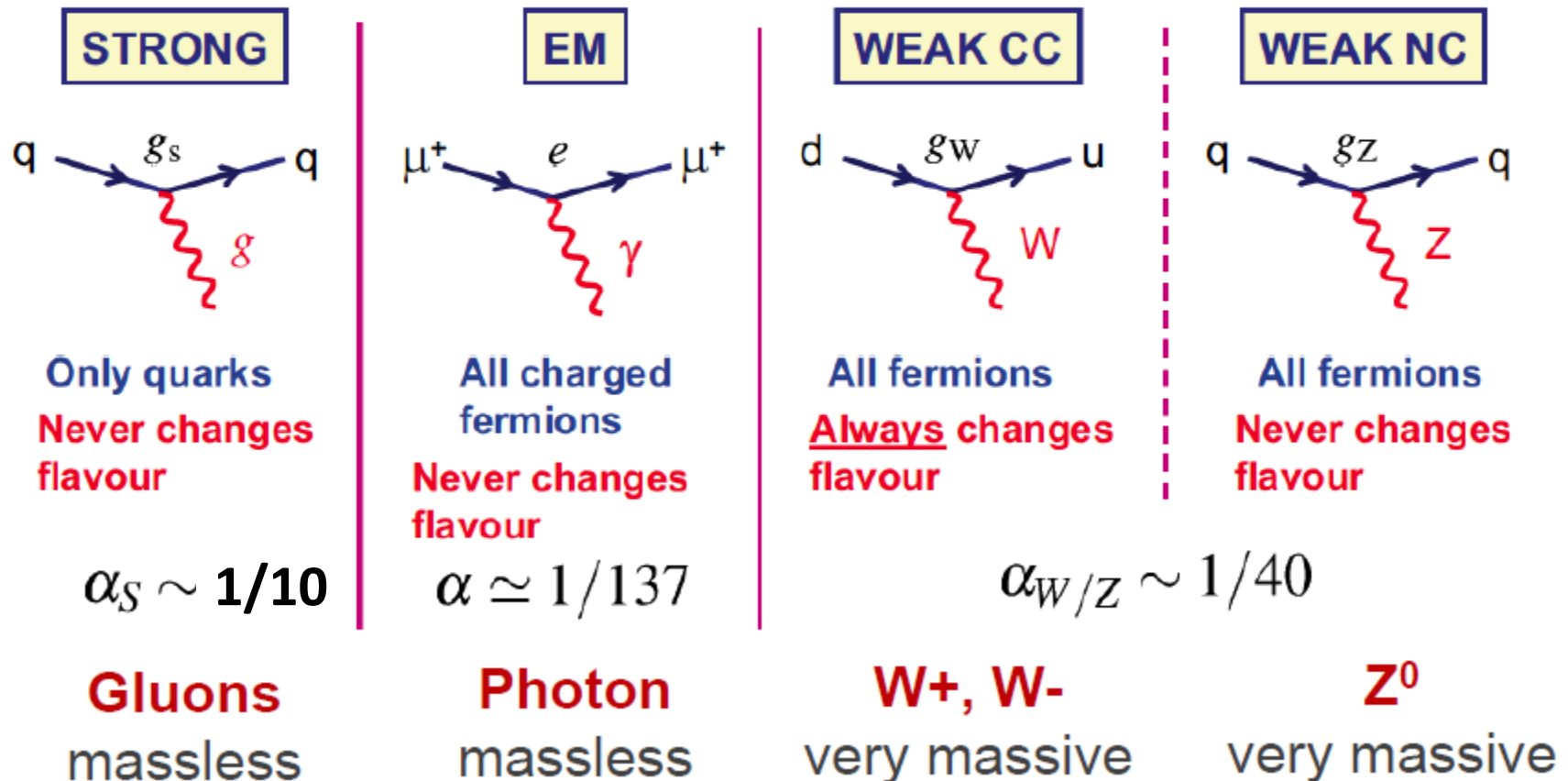
Theorised/explained
Discovered



Source: *The Economist*

Interactions

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



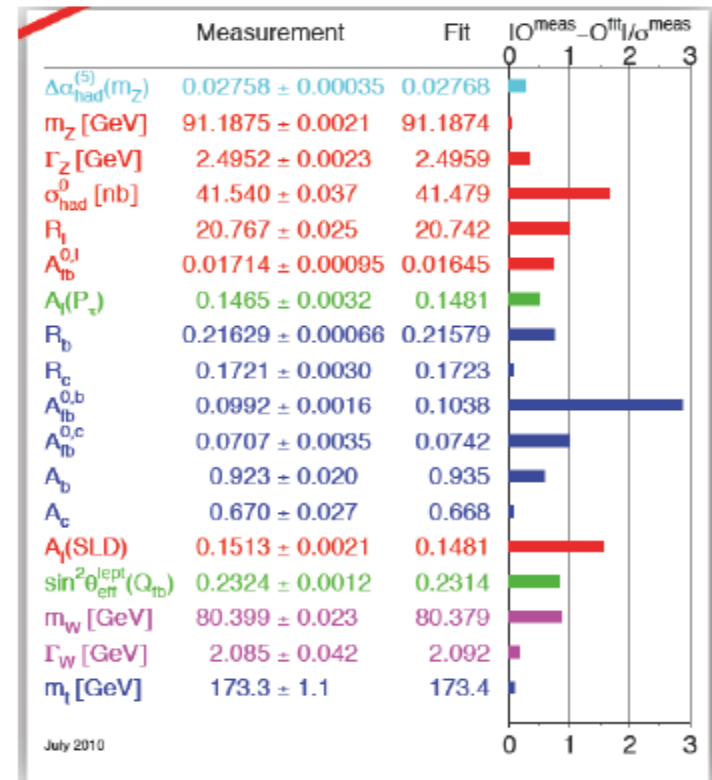
Standard Model confirmed by the data

| | I | II | III | |
|-------------------------------------------|---------------------------------------|--------------------------------------|---------------------------------|---------------------------------|
| mass → | 2.4 MeV/c ² | 1.27 GeV/c ² | 171.2 GeV/c ² | 0 |
| charge → | 2/3 | 2/3 | 2/3 | 0 |
| spin → | 1/2 | 1/2 | 1/2 | 1 |
| name → | u up | c charm | t top | γ photon |
| Quarks | 4.8 MeV/c ² | 104 MeV/c ² | 4.2 GeV/c ² | 0 |
| | -1/3 | -1/3 | -1/3 | 0 |
| | 1/2 | 1/2 | 1/2 | 1 |
| | d down | s strange | b bottom | g gluon |
| <2.2 eV/c ² | <0.17 MeV/c ² | <15.5 MeV/c ² | 91.2 GeV/c ² | |
| 0 | 0 | 0 | 0 | |
| 1/2 | 1/2 | 1/2 | 1 | |
| ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | Z⁰ Z boson | |
| Leptons | 0.511 MeV/c ² | 105.7 MeV/c ² | 1.777 GeV/c ² | 80.4 GeV/c ² |
| | -1 | -1 | -1 | ±1 |
| | 1/2 | 1/2 | 1/2 | 1 |
| | e electron | μ muon | τ tau | W[±] W boson |

Gauge bosons

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

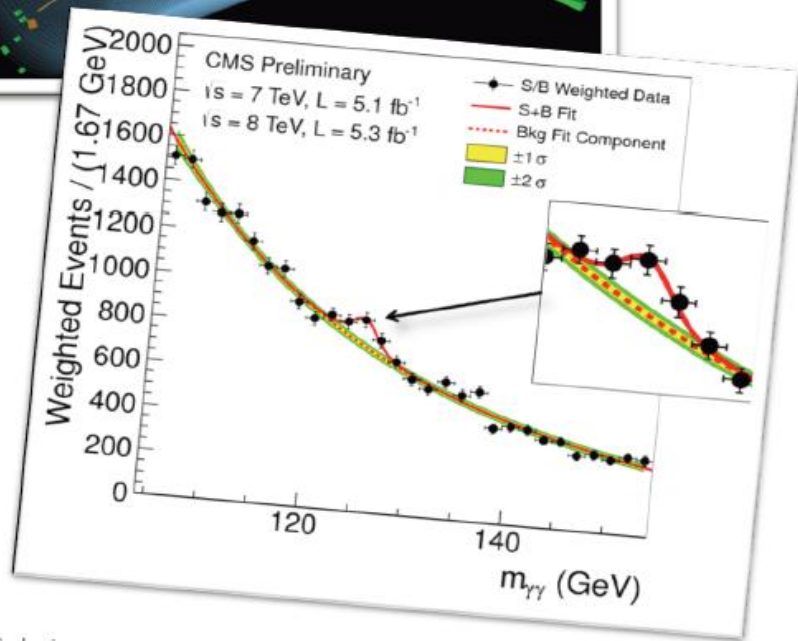
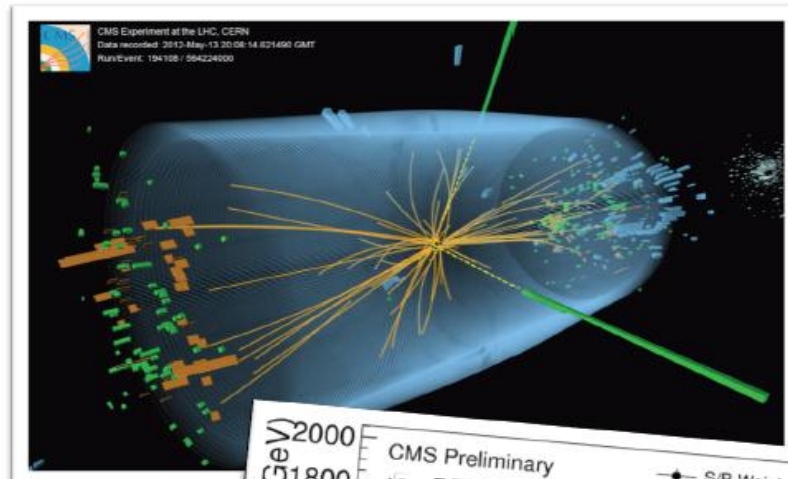
STANDARD MODEL OF ELEMENTARY PARTICLES



Confirmed at sub 1% level!

Experiment = probing theories with data

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^\nu \partial_\rho g_\mu^\rho - g_s f^{abc} \partial_\mu g_\rho^a g_\nu^b g_\mu^c - \frac{1}{2}g_s^2 f^{abc} f^{ade} g_\mu^a g_\nu^b g_\rho^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}g_1^2 (\partial_\mu^\nu \gamma^\mu \gamma^\nu) g_\mu^\rho + G^a \partial^\mu G^a + g_2 f^{abc} \partial_\mu G^a G^b G^c - \partial_\mu W_\nu^+ \partial_\mu W_\nu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2}M^2 \phi^0 \phi^0 - \beta_h \frac{[2M^2]}{2} + \\
 & \frac{2M^2}{\Lambda} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) + \frac{2M^2}{\Lambda} \alpha_h - ig_{c_w} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) - ig_{s_w} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \\
 & \frac{1}{2}g^2 W_\mu^- W_\nu^+ W_\nu^- W_\mu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^-) + g^2 s_w^2 (W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^- W_\mu^+) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^2 + H\phi^0 \phi^0 + 2(H\phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gMW_\mu^+ W_\nu^- H - \frac{1}{2}g\frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}igW_\mu^+ (\partial_\mu \phi^0 \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\nu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) + \frac{1}{2}ig[W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\nu^- (H\partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w} (Z_\mu^0 (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\frac{2s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \\
 & ig_{s_w} MA_\mu (W_\mu^+ \phi^- - W_\nu^- \phi^+) - ig\frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & ig_{s_w} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)\phi^+ \phi^-] - \frac{1}{2}g^2 \frac{2s_w}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) - \frac{1}{2}ig^2 \frac{2s_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{2s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\nu \phi^+ \phi^- - e^\lambda (\gamma^\partial + m_\nu^2) e^\lambda - \rho^\lambda \gamma^\partial \nu^\lambda - u_\nu^2 (\gamma^\partial + m_\nu^2) u_\nu^2 - \frac{1}{2}(d_\nu^2 \gamma^\partial d_\nu^2) + \\
 & d_\nu^2 (\gamma^\partial + m_\nu^2) d_\nu^2 + ig_{s_w} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{1}{2}(u_\nu^2 \gamma^\mu u_\nu^2)] + (u_\nu^2 \gamma^\mu (\frac{3}{2}s_w^2 - \\
 & \frac{1}{2}c_w^2) Z_\mu^0 [(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (u_\nu^2 \gamma^\mu (\frac{3}{2}s_w^2 - \\
 & 1 - \gamma^5) u_\nu^2) + (d_\nu^2 \gamma^\mu (1 - \frac{3}{2}s_w^2 - \gamma^5) d_\nu^2)] + \frac{19}{2\sqrt{2}} W_\mu^+ [(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
 & (d_\nu^2 \gamma^\mu (1 + \gamma^5) C_{\lambda\nu} d_\nu^2)] + \frac{19}{2\sqrt{2}} W_\nu^- [(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (d_\nu^2 \gamma^\mu (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} [-\phi^+ (e^\lambda \gamma^\mu e^\lambda) + \phi^- (e^\lambda (1 + \gamma^5) \nu^\lambda)] + \\
 & \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} [H (e^\lambda e^\lambda) + i\phi^0 (e^\lambda \gamma^5 e^\lambda)] + \frac{19}{2\sqrt{2}} \phi^+ [-m_\nu^2 (u_\nu^2 C_{\lambda\nu} (1 - \gamma^5) d_\nu^2) + \\
 & m_\nu^2 (d_\nu^2 C_{\lambda\nu} (1 + \gamma^5) u_\nu^2) - \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} \phi^0 (u_\nu^2 \gamma^0 u_\nu^2) - \\
 & \gamma^0 u_\nu^2] - \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} H (u_\nu^2 u_\nu^2) - \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} H (d_\nu^2 d_\nu^2) + \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} \phi^0 (u_\nu^2 \gamma^0 u_\nu^2) - \\
 & \frac{19}{2\sqrt{2}} \frac{m_\nu^2}{M} \phi^0 (d_\nu^2 \gamma^0 d_\nu^2) + X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \tilde{Y} \partial^2 Y + ig_{c_w} W_\mu^+ (\partial_\mu \tilde{X}^0 X^- - \partial_\mu \tilde{X}^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\mu \tilde{Y} X^- - \\
 & \partial_\mu \tilde{X}^+ Y) + ig_{c_w} W_\nu^- (\partial_\nu \tilde{X}^- X^0 - \partial_\nu \tilde{X}^0 X^+) + ig_{s_w} W_\nu^- (\partial_\nu \tilde{X}^- Y - \\
 & \partial_\nu \tilde{Y} X^+) + ig_{c_w} Z_\mu^0 (\partial_\mu \tilde{X}^+ X^- - \partial_\mu \tilde{X}^- X^+) + ig_{s_w} A_\mu (\partial_\mu \tilde{X}^+ X^- + \\
 & \partial_\mu \tilde{X}^- X^+) - \frac{1}{2}igM[\tilde{X}^+ X^+ H + \tilde{X}^- X^- H + \frac{1}{c_w} \tilde{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} igM[\tilde{X}^+ X^0 \phi^+ - \tilde{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM[\tilde{X}^0 X^- \phi^+ - \tilde{X}^+ X^+ \phi^-] + \\
 & igMs_w[\tilde{X}^0 X^- \phi^+ - \tilde{X}^+ X^+ \phi^-] + \frac{1}{2}igM[\tilde{X}^+ X^+ \phi^0 - \tilde{X}^- X^- \phi^0]
 \end{aligned}$$

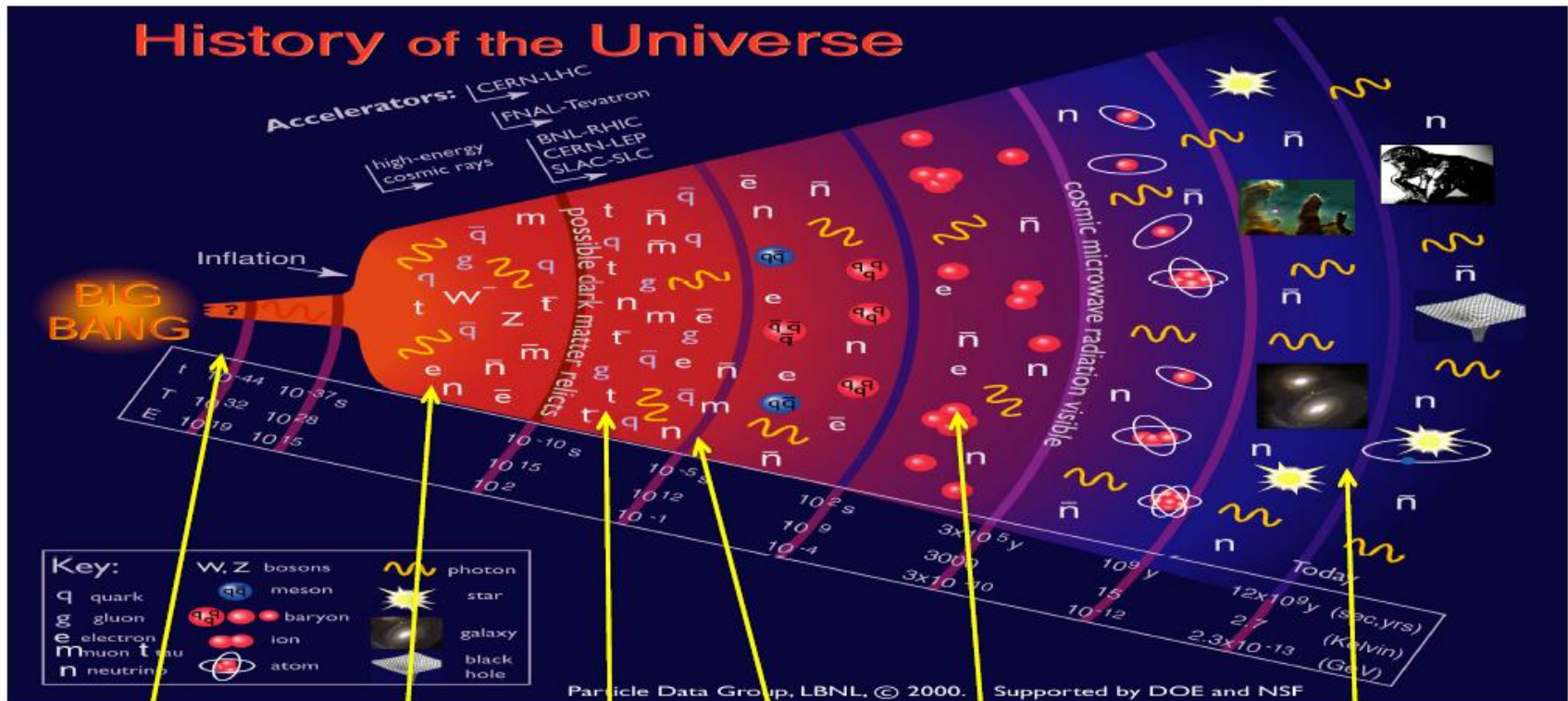


- Delamater

(experimental) LHC physics

Accelerators for high energy physics experiments

History of the Universe



Cosmology

Cosmic rays

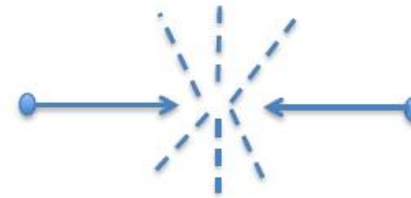
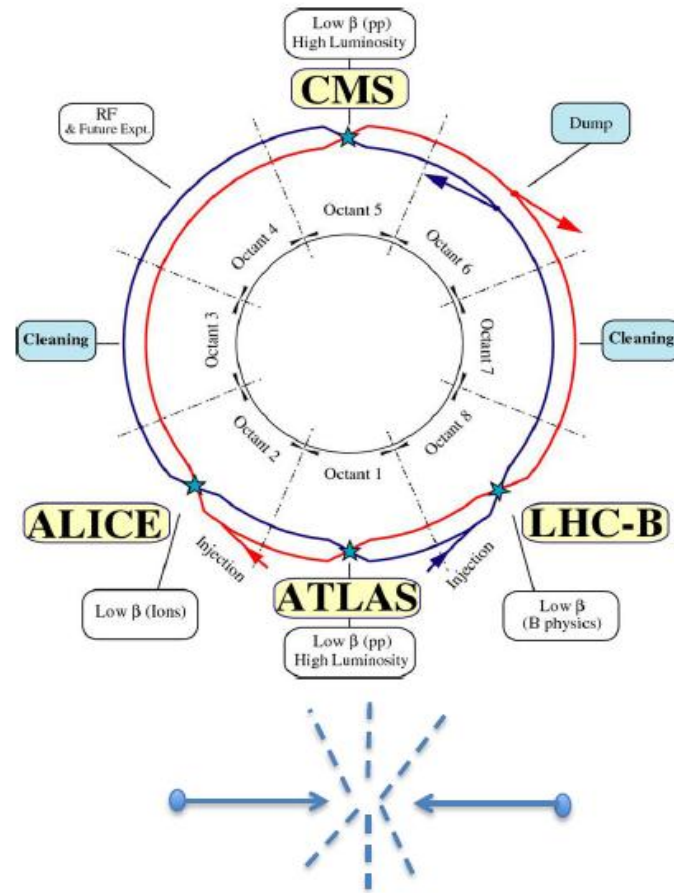
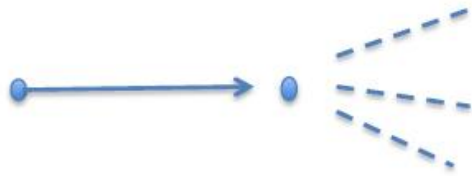
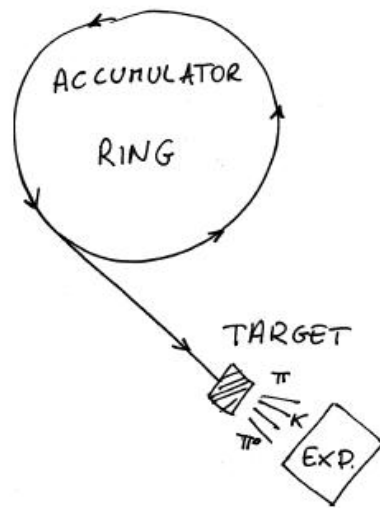
LHC

Quark/gluon plasma

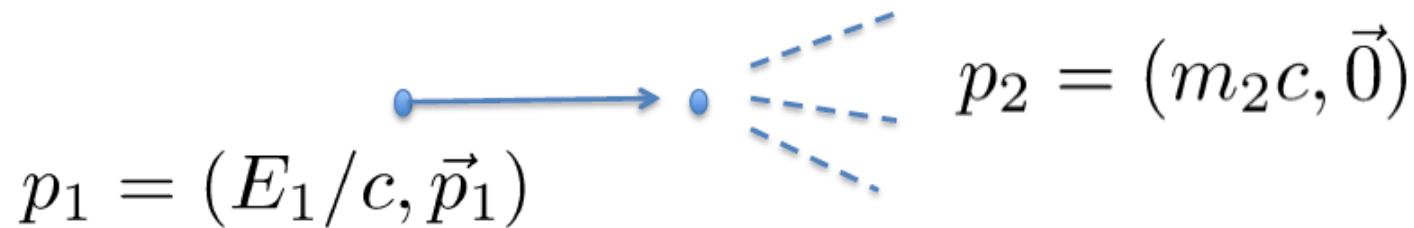
Nuclear physics

Astrophysics

Fixed target vs Colliders



E_{CM} in Fixed Target Experiment



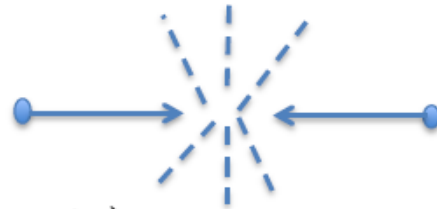
$$p_{tot} = (E_1/c + m_2c, \vec{p}_1)$$

$$E_{CM}^2 = (m_1^2 + m_2^2)c^4 + 2E_1m_2c^2$$

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

E_{CM} in Collider Experiment

Laboratory Frame = CM Frame



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

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

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

Acceleration

Lorentz force law

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

Electric field Velocity Magnetic field

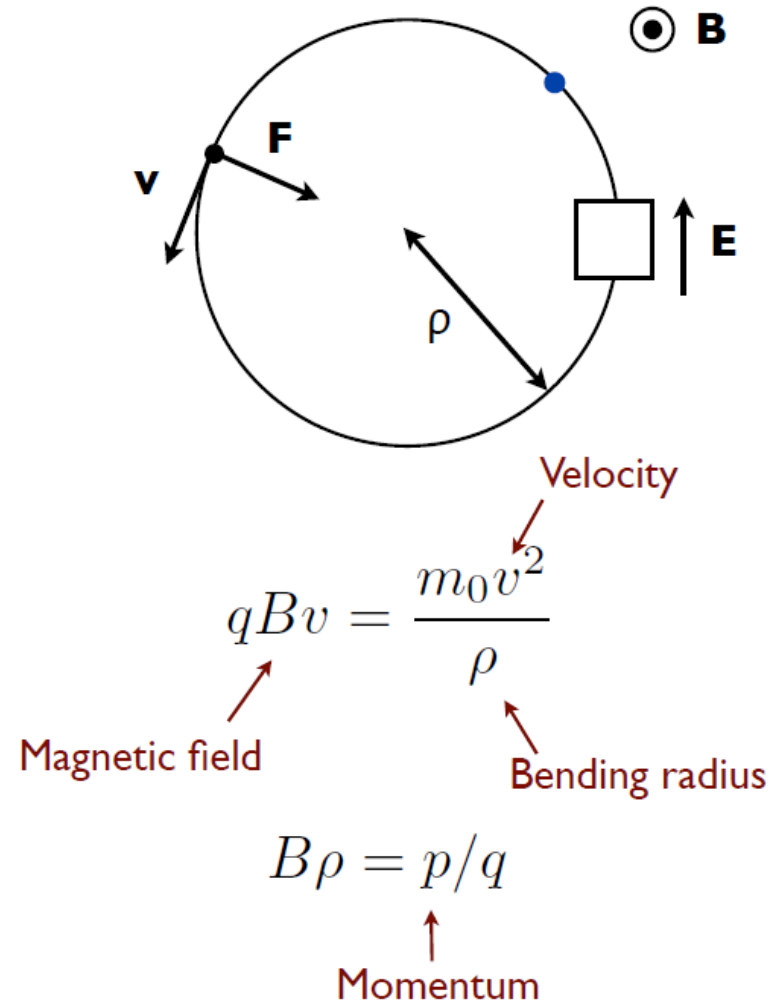
Energy change

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

- 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



Storage ring Colliders

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

The first one: AdA (Frascati), 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

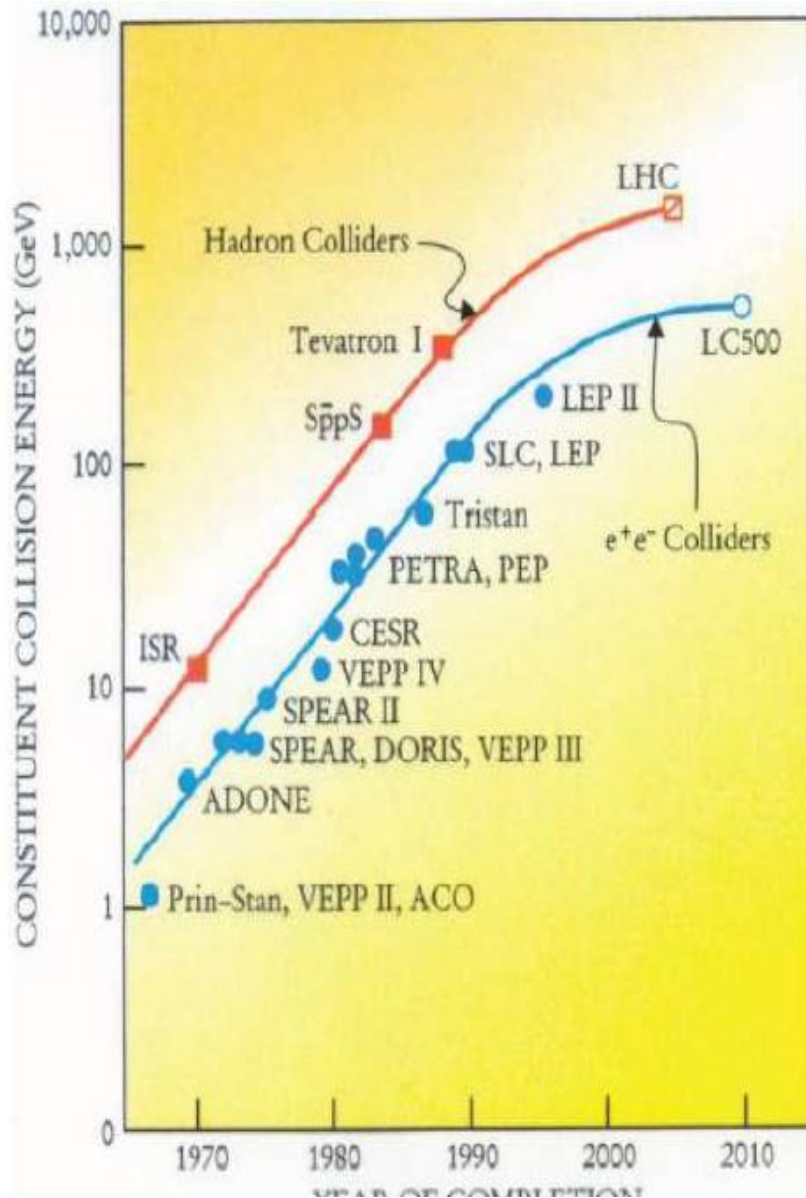
1971-1984: ISR (CERN), p^+,p^+ , 31.5 GeV, 948 m circumference

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

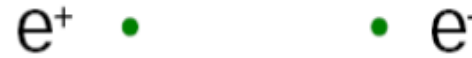
2008 - : LHC highest energy proton synchrotron, p^+,p^+ , heavy ions, 6.5 TeV (2.76 TeV per nucleon for $^{208}\text{Pb}^{82+}$); Discovery of Higgs

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 defined 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

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

Luminosity [$s^{-1} m^{-2}$] Bunch populations
 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)

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

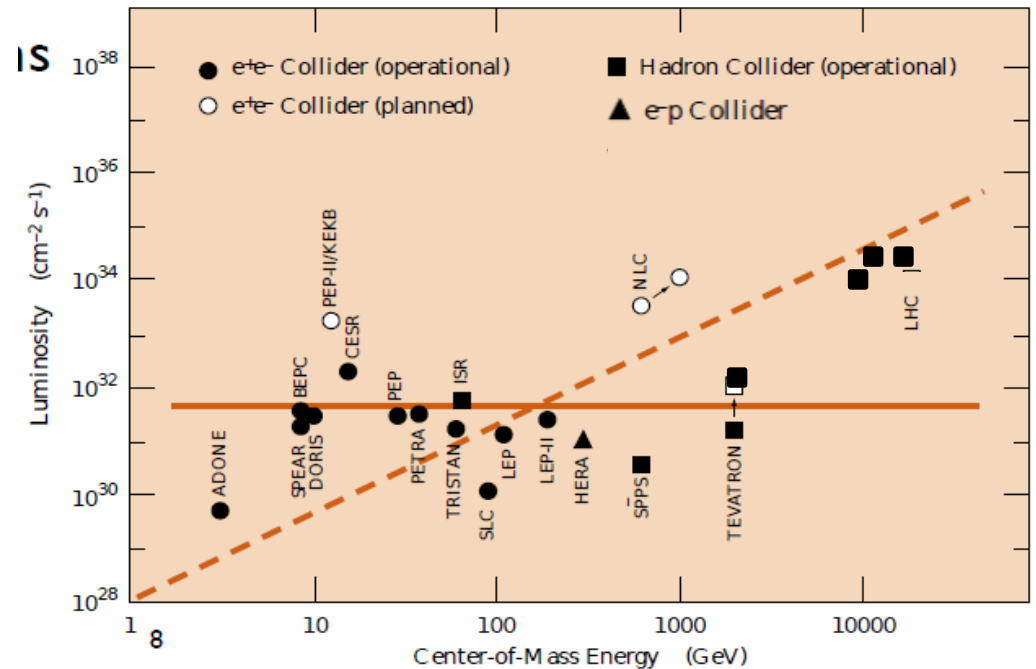
Number of events
Instantaneous luminosity

↓
↓

↑
↑

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,**

CERN laboratory (founded in 1954)

Mont Blanc

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

Jezioro Genewskie



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

CERN-
Prevezin

ALICE

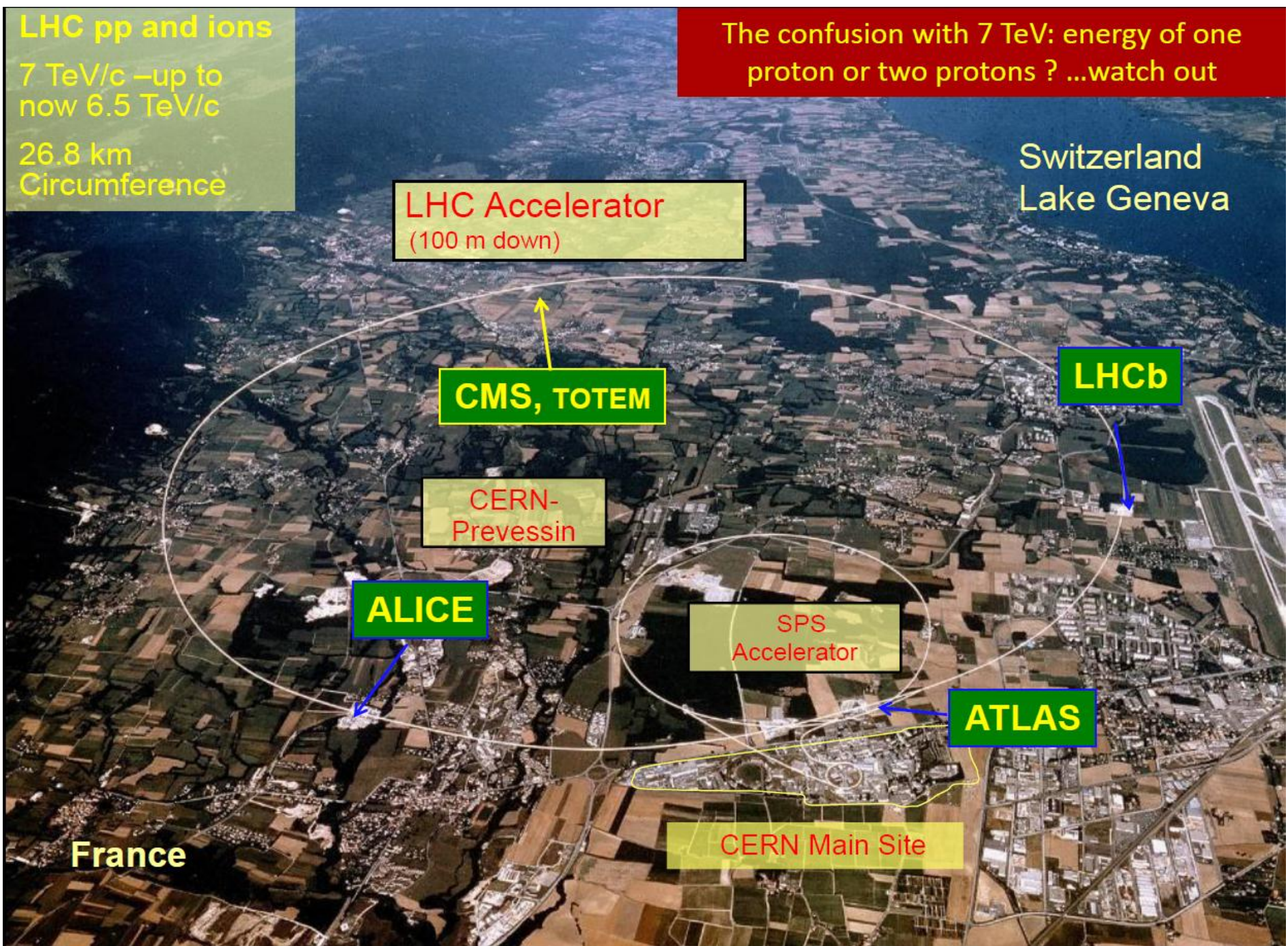
SPS
Accelerator

ATLAS

LHCb

CERN Main Site

France



Energy and luminosity

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy **substantially exceeding 1 TeV**
- In order to observe rare events, the luminosity should be in the order of **$10^{34} \text{ [cm}^{-2}\text{s}^{-1}]$** (challenge for the LHC accelerator)

- Event rate:

$$\frac{N}{\Delta t} = L[\text{cm}^{-2} \cdot \text{s}^{-1}] \cdot \sigma[\text{cm}^2]$$

- Assuming a total cross section of about 100 mbarn for pp collisions, the **event rate** for this luminosity is in the order of **10^9 events/second** (challenge for the LHC experiments)
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma)

Integrated luminosity

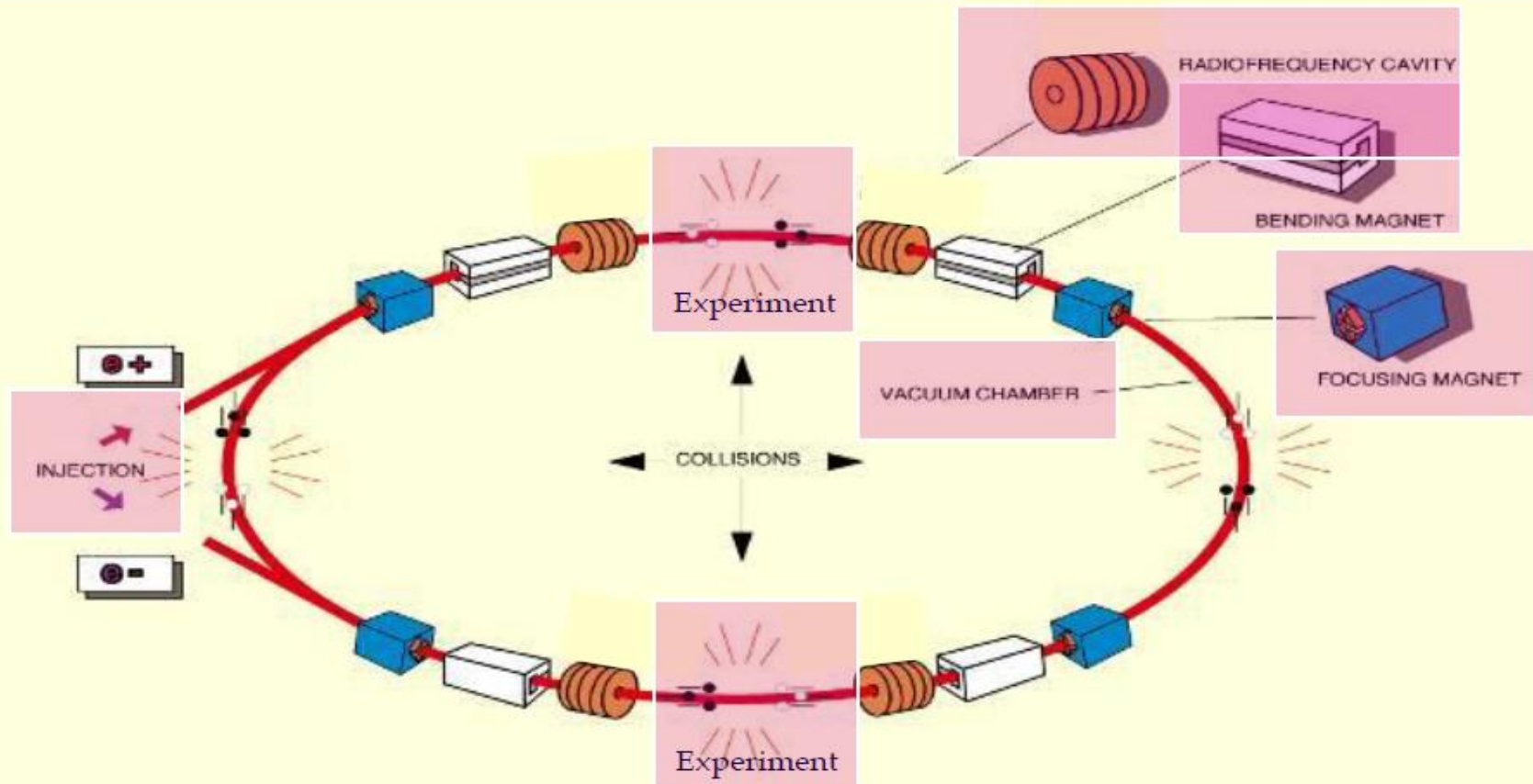
- The total number of particles created at an accelerator (the total number of Higgs bosons) is proportional to the **Integrated Luminosity**:

$$\int L(t) \times dt$$

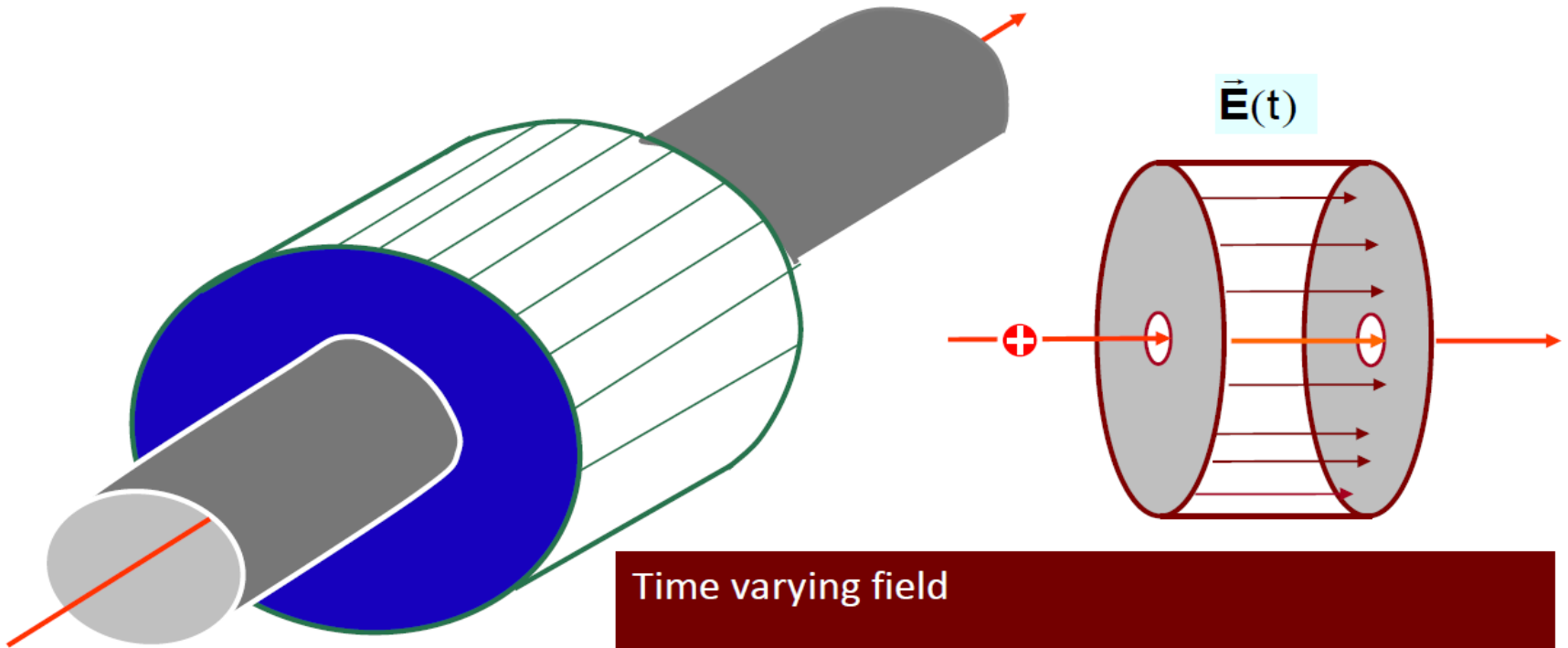
- It has the unit of $[\text{cm}^{-2}]$ and is expressed in **Inverse Picobarn** or **Inverse Femtobarn**

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

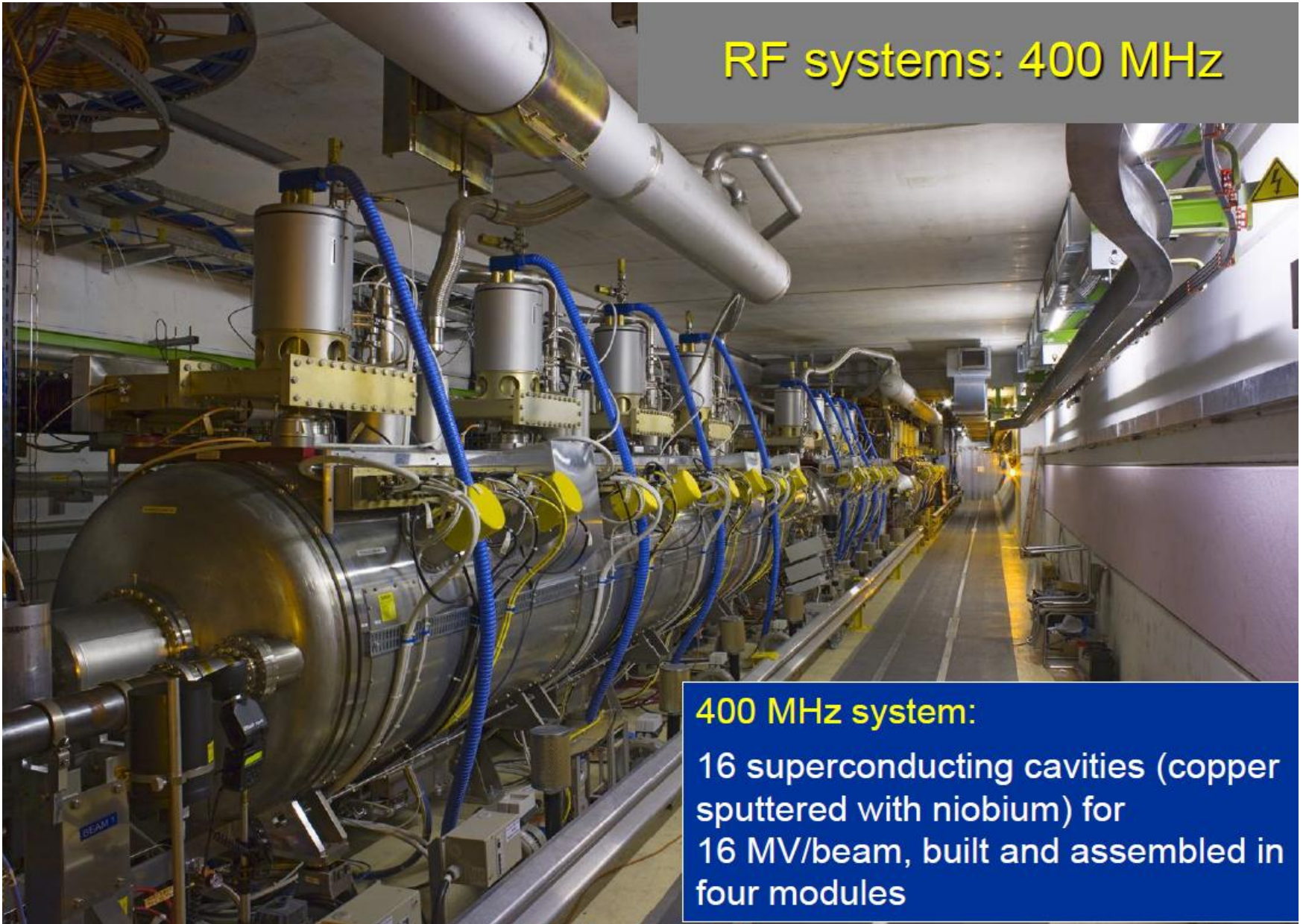
Time varying field

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

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:

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

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

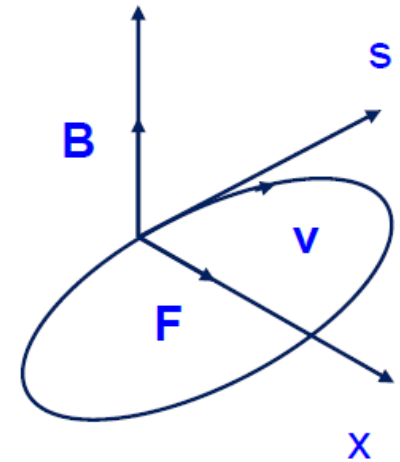
Maximum momentum 7000 GeV/c

Radius 2805 m fixed by LEP tunnel

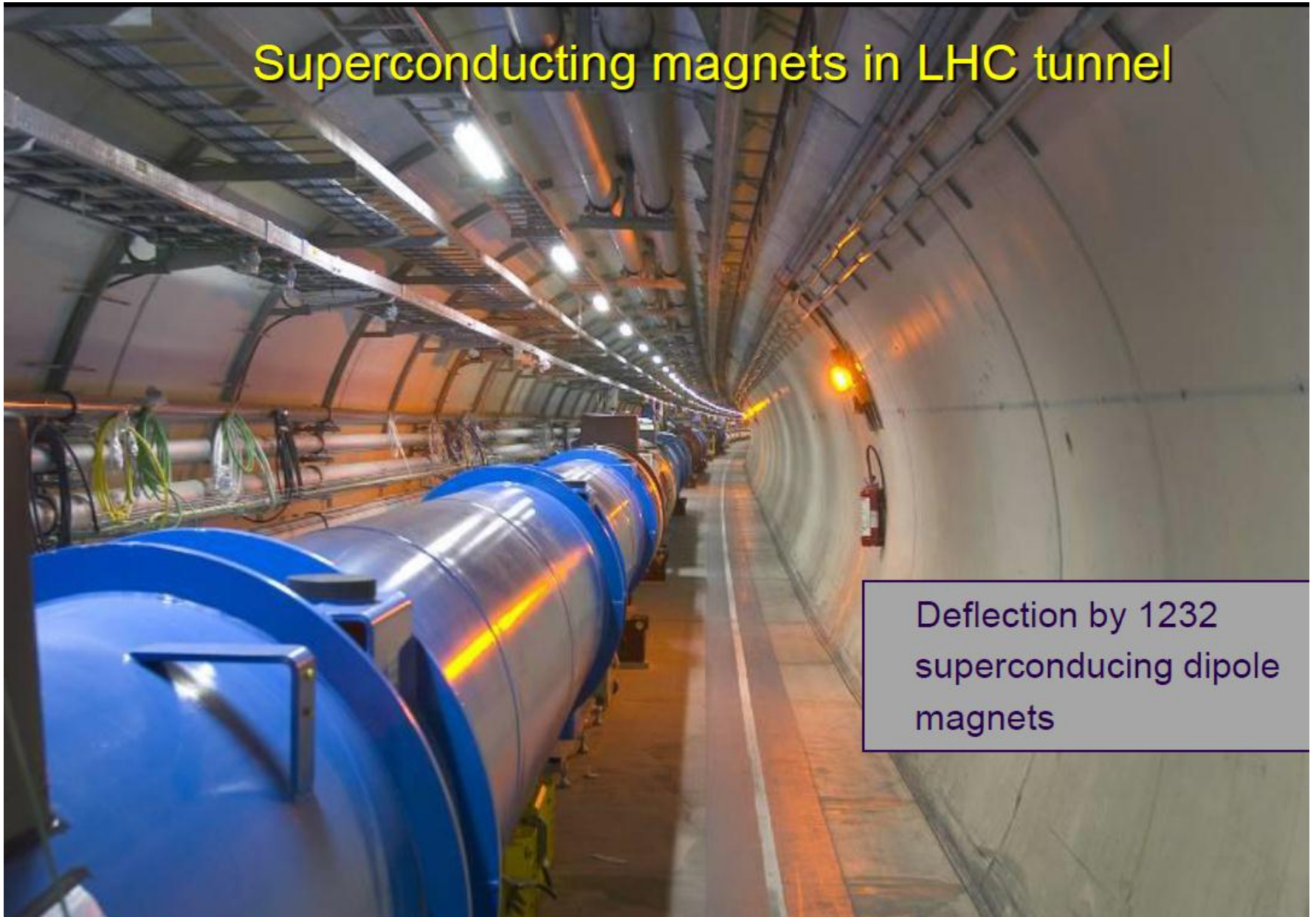
Magnetic field $B = 8.33$ Tesla

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
superconducting dipole
magnets

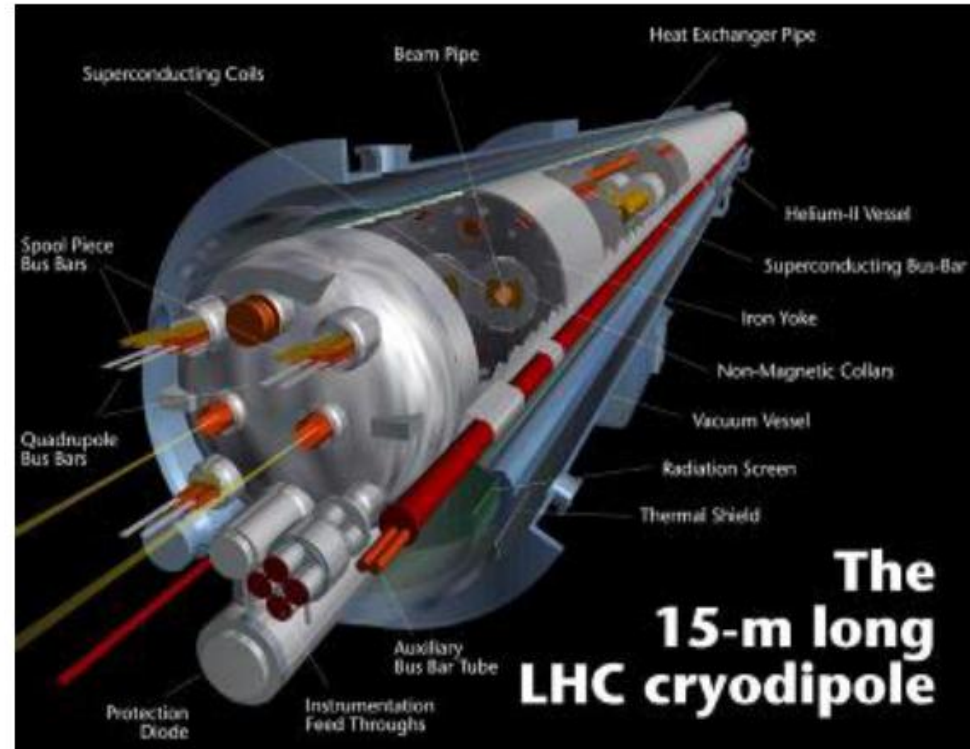
Dipole magnets for the LHC

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

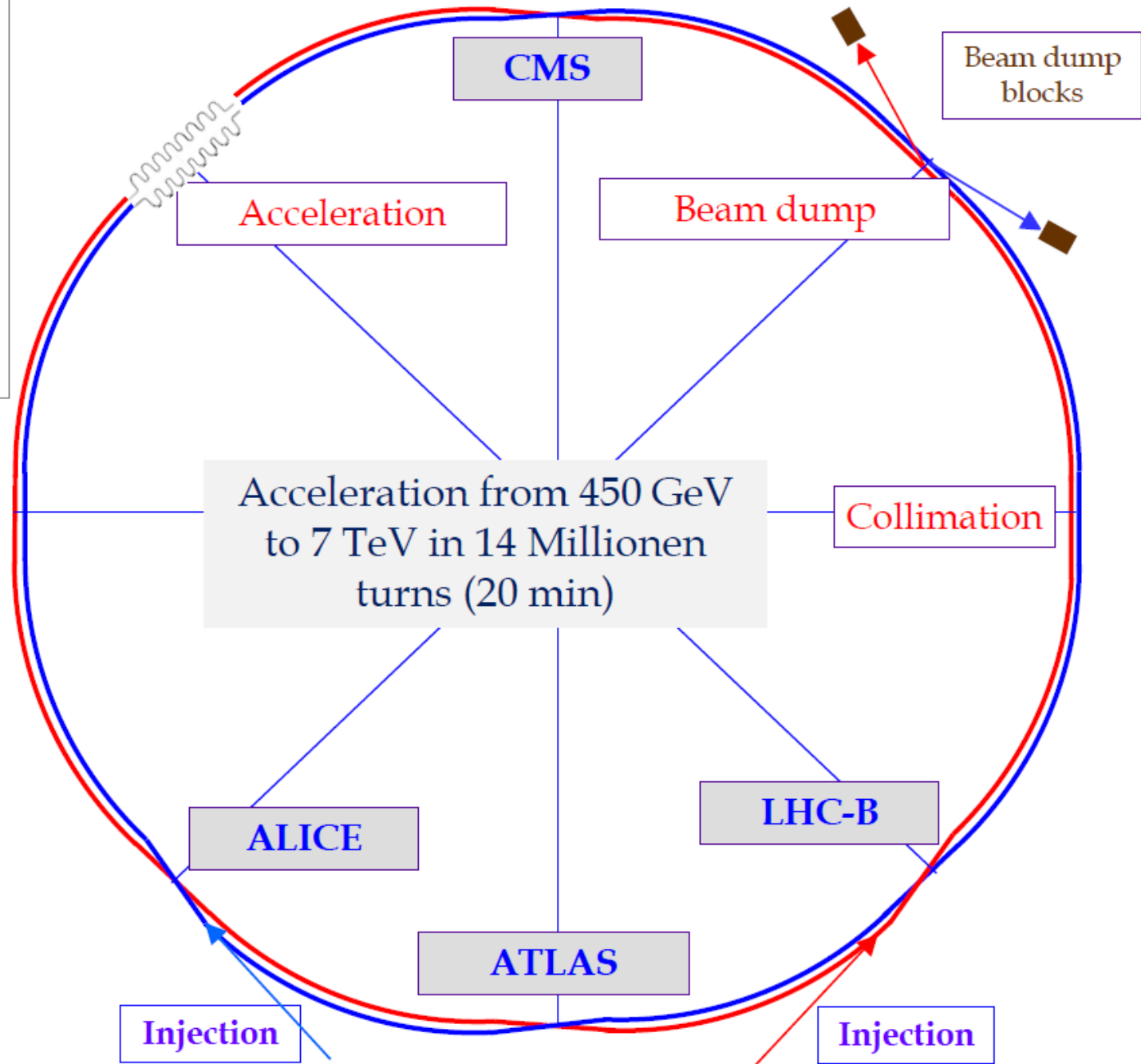
eight arcs (sectors)

eight long straight section (about 700 m long)

1232 deflecting dipole magnets

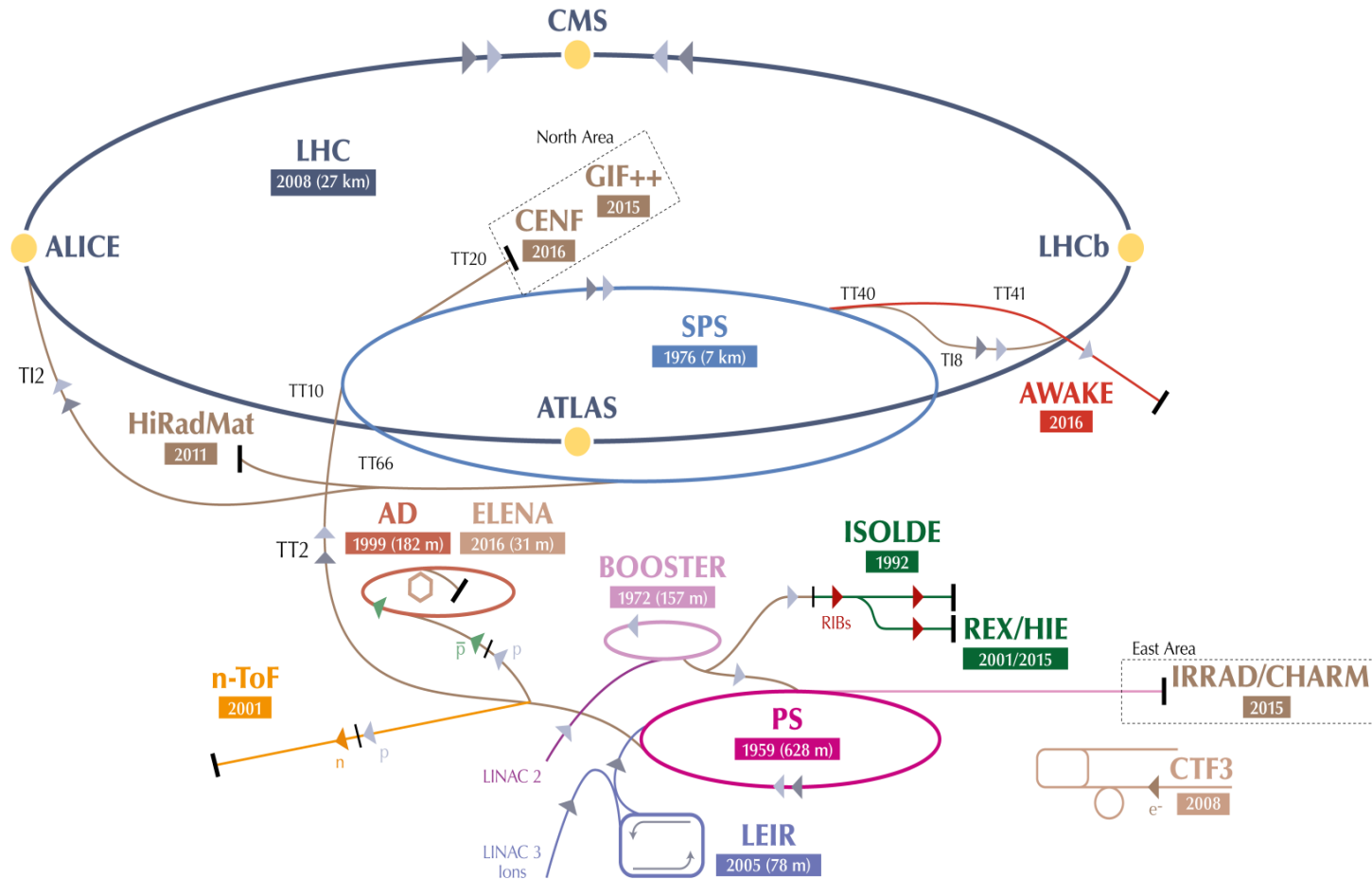
Collimation

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



CERN accelerator complex

CERN 2017



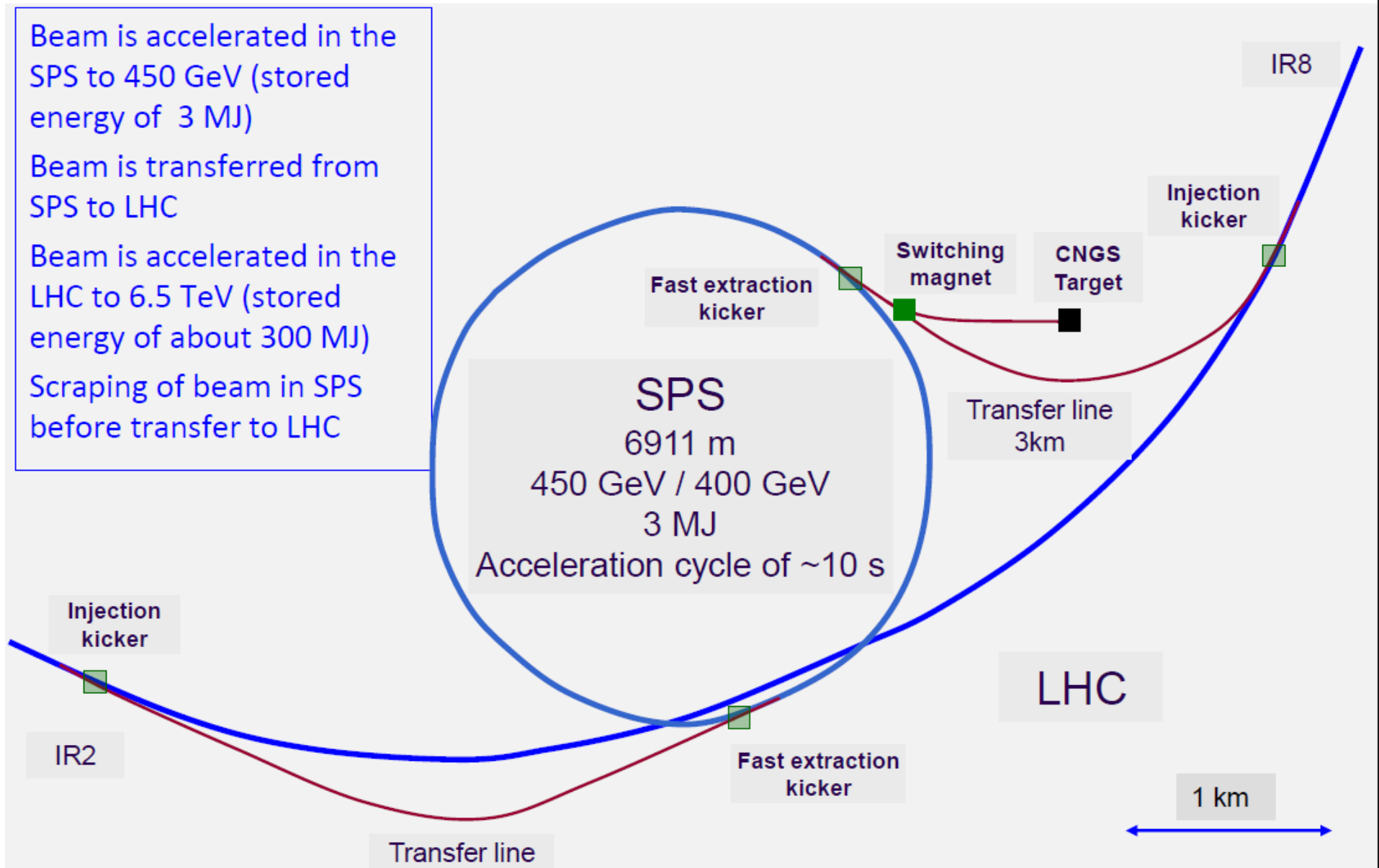
SPS, transfer line and the LHC

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

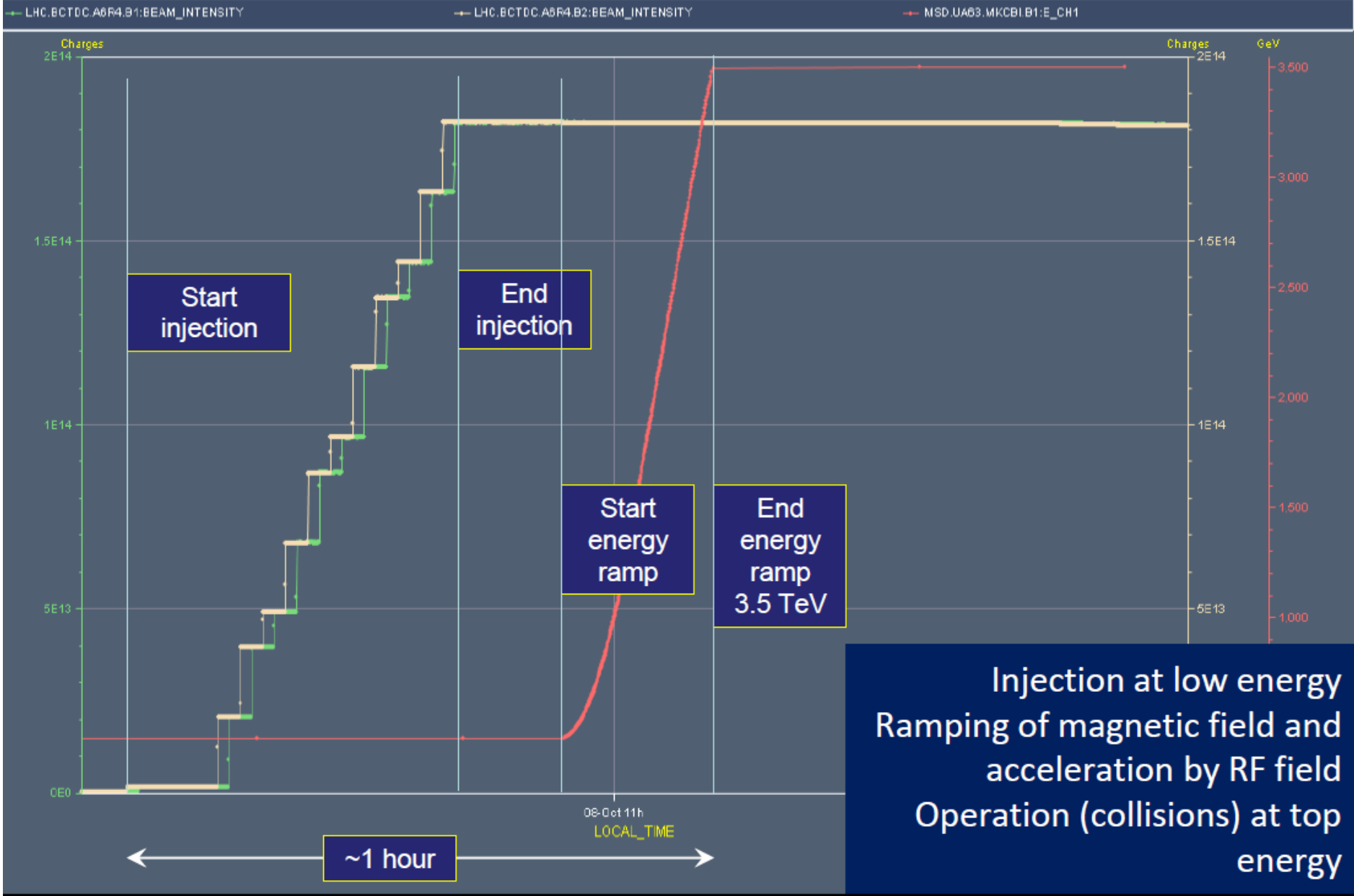
Beam is transferred from SPS to LHC

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

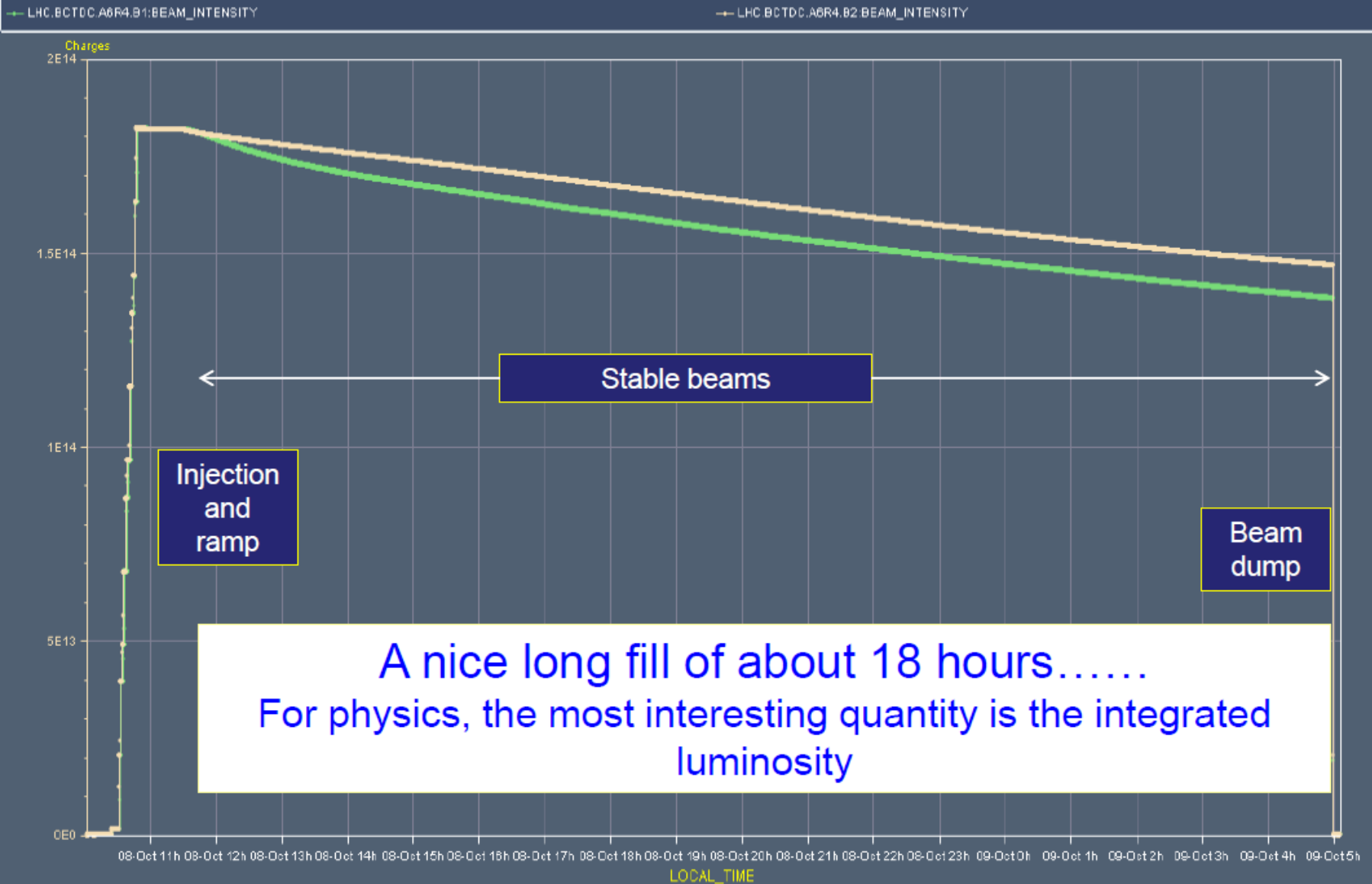
Scraping of beam in SPS before transfer to LHC



Synchrotron principle: LHC fill (2011)



Excellent fill (2011)



Colliding trains of bunches

Number of „New Particles“
per unit of time:

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

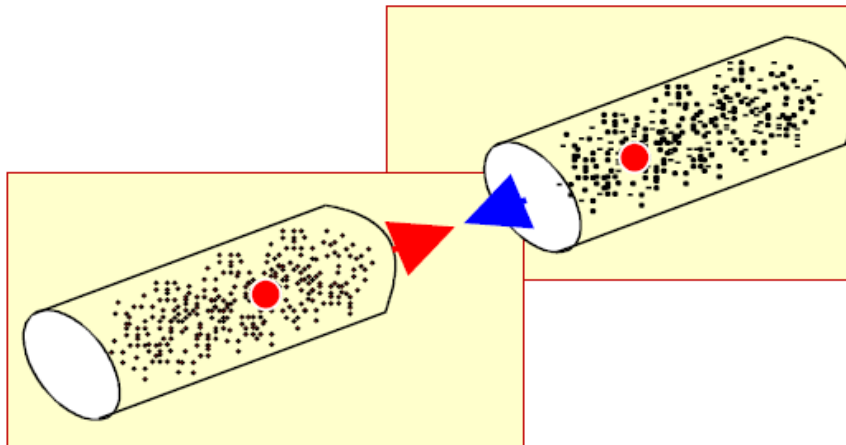
The objective for the LHC as proton – proton collider is a luminosity of about $10^{34} [\text{cm}^{-2}\text{s}^{-1}]$

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

Luminosity parameters

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

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



Luminosity parameters

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

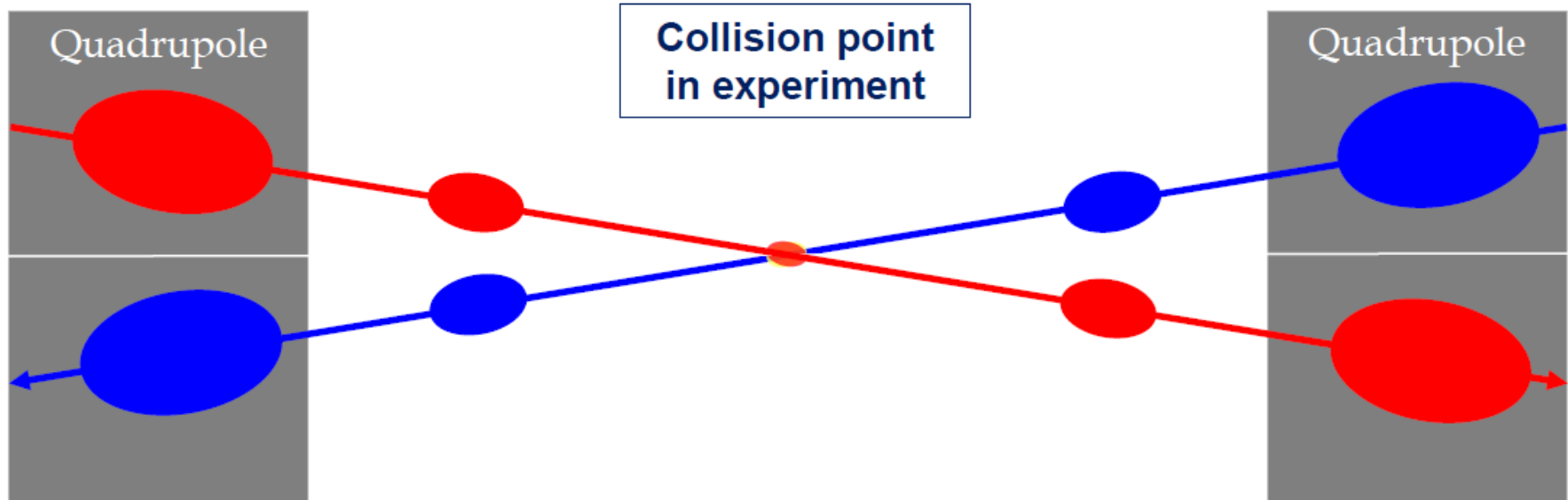
Beam size given by injectors and by space in vacuum chamber

$f = 11246 \text{ Hz}$

Beam size $16 \mu\text{m}$,
for $\beta = 0.5 \text{ m}$ (β is a function of the lattice)

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

Beam size

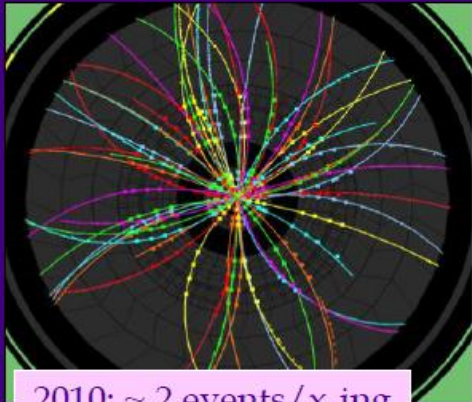


- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10σ
- Limitation is the aperture in quadrupoles
- Limitation of β function at IP to 0.4 m (2017)

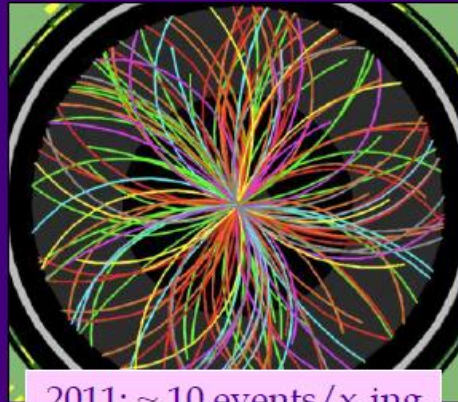
CMS

E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CERN
Run/Event: 195099 / 35488125
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 ATLAS & CMS for handling this pile-up !!



2010: ~ 2 events/x-ing

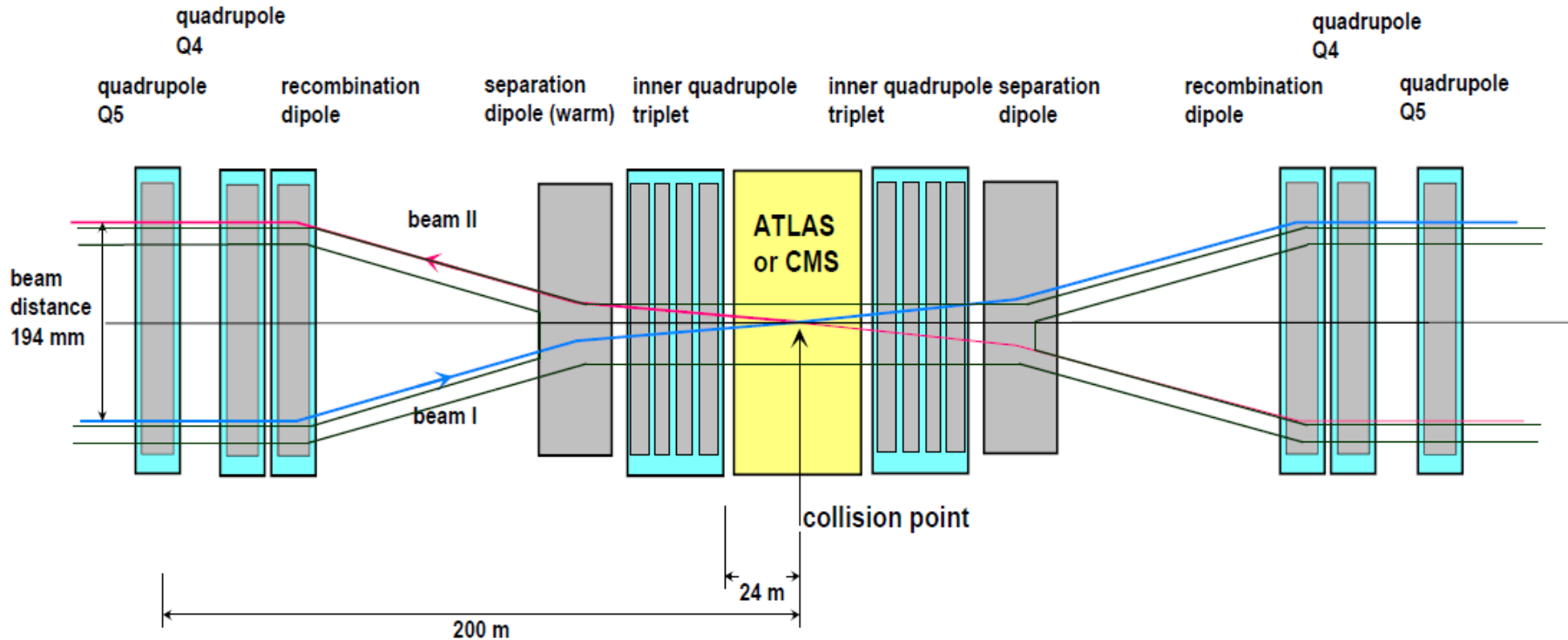


2011: ~ 10 events/x-ing



2012: ~ 20 events/x-ing

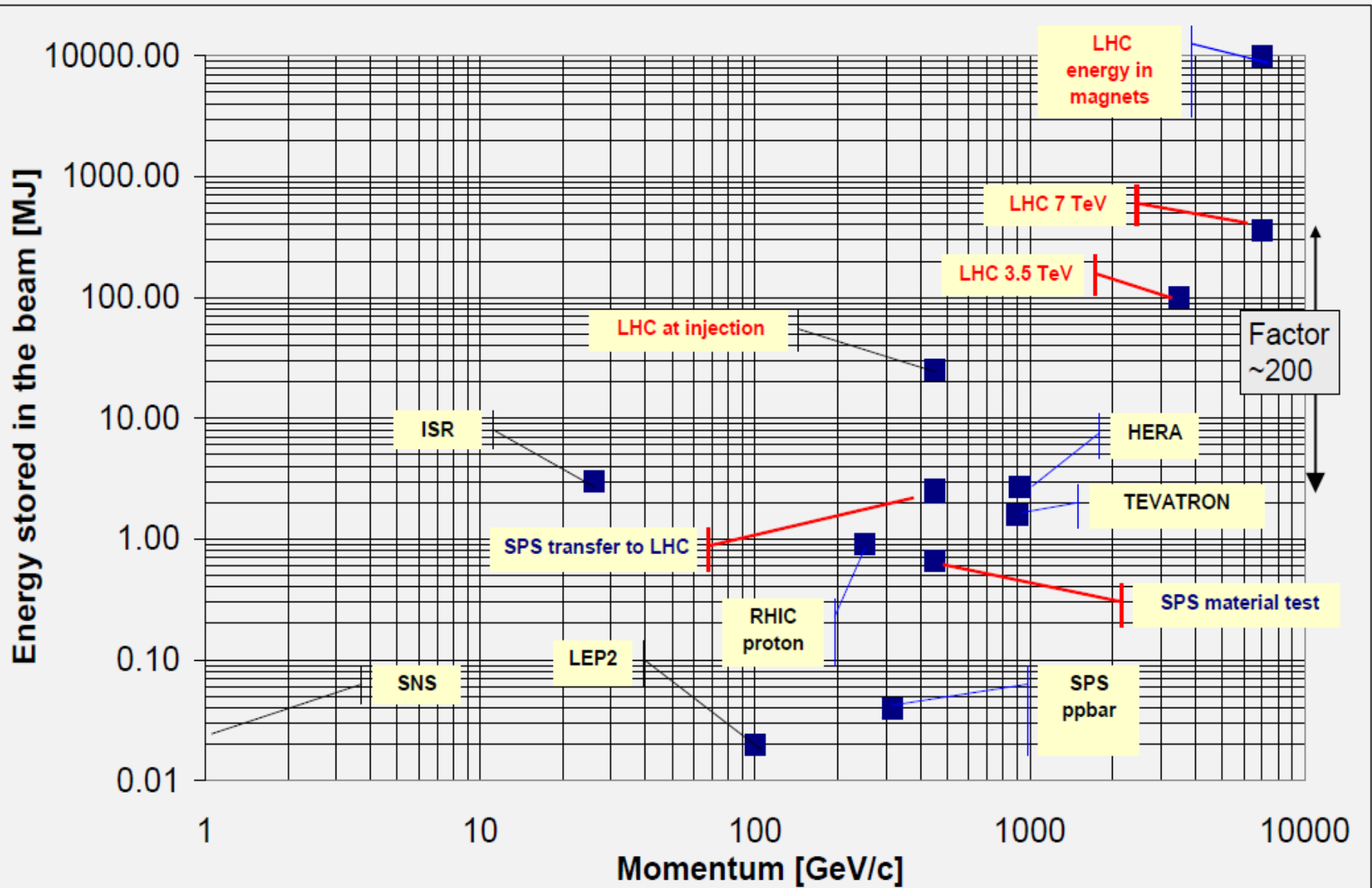
Experimental long straight section



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 $250 \mu\text{rad}$

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



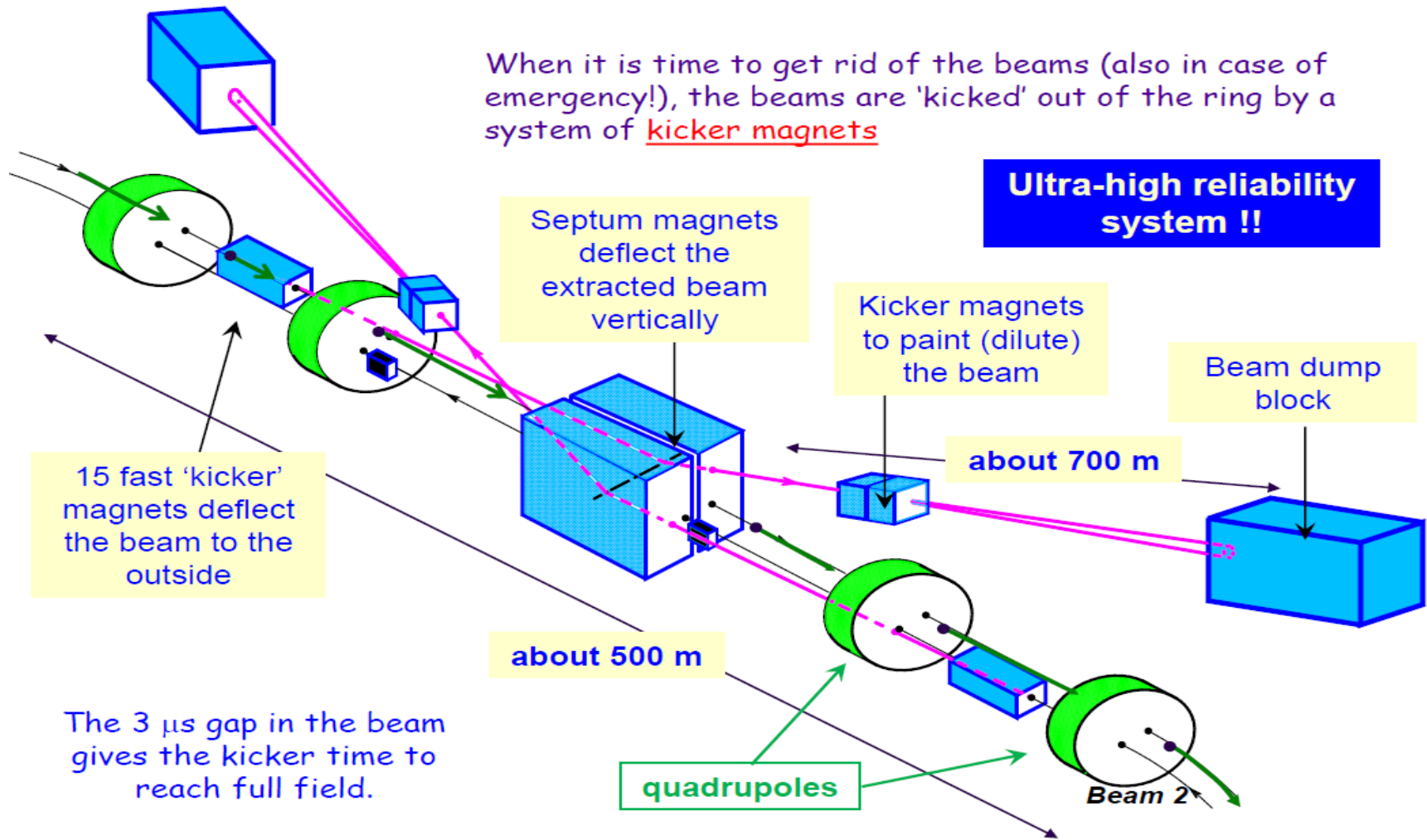
360 MJoule: the energy stored in one LHC beam corresponds approximately to...

- 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



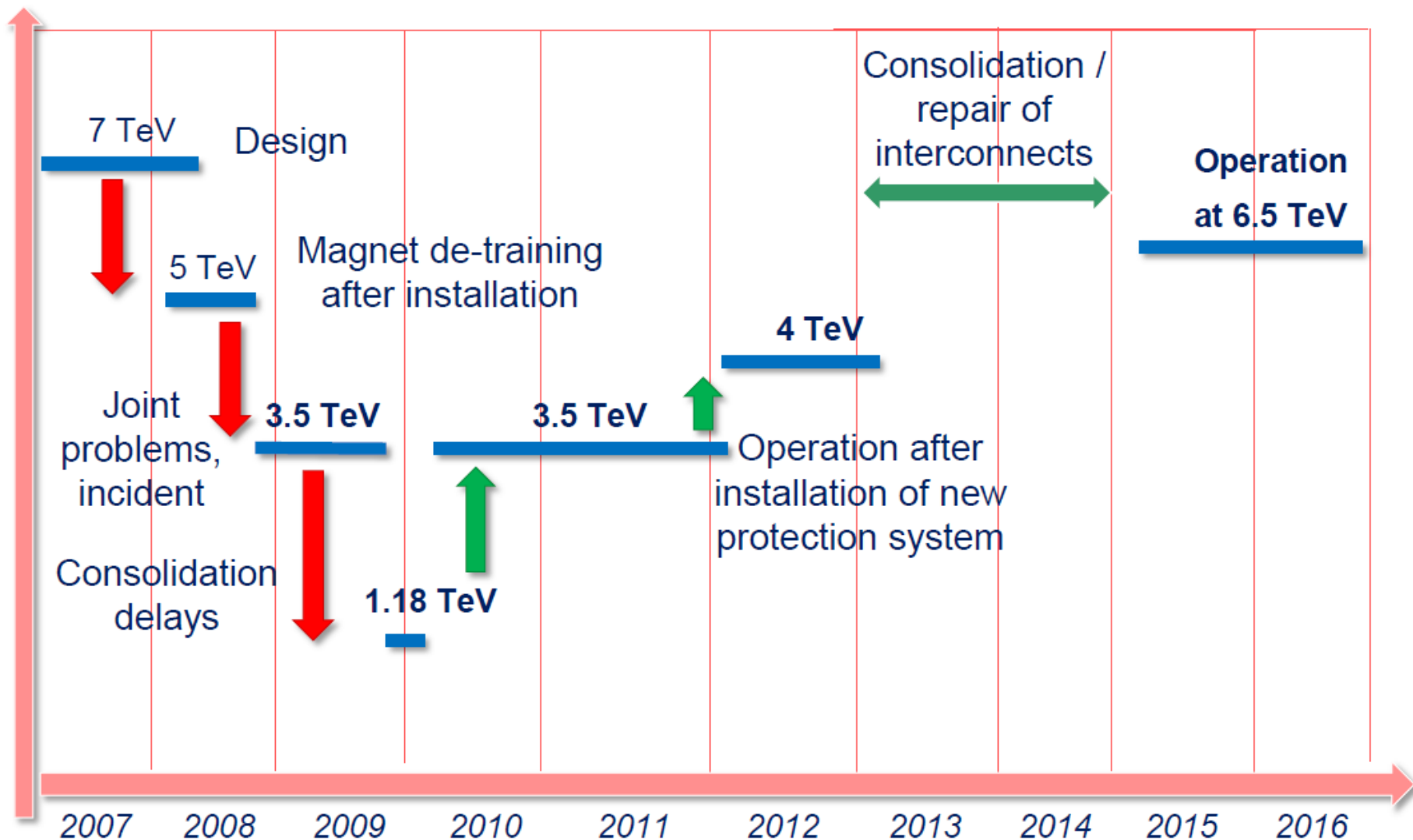
Beam Loss Monitors

- Ionization chambers to detect beam losses:
 - Reaction time $\sim \frac{1}{2}$ turn ($40 \mu\text{s}$)
 - 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

Energy (TeV)



The LHC: just another collider?

| | Start | Type | Max proton energy [GeV] | Length [m] | B Field [Tesla] | Lumi [$\text{cm}^{-2}\text{s}^{-1}$] | Stored beam energy [MJoule] |
|--------------------------------------|-------|------------------|-------------------------|------------|-----------------|----------------------------------------|-----------------------------|
| TEVATRON Fermilab Illinois USA | 1983 | p-pbar | 980 | 6300 | 4.5 | $4.3 \cdot 10^{32}$ | 1.6 for protons |
| HERA DESY Hamburg | 1992 | p – e+ p – e- | 920 | 6300 | 5.5 | $5.1 \cdot 10^{31}$ | 2.7 for protons |
| RHIC Brookhaven Long Island | 2000 | Ion-Ion p-p | 250 | 3834 | 4.3 | $1.5 \cdot 10^{32}$ | 0.9 per proton beam |
| LHC CERN | 2008 | Ion-Ion p-p | 7000 | 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

CERN-
Prevezin

ALICE

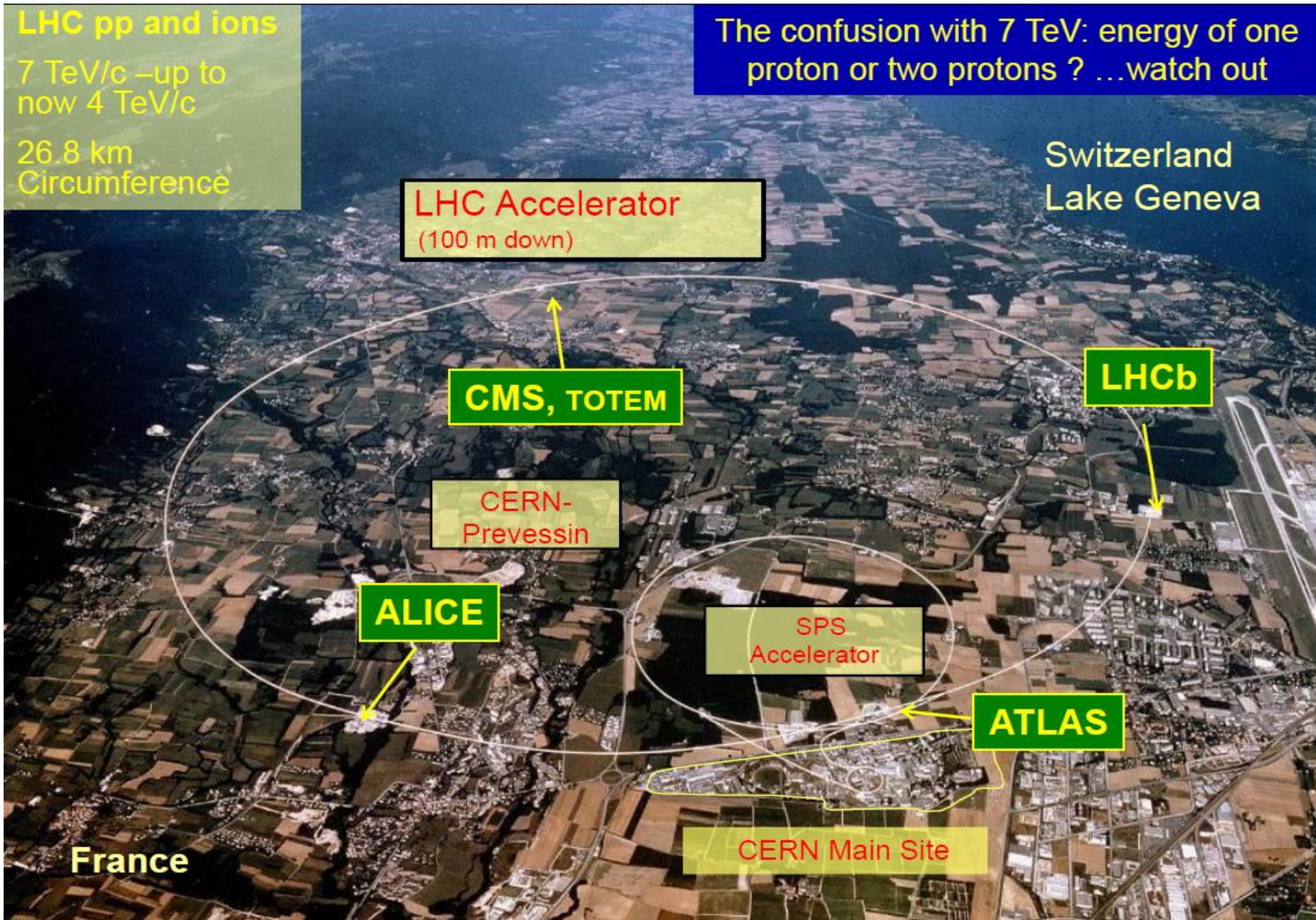
SPS
Accelerator

ATLAS

LHCb

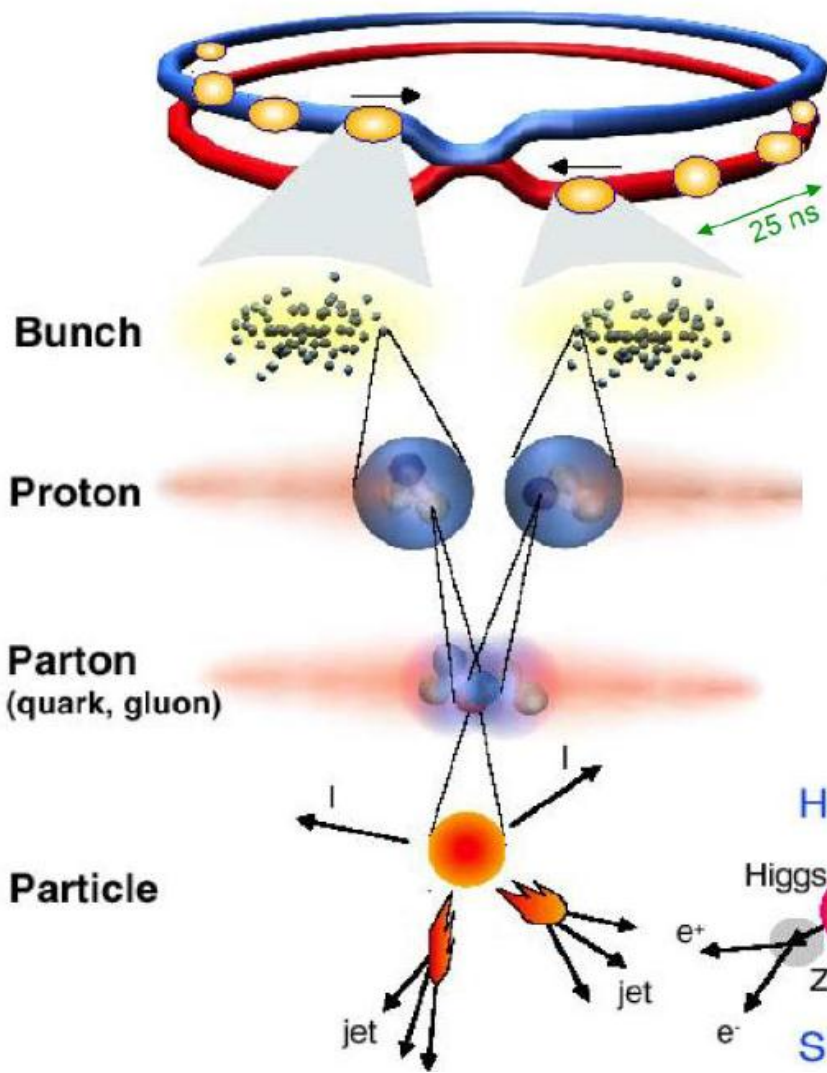
CERN Main Site

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 |



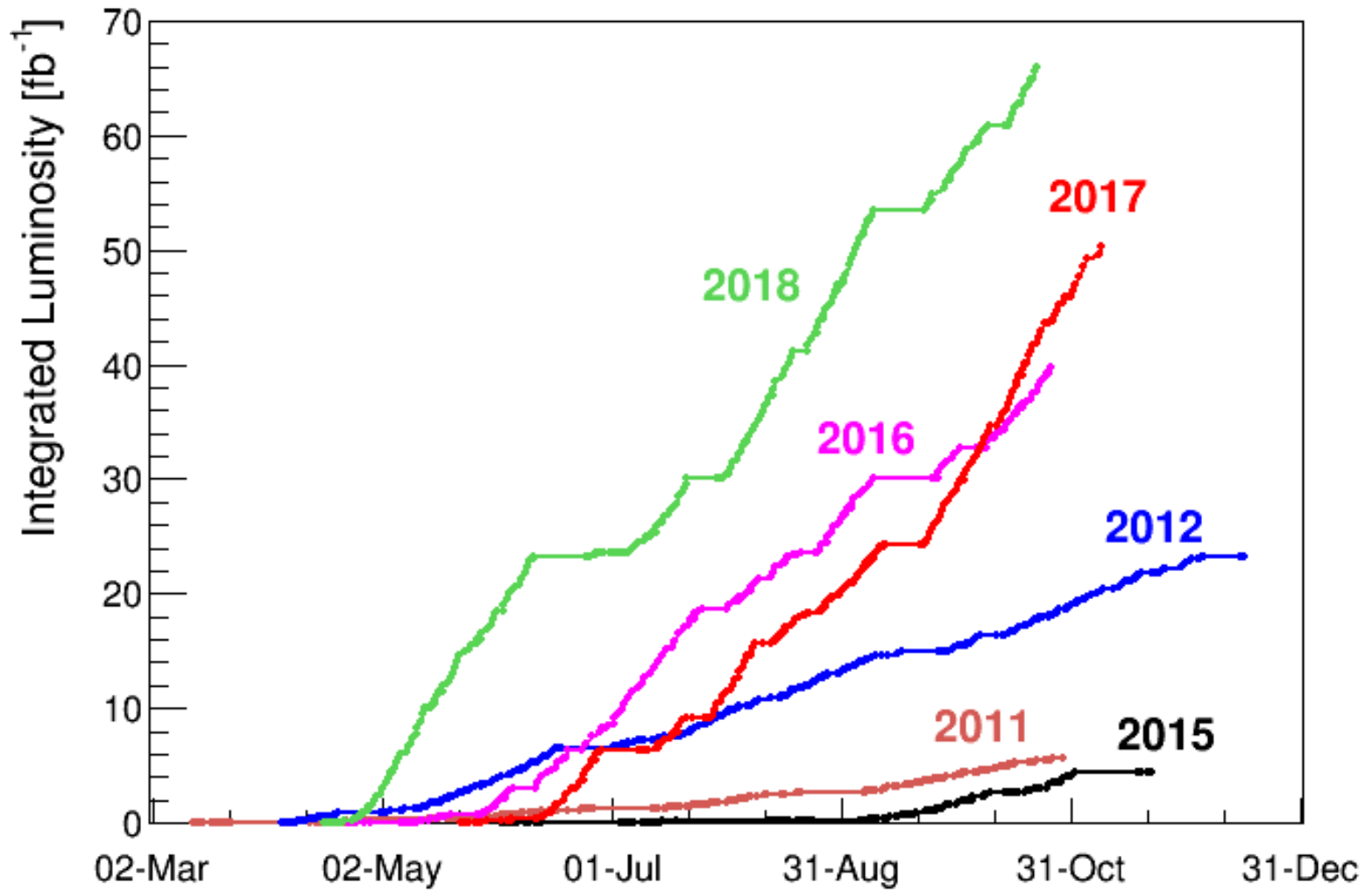
In the experiments:
 10^9 pp interactions per second
 ~ 1500 particles (p, n, π) produced in the detectors at each bunch-crossing

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

$$E = m c^2$$

LHC: Run 1 and Run 2

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



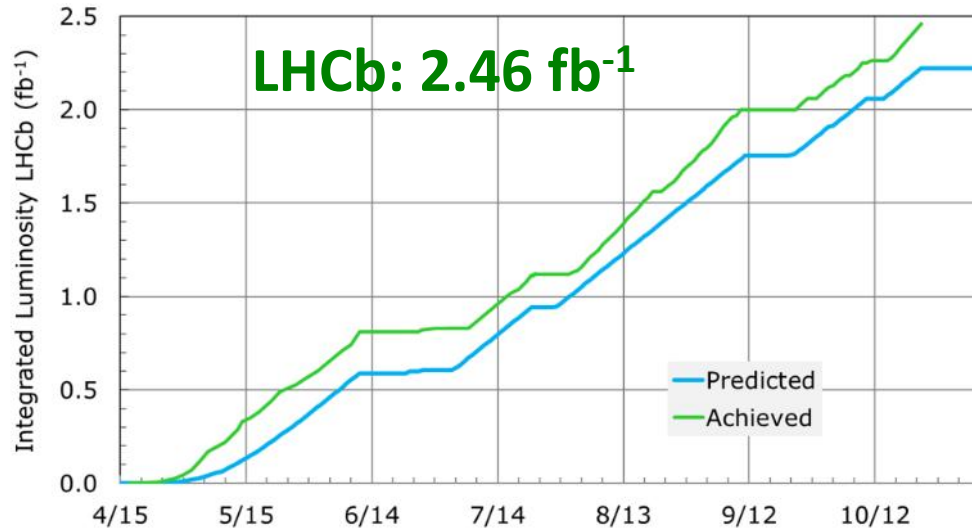
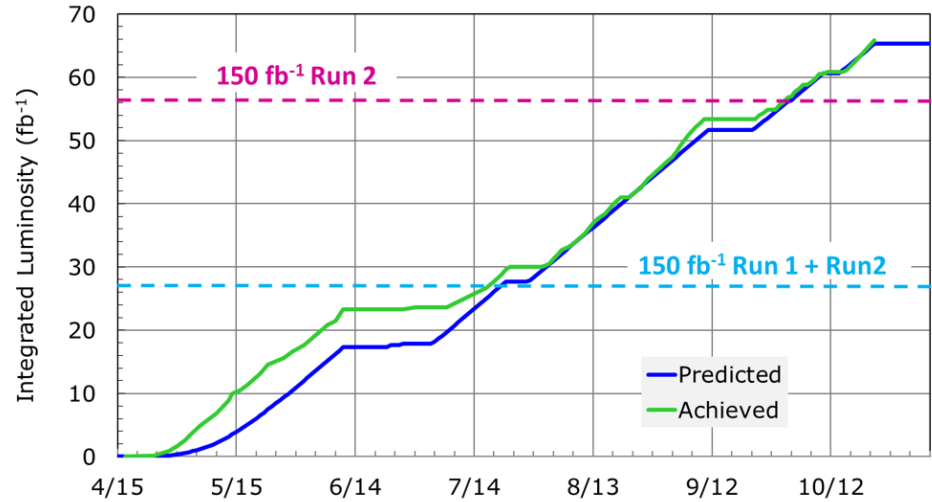
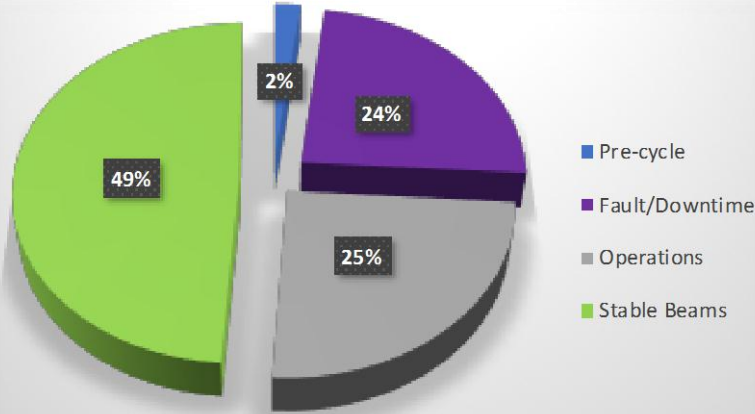
LHC Beam parameters achieved

| 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 \rightarrow 25 | 55 |
| p/bunch (typical value) [10^{11}] | 1.1 | 1.15 |
| Typical normalized emittance [μm] | ~ 1.8 | 3.75 |
| Peak luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$] | 2.1 | 1.0 |

LHC 2018: Beam Availability and Performance

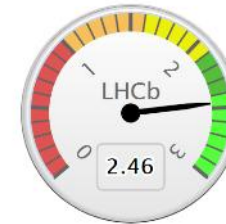
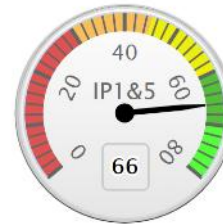
66 fb⁻¹

76 % availability



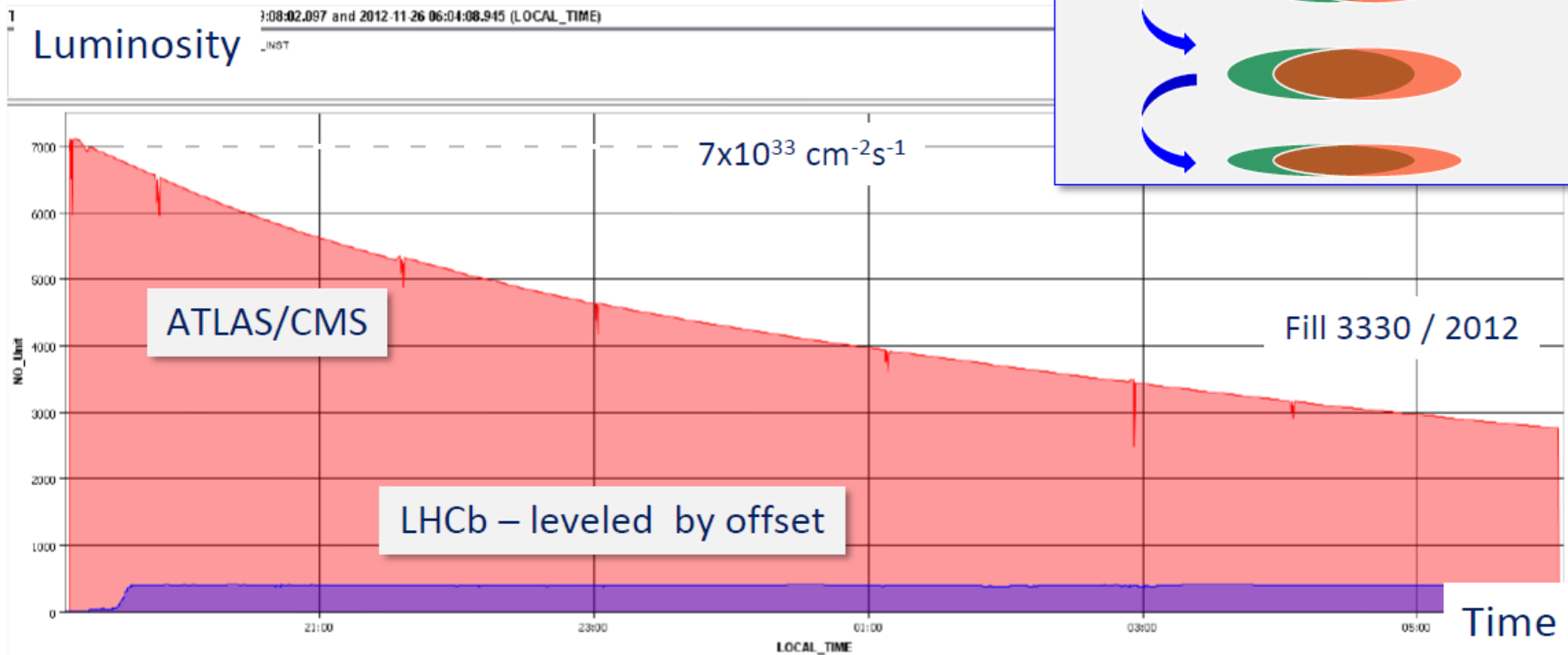
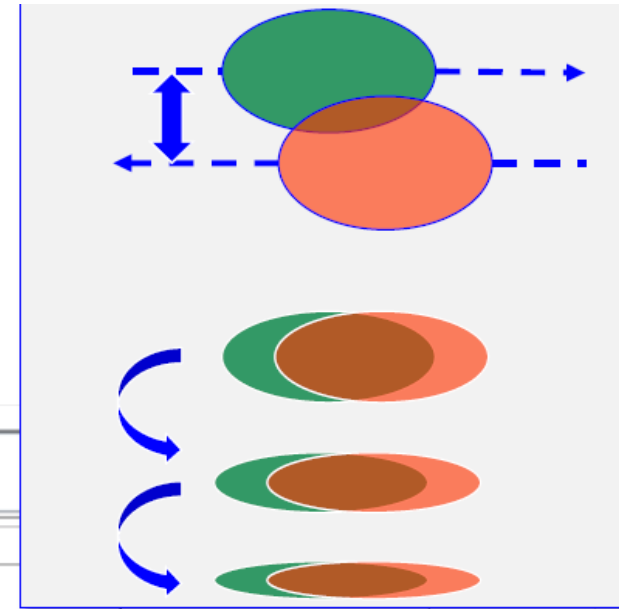
LHCb: 2.46 fb⁻¹

ATLAS : 65.1 fb⁻¹
CMS : 66.9 fb⁻¹

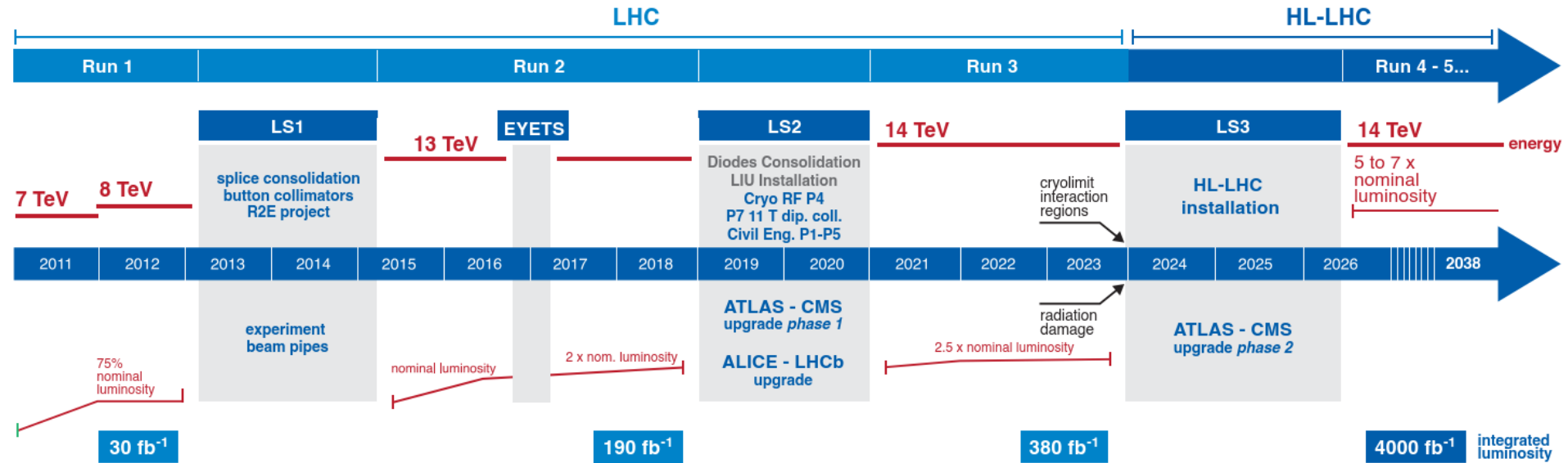


Leveling luminosities

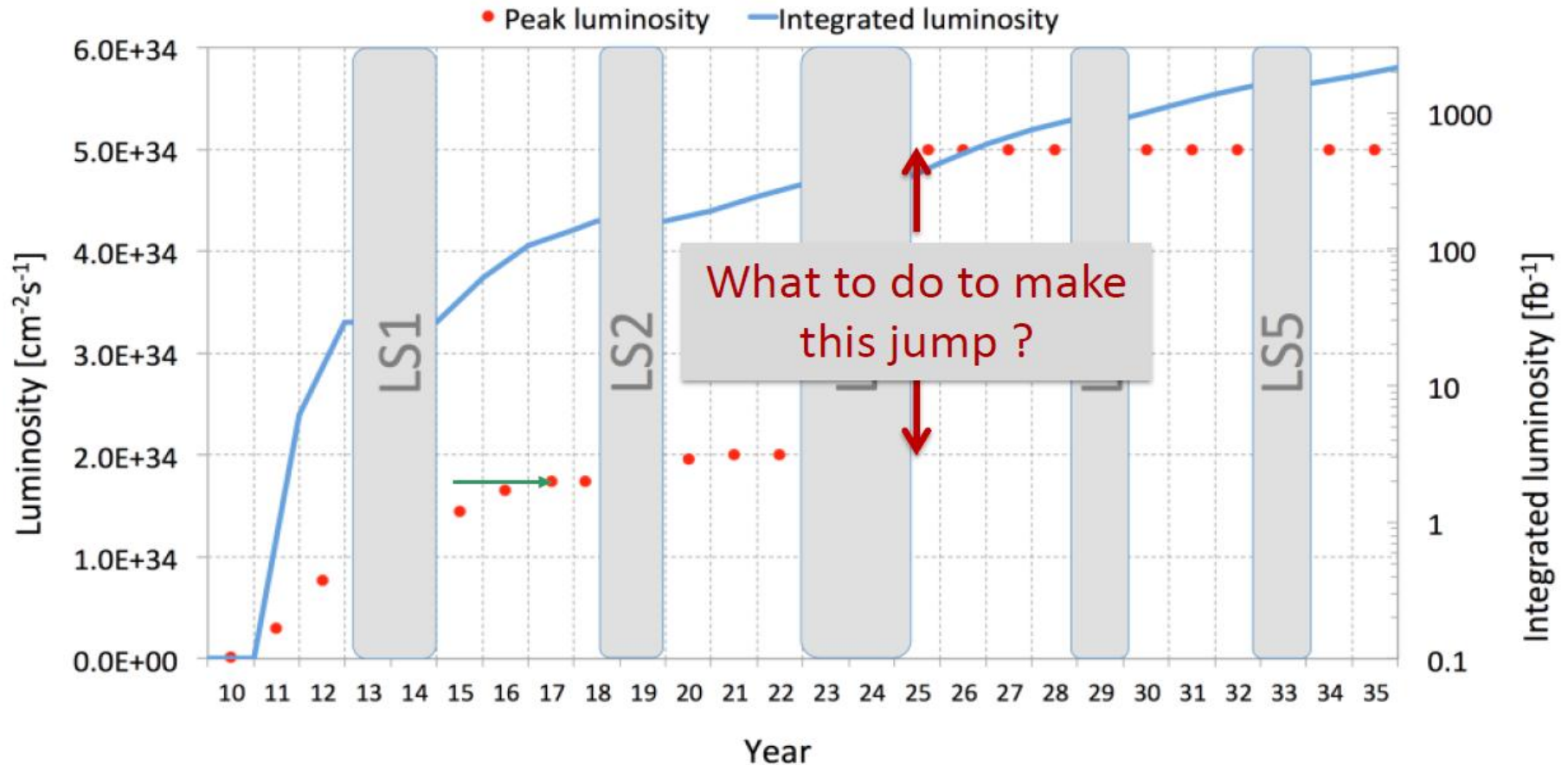
- We have levelled the luminosity of LHCb by adjusting the offsets between the beams.
- We are considering to level luminosities by adjusting the beam size at IP.
- Better / mandatory for beam stability.



Plans for next (two) decades



LHC high luminosity upgrade



High luminosity LHC performance 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 |
| β^* [m] | 0.55 | 0.15 |
| Normalized emittance ε_n [μm] | 3.75 | 2.5 |
| ε_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) [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$] | 1.2 (1.2) | 21.3 (7.2) |
| Max. Luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$] | 1 | 5.1 |
| Levelled Pile-up/Pile-up density [evt. / evt./mm] | 26/0.2 | 140/1.25 |

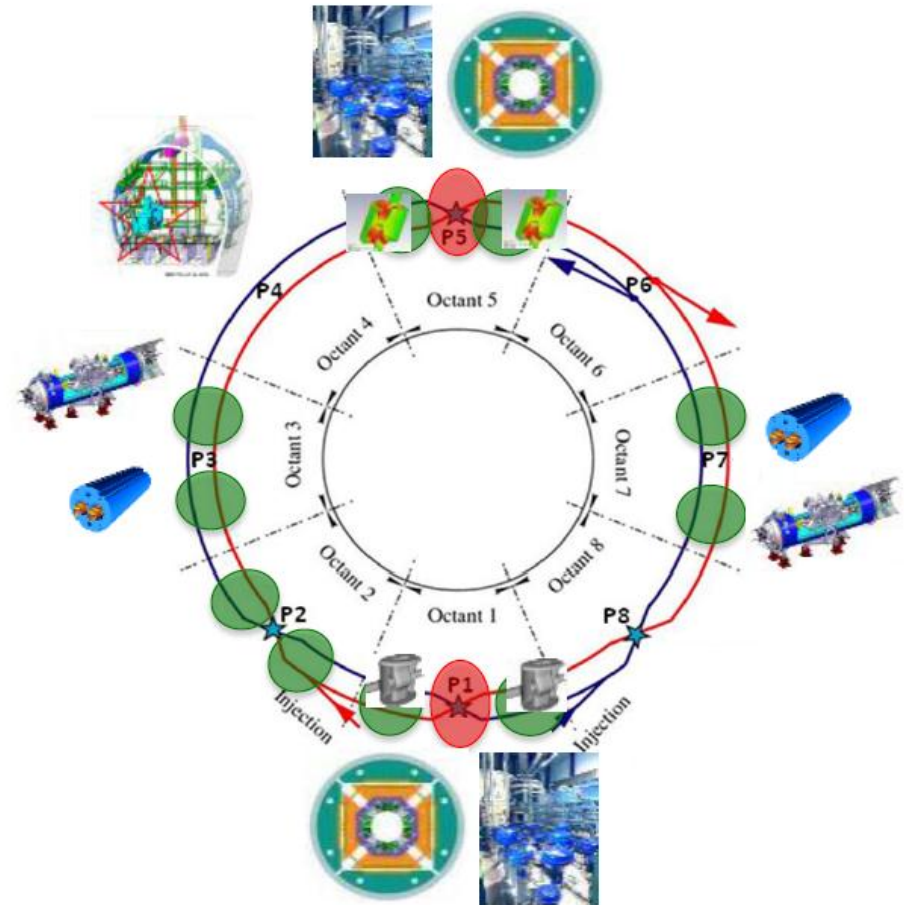
Aim for $\sim 250 \text{ fb}^{-1}/\text{y}$

$\Delta Q_{\text{bb}} \sim -0.01$

Hardware for the Upgrade

Main modifications

- New high field/larger aperture interaction region magnets
- Cryo-collimators and high field 11 T dipoles in dispersion suppressors
- Crab Cavities to take advantage of the small β^*
- New collimators (lower impedance)
- Additional cryo plants (P1, P4, P5)
- SC links to allow power converters to be moved to surface



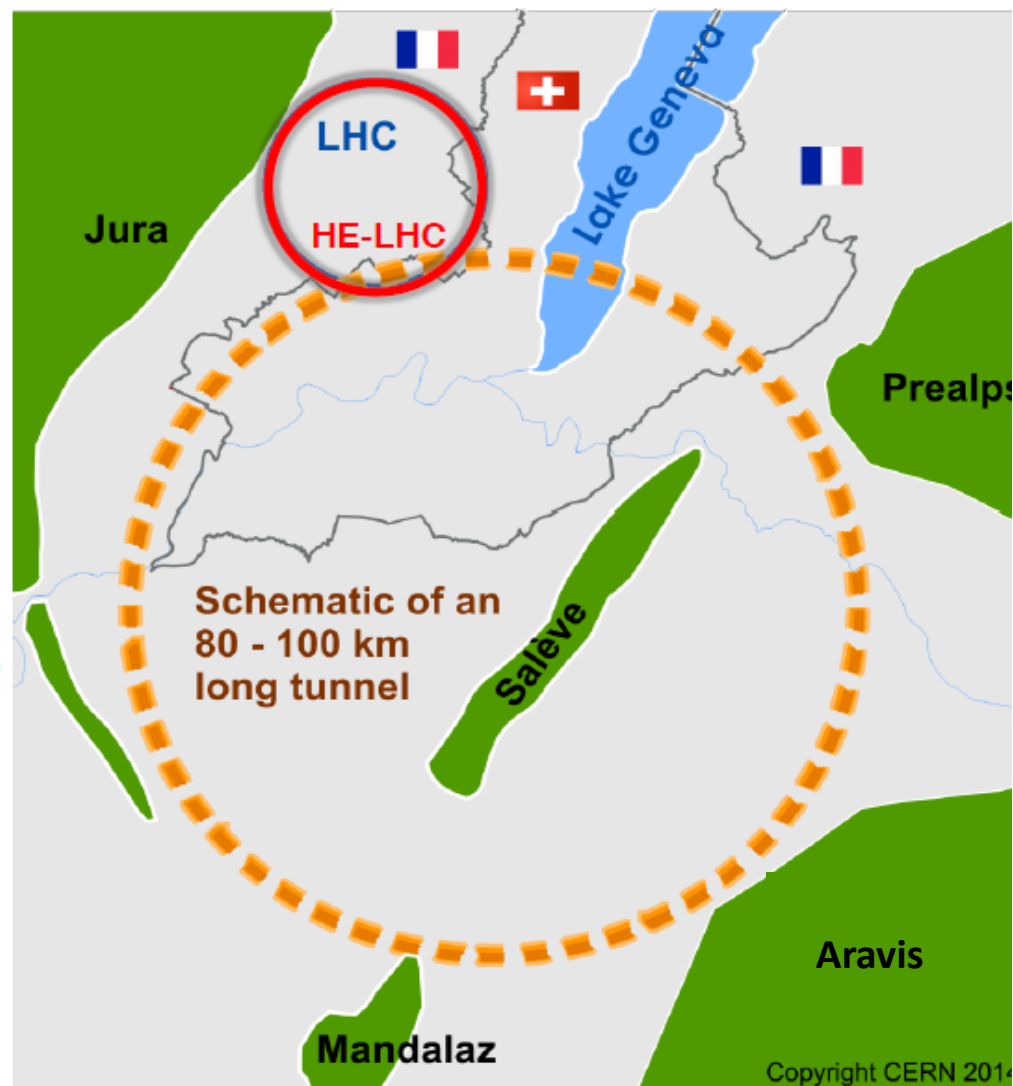
Future plans

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 | Particle Physics | Convert |
|---------------------------------------------|----------------------------|--------------------------------|
| Length m | Length fm | 1 eV = 1.6×10^{-19} J |
| Mass kg | Mass eV/c ² | 1 GeV = 10^9 eV |
| Time s | Time s | 1 TeV = 10^3 GeV |
| Energy kg m ² s ⁻² | Energy eV | 1 fm = 10^{-15} m |

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

HEP, SI and „natural” units

| Quantity | HEP units | SI units |
|------------------|-------------------------------|----------------------------|
| length | 1 fm | 10^{-15} m |
| charge | e | $1.602 \cdot 10^{-19}$ C |
| energy | 1 GeV | 1.602×10^{-10} J |
| mass | 1 GeV/c ² | 1.78×10^{-27} kg |
| $\hbar = h/2\pi$ | 6.588×10^{-25} GeV s | 1.055×10^{-34} Js |
| c | 2.988×10^{23} fm/s | 2.988×10^8 m/s |
| $\hbar c$ | 197 MeV fm | ... |

“natural” units ($\hbar = c = 1$)

| | |
|--------|------------------------------------------------|
| mass | 1 GeV |
| length | 1 GeV ⁻¹ = 0.1973 fm |
| time | 1 GeV ⁻¹ = 6.59×10^{-25} s |

Measuring particles

- Particles are characterized by
 - ✓ **Mass** [Unit: eV/c² or eV]
 - ✓ **Charge** [Unit: e]
 - ✓ **Energy** [Unit: eV]
 - ✓ **Momentum** [Unit: eV/c or eV]
 - ✓ (+ spin, lifetime, ...)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β, Q)
(p, m, Q) ...

- ... and move at **relativistic speed**

$$\beta = \frac{v}{c} \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$$l = \frac{l_0}{\gamma} \quad \text{length contraction}$$

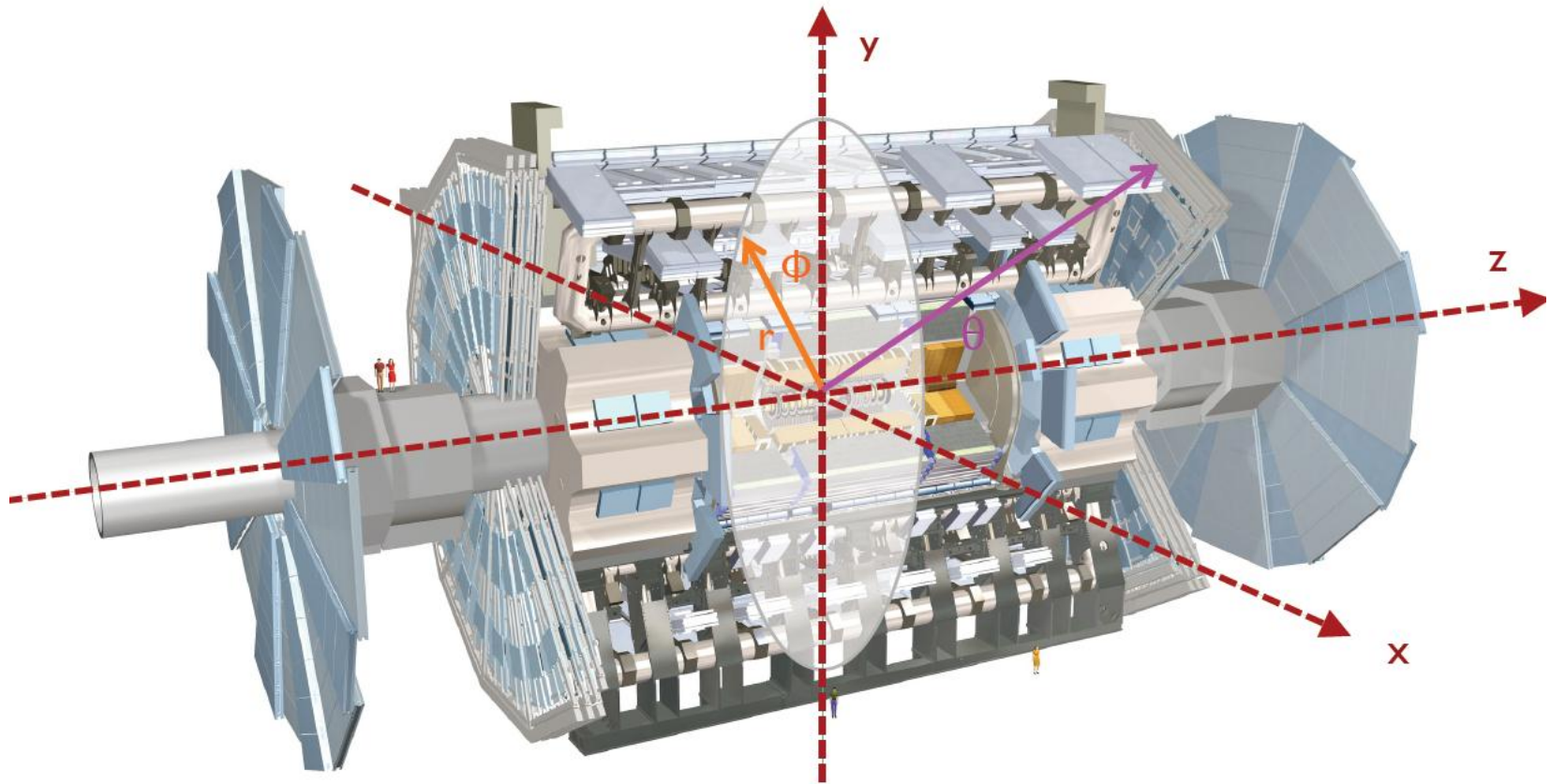
$$t = t_0 \gamma \quad \text{time dilatation}$$

$$E^2 = \vec{p}^2 c^2 + m^2 c^4$$

$$E = m \gamma c^2 = m c^2 + E_{\text{kin}}$$

$$\vec{\beta} = \frac{\vec{p}c}{E} \quad \vec{p} = m \gamma \vec{\beta} c$$

Collider experiment coordinates



Rapidity

Lorentz factor $\gamma = \frac{1}{\sqrt{1 - \beta^2}} = \cosh \varphi$ Hyperbolic cosine of “rapidity”

$$\begin{aligned} E &= m \cosh \varphi & \varphi &= \tanh^{-1} \frac{E}{|\vec{p}|} = \frac{1}{2} \ln \frac{E + |\vec{p}|}{E - |\vec{p}|} \\ |\vec{p}| &= m \sinh \varphi \end{aligned}$$

- Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

Pseudorapidity

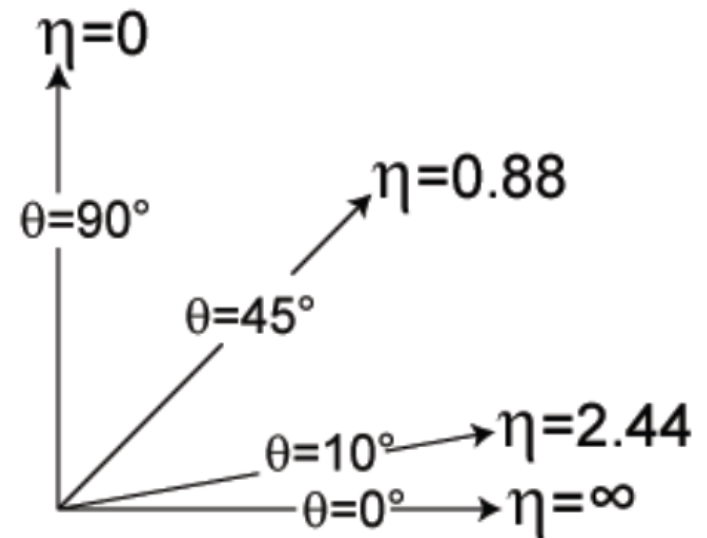
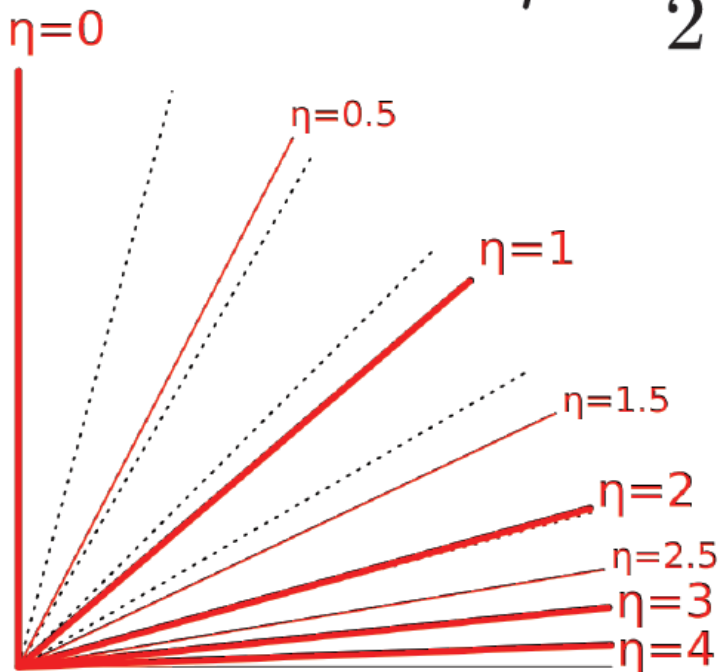
$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

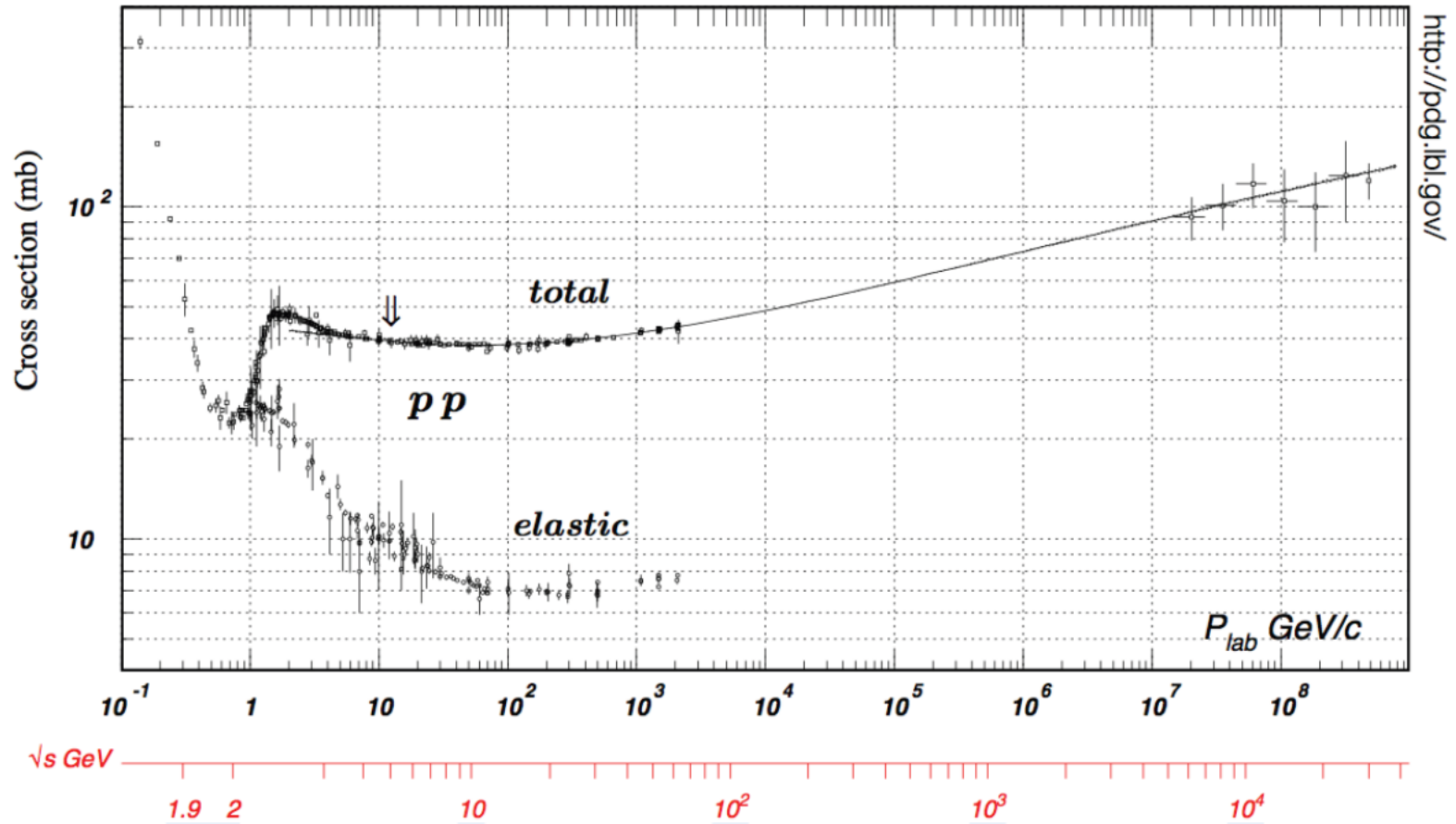
$$\eta \simeq y$$

if $E \gg m$

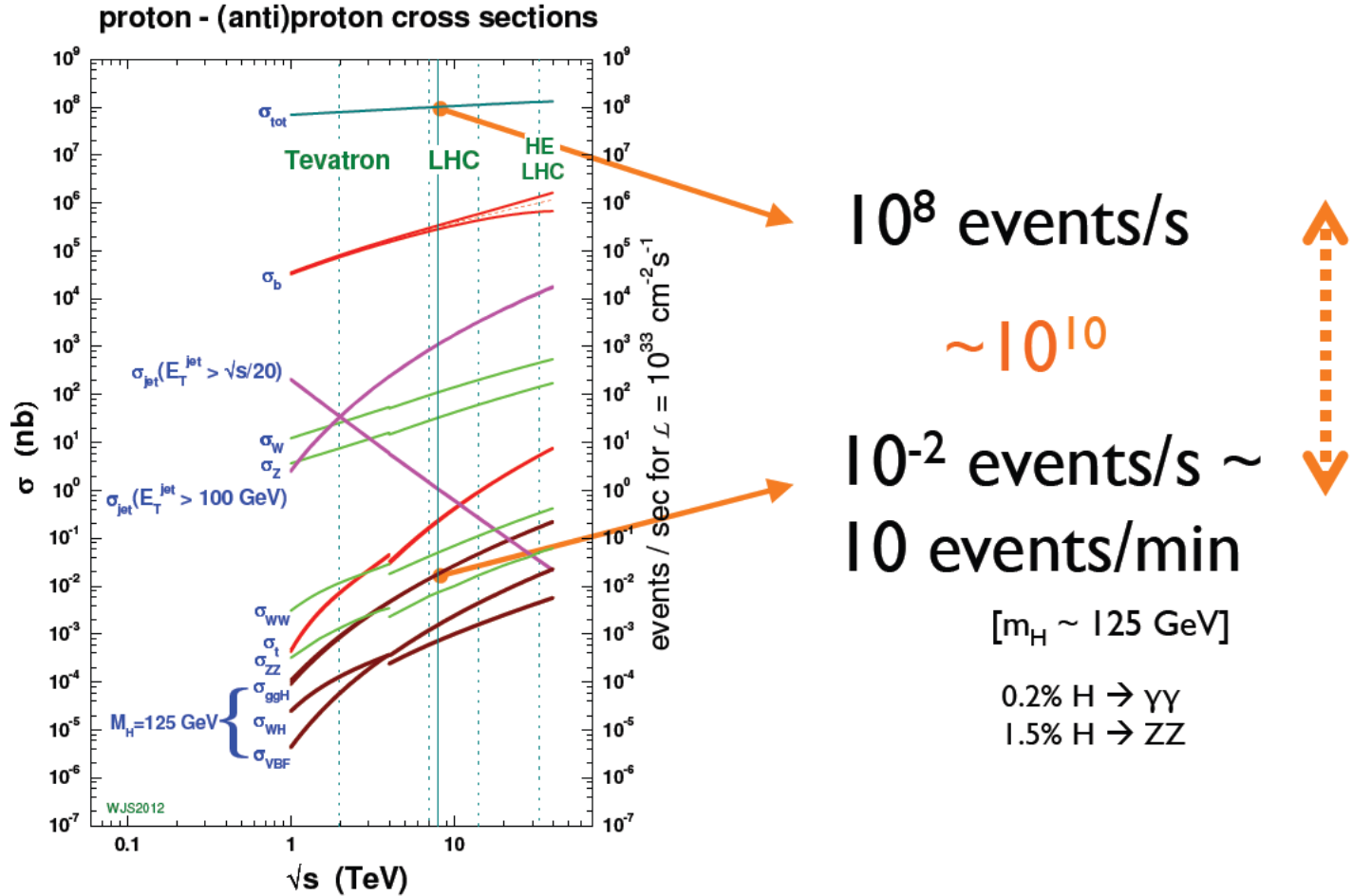
$$\eta = \frac{1}{2} \ln \left(\tan \frac{\theta}{2} \right)$$



Proton-proton scattering cross-section

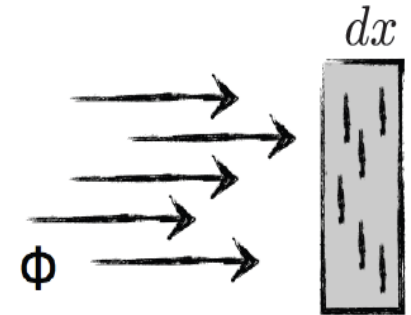


Cross-sections at LHC



Interaction cross-section

Flux $\Phi = \frac{1}{S} \frac{dN_i}{dt}$ $[L^{-2} t^{-1}]$



Reactions per unit of time $\frac{dN_{\text{reac}}}{dt} = \Phi \underbrace{\sigma}_{\text{area obscured by target particle}} N_{\text{target}} dx$ $[t^{-1}]$

$[L^{-2} t^{-1}]$ $[?]$ $[L^{-1}]$ $[L]$

Reaction rate per target particle $W_{if} = \Phi \sigma$ $[t^{-1}]$

Cross section per target particle $\sigma = \frac{W_{if}}{\Phi}$ $[L^2]$ = reaction rate per unit of flux

$1b = 10^{-28} \text{ m}^2$ (roughly the area of a nucleus with $A = 100$)

Fermi Golden rule

From non-relativistic perturbation theory...

transition probability matrix element energy density of final states

$$W_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \frac{dN}{dE_f}$$

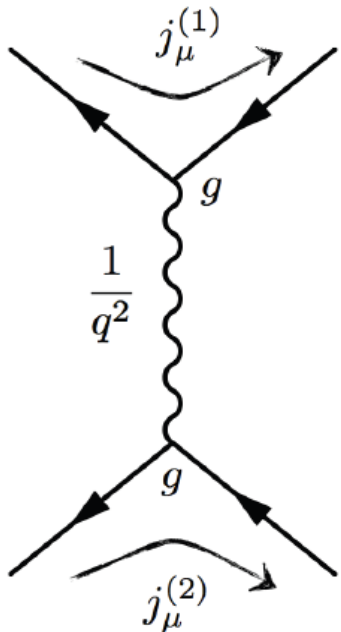
[t⁻¹]

[E]

[E⁻¹]

$$M_{if} = -i \int j_\mu^{(1)} \left(\frac{1}{q^2} \right) j_\mu^{(2)} d^4x$$

$$\sigma \sim |M_{if}|^2 \sim g^4 \left(\frac{1}{q^4} \right)$$



Cross-section: magnitude and units

Standard

cross section unit:

$$[\sigma] = \text{mb}$$

with $1 \text{ mb} = 10^{-27} \text{ cm}^2$

or in

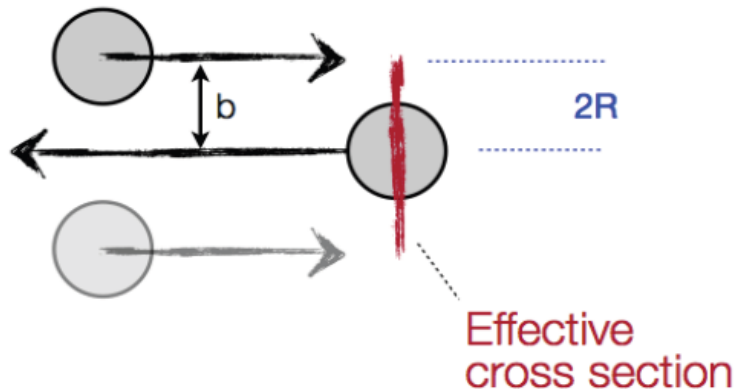
natural units:

$$[\sigma] = \text{GeV}^{-2}$$

with $1 \text{ GeV}^{-2} = 0.389 \text{ mb}$

$1 \text{ mb} = 2.57 \text{ GeV}^{-2}$

Estimating the
proton-proton cross section:



using: $\hbar c = 0.1973 \text{ GeV fm}$
 $(\hbar c)^2 = 0.389 \text{ GeV}^2 \text{ mb}$

Proton radius: $R = 0.8 \text{ fm}$

Strong interactions happens up to $b = 2R$

$$\begin{aligned}\sigma &= \pi (2R)^2 = \pi \cdot 1.6^2 \text{ fm}^2 \\ &= \pi \cdot 1.6^2 \cdot 10^{-26} \text{ cm}^2 \\ &= \pi \cdot 1.6^2 \cdot 10 \text{ mb} \\ &= 80 \text{ mb}\end{aligned}$$

Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$p_T = \sqrt{p_x^2 + p_y^2}$$
$$p_x = p_T \cos \phi$$
$$p_y = p_T \sin \phi$$
$$p_z = p_T \sinh \eta$$
$$|p| = p_T \cosh \eta$$
$$E_T = \frac{E}{\cosh \eta}$$

$$\sum p_x(i) = 0 \quad \sum p_y(i) = 0$$

Missing transverse energy and transverse mass

- If invisible particles are created, only their transverse momentum can be constrained: **missing transverse energy**

$$E_T^{\text{miss}} = \sum p_T(i)$$

- If a heavy particle is produced and decays into two particles one of which is invisible, the mass of the parent particle can be constrained with the **transverse mass quantity**

$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\mathbf{p}_T(1) + \mathbf{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \mathbf{p}_T(1) \cdot \mathbf{p}_T(2)] \end{aligned}$$

if $m_1 = m_2 = 0$ $M_T^2 = 2|\mathbf{p}_T(1)||\mathbf{p}_T(2)|(1 - \cos \phi_{12})$

Event pileup in LHC experiments

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

Event pile up for one bunch crossing:

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

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

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

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

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

$\text{frev}_{\text{LHC}} = 1.1246 \times 10^4 \frac{1}{\text{s}}$ and $N_{\text{bunches_1beam}} = 2808$

Number of events per bunch crossing: $L \cdot \frac{\sigma_{\text{tot}}}{\text{frev}_{\text{LHC}} \cdot N_{\text{bunches_1beam}}} = 31.7$