Introduction to particle physics: experimental part

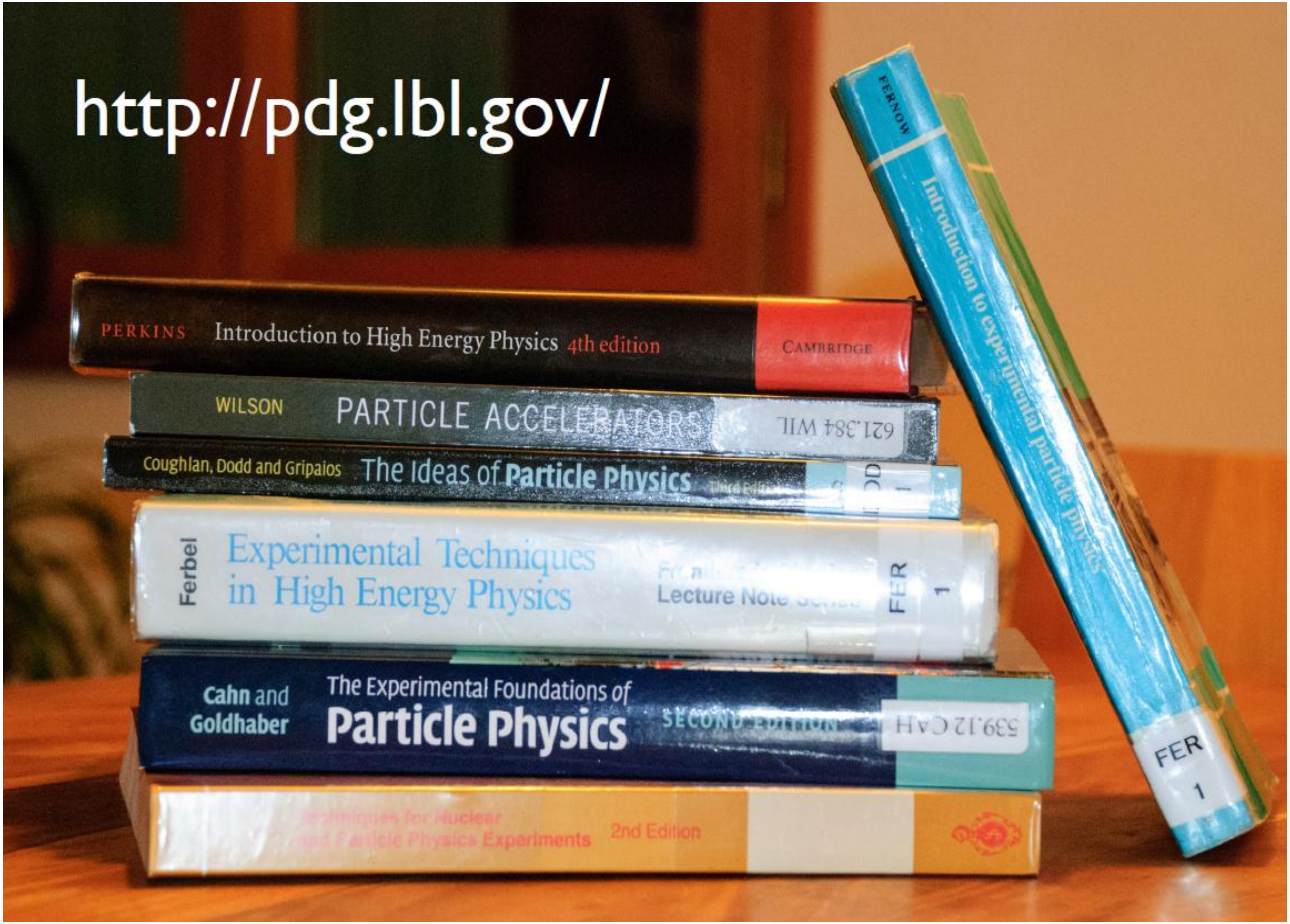
Few words about Standard Model

Accelerators

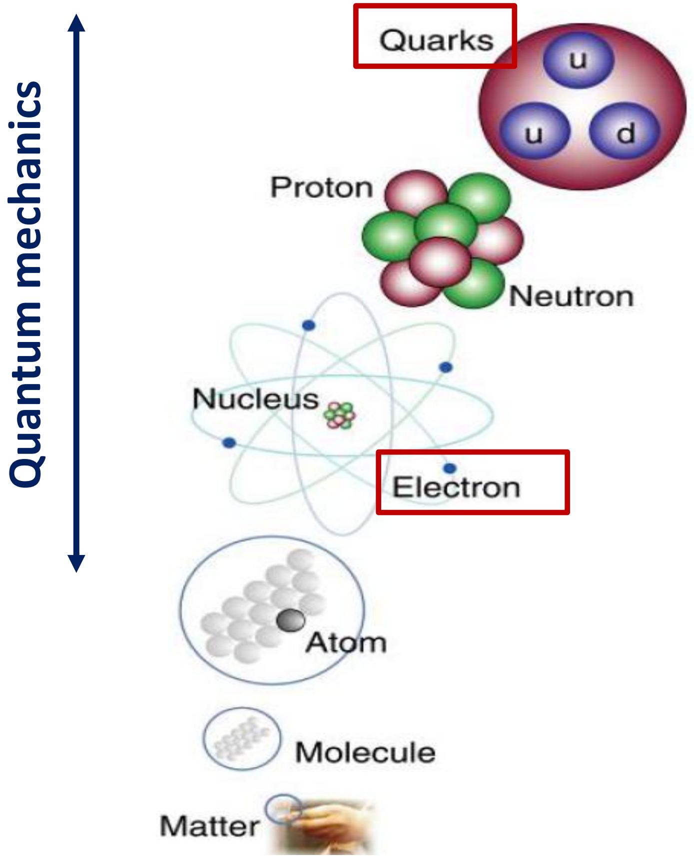
CERN and LHC

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

http://pdg.lbl.gov/

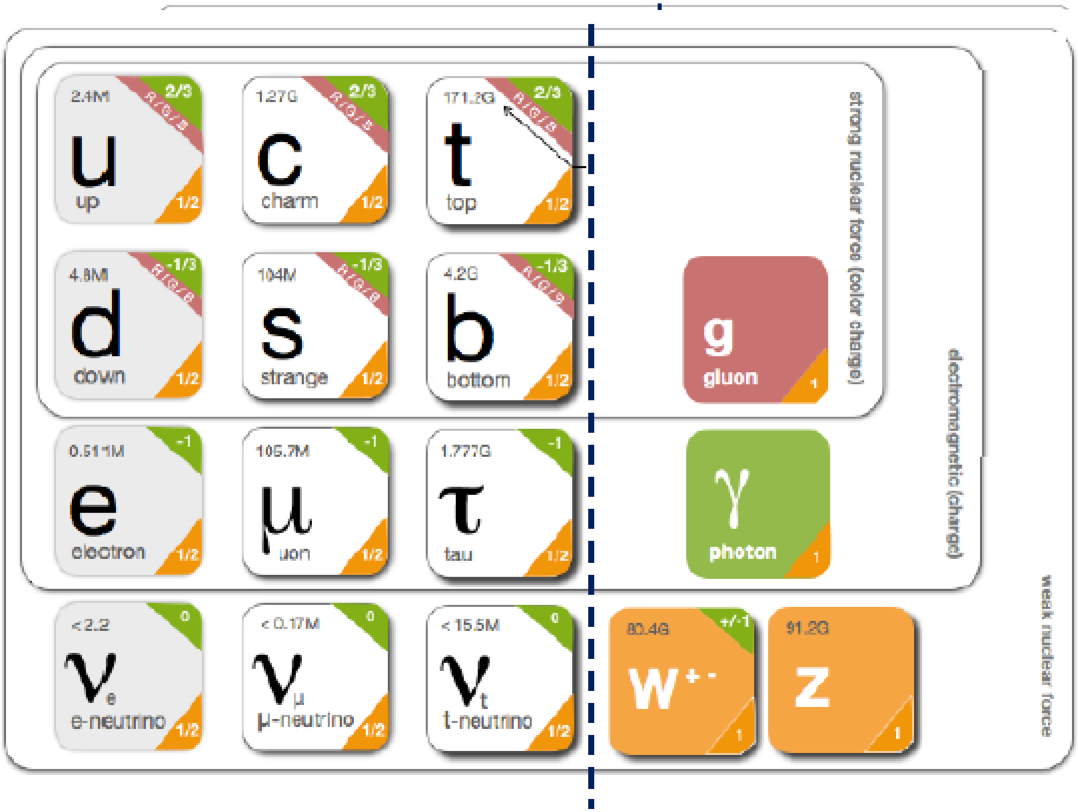


Particles of the Standard Model



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

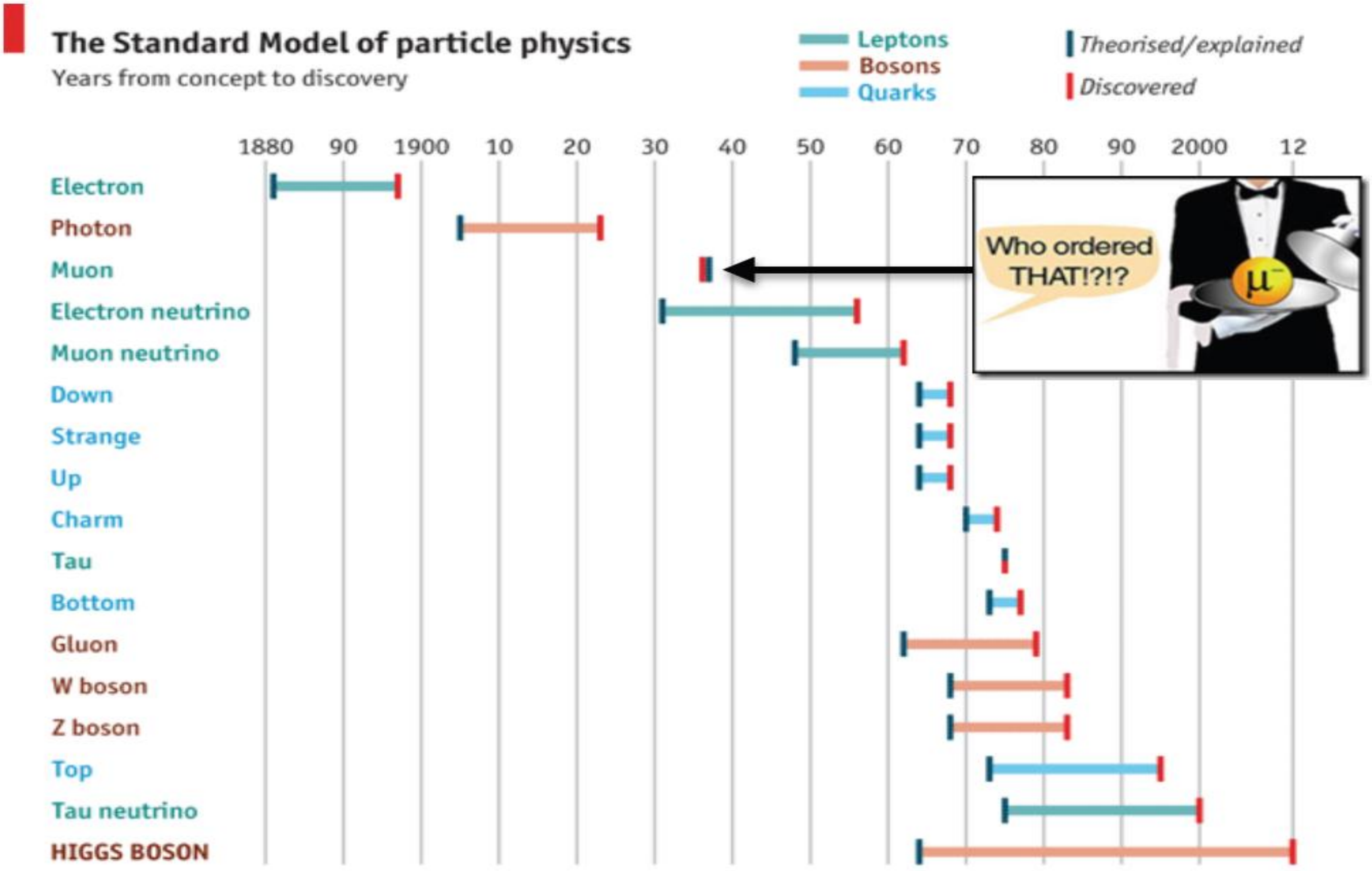
GREEN - theoretical
BLUE - experimental

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

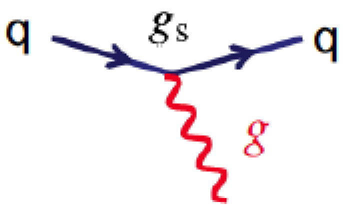
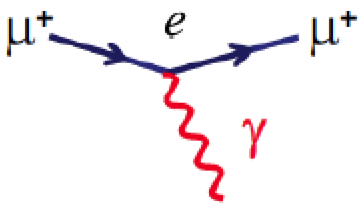
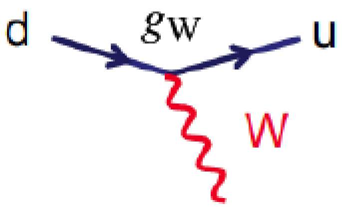
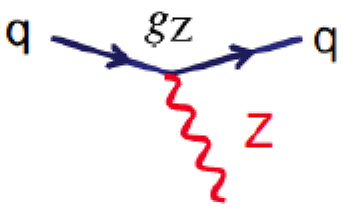
Uncharted discoveries?



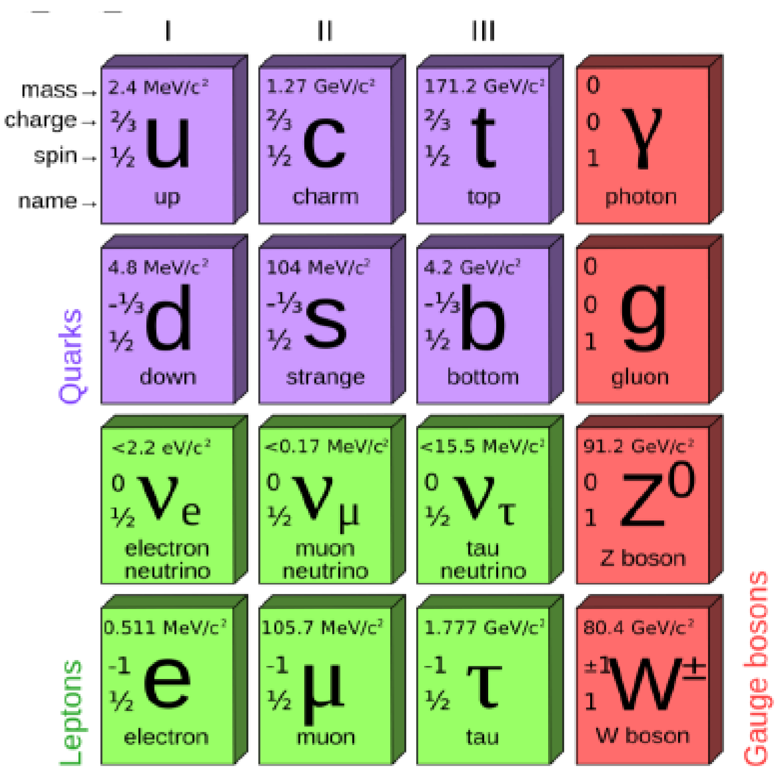
Source: *The Economist*

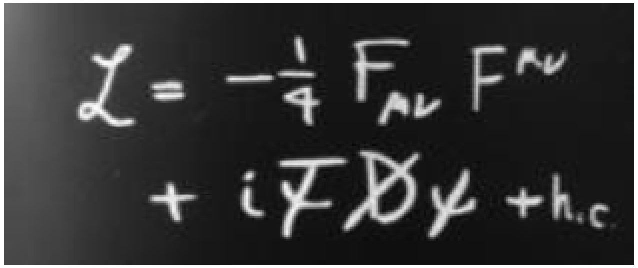
Interactions

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

STRONG	**EM**	**WEAK CC**	**WEAK NC**
			
Only quarks	All charged fermions	All fermions	All fermions
Never changes flavour	Never changes flavour	Always changes flavour	Never changes flavour
$\alpha_S \sim$ **1/10**	$\alpha \simeq 1/137$	$\alpha_{W/Z} \sim 1/40$	
Gluons	**Photon**	**W+, W-**	**Z^0**
massless	massless	very massive	very massive

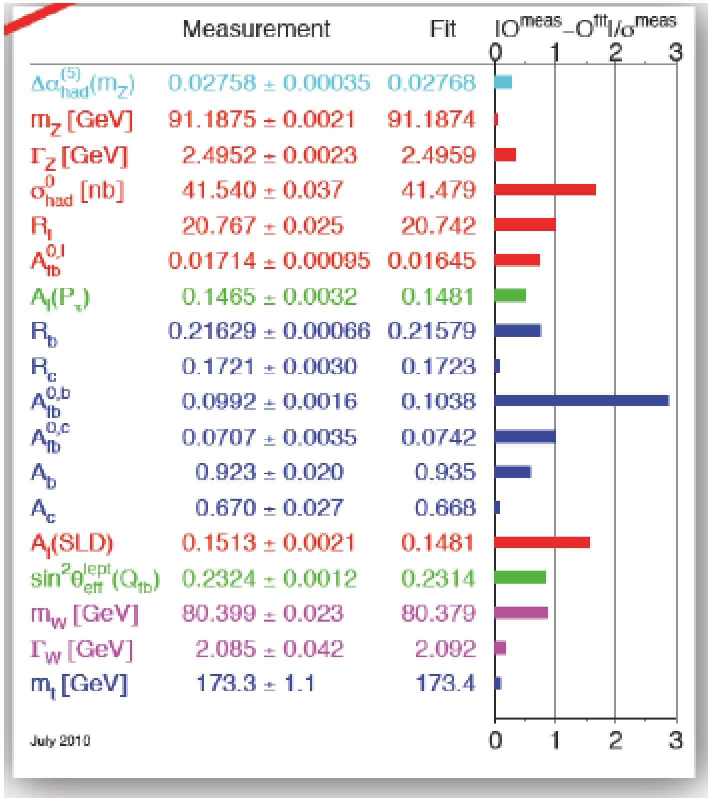
Standard Model confirmed by the data





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

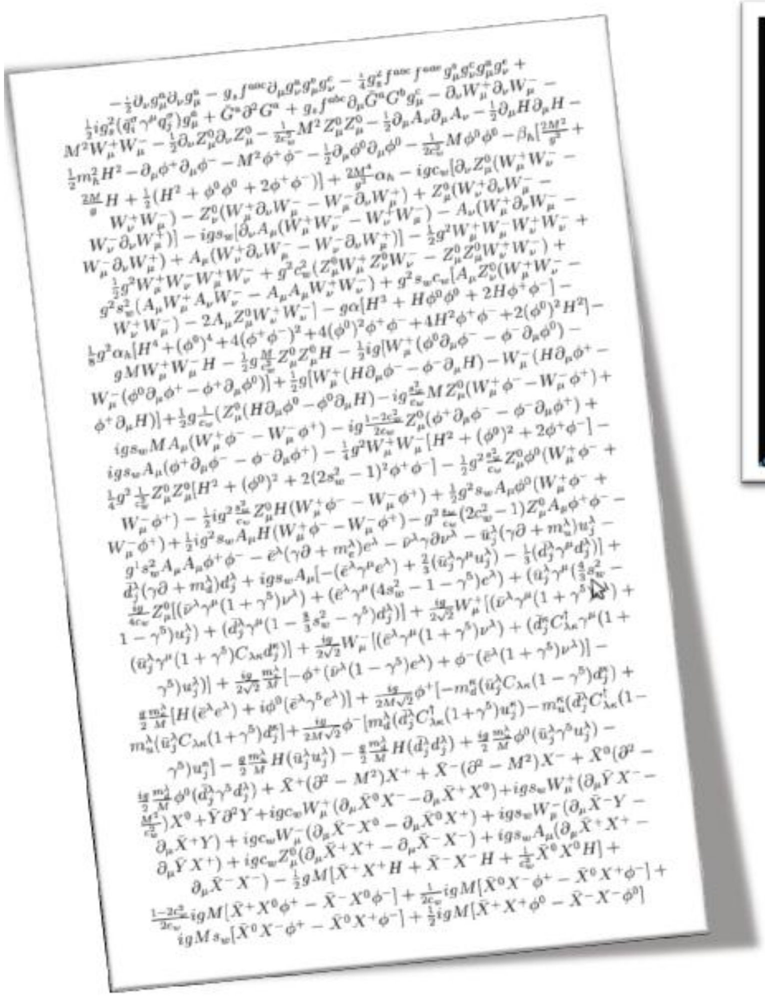
STANDARD MODEL OF ELEMENTARY PARTICLES

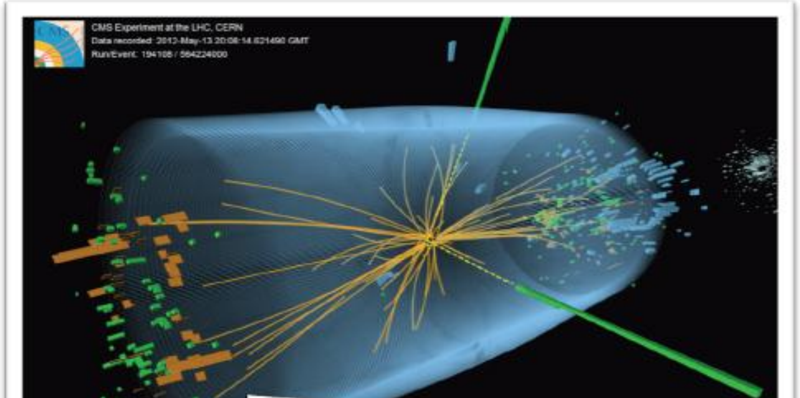


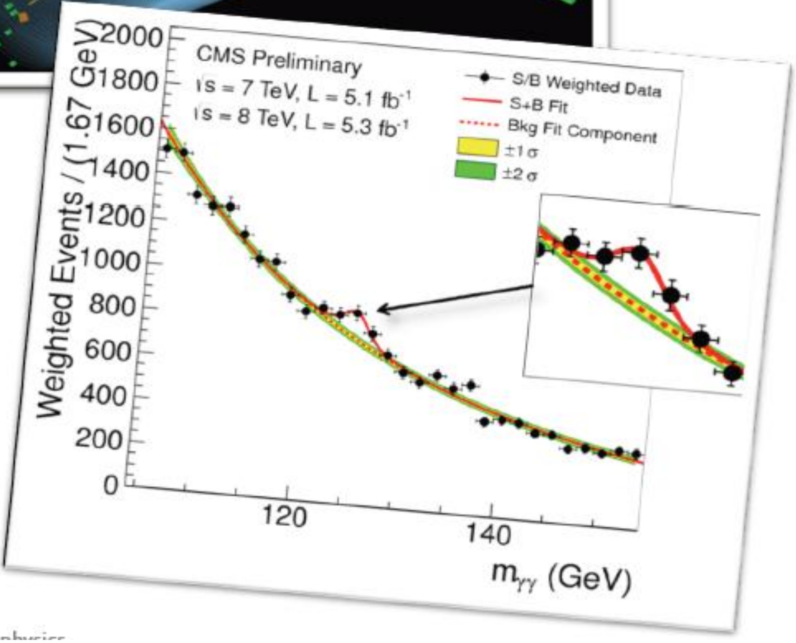
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	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
Γ_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

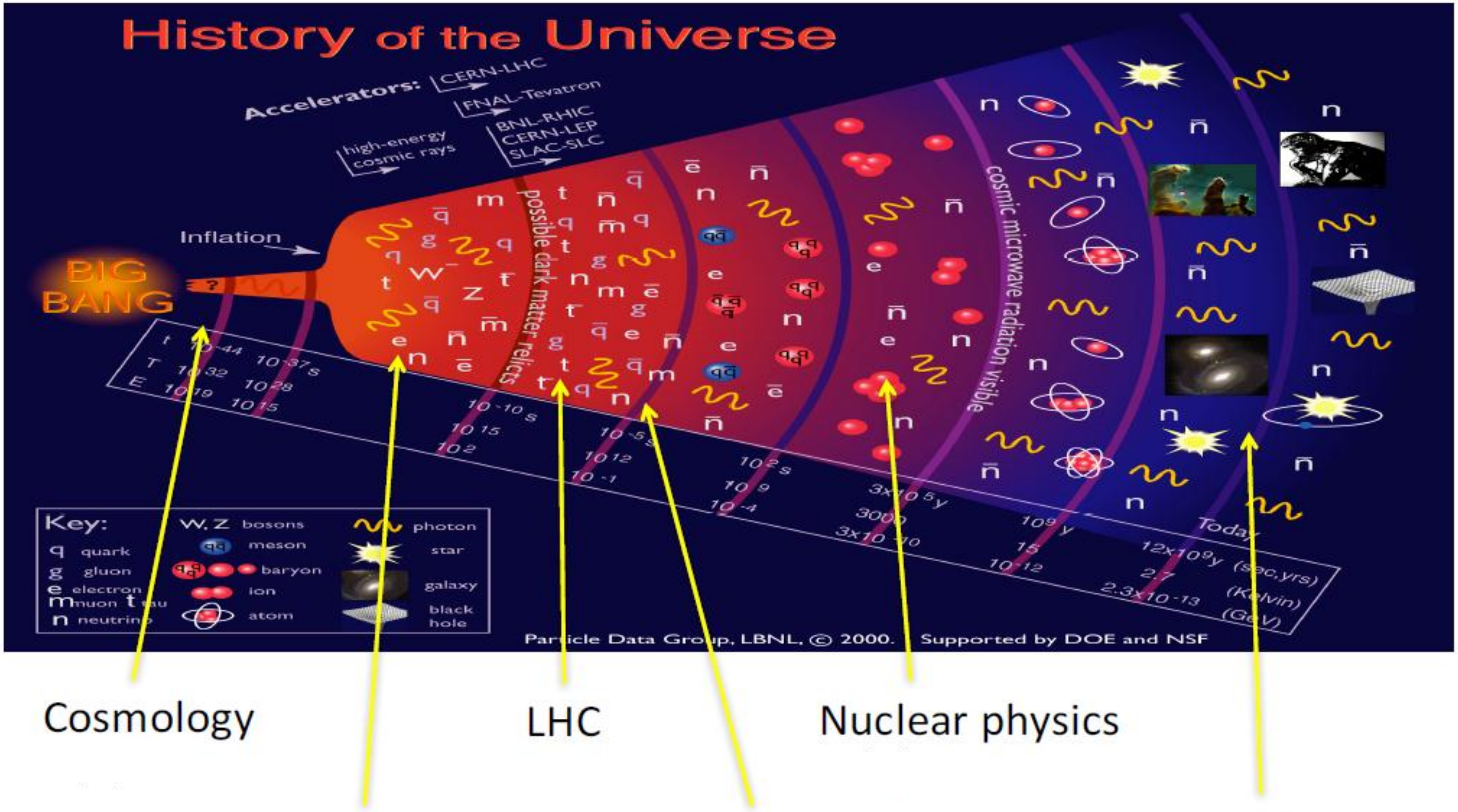






Accelerators for high energy physics experiments

History of the Universe



Cosmology

LHC

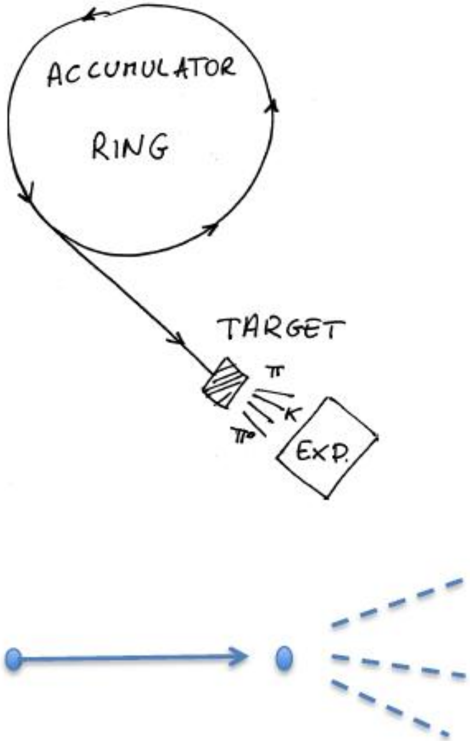
Nuclear physics

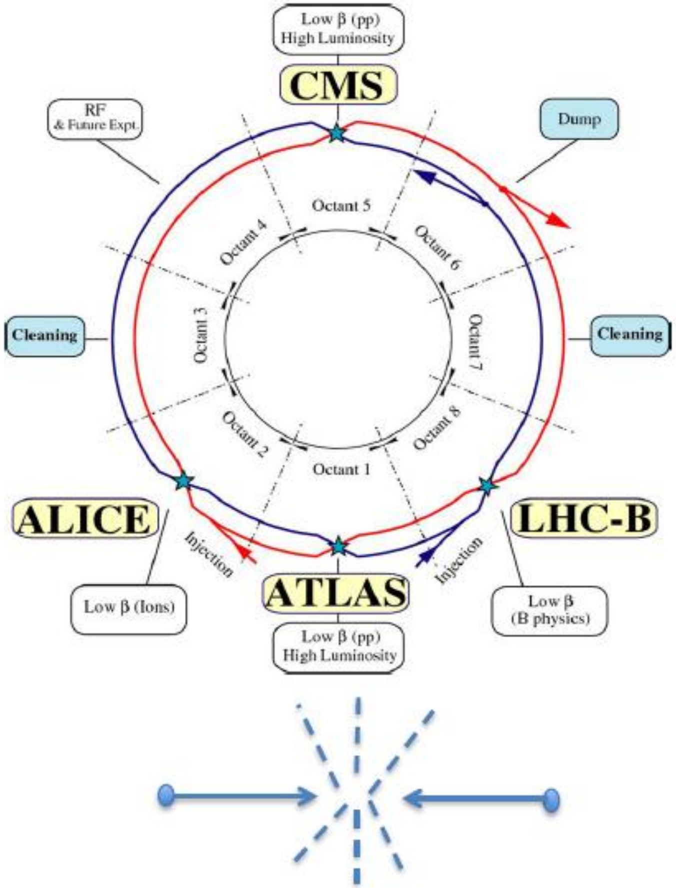
Cosmic rays

Quark/gluon plasma

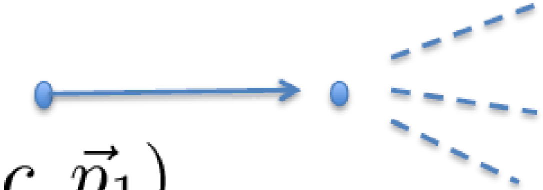
Astrophysics

Fixed target vs Colliders





E_{CM} in Fixed Target Experiment



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

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

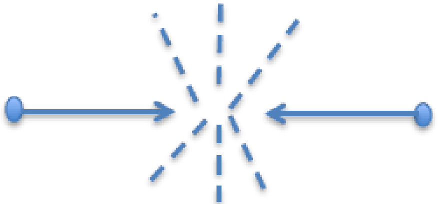
$$p_{tot} = (E_1/c + m_2 c, \vec{p}_1)$$

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

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

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

$$\mathbf{F} = q\left(\underset{\substack{\nearrow \\ \text{Electric field}}}{\mathbf{E}} + \underset{\substack{\uparrow \\ \text{Velocity}}}{\mathbf{v}} \times \underset{\substack{\nwarrow \\ \text{Magnetic field}}}{\mathbf{B}}\right)$$

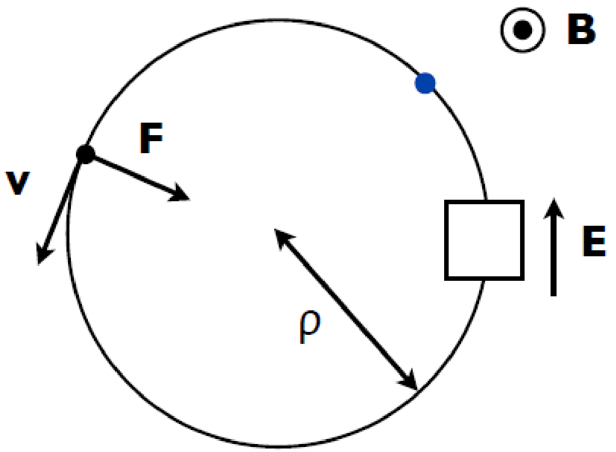
Energy change

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

- 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

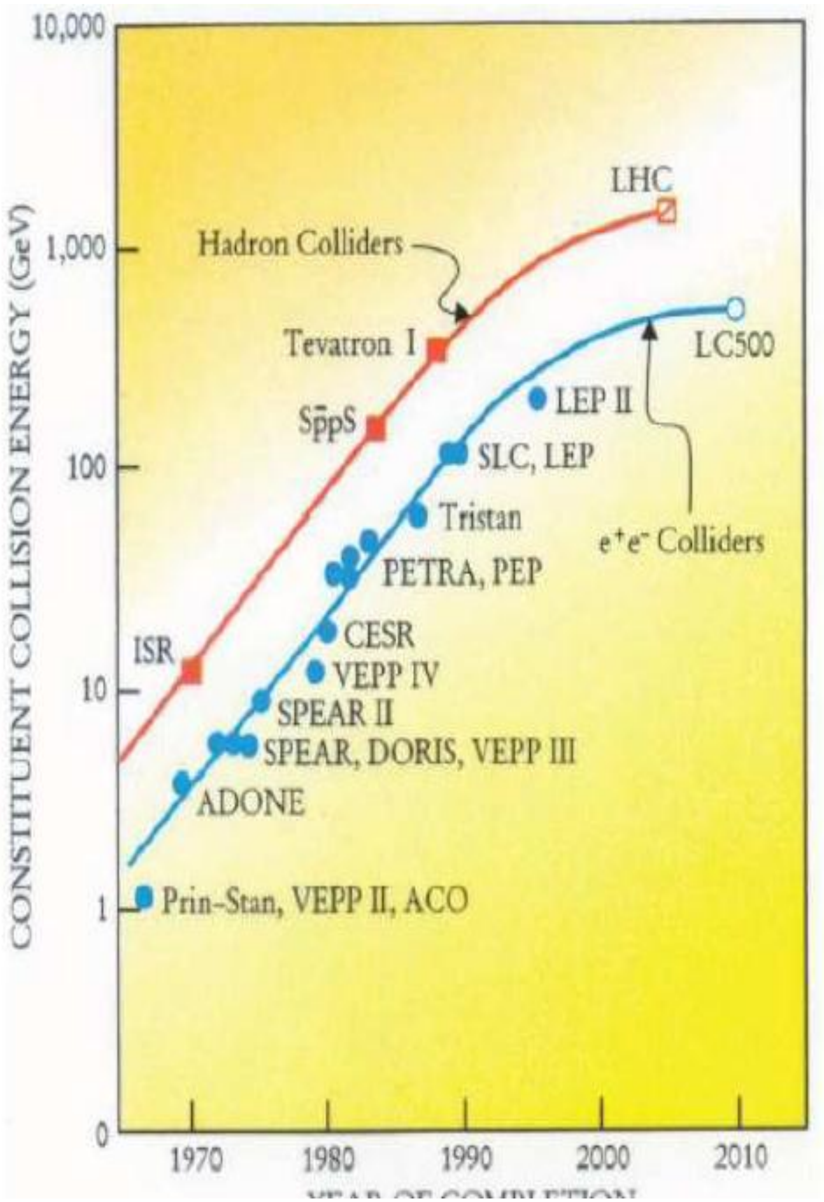
1971-1984: ISR (CERN), p+,p+, 31.5 GeV, 948 m circumference

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

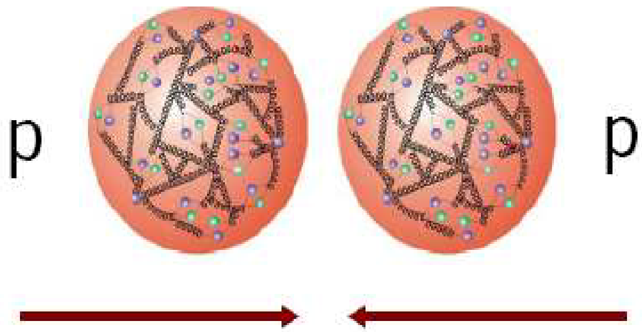
2008 - : LHC highest energy proton synchrotron, p+,p+, heavy ions, 6.5 TeV (2.76 TeV per nucleon for $^{208}\text{Pb}^{82+}$); Discovery of Higgs

Energy frontier

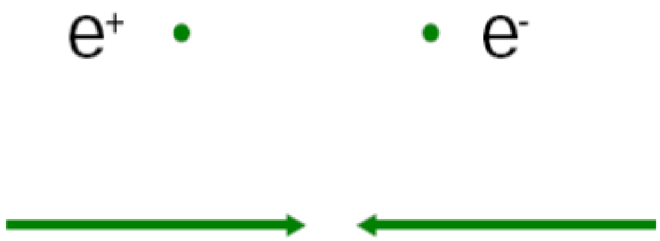


- The interplay between electron and hadron machines has a long and fruitful tradition
  - J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
  - Υ discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
  - …
  - top quark at LEP and Tevatron
- To be continued in the form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

Complementarity between pp and ee machines



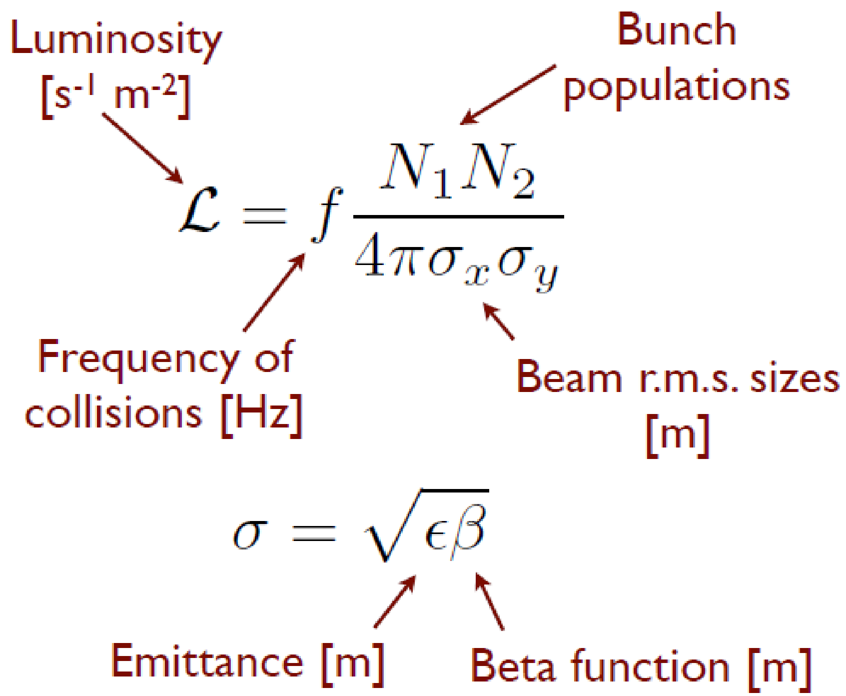
- Proton-(Anti-)Proton Colliders
  - Higher energy reach (limited by magnets)
  - Composite particles: unknown and different colliding constituents, energies in each collision
  - Confusing final states
- Discovery machines (W, Z, t)
- In some cases: precision measurements possible (W mass at the Tevatron)



- Electron-Positron-Colliders
  - Energy reach limited by RF
  - Point like particles, exactly 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]

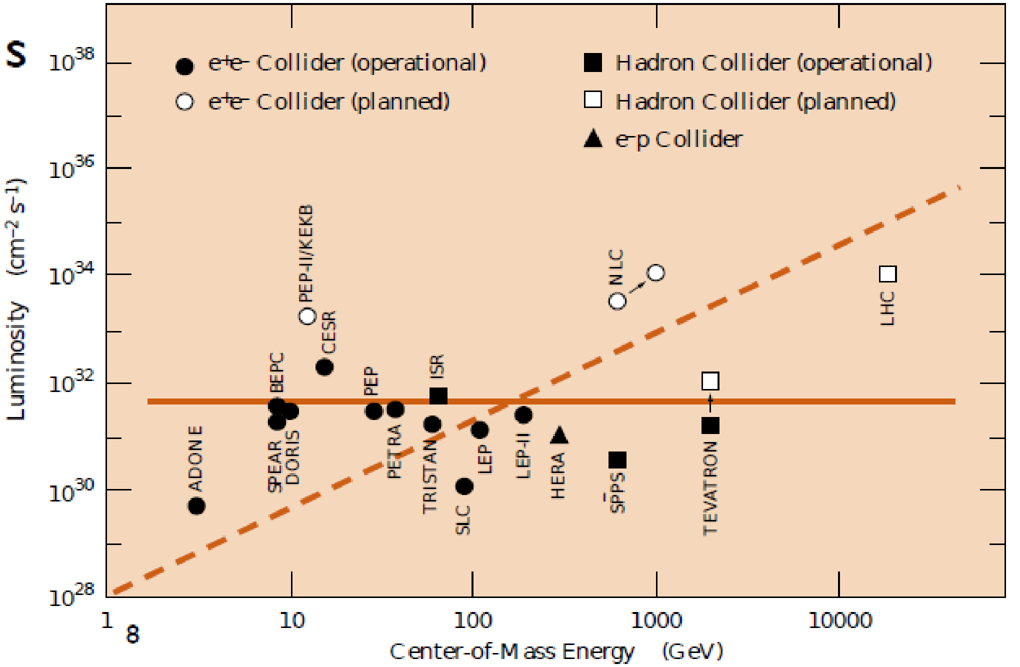
$$\mathcal{L} = f\frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

Luminosity frontier

- Need corresponding rise in luminosity (beam intensity)

$$\overset{\text{Number of events}}{N} = \underset{\text{Cross section}}{\sigma}\,\underset{\text{Integrated luminosity}}{L} = \sigma \int \overset{\text{Instantaneous luminosity}}{\mathcal{L}}\, dt$$

- 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

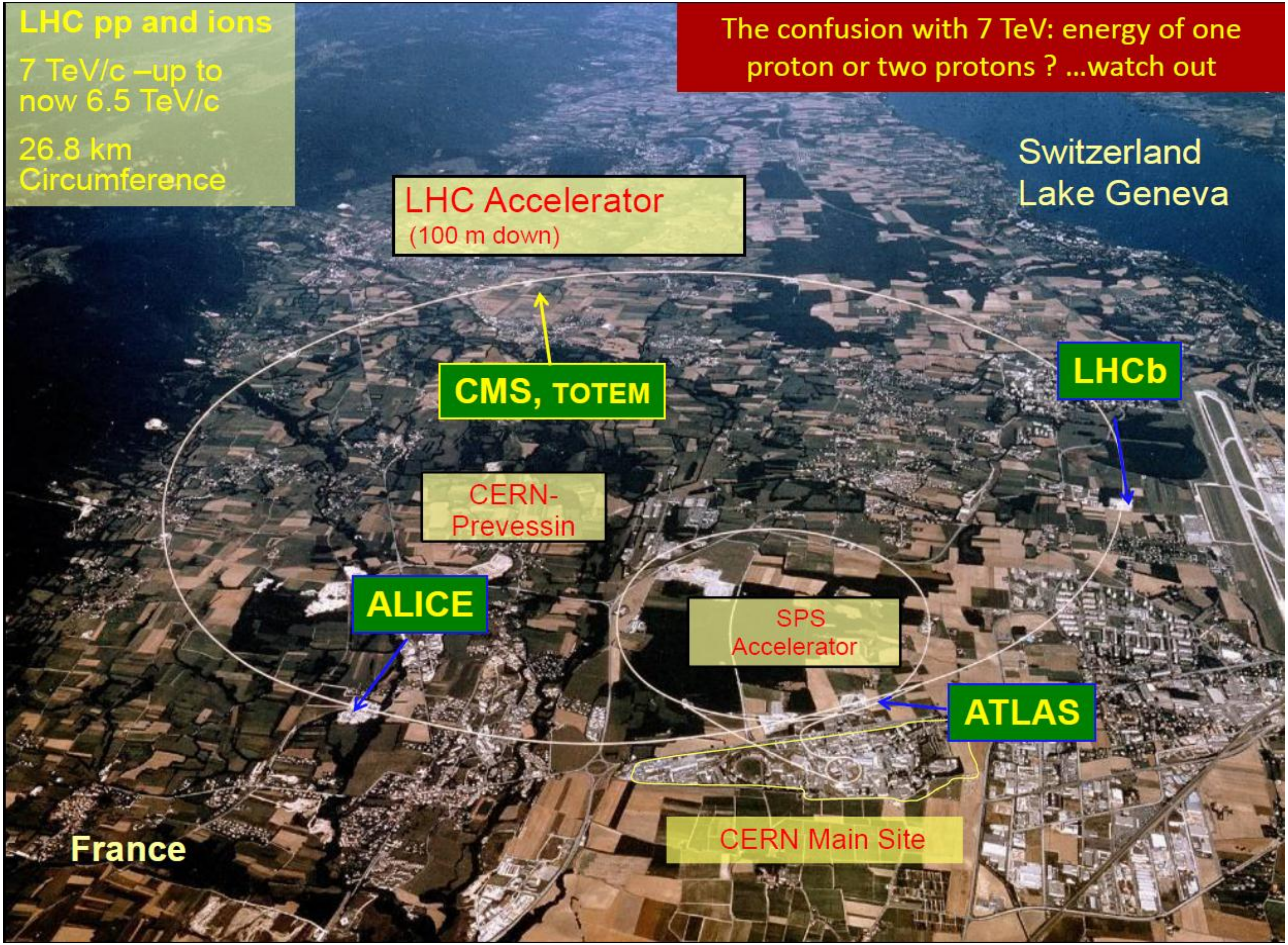
- How do you produce antiparticles?
- Ones produced how ones keep them (muon collider)?
- Ones collided what ones does with spent beams?
- Accelerator and detector protection

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



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

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} [cm^{-2}s^{-1}]** (challenge for the LHC accelerator)
- Event rate:

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

- 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

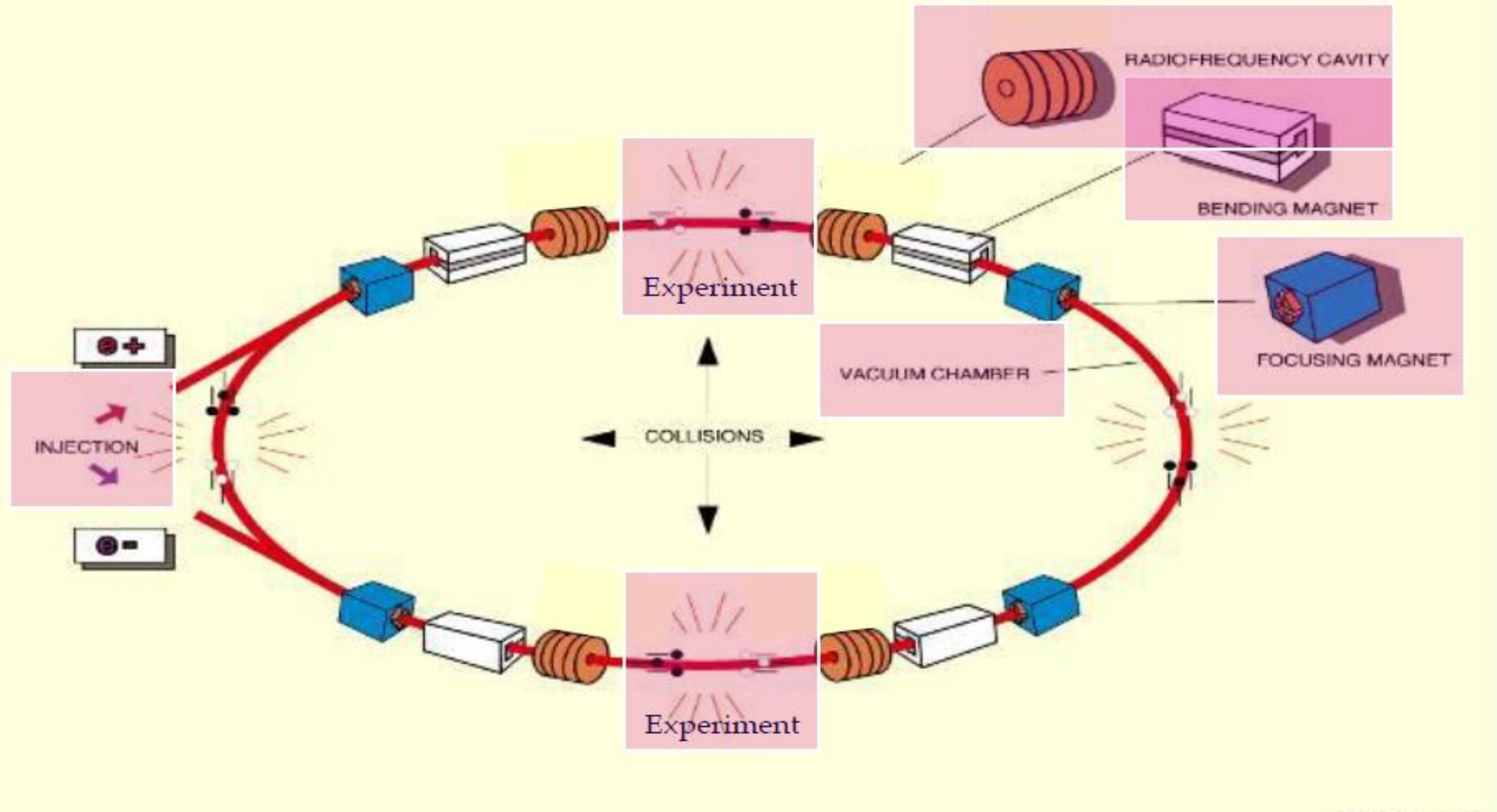
- The total number of particles created at an accelerator (the total number of Higgs bosons) is proportional to the Integrated Luminosity:

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

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

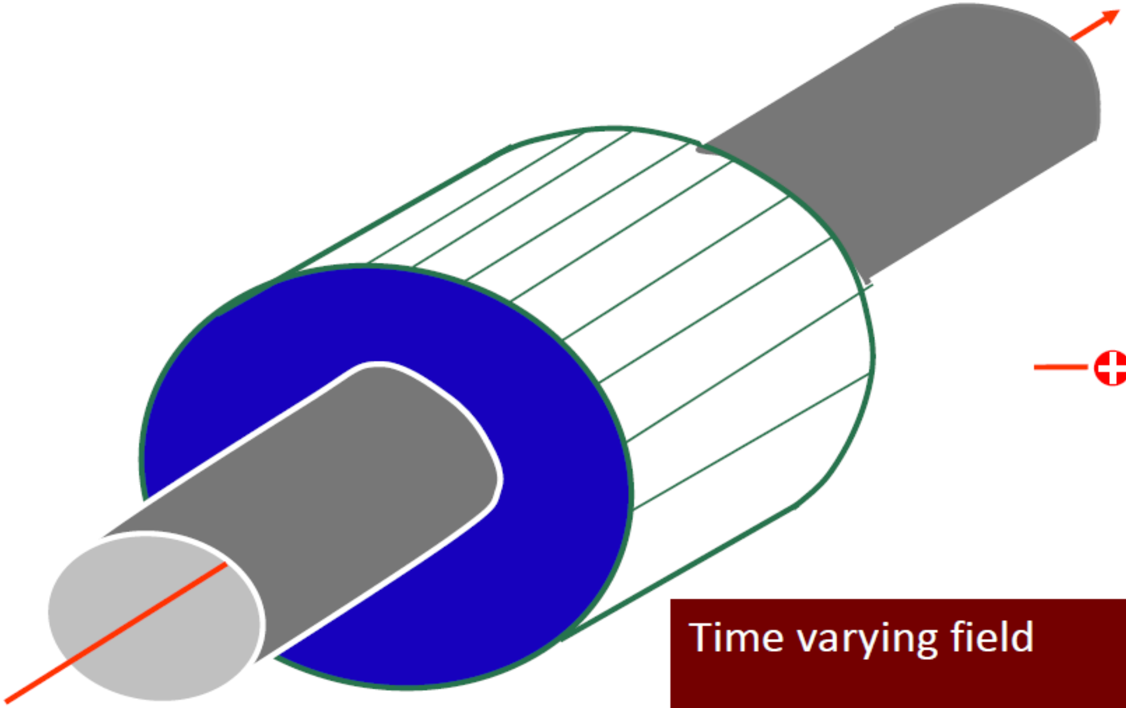
Synchrotron + many passages in RF cavities

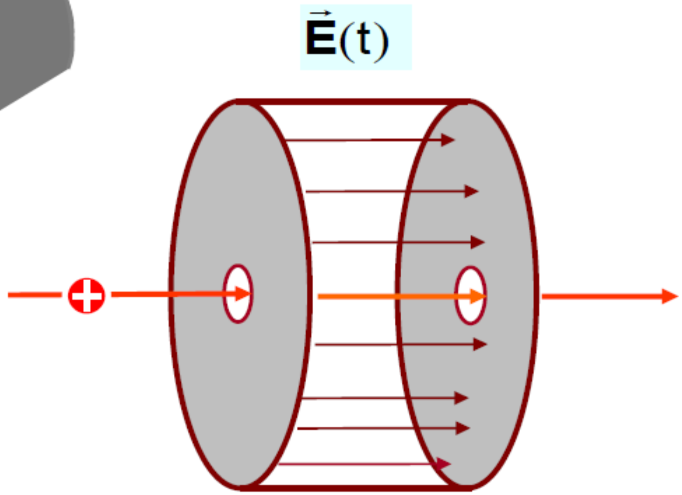
LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes



CERN AC - ES09

Particle acceleration in RF cavity





LHC RF frequency
400 MHz

Revolution frequency
11246 Hz

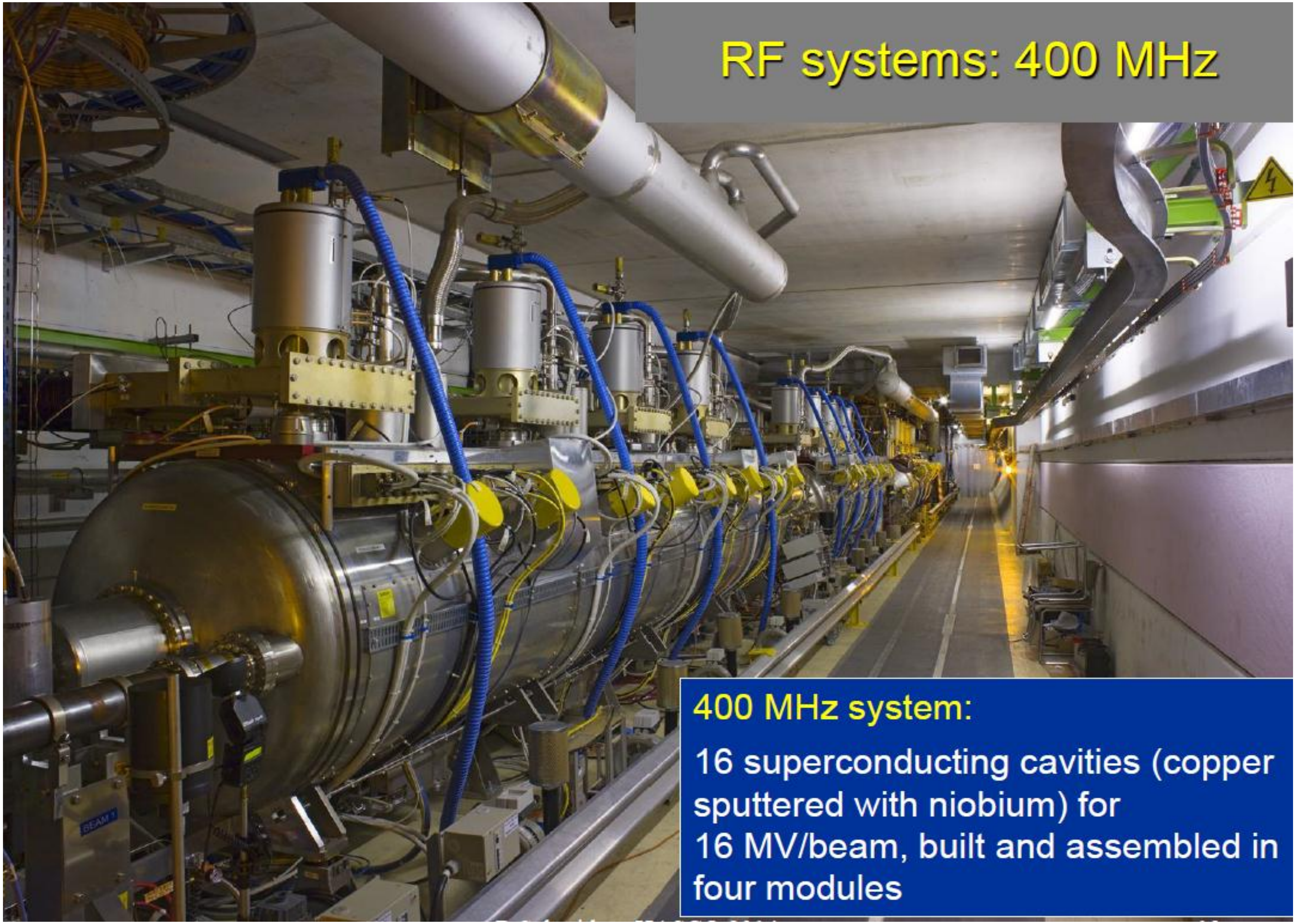
Time varying field

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

Maximum field about 20 MV/m

Beams are accelerated in bunches (no continuous beam)

RF systems: 400 MHz



400 MHz system:

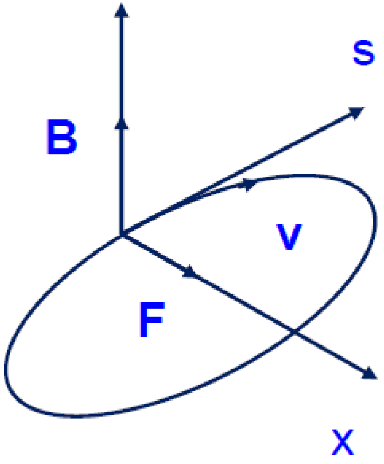
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

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

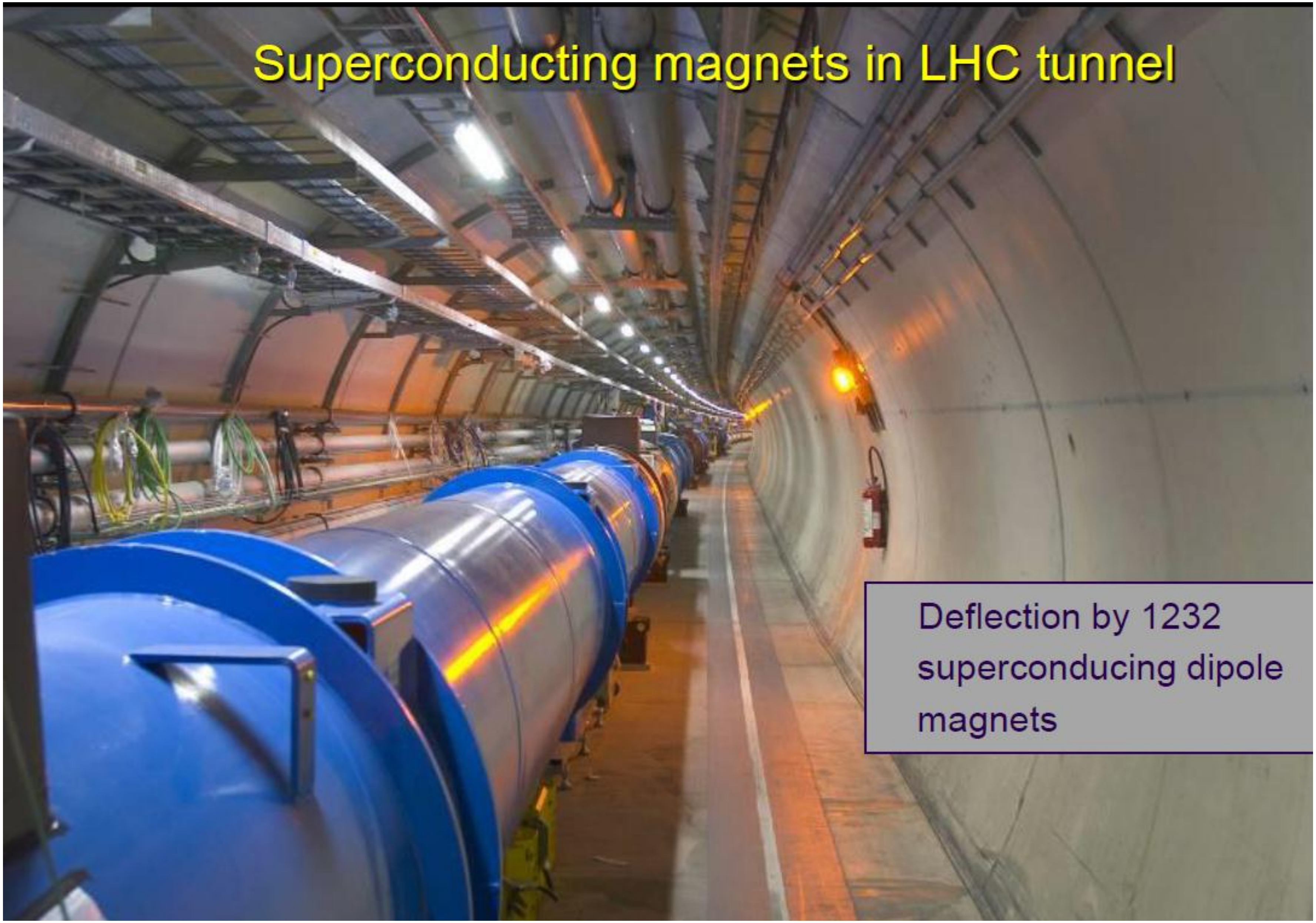
Radius 2805 m fixed by LEP tunnel

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



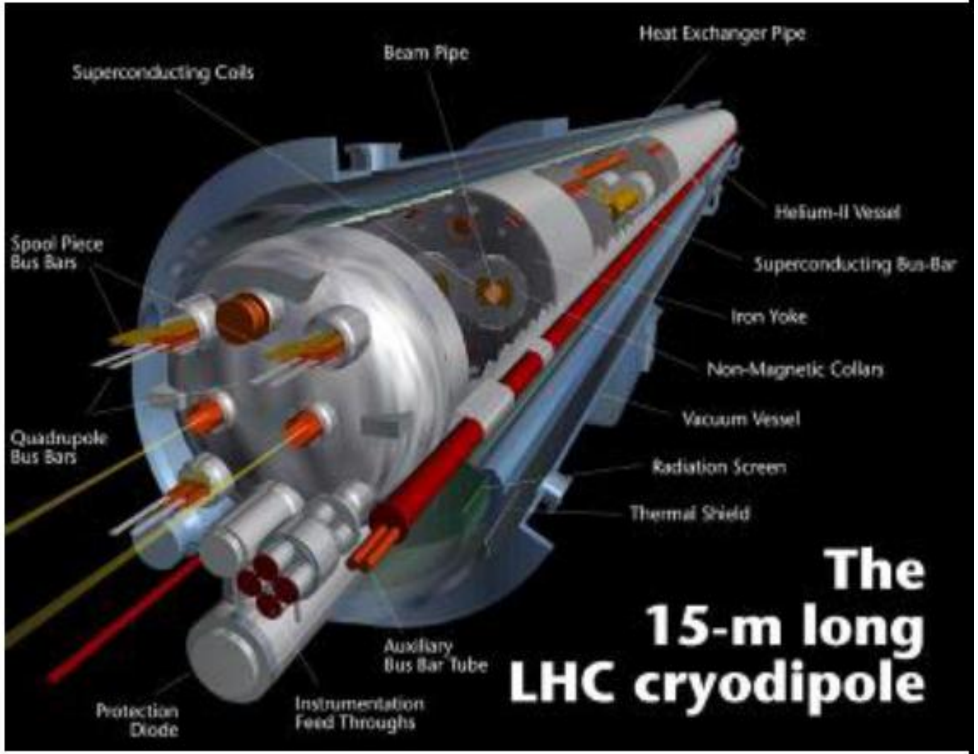
Deflection by 1232 superconducing dipole magnets

Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

Magnetic Field 8.3 T for 7 TeV

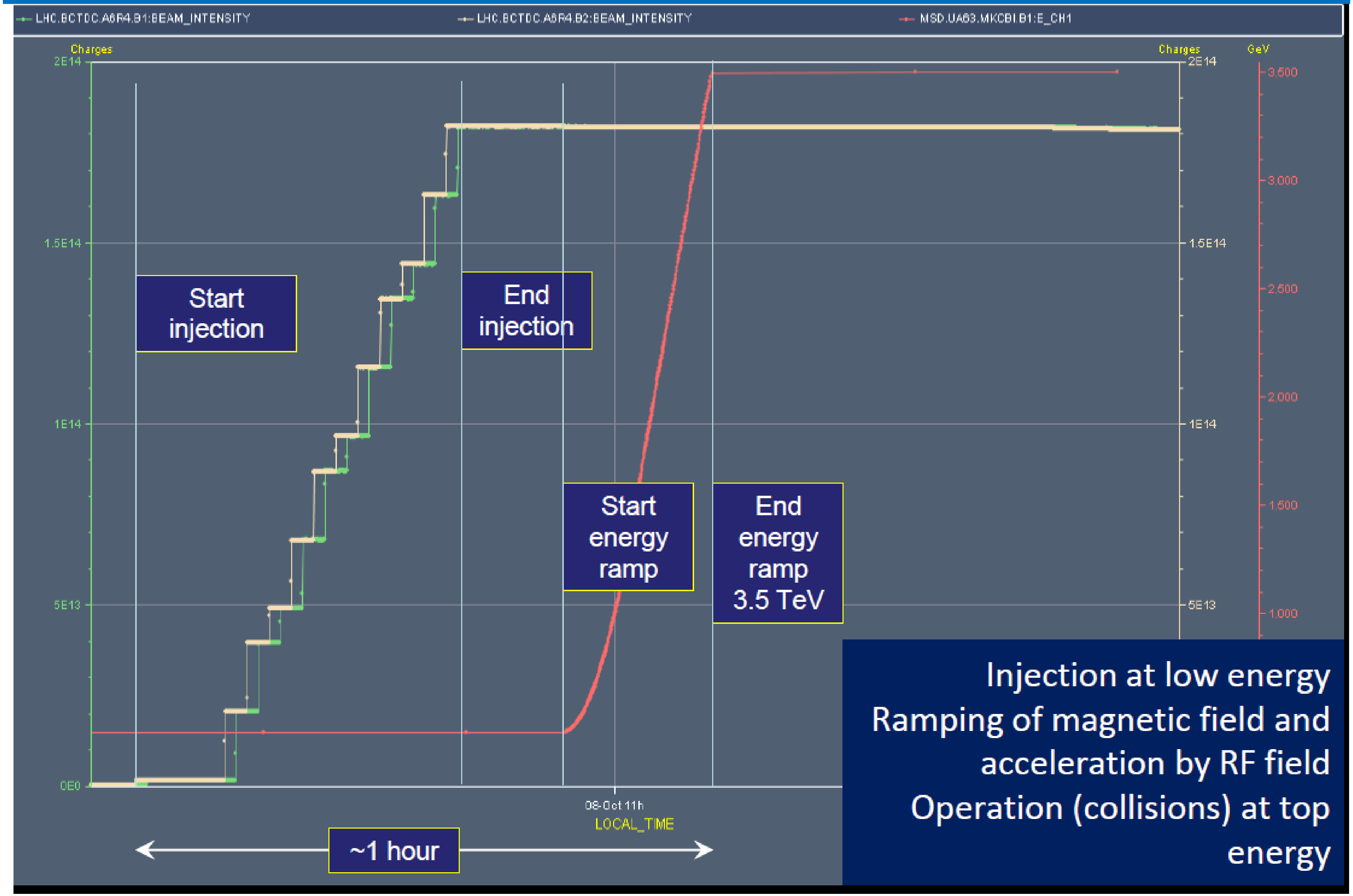
Two beam tubes with an opening of 56 mm



The 15-m long LHC cryodipole

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

Synchrotron principle: LHC fill (2011)



Start injection

End injection

Start energy ramp

End energy ramp 3.5 TeV

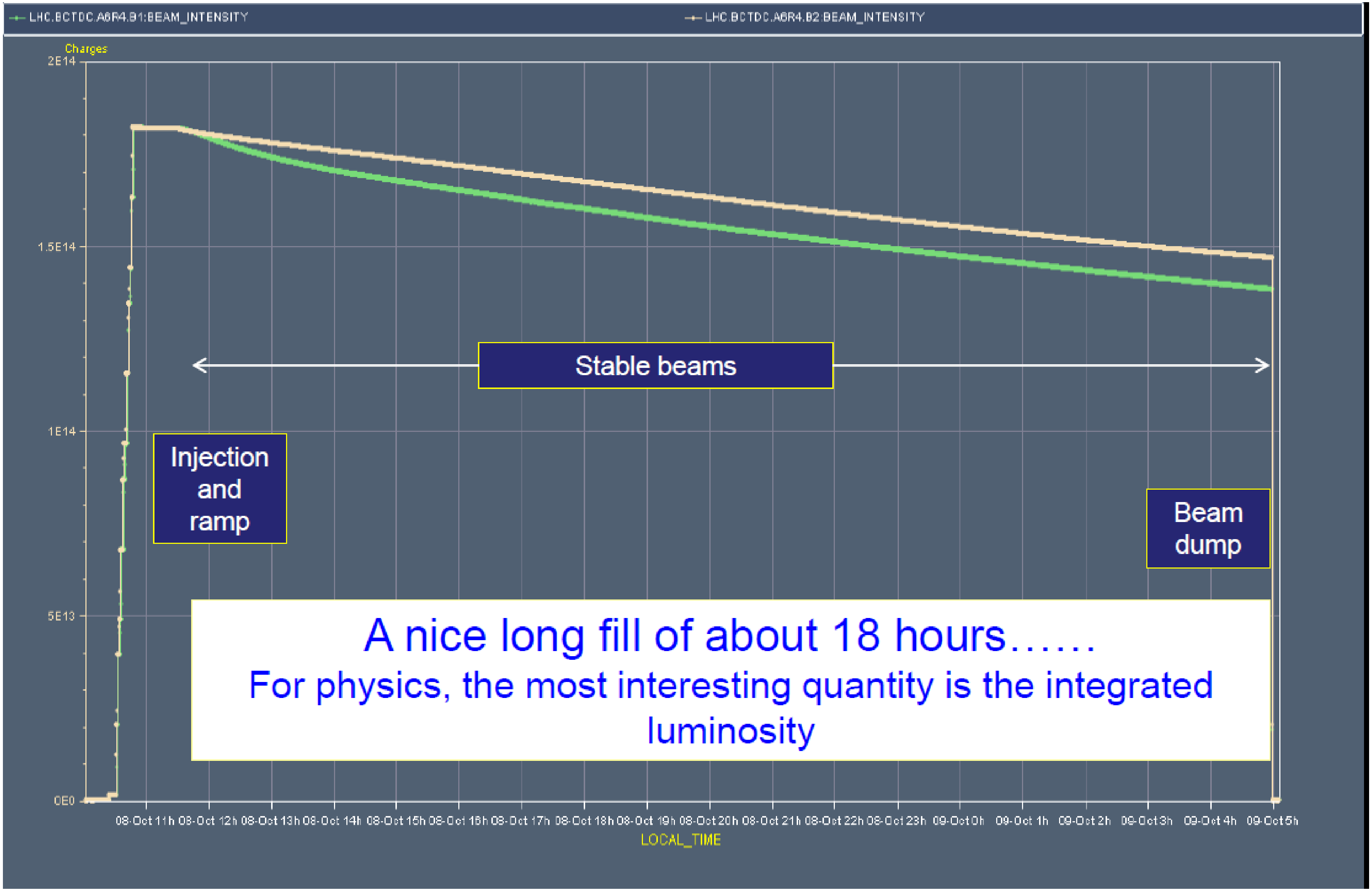
~1 hour

Injection at low energy

Ramping of magnetic field and acceleration by RF field

Operation (collisions) at top energy

Excelent fill (2011)



Stable beams

Injection and ramp

Beam dump

A nice long fill of about 18 hours……

For physics, the most interesting quantity is the integrated luminosity

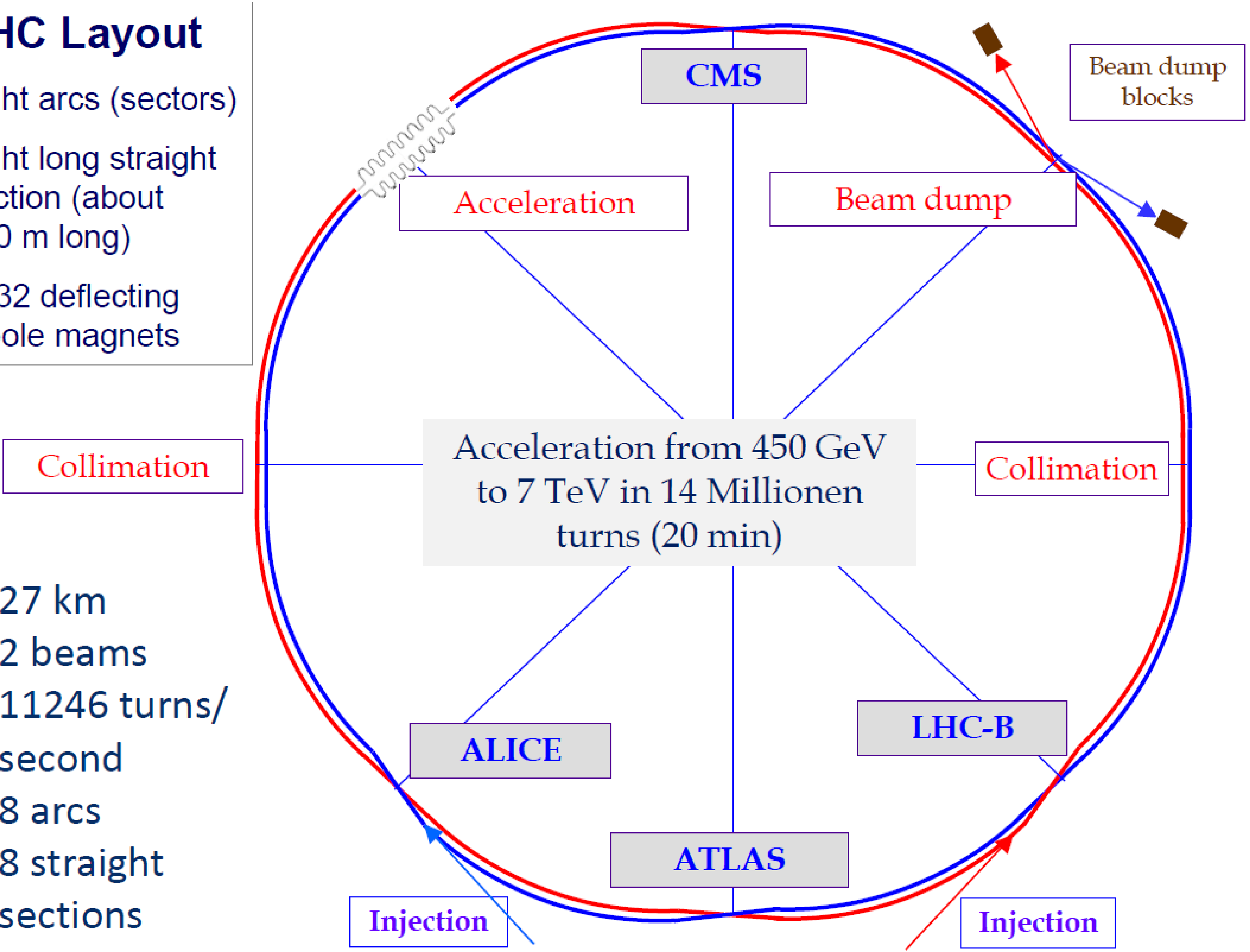
LHC Layout

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



CMS

Acceleration

Beam dump

Beam dump blocks

Collimation

Acceleration from 450 GeV to 7 TeV in 14 Millionen turns (20 min)

Collimation

ALICE

LHC-B

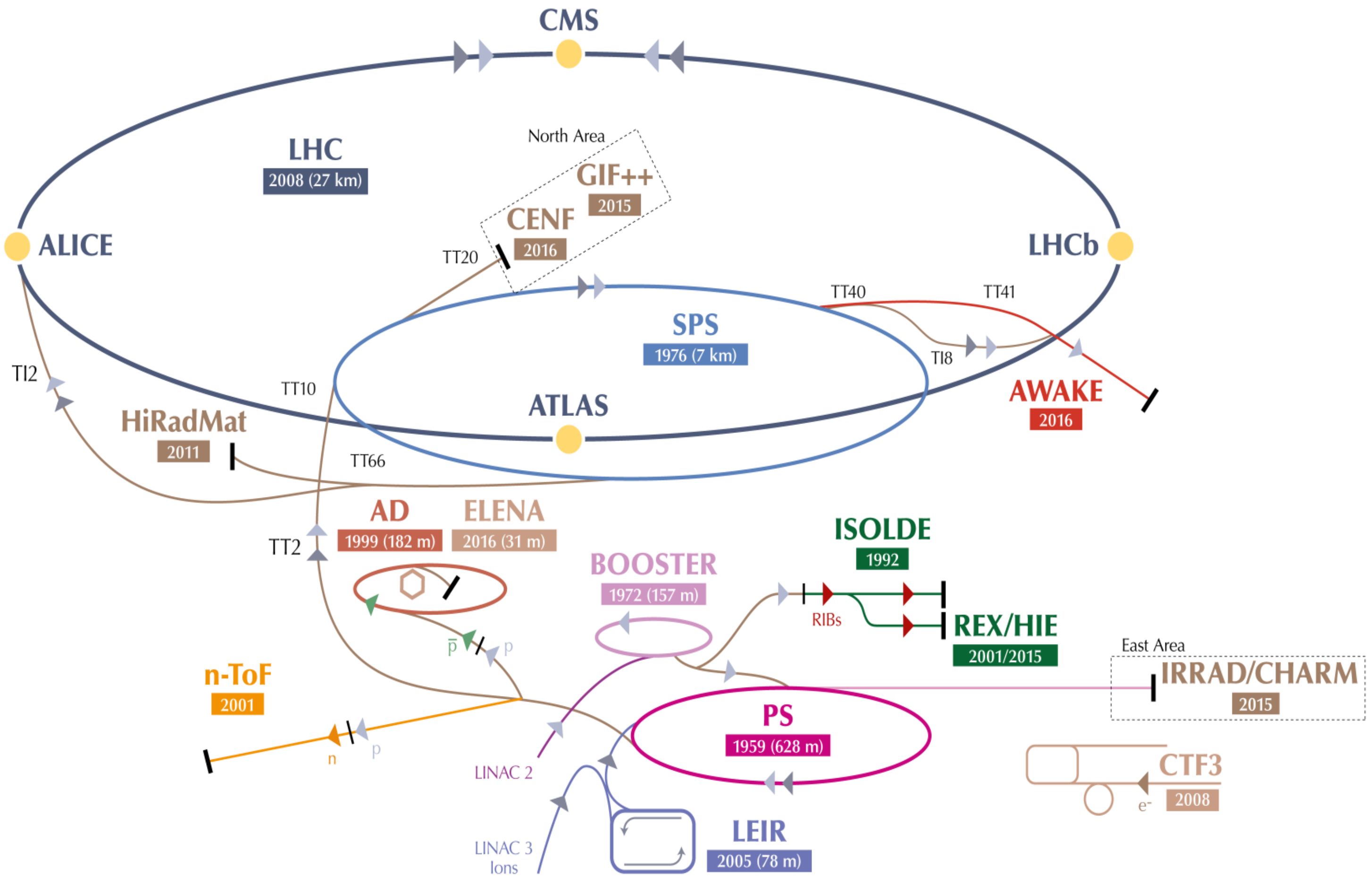
ATLAS

Injection

Injection

CERN accelerator complex

CERN 2017



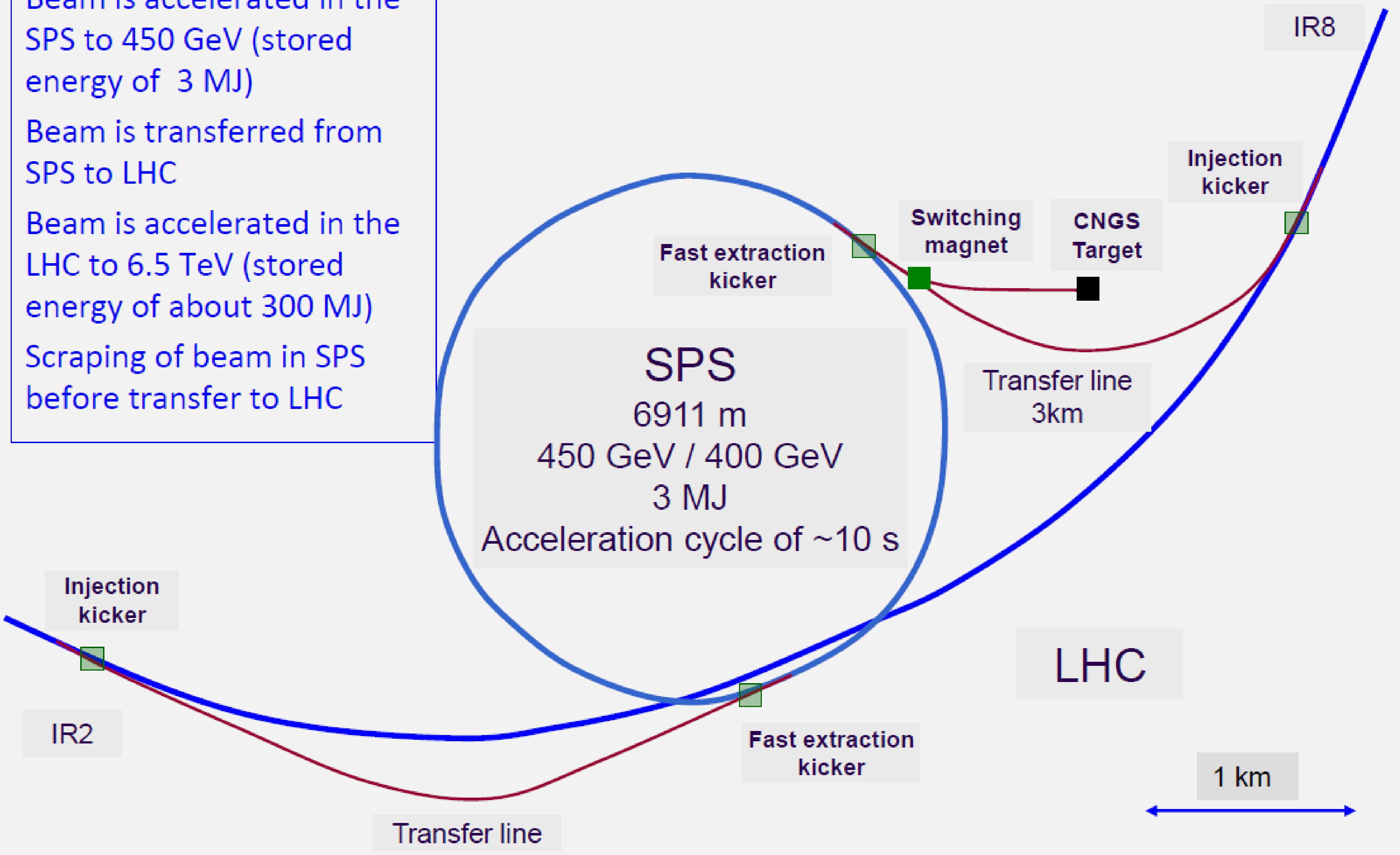
SPS, transfer line and the LHC

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



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

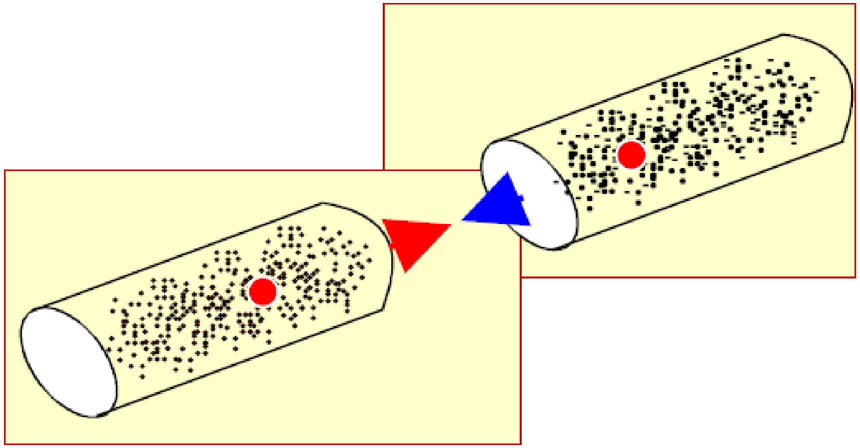
$$L = \frac{N^2 \times f \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

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 **1-3×10^{11}** due to the beam-beam interaction and beam instabilities

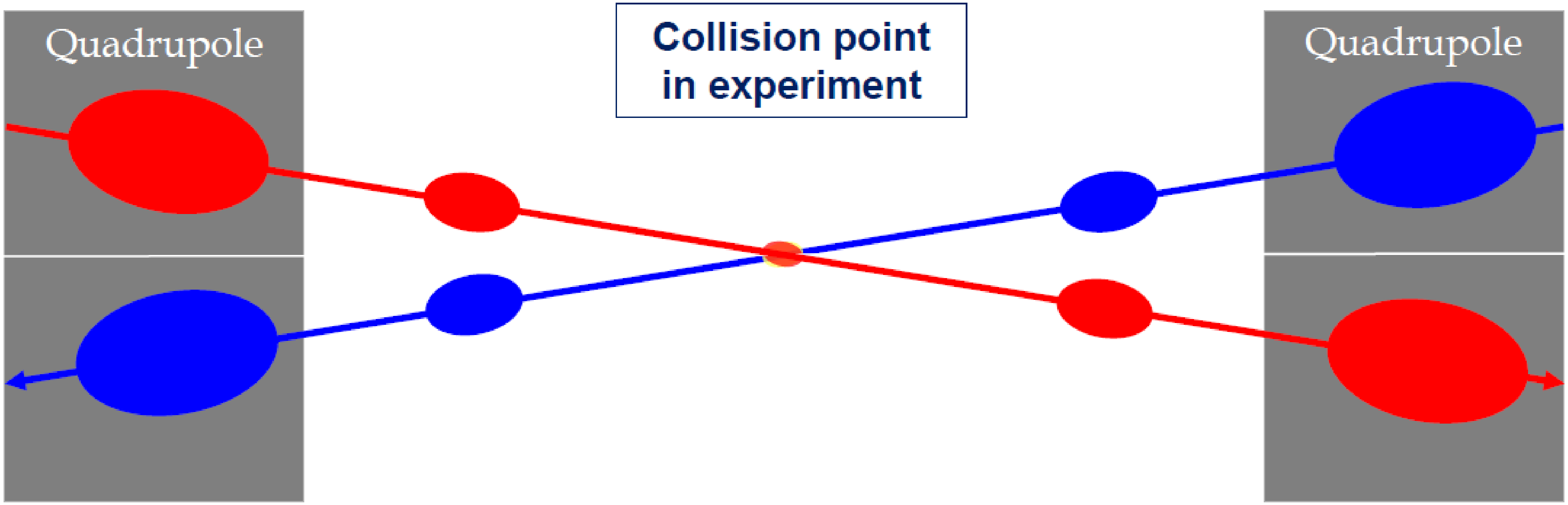
Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

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

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

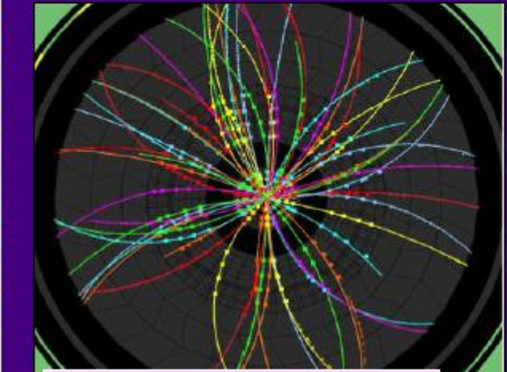
Beam size



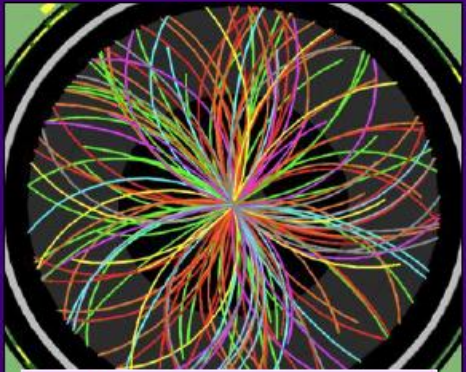
- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10 σ
- Limitation is the aperture in quadrupoles
- Limitation of β function at IP to 0.4 m (2017)

⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)

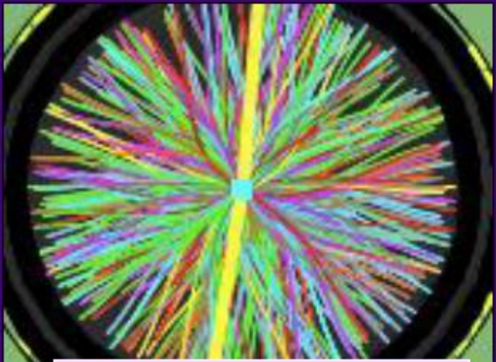
⇒ 'Hats off' to ALTAS & CMS for handling this pile-up !!



2010: ~ 2 events/x-ing

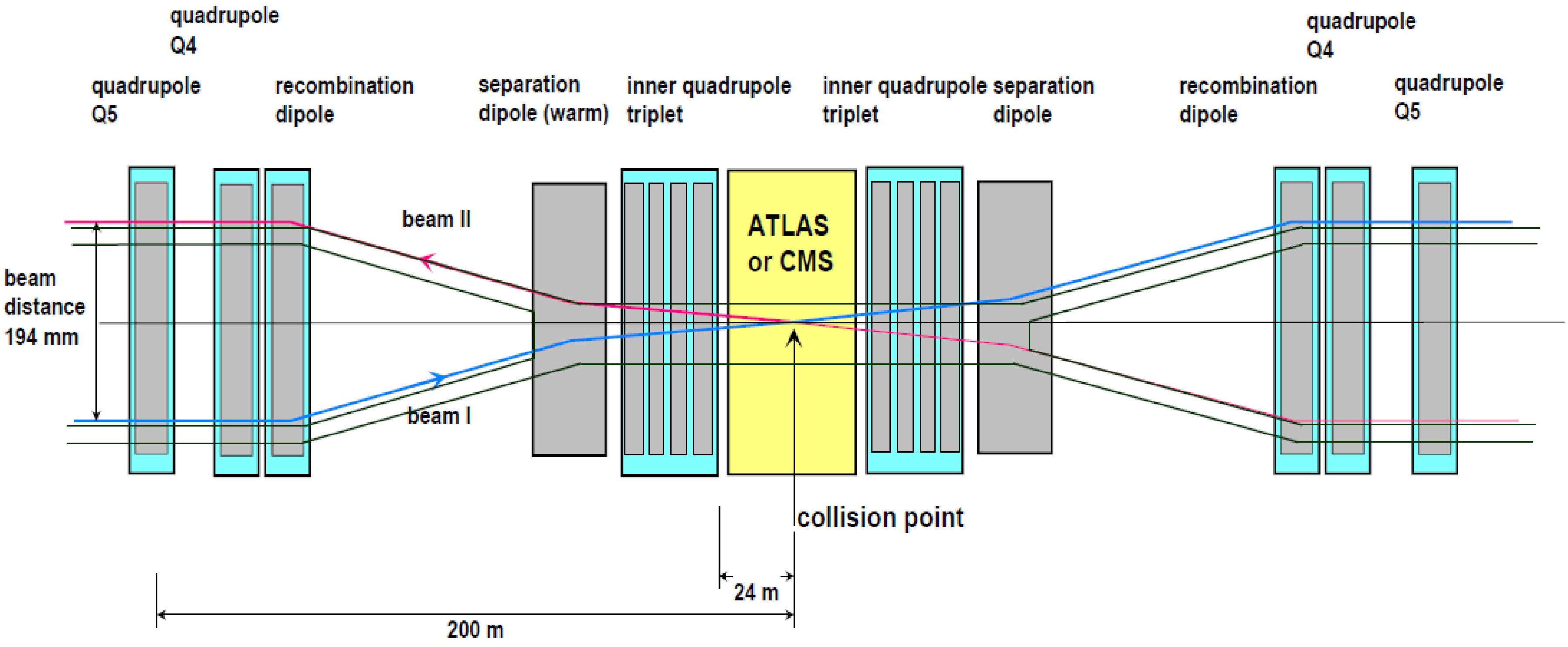


2011: ~ 10 events/x-ing



2012: ~ 20 events/x-ing

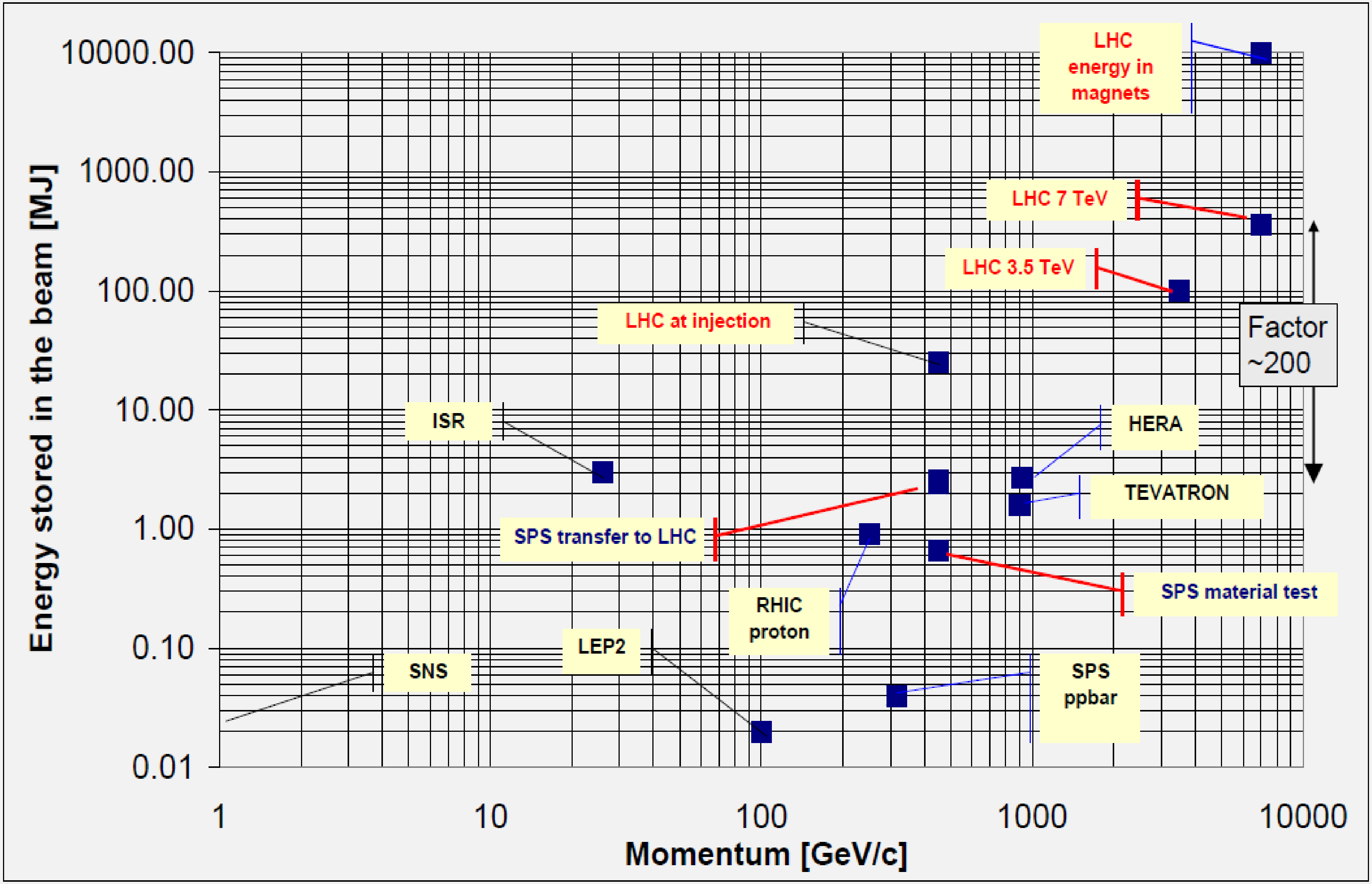
Experimental long straight section



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?

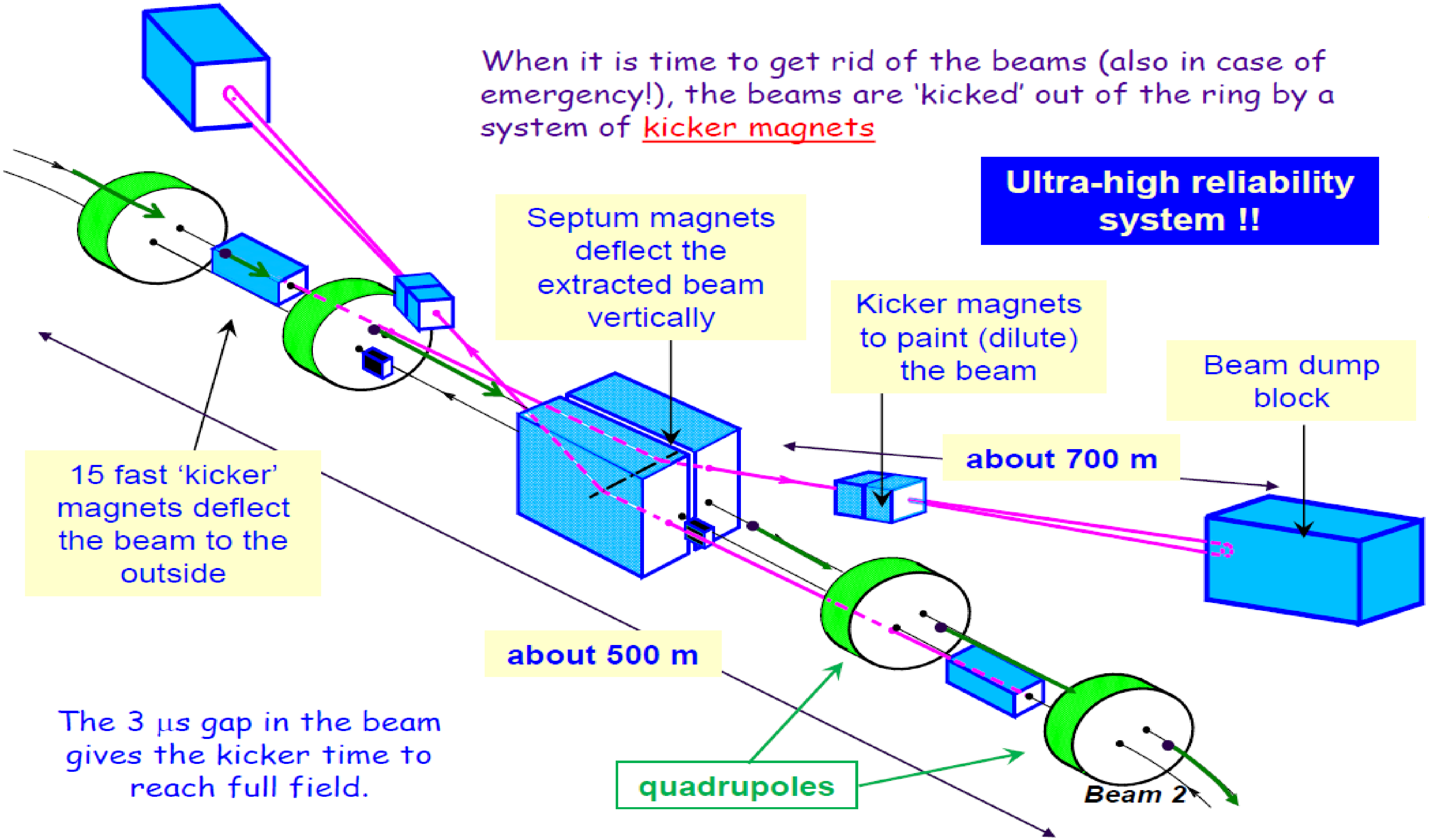
The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

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

Ultra-high reliability system !!

Septum magnets deflect the extracted beam vertically

Kicker magnets to paint (dilute) the beam

Beam dump block

about 700 m

15 fast 'kicker' magnets deflect the beam to the outside

about 500 m

quadrupoles

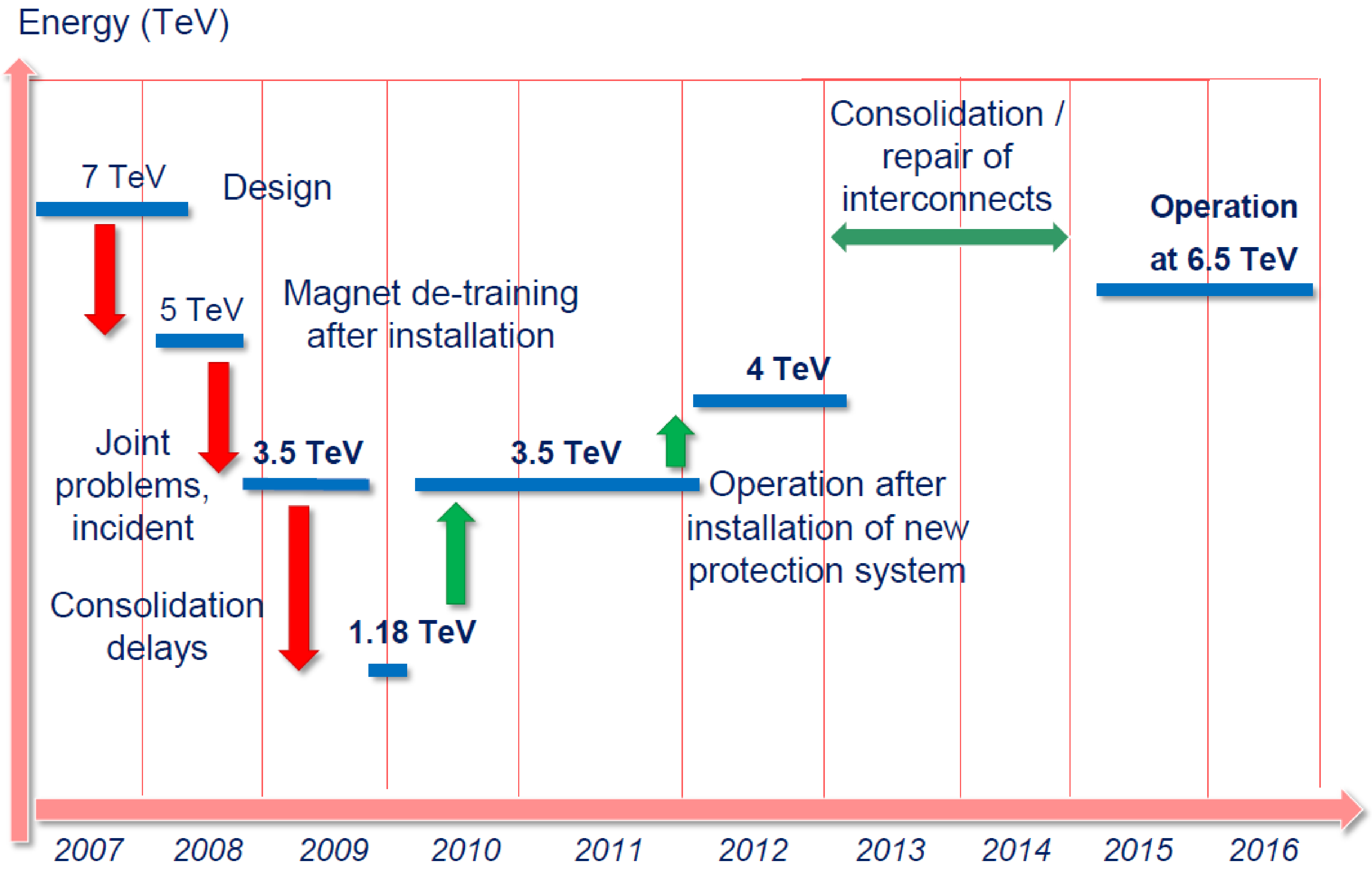
The 3 μs gap in the beam gives the kicker time to reach full field.

Dump line

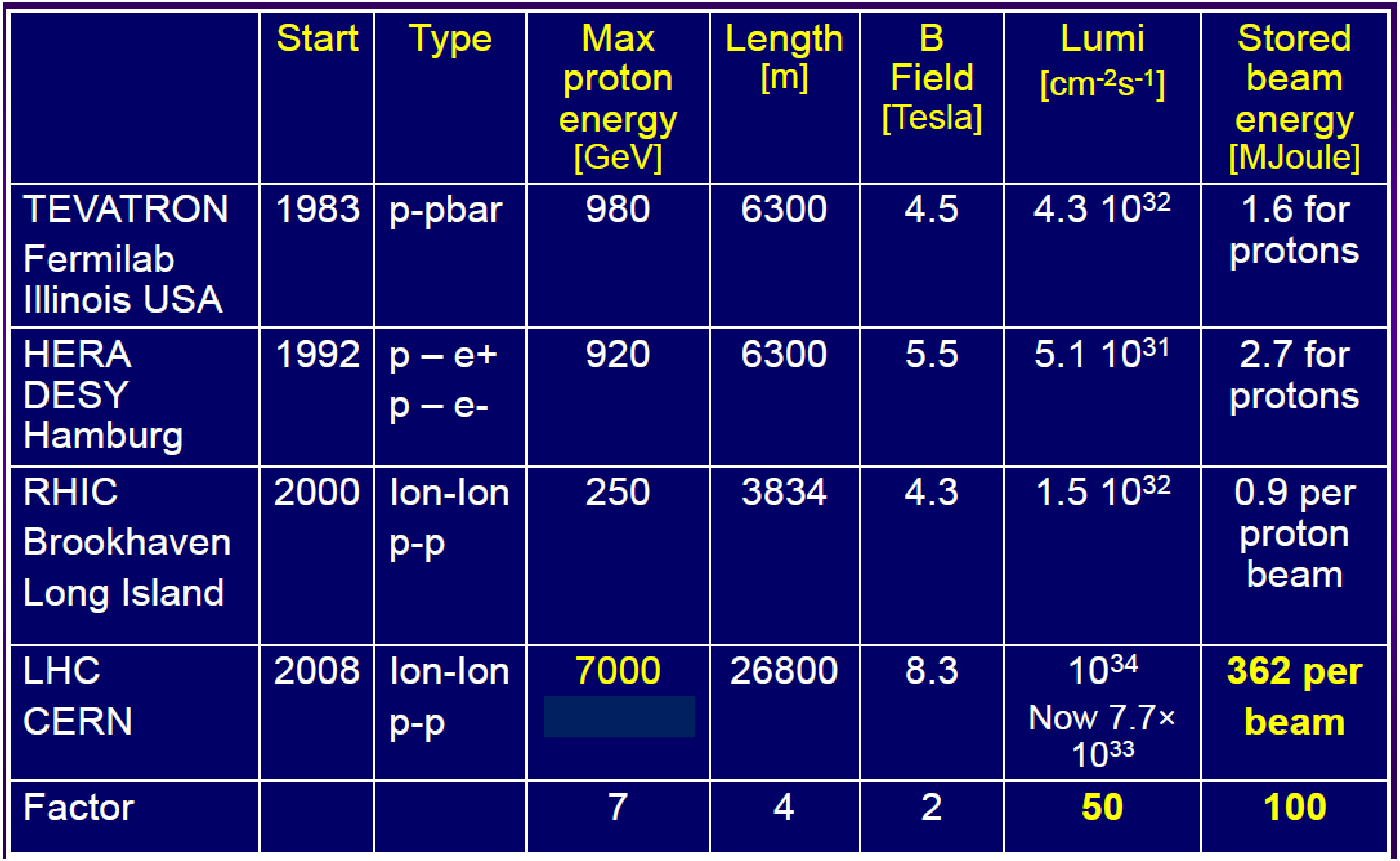
Beam Loss Monitors

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

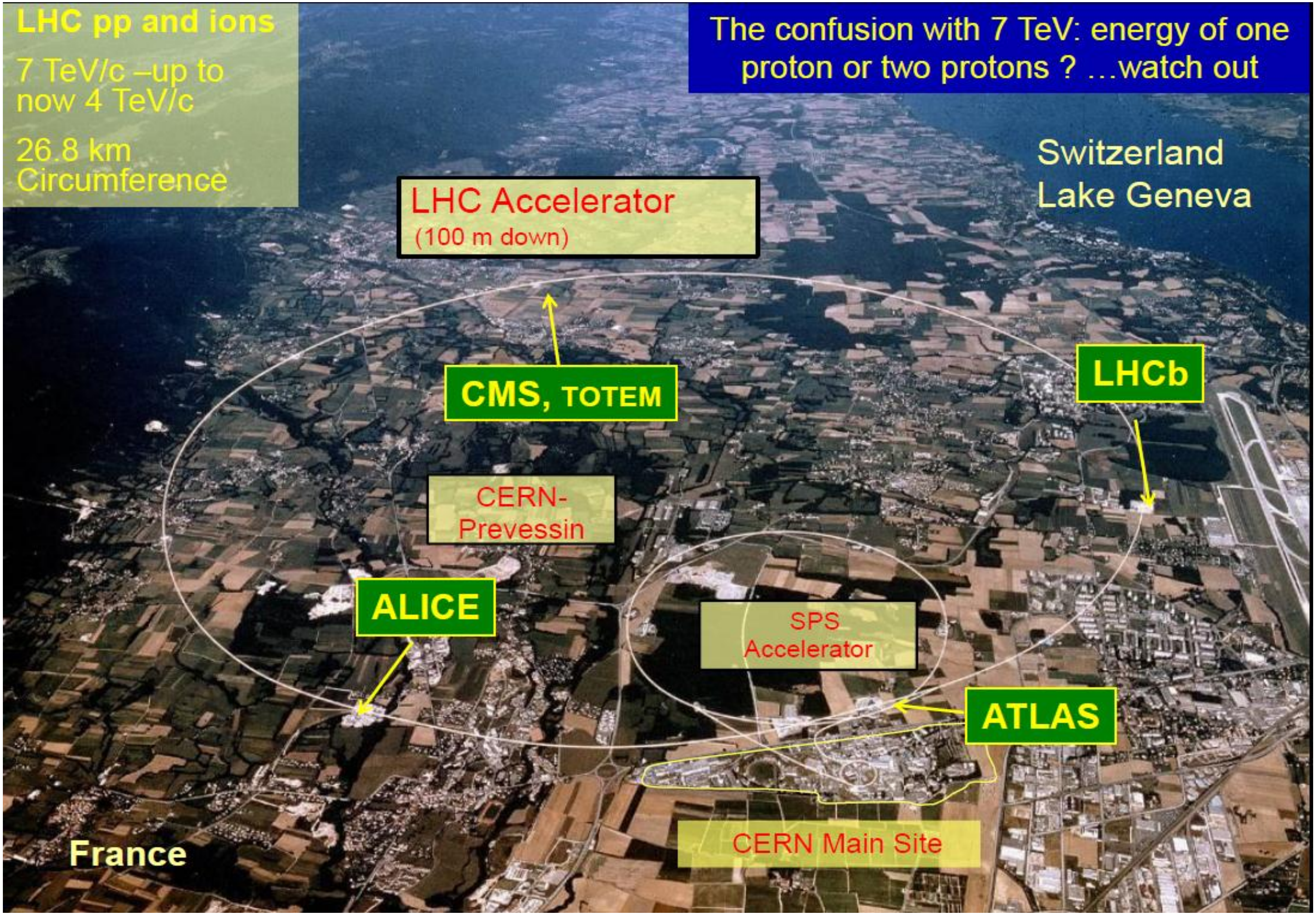
LHC energy evolution



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+ 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× 10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**



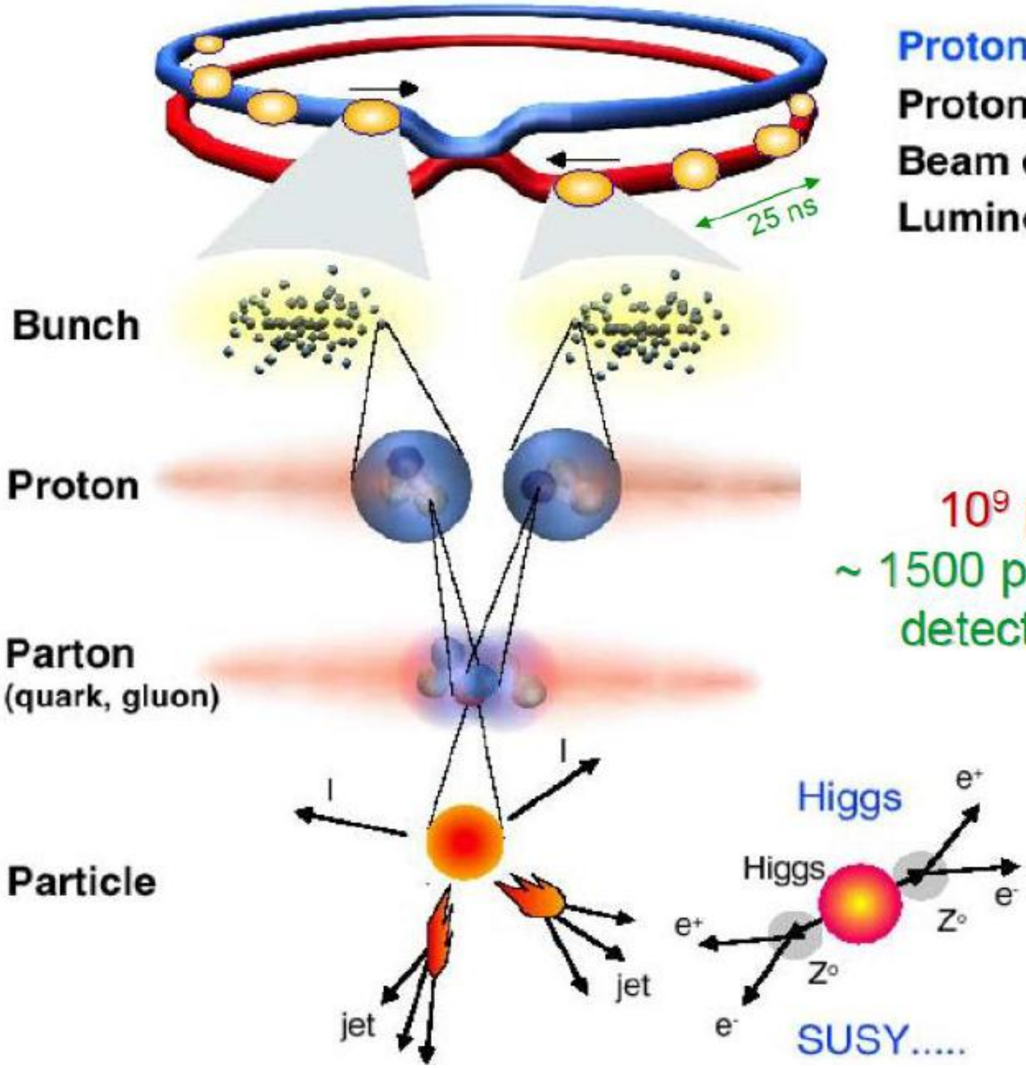
LHC pp and ions

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

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

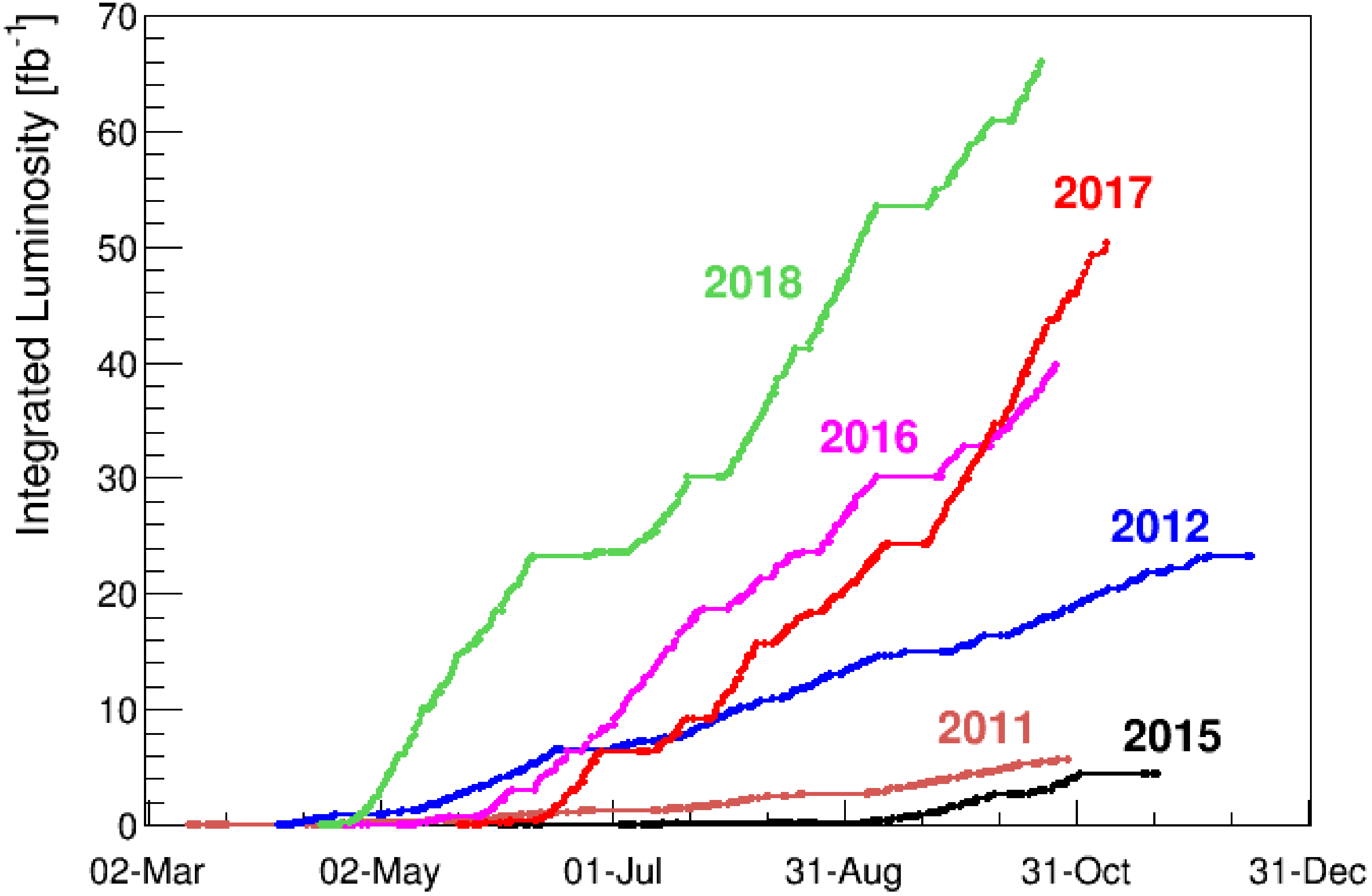
~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

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

$E = m c^2$

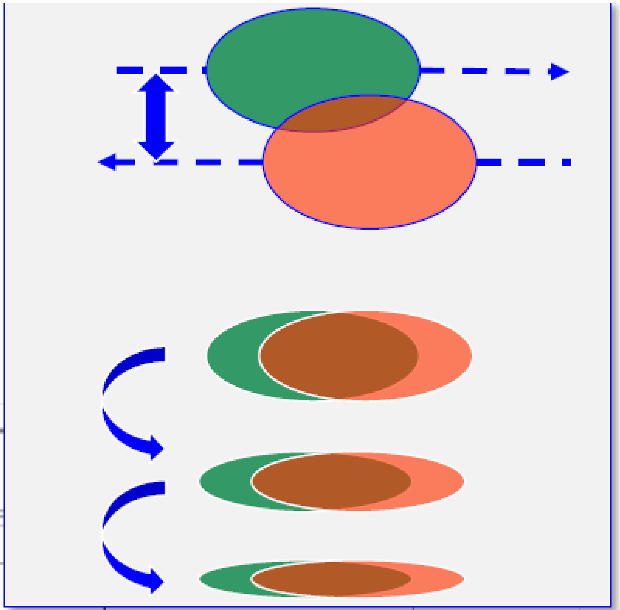
LHC: Run 1 and Run 2

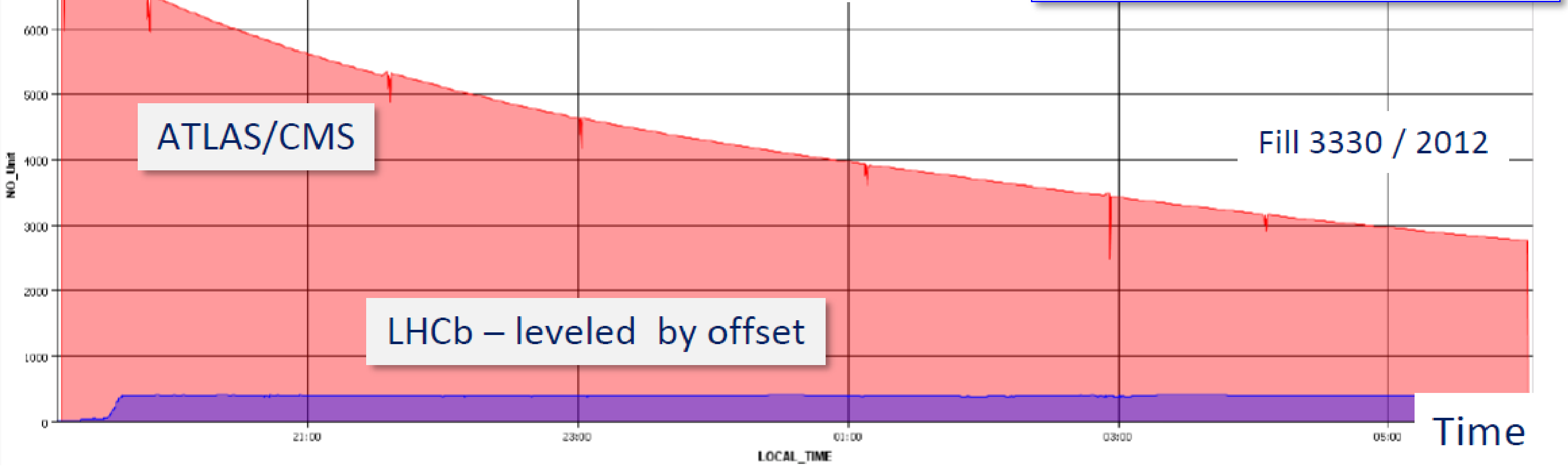
Run 2 at 13 TeV:
2015, 2016, 2017, 2018



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.





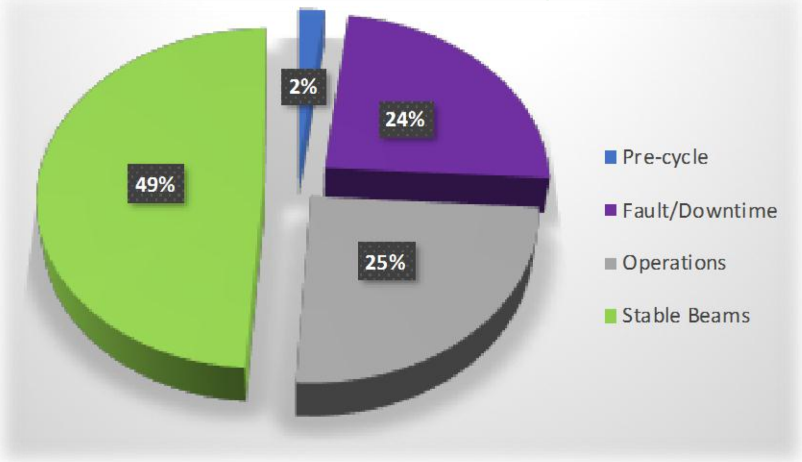
LHC Beam parameters achieved

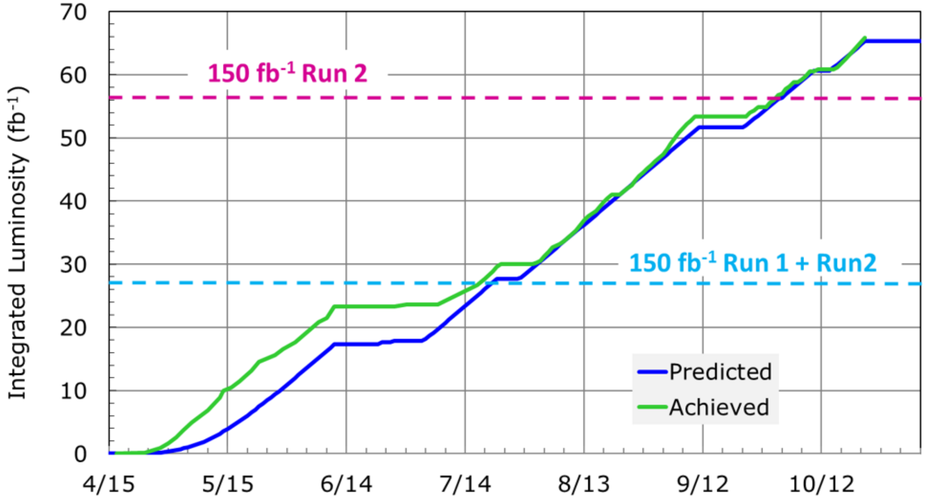
Parameter	**2018**	**Design**
Energy [TeV]	**6.5**	7.0
No. of bunches	**2556**	2808
Max. stored energy per beam (MJ)	**312**	362
β* [cm]	**30→25**	55
p/bunch (typical value) [10^{11}]	**1.1**	1.15
Typical normalized **emittance** [μm]	**~1.8**	3.75
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	**2.1**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

LHC 2018: Beam Availability and Performance

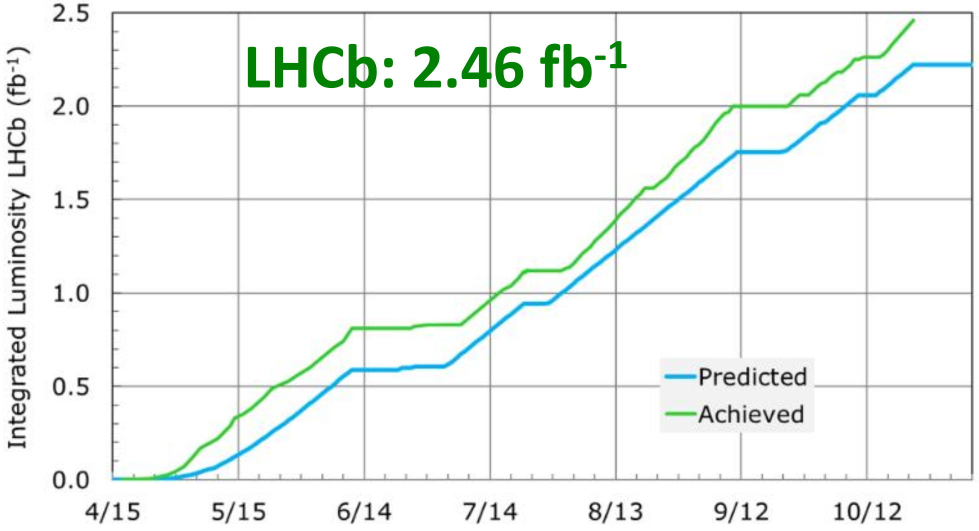
66 fb^{-1}

76 % availability

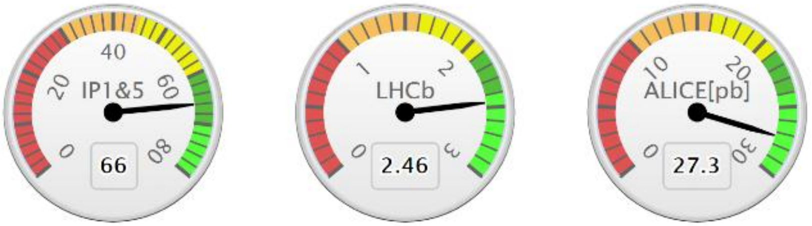




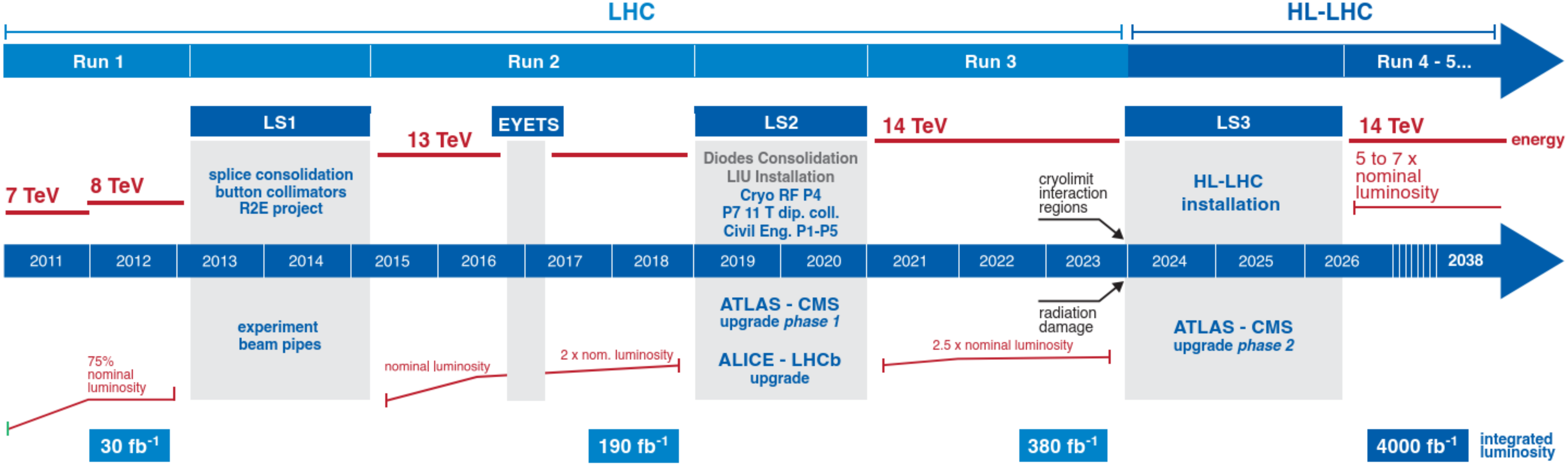
LHCb: 2.46 fb^{-1}



ATLAS : 65.1 fb^{-1}
CMS : 66.9 fb^{-1}



Plans for next (two) decades



LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

splice consolidation
button collimators
R2E project

experiment
beam pipes

EYETS

LS2

Diodes Consolidation
LIU Installation
Cryo RF P4
P7 11 T dip. coll.
Civil Eng. P1-P5

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

LS3

HL-LHC
installation

ATLAS - CMS
upgrade *phase 2*

7 TeV

8 TeV

13 TeV

14 TeV

14 TeV

energy

5 to 7 x
nominal
luminosity

cryolimit
interaction
regions

radiation
damage

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2038

75%
nominal
luminosity

nominal luminosity

2 x nom. luminosity

2.5 x nominal luminosity

30 fb^{-1}

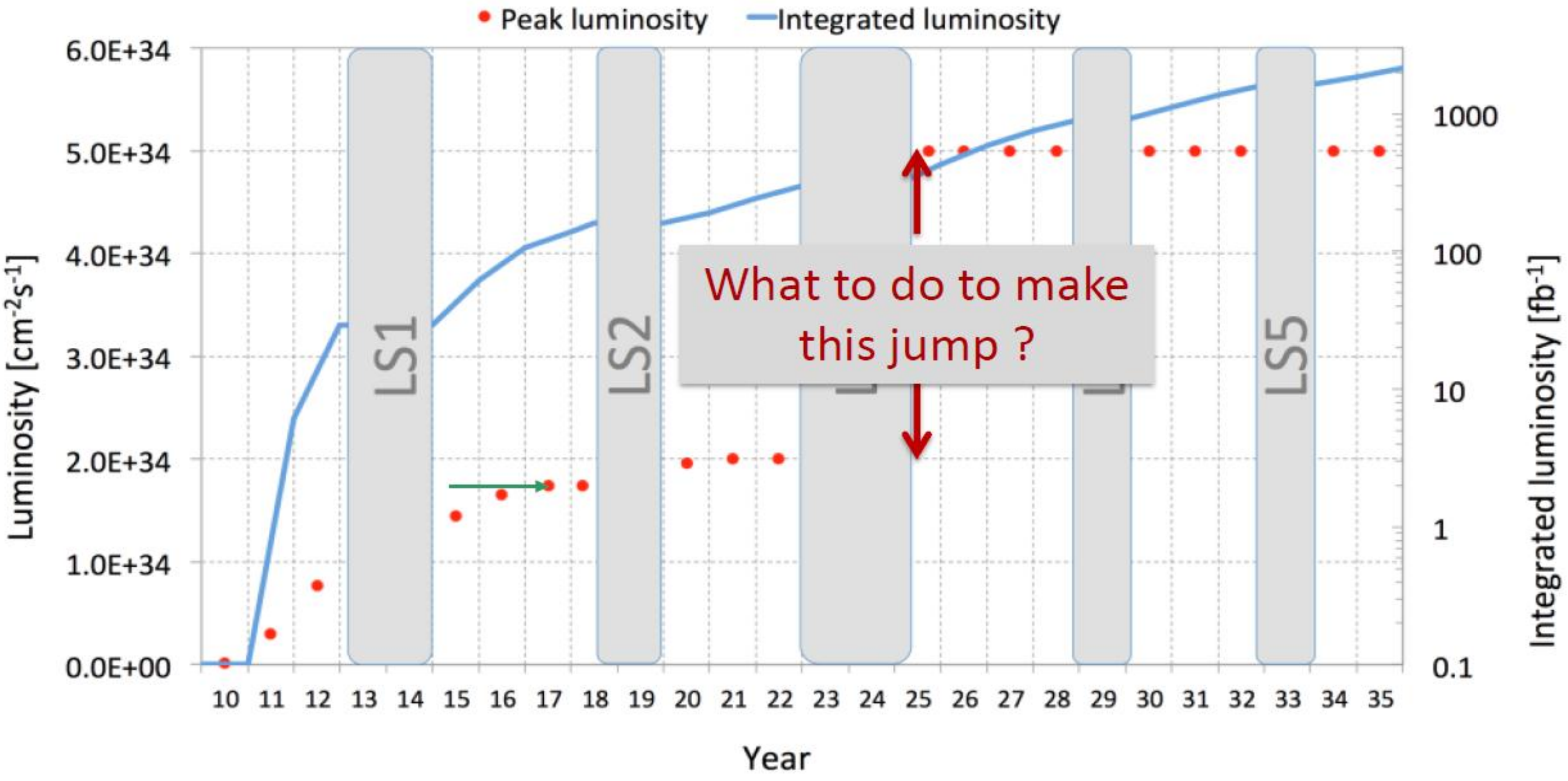
190 fb^{-1}

380 fb^{-1}

4000 fb^{-1}

integrated
luminosity

LHC high luminosity upgrade



What to do to make this jump ?

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
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} 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

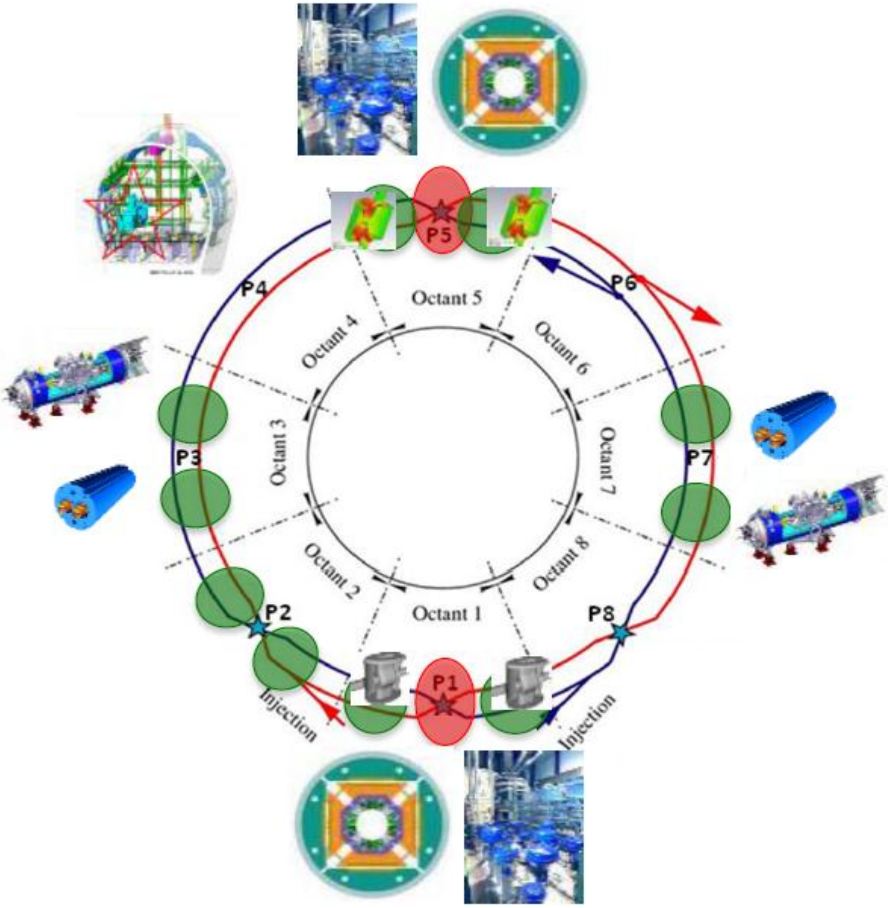
Aim for ~250 fb^{-1}/y

ΔQ_{bb} ~ -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



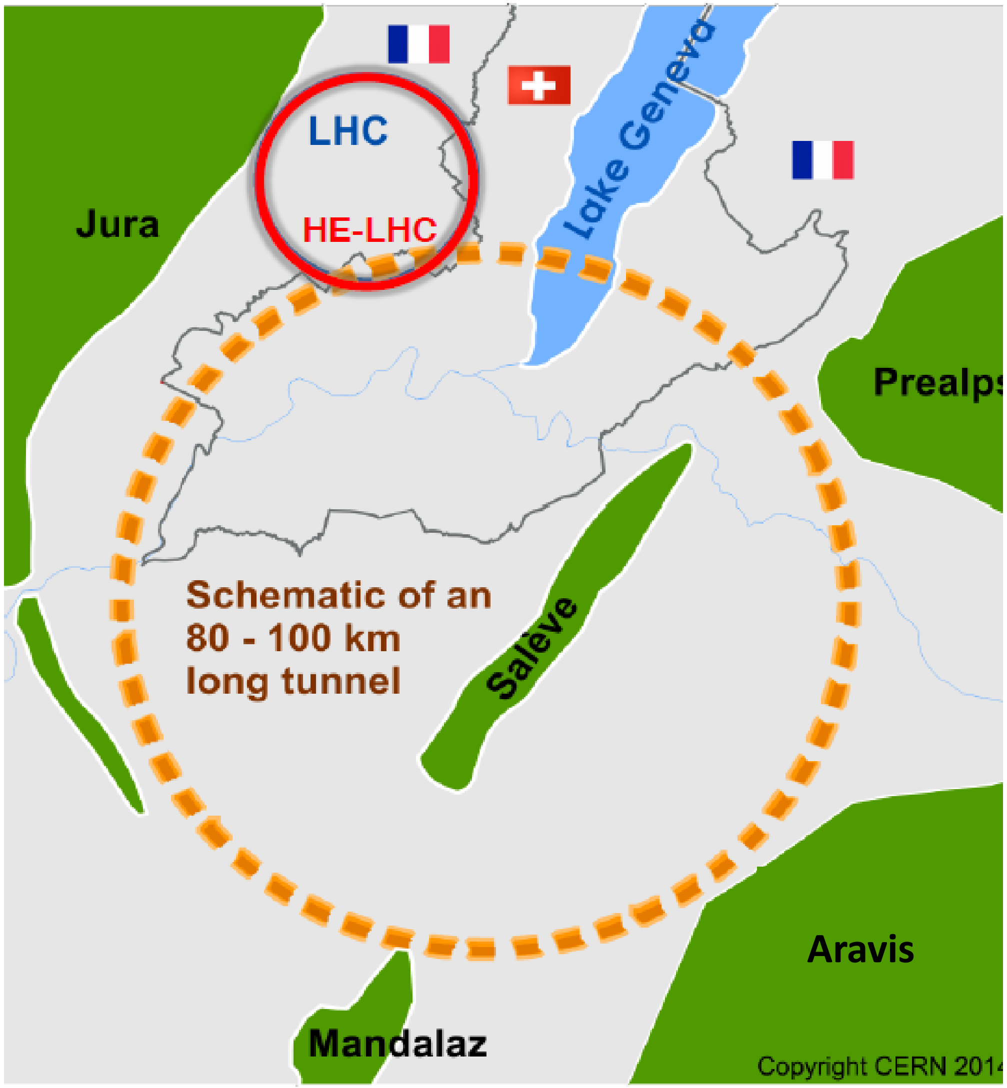
Future plans

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

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

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

$1\ \text{GeV} = 10^{9}\ \text{eV}$

$1\ \text{TeV} = 10^{3}\ \text{GeV}$

$1\ \text{fm} = 10^{-15}\ \text{m}$

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
$\hbar = h/2$	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	$1\ \text{GeV}^{-1} = 0.1973$ fm	
time	$1\ \text{GeV}^{-1} = 6.59 \times 10^{-25}$ s	

Measuring particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 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

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

$$\ell = \frac{\ell_0}{\gamma}$$ length contraption

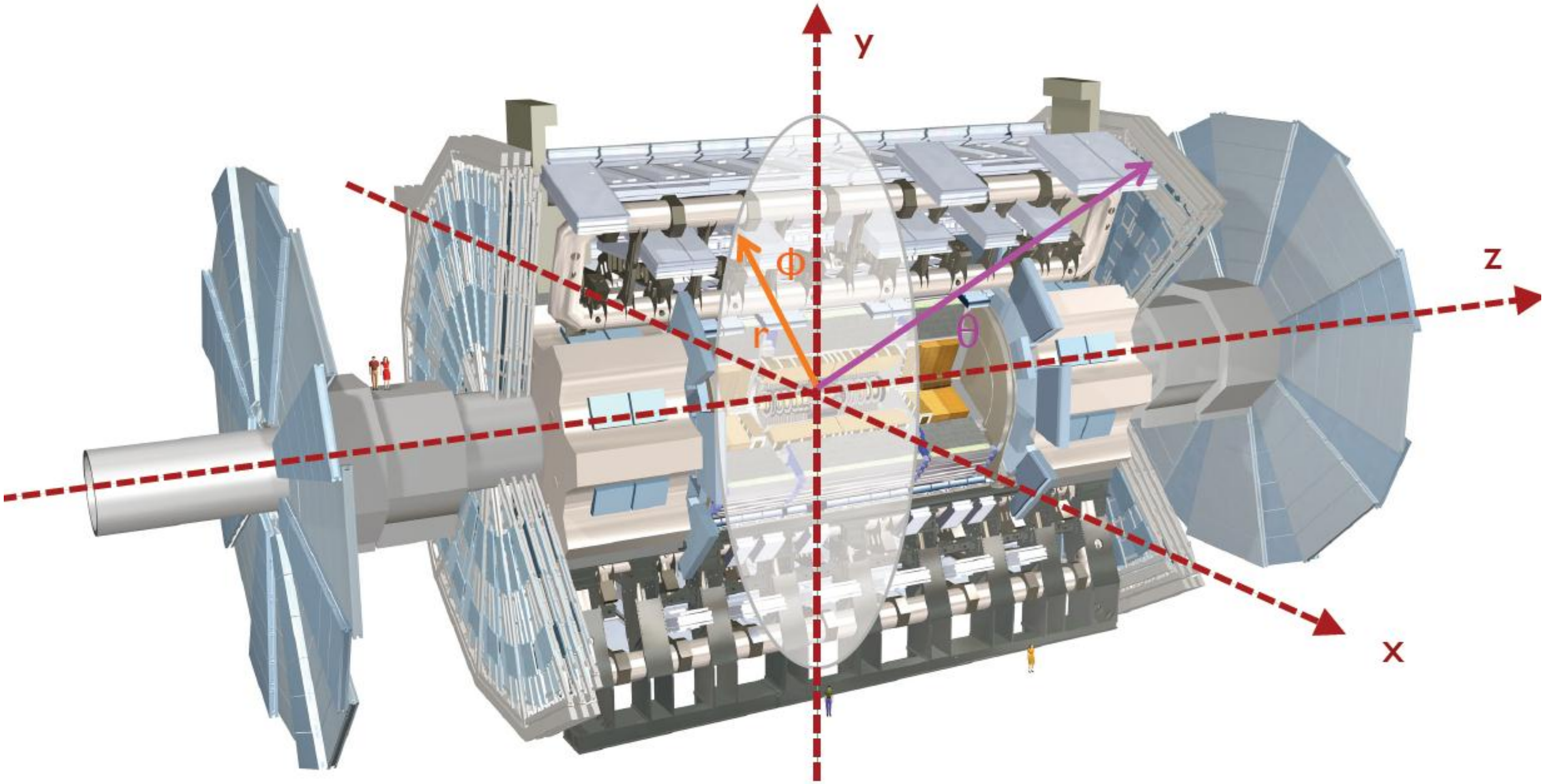
$$t = t_0\gamma$$ time dilatation

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

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

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

Collider experiment coordinates



Rapidity

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

$$E = m\cosh\varphi$$
$$|\vec{p}| = m\sinh\varphi$$

$$\varphi = \tanh^{-1}\frac{E}{|\vec{p}|} = \frac{1}{2}\ln\frac{E+|\vec{p}|}{E-|\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

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

Pseudorapidity

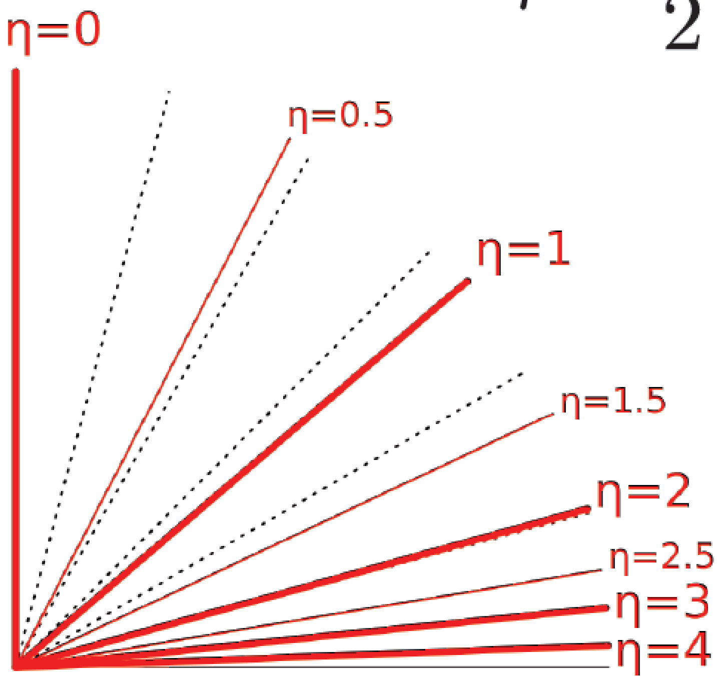
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

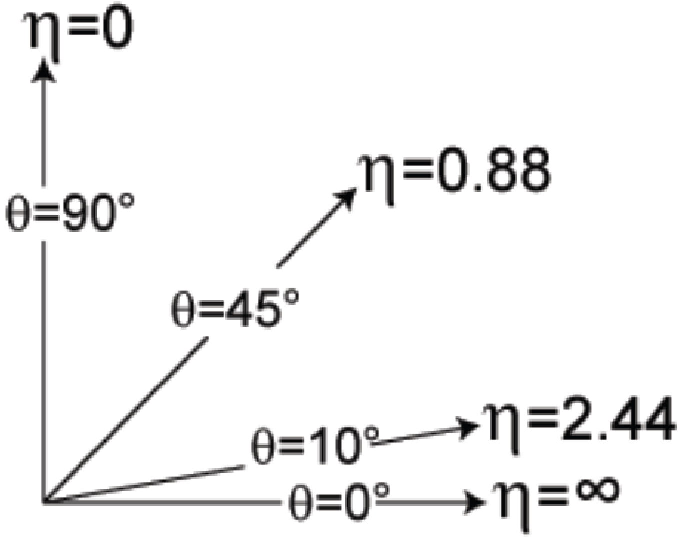
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

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

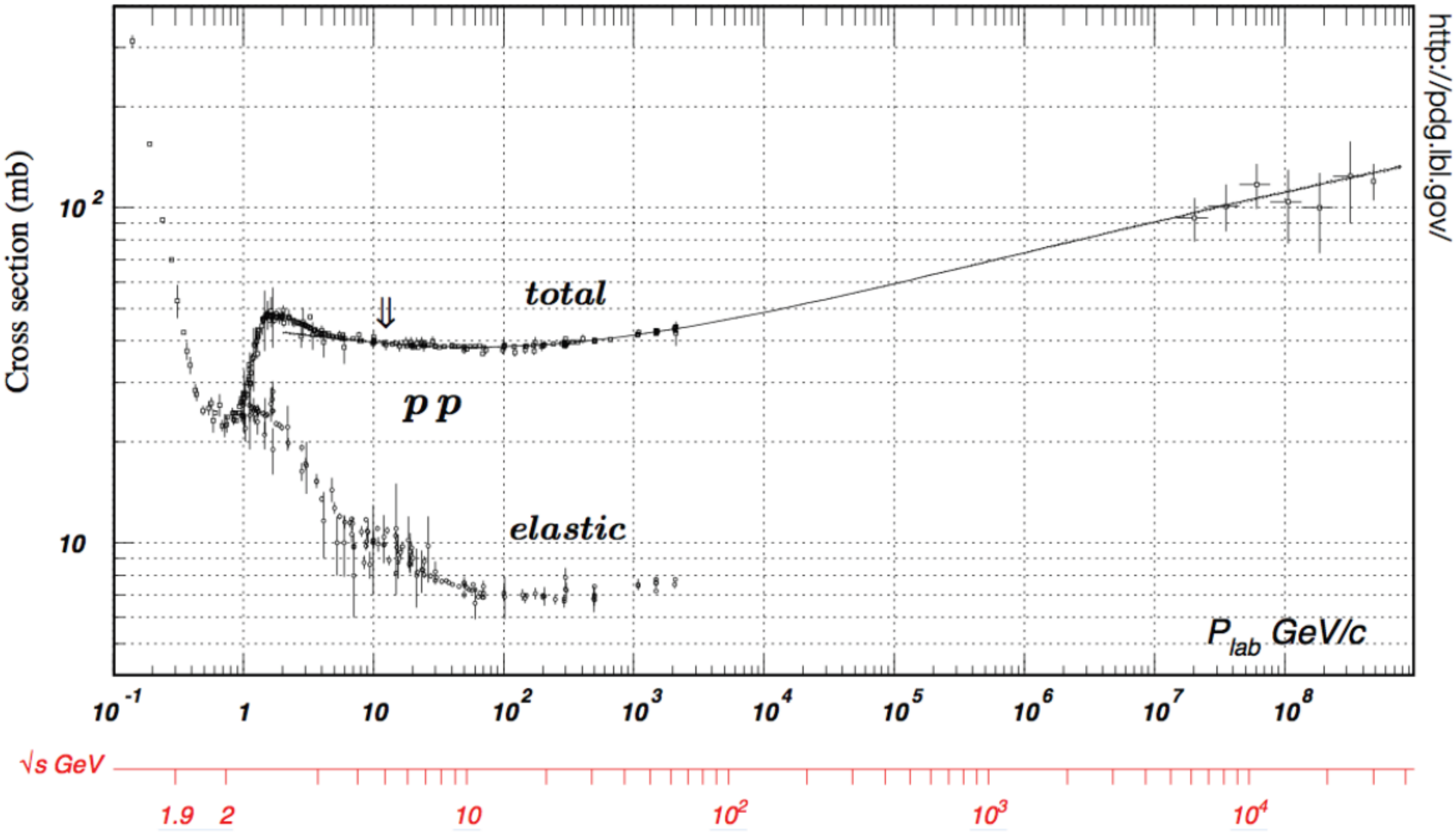
$$\eta \simeq y$$

if E >> m

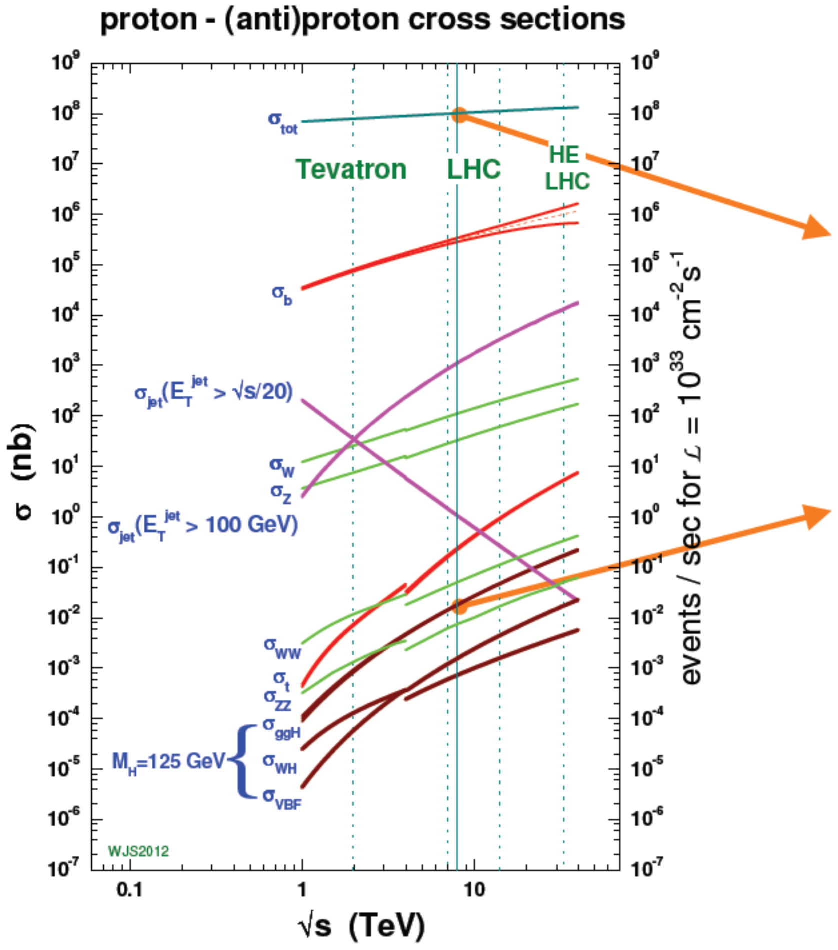




Proton-proton scattering cross-section



Cross-sections at LHC



10^8 events/s

~10^{10}

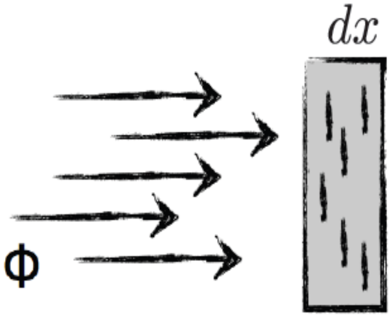
10^{-2} events/s ~

10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ
1.5% H → ZZ

Interaction cross-section



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

Reactions per unit of time

$$\frac{dN_{\mathrm{reac}}}{dt} = \underbrace{\underset{[L^{-2}t^{-1}]}{\Phi}\;\underset{[?]}{\sigma}}_{}\overbrace{}^{}\!\!\!\!\!\overbrace{N_{\mathrm{target}}\,dx}^{\text{area obscured by target particle}} \qquad [t^{-1}]$$

$$\frac{dN_{\mathrm{reac}}}{dt} = \Phi\,\overbrace{\sigma\, N_{\mathrm{target}}\, dx}^{\text{area obscured by target particle}}$$

$$\underbrace{\underset{[L^{-2}t^{-1}]}{\Phi}\;\underset{[?]}{\sigma}}_{}\qquad \underset{[L^{-1}]}{N_{\mathrm{target}}}\qquad \underset{[L]}{dx} \qquad [t^{-1}]$$

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

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

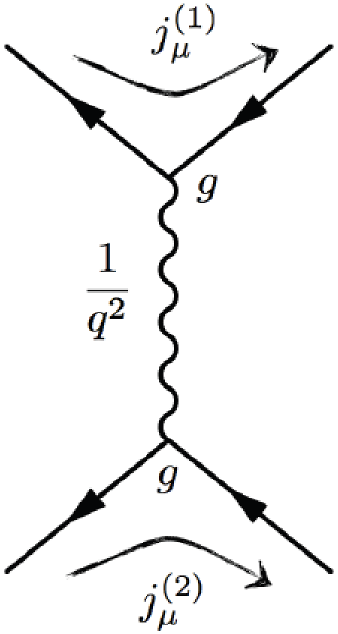
1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

Fermi Golden rule

From non-relativistic perturbation theory…

$$\overbrace{W_{if}}^{\textit{transition probability}} = \frac{2\pi}{\hbar}\overbrace{|M_{if}|}^{\textit{matrix element}}{}^2\,\overbrace{\frac{dN}{dE_f}}^{\textit{energy density of final states}}$$

$[t^{-1}]$ $[E]$ $[E^{-1}]$



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

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

Cross-section: magnitude and units

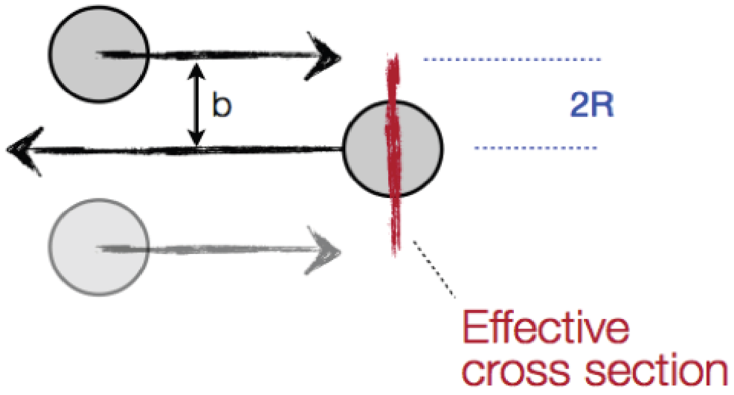
Standard
cross section unit: $[\sigma] = \text{mb}$ with $1\ \text{mb} = 10^{-27}\ \text{cm}^2$

or in
natural units: $[\sigma] = \text{GeV}^{-2}$ with $1\ \text{GeV}^{-2} = 0.389\ \text{mb}$
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

---

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

Estimating the
proton-proton cross section:



Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

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

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!

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T \cos\phi$$

$$p_y = p_T \sin\phi$$

$$p_z = p_T \sinh\eta$$

$$|p| = p_T \cosh\eta$$

$$E_T = \frac{E}{\cosh\eta}$$

$$\sum p_X(i) = 0 \qquad \sum p_Y(i) = 0$$

Missing transverse energy and transverse mass

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

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

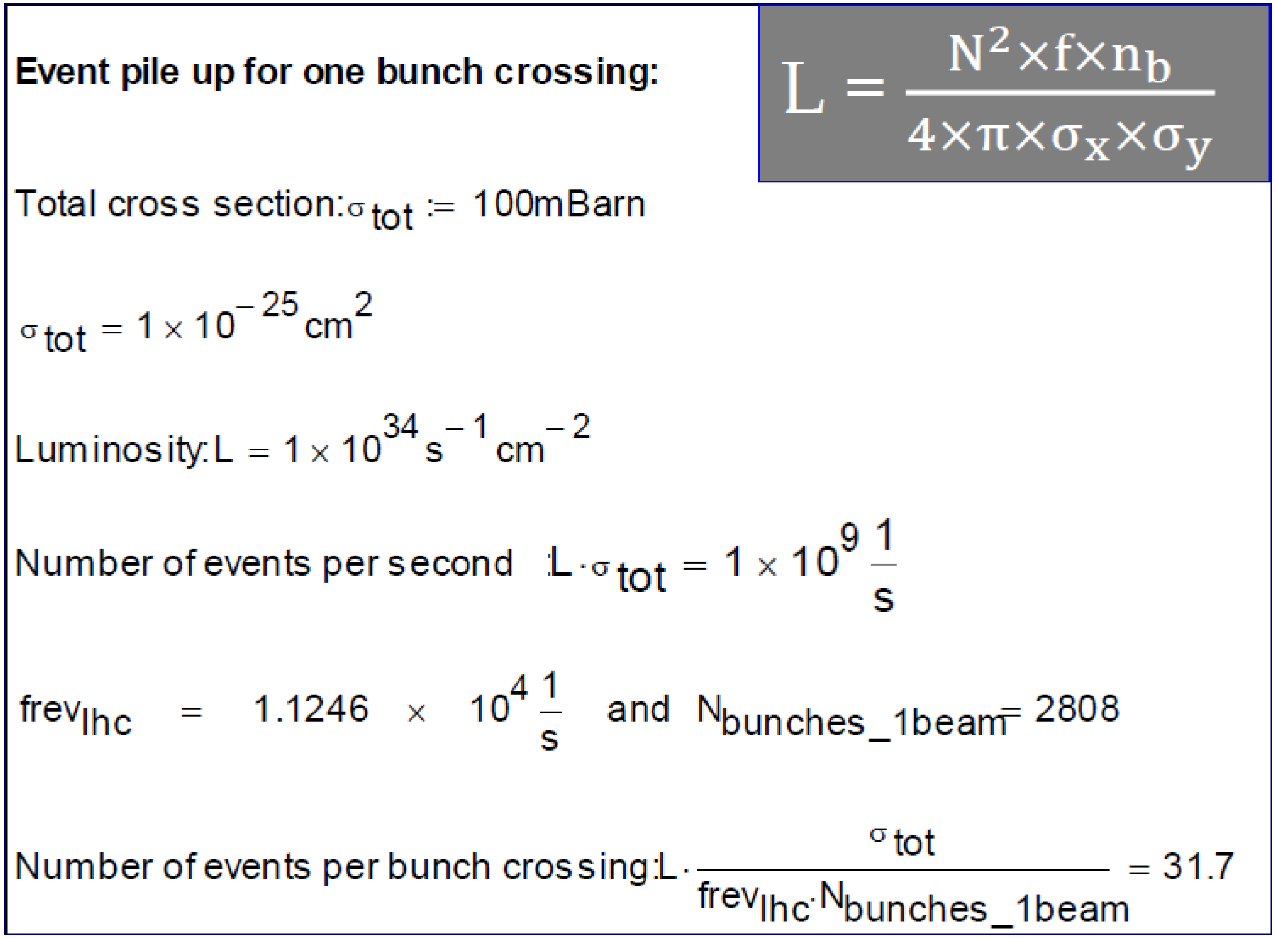
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

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

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

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: $\sigma_{tot} := 100\text{mBarn}$

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

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

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

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

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