

Introduction to particle physics: experimental part

Few words about Standard Model

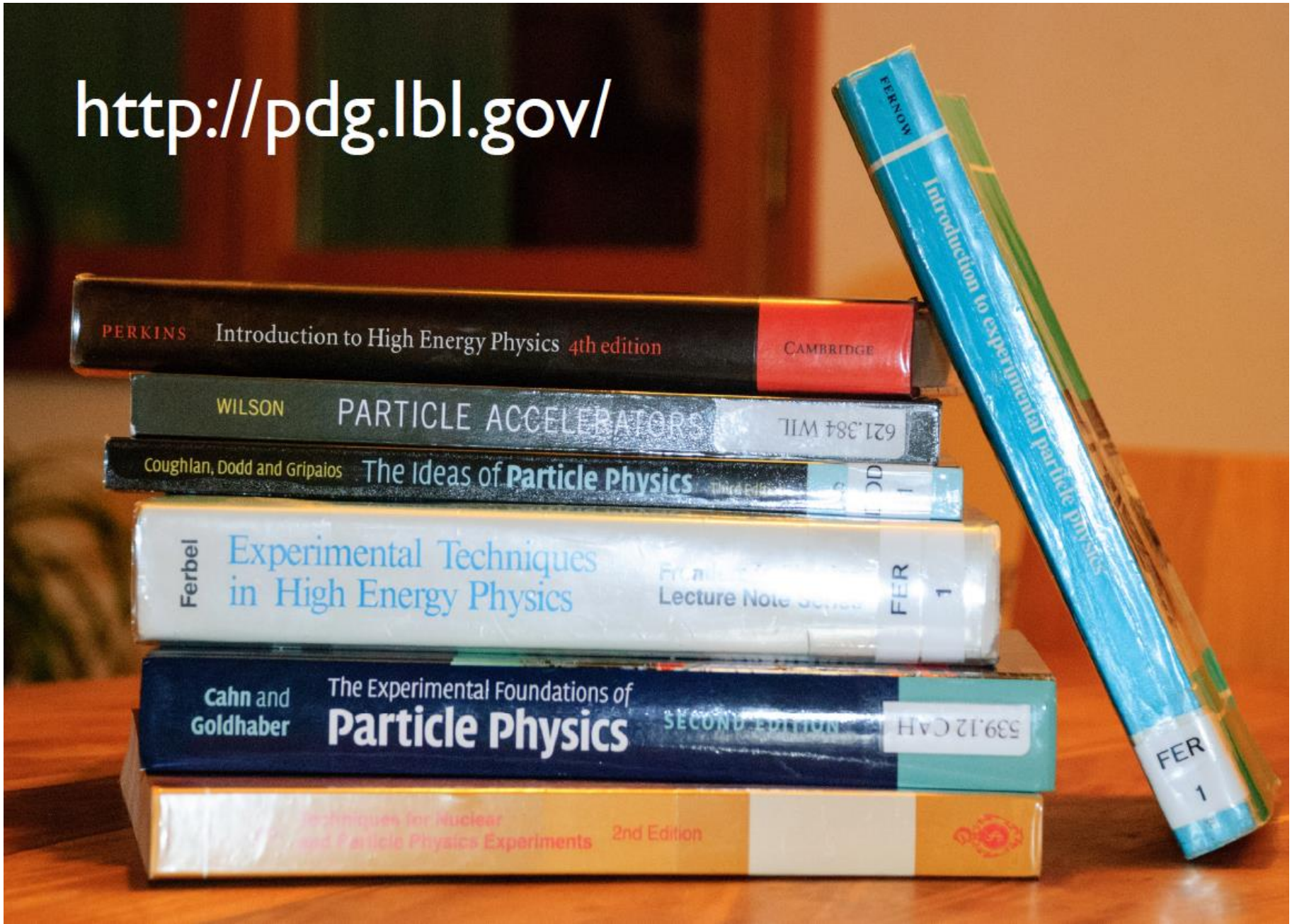
Accelerators

CERN and LHC

Credits:

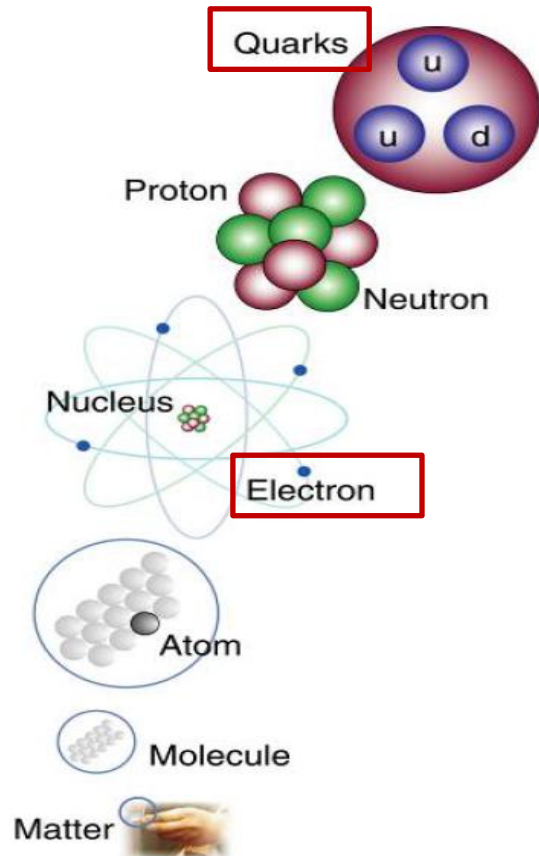
a lot of material in this lecture is from lectures by R.Schmidth at HASCO2017 school.

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



Particles of the Standard Model

Quantum mechanics



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

Interaction particles

<p>2.4M $\frac{2}{3}$</p> <p>u</p> <p>up $\frac{1}{2}$</p>	<p>1.27G $\frac{2}{3}$</p> <p>c</p> <p>charm $\frac{1}{2}$</p>	<p>171.2G $\frac{2}{3}$</p> <p>t</p> <p>top $\frac{1}{2}$</p>	<p>strong nuclear force (color charge)</p> <p>g</p> <p>gluon 1</p>	<p>electromagnetic (charge)</p> <p>γ</p> <p>photon 1</p>
<p>4.8M $-\frac{1}{3}$</p> <p>d</p> <p>down $\frac{1}{2}$</p>	<p>104M $-\frac{1}{3}$</p> <p>s</p> <p>strange $\frac{1}{2}$</p>	<p>4.2G $-\frac{1}{3}$</p> <p>b</p> <p>bottom $\frac{1}{2}$</p>		
<p>0.511M -1</p> <p>e</p> <p>electron $\frac{1}{2}$</p>	<p>105.7M -1</p> <p>μ</p> <p>muon $\frac{1}{2}$</p>	<p>1.777G -1</p> <p>τ</p> <p>tau $\frac{1}{2}$</p>	<p>weak nuclear force</p> <p>W^{+}</p> <p>Z</p>	
<p>< 2.2 0</p> <p>ν_e</p> <p>e-neutrino $\frac{1}{2}$</p>	<p>$< 0.17M$ 0</p> <p>ν_μ</p> <p>μ-neutrino $\frac{1}{2}$</p>	<p>$< 15.5M$ 0</p> <p>ν_τ</p> <p>τ-neutrino $\frac{1}{2}$</p>		



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

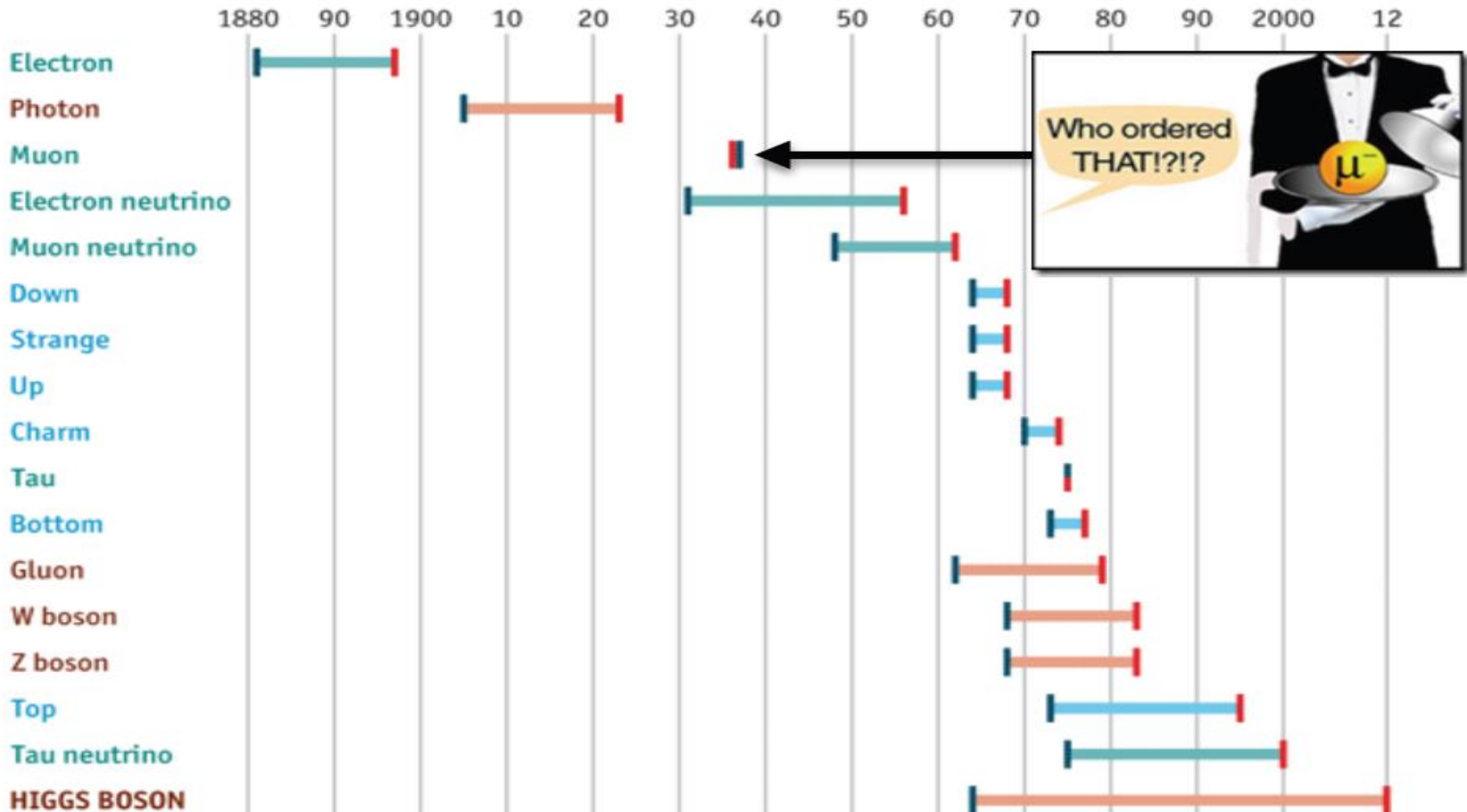
Uncharted discoveries?

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

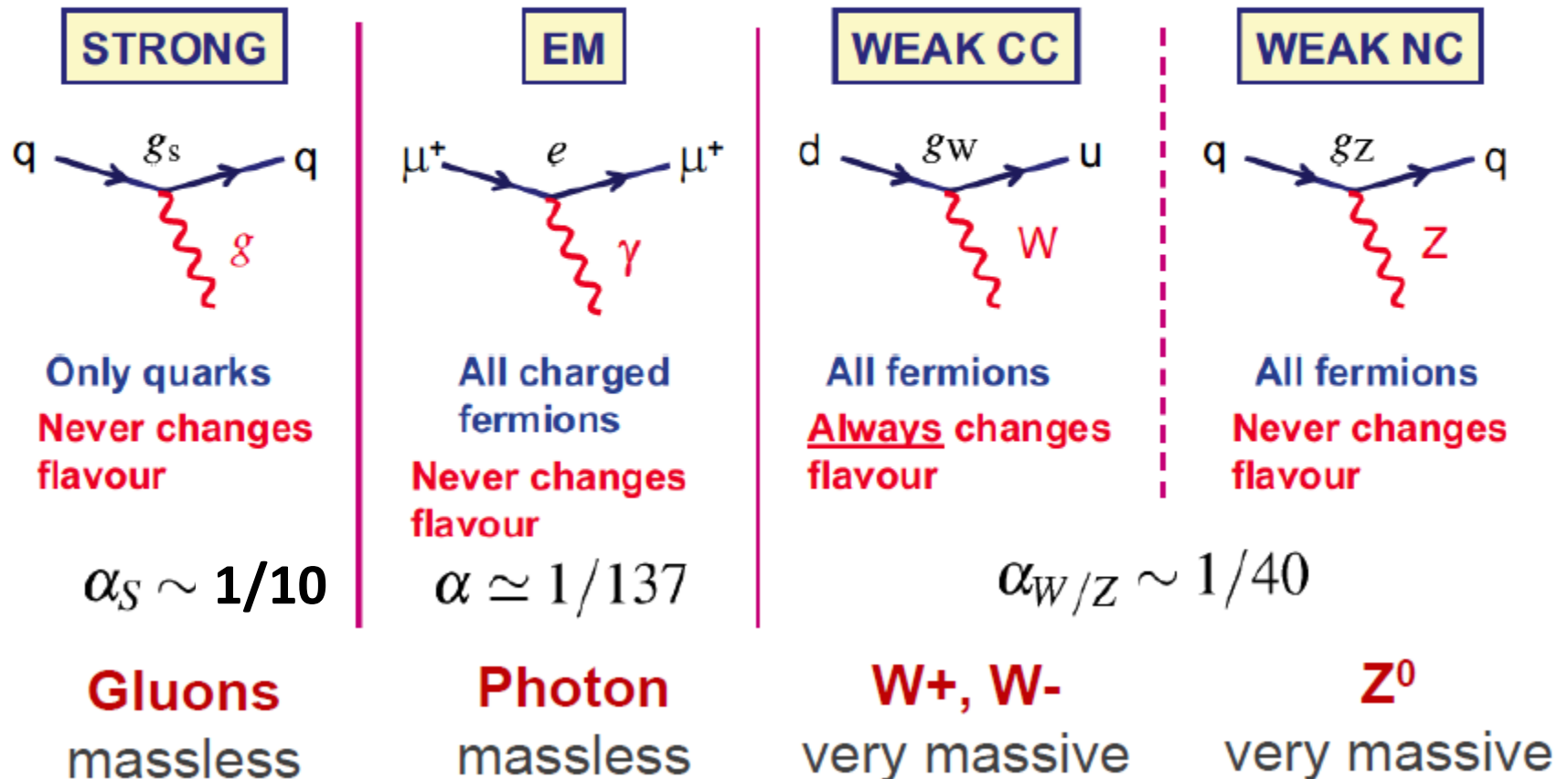
Theorised/explained
Discovered



Source: *The Economist*

Interactions

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



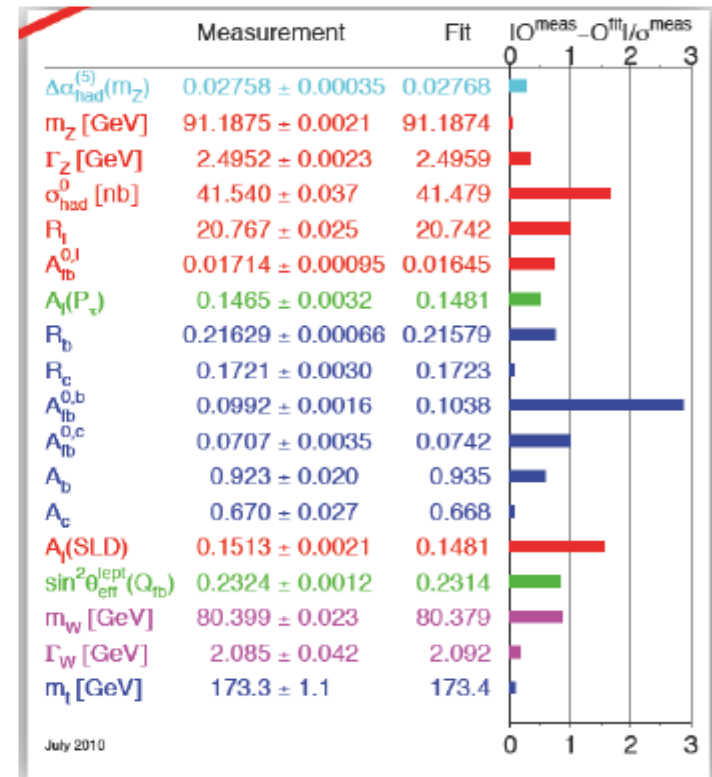
Standard Model confirmed by the data

	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
	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
Quarks	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
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	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

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

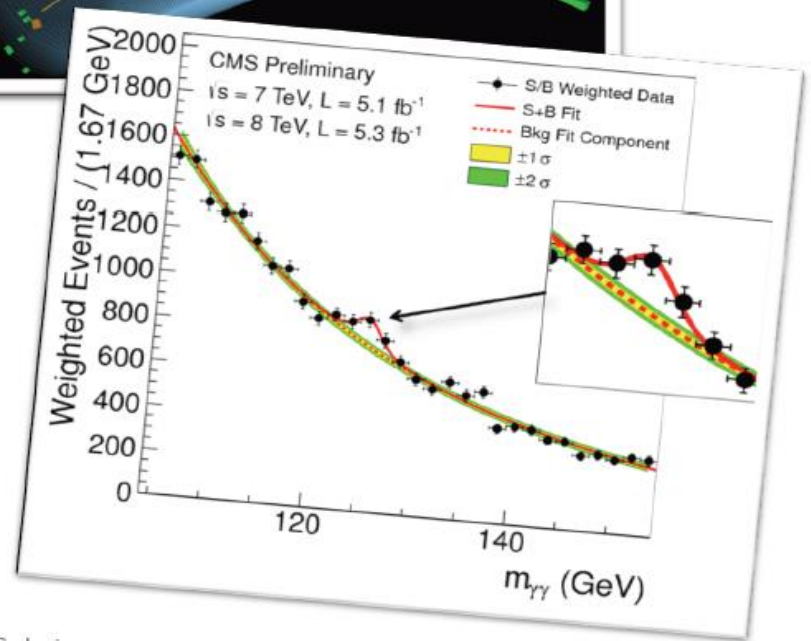
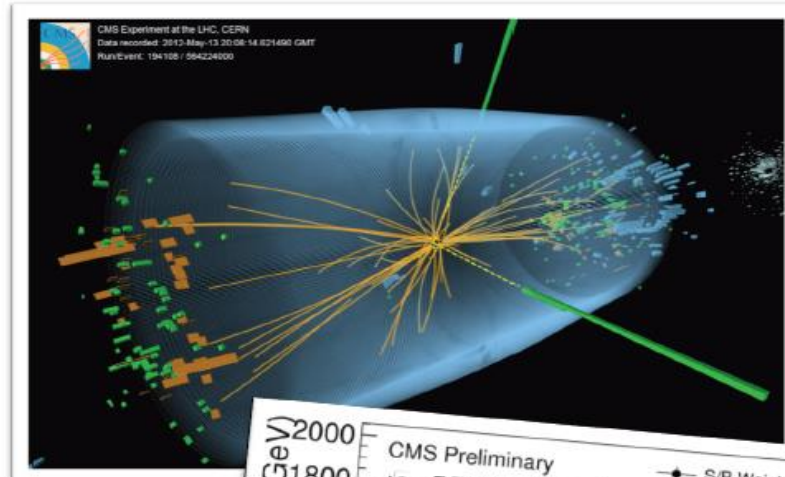
STANDARD MODEL OF ELEMENTARY PARTICLES



Confirmed at sub 1% level!

Experiment = probing theories with data

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^\nu \partial_\nu g_\mu^\nu - g_s f^{abc} \partial_\mu g_\nu^\mu \partial_\nu g_\mu^\nu - \frac{1}{2}g_s^2 f^{abc} f^{ade} g_\mu^\mu g_\nu^\nu g_\rho^\rho g_\sigma^\sigma + \\
 & \frac{1}{2}g_s^2 (g_1^\mu g_2^\nu g_3^\rho + G^{\mu\nu} G^{\rho\sigma} + g_s f^{abc} \partial_\mu G^{\mu\nu} \partial_\nu G^{\rho\sigma} - \partial_\mu W_\nu^\mu \partial_\nu W_\mu^\nu - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}g_s^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_\nu \phi^\mu \partial_\nu \phi^\mu - \frac{1}{2}M \phi^\mu \phi^\mu - \beta_h \frac{[2M]^2}{2} + \\
 & 2M H + \frac{1}{2}(H^2 + \phi^\mu \phi^\mu + 2\phi^+ \phi^-) + \frac{2M^2}{g_s} \alpha_h - ig_{c_w} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) - ig_{s_w} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^- W_\mu^+) - A_\mu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) - \frac{1}{2}g_s^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g_s^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g_s^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^-) + g_s^2 s_w^2 (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & g_s^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g_s^2 s_w^2 c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^- W_\mu^+) - 2A_\mu Z_\nu^0 W_\mu^+ W_\nu^-] - g_s \alpha [H^2 + H \phi^\mu \phi^\mu + 2(\phi^\mu)^2 H^2] - \\
 & \frac{1}{2}g_s^2 \alpha_h [H^4 + (\phi^\mu)^4 + 4(\phi^\mu)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^\mu)^2 H^2] - \\
 & g M W_\mu^+ W_\nu^- H - \frac{1}{2}g_s \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig [W_\mu^+ (H \partial_\nu \phi^- - \phi^- \partial_\nu H) - W_\nu^- (H \partial_\mu \phi^+ - \\
 & W_\mu^+ \partial_\nu \phi^+ - \phi^+ \partial_\nu \phi^\mu)] + \frac{1}{2}ig [W_\mu^+ (H \partial_\nu \phi^- - \phi^- \partial_\nu H) - W_\nu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\nu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 H \partial_\nu \phi^\mu - \phi^\mu \partial_\nu H) - ig_{c_w}^2 M Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \\
 & ig_{s_w} M A_\mu (W_\mu^+ \phi^- - W_\nu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \\
 & ig_{s_w} A_\mu (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- [H^2 + (\phi^\mu)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^\mu)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 s_w^2 Z_\mu^0 \phi^\mu (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2}g^2 s_w^2 A_\mu \phi^\mu (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) + \frac{1}{2}ig^2 s_w^2 A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- - e^2 (\gamma \partial + m_\nu^2) e^\lambda - \rho^2 \gamma \partial \nu^\lambda - u_2^2 (\gamma \partial + m_\nu^2) u_2^\lambda + \\
 & d_2^2 (\gamma \partial + m_\nu^2) d_2^\lambda + ig_{s_w} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(u_2^\lambda \gamma^\mu u_2^\lambda) - \frac{1}{3}(d_2^\lambda \gamma^\mu d_2^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\nu^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (u_2^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - \\
 & 1 - \gamma^5) u_2^\lambda) + (d_2^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_2^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\nu^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
 & (u_2^\lambda \gamma^\mu (1 + \gamma^5) C_{3\lambda} d_2^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(e^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (d_2^\lambda \gamma^\mu C_{3\lambda} \nu^\lambda) + \\
 & (\nu^\lambda \gamma^\mu u_2^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_\nu^2}{M} [-\phi^+ (\nu^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (e^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{ig}{2} \frac{m_\nu^2}{M} [H (e^\lambda e^\lambda) + i\phi^0 (e^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\nu^2 (u_2^\lambda C_{3\lambda} (1 - \gamma^5) d_2^\lambda) + \\
 & m_\nu^2 (u_2^\lambda C_{3\lambda} (1 + \gamma^5) d_2^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_\nu^2 (d_2^\lambda C_{3\lambda}^1 (1 + \gamma^5) u_2^\lambda) - m_\nu^2 (d_2^\lambda C_{3\lambda}^1 (1 - \\
 & \gamma^5) u_2^\lambda)] - \frac{ig}{2} \frac{m_\nu^2}{M} H (u_2^\lambda u_2^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} H (d_2^\lambda d_2^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (u_2^\lambda \gamma^5 u_2^\lambda) - \\
 & \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (d_2^\lambda \gamma^5 d_2^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w}) X^0 + \bar{Y} \partial^2 Y + ig_{c_w} W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig_{c_w} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig_{s_w} W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + ig_{c_w} Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^0) + ig_{s_w} A_\mu (\partial_\mu \bar{X}^+ X^- + \\
 & \partial_\mu \bar{X}^- X^0) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^+ X^+ \phi^-] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^+ X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

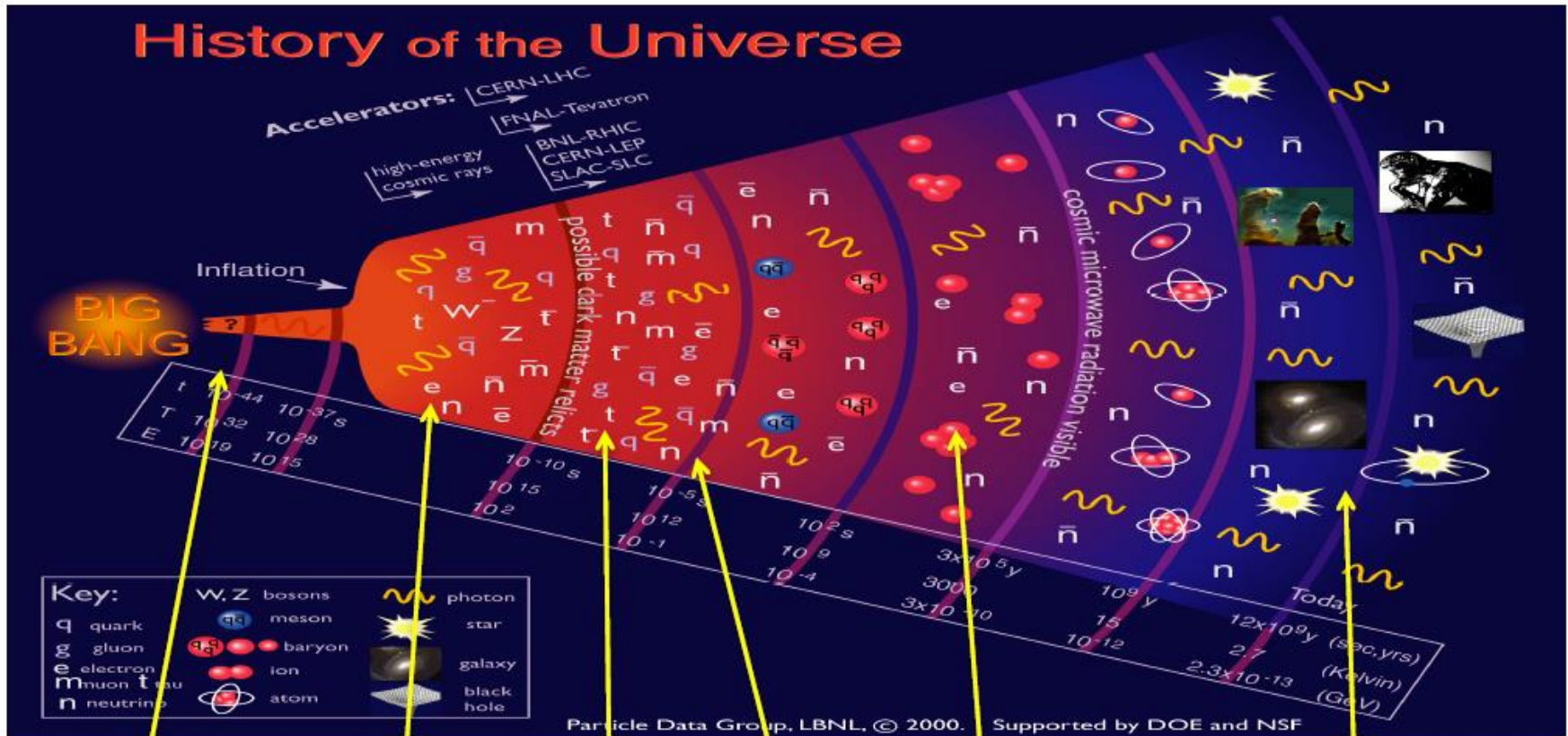


- Delamater

(experimental) LHC physics

Accelerators for high energy physics experiments

History of the Universe



Cosmology

Cosmic rays

LHC

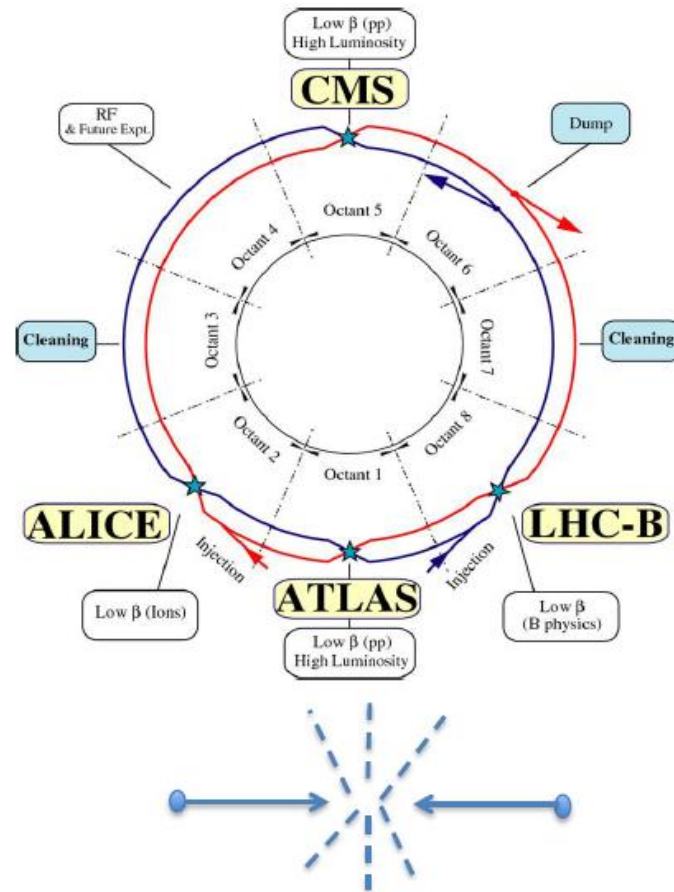
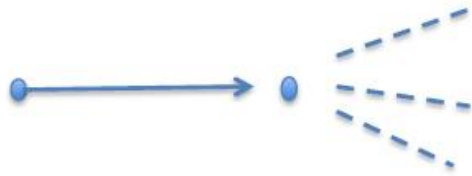
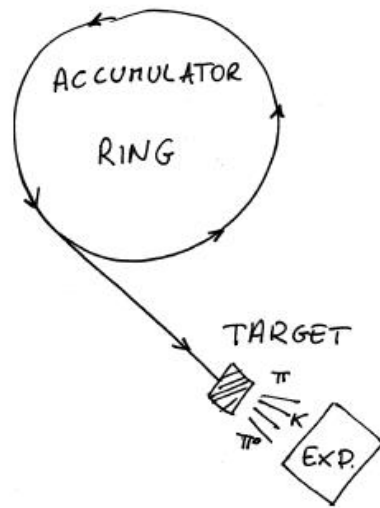
Quark/gluon plasma

Nuclear physics

Astrophysics

Plus

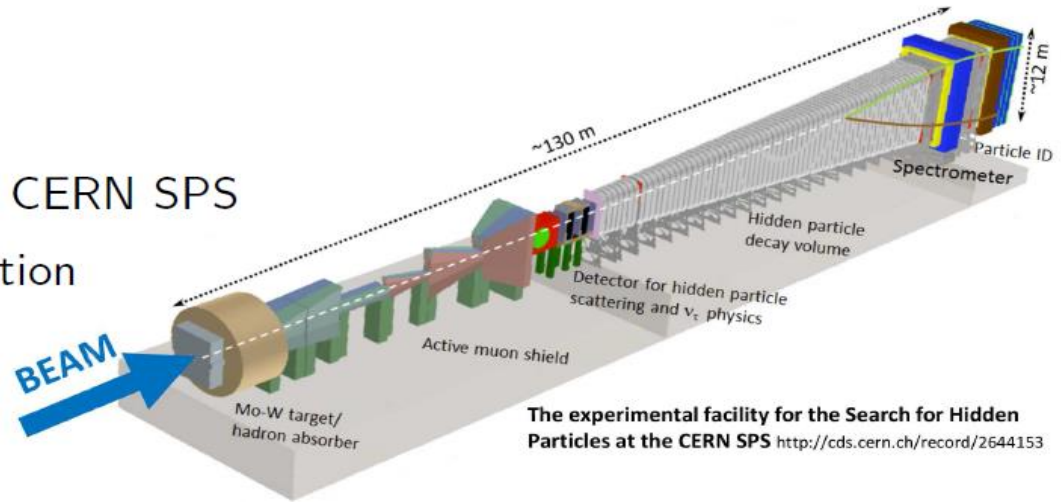
Fixed target vs Colliders



Fixed target vs Colliders

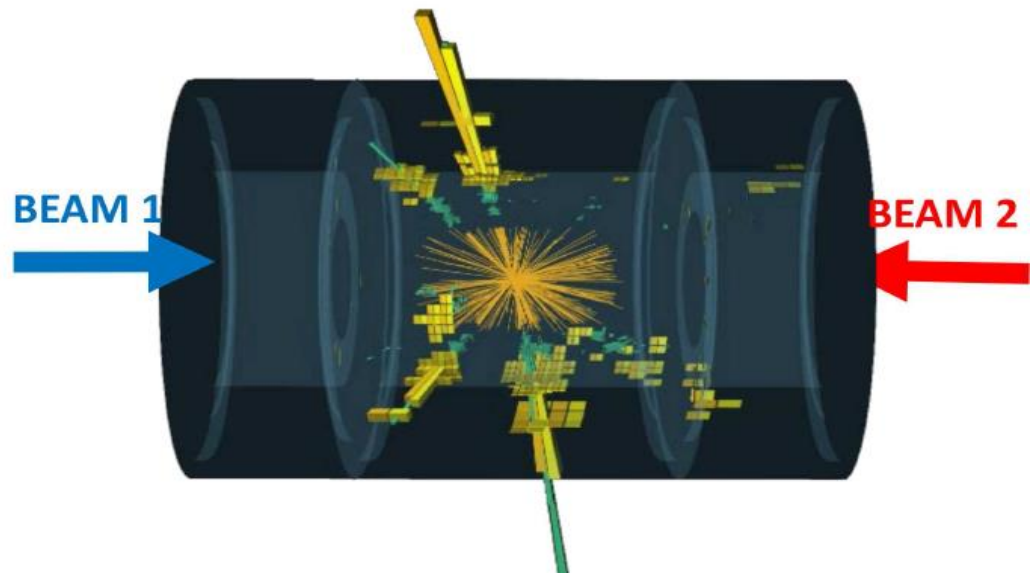
Fixed target e.g. SHIP @ CERN SPS

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

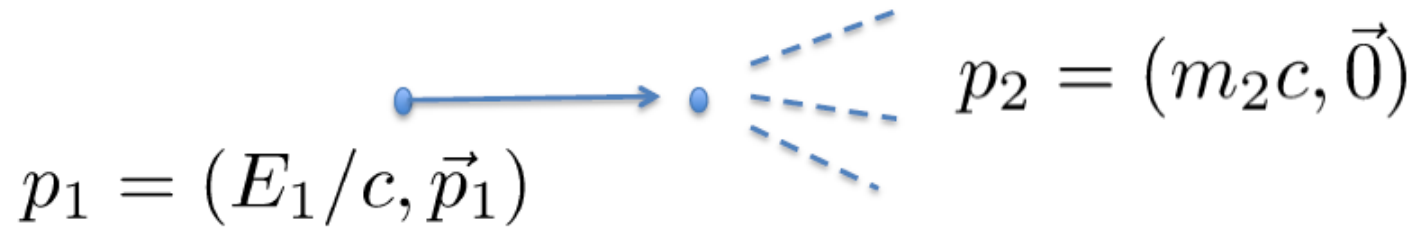


Collider e.g. LHC @ CERN

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



E_{CM} in Fixed Target Experiment




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

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

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

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

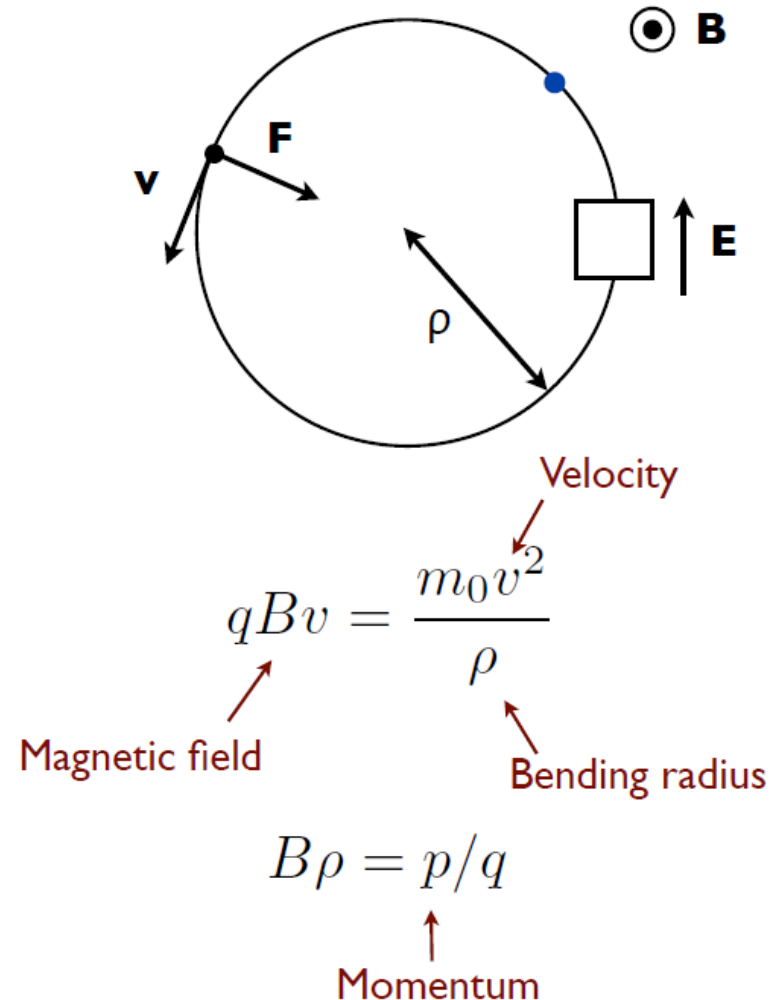
Energy change

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

- 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

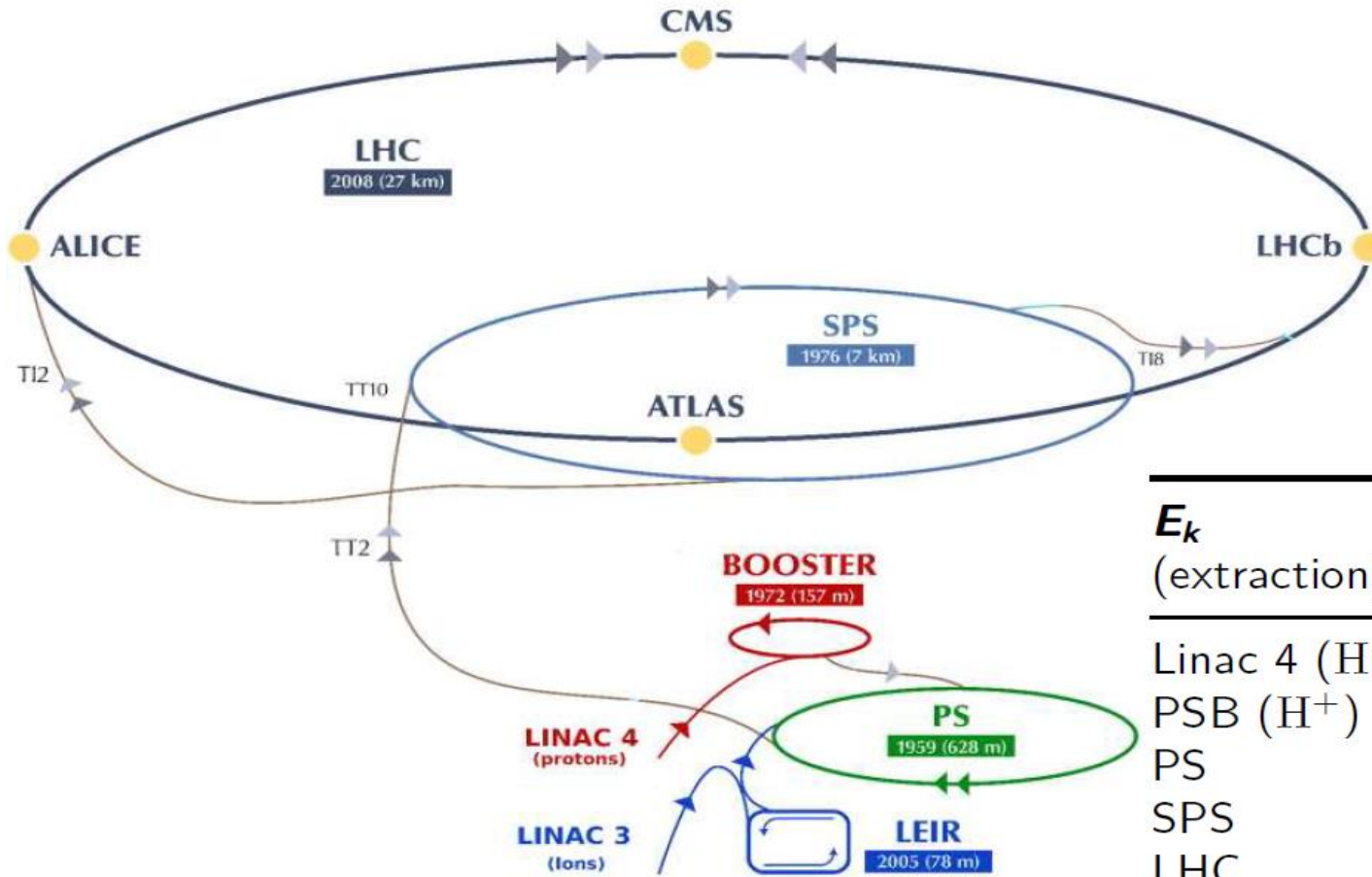
Synchrotron

- 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



CERN accelerator complex

LHC injector chain



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

Linac

Linear Accelerator → 'Linac'

Colloquially 'Linac' can refer both to a general Linear Accelerator facility or to a specific accelerating structure

- **Single pass accelerator**

→ beam goes through once

→ facility not always straight, e.g. SLC

- **Energy depends on length**

For HEP 2 main applications:

- **Low energy hadrons**

- **High energy e^- or e^+ collider**

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

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

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



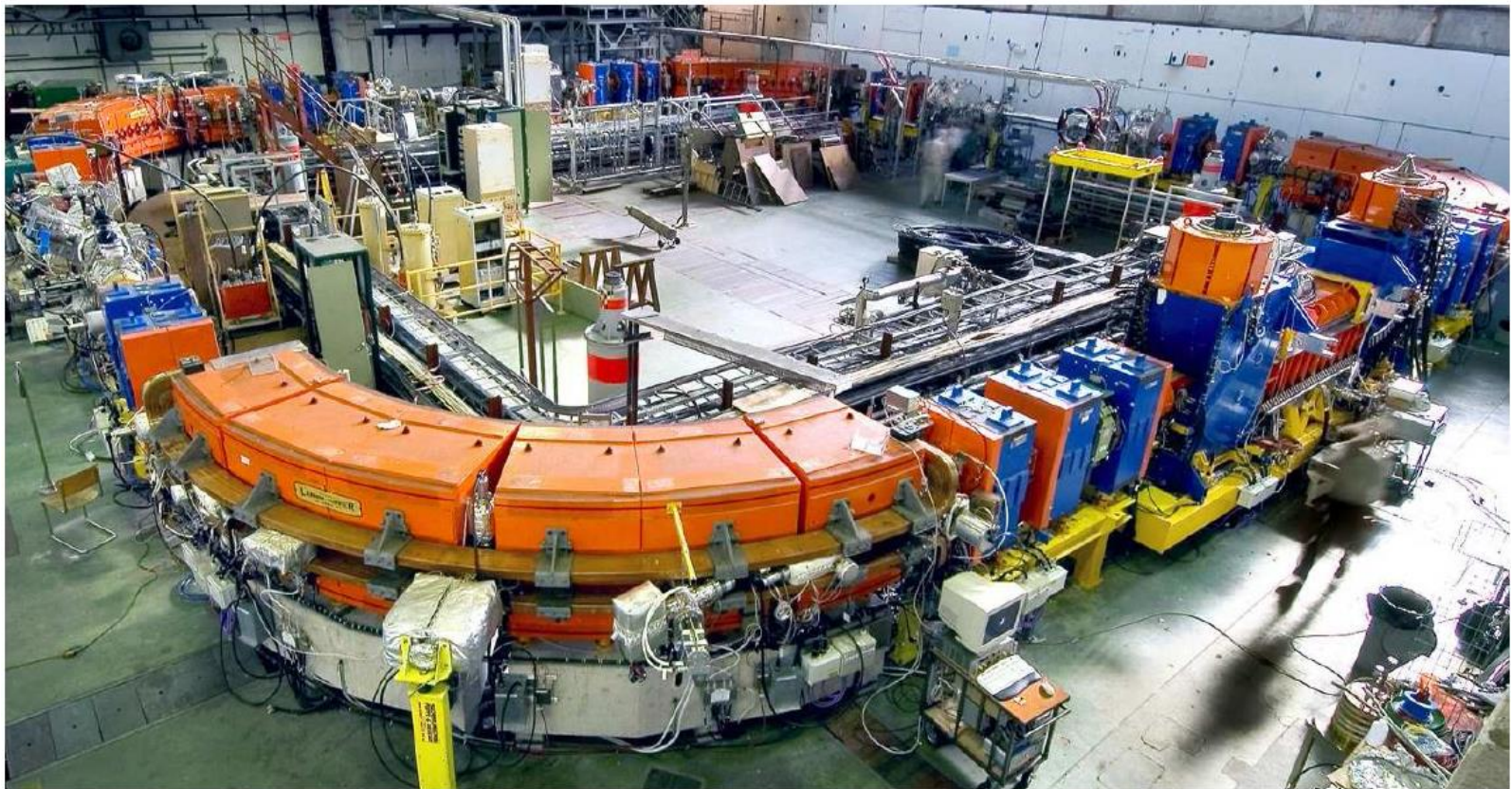
Synchrotron

Synchrotron

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

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

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



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

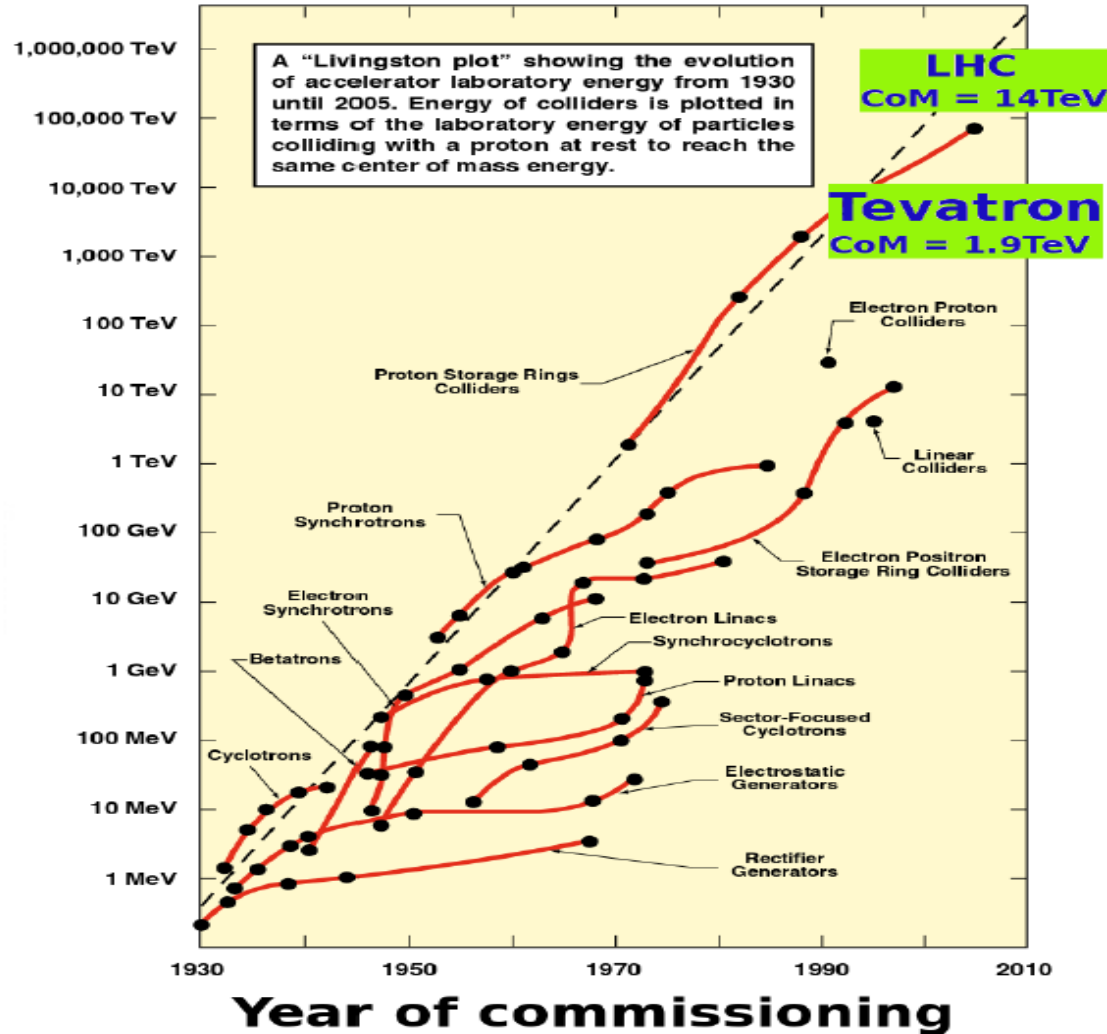
1989-2000: LEP highest energy electron synchrotron, e^+,e^- , 104 GeV, 27 km circumference; three generations of quarks, gluons and leptons

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

Equivalent Beam Energy of Fixed Target Collider

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

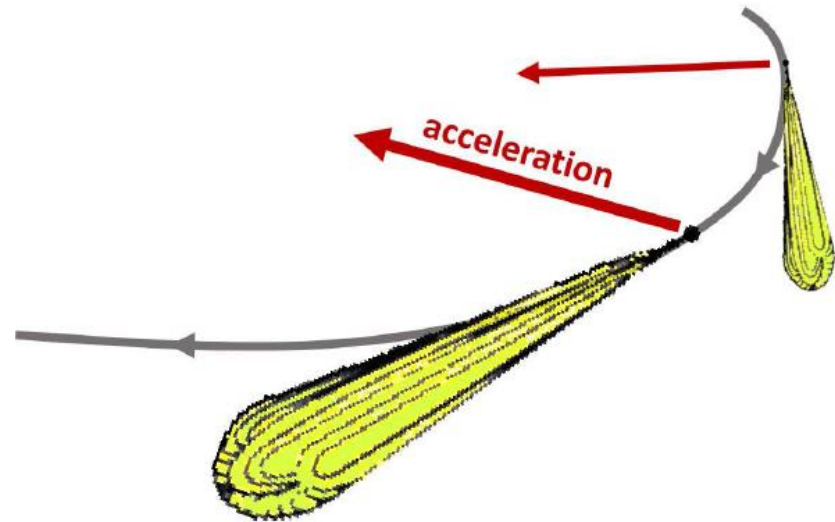


Energy frontier

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

→ particles emit **synchrotron radiation** as they are bent around ring

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



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

Energy frontier

Limiting factor for circular hadron collider:

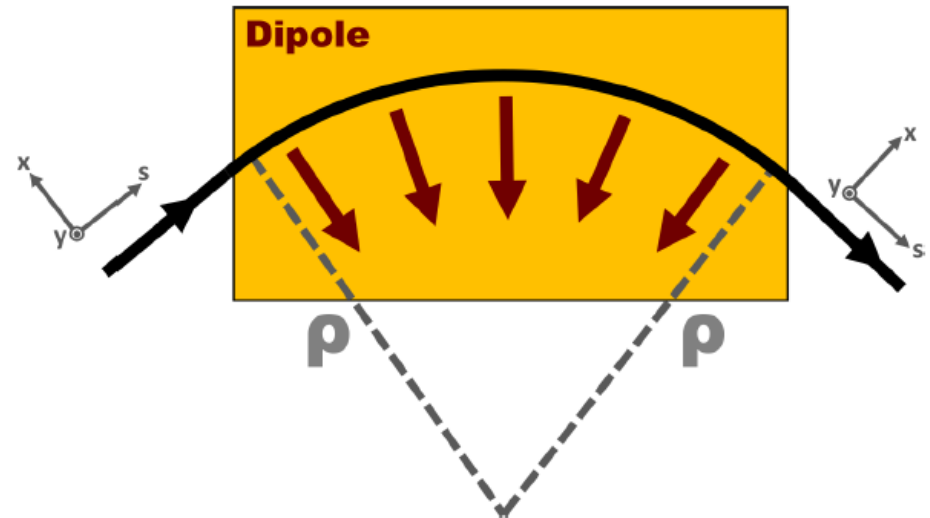
→ need sufficient dipole field strength to bend beams around the ring

→ **High Energy = high magnetic rigidity**

$$F_{\text{Lorentz}} = F_{\text{centrip}}$$

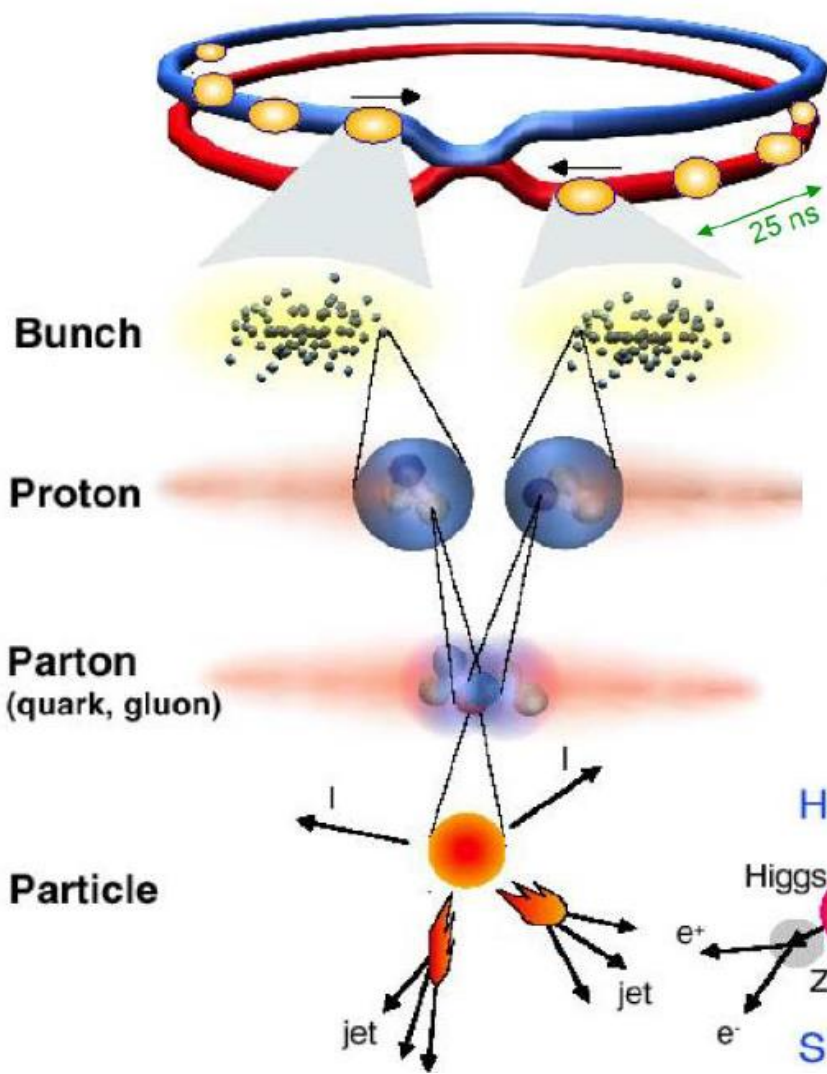
$$qvB = \frac{\gamma m_{\text{rest}} v^2}{\rho} = \frac{pv}{\rho}$$

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



Collisions at LHC

Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{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**

$$E = m c^2$$

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]

Beamsize:

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

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

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

Luminosity frontier

- Need corresponding rise in luminosity (beam intensity)

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

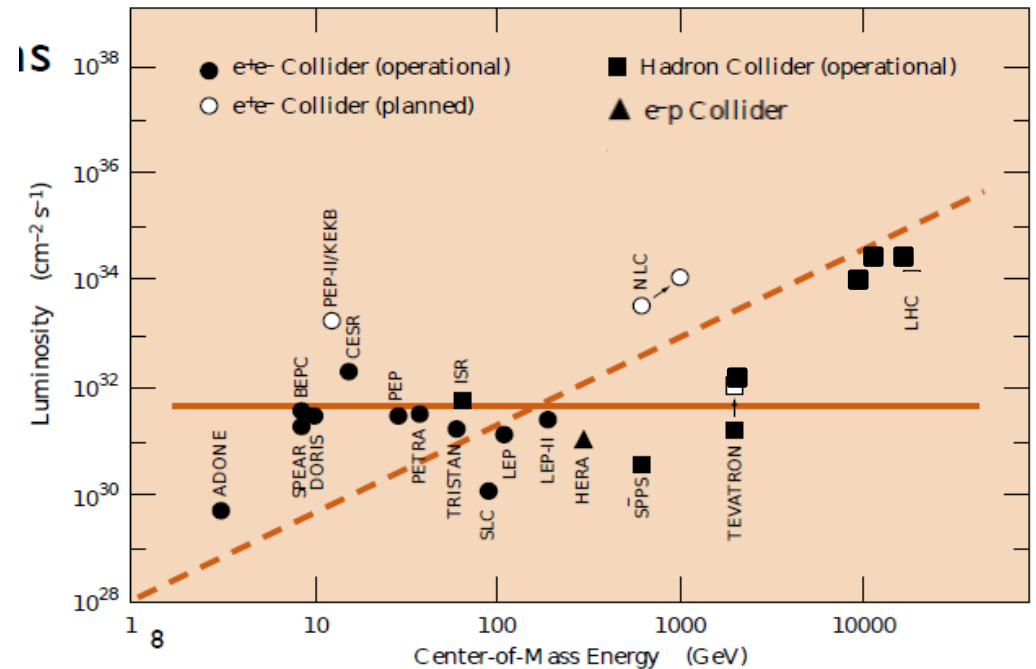
Number of events
Instantaneous luminosity

↓
↓

↑
↑

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,**

Particle Physics Labs

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

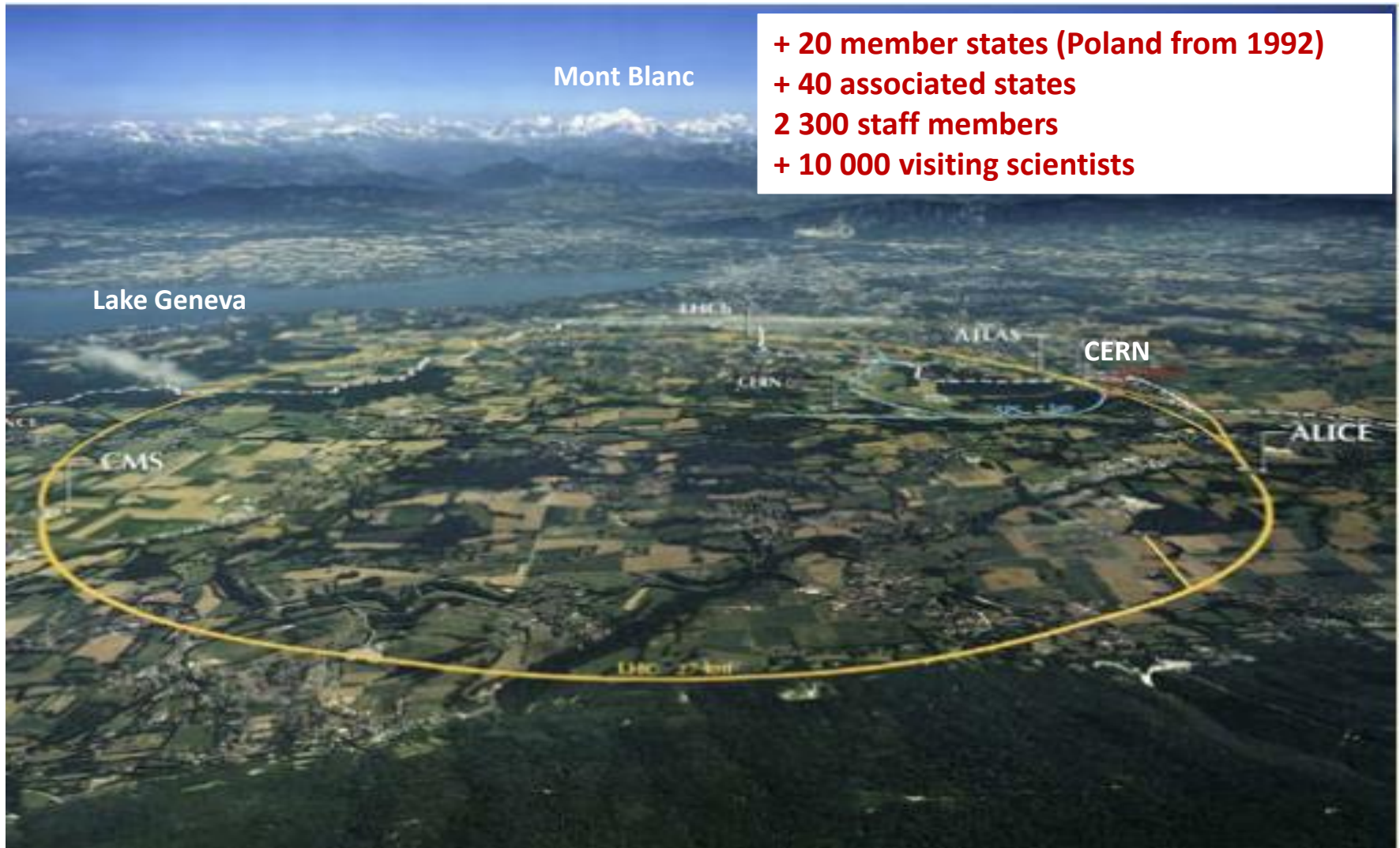


CERN laboratory (founded in 1954)

Mont Blanc

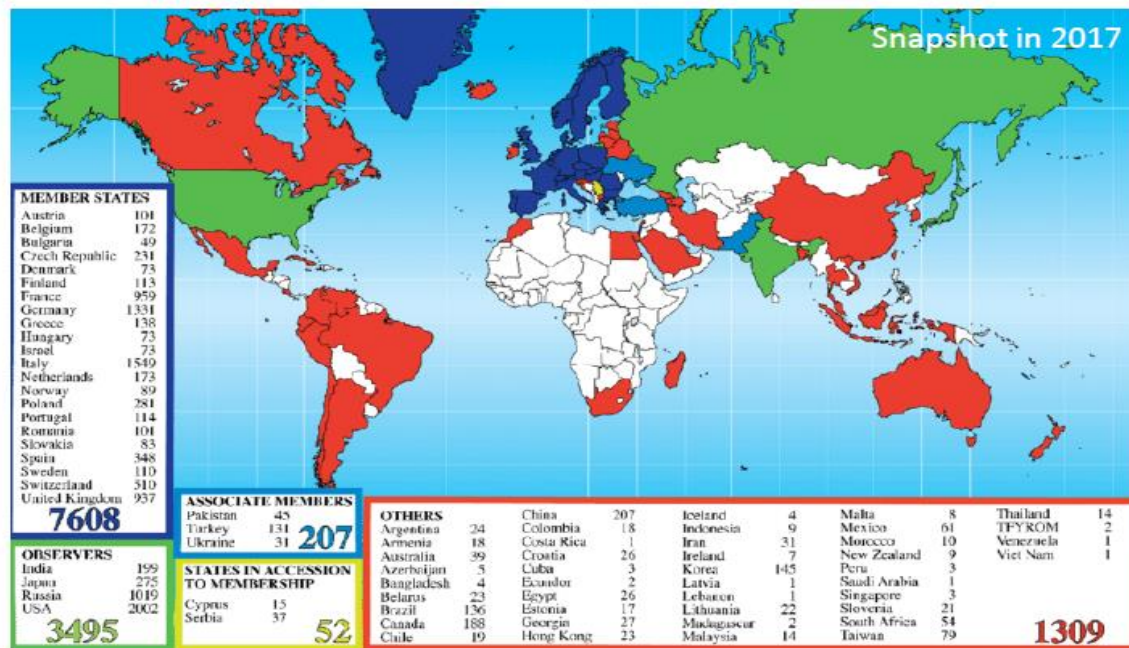
+ 20 member states (Poland from 1992)
+ 40 associated states
2 300 staff members
+ 10 000 visiting scientists

Lake Geneva



CERN laboratory: users

CERN users



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

LHC pp and ions

7 TeV/c – up to now 6.5 TeV/c

26.8 km
Circumference

The confusion with 7 TeV: energy of one proton or two protons ? ...watch out

Switzerland
Lake Geneva

LHC Accelerator
(100 m down)

CMS, TOTEM

CERN-
Prevezin

ALICE

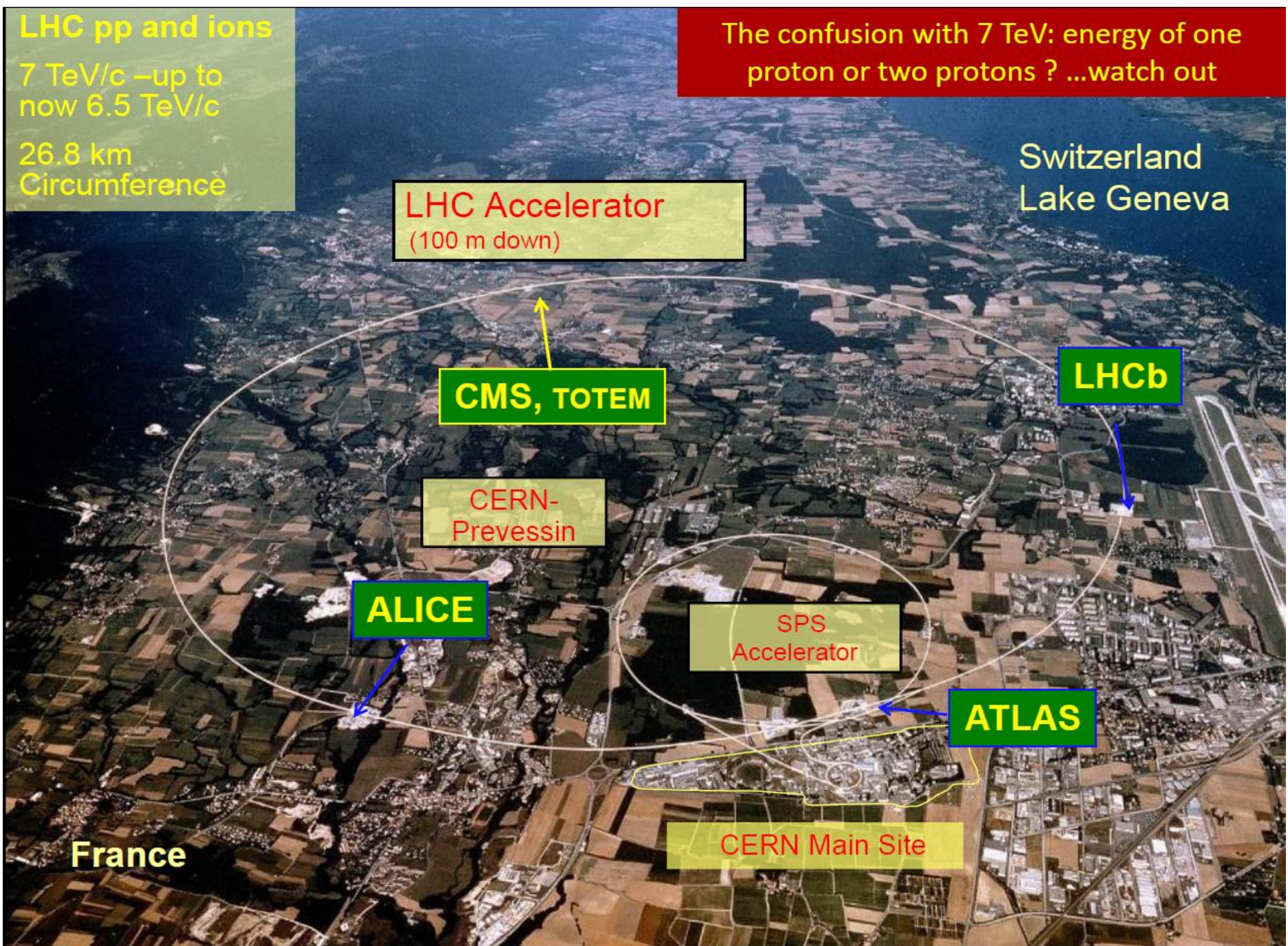
SPS
Accelerator

ATLAS

LHCb

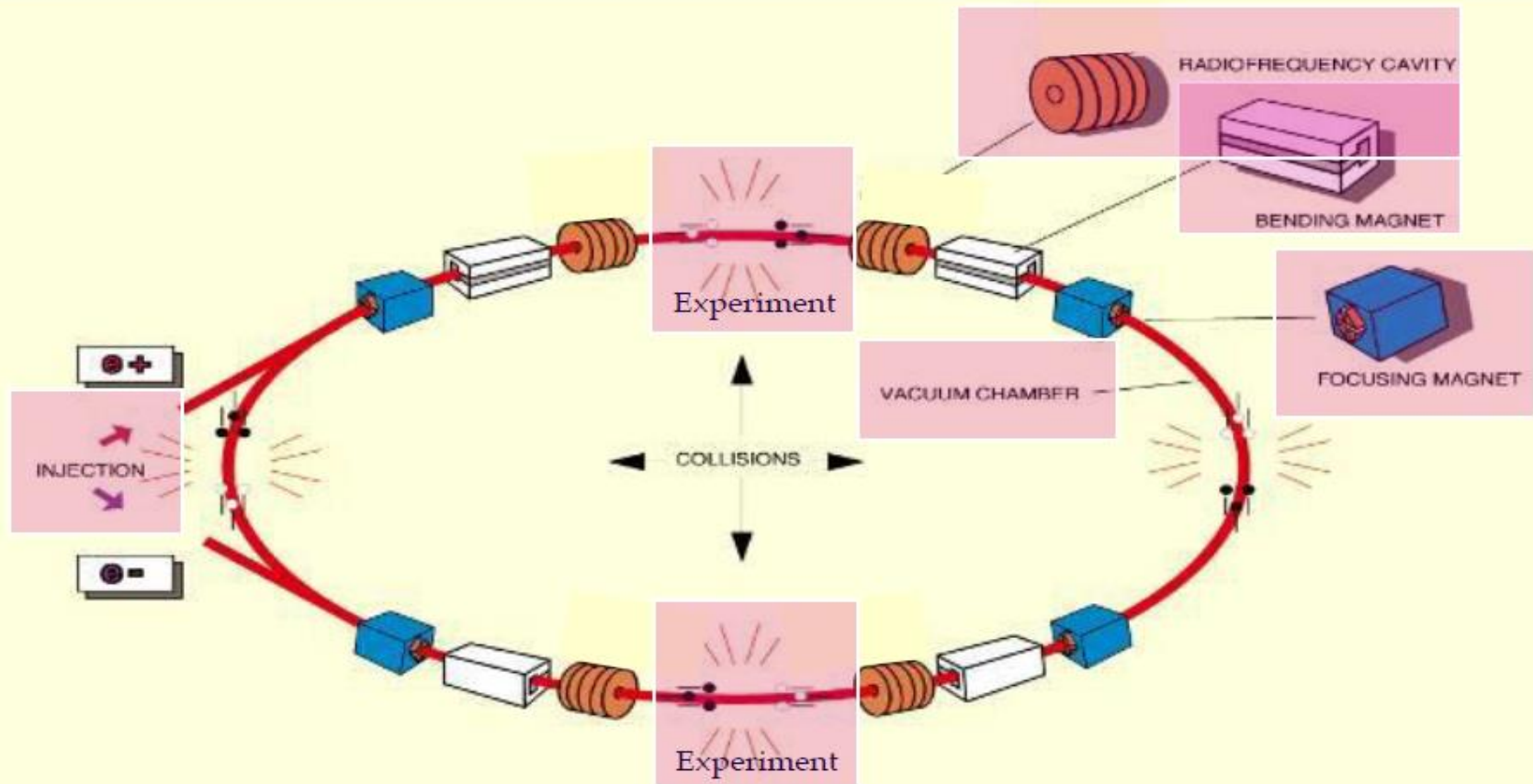
CERN Main Site

France

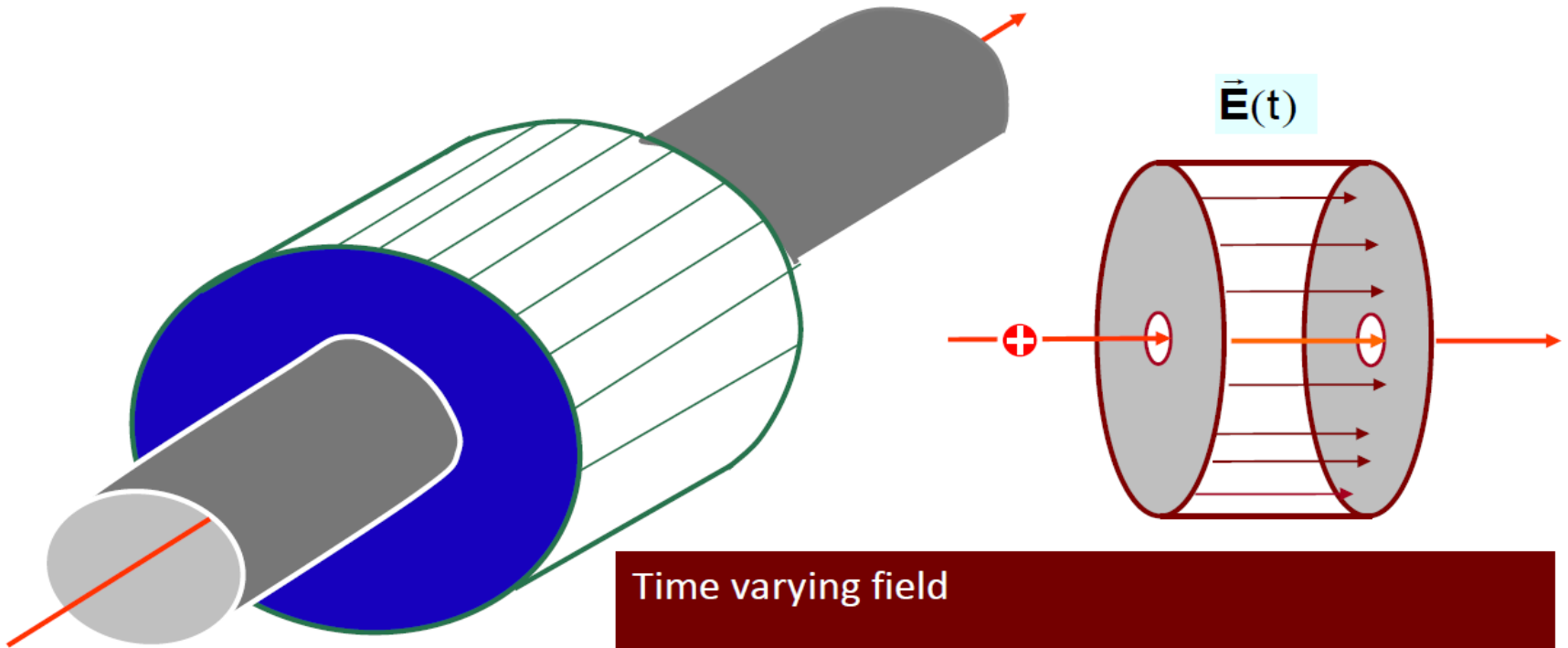


Synchrotron + many passages in RF cavities

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

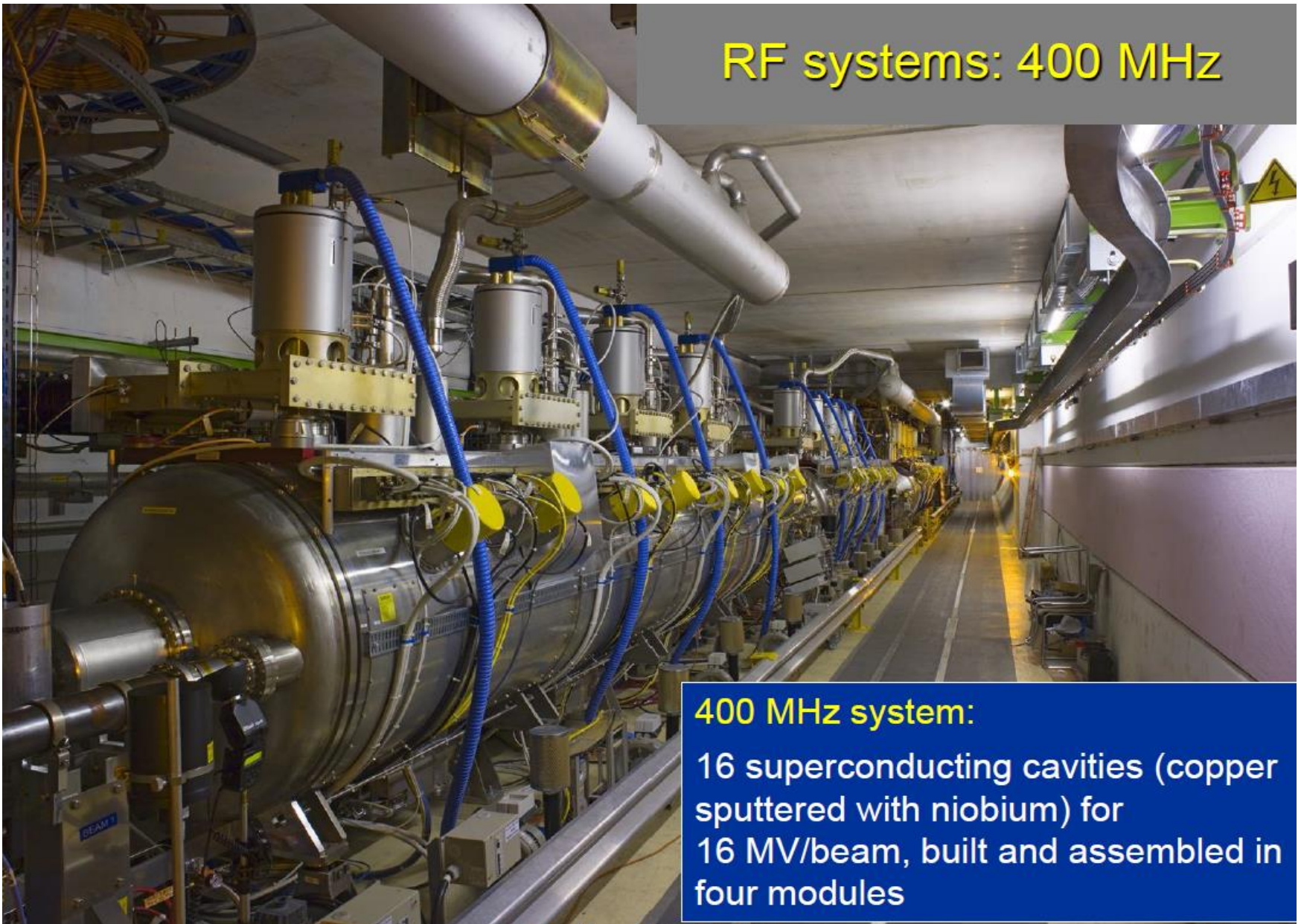
Time varying field

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

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:

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

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

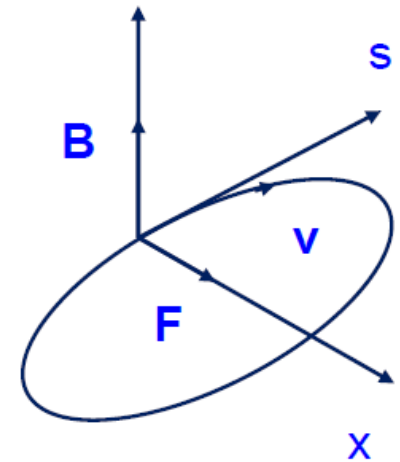
Maximum momentum 7000 GeV/c

Radius 2805 m fixed by LEP tunnel

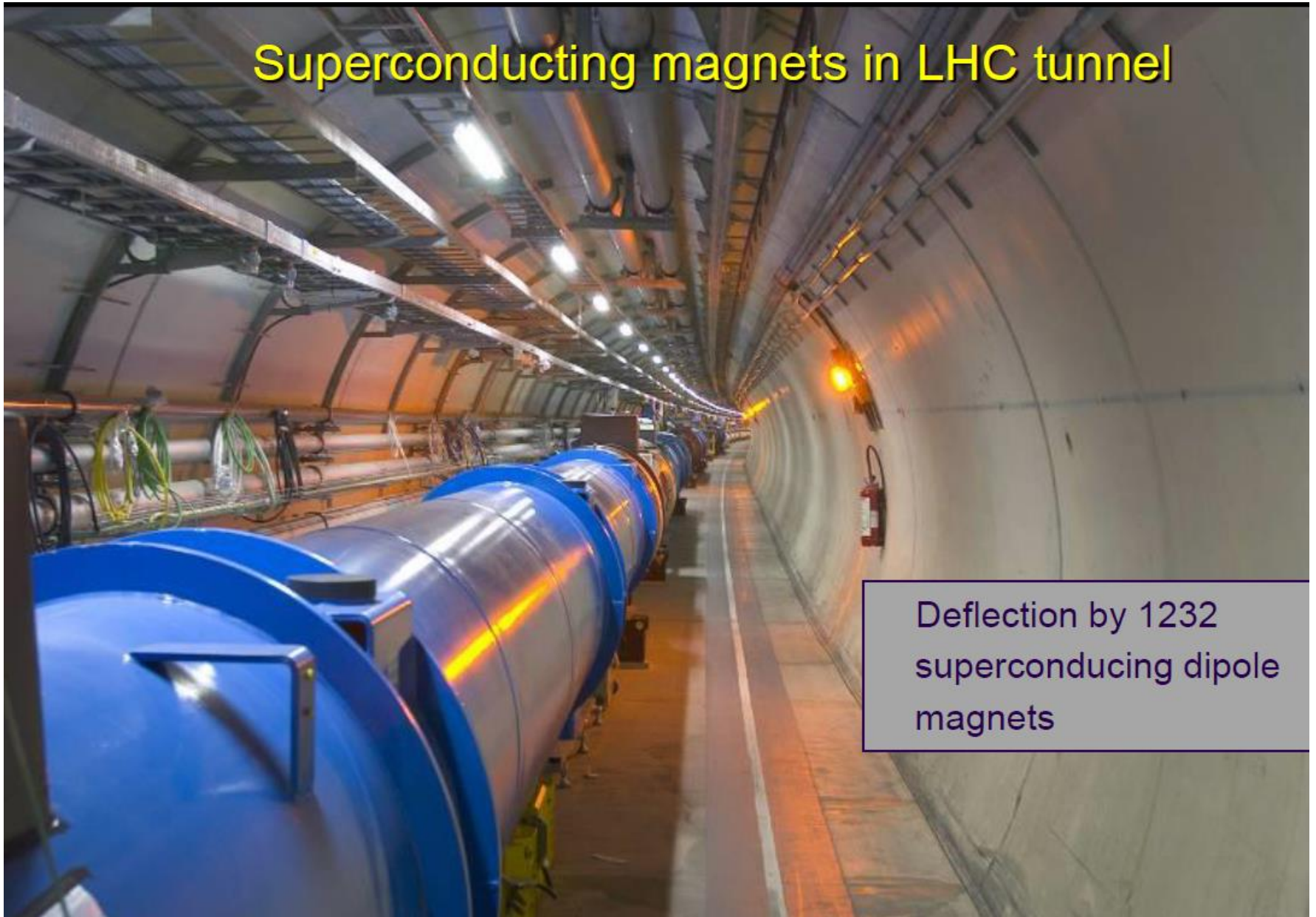
Magnetic field $B = 8.33$ Tesla

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

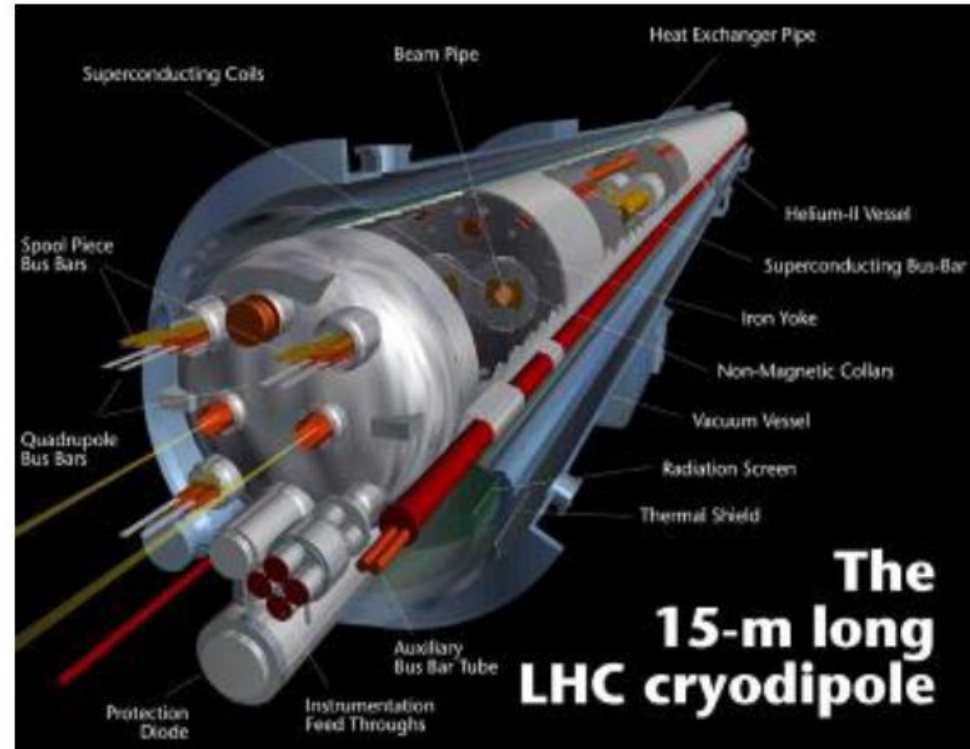
Dipole magnets for the LHC

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

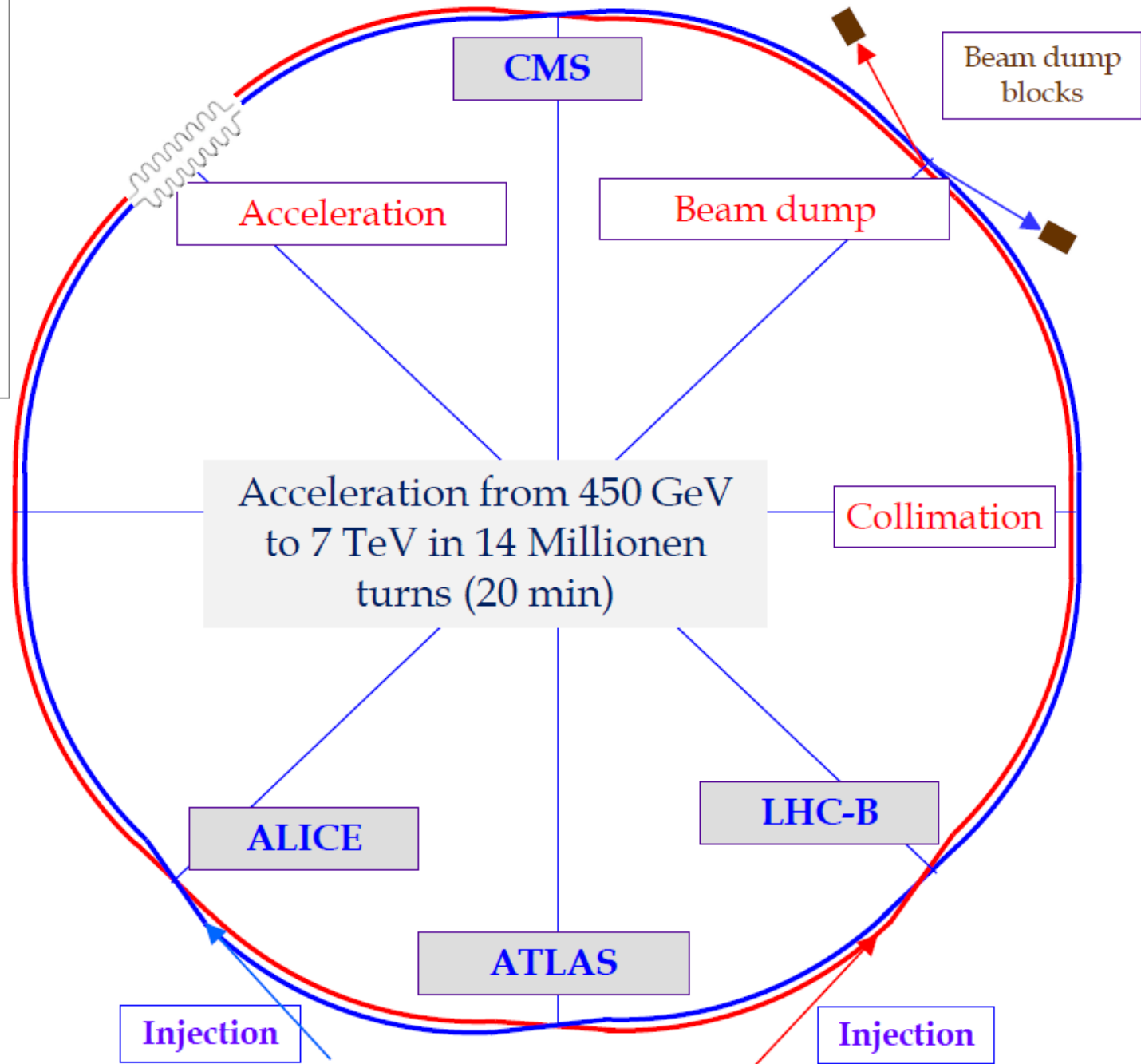
eight arcs (sectors)

eight long straight section (about 700 m long)

1232 deflecting dipole magnets

Collimation

- 27 km
- 2 beams
- 11246 turns/second



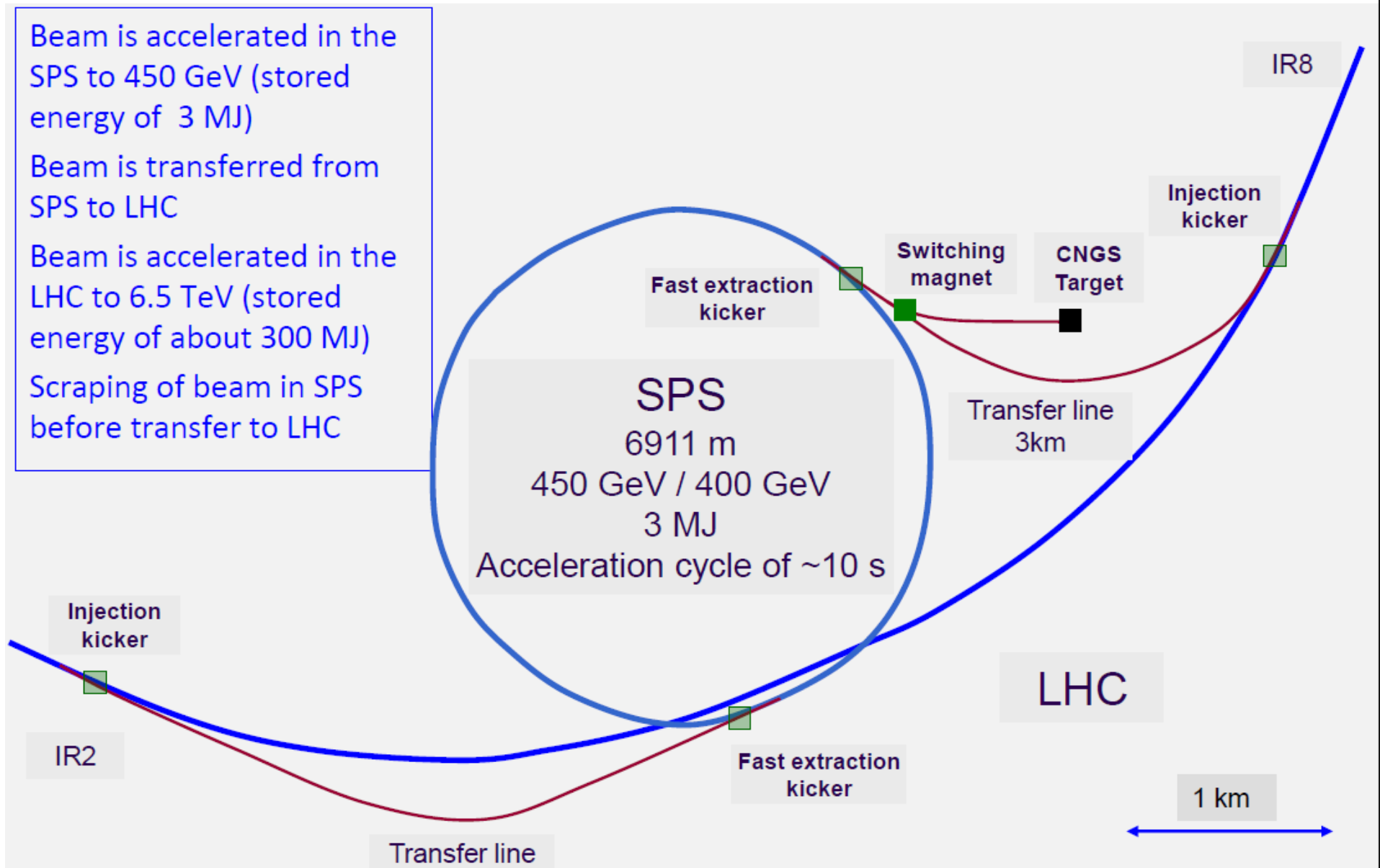
SPS, transfer line and the LHC

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

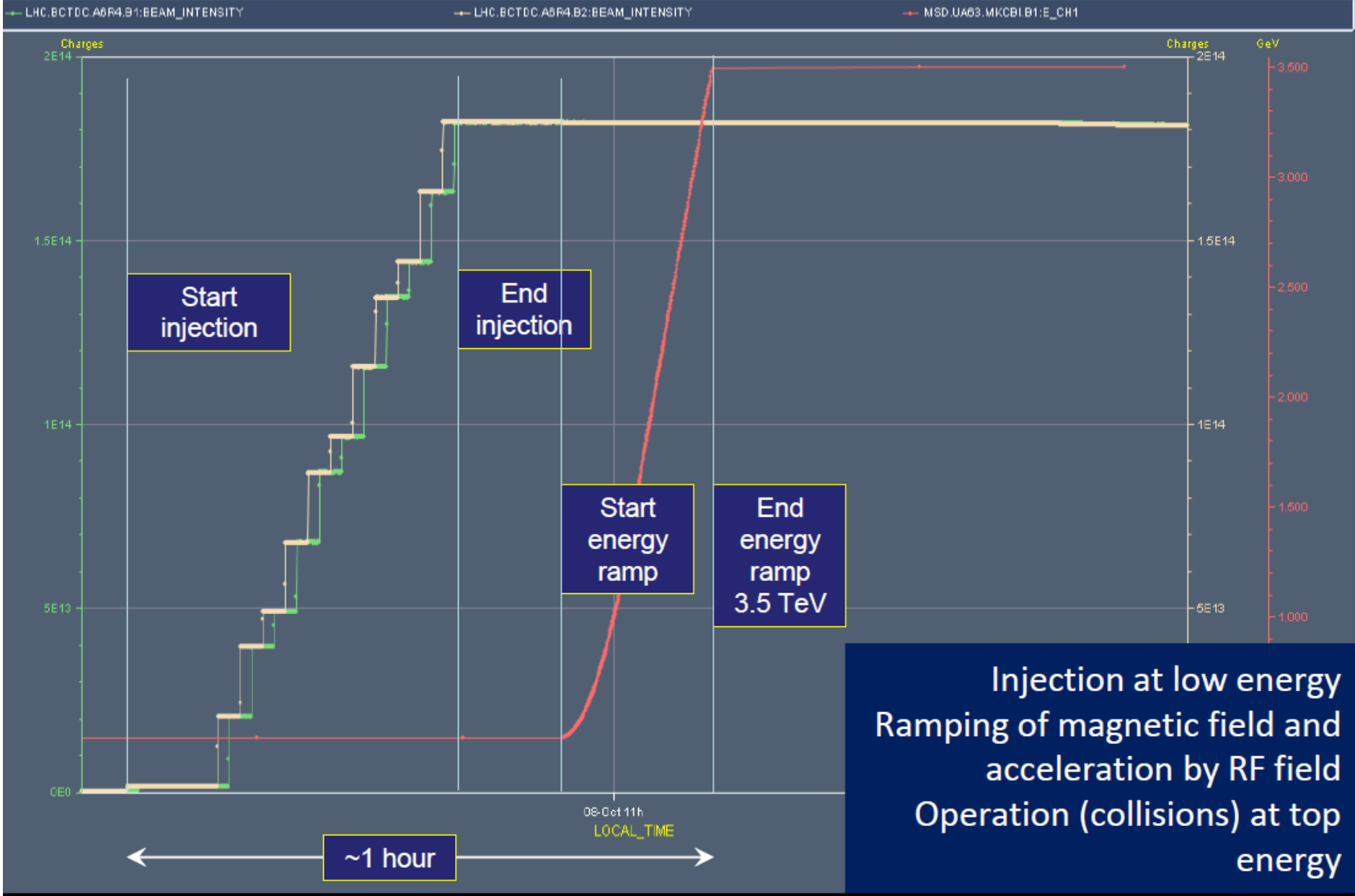
Beam is transferred from SPS to LHC

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

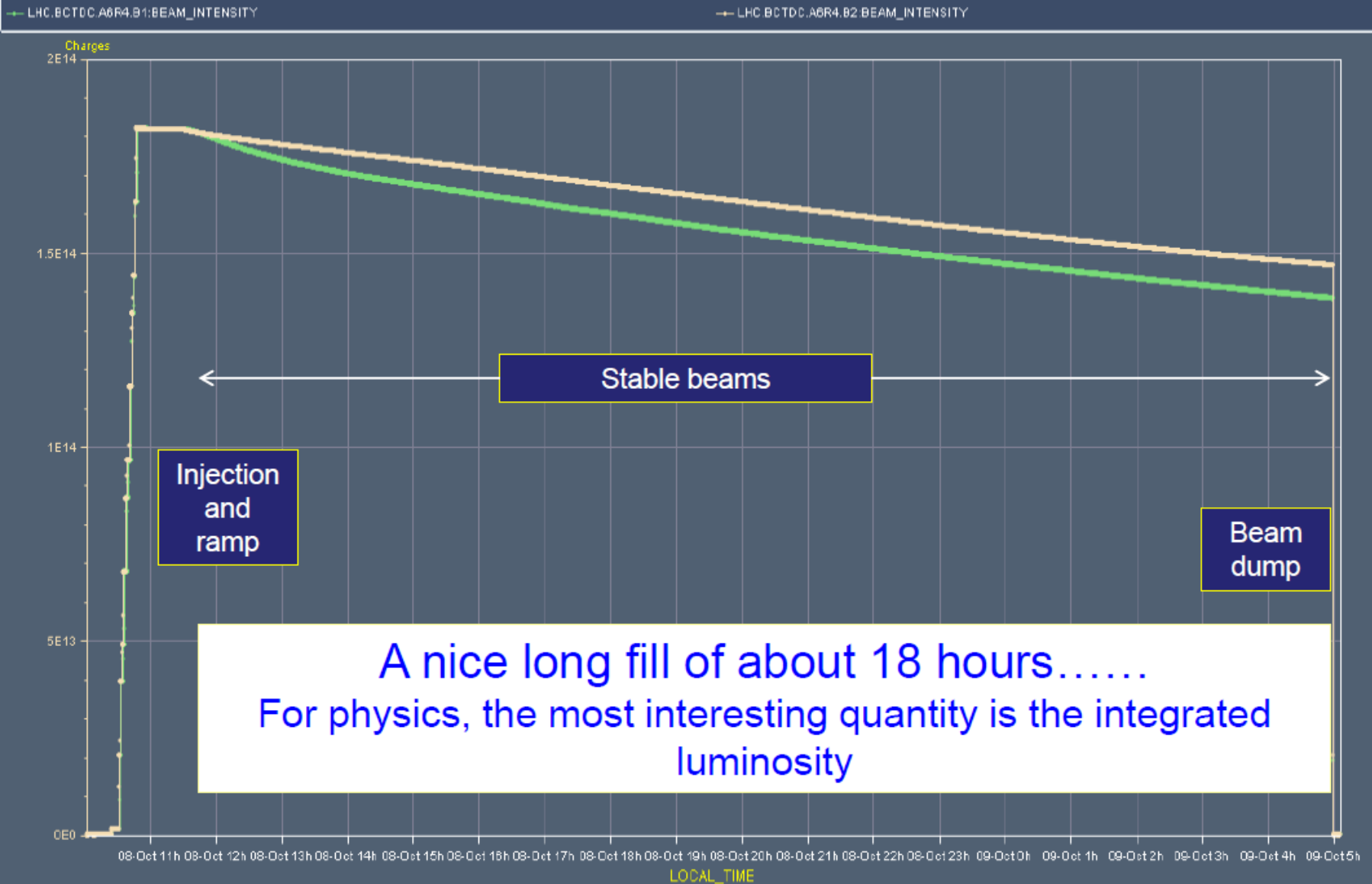
Scraping of beam in SPS before transfer to LHC



Synchrotron principle: LHC fill (2011)



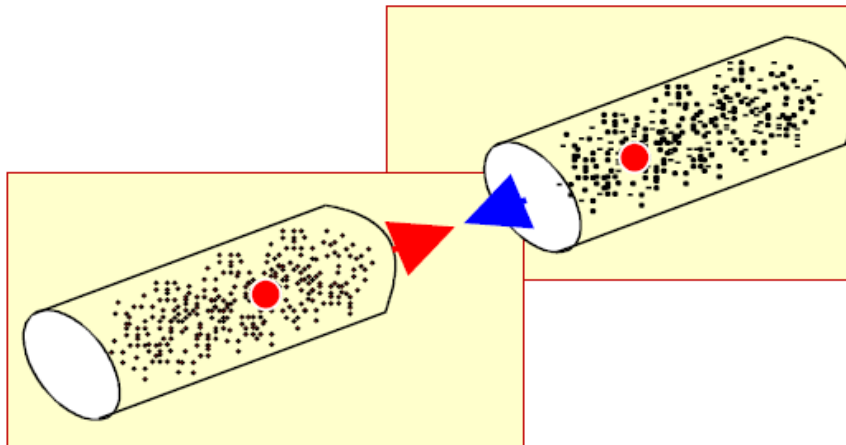
Excellent fill (2011)



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 $1\text{-}3 \times 10^{11}$ due to the beam-beam interaction and beam instabilities

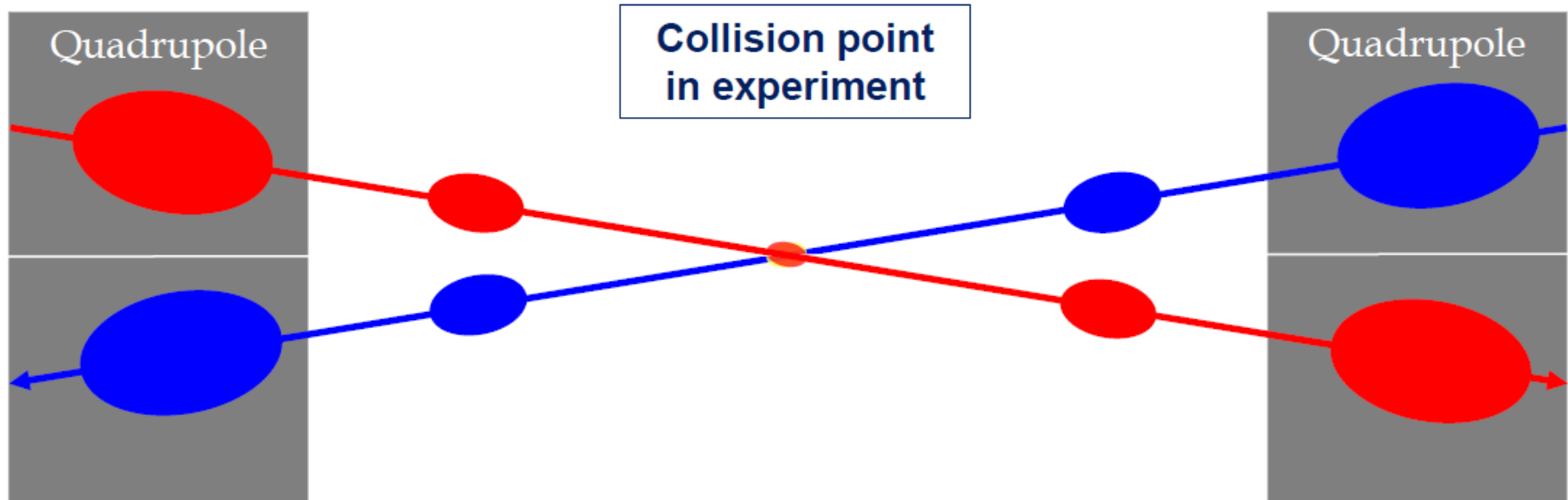
Beam size given by injectors and by space in vacuum chamber

$f = 11246 \text{ Hz}$

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

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

Beam size

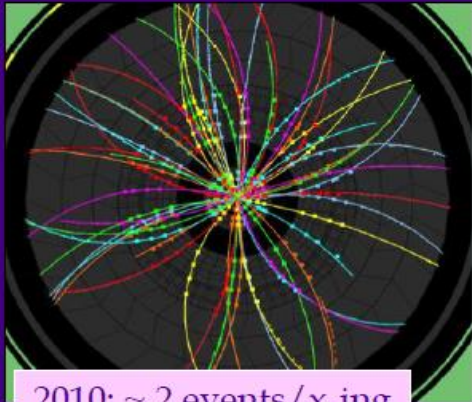


- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10σ
- Limitation is the aperture in quadrupoles
- Limitation of β function at IP to 0.4 m (2017)

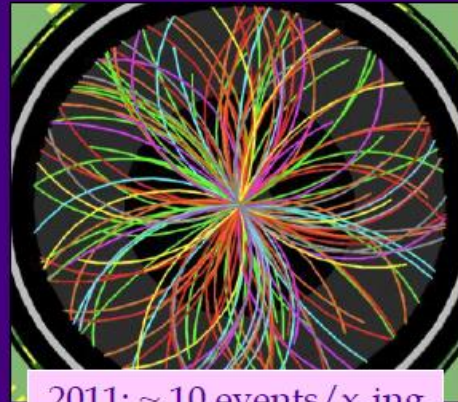
CMS

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

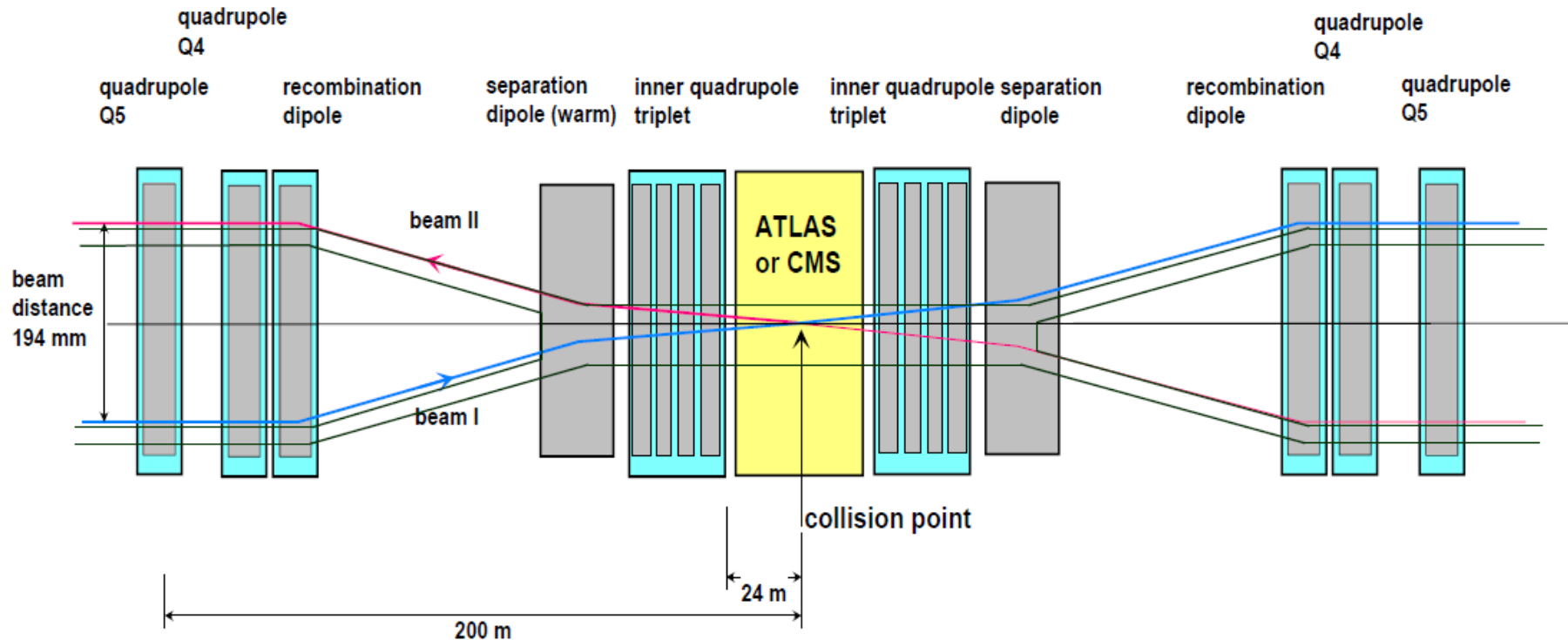


2011: ~ 10 events/x-ing



2012: ~ 20 events/x-ing

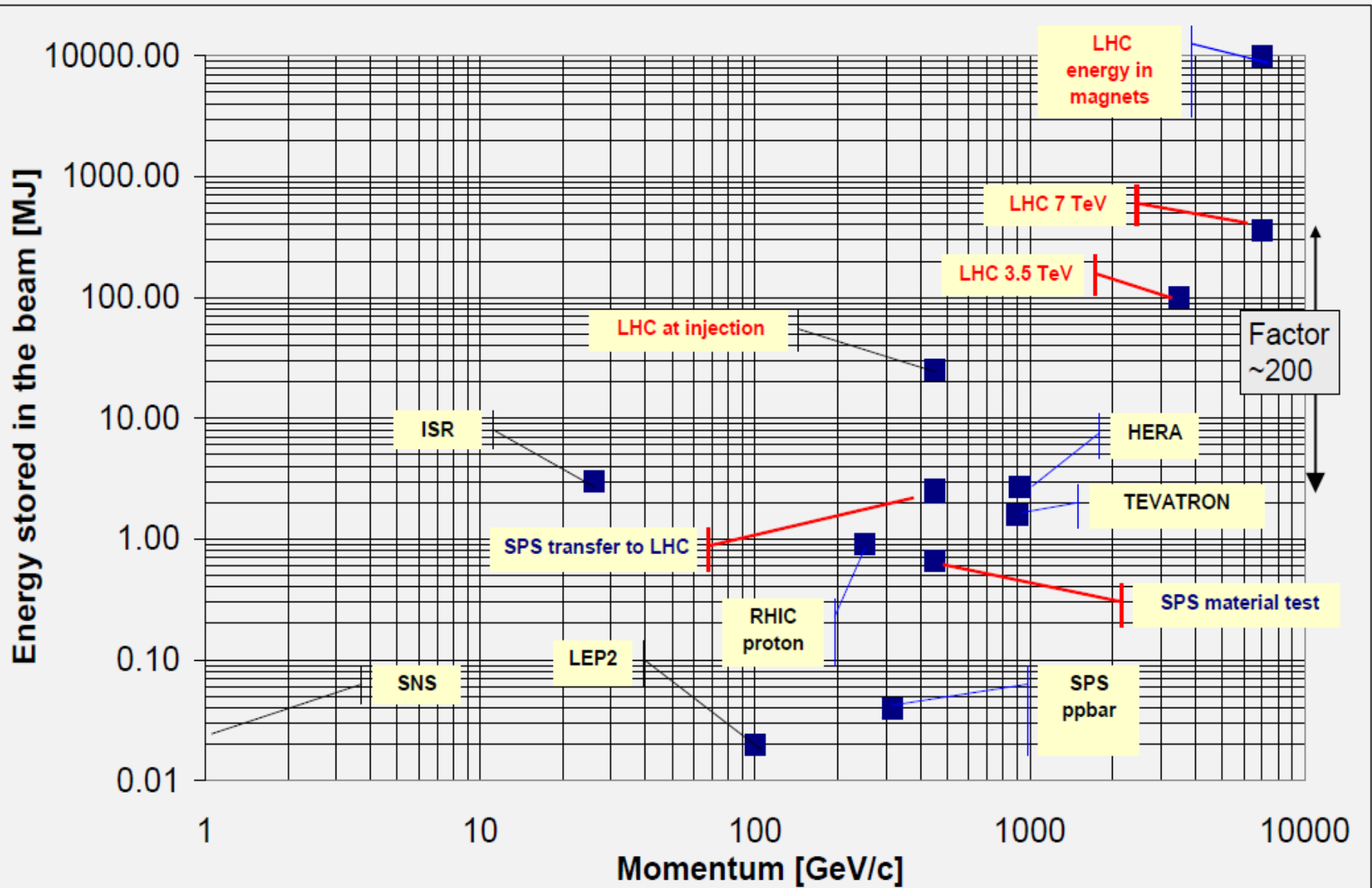
Experimental long straight section



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



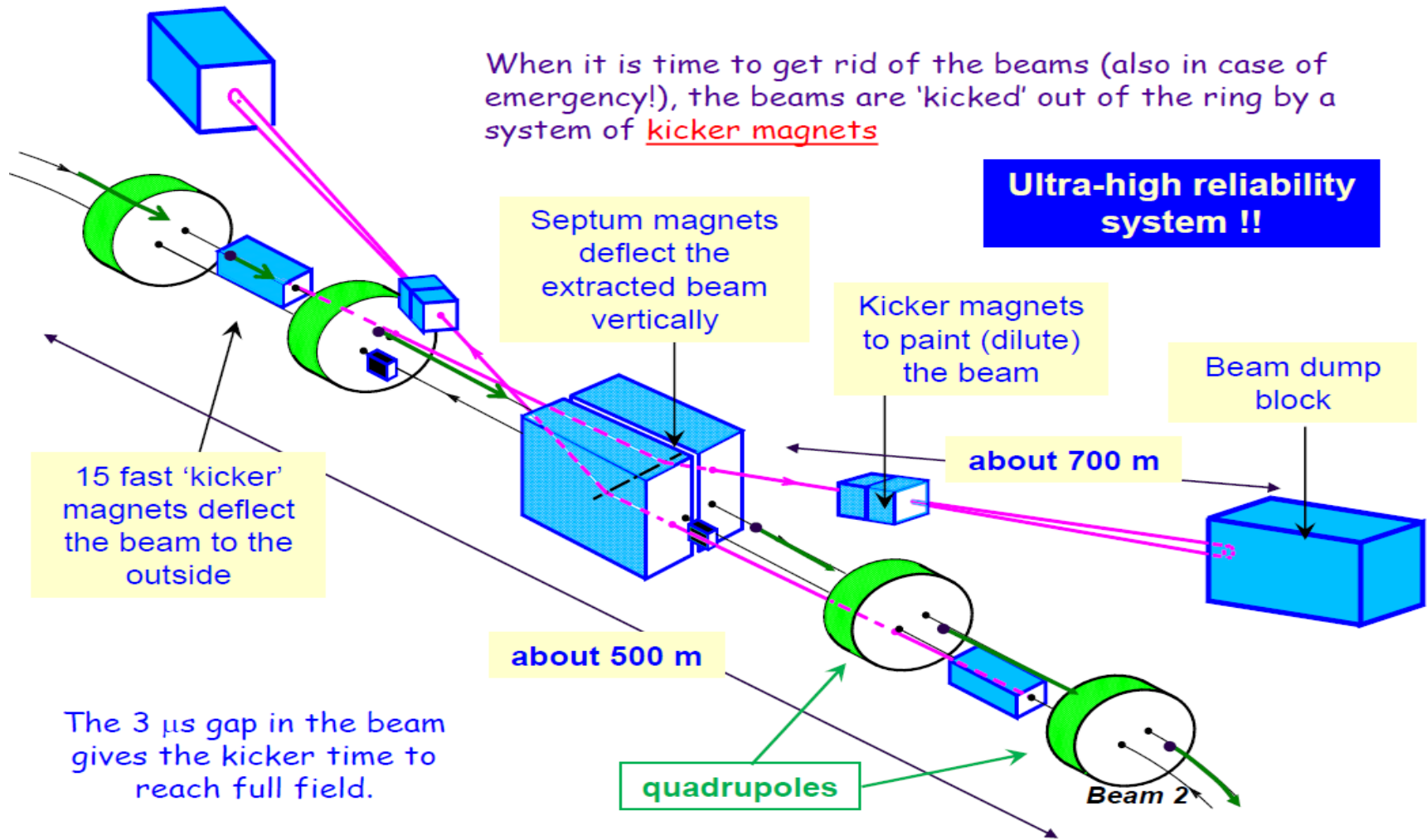
360 MJoule: the energy stored in one LHC beam corresponds approximately to...

- 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!



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

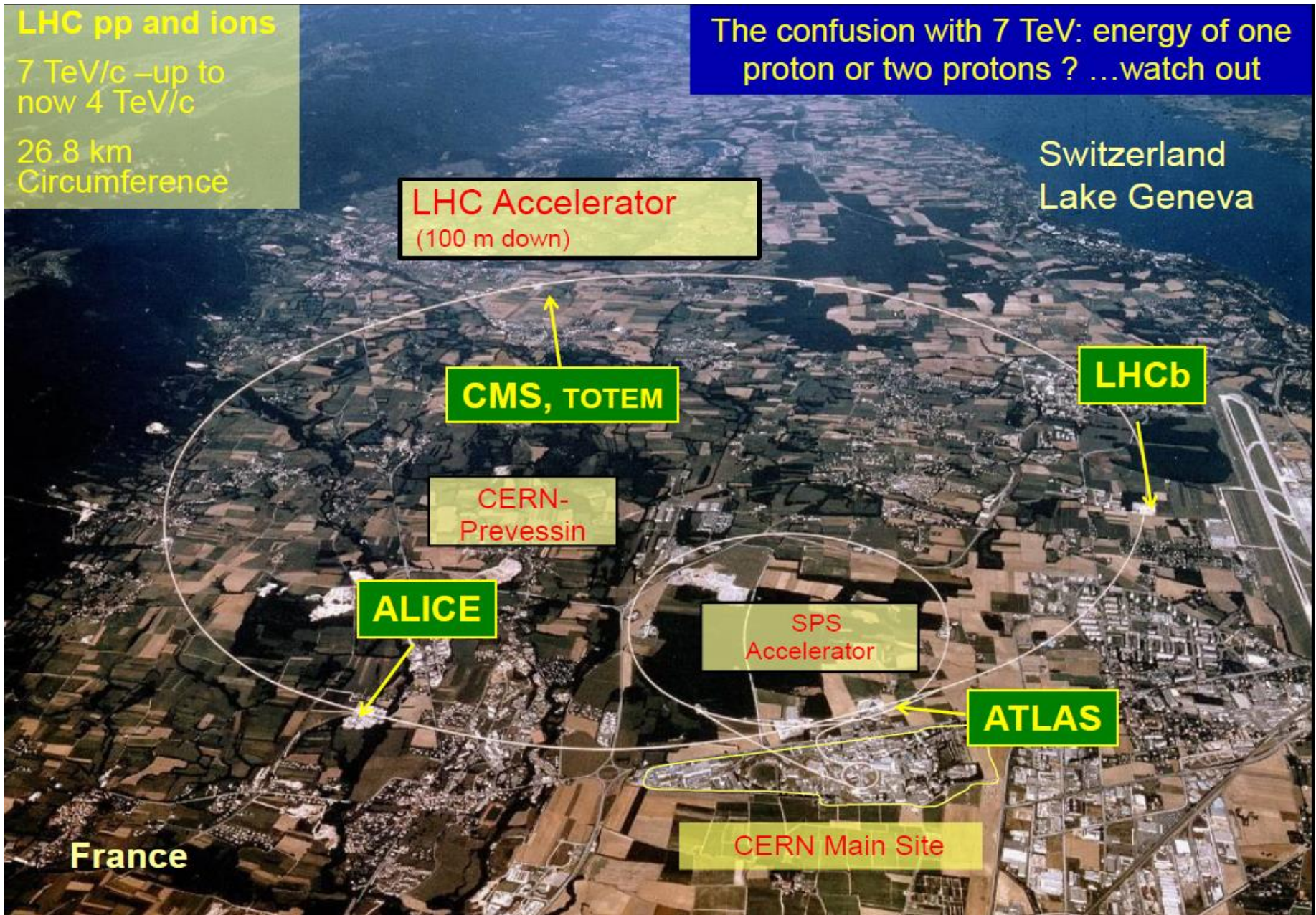
SPS
Accelerator

ATLAS

LHCb

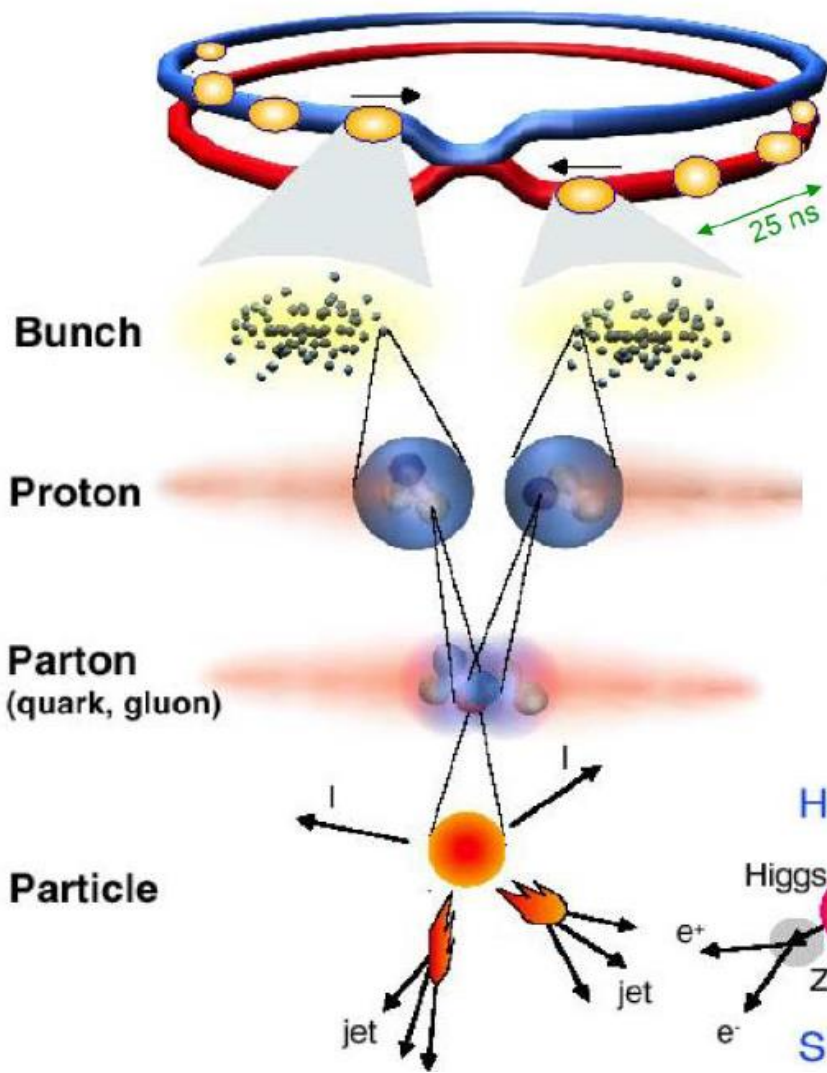
CERN Main Site

France



Collisions at LHC

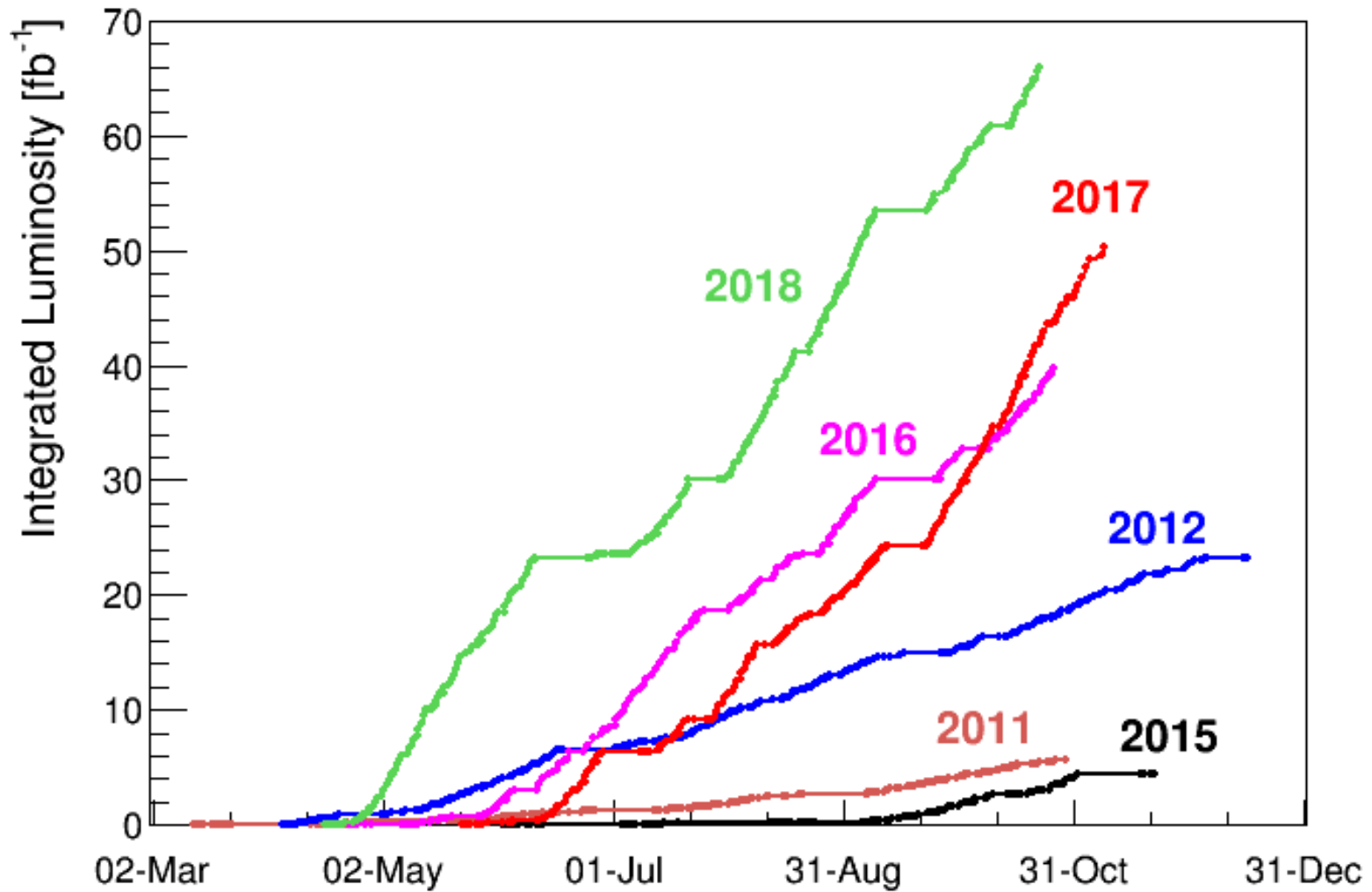
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm ⁻² s ⁻¹



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**

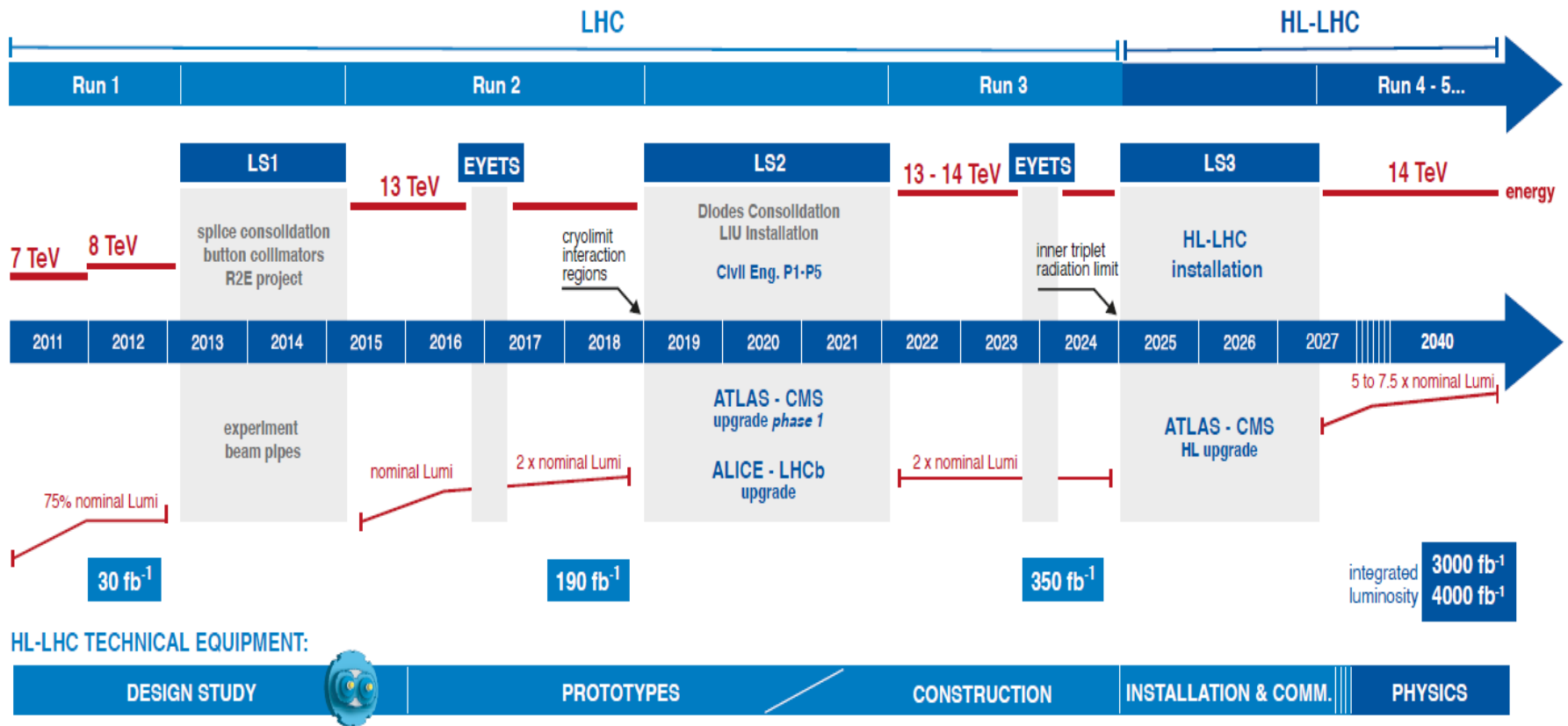
$$E = m c^2$$



LHC Beam parameters achieved

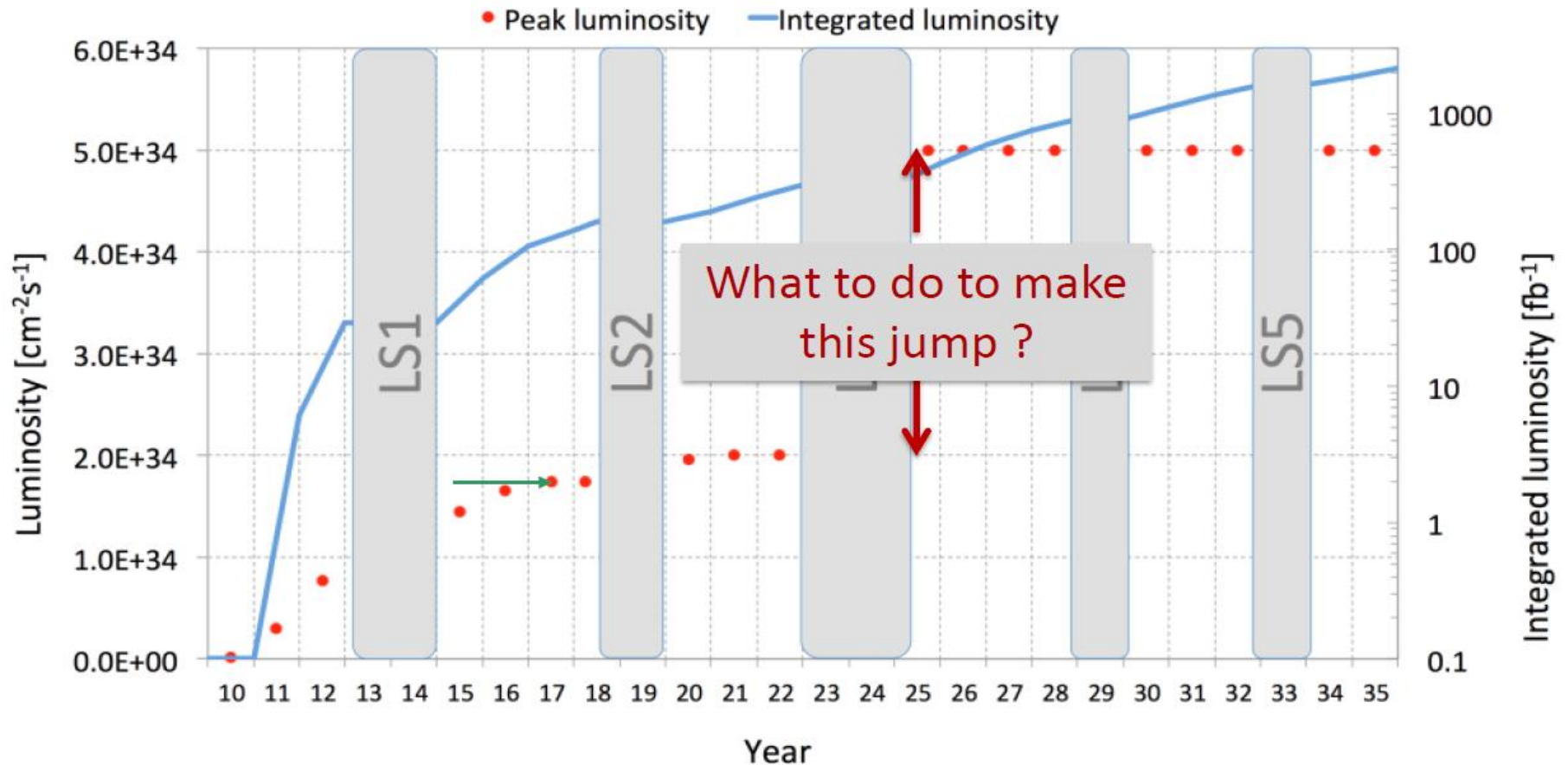
Parameter	2018	Design
Energy [TeV]	6.5	7.0
No. of bunches	2556	2808
Max. stored energy per beam (MJ)	312	362
β^* [cm]	30 \rightarrow 25	55
p/bunch (typical value) [10^{11}]	1.1	1.15
Typical normalized emittance [μm]	~ 1.8	3.75
Peak luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	2.1	1.0

Plans for next (two) decades



For next 2 years, 2024 and 2025 we will continue taking data of Run3. Great opportunity and timing to start analysing them for your master thesis and then continue with PhD for full set of Run3 data.

LHC high luminosity upgrade



High luminosity LHC performance estimates

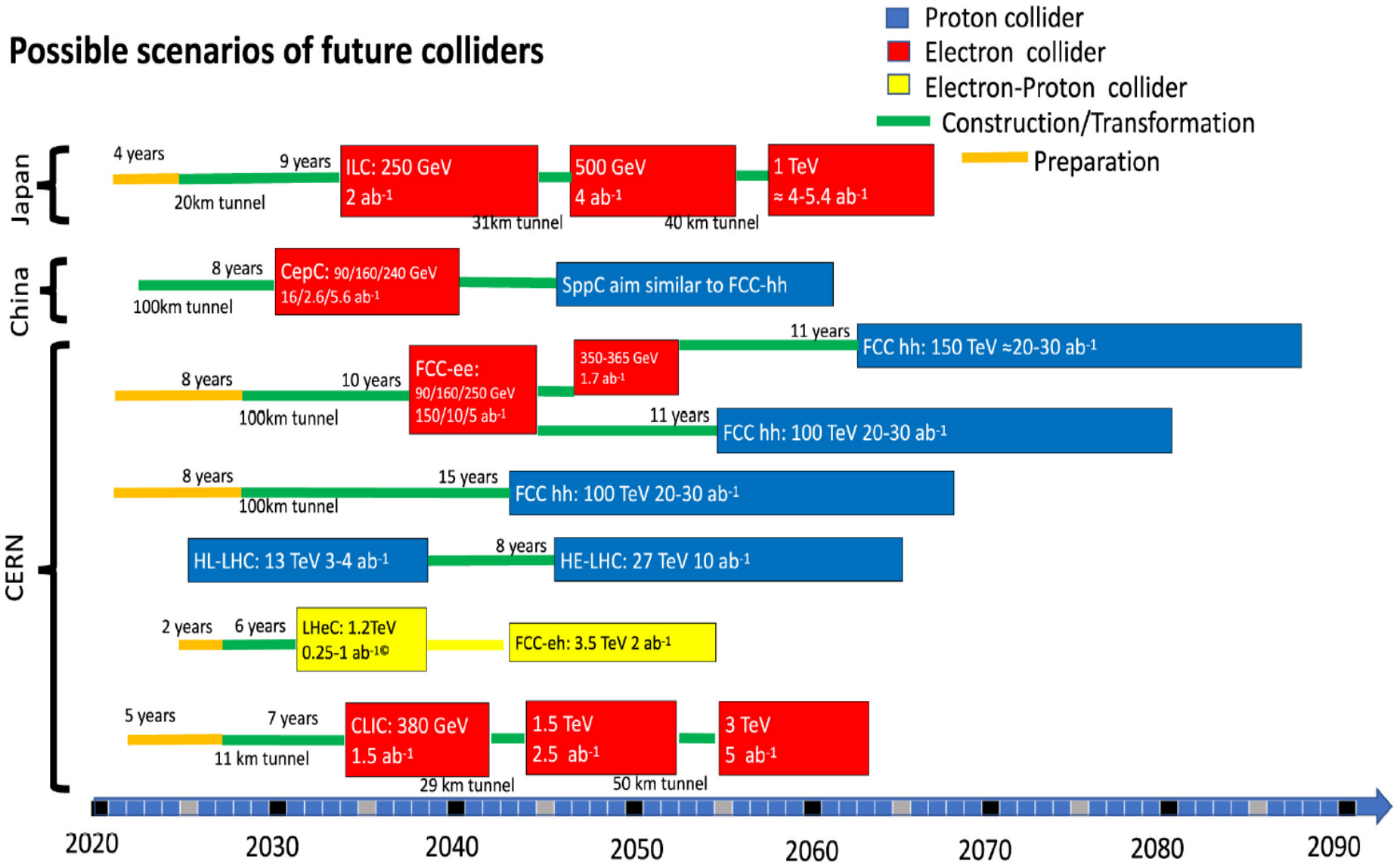
Parameter	Nominal	25ns – HL-LHC
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.12
Crossing angle [μrad]	300	590
Beam separation [σ]	9.9	12.5
β^* [m]	0.55	0.15
Normalized emittance ε_n [μm]	3.75	2.5
ε_L [eVs]	2.51	2.51
Relative energy spread [10^{-4}]	1.20	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 $\sim 250 \text{ fb}^{-1}/\text{y}$

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

Scenarios for future colliders

Possible scenarios of future colliders



Plans for FCC

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

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

~16 T ⇒ 100 TeV pp in 100 km

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

