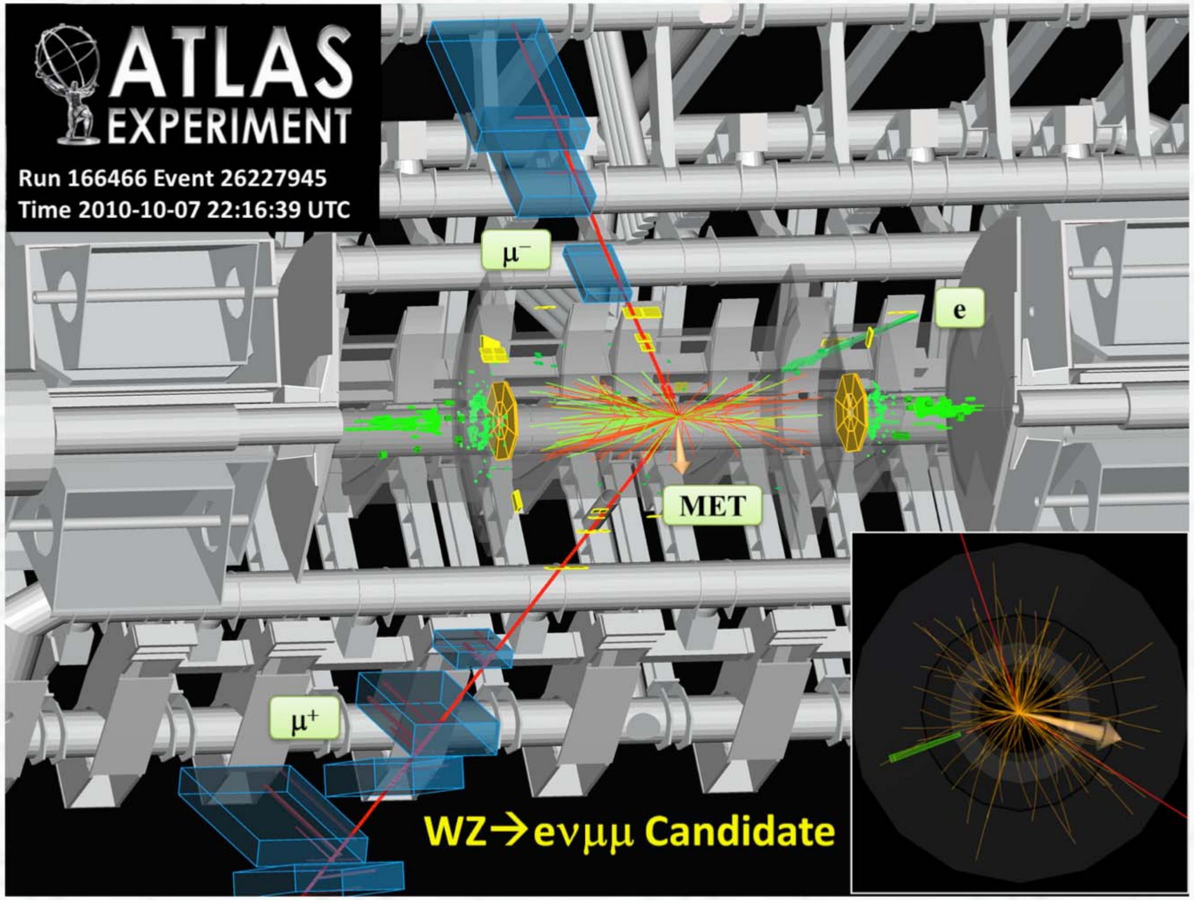
Physics at Hadron Collider



1. Introduction, Particle Accelerators

1.1 Why hadron collider?

1.2 Principles on particle accelerators

1.3 The *Large Hadron Collider* (LHC) at CERN

1.4 The Tevatron Collider at Fermilab

1.1 Why Hadron Collider?

Key questions investigated in particle physics:

(i) Structure of matter; fundamental constituents $\lambda = h / p$

(ii) Search for new particles, new types of matter $E = m c^2$

For the investigation of both questions, high energies and thereby particle accelerators are needed

High Energy Particle Accelerators (last 20 years):

Accelerator	type, laboratory	energy $\sqrt{s}$	years of operation
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, phase I	pp collider, CERN	7 TeV	2010- 2012
LHC, phase II	pp collider, CERN	14 TeV	2014- …….

Important parameters of accelerators:

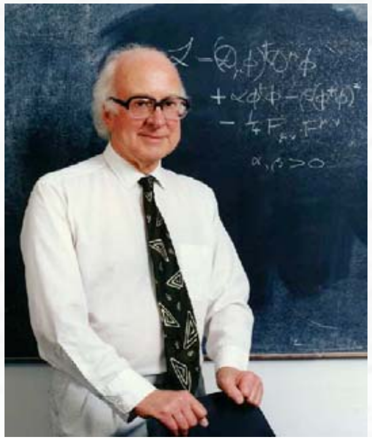
- Beam energy,   centre-of-mass energy $\sqrt{s}$
- Type of particles (ee, ep, or pp) and form of accelerator (circular or linear accelerator)
- Luminosity L, or integrated Luminosity
  (measured in units of cm^{-2} s^{-1})

Where do we stand today?

e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ HERA at DESY + many other experiments (fixed target…….)
have explored the energy range up to **~100 GeV** with incredible precision

- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed
  (except clear evidence for neutrino masses)
- No Higgs seen (yet)

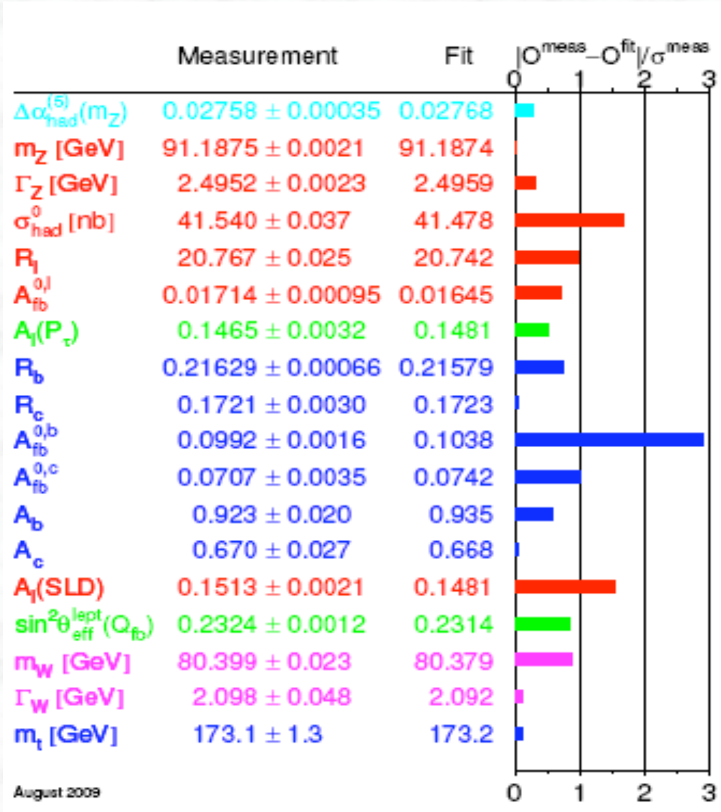
Direct searches: (95% CL limits)
m_H > 114.4 GeV/c^2
m_H < 163 GeV/c^2 or m_H > 166 GeV/c^2



Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

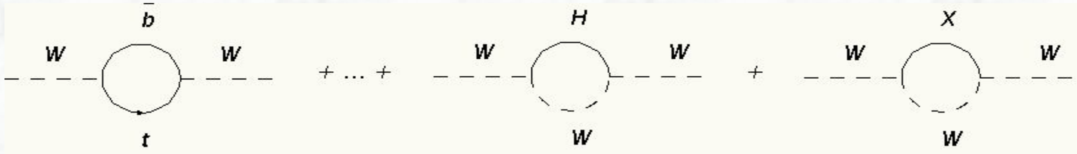
Summer 2009

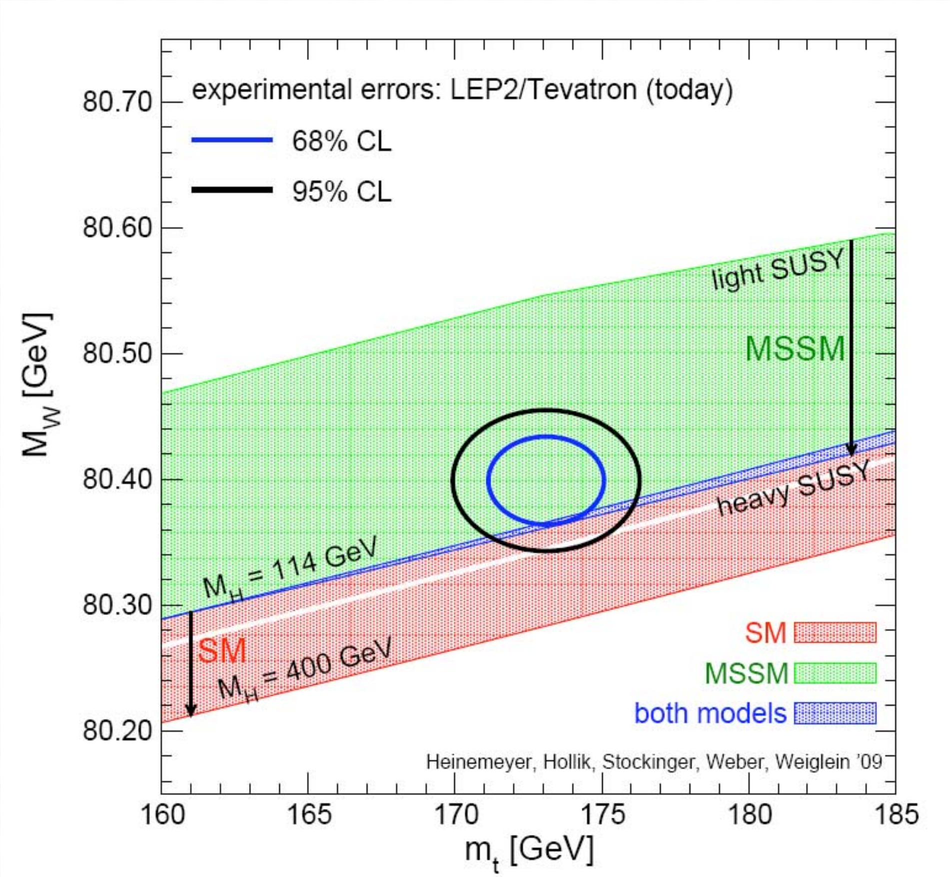


	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

Consistency with the Standard Model

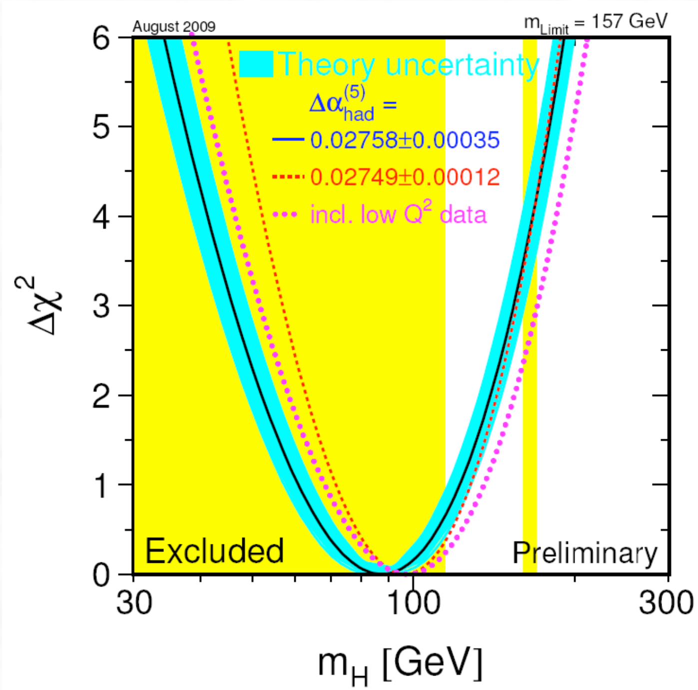
Sensitivity to the Higgs boson and other new particles via quantum corrections:





Interpretation within the Standard Model

(incl. new (2009) m_W and m_t measurements)



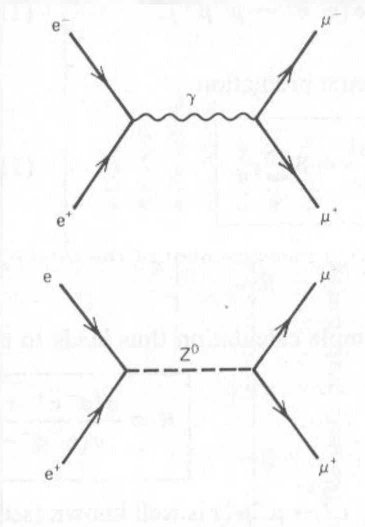
m_H = 87 (+35) (-26) GeV/c^2

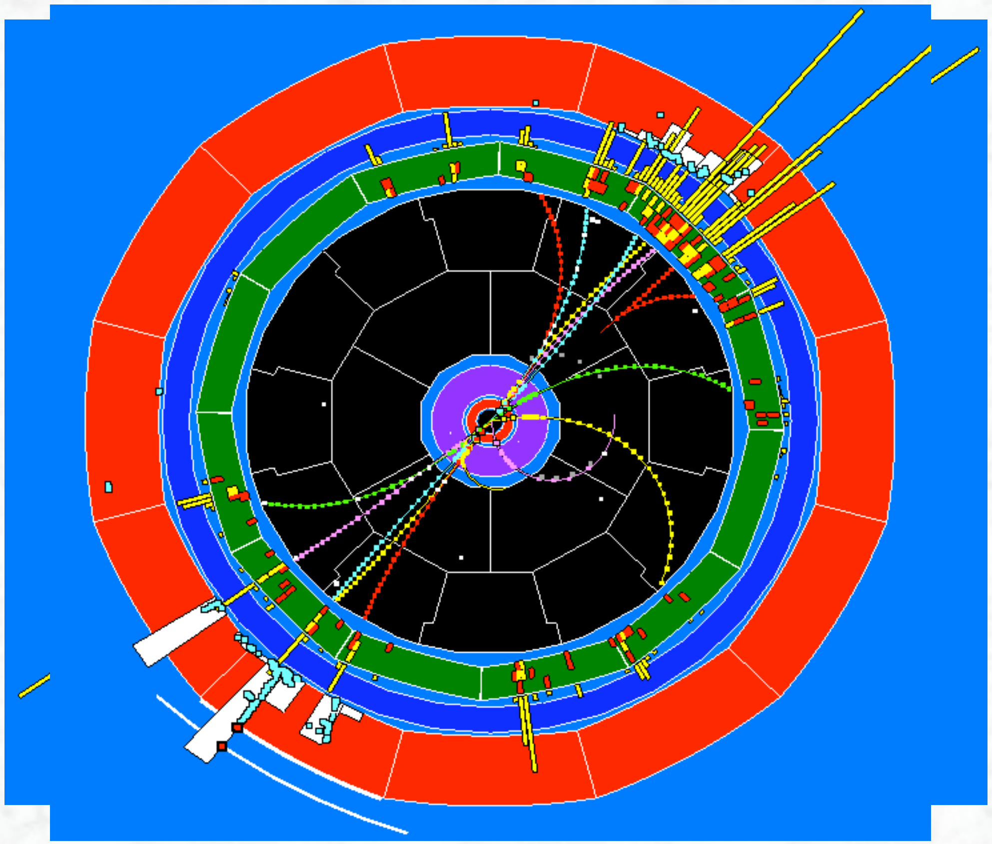
m_H < 157 GeV/c^2 (95 % CL)

Why a hadron collider ?

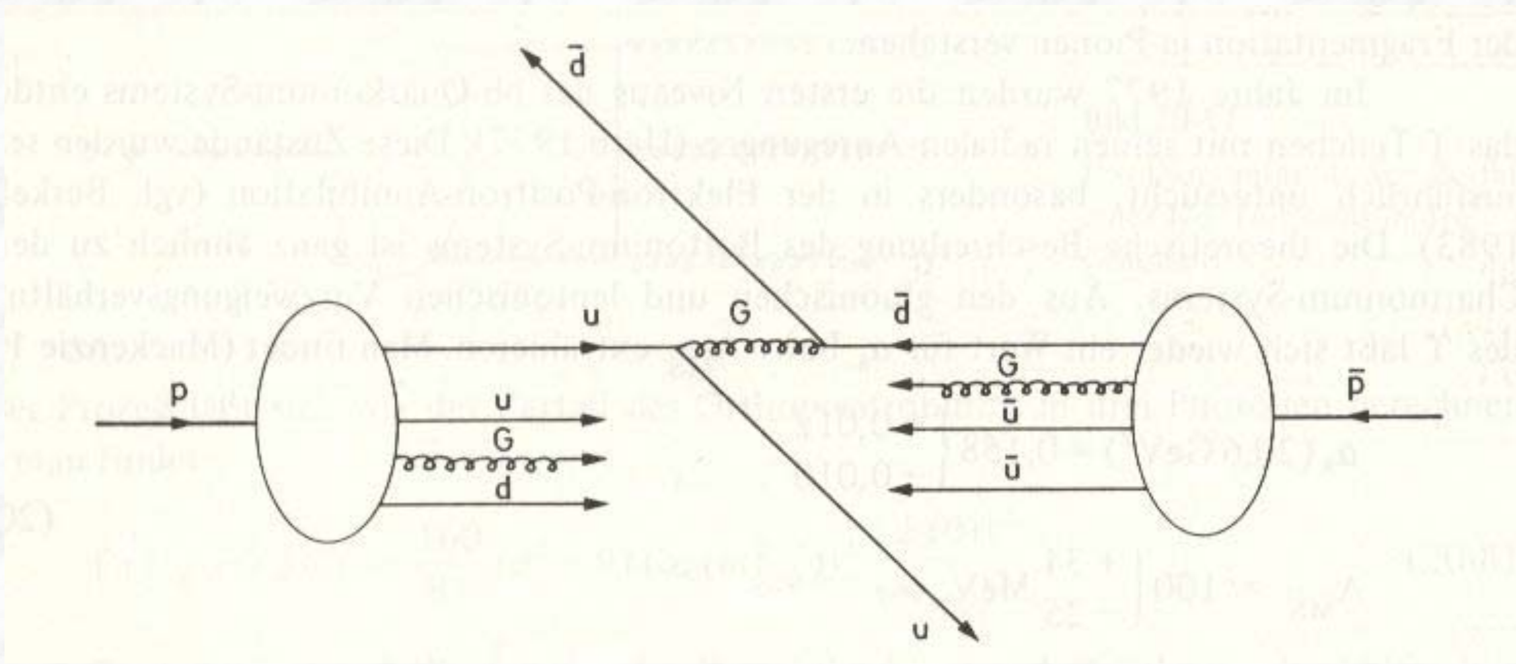
e^+e^- colliders are excellent machines for precision physics !!

- e+ e^- are point-like particles, no substructure → clean events
- complete annihilation, centre-of-mass system, kinematic fixed

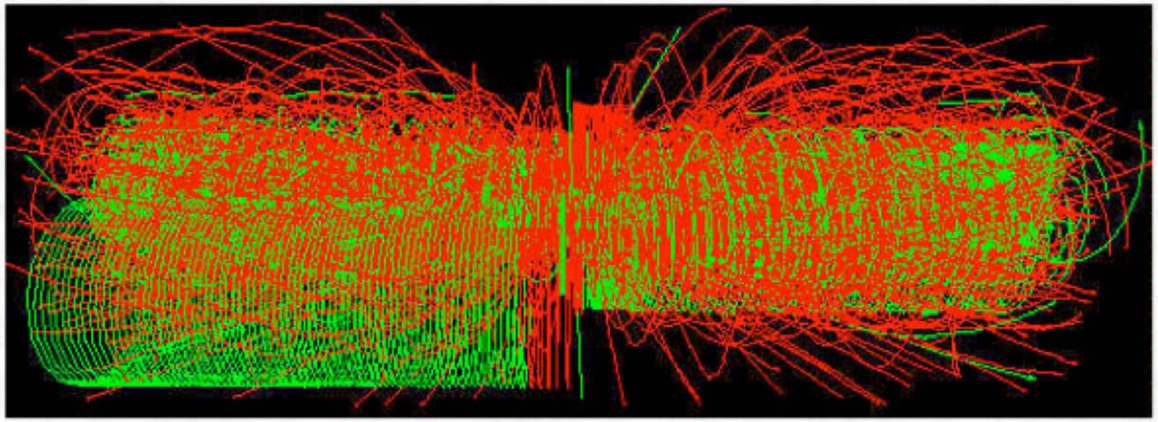


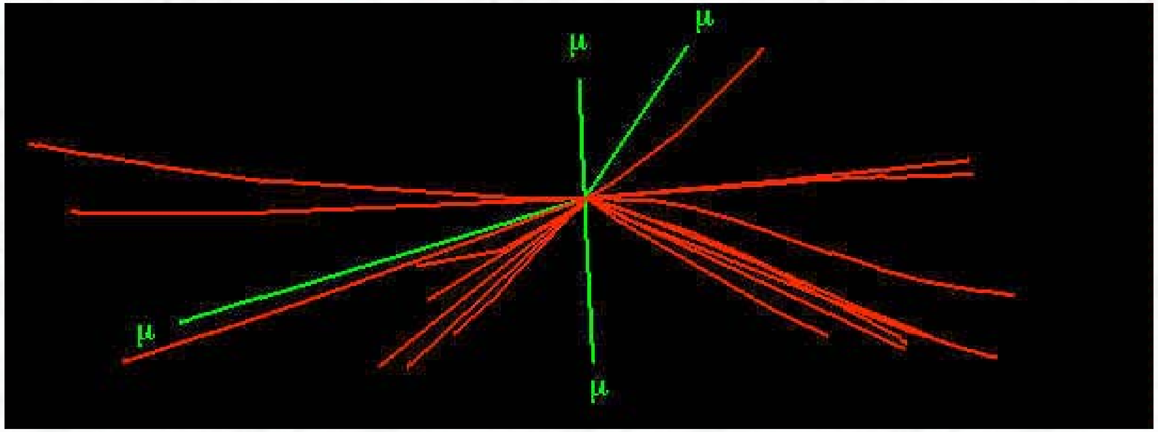


Proton proton collisions are more complex



Simulation of a pp collision at the LHC: $\sqrt{s}$ = 14 TeV, L = 10^{34} cm^{-2} s^{-1}





Reconstruction of particles with high transverse momentum reduces the number of particles drastically
(interesting object largely kept, background from soft inelastic pp collisions rejected)

Main drawbacks of e^+e^- circular accelerators:

1. Energy loss due to synchrotron radiation
   (basic electrodynamics: accelerated charges radiate,
   x-ray production via bremsstrahlung, synchrotron radiation……)

   - Radiated power (synchrotron radiation):
     Ring with radius R and energy E

$$P = \frac{2\, e^2\, c}{3\, R^2} \left(\frac{E}{mc^2}\right)^4$$

   - Energy loss per turn:
     (2 GeV at LEP-II)

$$-\Delta E \approx \frac{4\, \pi\, e^2}{3\, R} \left(\frac{E}{mc^2}\right)^4$$

   - Ratio of the energy loss between protons and electrons:

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

Future accelerators:

- pp ring accelerators (LHC, using existing LEP tunnel)
- or e^+e^- linear accelerators, International Linear Collider ILC or CLIC (under study / planning)

Limiting factors:

$e^+ e^-$ accelerators:

- Energy loss is circular rings
- Acceleration gradient in linear accelerators
  (ILC design, 40 MV / m)
- Fixed centre-of-mass energy….

pp accelerators:

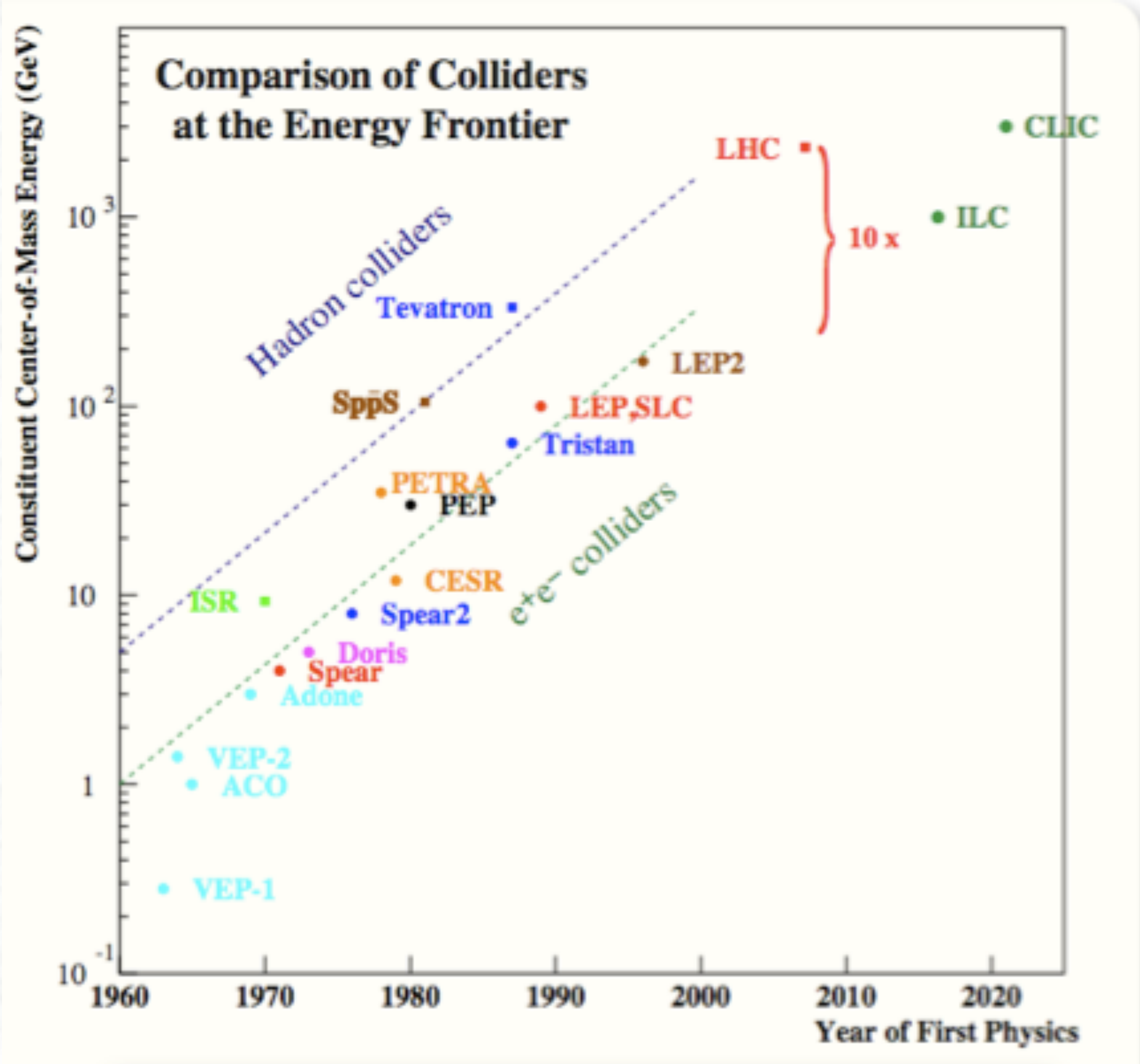
- More complex interactions due to proton substructure
- Only part of the pp centre-of-mass energy available in the hard scattering
  process (see later)
  however: higher mass values can be reached with longer running times
- Magnetic field in bending magnets (8.3 T in LHC magnets)

Accelerators at the energy frontier

Livingston plot

Exponential growth of
√s with time
(at least in the past)

Factor 4 every 10 years

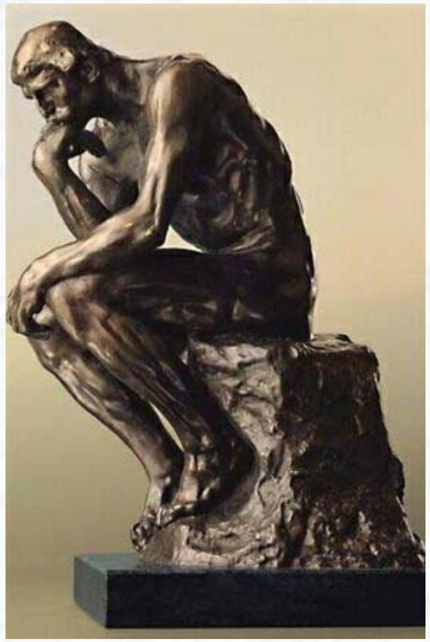


pp: discovery machines
(W/Z, top, ….)

e^+e^-: precision
(LEP, QCD and el.weak)

Both required !

Today's open questions
in particle physics



Key Questions of Particle Physics

1. Mass: What is the origin of mass?

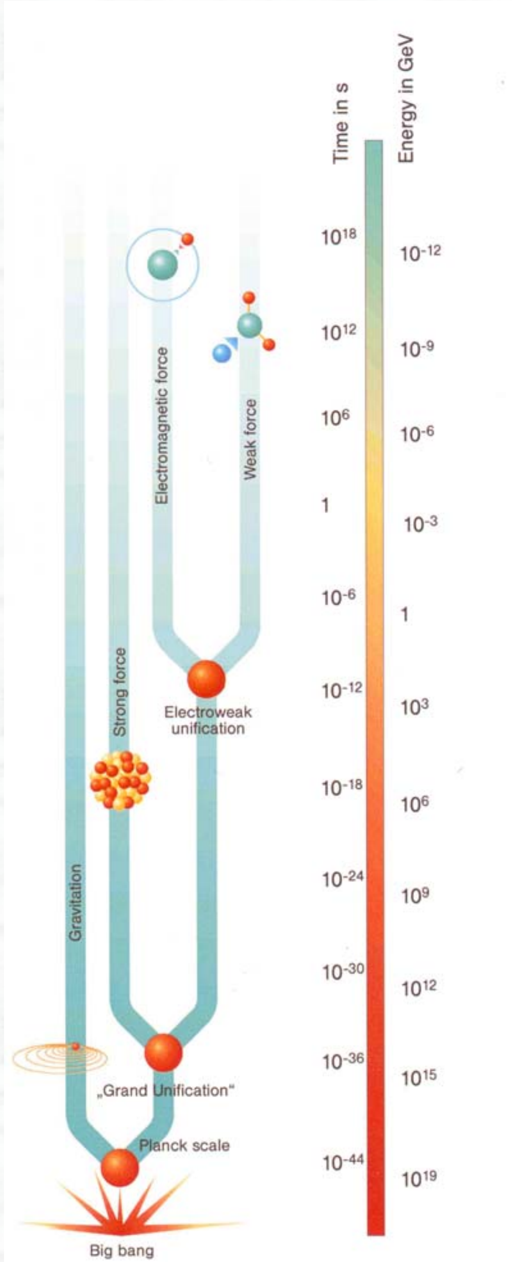
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: **What is the underlying fundamental theory ?**

- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- ….

3. Flavour: **or the generation problem**

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?



Answers to some of these questions are expected on the TeV mass scale → LHC

The role of the present Hadron Colliders

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?

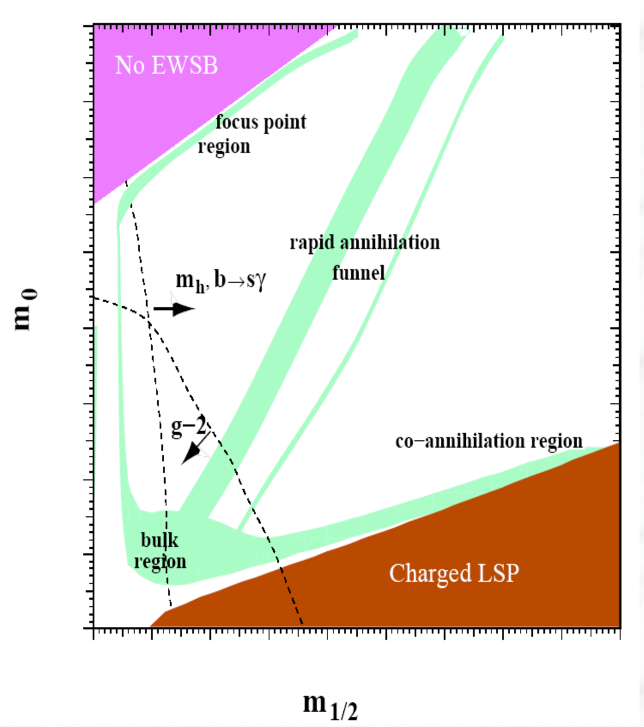
- The search for “low energy” supersymmetry

  Can a link between SUSY and dark matter be established?

- Other scenarios beyond the Standard Model
- …….

Look for the “expected”, but we need to be open for surprises

The link between SUSY and Dark Matter ?

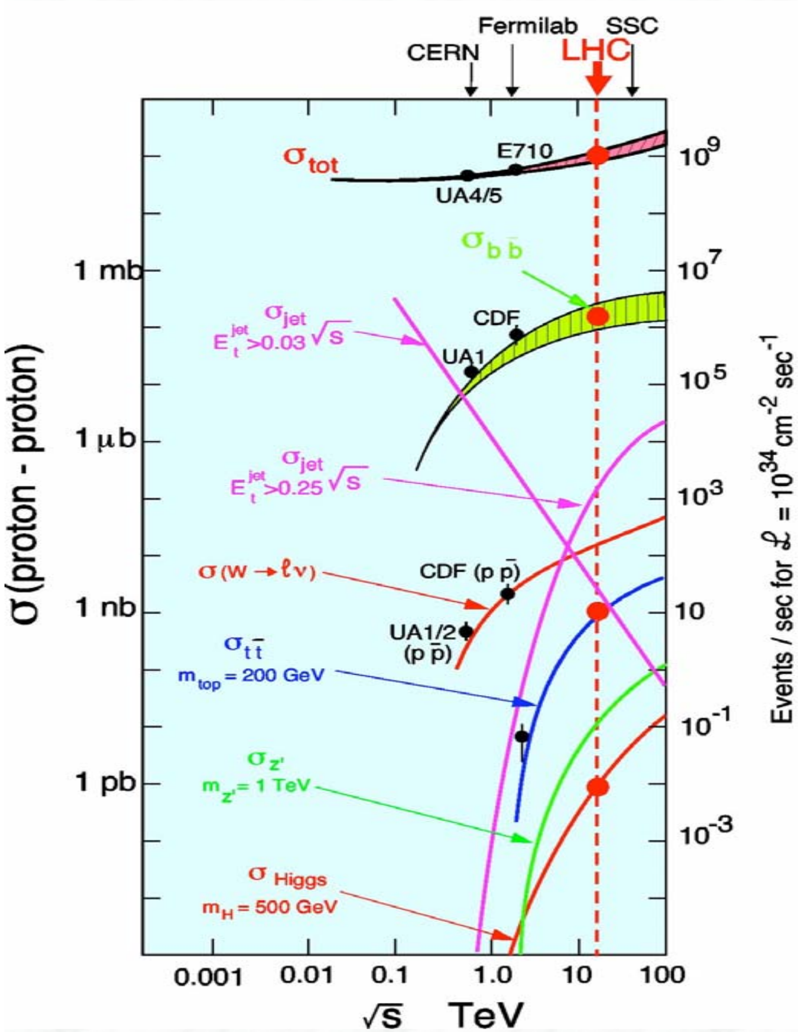


M. Battaglia, I. Hinchliffe, D.Tovey, hep-ph/0406147

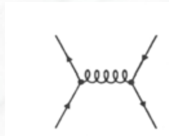
2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area
- Many Standard Model measurements can be used to test and to tune the detector performance

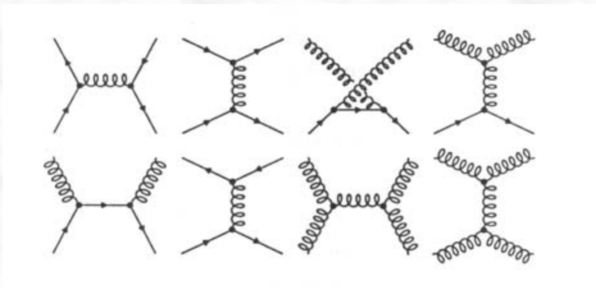
Erwartete Produktionsraten am LHC



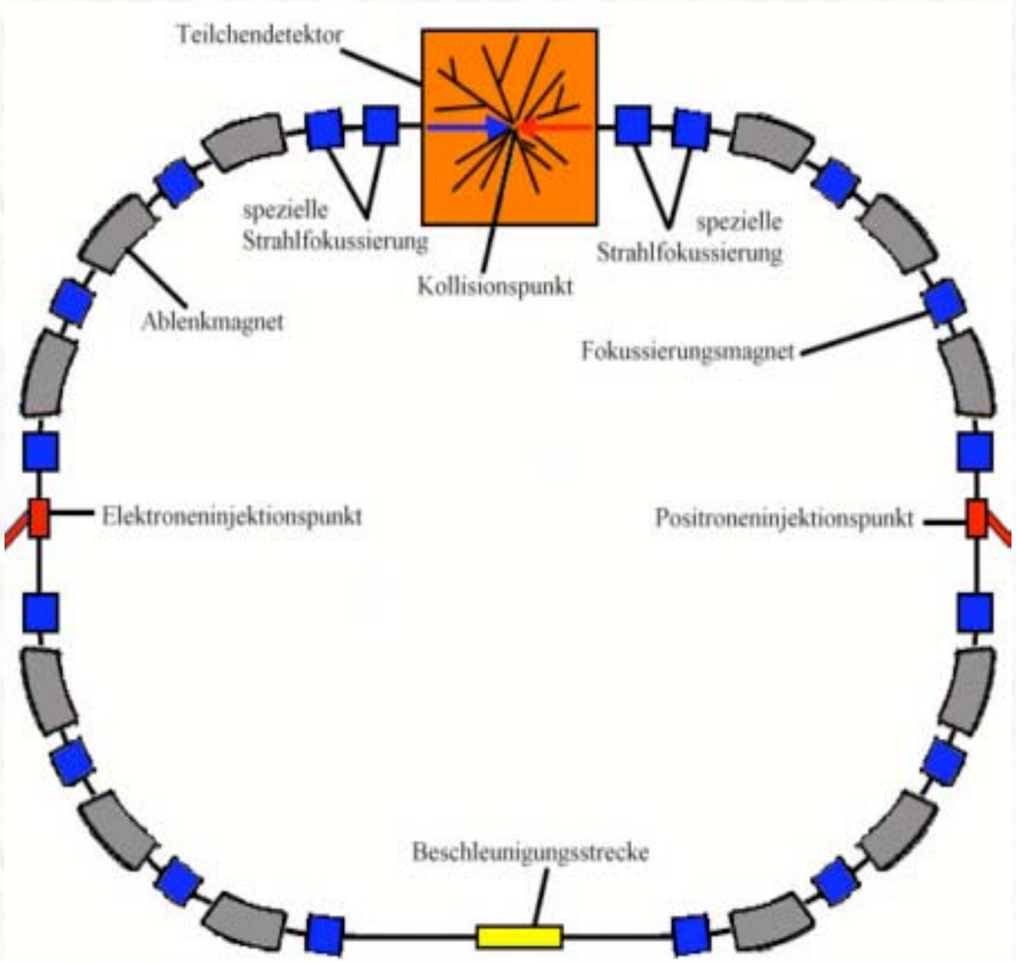
• Inelastische Proton-Proton Reaktionen:	1 Milliarde / sec
• Quark -Quark/Gluon Streuungen mit großen transversalen Impulsen	~100 Millionen/ sec
• b-Quark Paare	5 Millionen / sec
• Top-Quark Paare	8 / sec
• W → e ν	150 / sec
• Z → e e	15 / sec
• Higgs (150 GeV)	0.2 / sec
• Gluino, Squarks (1 TeV)	0.03 / sec



Dominante harte Streuprozesse: Quark - Quark
Quark - Gluon
Gluon - Gluon



1.2 Principles of particle accelerators

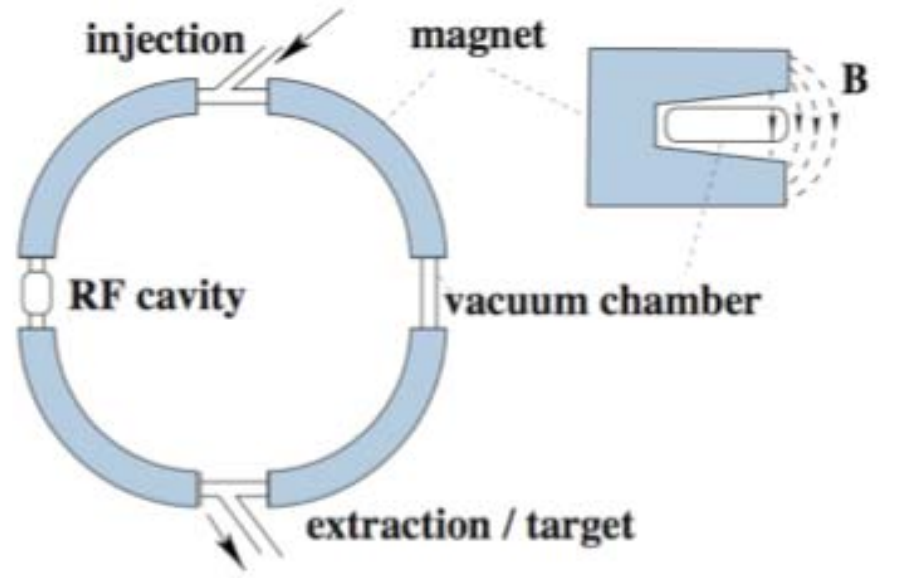


Circular accelerator principles

- Cyclotron: constant RF
  magnetic field radius ρ increases with energy
  used for smaller machines

- Synchrotron: ρ = const
  B increases with energy
  RF frequency adjusted slightly (β = 0.999 …..1.0)

Most High Energy accelerators and all CERN ring accelerators (PS, SPS, LEP, LHC) are of this type



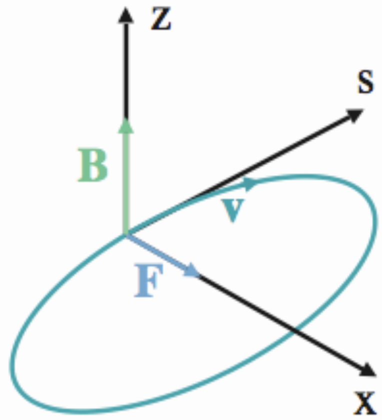
Basic parameters, Lorentz Force

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

charge q, normally $q = e$; $q = Z\,e$ for ions

- Electric field **E** provides the acceleration or rather energy gain
- The magnetic field **B** keeps the particles on their path

Circular motion for
$\mathbf{E} = 0$
$\mathbf{v} \perp \mathbf{B}$



ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called

- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

Bρ known as magnetic rigidity, units Tm

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

for $q = e$ numerically

$B\,[\mathrm{T}] = p\,[\mathrm{GeV/c}]\quad 3.336\,\mathrm{m} / \rho$

high energy, $v = c$ "$p = E$"

$E < E_H = q\,B\,\rho$ Hillas criterion

LHC

- **Momentum $p = 7$ TeV/c**
- **LHC bending radius $\rho = 2804$ m**
- **Bending field B = 8.33 Tesla**
- **magnets at 1.9 K, super-fluid He**

Astroparticle

units $10^{-4}\mathrm{T} = 1\mathrm{Gauss}$; a.u. $= 1.5\times10^{11}$m

Solar system $B = 10\,\mu\mathrm{G}$ $E = 5$ TeV $\rho = 11$ a.u.

Intergalactic $B = 1\,\mathrm{nG}$ $E = 5$ PeV (knee)

$\rho = 1.7\times10^{19}$m (4 % of galaxy-radius)

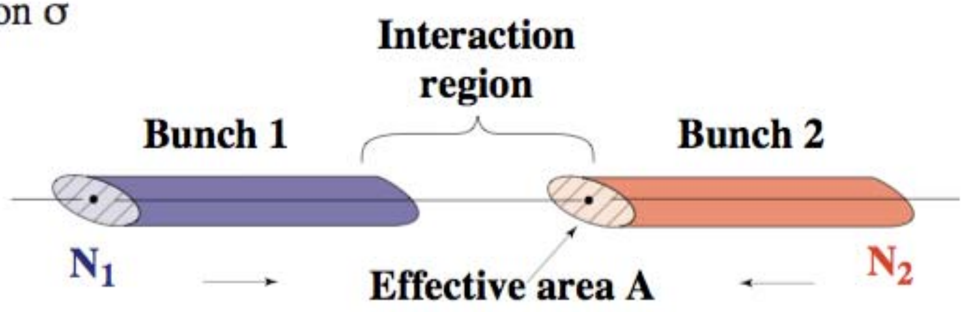
Luminosity and collision rates

Event rate for process with cross section σ

$$\dot{n} = \mathcal{L}\sigma$$

Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$



for Gaussian bunches with rms sizes $\sigma_x\, \sigma_y$ $\mathbf{A} = 4\,\pi\,\sigma_x\,\sigma_y$

High luminosity: Large number of particles (N_1, N_2)
Small beam dimensions (A) in the interaction point
Large f (large number of bunches,
→ small time difference between bunch crossings)

LHC: $N = 1.15\ 10^{11}$, $n_b = 2808$ (number of bunches)
bunch separation: 25 ns (corresponds to 7.5 m)
A: beams squeezed (using strong, large aperture quadrupoles close to the interaction region) from σ = 0.2 mm to 16 μm

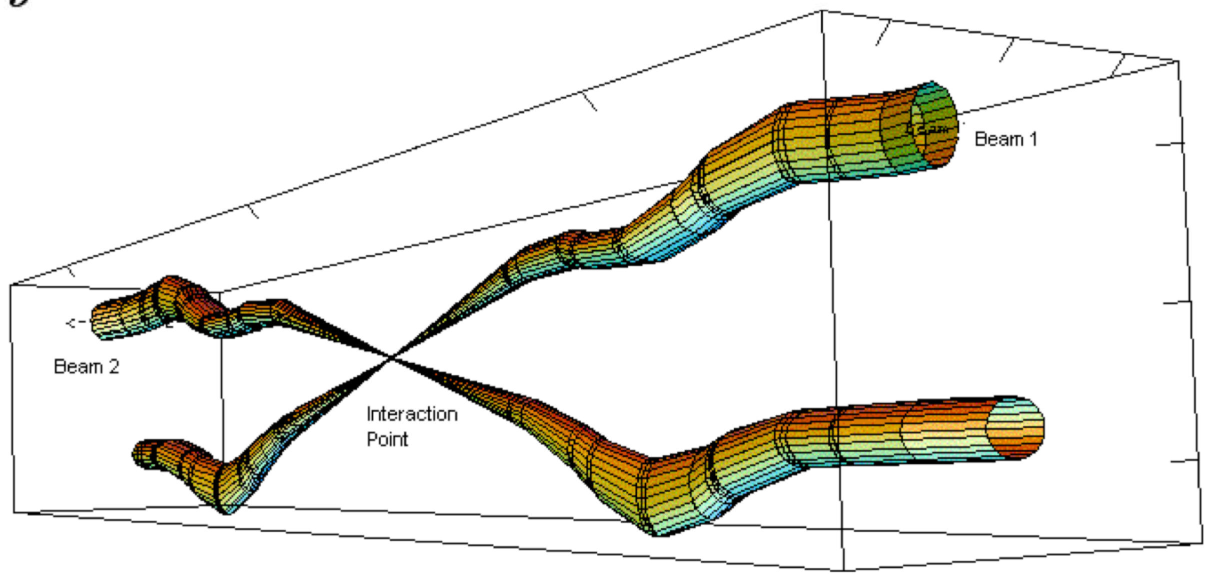
$$L = f \frac{N_1 \; N_2}{4\pi \; \sigma_x \sigma_y} = f \frac{N}{4\pi \; \sigma^2}$$

for $N = N_1 = N_2$ particles per bunch with transverse r.m.s. beam size $\sigma = \sigma_x = \sigma_y$ and frequency f

Accelerator physicist express this often using the transverse emittance ε and the β function:

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

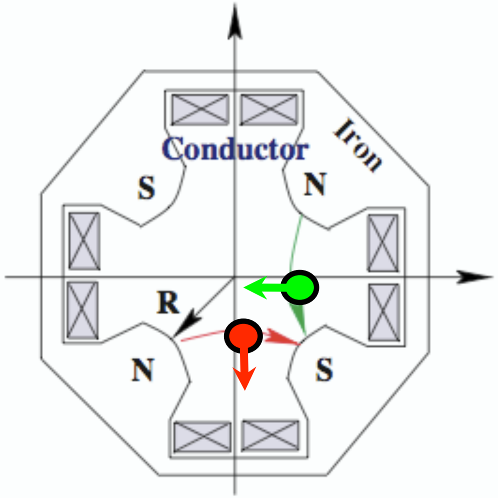
where $\epsilon = \pi\sigma^2/\beta$

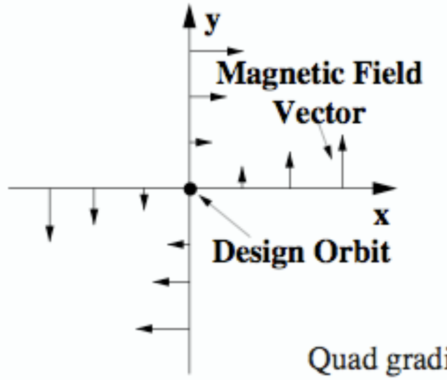


Relative beam sizes around IP1 (Atlas) in collision

Alternate gradient focusing

Quadrupole lens focusing in x, defocusing in y or vice versa





$B_x = k\,y$
$B_y = k\,x$
$B_z = 0$

$\nabla \times \boldsymbol{B} = \mathbf{0}$

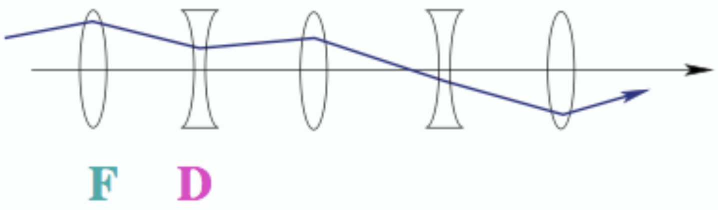
Quad gradients in the LHC
$K = 1/B\varrho \;\; \partial B_y/\partial x \approx 200$ T/m

$\mathbf{F} = e\,(\mathbf{v} \times \mathbf{B})$
here
$\mathbf{F} = e\,(0, 0, v) \times (B_x,\; B_y, 0)$
$\;\; = e\,(-v\,B_y,\; +v\,B_x,\; 0)$

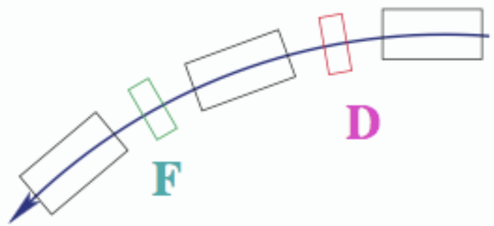
Combine F D
Defocusing when at small amplitude
Overall focusing

Normal (light) optics :
Focal length of two lenses at distance D
$1/f = 1/f_1 + 1/f_2 - D/f_1 f_2$
is overall focusing
with $1/f = D/f^2$
for $f = f_1 = -f_2$

alternate gradient focusing



together with bending magnets FODO lattice



N. C. Christofilos, unpublished manuscript in 1950 and patent
Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in Annals of Physics 3 (1958)

Betatron motion

Equation of motion of particles in a ring (with bending fields) **and quadrupoles** (field gradients $\propto \partial B/\partial r$)

In both transverse planes, here written with x for x, y : $x' = dx(s)/ds$; $x'' = d^2x(s)/ds^2$

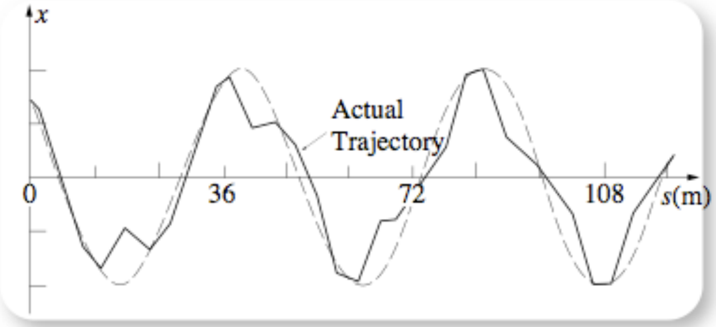
$x''(s) + k(s)\, x(s) = 0$ known as Hill's equation, derived in 1801 to describe planetary motion

Generalised oscillator equation with position dependent, periodic restoring force $k(L+s) = k(s)$ given by the quadrupole gradients (+ the small weakly focusing bending term in the ring plane)

Solution : $$x(s) = \sqrt{\epsilon\,\beta(s)}\,\cos(\mu(s) + \phi)$$

Phase advance $$\mu(s) = \int_0^s \frac{ds}{\beta(s)}$$

Tune # of betatron oscillations $$Q = \mu / 2\pi$$



motion $x/\sqrt{\beta}$ *plotted with phase advance*
normalised coordinates - becomes simple cos

$\beta(s)$ **beta function**, describes the focusing properties of the magnetic lattice

ϵ invariant, together with $\beta(s)$ amplitude. "single particle emittance"

Motion conveniently described in phase space (x, x′) with local slopes or angles $x' = p_x / p$
and linear optics elements as matrices ; with simple case for M, applies for IP to IP

$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} x(s_0) \\ x'(s_0) \end{pmatrix} \qquad \mathbf{M} = \begin{pmatrix} \cos 2\pi Q & \beta \sin 2\pi Q \\ -\frac{1}{\beta}\sin 2\pi Q & \cos 2\pi Q \end{pmatrix}$$

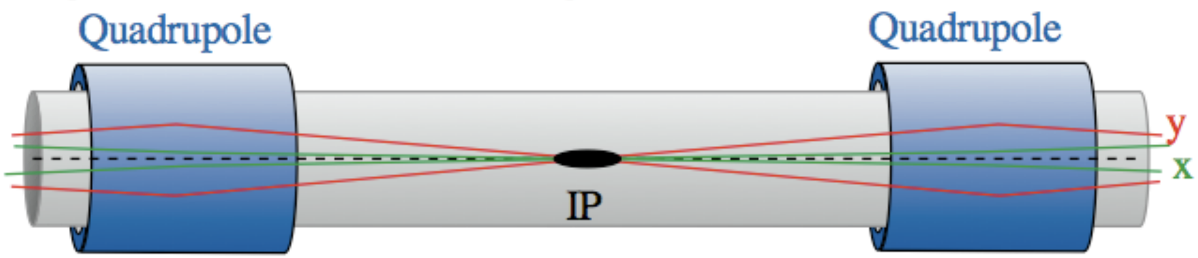
Transverse beam size and emittance

consider : **beam of many particles on stable orbit** and
simple case : **dispersion and slope $\beta' = 0$** by default at IP - relevant for experiments

beam size, r.m.s.	$\sigma(s) = \sqrt{\varepsilon\beta(s)}$
beam divergence, r.m.s.	$\theta(s) = \sqrt{\varepsilon/\beta(s)}$
product	$\varepsilon = \sigma(s)\theta(s)$

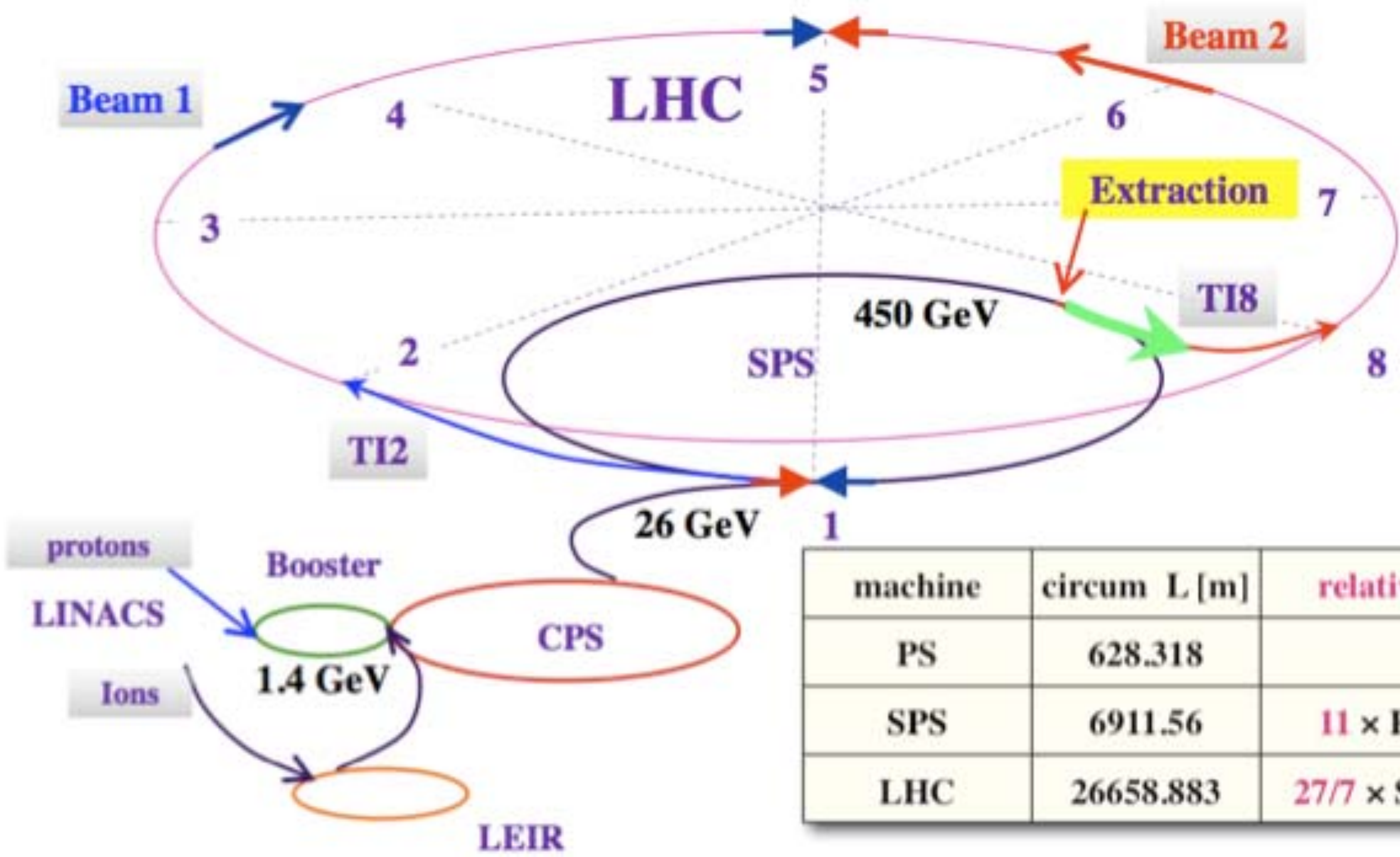
β - function : **local machine quantity - focusing of lattice**
Emittance ε : **beam quantity -** the average action
related to phase space density or kind of beam temperature
given by initial conditions (injected beam)
or equilibrium of quantum excitation and damping - 2nd lecture
in ideal machine : x, y, z motion uncoupled, 3 emittances ε_x, ε_y, ε_z

IP: squeeze β to a minimum, called β^* $\Rightarrow$ maximum of divergence, needs aperture



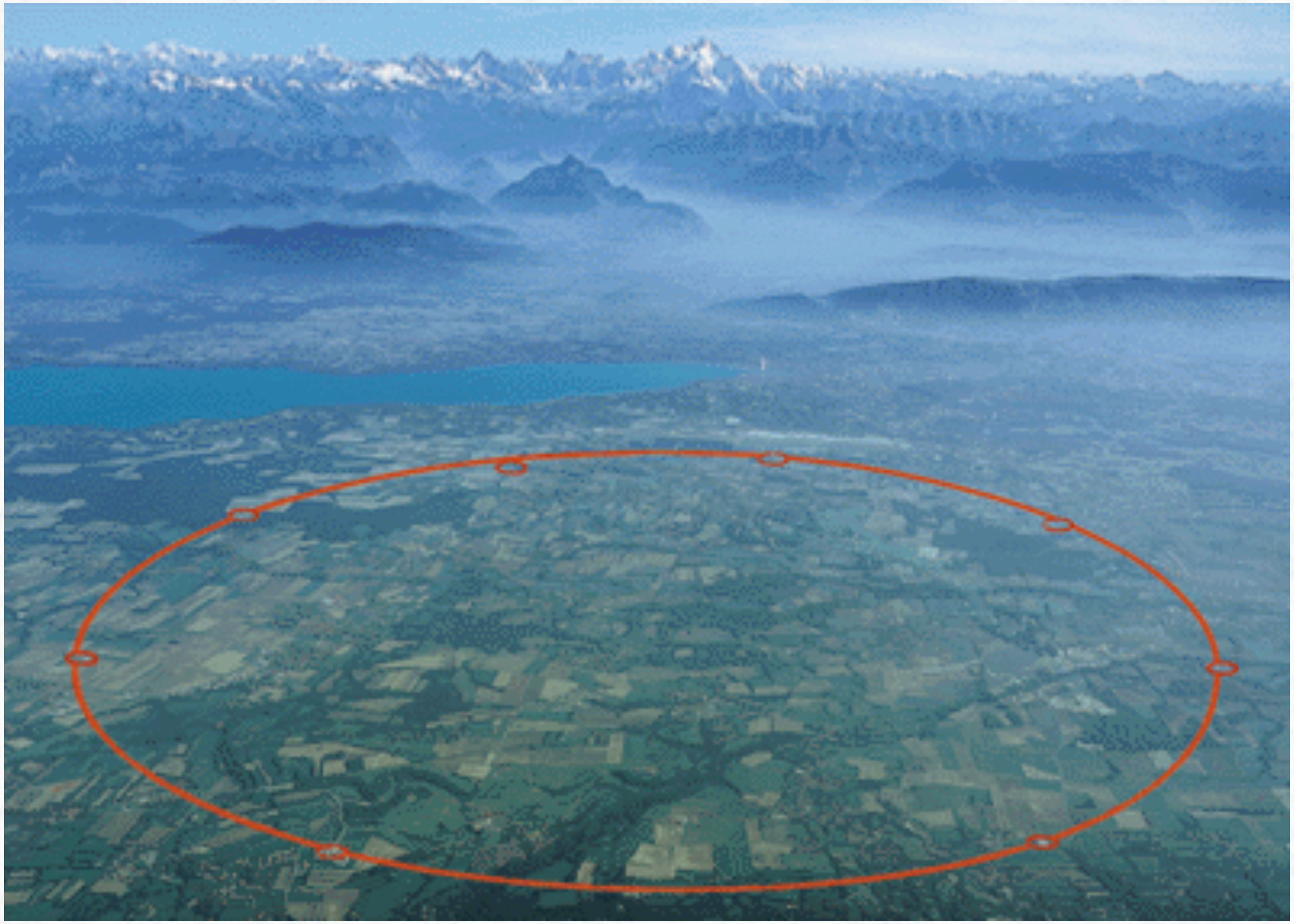
LHC $\varepsilon_N = \varepsilon\,\beta\gamma = 3.75\ \mu m$, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63\ \mu m$, $\theta^* = 30\ \mu rad$

The CERN accelerator complex: injectors and transfer

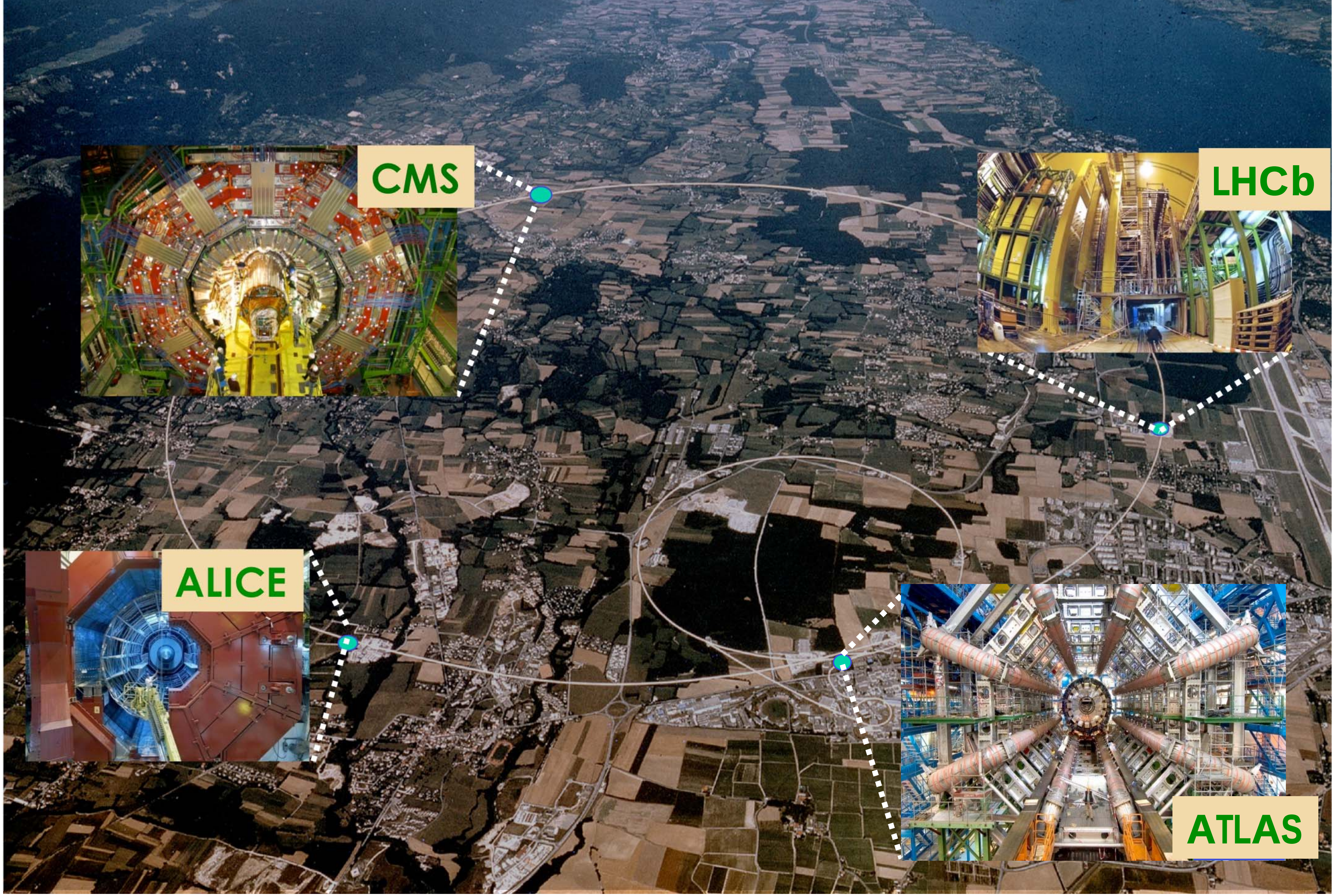


machine	circum L [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

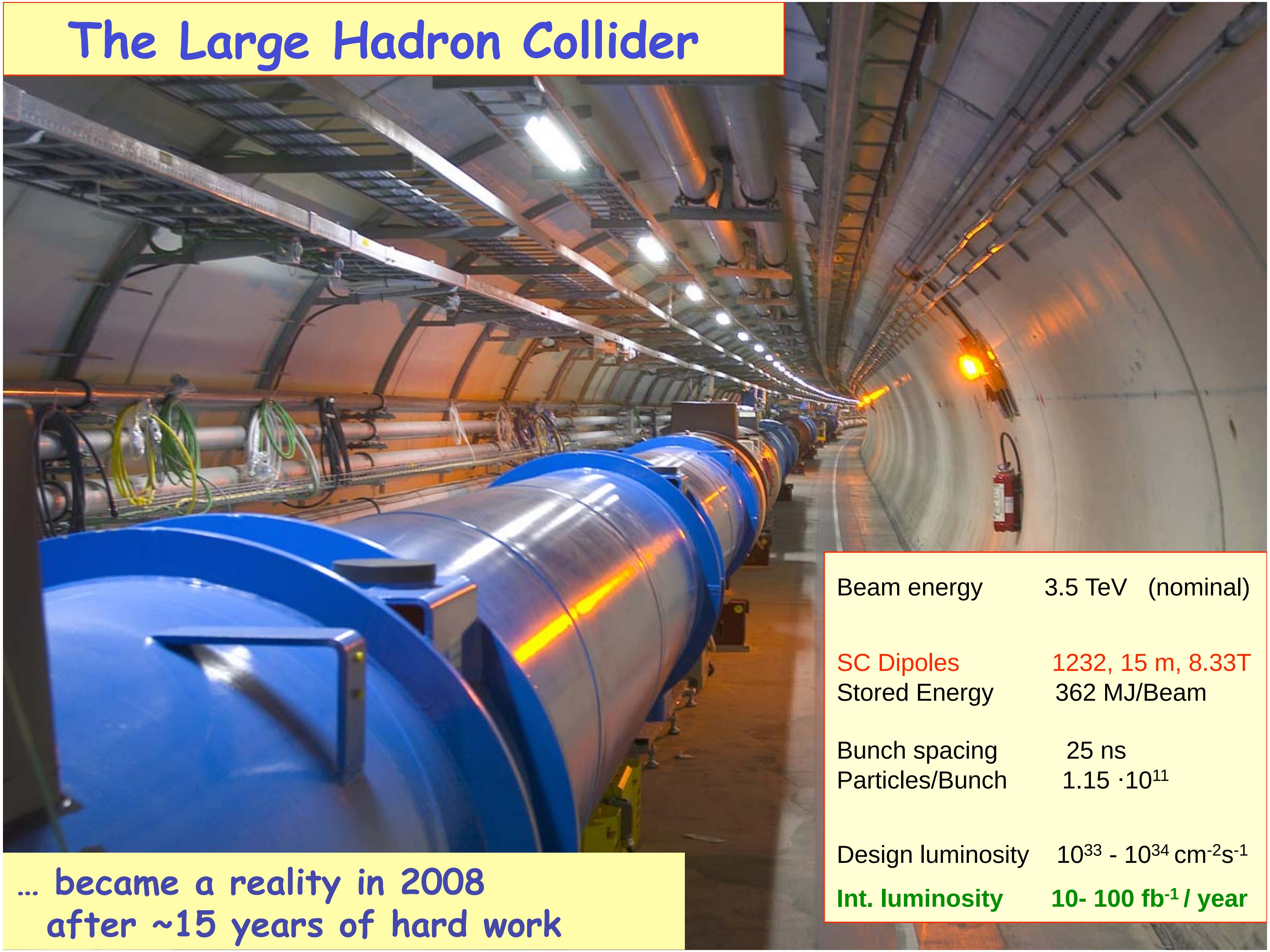
1.3 The Large Hadron Collider (LHC)



Begin of a new era in particle physics



The Large Hadron Collider



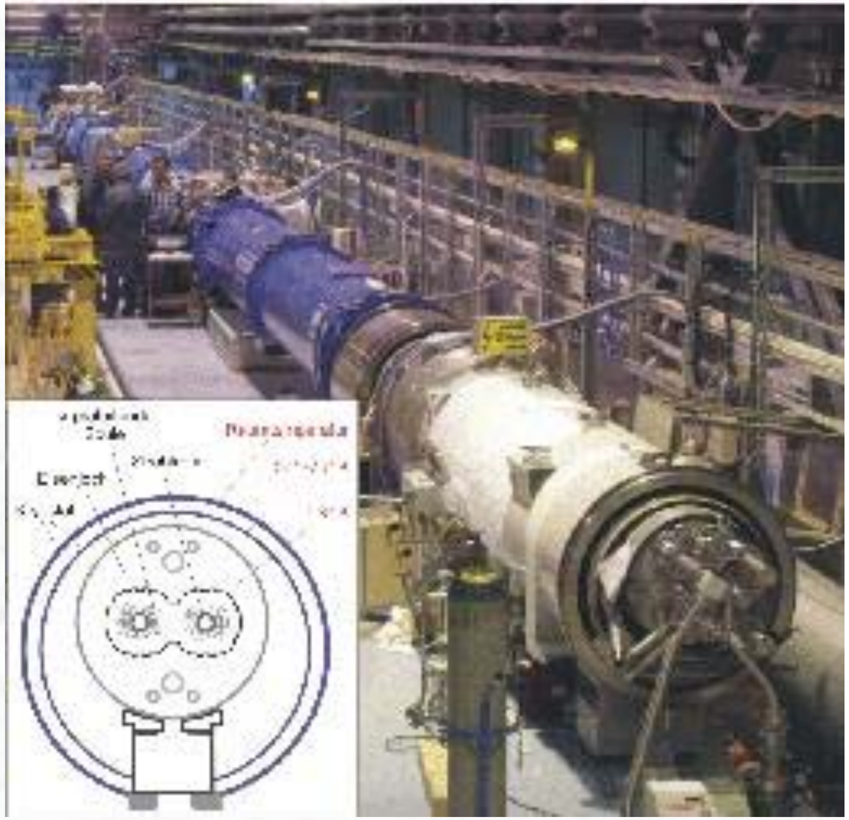
Beam energy	3.5 TeV (nominal)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Design luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**10- 100 fb^{-1} / year**

… became a reality in 2008
after ~15 years of hard work

Important components of the accelerator

- Superconducting dipole magnets
  (the largest challenge)

  - Magnetic field of 8.33 Tesla
  - in total 1232, 15 m long
  - Operation temperature of 1.9 K



- Eight acceleration structures,
  Field gradient of 5 MV/m