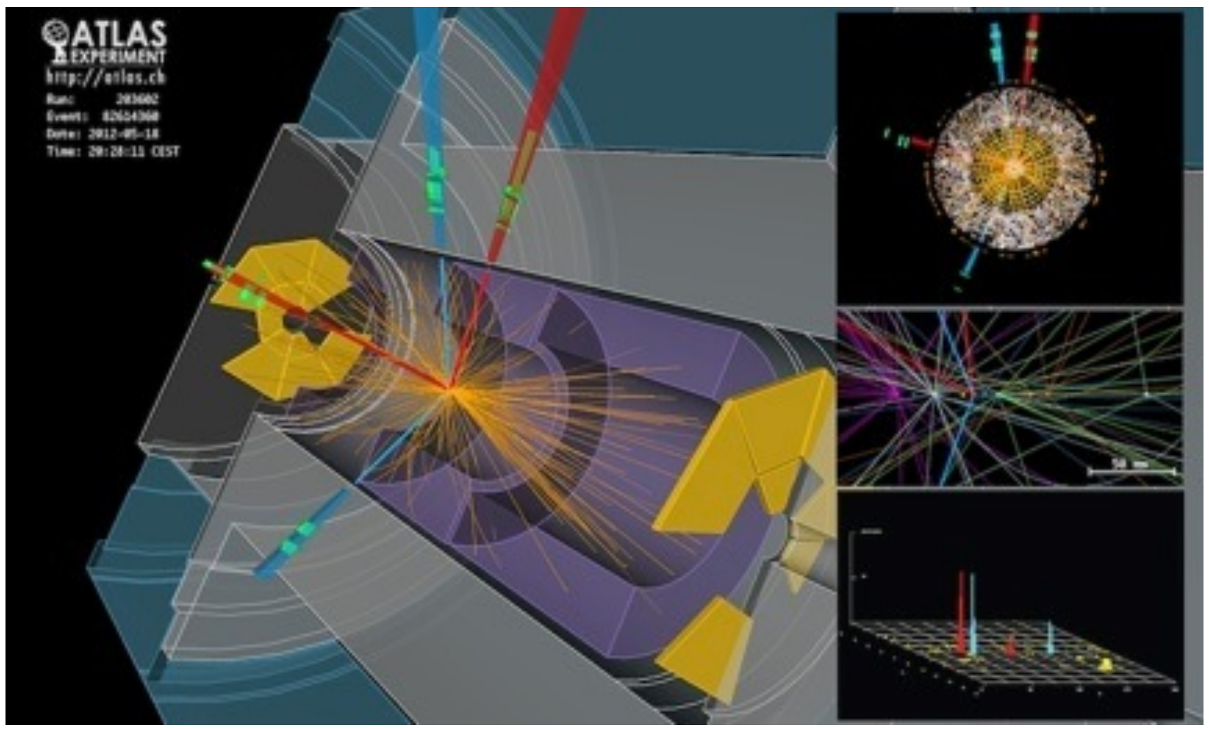
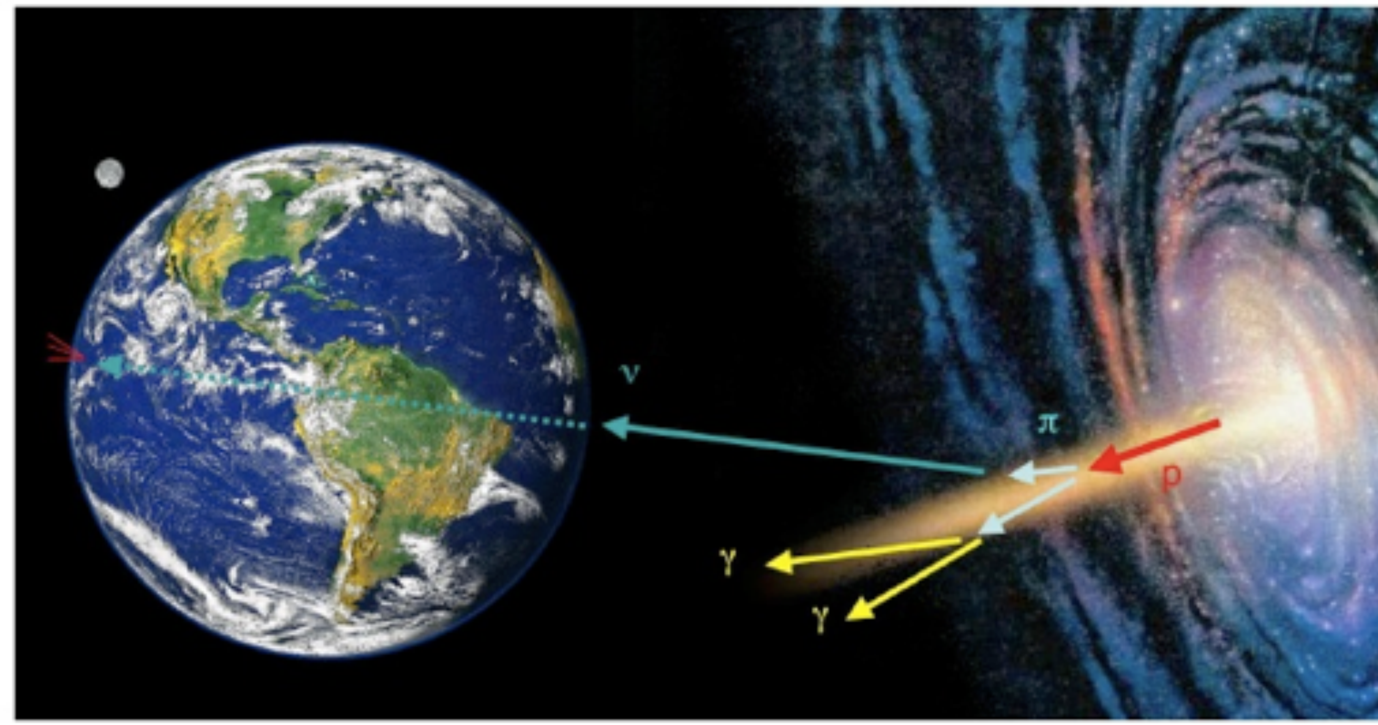
Particle Physics at Colliders and in the High Energy Universe





8. Particle Colliders

02.12.2019

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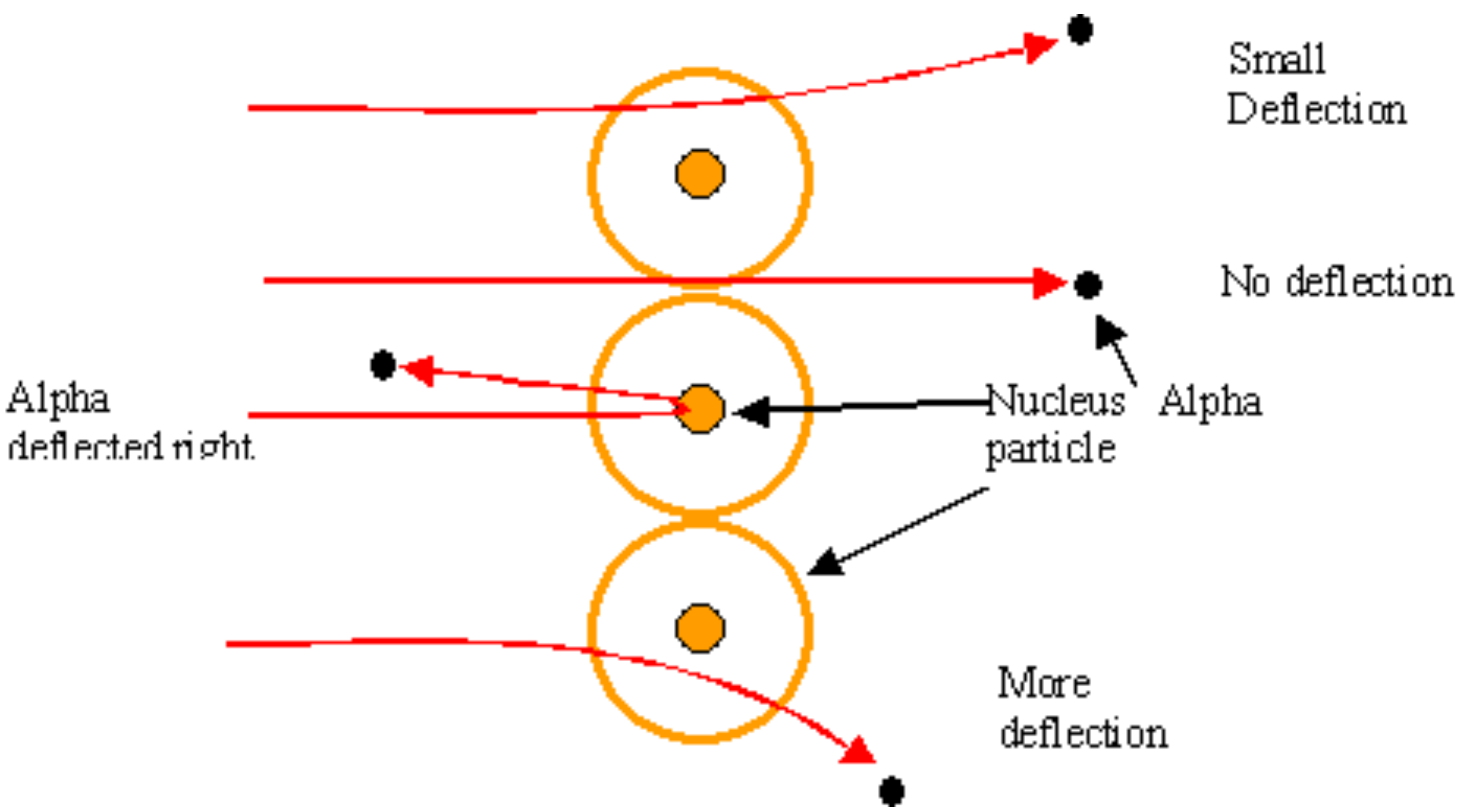
Overview

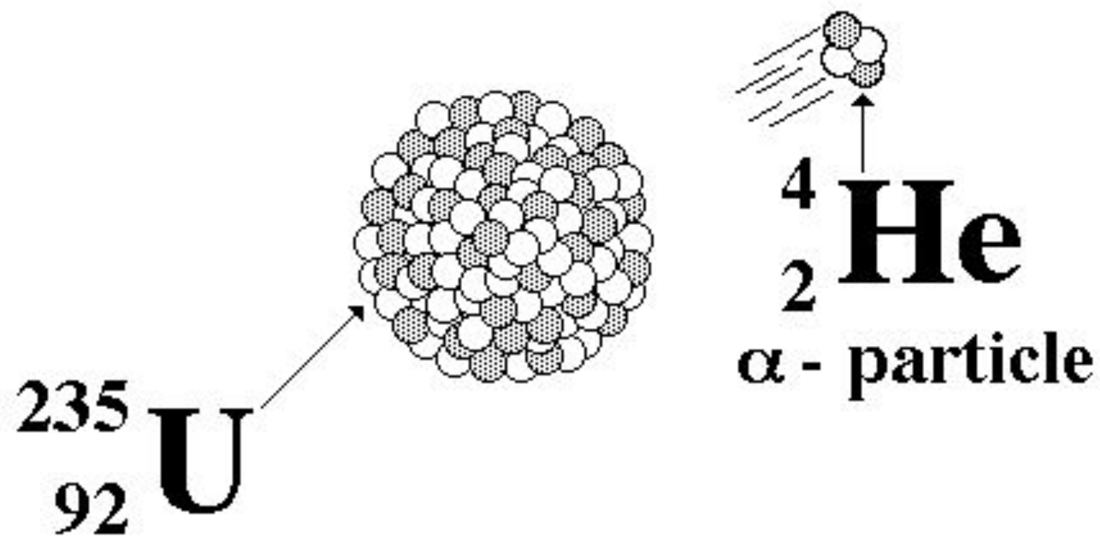
- Historical Introduction, The Role of Accelerators Today
- Accelerator Basics
- The Large Hadron Collider

100 Years ago: How it started

- 1911 Rutherford discovered the atomic nucleus by experiments with α particles on a thin Gold foil



- Uranium as natural "accelerator" MeV - scale particles from radioactive decay



Motivation for Accelerators

- Initially, accelerators were only used for basic research:
  To look into the structure of matter, you need short wavelengths, e.g. high energies

$$\lambda = \frac{h}{p} \approx \frac{(1.2\ \mathrm{fm})}{p\ (\mathrm{in\ GeV/c})}$$

1 GeV probes the size of the proton!

- To create new, previously unknown particles, you need energy

$$E = mc^2$$

- If you are looking for something that is rare (small cross-section!), you need

Intensity

Historical Overview

- 1928: R. Wideroe reports the operation of the first linear accelerator (Ka and Na-Ions)
- 1931: Van de Graaff constructs the first high voltage generator
- 1932: Lawrence and Livingston present first proton beams from a 1.2 MeV Cyclotron
- 1939: Hansen, Varian and Varian invent the Klystron
- 1941: Kerst and Serber introduce the Betatron
  Touschek and Wideroe invent the principle of ring accelerators

E.O. Lawrence

- 1947: Alvarez develops the first proton linear accelerator
- 1950 Christofilos formulates the concept of strong focusing

Accelerators - Today

Accelerators - Today

More than **400 B€** of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

More than **24 000** particle accelerators have been built globally over the past **60 years** to produce charged particle beams for use in industrial processes. This number does not include the more than **11 000** particle accelerators that have been produced exclusively for medical therapy with electrons, ions, neutrons, or X-rays.

More than **24 000** patients have been treated by hadron therapy in Europe.

More than **75 000** patients have been treated by hadron therapy in the world.

Around **200** accelerators are used for research worldwide, with an estimated yearly consolidated cost of **1 B€**.

The world's largest particle accelerator, the Large Hadron Collider (LHC), is installed in a tunnel **27 km** in circumference, buried 50-175 m below ground.

The temperature of the superconducting magnets in the LHC reaches **– 271 °C.** In contrast, the temperature at collision point is 1000 million times hotter than that of the Sun's core.

Accelerator Basics

The Basics of Particle Acceleration

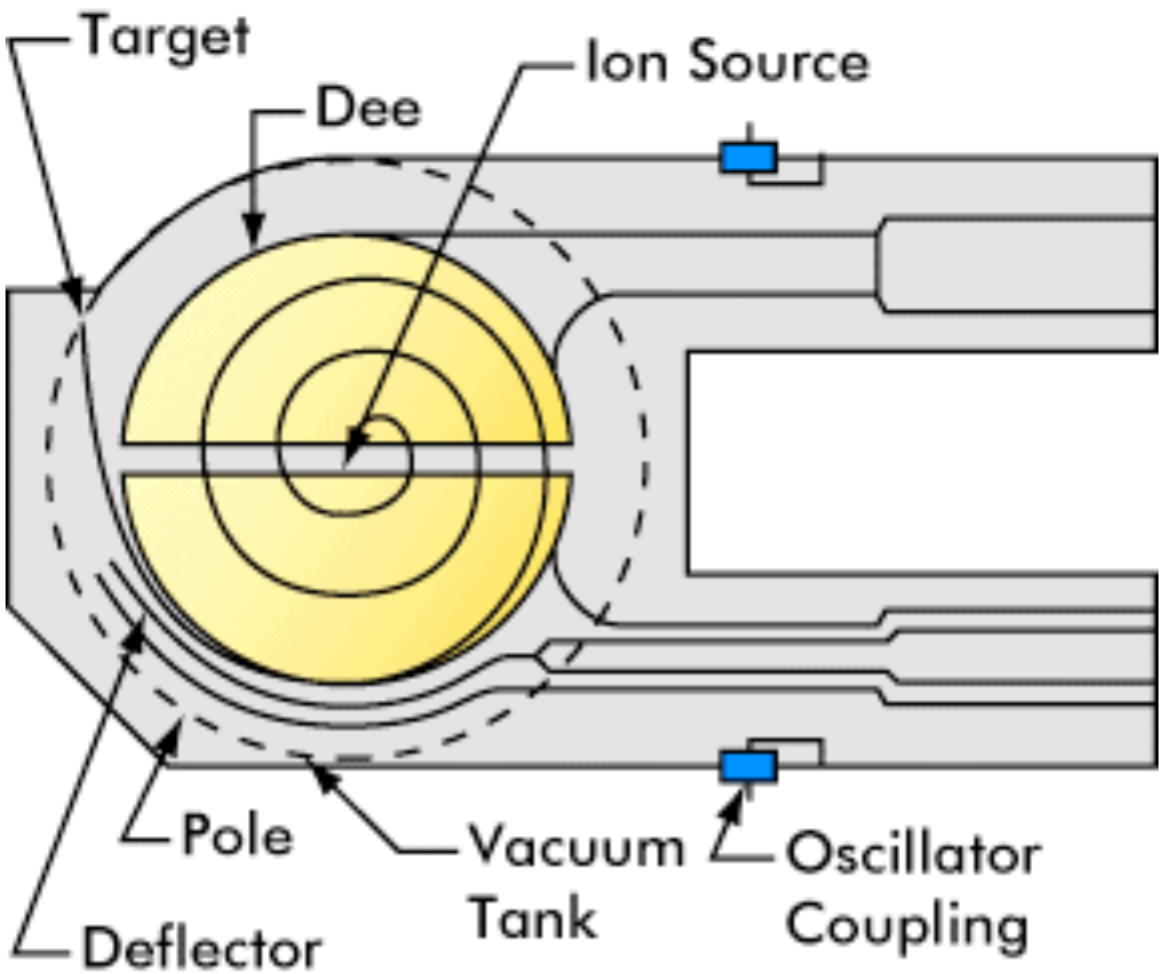
- The underlying equations: Maxwell-Equations

Differentialform	Integralform
$\mathrm{div}\ \vec{D} = \rho_{\mathrm{frei}}$	$\oint \vec{D} \cdot d\vec{A} = Q$
$\mathrm{div}\ \vec{B} = 0$	$\oint \vec{B} \cdot d\vec{A} = 0$
$\mathrm{rot}\ \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E} \cdot d\vec{s} = -\frac{d}{dt}\int \vec{B} \cdot d\vec{A}$
$\mathrm{rot}\ \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$	$\oint \vec{H} \cdot d\vec{s} = I + \frac{d}{dt}\int \vec{D} \cdot d\vec{A}$

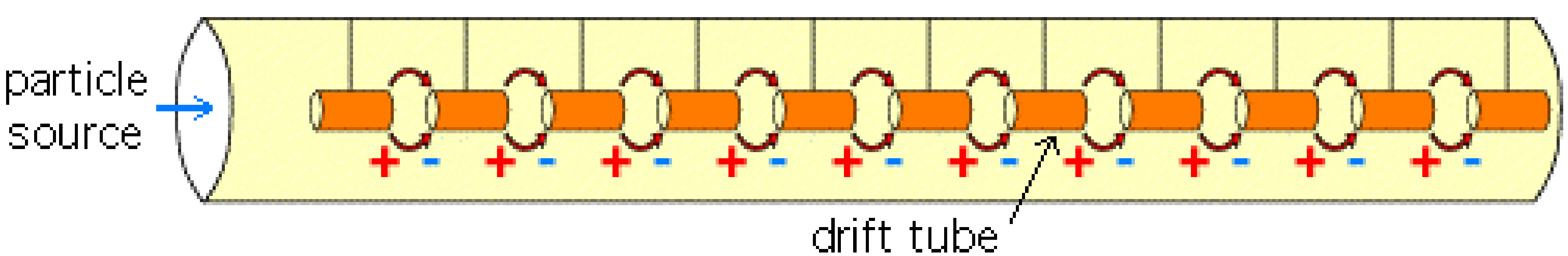
The key: Lorentz-Force $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$

n.b.: The Lorentz-force is non-conservative for time-dependent fields!

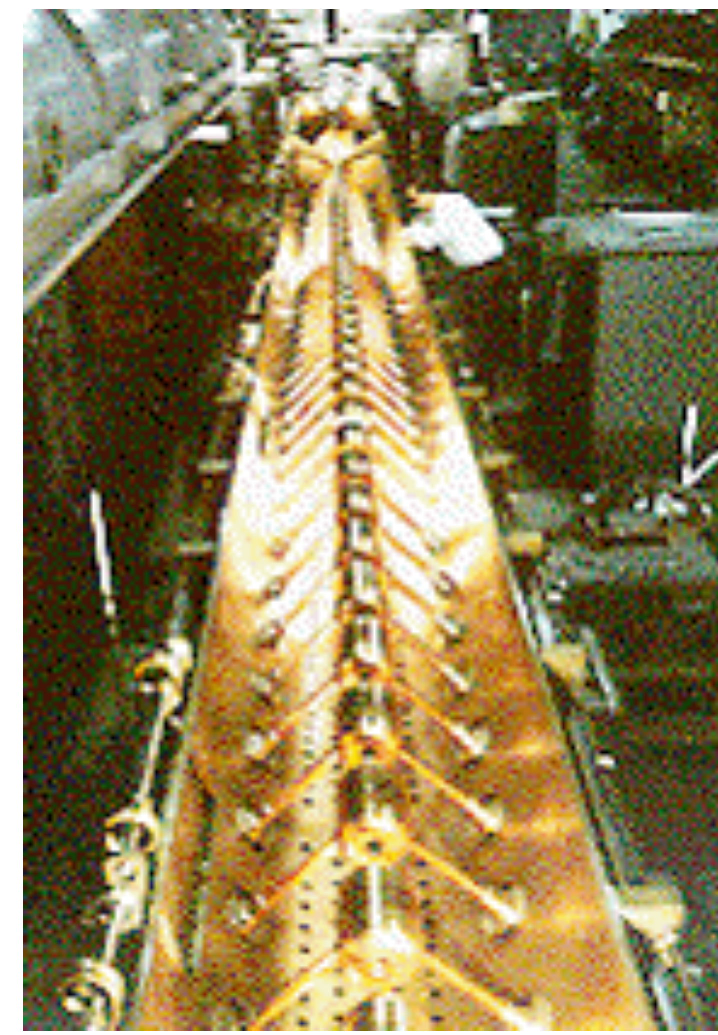
Basic Accelerator Types: Cyclotron, Linac



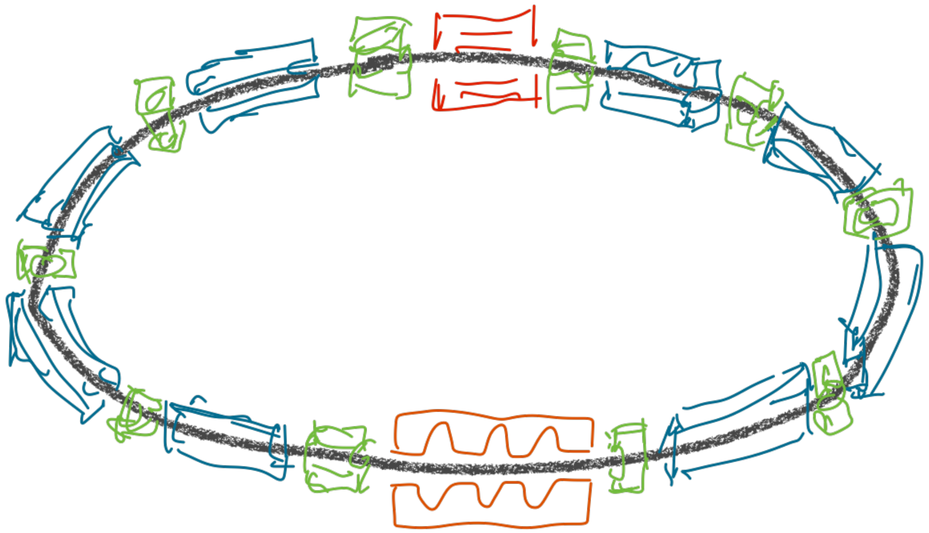
- Cyclotron:
  - Magnetic field to bend particles
  - Alternating electric field for acceleration



- Linear accelerator:
  - Alternating electric field for acceleration

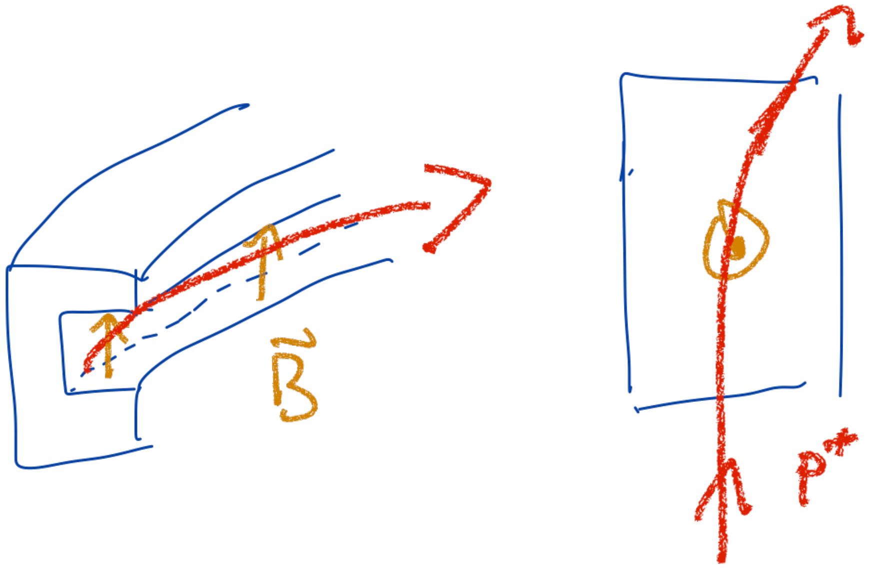


Basic Accelerator Types: Synchrotron



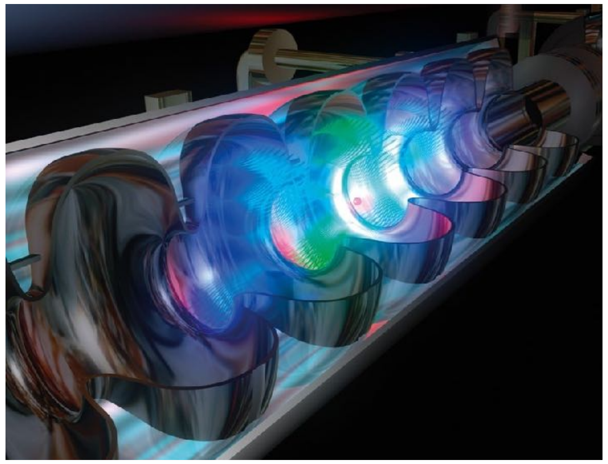
Bending magnets:

Dipole magnets keep the particles on a circular path



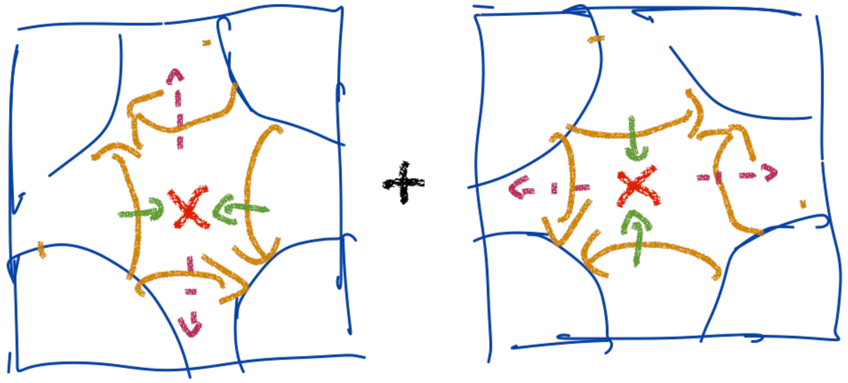
Accelerating Structures:

Electric fields accelerate particles



Focussing magnets:

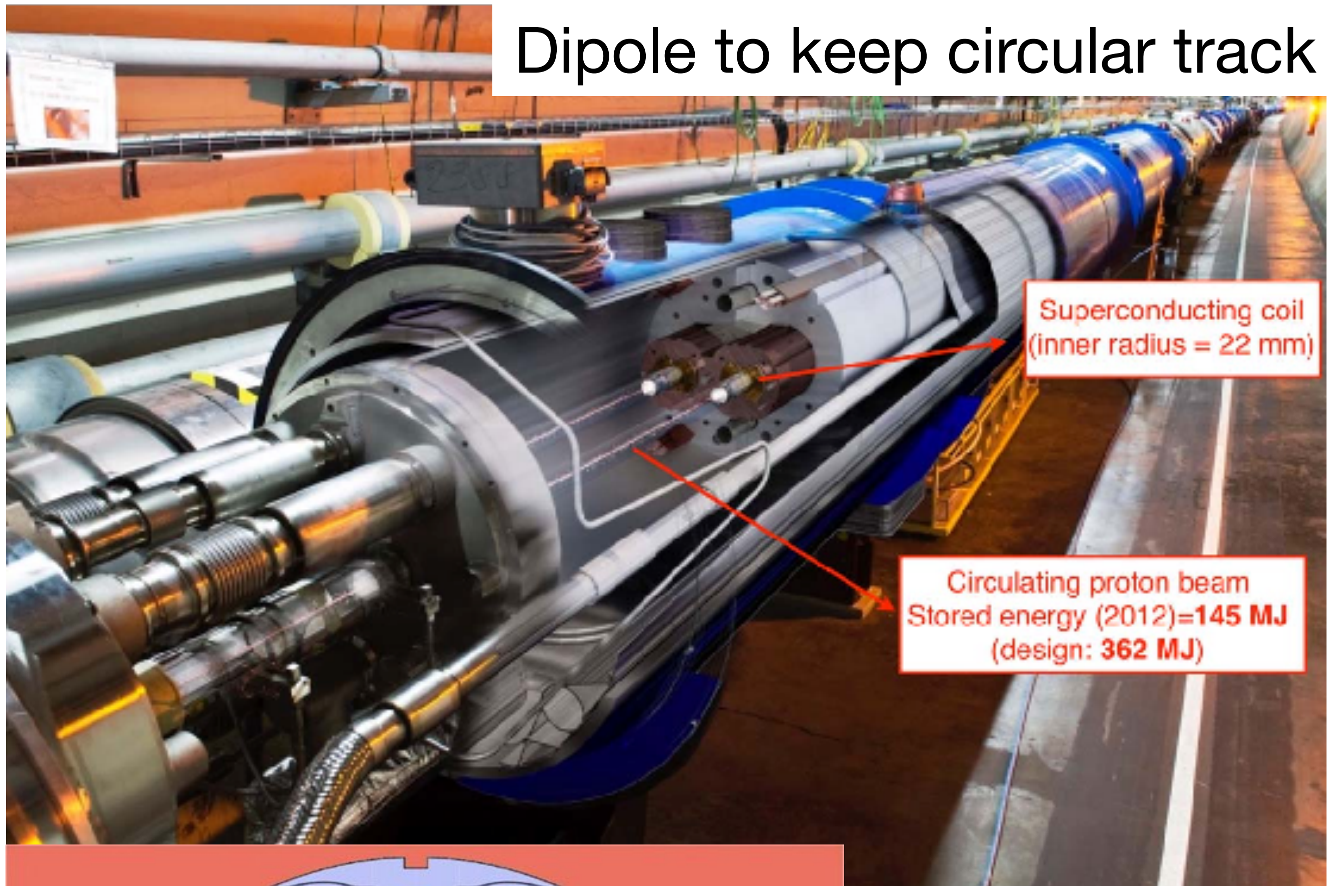
Magnetic lenses are focussing the beam



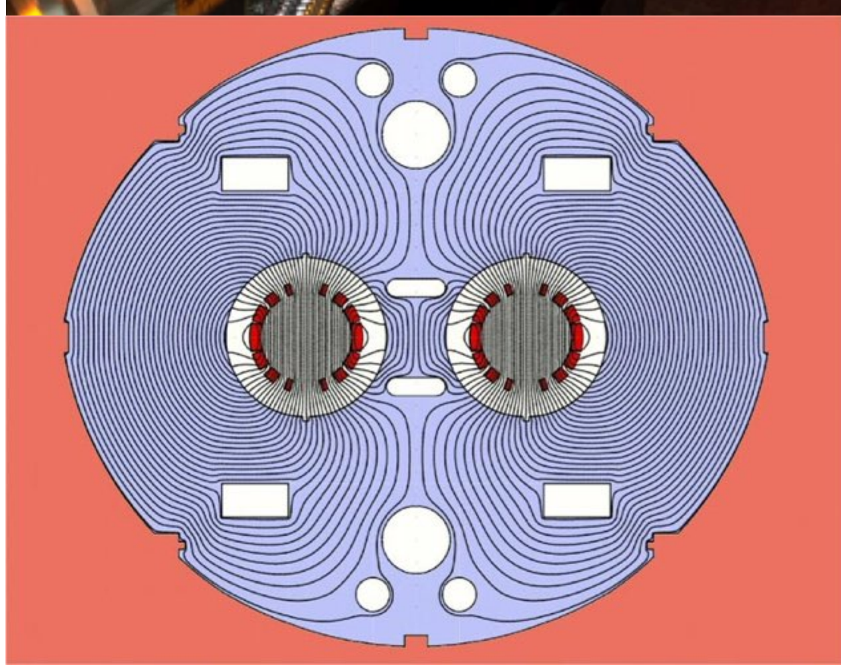
- Synchrotron:
  (key features)

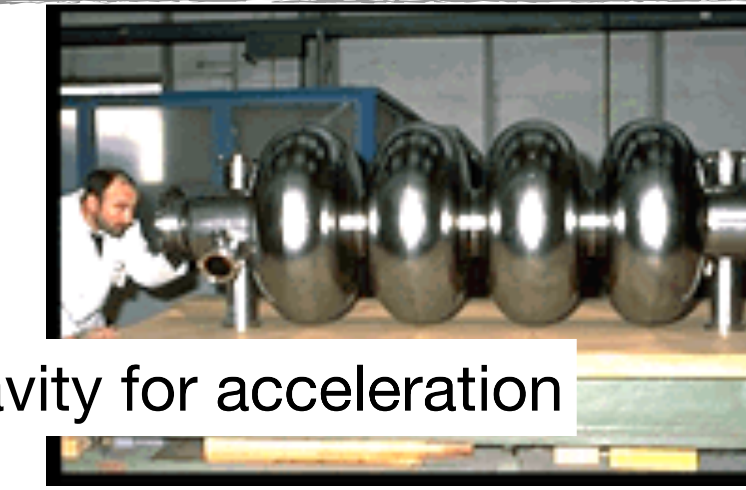
- Magnetic bending field gets ramped up with particle energy: Particles can stay on fixed path
- Magnetic field only needed locally
- Same accelerating cavities get passed many times

Functional Parts of Ring Accelerators



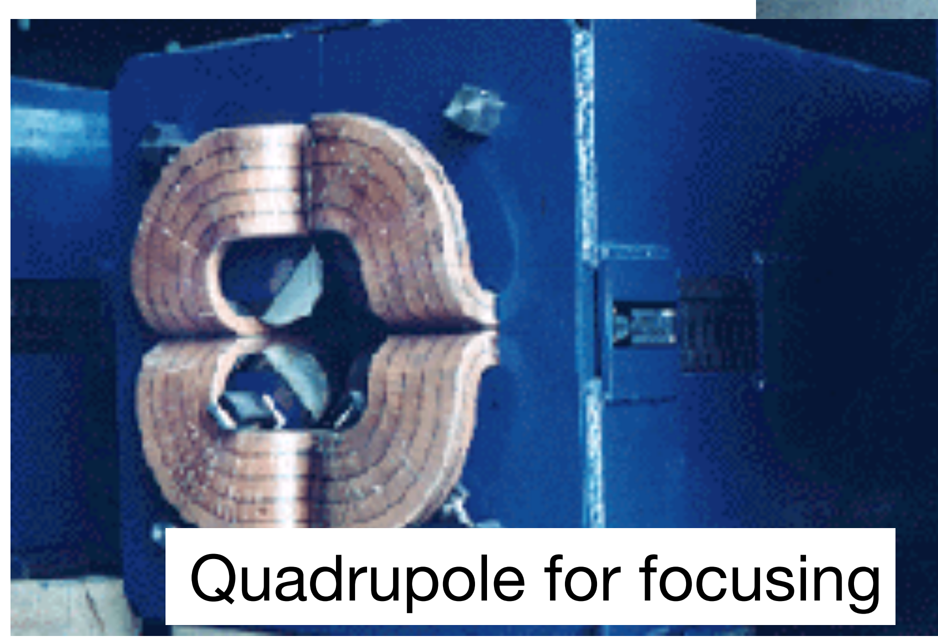
Dipole to keep circular track





RF cavity for acceleration

Sextupole for higher order focusing, additional beam line elements: beam pipe, pumps, …



Quadrupole for focusing

Limits for Ring Accelerators: Bending Power

- Strong dipole magnets keep particles on their track in a synchrotron
  Magnetic field and radius define energy!

$$\vec{F} = \frac{d\vec{p}}{dt} = q\left(\vec{v} \times \vec{B}\right)$$

Lorentz force acts on moving charge

It forces the particle on a circular track:

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \rho[\mathrm{m}] \approx \frac{p[\mathrm{MeV/c}]/300}{B[\mathrm{T}]}$$

Often, the term “stiffness” is used:

$$(B\rho) = \frac{p}{q} \Rightarrow (B\rho)[\mathrm{Tm}] \approx \frac{p[\mathrm{MeV/c}]}{300}$$

LHC : (Bρ)~23000 Tm

Maximum dipole field and radius define maximum energy

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

scales with γ^4, at constant energy with $1/m^4$ ➩ Electrons loose 10^{13} times more energy than protons!

- Energy loss of electrons per turn in a storage ring

$$\Delta E = 8.85 \times 10^{-5} \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

- Energy loss of protons

$$\Delta E = 7.8 \times 10^{-6} \frac{E^4[\mathrm{TeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

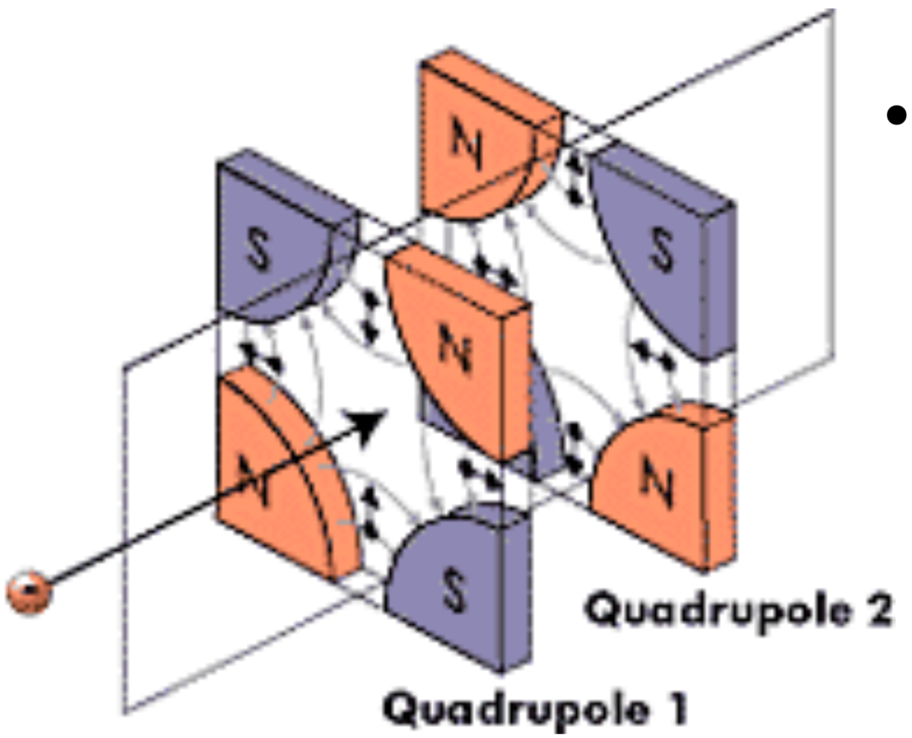
- Example: 100 GeV electrons in LHC-tunnel (ρ ~ 4.3 km), e.g. LEP: ΔE ~ 2 GeV

- Example: 7 TeV protons in LHC-tunnel (ρ ~ 4.3 km): ΔE ~ 4.4 keV

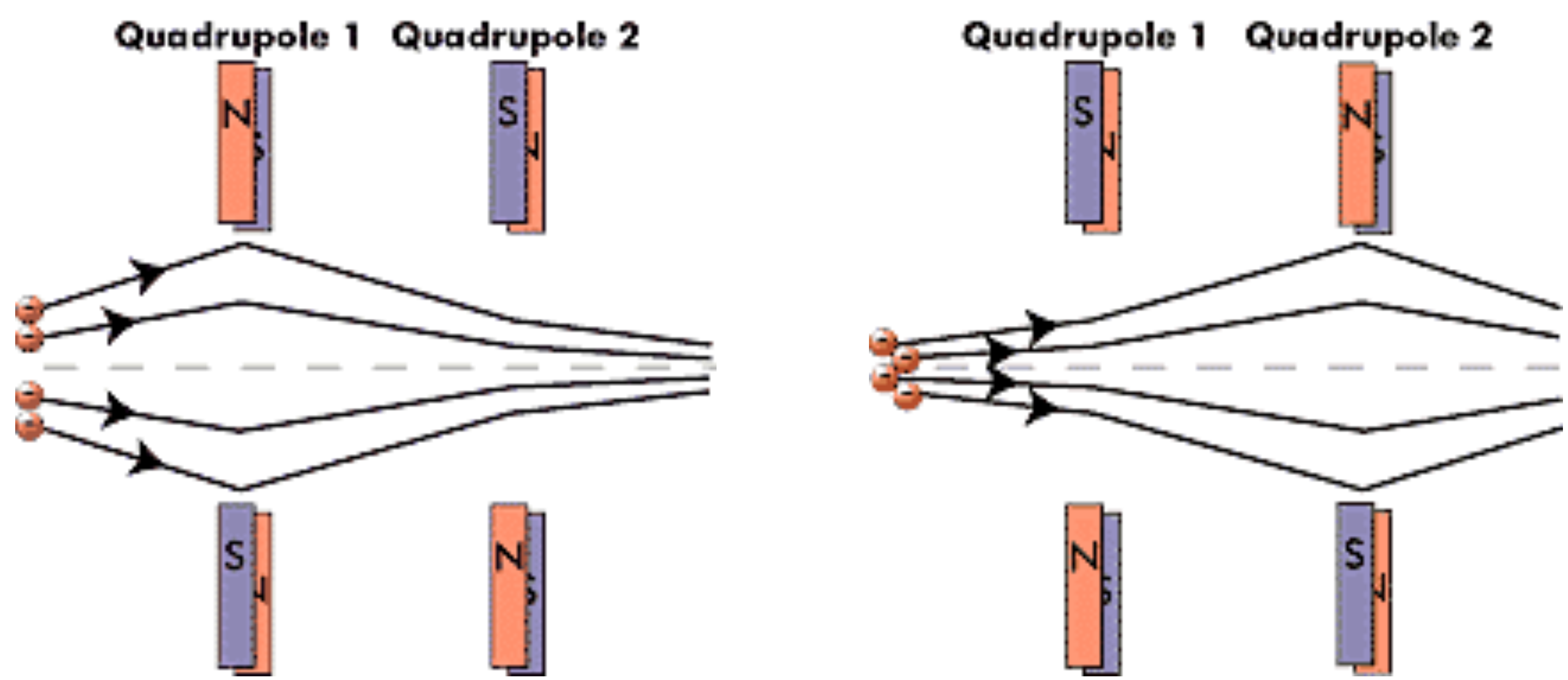
➩ Highest energies are not possible with electrons using synchrotrons!

Strong Focusing

- Strong Focusing, or Alternating Gradient Synchroton: Breakthrough that allowed to reach high energies of 10 GeV and more



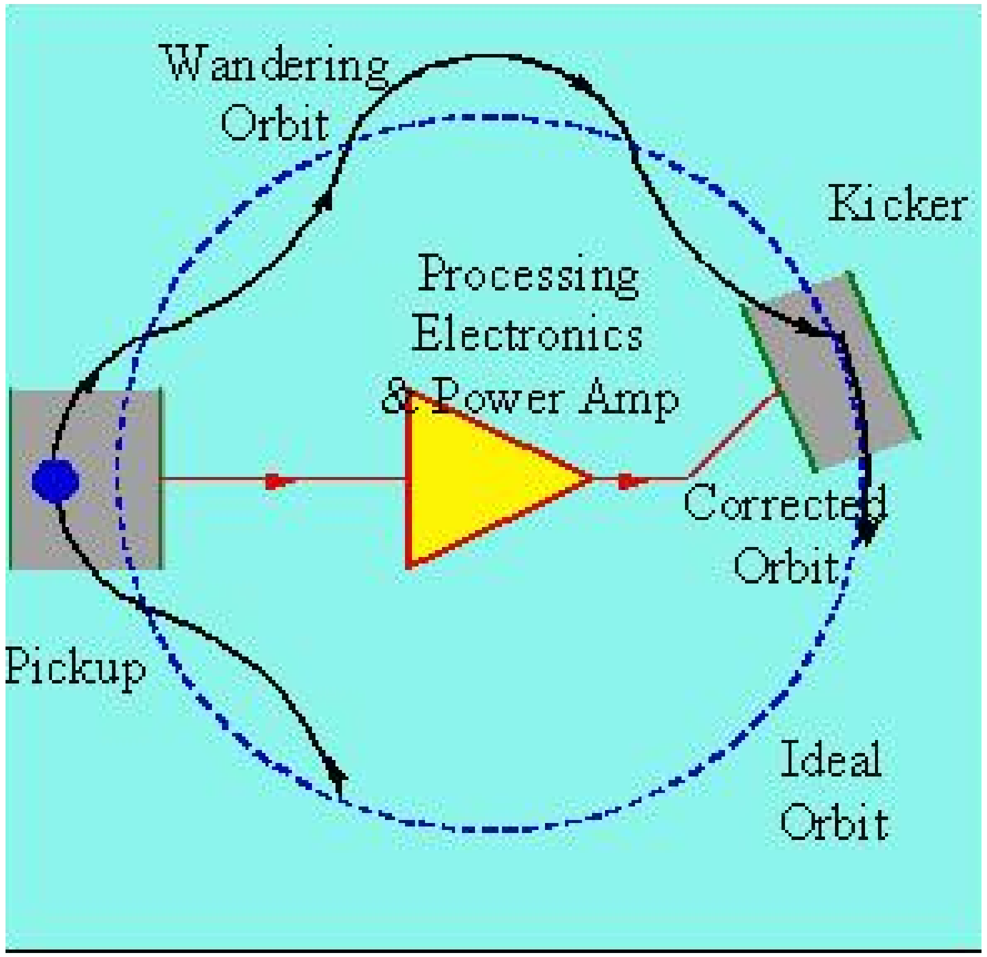
- Two crossed quadrupole fields have a net focusing effect, if they are placed at the right distance d (smaller than the focal length) - Just like a lens system in optics!



$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

Stochastic Cooling

- Nobel prize to Simon van der Meer (1984)
- Reduction of transversal phase space particle bunches: picking up displacements on one side of the ring, applying correctly timed correction pulses on the other side of the ring

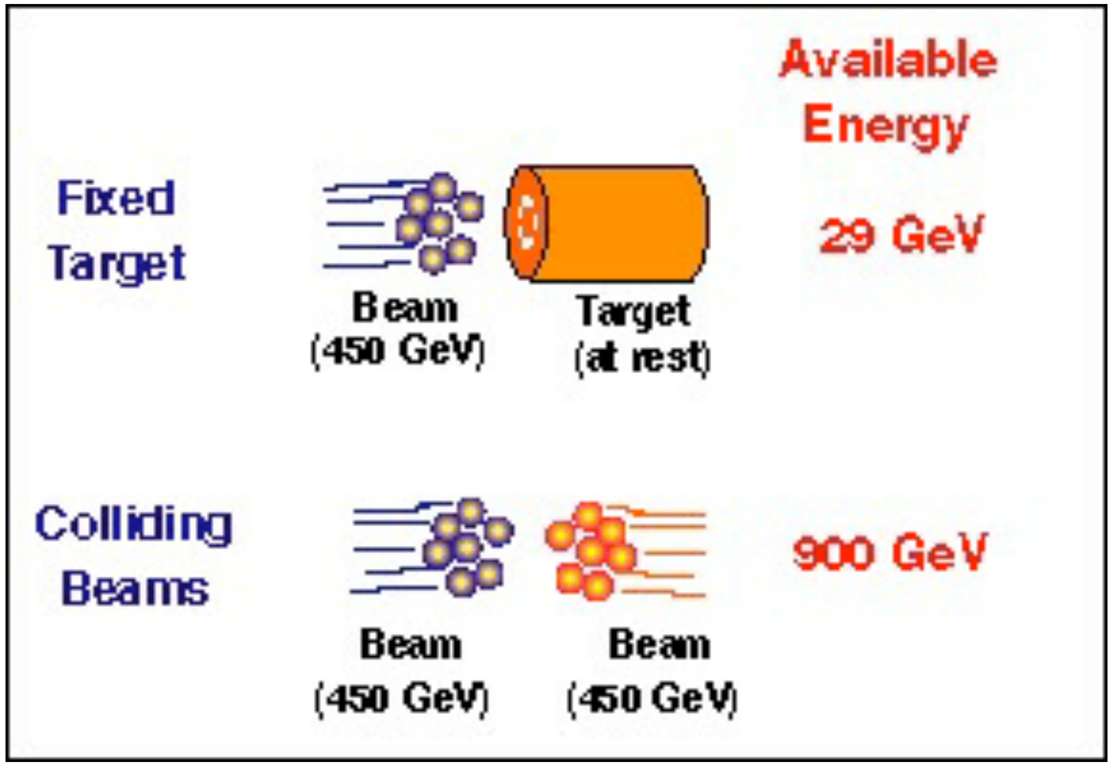


- Crucial for particle beams that naturally come with larger emittance:
  - Anti-protons: Made p-anti-p colliders possible - introduced for the SppS, also extensively used at Tevatron
  - Heavy ions: Used at RHIC

amplification of pick-up signal by 150 dB (10^{15}).

High Energies: Colliders

- The first experiments with accelerators were fixed-target experiments: (Relatively) easy to manage: Shoot a beam at a target
- Much higher energy can be obtained in collider mode: Two beams collider, the center of mass can be at rest in the laboratory



For colliding protons

$$E_{cm} = \sqrt{2(\gamma + 1)} m_p c^2$$

$$E_{cm} = 2E = 2\gamma m_p c^2$$

Key Collider Parameters

- Event Rate $$\mathrm{R} = L \cdot \sigma$$

- Luminosity $$L = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

f: Collision frequency

n_i: Number of particles in bunch i

σ_x: horizontal beam size

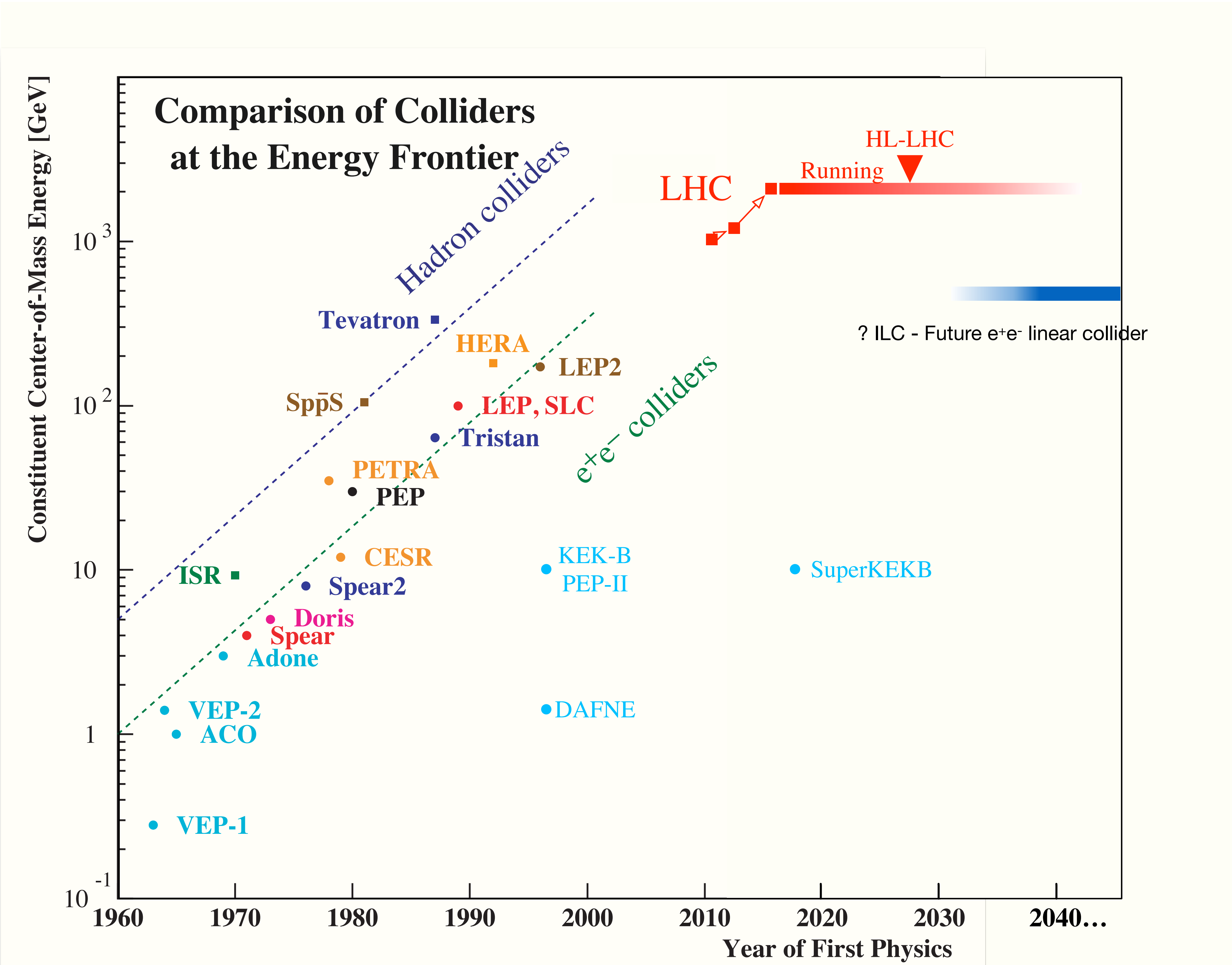
σ_y: vertical beam size

... assuming a gaussian beam profile and perfect overlap

- Luminosity is often expressed in terms of the “β function” at the collision point and in terms of “emittance”
  - β^* is related to the beam optics
  - ε is related to the beam quality, and gives the phase space of the beam particles (units length * angle)

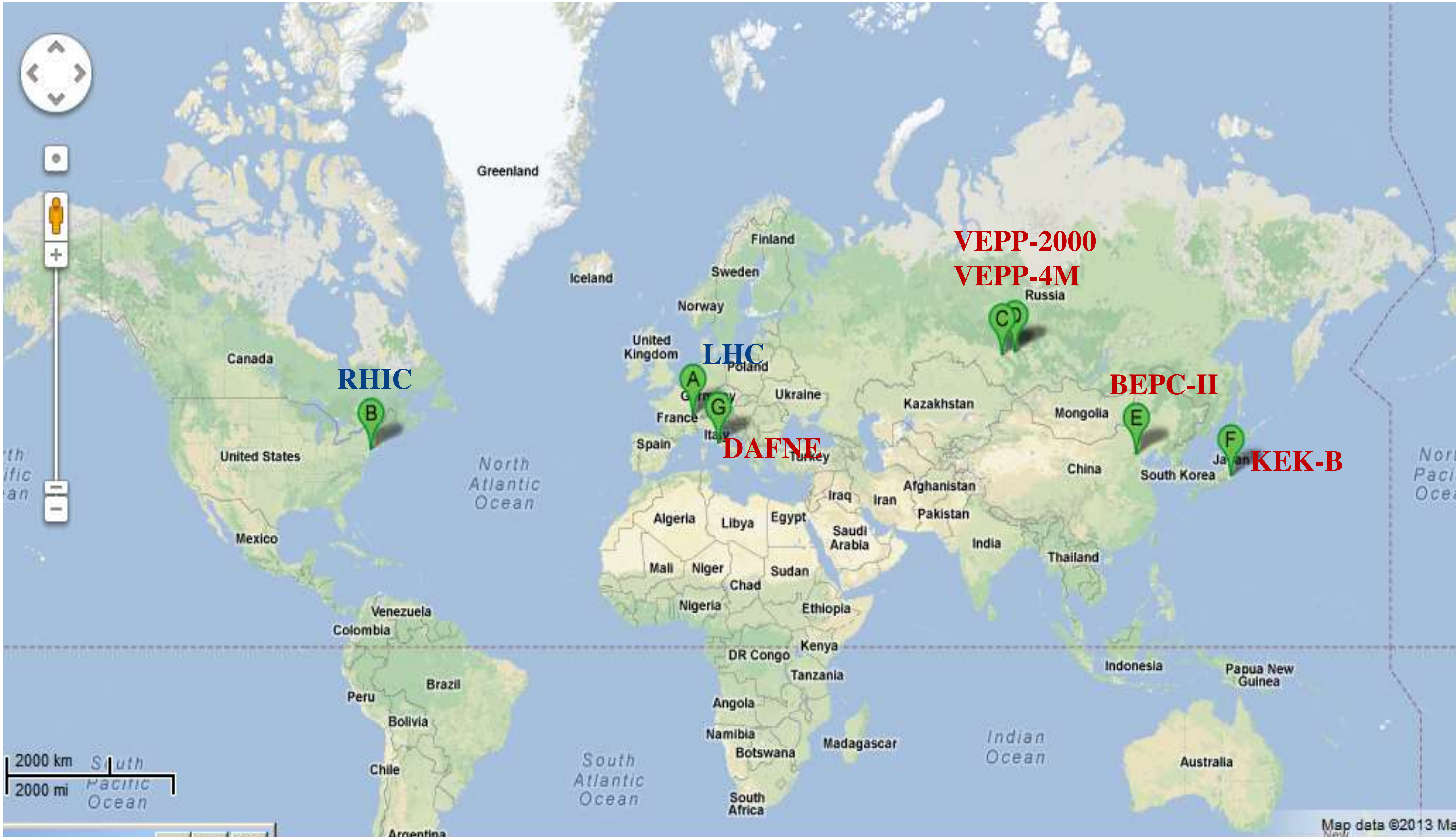
$$L = f \frac{n_1 n_2}{4\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$$

Evolution of Energy - The Livingston Plot



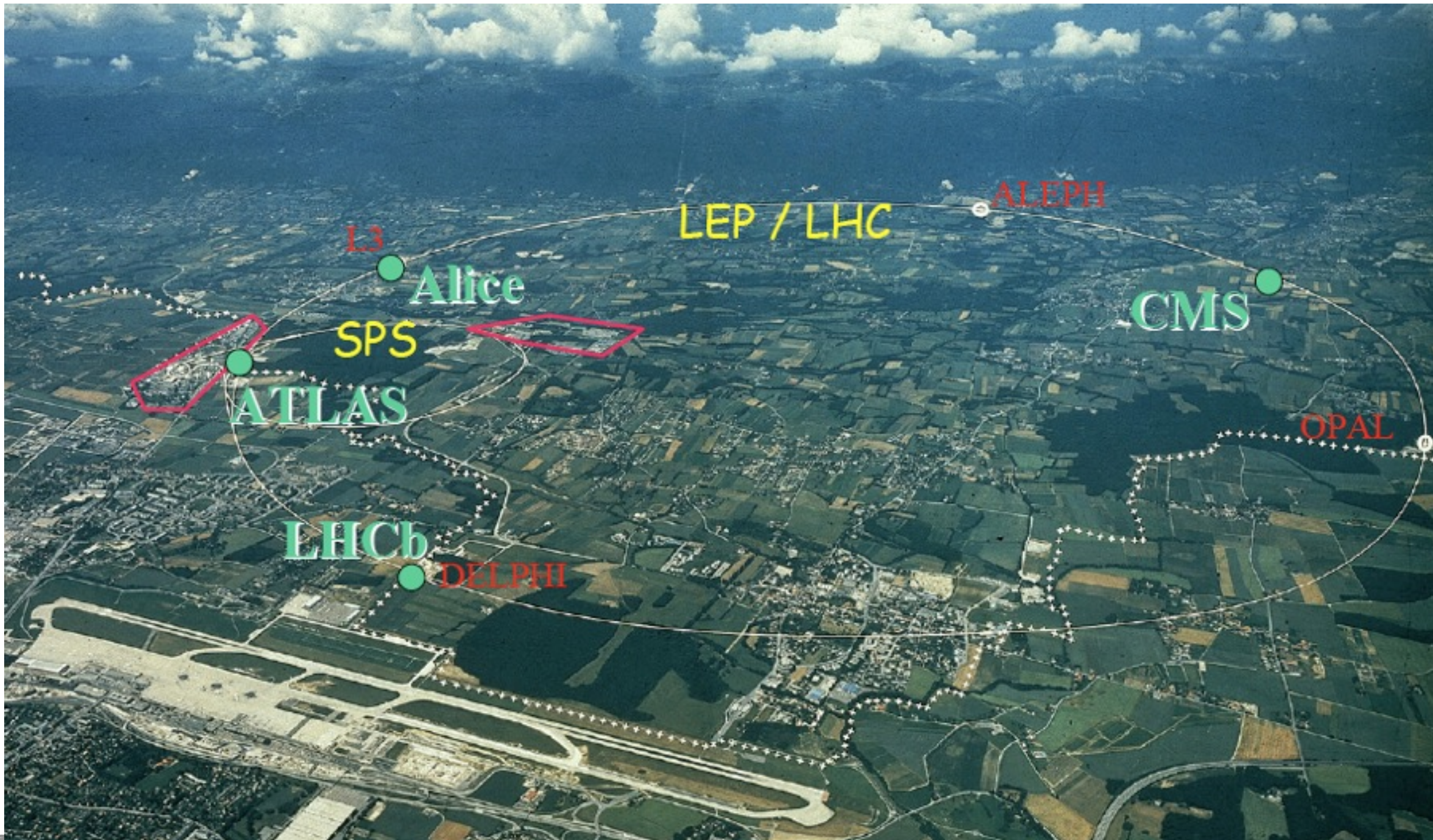
Colliders - Now and Then

- 29 Colliders built, 7 work "now"

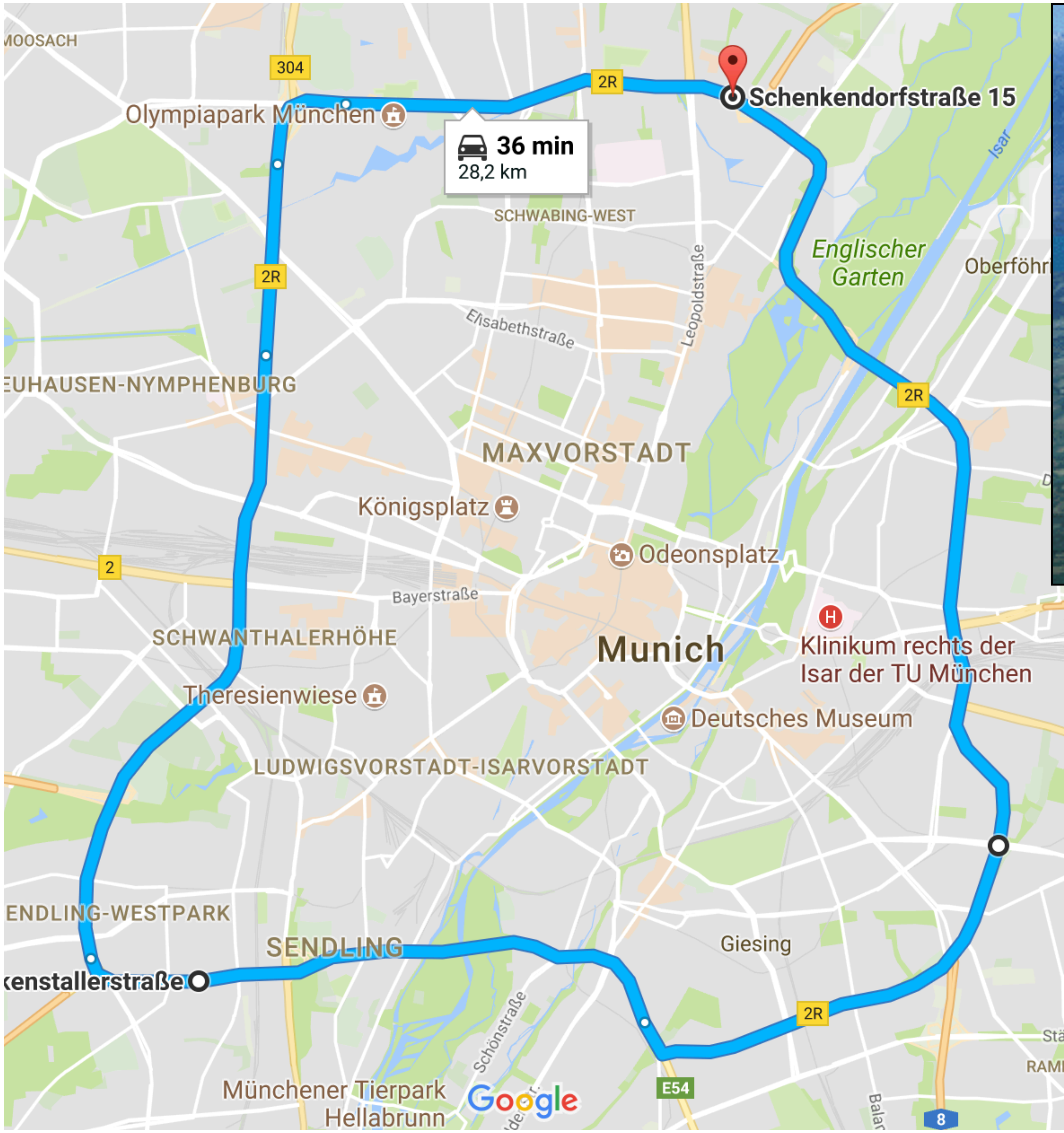


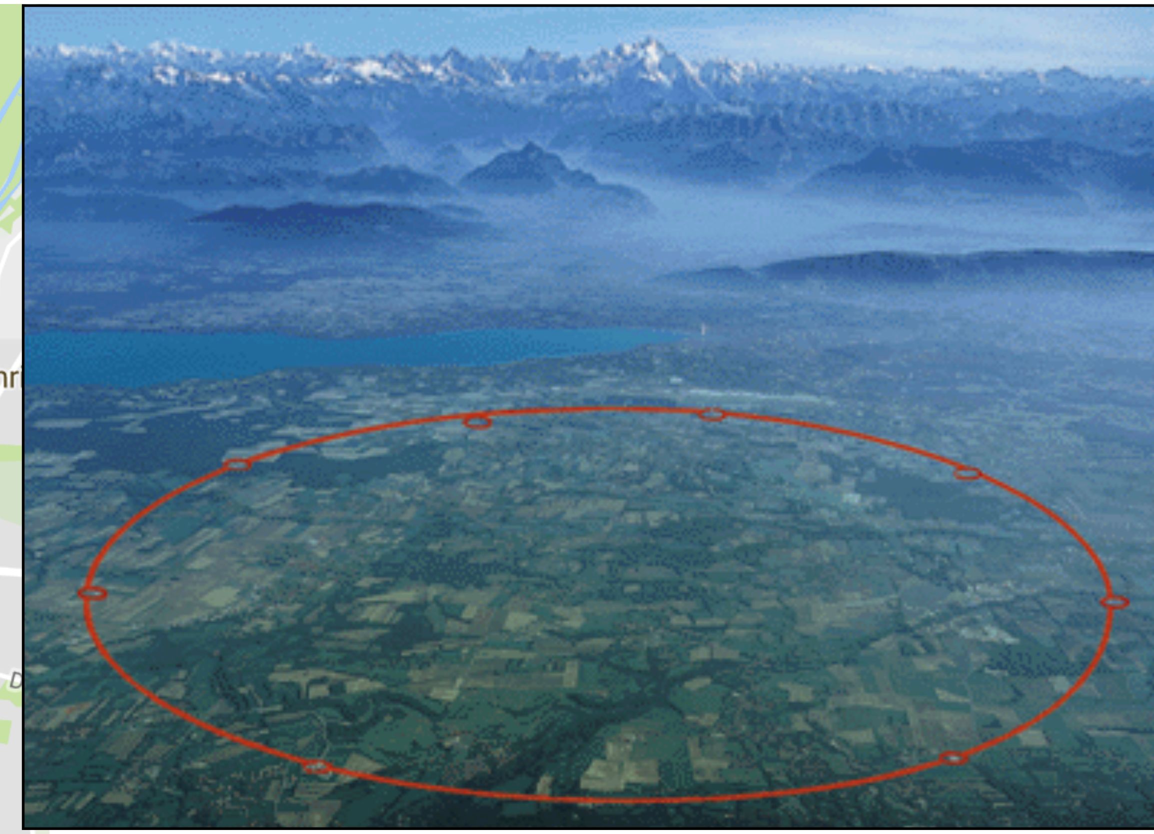
The Highest Energy e^+e^- Collider to date: LEP

- Up to now the highest energy collider for leptons: Up to 209 GeV center of mass energy



The Size - In Perspective





In the LEP Tunnel

- Focusing quadrupoles
- Main dipoles

Now: Home of the LHC

Much higher energy for protons: Limited by dipole magnet strength, LEP was limited by accelerating cavity power (synchrotron radiation!)

Foto: CERN

The Large Hadron Collider

The LHC: Visions (1980ies)

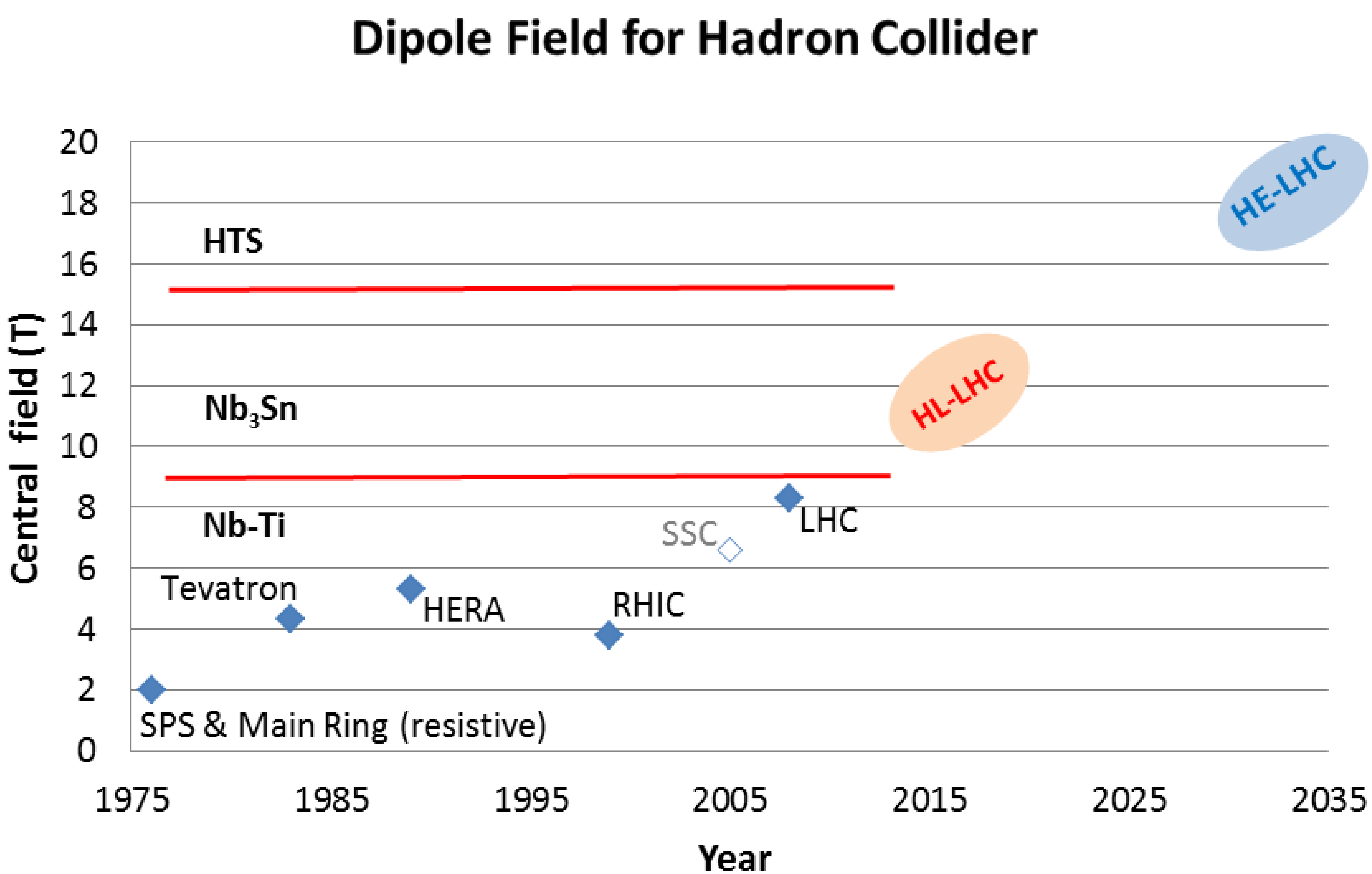
- particle accelerator with the highest collision energies aiming at:
  - test of the Standard Model beyond energies of 1 TeV
  - finding the missing pieces of the SM: top quark
  - investigate the mechanism of electroweak symmetry breaking: find the Higgs boson
  - search for New Physics beyond the Standard Model (Supersymmetry, large extra dimensions, …)
  - find the unexpected

The Challenges

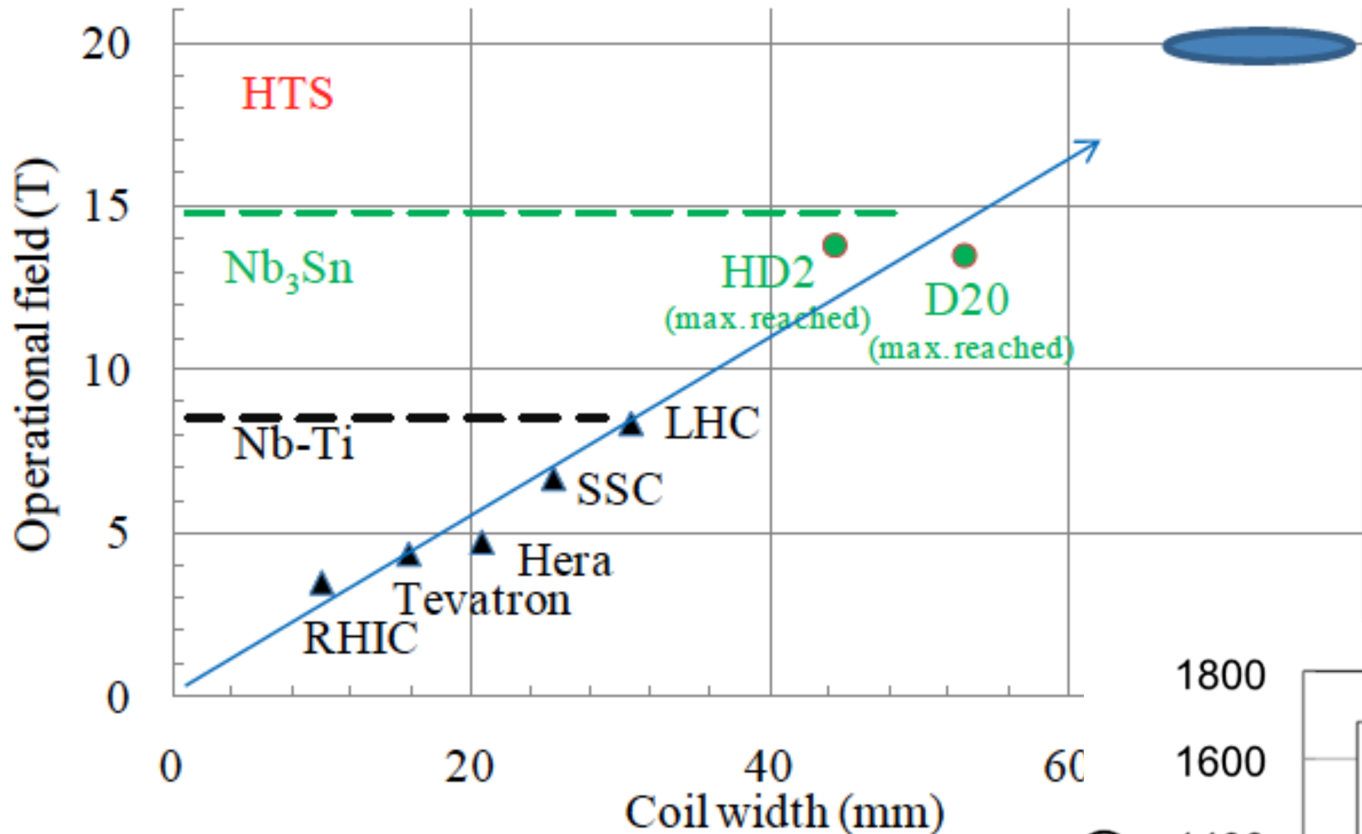
- "fast" and „cheap" ➩ use existing LEP tunnel and pre-accelerators of CERN
- highest energies at given radius of tunnel ➩ accelerate protons (instead of electrons at LEP)
- collision energies of constituents of ~TeV ➩ Proton energies of at least 5 TeV
- Proton energies of at least 5 TeV ➩ superconducting magnets at ~ 8 Tesla
- generate objects of very high masses ➩ need high luminosity ($L \sim 10^{34}$ cm^{-2} s^{-1})
- $L \sim 10^{34}$ cm^{-2} s^{-1} ➩ high data rates; radiation damage

The Key for High Energies: Dipole Magnets

- The field of the main dipoles (and the radius) determine the energy of a proton collider: Need strong magnets!

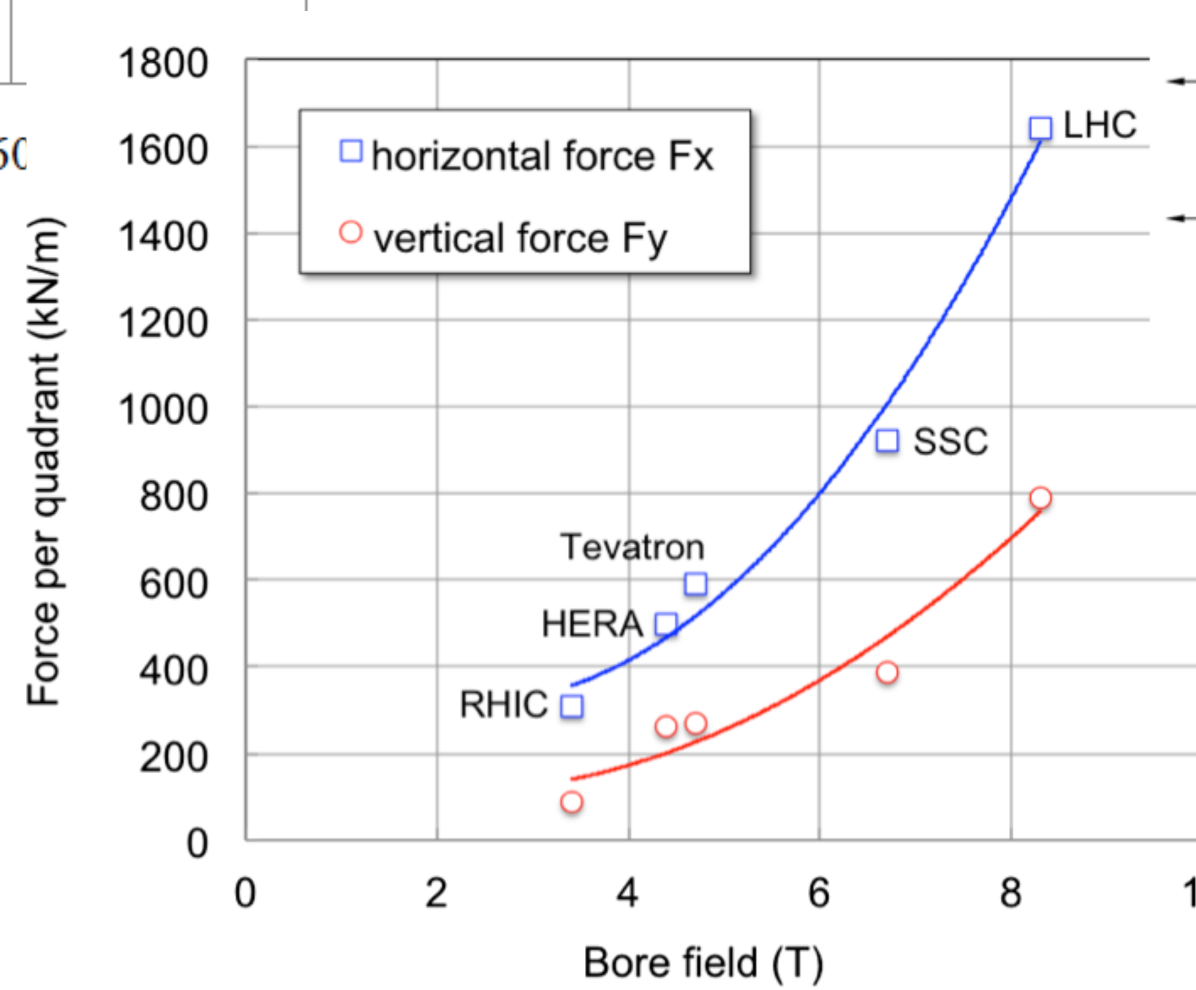


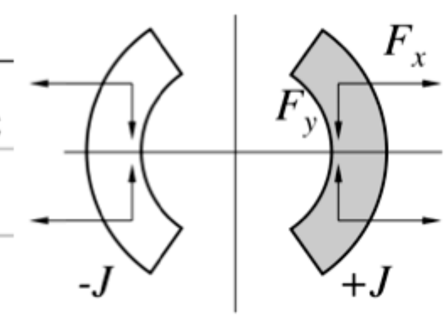
Larger Fields: Large Coils, Large Forces



- Magnets get larger for larger fields

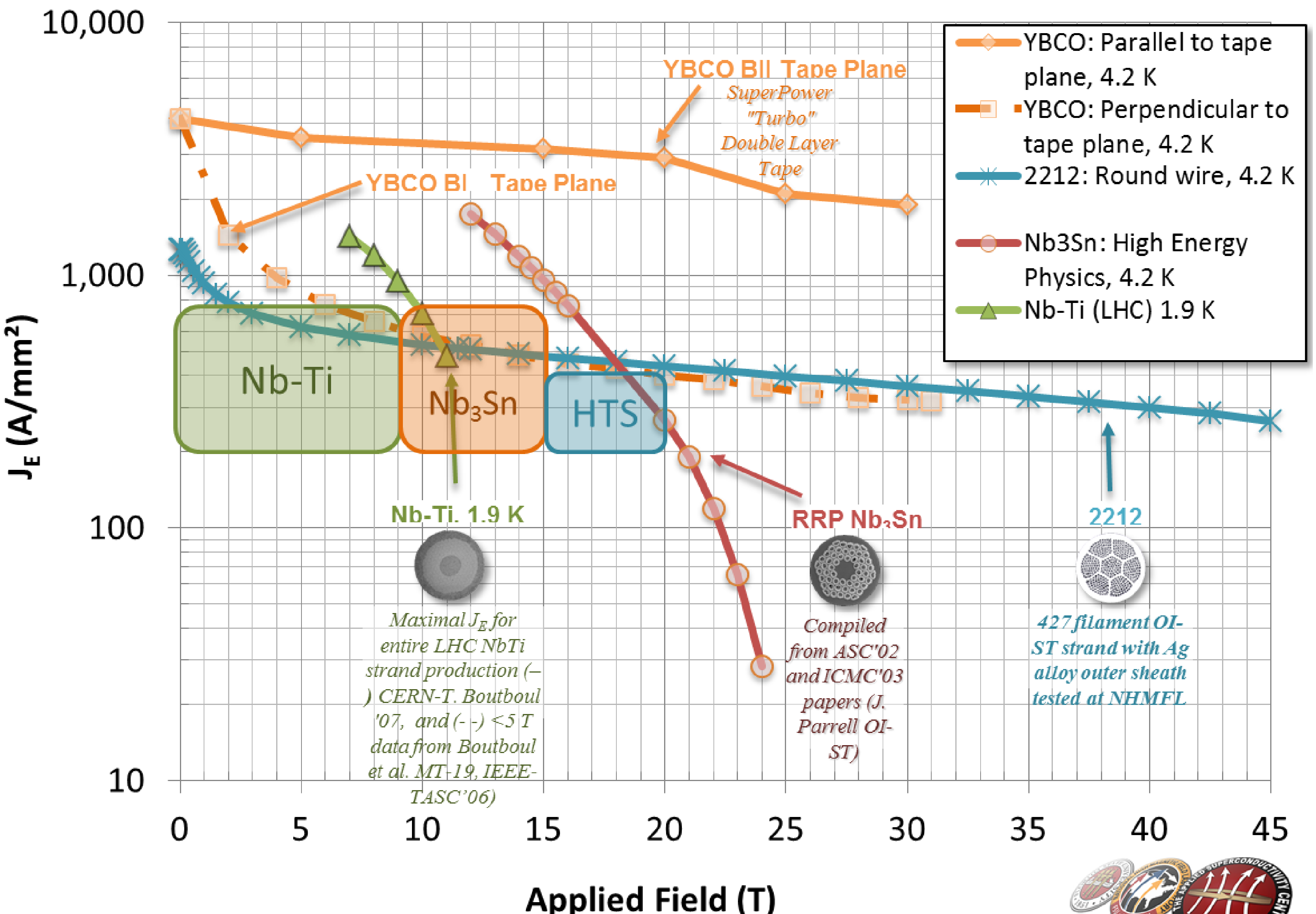
- … and have to hold large forces

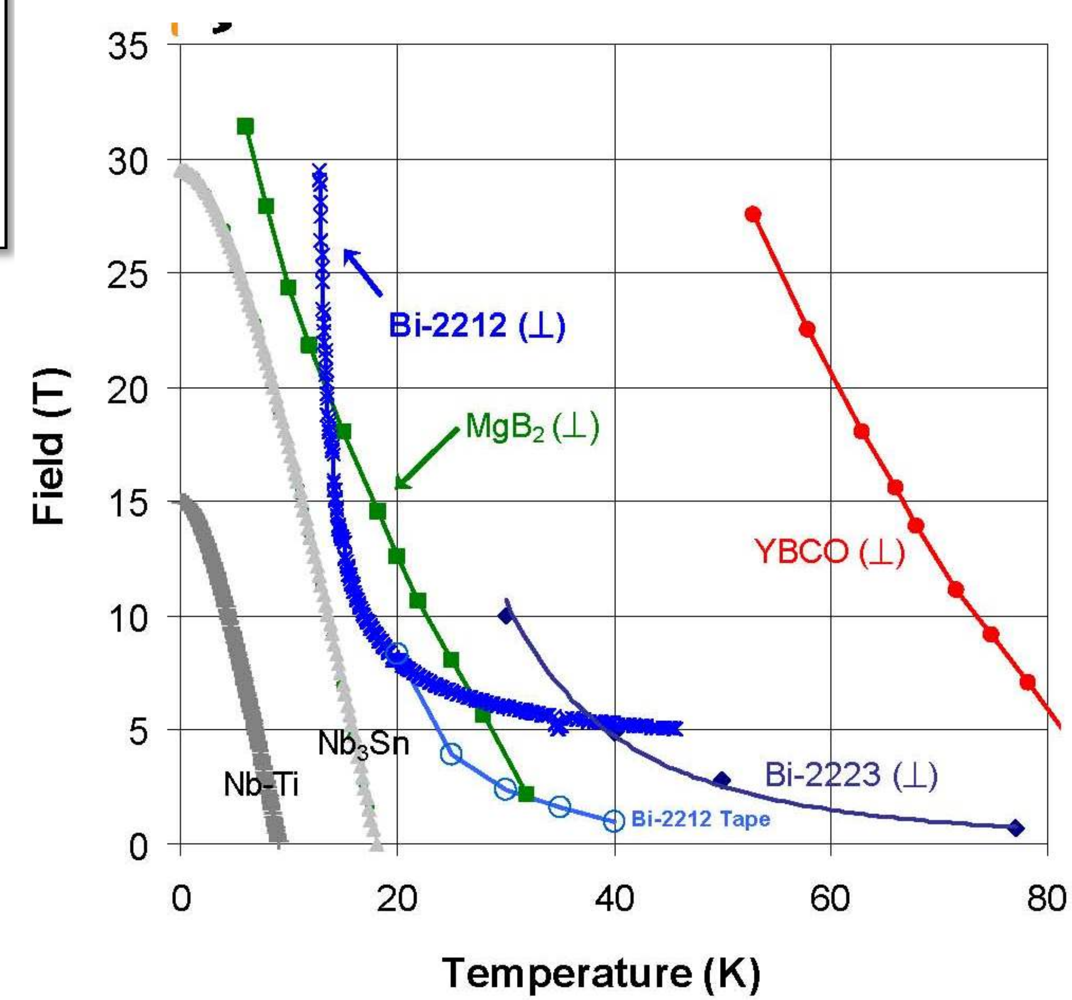




Magnetic Fields, Currents & Temperature

- Superconducting state depends on current density J_E, magnetic field and temperature





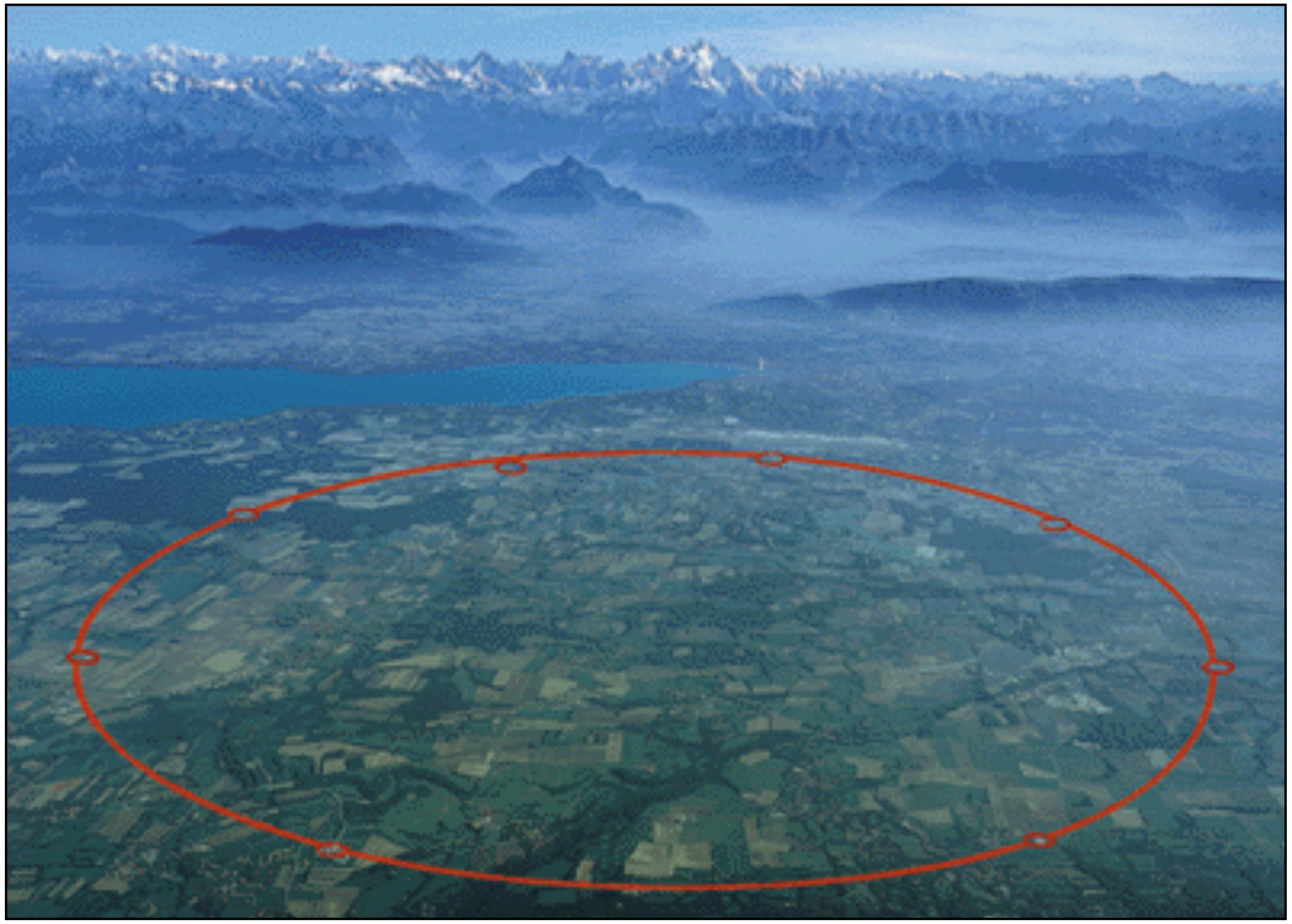
- => Prefer materials with high T_C, operated at low temperature

The Large Hadron Collider LHC

- Proton-proton collider in a 27 km tunnel at CERN

7 TeV 7 TeV

- Highest collision energies
- Highest luminosity

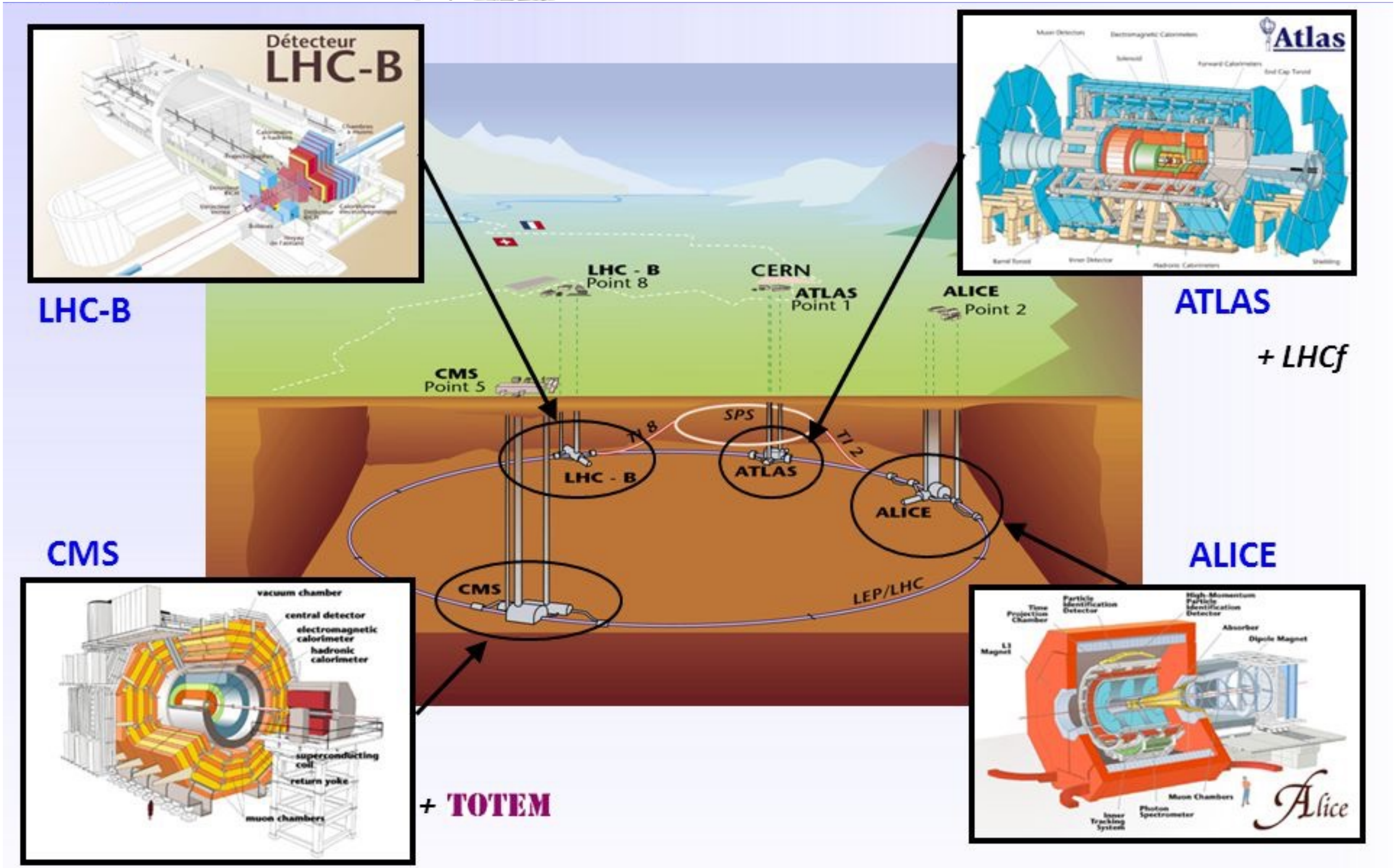


constructed & operated in collaboration with ~ 40 nations

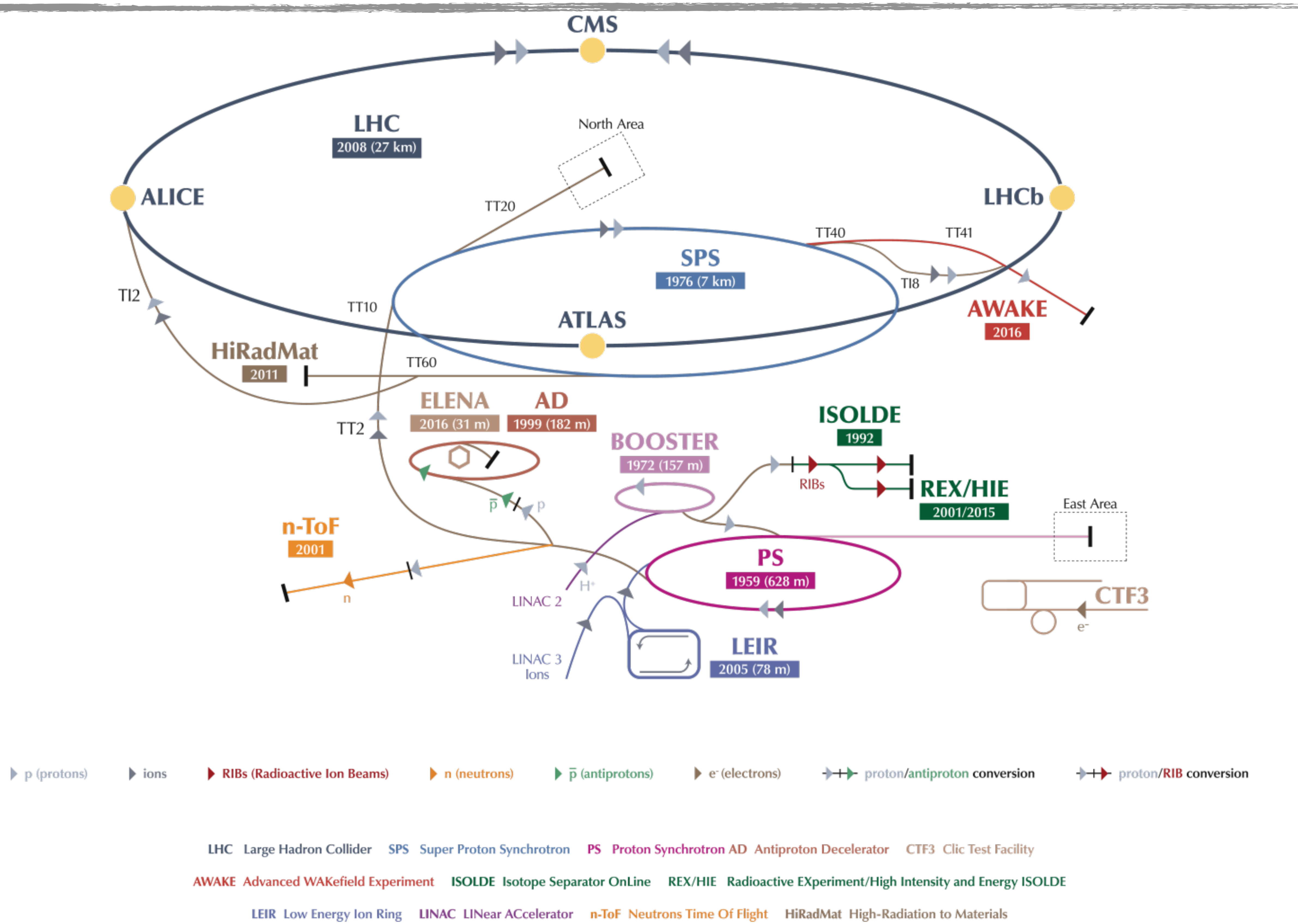
- 4 large experiments:
  - ATLAS & CMS (general purpose p+p)
  - ALICE (Heavy Ion collisions)
  - LHCb (heavy quark physics)

- Start of operations 2009 (originally planned for 2005), running until ~ 2035

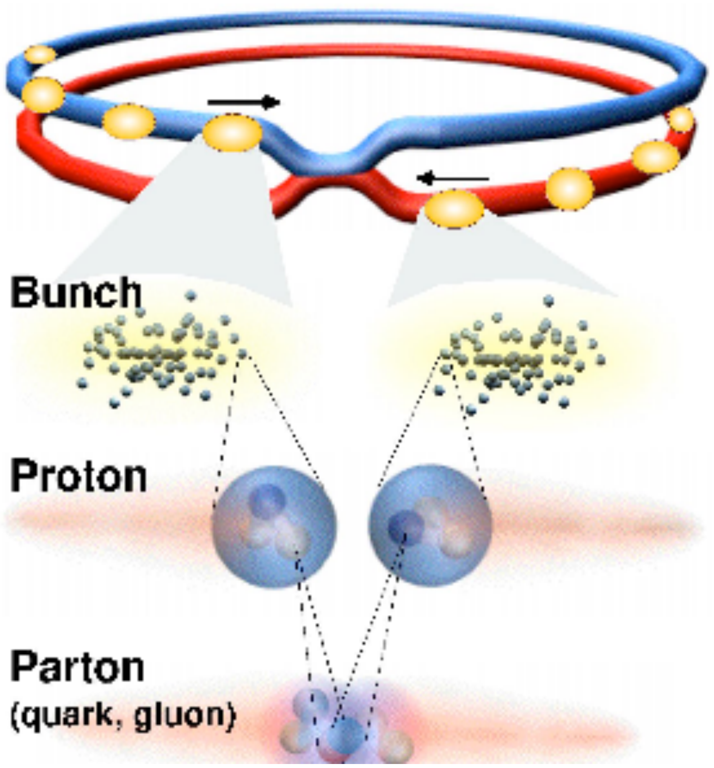
The LHC Complex at CERN

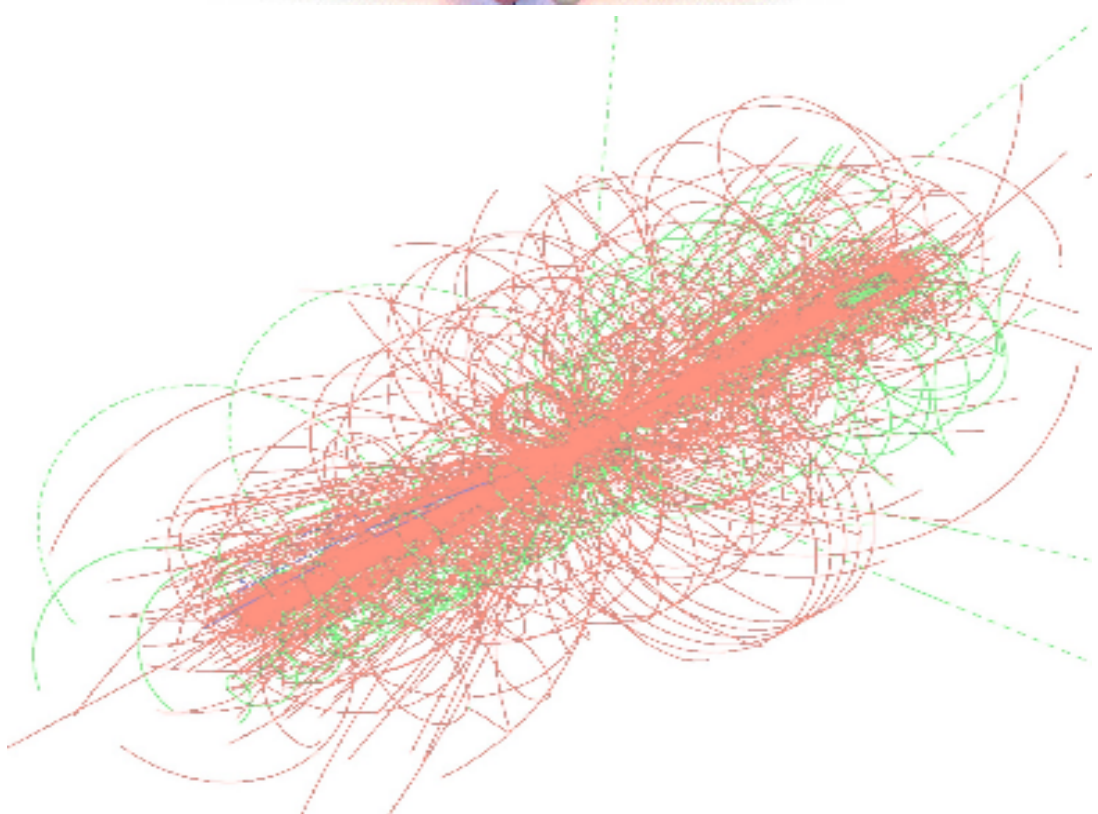


The Full CERN Accelerator Complex



LHC: Parameters





Proton – Proton collisions:

2835 x 2835 bunches
distance: 7.5 m   (25 ns)

10^{11} protons / bunch
collision rate: 40 million / second
Luminosity: L = 1034 cm-2 s-1

Proton-Proton collisions: ~10^9 / s
(pile-up of 20-30 pp-interactions
for each beam crossing)

~1600 charged particles in detector

⇒   highest demands on detectors

Production Cross Sections: Physics Expectations

$N_{events} / s = \sigma \times L$

$N_{events} = \sigma \times \int L \, dt$

1 nb = 10^{-33} cm^2

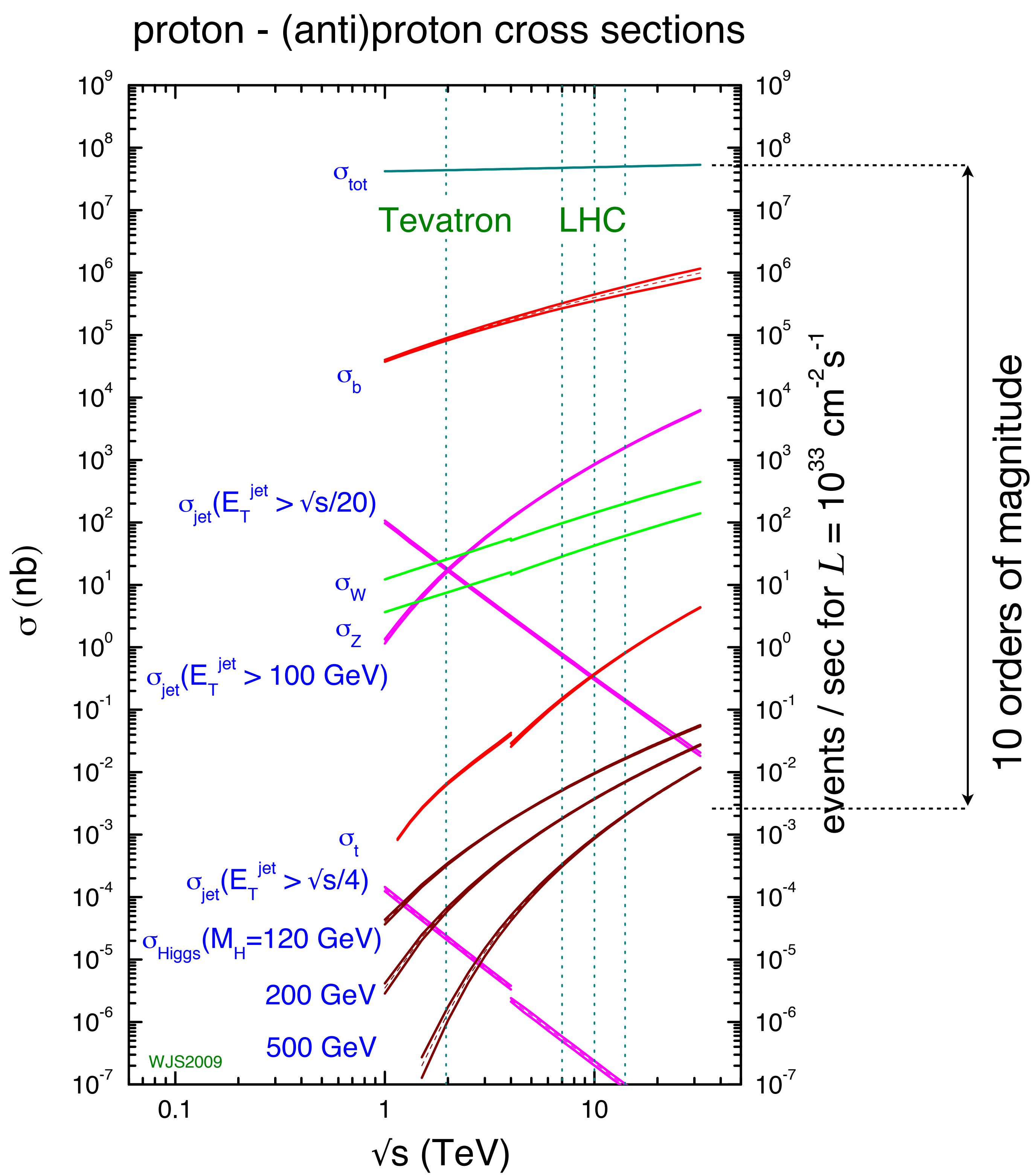
calculus (example):

End of 2010:
$\int L dt$ = 40 pb^{-1} = 40 x10^3 nb-1

corresp. to ~ 4 x10^3 top-quark-events (σ_t ~ 10^{-1} nb at 7 TeV)

corresp. to ~200 Higgs-evts. with M_H =120 GeV at 7 TeV

data sample 2011: ~ 5 fb^{-1}
data sample 2012: ~20 fb^{-1}
data sample 2015: ~4 fb^{-1}
data sample 2016: ~40 fb^{-1}
data sample 2017: ~50 fb^{-1}
data sample 2018: ~70 fb^{-1}



Production Rates at LHC

• Inelastic Proton-Proton collisions:	1 Billion / second
• Quark -Quark/Gluon scatterings with large transverse momenta (> 20 GeV)	~100 Millions/ sec
• b-Quark pairs	5 Millions / sec
• top-Quark pairs	8 / sec
• W → e ν	150 / sec
• Z → e e	15 / sec
• Higgs (Mass = 150 GeV)	0.2 / sec
• Gluino, Squarks (Mass = 1 TeV)	0.03 / sec

- Interesting physics processes are extremely rare:
  ⇒ high luminosities !

extremely powerful detectors (to suppress background)

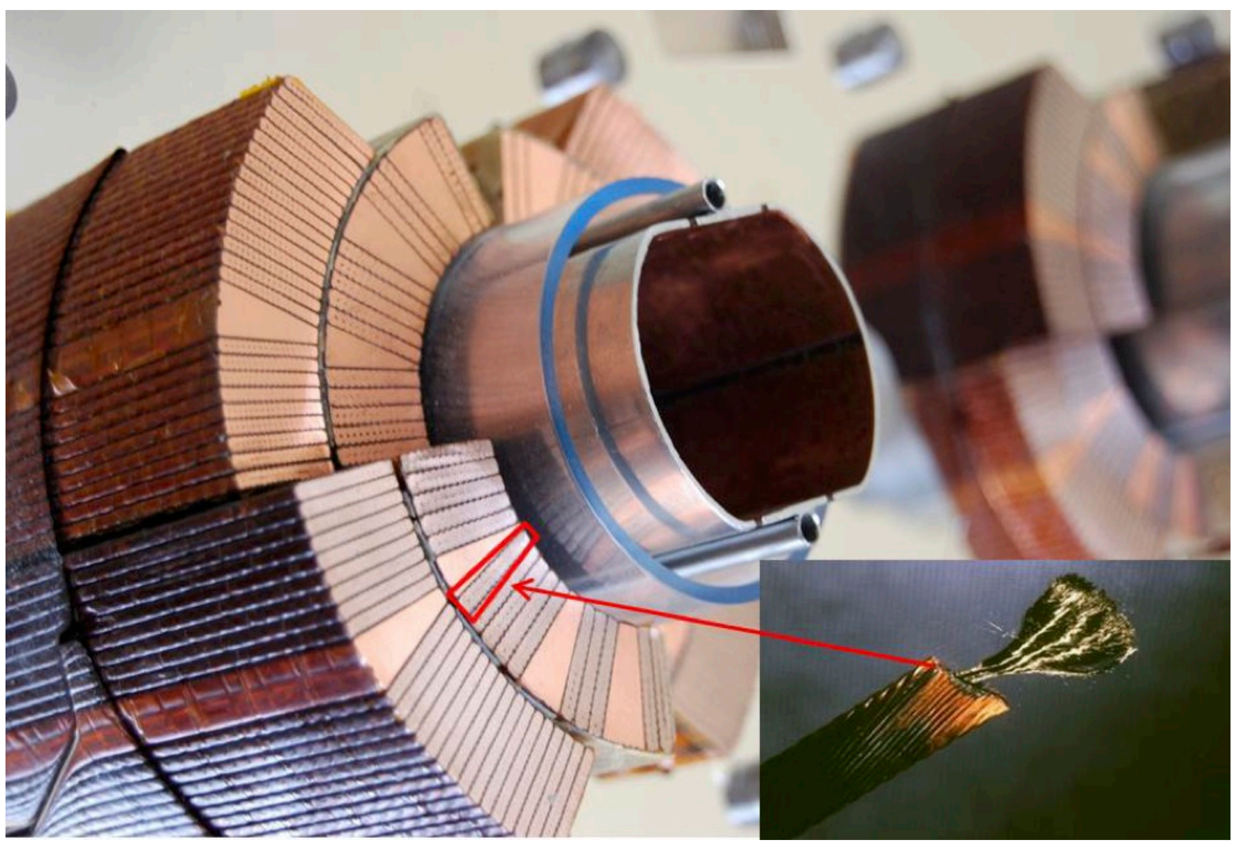
LHC Parameters: Technical Details

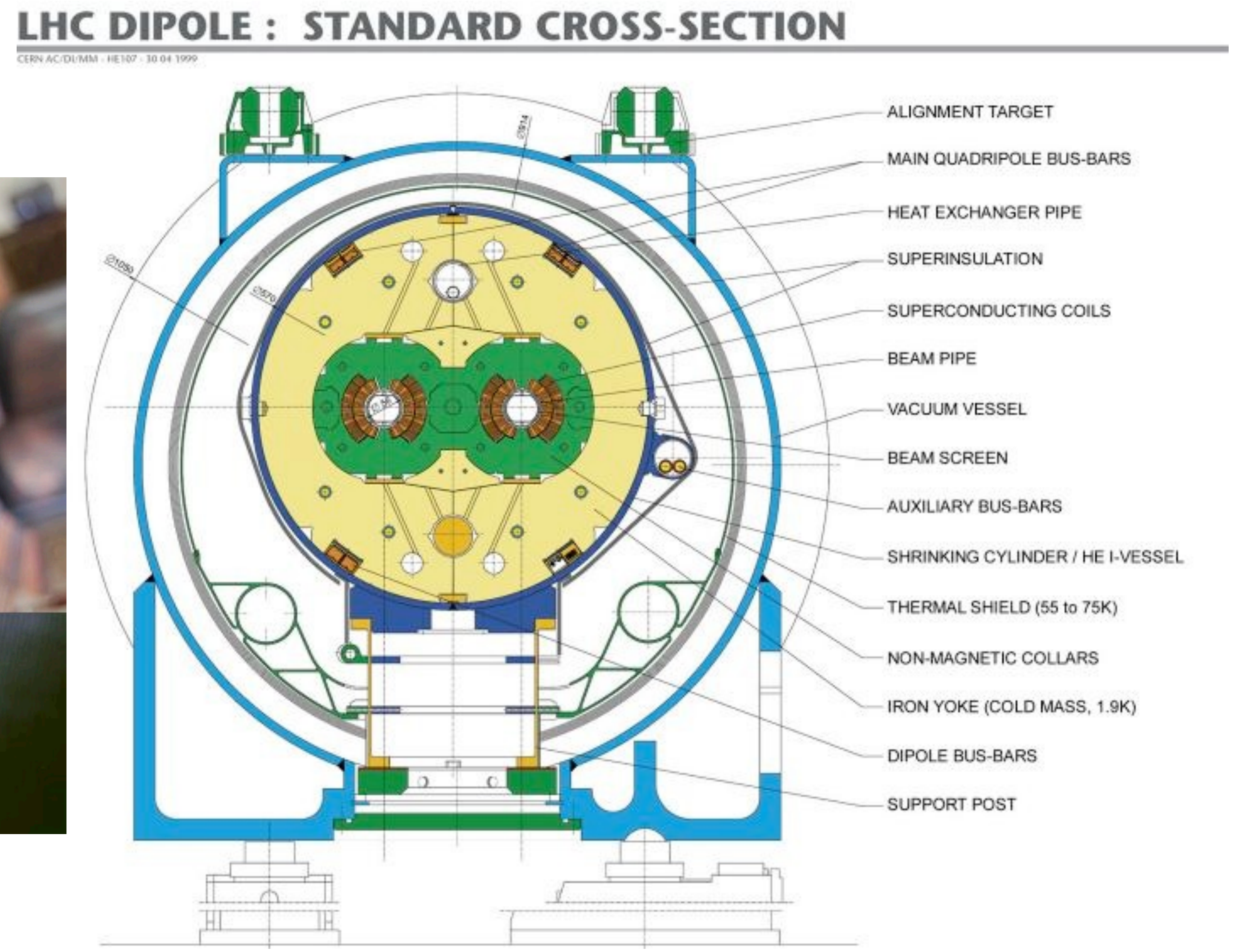
General LHC Parameters Version 4.0 (These parameters correspond to optics version 6.4 and the RF parameter update from the 14. LTC meeting (15. October 2003)) (the Version 3 parameters can be found here)		
Momentum at collision	7	TeV / c
Momentum at injection	450	GeV / c
Machine Circumference	26658.883	m
Revolution frequency	11.2455 (*)	kHz
Super-periodicity	1	
Lattice Type	FODO, 2-in-1	
Number of lattice cells per arc	23	
Number of insertions	8	
Number of experimental insertions	4	
Utility insertions	2 collimation 1 RF and 1 extraction	
Dipole field at 450 GeV	0.535	T
Dipole field at 7 TeV	8.33	T
Bending radius	2803.95	m
Main dipole coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Main Dipole Length	14.3	m
Main Dipole Ends	236.5	mm
Half Cell Length	53.45	m
Phase advance per cell	90	degree
Horizontal tune at injection	64.28	
Vertical tune at injection	59.31	
Horizontal tune at collision	64.31	
Vertical tune at collision	59.32	
Maximum beta-function (cell)	177 / 180 (**)	m
Minimum beta-function (cell)	30 / 30 (**)	m

Maximum dispersion (cell)	2.018 / 0.0 (**)	m
Maximum beta-function (service insertions)	594.5 / 609.3 (**)	m
Free space for detectors	+/-23	m
Gamma Transition	55.678	
Momentum Compaction	0.0003225 (**)	
Main RF System	400.8	MHz
Harmonic number	35640	
Voltage of 400 MHz RF system at 7 TeV	16	MV
Synchrotron frequency at 7 TeV	23.0	Hz
Bucket area at 7 TeV	7.91	eV.s
Bucket half-height at 7 TeV	3.56	10^{-4}
Voltage of 400 MHz RF system at 450 GeV	8	MV
Synchrotron frequency at 450 GeV (without 200 MHz RF)	63.7	Hz
Bucket area at 450 GeV	1.43	eV.s
Bucket half-height at 450 GeV	10	10^{-4}
Capture RF system	200.4	MHz

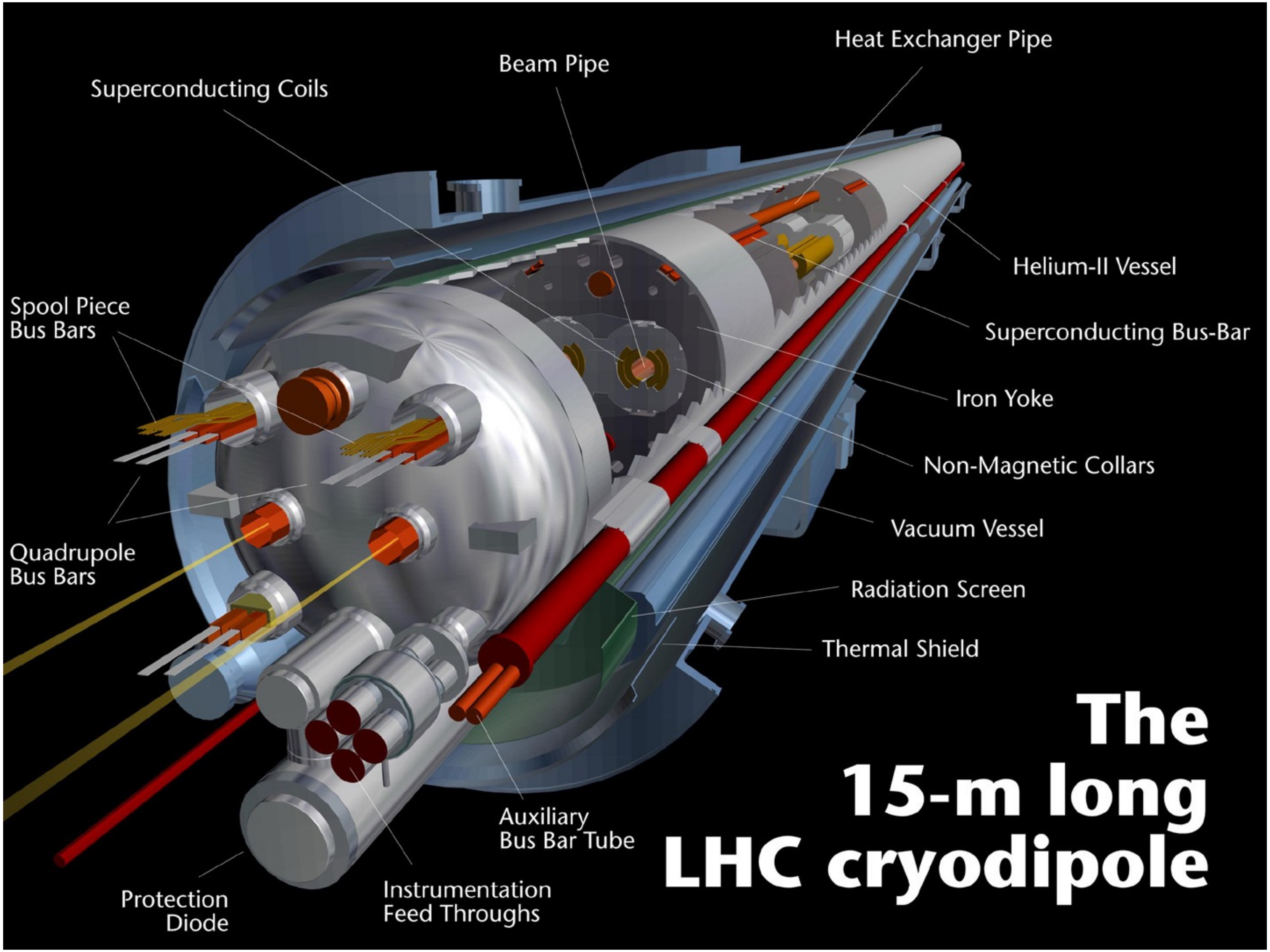
The LHC Magnets

- Superconducting main dipoles
  - biggest challenge: magnetic field of ~ 9 T
  - overall 1300 main dipoles, each 15 m long
  - operated at 1.9 K (superfluid helium)





The LHC Magnets

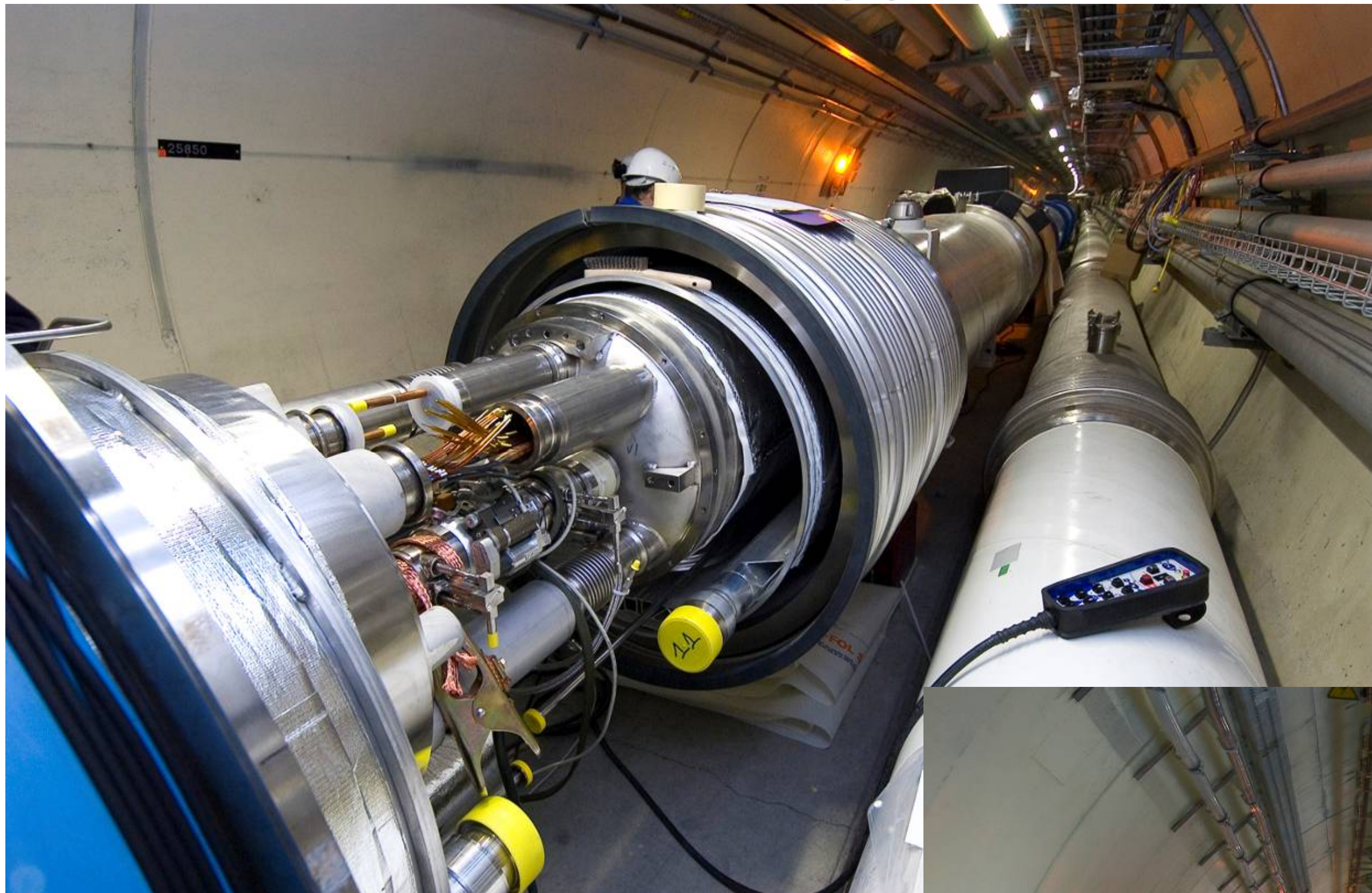


LHC Installation

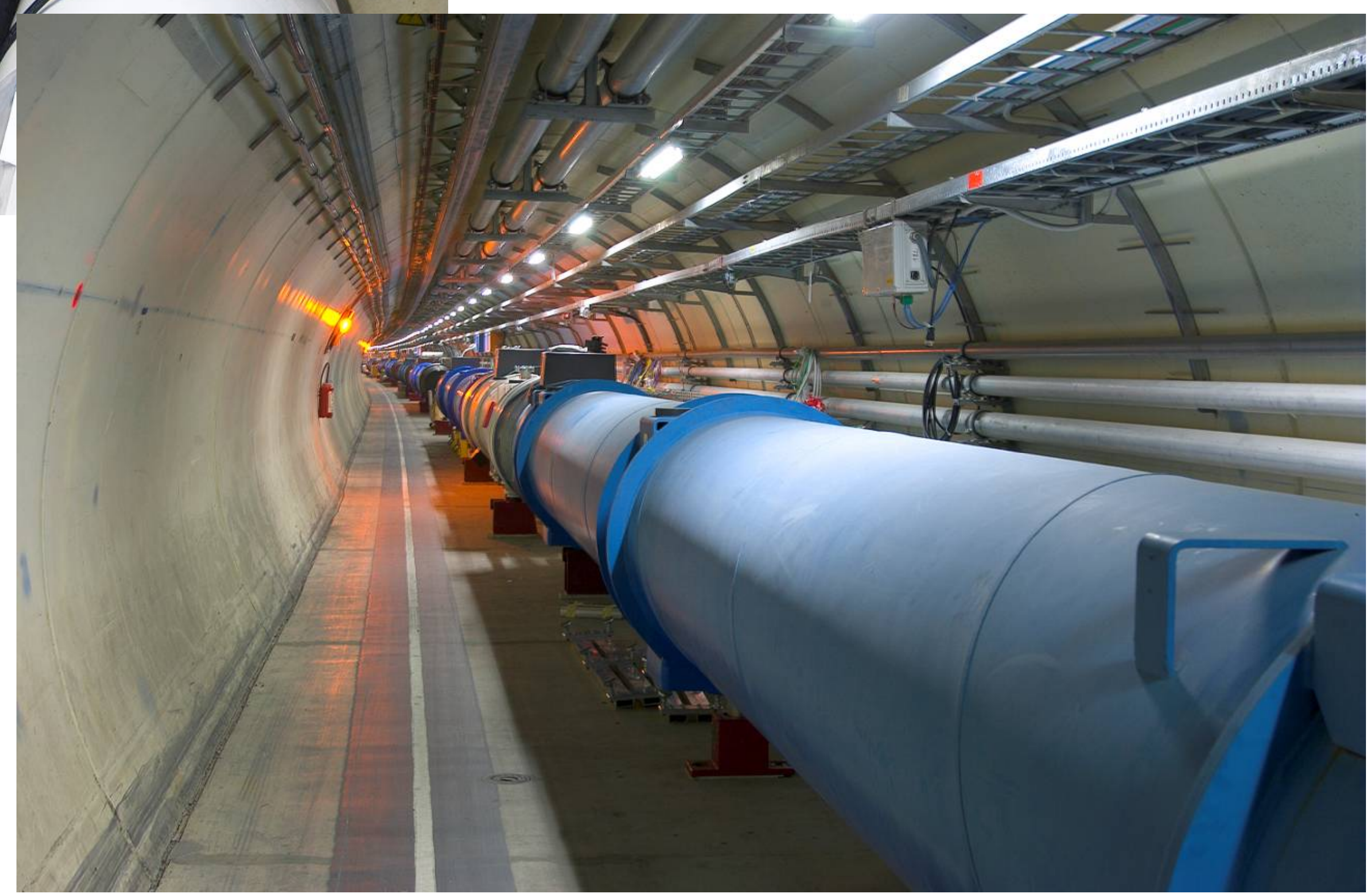
Lowering of the first dipole into the tunnel (March 2005)

Installation of dipoles in the LHC ring

LHC Installation



Interconnection of the dipoles and connection to the cryoline



A view of the tunnel…

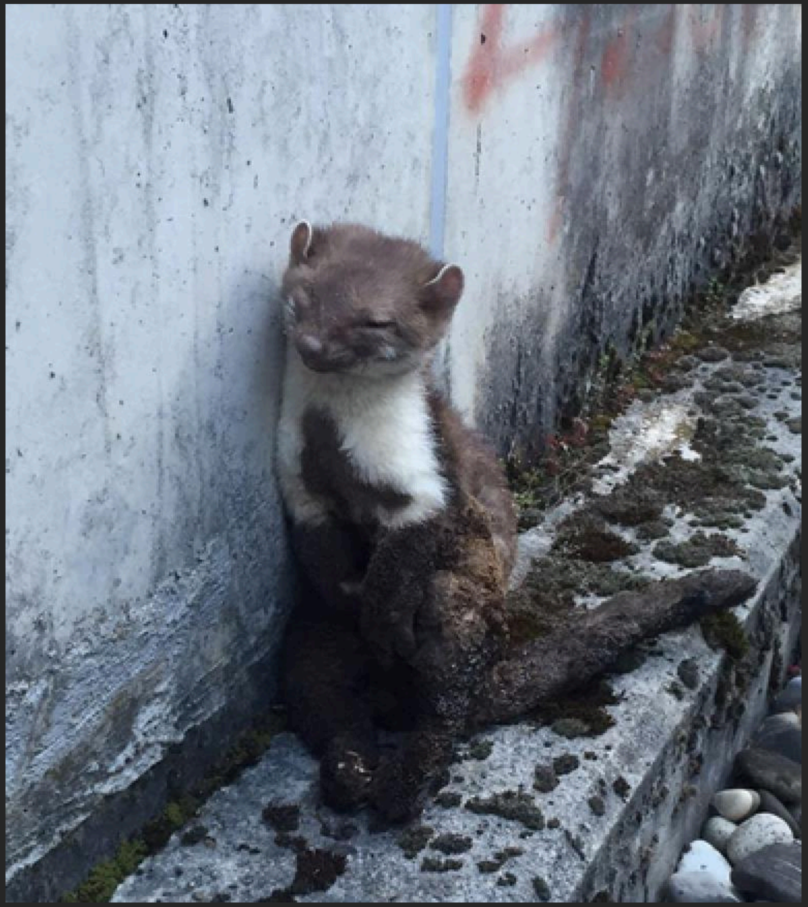
LHC Installation

LHC Status

- 09.09.2008: first stable „beam“ in LHC
- 19.09.2008: technical problems with large impact:
  destruction of parts of LHC ring; repair of ~1 Jahr.
- 20.11.2009: restart after repair; first collisions!
- 11.12.2009: world record: collisions at 2.36 TeV! (2·1.18 TeV)
- 30.03.2010: collisions at 7 TeV (2 · 3.5 TeV)
- Nov. 2011: 5 fb-1 at 7 TeV per experiment
- 2012: - collisions at 8 TeV
  - until Dec: ~20 fb-1
  - 4. July 2012: a new Boson ...
- 2013/14: long shut-down (LS1);
- 2015: operation at 13 TeV; 25 ns bunch spacing

LHC Operations: Always an Adventure

WEASEL

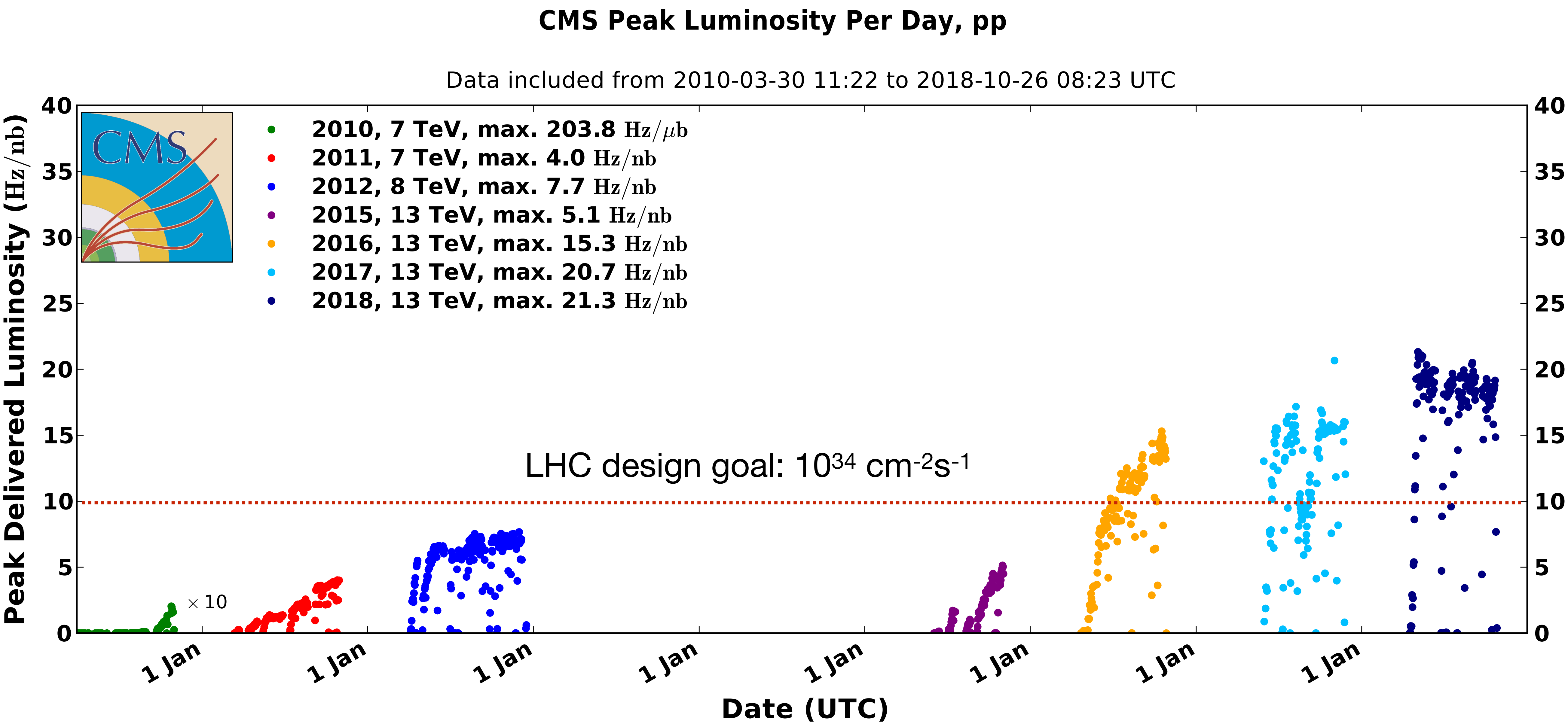


PS MAIN POWER SUPPLY

SPS BEAM DUMP

- Limited to 96 bunches per injection
- 2076 bunches per beam cf. 2750

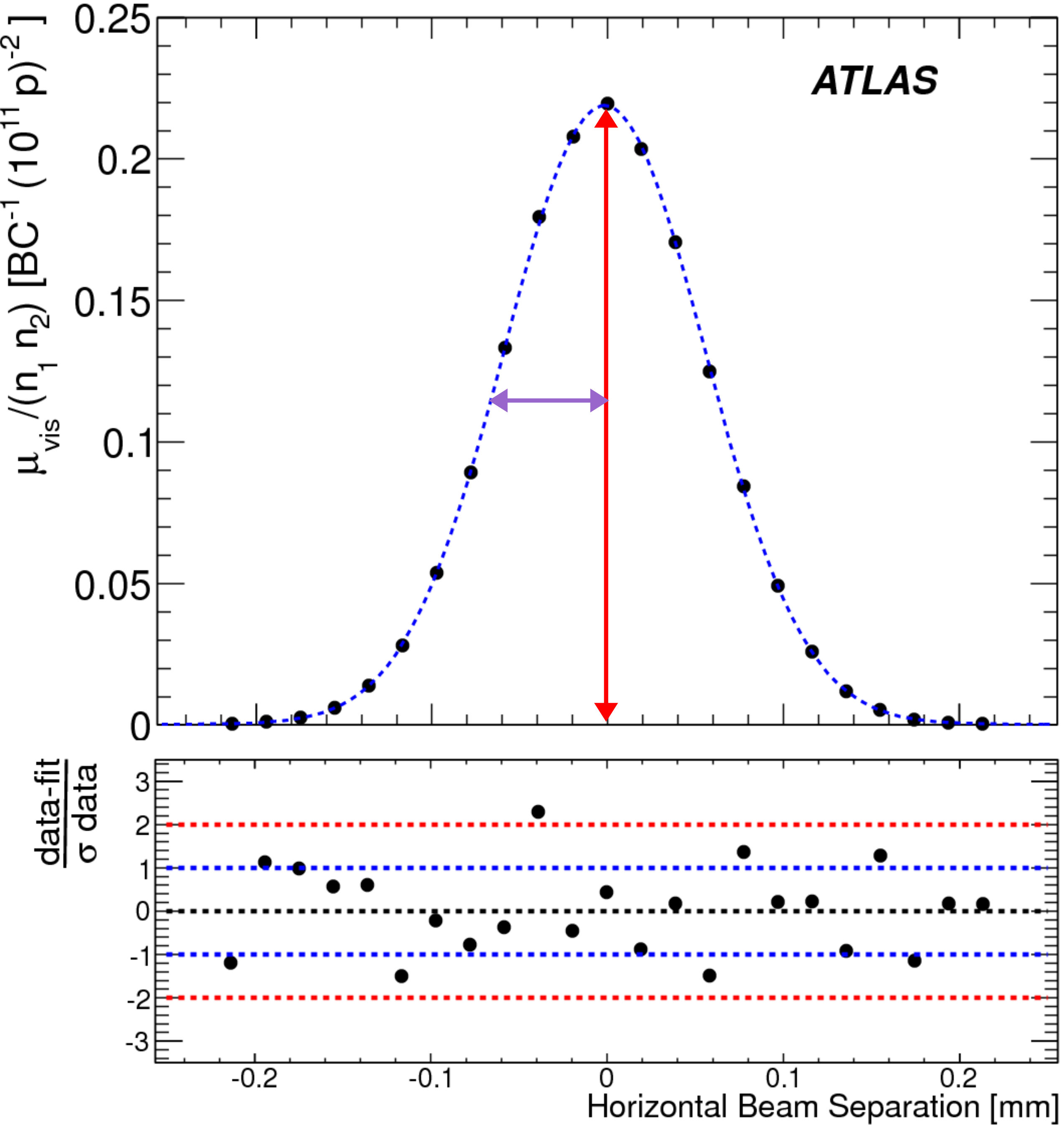
LHC Luminosity

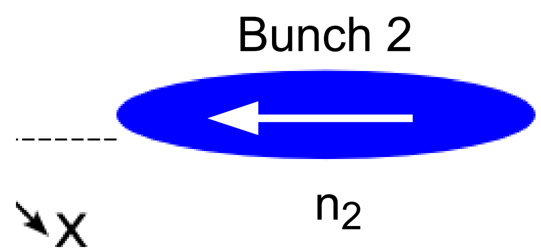


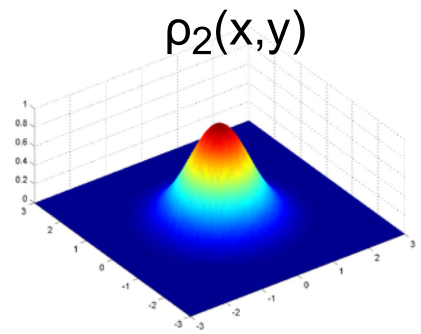
- Design luminosity reached end of June 2016

Measuring the Luminosity

- Different techniques in use - the most “basic” one: Van der Meer - Scans







$$\rho_2(x,y)\,dxdy = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

number of bunches

revolution frequency

no. of protons per bunch

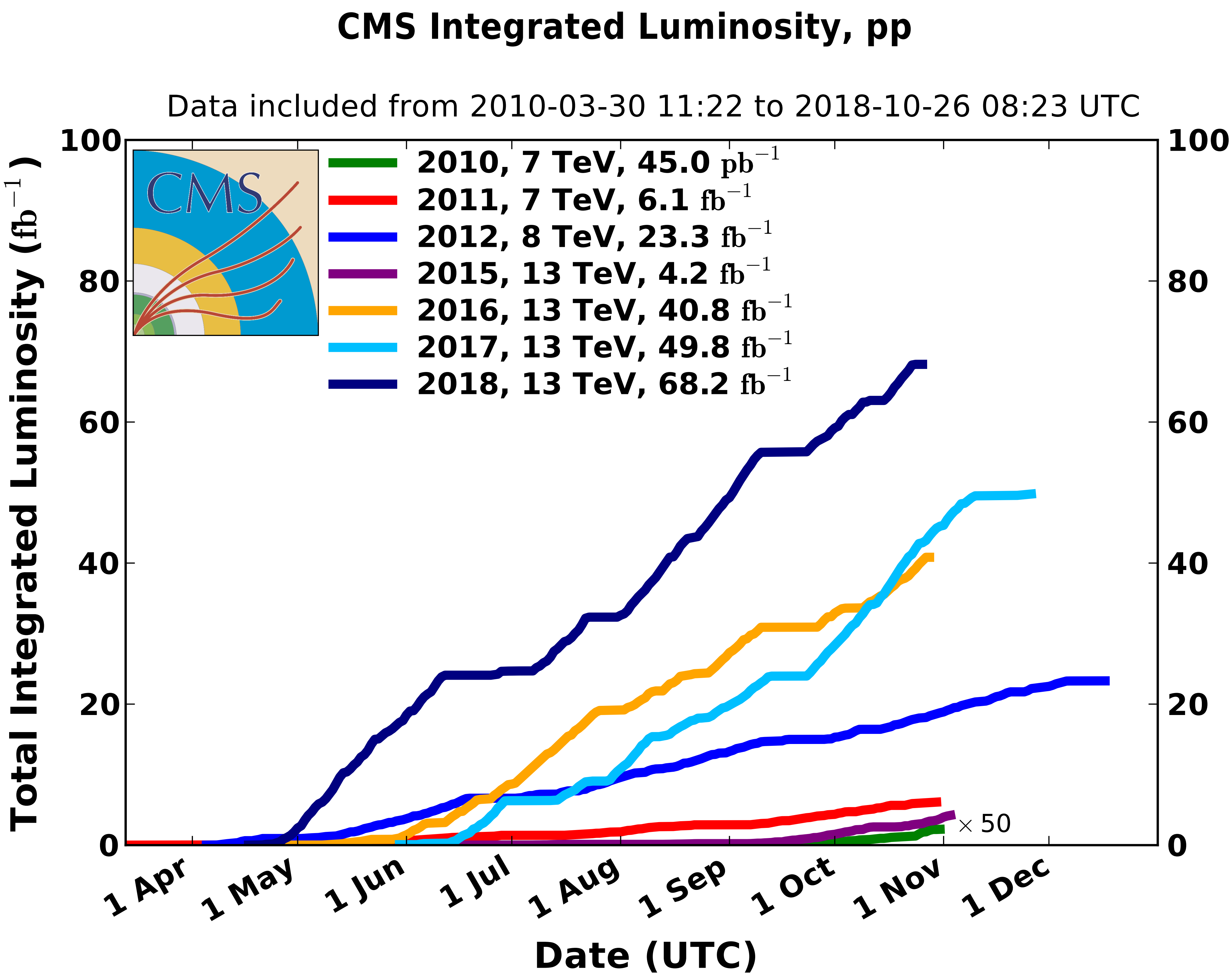
beam width

Scan determines beam width

bunch population from external measurement

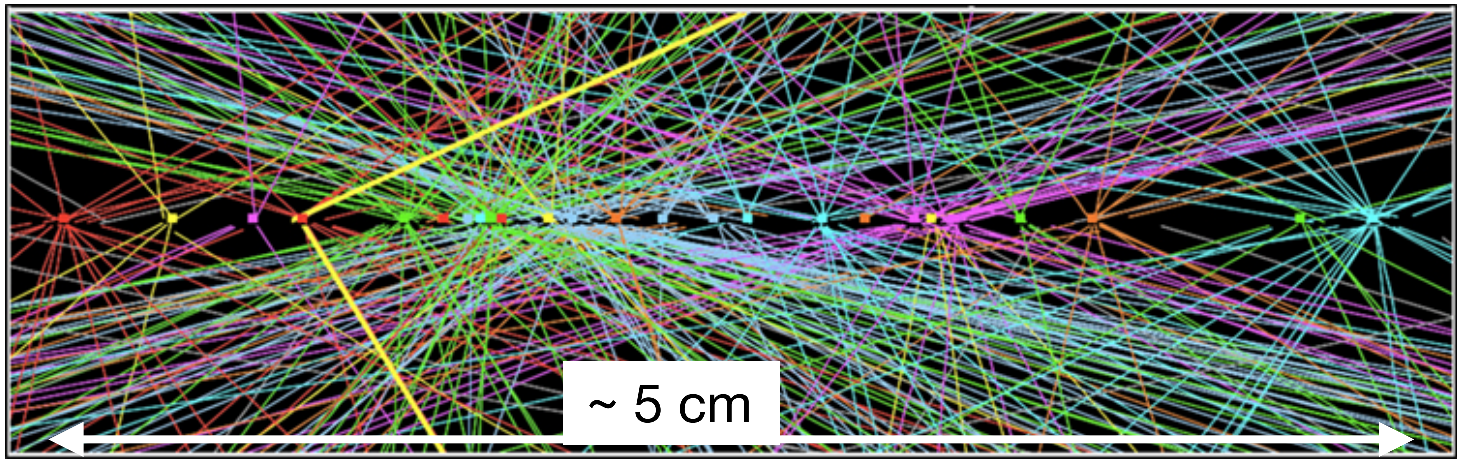
Accuracy on the 2% level

LHC Integrated Luminosity

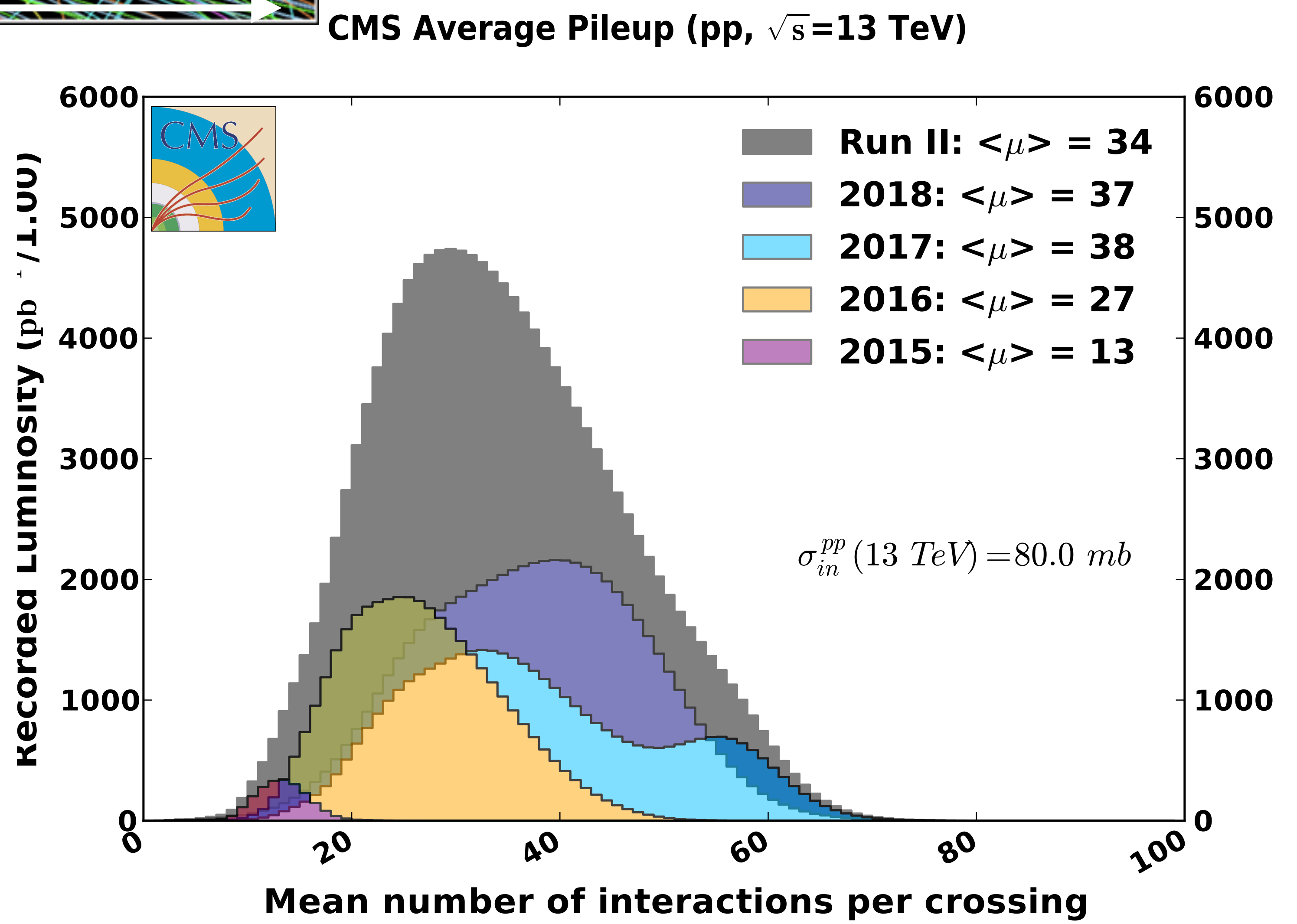


A Consequence: Pile-Up

- High luminosity results in multiple interactions per bunch crossing

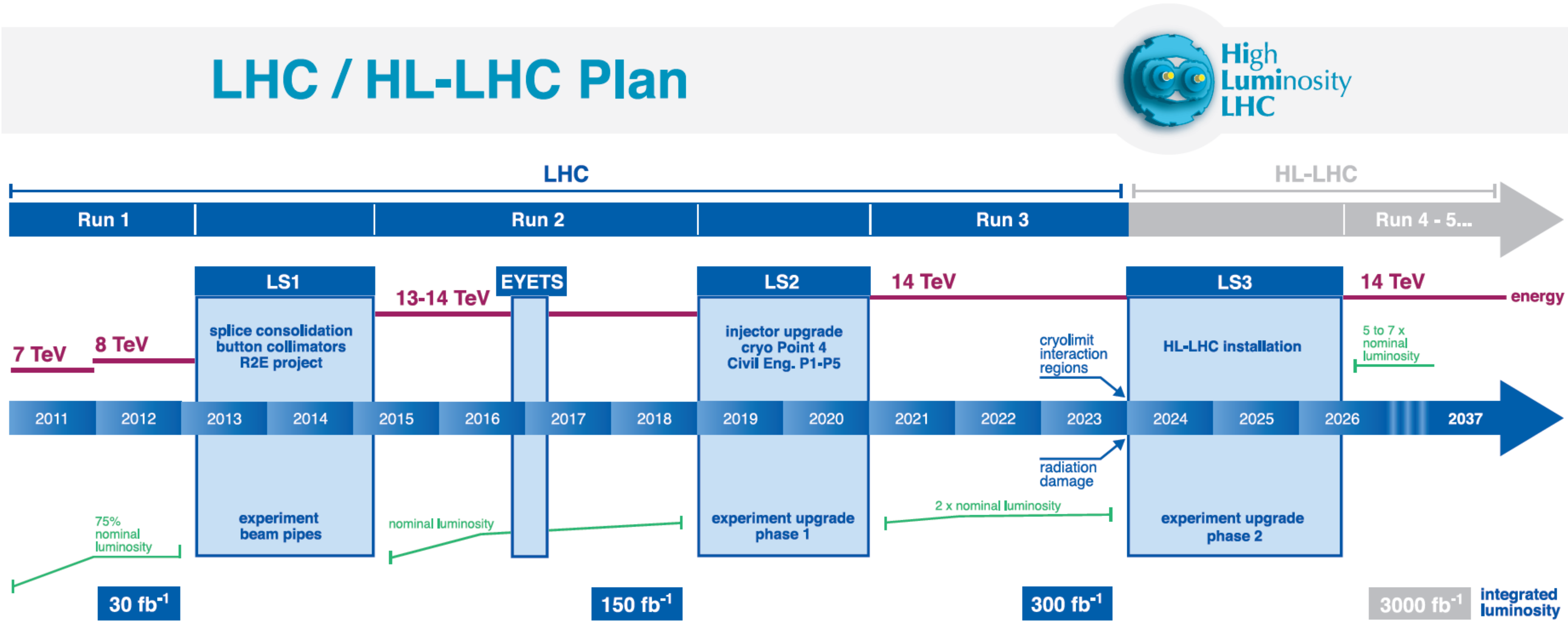


Example: Z->μμ process, in an event with 25 reconstructed interaction vertices



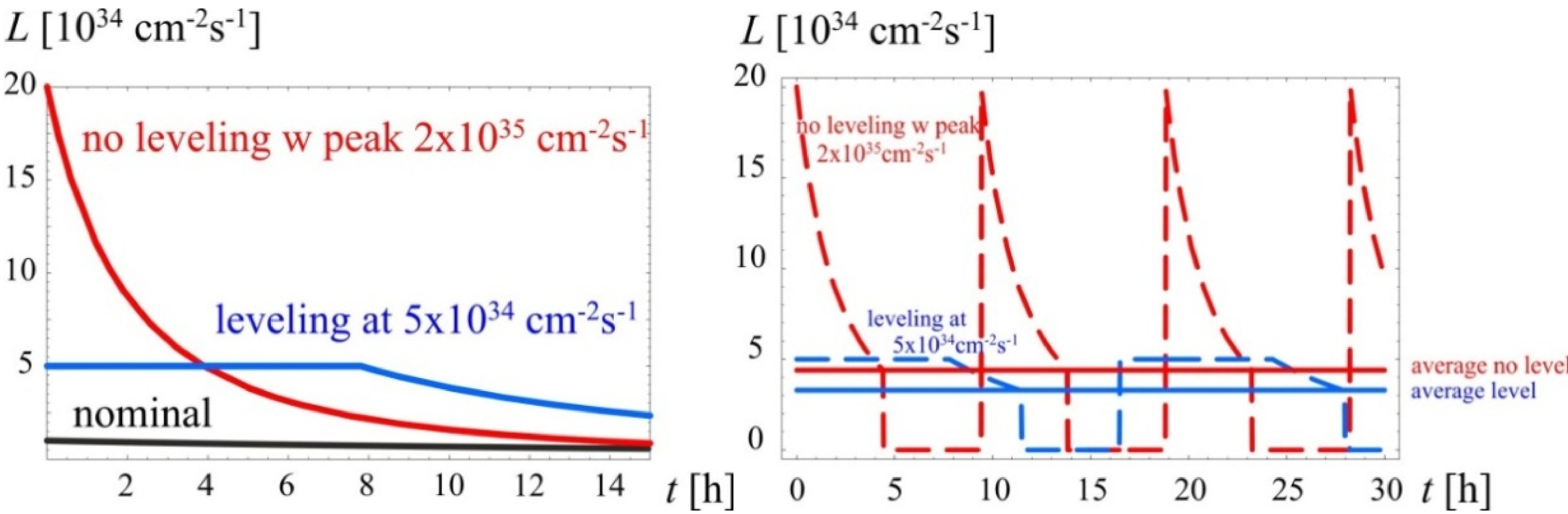
Remember Lecture 4:
large total cross section, small cross section for "interesting" processes

LHC Long Term Plan



HL-LHC: Luminosity Levelling

- A key “feature” to limit excessive pileup: Luminosity leveling



- Allows longer running at high luminosity per fill, only mild impact on average luminosity, with substantial gain in terms of experimental conditions

Novel Acceleration Techniques

- For linear accelerators (the only way to accelerate electrons to energies > 200 GeV) the acceleration gradient is key: A main driver for the length of the overall collider complex
  - “Conventional” acceleration structures (normal-conducting Cu or SCRF cavities) are limited to ~ < 100 MV/m: (significantly) more than 10 km accelerator per TeV!

- Higher gradients are possible if one can “side step” the breakdown limits of the acceleration structures: *Use plasmas as accelerators.*

=> Journal Club!

Summary

- Accelerators are key instruments in particle physics - with many applications beyond fundamental research
- Proton synchrotrons in “collider mode” reach the highest energies - limited by accelerator radius and main dipole field
- The Large Hadron Collider LHC is the current energy record holder - and has now exceeded its design luminosity
  - Physics program with luminosity upgrade extending to 2037

Next Lecture: The Universe as a High Energy Laboratory: CMB,
B. Majorovits, 09.12.2019

Lecture Overview

14.10.	Introduction, Particle Physics Refresher	*F. Simon*
21.10.	Introduction to Cosmology I	*B. Majorovits*
28.10.	Introduction to Cosmology II	*B. Majorovits*
04.11.	Particle Collisions at High Energy	*F. Simon*
11.11.	The Higgs Boson	*F. Simon*
18.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
25.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
02.12.	Particle Colliders	*F. Simon*
09.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
16.12.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
	Christmas Break	
13.01.	Detectors for Particle Colliders	*F. Simon*
20.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
27.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
03.02.	Physics beyond the Standard Model in the Early Universe	*B. Majorovits*