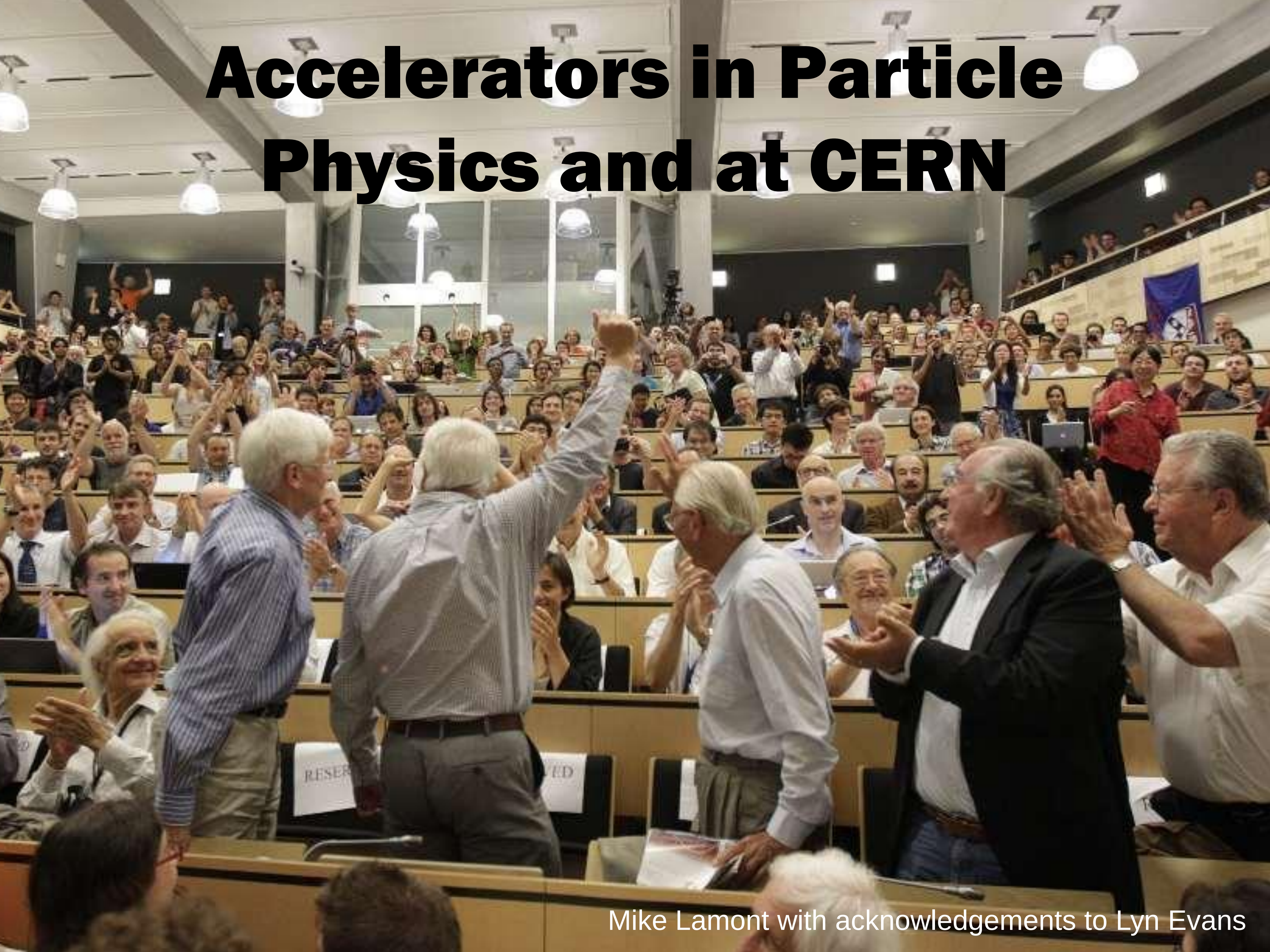
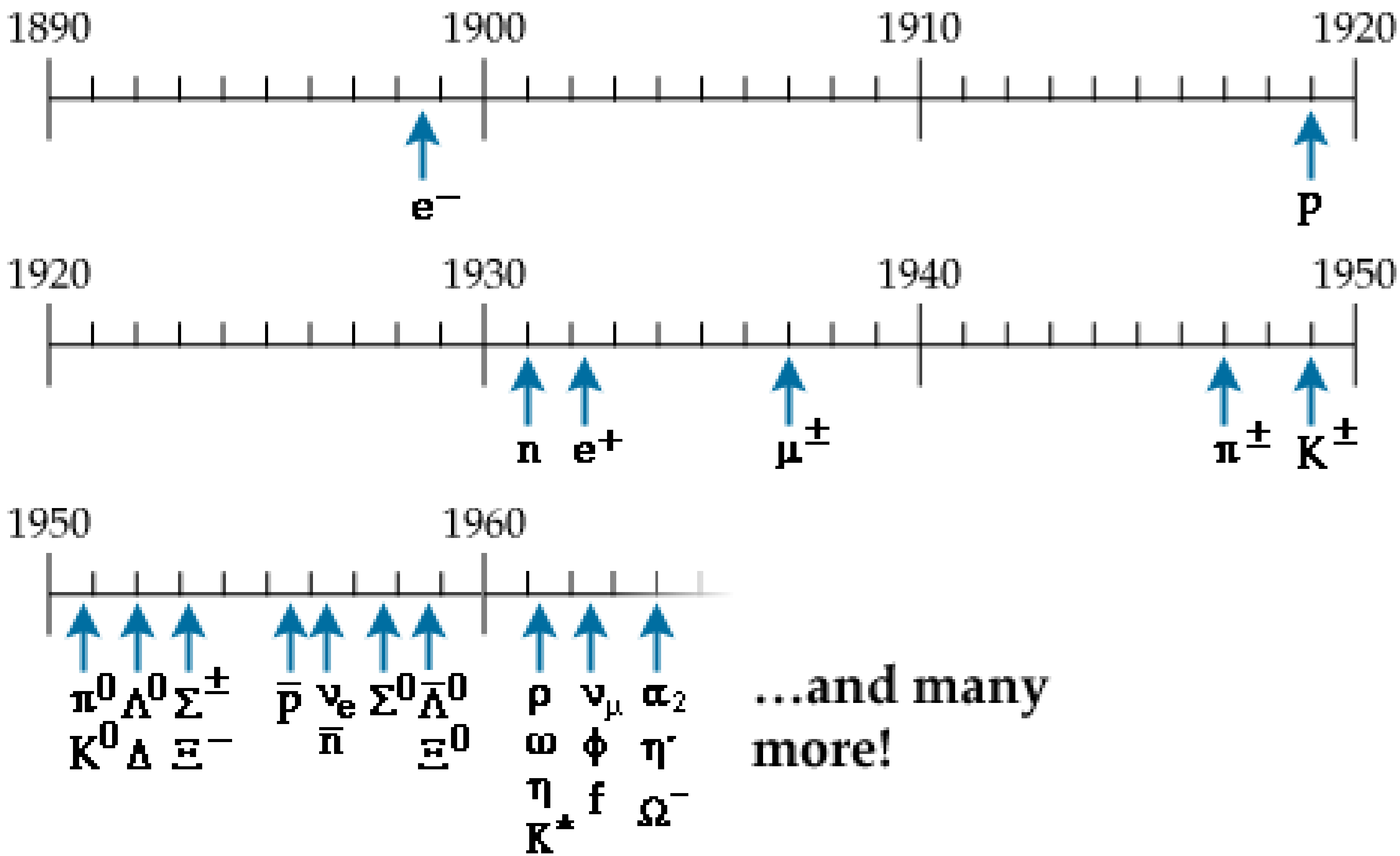
Accelerators in Particle Physics and at CERN



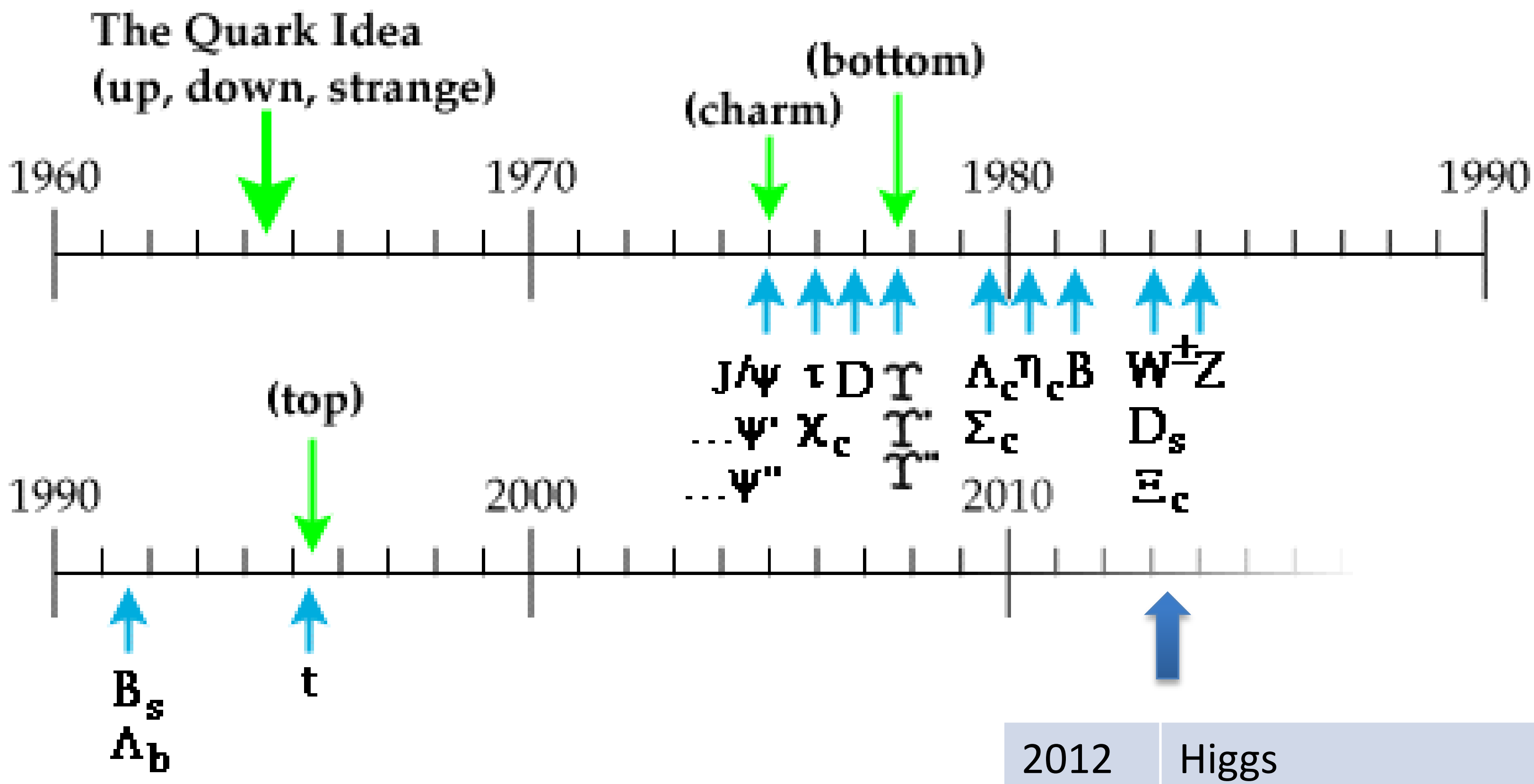
Mike Lamont with acknowledgements to Lyn Evans

Particles discovered 1898 - 1964



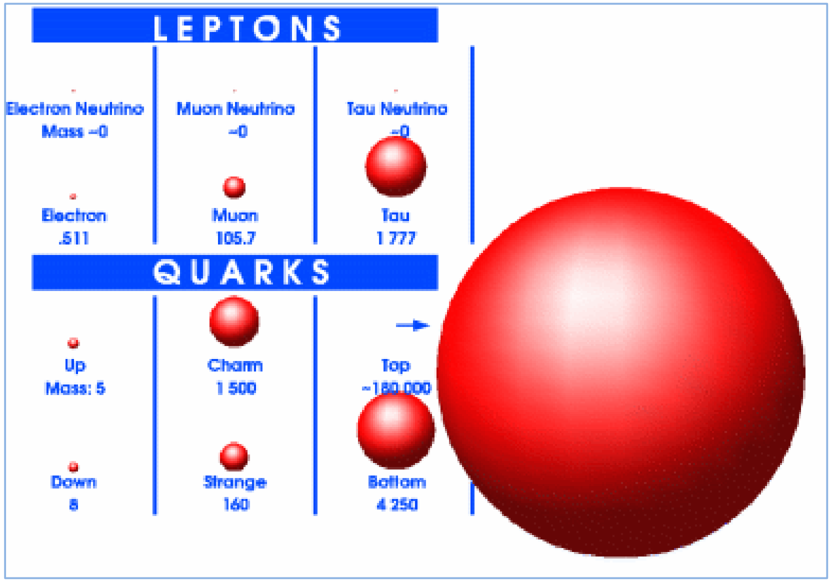
Cosmic rays Accelerators

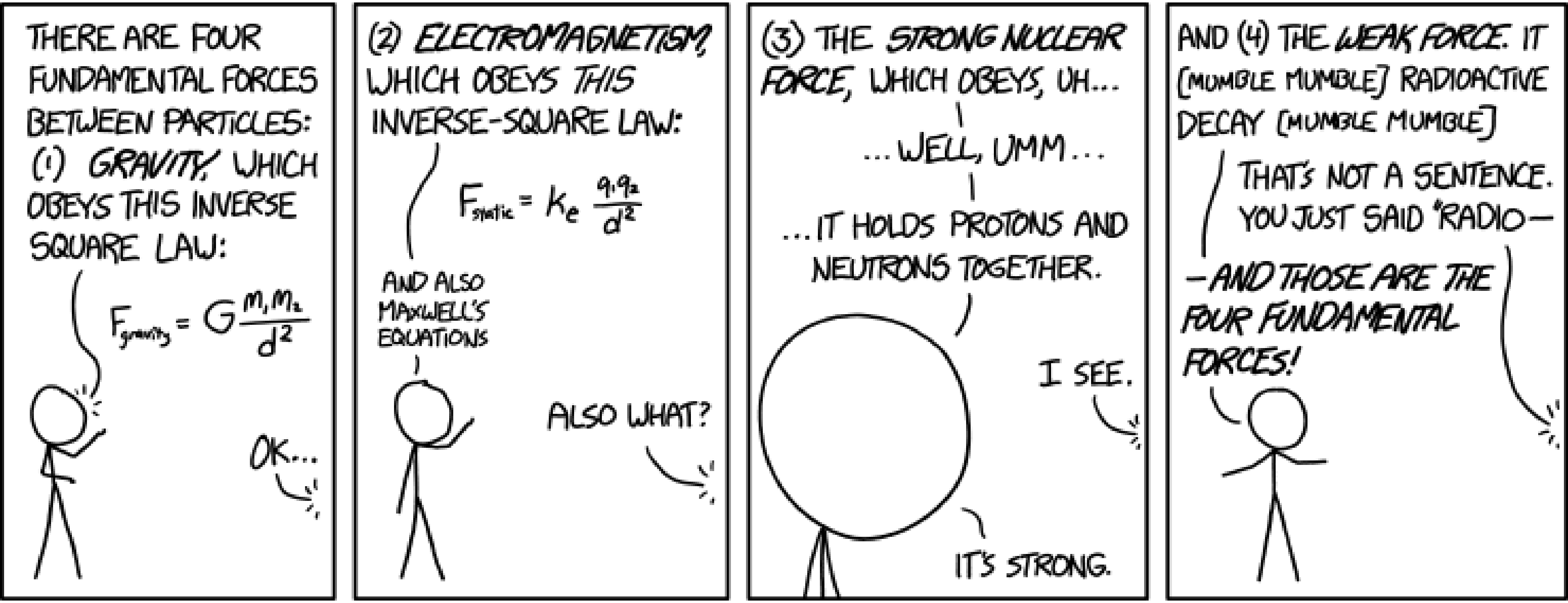
Particles discovered 1964 - present:



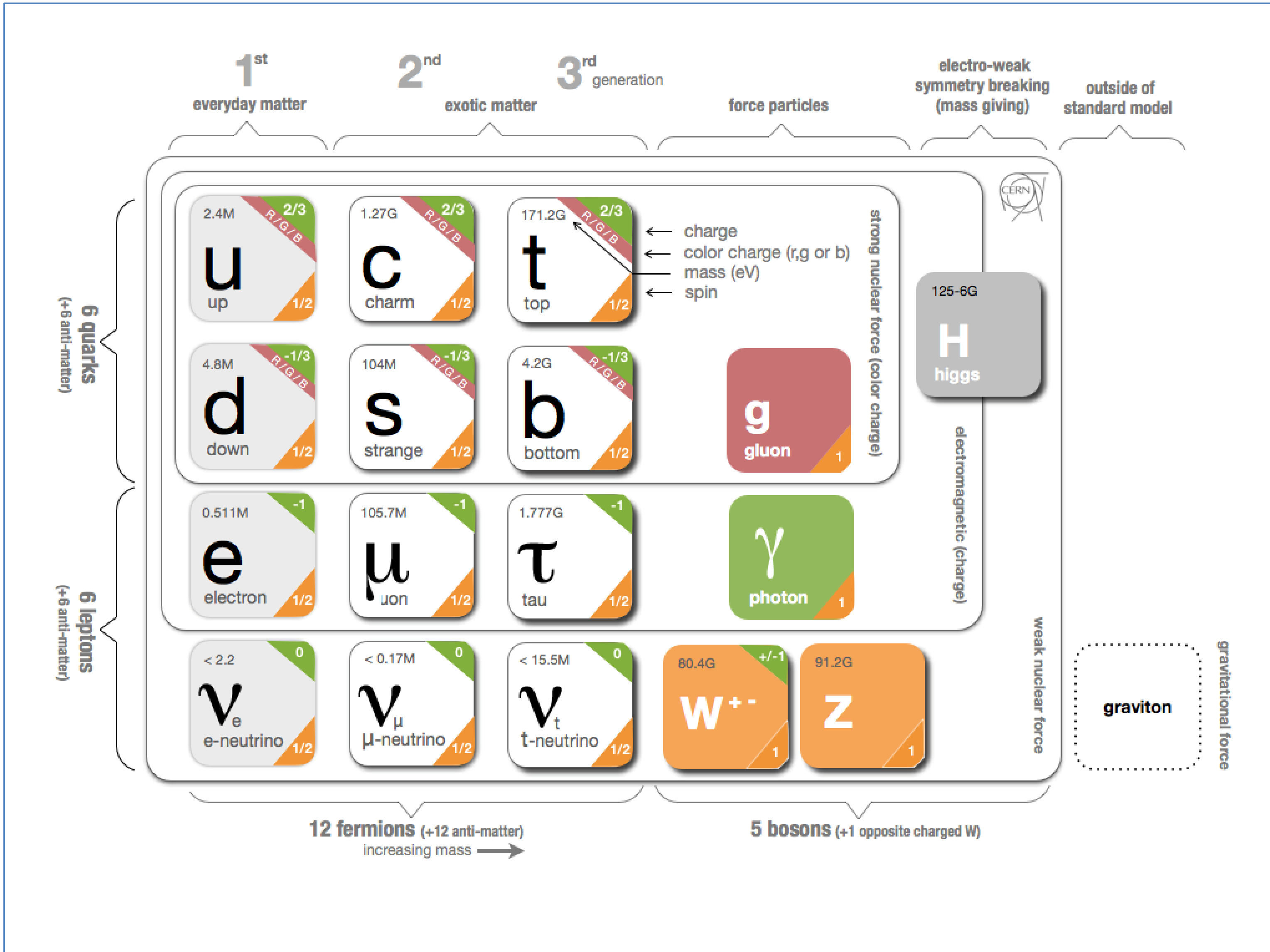
2012	Higgs
2015	Pentaquark

There is still a huge amount going on out there!

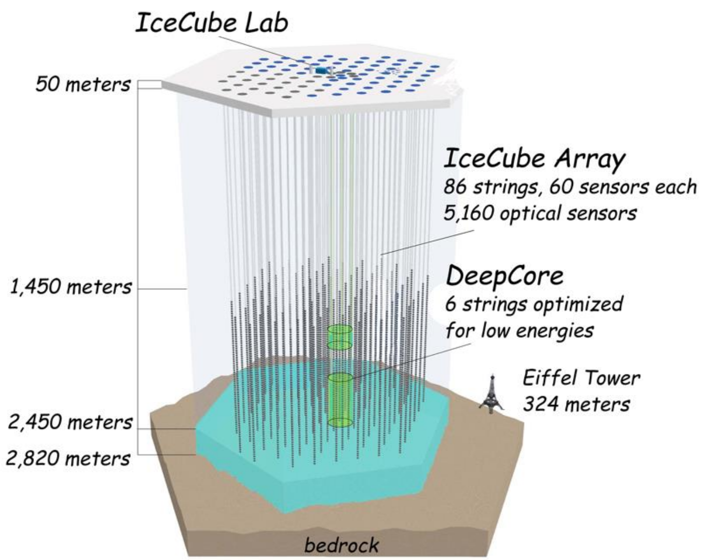

LEPTONS
Electron Neutrino
Mass ~0
Muon Neutrino
~0
Tau Neutrino
~0
Electron
.511
Muon
105.7
Tau
1 777
QUARKS
Up
Mass: 5
Charm
1 500
Top
~180 000
Down
8
Strange
160
Bottom
4 250

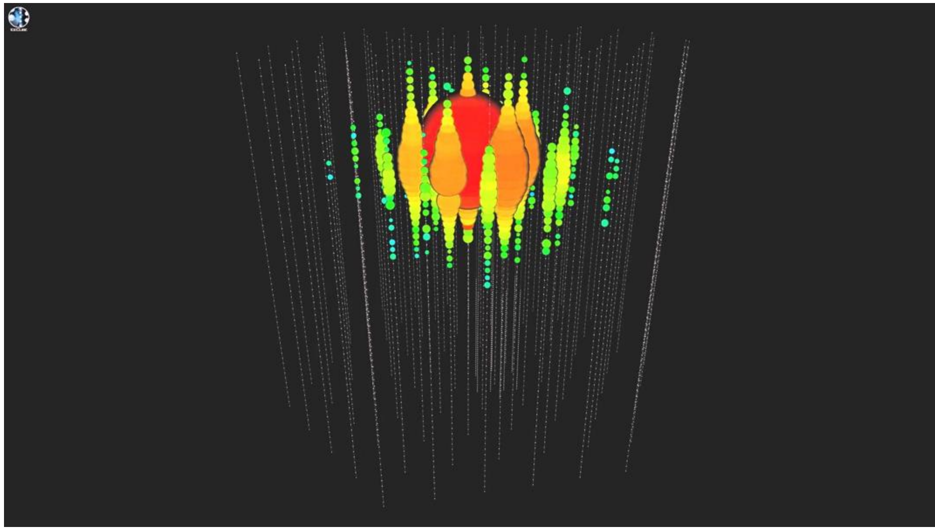

THERE ARE FOUR FUNDAMENTAL FORCES BETWEEN PARTICLES: (1) GRAVITY, WHICH OBEYS THIS INVERSE SQUARE LAW:
$F_{gravity} = G\frac{m_1 m_2}{d^2}$
OK...
(2) ELECTROMAGNETISM, WHICH OBEYS THIS INVERSE-SQUARE LAW:
$F_{static} = k_e \frac{q_1 q_2}{d^2}$
AND ALSO MAXWELL'S EQUATIONS
ALSO WHAT?
(3) THE STRONG NUCLEAR FORCE, WHICH OBEYS, UH...
...WELL, UMM...
...IT HOLDS PROTONS AND NEUTRONS TOGETHER.
I SEE.
IT'S STRONG.
AND (4) THE WEAK FORCE. IT [MUMBLE MUMBLE] RADIOACTIVE DECAY [MUMBLE MUMBLE]
THAT'S NOT A SENTENCE. YOU JUST SAID "RADIO—
—AND THOSE ARE THE FOUR FUNDAMENTAL FORCES!

Cracks? Dark matter?

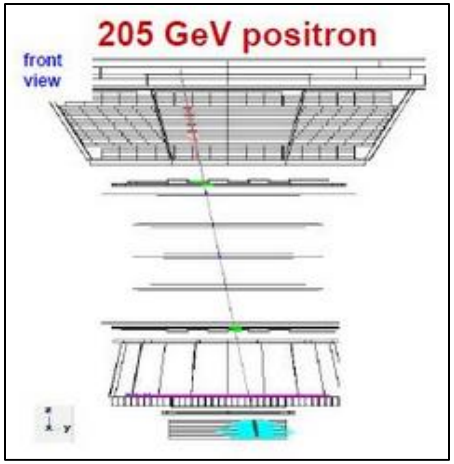


Cosmic acceleration

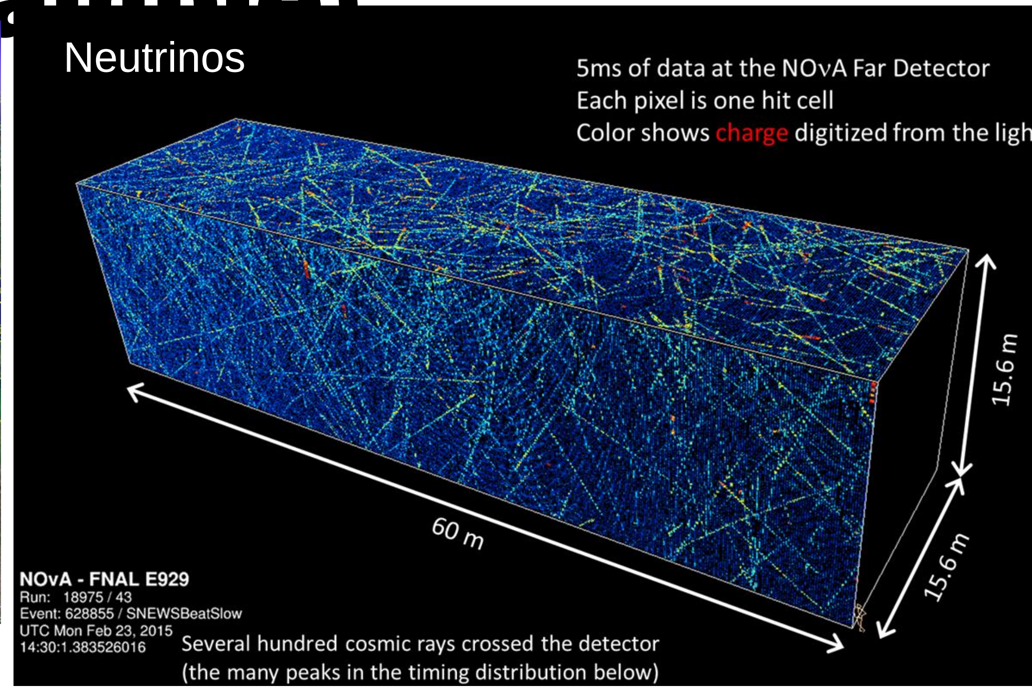




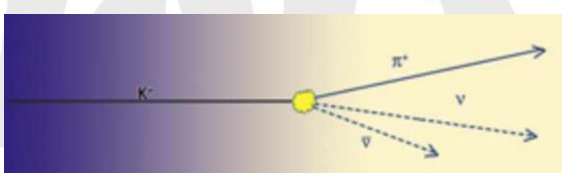
2 PeV neutrino "Big Bird"

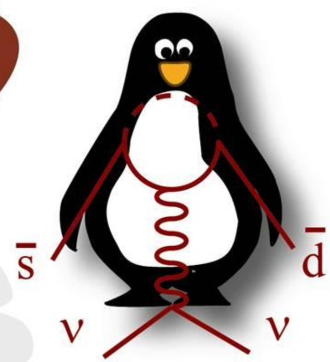


More traditionally (for example)



NA62 P326

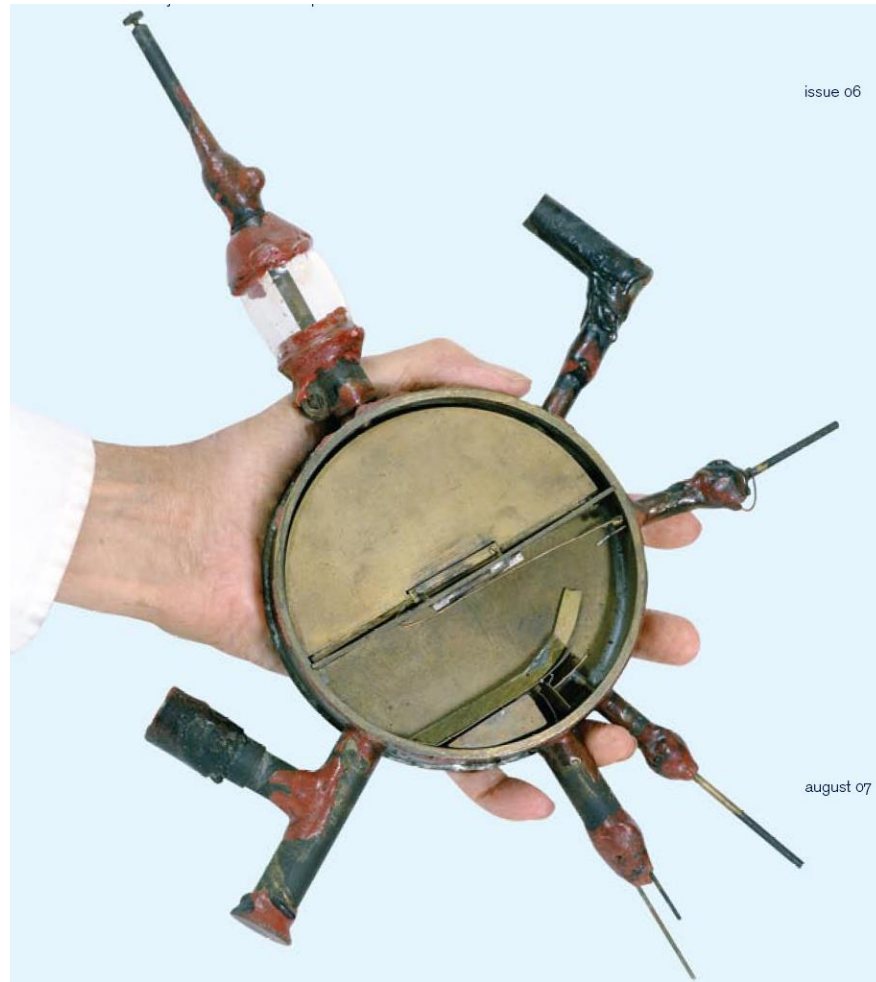




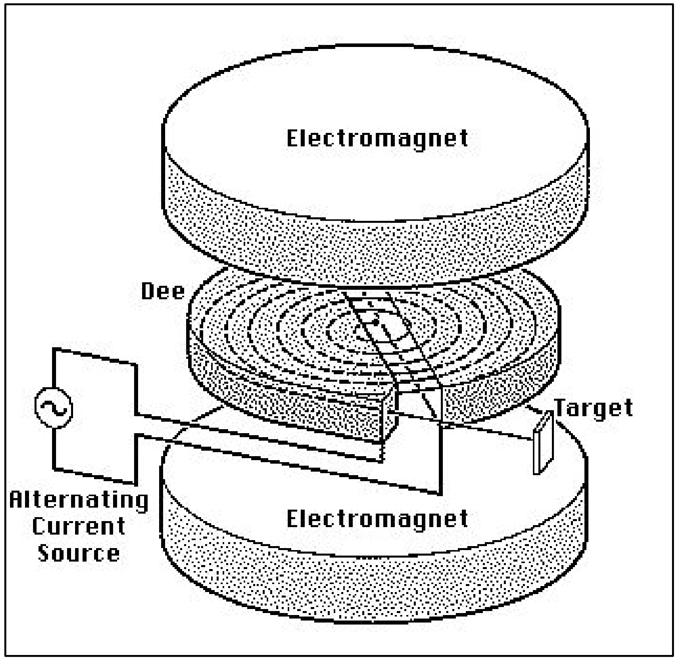
Rare decays of K mesons

The first circular accelerator
Lawrence and Livingston's 80 keV cyclotron (1930)

Ernest O. Lawrence

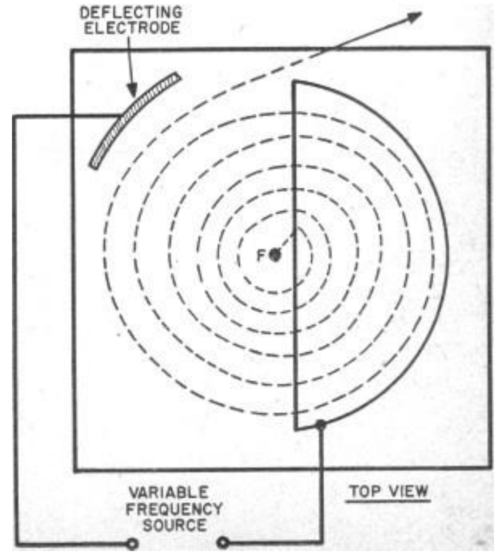


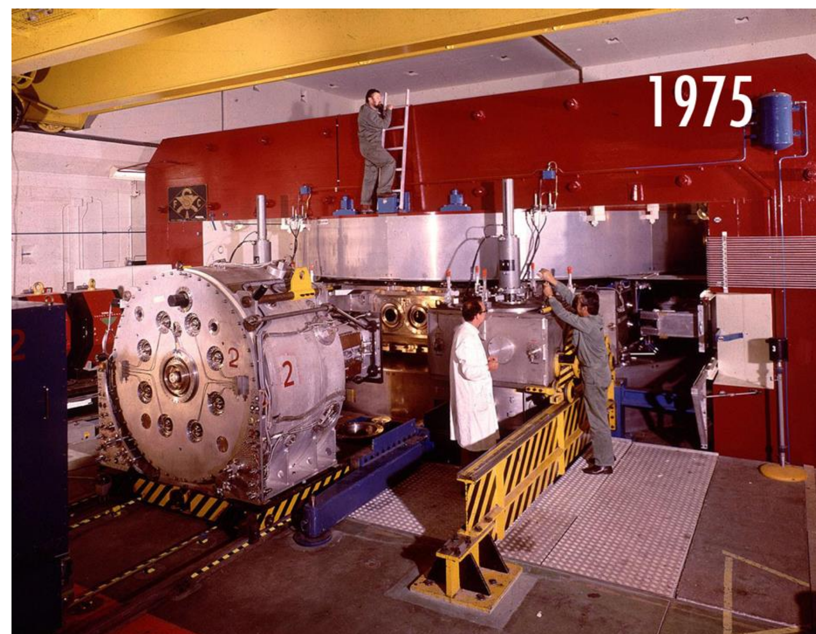
Cyclotron



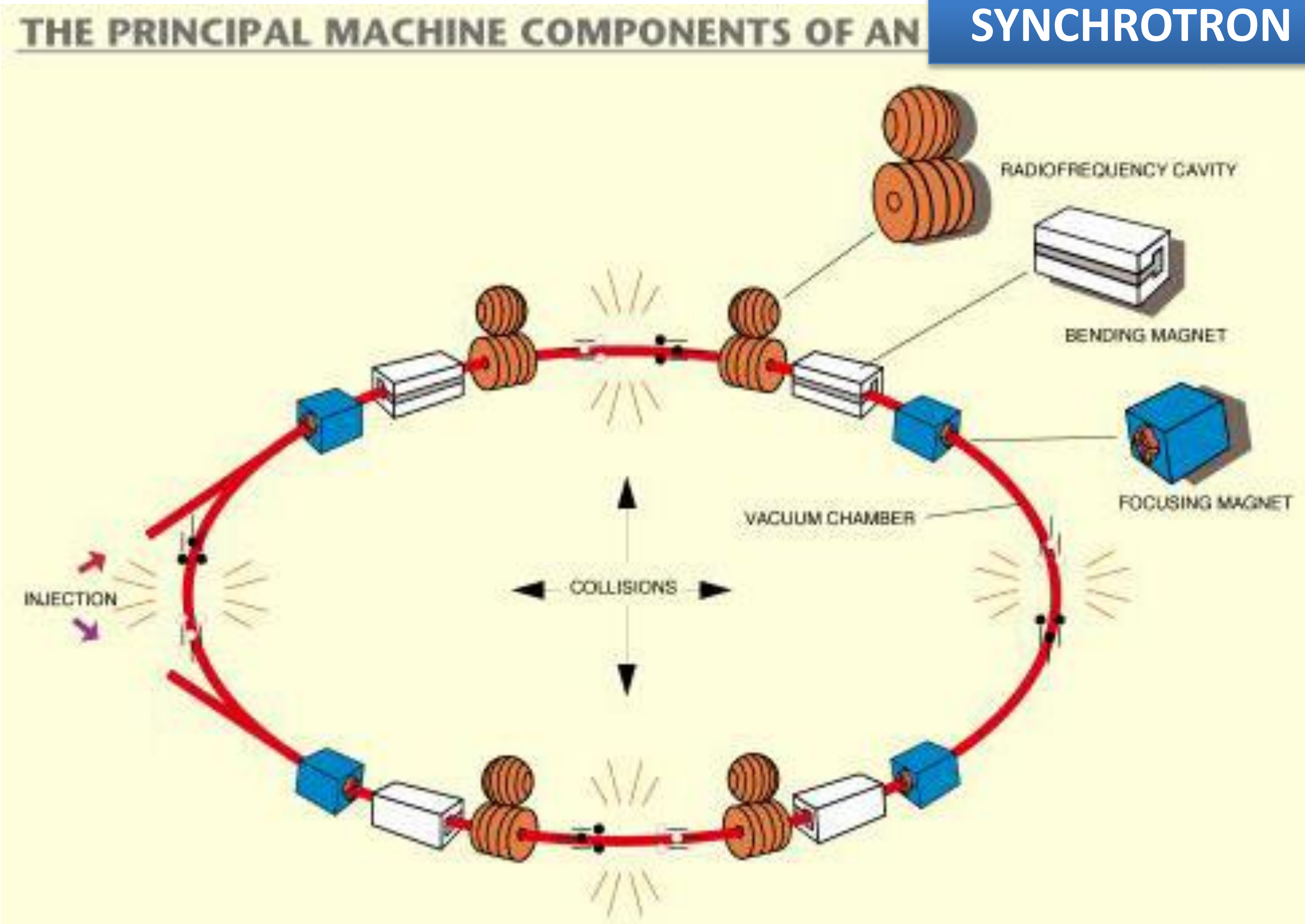
Livingston and Lawrence standing beside the 27-inch cyclotron, built in 1934

Synchrocyclotron

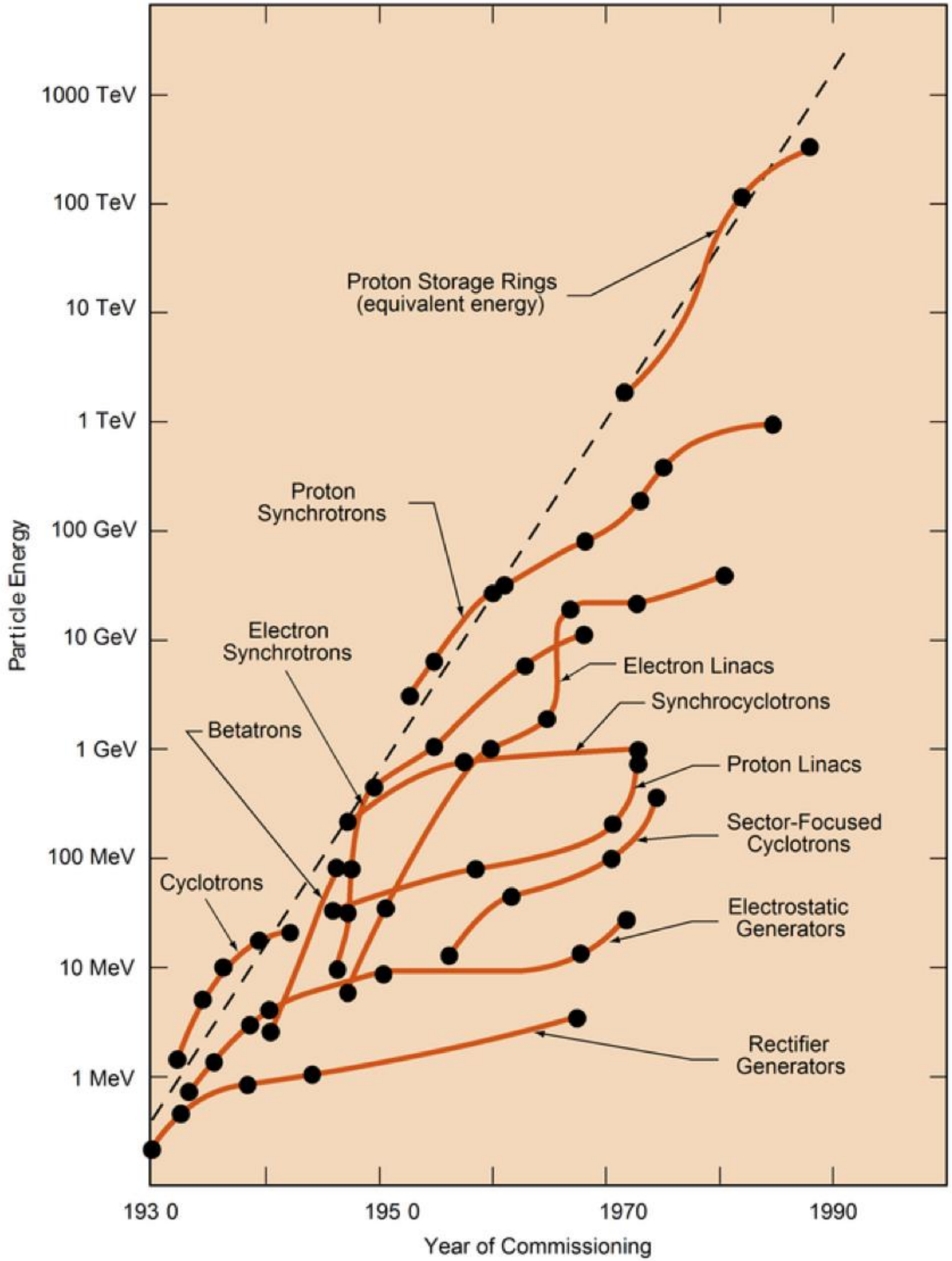




SYNCHROTRON



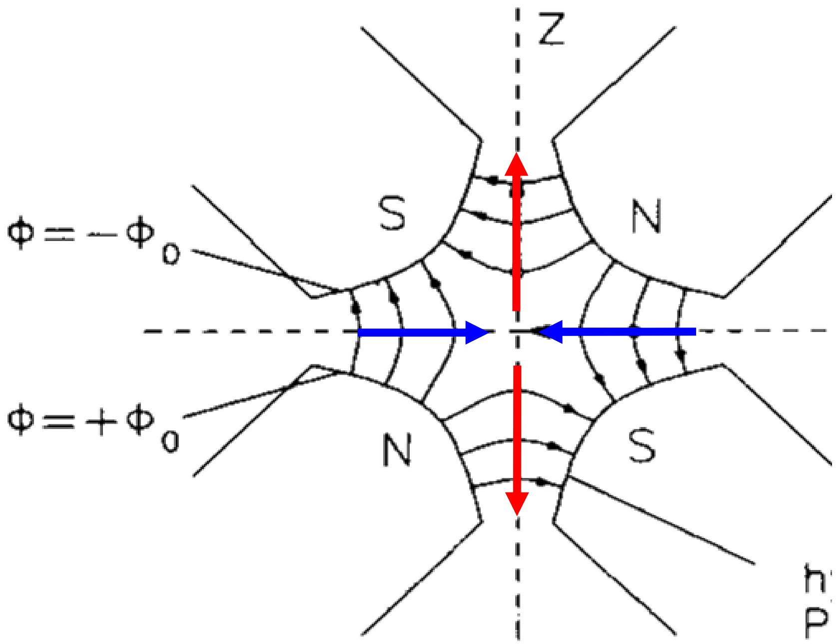
The basic principle of the Synchrotron is to maintain the accelerated particles at a constant orbital radius.

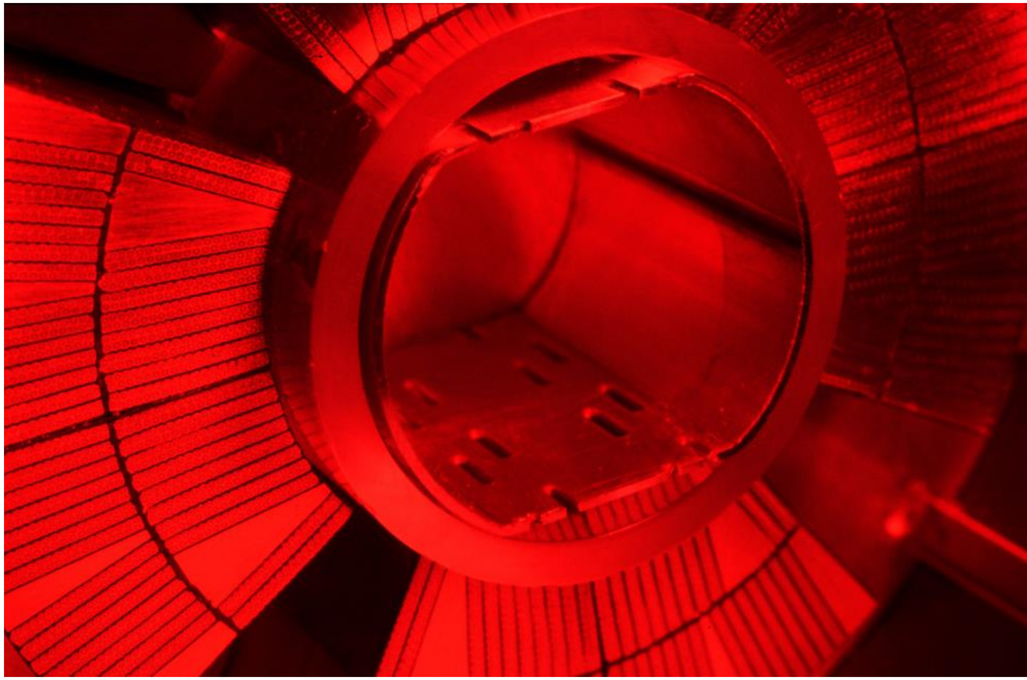


1000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
Particle Energy
Proton Storage Rings
(equivalent energy)
Proton
Synchrotrons
Electron
Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused
Cyclotrons
Cyclotrons
Electrostatic
Generators
Rectifier
Generators
193 0
195 0
1970
1990
Year of Commissioning

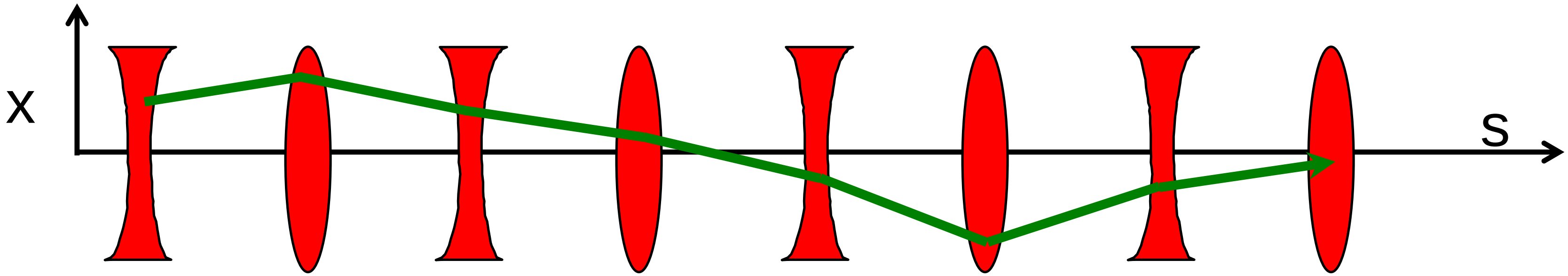
SPS dipoles

Quadrupoles





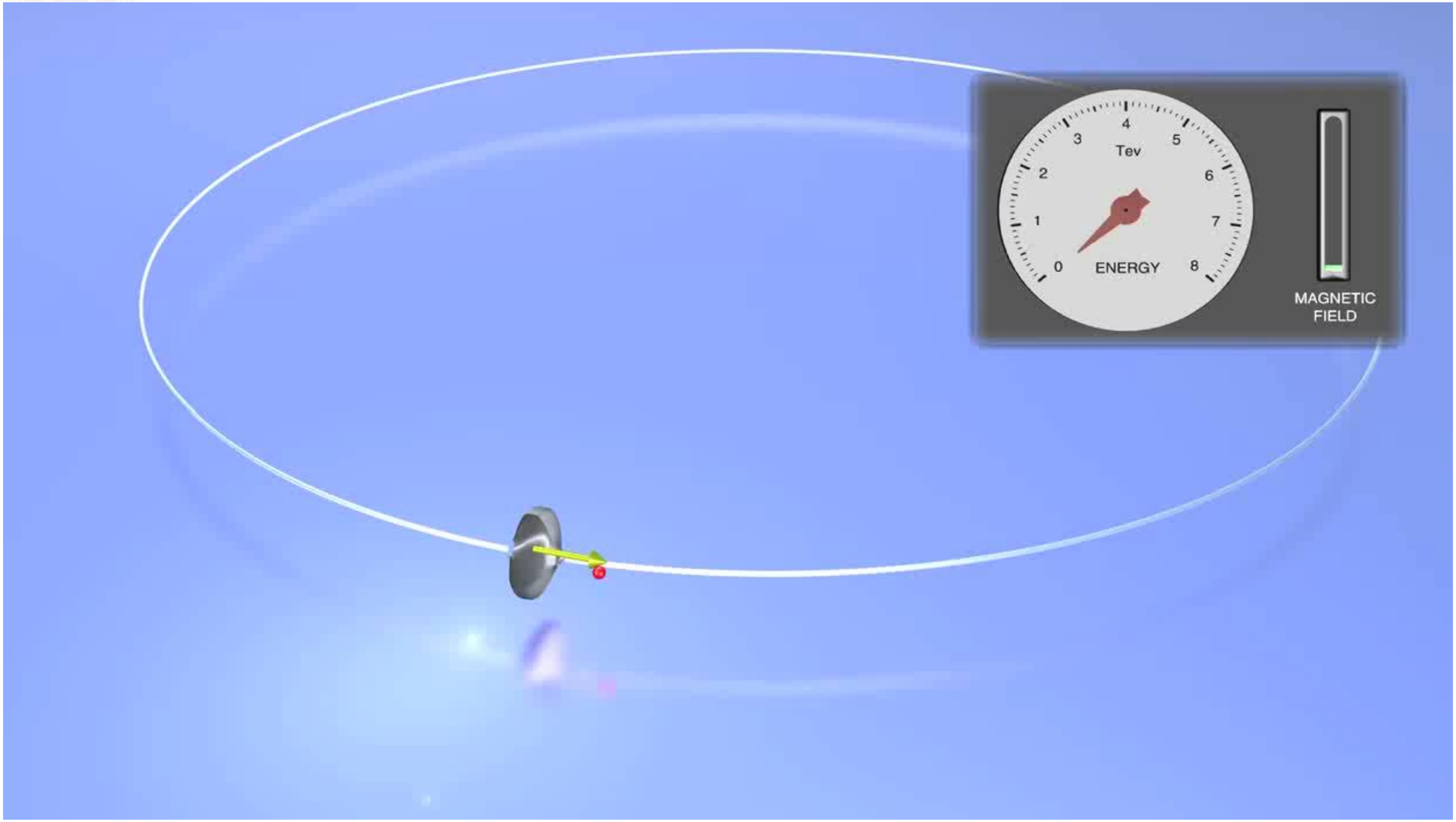
- A quadrupole magnet will focus in plane and de-focus in the other.



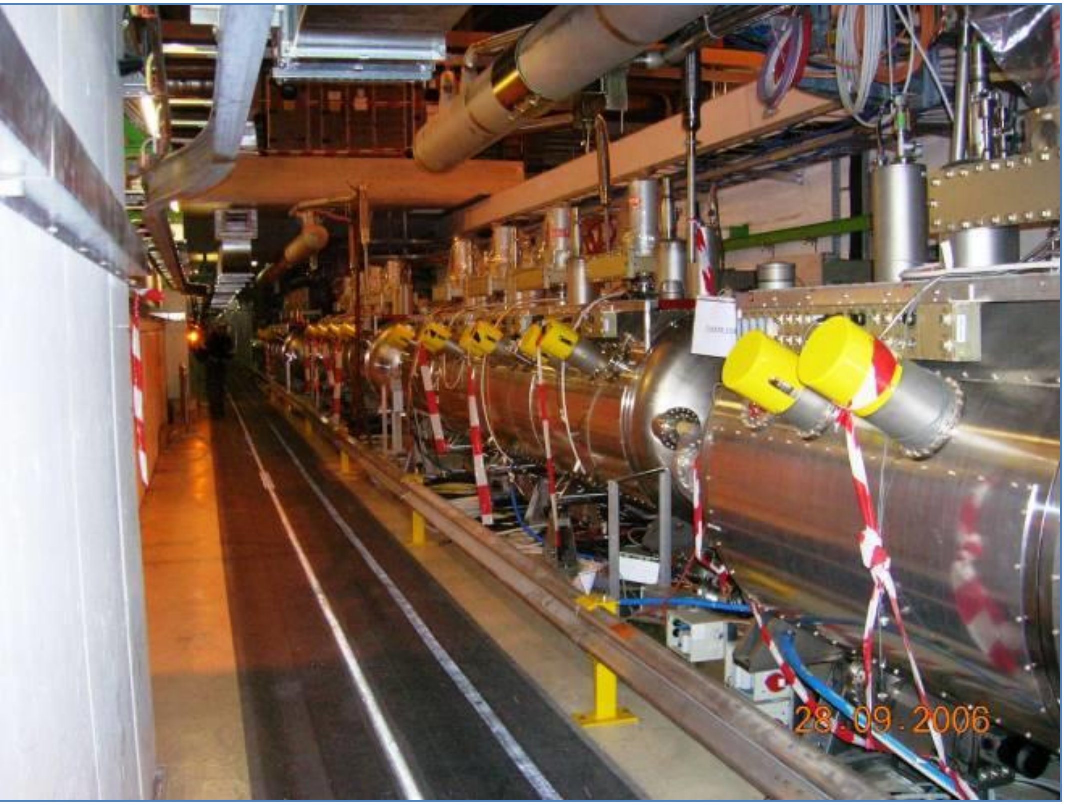
LHC tunnel

Video 1’22’’

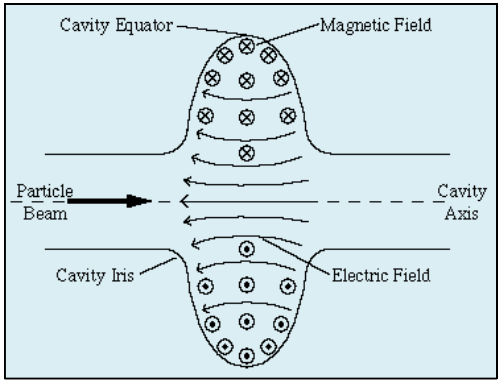
Acceleration principle

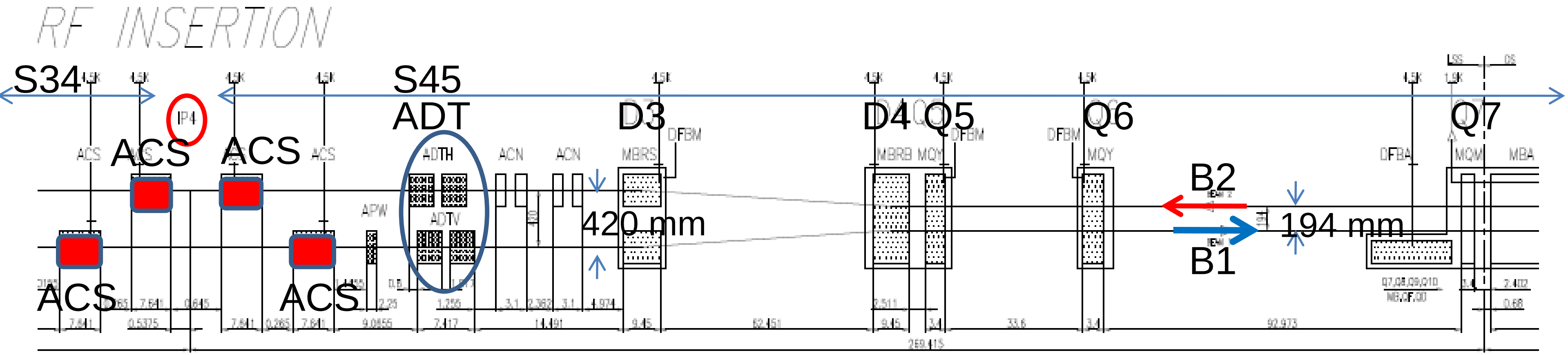


LHC RF



- 2 x four cavity cryomodule per beam
- 400 MHz
- 16 MV/beam
- Niobium on Copper cavities @4.5 K





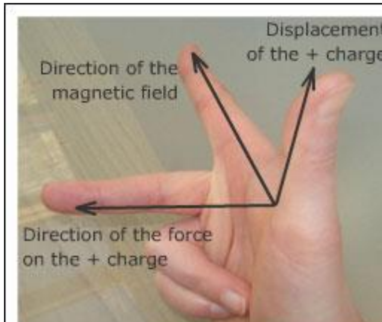
$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

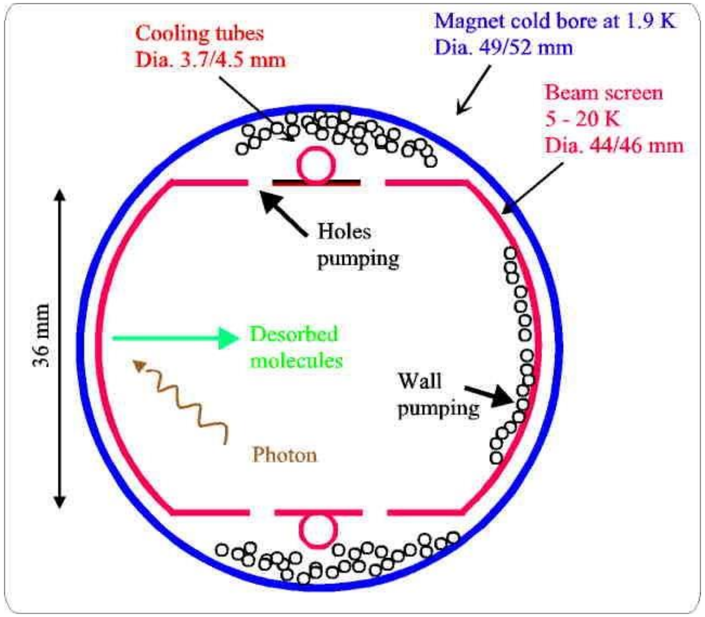
$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

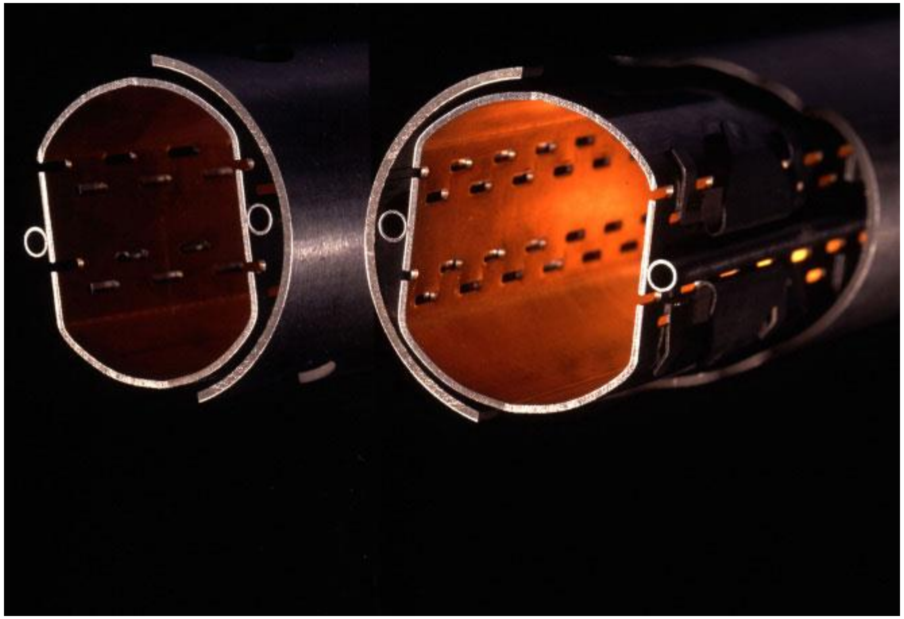
$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$



LHC vacuum

Beam vacuum ~10^{-10} mbar (~3 million molecules/cm^3)

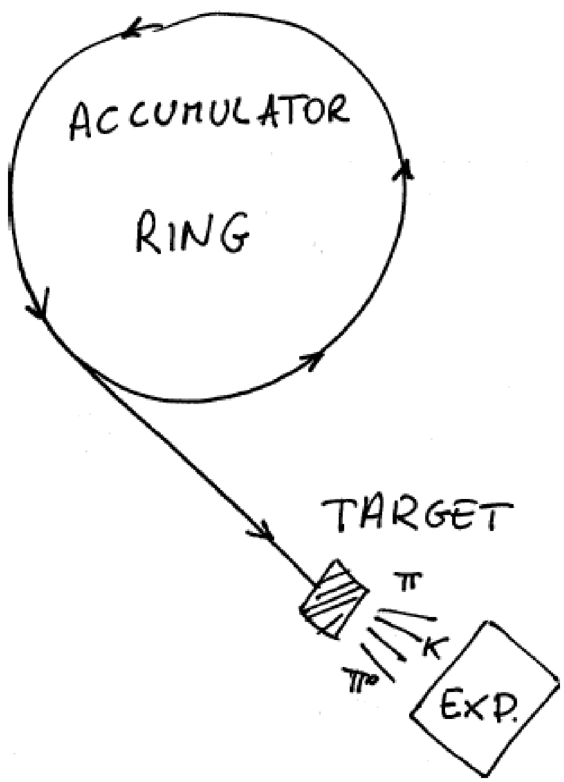




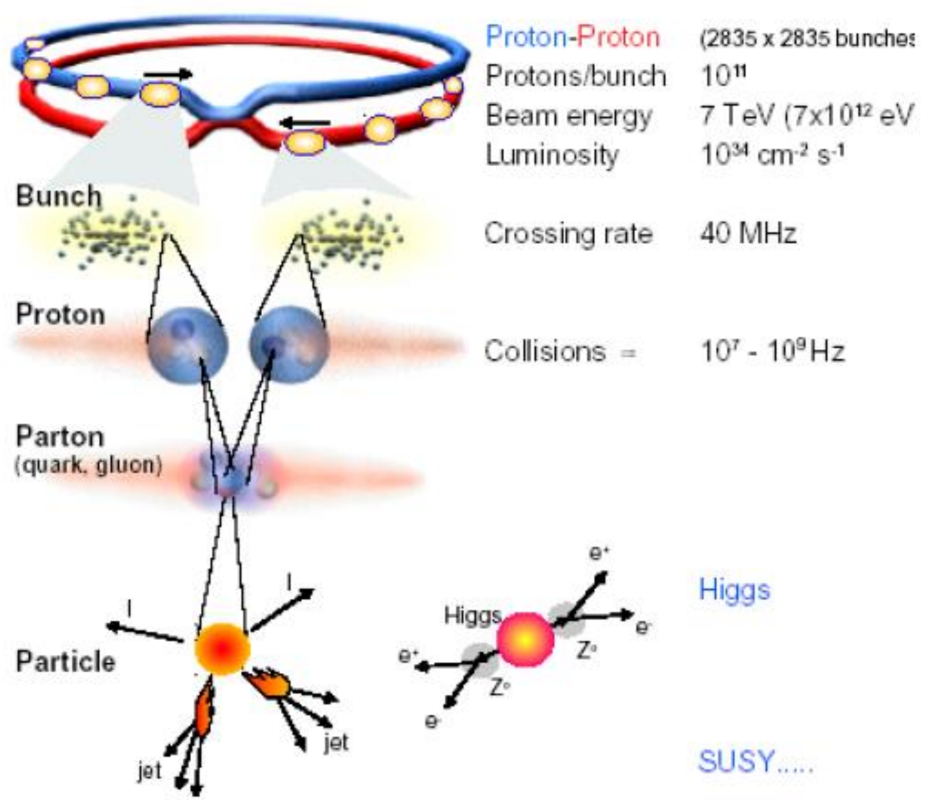
- **Cold**
  - Pumping is insured by cold surfaces for all gases except helium. Low initial pressures are required before cool-down, and this is ensured by turbo molecular pumps etc.
- **Warm**
  - Non-evaporable getter (NEG) provides most of the pumping capacity

Different approaches: fixed target vs collider

Fixed target



Storage ring/collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

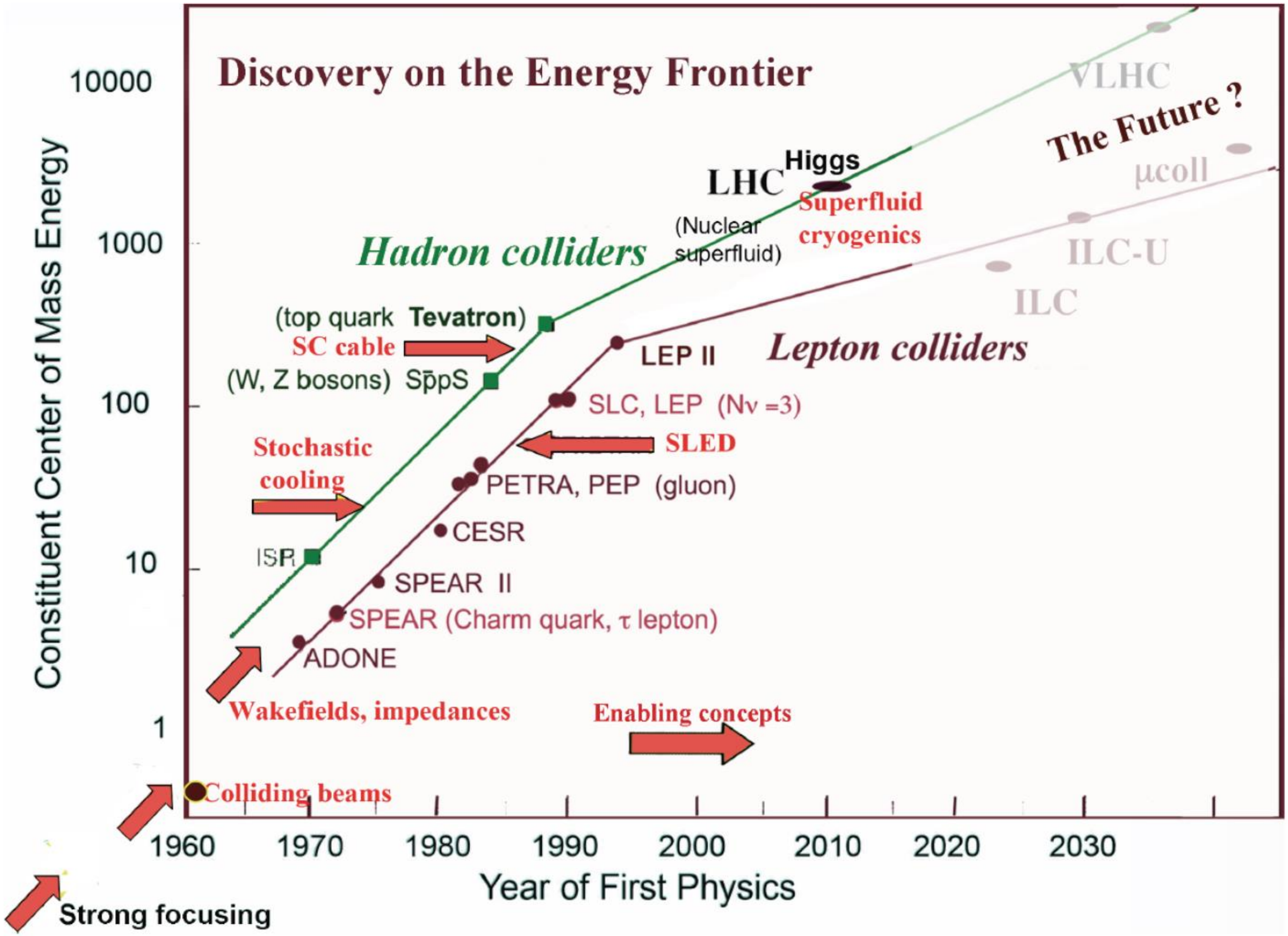


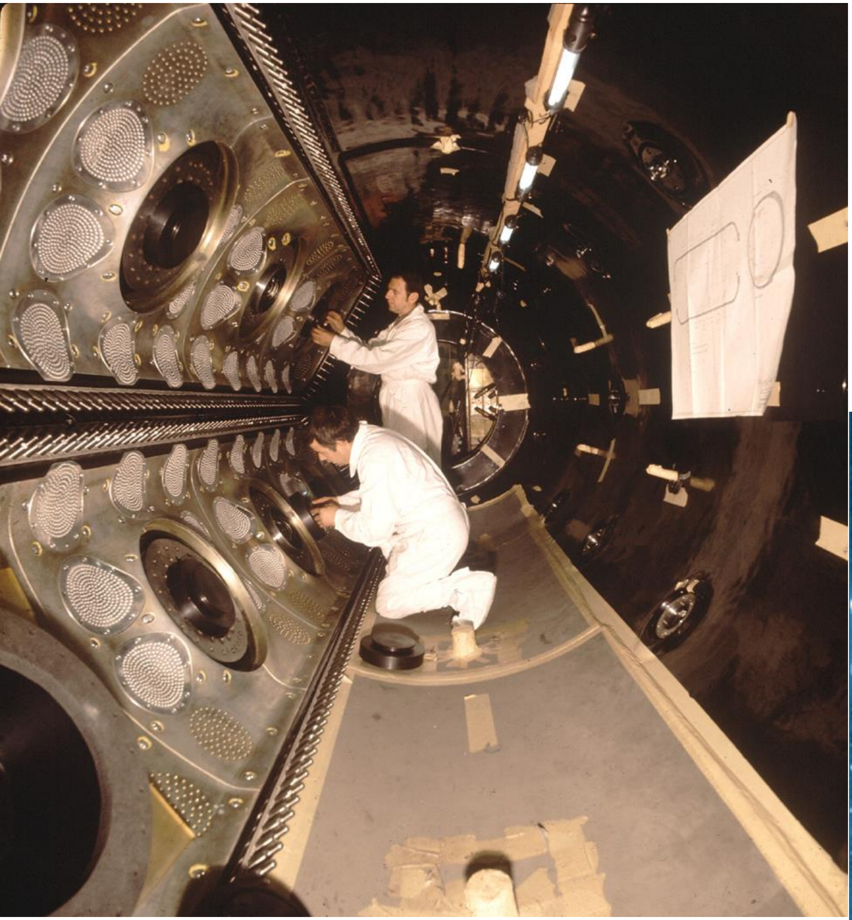
Figure 6-1. *The so-called Livingston plot illustrates how history of discovery on the energy frontier has been enabled by the history of invention (red arrows) in accelerator science and technology.*

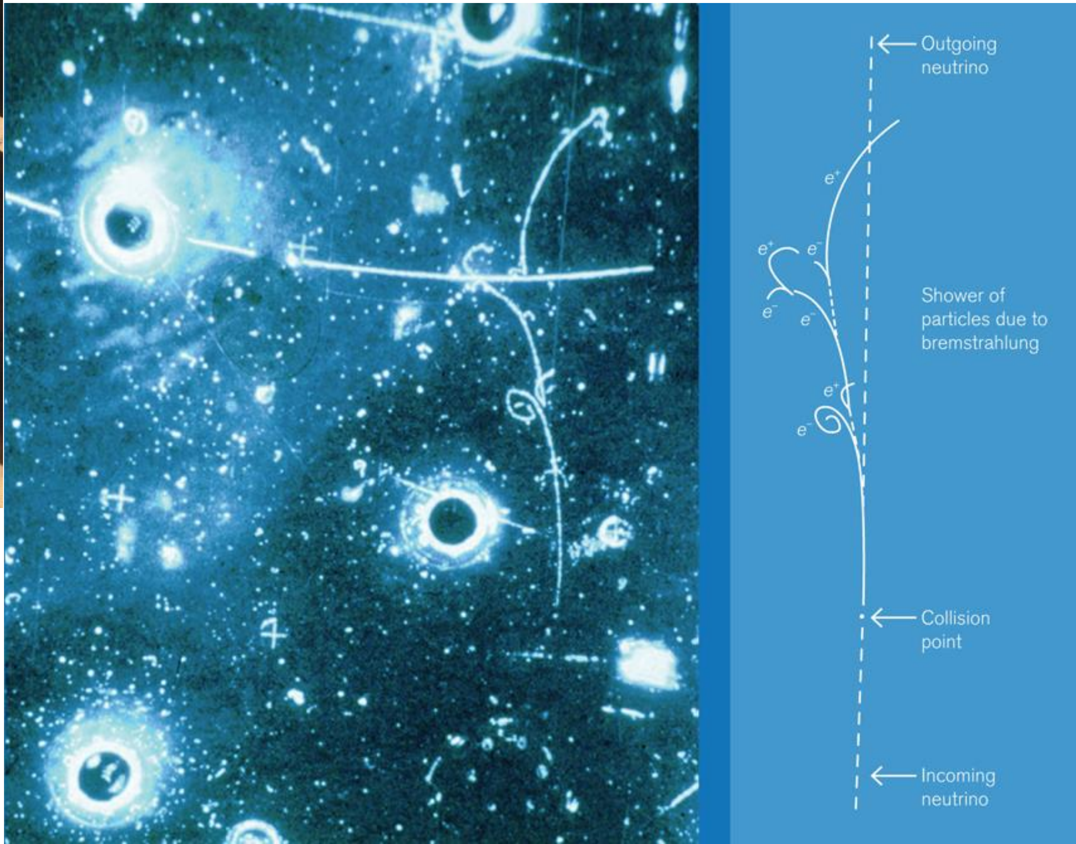
ISR

1971 to 1984, proton-proton, maximum centre of mass energy of 62 GeV

Interaction point
with crossing angle

Gargamelle/PS



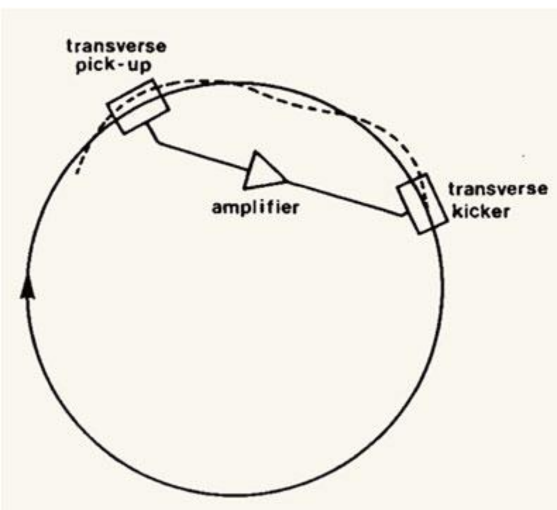


1974: discovery of weak neutral currents

S. Van Der Meer CERN/ISR-PO/72-31

4. FINAL NOTE

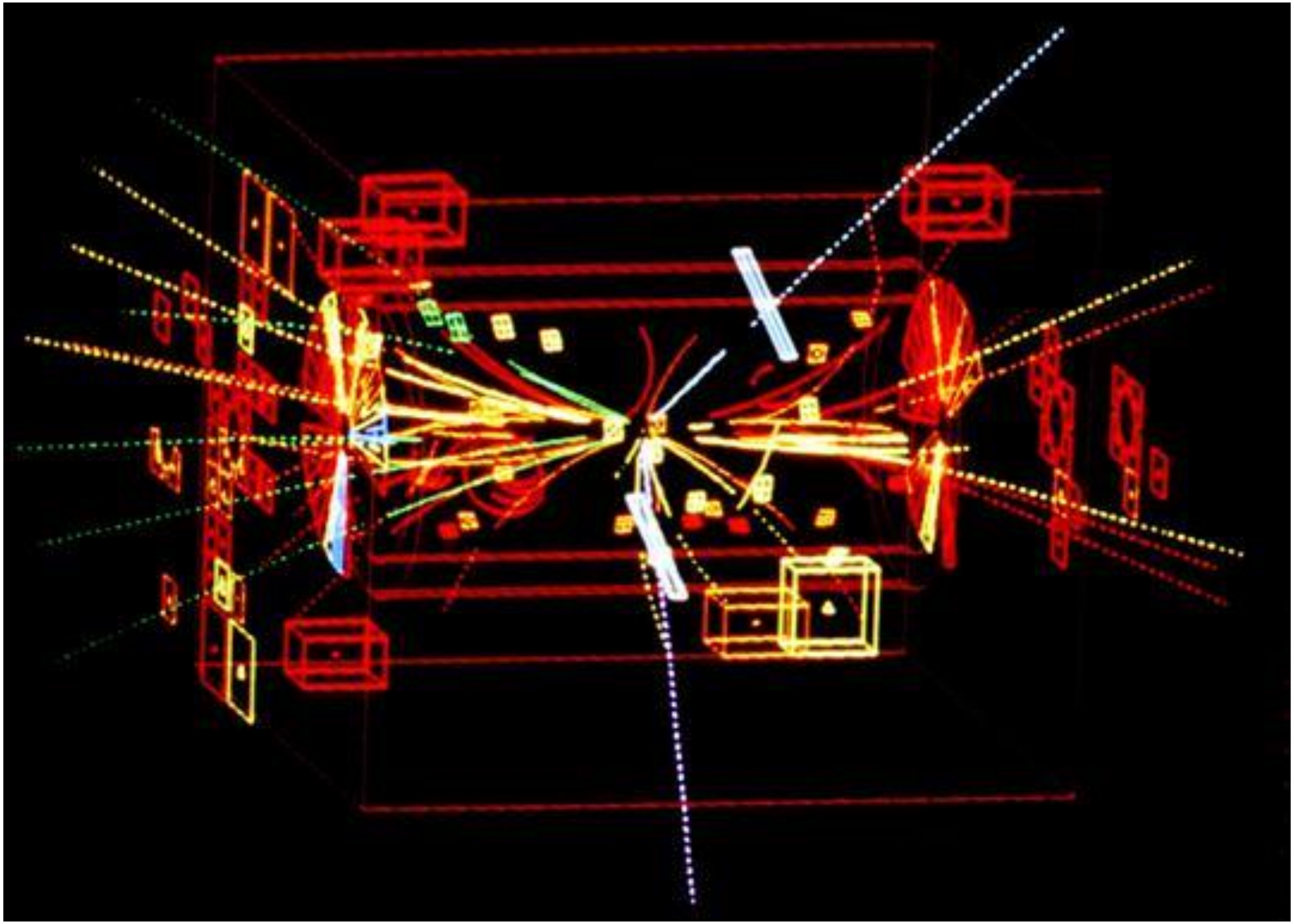
This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect.



With a mild push from friends and colleagues, Simon finally published the first internal note on stochastic cooling in 1972 (van der Meer 1972).

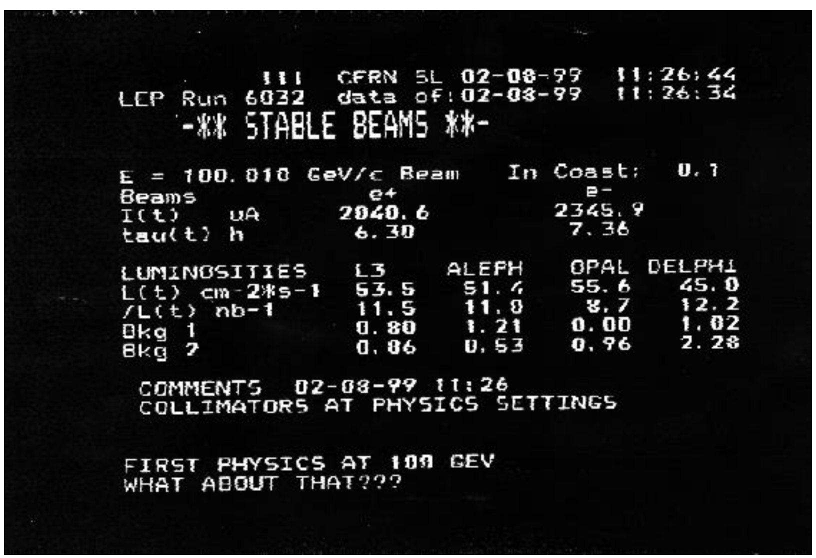
The control room of the anti-proton accumulator (AA) in 1981

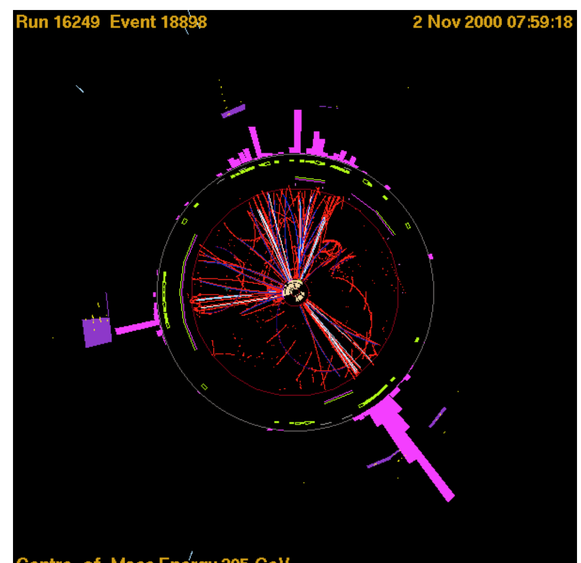

LeCroy 3500
LeCroy 3500



1983: discovery of W^+,W^- and Z^0 at the SPS

LEP
18 million Zs
80,000 Ws





Electron and low intensity hadron accelerators

Accelerator	Location	Years of operation	Shape and size	Accelerated particle	Kinetic Energy
Antiproton Accumulator	CERN	1980-1996			
Antiproton collector	CERN	1986-1996		Antiprotons	
Antiproton Decelerator	CERN	2000–present	Storage ring	Protons and antiprotons	26 GeV
Low Energy Antiproton Ring	CERN	1982-1996		Antiprotons	
Cambridge Electron Accelerator	Harvard University and MIT, Cambridge, MA	1962-1974[4]	236 ft diameter synchrotron[5]	Electrons	6 GeV
SLAC Linac	SLAC National Accelerator Laboratory	1966–present	3 km linear accelerator	Electron/ Positron	50 GeV
Fermilab Booster	Fermilab	1970–present	Circular Synchrotron	Protons	8 GeV
Fermilab Main Injector	Fermilab	1995–present	Circular Synchrotron	Protons and antiprotons	150 GeV
Fermilab Main Ring	Fermilab	1970–1995	Circular Synchrotron	Protons and antiprotons	400 GeV (until 1979), 150 GeV thereafter
Bates Linear Accelerator	Middleton, MA	1967–2005	500 MeV recirculating linac and storage ring	Polarized electrons	1 GeV
Continuous Electron Beam Accelerator Facility (CEBAF)	Thomas Jefferson National Accelerator Facility, Newport News, VA	1995–present	6 GeV recirculating linac (upgrading to 12 GeV)	Polarized electrons	6 GeV
ELSA	Physikalisches Institut der Universität Bonn, Germany	1987–present	Synchrotron and stretcher	(Polarized) electrons	3.5 GeV
MAMI	Mainz, Germany	1975–Present	multilevel racetrack microtron	Polarized electrons	1.5 GeV accelerator
Tevatron	Fermilab	1983–2011	Superconducting Circular Synchrotron	Protons	980 GeV
Universal Linear Accelerator (UNILAC)	GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany	1974–Present	Linear (120 m)	Ions of all naturally occurring elements	
Schwerionensynchrotron (SIS18)	GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany	1990–Present	Synchrotron with 271 m circumference	Ions of all naturally occurring elements	U: 50-1000 MeV/u Ne: 50-2000 MeV/u p: 4,5 GeV
J-PARC Main Ring	Tōkai, Ibaraki	2009–Present	Triangular, 500m diameter	Protons	30 GeV
ALBA	CELLS[6] Cerdanyola del Vallès, Catalonia, Spain	2010–Present	Synchrotron with 270 m circumference	(Polarized) electrons	3 GeV

Some others

Fixed target

Proton Synchrotron	CERN	1959–present	Circular ring (600 meters around)
Proton Synchrotron Booster	CERN	1972–present	Circular Synchrotron
Super Proton Synchrotron	CERN	1980–present	Circular Synchrotron
Alternating Gradient Synchrotron	BNL	1960-	Circular ring (808 meters around)

Lepton colliders

PEP-II	SLAC	1998–2008	Circular, 2.2 km	9 GeV	3.1 GeV	BaBar
KEKB	KEK	1999–2009	Circular, 3 km	8.0 GeV	3.5 GeV	Belle
DAΦNE	Frascati, Italy	1999-	Circular, 98m	0.7 GeV	0.7 GeV	KLOE
CESR-c	Cornell University	2002–2008	Circular, 768m	6 GeV	6 GeV	CHESS, CLEO-c
VEPP-2000	BINP, Novosibirsk	2006-	Circular, 24.4m	1.0 GeV	1.0 GeV	SND, CMD-3
BEPC II	China	2008-	Circular, 240m	3.7 GeV	3.7 GeV	Beijing Spectrometer III

Hadron colliders

Relativistic Heavy Ion Collider (RHIC) polarized proton mode	Brookhaven National Laboratory, New York	2001–present	Hexagonal rings (3.8 km circumference)	Polarized Proton/ Proton	100-255 GeV	PHENIX, STAR
Relativistic Heavy Ion Collider (RHIC) ion mode	Brookhaven National Laboratory, New York	2000–present	Hexagonal rings (3.8 km circumference)	d-$^{197}Au^{79+}$; $^{63}Cu^{29+}$-$^{63}Cu^{29+}$; $^{63}Cu^{29+}$-$^{197}Au^{79+}$; $^{197}Au^{79+}$-$^{197}Au^{79+}$; $^{238}U^{92+}$-$^{238}U^{92+}$	3.85-100 GeV per nucleon	STAR, PHENIX, BRAHMS, PHOBOS
Large Hadron Collider (LHC) proton mode	CERN	2008–present	Circular rings (27 km circumference)	Proton/ Proton	6.5 TeV (design: 7 TeV)	ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM
Large Hadron Collider (LHC) ion mode	CERN	2008–present	Circular rings (27 km circumference)	$^{208}Pb^{82+}$-$^{208}Pb^{82+}$	2.76 TeV per nucleon	ALICE, ATLAS, CMS

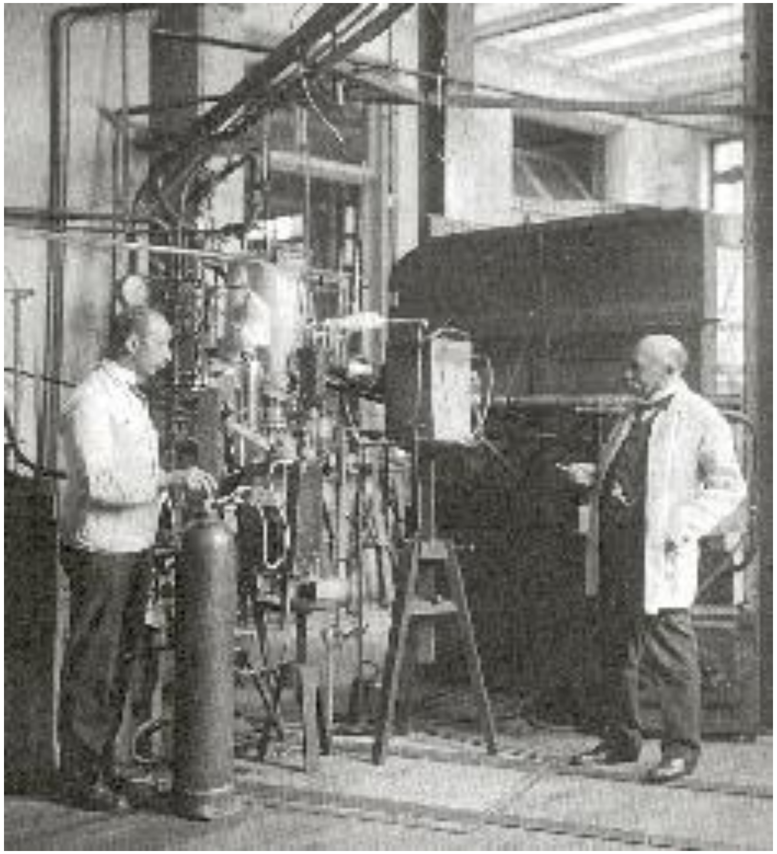
e+ on e- : 4 on 7 GeV – to produce a huge number of B mesons

What seest thou else
In the dark backward and abysm of time?

…at the physics laboratory of Leyden, helium was first liquified

10 July 1908

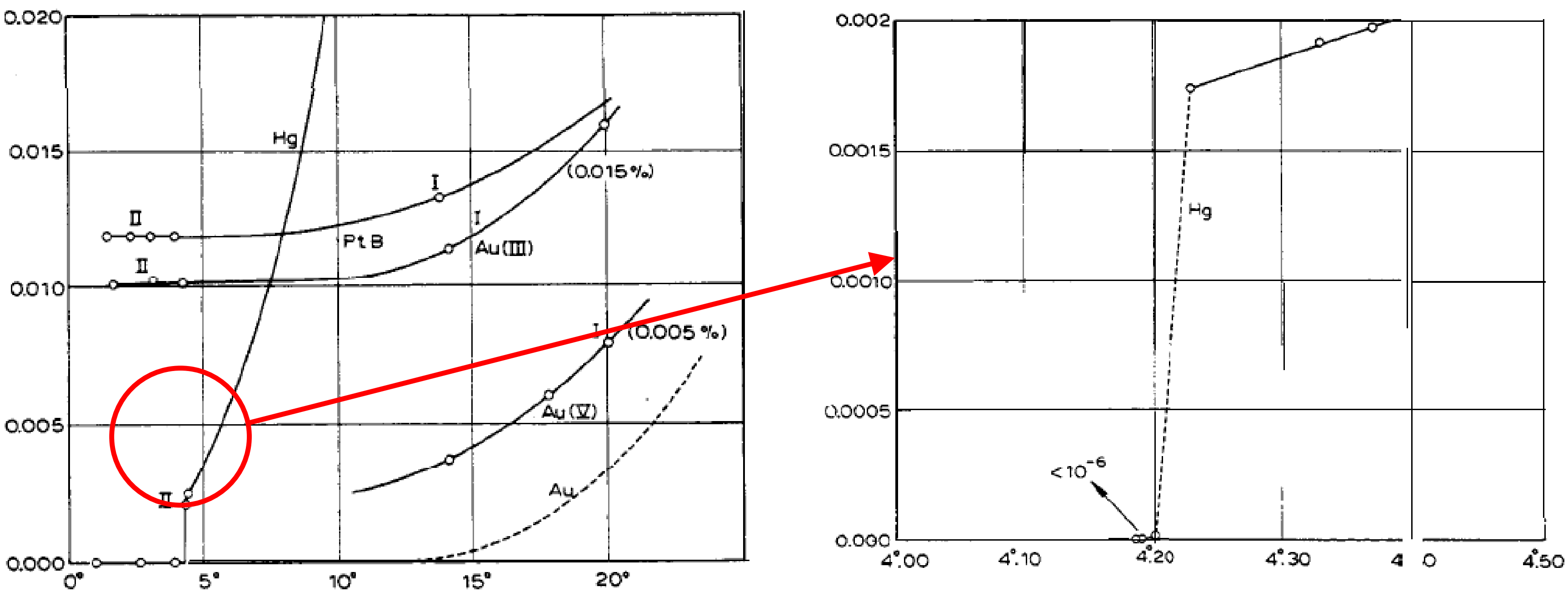
Heike Kamerlingh Onnes



"Door meten tot weten"
To knowledge through measurement

Discovery of superconductivity

On 8 April 1911, Kamerlingh Onnes found that at 4.2 K the resistance in a solid mercury wire immersed in liquid helium suddenly vanished.

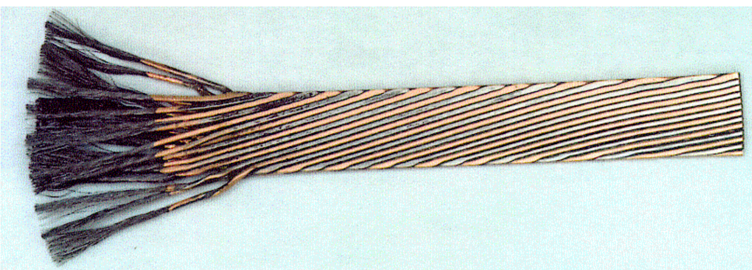


> Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

Fast forward to the LHC – the superconductor

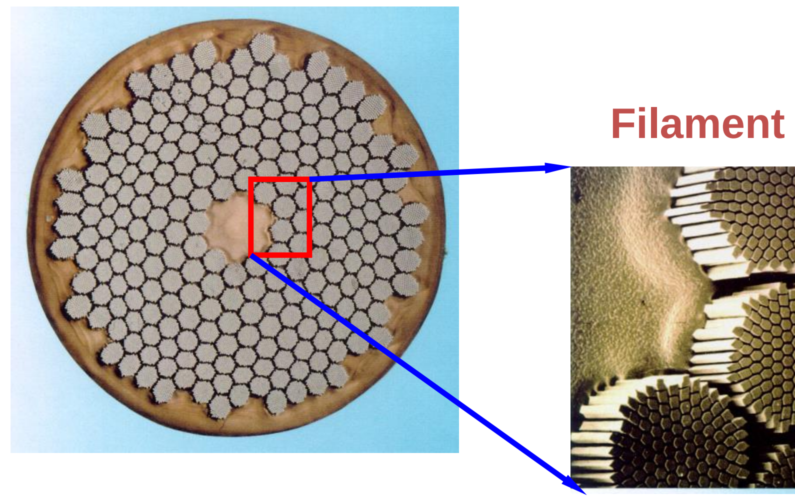
Niobium-titanium Rutherford cable

Cable



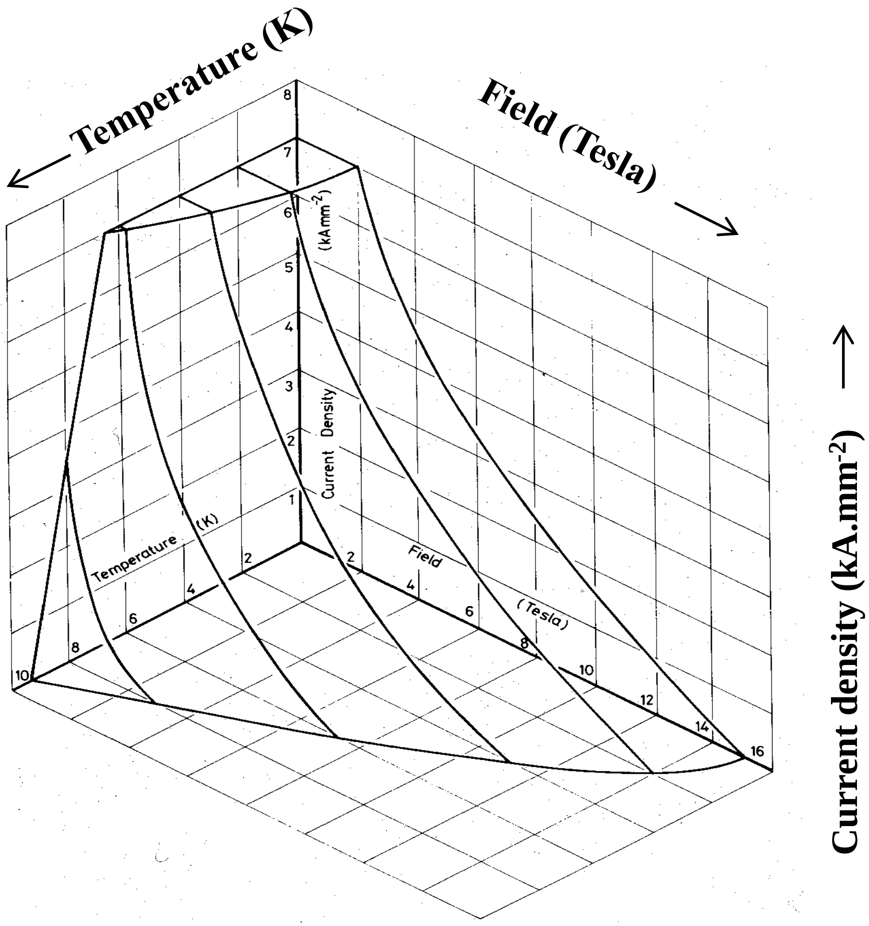
Strand

Filament



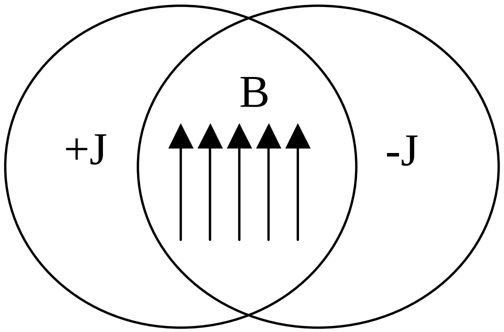
Used 1200 tonnes/7600 km of cable

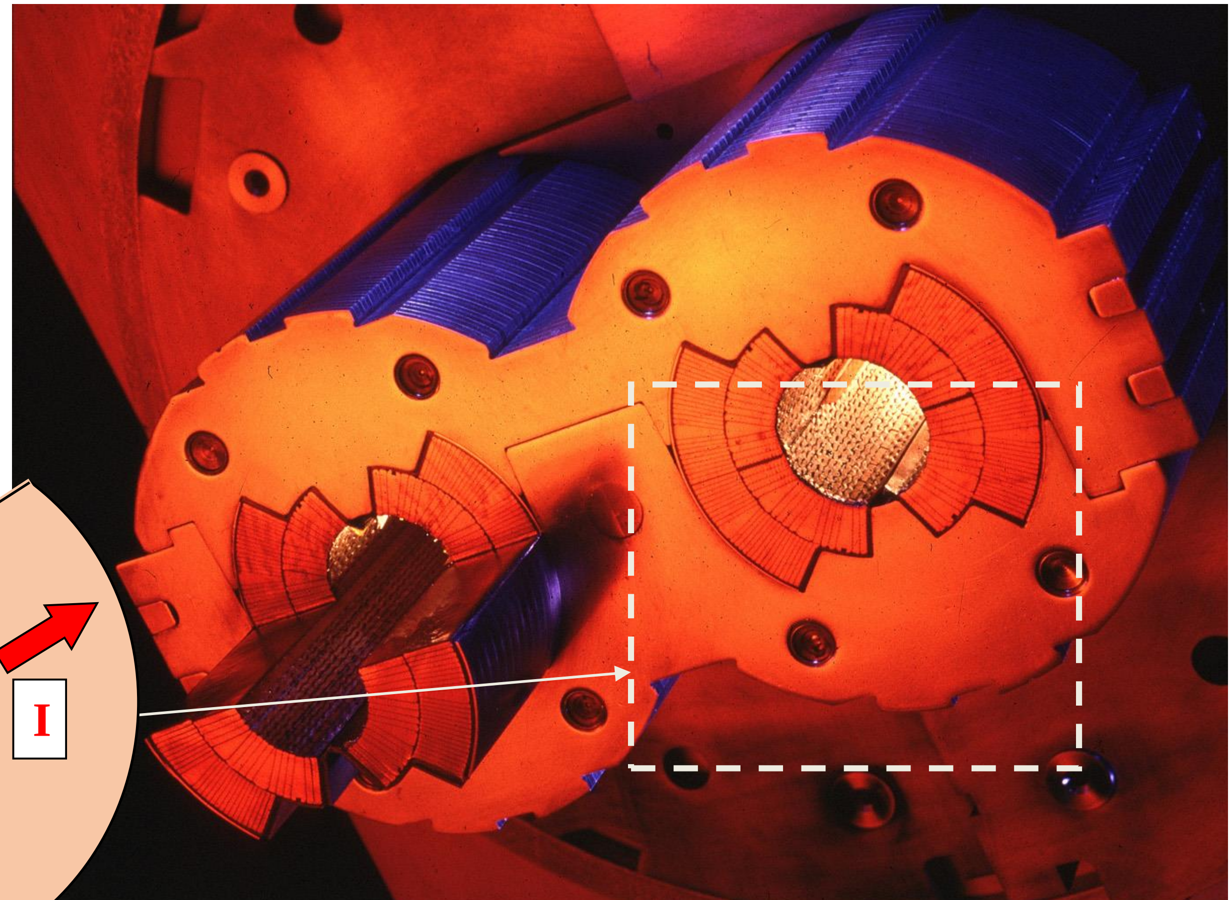
Critical surface of niobium-titanium

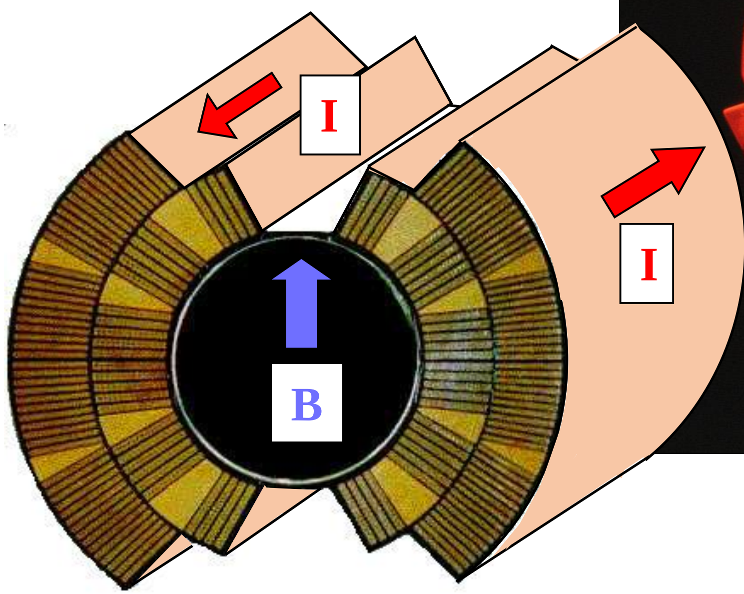


- Niobium-titanium **NbTi** is the standard 'work horse' of the superconducting magnet business
- Picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity
- Superconductivity prevails everywhere below the surface, resistance everywhere above it

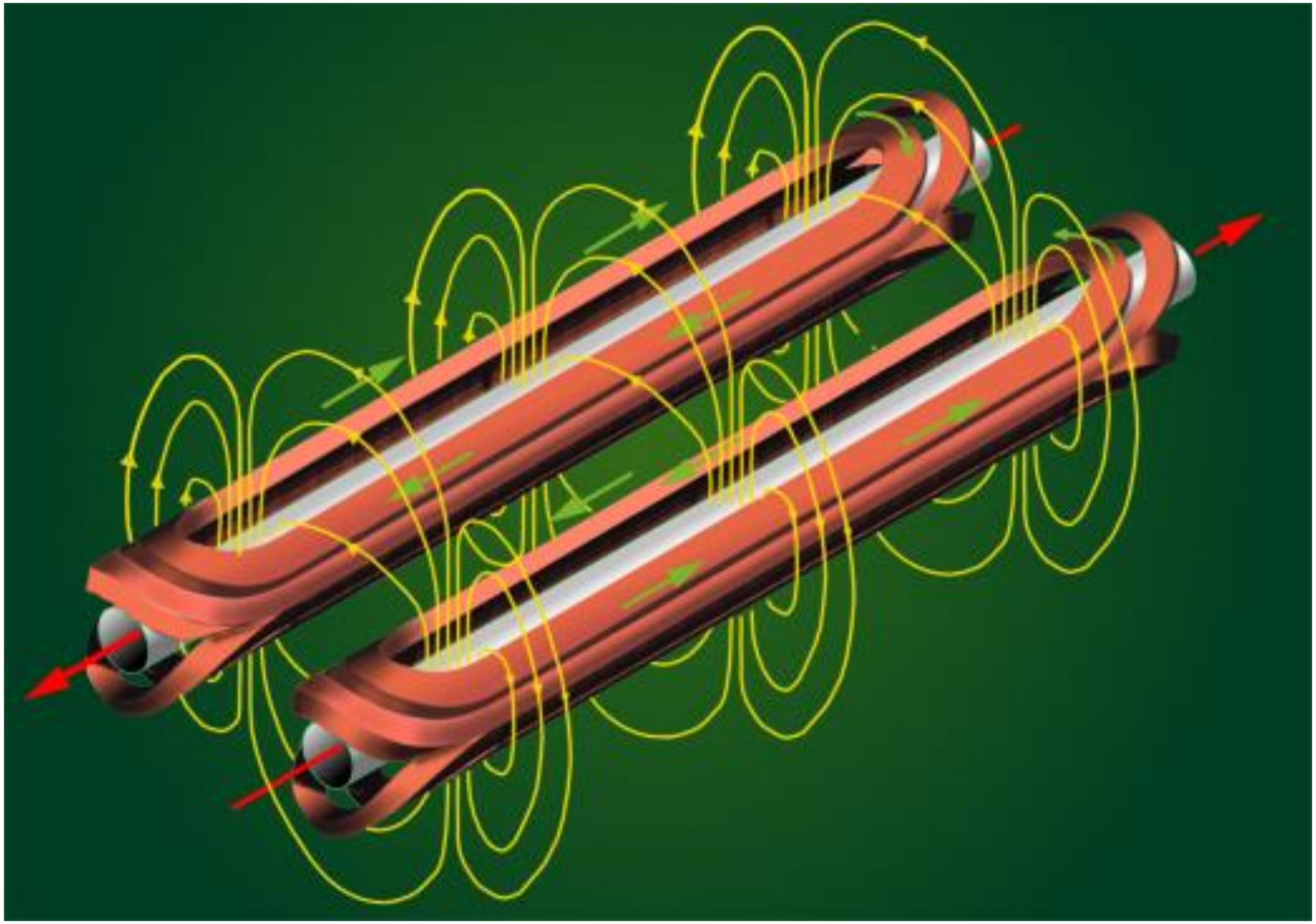
Main components – dipole magnets







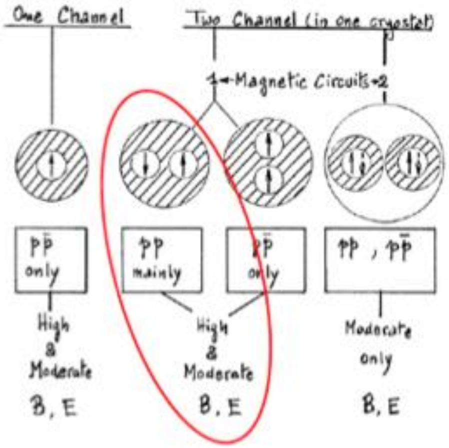
• Number of dipoles	1232
• Dipole field at 450 GeV	0.535 T
• Dipole field at 7 TeV	8.33 T
• Bending radius	2803.95 m
• Main Dipole Length	14.3 m



Horizontal force component per quadrant (nominal field) 1.7 MN/m

Force tends to “open” the magnet, hence the Austenitic steel collars

ECFA-CERN workshop



June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

SSC cancelled

Main contracts signed

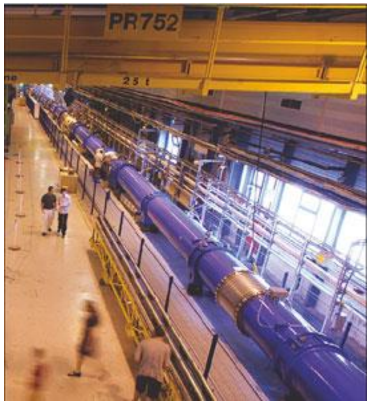
June 2007 First sector cold

April 2008
Last dipole down

84	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

First set of twin 1 m prototypes
Over 9 T

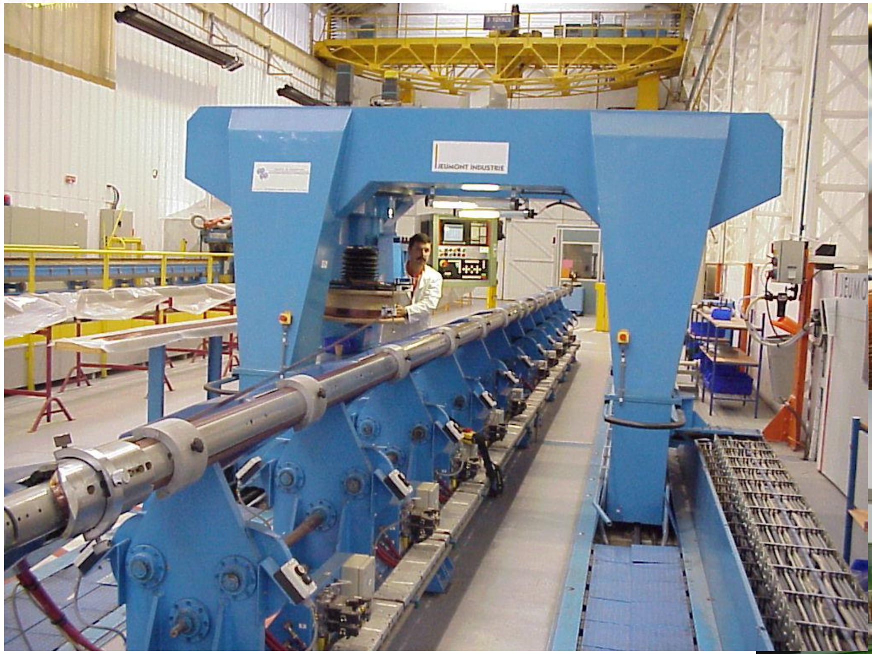
2002 String 2



November 2006
1232 delivered

September 19, 2008

Manufacturing of superconducting coils



Assembly of dipole cold masses

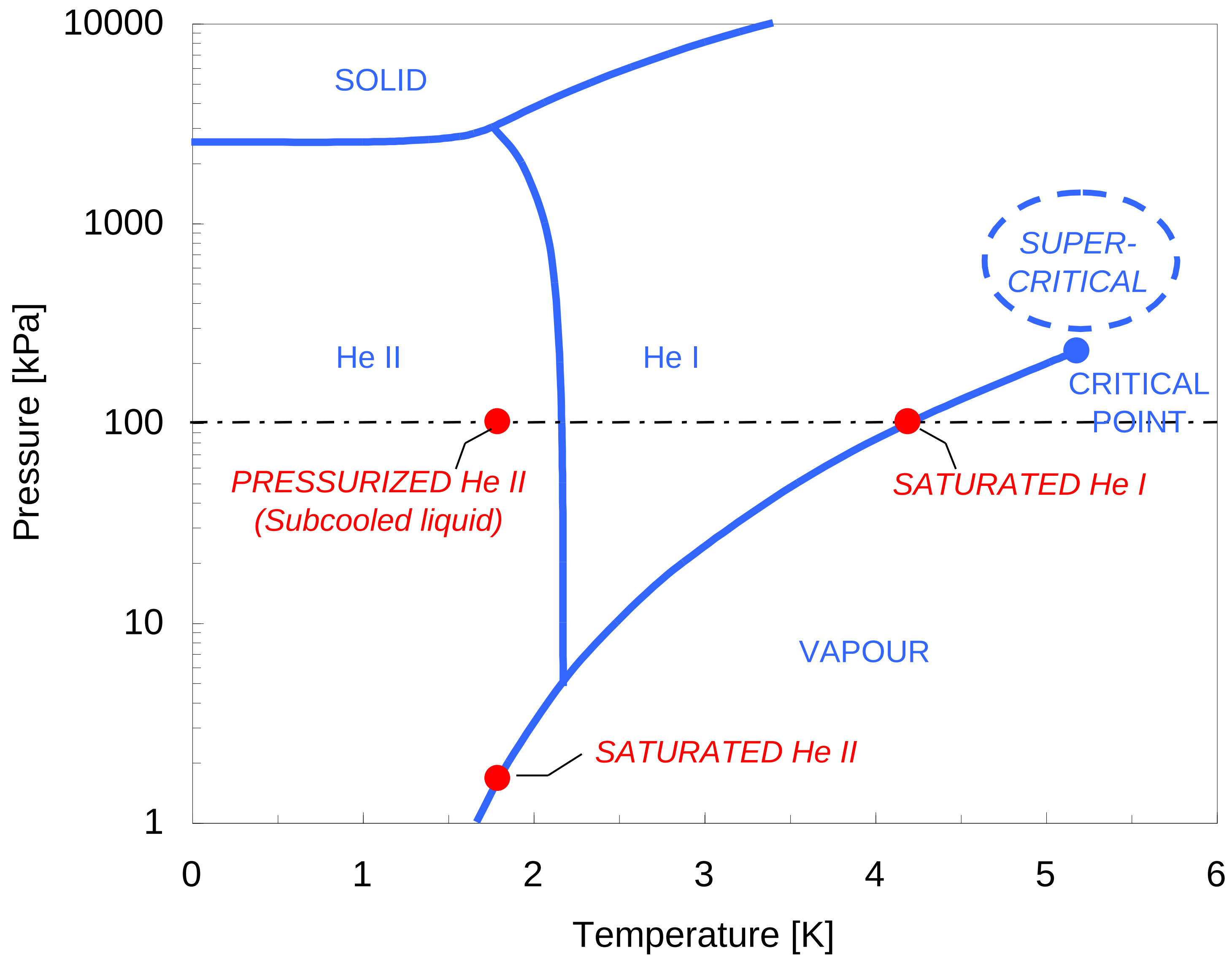
Cryogenic test benches

Superfluid helium

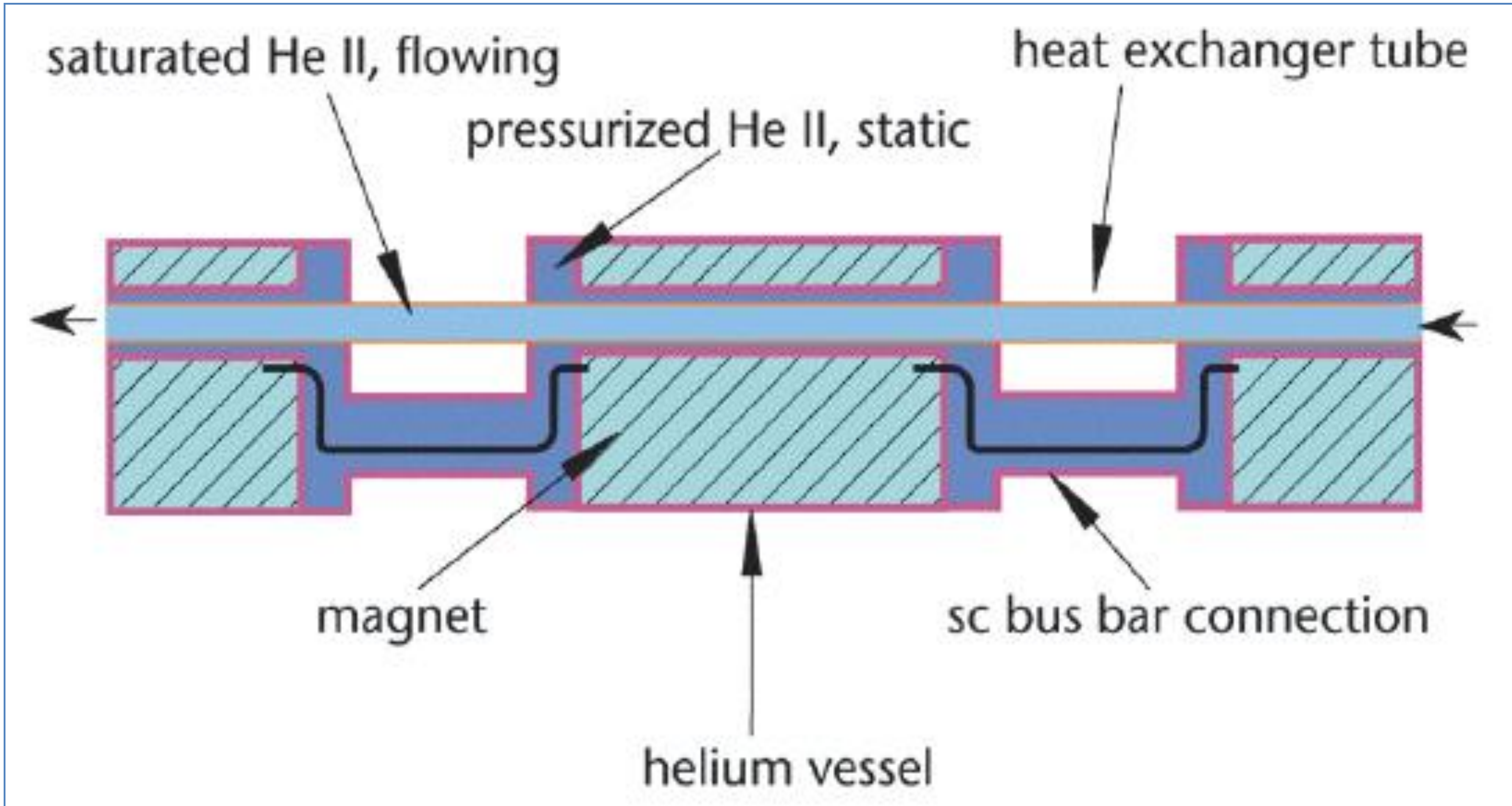
- To produce the high magnetic fields we need very high currents…
- Make use of the remarkable properties of He II
- Superfluid helium:
  - Very high thermal conductivity (3000 time high grade copper)
  - Very low coefficient of viscosity… can penetrate tiny cracks, deep inside the magnet coils to absorb any generated heat.
  - Very high heat capacity…stablizes small transient temperature fluctuations

Video 1’44’’

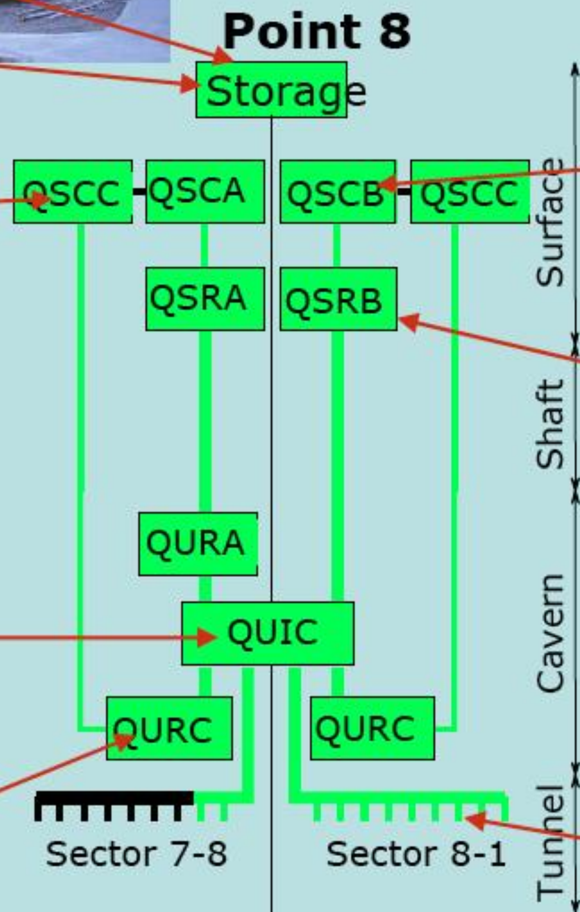
Phase diagram of Helium



Cooling magnets with superfluid helium

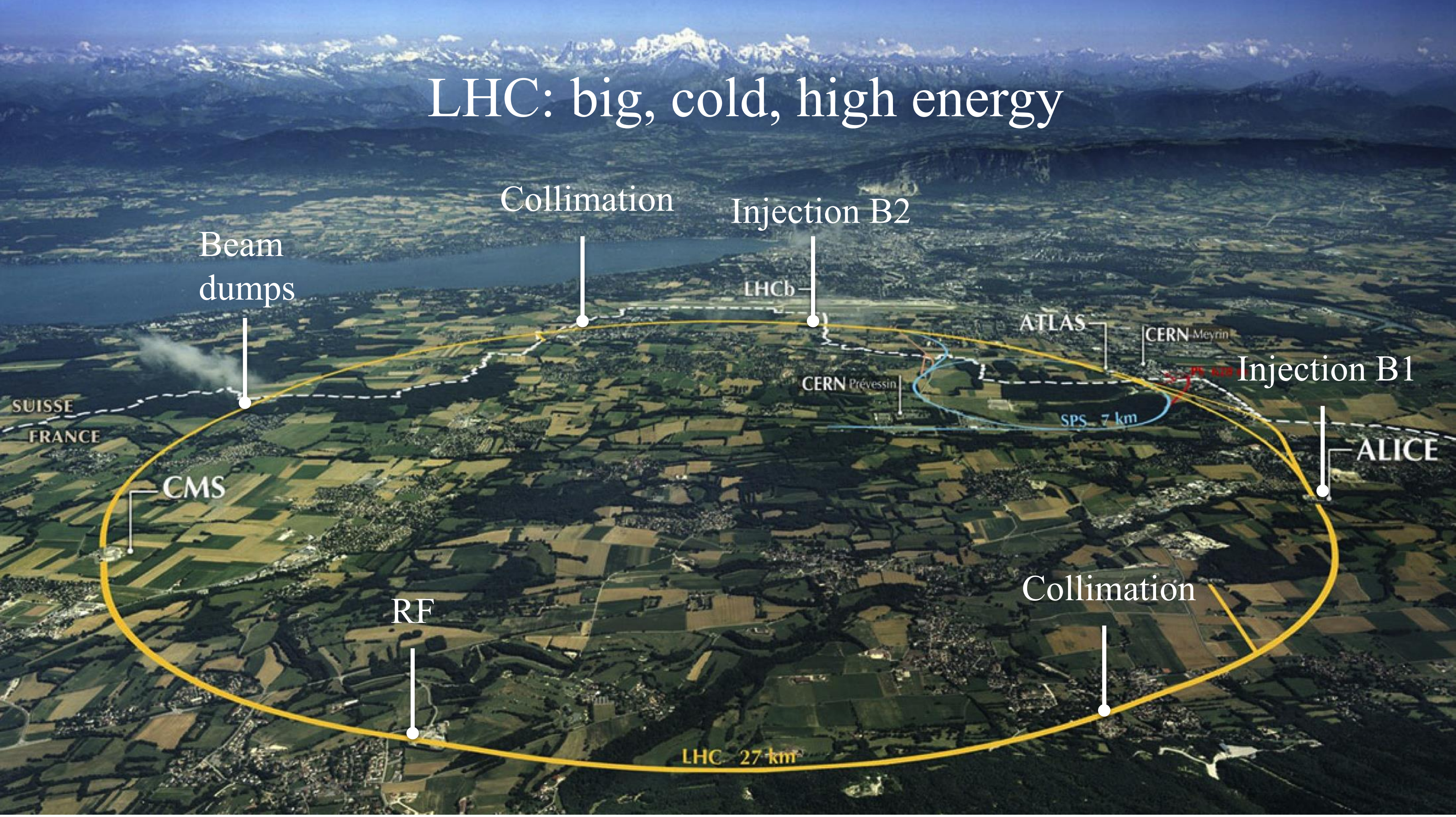


CRYOGENICS



- **24 km of superconducting magnets @1.9 K**
- **88 tons of superfluid helium at 1.9 K**

LHC: big, cold, high energy

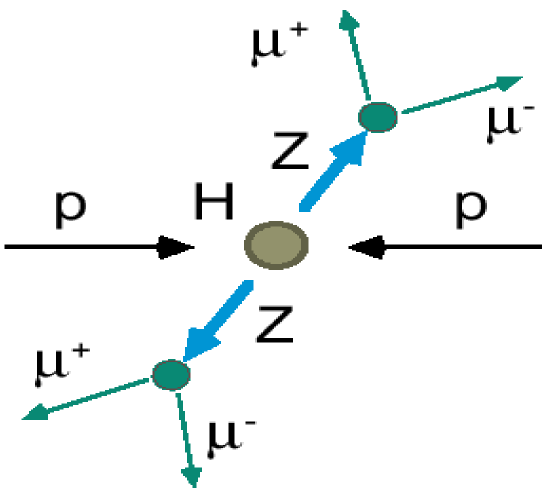


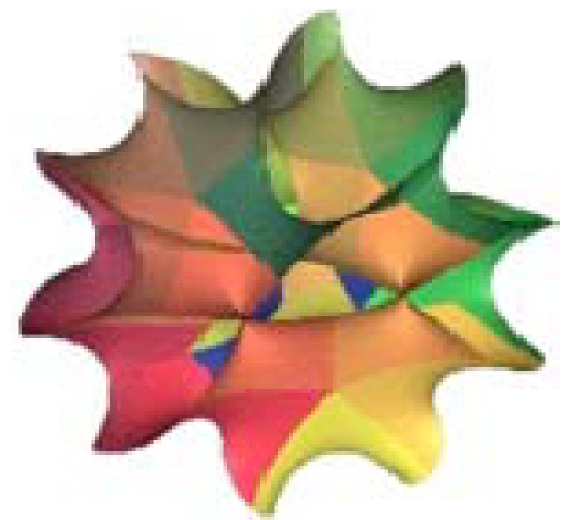
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

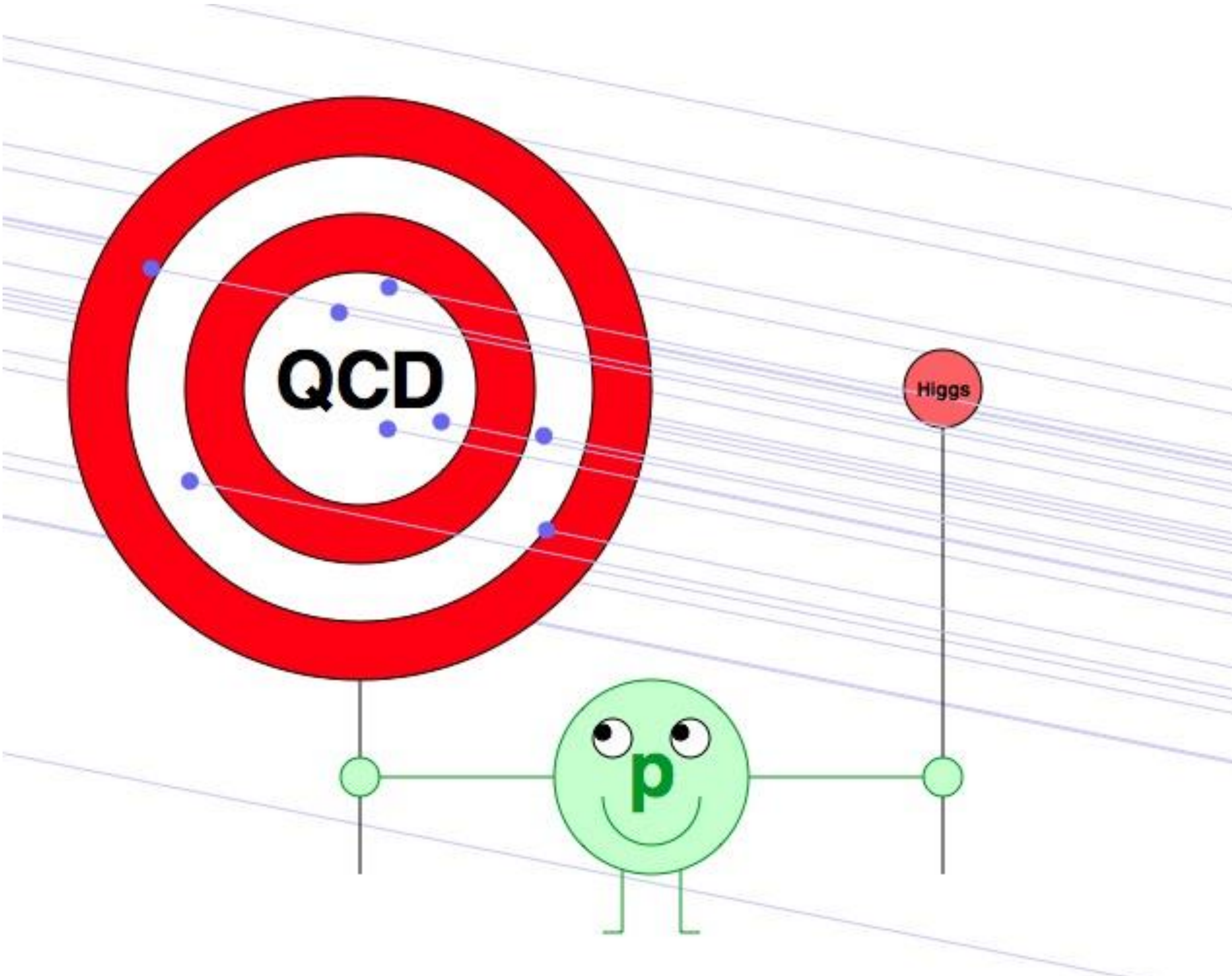
150 tonnes helium, ~90 tonnes at 1.9 K
250 MJ stored beam energy in 2016
1.2 GJ magnetic energy per sector at 6.5 TeV

Aim of the game

We want to deliver maximum number of collisions at the maximum beam energy for maximum physics reach

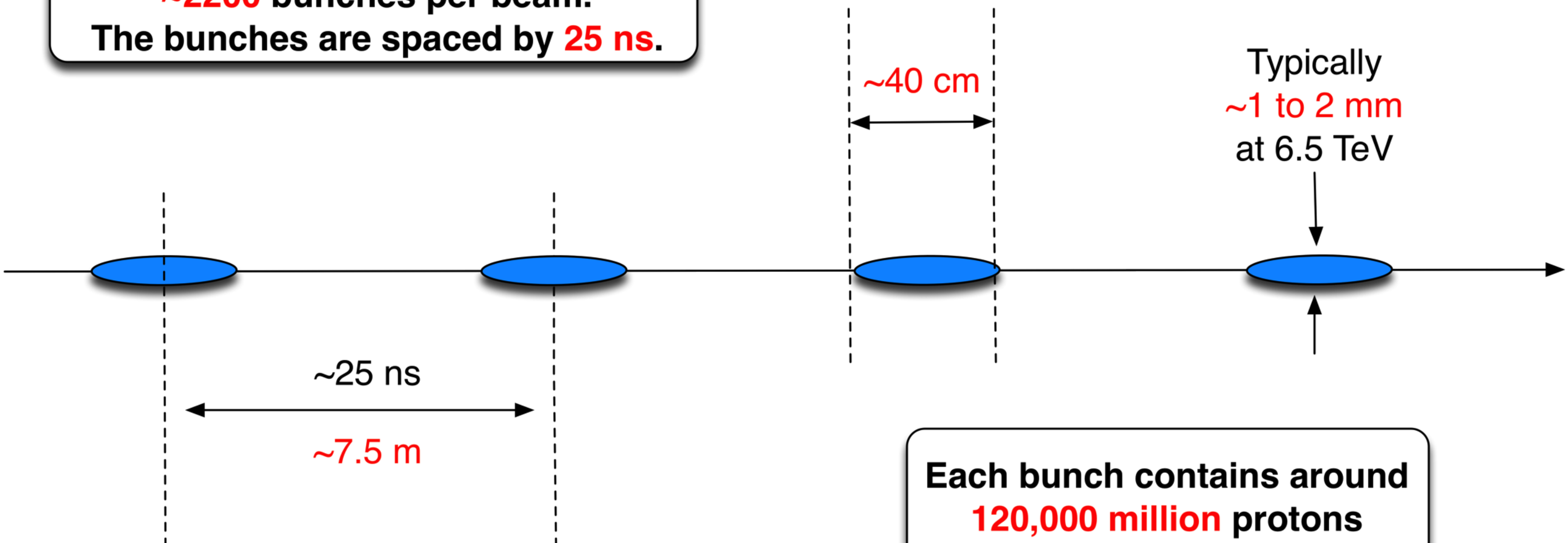




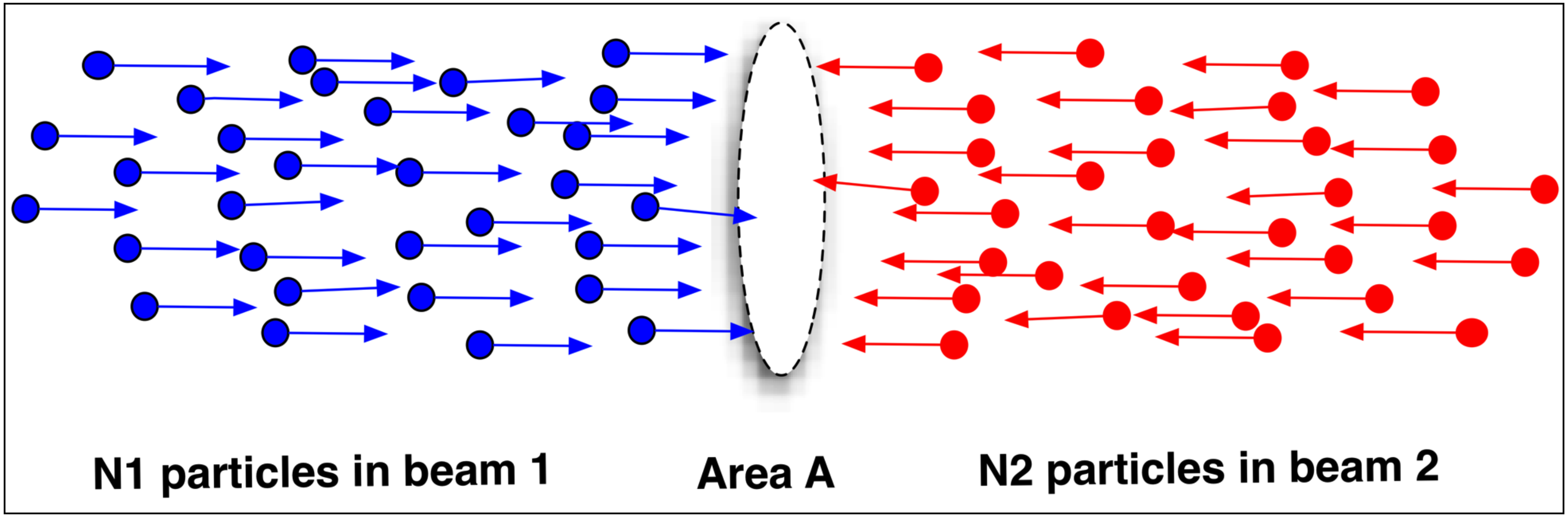

QCD
Higgs
p

Lots of bunches

In 2016 the LHC operated with ~2200 bunches per beam. The bunches are spaced by 25 ns.

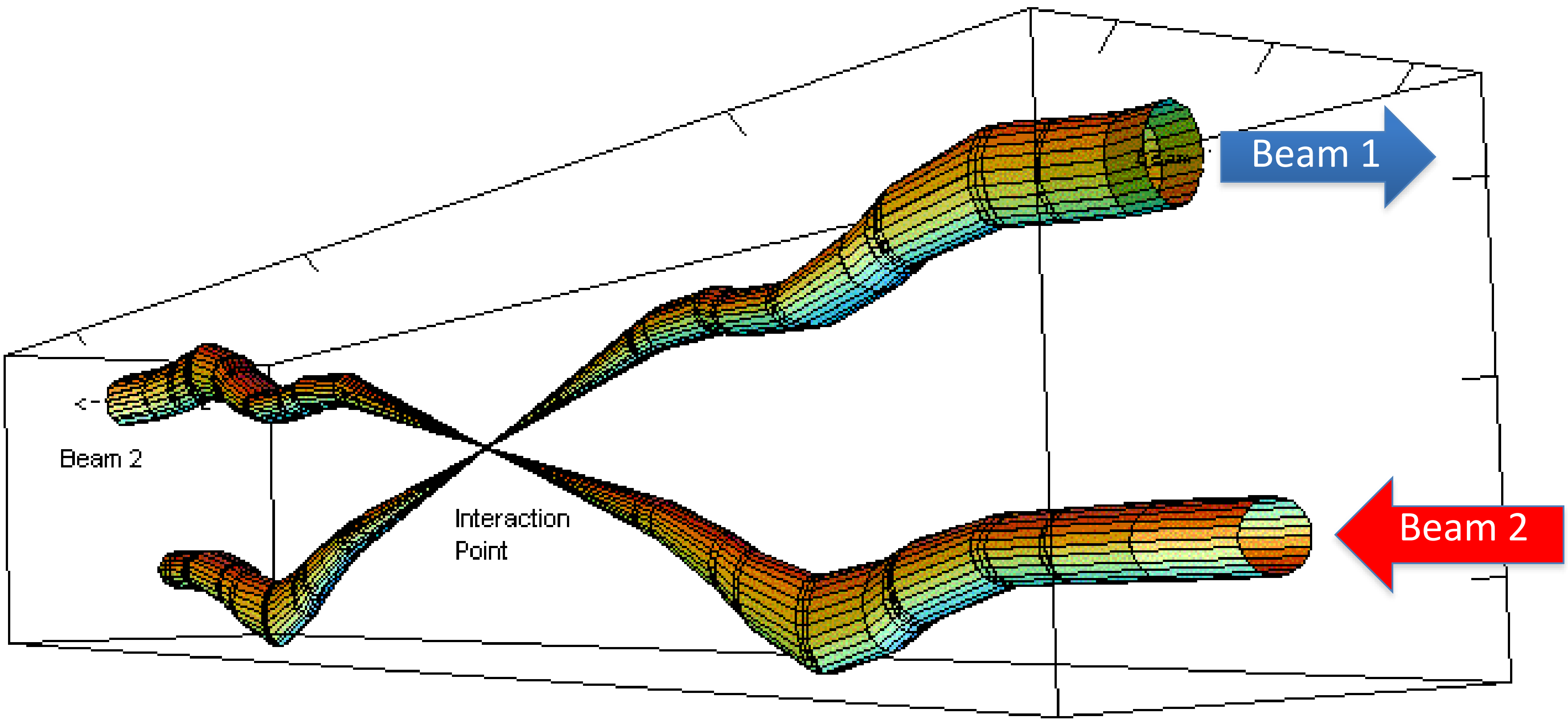


Each bunch contains around 120,000 million protons



$$\text{Number of potential collisions per unit area} = \frac{N_1 N_2}{A}$$

Squeeze



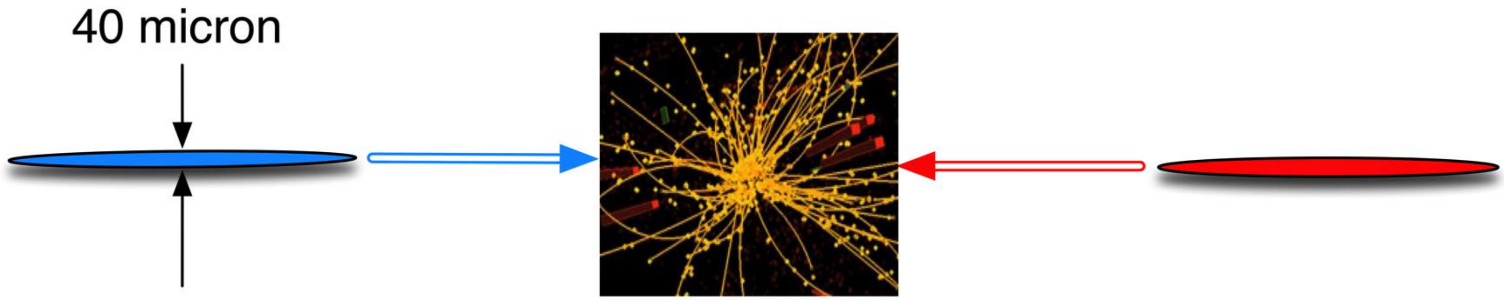
Relative beam sizes around IP1 (Atlas) in collision

Focus beam down to very small sizes in the experiments using quadrupole magnets

Triplet

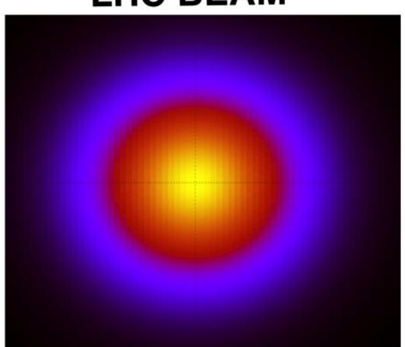
Video 58’’

120,000,000,000 protons a bunch
~40 collide at each bunch crossing

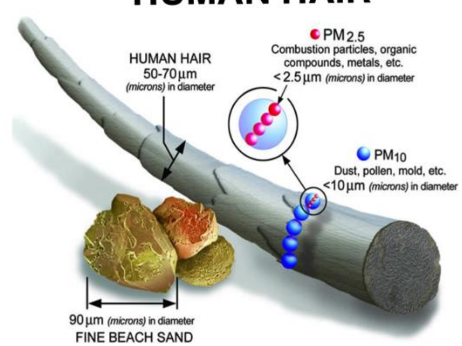


~40 collisions per crossing
11,000 crossings per second per bunch
2200 bunches
~1000 million collisions per second

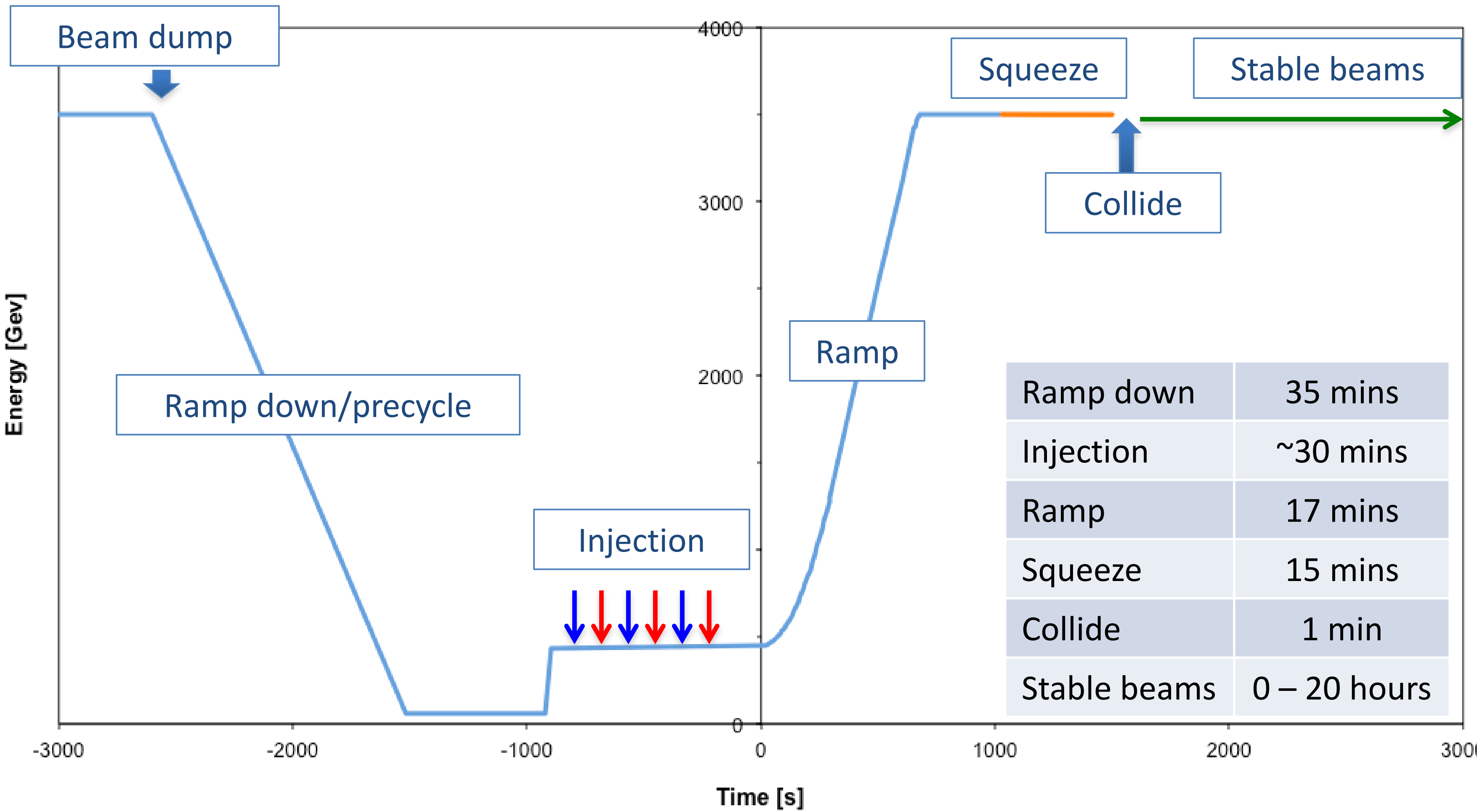
LHC BEAM



HUMAN HAIR



A day in the life of the LHC

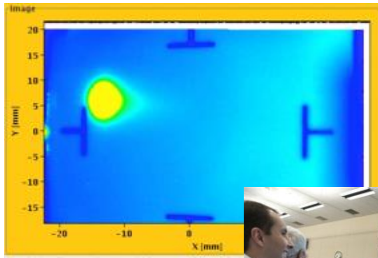


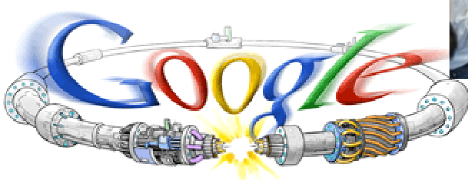
Ramp down	35 mins
Injection	~30 mins
Ramp	17 mins
Squeeze	15 mins
Collide	1 min
Stable beams	0 – 20 hours

TURN AROUND TIME ~3 hours

LHC Run 1

August 2008
First injection test



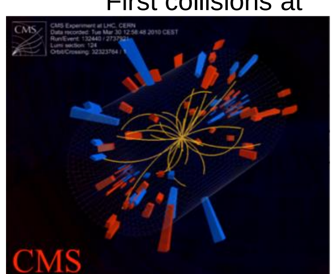


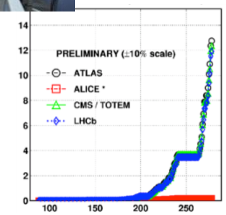
September 10, 2008
First beams around

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

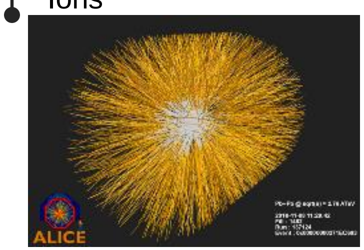
March 30, 2010
First collisions at





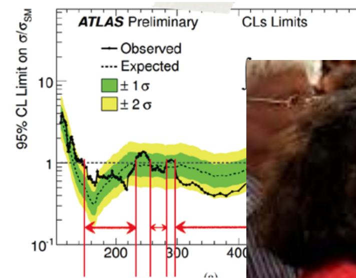
October 14 2010
1e32
248 bunches

November 2010
Ions



June 28 2011
1380 bunches

1380



August
2.3e33, 2
1380 bur

6 June, 2012
6.8e33

18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

4 July, 2012

2008 | 2009 | 2010 | 2011 | 2012

September 10th 2008

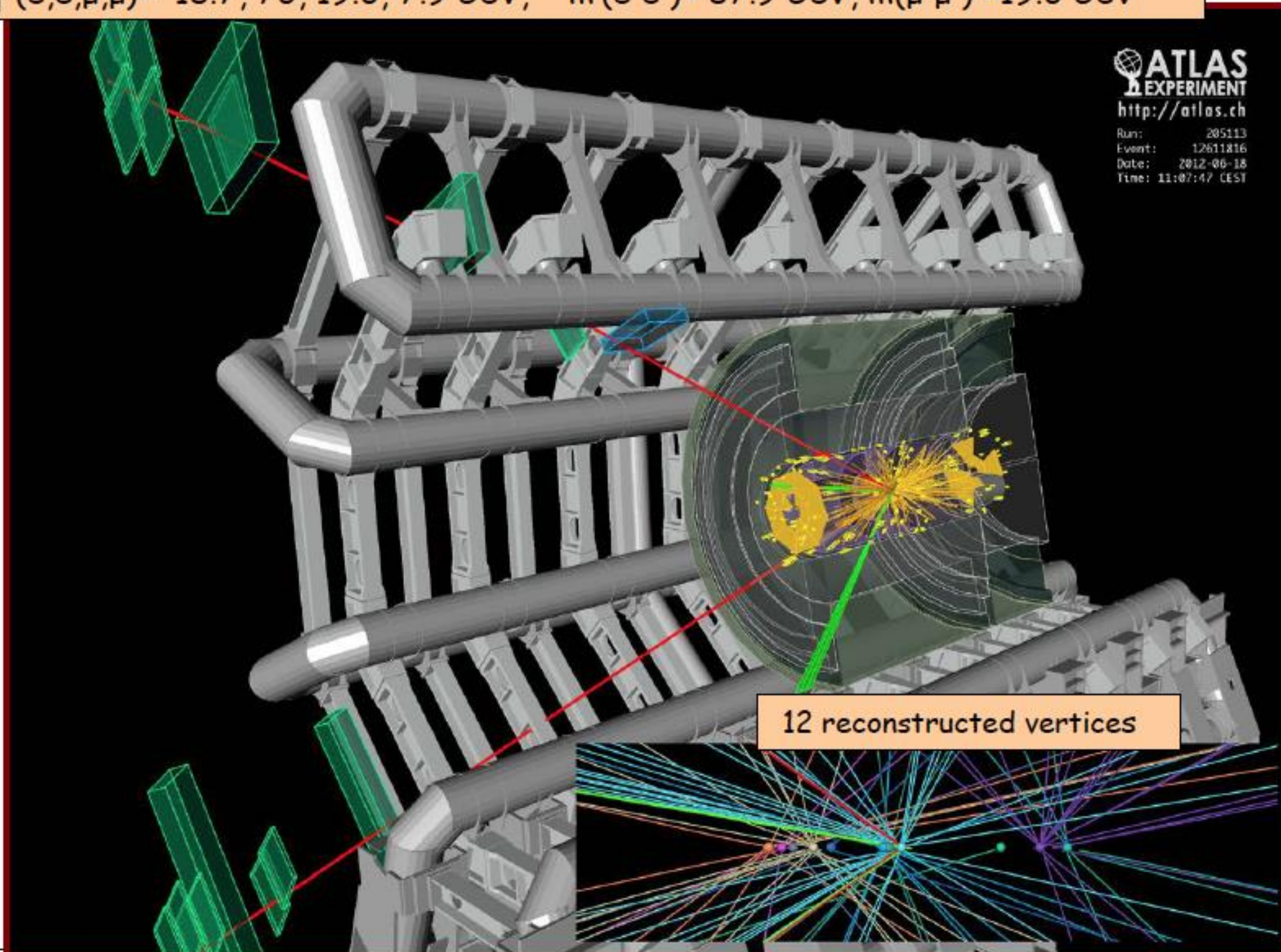
Restart 2009

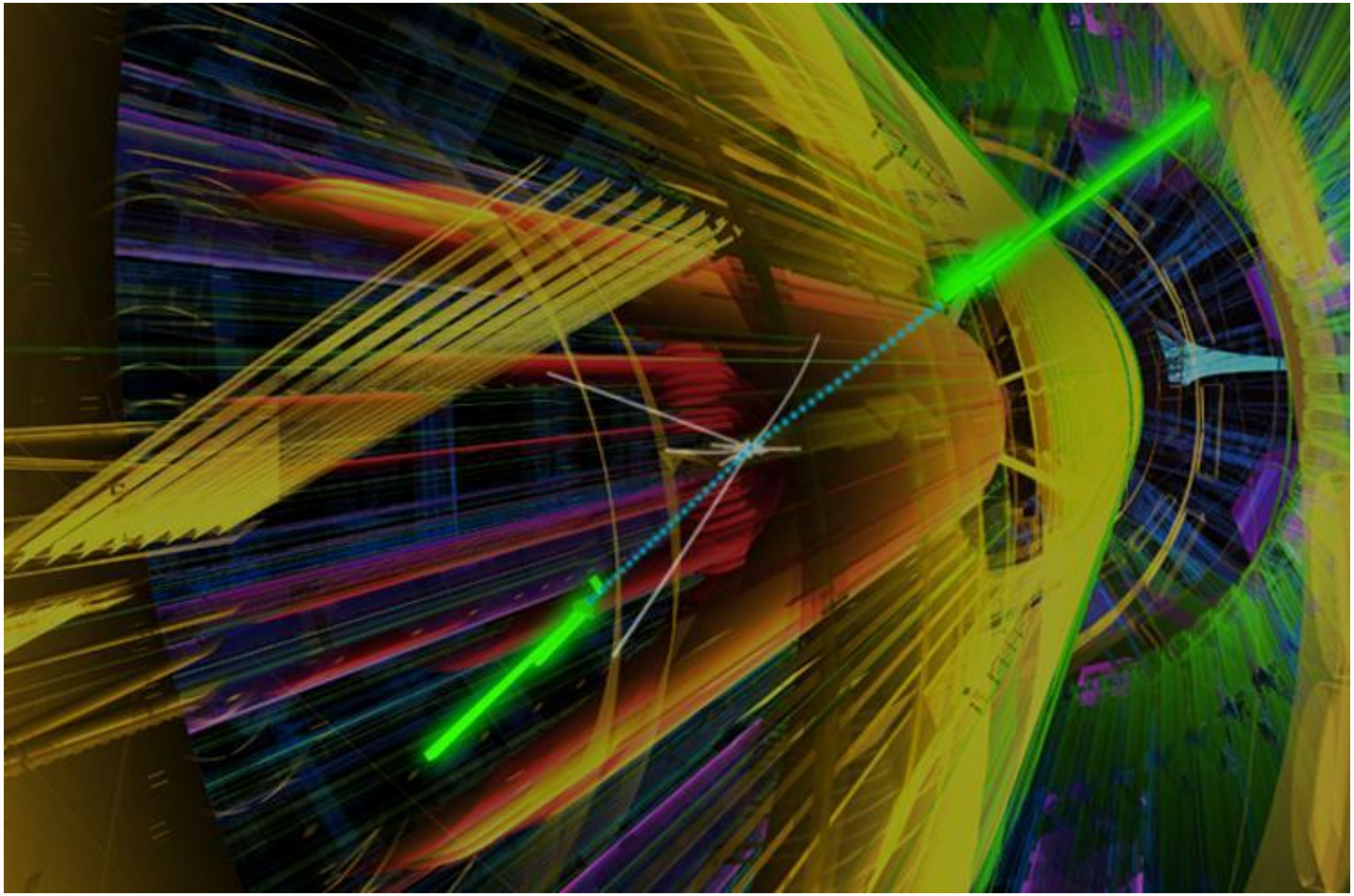
First physics at 3.5 TeV – March 30 2010

We delivered 5.6 fb^{-1} to Atlas in 2011 and all we got was a blooming tee shirt

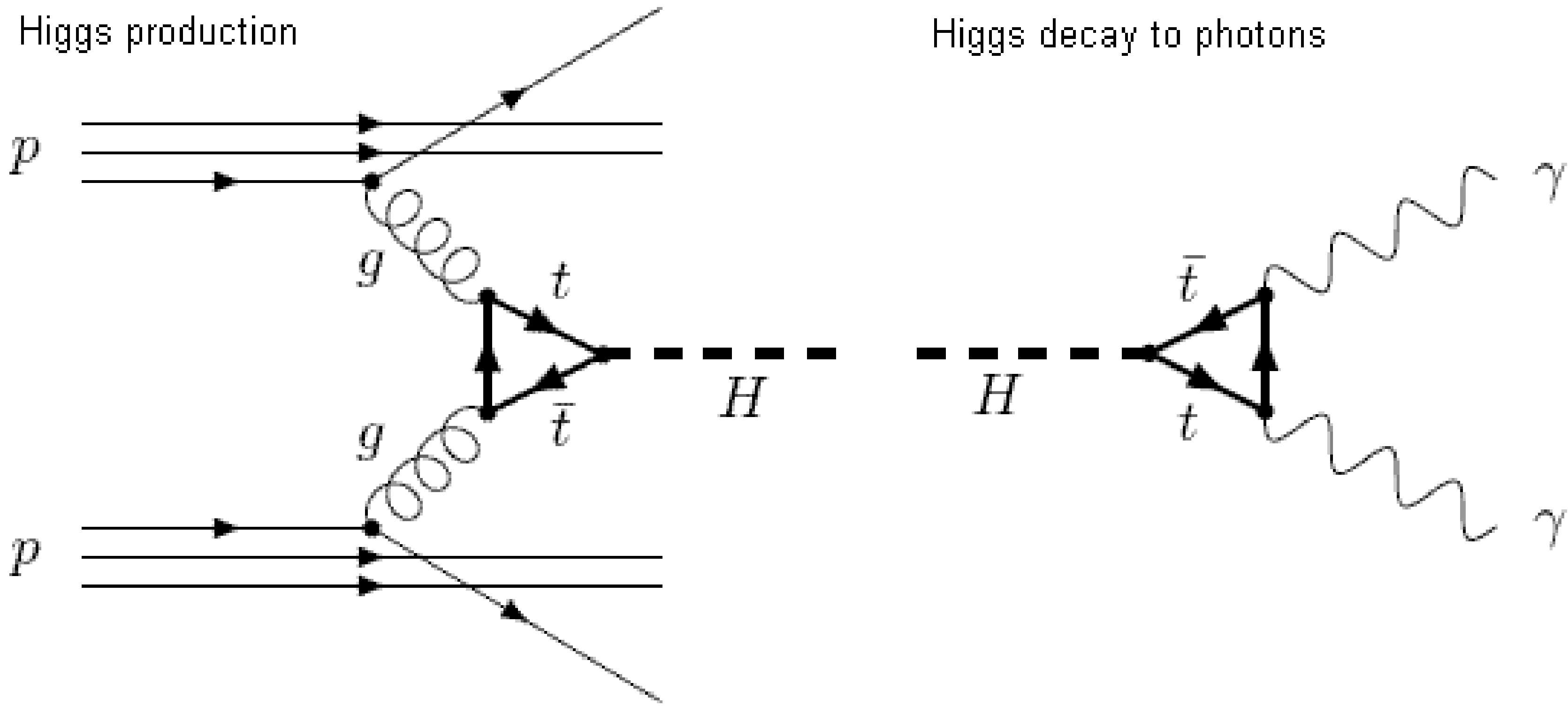
2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV





July 4th 2012: discovery of Higgs at the LHC

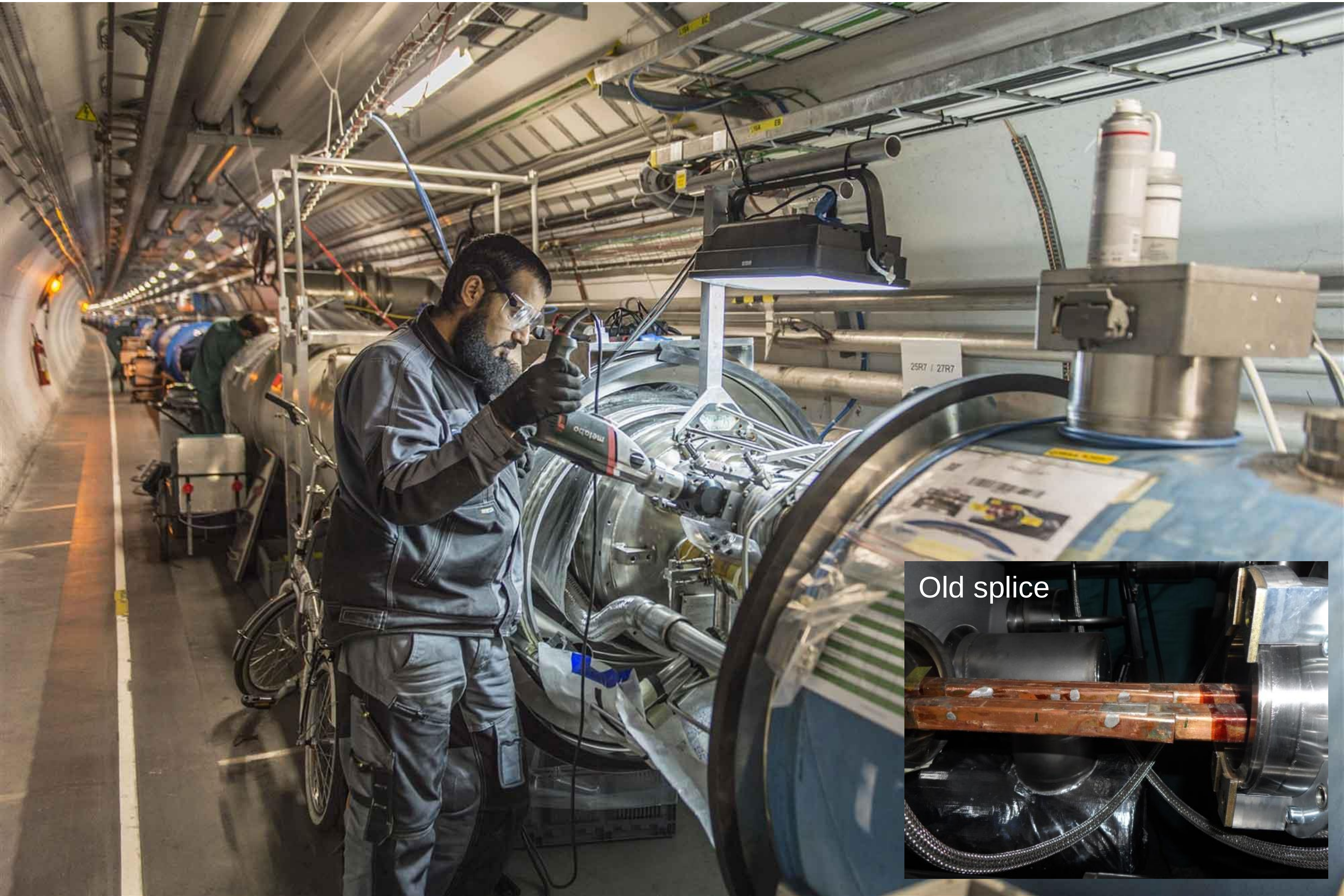


Higgs production
Higgs decay to photons
p
p
g
g
t
t̄
H
H
t̄
t
γ
γ

With a quadrillion collisions…

0.5 and 0.25 million dollar

Open heart surgery



Run 2

2013 - 2015

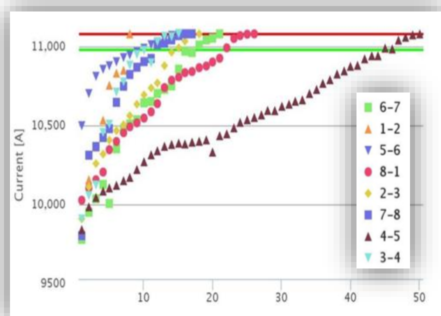
April ‘13 to Sep. ‘14

5th April

3rd June
First Stable Beams

28th October
Physics with record number of bunches
Peak luminosity 5 x 10^{33} $cm^{-2}s^{-1}$

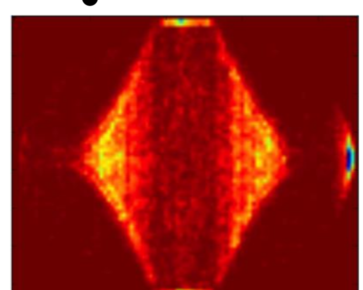
13-14 | Aug 14-Apr 15 | 2015



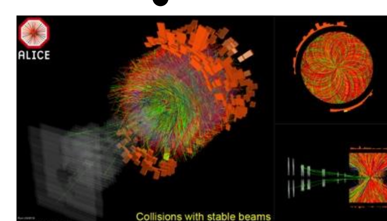
Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



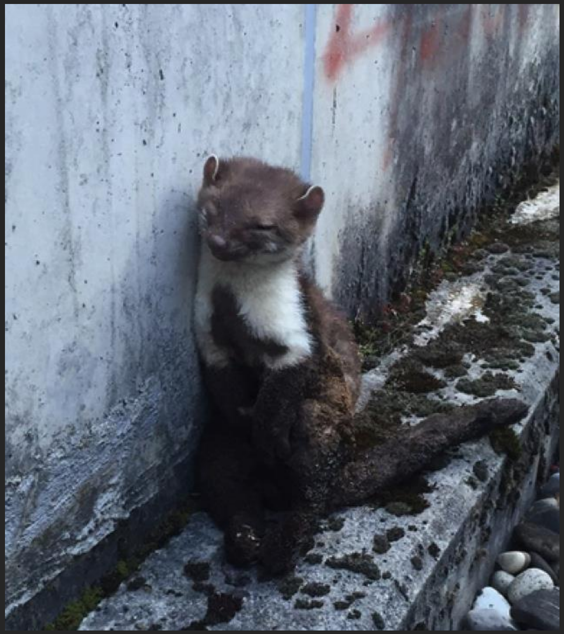
IONS



Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

2016 - Overcome a few problems

WEASEL

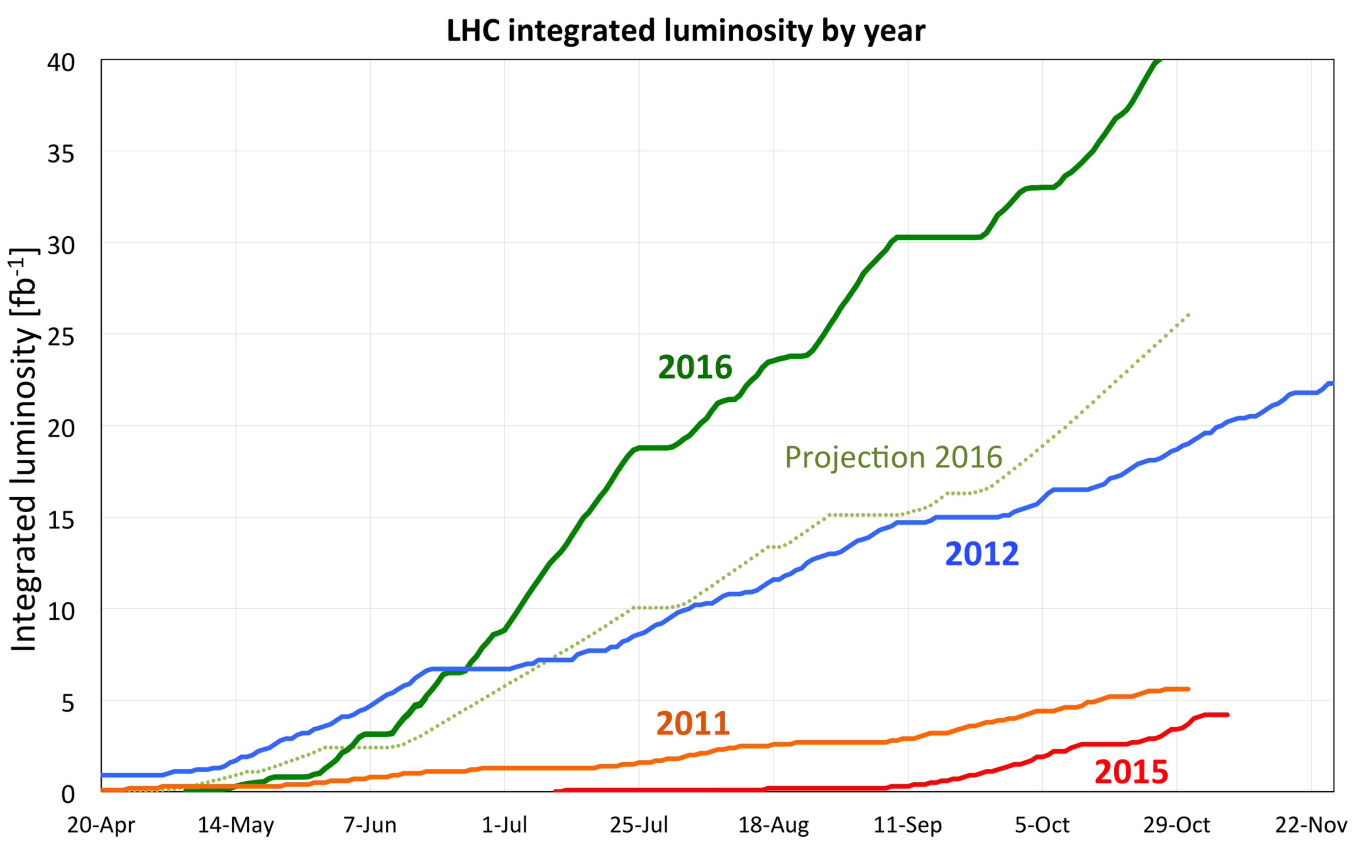


PS MAIN POWER SUPPLY

SPS BEAM DUMP

- Limited to 96 bunches per injection
- Max. 2220 bunches per beam instead of 2750

Design luminosity reached



2016 was huge!

What did we accomplish so far ?

Three main results from LHC Run-1

We have consolidated the Standard Model
(wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)
→ it works BEAUTIFULLY ...

We have completed the Standard Model: Higgs boson discovery
(almost 100 years of theoretical and experimental efforts !)

We have NO evidence of new physics

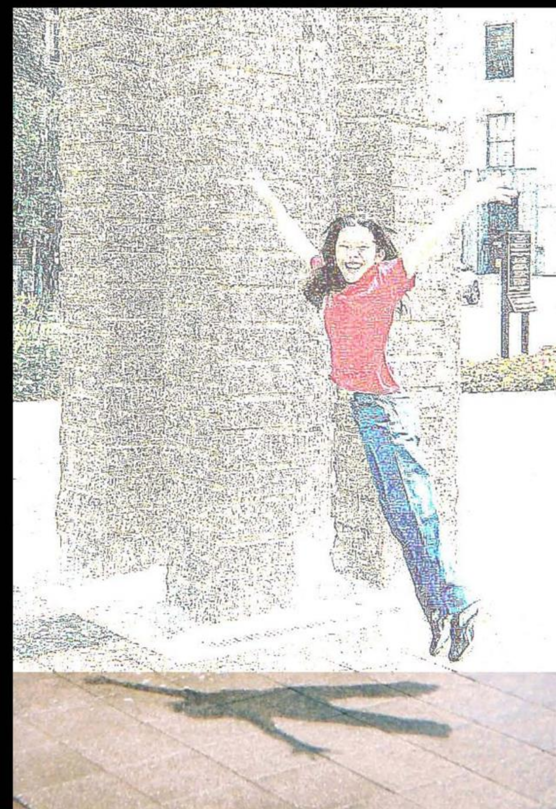
Note: the last point implies that, if New Physics exists at the TeV scale and is discovered at $\sqrt{s}$ ~ 14 TeV in 2015++, its spectrum is quite heavy → it will require a lot of luminosity (→ HL-LHC 3000 fb^{-1}) and energy to study it in detail → implications for future machines (e.g. most likely not accessible at a 0.5 TeV LC)

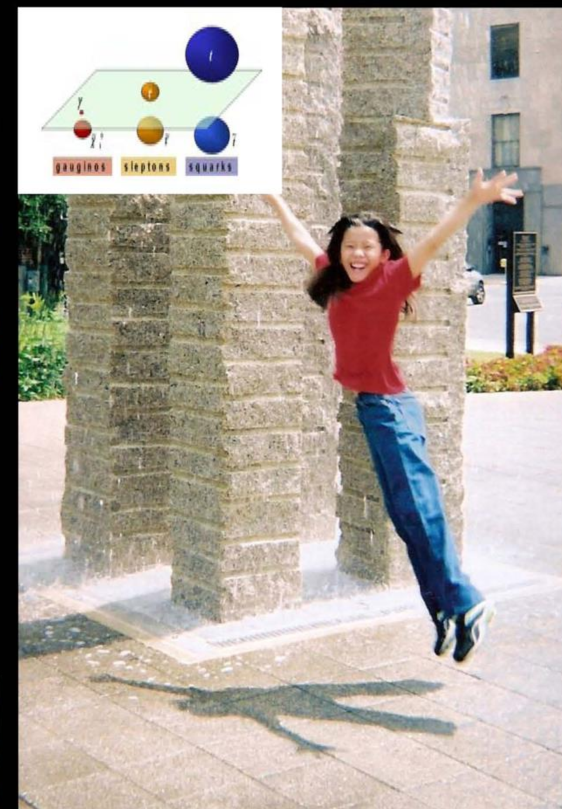
F. Gianotti, RLIUP, 28/10/2013

TEV → LHC → ILC

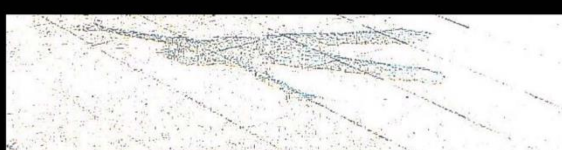
E

LHC **ILC**



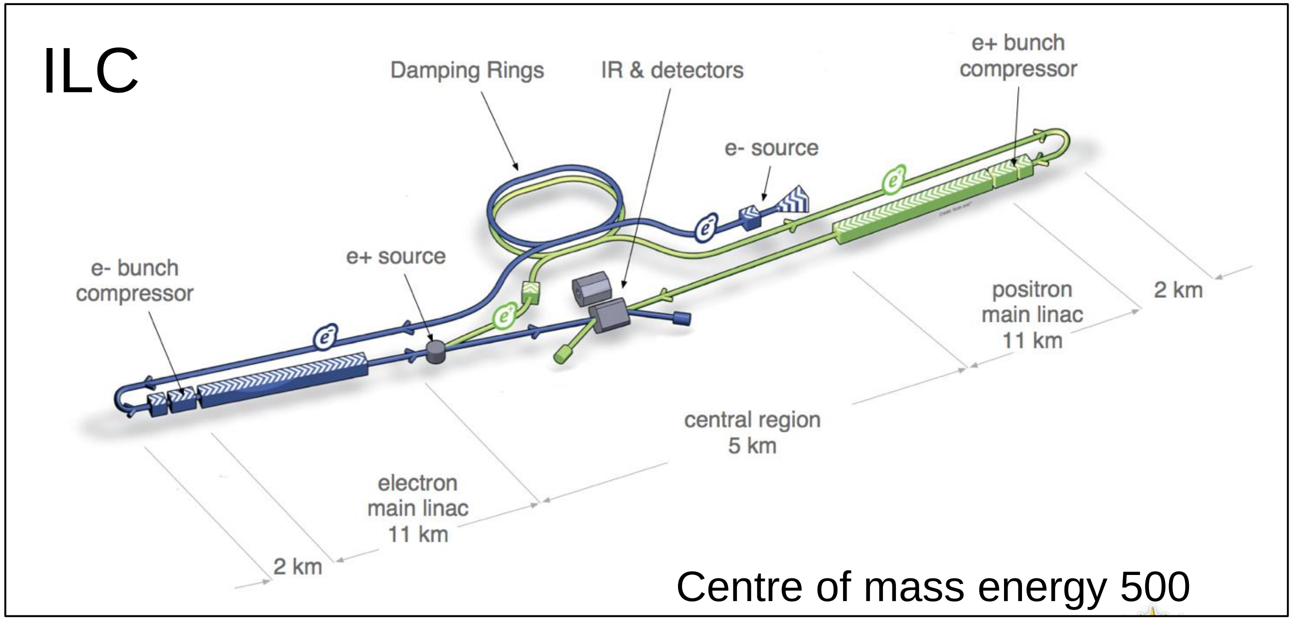


Tevatron
HERA
LEP2



Precision

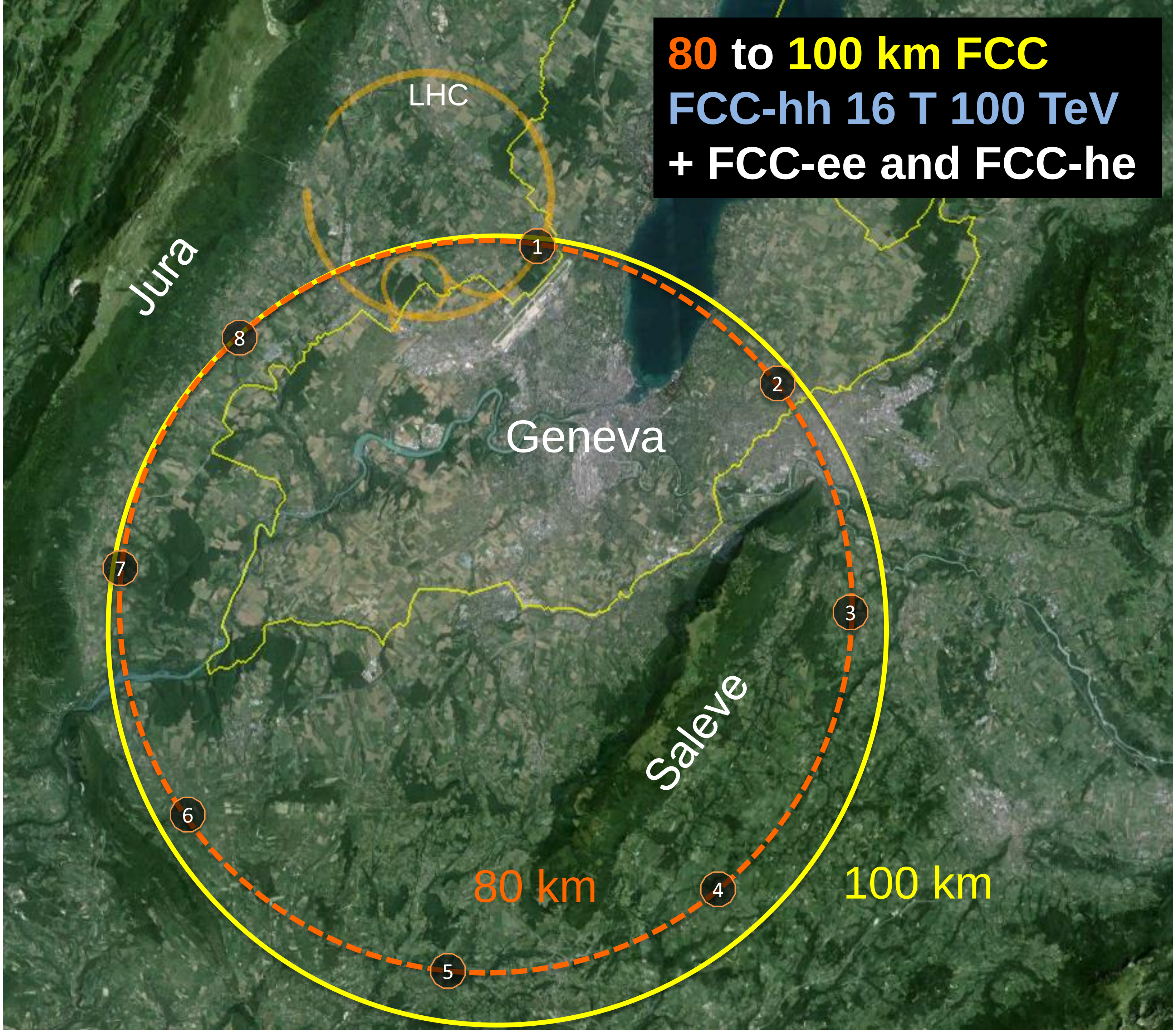
Linear Colliders



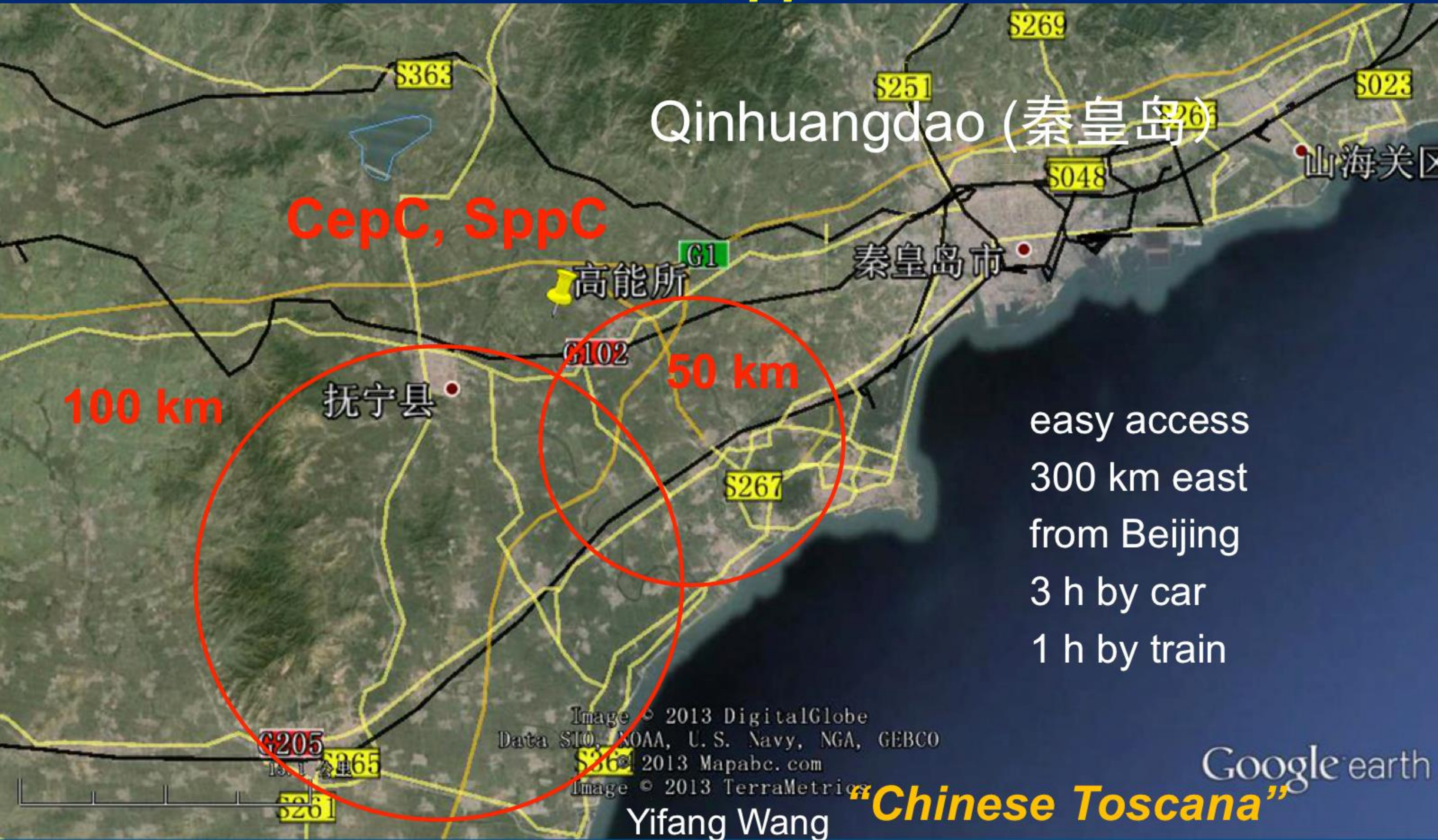
Centre of mass energy 500 GeV

The Linear Collider Collaboration bring the ILC and CLIC together under one roof. Headed by former LHC Project Manager Lyn Evans…

ILC cryomodule


80 to 100 km FCC
FCC-hh 16 T 100 TeV
+ FCC-ee and FCC-he
LHC
Jura
Geneva
Saleve
1
2
3
4
5
6
7
8
80 km
100 km

CepC/SppC study (CAS-IHEP) 54 km (baseline)
e^+e^- collisions ~2028; *pp* collisions ~2042



easy access
300 km east
from Beijing
3 h by car
1 h by train

"Chinese Toscana"

Yifang Wang

Big Bang ↔ Little Bangs

- The matter content of the Universe
  - Dark matter
  - Dark energy
  - Origin of matter

- Experiments at particle colliders
  - Early Universe
  - Supersymmetry
  - Matter-antimattter asymmetry

Learn particle physics from the Universe
Use particle physics to understand the Universe

John Ellis

Conclusion

We still live in exciting times!

Peter Higgs, François Englert y Sergio Bertolucci, director de investigación del CERN, participan en un encuentro científico en la Facultad de Ciencias de la Universidad de Oviedo. Foto: © Iván Martínez/FPA

"Much more interesting to live no knowing than to have answers which might be wrong." Richard Feynman