Introduction to particle accelerators

S. Gilardoni SY/STI,

What are we doing today ?

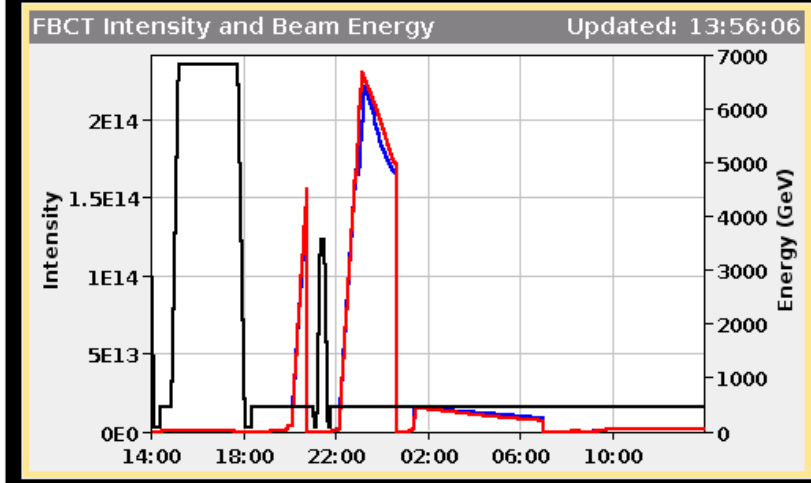
https://op-webtools.web.cern.ch/vistar/vistars.php

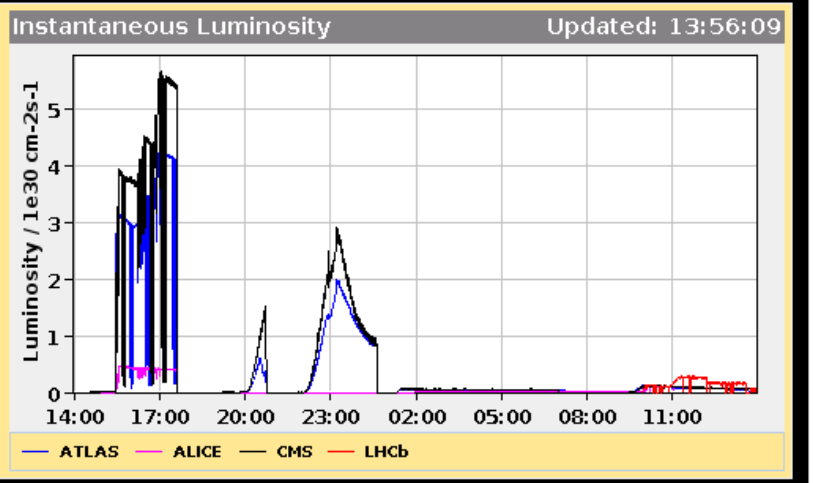
LHC Page1 | Fill: 7822 | E: 450 GeV | t(SB): 04:00:18 | 20-06-22 13:56:08

PROTON PHYSICS: STABLE BEAMS

Energy:	450 GeV	I B1:	1.11e+12	I B2:	1.33e+12

Inst. Lumi [(ub.s)^-1] IP1: 0.05 IP2: 0.05 IP5: 0.05 IP8: 0.00





Comments (20-Jun-2022 13:19:22)
** STABLE BEAMS **
16 bunches per beam, 8 collisions per IP

gas injection at the BGC (point 4)

we will keep this fill until ~14:00, then access

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_16b_8_8_8_noLR2

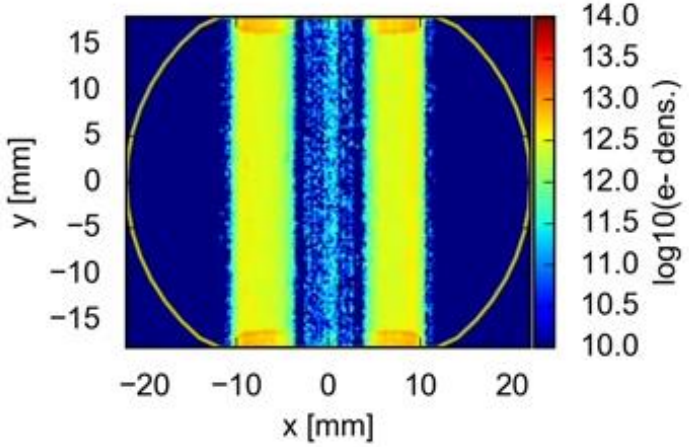
PM Status B1 ENABLED PM Status B2 ENABLED

Electron clouds and scrubbing

G. Iadarola

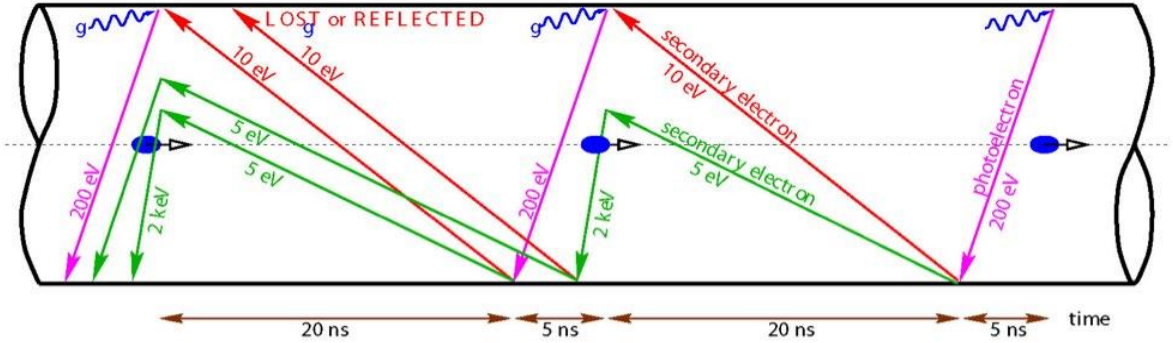
Electron cloud in the vacuum beam pipe can be created by "avalanche" process :

1. few primary **e⁻ generated** by as photoelectrons, from residual gas ionization, extract by synchrotron radiation
2. **p+ bunches accelerate e⁻** (this depends frombunch separation, 25 nsec in LHC)
3. **e⁻ impact on the wall and extract secondary e⁻**

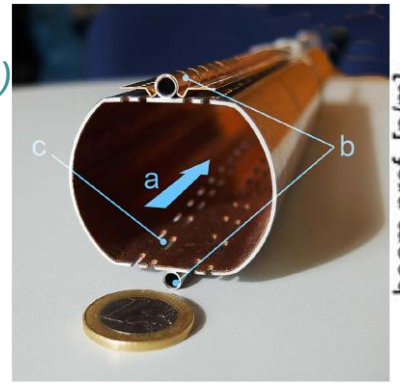


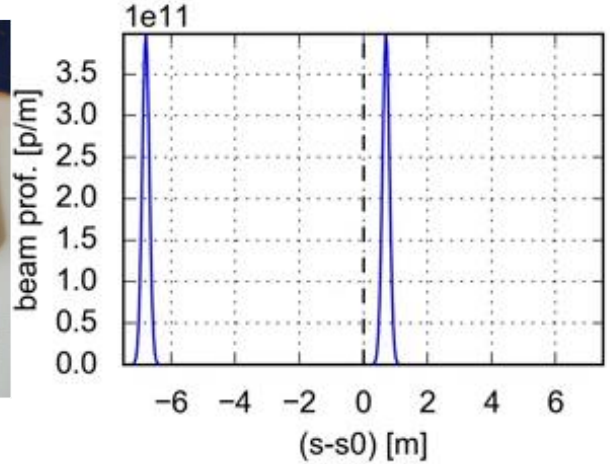
and so on ... and the cloud can generate:

a) heating of the beam pipe ⇒ magnet heating **b) beam instabilities**



(Courtesy F.Ruggiero)

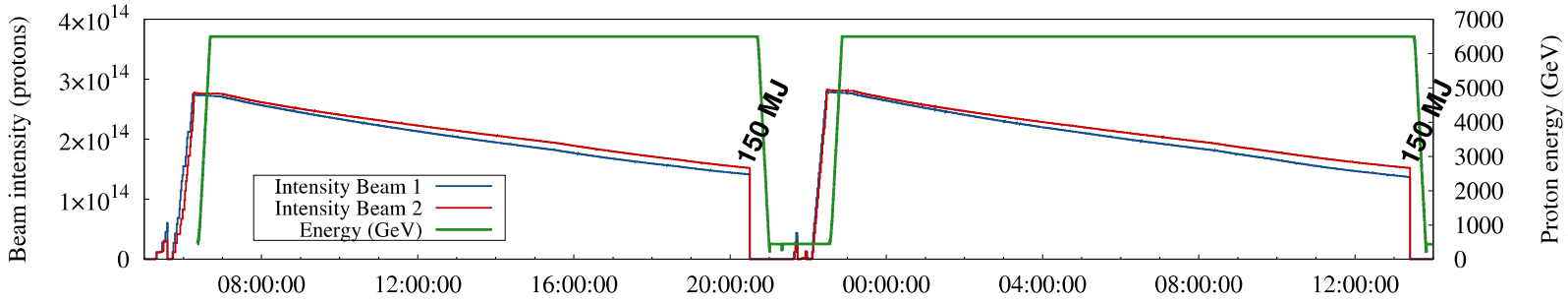




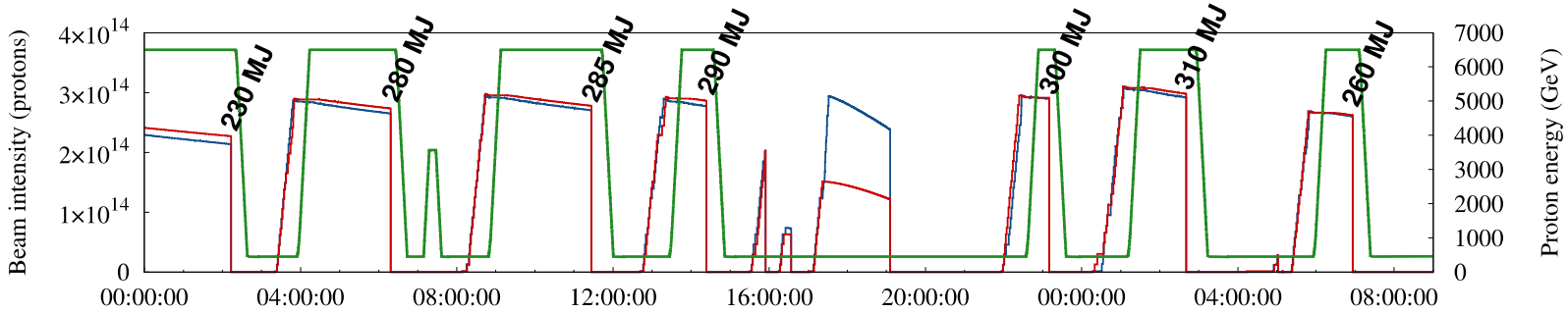
LHC cycles: typical days (good and bad ....)

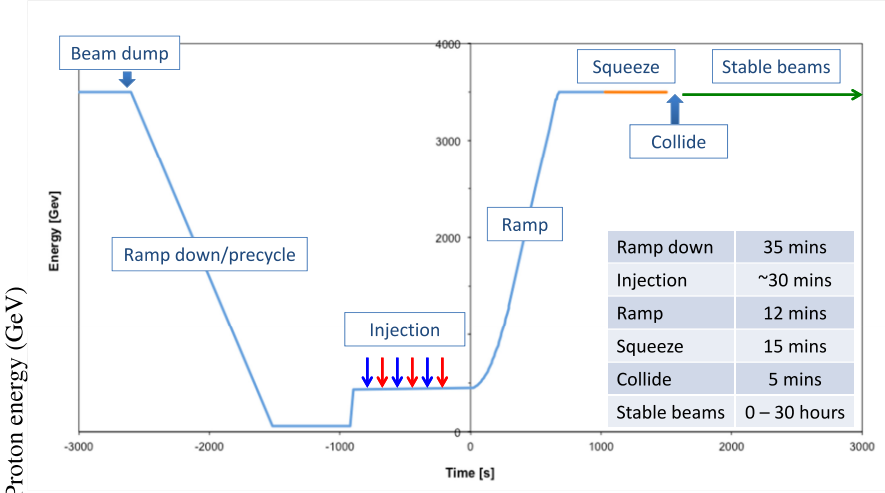
*Dumped energy = **proton energy** × **beam intensity** at the moment of beam extraction*

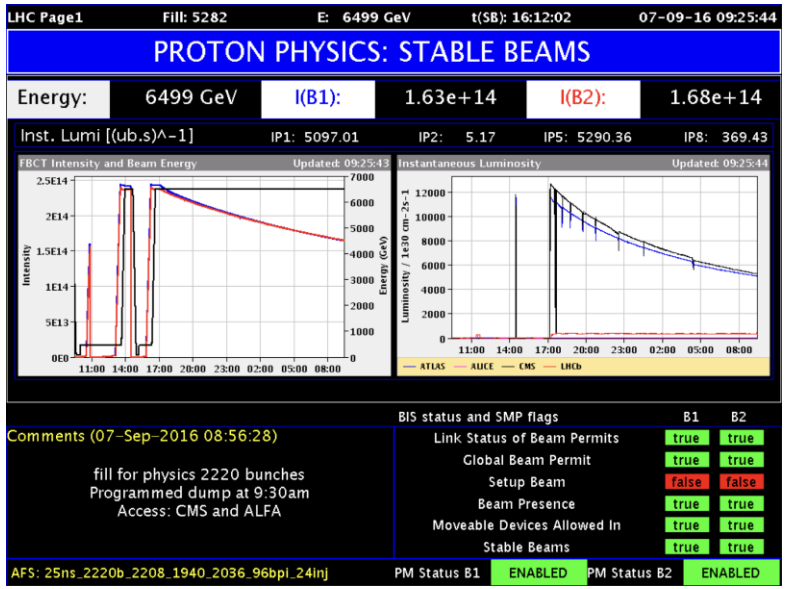
Good day:



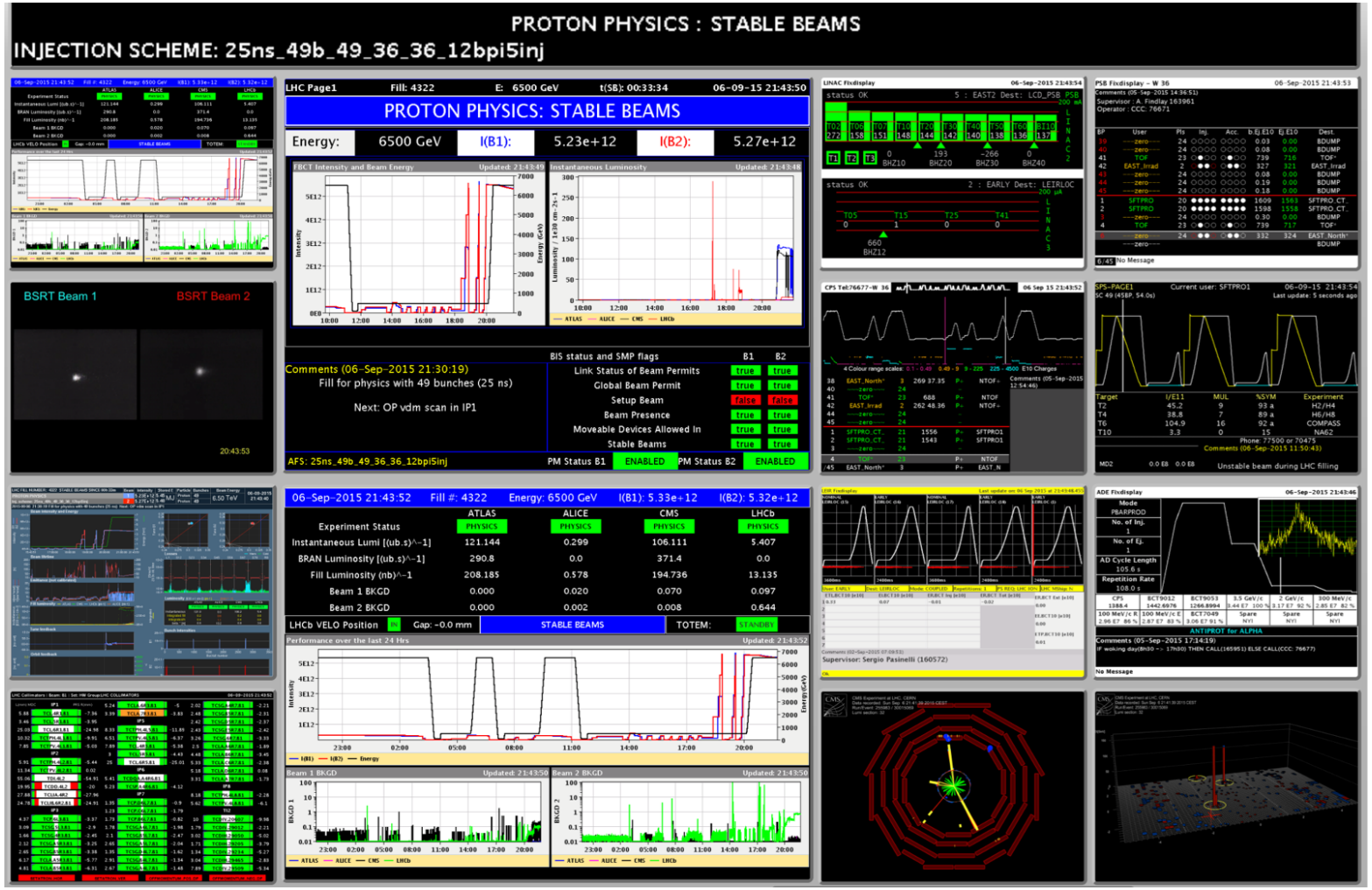
Bad day:





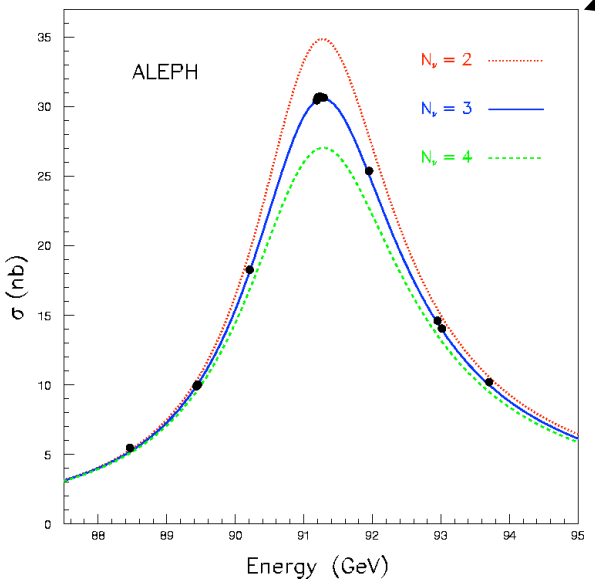


What we are doing today : CERN VISTARS



https://op-webtools.web.cern.ch/vistar/vistars.php

First question: what is the relationship between this, the moon, and a train?

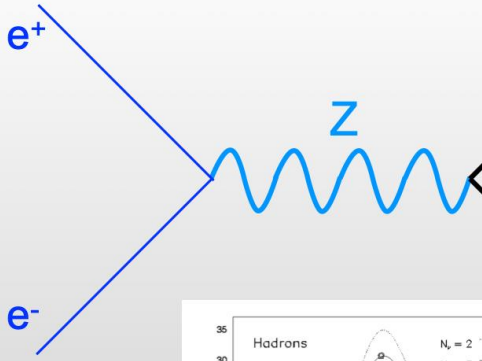


I diagrammi di Fey

Esempio 1: collisione e^+e^-

(semirigoroso)

LEP
105 GeV



$e^+, \mu^+, \tau^+, \nu_e, \nu_\mu, \nu_\tau$

$u, d, s, c, b \quad \times 3$

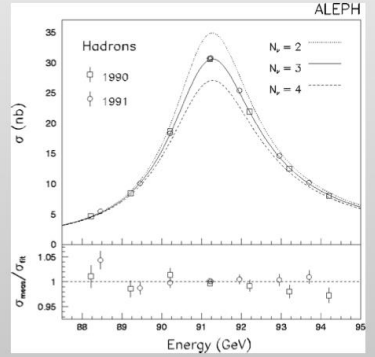
- ☑ *carica elettrica*
- ☑ *sapore leptonico indiv.*
- ☑ *colore*
- ☑ *sapore barionico tot.*

$\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b} \quad \times 3$

$e^-, \mu^-, \tau^-, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

La *larghezza* della Z permette di determinare il numero di famiglie:

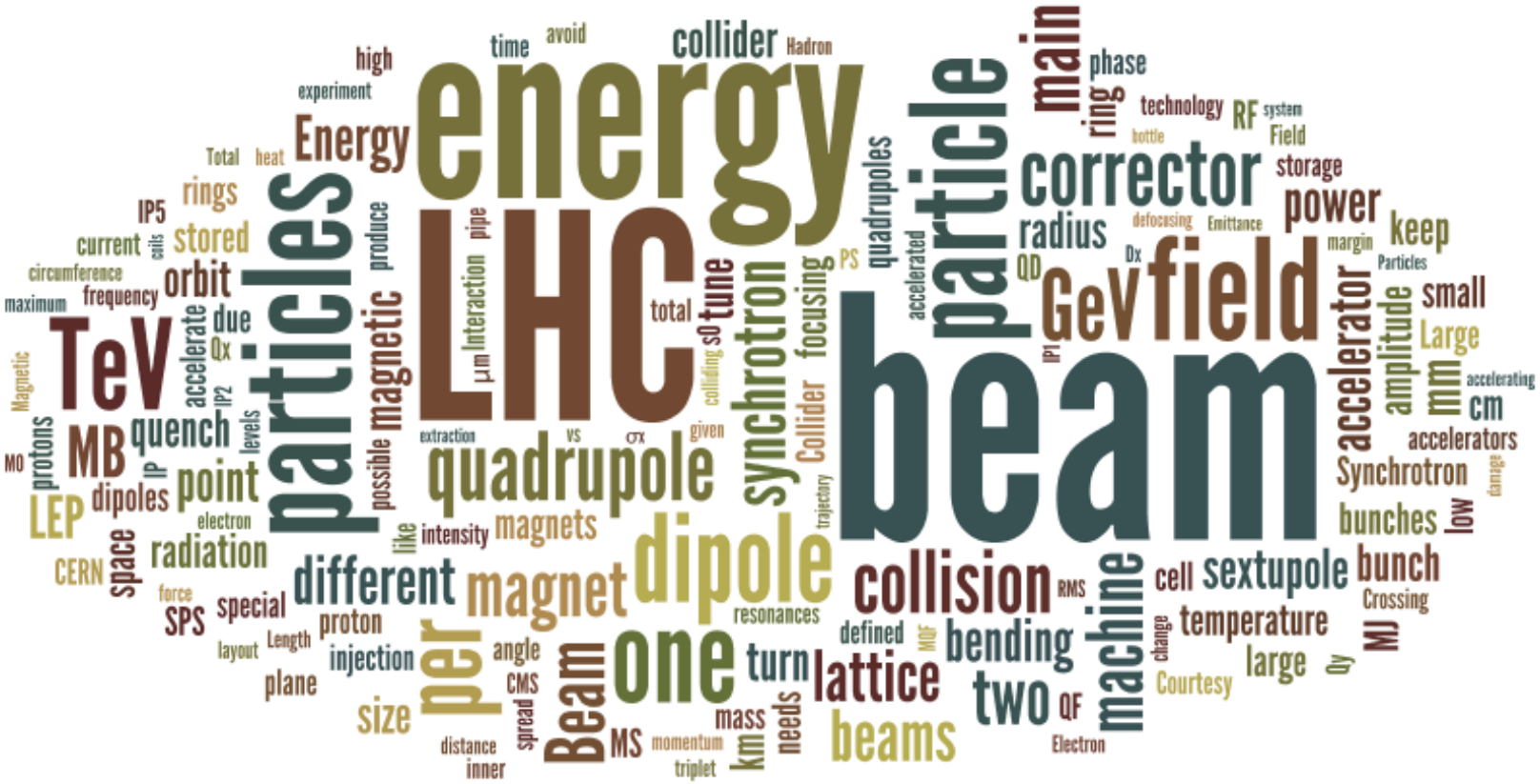
più canali aperti = decadimento più veloce = più larga



⇒ 3 famiglie!

(a meno che il quarto neutrino non abbia massa > ~45 GeV)

The agenda...


energy
LHC
beam
particle
particles
field
GeV
TeV
quadrupole
dipole
collision
corrector
accelerator
synchrotron
magnet
one
per
Beam
lattice
two
beams
machine
bending
sextupole
temperature
collider
main
power
keep
small
Large
amplitude
mm
cm
accelerators
Synchrotron
bunches
bunch
Crossing
MJ
low
cell
RF
technology
phase
ring
Field
storage
radius
defocusing
Emittance
Particles
margin
Dx
QD
accelerated
quadrupoles
focusing
Collider
tune
total
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Interaction
pipe
produce
magnetic
possible
extraction
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colliding
trajectory
intensity
like
magnets
different
proton
injection
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spread
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momentum
triplet
distance
inner
MS
resonances
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MQF
QF
Electron
RMS
change
Courtesy
large
Qy
Energy
high
experiment
time
avoid
Hadron
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IP5
current
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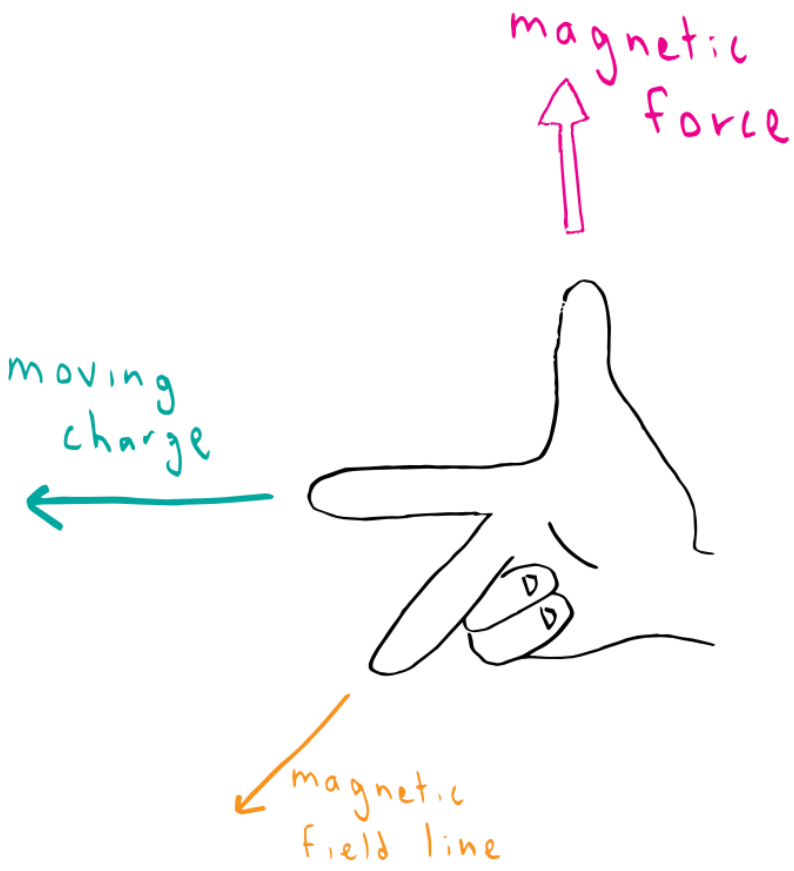
MJ
Qy
Courtesy
Electron
QF
MQF
IP1
PS
μm
σx
s0
μ
Qx
Dx
Qy

The “law” for these days : right hand rule



$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Interlude: a brief recall of energy scales

- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
  - Energy[GeV], Momentum [GeV/c], Masses [GeV/c^2]
    (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a rule of thumb: **0.511 MeV/c^2** (electron mass) corresponds to about **9.109 10^{-31} kg**

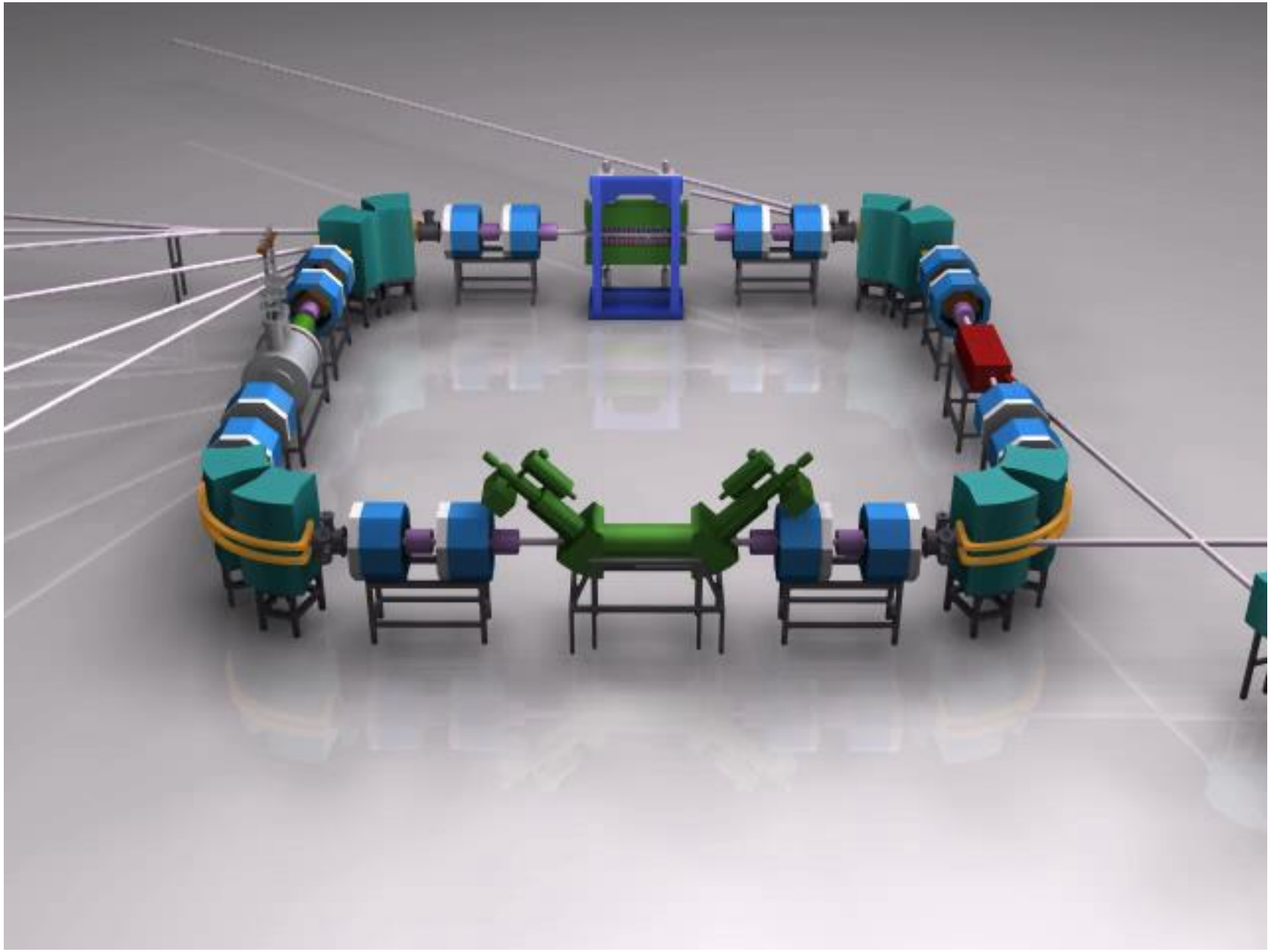
An Example about energy scales: my cellular phone battery.

Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to a proton mass:

1 GeV/3.7 eV = 270 270 270 batteries
270 270 270 batteries * 0.045 m ~ 12 000 000 m

12 000 000 m ~ THE EARTH DIAMETER

Obviously one has to find a smarter way to accelerate particles to high energies instead of piling up cellular phone batteries ....



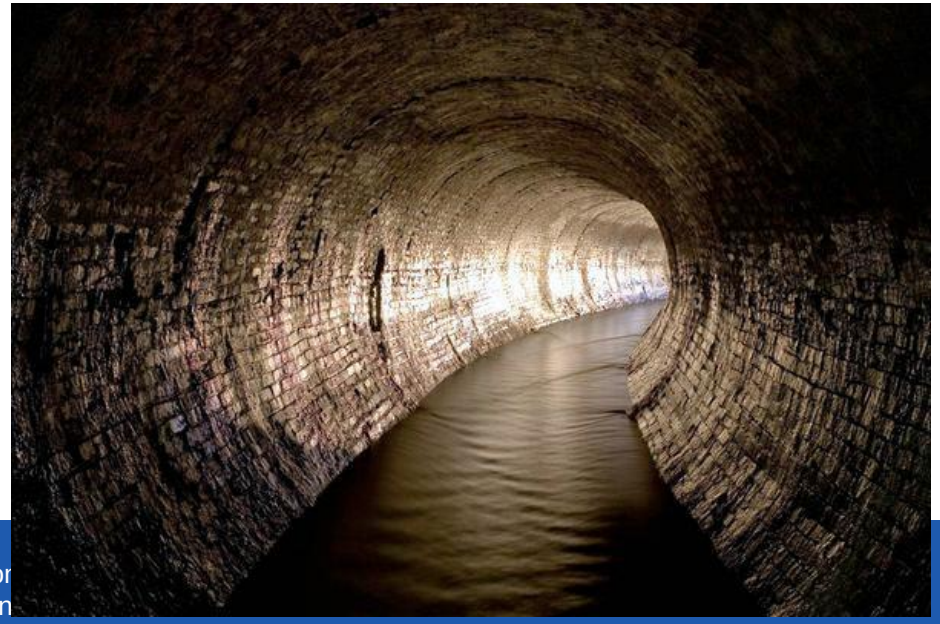
Electron Injection, Storage and Synchrotron Radiation Light Generation in the Storage Ring ASTRID. (Credit: Coldvision Studio/ISA)

Building Blocks of an accelerator

1) A particle source

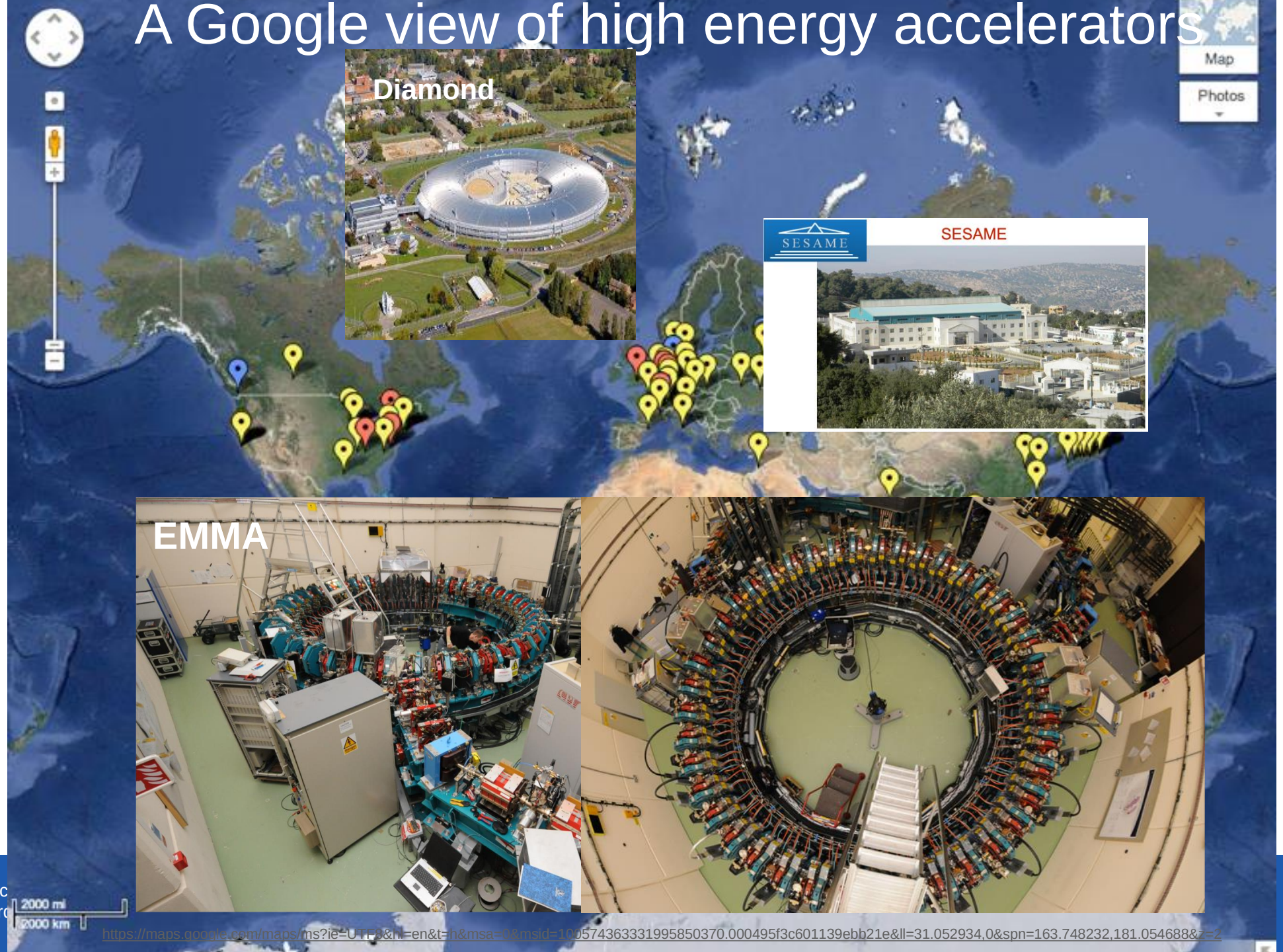
2) An accelerating system

3) A series of guiding and storage devices



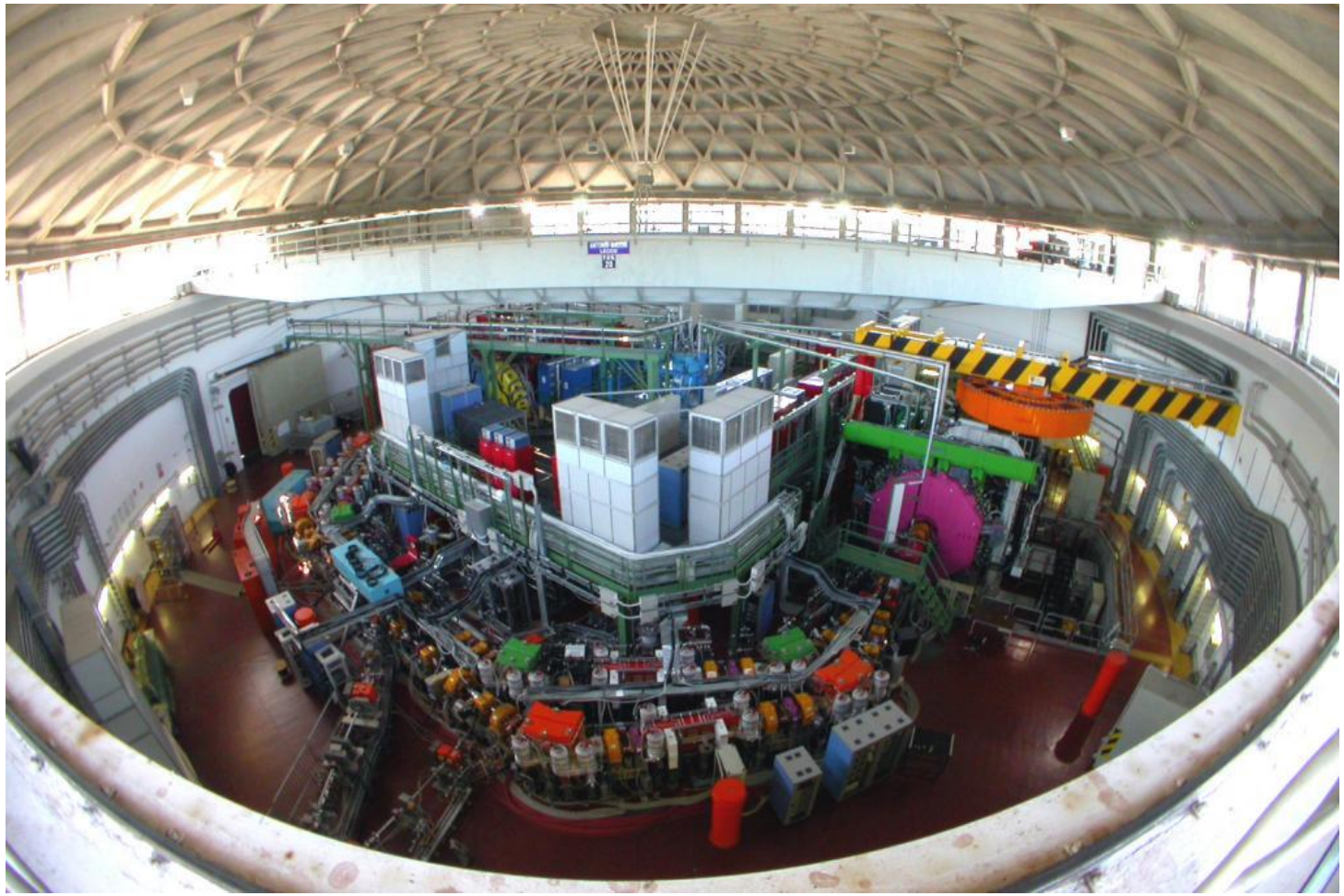
Everything under vacuum

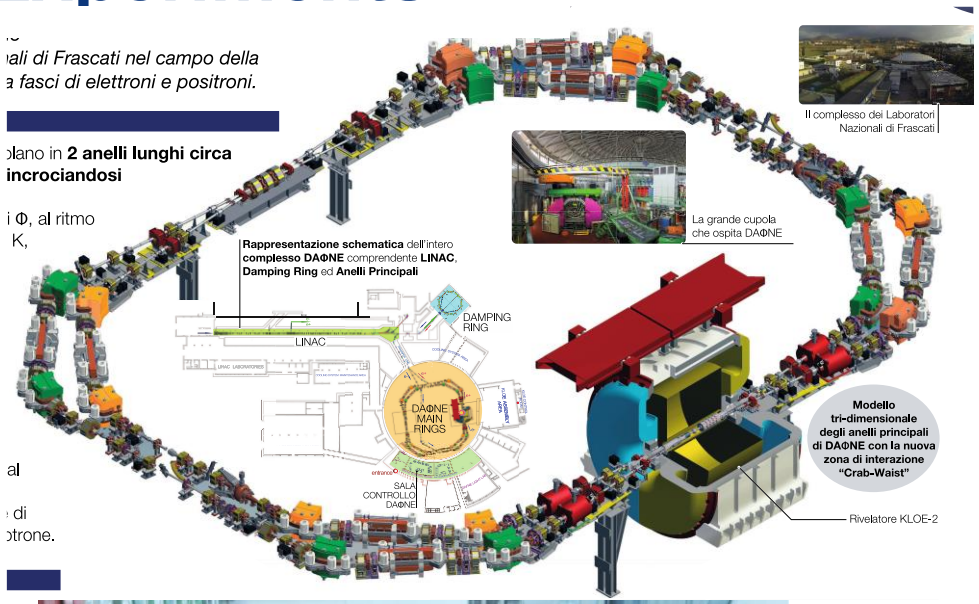
A Google view of high energy accelerators

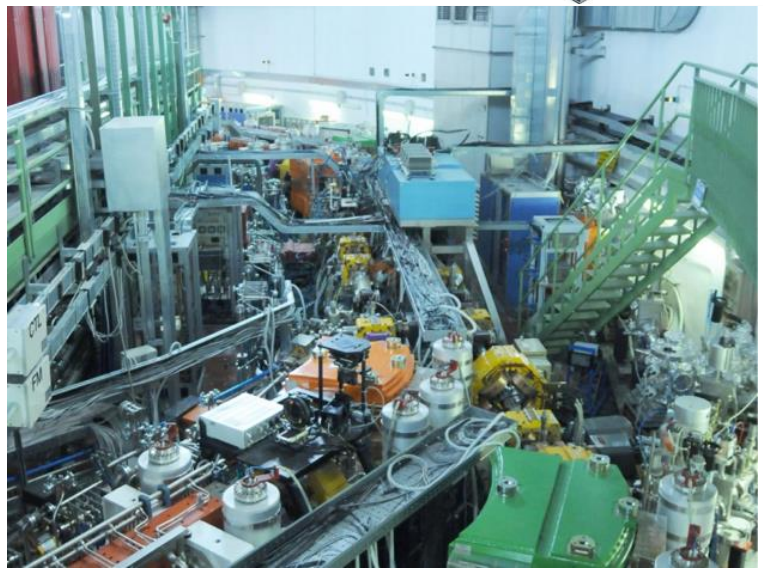


https://maps.google.com/maps/ms?ie=UTF8&hl=en&t=h&msa=0&msid=100574363331995850370.000495f3c601139ebb21e&ll=31.052934,0&spn=163.748232,181.054688&z=2

DAFNE: Double Annular Factory for Nice Experiments
e+ e- Frascati collider







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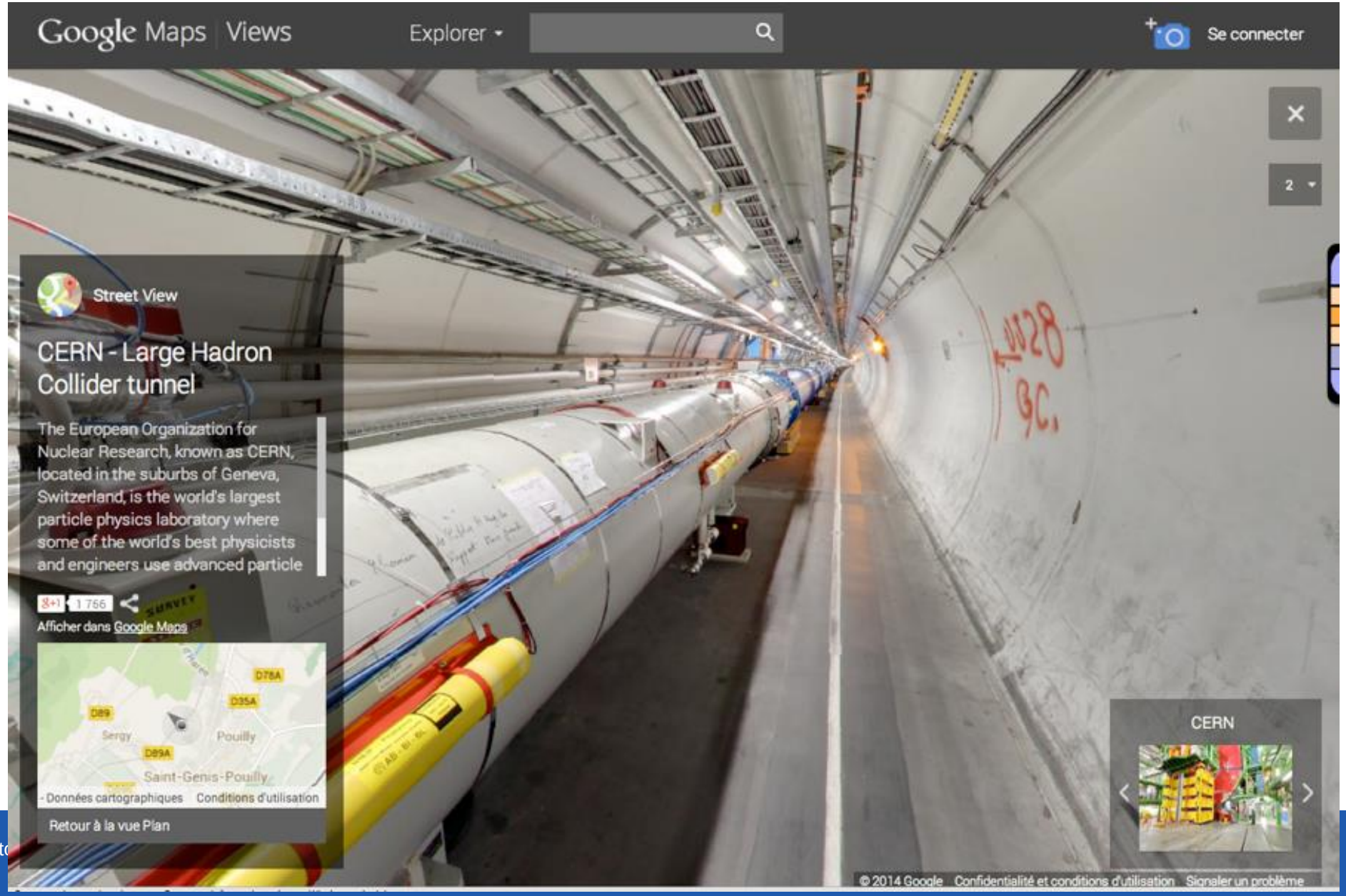
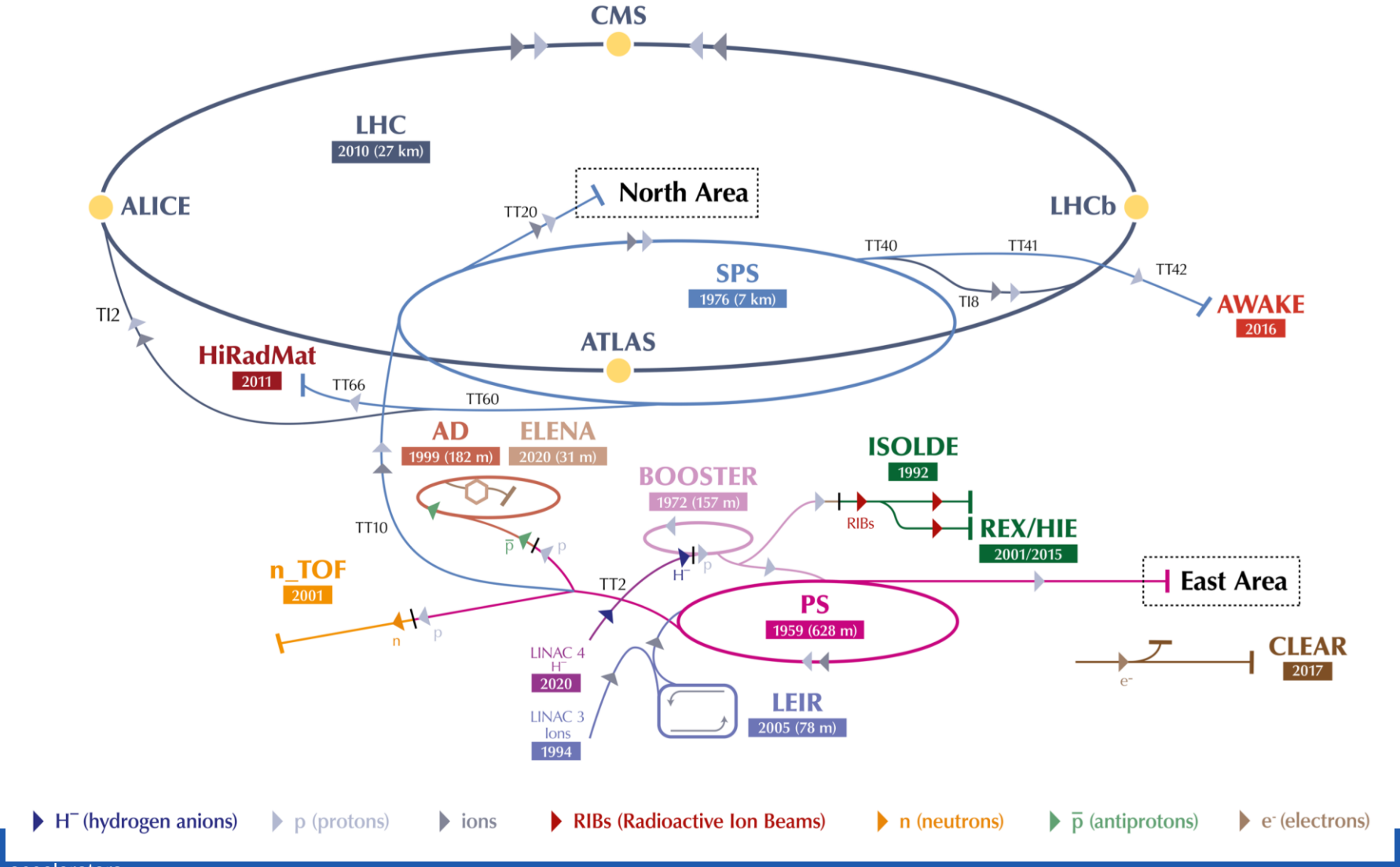
Where we are going to go ....

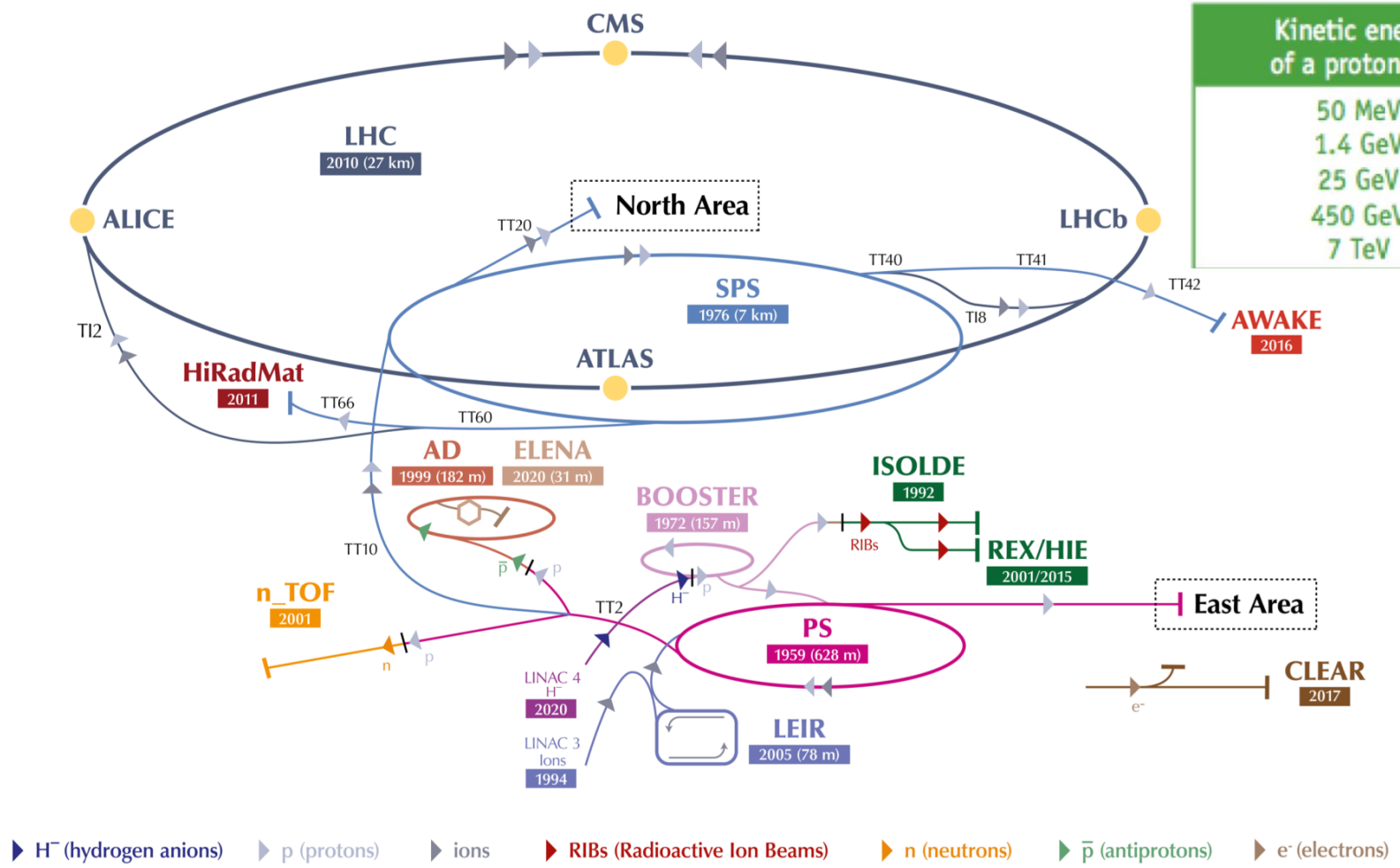


CERN accelerator complex overview



A view from the sky…

CERN accelerator complex as now

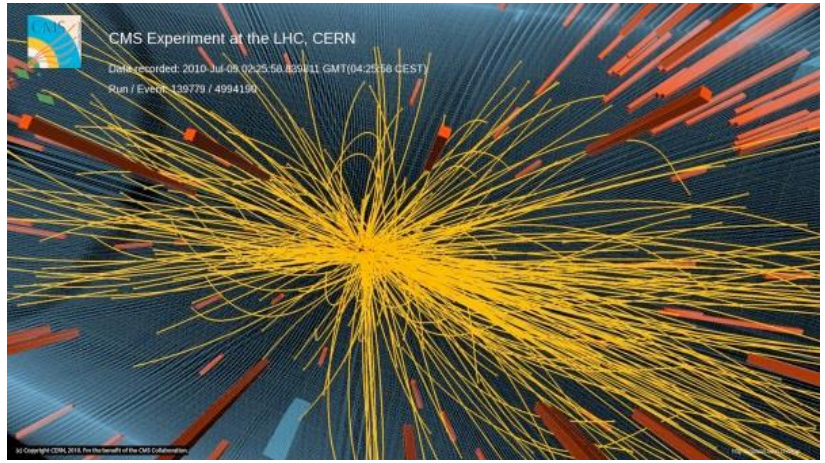


Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Basically accelerators brings you ...

from nearly a bottle of hydrogen

to a little bit before this

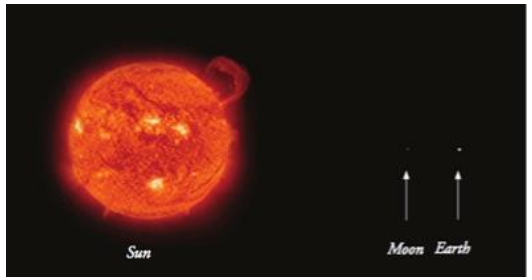


How much time(distance) does it take from the source to collisions ?
(assumption, protons travels always at the speed of light)

In the Linac 4, basically nothing.
In the **PSB,** a bit less than than 1.2 s.
In the **PS**, a bit less than 3.6 s
In the **SPS**, a bit less than 16.8 s
In the **LHC**, minimum 30 minutes

1 821.6 s → 546 480 000 km

about 3.7 time the distance Sun-Earth



How long does it takes a turn in the LHC ?

89 microseconds → 1 LHC turn

5 milliseconds – **a honey bee's wing flap** OR **~ 56 LHC turns**

The average human eye blink takes 350,000 microseconds OR ~ 3930 LHC turn

Why particle accelerators?

La ricerca di nuove particelle

Vogliamo dunque:

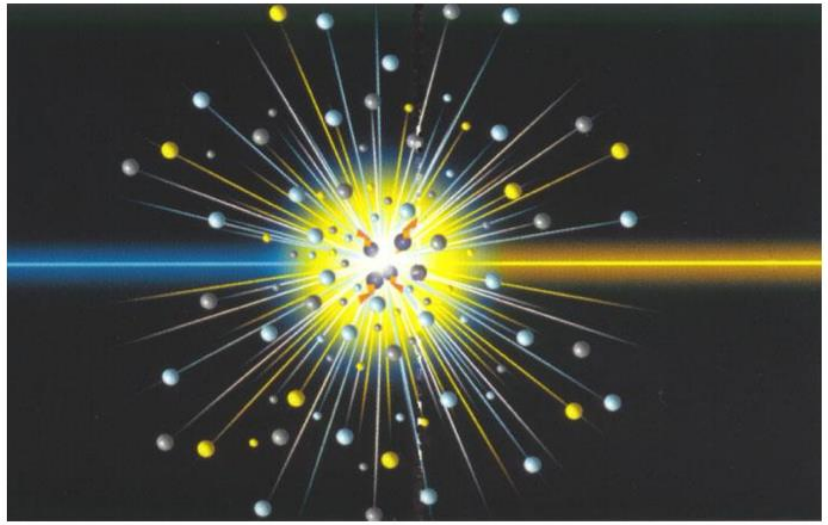
- scoprire se esiste il bosone di Higgs
- Cercare il meccanismo responsabile dell'origine delle masse
- cercare nuova fisica / nuove particelle
- verificare altre e nuove teorie

Al CERN e' stato costruito l'acceleratore chiamato LHC (Large Hadron Collider) che sara' in grado di dare una risposta a queste domande.

E' entrato in funzione alla fine del 2009.

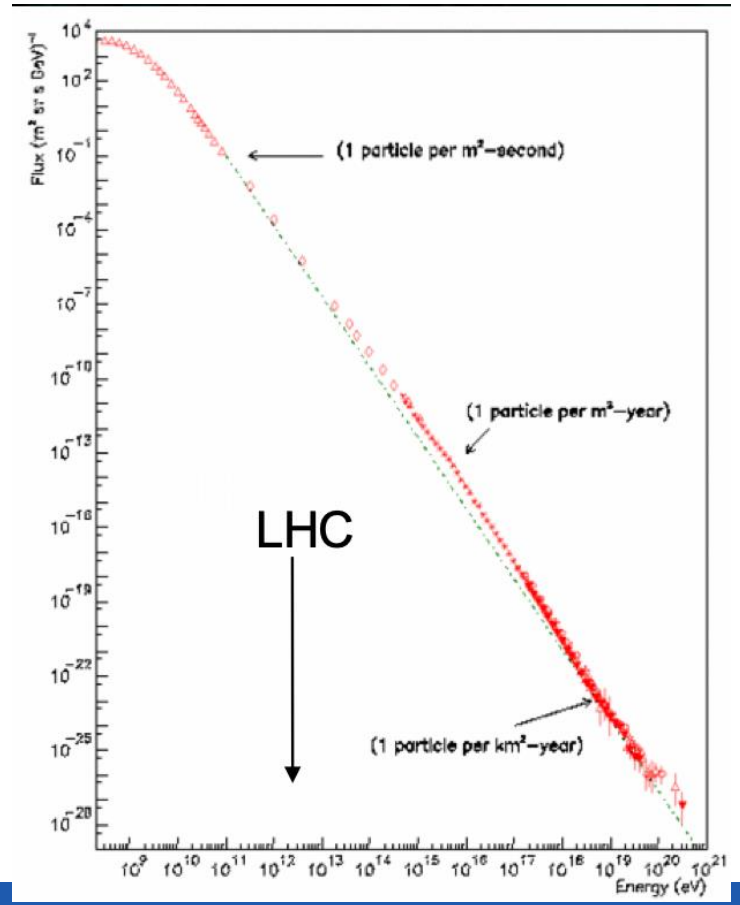
29

$$E=mc^2$$



Why particle accelerators ?

- *Why accelerators?:* need to produce under <u>controlled conditions</u> HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT
- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.

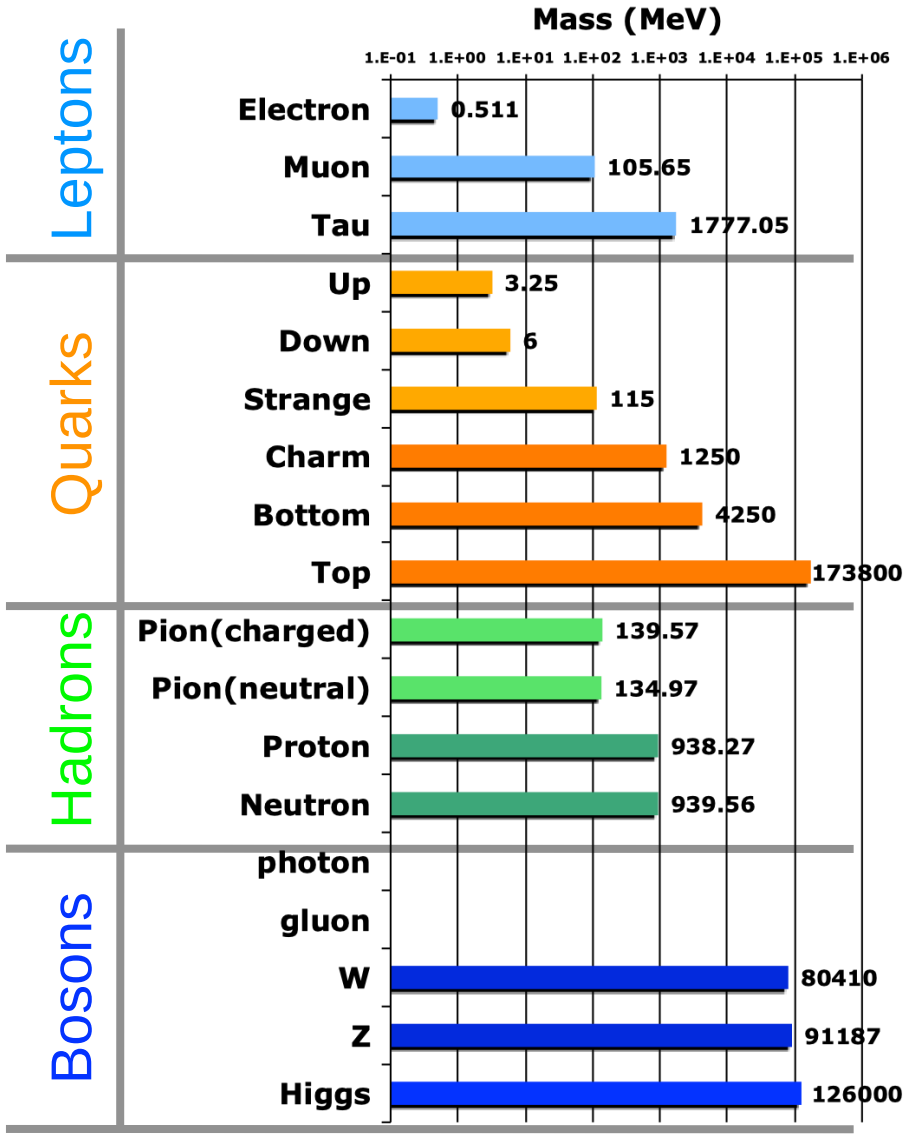


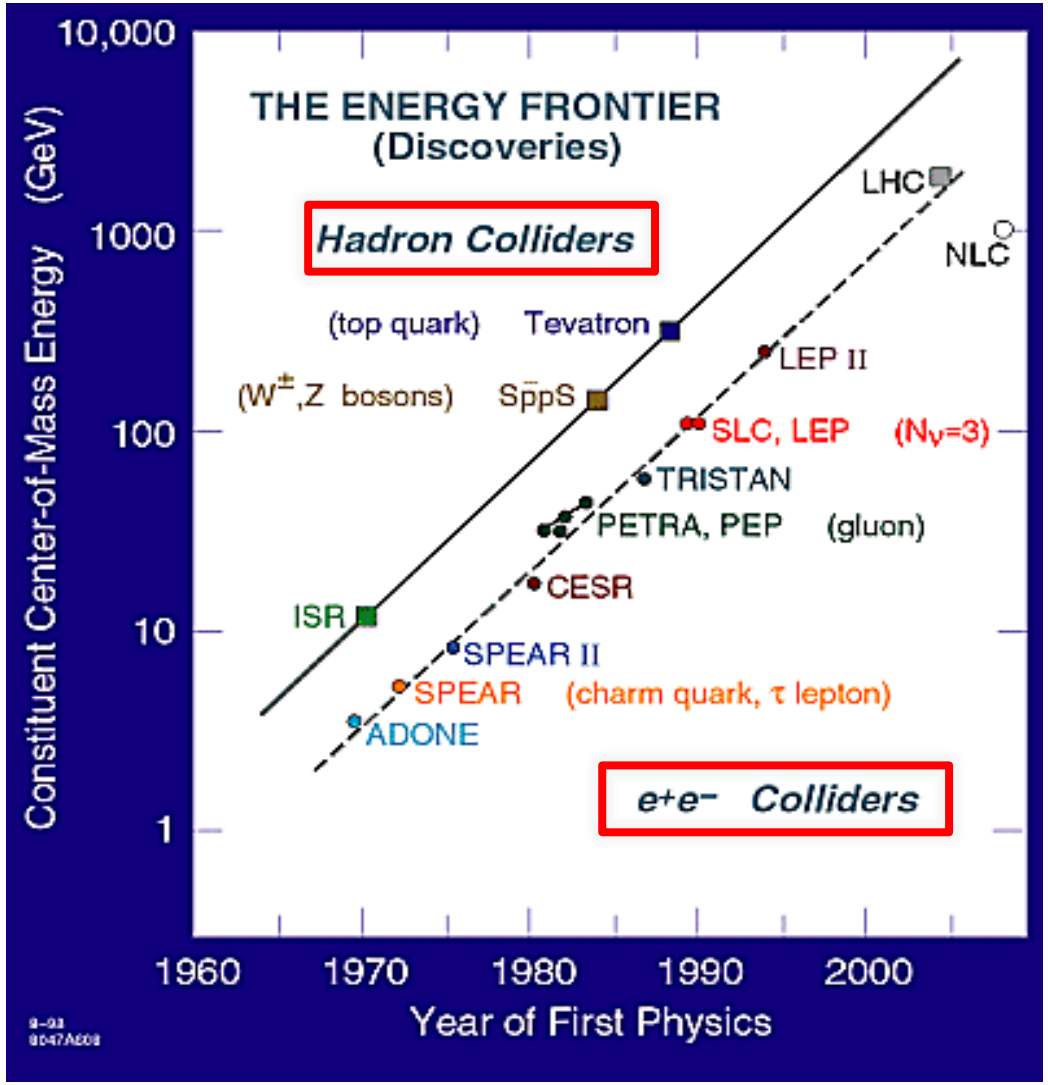
The cosmos accelerates already particles more than the TeV
While I am speaking about **66 10^9 particles/cm^2/s** are traversing your body, about 10^5 LHC-equivalent experiment done by cosmic rays
With a space distribution too dispersed for today's HEP physics!

Cloud chamber, from YOUTUBE

To accelerate particles, nature can count on exceptional phenomena

History/Energy line vs discovery potentials

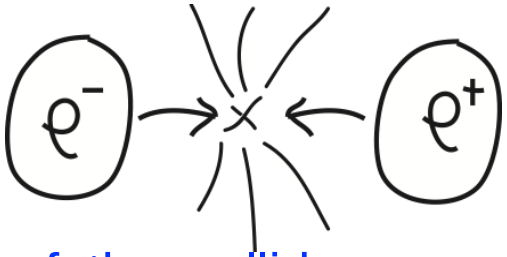




Different particle species used in the different collider: Why?

The right particle for the right scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

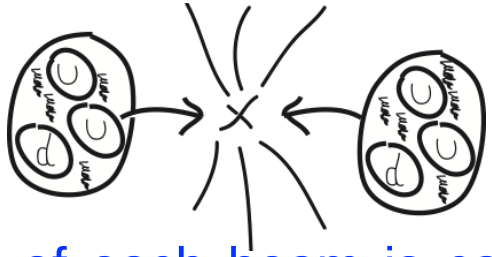
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

<u>Pros:</u> the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

<u>Cons:</u> above a certain energy is no more possible to use electrons because of too high <u>synchrotron radiation</u>

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll (about 2 TeV at LHC) < 2 Eb (14 TeV)

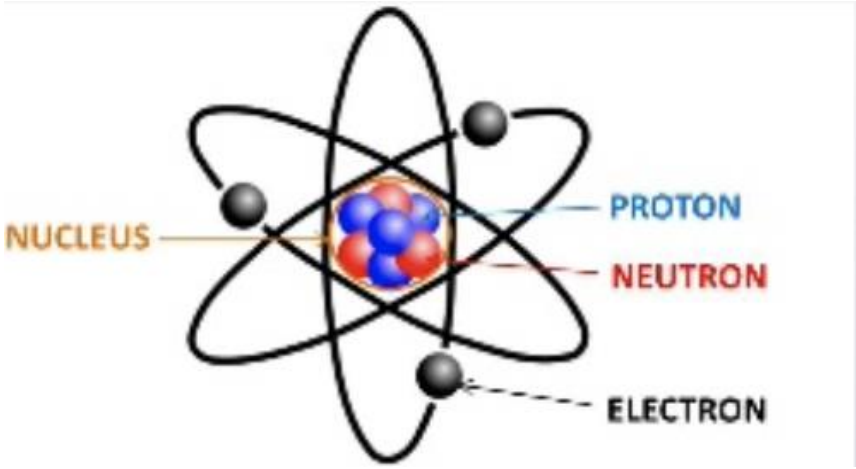
<u>Pros:</u> with a single energy possible to scan different processes at different energies.

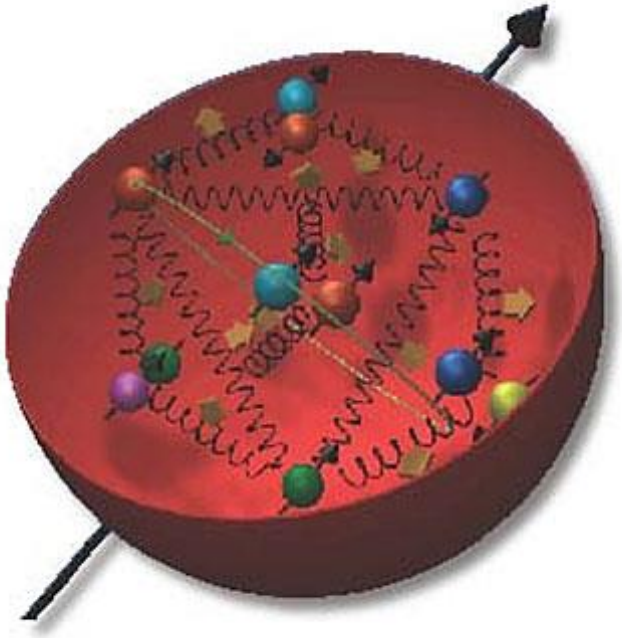
Discovery machine (LHC)

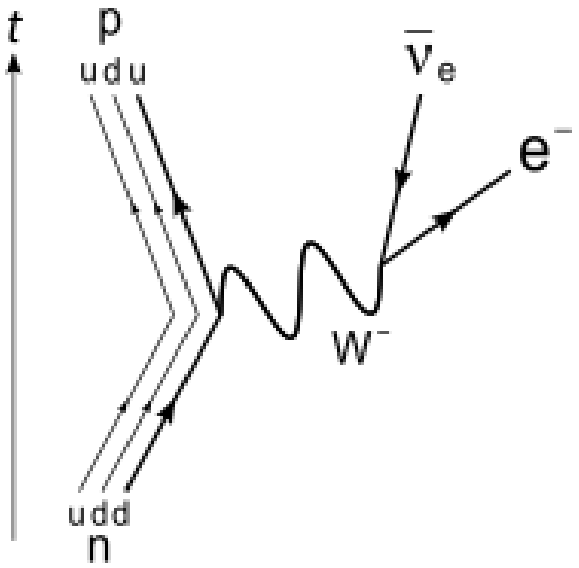
<u>Cons:</u> the energy available for the collision is lower than the accelerator energy

What is the LHC ? H = HADRON

- Protons are hadrons because are made of quarks



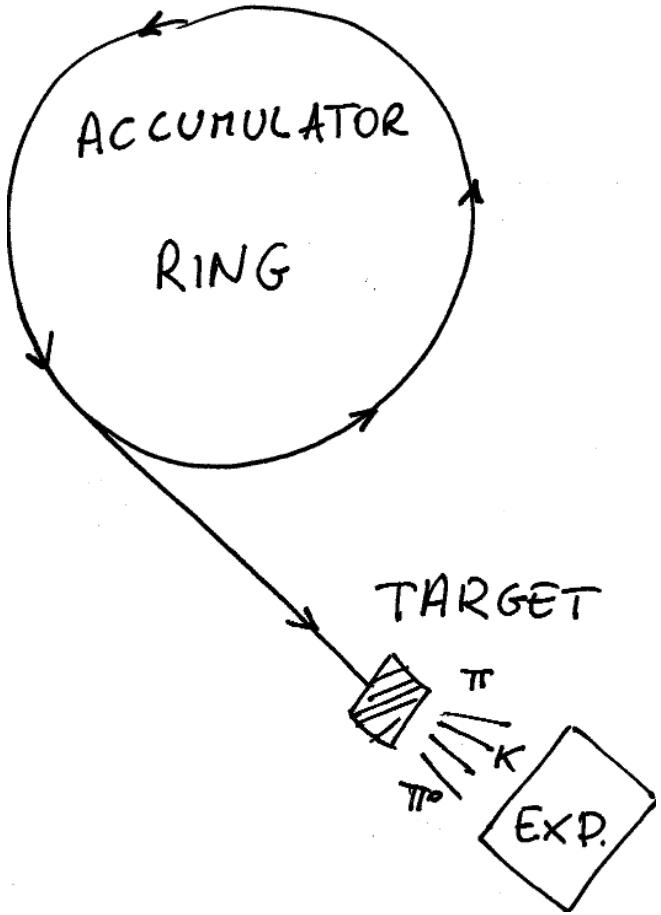




How many quarks in a proton?

Different approaches: fixed target vs collider

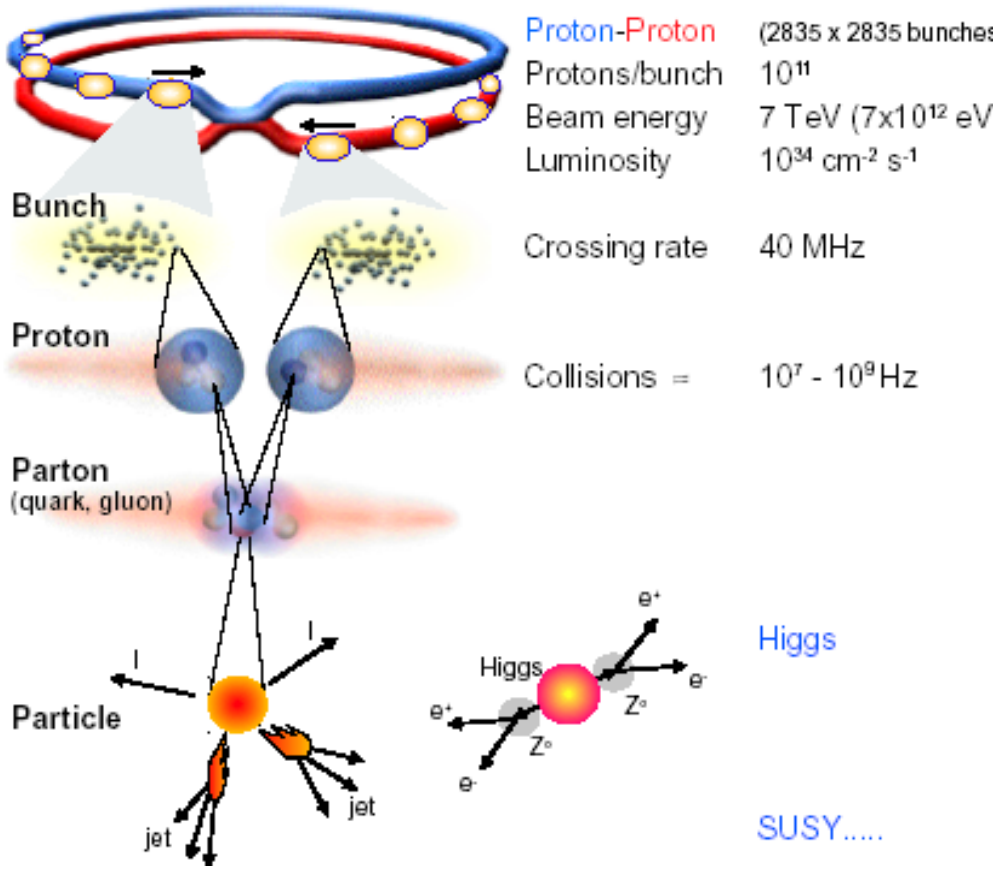
Fixed target



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

<<

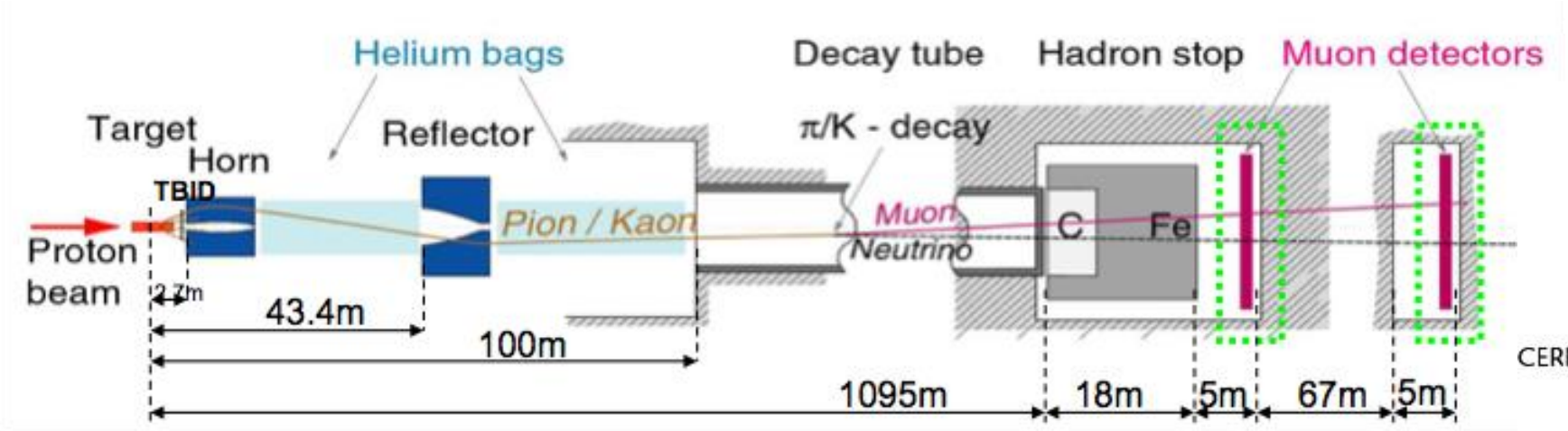
Storage ring/collider

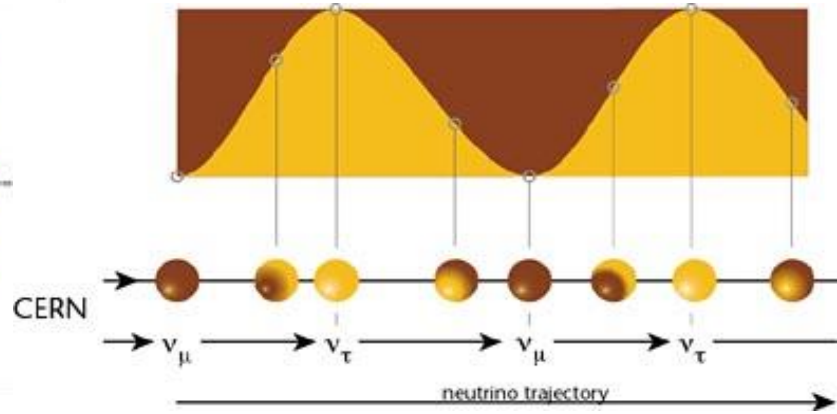


$$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

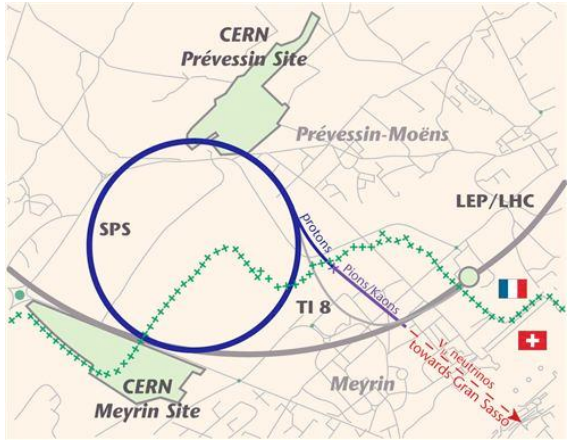
This usually is defined as √s

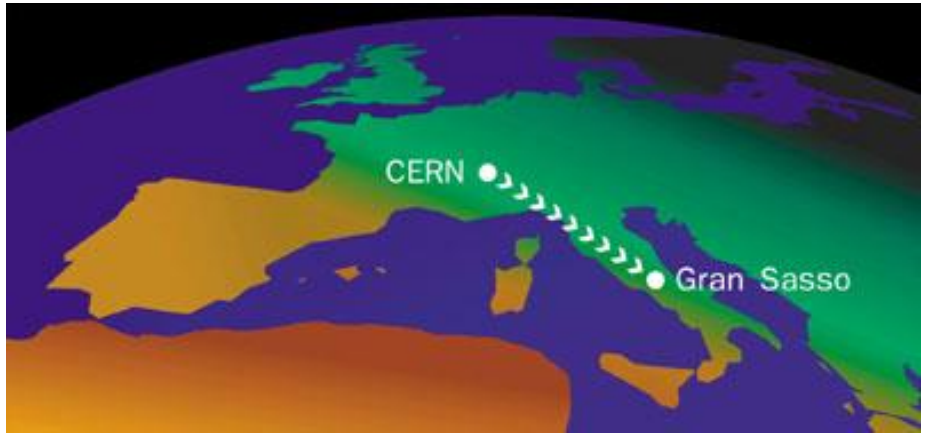
CNGS, conventional man-made neutrino beam

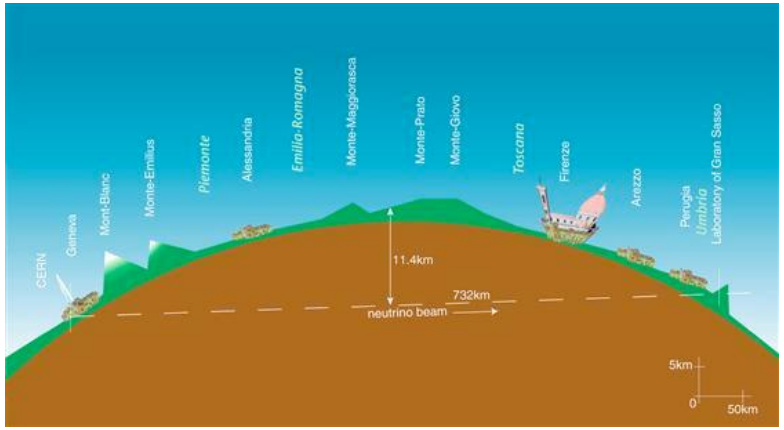




CERN to Grans Sasso



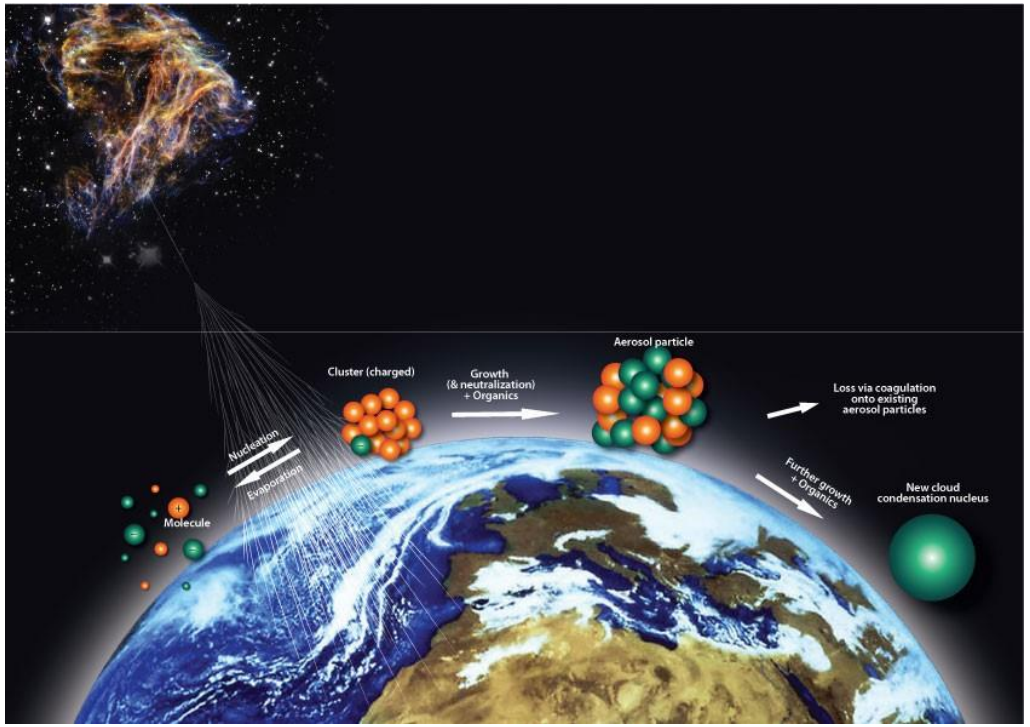




CNGS looked for ν_τ appearance in a beam of ν_μ
The beam was sent from the SPS at 400 GeV/c on the C target. **It was "only" a 450 kW beam**

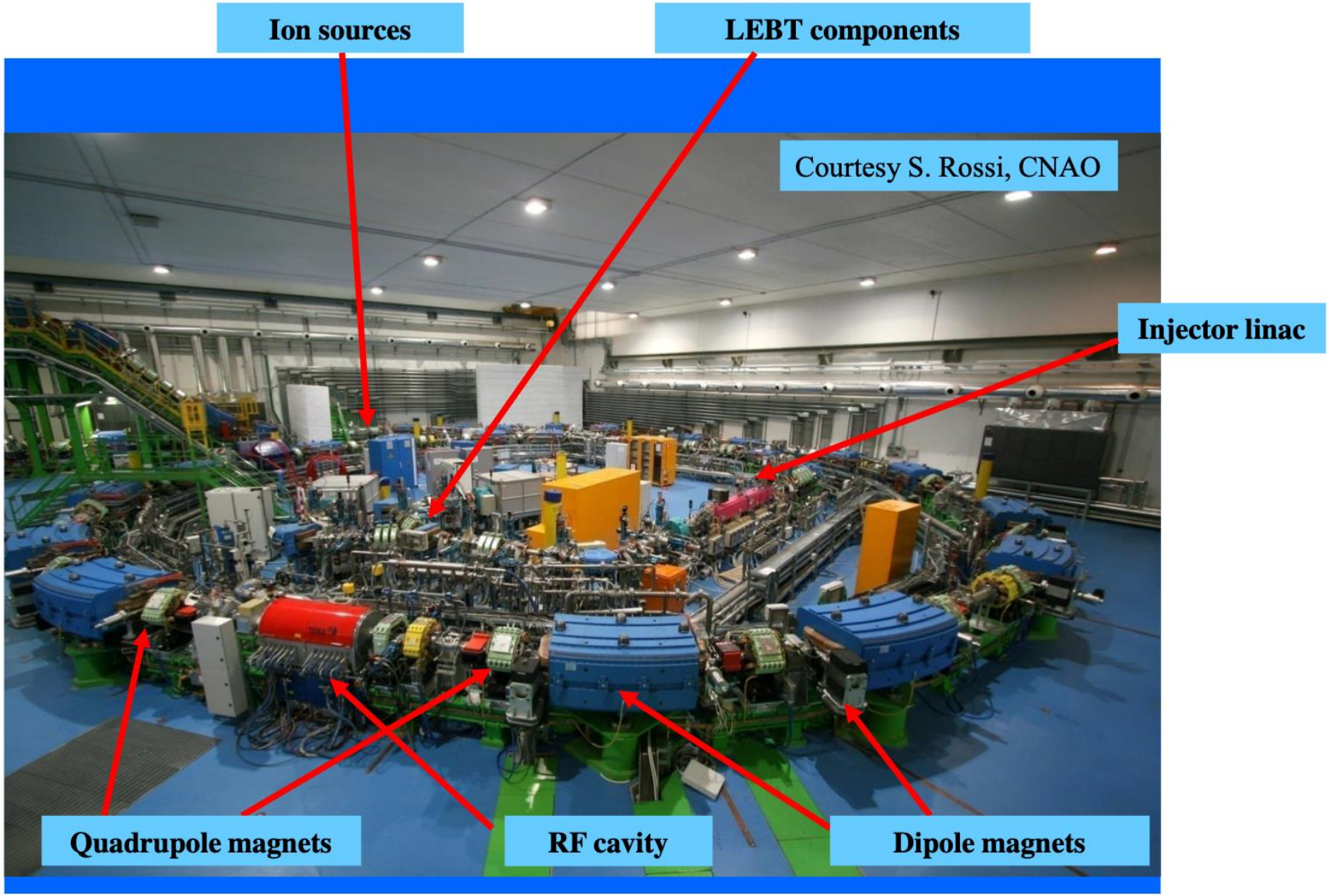
CLOUD: Cosmics Leaving Outdoor Droplets

Study effect of cosmic rays on clouds formation
(cosmic rays “simulated “ by EAST-HALL T11 beam, clouds created in a large climatic chamber



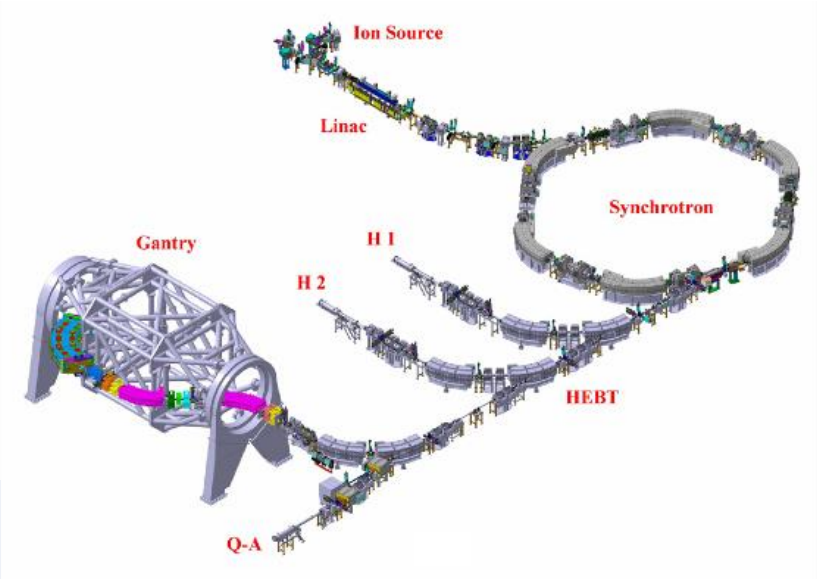
CNAO = Centro Nazionale di Adroterapia at Pavia

National Centre for Oncological Hadrontherapy, CNAO, Pavia, Italy

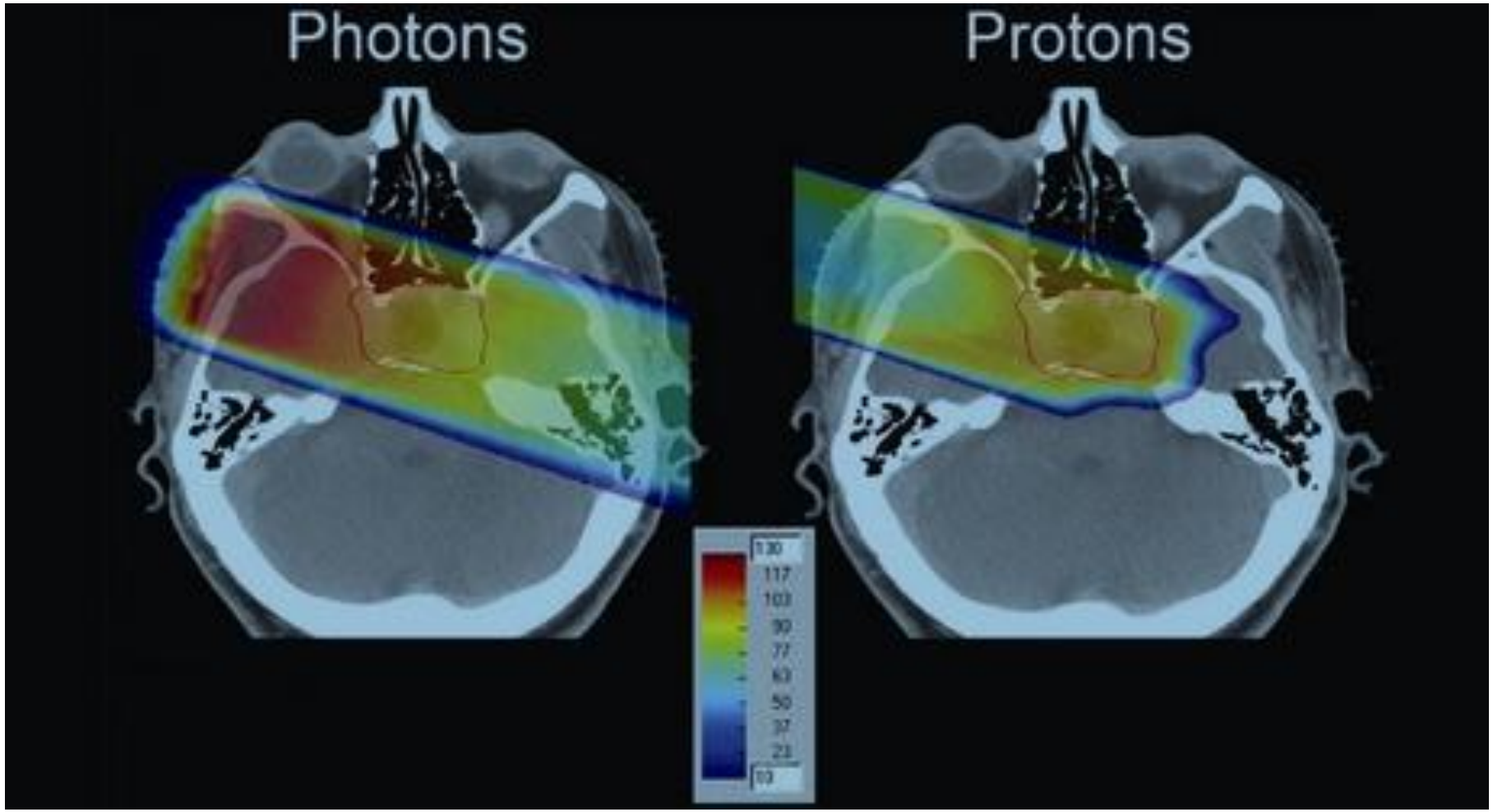


Accelerators for cancer therapy

THE HEIDELBERG ION THERAPY (HIT)



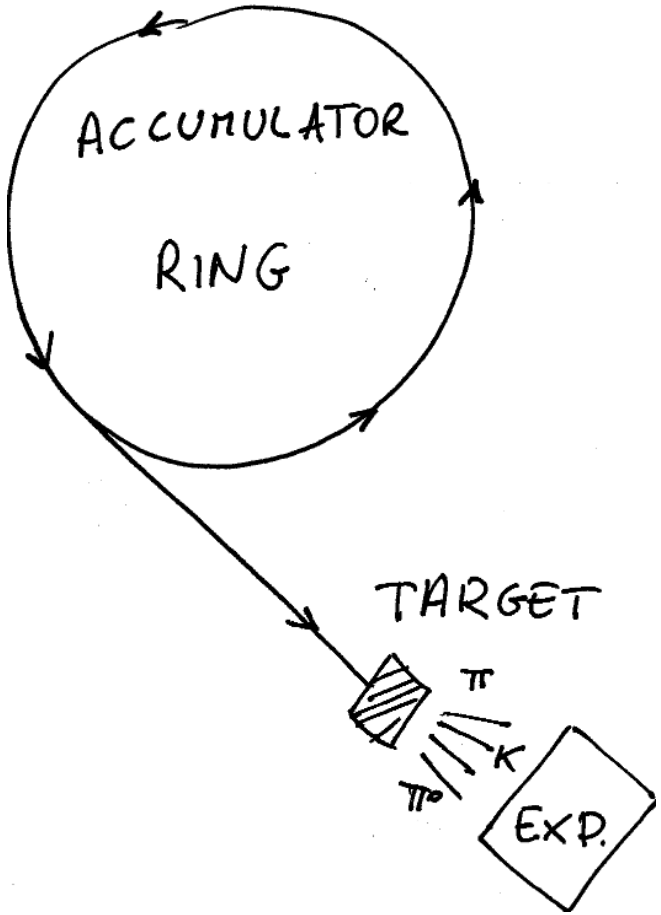
Cyclotron application: cancer therapy, photons vs protons



https://kce.fgov.be/publication/report/hadron-therapy-in-children-–-an-update-of-the-scientific-evidence-for-15-paediatr#.VehXyIuNeDs

Different approaches: fixed target vs collider

Fixed target



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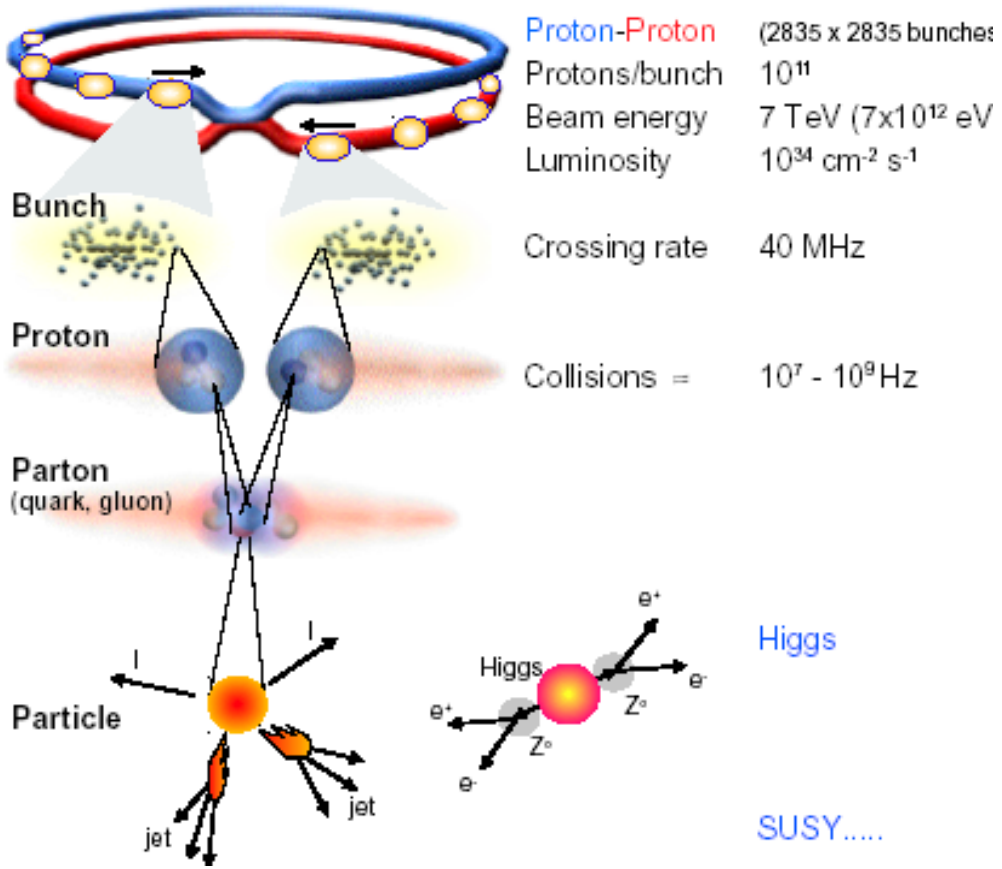
<<

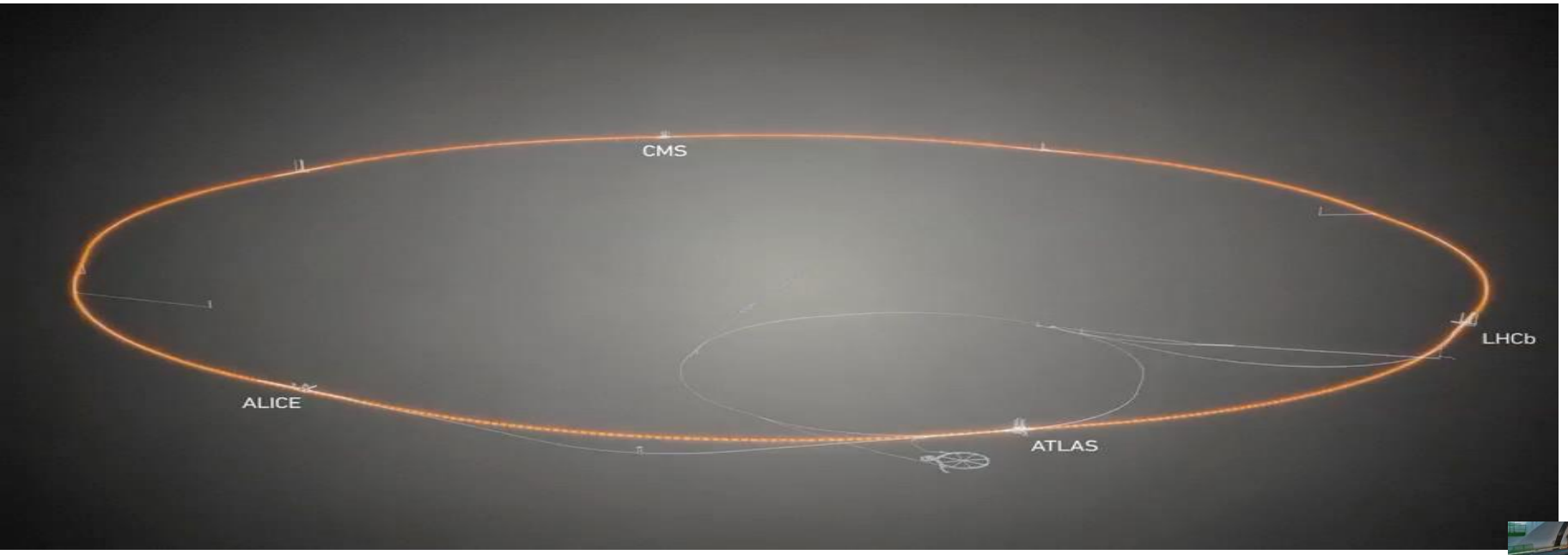
Storage ring/collider

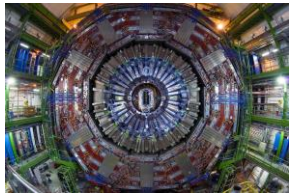


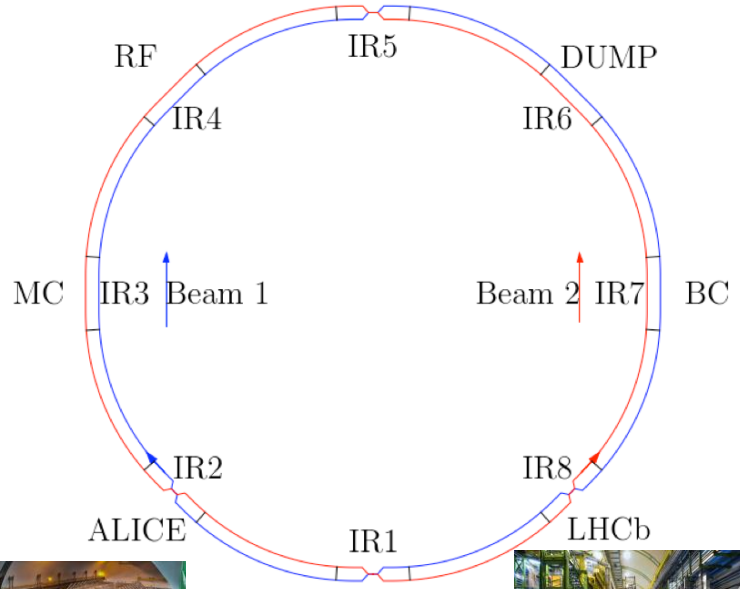
$$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

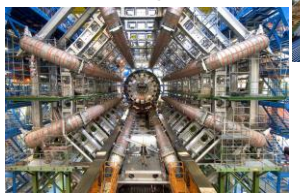
This usually is defined as √s

Collider: LHC with 4 collision points (IP)









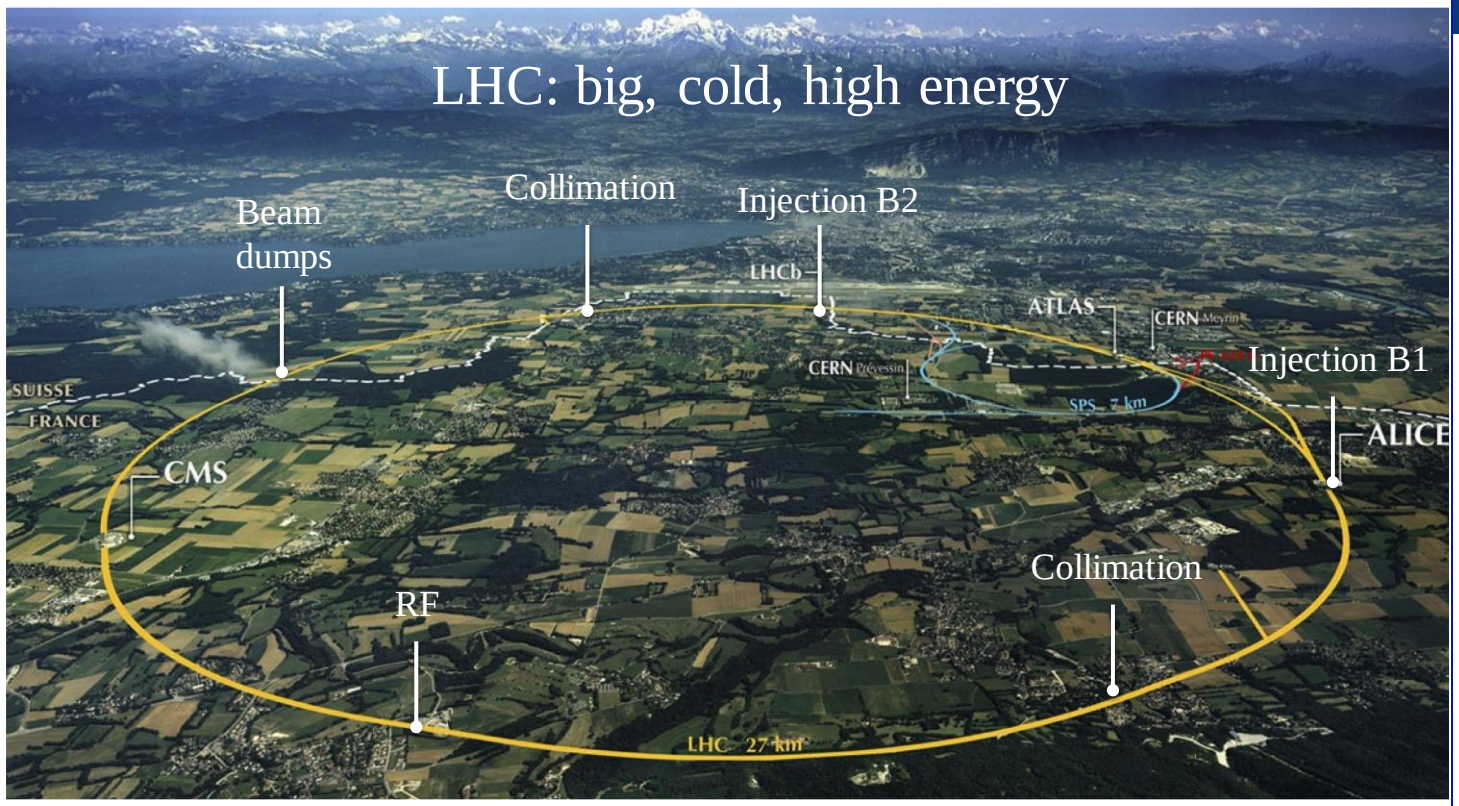
4 main experiments → Alice, ATLAS, CMS, LHb

Where the beam size is reduced to a minimum → important for later on…

The Large Hadron Collider : the LHC

The largest machine and scientific instrument ever built by mankind

…. For the moment….

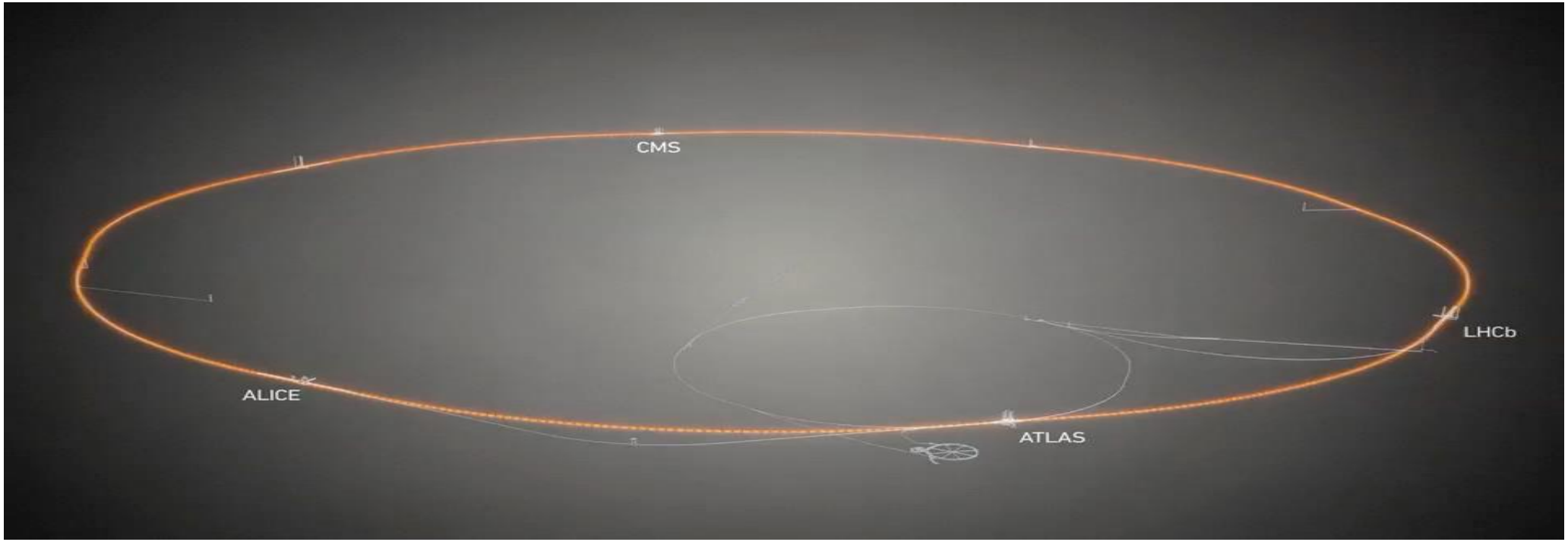


Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Nominal energy, protons	6.5 TeV (6.8 TeV)
Nominal energy, protons collisions	13 TeV (13.6 TeV)
No. of protons	Some 10^{14}
Number of turns per second	11245
Number of collisions per second	1 billion

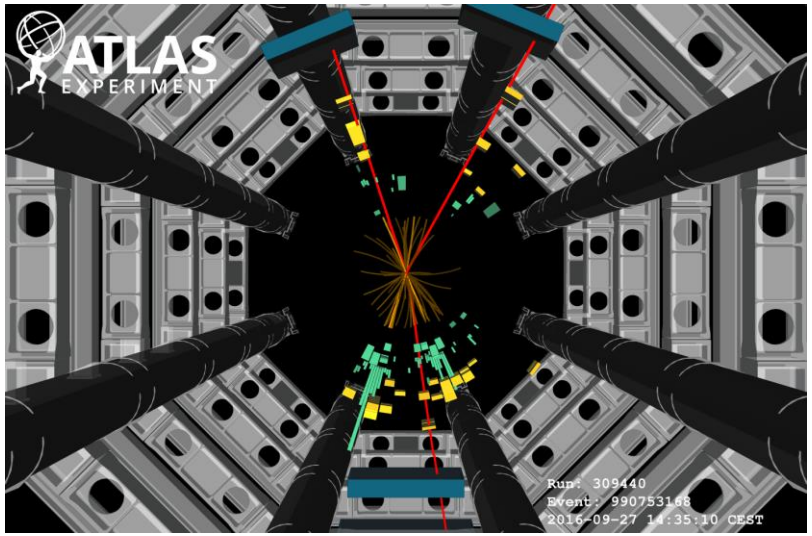
Why the LHC is so complicated?

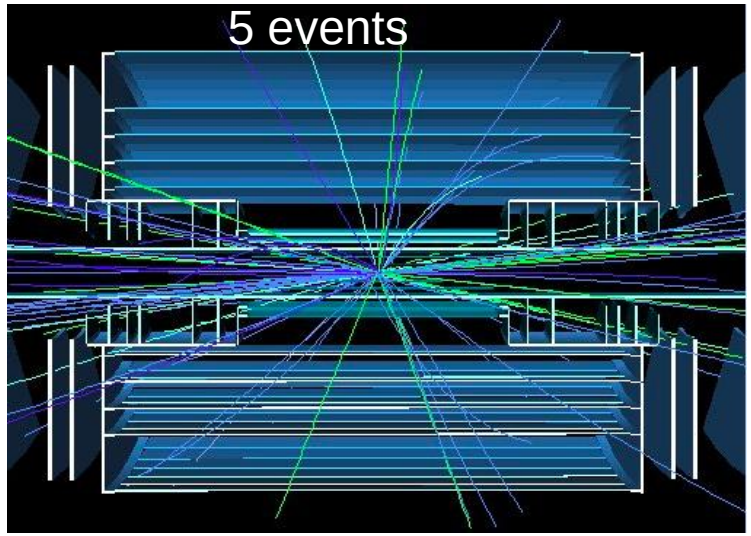
One has to control **~2000 needles travelling at the speed of light** with the **energy sufficient to melt 2.5 tons of copper** in such a way that they **meet each and every single second about 11000 times.**

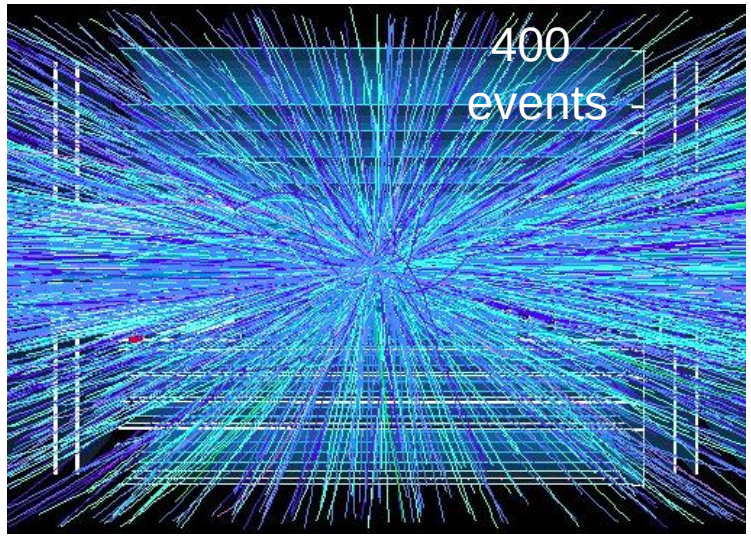
While leaving at a temperature which is cooler that the empty space and 100 m underground.

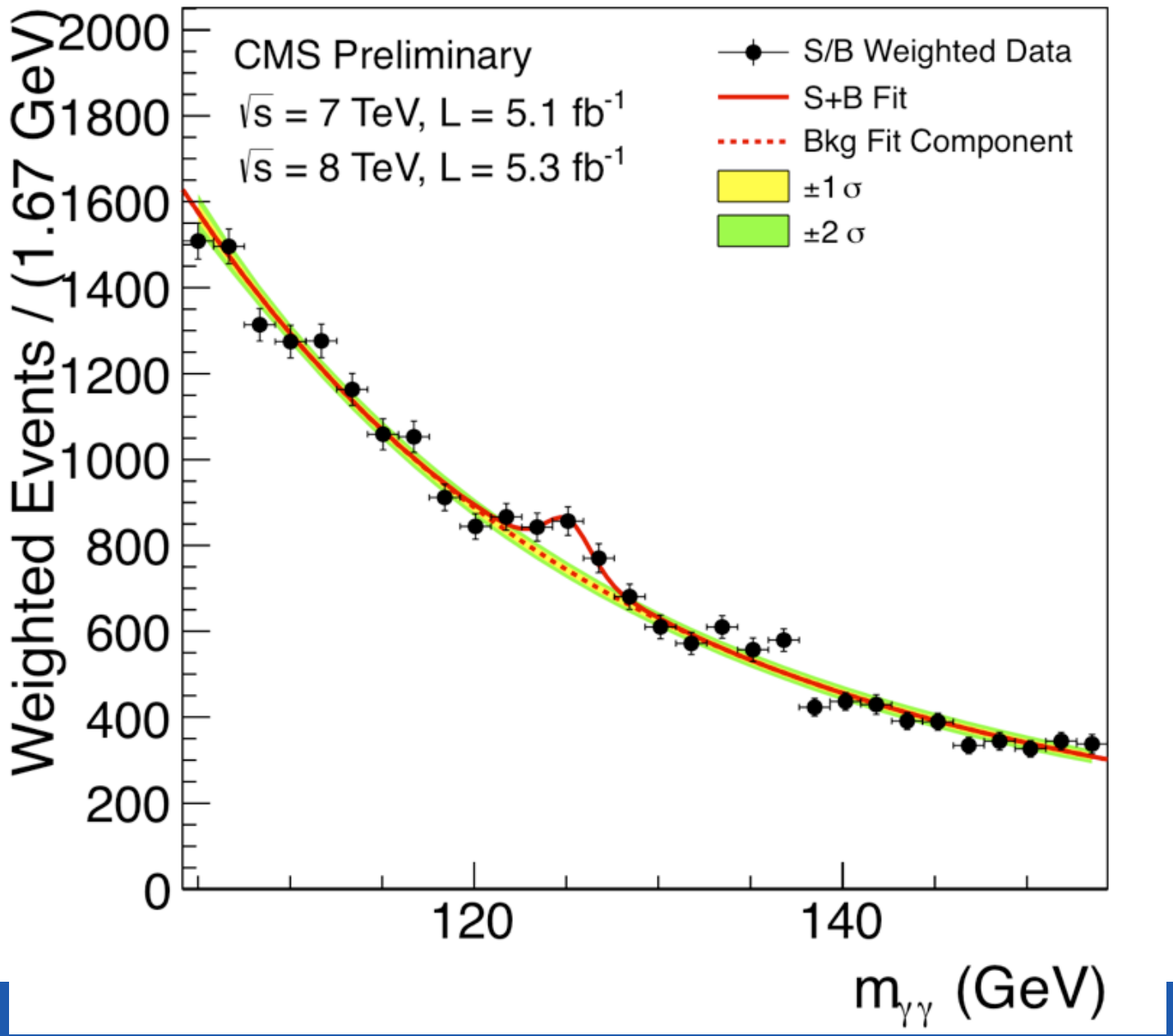


A collider event ….








CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

Press Release PR/56
12 February, 1960

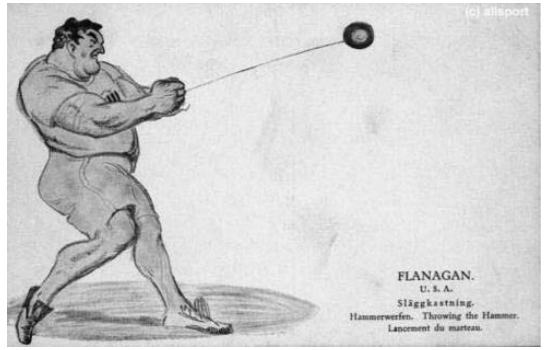
It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

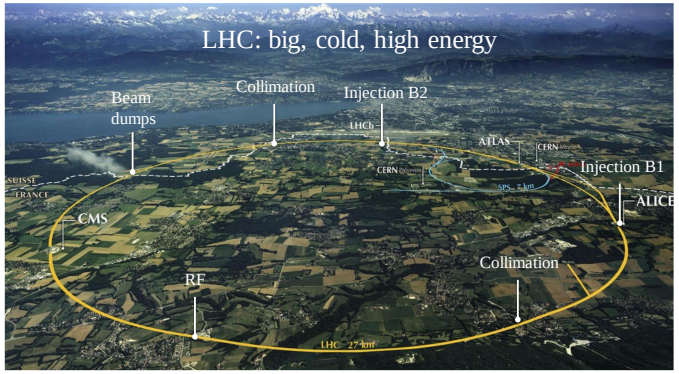
All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC.

Small detail... Bohr was not completely right, the “new” elementary particles are not elementary but mesons, namely formed by quarks

What is the LHC ? L = LARGE →27 km

Large: high energy needs large bending radius due to the maximum magnetic field existing technology can produce 26.7 km circumference





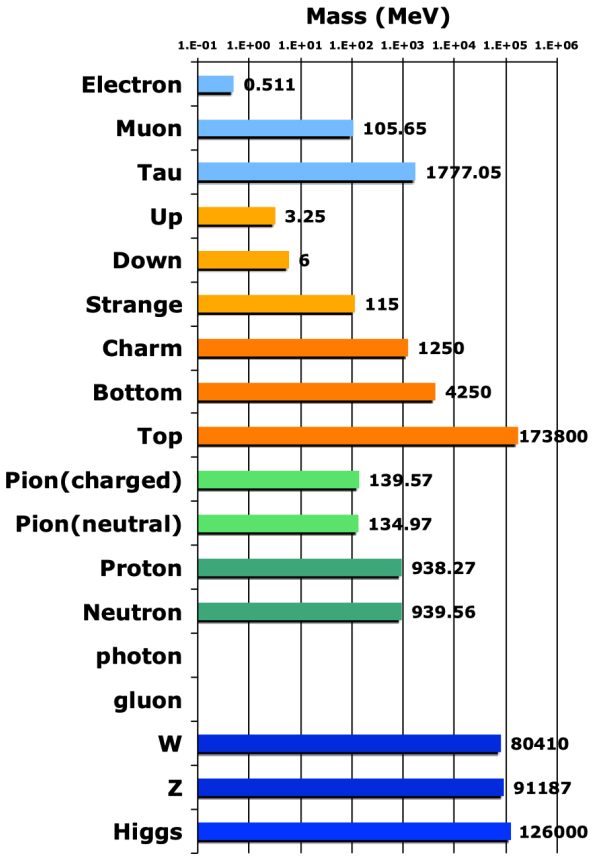
Something related to the **force to keep particles on track**

Magnetic Field
Limited by technology

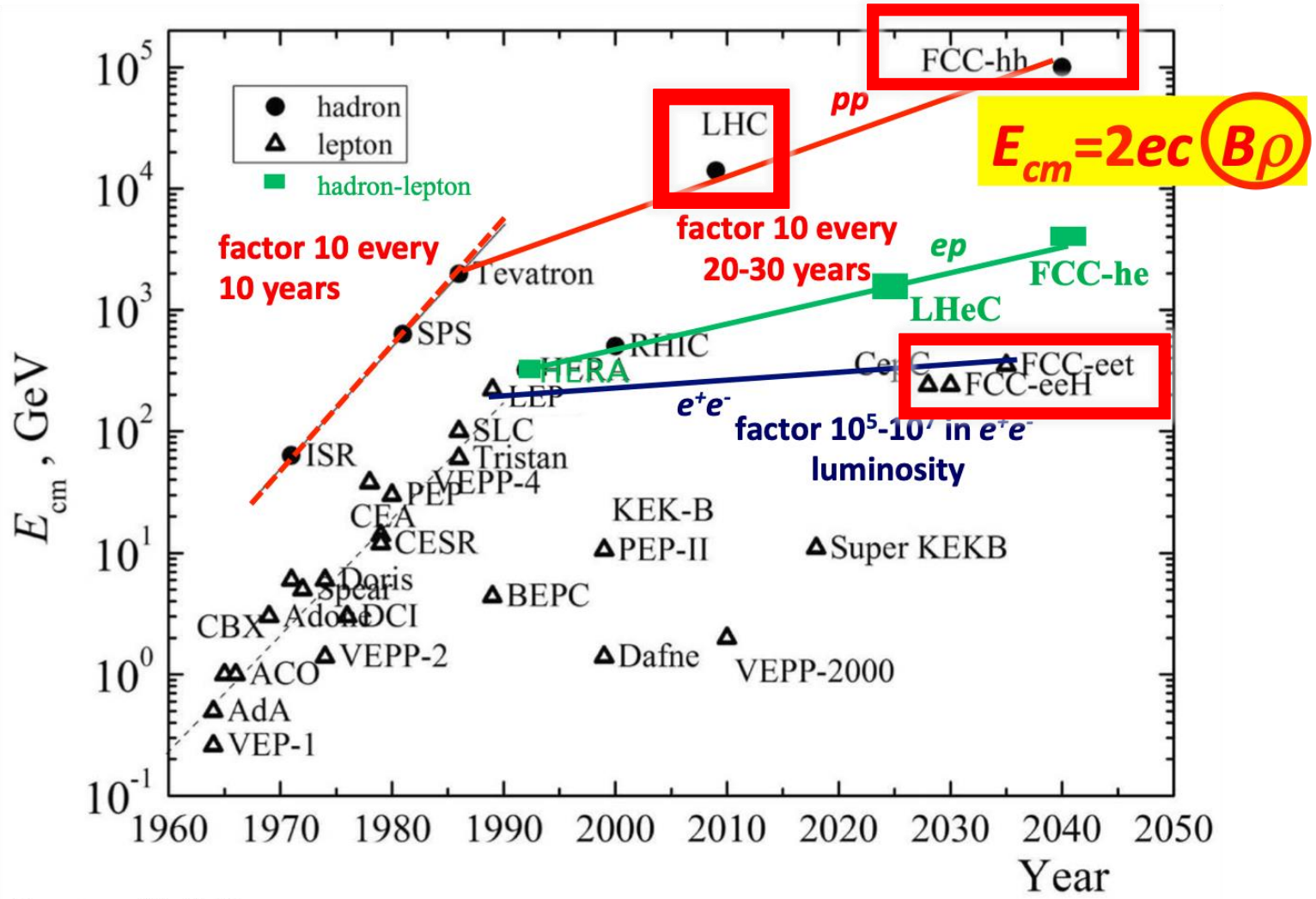
$$k = \frac{1}{\rho} = \frac{e}{p}B = \frac{e\mu_0}{p}\frac{nI}{h}$$

Radius: limited by cost, **and by the radius of the Earth...**

Energy : given by the physics
This will depend on the mass of the particles we want to discover



What's next: LARGE?

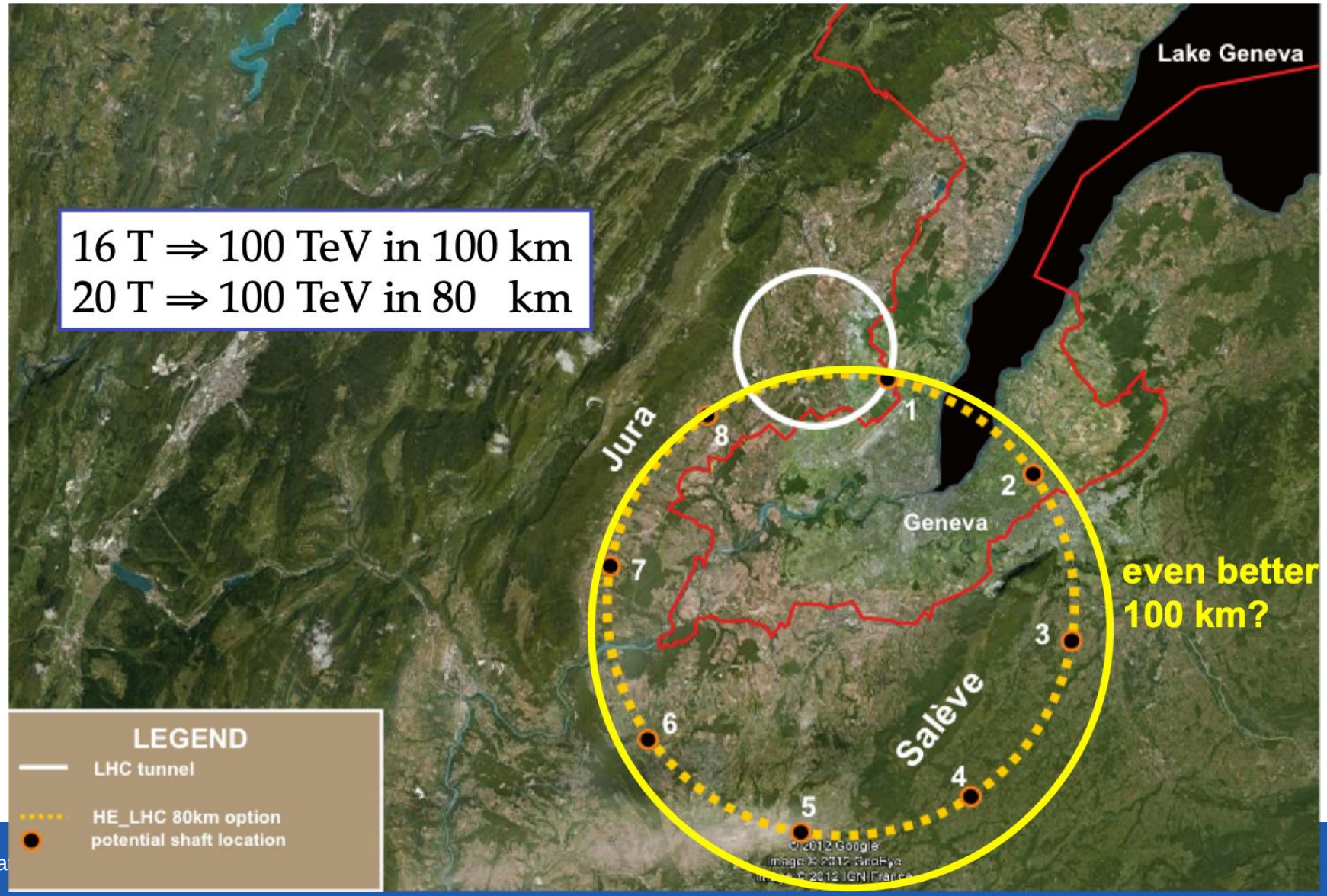


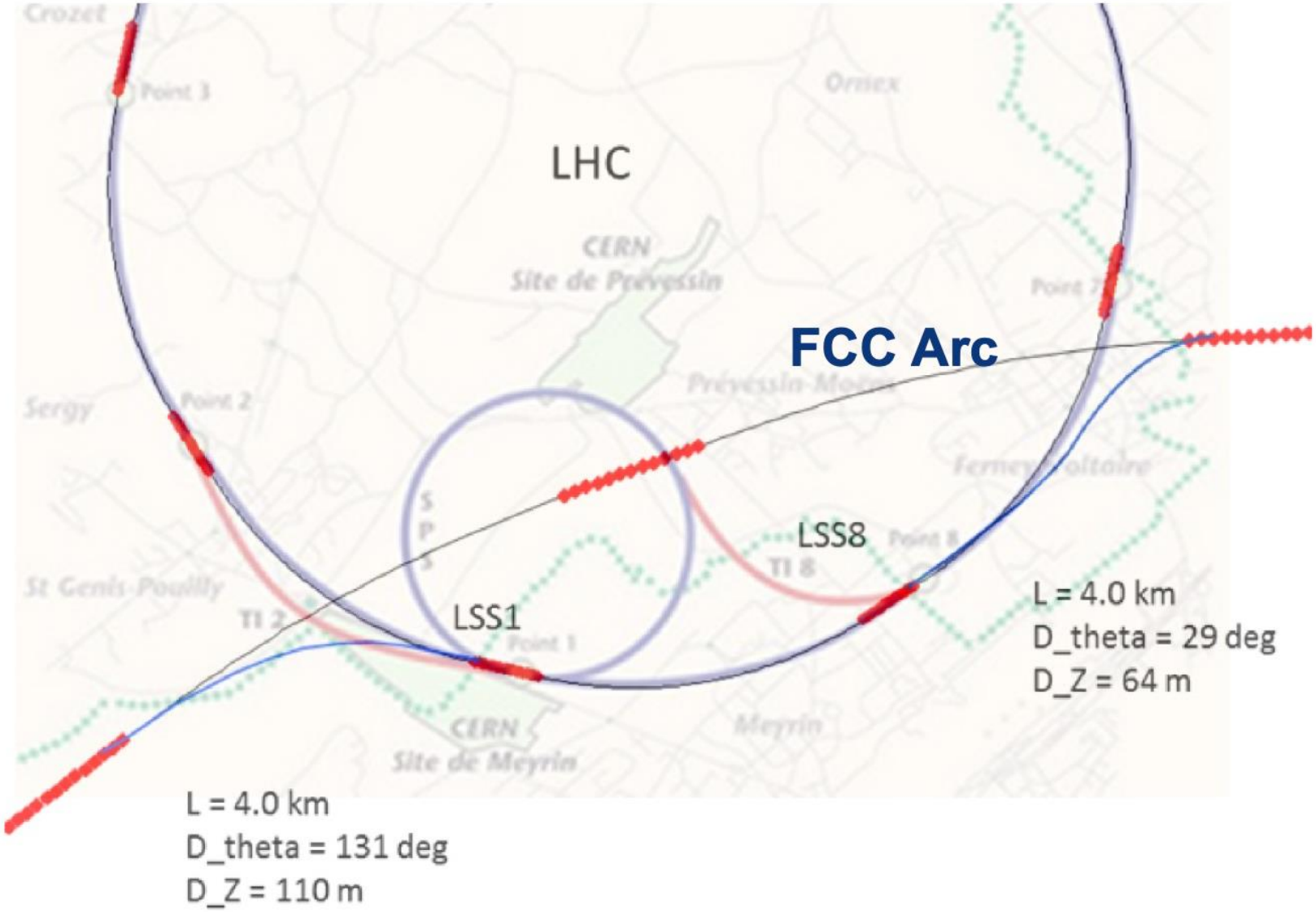
$E_{cm}=2ec\,B\rho$

$$k = \frac{1}{\rho} = \frac{e}{p}B$$

Courtesy V. Shiltsev

What's the future ? Going bigger ….

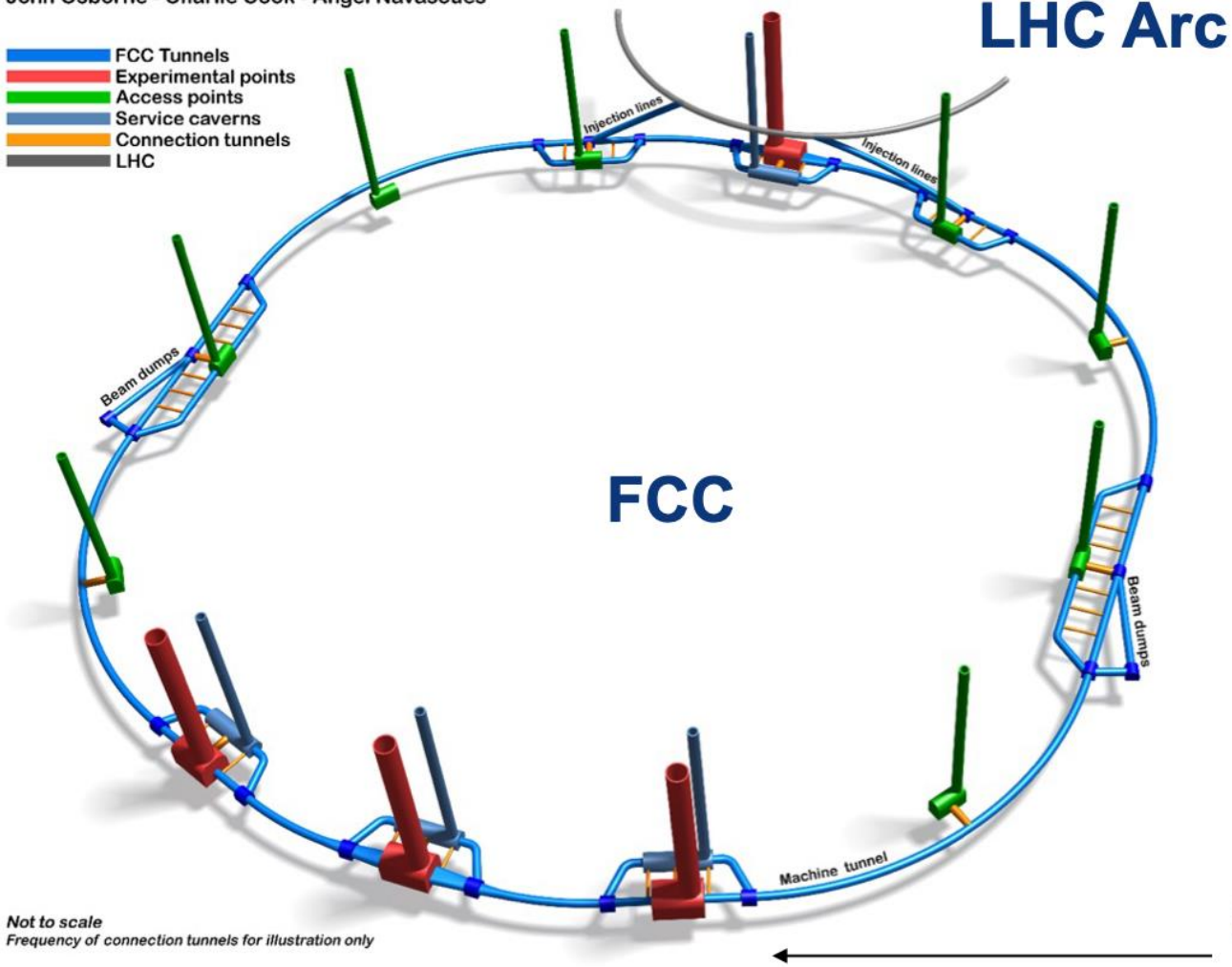


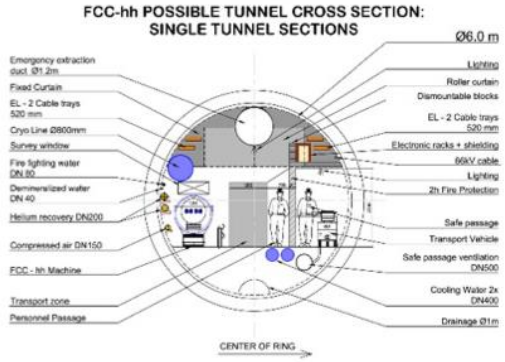

LHC
FCC Arc
LSS8
LSS1
L = 4.0 km
D_theta = 29 deg
D_Z = 64 m
L = 4.0 km
D_theta = 131 deg
D_Z = 110 m

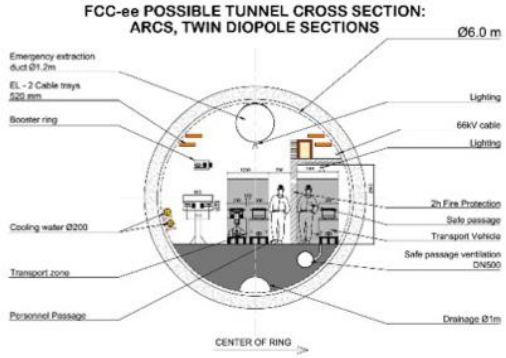
FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic

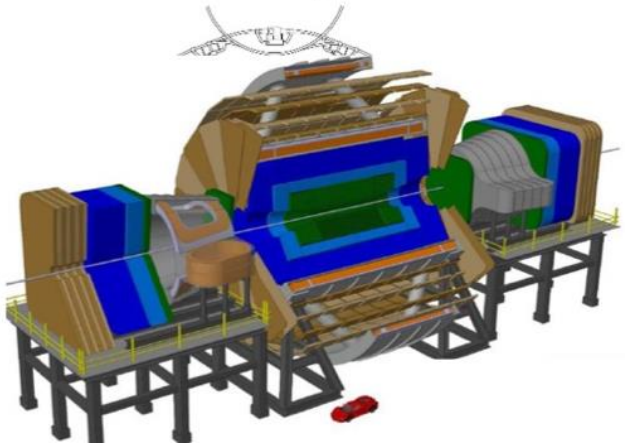
Underground Infrastructure - Single Tunnel Design

John Osborne - Charlie Cook - Ángel Navascués



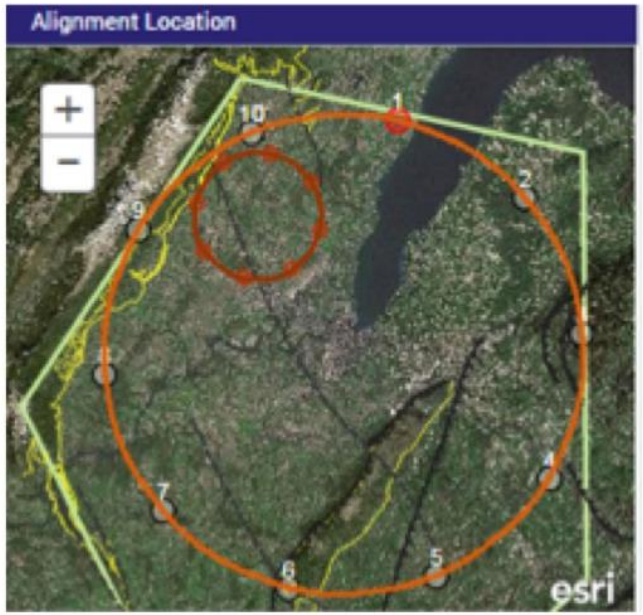


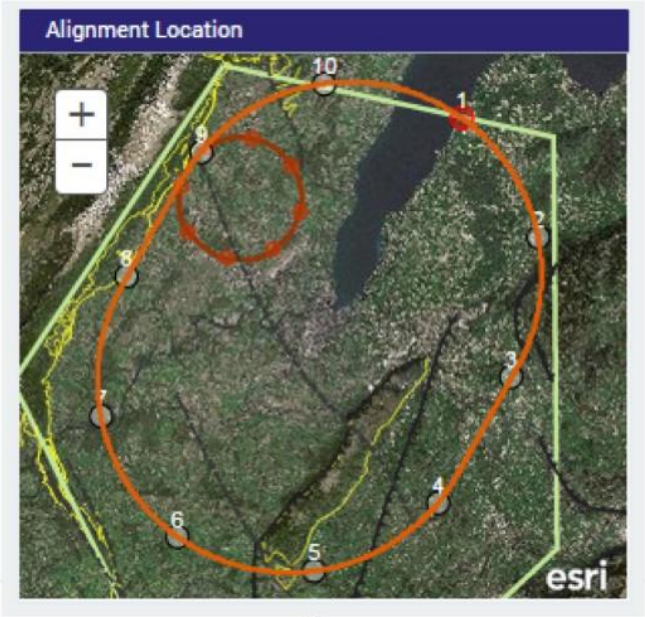


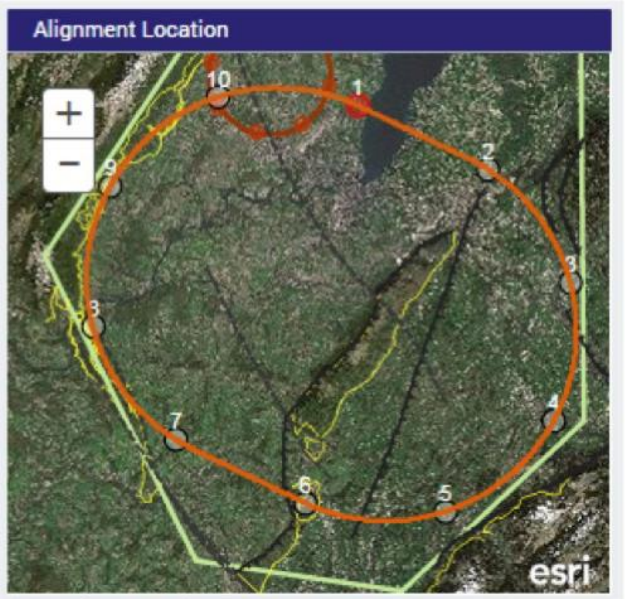


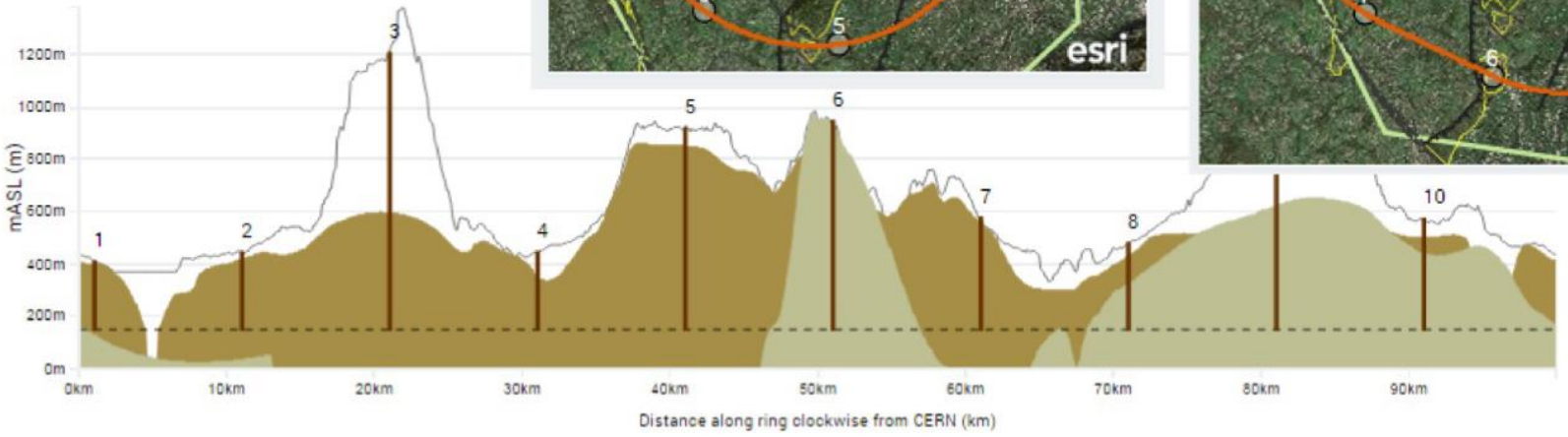
J. Osborne and Family

FCC landscape (with options)

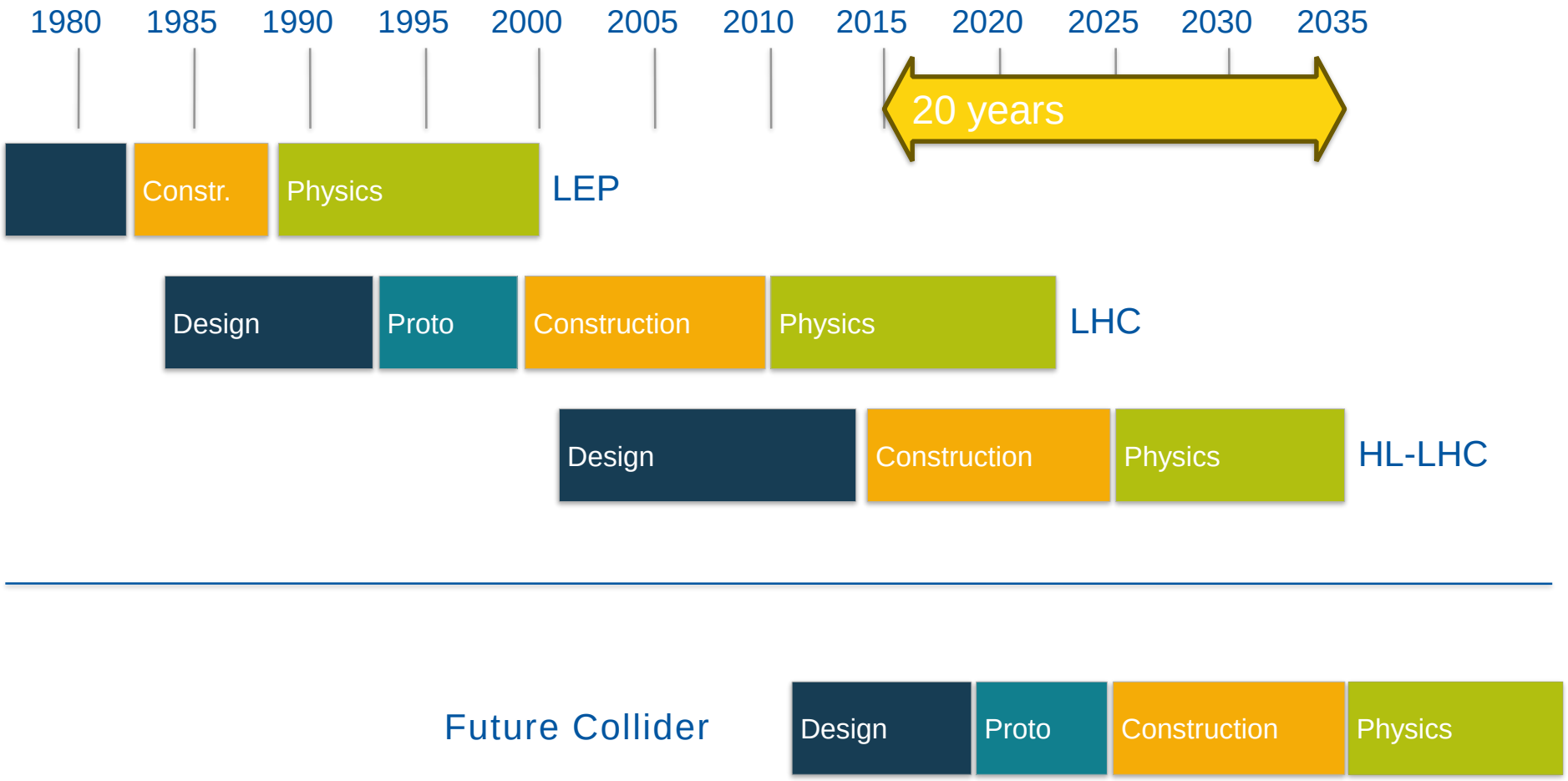






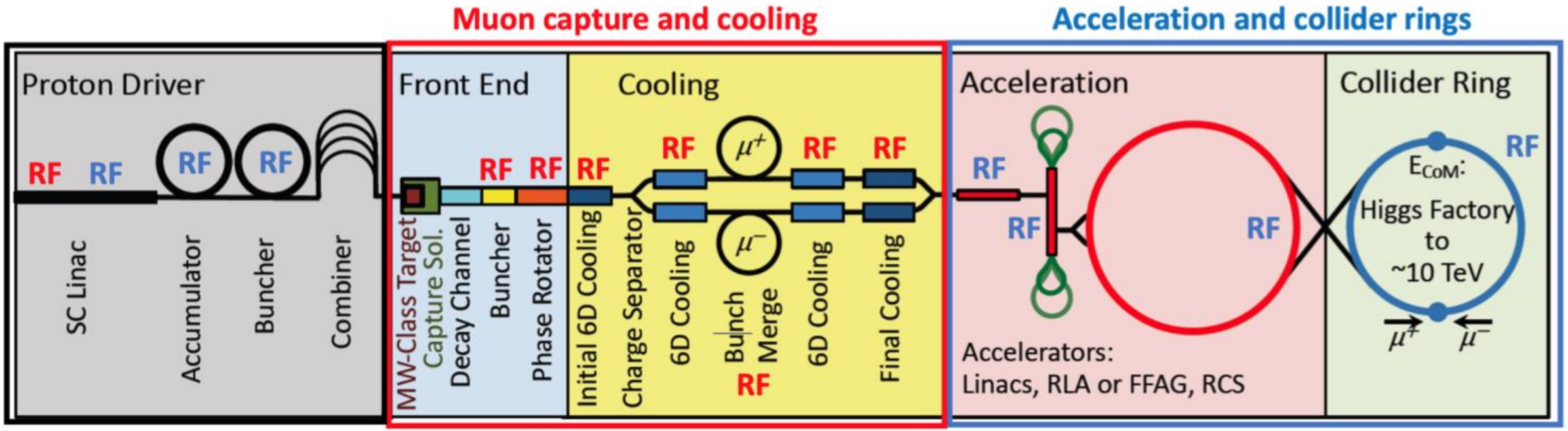


CERN Circular Colliders : FCC



from F. Zimmermann

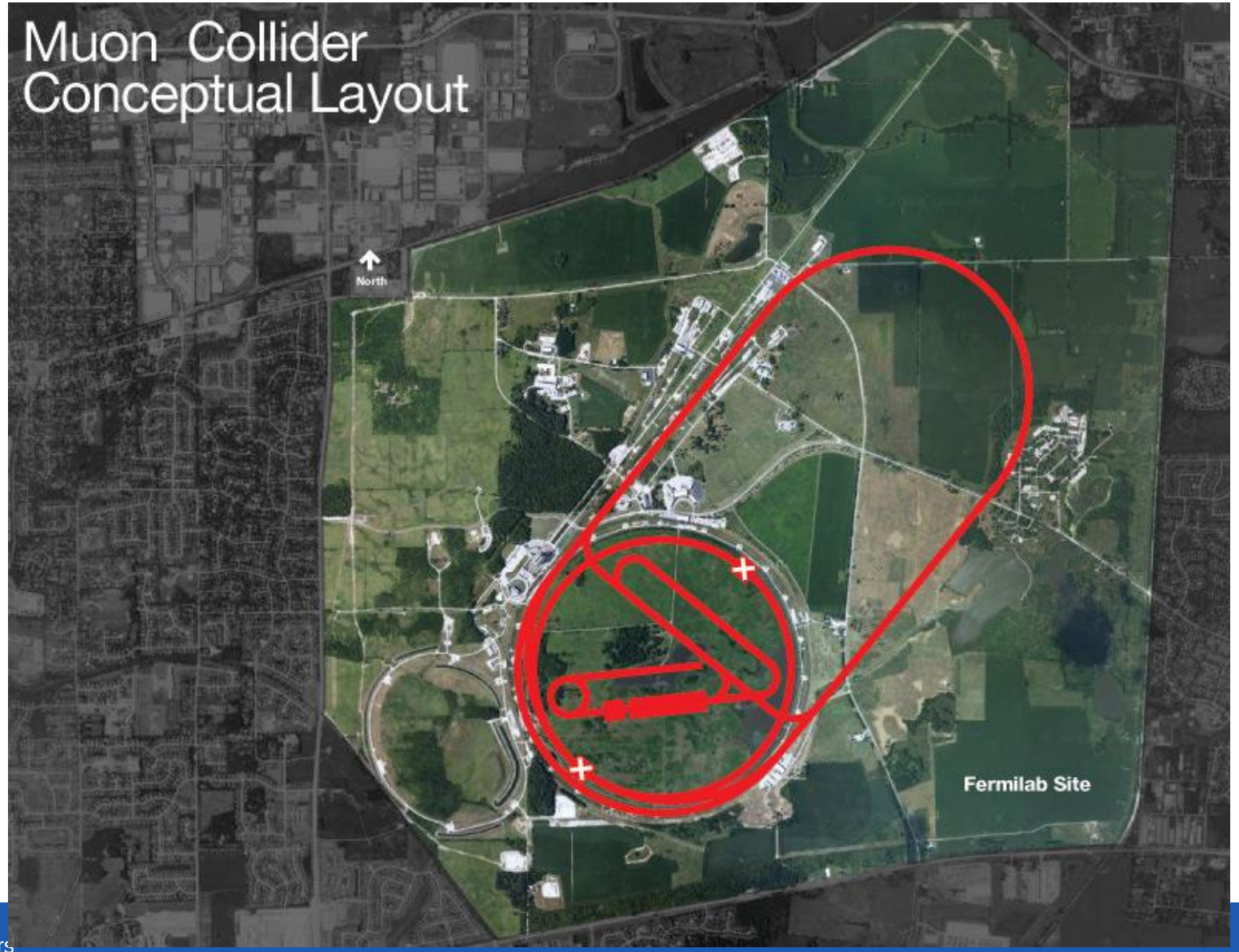
An alternative: the muon collider



Are muons stable particles?

Courtesy of A. Grudiev et al.

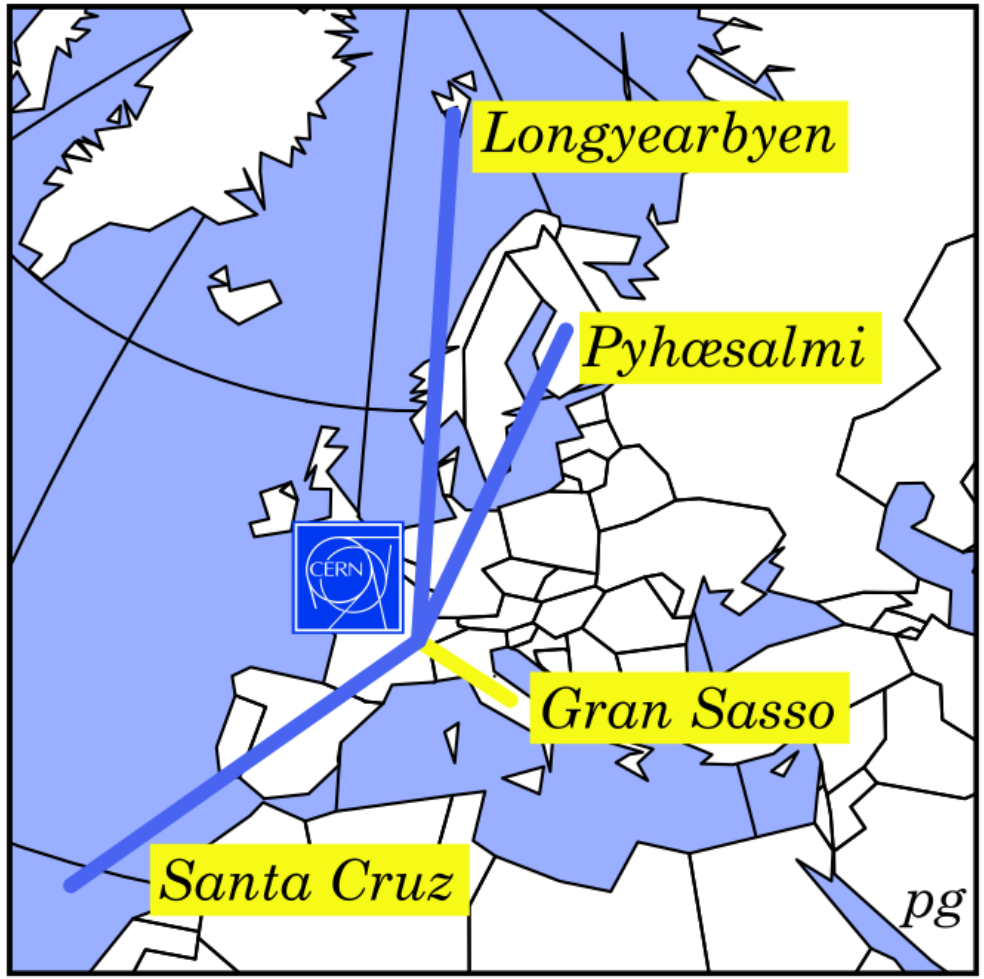
Muon collider proposal at Fermilab (US)



Where do you want to take shifts (old sites)?

Now we are discussing other places....

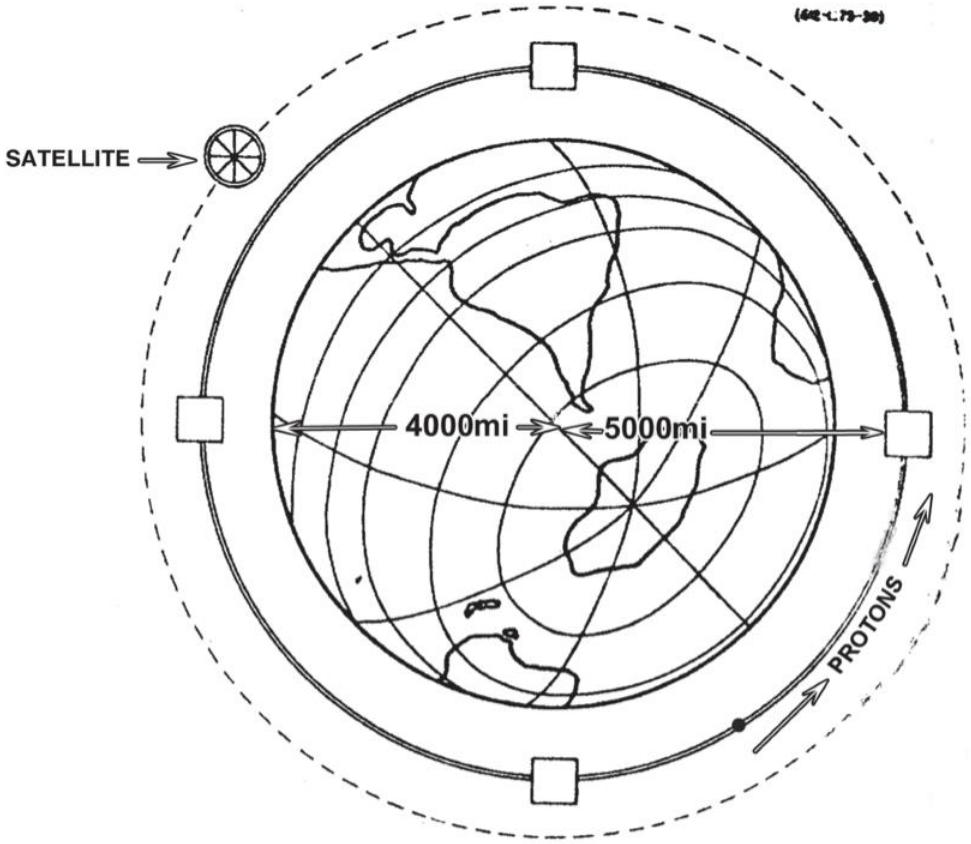
Our playground…



… or back to the future

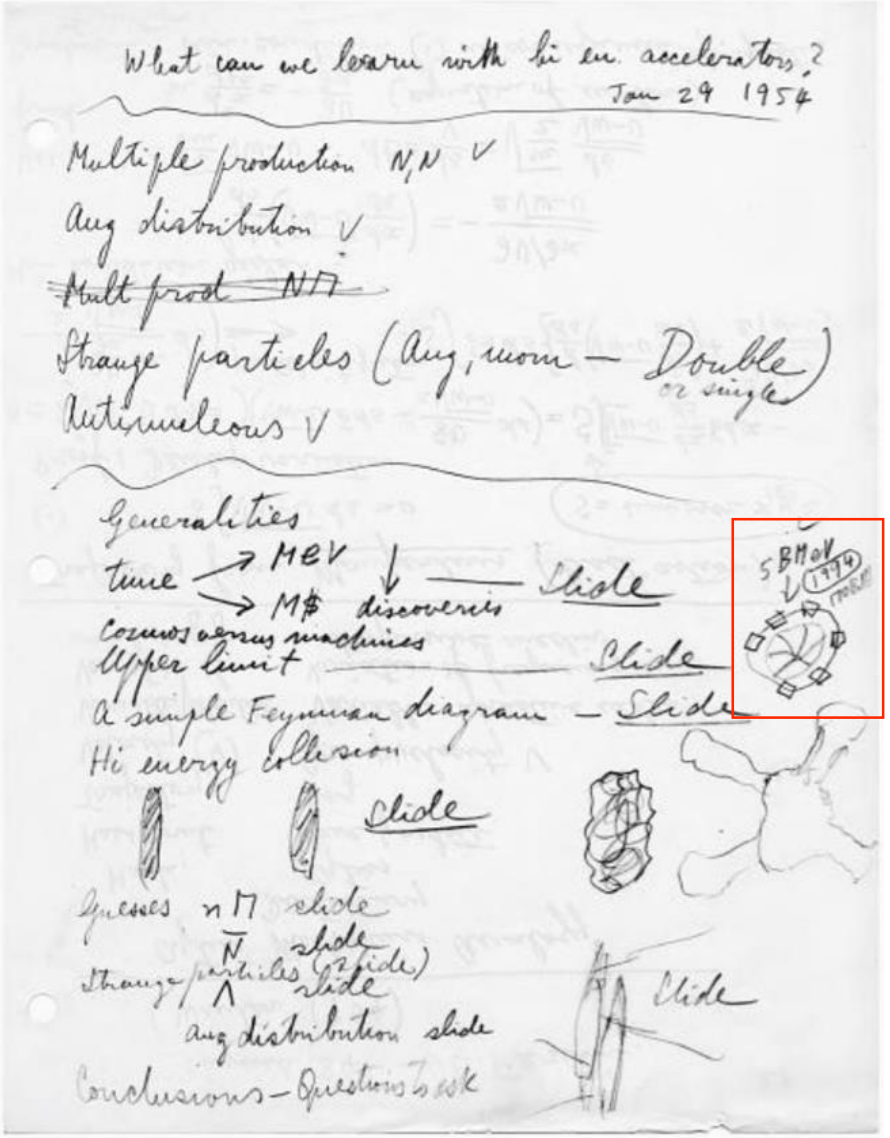
5000 TeV

B=2 T R = 8000 km



By E. Fermi

"Preliminary design...8000 km, 20.000 gauss" for 1994



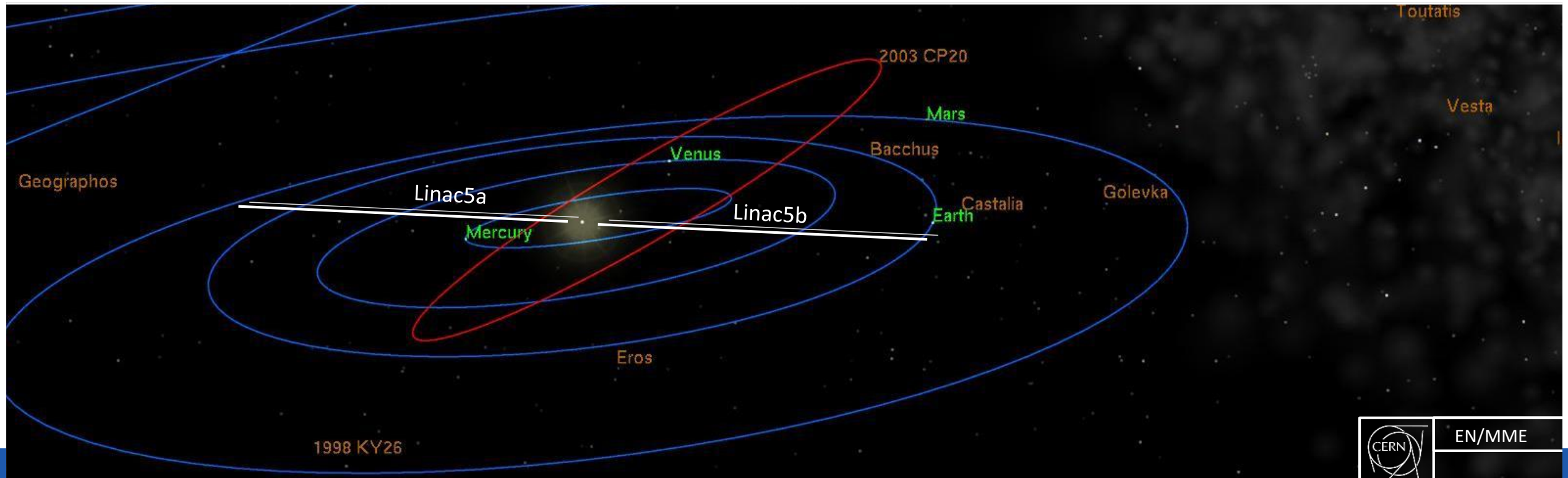
Images courtesy of the Special Collections Research Center, University of Chicago Library and Cronin J (ed.) Fermi Remembered (University of Chicago Press, 2004)

From: B. Goddard

Where is the limit?

Ultimate physical limits?

- Maximum voltage gradient: limited by spontaneous e+e- pair production in vacuum to *Scwinger critical field* of 10^{18} V/m
  - Assume a comfortable engineering margin: take 10^{17} V/m
- Linac length to reach Planck scale: ~10^{11} m (per Linac)
- Earth-sun distance: 149’000’000 km = 1.5 x 10^{11} m
- So: Linear collider at scale of earth orbit, at 10% of vacuum critical field gradient
- Circular colliders are out: with 1’000 T bend field, takes a 10 light year diameter to reach 10^{28} eV. Beam revolution period is 31 years….



Beam loss control will be important: a single proton at 1e28 eV = 1’600 MJ

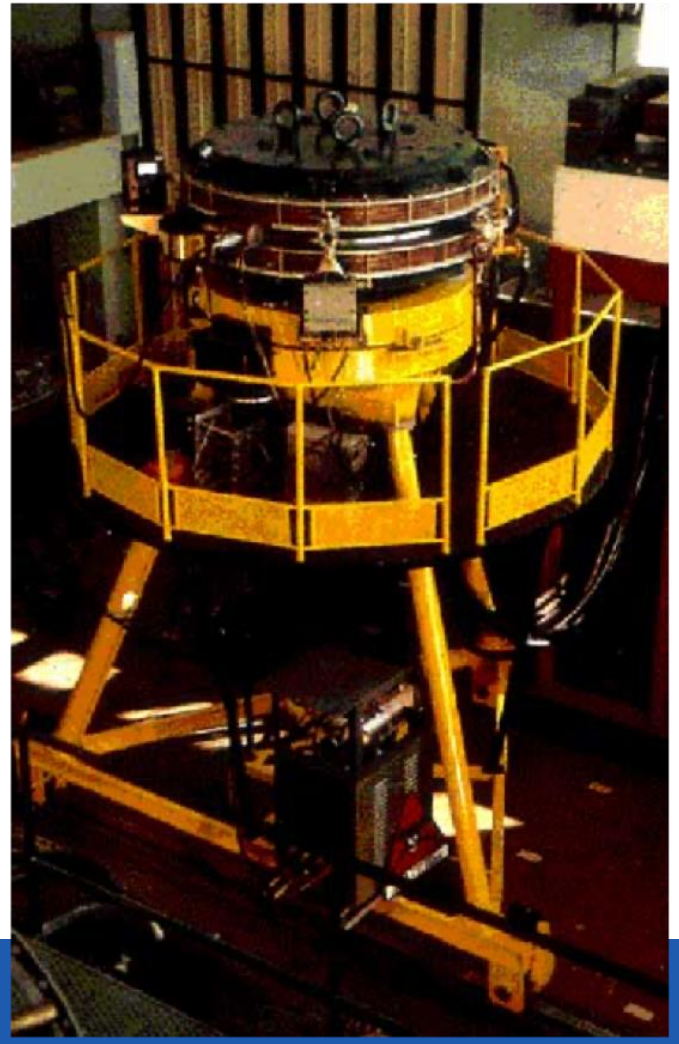
EN/MME

Not for execution

A bit of hystory

The first electron-positron 250 MeV collider/storage ring, AdA (1960), built and operated at Frascati

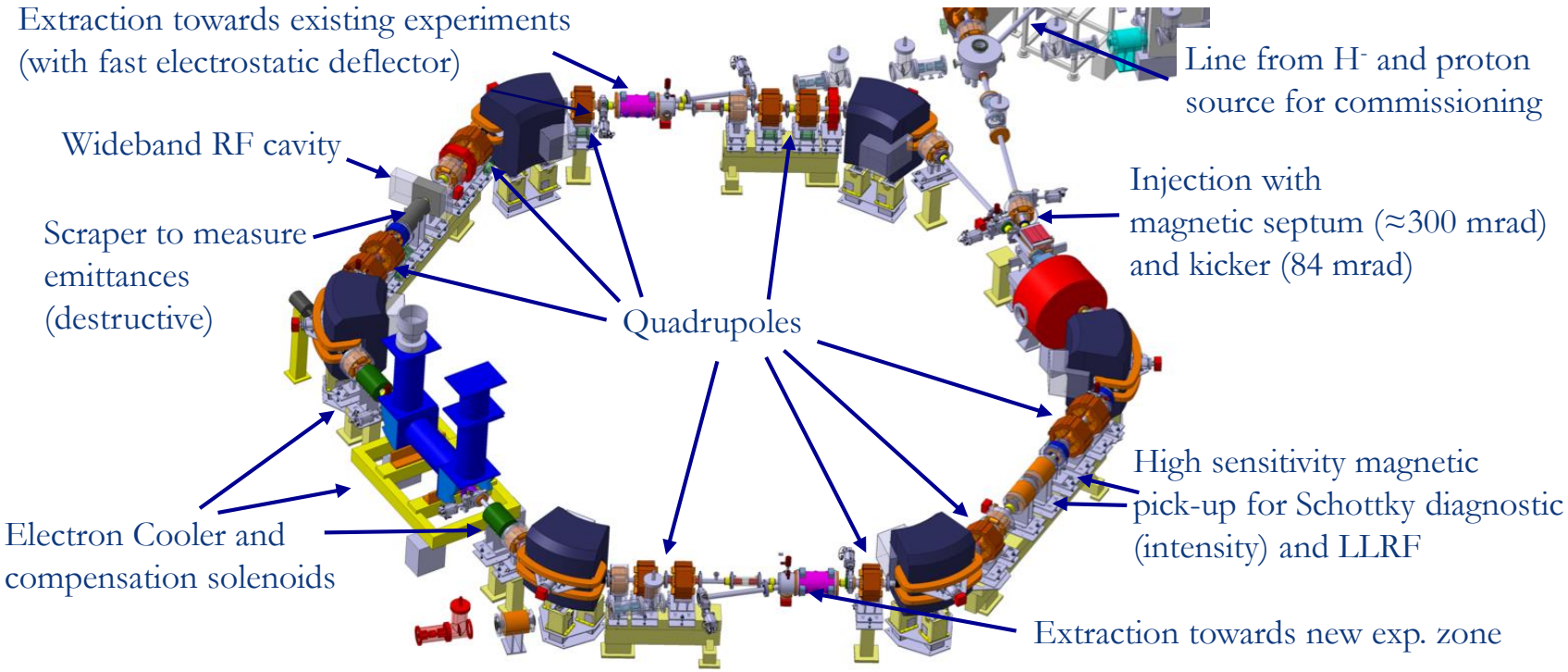
AdA = Anello di Accumulazione



First collisions in 1963: not for producing HEP data but to bring better understanding of beam dynamics

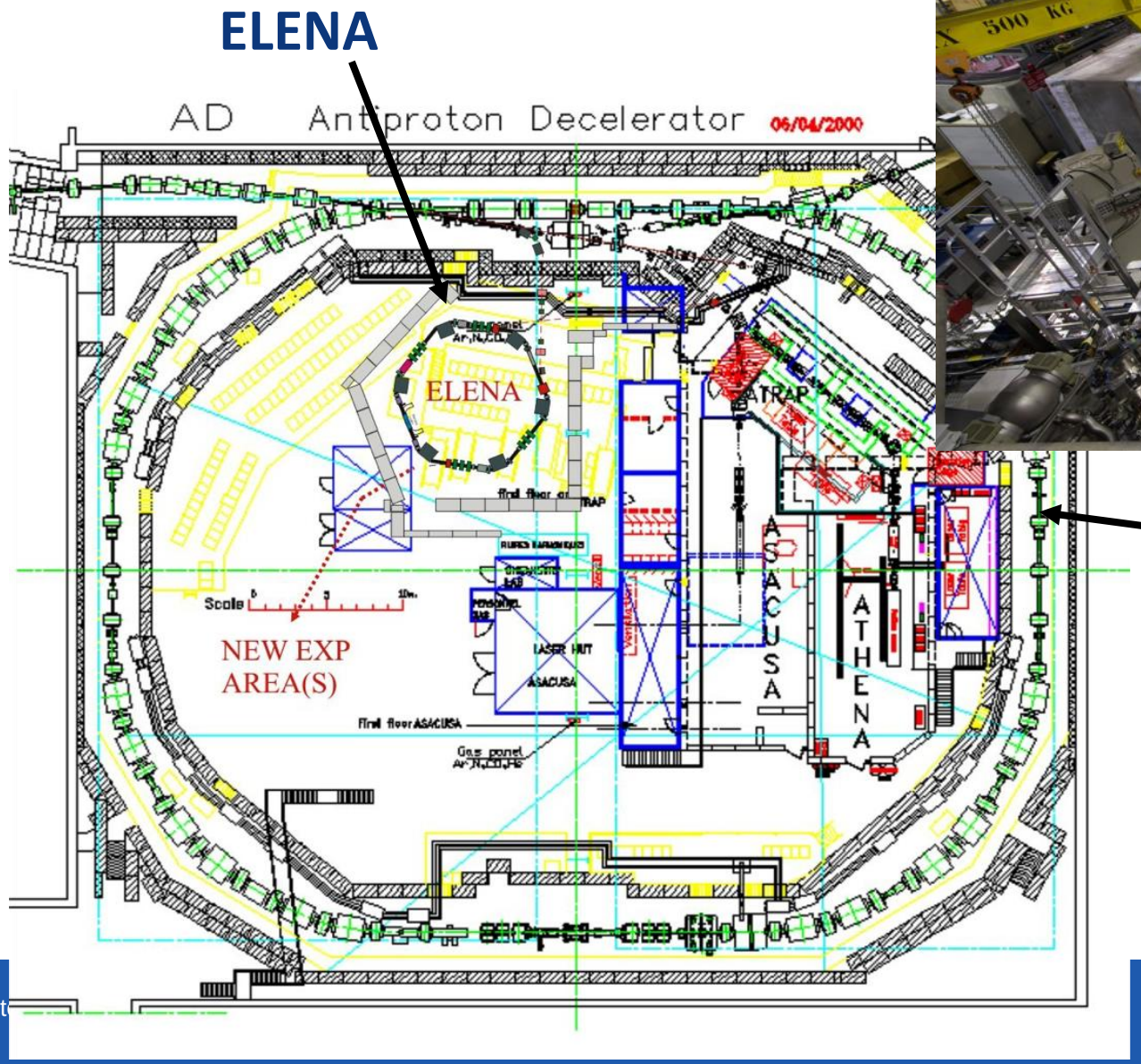
https://cas.web.cern.ch/cas/Baden/PDF/Bernardini.pdf

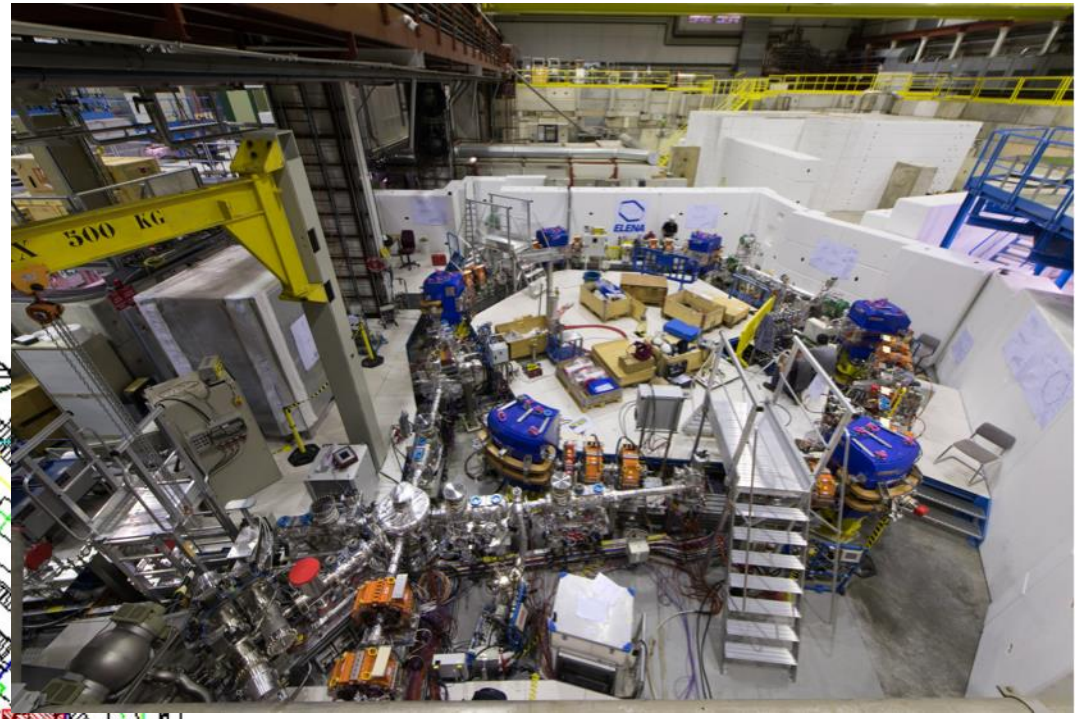
The most recent CERN (de)celerator… ELENA



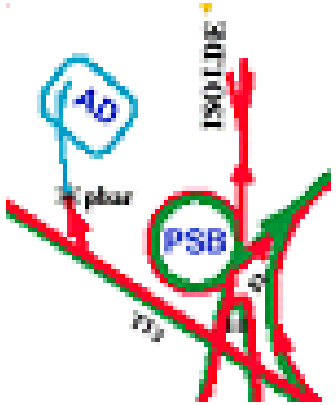
- **Deceleration of antiprotons from 5.3 MeV to 100 keV** to improve efficiency of antimatter experiments
- **Circumference 30.4 m**
  - Fits in available space in AD hall and allows installing all equipment without particular efforts
  - Lowest average field (beam rigidity over average radius) Bρ/R = 94 G (smaller than for AD 115 G)

ELENA in AD hall





AD



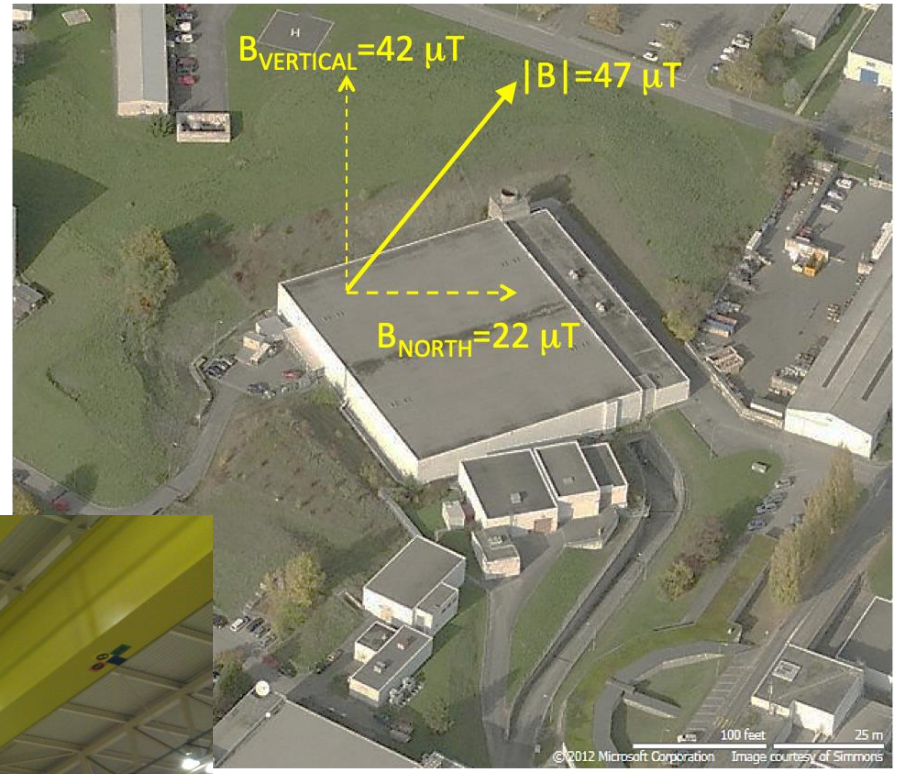
Influence of environmental magnetic fields

General tolerance for the background field 0.1 G i.e. 10 µT (~1 mm/m deflection @ 100 keV)
Lowest field at extraction : 94 G

Field sources:
- geomagnetic field
- DC and AC currents: power lines, busbars …
- remanent magnetization in steel components (typical in welded/cold worked parts)
- electrical machinery (motors, pumps …)

Field decays with distance from source *r* as $1/r^n$

Steel structures (beams, scaffolding, rebars in concrete etc.) may both shield or amplify locally the field according to the geometry, material properties, magnetic history ……

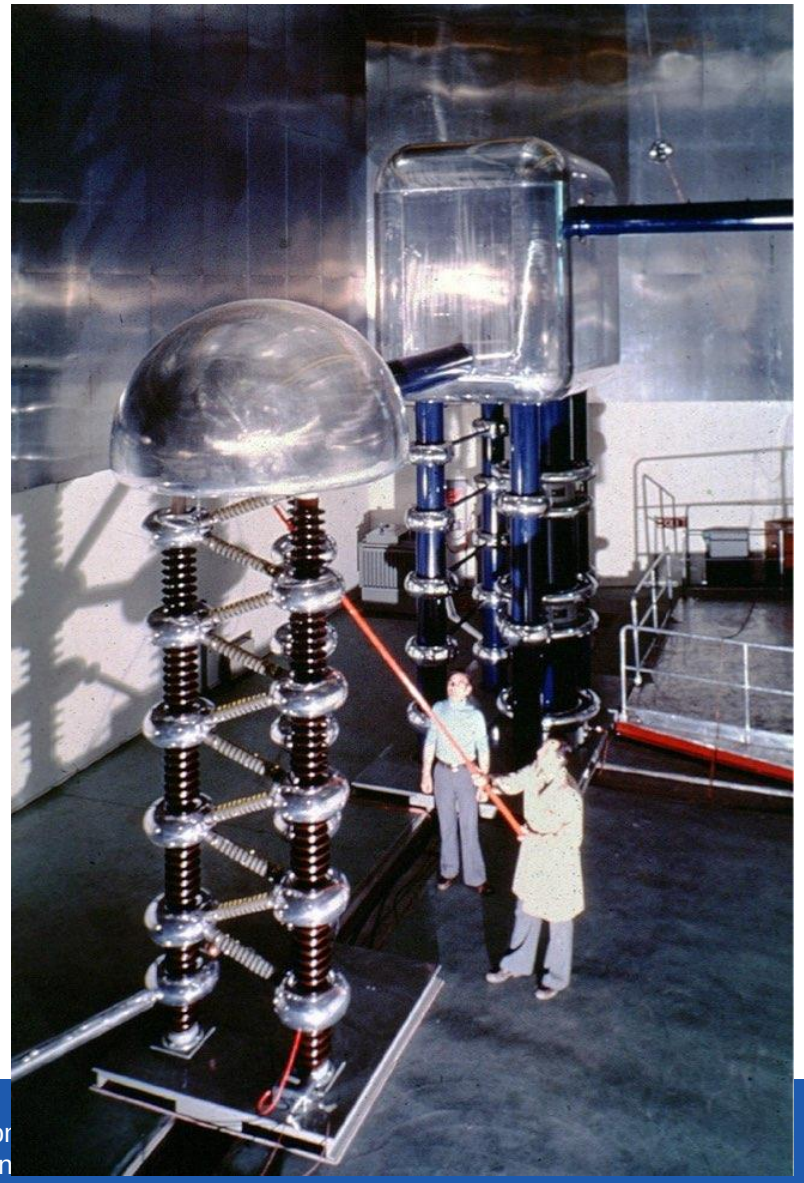


Daily and yearly change < 1%

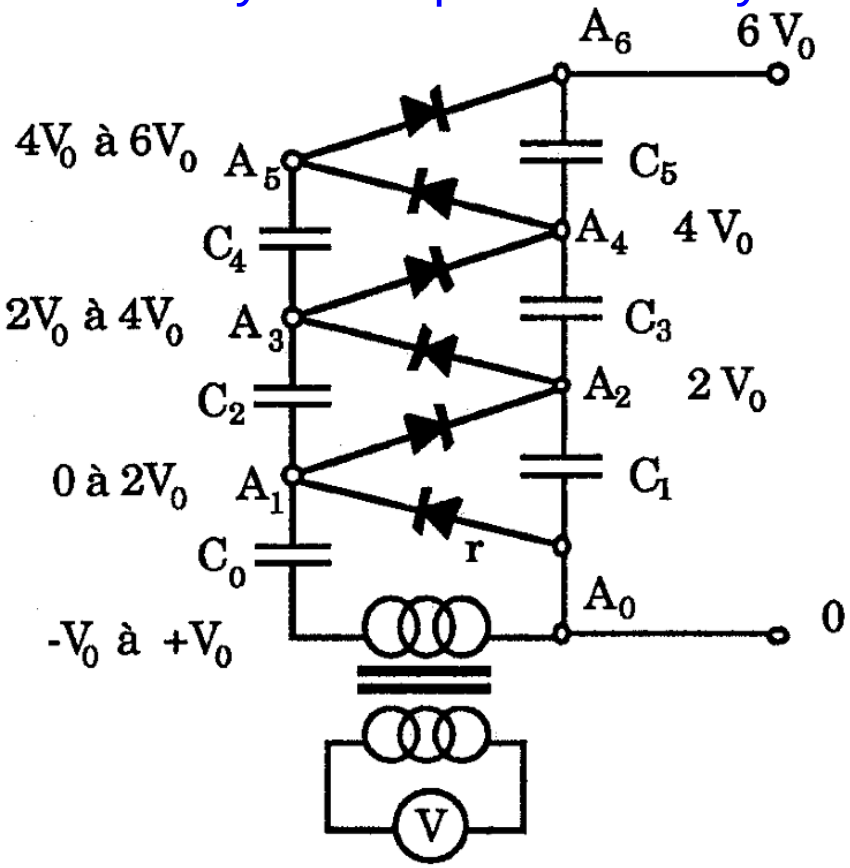
Magnetic field measured at 1.3 m from the floor as the crane passes overhead ± 2.5 µT $B_{vertical}$ fluctuation correlated with the position of the beam.

From M. Buzio

Cockroft-Walton. Old CERN proton pre-injector



High voltage unit composed by a multiple rectifier system

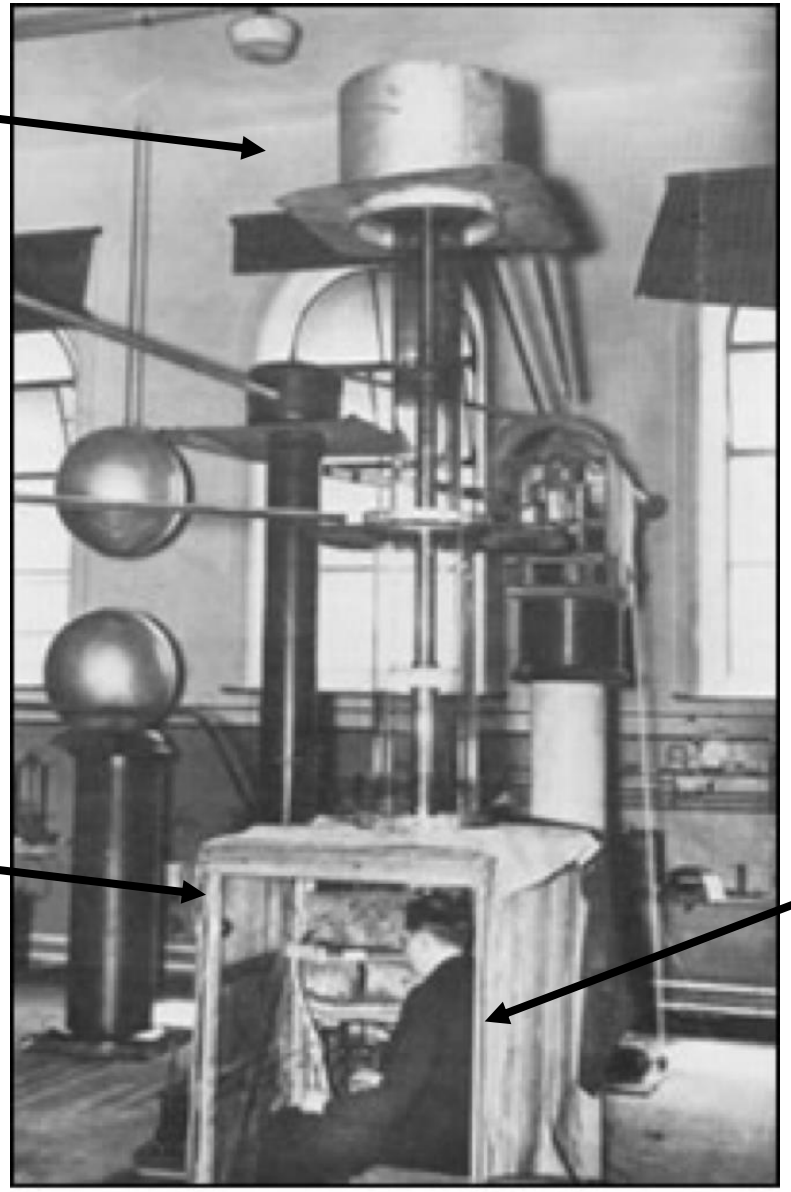


CERN: 750 kV

Accelerator

Experimental Hall

Walton



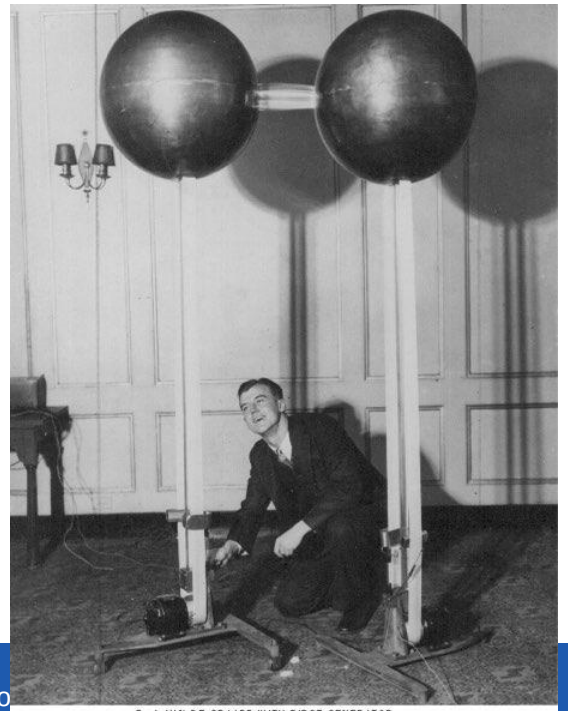
Walton and the machine used to "split the atom"

Van De Graaf electrostatic generator (1928)

A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



R. J. VAN DE GRAAFF WITH FIRST GENERATOR

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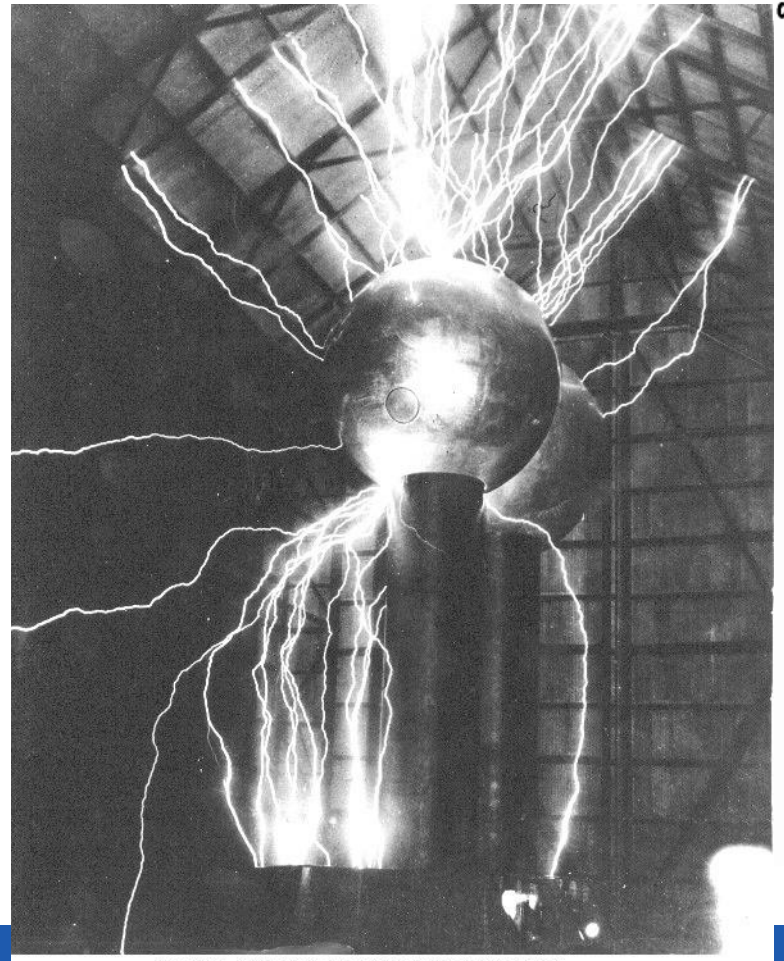

AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

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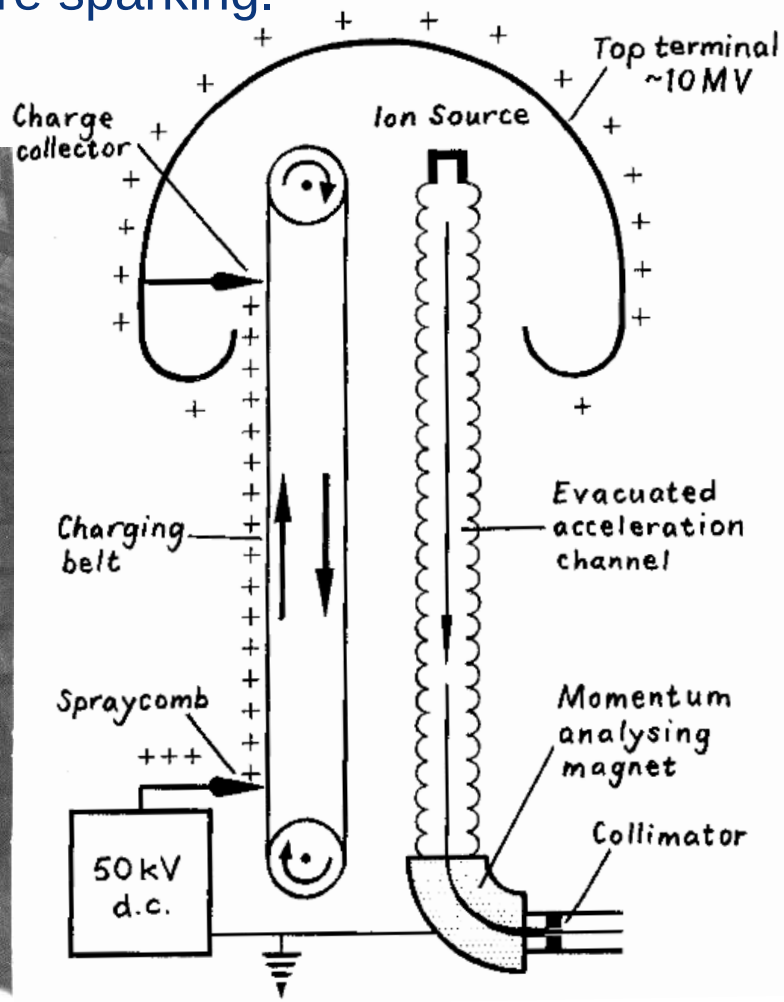
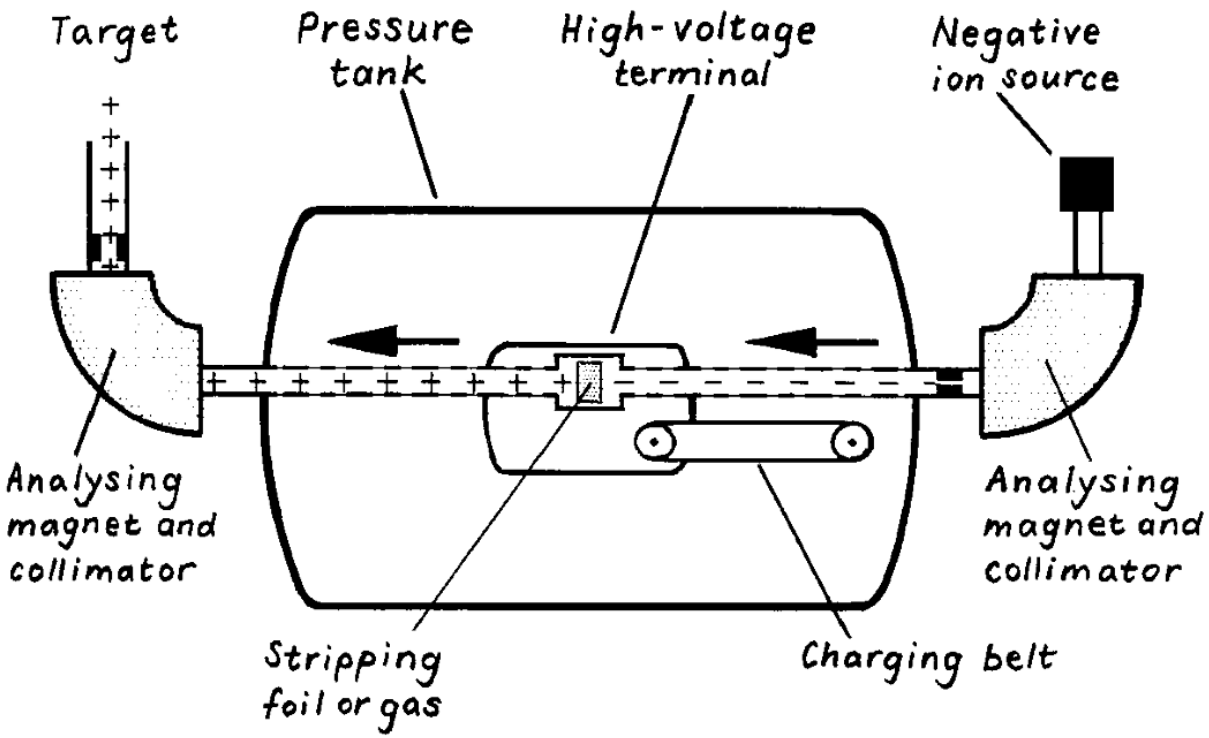


Tandem



Application of Van der Graaf generator

a) Source of negative ions (150 keV)
b) Van Der Graff column (25 MV)
c) Stripping foil
change in charge
d) Further re-acceleration

Everything in a pressurized vacuum tank

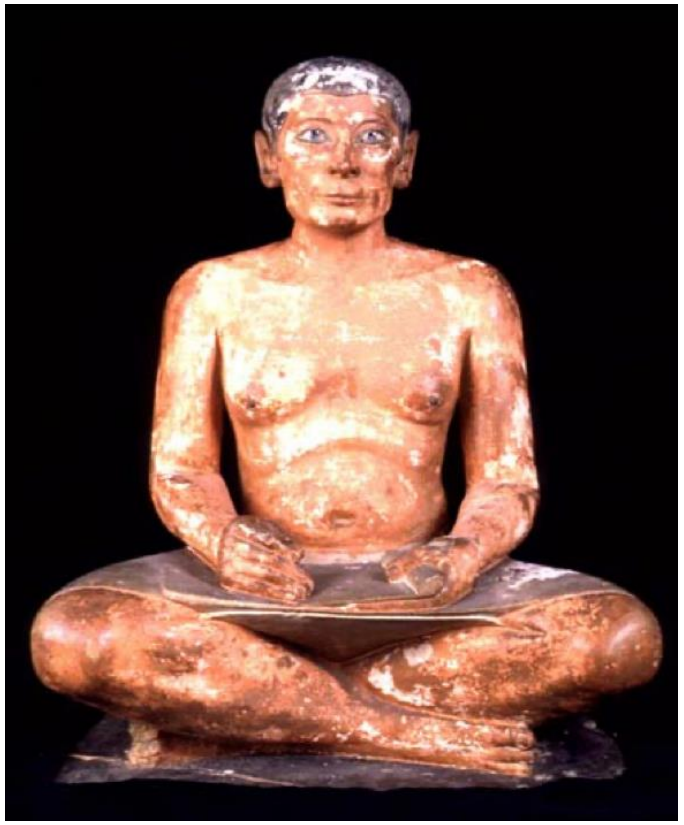
Since negative and positive multicharge states are used, different energies can be obtained

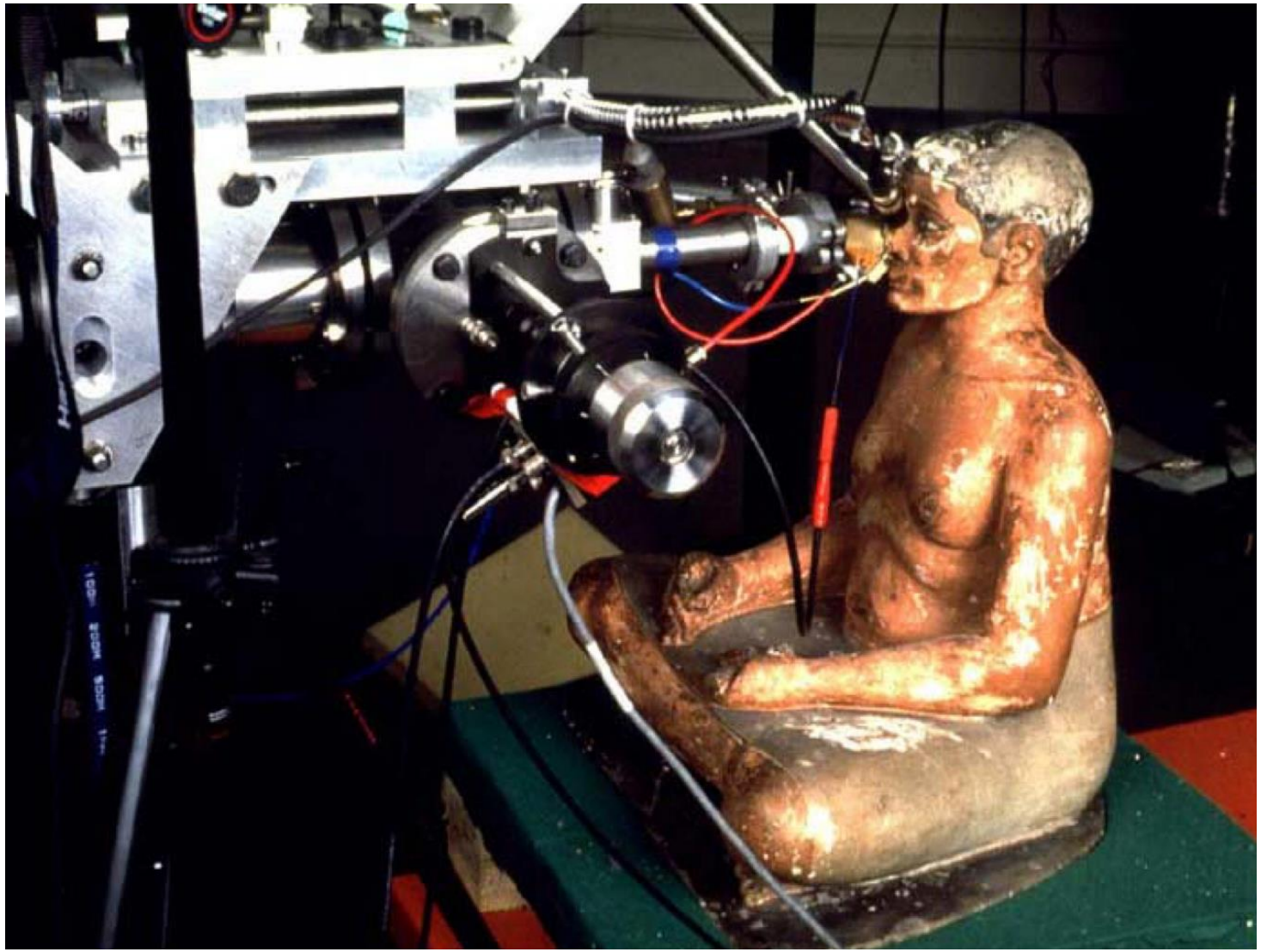
Current applications:

a) Low energy injector for Ions
Still in use at Brookeven (US) as injector for Cu and Au ions

b) Compact system for “other uses” : Dating of samples at Louvre.

Application of Louvre Tandem: composition of scribe eyes



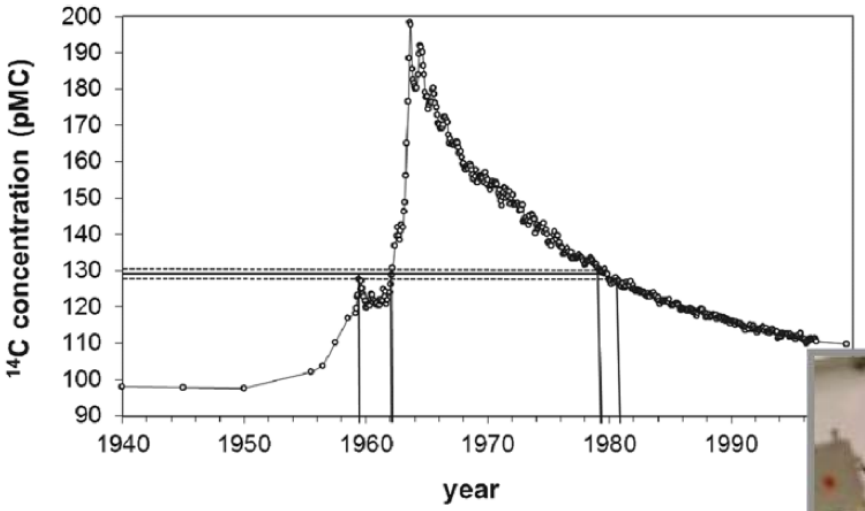


http://accelconf.web.cern.ch/AccelConf/e02/TALKS/FRYGB001.pdf

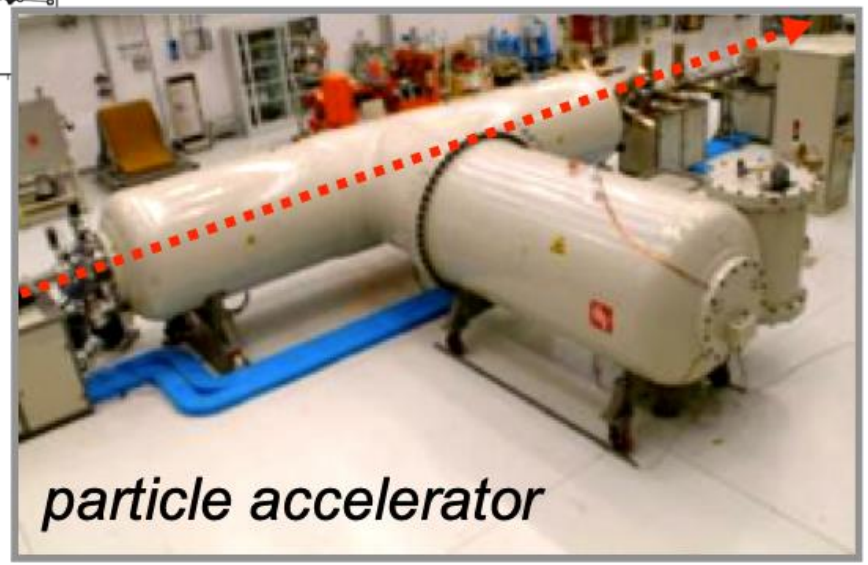
Discovering forgeries of modern art by the 14C Bomb Peak

Contraste de formes, Fernard Leger (?)
Peggy Guggenheim Collection, Venice.

Accelerator Mass Spectrometry (AMS) to measure rare isotopes abundance with 3MV Tandetron accelerator of INFN-LABEC in Florence.



Eur. Phys. J. Plus (2014) **129**: 6
DOI 10.1140/epjp/i2014-14006-6



Synchrotron (1952, 3 GeV, BNL)

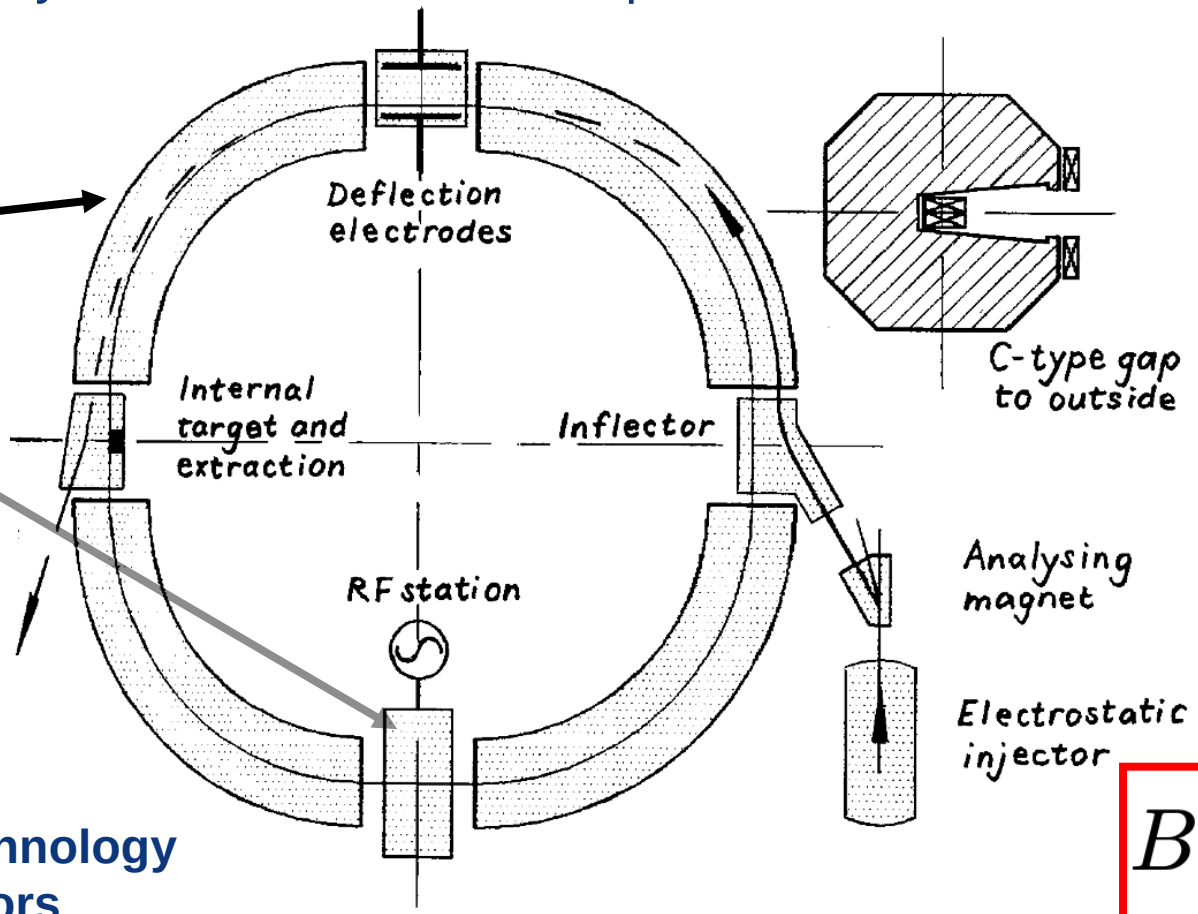
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

ρ constant radius of curvature



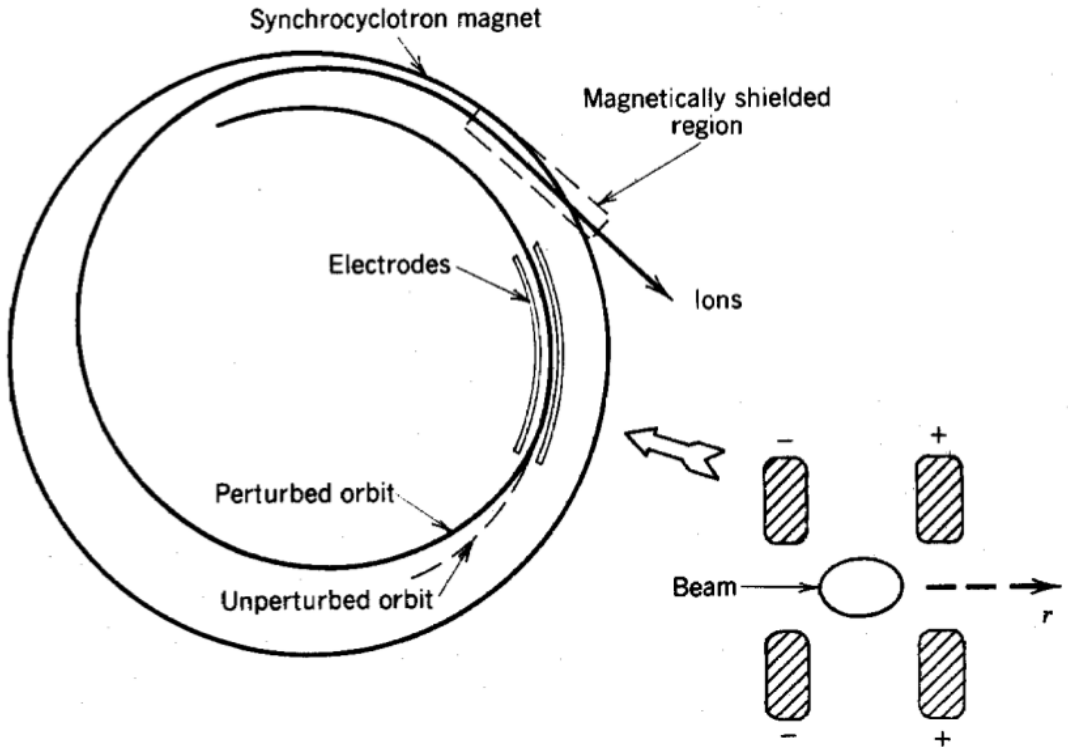
Bending strength limited by used technology to max ~ 1 T for room temperature conductors

Particle rigidity:

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

Synchrocyclotron

Synchrocyclotrons have a constant magnetic field with geometry similar to the uniform-field cyclotron. The main difference is that the rf frequency is varied to maintain particle synchronization into the relativistic regime.



Next tomorrow