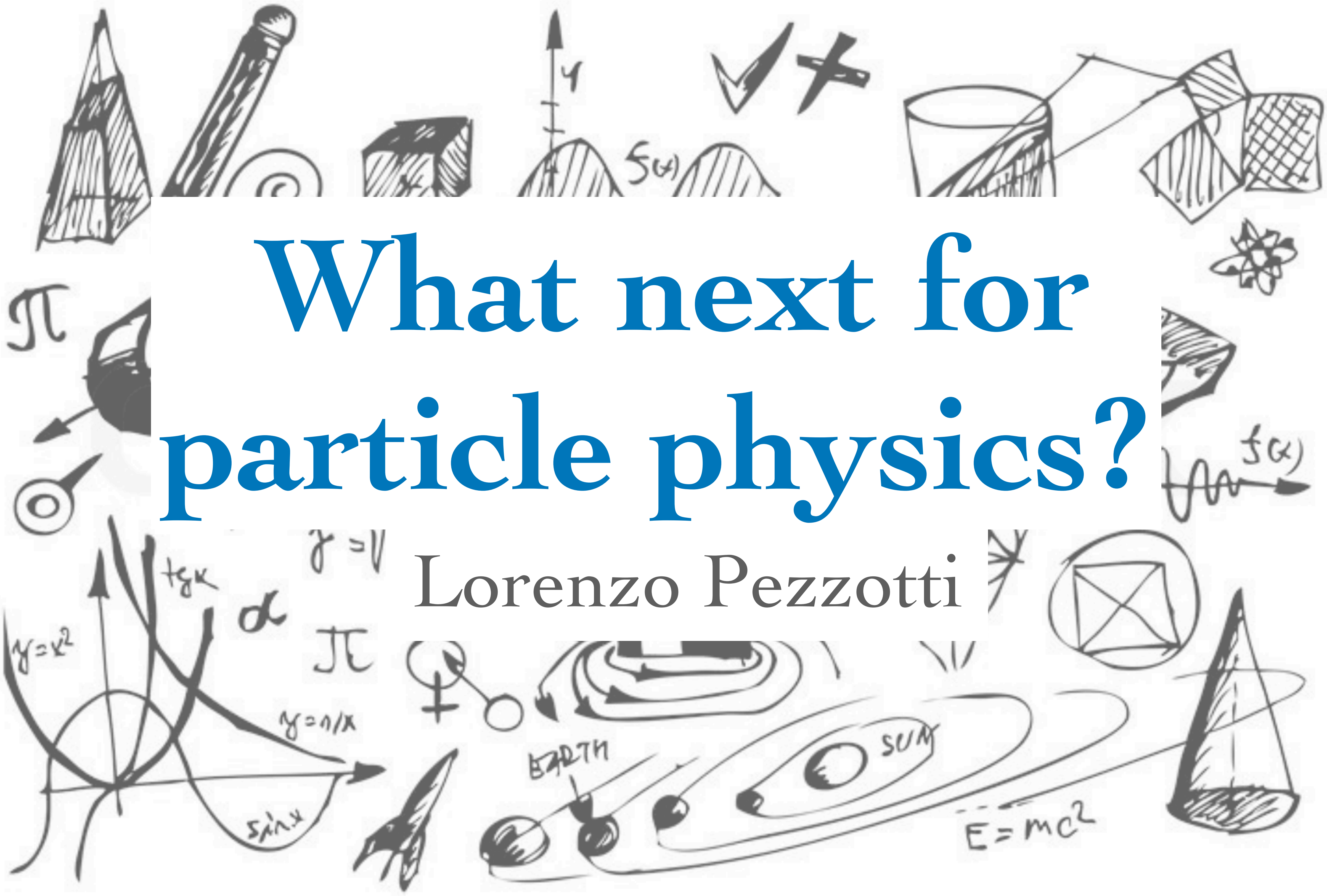
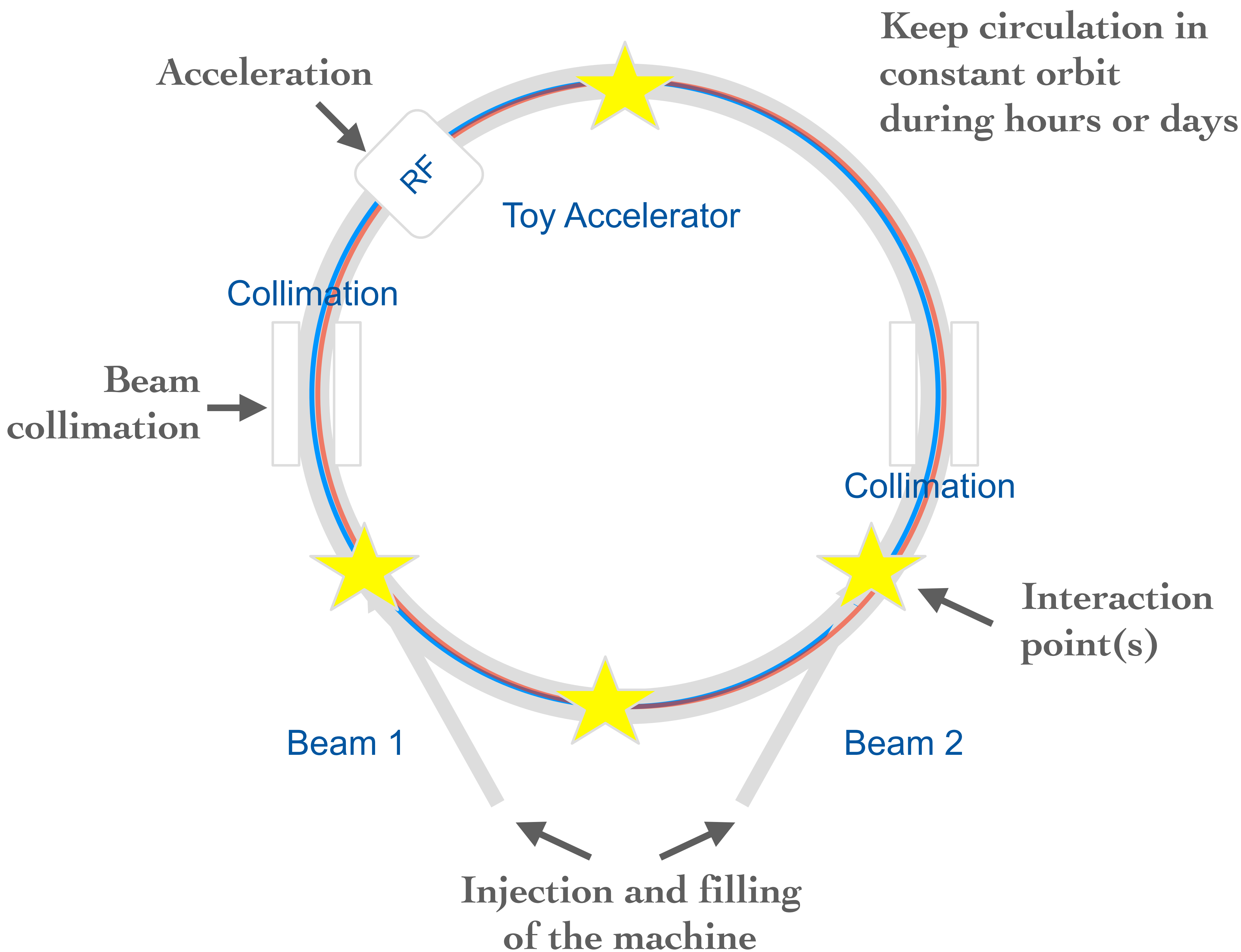


What next for particle physics?

Lorenzo Pezzotti

Incontri del martedì - 5 Novembre 2019

Basic accelerator concepts



Lorentz force

Newton-Lorentz force describes the interaction of charged particles with electro-magnetic fields:

Particle charge

Electric field

Particle instantaneous velocity

Magnetic field

$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})$$

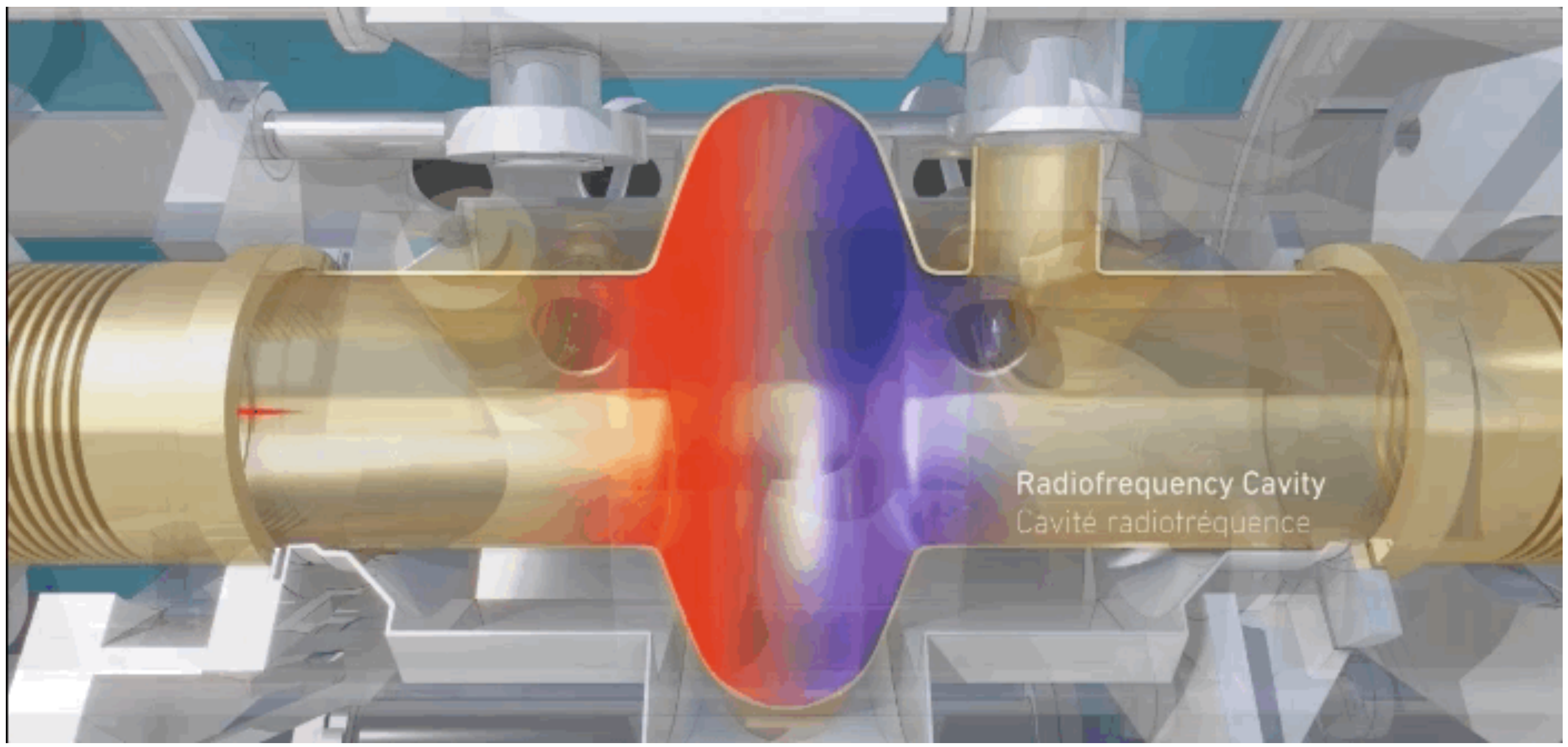
Longitudinal Motion
Parallel to the direction of motion.
Used to accelerate charged particles.

Transverse Motion
Perpendicular to the direction of motion.
Used to keep circulating orbit and beam steering.

3

Acceleration

Acceleration has to be done by an electric field in the direction of the motion



Apply an E-field which is reversed while the particle travels inside the tube.

Build the acceleration with one or more series of drift tubes with gaps in between them.

Transverse Motion: trajectory

In order to keep circular trajectory, Lorentz force should compensate the centrifugal force

$$F_L = evB \qquad F_c = \frac{mv^2}{\rho}$$

Radius

$$\frac{mv^2}{\rho} = evB \rightarrow \frac{p}{e} = \rho B \rightarrow \boxed{0.3B[\mathrm{T}] \approx \frac{p[\mathrm{GeV/c}]}{\rho[\mathrm{m}]}}$$

$$p = mv$$

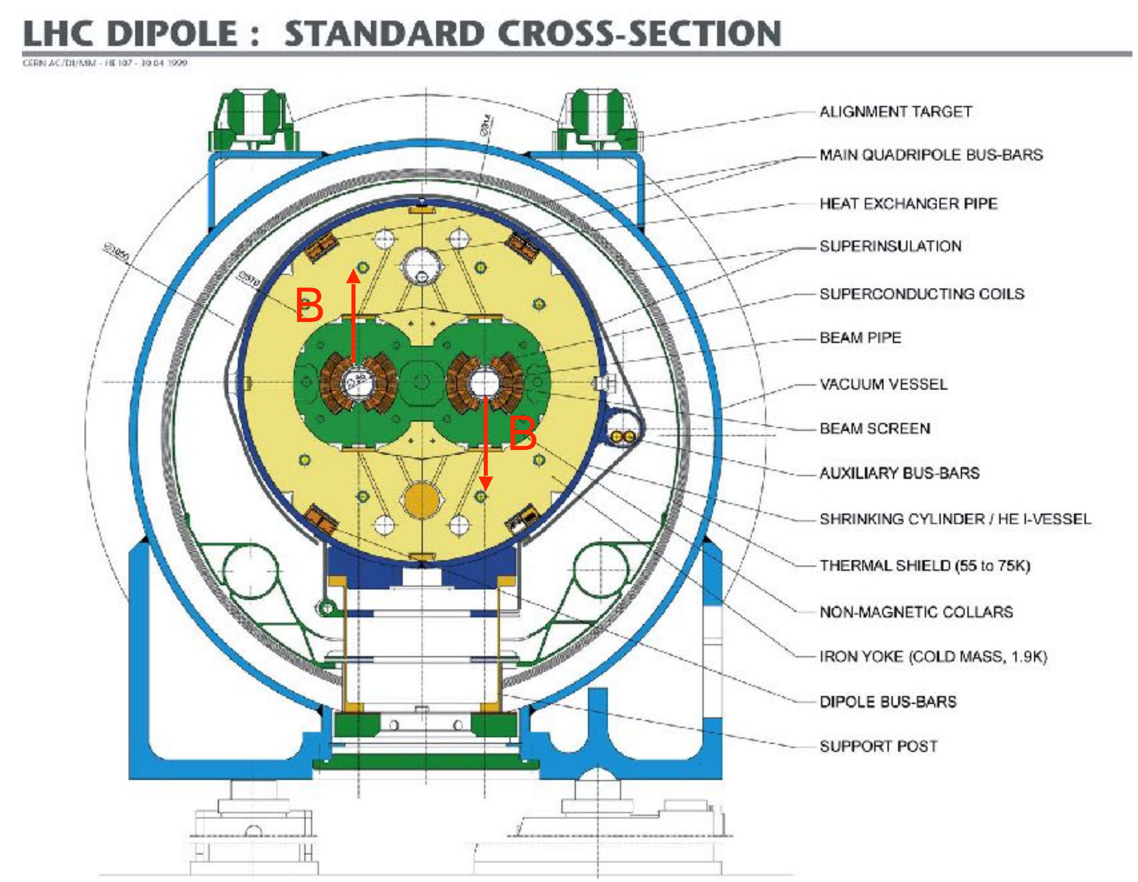
Magnetic Rigidity

Because particles need to follow a circulate trajectory **the magnetic field should increase proportionally to the particles momentum.**

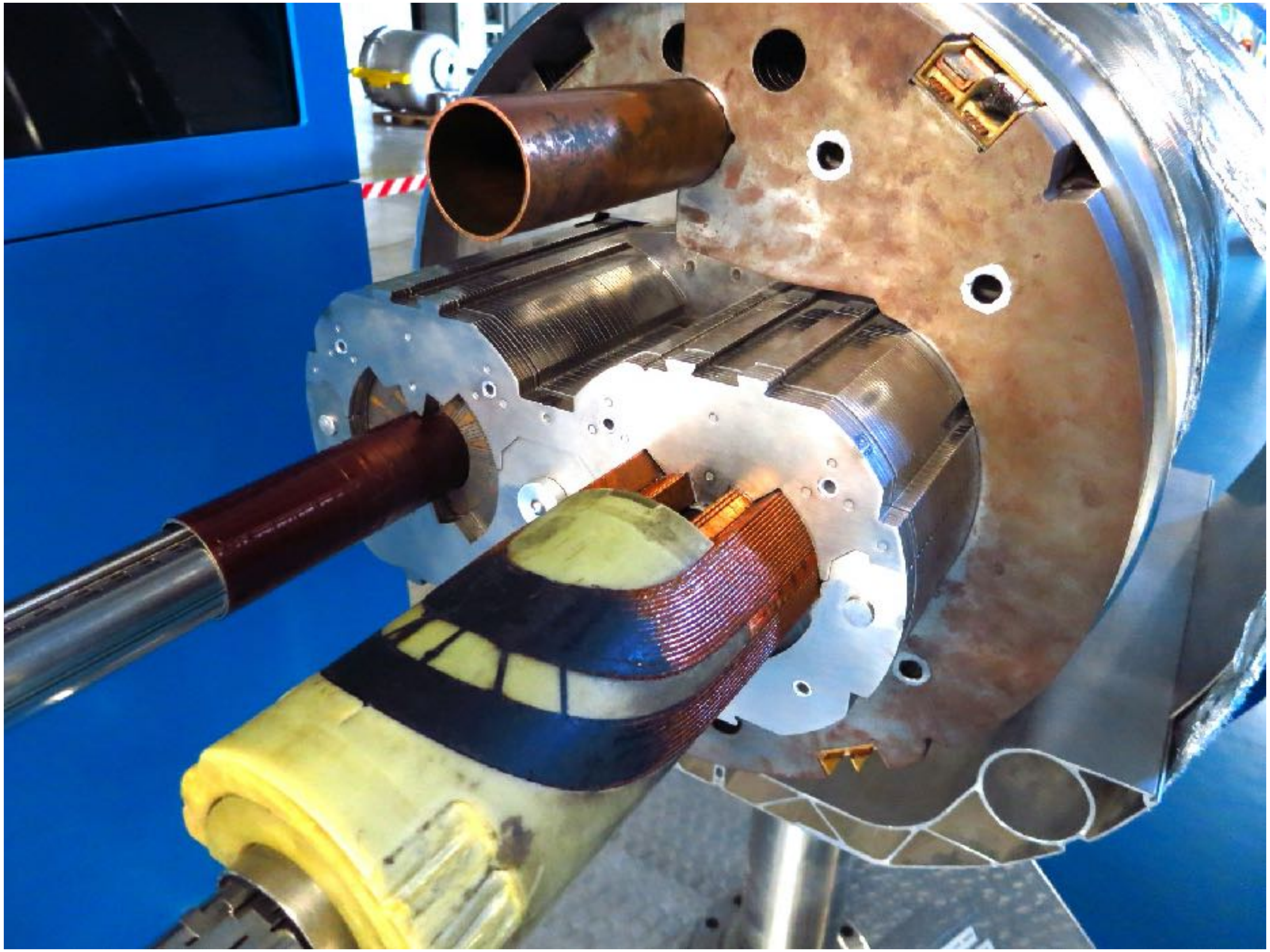
$$\rho \approx 2.8 \text{ Km} \approx \frac{0.65 \times 26.7 \text{ Km}}{2\pi}$$

$$B[\mathrm{T}] \approx \frac{7000 \text{ GeV/c}}{0.3 \times 2.8 \text{ Km}} = 8.33\mathrm{T}$$

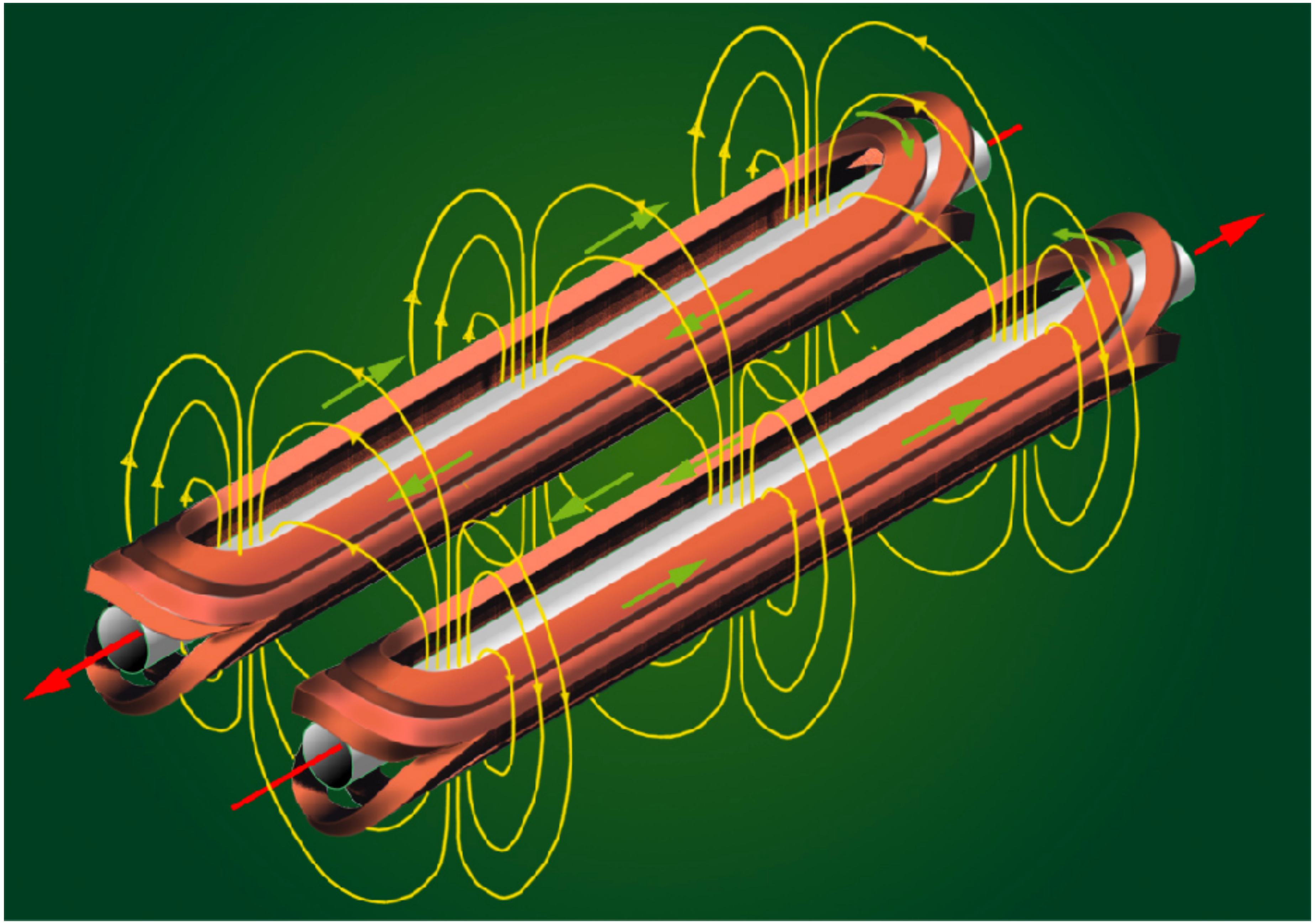
LHC Nominal dipole field 8.33 T



Transverse Motion: trajectory



Transverse Motion: trajectory



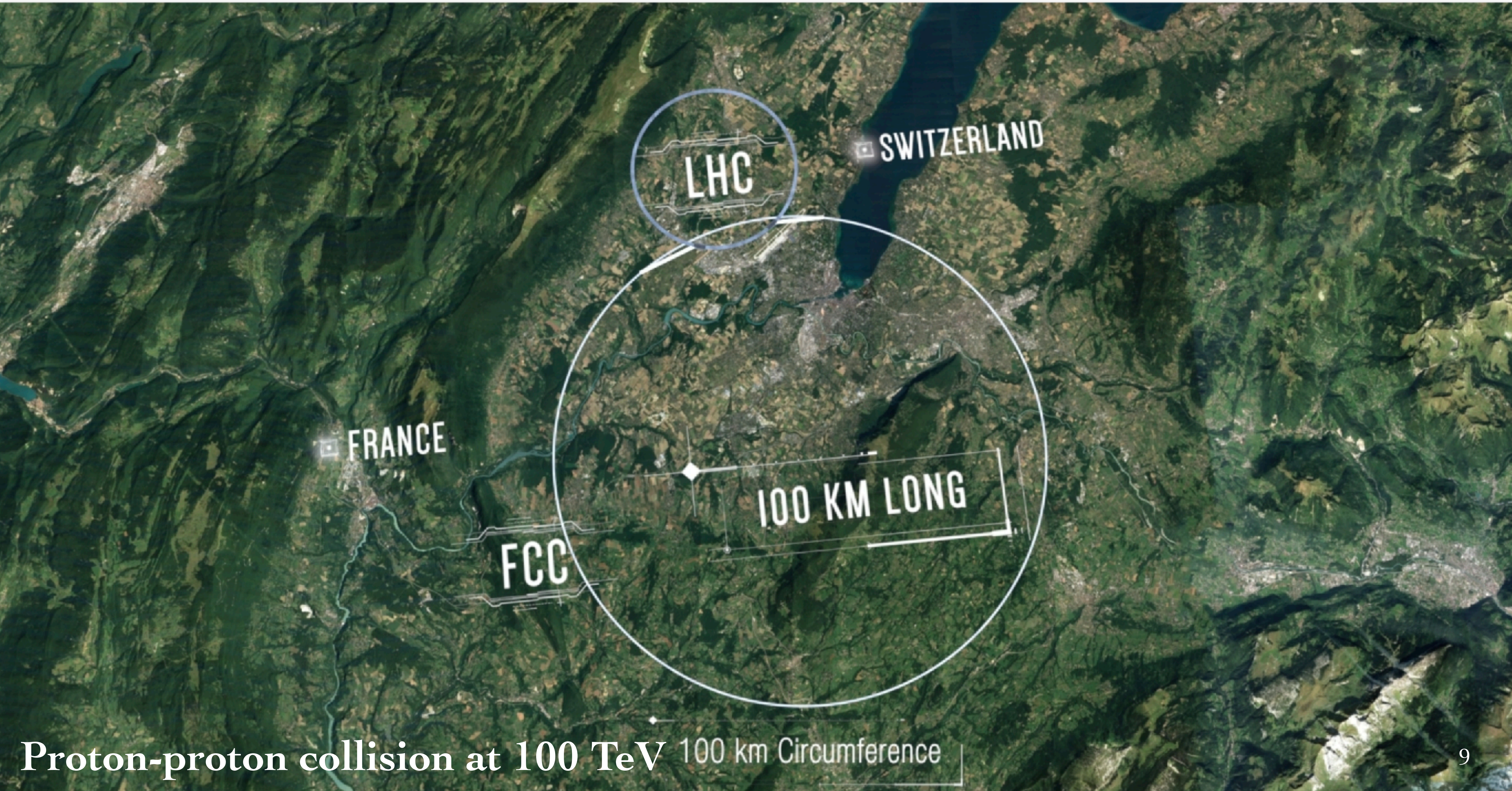

LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
16 Radiofrequency cavities at 400 MHz
1232 Superconductive Nb-Ti magnets at 1.9 K,
generating a magnetic field of 8.33 T
Proton-proton collision at 14 TeV until 2040

The Future Circular Collider (FCC)

FCC Nominal dipole field (Nb_3Sn) 16.11 T

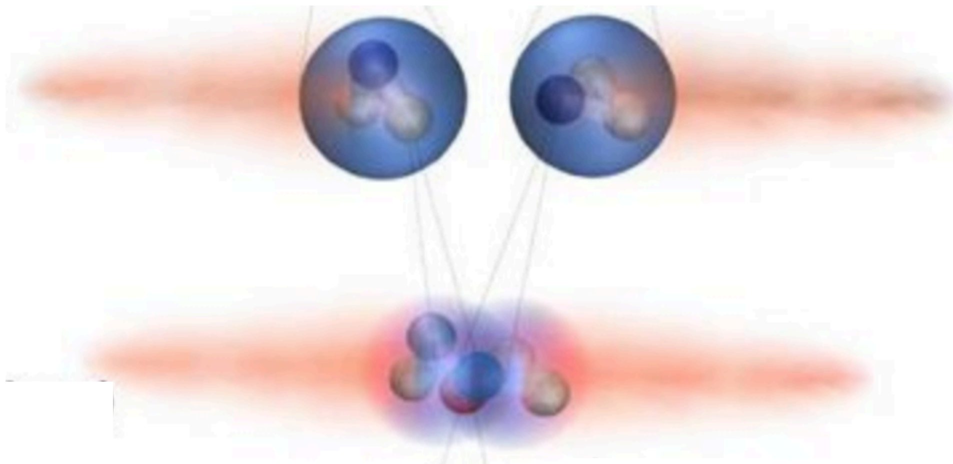
$$B[\mathrm{T}] \approx \frac{50000\ \mathrm{GeV/c}}{0.3 \times 10.4\ \mathrm{Km}} = 16.11\mathrm{T}$$

$$\rho \approx 10.4\ \mathrm{Km} \approx \frac{0.65 \times 100\ \mathrm{Km}}{2\pi}$$

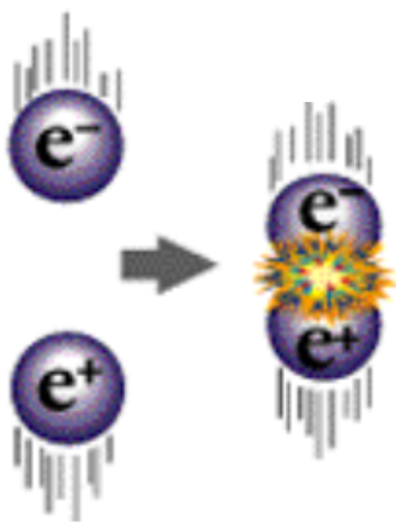


Proton-proton collision at 100 TeV

Proton-proton collision



Electron-positron collision



The 2013 Update of the European Strategy for Particle Physics (ESPPU) [1] stated, inter alia, that "*... Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update*" and that "*CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide*".

In response to this recommendation, the Future Circular Collider (FCC) study was launched [2] as a world-wide international collaboration under the auspices of the European Committee for Future Accelerators (ECFA). The FCC study was mandated to deliver a Conceptual Design Report (CDR) in time for the following update of the European Strategy for Particle Physics.

European studies of post-LHC circular energy-frontier accelerators at CERN had actually started a few years earlier, in 2010–2013, for both hadron [3–5] and lepton colliders [6–8], at the time called HE-LHC/VHE-LHC and LEP3/DLEP/TLEP, respectively. In response to the 2013 ESPPU, in early 2014 these efforts were combined and expanded into the FCC study.

The 2013 ESPPU recognised the importance of electron-positron colliders for the precise measurement of the properties of the Higgs boson. Since its inception, the international FCC collaboration has worked on delivering the conceptual design for a staged e^+e^- collider (FCC-ee) that would allow detailed studies of the heaviest known particles (Z, W and H bosons and the top quark) and offer great direct and indirect sensitivity to new physics.

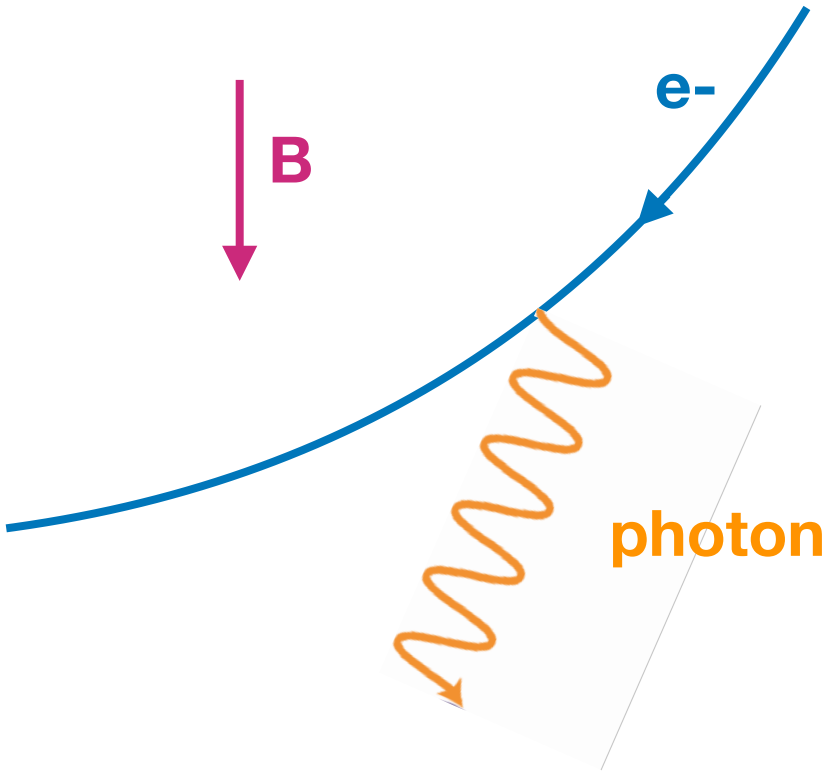
Five years of intense work and a steadily growing international collaboration have resulted in the present Conceptual Design Report, consisting of four volumes covering the physics opportunities, technical challenges, cost and schedule of several different circular colliders, some of which could be part of an integrated programme extending until the end of the 21st century.

Geneva, December 2018

Rolf Heuer
CERN Director-General 2009–2015

Fabiola Gianotti
CERN Director-General since 2016

Accelerating electrons (positrons)



Energy loss by synchrotron radiation of charged particles bent by a magnetic field

$$\Delta E \simeq \left(\frac{E}{m}\right)^4 \times \frac{1}{R}$$

Electron mass m_e: 0.5 MeV

2.75 GeV/turn lost at LEP for E = 105 GeV

Proton mass ~2000 m_e

Energy loss reduced by a factor

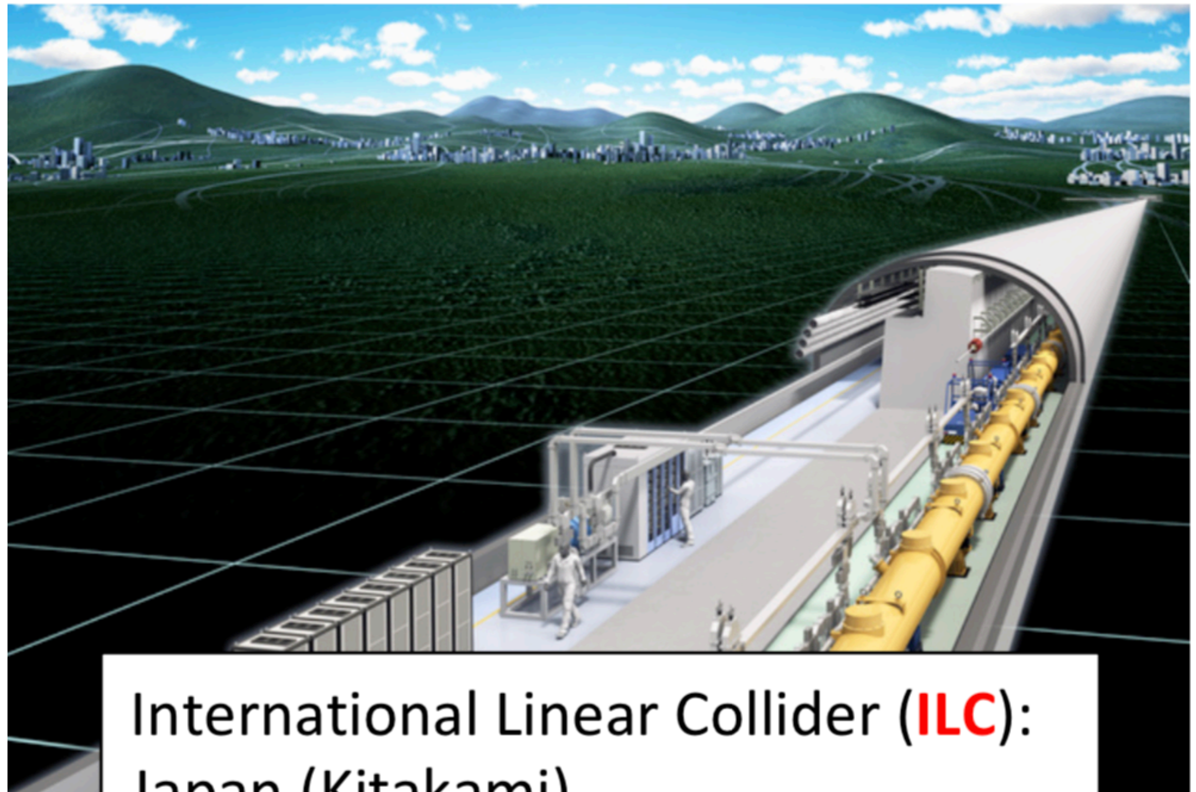
$$\left(\frac{1}{2000}\right)^4 \approx 6 \cdot 10^{-14}$$

Muon mass ~200 m_e

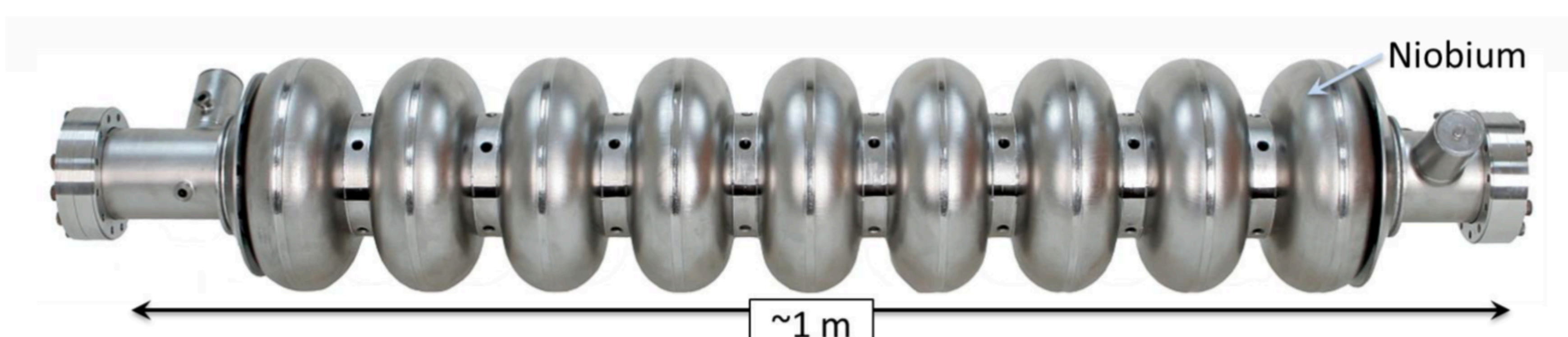
Energy loss reduced by a factor

$$\left(\frac{1}{200}\right)^4 \approx 6 \cdot 10^{-10}$$

Linear e^+e^- collider

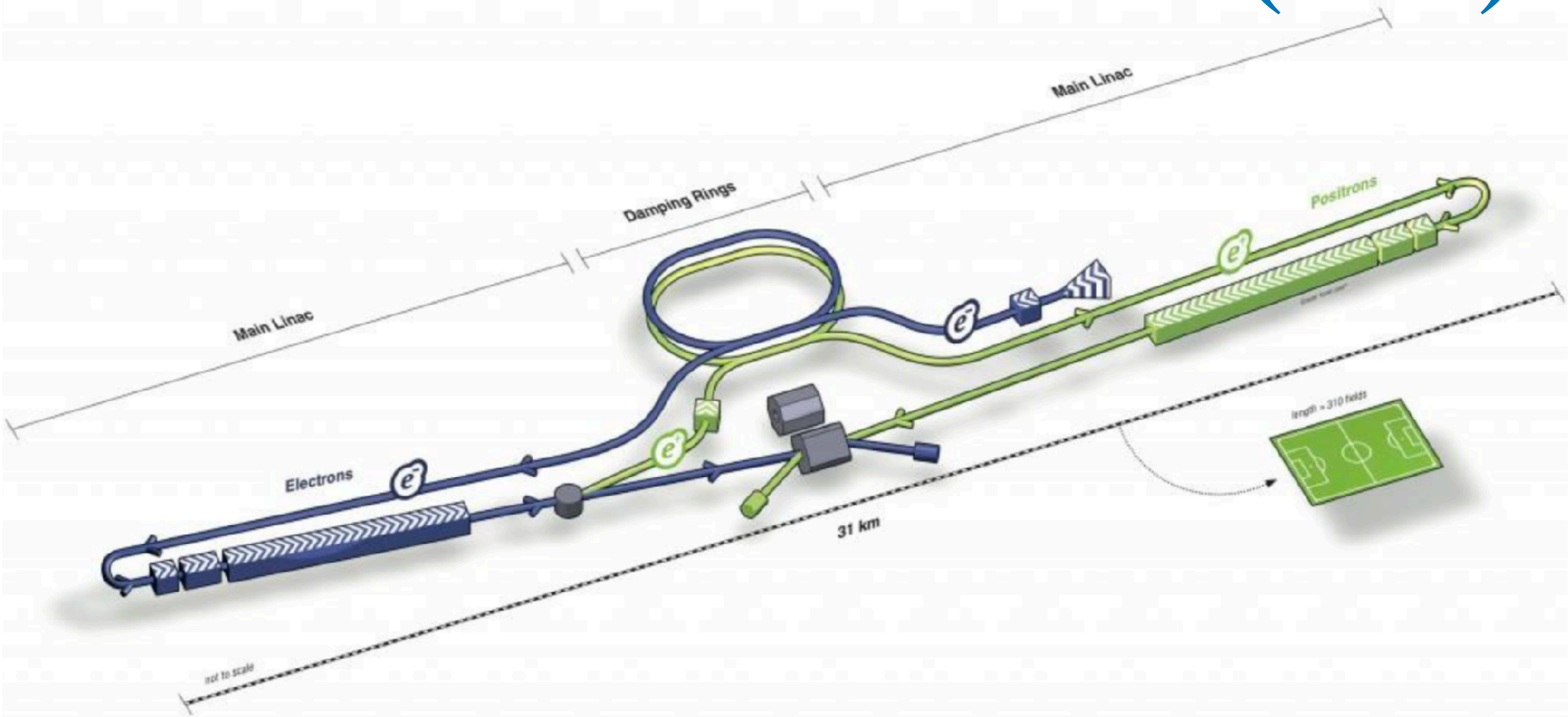


International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



ILC accelerator unit:
9 cells niobium cavities oscillating at 1.3 GHz
with an average accelerating gradient of 31.5 MV/m

International linear collider (ILC)



ILC colliding e+e- at 500 GeV,
main Linac accelerates electrons (positrons) from 15 GeV to 250 GeV:

$2 \times 235[\text{GeV}]/31.5[\text{MeV/m}] \simeq 15$ Km $\xrightarrow{\times 2}$ **ILC at 500 GeV is 31 Km long**

$100[\text{TeV}]/31.5[\text{MeV/m}] > 3000$ Km $\longrightarrow$ **we cannot have a linear proton-proton collider**

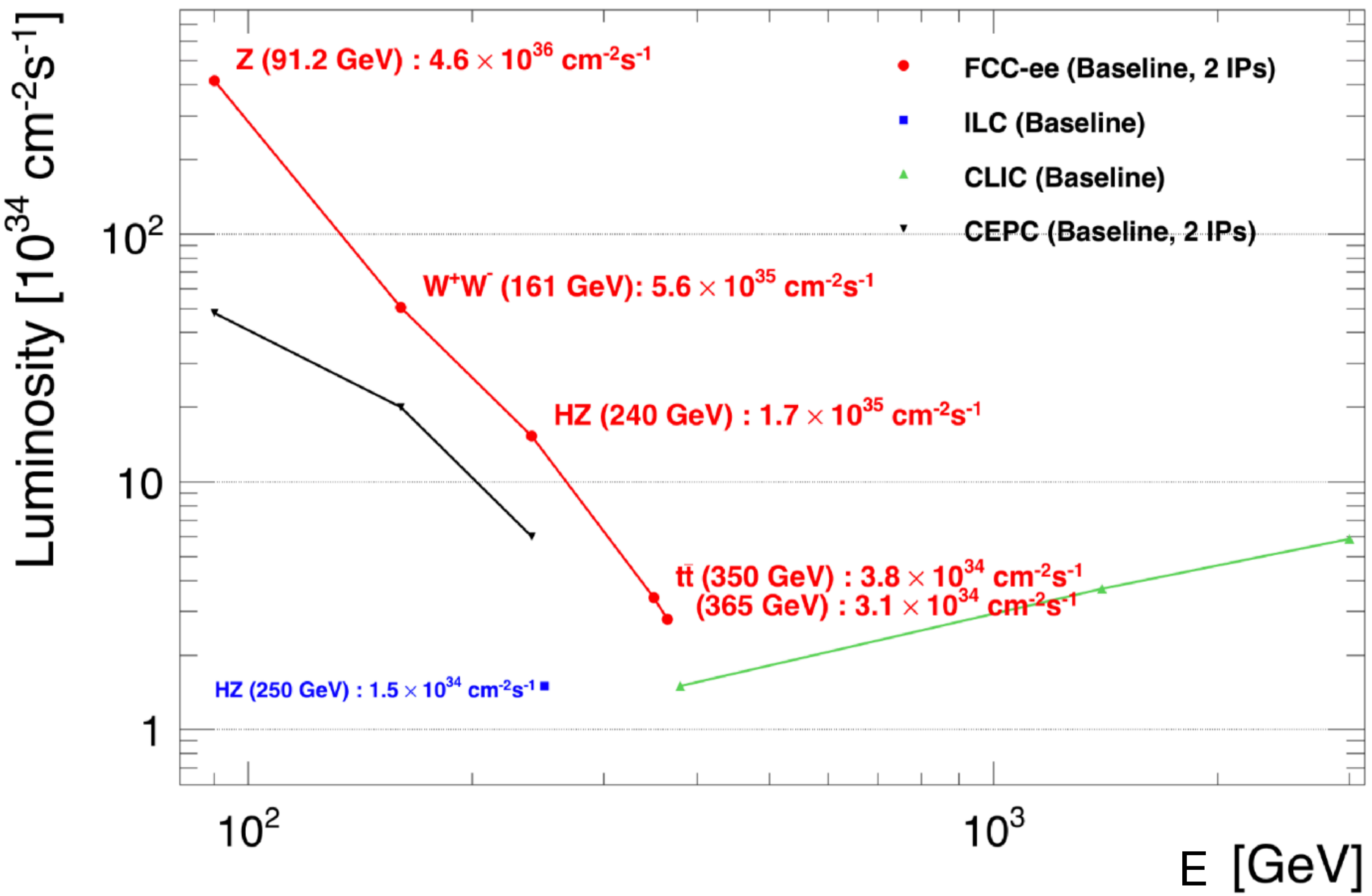
Linear vs. circular e^+e^- colliders

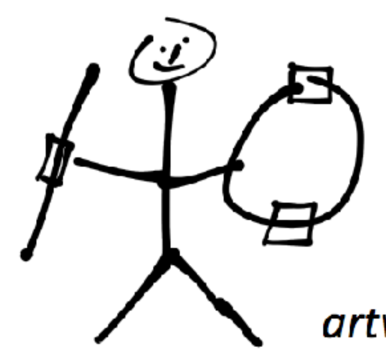
The collider luminosity is the proportionality factor between the number of events per second and the cross section

$$\frac{dN}{dt} = \mathscr{L}\,\sigma$$

Given by physics

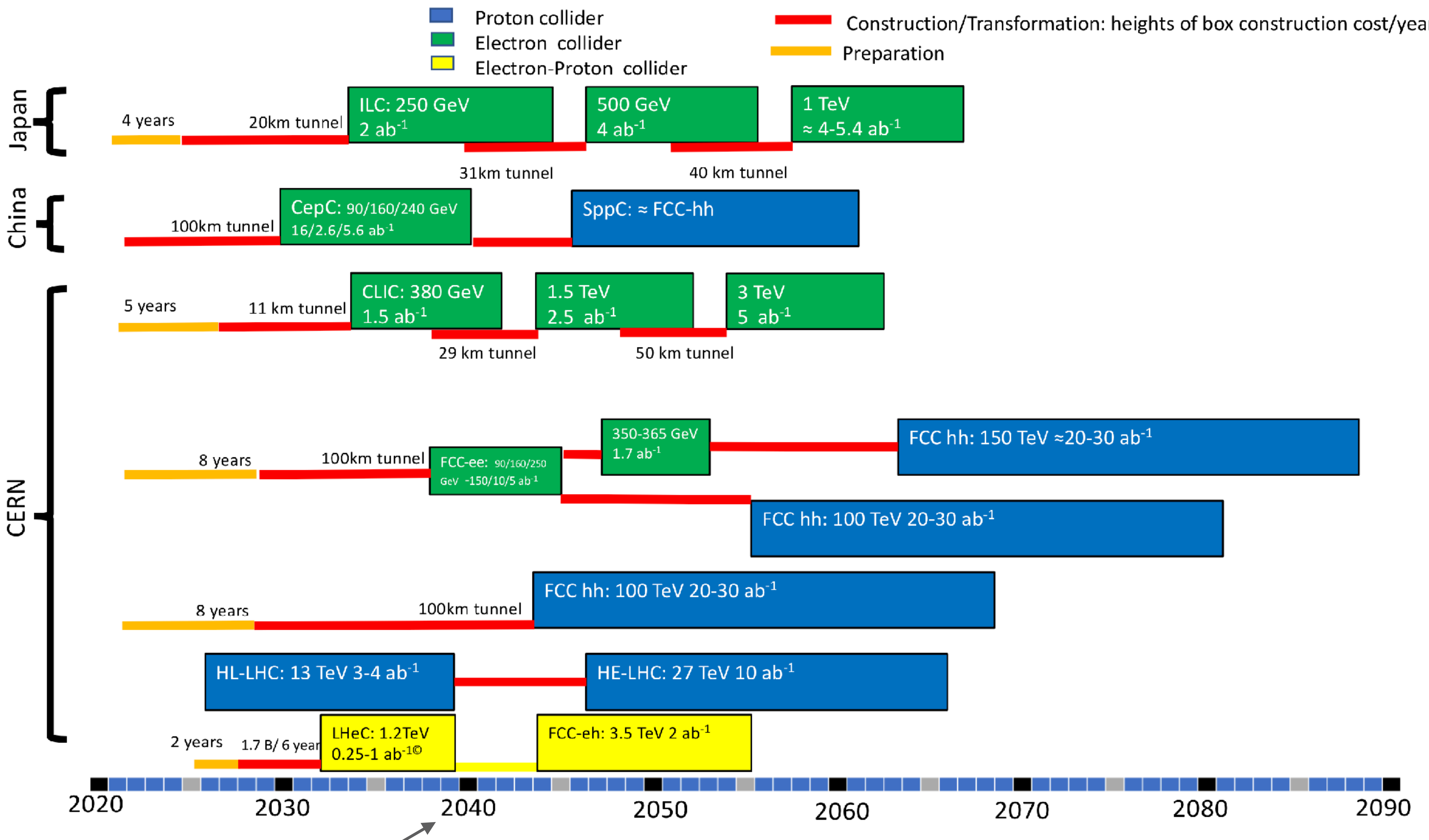
Given by the machine





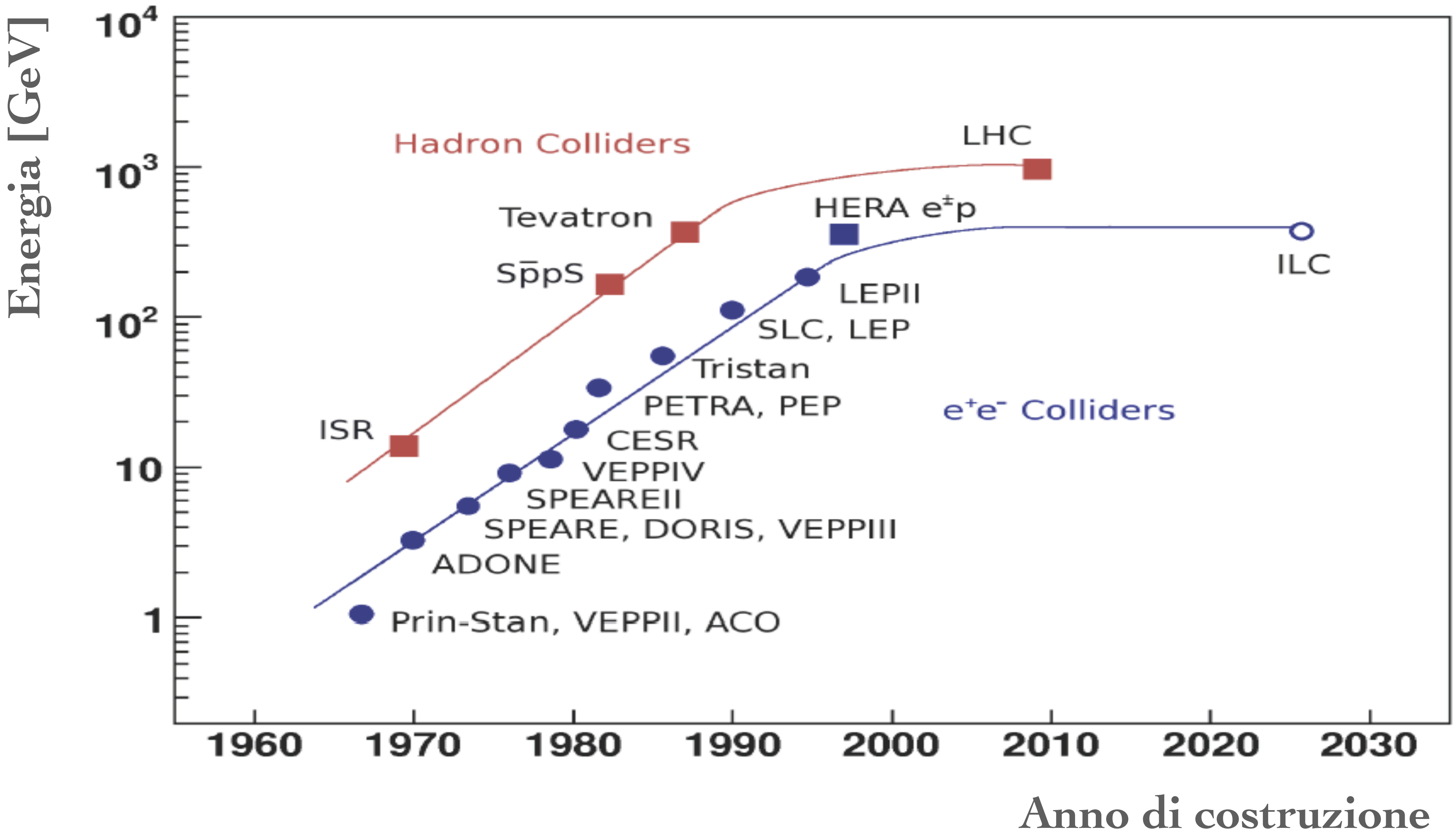
artwork by F. Simon

Possible scenarios of future colliders

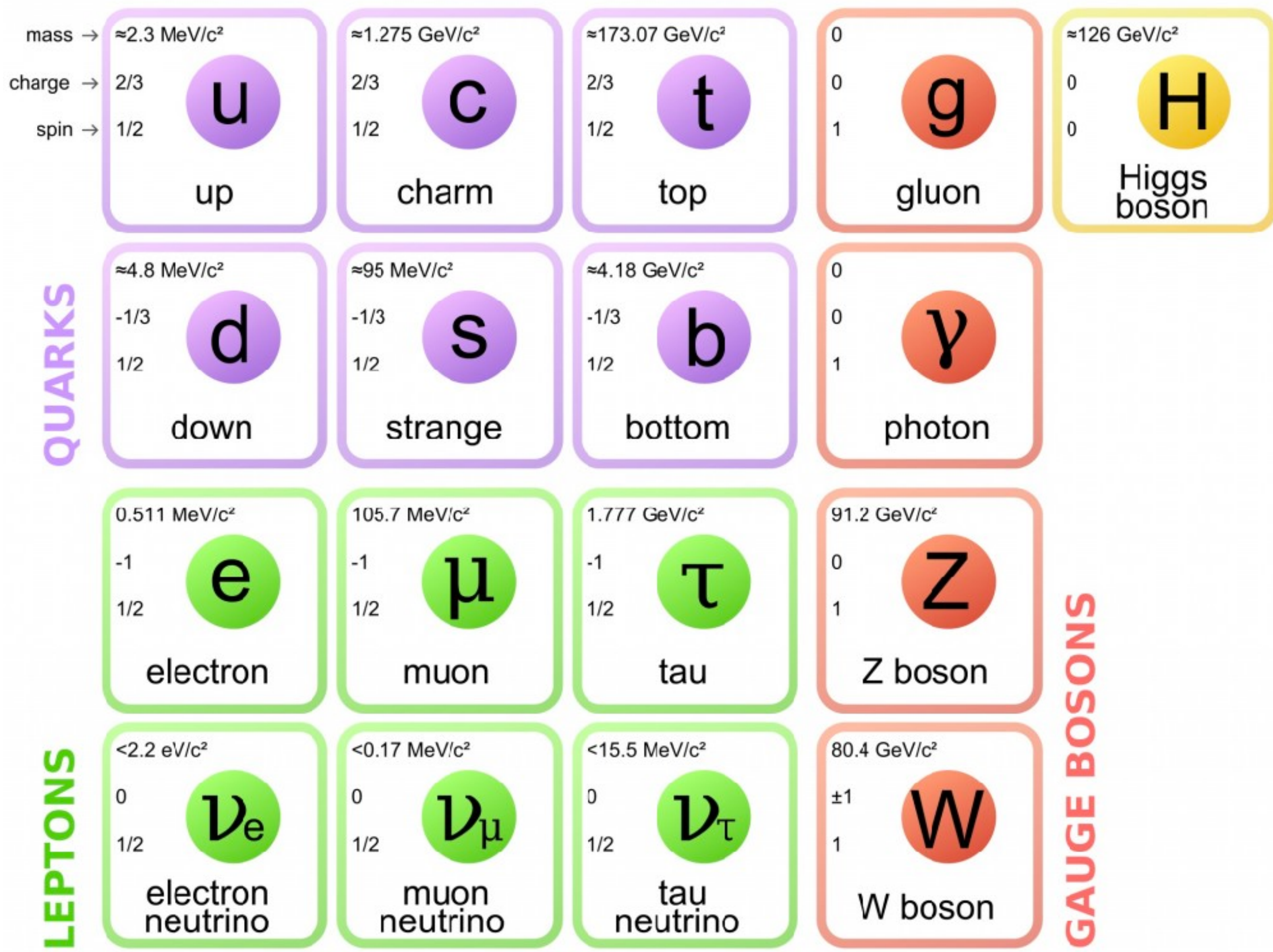


Fine degli esperimenti ad LHC

How far can it go?



Colliding muons?

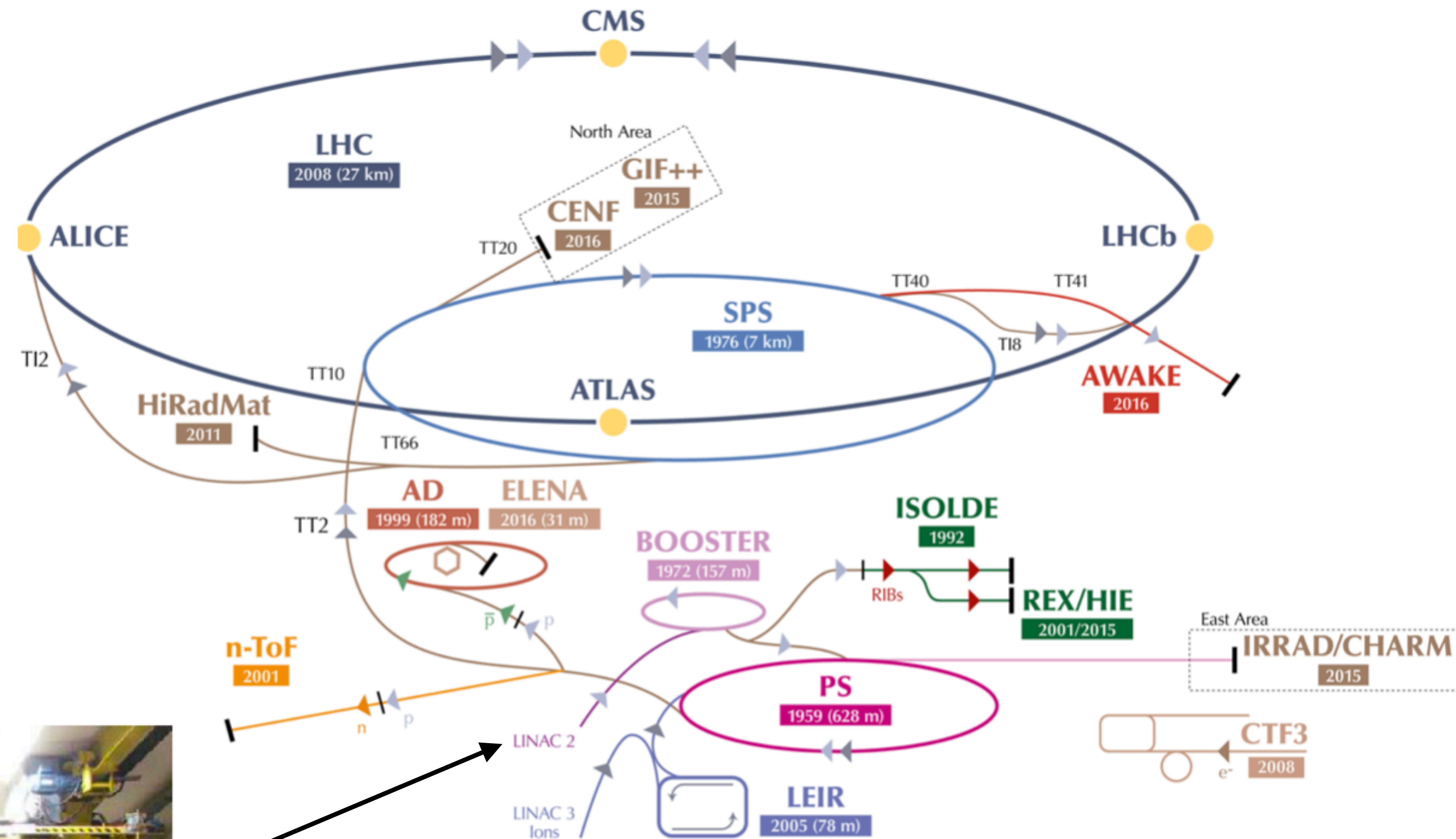


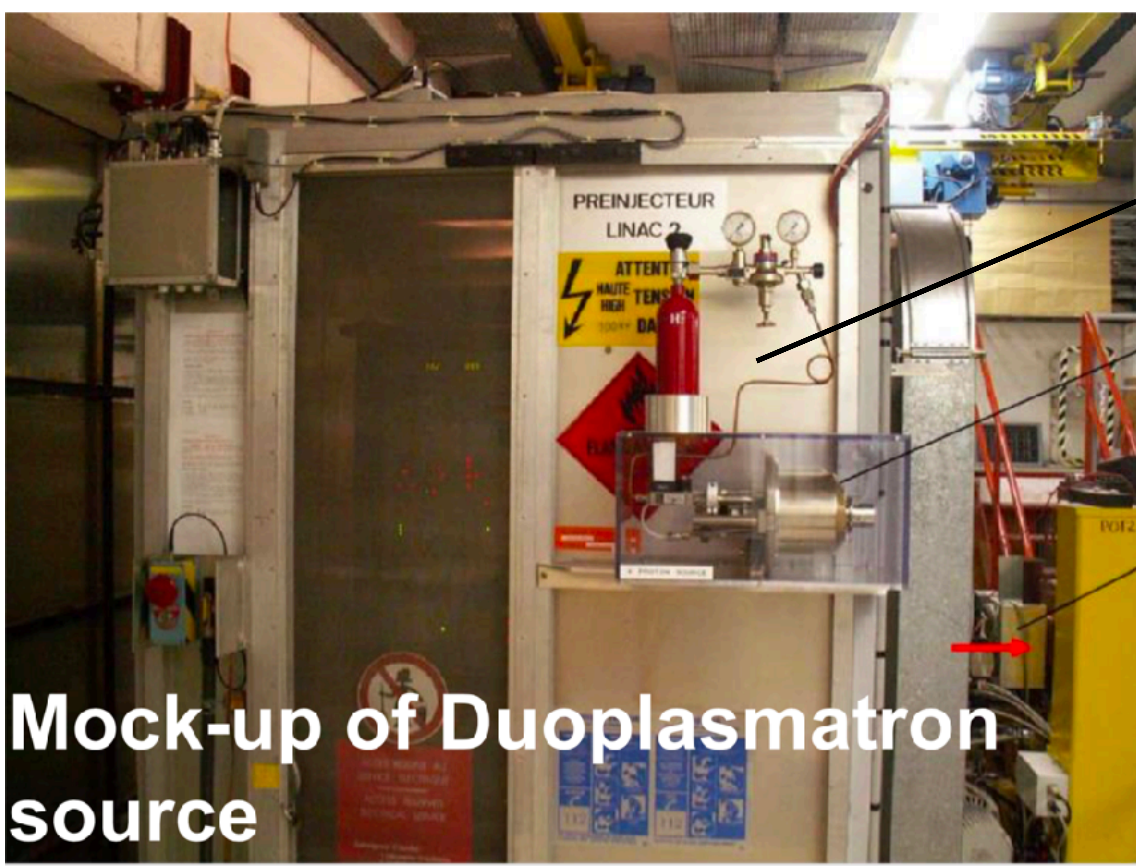
- Muon mass ~200 m_e → **no synchrotron radiation** in circular acceleration: possible to accelerate muons at higher energies in circular colliders

- **All beam energy available in collision** → a 14 TeV muon collider would be able to collide elementary particles at energies similar to the ones of a 100 TeV proton collider

- A 14 TeV muon collider can be housed in the 27 Km LHC tunnel → **no need to drill half Europe!**

Where are the muons?





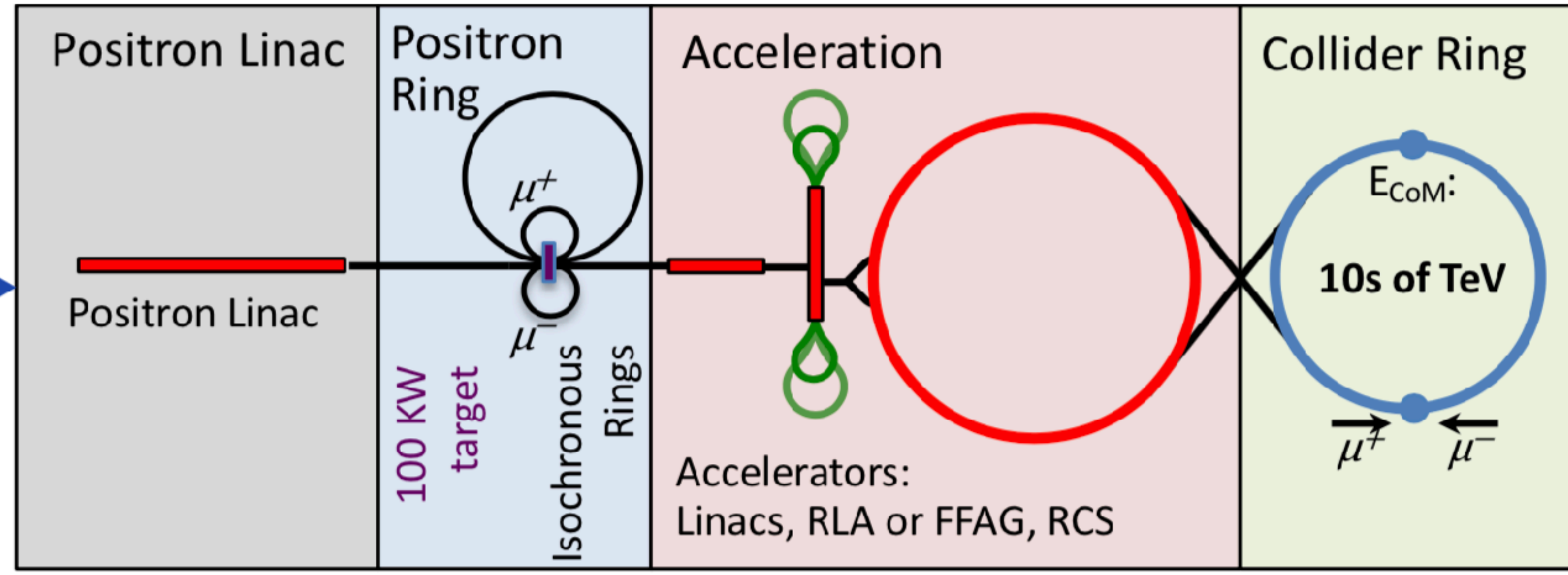
Mock-up of Duoplasmatron source

Everything starts from an hydrogen source…

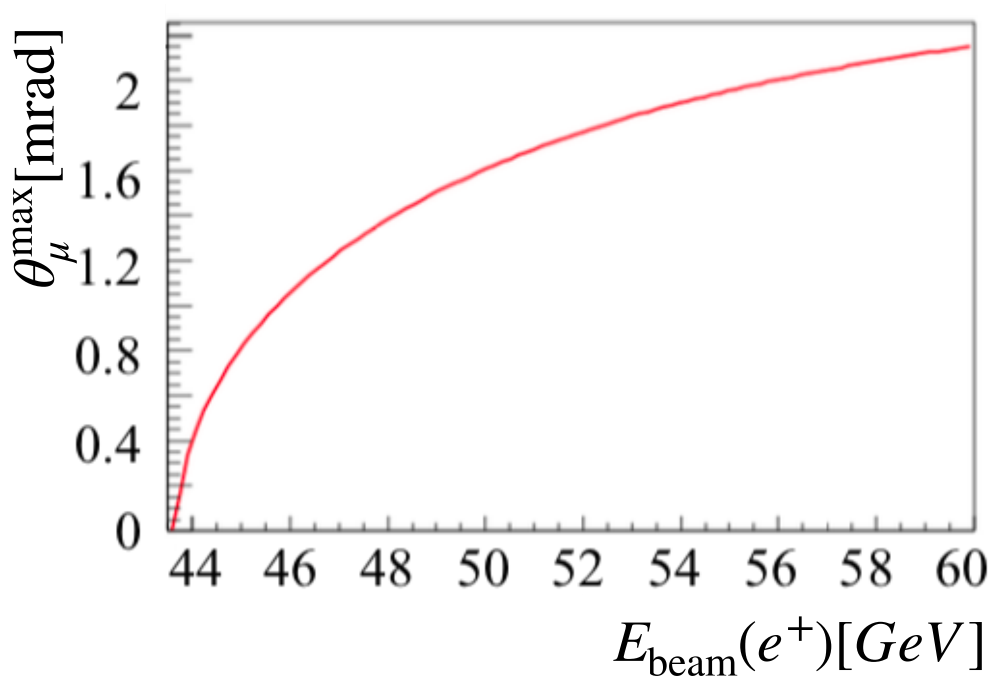
…but there is no muon source

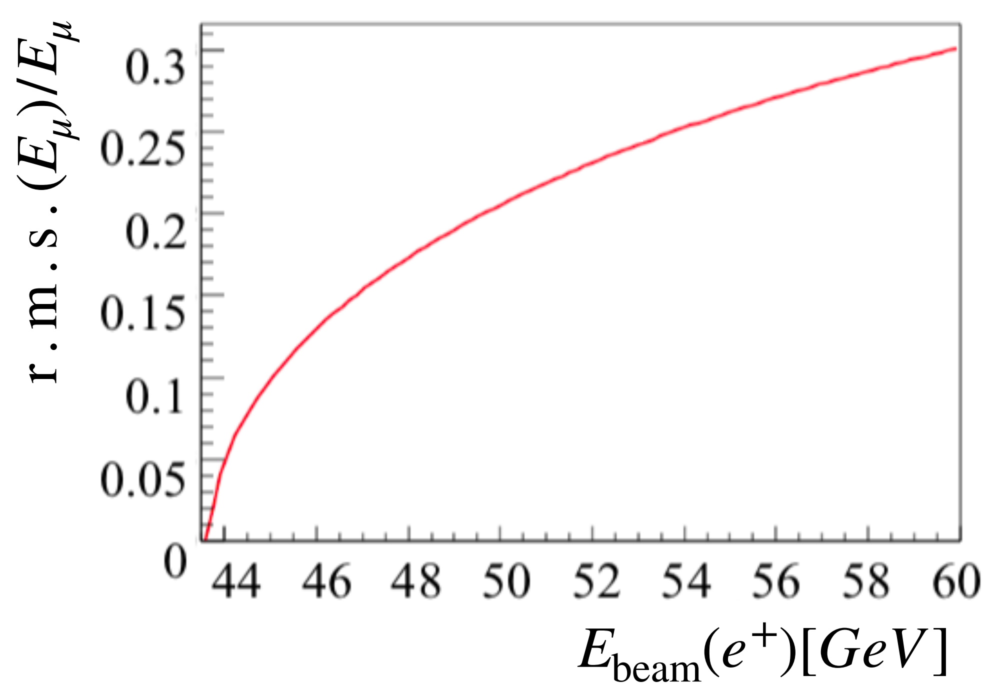
The LEMMA Project

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

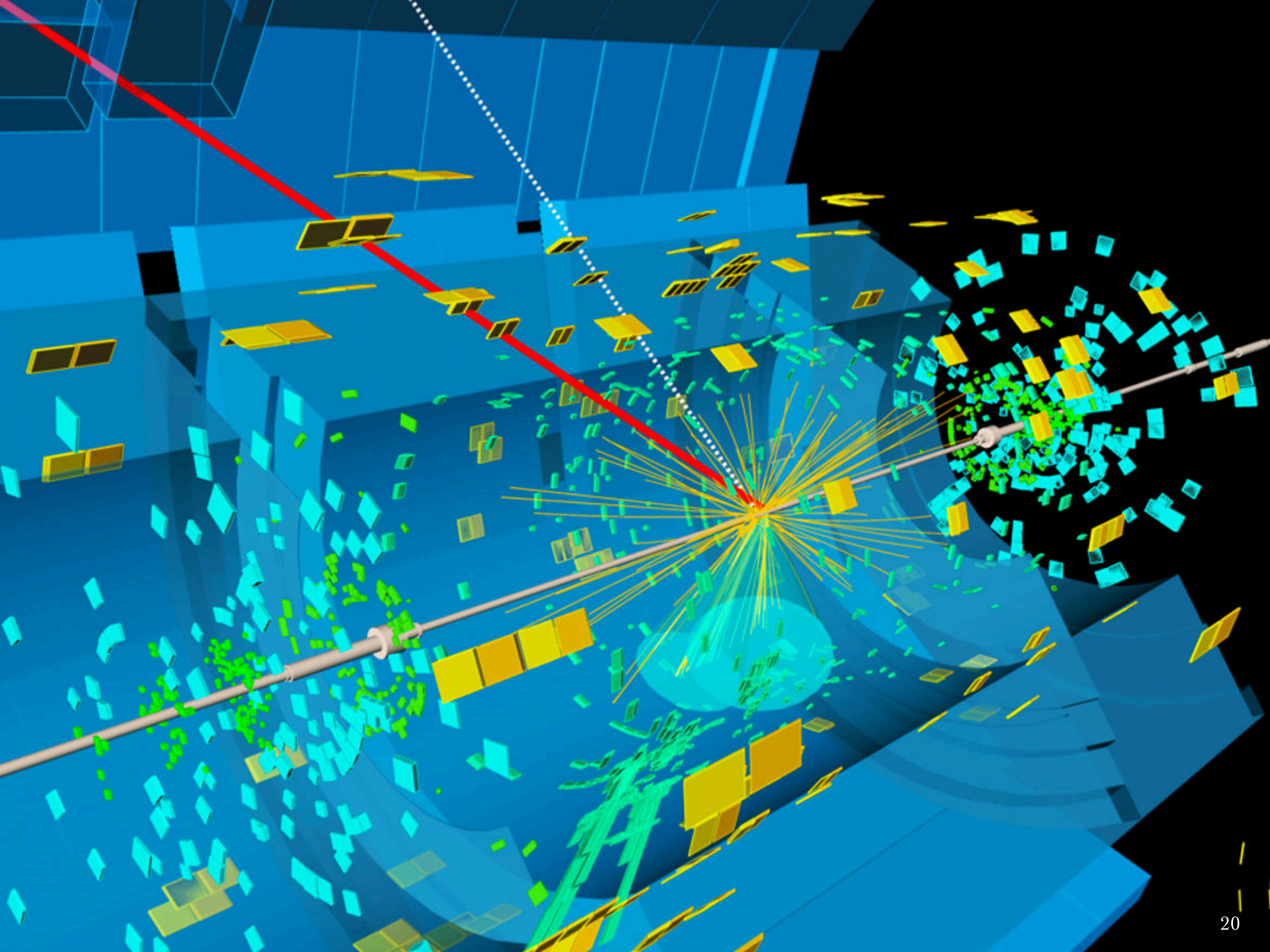


In the LEMMA scheme 45 GeV positrons annihilate with the electrons of a beryllium target: a beam of muons and antimuons with collimated energy and emission angle can be obtained.





Novel proposal for a low emittance muon beam using positron beam on target, arXiv:1509.04454v1



The particle sea…

A selection of particles listed by the particle data group.

How can we tell them apart in our detector ?!

http://pdg.lbl.gov ~ 180 Selected Particles

$\gamma, W^{\pm}, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^0, \eta, f_0(600), \rho(770)$,
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235)$,
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320)$,
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450)$,
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680)$,
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010)$,
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^0, K^0_S, K^0_L, K^*(892)$,
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680)$,
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^{\pm}, D^0, D^*(2007)^0$,
$D^*(2010)^{\pm}, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^0, B^*, B_s^0, B_c^{\pm}, \eta_c(1S), J/\psi(1S)$,
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160)$,
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P)$,
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440)$,
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710)$,
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600)$,
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950)$,
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690)$,
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100)$,
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670)$,
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-$,
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-$,
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2790), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

There are Many more

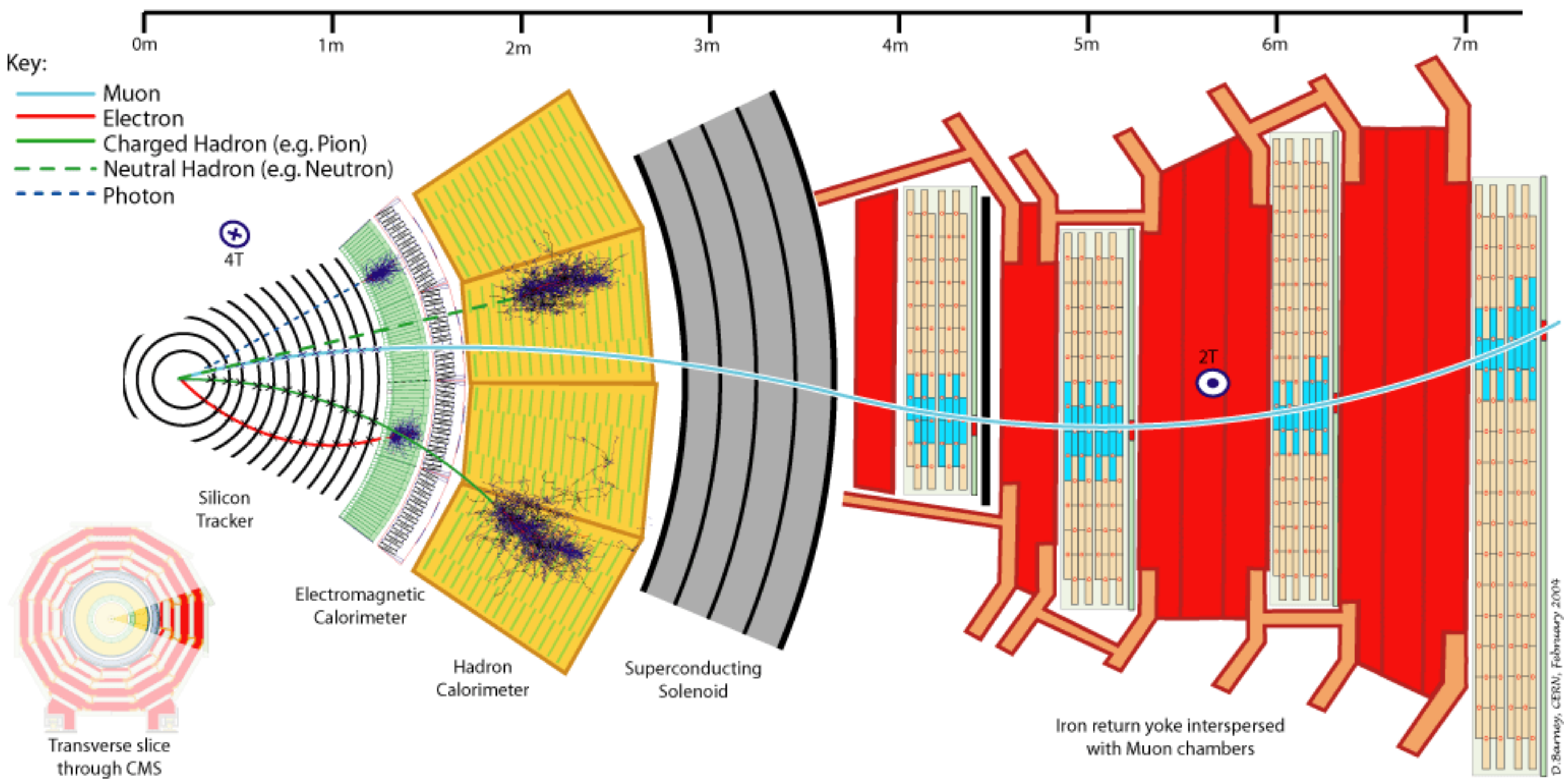
The particle sea…

Out of ~ 400 particles only ~ 20 have a

$$c\tau > 500\ \mu m$$

by far the most relevant are:

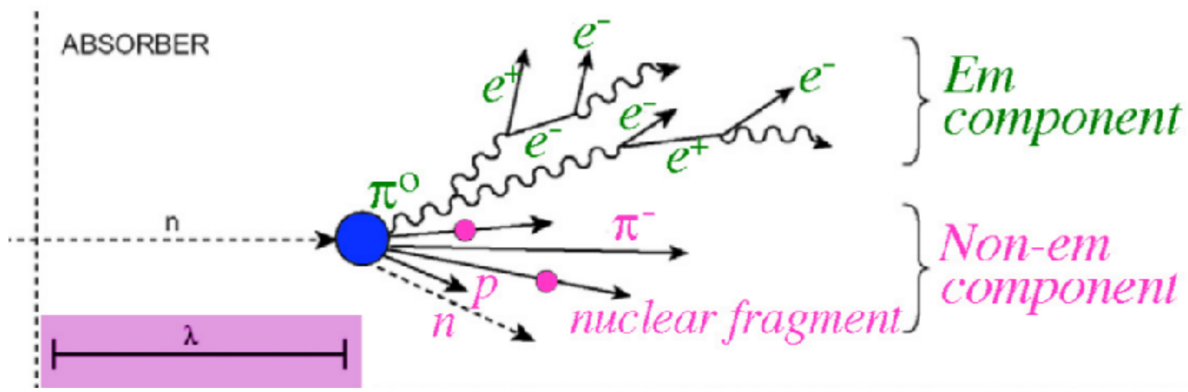
$$e^{+-}, \mu^{+-}, \gamma, \pi^{+-}, k^{+-}, K_s^0, K_L^0, p^{+-}, n$$



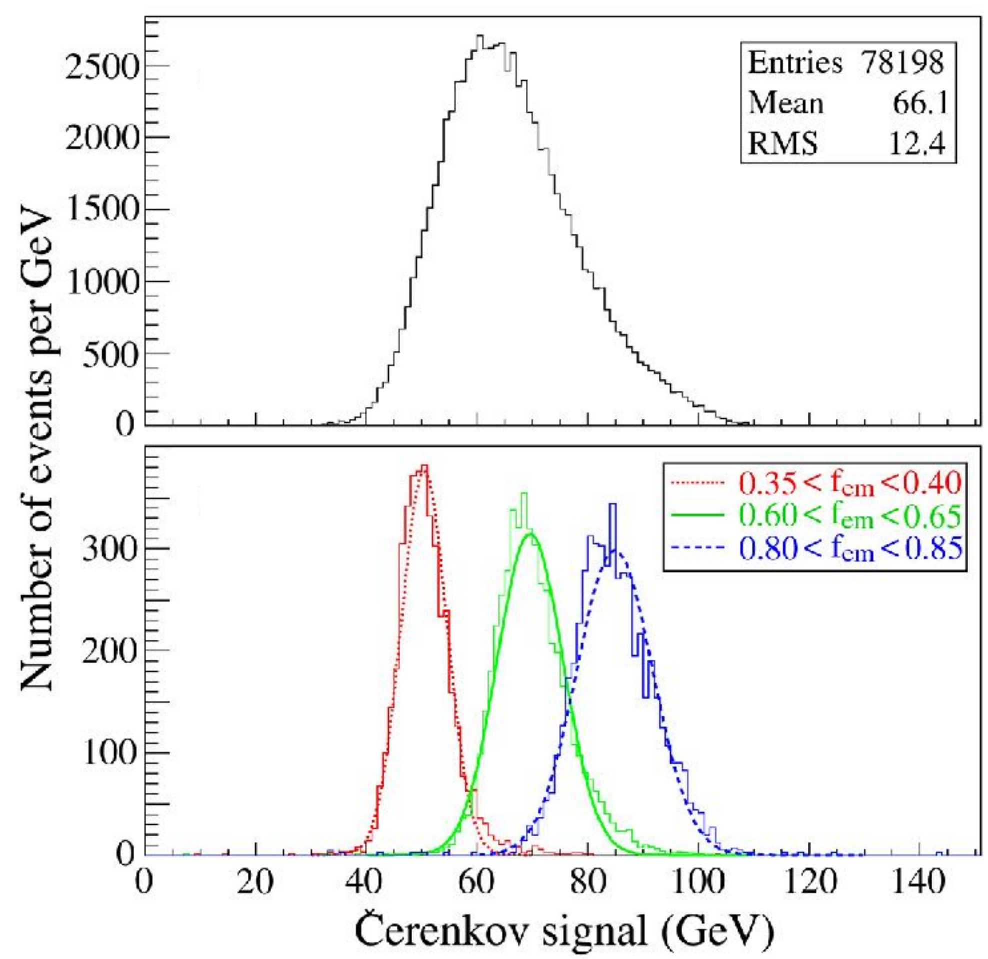
A particle detector is an (almost) irreducible representation of the properties of these particles.

Dual read-out calorimetry

Calorimeters are particle detectors used to reconstruct particle energies by means of total absorption.

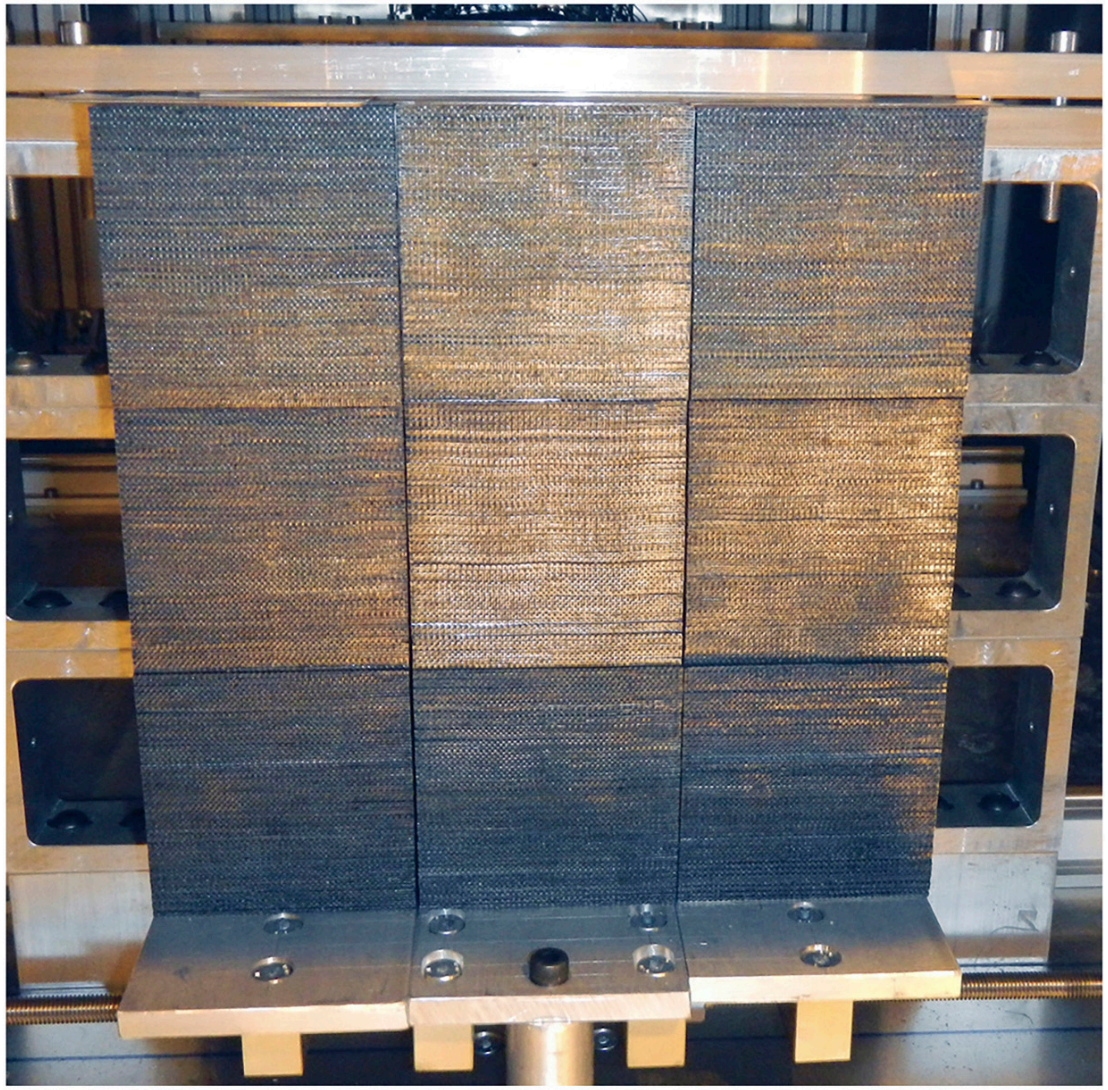


Showers induced by hadrons are made of two components:
Em component: electrons, positrons and photons (from $\pi^0 \rightarrow \gamma\gamma$ decays).
Non-em component: charged hadrons, neutrons, invisible energy.



Reconstructed energy from 100 GeV pions

Dual read-out calorimeters

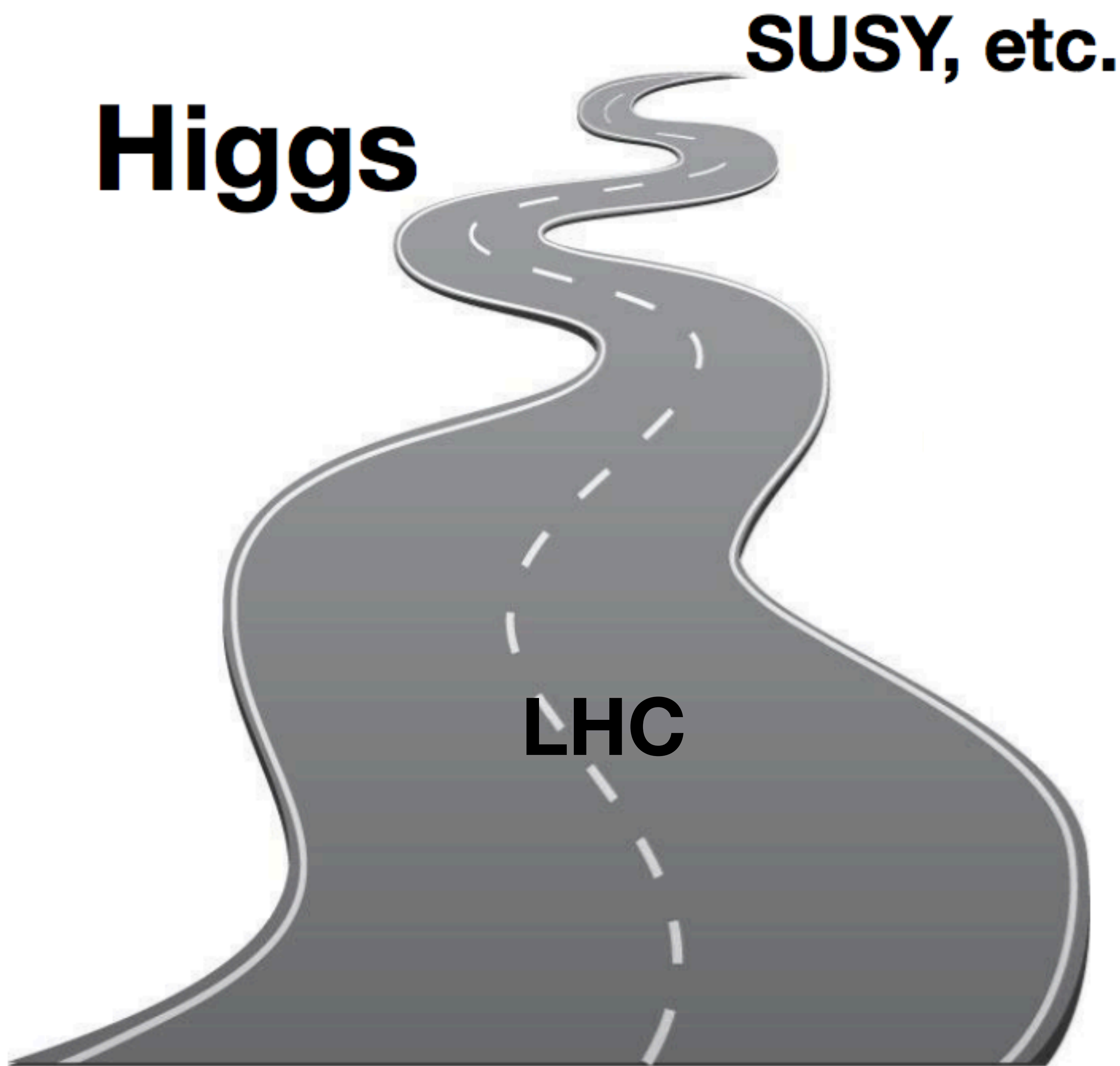


Proudly made at University of Pavia and INFN Sezione di Pavia


volunteer
ICPS
torino2017

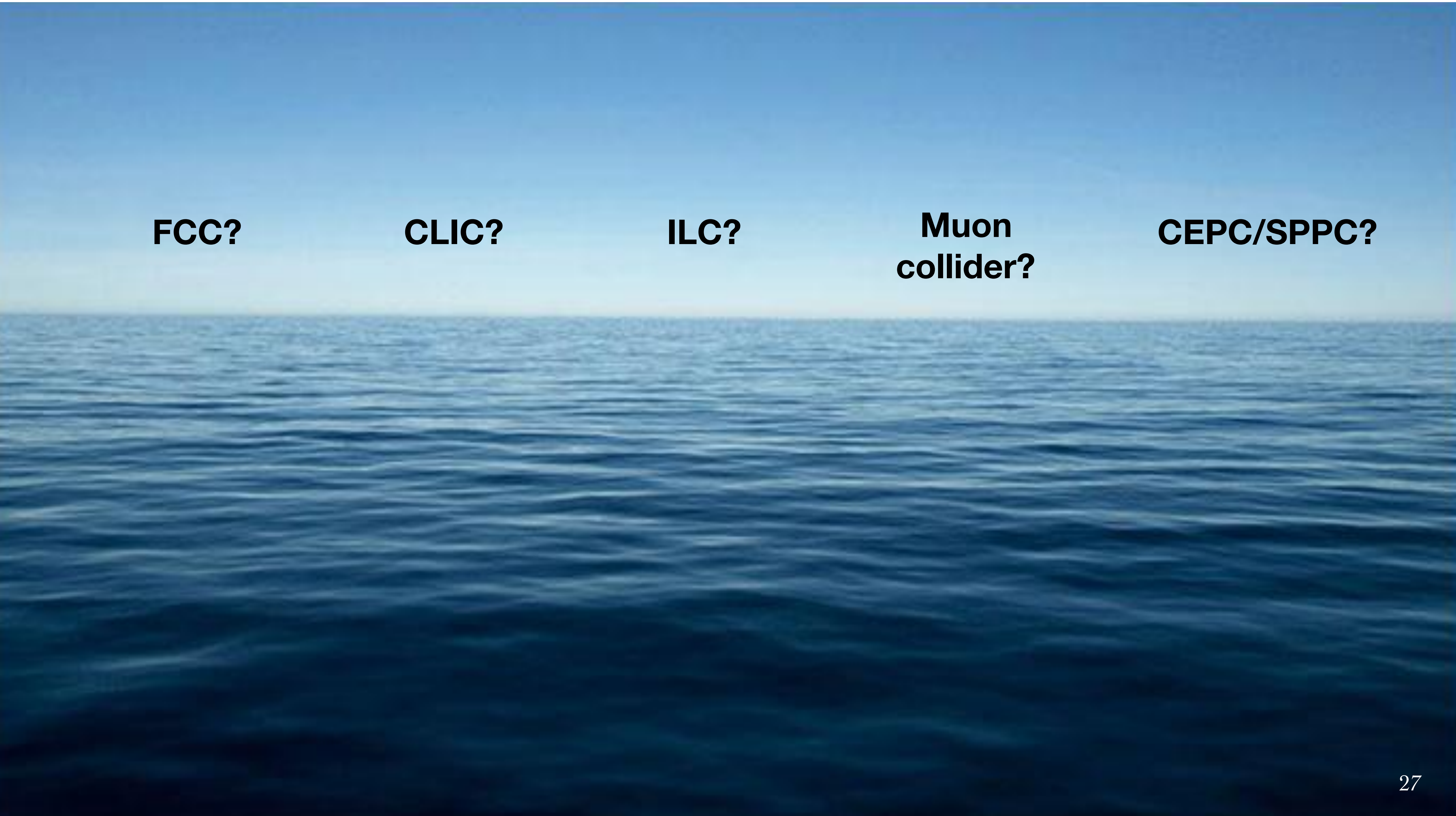
What next for particle physics?

HEP before the LHC



What next for particle physics?

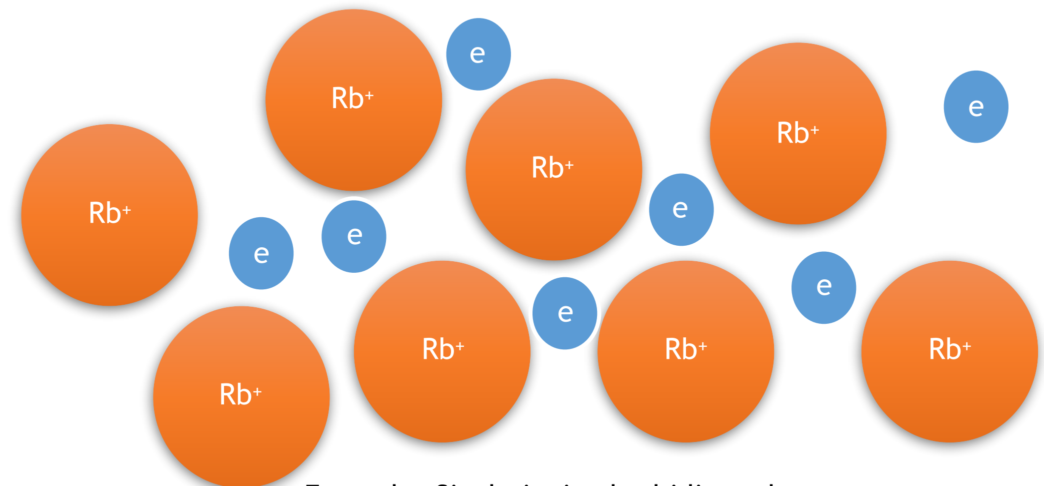
HEP after the LHC



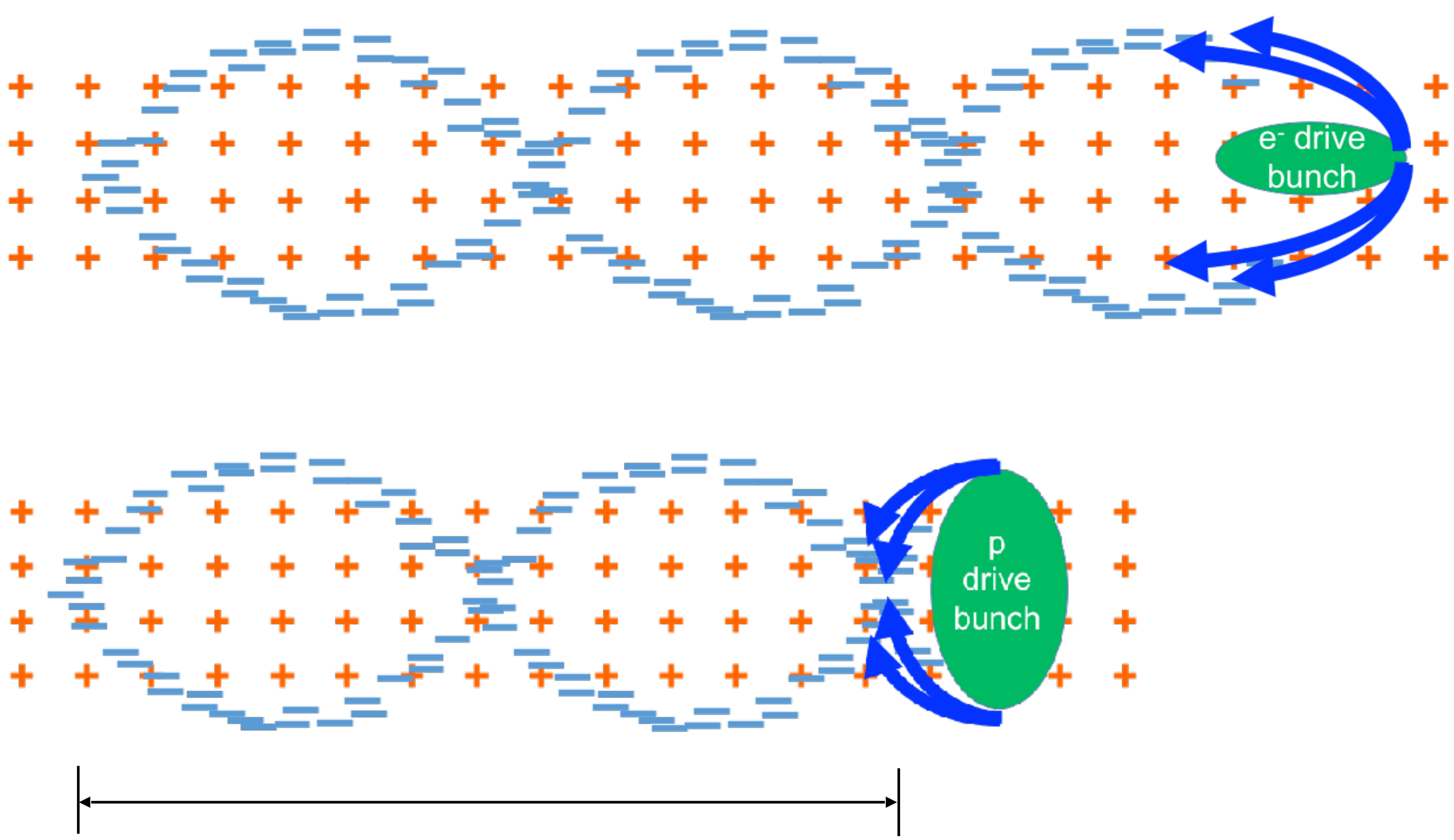
Backup

Plasma Wakefield

What is a plasma?



Example: Single ionized rubidium plasma

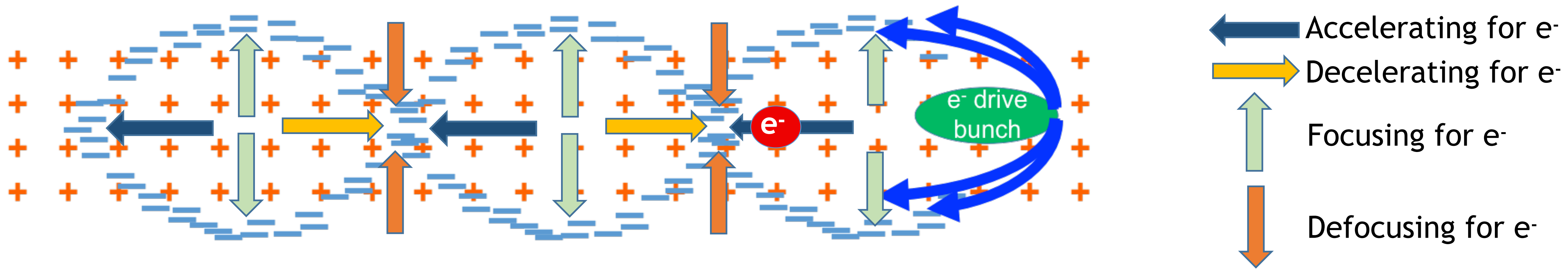


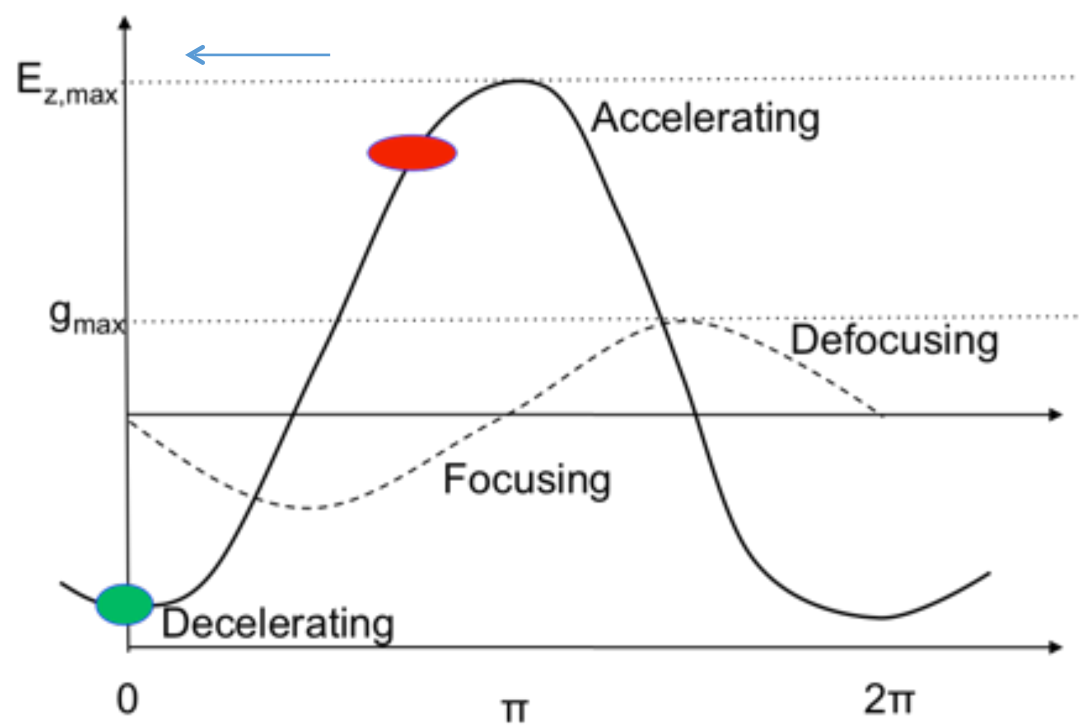
Plasma wavelength ~1 mm

Driver beam

- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis

Plasma Wakefield Acceleration (PWFA)

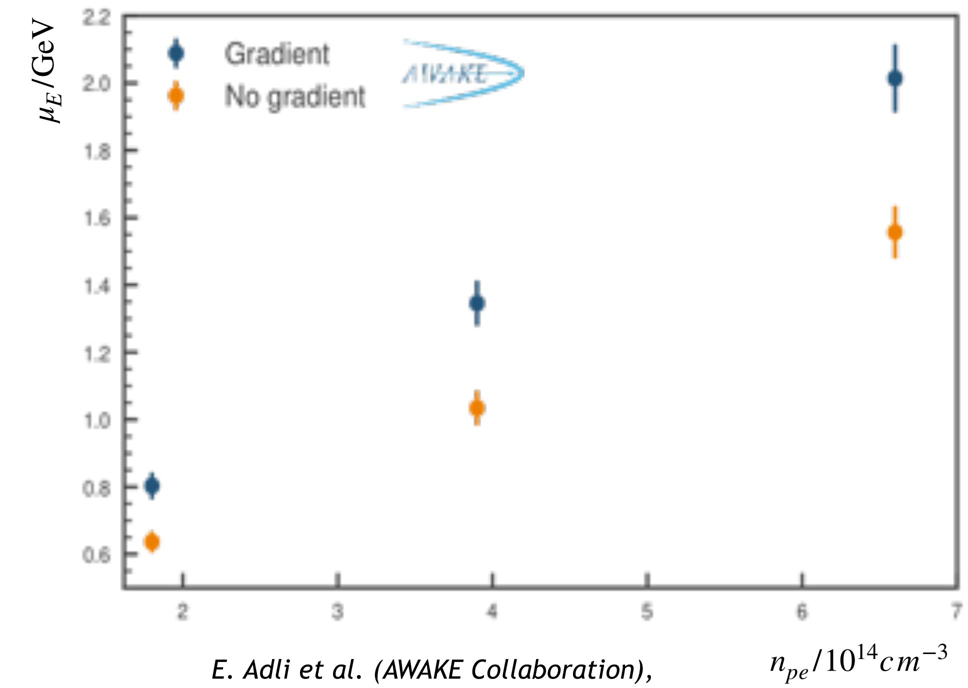




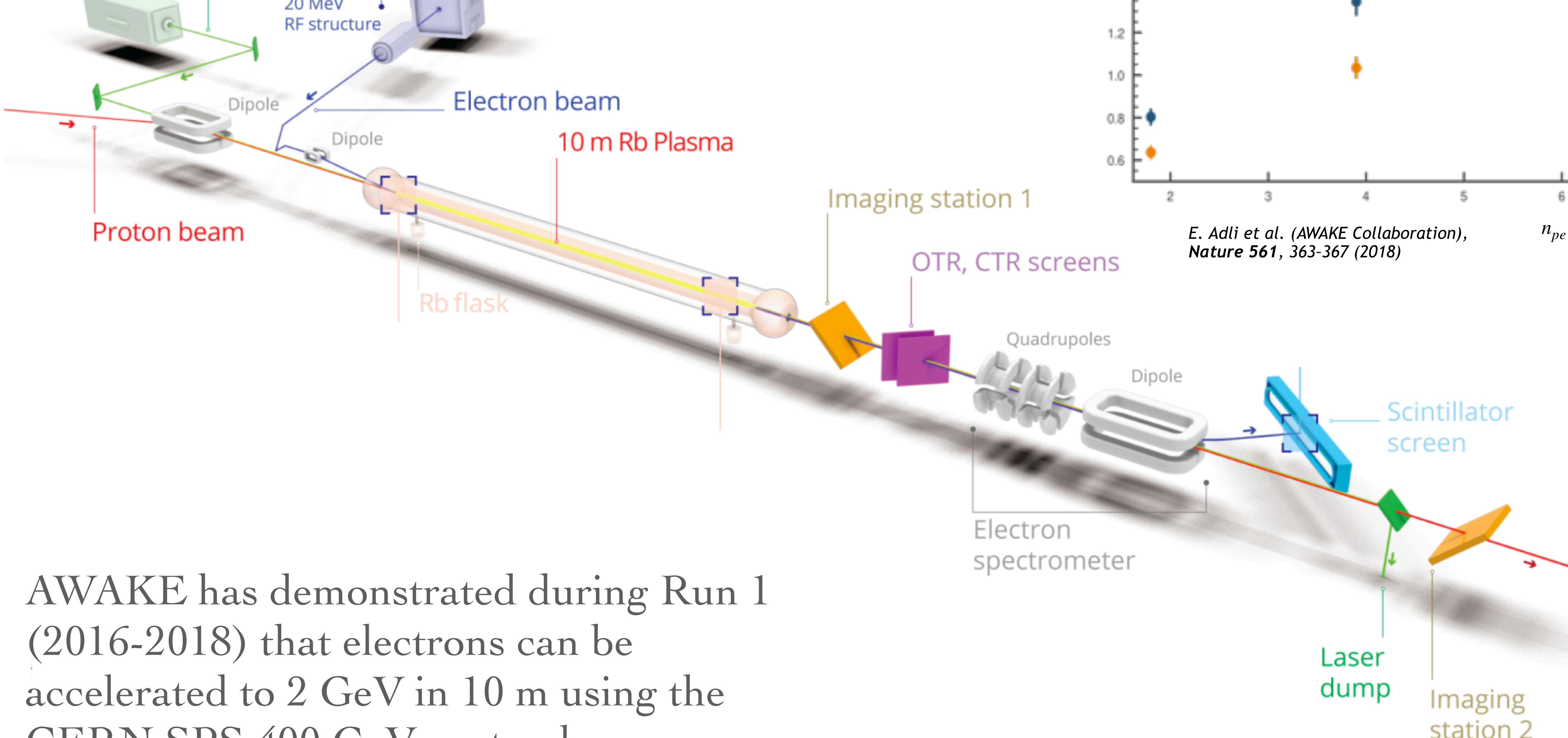
How strong can the fields be? $E_{WB} = 96\frac{\mathrm{V}}{\mathrm{m}}\sqrt{\frac{n_{pe}}{\mathrm{cm}^{-3}}}$

Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) → E_{WB} = 2.5 GV/m
Example: n_{pe} = 7x10^{17} cm^{-3} → E_{WB} = 80 GV/m

AWAKE (CERN)



E. Adli et al. (AWAKE Collaboration),
***Nature 561**, 363-367 (2018)*



AWAKE has demonstrated during Run 1 (2016-2018) that electrons can be accelerated to 2 GeV in 10 m using the CERN SPS 400 GeV proton beams.