Future Accelerators at the High Energy Frontier

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Accelerator Physics Graduate Course

John Adams Institute for Accelerator Science

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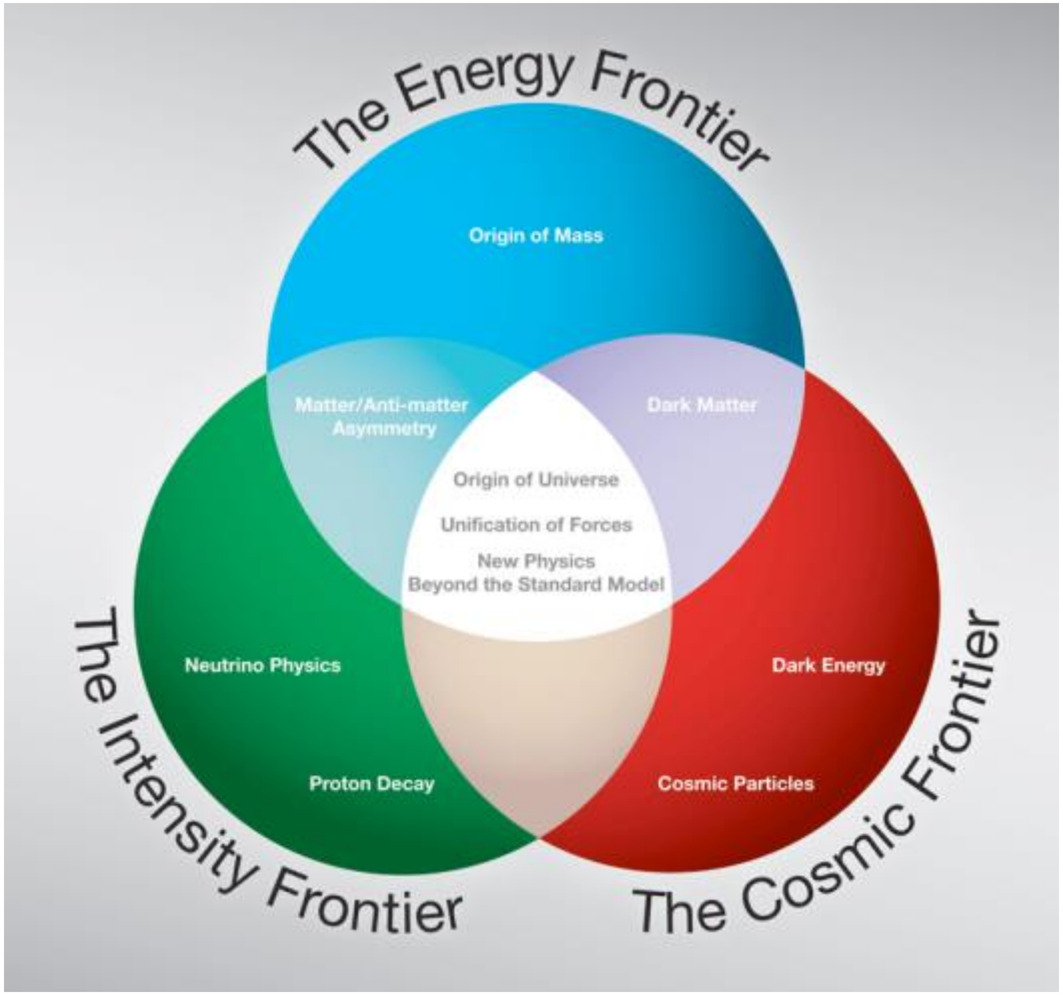
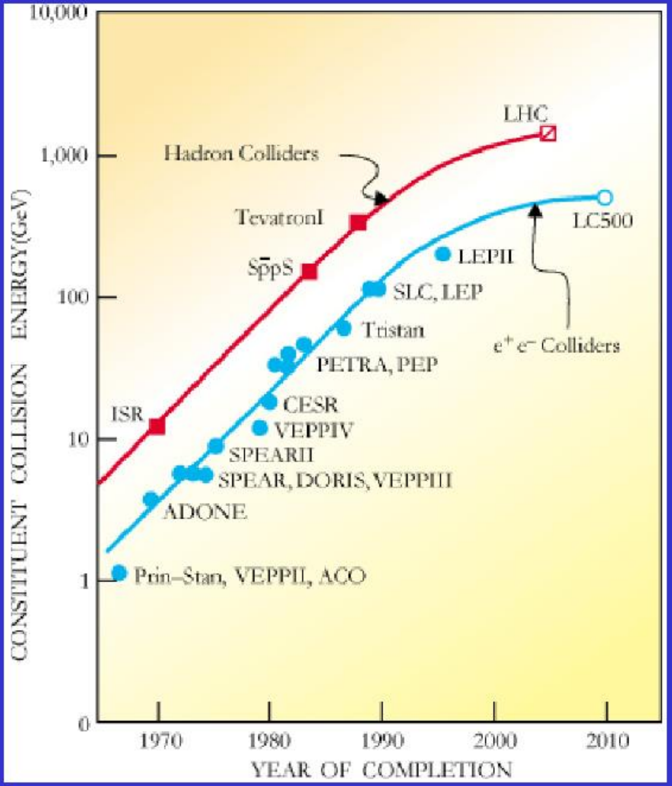
Aims of Lecture

- Present overview of various future collider projects, including beam parameters.
- Compare potential science goals & reach at each future collider.
- Characterize required R&D to be carried out prior to construction.
- Juxtapose possible timelines of each project.

The Three Frontiers



Colliders – Energy vs. Time



M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

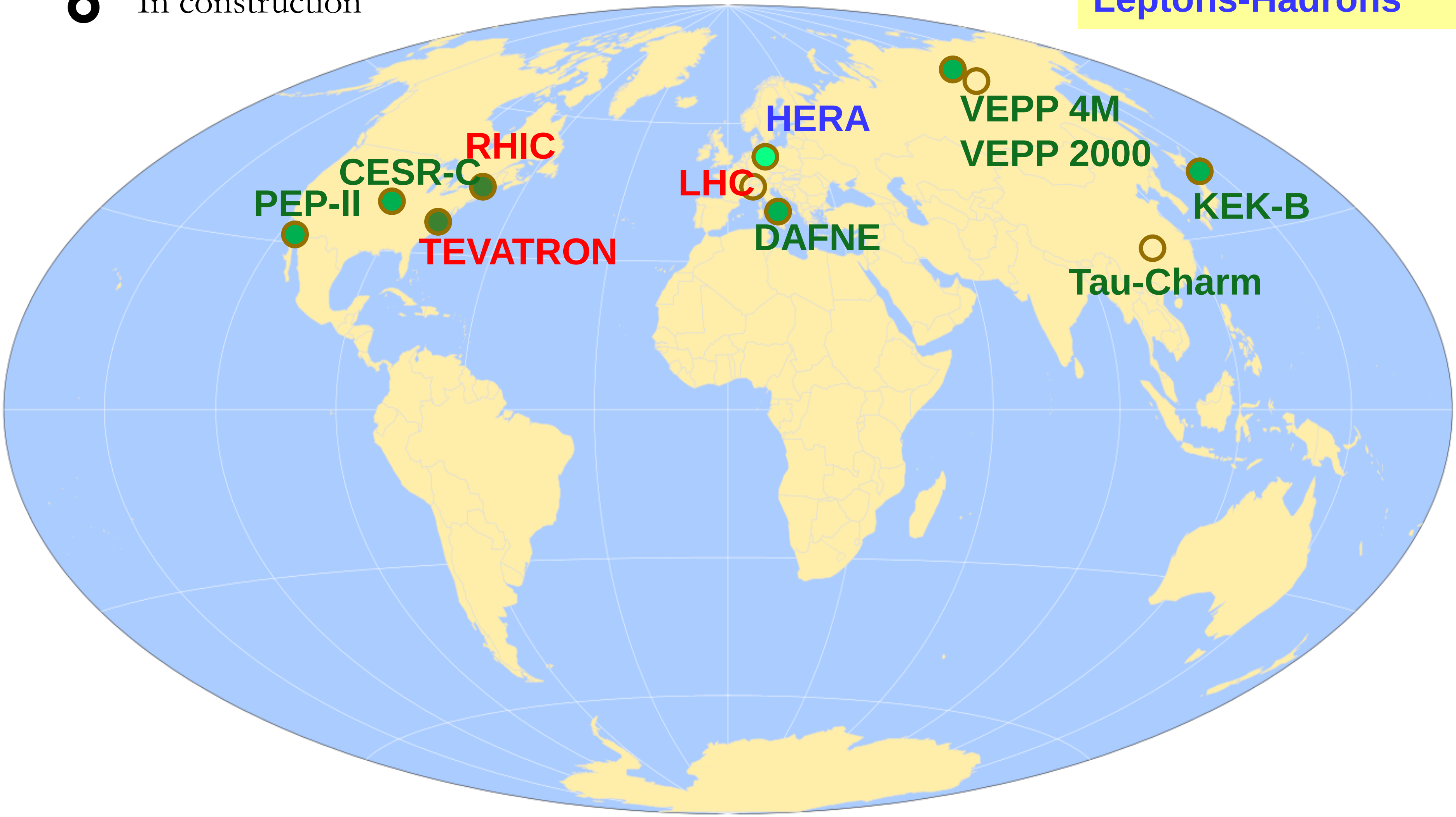
Not enough: Project cost increased by factor 200!

New technology needed…

Colliders - 2006

- In operation
- In construction

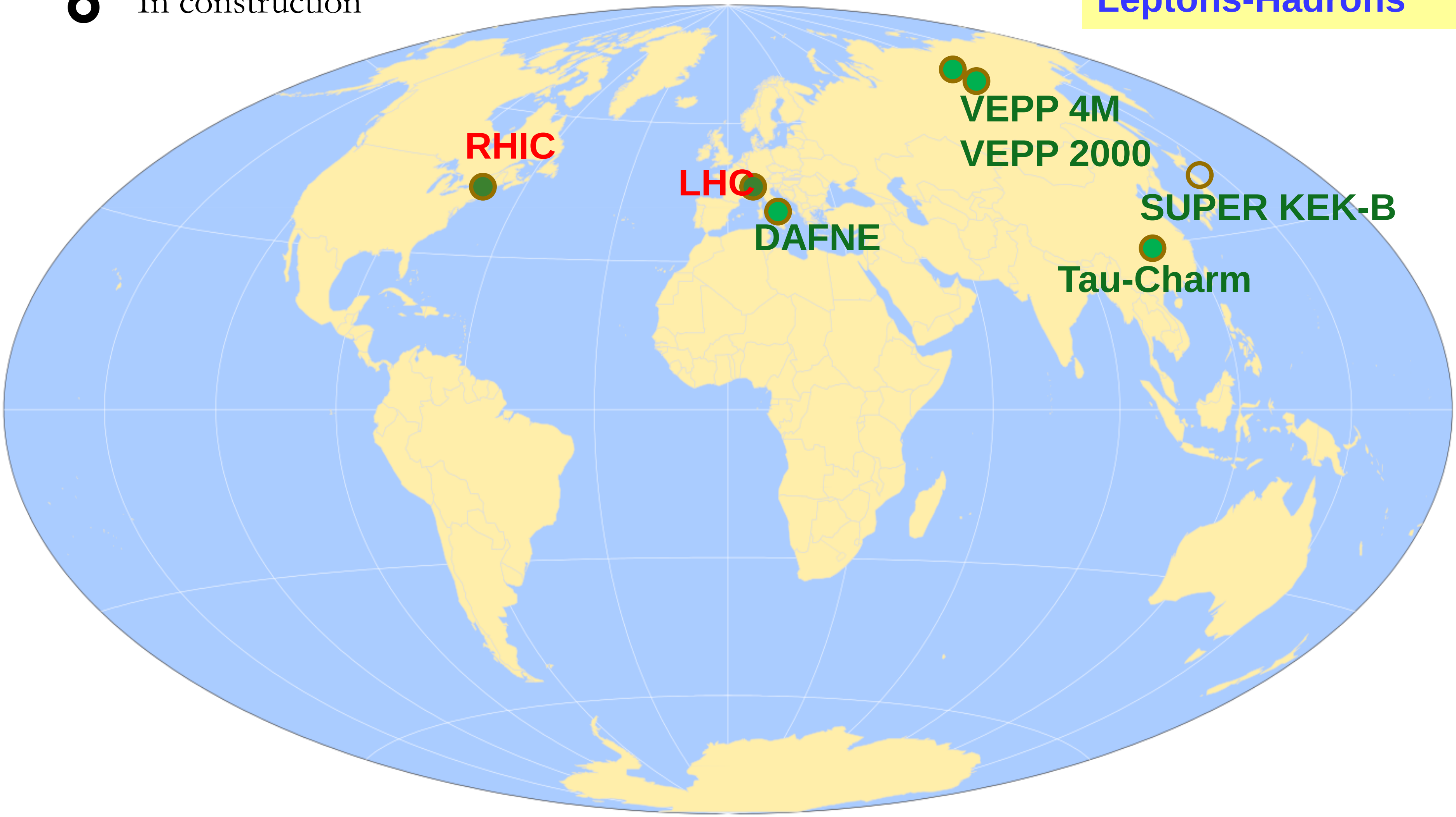
Hadrons
Leptons
Leptons-Hadrons



Colliders - 2012

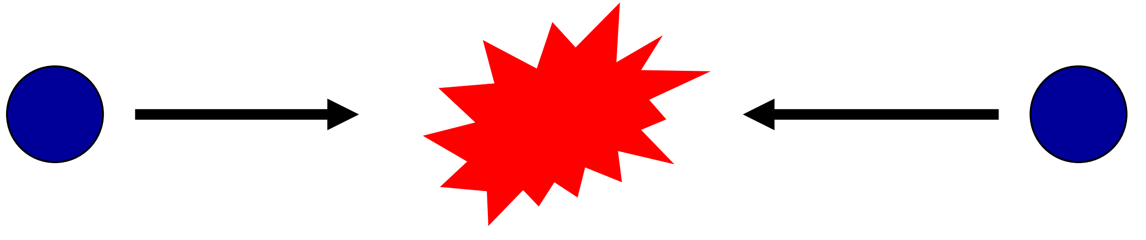
- In operation
- In construction

Hadrons
Leptons
Leptons-Hadrons



Why Build Colliders?

- **Want to see constituents of matter .**
- **Smash matter together and look for the building blocks.**
- **Take small pieces of matter:**
  - **accelerate them to very high energy**
  - **crash them into one another**



$E = mc^2 = \gamma m_0 c^2$

Higher energy produces more massive particles.

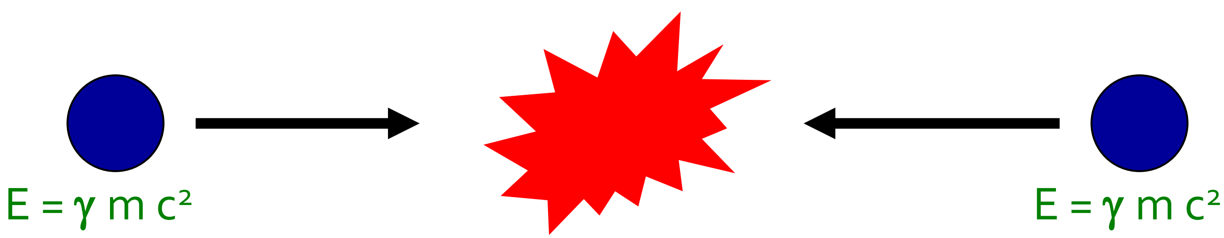
When particles approach speed of light, they get more massive but not faster.

Why Colliders?

$E = \gamma m c^2$

$P = \gamma m v$

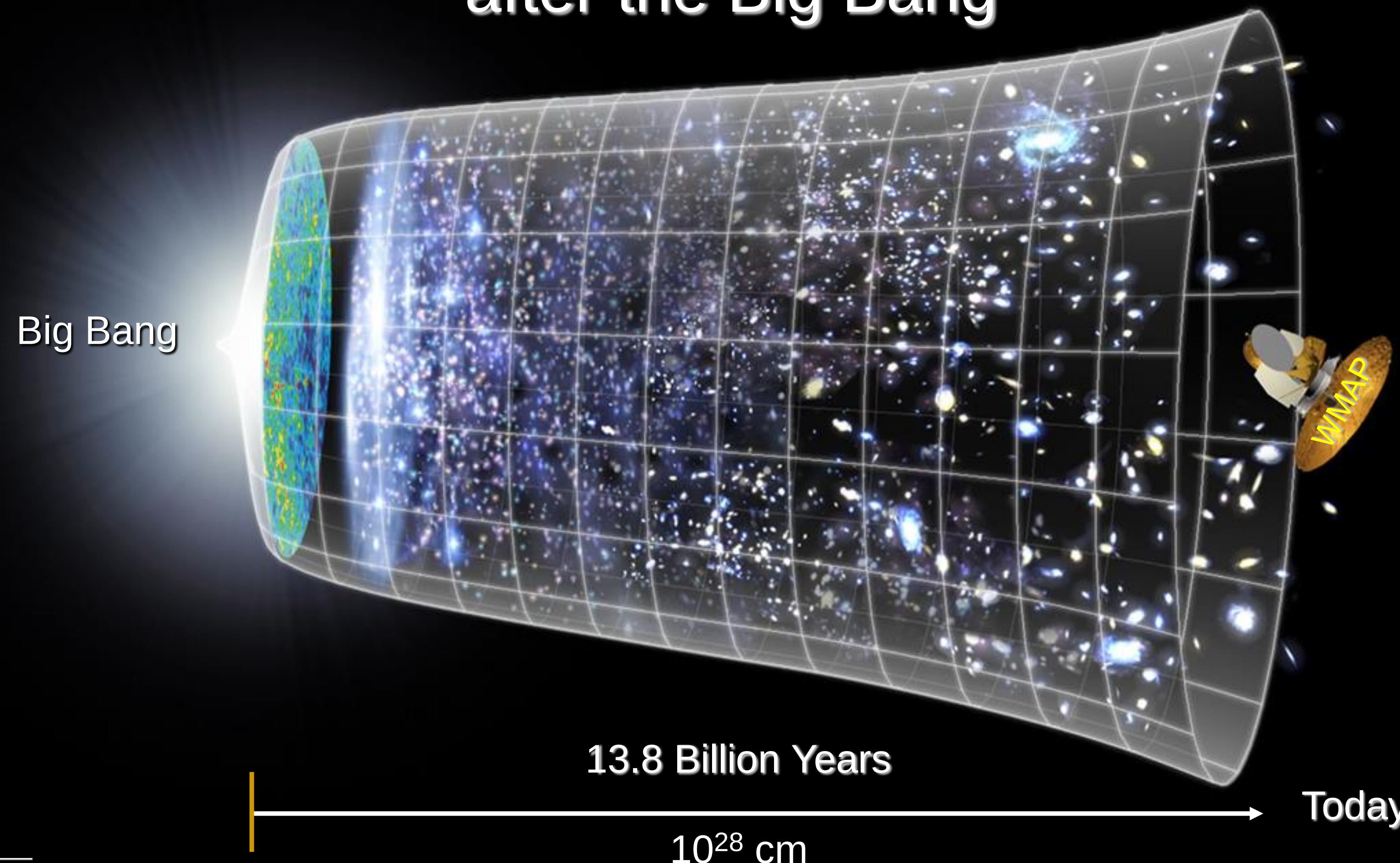
Only a tiny fraction of energy converted into mass of new particles
(due to energy and <u>momentum</u> conservation)

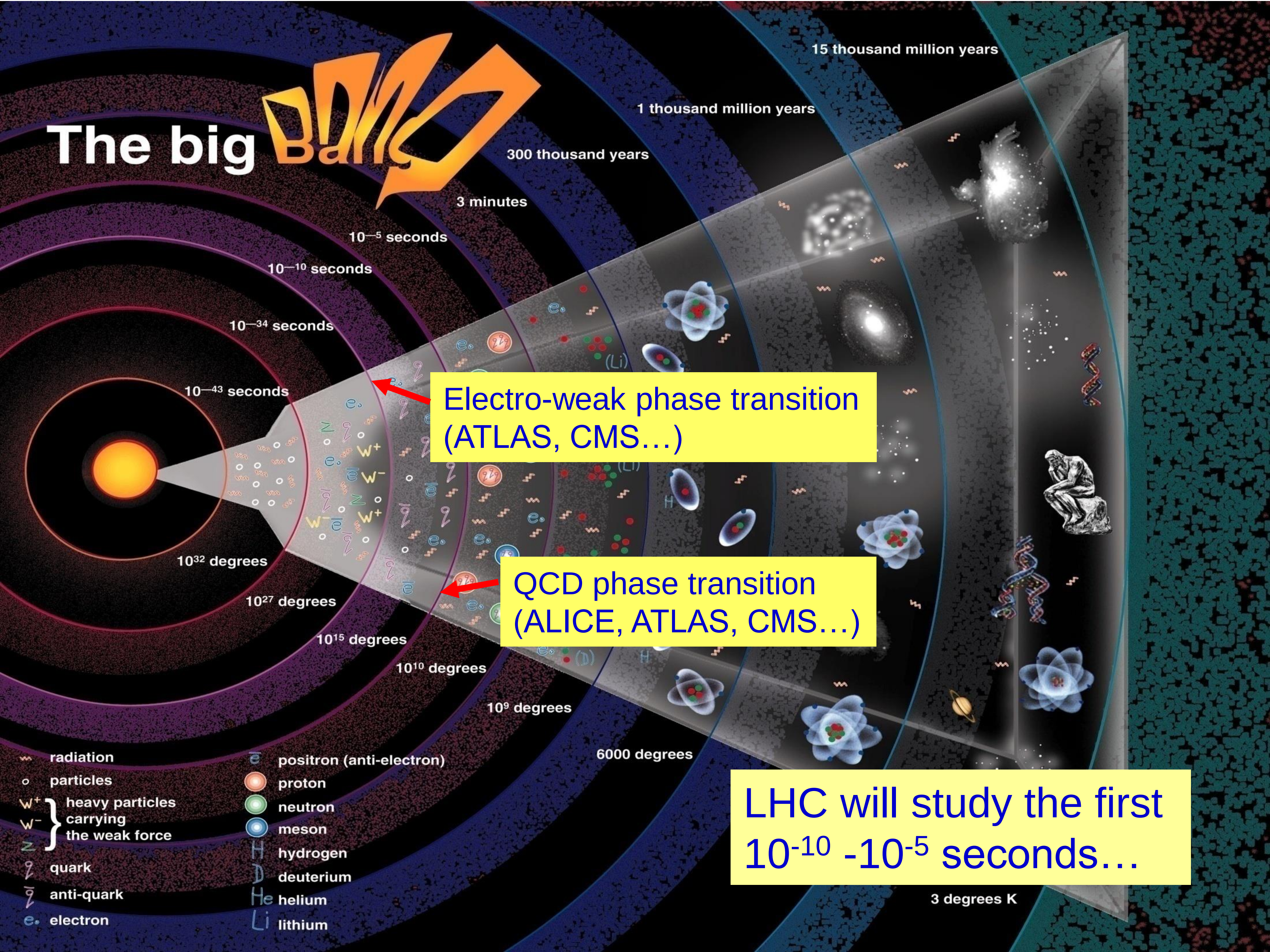


Entire energy converted into the mass of new particles

Next Scientific Challenge:

to understand the very first moments of our Universe after the Big Bang




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
3 degrees K
Electro-weak phase transition (ATLAS, CMS…)
QCD phase transition (ALICE, ATLAS, CMS…)
LHC will study the first 10⁻¹⁰ -10⁻⁵ seconds…
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Key Equation

Momentum

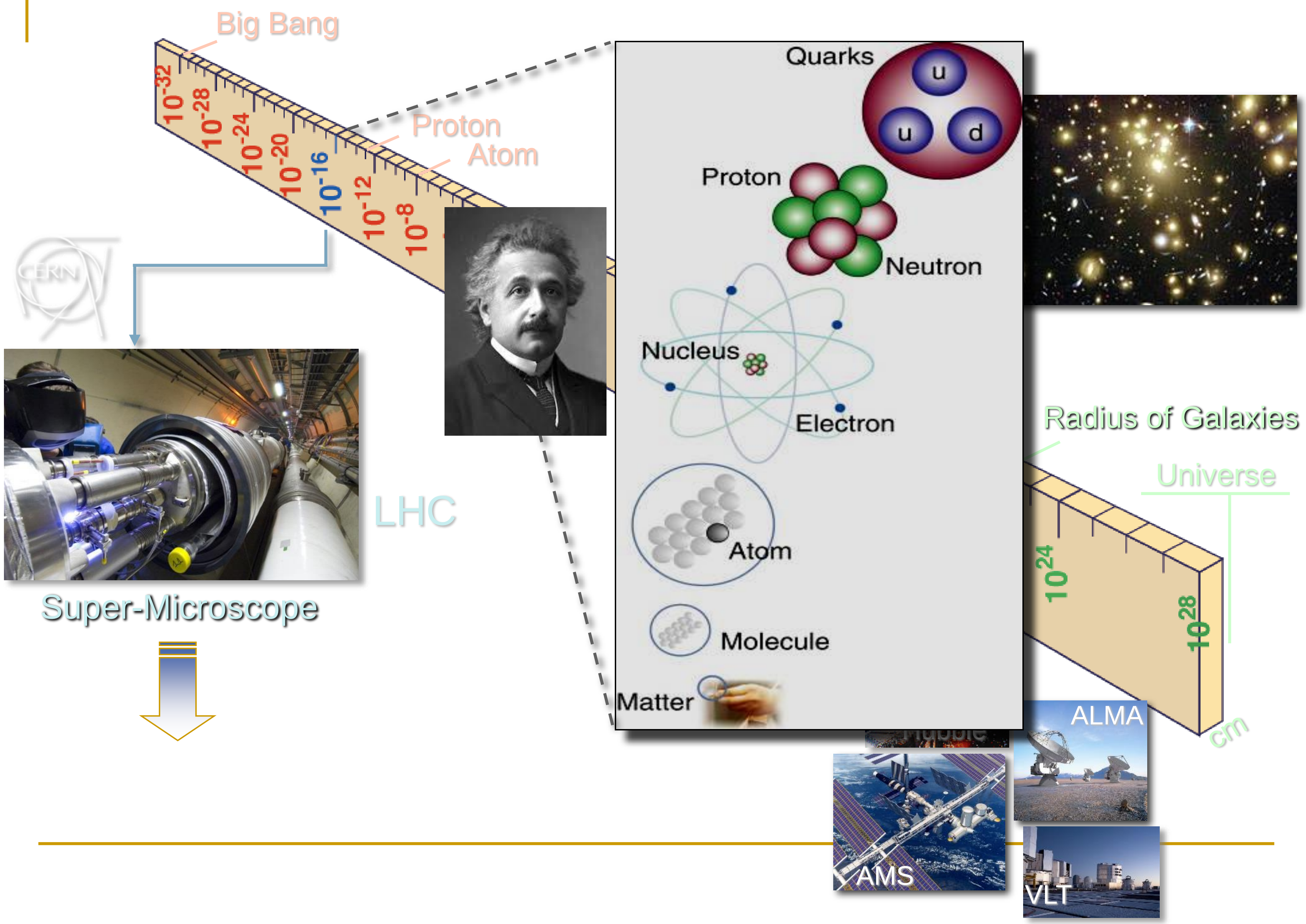
$$\lambda = h / p \; (1.2\,\mathrm{fm} / \mathrm{p}\,[\mathrm{GeV/c}]\,)$$

De Broglie wavelength

Planck Constant

De Broglie Wavelength

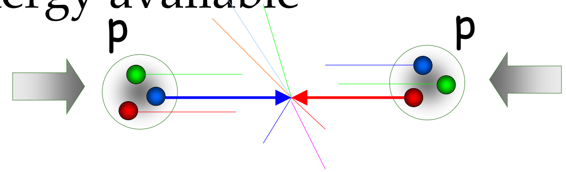
- **Wave-particle duality**
- **For higher E, probe shorter distances inside matter**



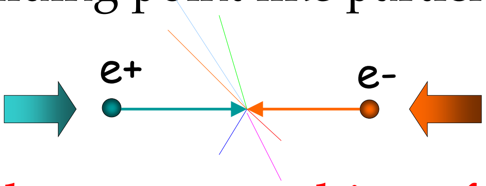
Big Bang
Proton
Atom
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
Quarks
u
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter
Radius of Galaxies
Universe
10^{24}
10^{28}
cm
LHC
Super-Microscope
ALMA
AMS
VLT

Collider Characteristics

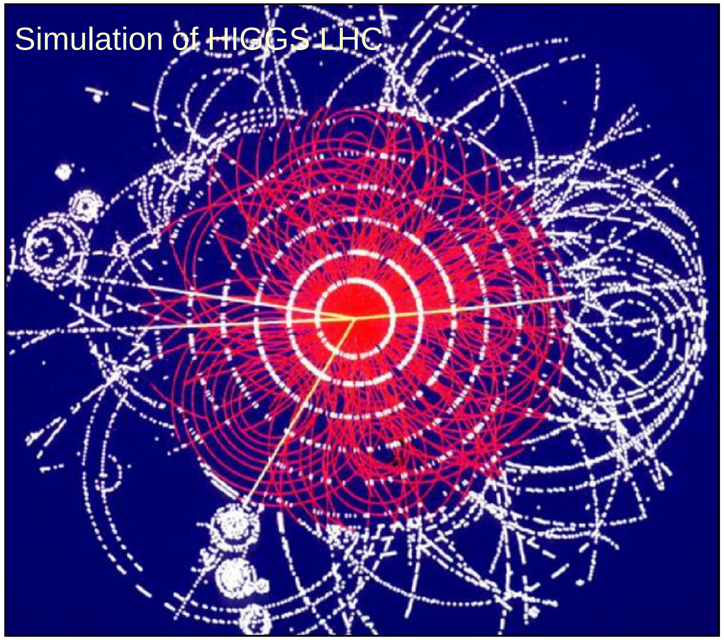
- Hadron collider at the frontier of physics
  - huge QCD background
  - not all nucleon energy available in collision

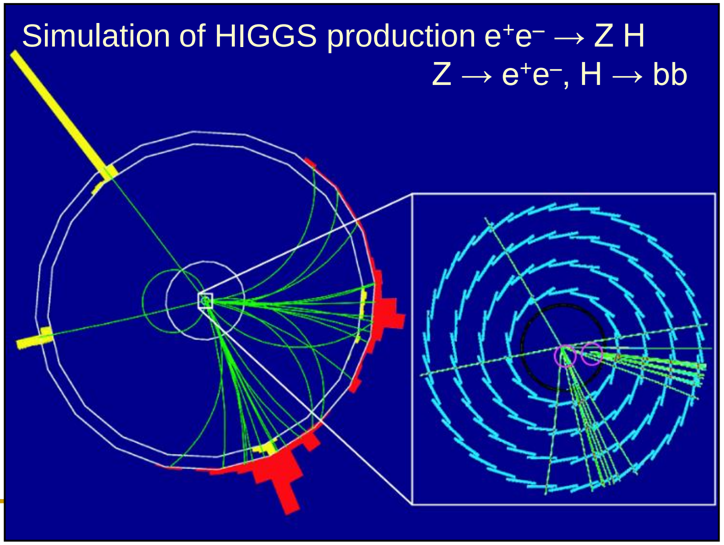


- Lepton collider for precision physics
  - well defined initial energy for reaction
  - Colliding point like particles

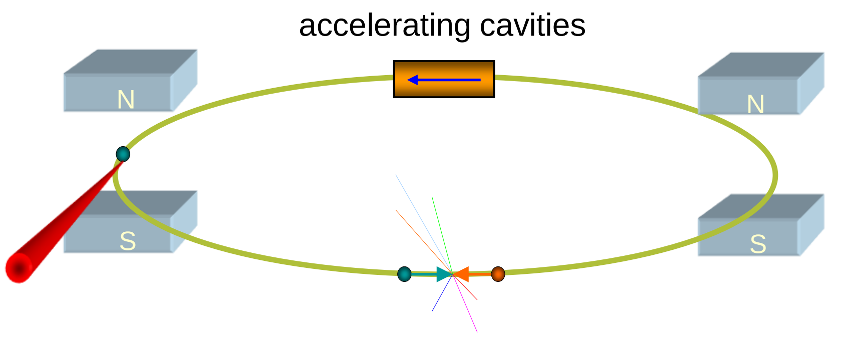


- Candidate next machine after LHC
  - e^+e^- collider
  - energy determined by LHC discoveries
  - study in detail the properties of the new physics that the LHC finds





Circular versus Linear Collider

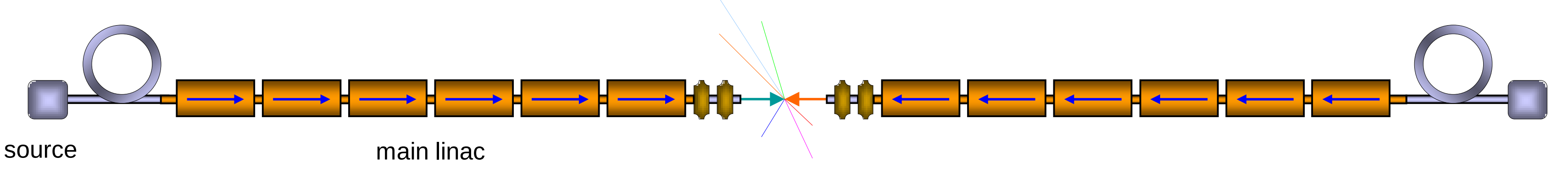


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

Today's Accelerators

Hadron Colliders

- Protons are composite particles
  - Only ~10% of beam energy available for hard collisions producing new particles
    - Need *O*(10 TeV) Collider to probe 1 TeV mass scale
    - Desired high energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
- Anti-protons difficult to produce if beam is lost
  - Use proton-proton collisions instead
  - Demand for ever-higher luminosity has led LHC to choose proton-proton collisions
  - Many bunches (high bunch frequency)
  - Two separate rings that intersect at select locations

Today's Accelerators

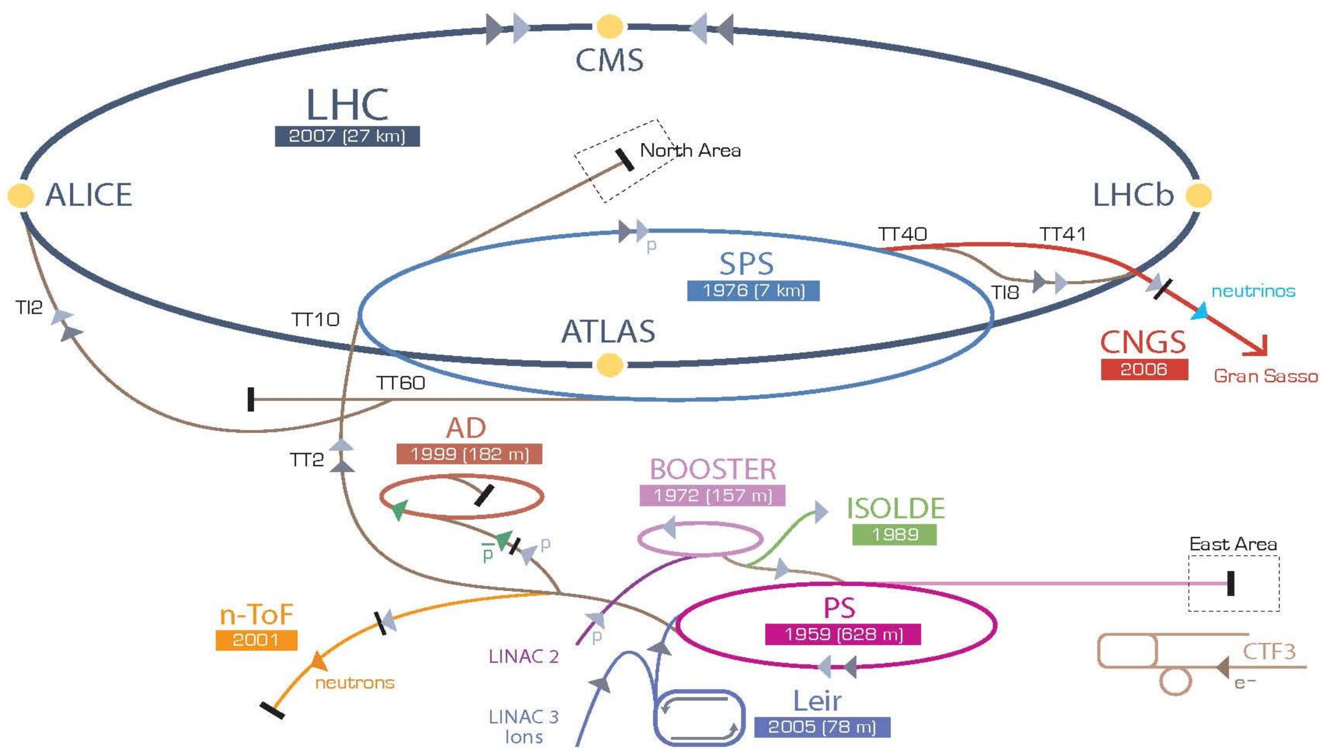
- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

    - For a 1 TeV CM energy Collider in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
      - Would need to replenish radiated power with RF
      - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider (ILC,CLIC)

THE LHC AND ITS UPGRADES

CERN Accelerator Complex



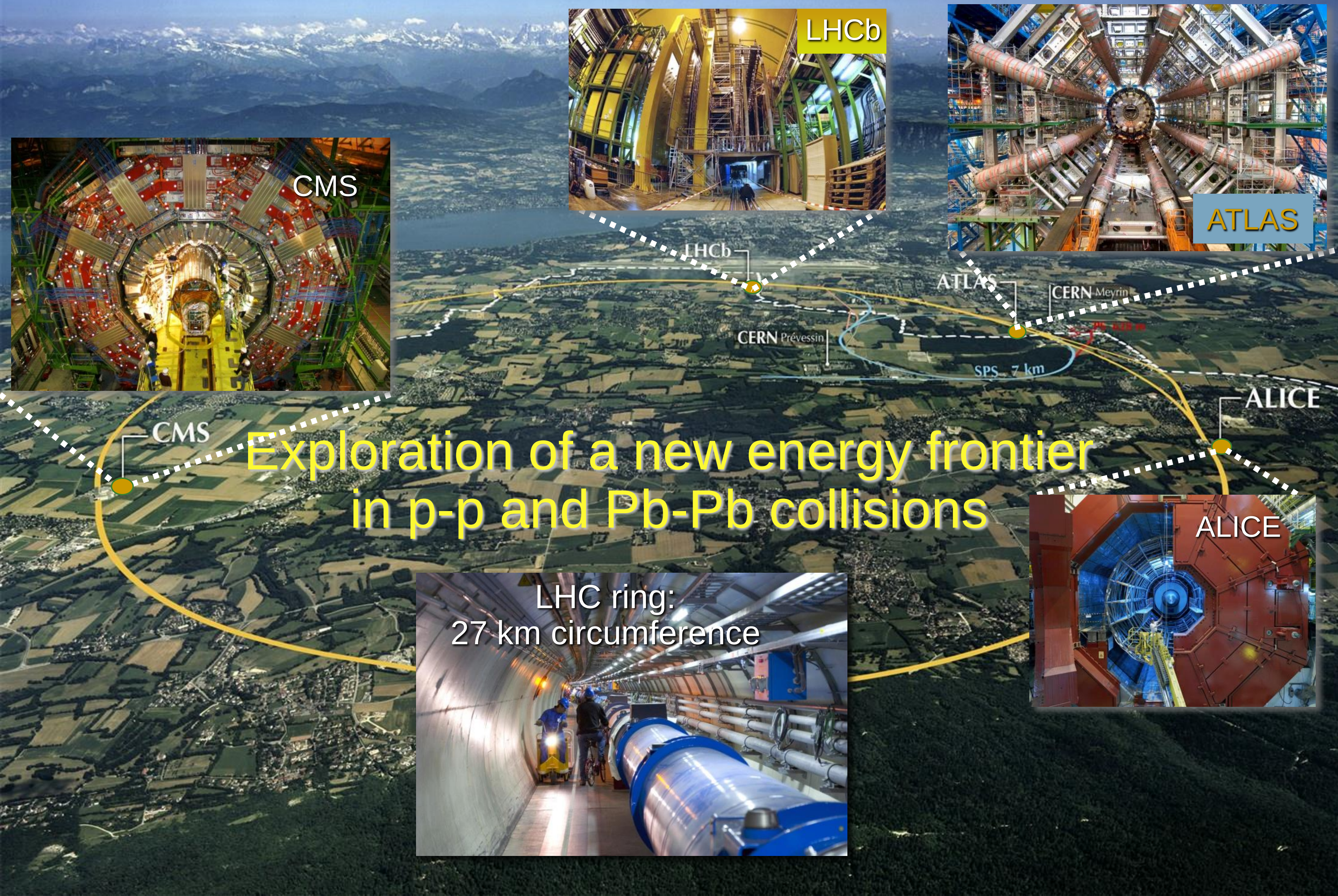
p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

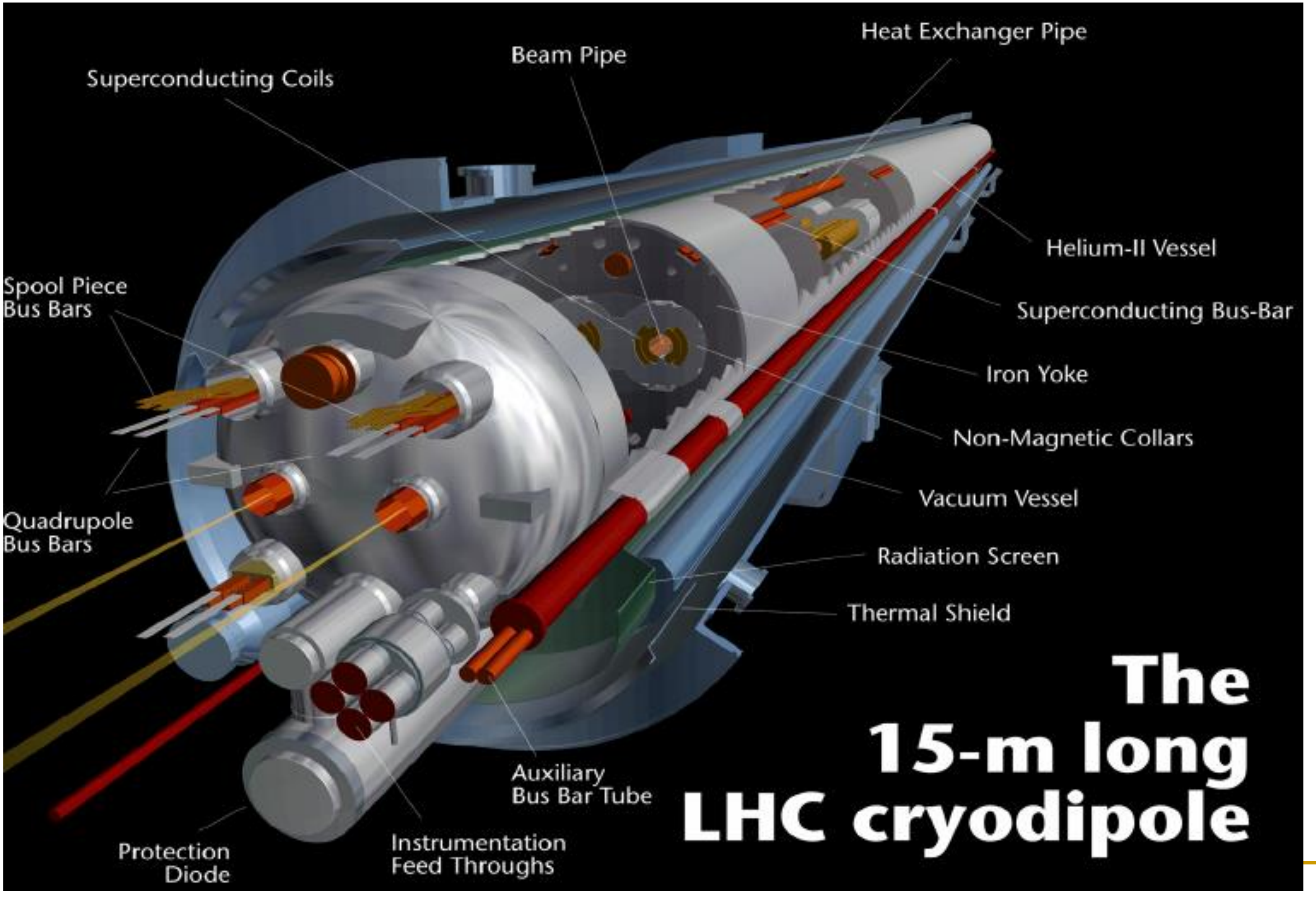
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

A New Era in Fundamental Science



LHC Main Bending Cryodipole



8.3 T
nominal field

11850 A
nominal field

The LHC Arcs

The LHC Experimental Challenge

LHC Machine Parameters

pp collisions at	$\sqrt{s}$ = 14 TeV
bunch crossing interval	25 nanoseconds
pp interaction rate	10^9 interactions/s

High Interaction Rate

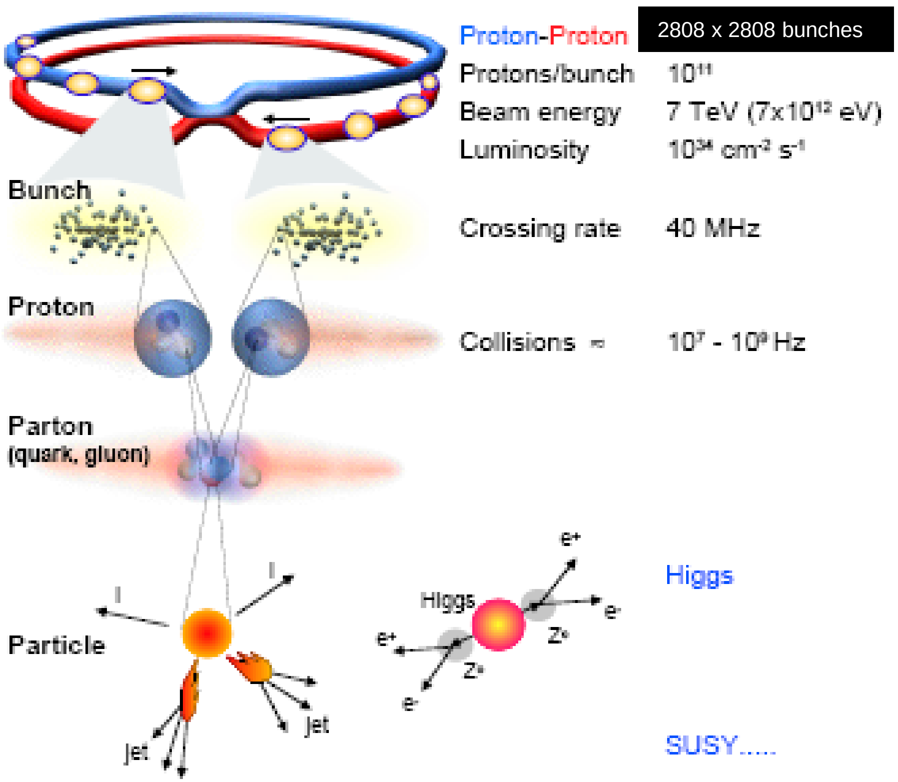
data for only ~100 out of the 40 million crossings can be recorded per second
First trigger decision will take ~2-3 μs
⇒ electronics needs to store data locally (pipelining)

Large Particle Multiplicity

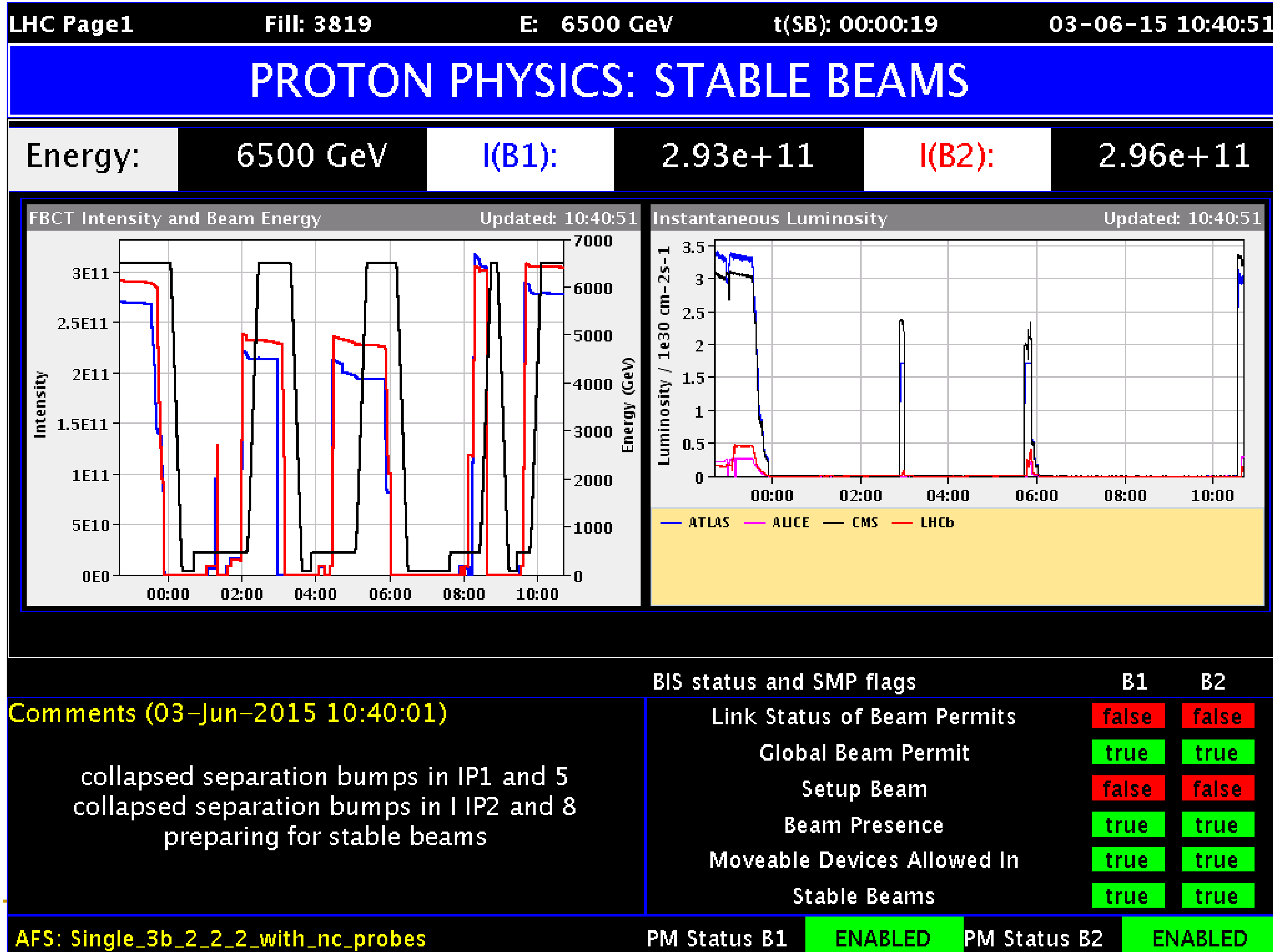
~ <20> superposed events in each crossing
~ 1000 tracks emerge rinto the detector every 25ns
need highly granular detectors
⇒ large number of channels

High Radiation Levels

⇒ radiation hard detectors and electronics



Selection of 1 in 10,000,000,000,000


LHC Page1
Fill: 3819
E: 6500 GeV
t(SB): 00:00:19
03-06-15 10:40:51
PROTON PHYSICS: STABLE BEAMS
Energy:
6500 GeV
I(B1):
2.93e+11
I(B2):
2.96e+11
FBCT Intensity and Beam Energy
Updated: 10:40:51
Intensity
Energy (GeV)
Instantaneous Luminosity
Updated: 10:40:51
Luminosity / 1e30 cm-2s-1
ATLAS
ALICE
CMS
LHCb
BIS status and SMP flags
B1
B2
Comments (03-Jun-2015 10:40:01)
collapsed separation bumps in IP1 and 5
collapsed separation bumps in I IP2 and 8
preparing for stable beams
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_3b_2_2_2_with_nc_probes
PM Status B1 ENABLED
PM Status B2 ENABLED

The Predictable Future - *LHC Timeline*

2009 — Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to several 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14 — LS1 - LHC shut-down to prepar...
design energy and n...

...minal (10^{34} cm^{-2} s^{-1}, ~50 to 100 fb^{-1}) and
...gy (13 and 14 TeV)

2018 — ... injector and LHC upgrades to go to ultim...

Run 3: Ram... nominal, reaching ~100 fb^{-1} / year
... fb^{-1}

~202... — LS3 – High-luminosity LHC (HL-LHC). New focusing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

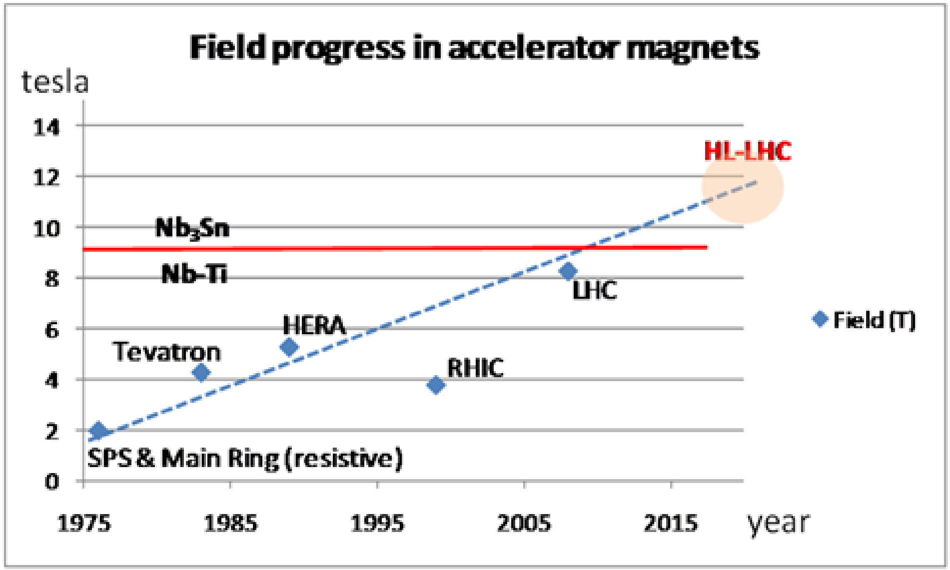
>2035

Study of the properties of the Higgs Boson & physics beyond the Standard Model

LHC results will guide the way at the energy frontier

Beam Focusing High-Field SC Magnets

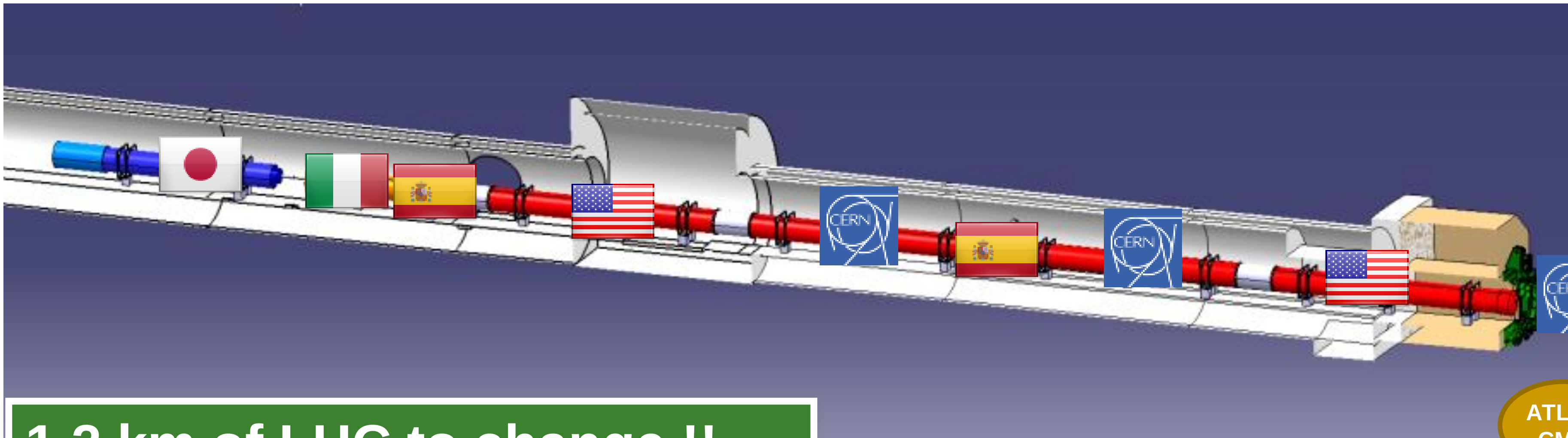
- 13 T, 150 mm aperture quadrupoles for the inner triplet:
  - LHC: 8 T, 70 mm.
- More focus strength, β* as low as 15 cm (55 cm in LHC).
  - In same scheme even β* down to 7.5 cm considered.
- Dipole separators capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)



Goal:

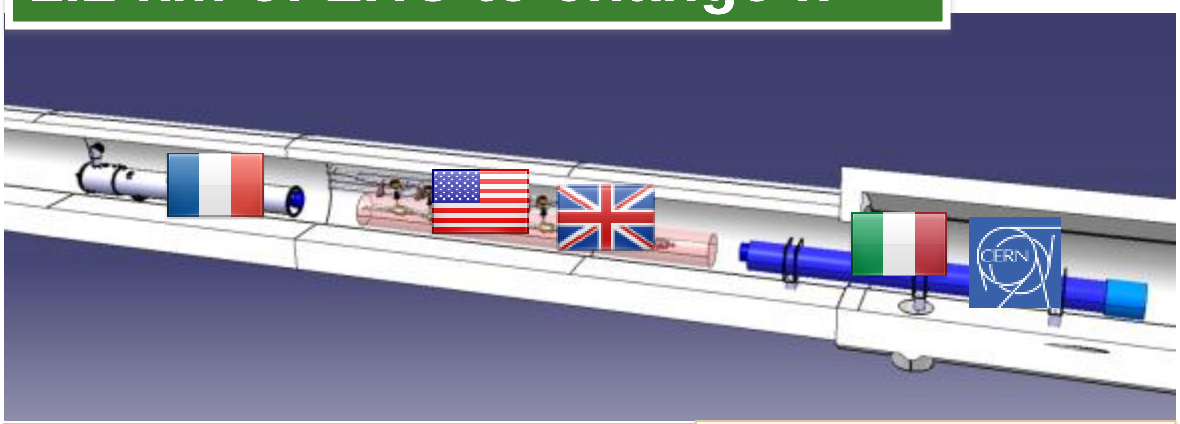
Enable focusing of the beams to *β*=0.15 m* in IP1 and IP5.

HL-LHC: In-kind Contribution and Collaboration for Design and Prototypes



ATLAS CMS

1.2 km of LHC to change !!

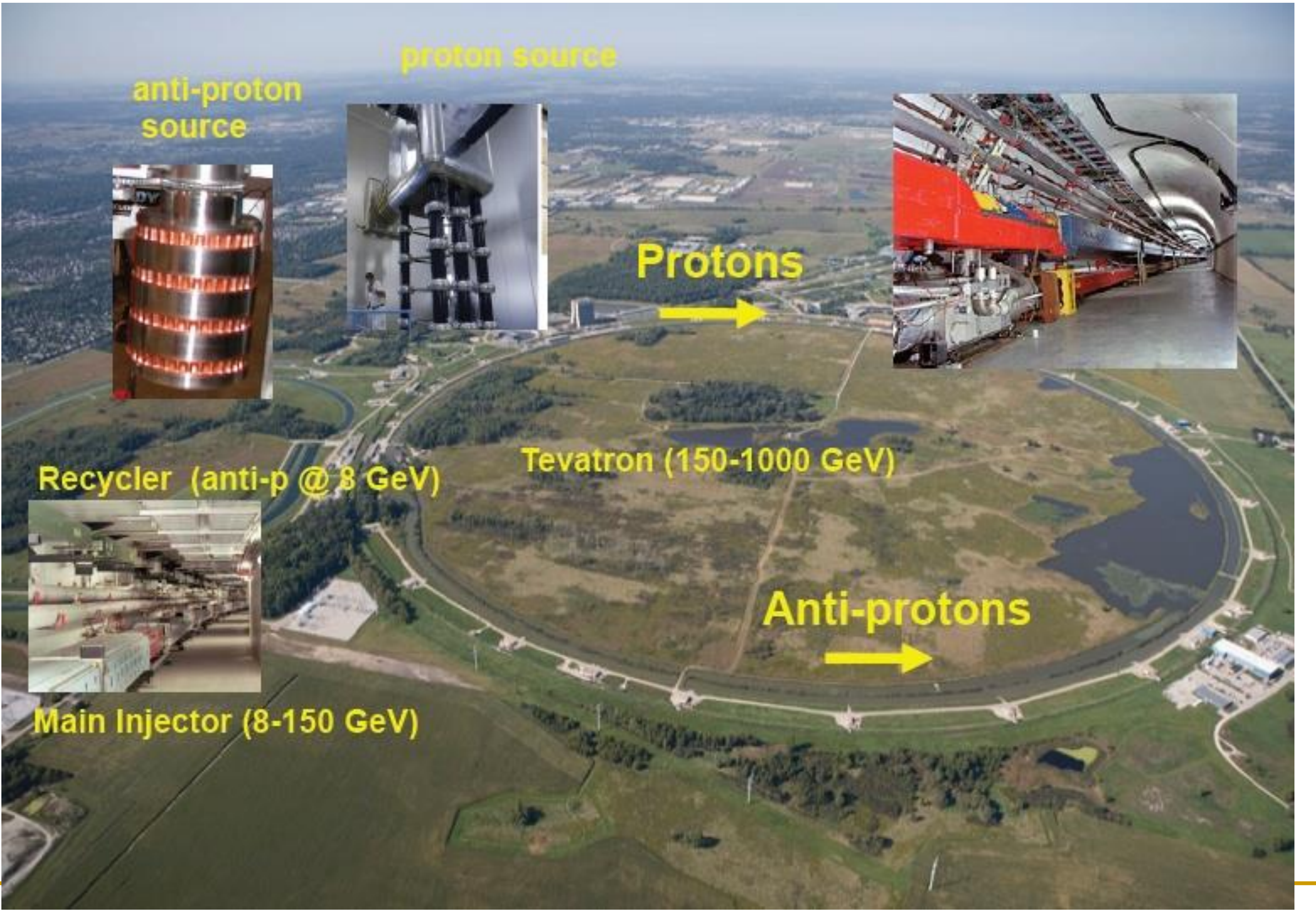


CC : R&D, Design and in-kind **USA**

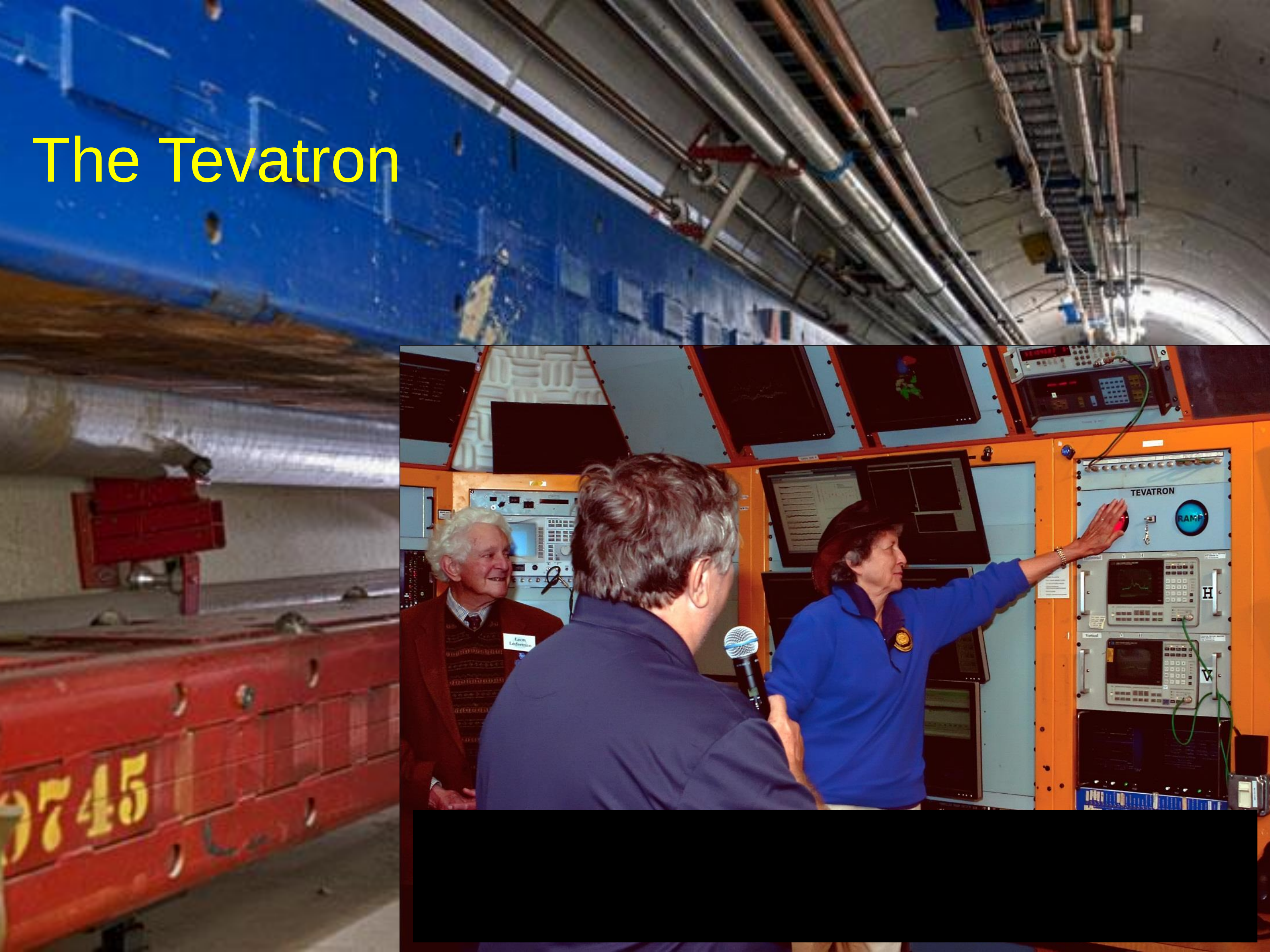
CC : R&D and Design **UK**

Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

The Tevatron at FERMILAB



The Tevatron



BEYOND THE LHC
CIRCULAR COLLIDERS

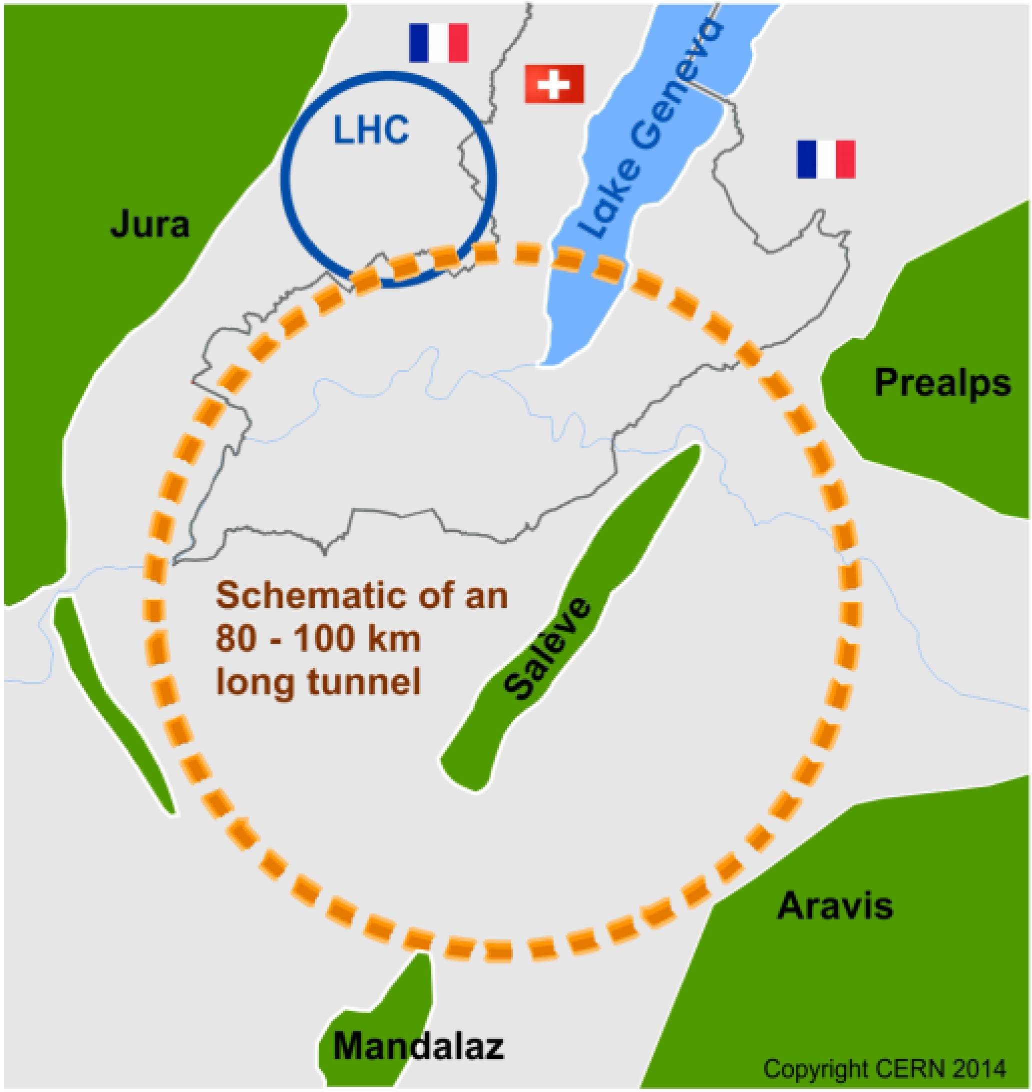
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

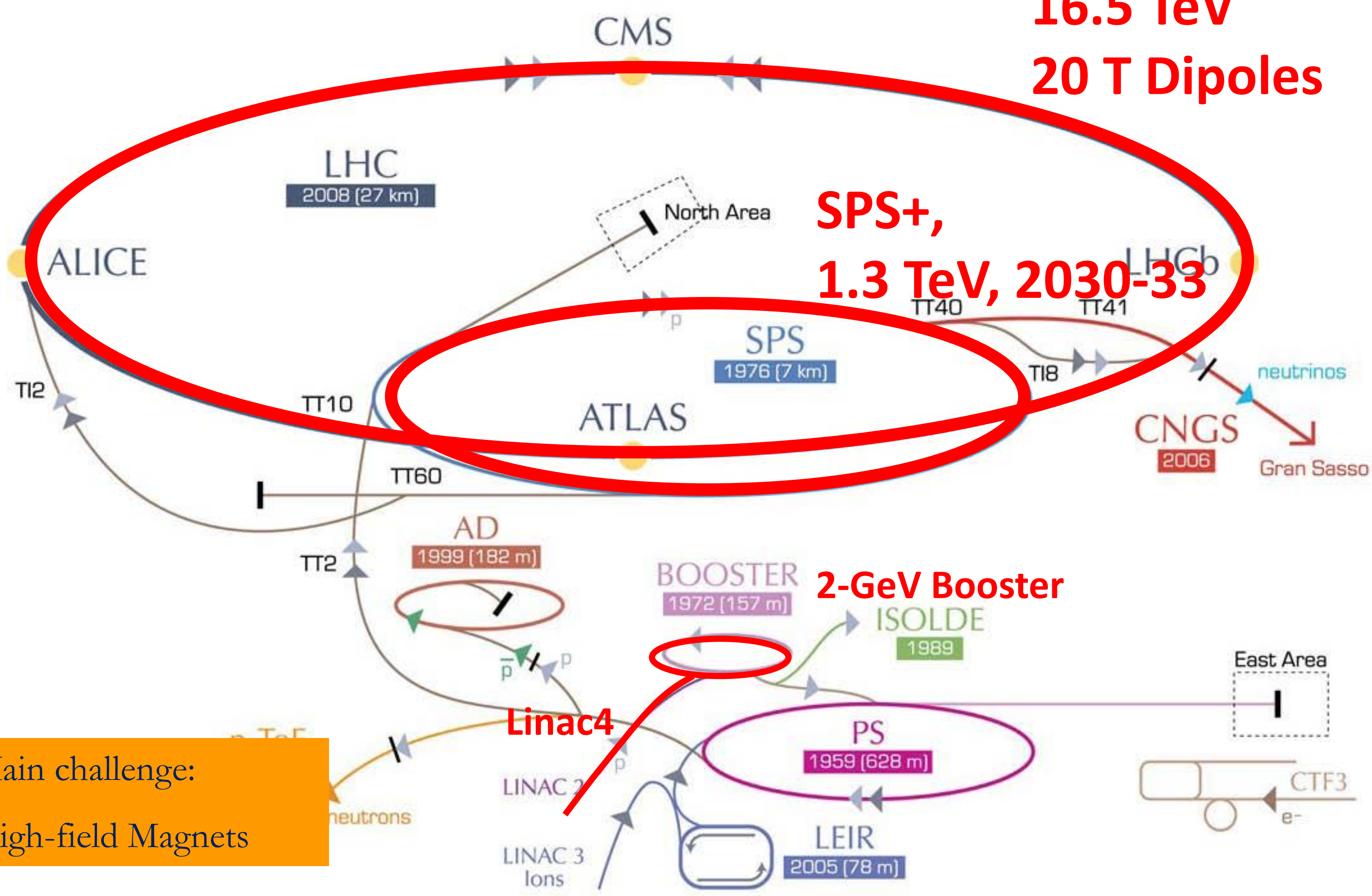
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



High-Energy LHC (HE-LHC)?

HE-LHC >2035
16.5 TeV
20 T Dipoles



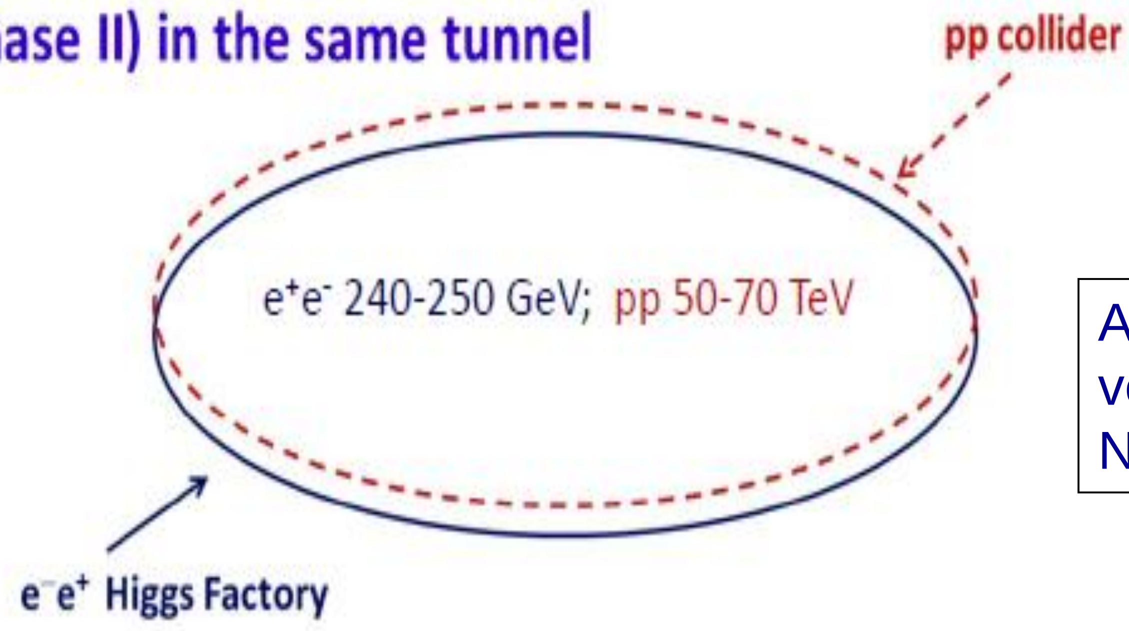
Main challenge:

High-field Magnets

CEPC+SppC

- For about 8 years, we have been talking about "What can be done after BEPCII in China"
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012

- **Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel**



Yifang Wang
Feb. 2014

A 50-70 km tunnel is very affordable in China NOW

Site

- Preliminary selected: Qinhuangdao (秦皇岛）
- Strong support by the local government

CEPC+SppC Current Design

CEPC Basic Parameters:

- Beam energy ~120 -125 GeV
- Synchrotron radiation power ~50 MW
- 50/70 km in circumference

SppC Basic Parameters:

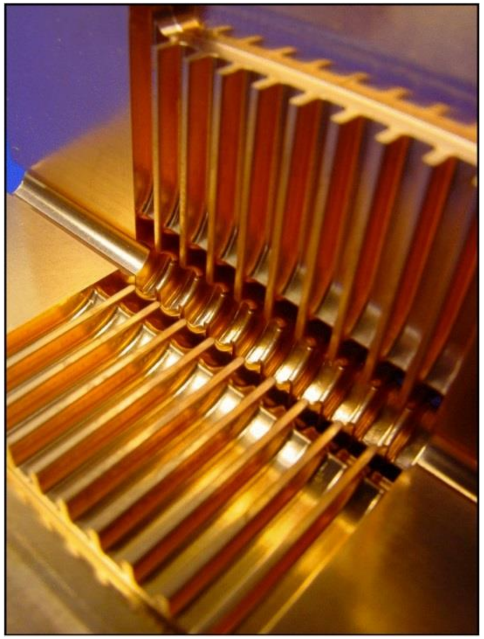
- Beam energy ~50-90 TeV
- 50/70 km in circumference
- Needs B_{max} ~20T

CEPC circumference determined later based on cost estimate.

BEYOND THE LHC
LINEAR COLLIDERS

ILC (and the Compact Linear Collider CLIC)

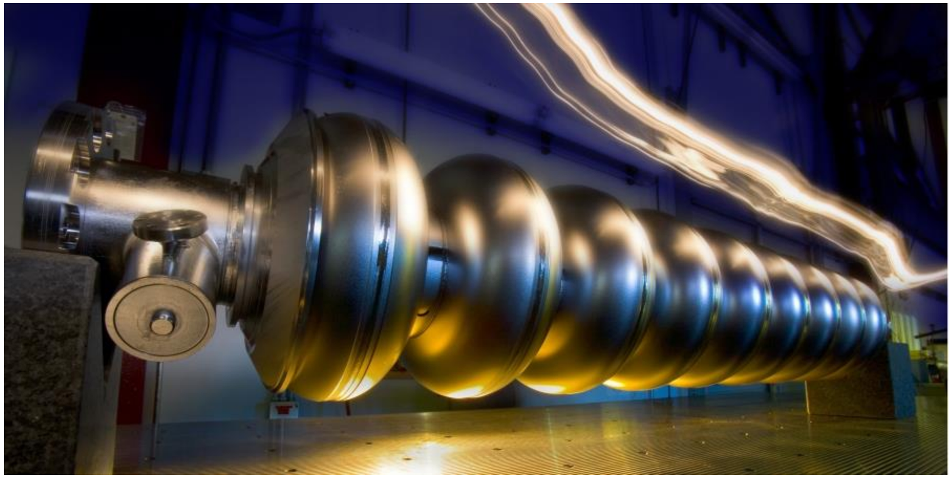
CLIC



•2-beam acceleration scheme at room temperature
•Gradient 100 MV/m
•$\sqrt{s}$ up to 3 TeV
•Physics + Detector studies for 350 GeV - 3 TeV

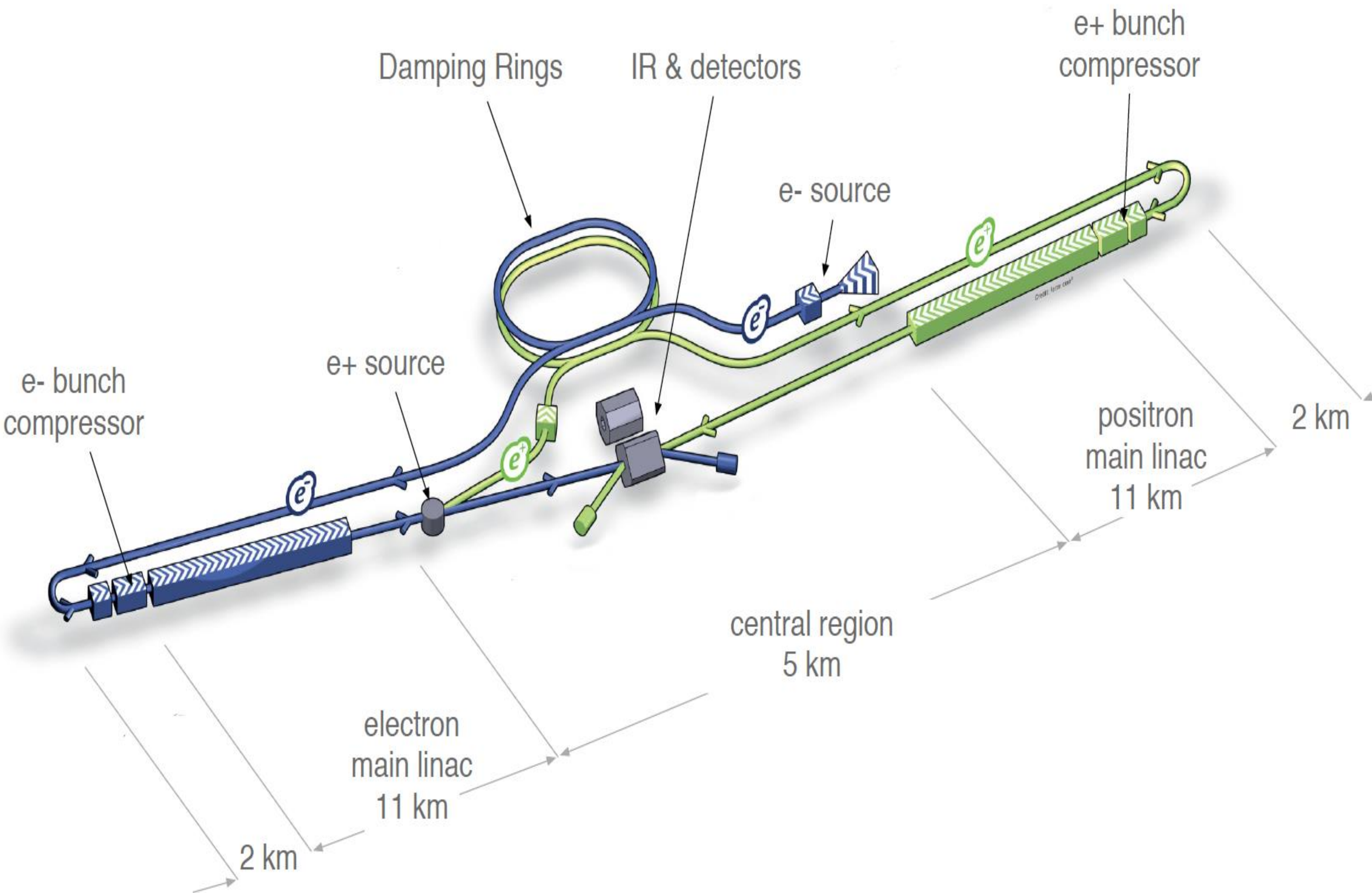
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC



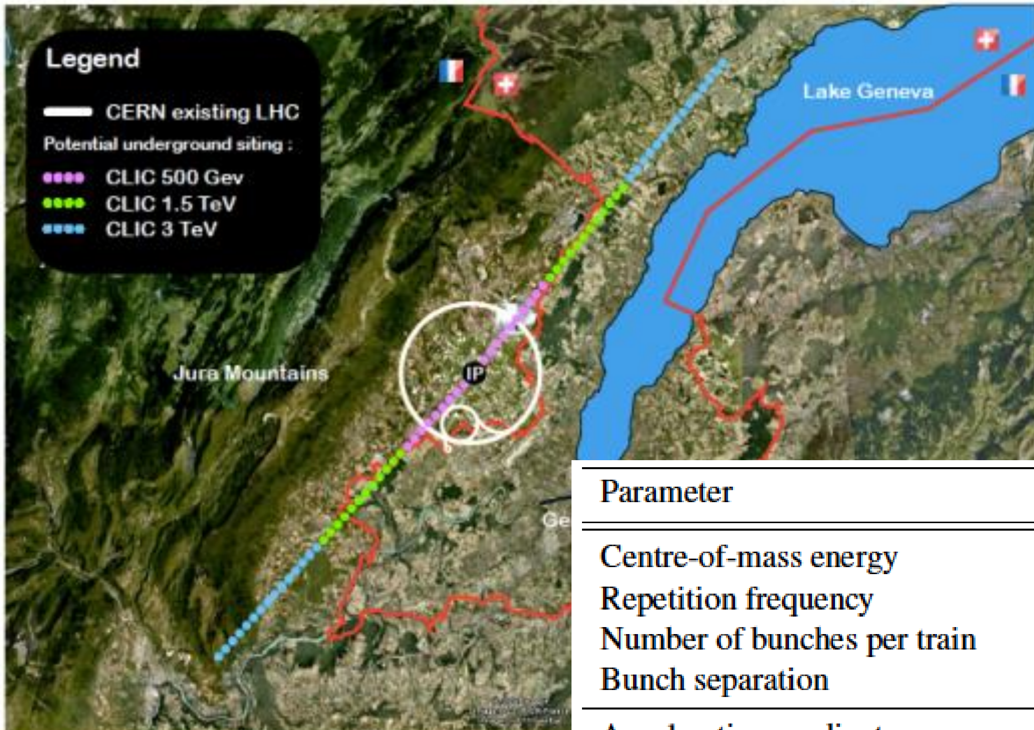
•Superconducting RF cavities (like XFEL)
•Gradient 32 MV/m
•$\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
•Focus on ≤ 500 GeV, physics studies also for 1 TeV

The International Linear Collider




shield wall removed
©Rey.Hori/KEK

CLIC Implementation



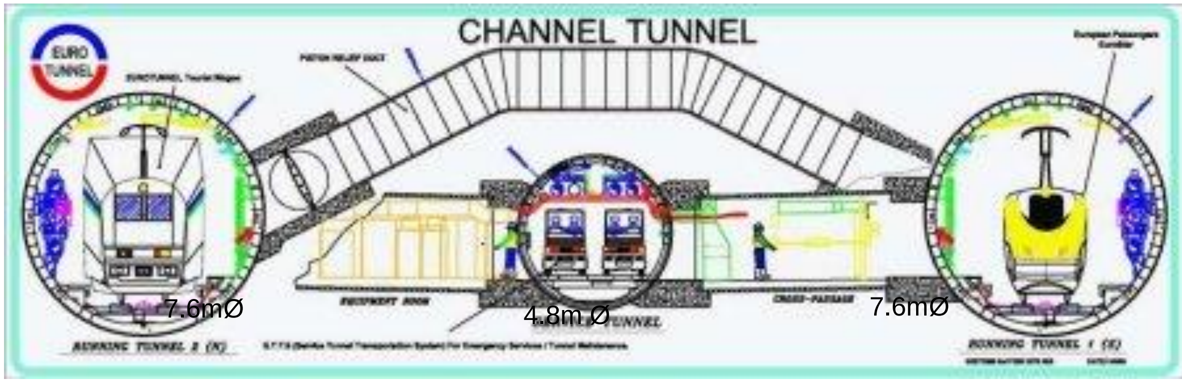
← Possible lay-out near CERN

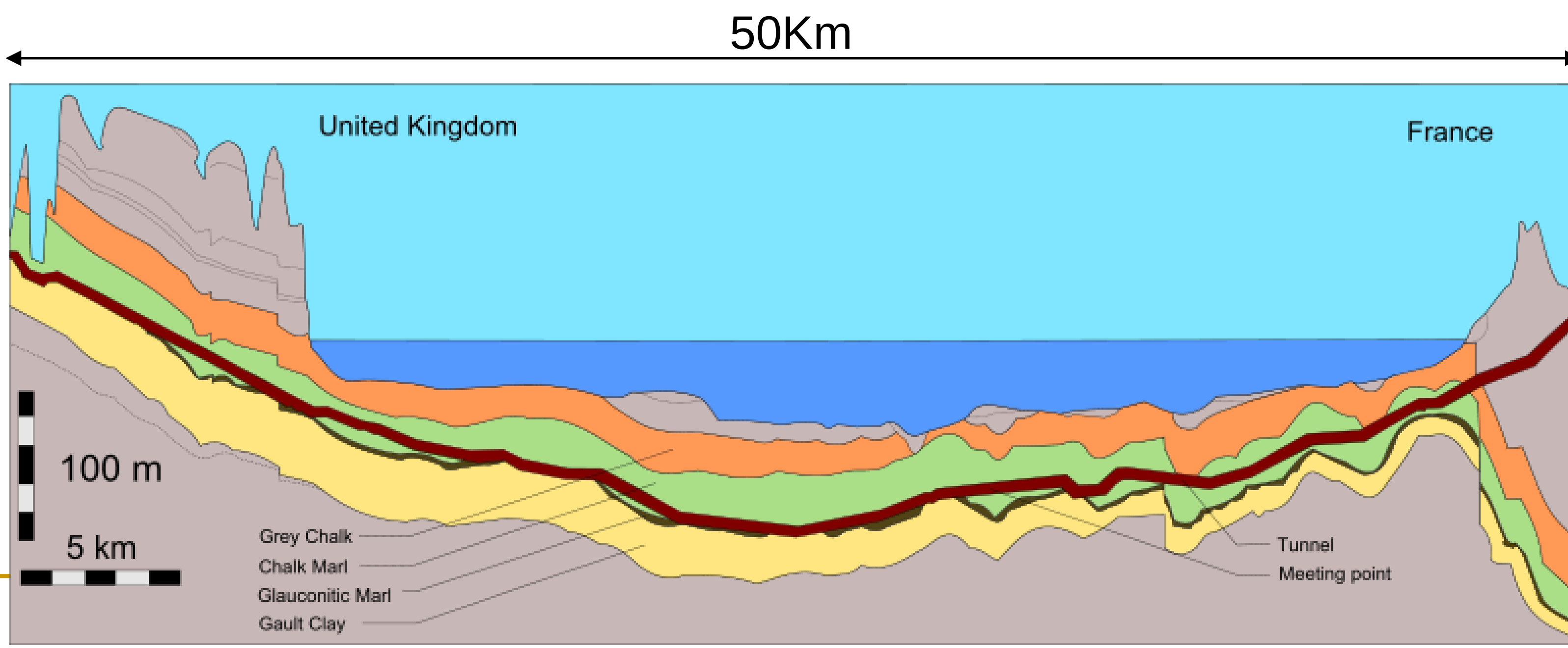
↓ CLIC parameters

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

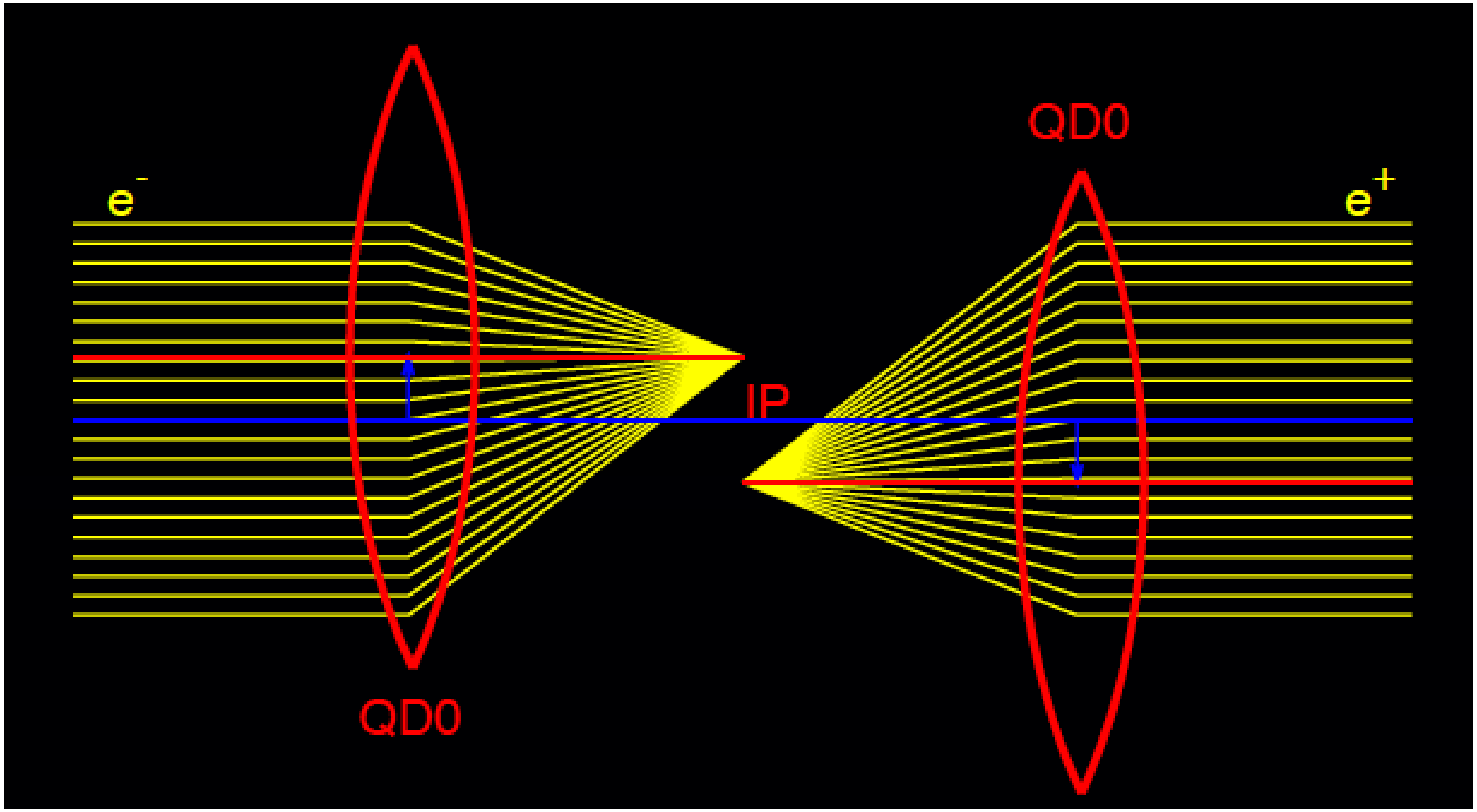
Note: the design is currently being re-optmised, e.g. to include 350 GeV as the first stage

For CLIC & ILC - Similar World Projects: Channel Tunnel





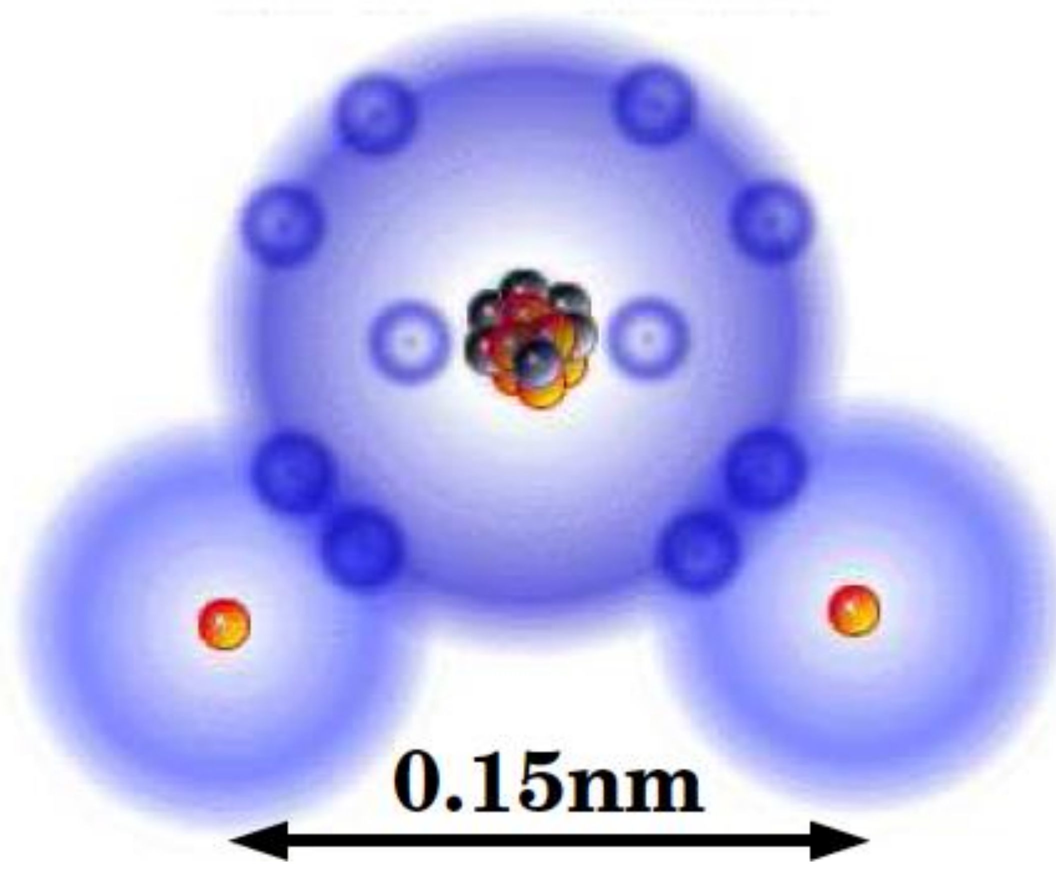
Other Technological Challenges



The final focusing quadruple should be stabilized to 0.15 nm

for frequencies about 4 Hz

Other Technological Challenges



MUON ACCELERATORS

Physics with Muon Beams

- Neutrino Sector

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

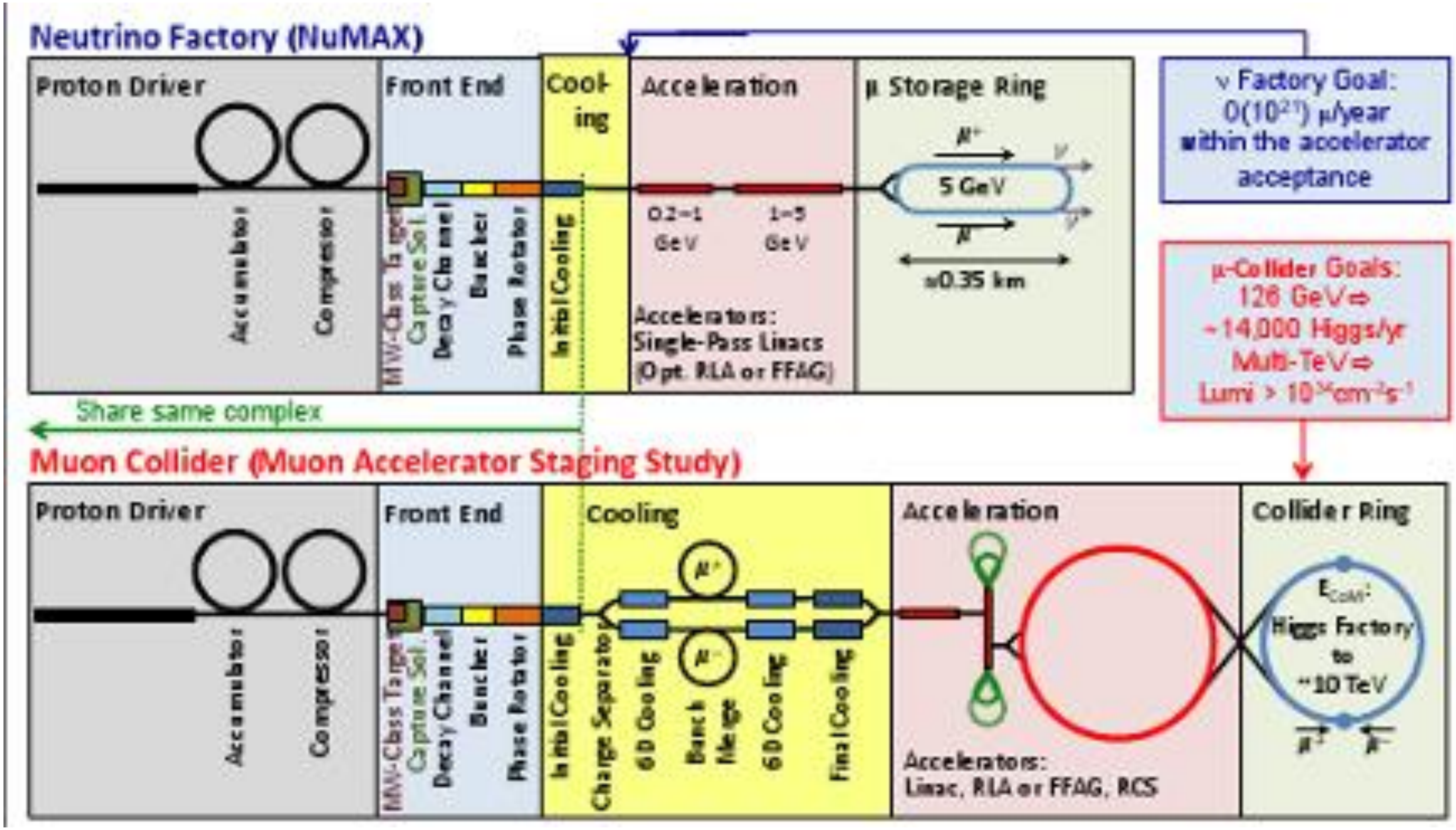
Produces high energy neutrinos

  - Decay kinematics well known
  - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable wrong-sign μ
- Energy Frontier
  - Point particle makes full beam energy available for particle production
    - Couples strongly to Higgs sector
  - Muon Collider has almost no synchrotron radiation
    - Narrow energy spread
    - Fits on existing laboratory sites

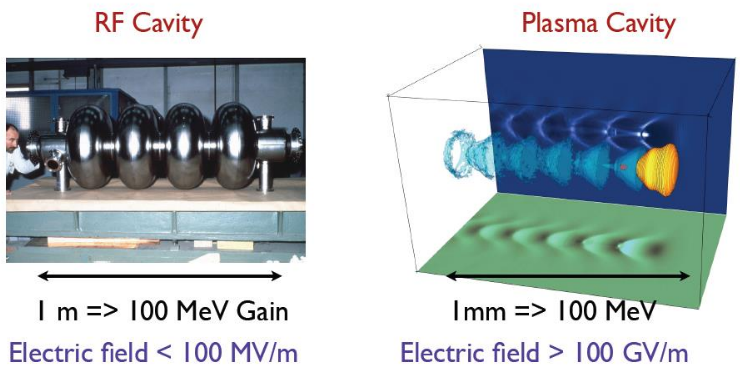
Muon Beam Challenges

- Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - Low production rate
    - Need target that can tolerate multi-MW beam
  - Large energy spread and transverse phase space
    - Need solenoidal focusing for the low-energy portions of the facility
      - (solenoids focus in both planes simultaneously)
    - Need acceptance cooling
    - High-acceptance acceleration system and decay ring
- Muons have short lifetime (2.2 μs at rest)
  - Puts premium on rapid beam manipulations
    - Presently untested ionization cooling technique
      - High-gradient RF cavities (in magnetic field)
  - Fast acceleration system
- Decay electrons give backgrounds in Collider detectors and instrumentation & heat load to magnets

Muon Collider (?)



Plasma Accelerators



V. Malka *et al.*, Science **298**, 1596 (2002)

e.g. AWAKE at CERN

Demonstration experiment to verify novel technique of p-driven plasma wakefield acceleration

Plasma accelerators:

Transform transverse fields into longitudinal fields.

Significantly higher accelereating gradients than conventional RF.

- **Laser driven**
- **e- driven**
- **p driven**
- **Dielectric wakefields**

The Sub-Fermi Scale (2015-2050)?