After the Higgs Discovery:

Linear Colliders for Higgs Factories!

Philip Burrows

Interim Director,

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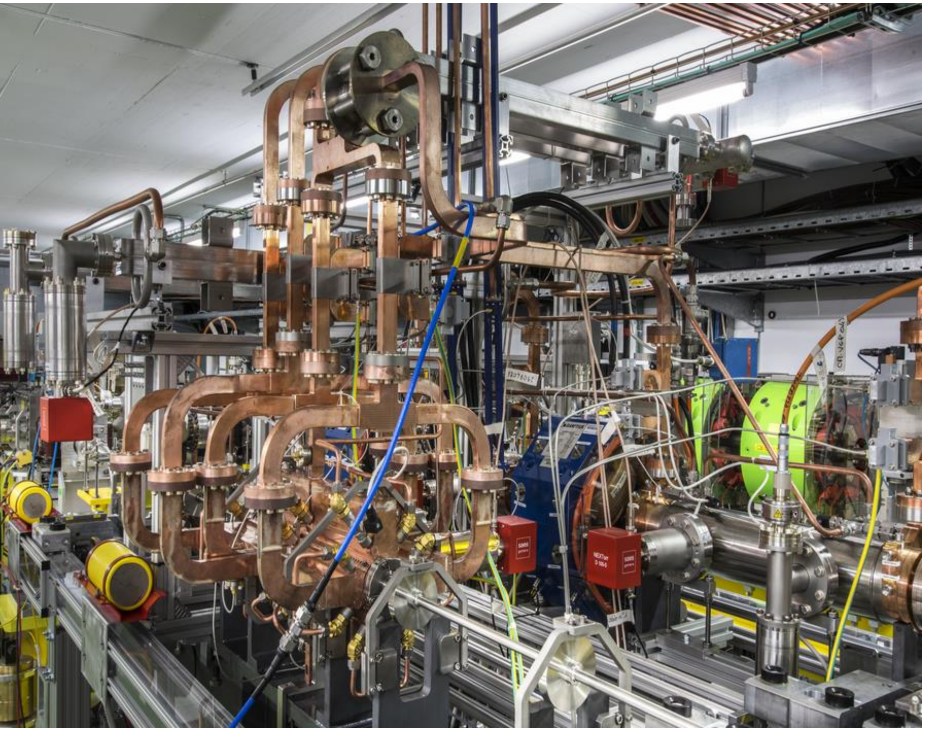
John Adams Institute



A centre of excellence for advanced and novel accelerator technology, providing expertise, research, development and training in accelerator techniques, and promoting advanced accelerator applications in science and society

JAI John Adams Institute for Accelerator Science

John Adams Institute

Oxford University, Royal Holloway, Imperial College

One of two UK national academic centres of excellence in accelerator science, set up in 2004

23 faculty

30 staff

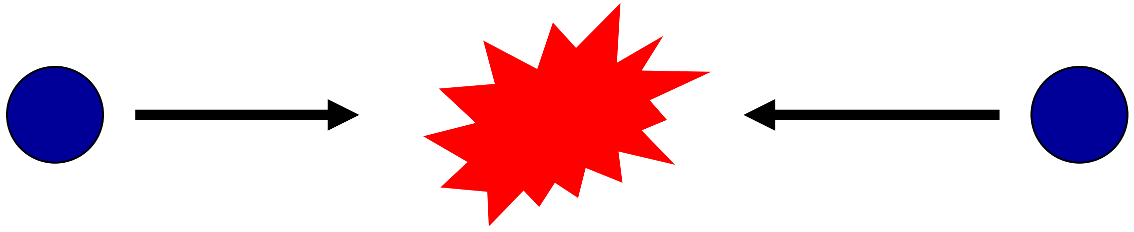
37 PhD students

Research projects at: CERN, DESY, KEK, Daresbury, Diamond, ISIS, CLF …

Comprehensive PhD training programme

Smashing matter apart

- Want to see what matter is made of
- Smash matter apart and look for the building blocks
- Take small pieces of matter:
  - accelerate them to very high energy
  - crash them into one another



- LHC: protons crashing into protons head-on

Scientific importance of accelerators

- 30% of physics Nobel Prizes awarded for work based on accelerators

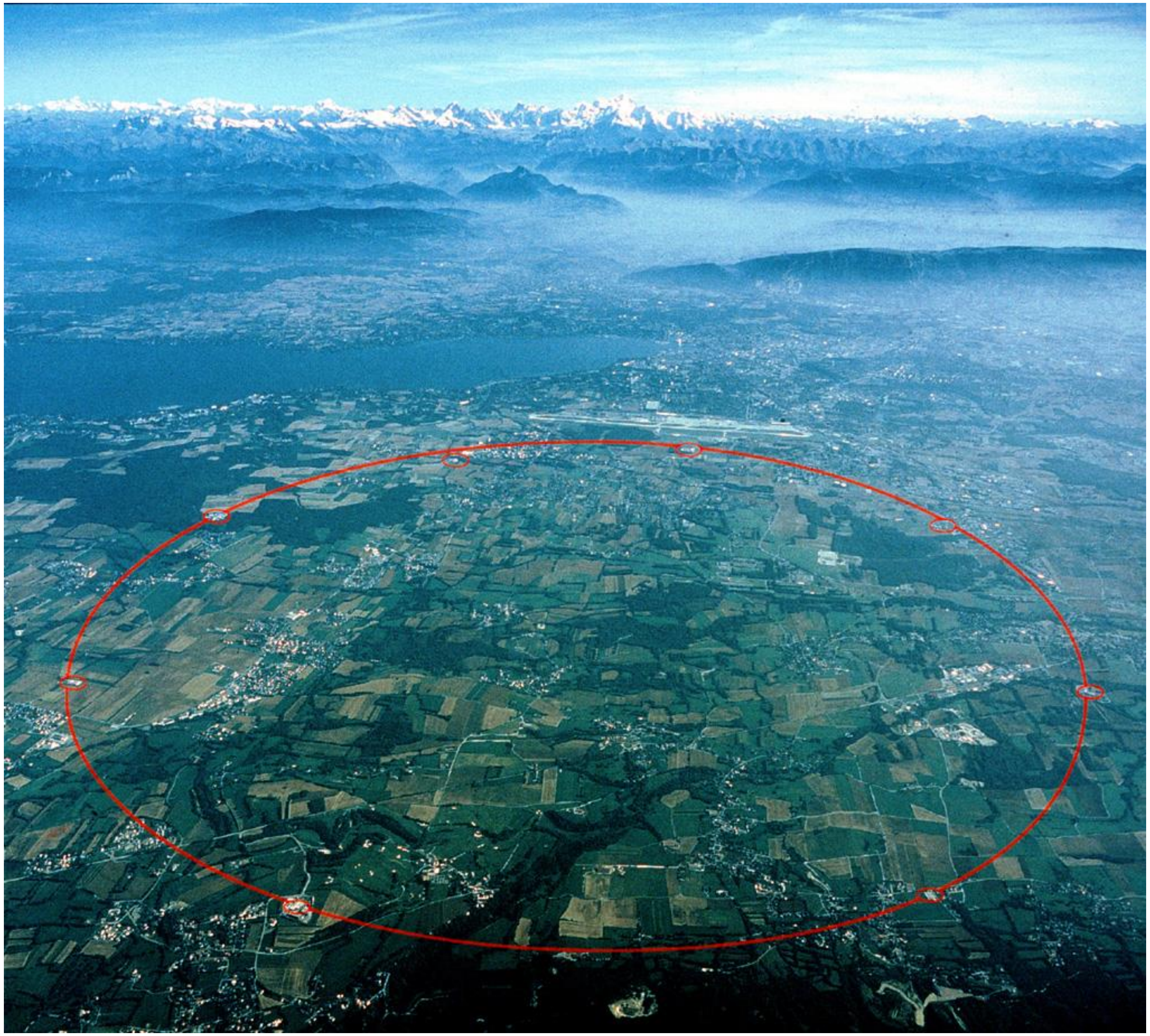
- Increasing number of non-physics Nobel Prizes being awarded for work reliant on accelerators!

Accelerator-related Physics Nobel Prizes

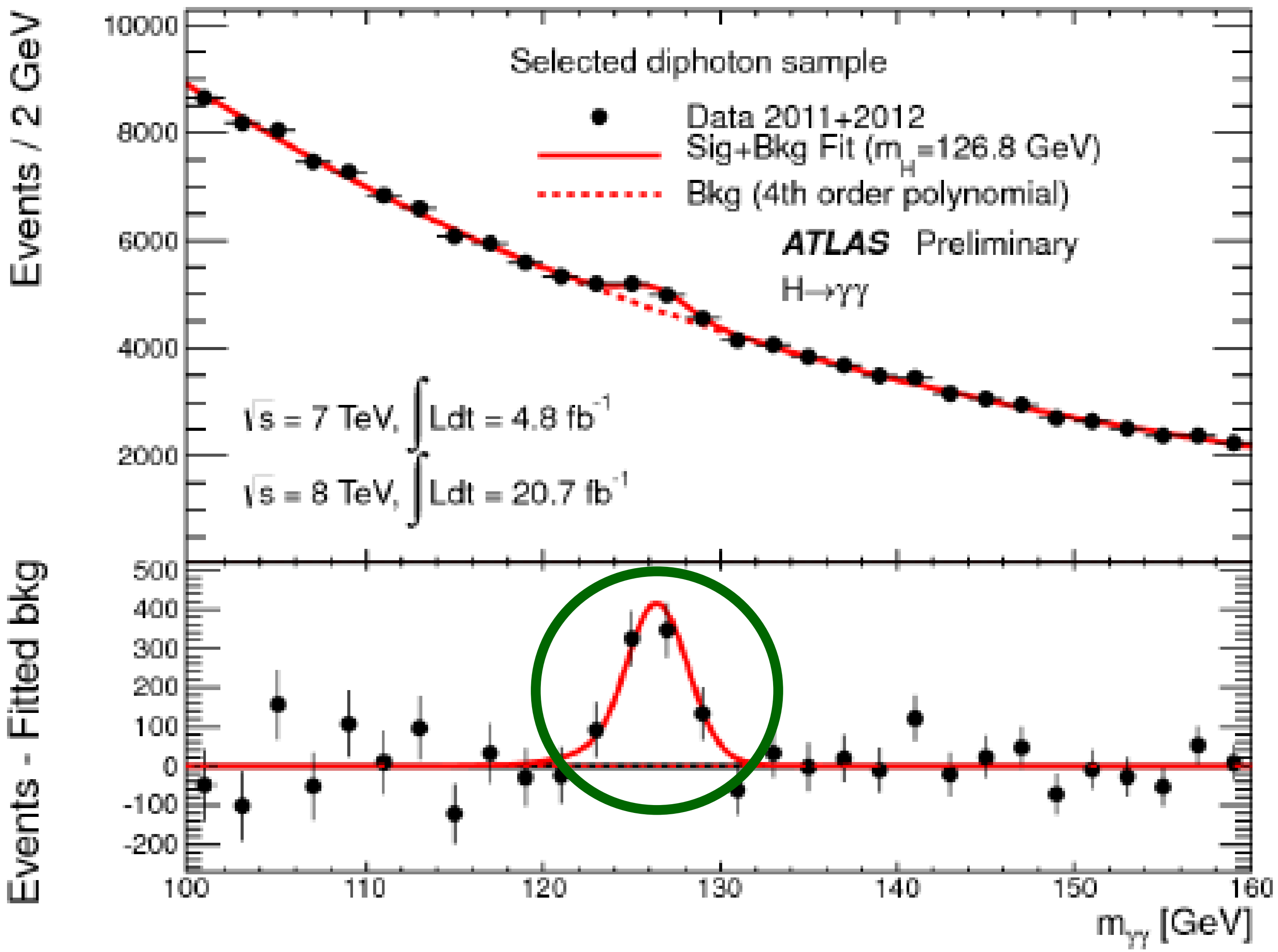
- 1901 Roentgen: X rays
- 1905 Lenard: cathode rays
- 1906 JJ Thomson: electron
- 1914 von Laue: X-ray diffraction
- 1915 WH+WL Bragg: X-ray crystallography
- 1925 Franck, Hertz: laws of impact of e on atoms
- 1927 Compton: X-ray scattering
- 1937 Davisson, Germer: diffraction of electrons
- 1939 Lawrence: cyclotron
- 1943 Stern: magnetic moment of proton
- 1951 Cockcroft, Walton: artificial acceleration
- 1959 Segre, Chamberlain: antiproton discovery
- 1961 Hofstadter: structure of nucleons
- 1968 Alvarez: discovery of particle resonances
- 1969 Gell-Mann: classification of el. particles
- 1976 Richter, Ting: charmed quark
- 1979 Glashow, Salam, Weinberg: Standard Model
- 1980 Cronin, Fitch: symmetry violation in kaons
- 1984 Rubbia, van der Meer: W + Z particles
- 1986 Ruska: electron microscope
- 1988 Ledermann, Schwartz, Steinberger: mu nu
- 1990 Friedmann, Kendall, Taylor: quarks
- 1992 Charpak: multi-wire proportional chamber
- 1994 Brockhouse, Shull: neutron scattering
- 1995 Perl: tau lepton discovery
- 2004 Gross, Pollitzer, Wilczek: asymptotic freedom
- 2008 Nambu, Kobayashi, Maskawa: broken symmetries
- 2013 Englert, Higgs: Higgs boson

Large Hadron Collider (LHC)

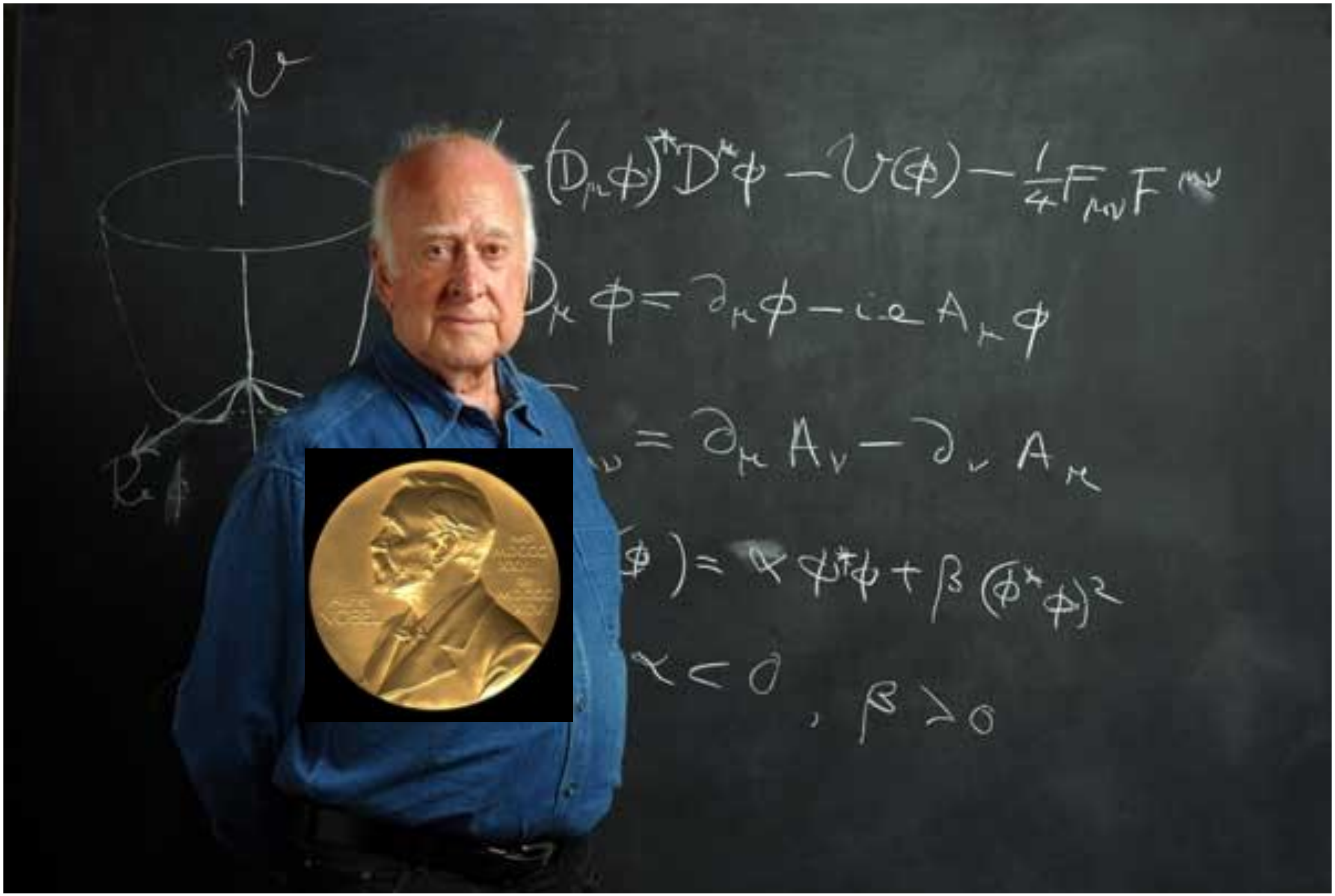
Best window we have on matter in the universe, at ultra-early times and at ultra-small scales



The new boson discovered 2012



2013



After LHC?

LHC:

protons

with energy

E = 7000 GeV

Before LHC?

Before LHC

Before LHC

Large Electron Positron (LEP):

c. 100 GeV electrons + positrons

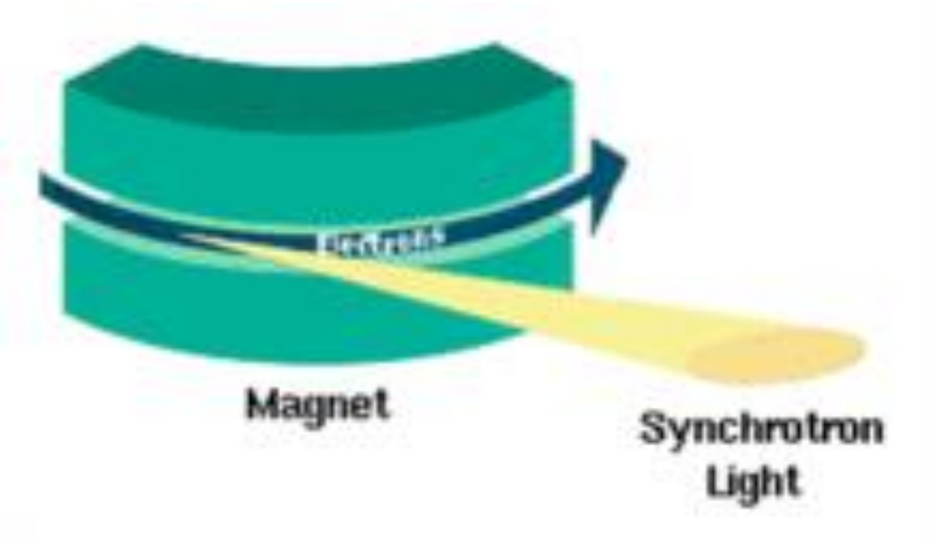
Super Large Electron Positron collider?

500 GeV

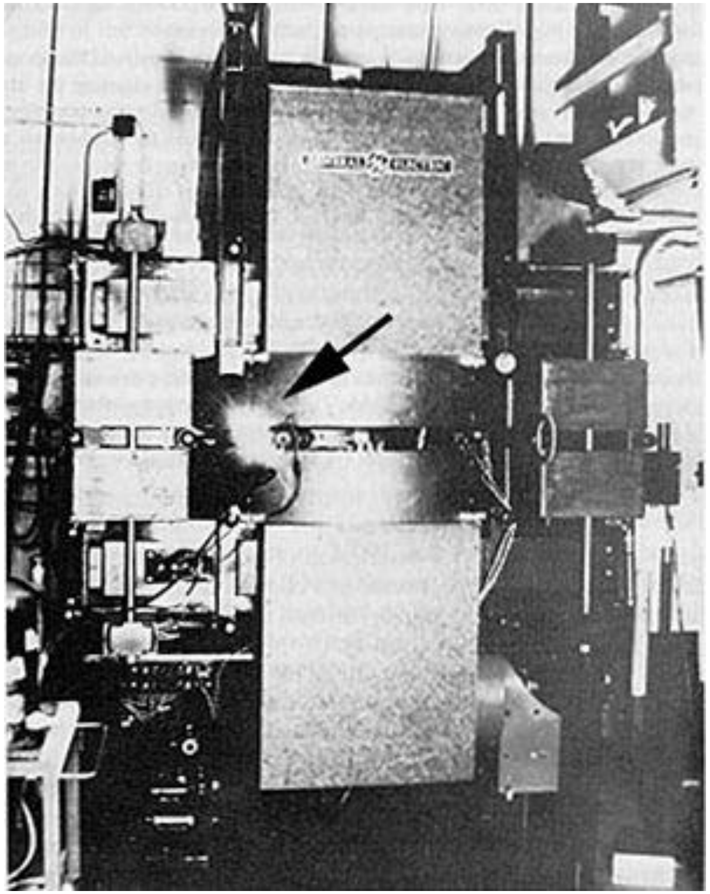
beams?

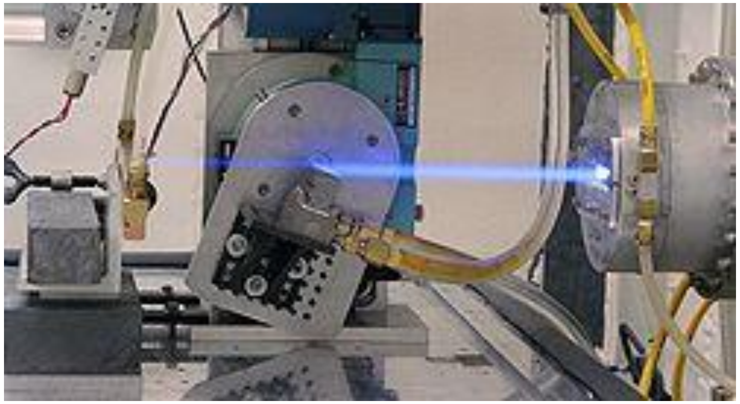
(5 x LEP)

Synchrotron radiation



Discovered Elder et al 1947 (General Electric)





Synchrotron radiation

Power lost due to synchrotron radiation

$$P \sim E^4 / r^2$$

E = beam energy

r = radius of trajectory

Synchrotron radiation

Power lost due to synchrotron radiation

$$P \sim E^4 / r^2$$

E = beam energy

r = radius of trajectory

For LEP each electron lost ~ 3 GeV per turn (3%!)

P = 10^{-6} Watts/electron → 18 MW total

→ Must be compensated by accelerating cavities

Synchrotron radiation

Suppose we increase LEP beam energy (100 GeV) by factor 5: E → 500 GeV, in the same tunnel

$P \sim E^4 / r^2$

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E increases by factor 5, so P increases by 5^4

this would give $P = 5^4 * 18$ MW = 11 GW!

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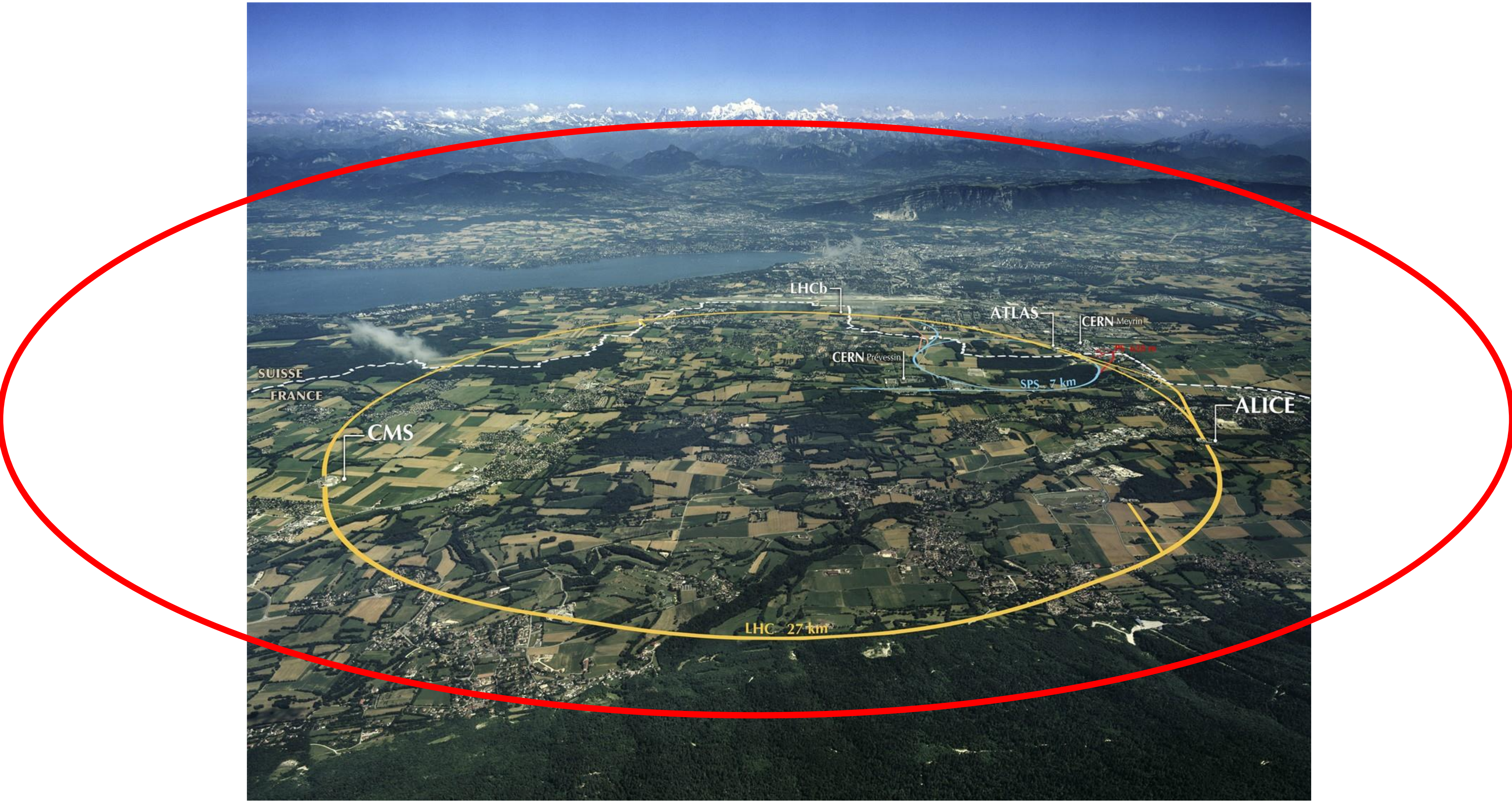
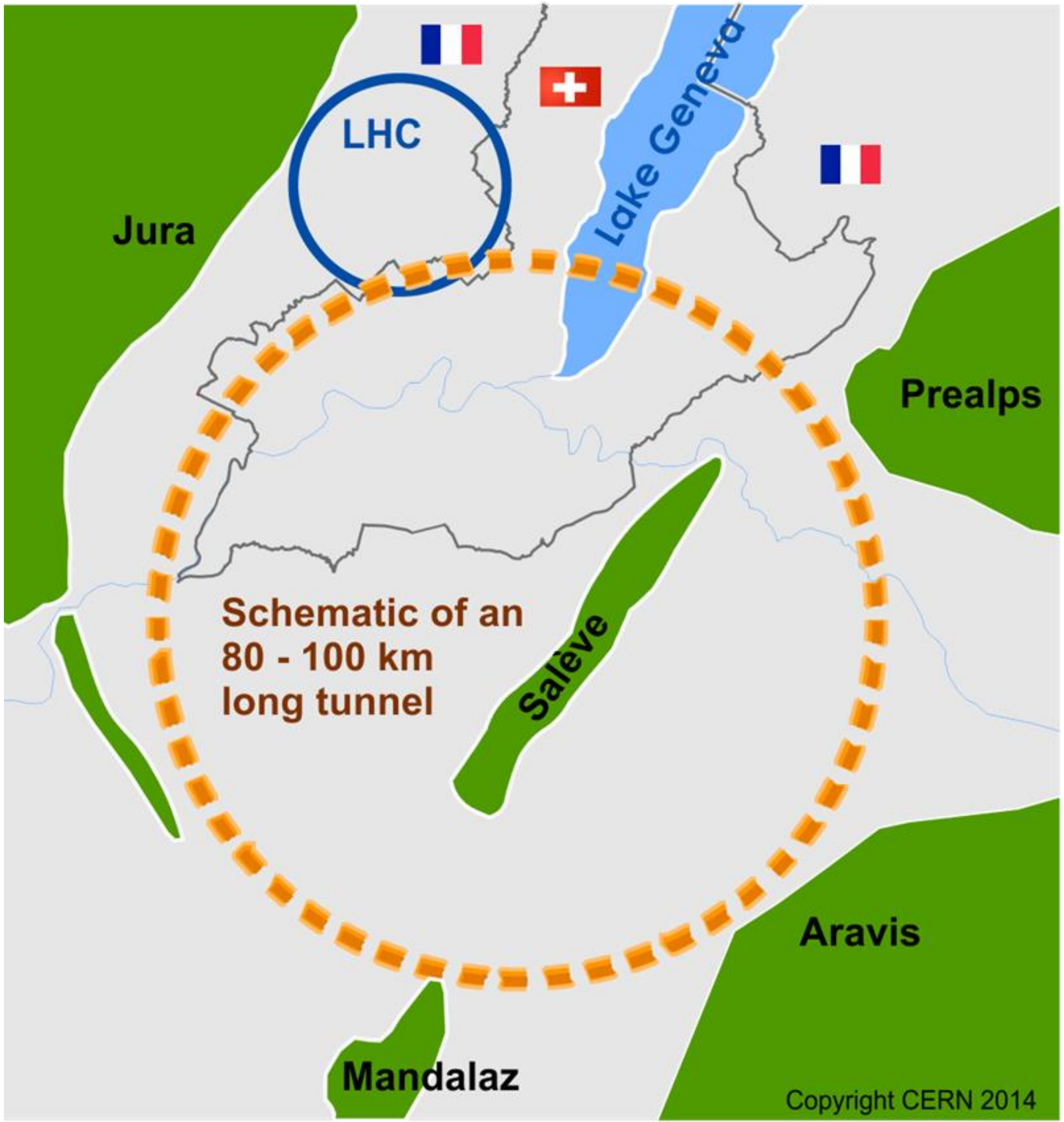
Compensate by increasing radius r?

Need 10 x r to reduce P by 100 → 270km tunnel!

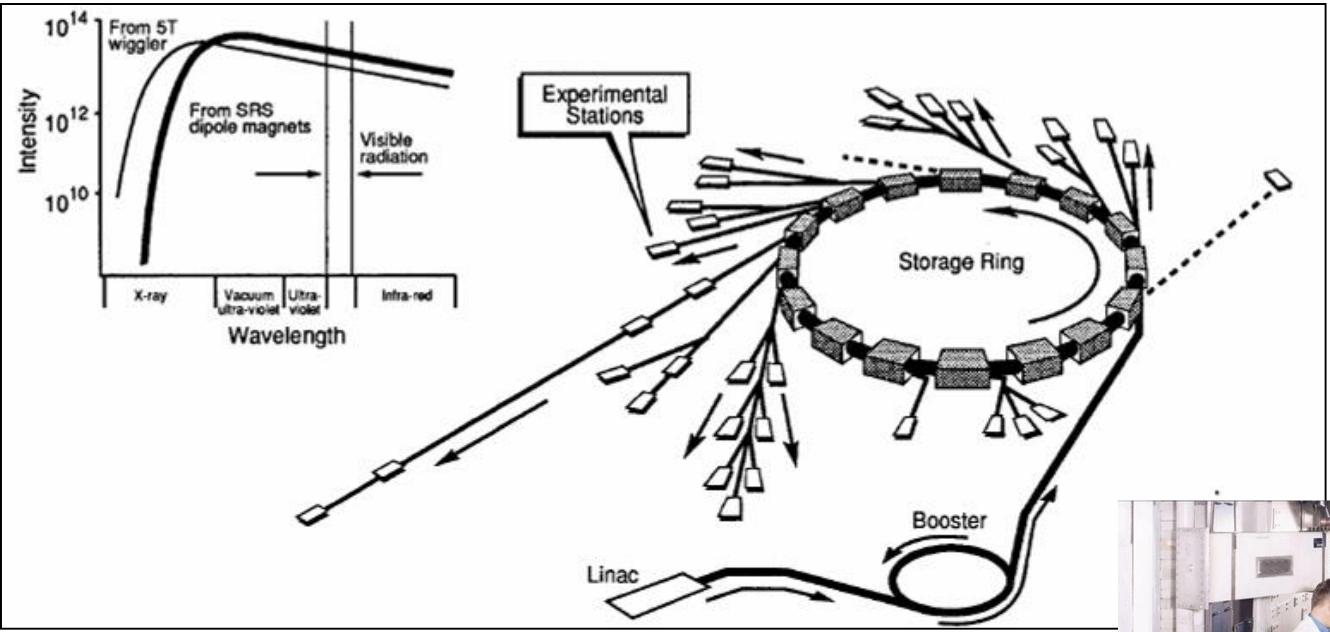
270km tunnel???



Future 100km tunnel???



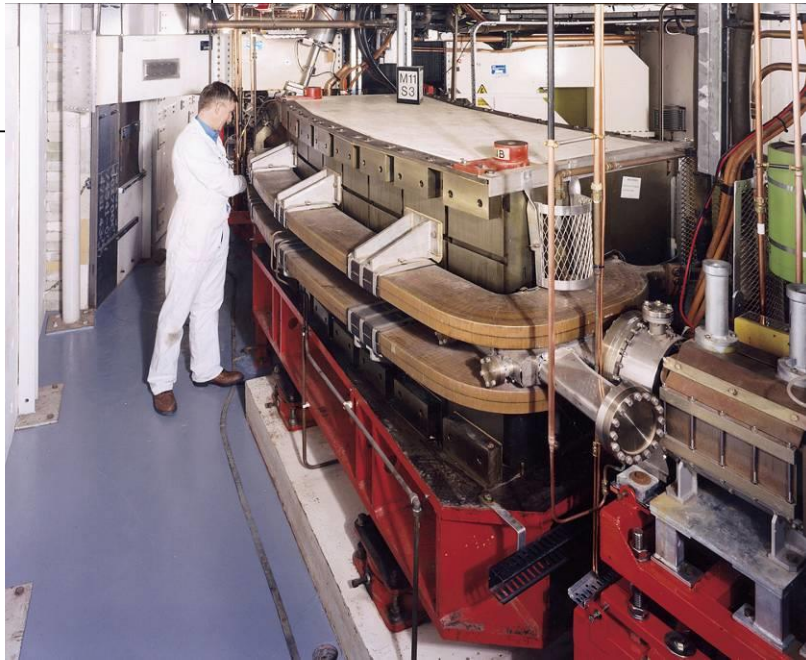
First purpose-built SR source



SRS

Daresbury, UK

1967

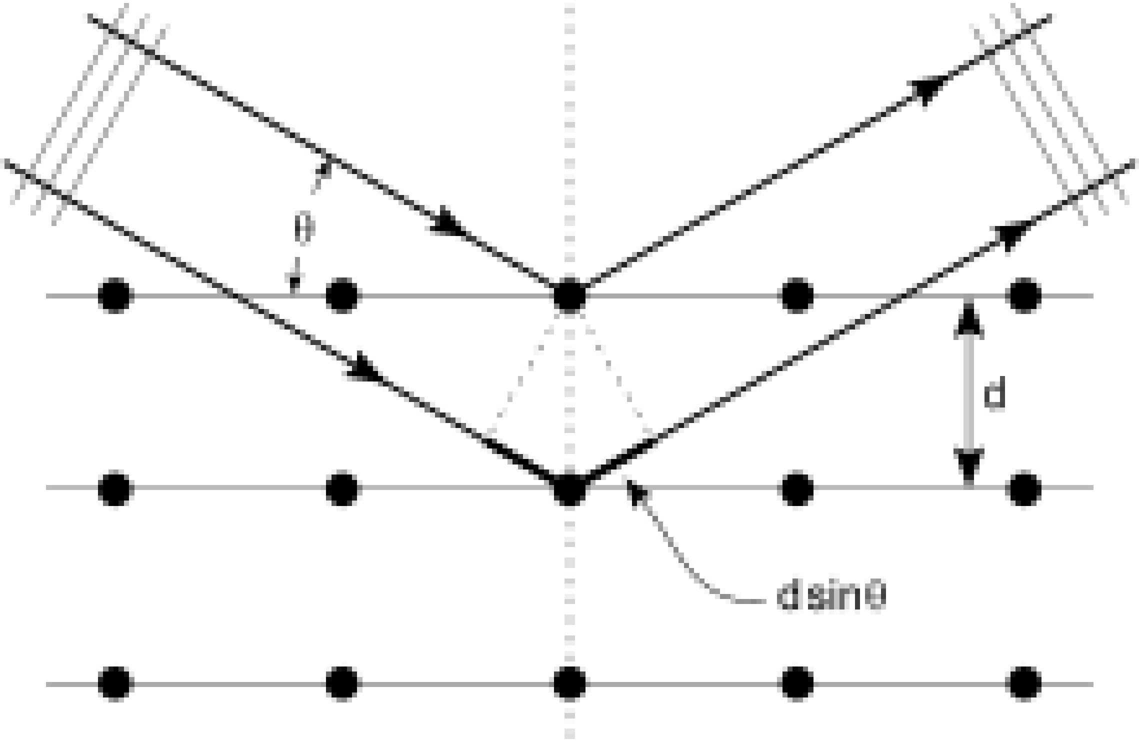


Applications of synchrotron radiation

- **Structures of crystalline materials**
- **Protein structures**
- **Phase transitions**
- **Diffusion in solids**
- **Interfaces in solids**
- **Magnetic properties**
- **Polymers**
- **Defect structures (stress + fatigue)**

… …

X-ray diffraction



Max von Laue

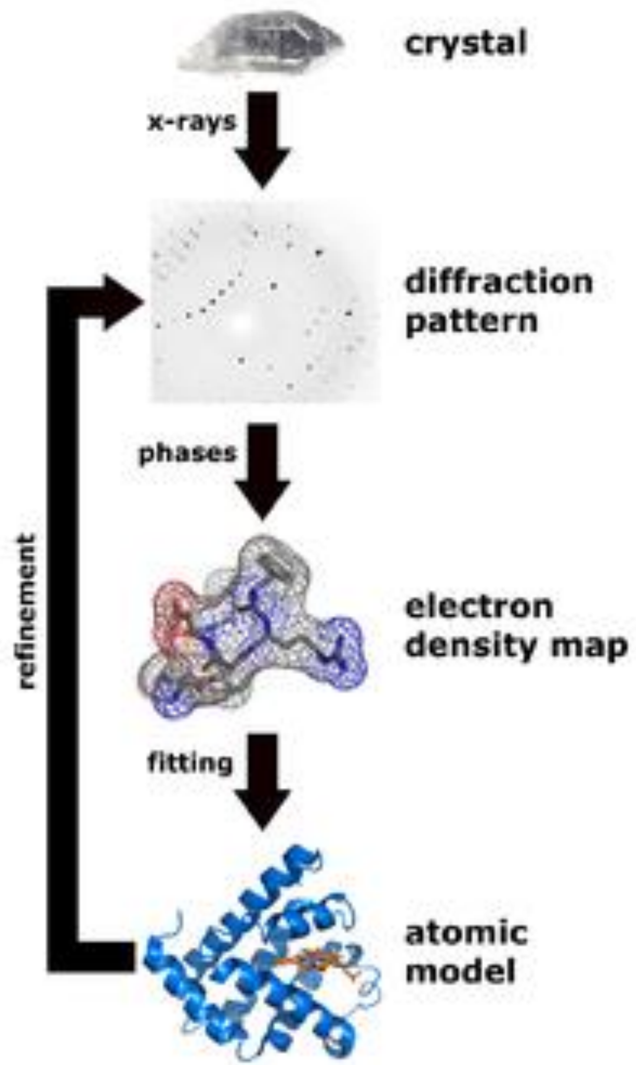
1914 Nobel Prize:

'For his discovery of the diffraction of X-rays by crystals'

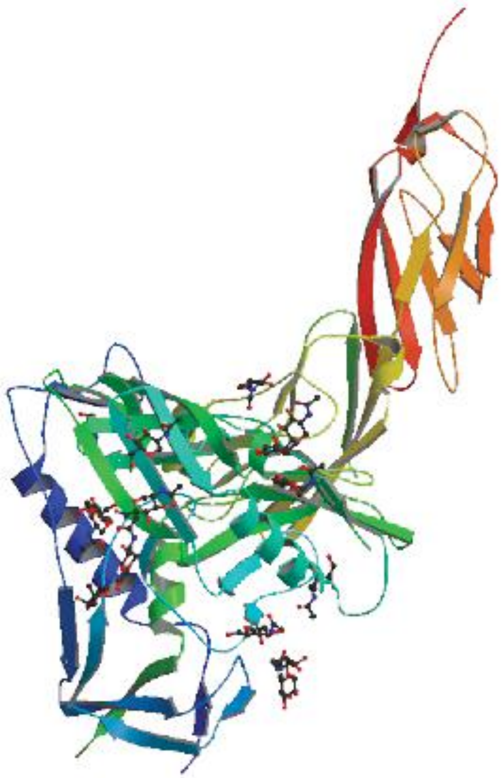
Constructive interference:

$2\,d\,\sin\theta = n\,\lambda$

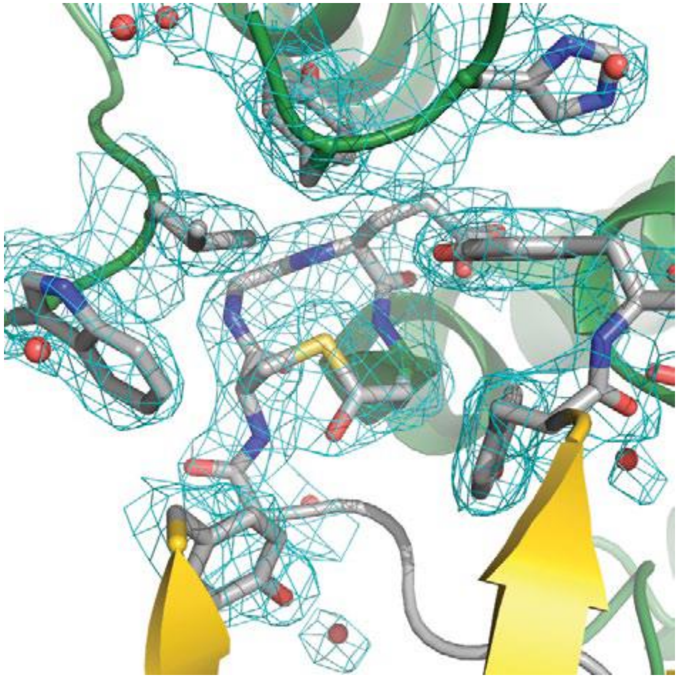
X-ray diffraction today



Protein structures



HIV glycoprotein

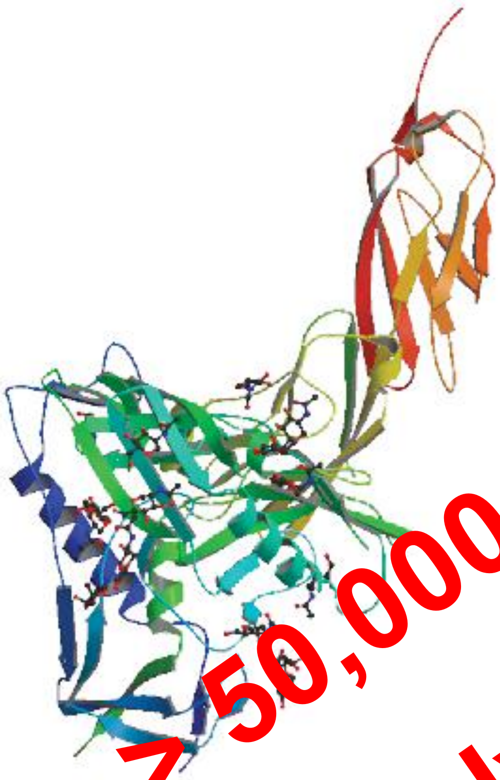


mosquito

immune system

yeast enzyme

Protein structures



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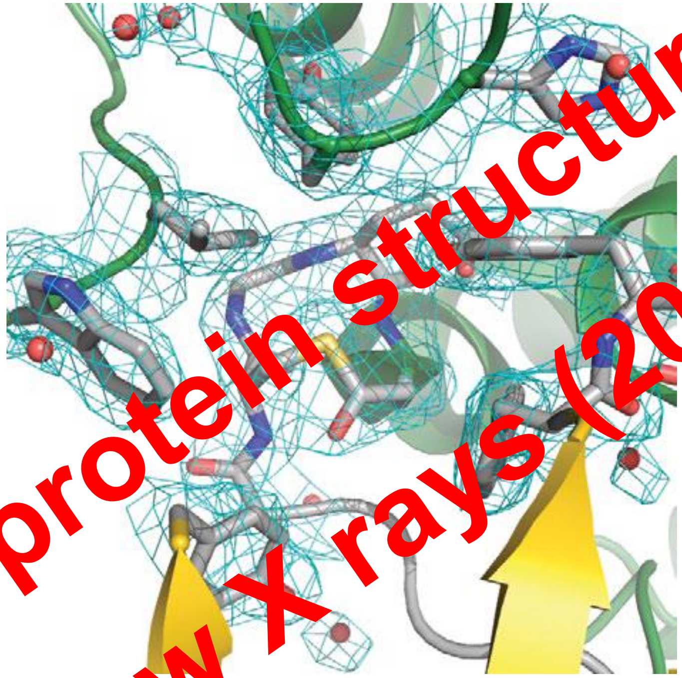
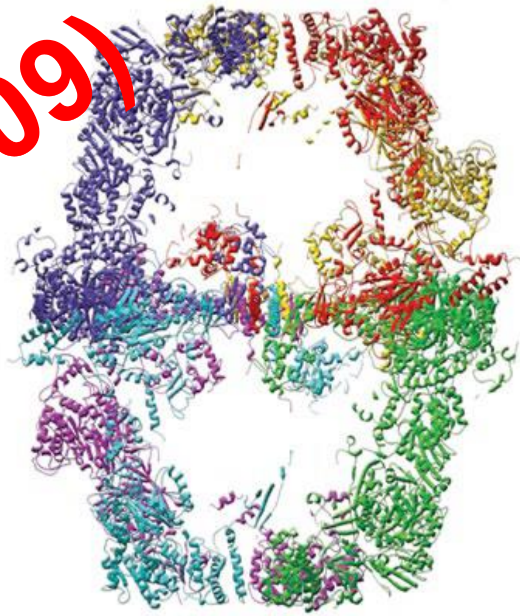


mosquito

immune system



yeast enzyme

> 50,000 protein structures solved w X rays (2009)

Diamond: synchrotron source of X-rays

Nobel Prizes based on X-ray work

19 Nobel Prizes Based on X-ray Work

CHEMISTRY:

1936 – Peter Debye

1962 – Max Perutz & Sir John Kendrew

1964 – Dorothy Hodgkin

1976 – William Lipscomb

1985 – Herbert Hauptman & Jerome Karle

1988 – Johann Deisenhofer, Robert Huber & Hartmut Michel*

1997 – Paul D. Boyer & John E. Walker*

2003 – Peter Agre & Roderick Mackinnon*

2006 – Roger Kornberg*

PHYSICS:

1901 – Wilhelm Röntgen

1914 – Max Von Laue

1915 – Sir William Henry Bragg & Sir William Lawrence Bragg

1917 – Charles Barkla

1924 – Karl Manne Siegbahn

1927 – Arthur Compton

1981 – Kai Siegbahn

MEDICINE:

1946 – Hermann Joseph Muller

1962 – Francis Crick, James Watson & Maurice Wilkins

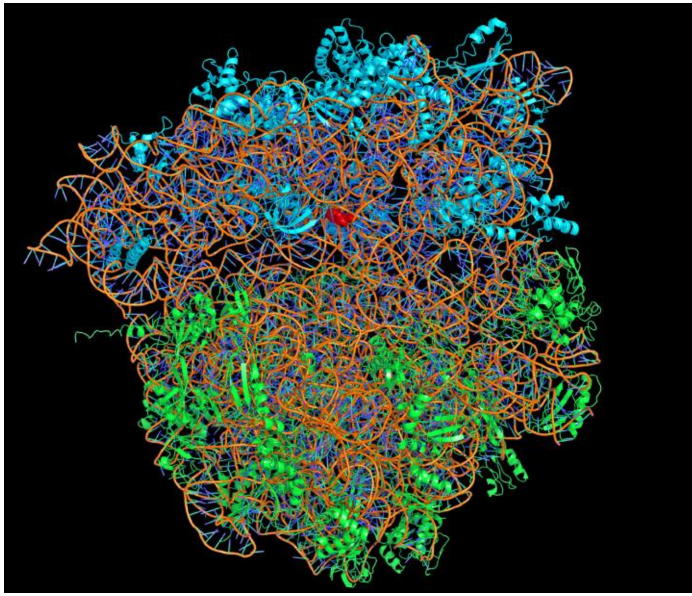
1979 – Alan M. Cormack & Sir Godfrey N. Hounsfield

* Used SYNCHROTRON RADIATION

2009 Chemistry Nobel Prize

Ramakrishnan, Steitz, Yonath

‘studies of the structure and function of the ribosome’



Synchrotron radiation: LHC?

Why isn't this a problem for LHC?

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$$P \sim (E/m)^4 \; / \; r^2$$

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m_proton ~ 2000 * m_electron

P_proton ~ 2000^{-4} * P_electron

Synchrotron radiation: LHC?

Why isn't this a problem for LHC?

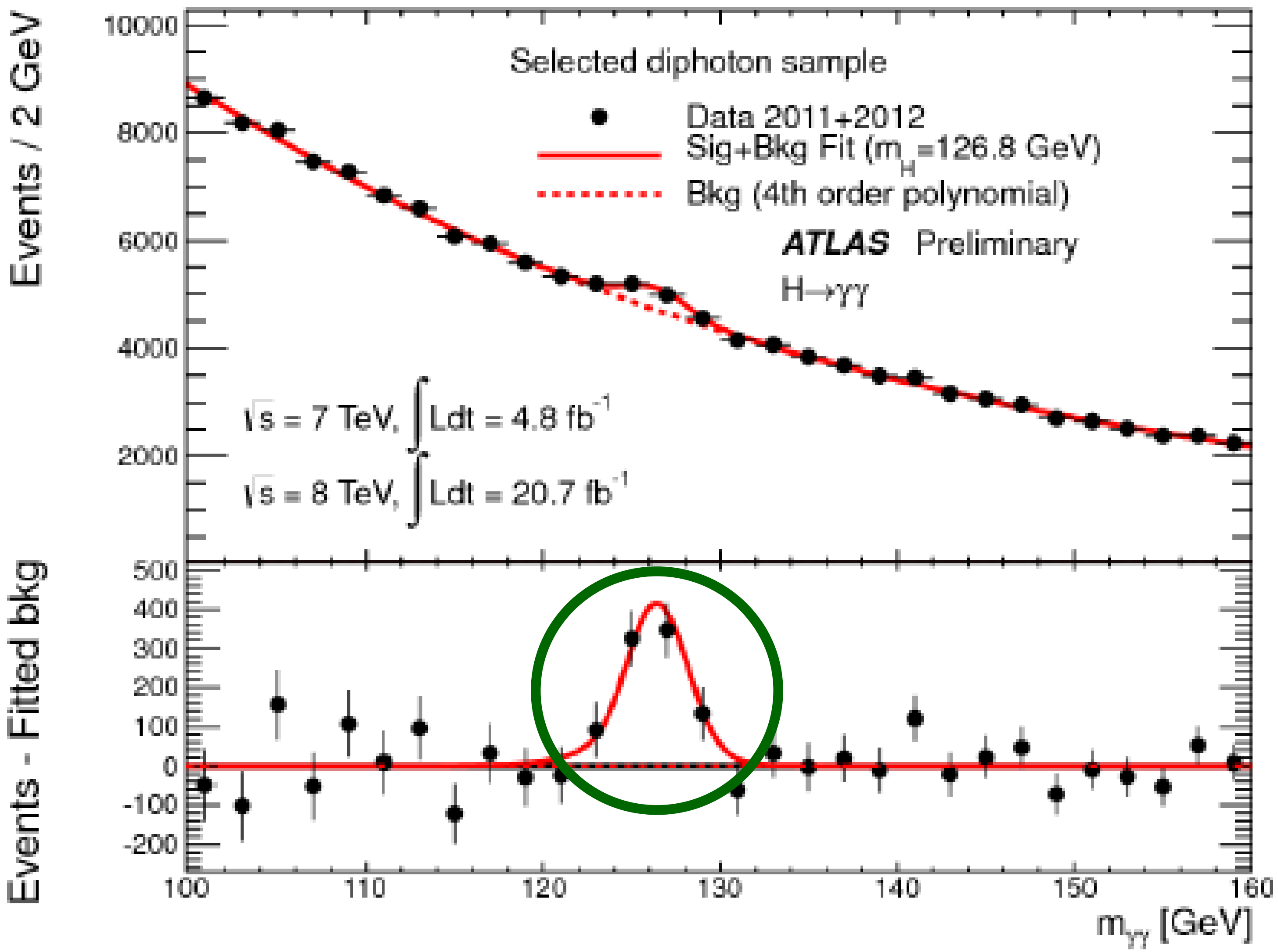
$P \sim (E / m)^4 \; / \; r^2$

m_proton ~ 2000 * m_electron

P_proton ~ 2000^{-4} * P_electron

Even for LHC, E = 70 * LEP, each proton loses only
5 keV per turn (0.000 000 1% negligible!)

The new boson



Finger-printing the new boson

Is it:

The Standard Model Higgs boson?

Another type of Higgs boson?

Not a Higgs boson at all?

Finger-printing the new boson

Determine its 'profile':

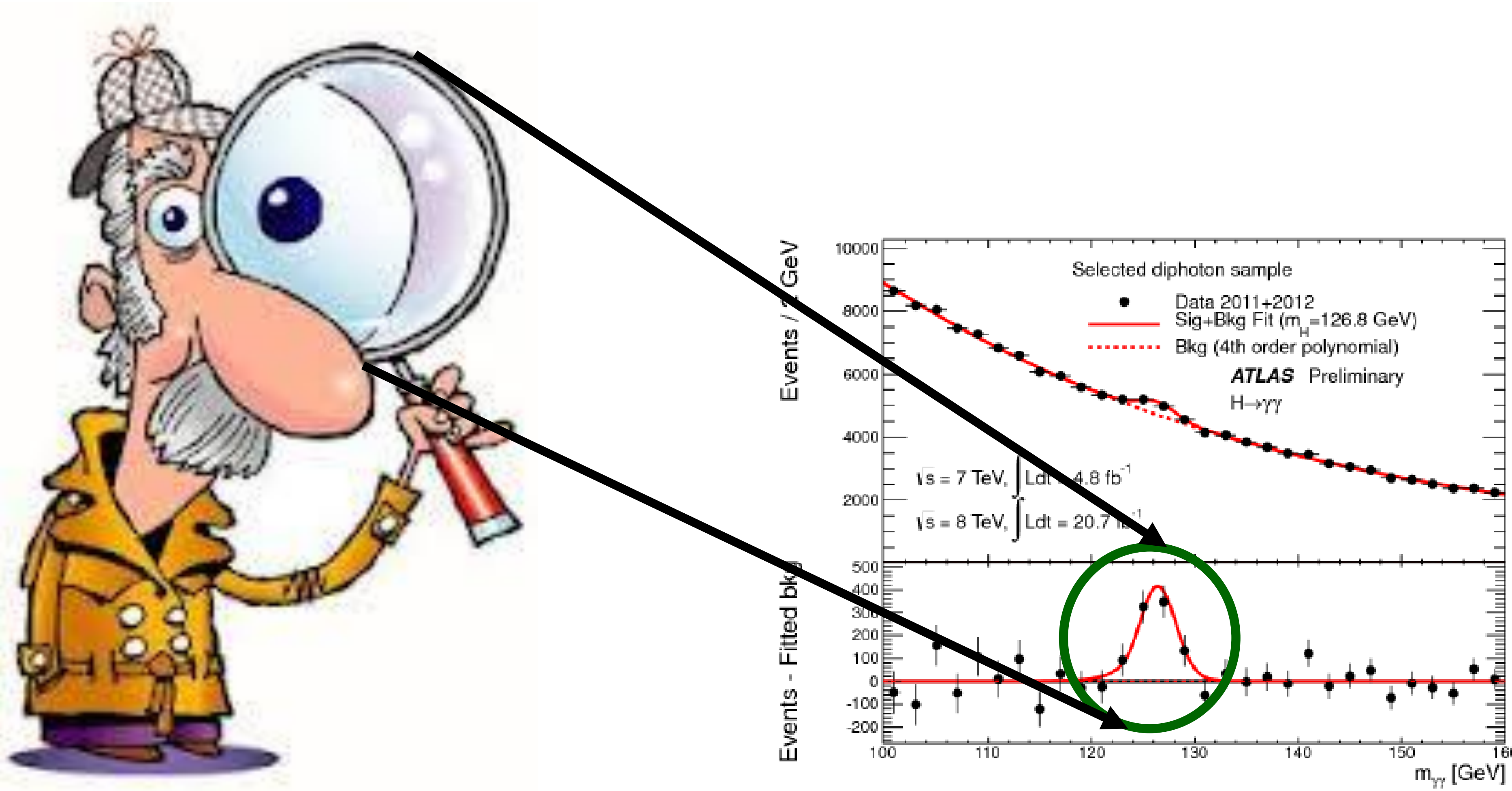
- **Mass**
- **Width**
- **Spin**
- **CP nature**
- **Coupling to fermions (quarks + leptons)**
- **Coupling to gauge bosons (W + Z)**
- **Yukawa coupling to top quark**
- **Self coupling → Higgs potential**

Finger-printing the new boson

The LHC has started this endeavour!

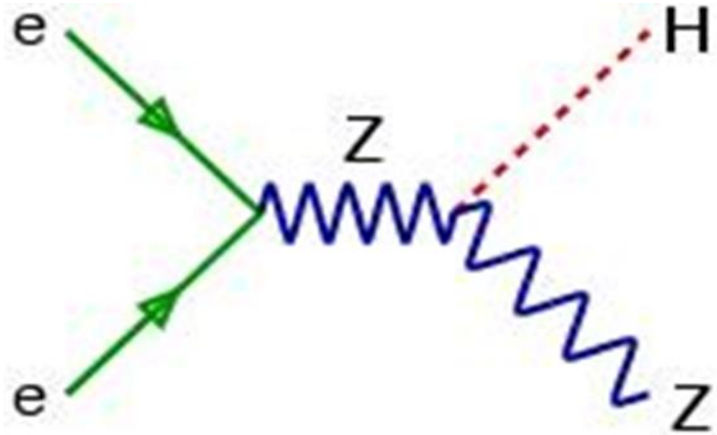
and next ….

Microscope on the new boson



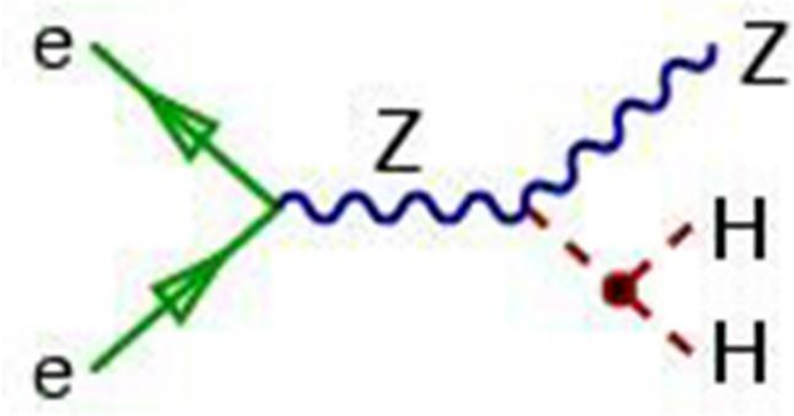
Higgs Factory

e+e- annihilations:



E > 91 + 125 = 216 GeV

E ~ 250 GeV



E > 91 + 250 = 341 GeV

E ~ 350 - 500 GeV

e+e- colliders

- Produce annihilations of point-like particles under controlled conditions:

e+e- colliders

- **Produce annihilations of point-like particles under controlled conditions:**

well defined centre of mass energy: 2E

e+e- colliders

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complete control of event kinematics:

p = 0, M = 2E

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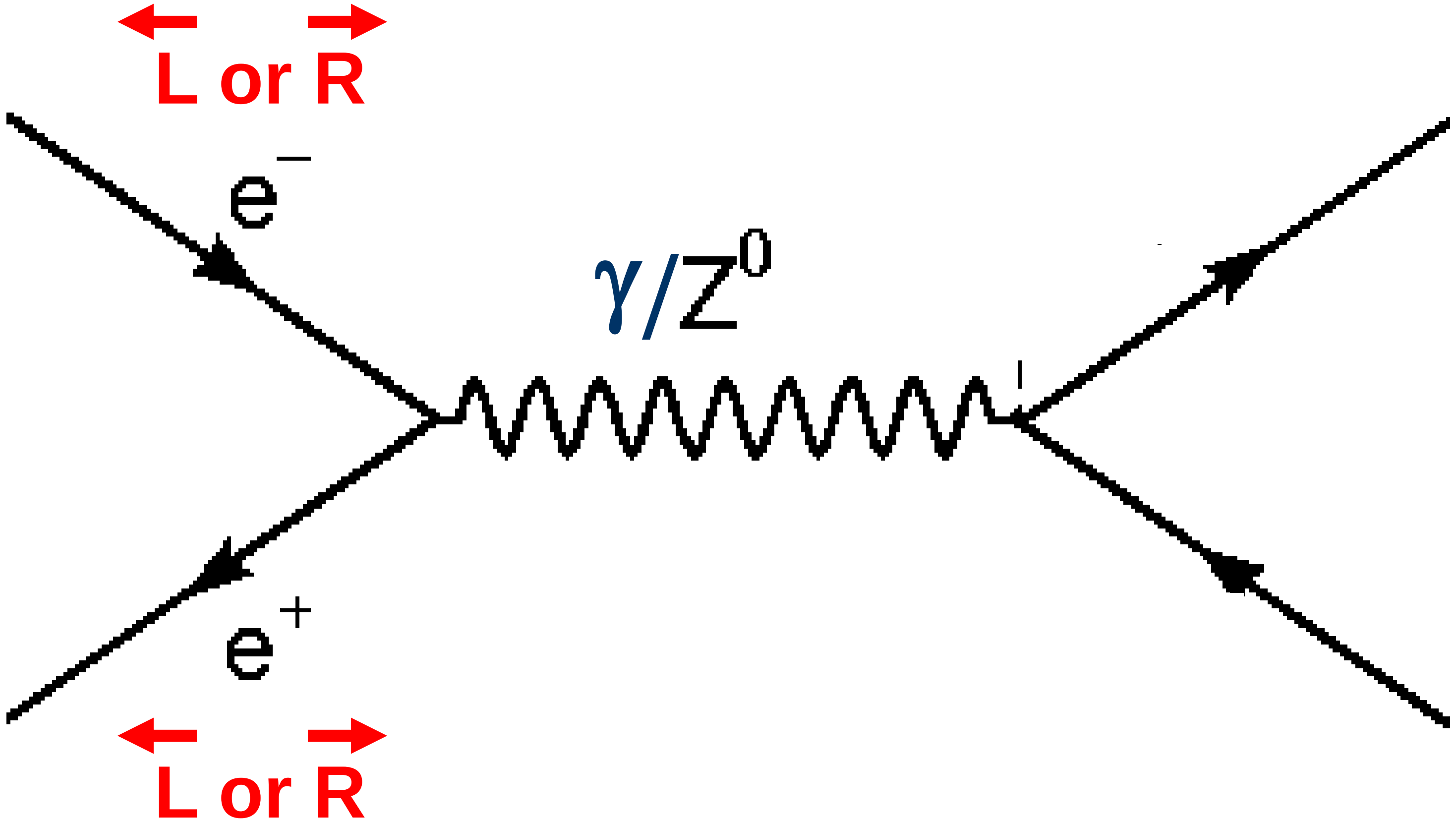
polarised beam(s)

e+e- annihilations



e+e- colliders

- **Produce annihilations of point-like particles under controlled conditions:**

well defined centre of mass energy: 2E

complete control of event kinematics:

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polarised beam(s)

clean experimental environment

e+e- colliders

- **Produce annihilations of point-like particles under controlled conditions:**

  well defined centre of mass energy: 2E

  complete control of event kinematics: p = 0, M = 2E

  polarised beam(s)

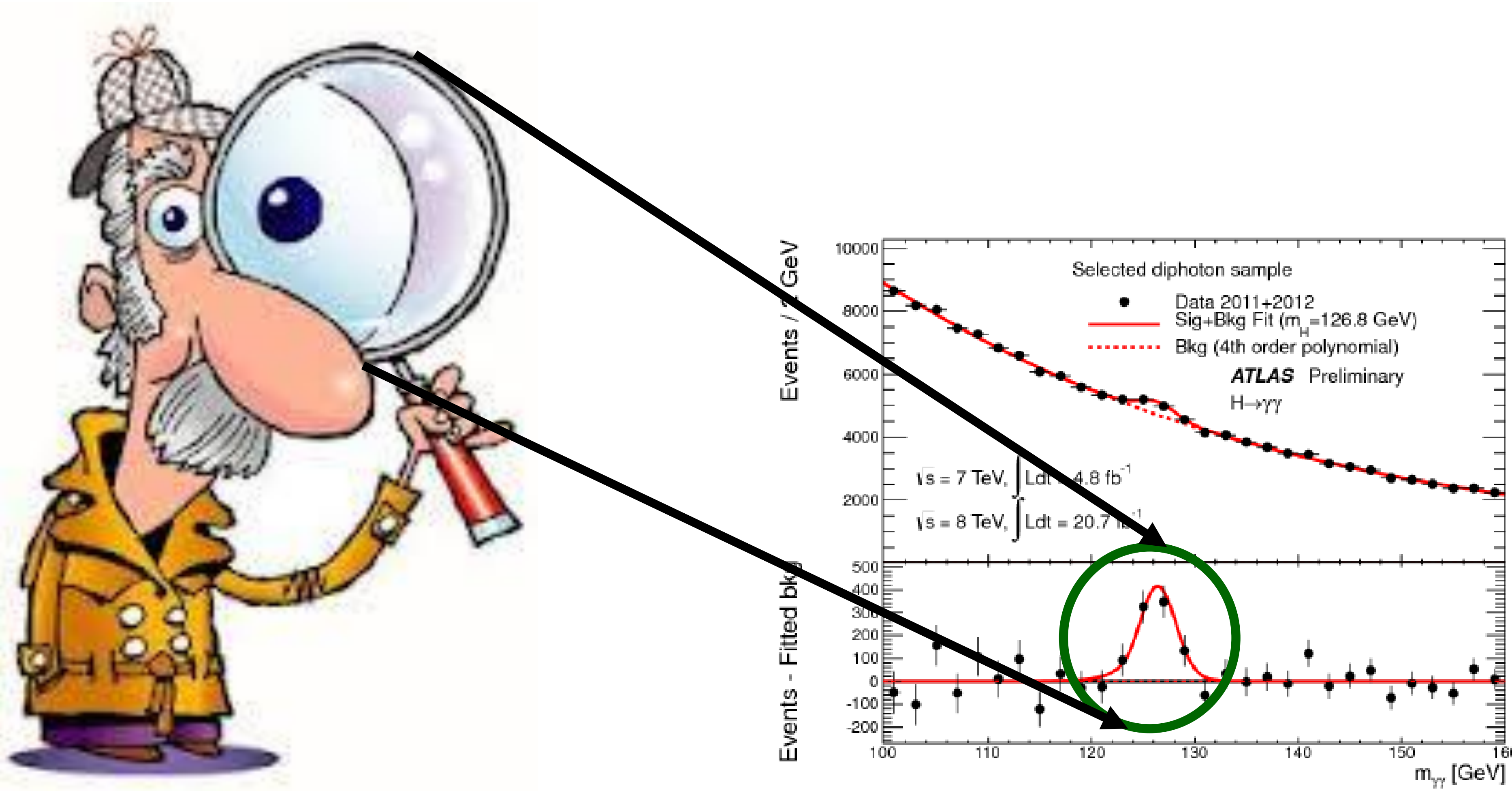
  clean experimental environment

- **Give us a precision microscope:**

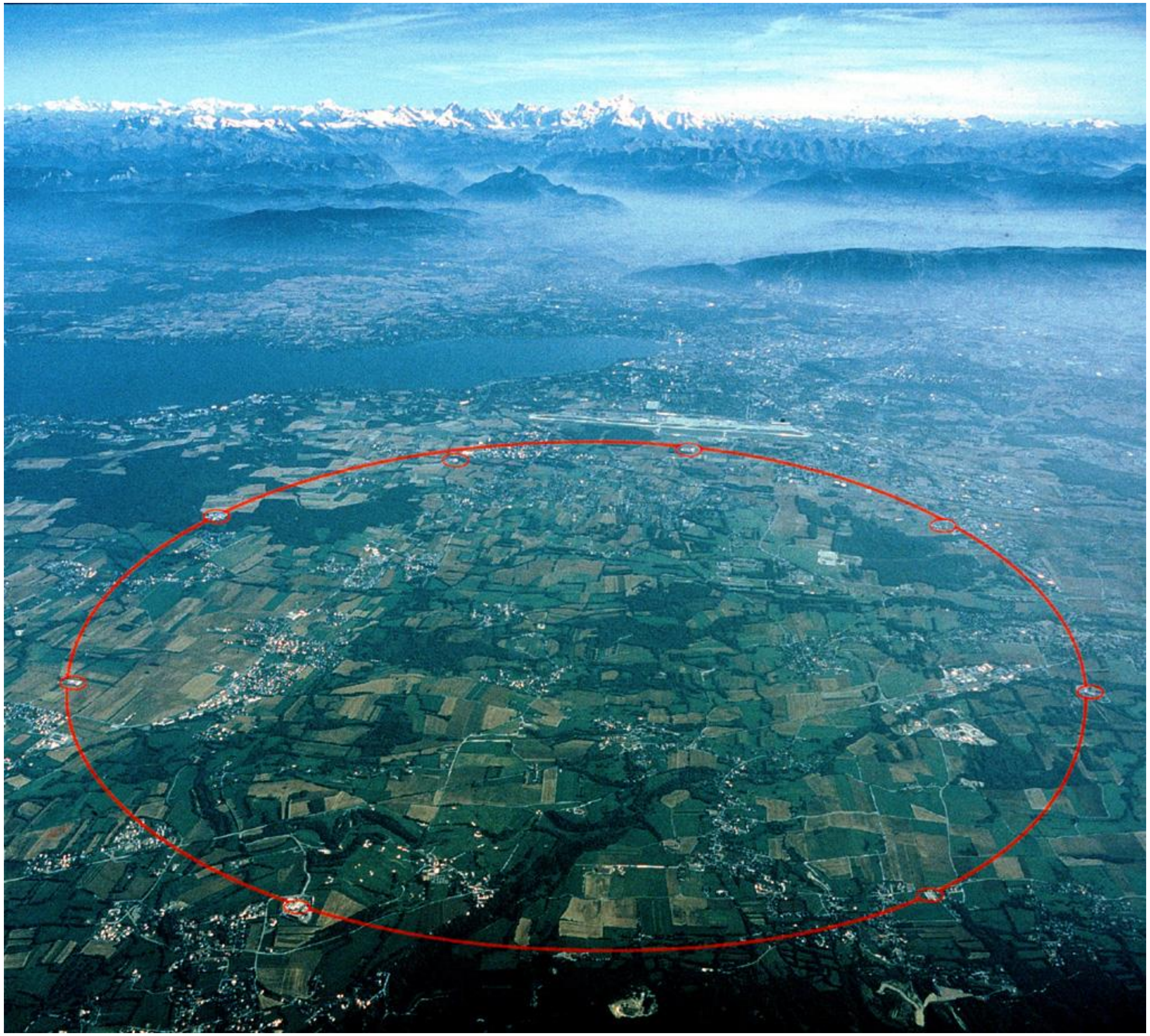
  masses, decay-modes, couplings, spins,

  CP properties … of new particles

Microscope on the new boson



Super Large Electron Positron collider?



250 GeV

beams?

(2.5 x LEP)

Synchrotron

radiation → 700 MW

Super Large Electron Positron collider?

250 GeV beams?

(2.5 x LEP)

Synchrotron radiation → 700 MW

High energy electron-positron colliders

The path ahead is …

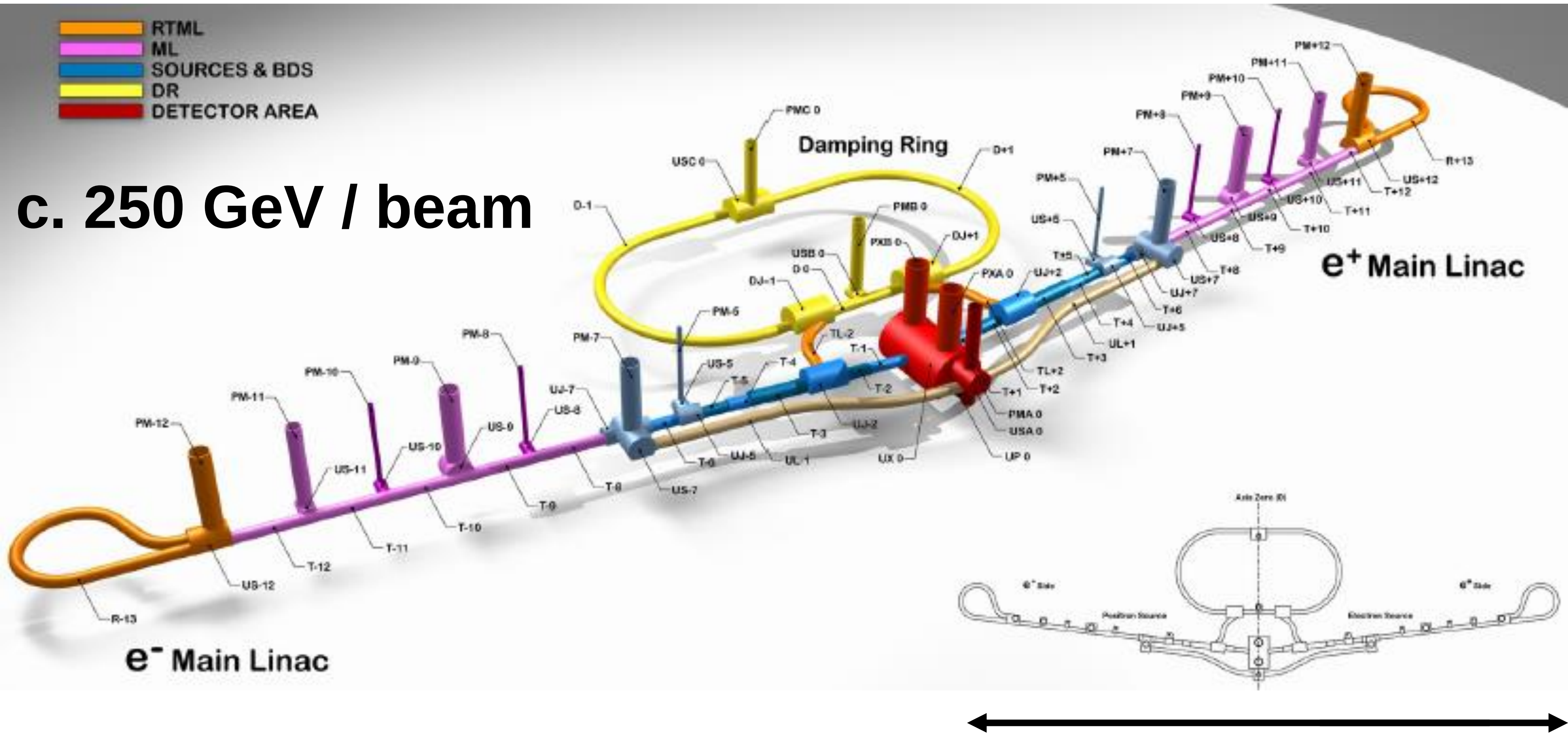
linear

SLAC Linear Collider

c. 50 GeV

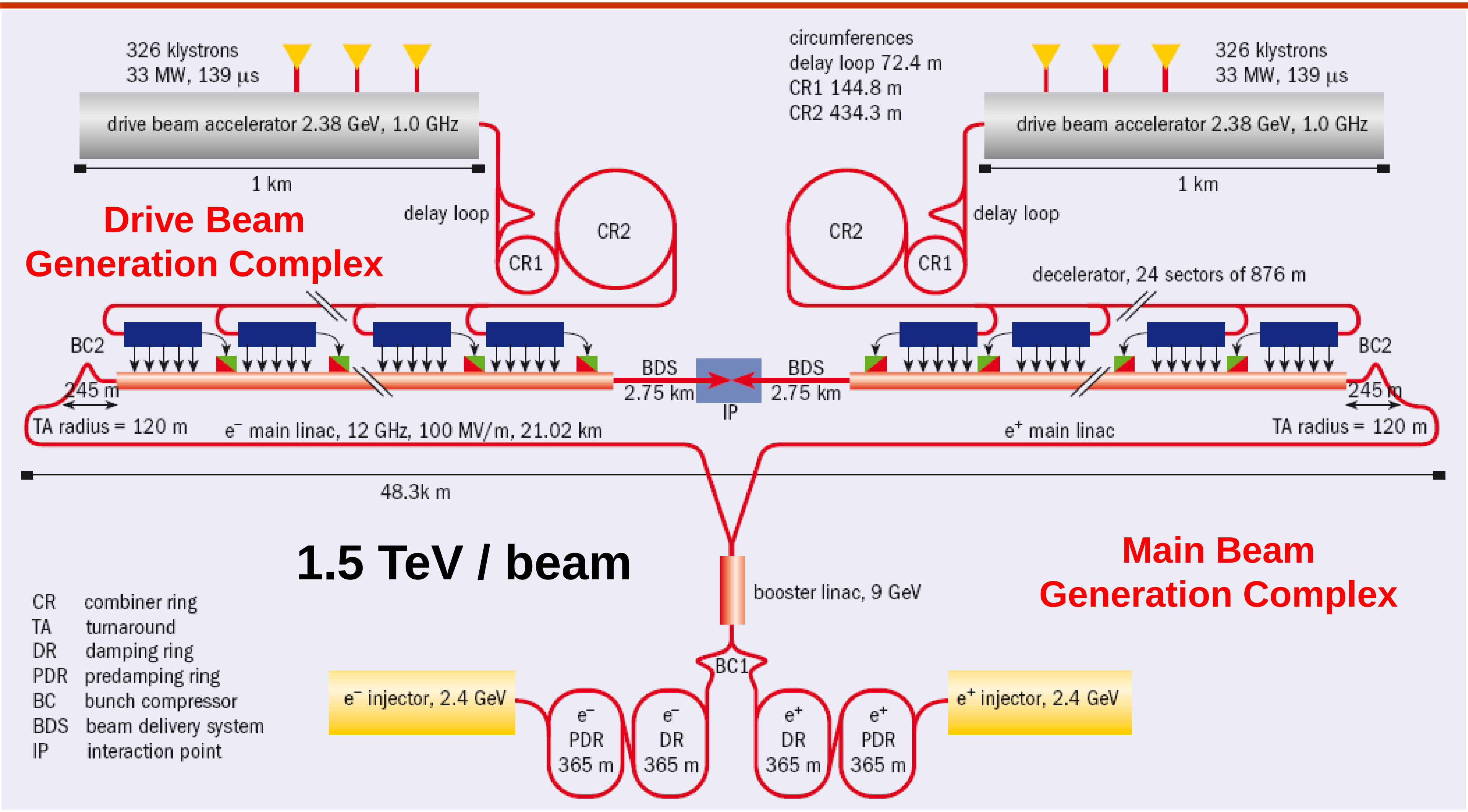
per beam

International Linear Collider (ILC)



31 km

Compact Linear Collider (CLIC)



Ingredients for a linear collider

	ILC 500 GeV	
Electrons/bunch	2	10^{10}
Bunches/train	1312	
Bunch separation	544	ns
Train length	727	us
Train repetition rate	4	Hz
Horizontal IP beam size	474	nm
Vertical IP beam size	6	nm
Luminosity	2	10^{34} /cm ^{2} /s

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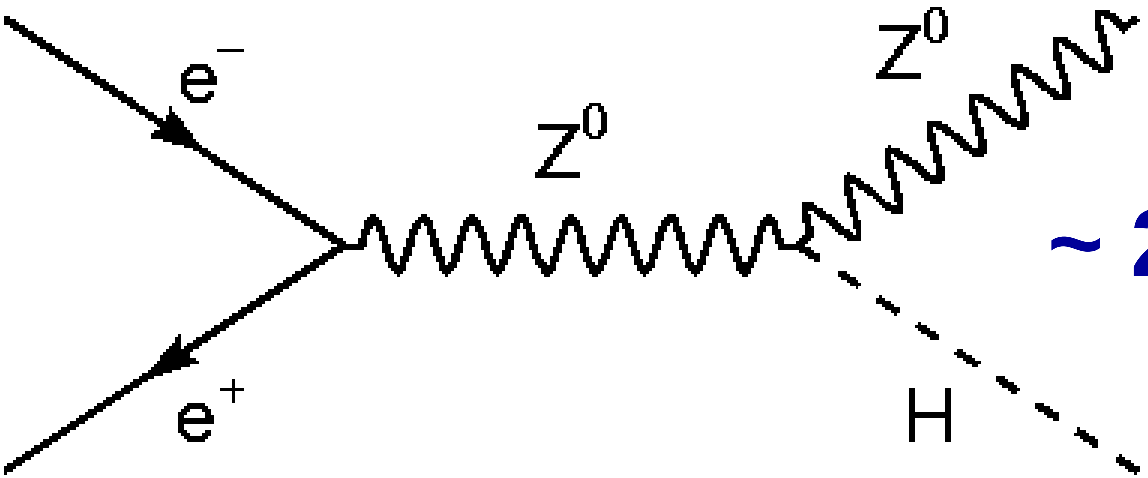
Like firing bullets to hit in middle …

electrons

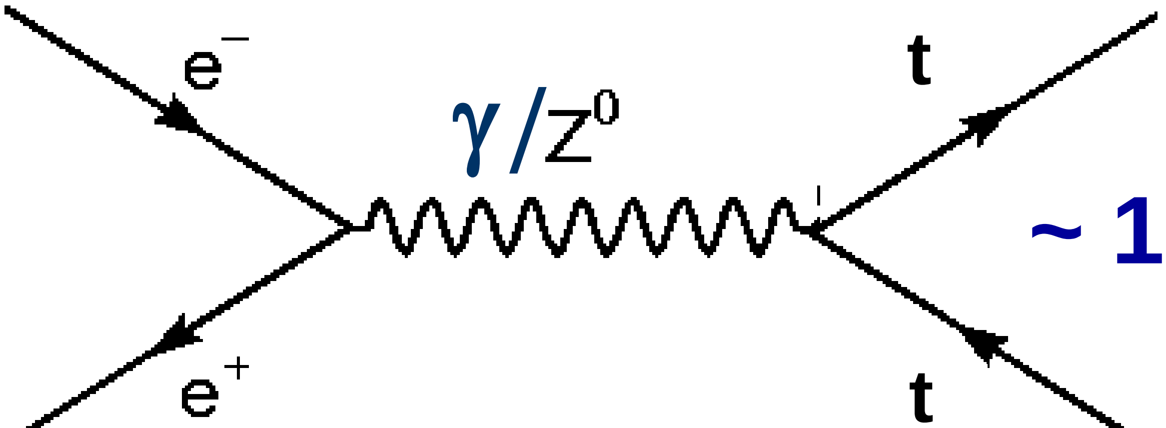
positrons

Except that …

A Higgs and top factory



~ 20,000 H / year



~ 100,000 t / year

European particle physics strategy 2013

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

European particle physics strategy 2013

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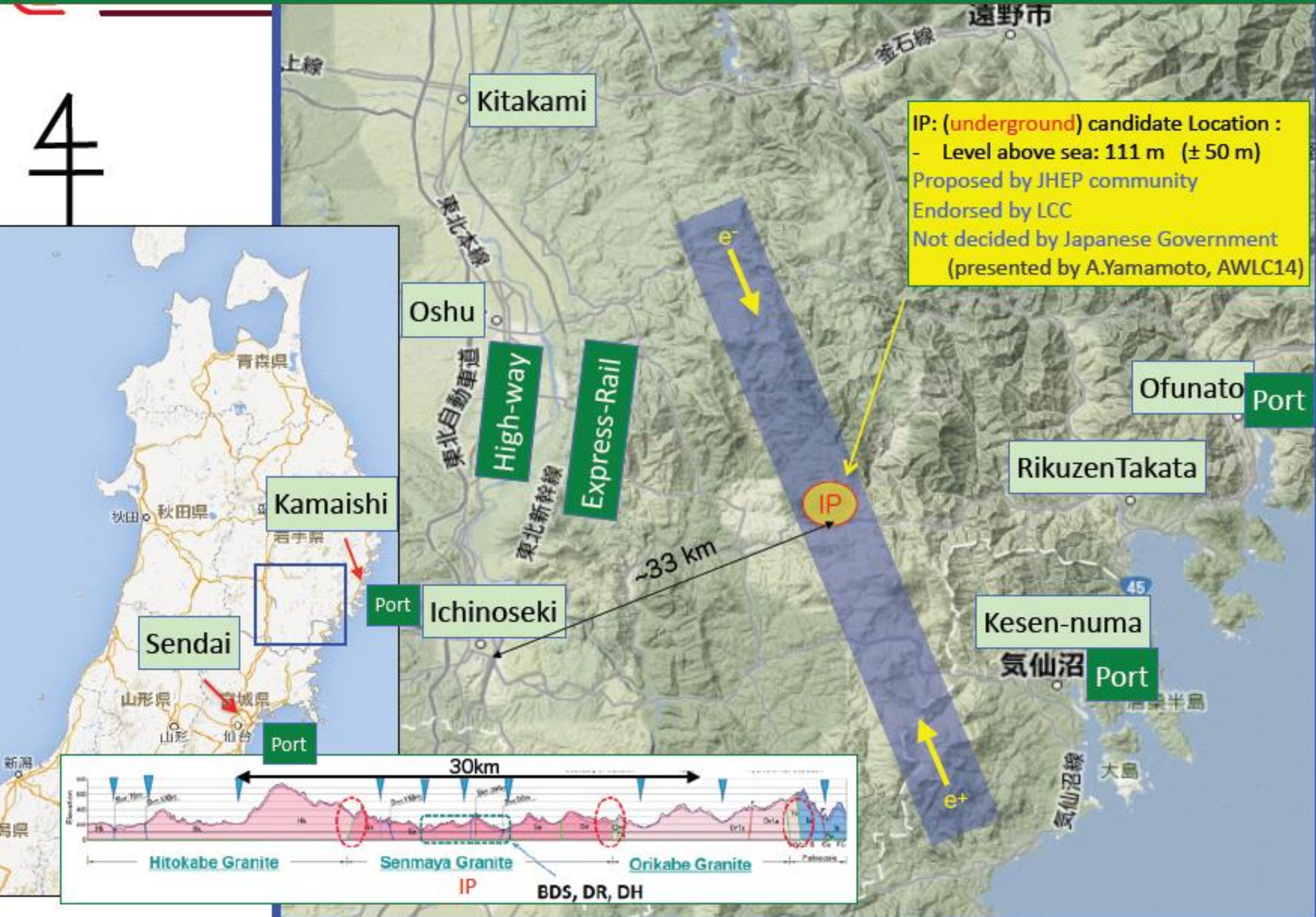
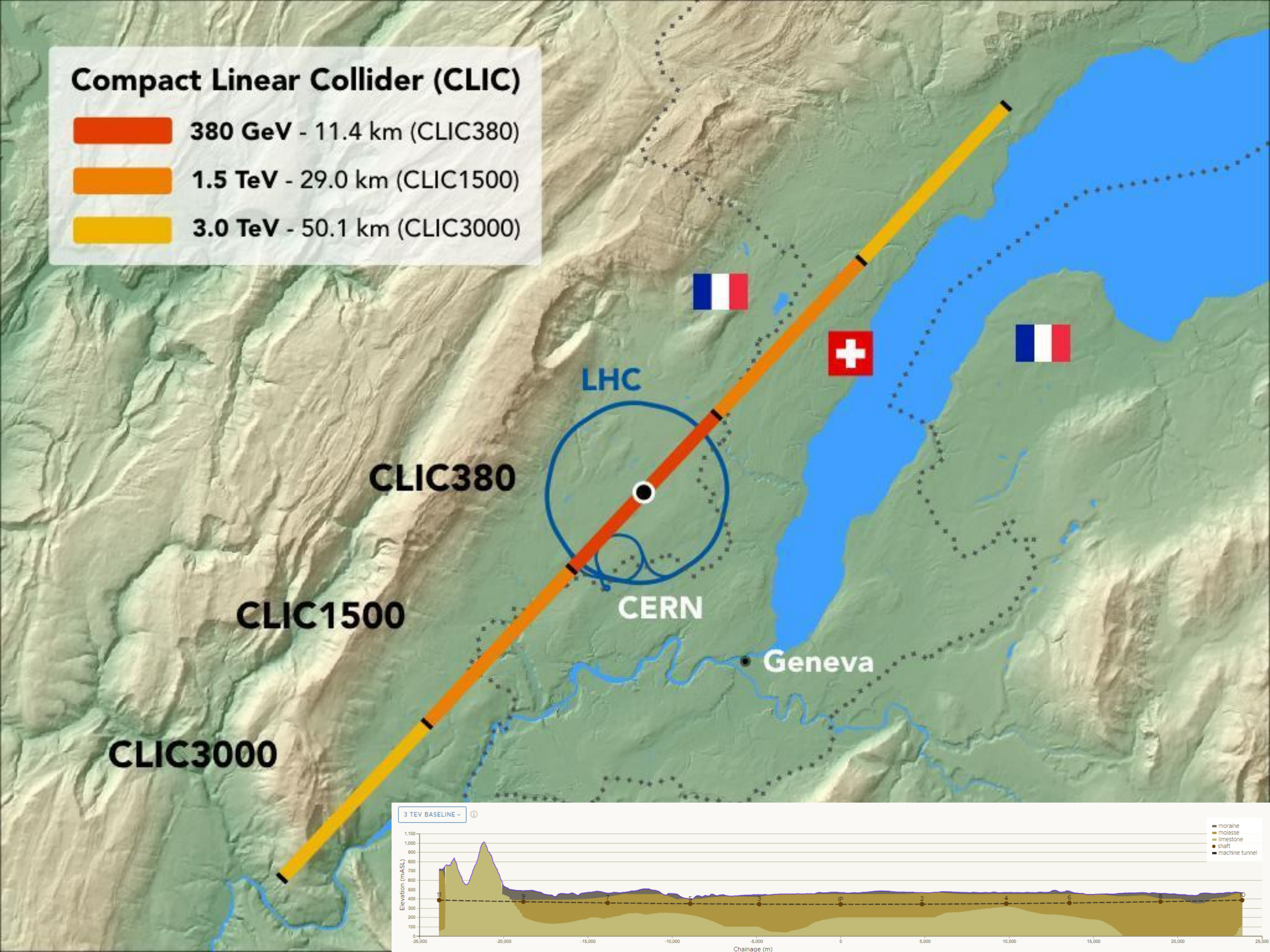
Europe looks forward to a proposal from Japan to discuss a possible participation.

ILC Candidate Location: Kitakami Area




Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)
11
9
7
5
3
IP
2
4
6
8
10

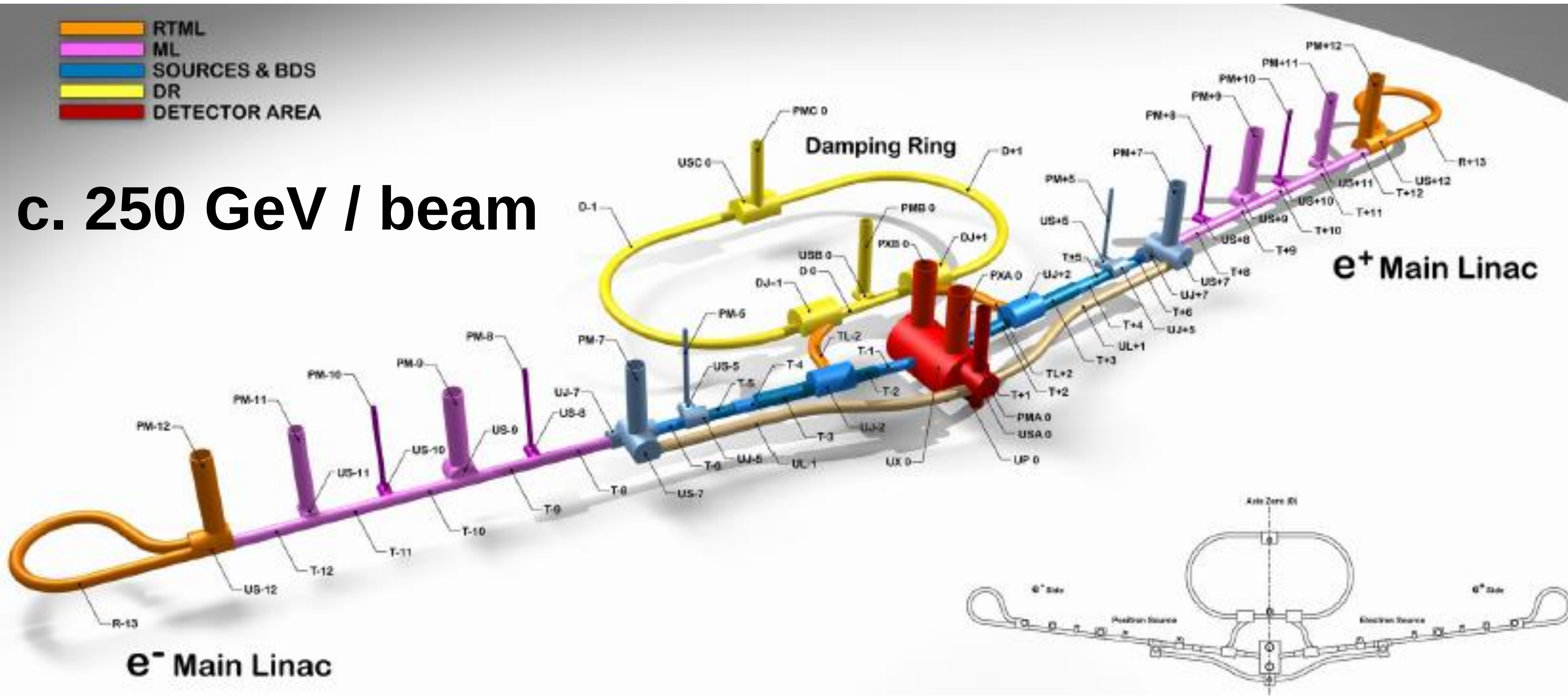
The future ?

SLAC Linear Collider

c. 50 GeV

per beam

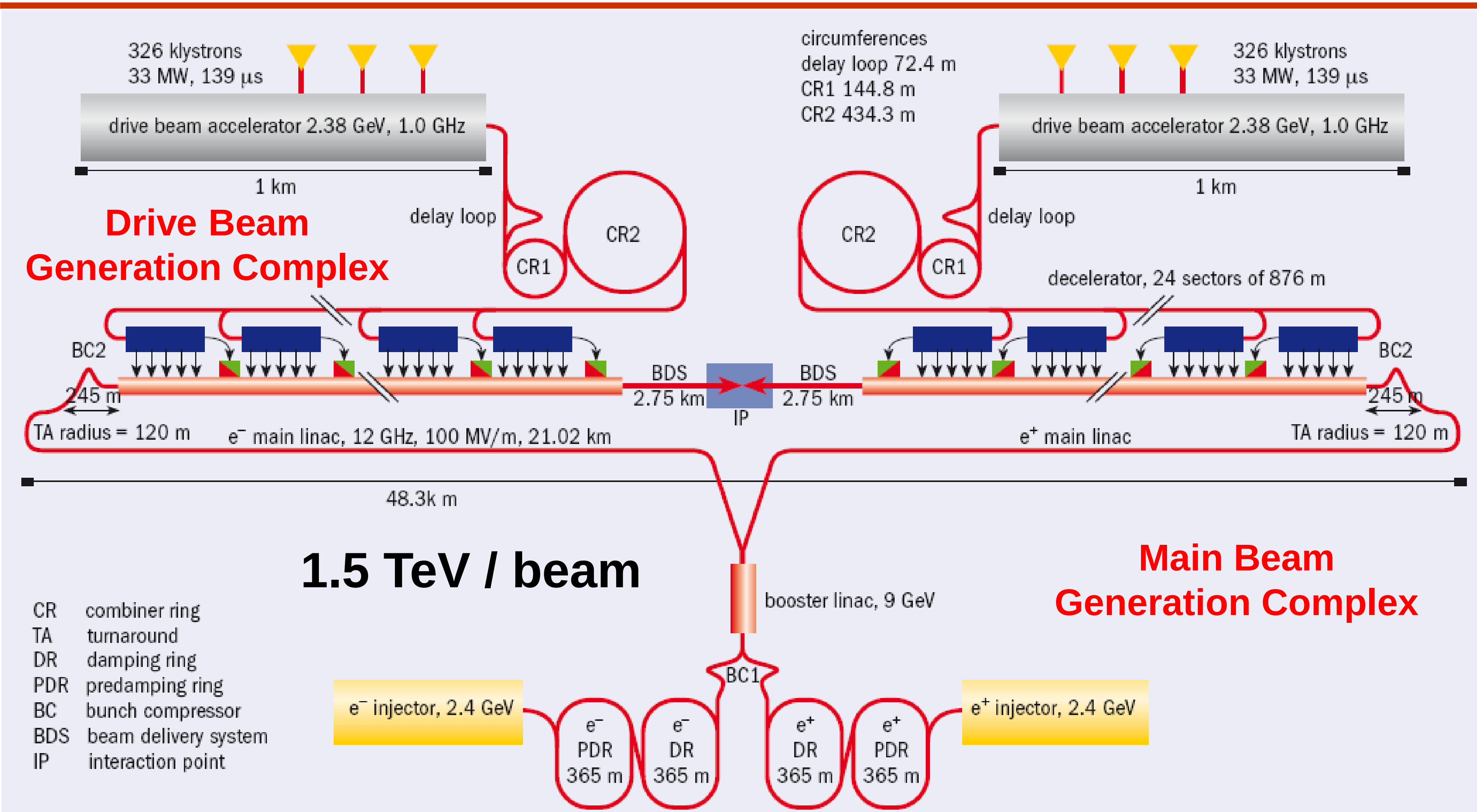
International Linear Collider (ILC)



c. 250 GeV / beam

31 km

Compact Linear Collider (CLIC)



CLIC Collaboration January 2019