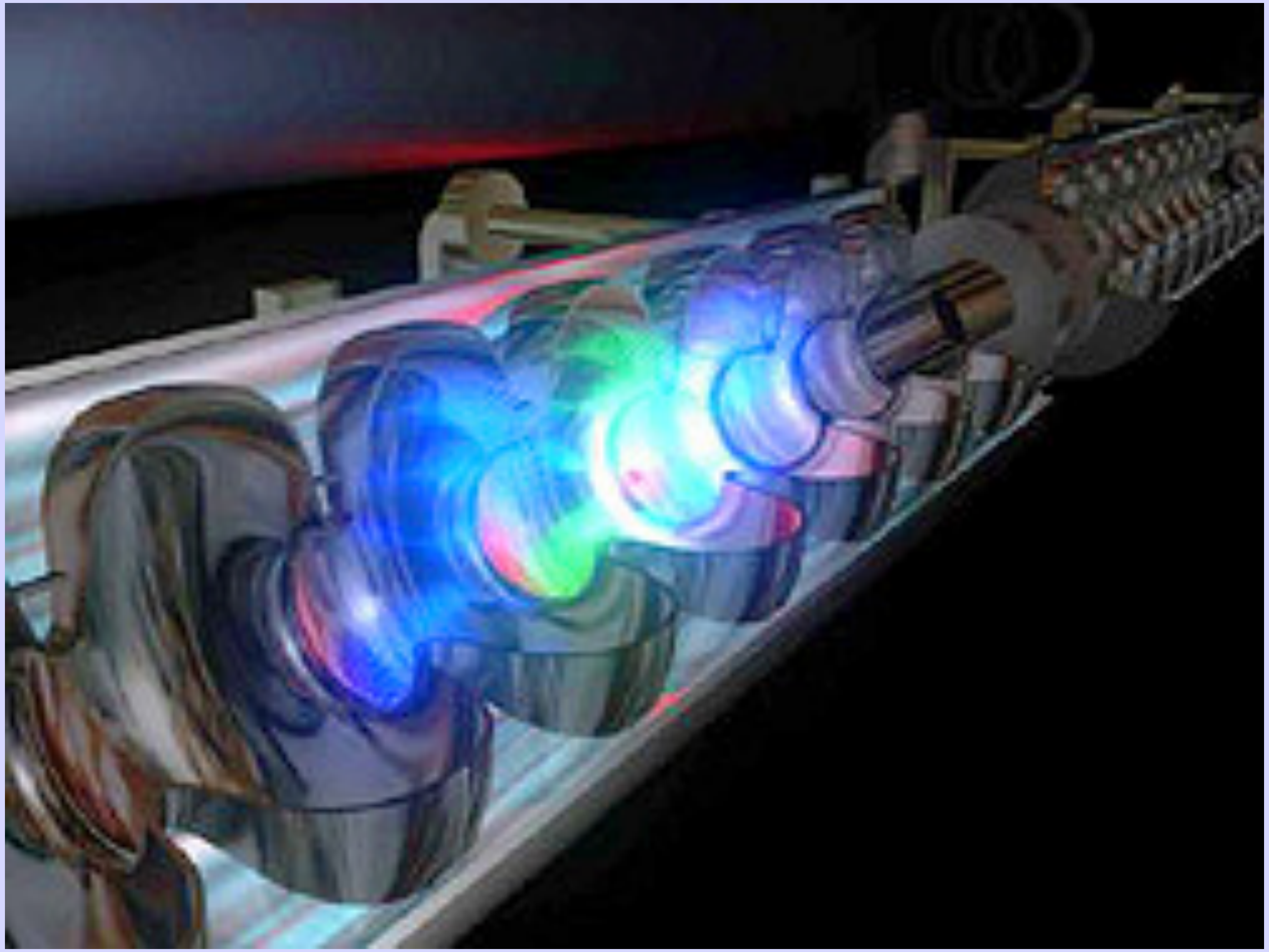
The International Linear Collider and Future of Particle Accelerators

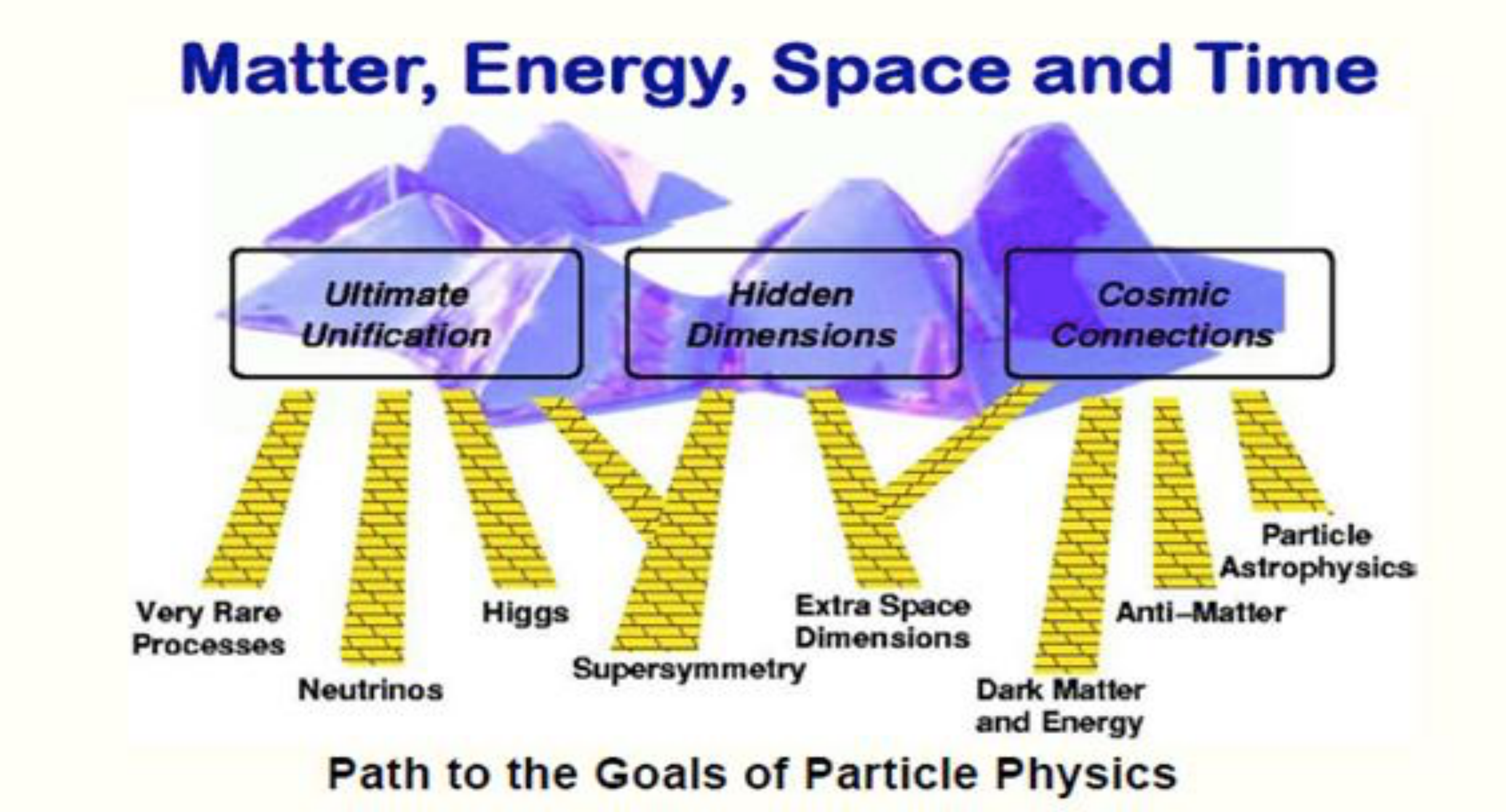


Barry Barish

Caltech

3-June-2016

What is Particle Physics?



Today's biggest question

What's beyond the Standard Model?

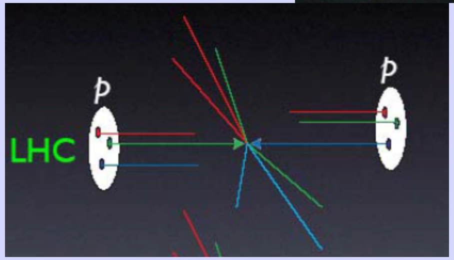
1. Are there undiscovered principles of nature:
   New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

from the Quantum Universe

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

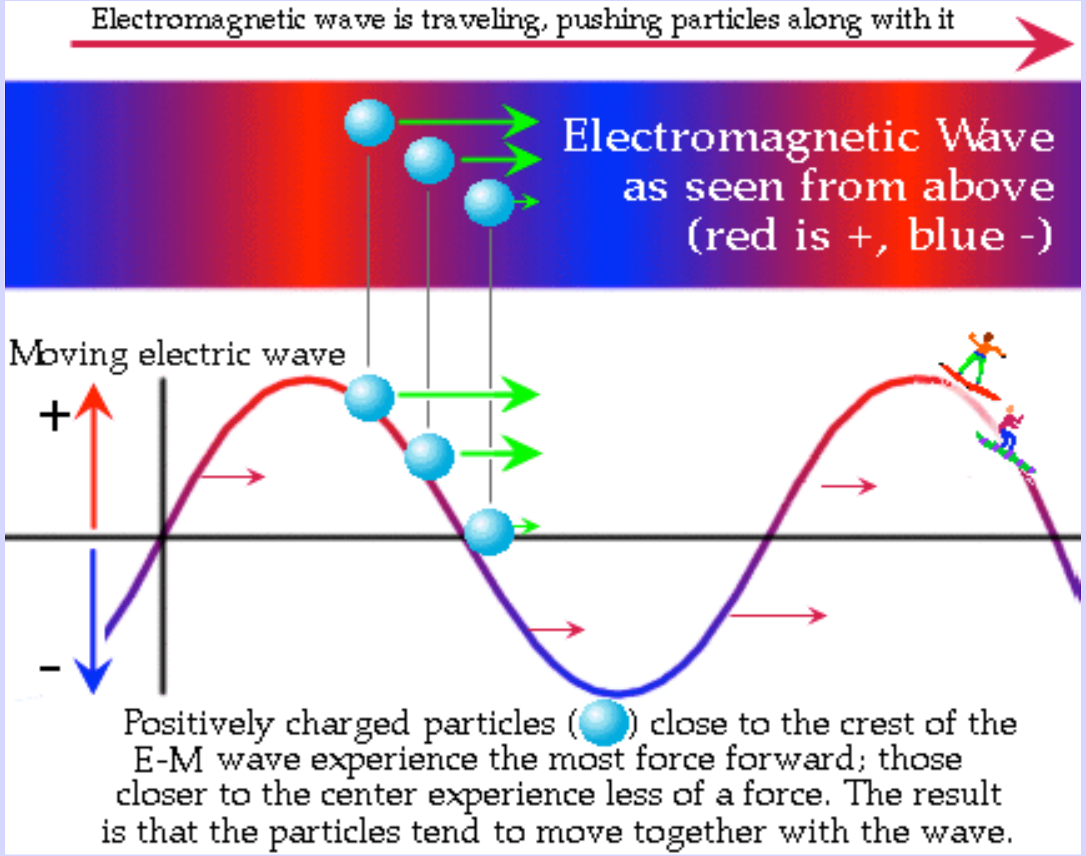
- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc
- High Energy pp Colliders
  - Opening up a new energy frontier (~ 1 TeV scale)

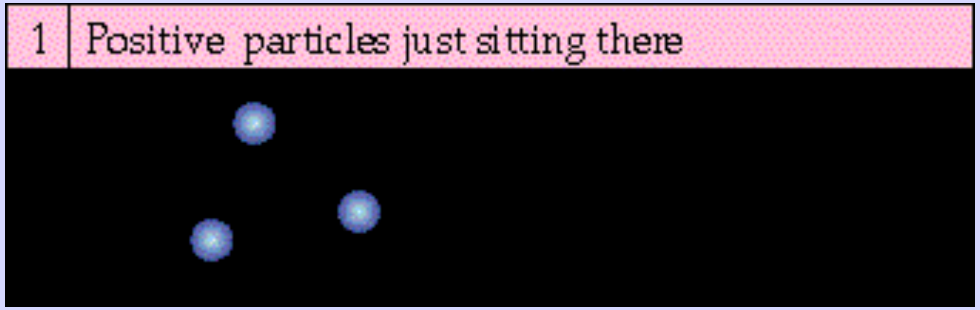


- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

Accelerating Charged Particles

Accelerators speed up charged particles by creating large electric fields which attract or repel the particles. This field can then be moved down the accelerator, "pushing" the particles along.





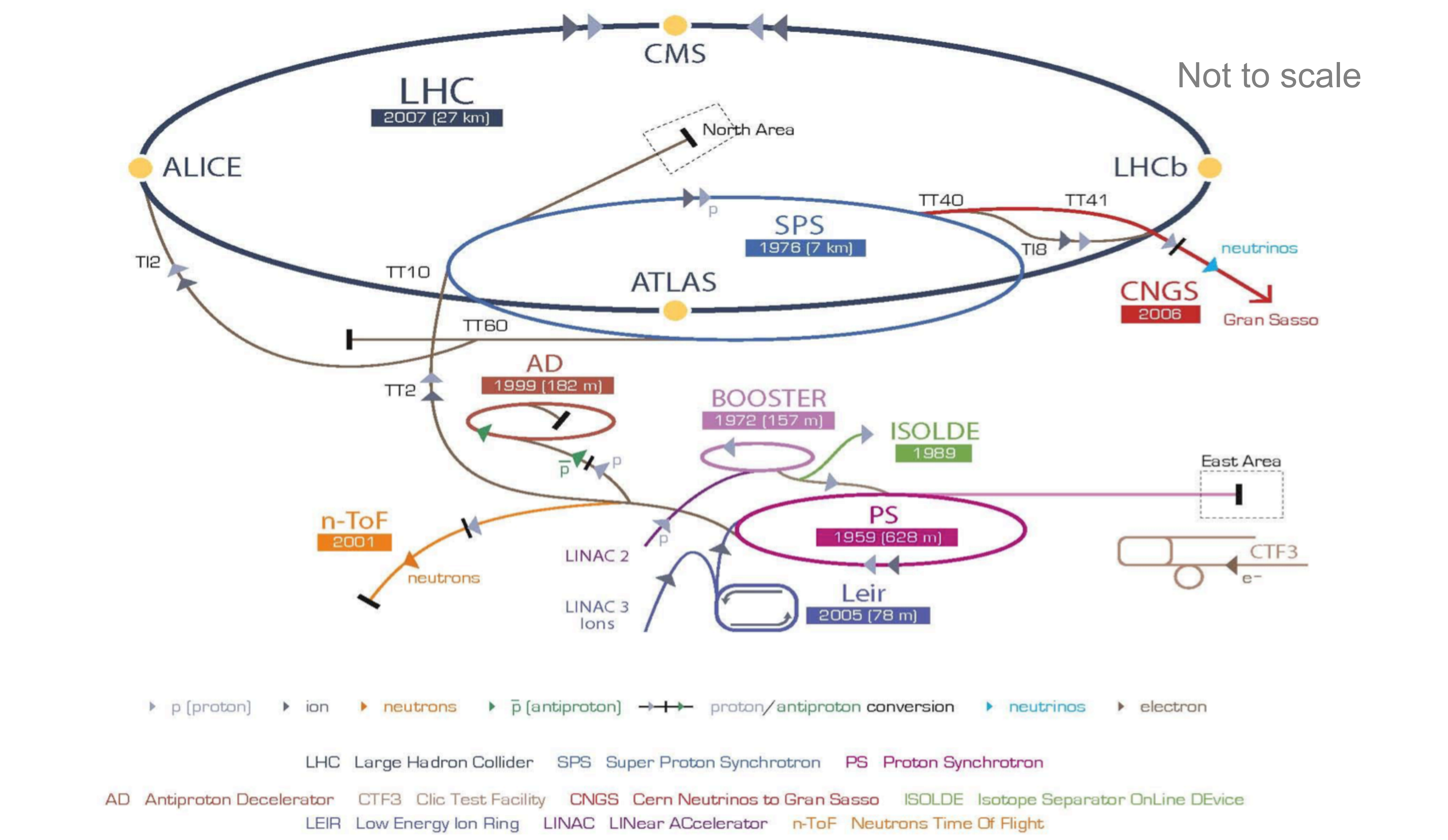
Reaching High Collision Energies

-

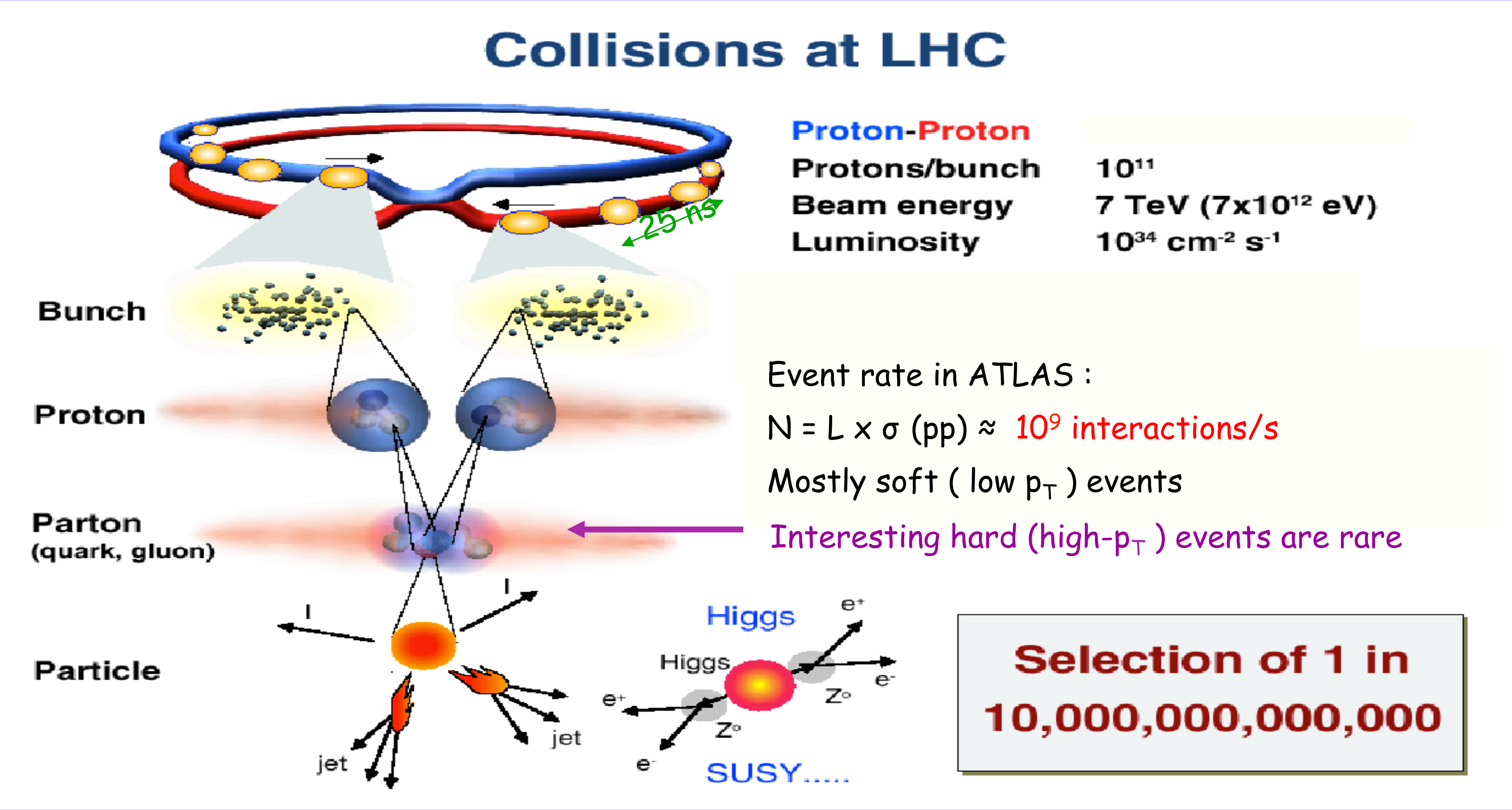
$$E_{com} = \sim \sqrt{2E_1 m_2}$$

$$E_{com} = \sim \sqrt{4E_1 E_2}$$

LHC – CERN Accelerator Complex



Experimental High-Energy Particle Physics



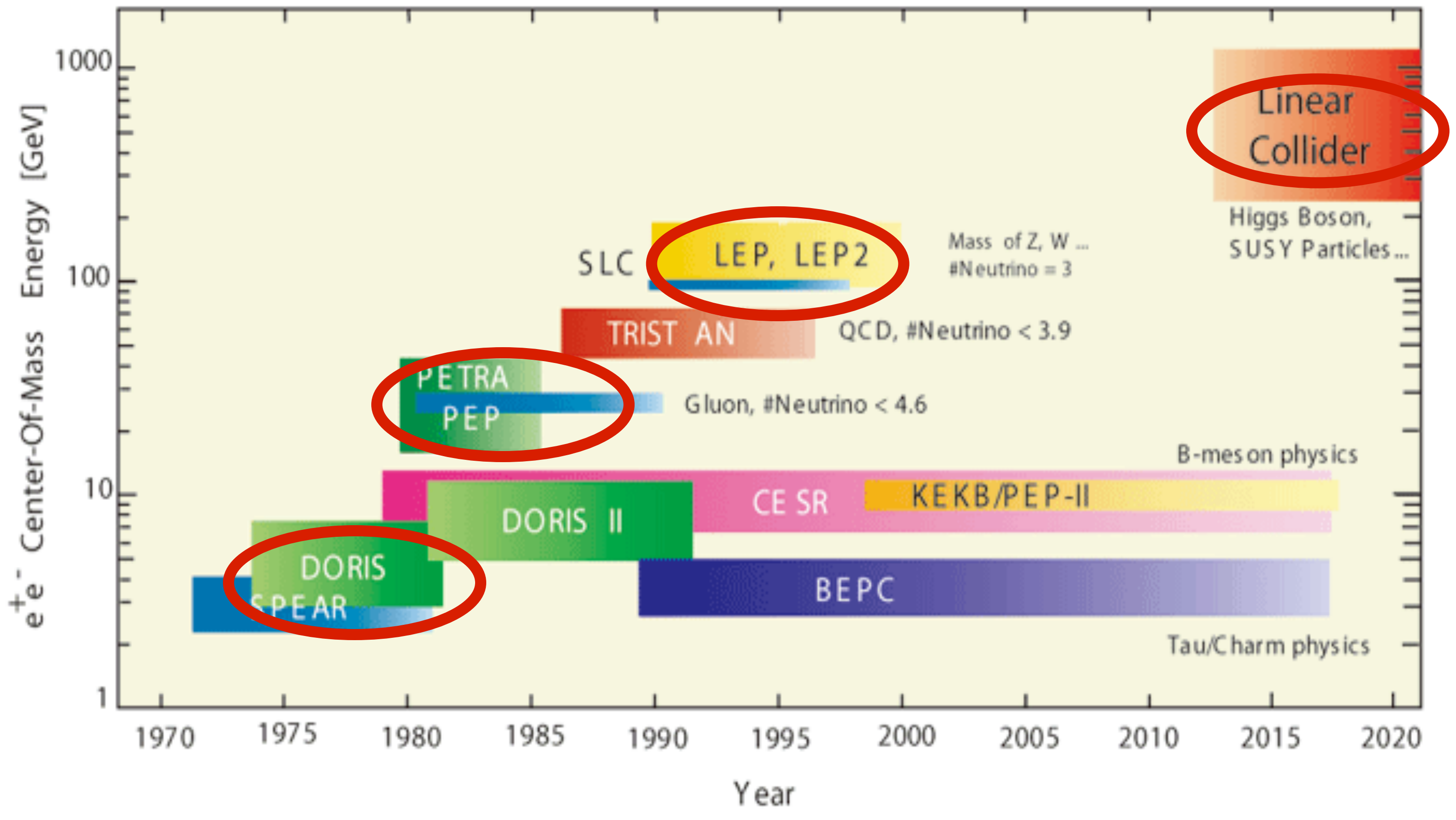
Large Hadron Collider

Large Hadron Collider

Proton beam stores 700 MegaJoules
equiv. to 747 energy on take-off
enough to melt 1/2 ton copper

Three Generations of e^+e^- Colliders

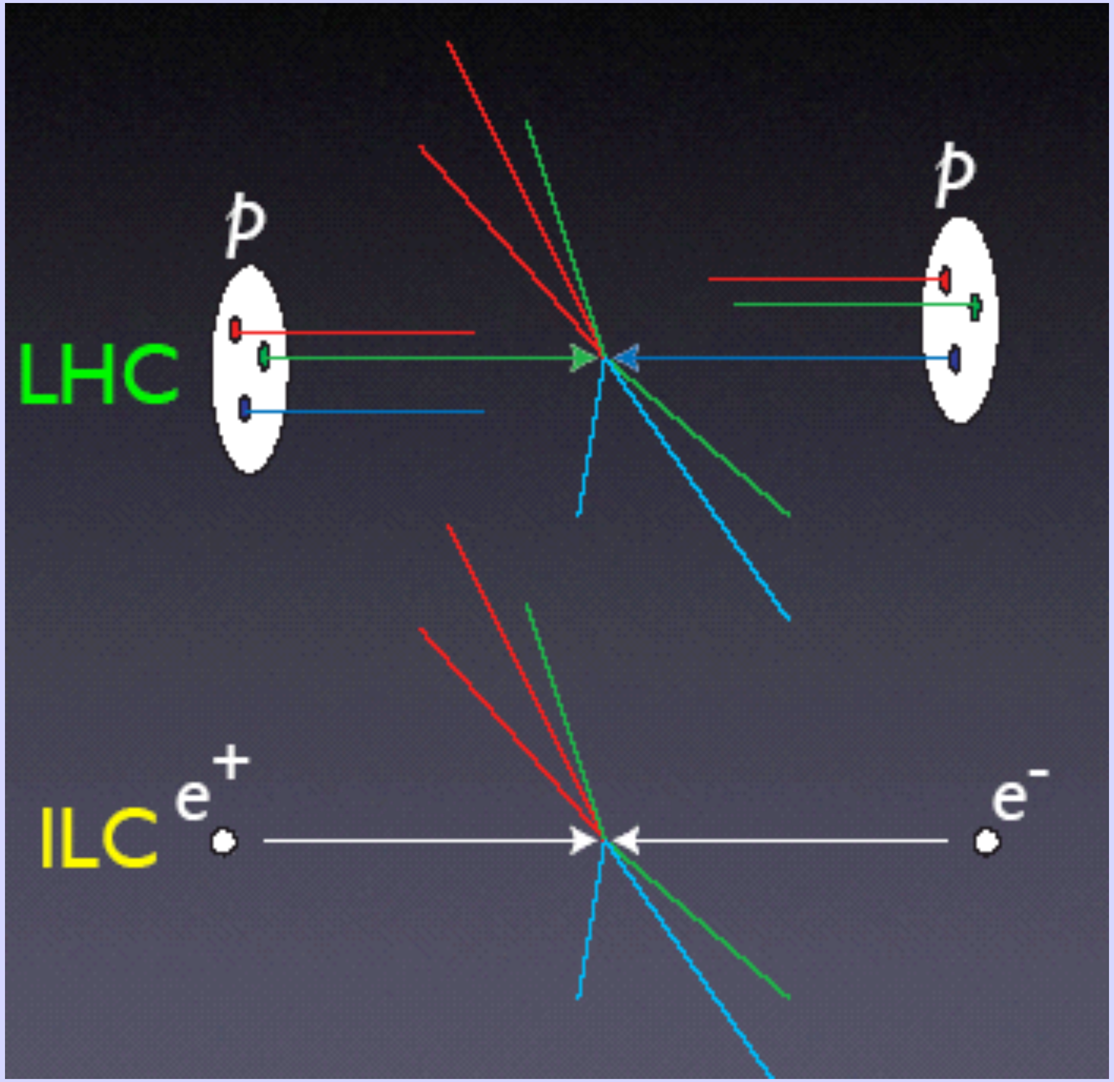
The Energy Frontier



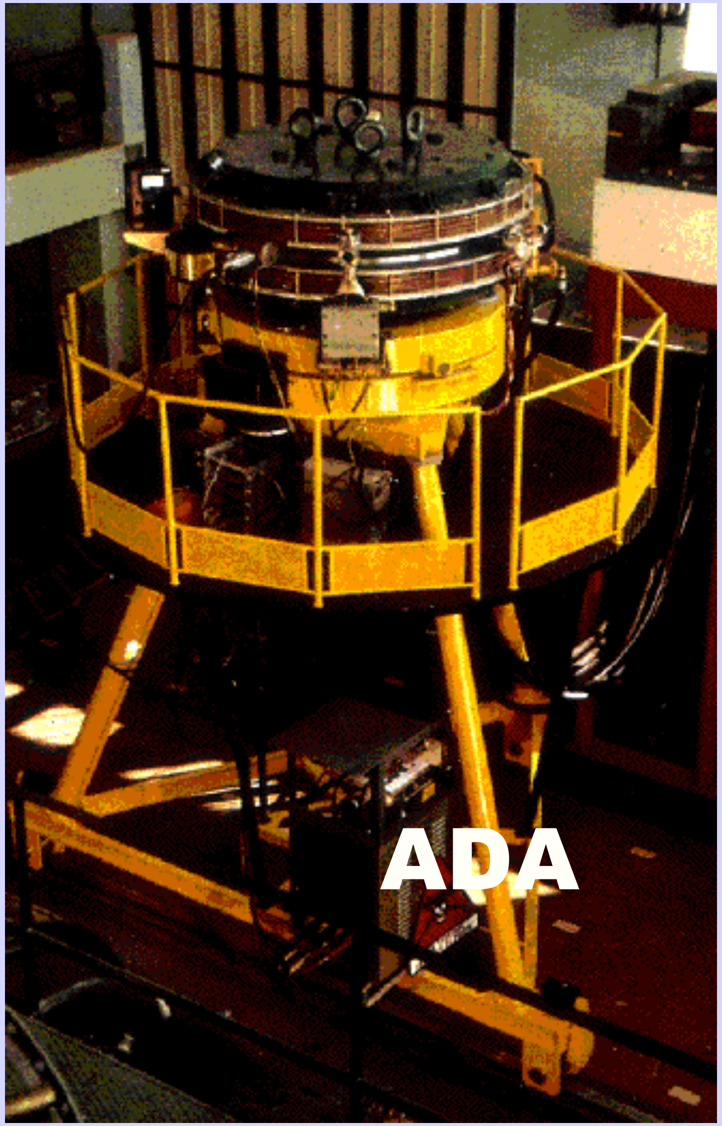
Fourth Generation?

Why e^+e^- Collisions ?

- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



Electron-Positron Colliders

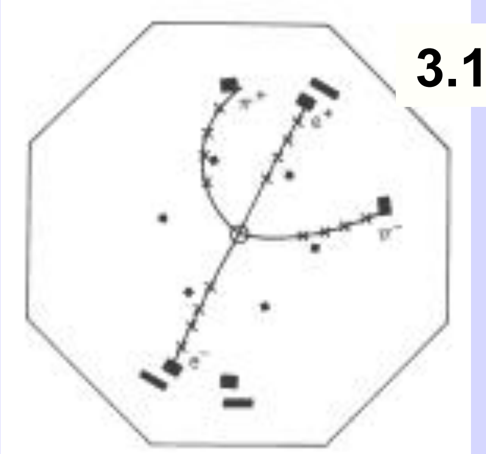


Bruno Touschek built the first successful electron-positron collider at Frascati, Italy (1960)

Eventually, went up to 3 GeV

But, not quite high enough energy ….

SPEAR at SLAC

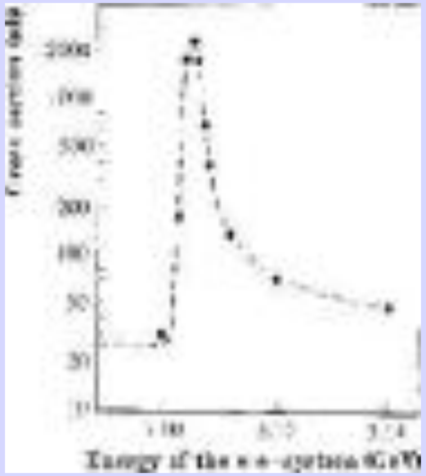


3.1 GeV

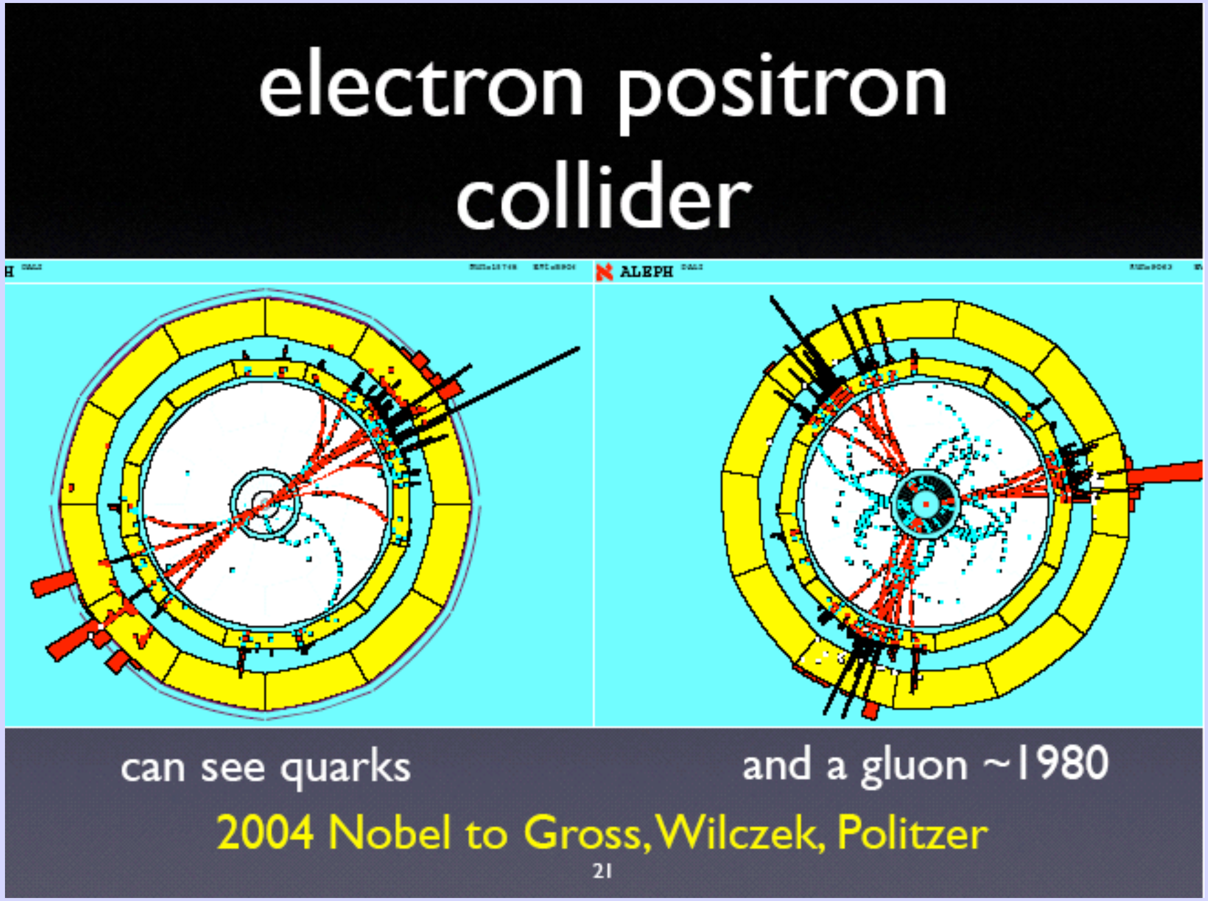
Burt Richter
Nobel Prize

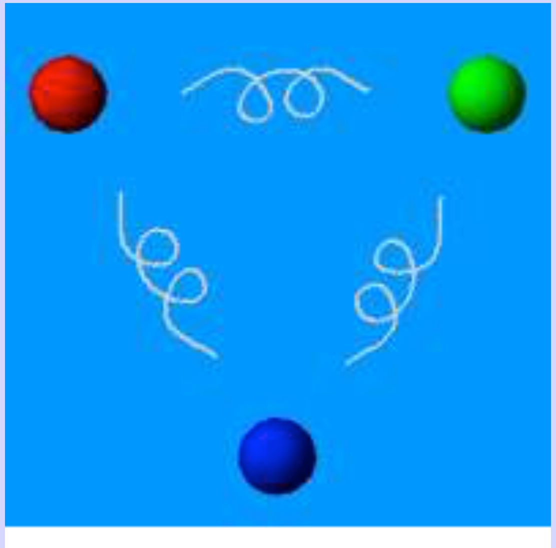
and

Discovery
Of
Charm
Particles



The rich history for e^+e^- continued as higher energies were achieved …

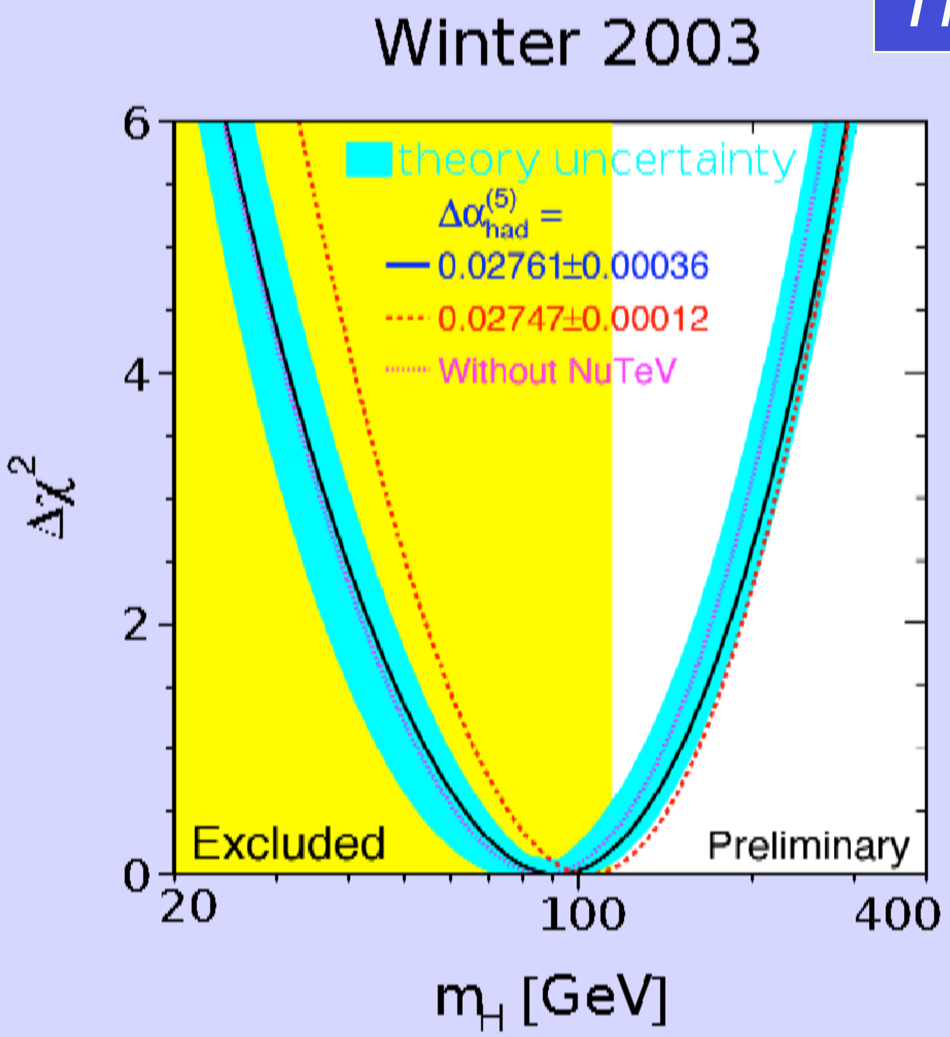




DESY PETRA Collider

Precision Measurements – Standard Model

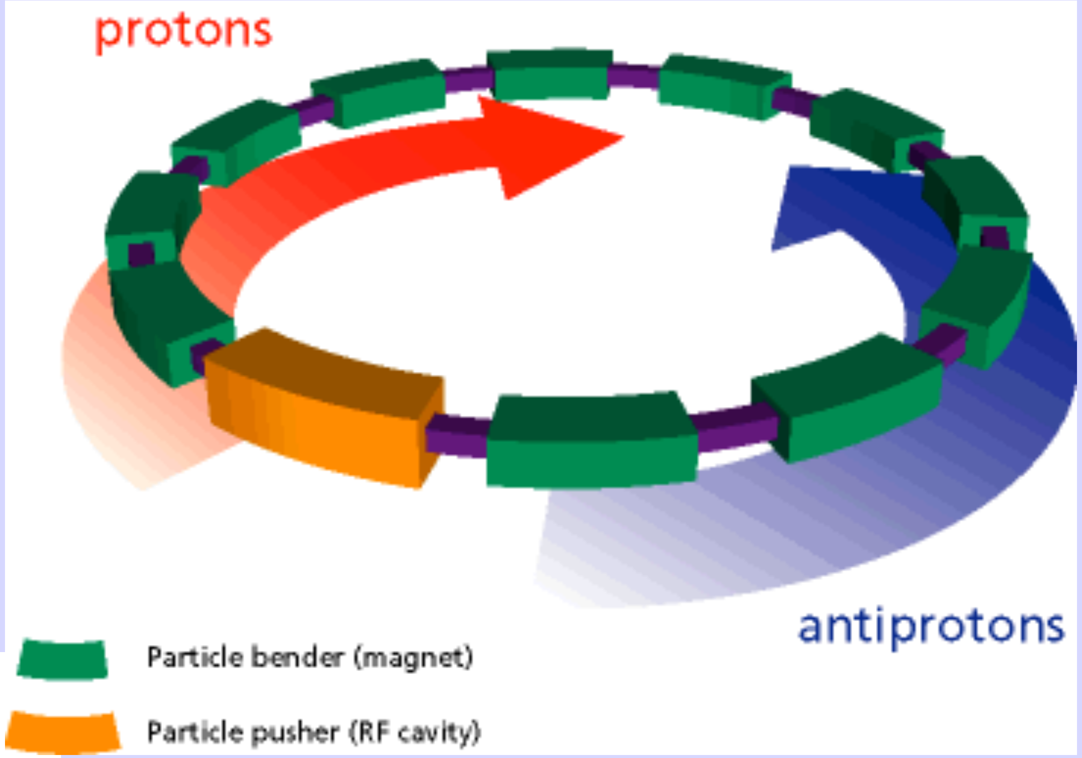
Third generation



CERN's LEP Collider set the stage for Terascale physics

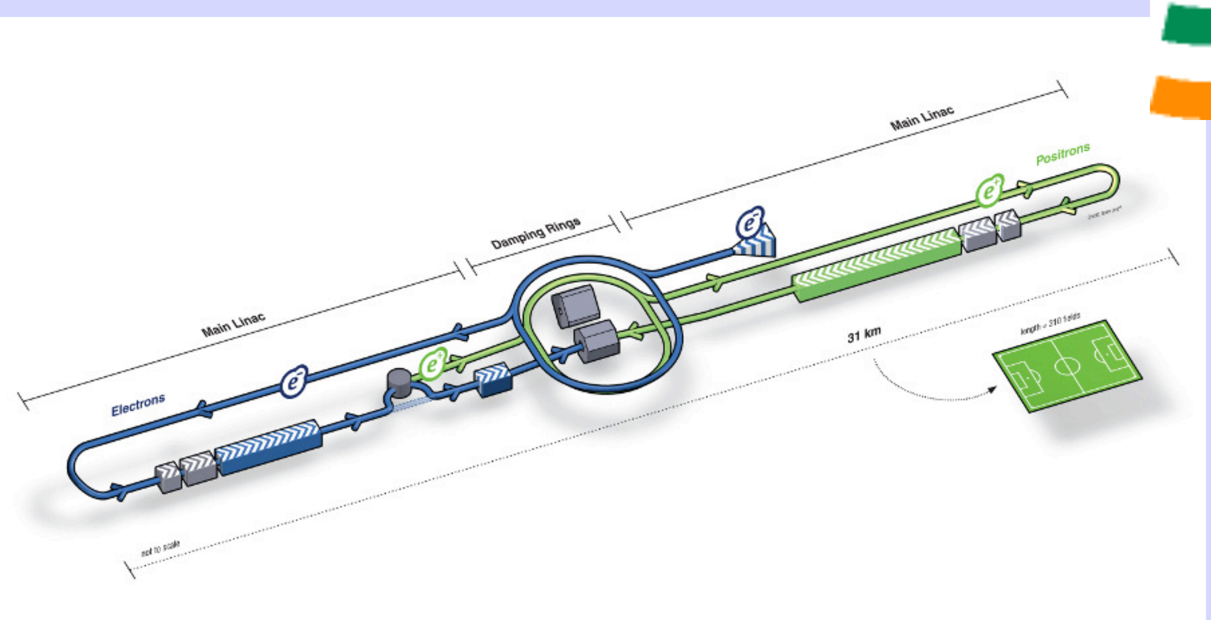
- **Reveal the origin of quark and lepton mass**
- **Produce dark matter in the laboratory**
- **Test exotic theories of space and time**

Particle Colliders



Hadron colliders:

Higher energies, but energy of collision of point-like constitutents have large variance.

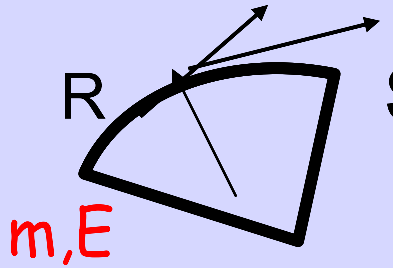


Lepton (e^-e^+) colliders:

Lower energies, but well-known, controllable E_{CM} of collisions, much cleaner final states.

Circular or Linear Collider?

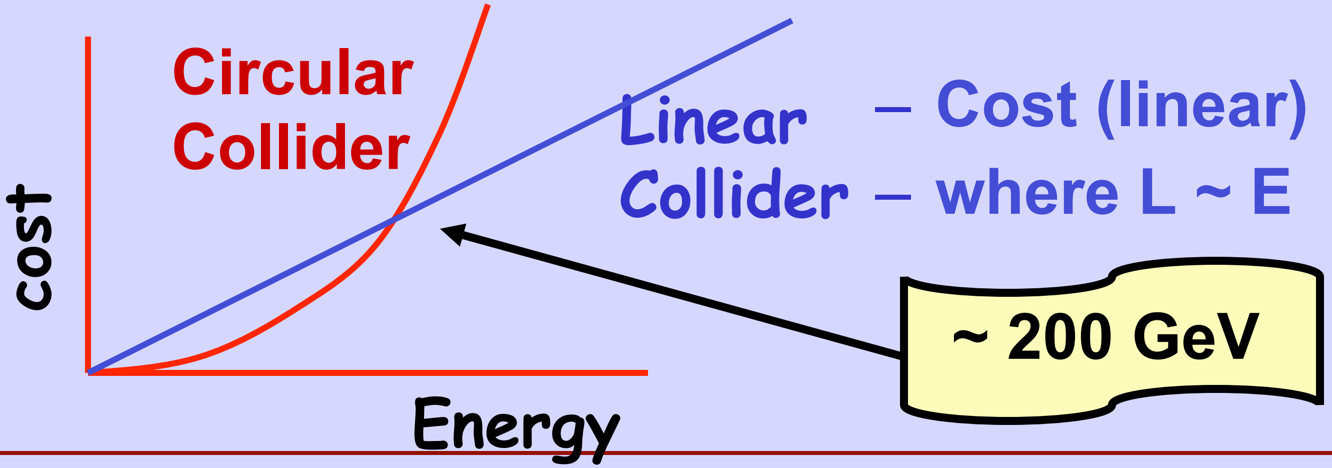
- **Circular Machine**



Synchrotron Radiation

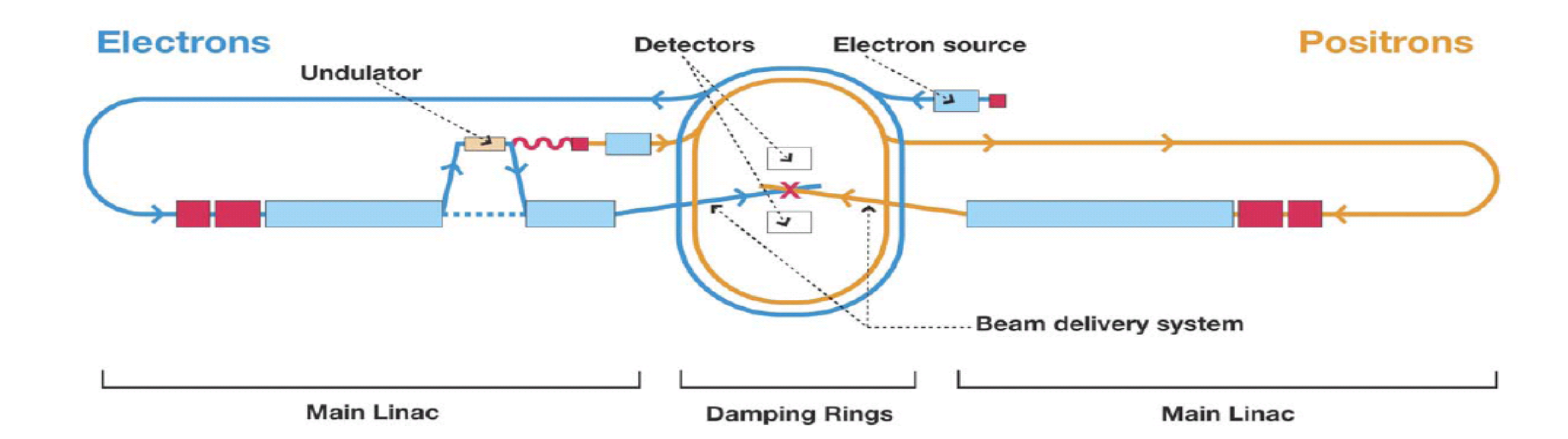
  - $\Delta E \sim (E^4 / m^4 R)$
  - Cost $\sim a R + b \Delta E$

    $\sim a R + b (E^4 / m^4 R)$
  - **Optimization : $R \sim E^2 \Rightarrow$ Cost $\sim c E^2$**



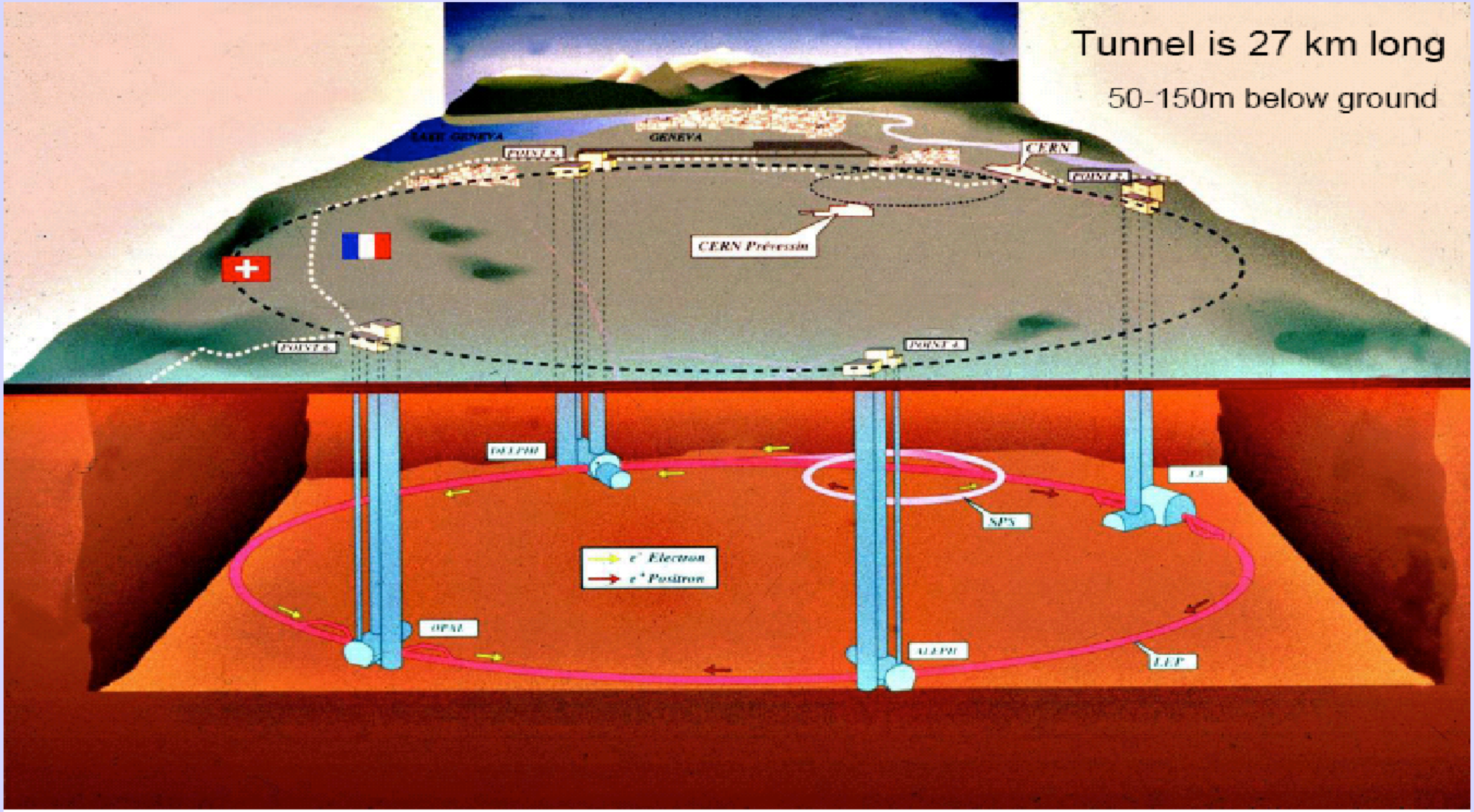
- Cost (linear) $\sim a' L$
- where $L \sim E$

The ILC

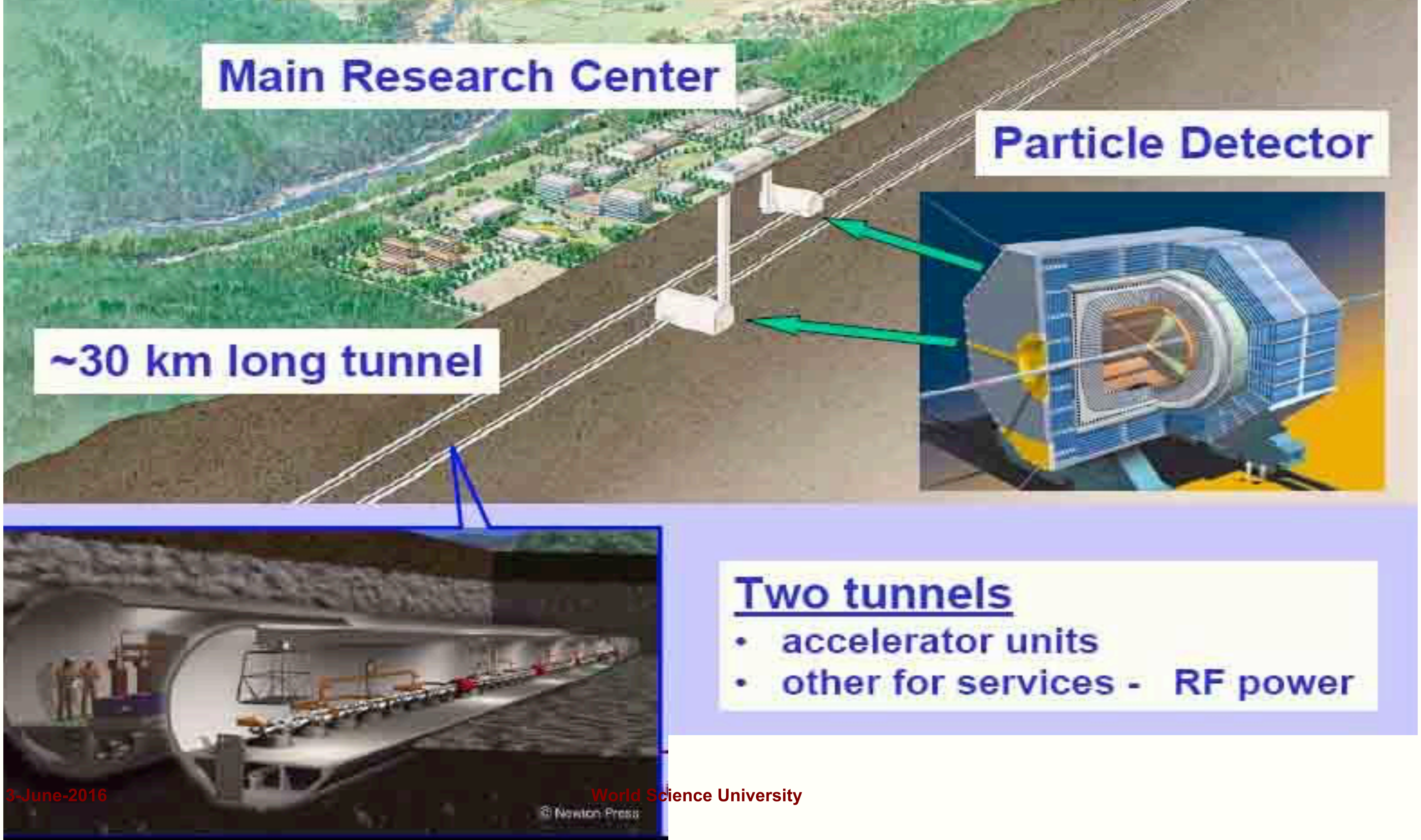


- Two linear accelerators, with tiny intense beams of electrons and positrons colliding head-on-head
- Total length ~ 30 km long (comparable scale to LHC)
- COM energy = 500 GeV, upgradeable to 1 TeV

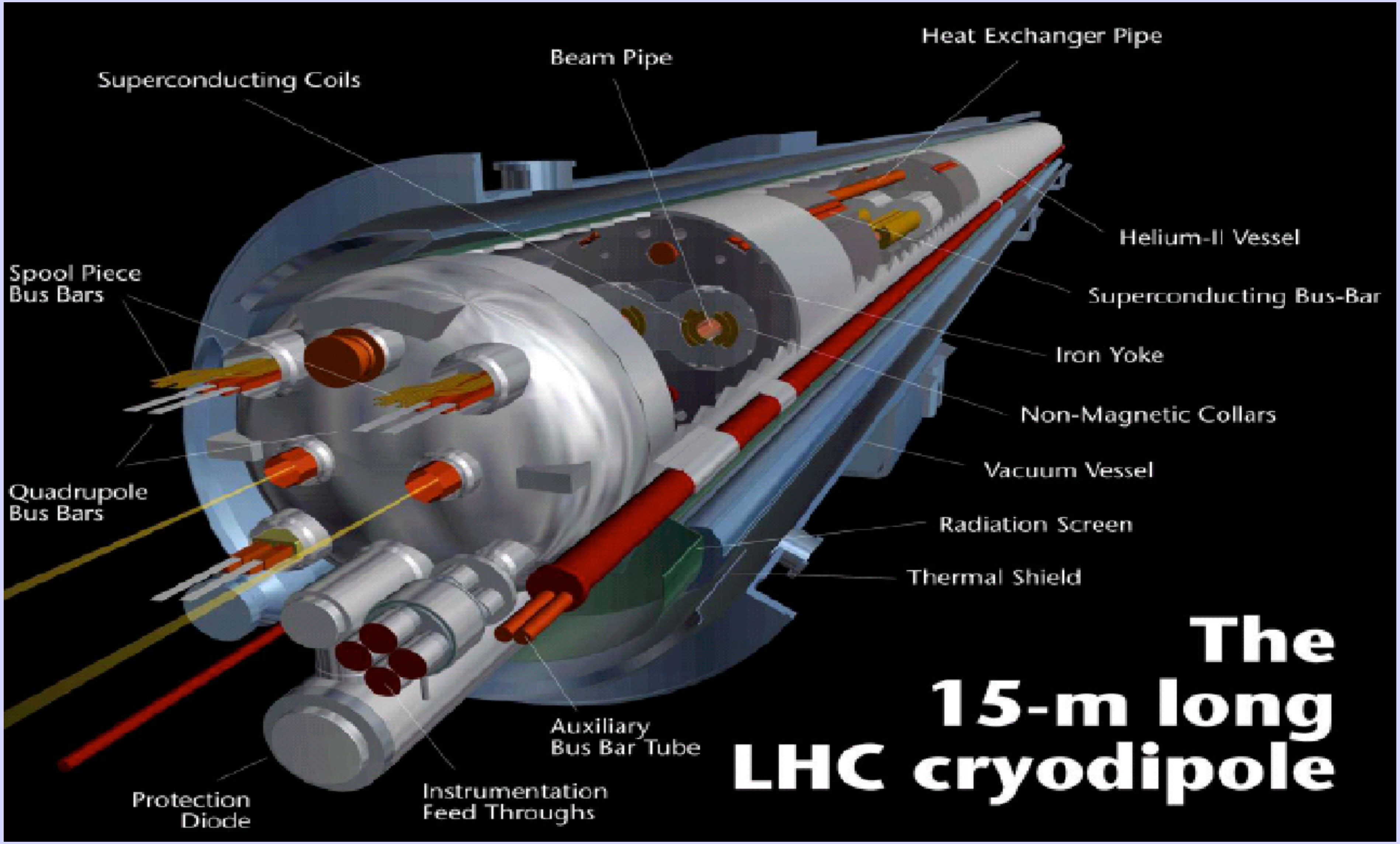
LHC --- Deep Underground



ILC --- Deep Underground



LHC --- Superconducting Magnet



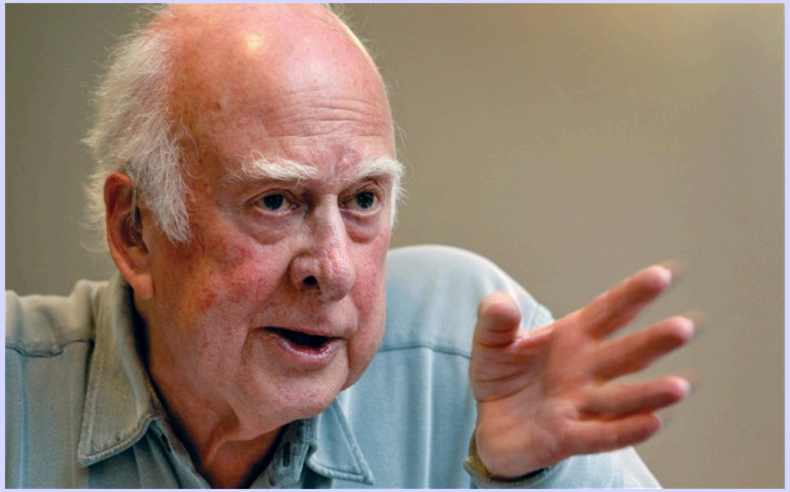
ILC - Superconducting RF Cryomodule

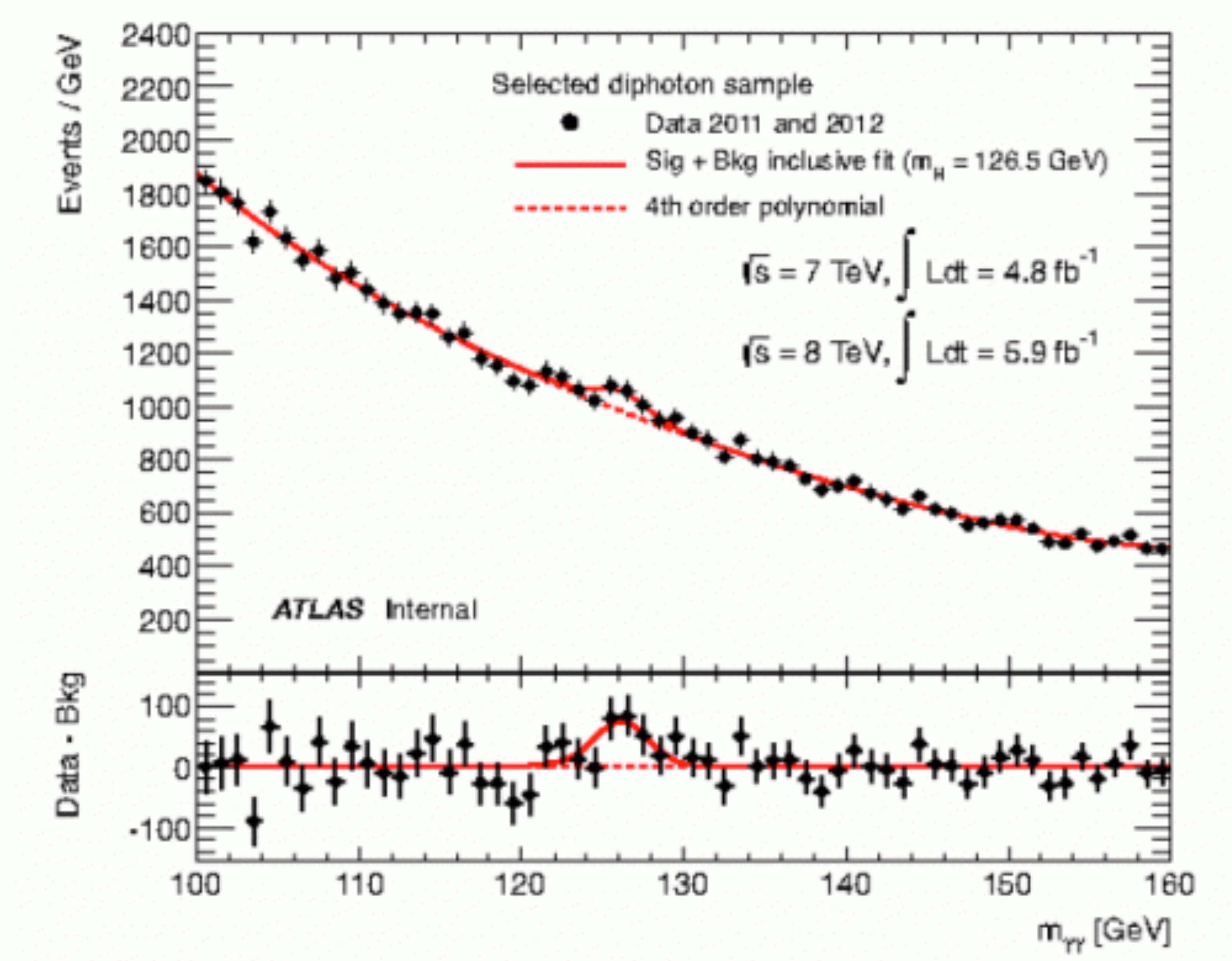
Comparison: ILC and LHC

	ILC	LHC
Beam Particle :	Electron x Positron	Proton x Proton
CMS Energy :	0.5 – 1 TeV	14 TeV
Luminosity Goal :	2 x 10^{34} /cm^2/sec	1 x10^{34} /cm^2/sec
Accelerator Type :	Linear	Circular Storage Rings
Technology :	Supercond. RF	Supercond. Magnet

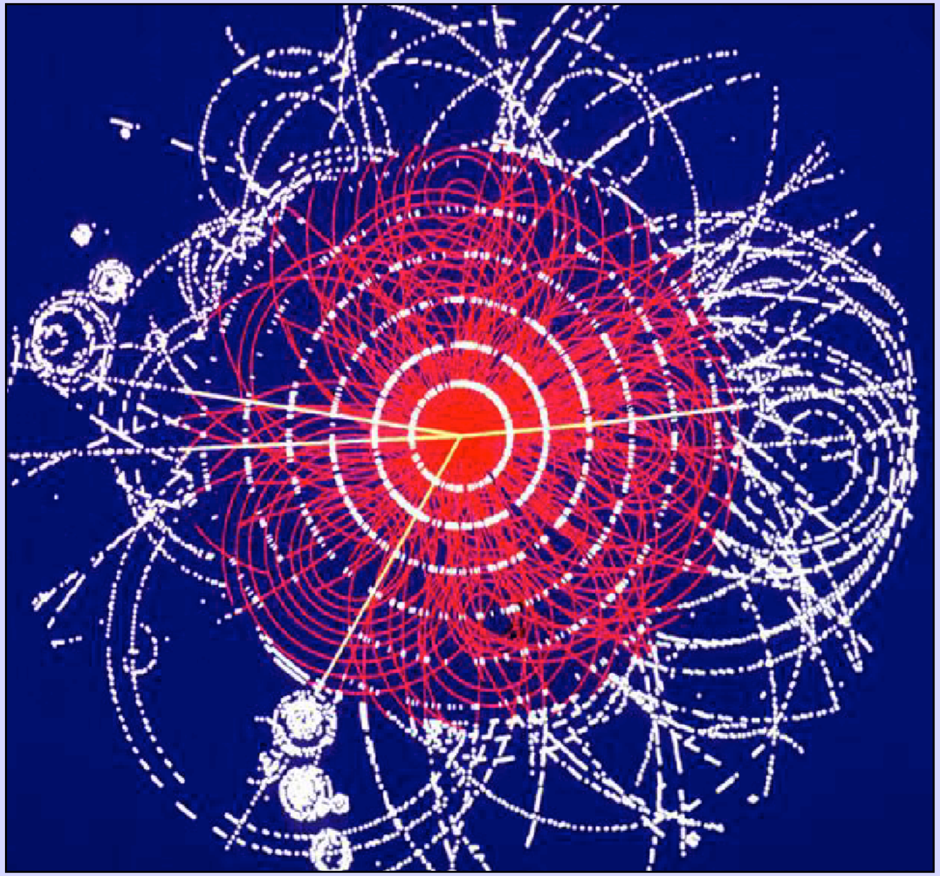
Discovery of Higg-like particle

Peter Higgs

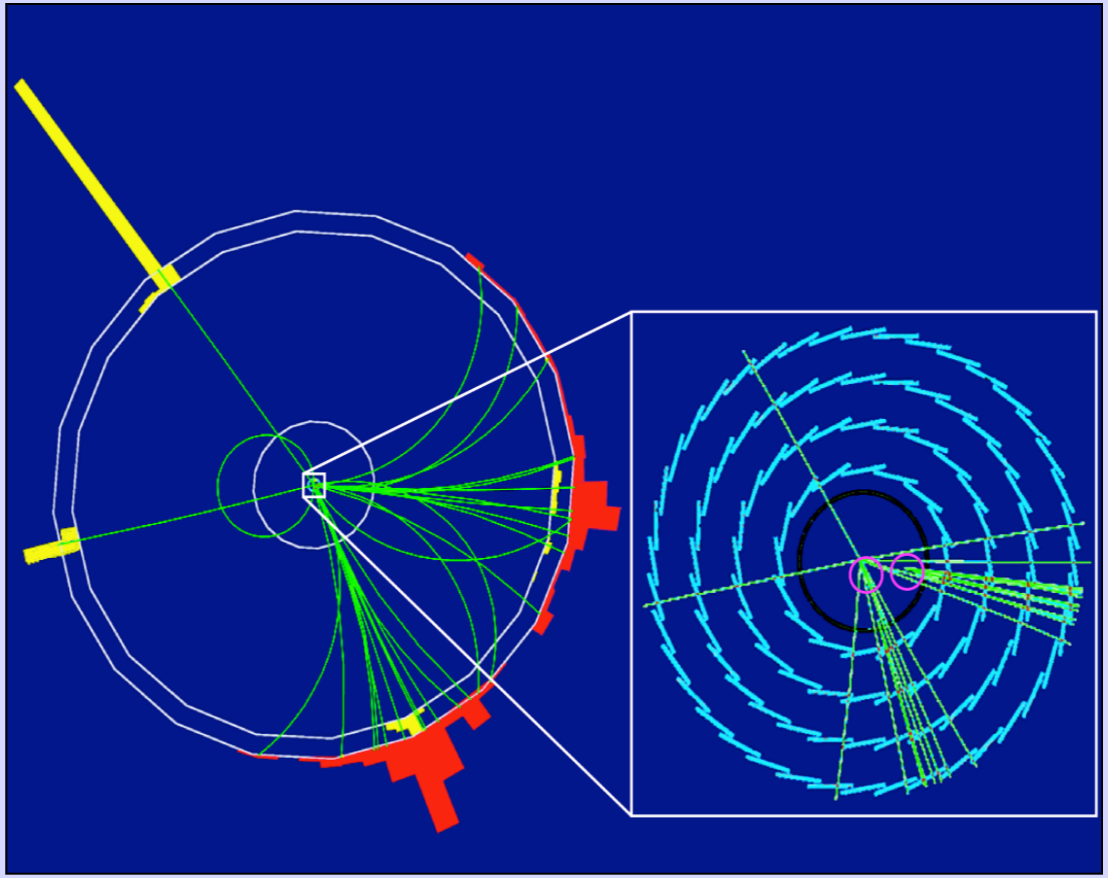




LHC/ILC Higgs Event Comparison



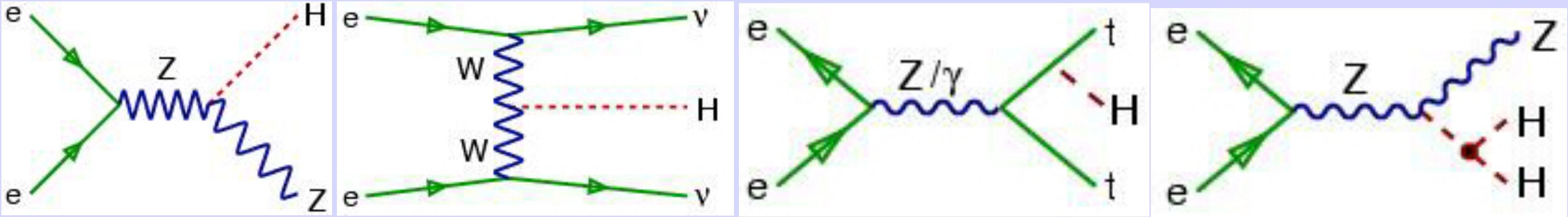
LHC

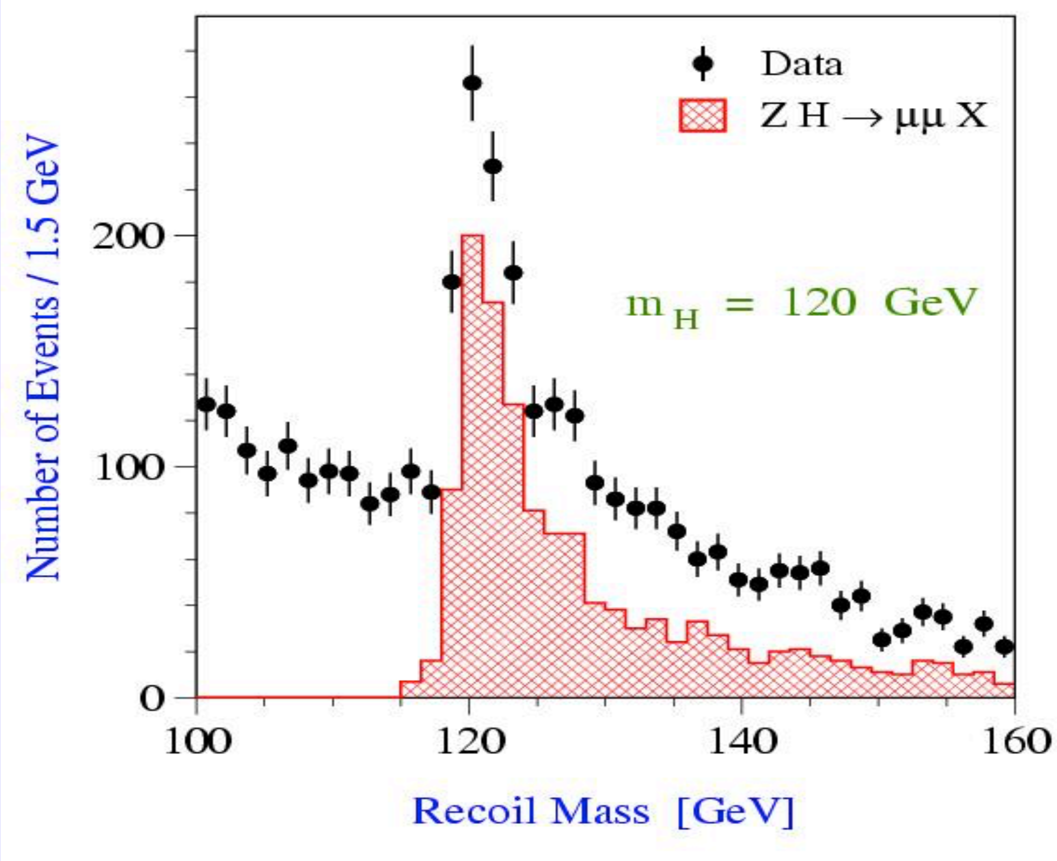


ILC

$e^+ e^-$? Z H then, Z ? $e^+ e^-$, H ? $b\bar{b}$…

ILC Precision Higgs physics

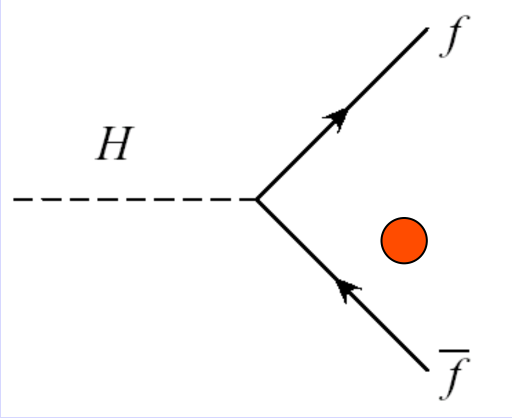


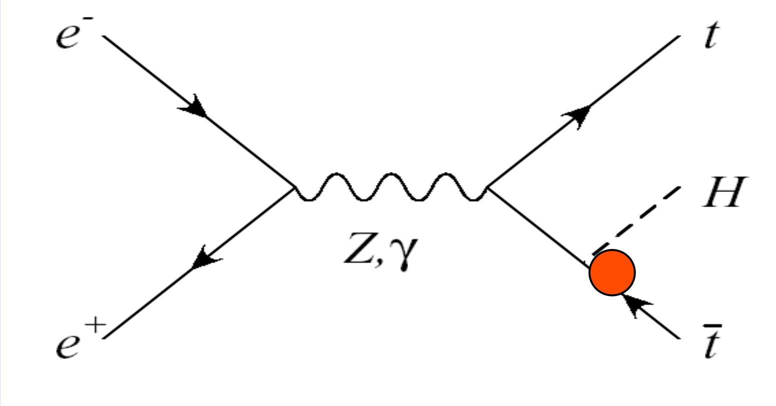


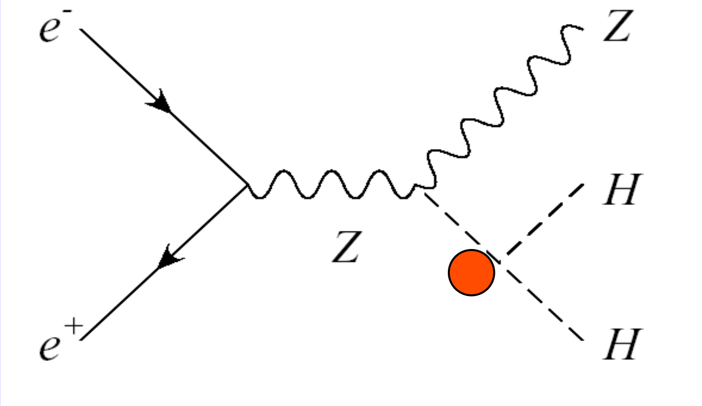
- **Model-independent Studies**
  - **mass**
  - **absolute branching ratios**
  - **total width**
  - **spin**
  - **top Yukawa coupling**
  - **self coupling**
- **Precision Measurements**

Higgs is not like other particles!

- It is a zero spin particle that fills the vacuum
- It couples to mass; masses and decay rates are related



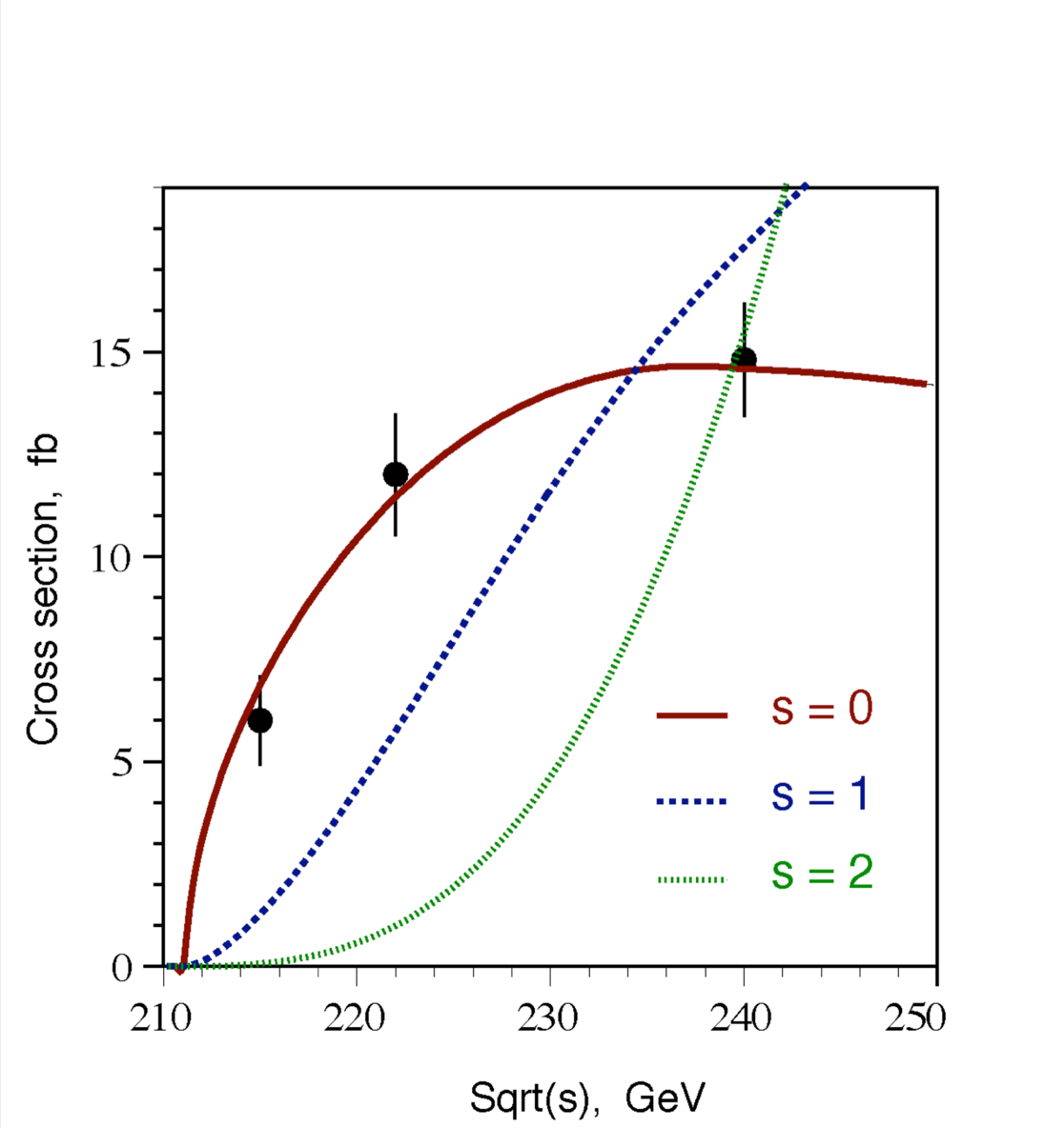




Higgs Coupling-mass relation

$$m_i = v \times \kappa_i$$

ILC: Is it really the Higgs ?

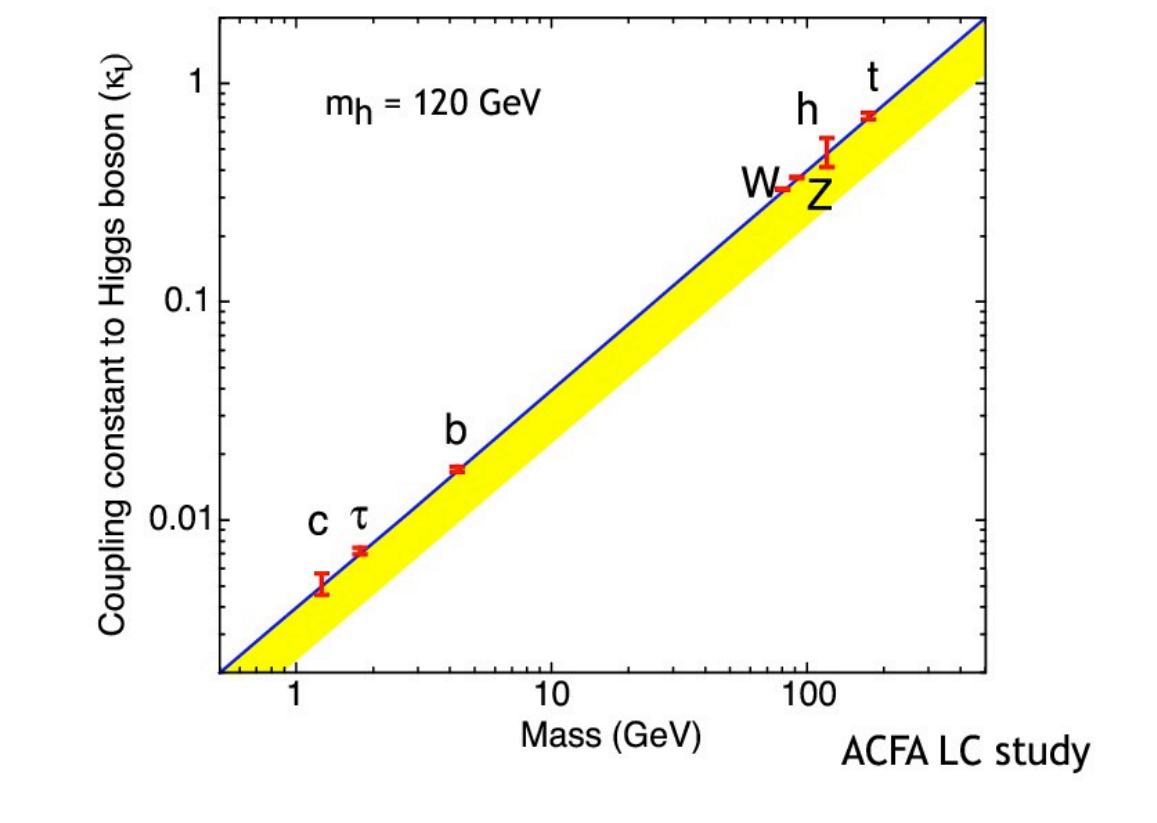


Measure the quantum numbers. The Higgs must have spin zero !

The linear collider will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

What can we learn from the Higgs?

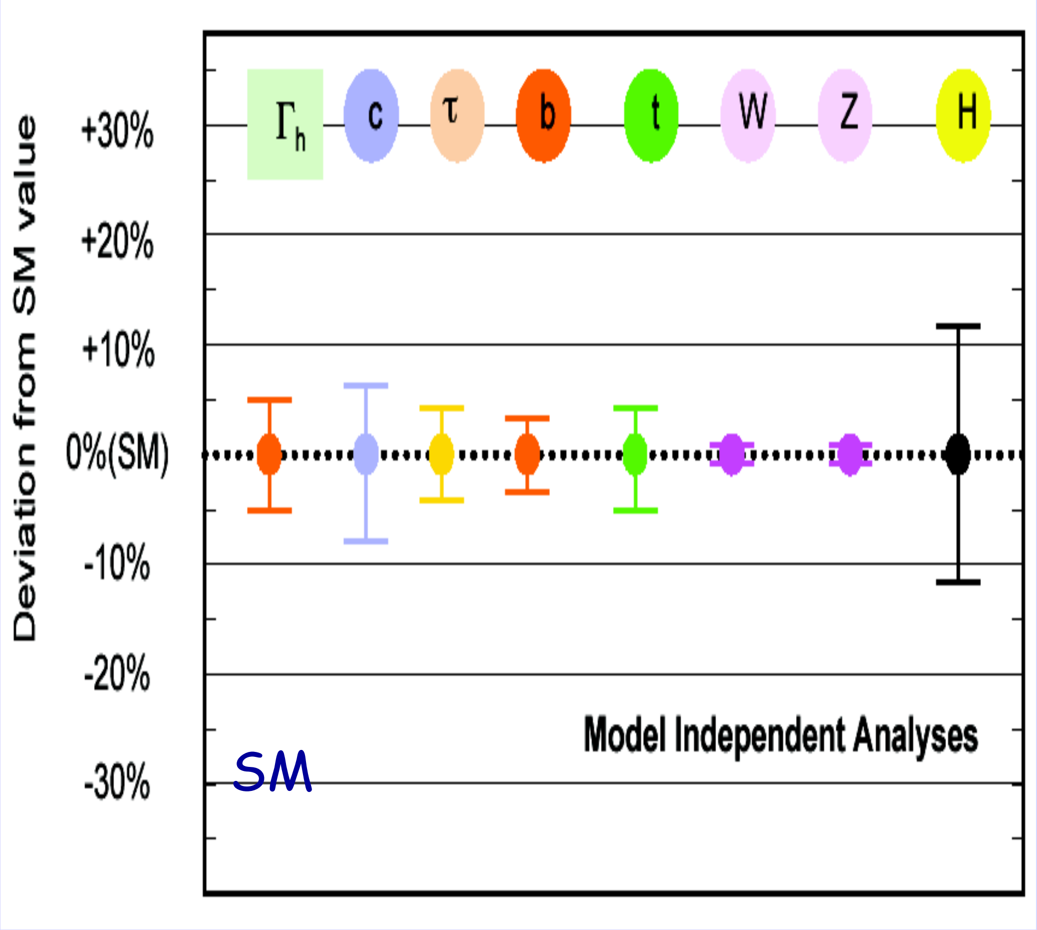
Precision measurements of Higgs coupling



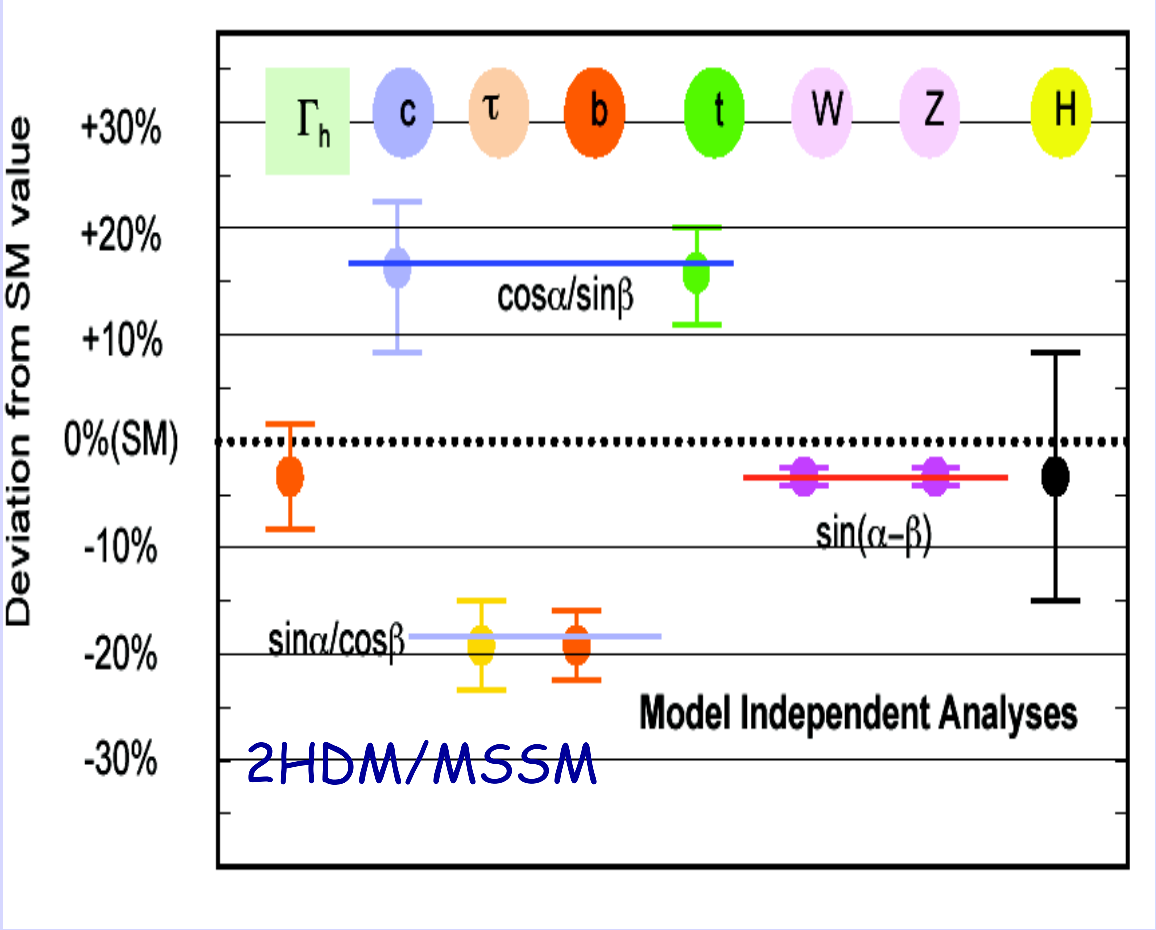
Higgs Coupling strength is proportional to Mass

e^+e^- : Studying the Higgs

determine the underlying model

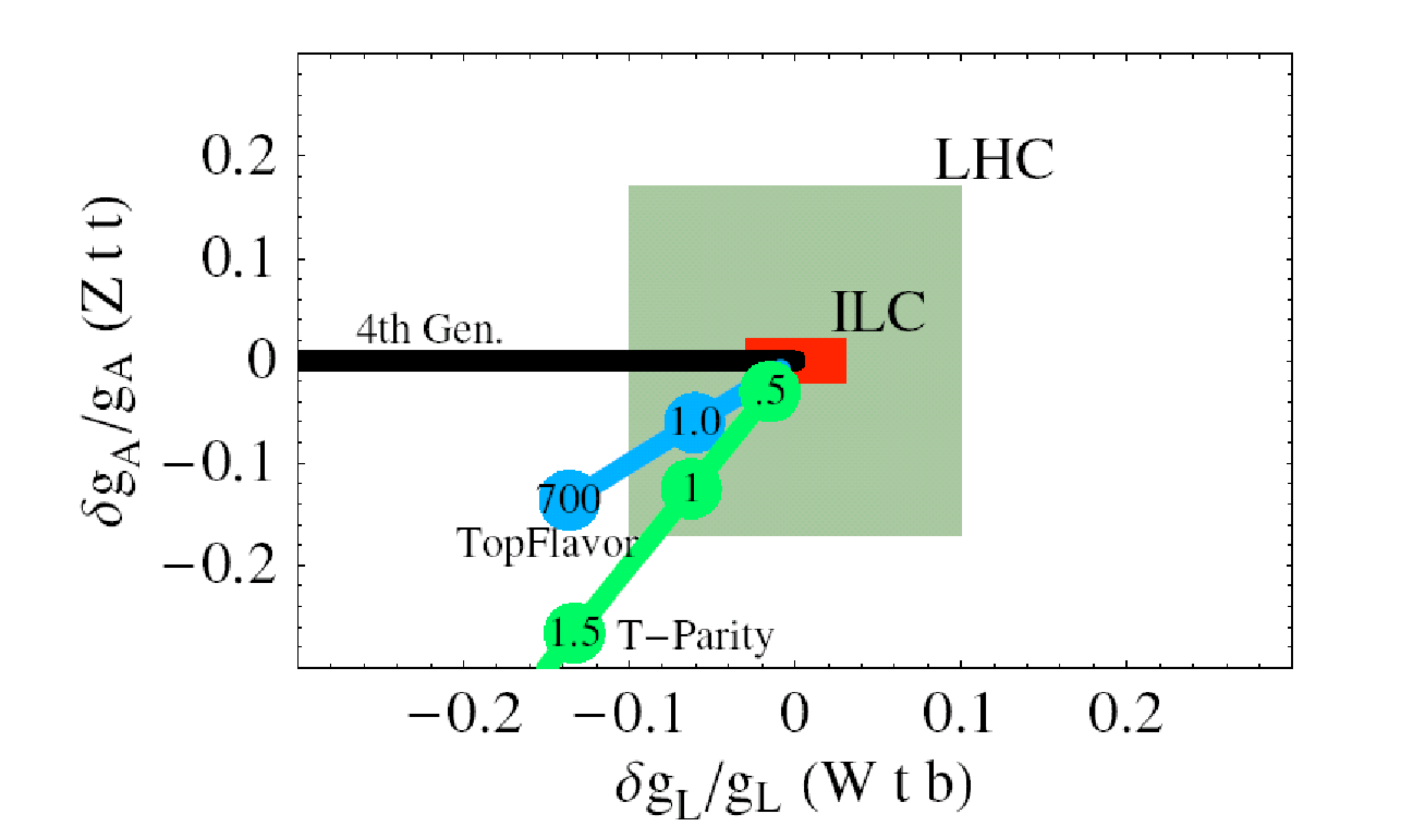


Yamashita et al



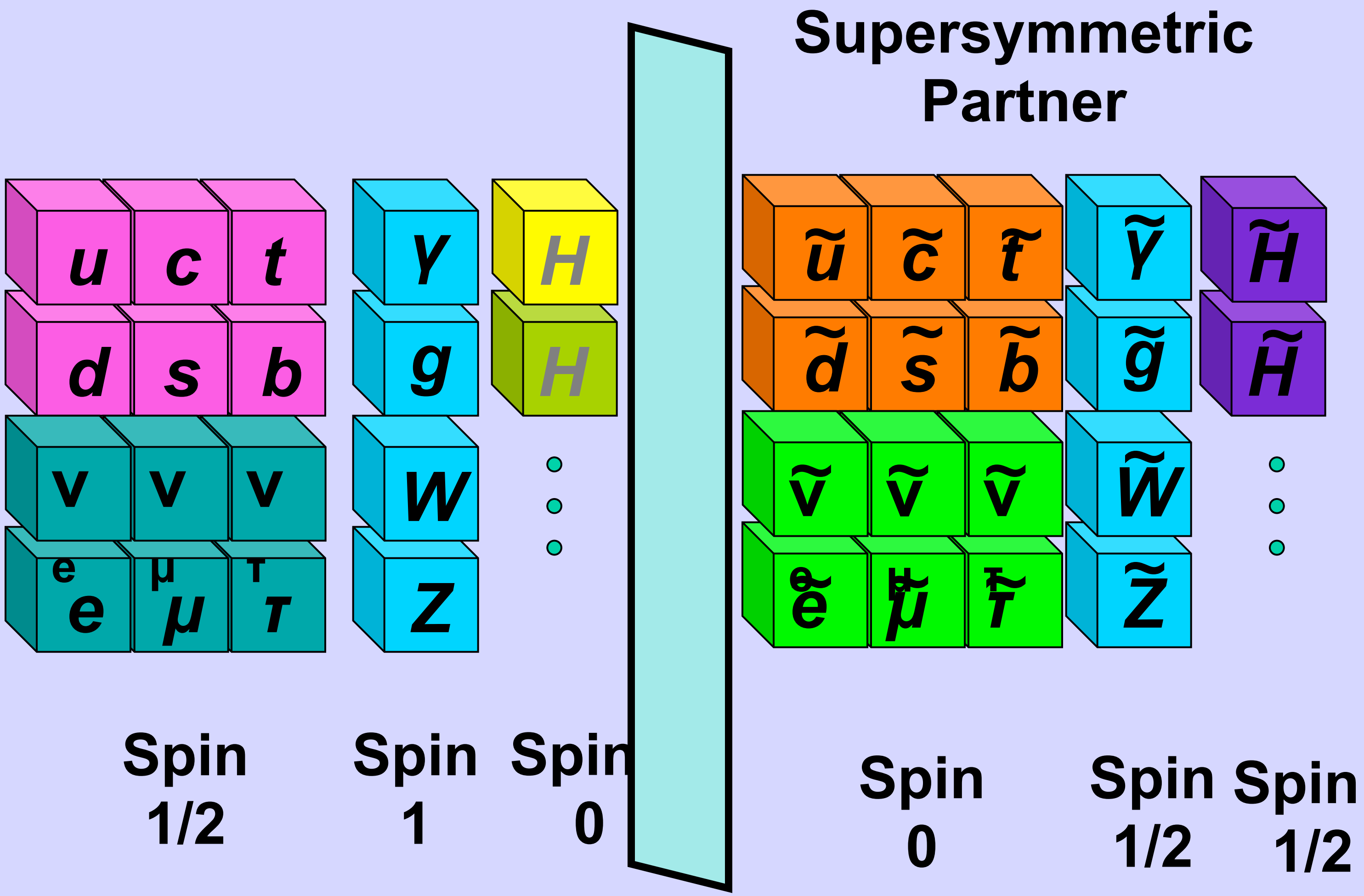
Zivkovic et al

Top Quark Measurements



Bounds on axial ttbarZ and left handed tbW for LHC and ILC compared to deviations in various models

Supersymmetry

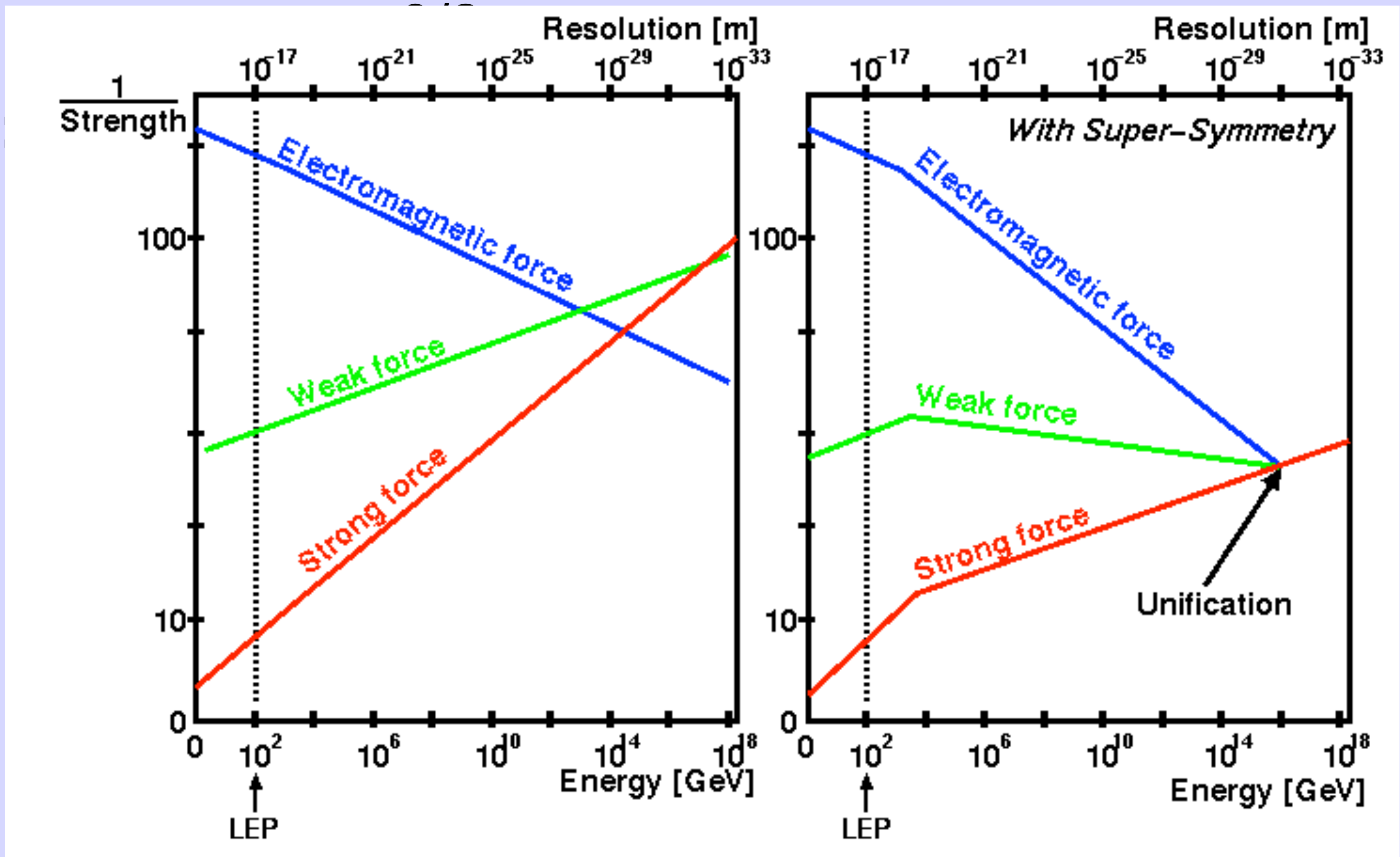


Is there a New Symmetry in Nature?

Bosons ⟷ **Fermions**

Integer Spin: 0, 1,..

Half integer Spin: 1/2,



The virtues of Super-symmetry:

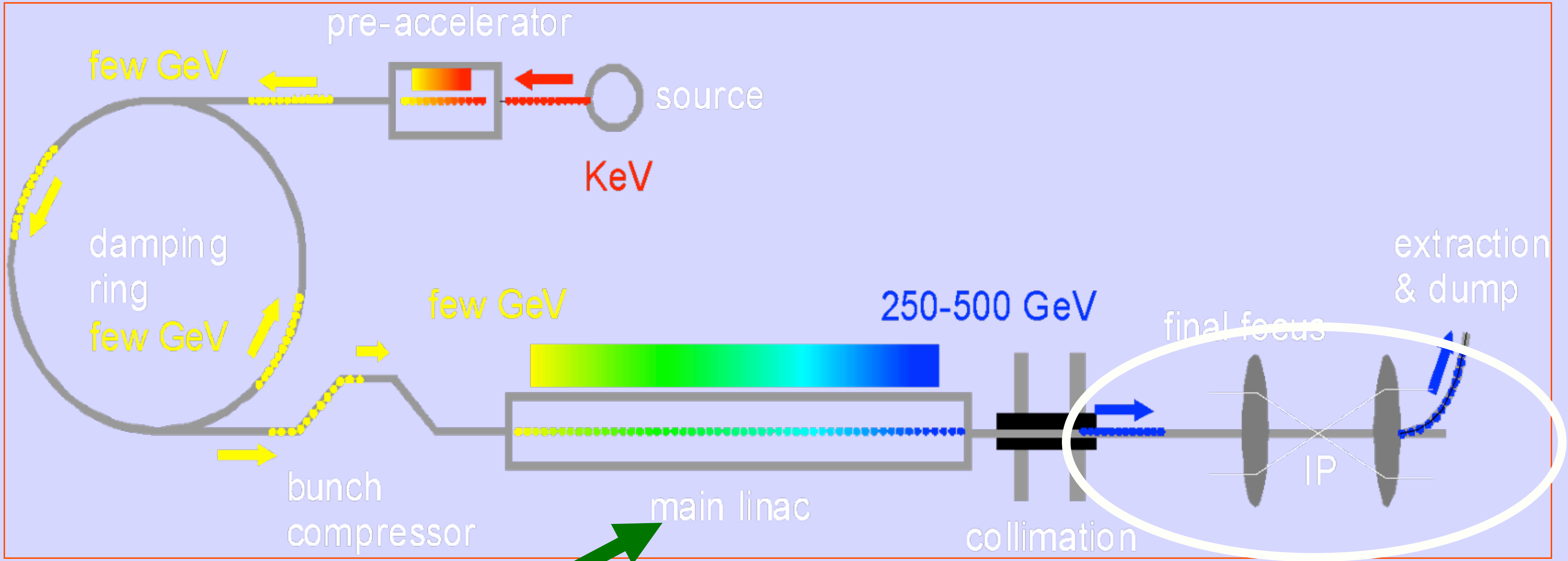
- **Unification of Forces**
- **The Hierarchy Problem**
- **Candidate for the Dark Matter**
- …

Parameters for the ILC

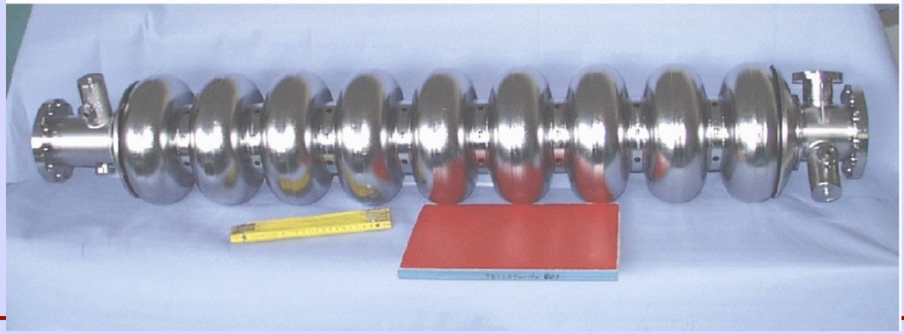
- E_{cm} adjustable from 200 – 500 GeV
- Luminosity ? $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%

- The machine must be upgradeable to 1 TeV

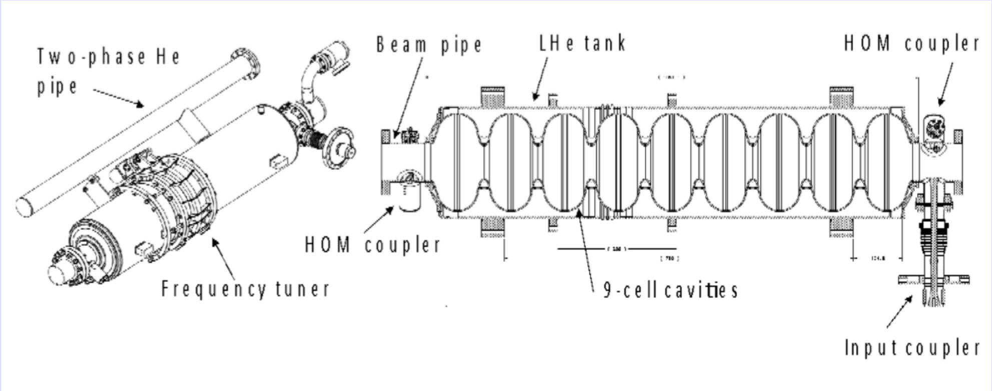
Designing a Linear Collider



Superconducting RF Main Linac



SCRF Linac Technology

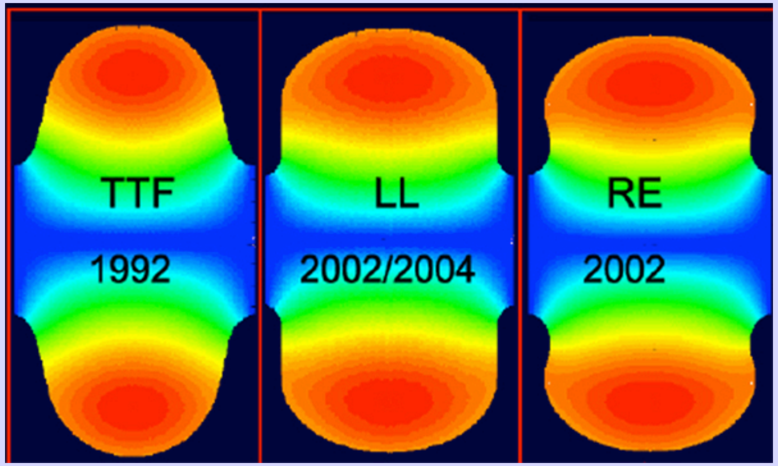


1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436 / 471 *

* site dependent

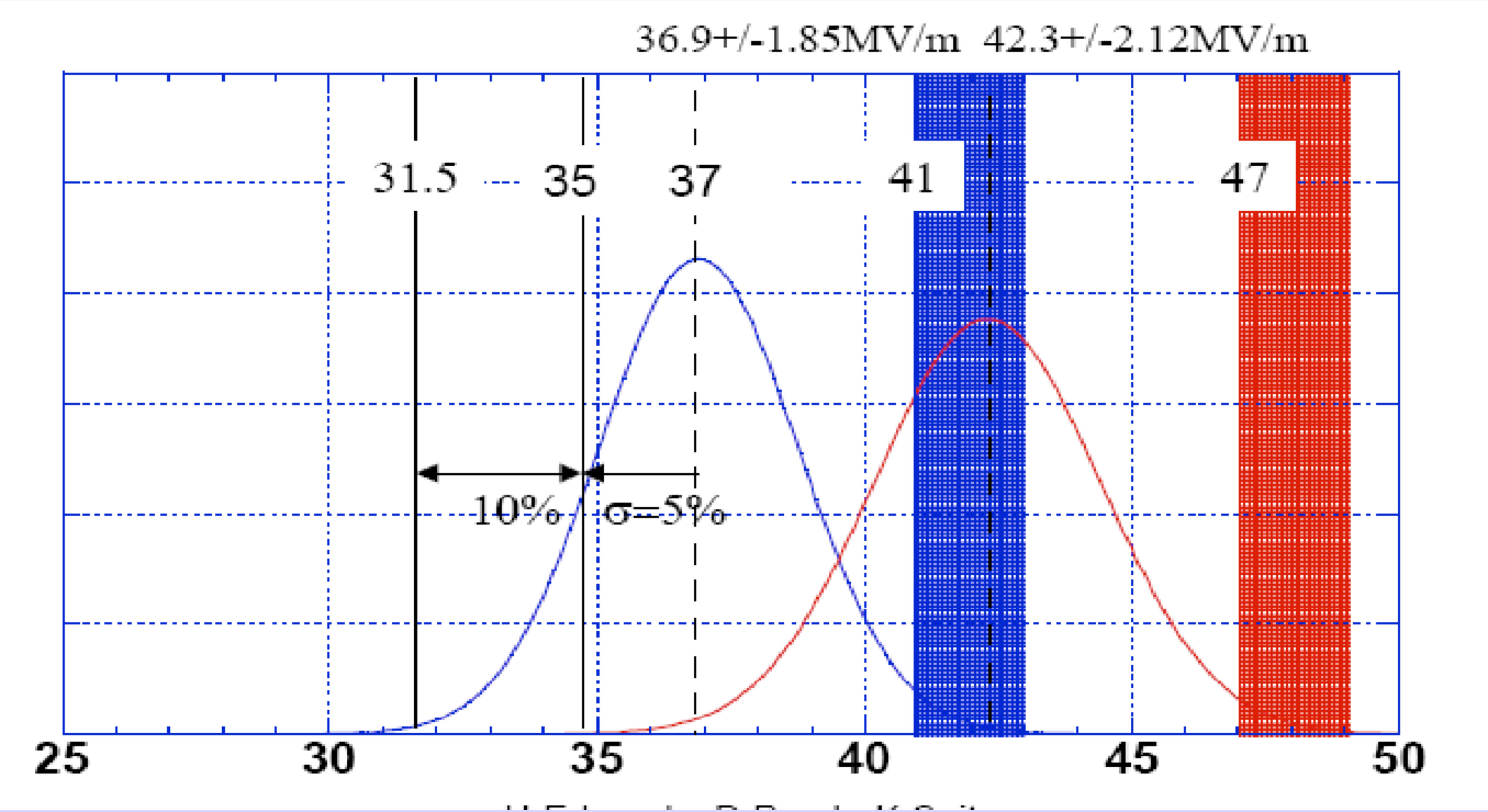
Approximately 20 years of R&D worldwide
? Mature technology

Superconducting RF Cavities

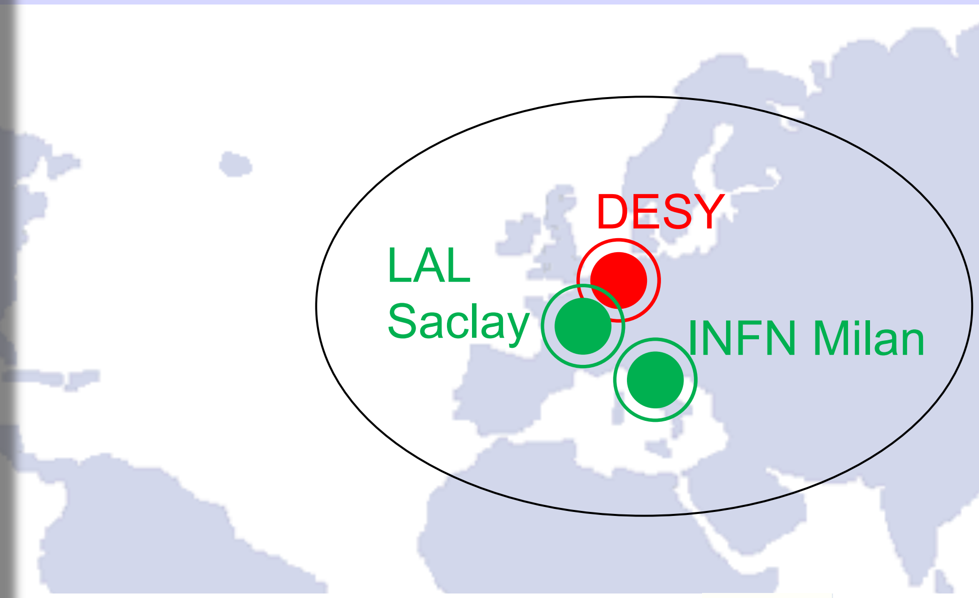


High Gradient Accelerator
35 MV/meter -- 40 km linear collider

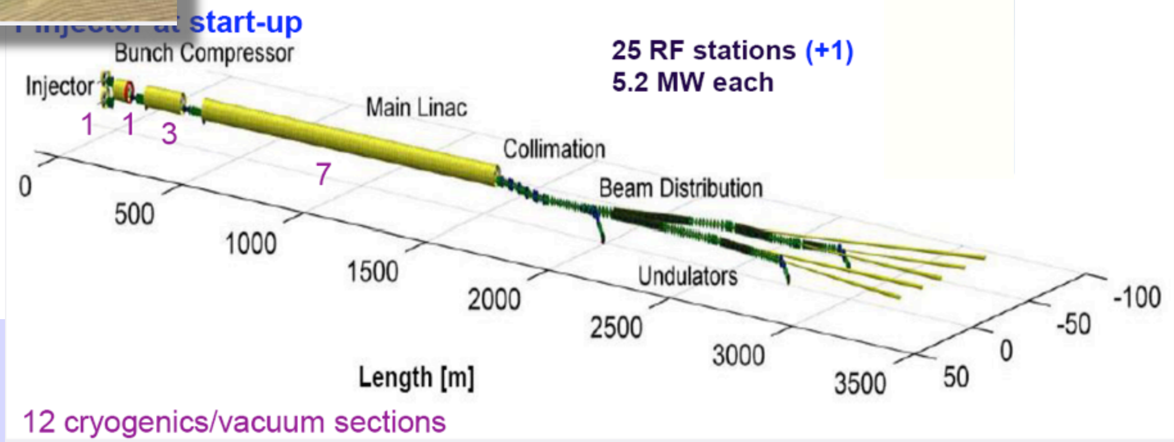
Baseline Gradient



European XFEL



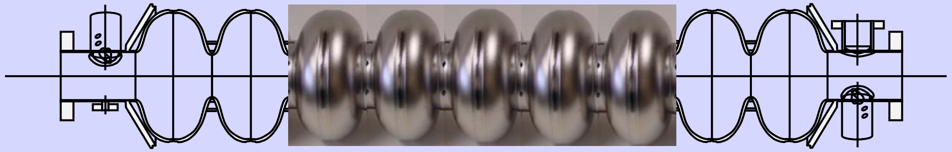
- 17.5 GeV (20 GeV)
- 100 Cryomodules
- 800 cavities
- Gradient:
  - 23.5 MV/m
  - (28 MV/m)

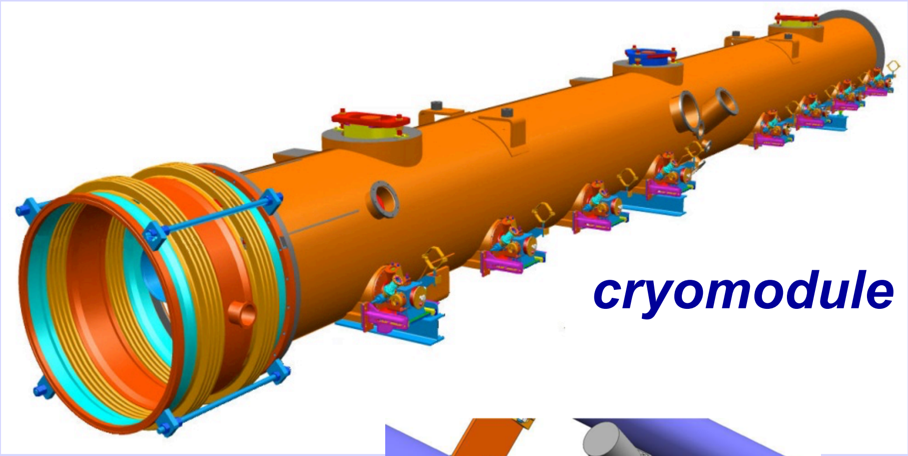


- Industrialisation & mass production
  - 1 CM / week
- “In-kind” international model

Superconducting RF Linac Technology

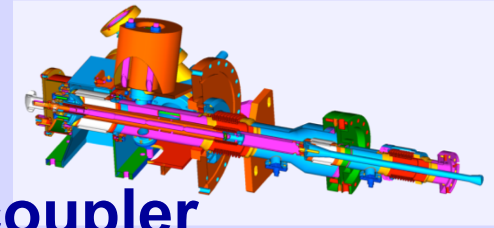
cavity



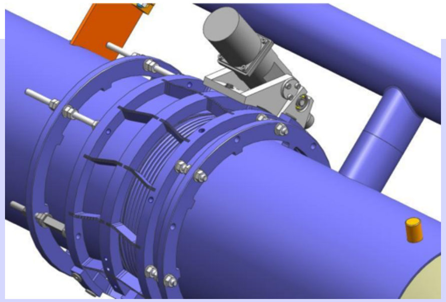


cryomodule

SCRF Linac Technology

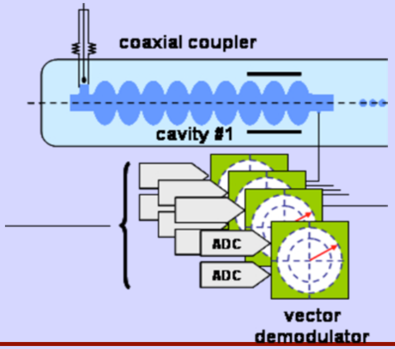


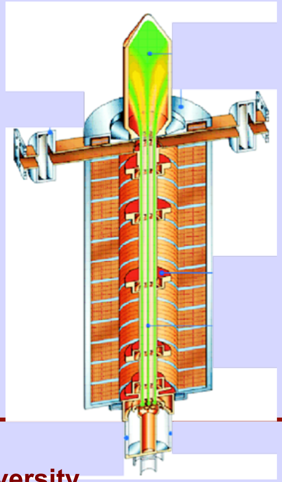
coupler



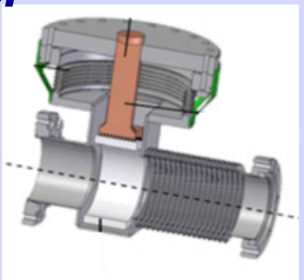
tuner

LLRF





RF



HOMs

Luminosity & Beam Size

$$L = \frac{n_b N^2 f_{rep}}{2\pi\sigma_x\sigma_y} H_D$$

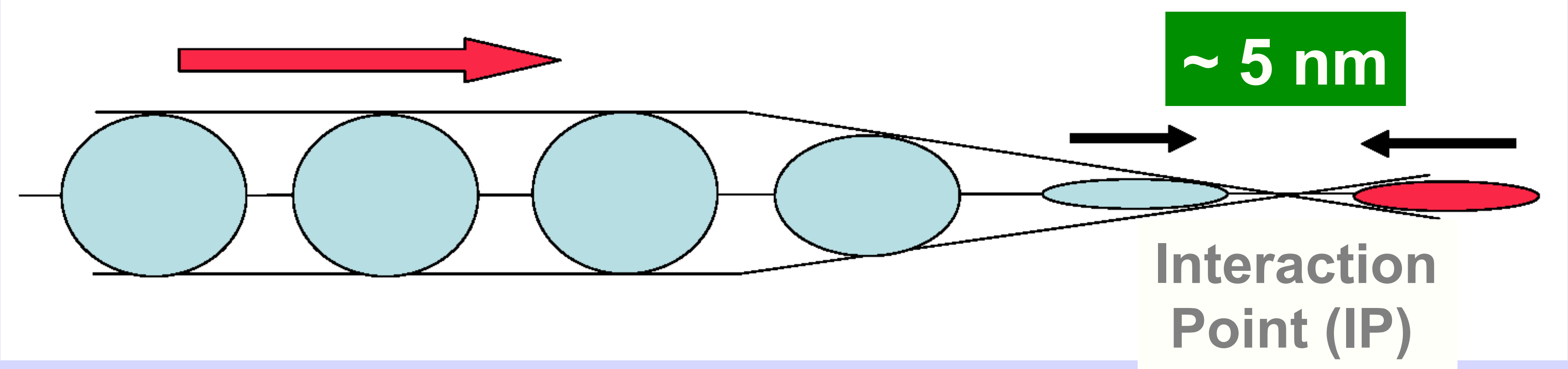
- f_{rep} * n_b tends to be low in a linear collider

	L	f_{rep} [Hz]	n_b	N [10^{10}]	σ_x [μm]	σ_y [μm]
ILC	2×10^{34}	5	3000	2	0.5	0.005
SLC	2×10^{30}	120	1	4	1.5	0.5
LEP2	5×10^{31}	10,000	8	30	240	4
PEP-II	1×10^{34}	140,000	1700	6	155	4

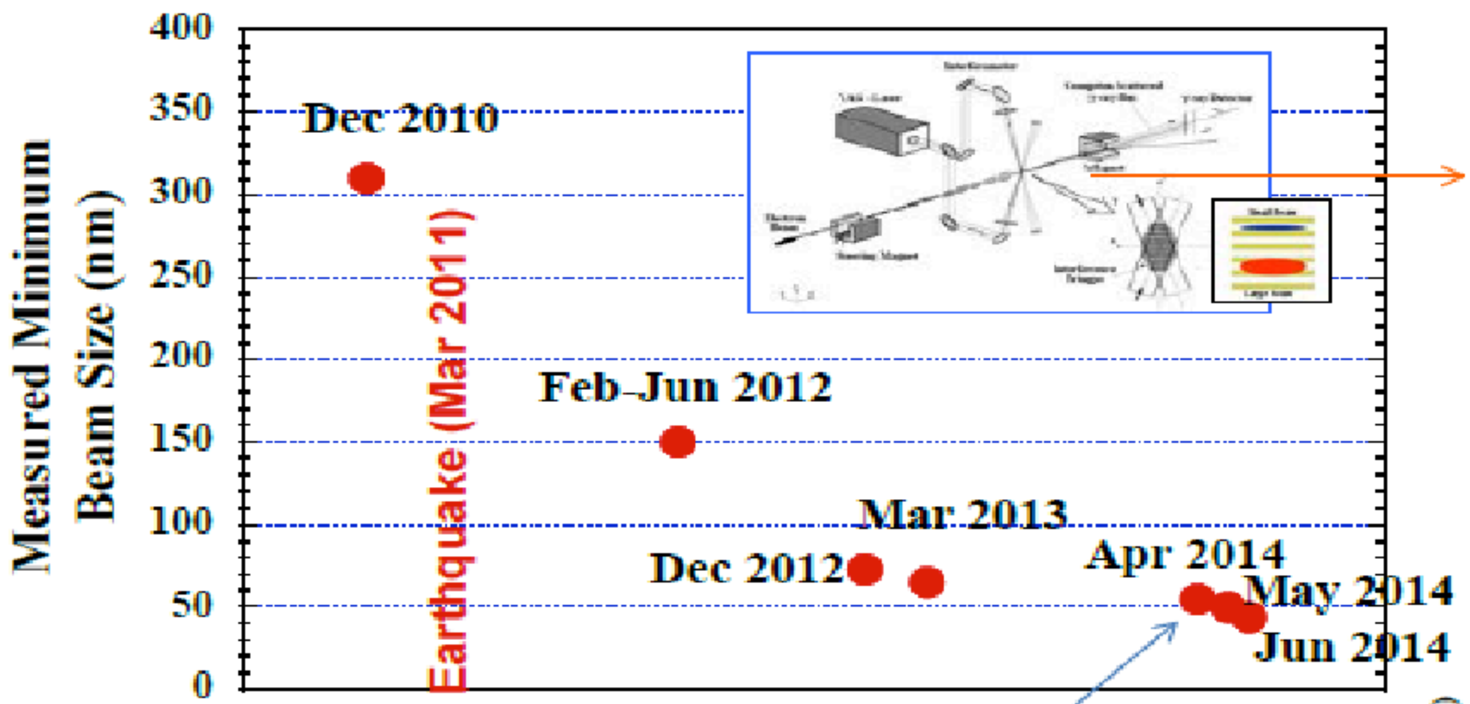
- Achieve luminosity with spot size and bunch charge

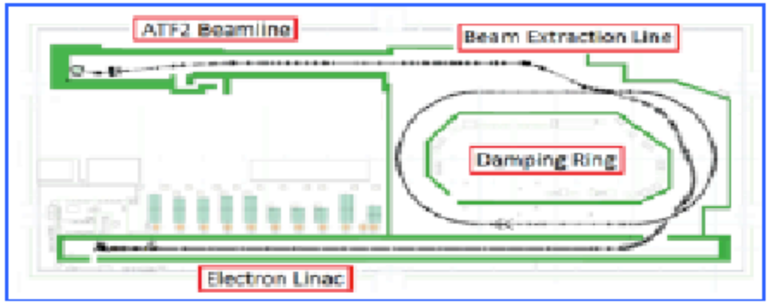
Achieving High Luminosity

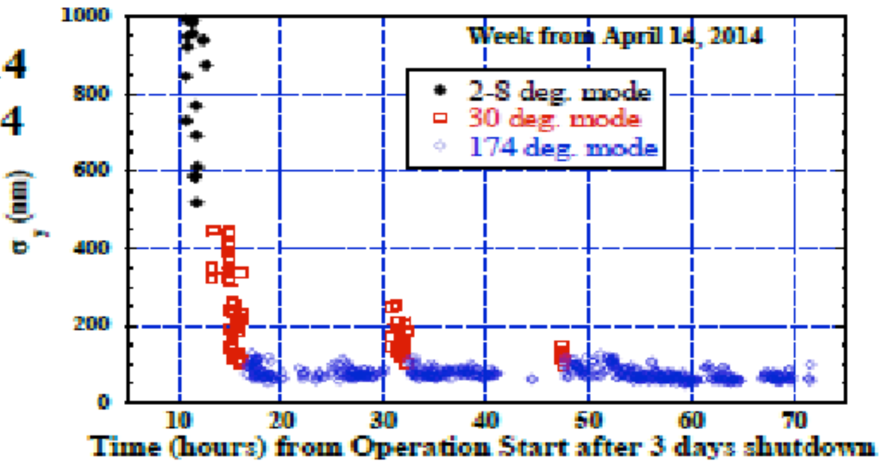
- Low emittance machine optics
- Contain emittance growth
- Squeeze the beam as small as possible



Progress in Beam Size at ATF2



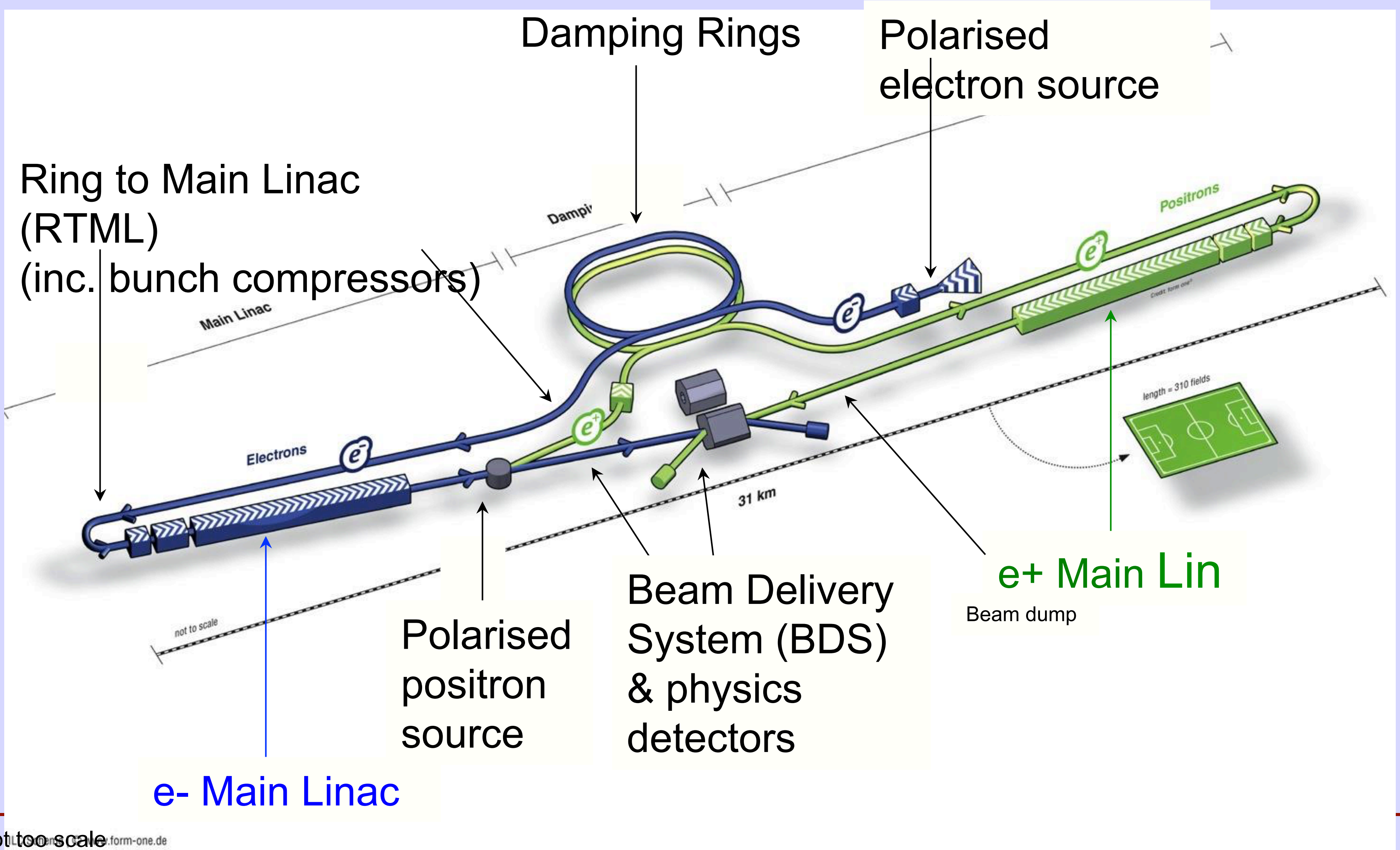




Beam Size 44 nm observed,
(Goal : 37 nm
corresponding to 6 nm at ILC)

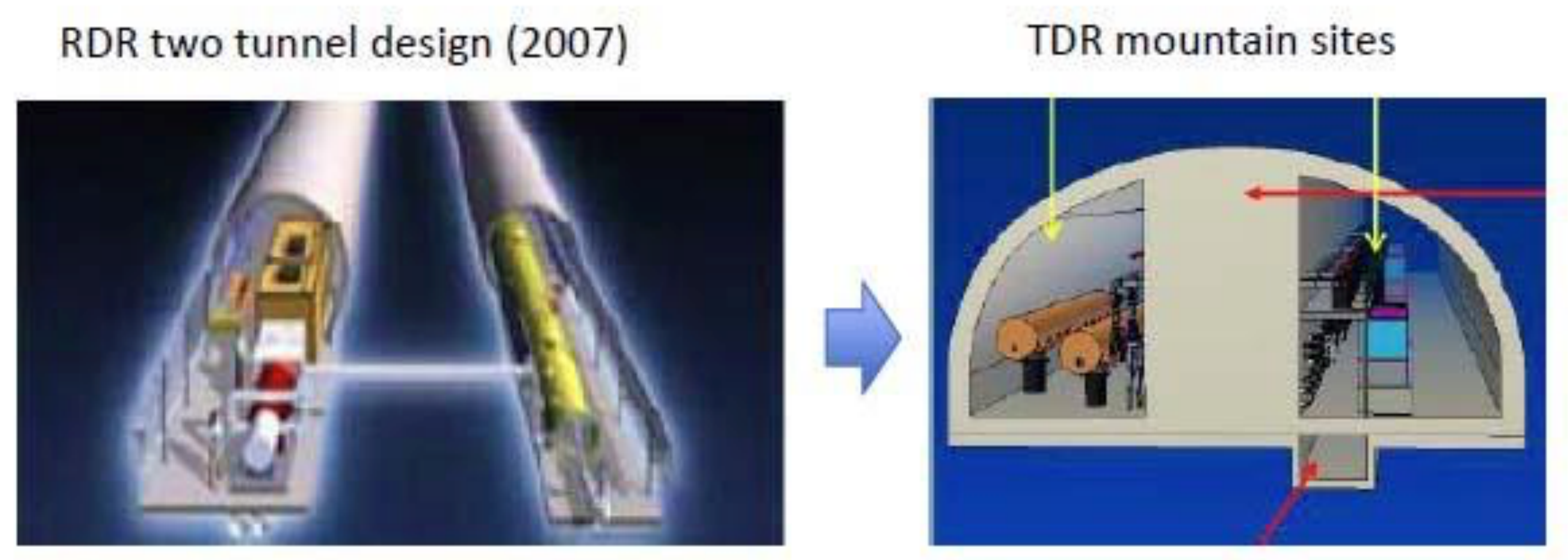
A. Yamamoto, 160120

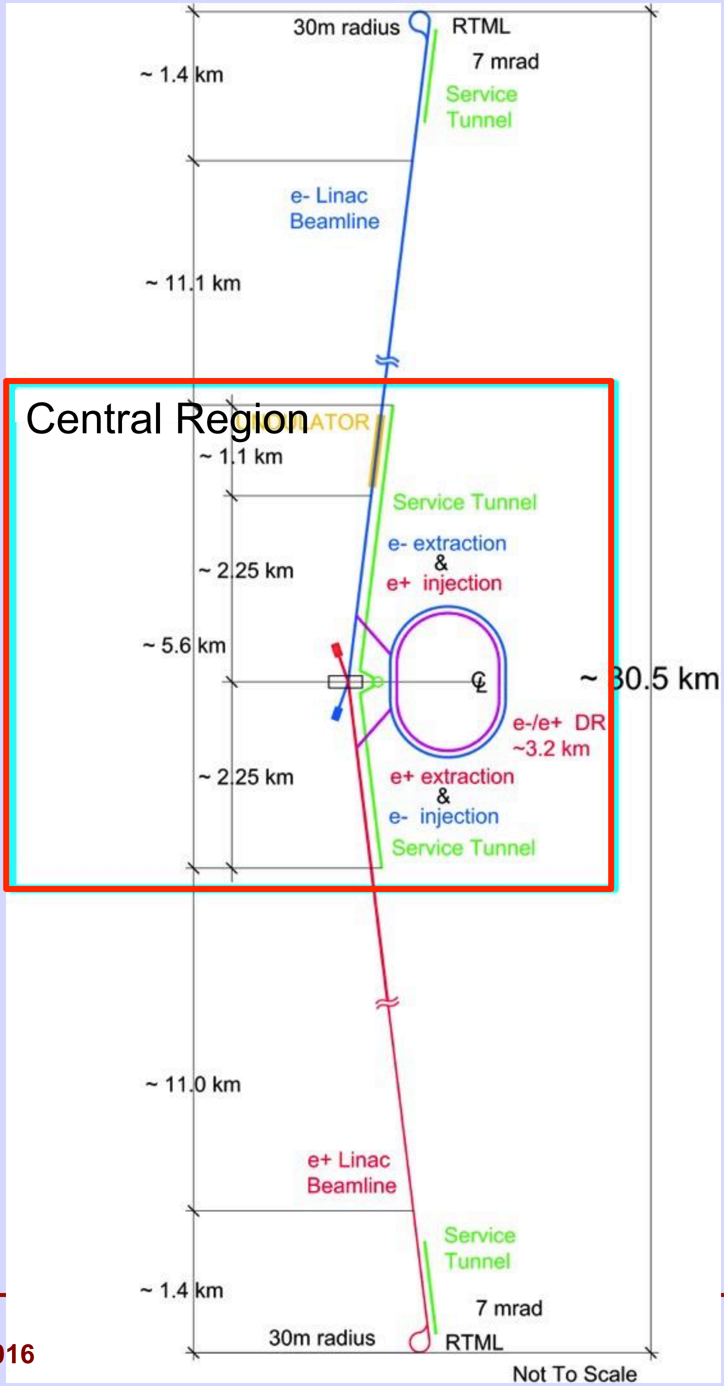
ILC General Layout



Conventional Facilities

Japan -- Tunnel Shape





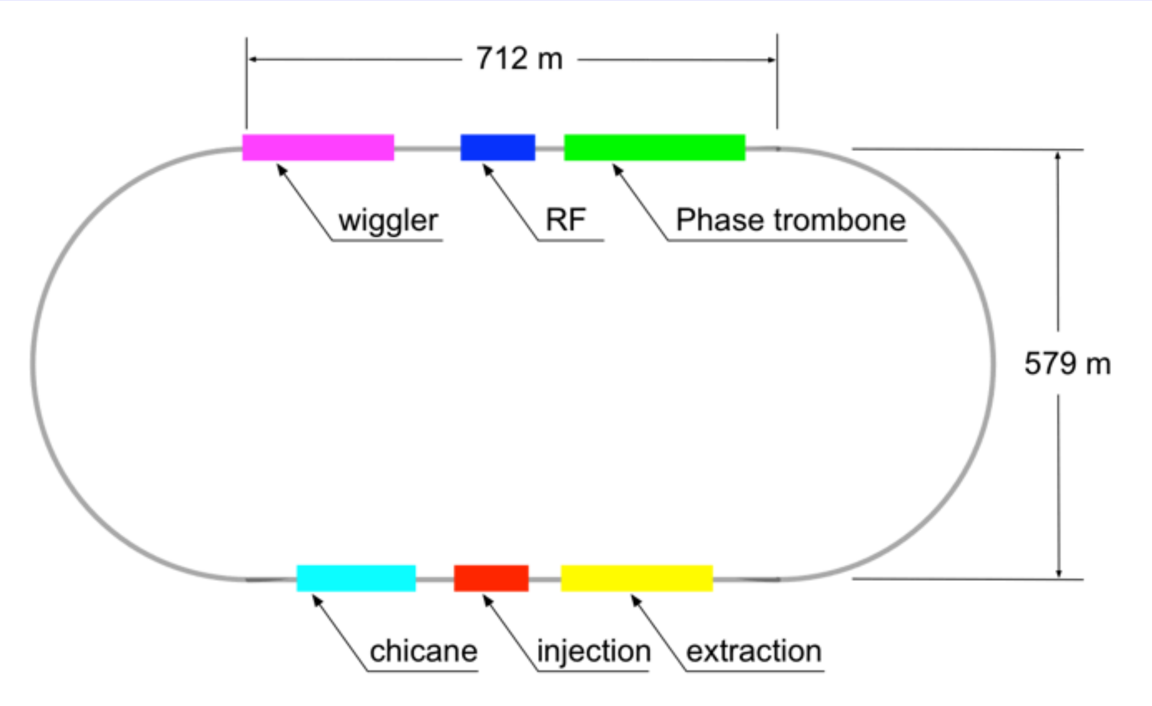
Central Region

- **5.6 km region around IR**
- **Systems:**
  - **electron source**
  - **positron source**
  - **beam delivery system**
  - **RTML (return line)**
  - **IR (detector hall)**
  - **damping rings**

common tunnel

- **Complex and crowded area**

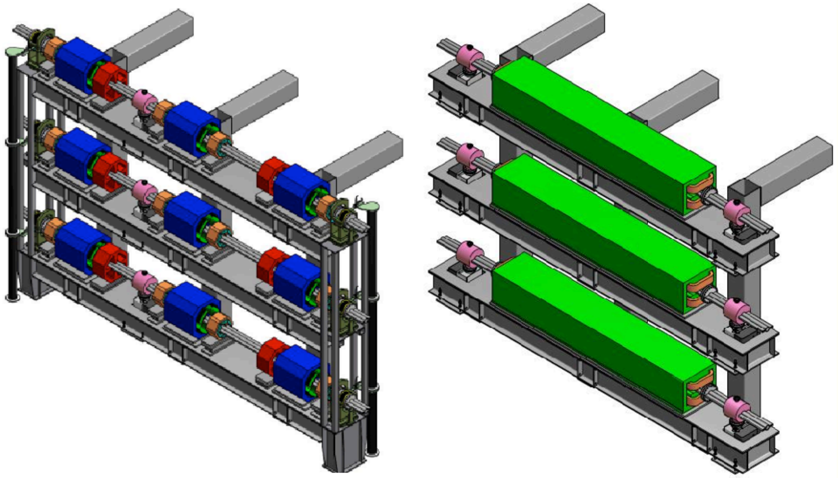
Damping Rings



Circumference		3.2	km
Energy		5	GeV
RF frequency		650	MHz
Beam current		390	mA
Store time		200 (100)	ms
Trans. damping time		24 (13)	ms
Extracted emittance	x	5.5	µm
(normalised)	y	20	nm
No. cavities		10 (12)	
Total voltage		14 (22)	MV
RF power / coupler		176 (272)	kW
No.wiggler magnets		54	
Total length wiggler		113	m
Wiggler field		1.5 (2.2)	T
Beam power		1.76 (2.38)	MW

Values in () are for 10-Hz mode

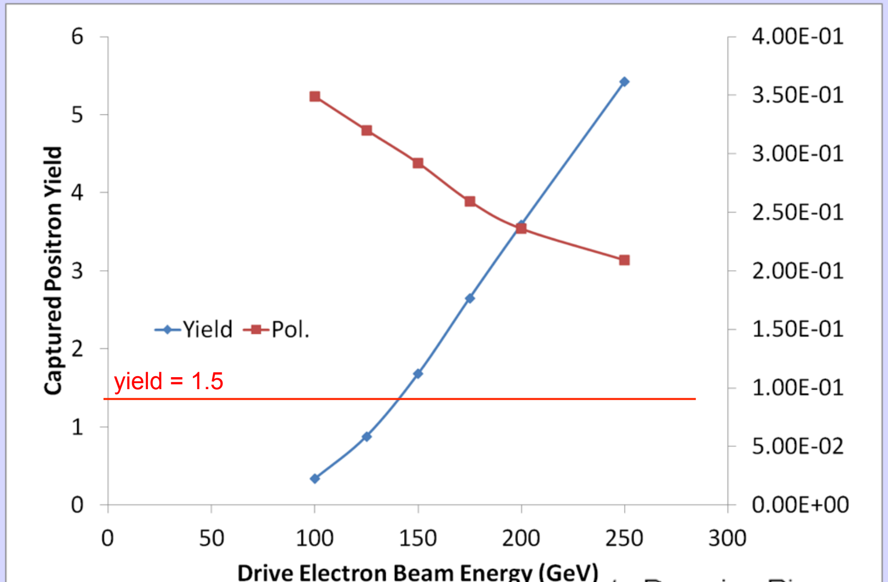
Many similarities to modern 3rd-generation light sources

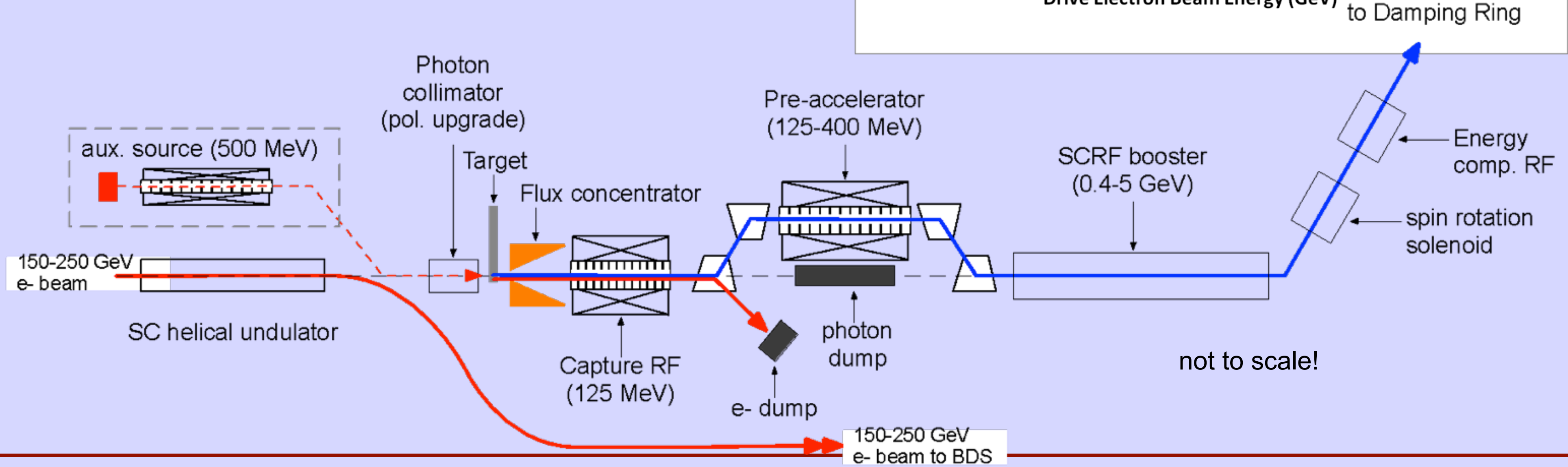


Arc quadrupole section   Dipole section

Positron Source (central region)

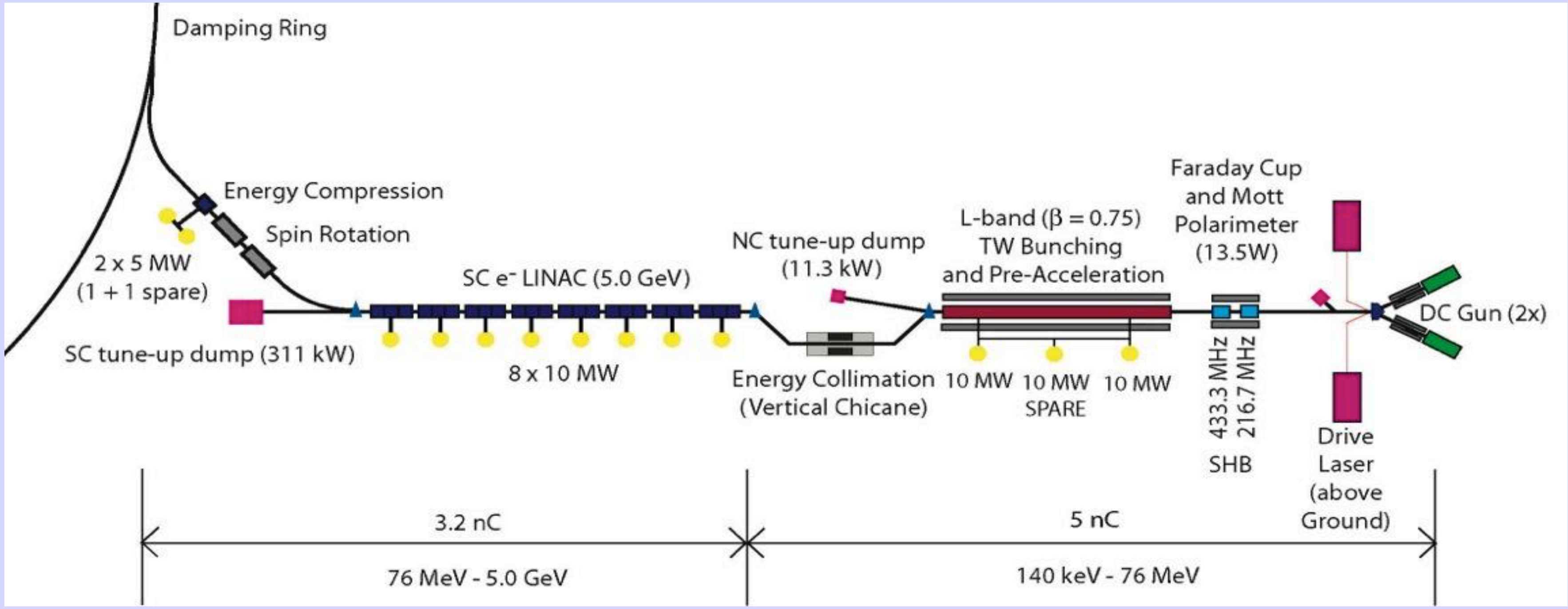
- located at exit of electron Main Linac
- 147m SC helical undulator
- driven by primary electron beam (150-250 GeV)
- produces ~30 MeV photons
- converted in thin target into e+e- pairs



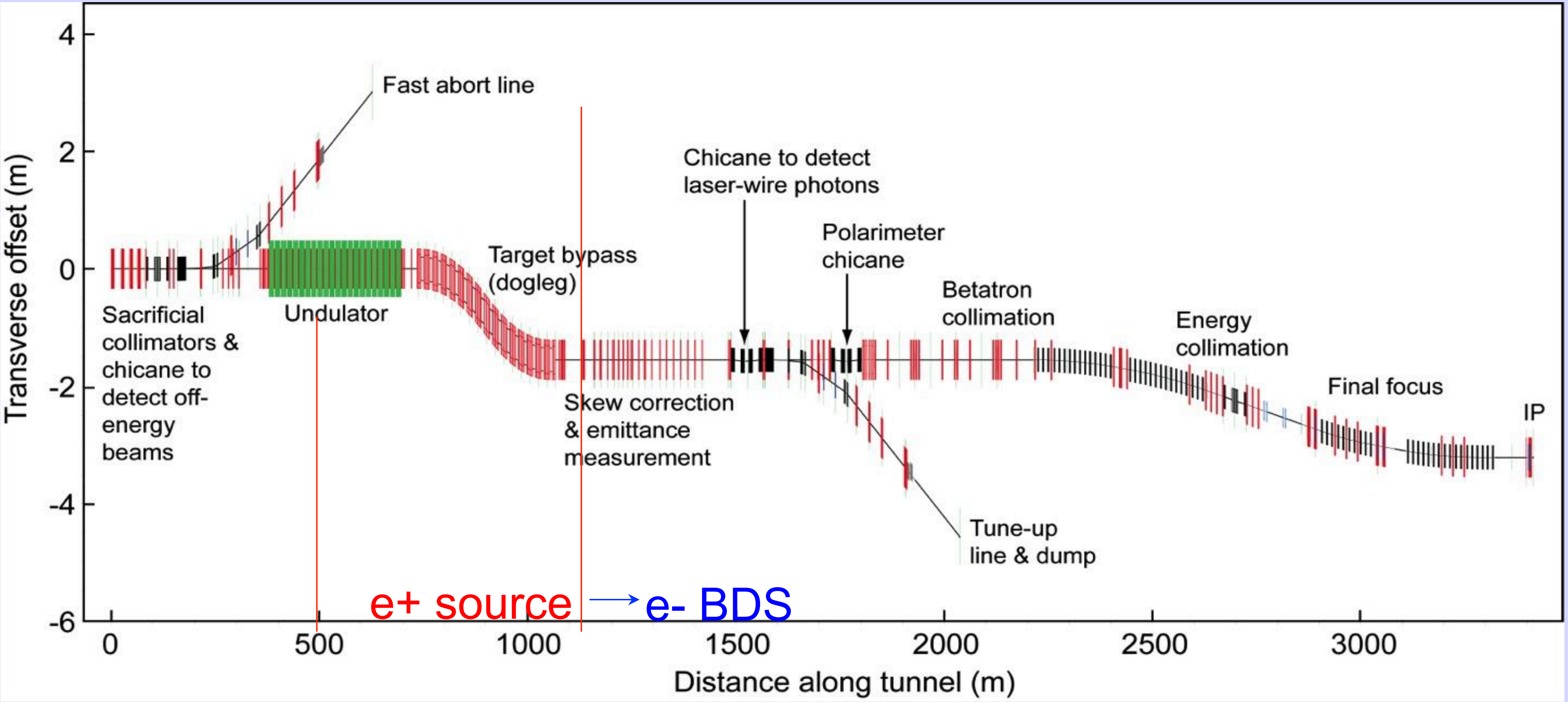


Polarised Electron Source

- **Laser-driven photo cathode (GaAs)**
- **DC gun**
- **Integrated into common tunnel with positron BDS**

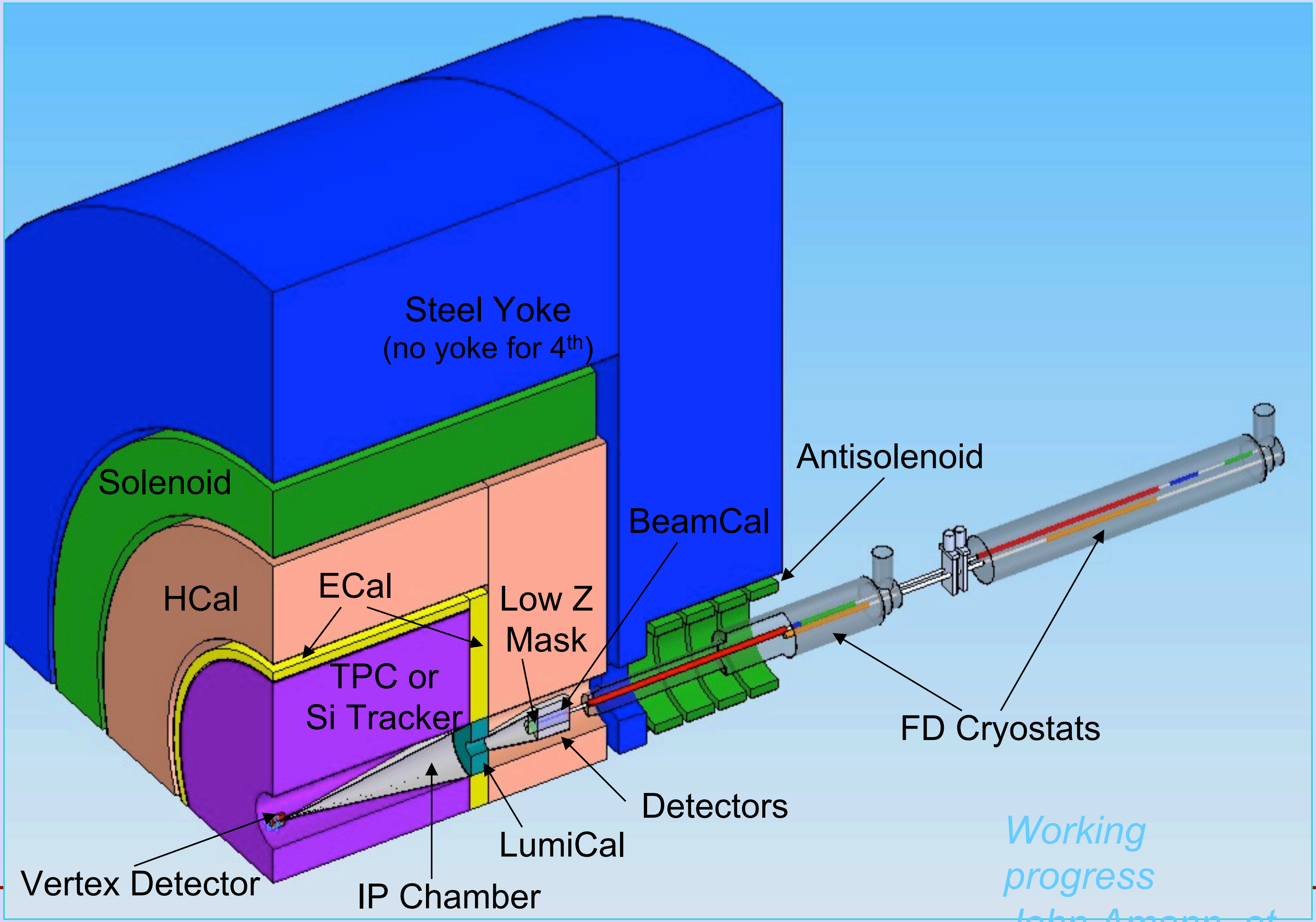


Beam Delivery System



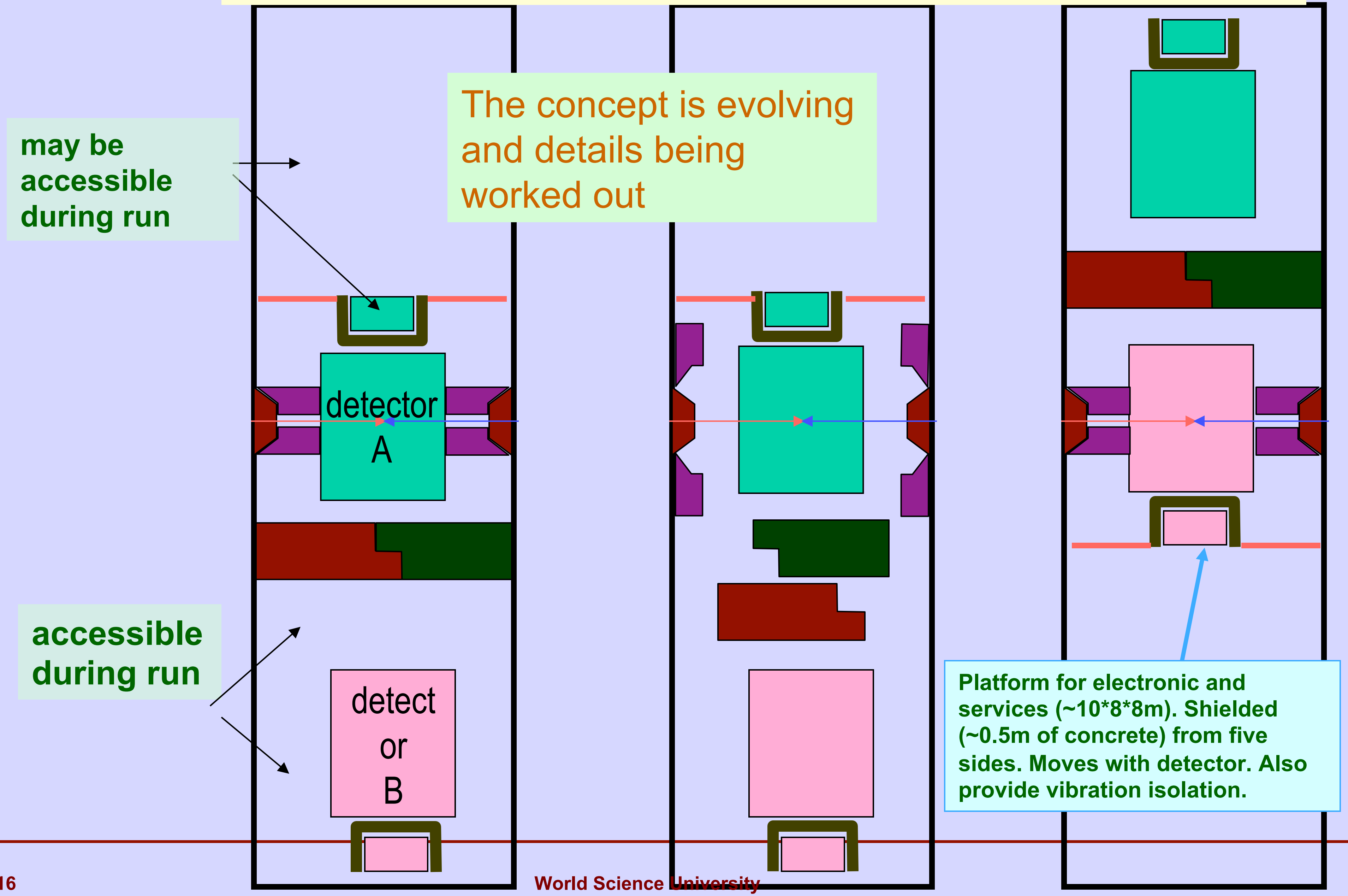
Electron Beam Delivery System

Generic Detector - IR Details



Working progress John Amann, et al

Concept of IR hall with two detectors



Detector Performance Goals

- **ILC detector performance requirements and comparison to the LHC detectors:**
  - **Inner vertex layer ~ 3-6 times closer to IP**
  - **Vertex pixel size ~ 30 times smaller**
  - **Vertex detector layer ~ 30 times thinner**

  Impact param resolution $\Delta d = 5\ [\mu m] \oplus 10\ [\mu m] / (p[GeV] \sin 3/2\theta)$

  - **Material in the tracker ~ 30 times less**
  - **Track momentum resolution ~ 10 times better**

  Momentum resolution $\Delta p / p^2 = 5 \times 10^{-5}\ [GeV^{-1}]$ central region

  $\Delta p / p^2 = 3 \times 10^{-5}\ [GeV^{-1}]$ forward region

  - **Granularity of EM calorimeter ~ 200 times better**

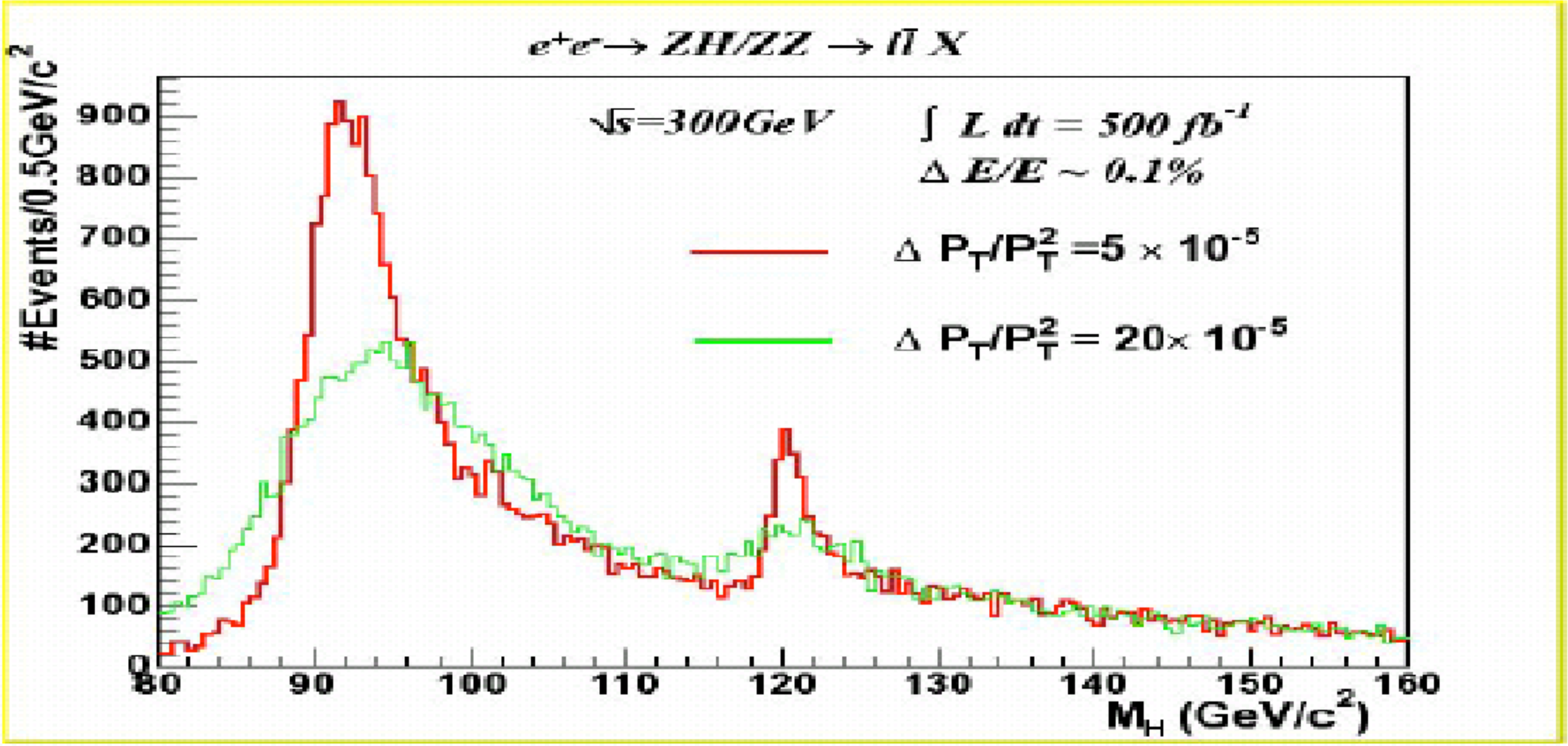
  Jet energy resolution $\Delta E_{jet} / E_{jet} = 0.3 / \sqrt{E_{jet}}$

  Forward Hermeticity down to θ = 5-10 [mrad]

Detector Performance Goals

e.g: The Higgs tagging mode

$$e^+e^- \to ZH, \quad Z \to \ell^+\ell^-$$



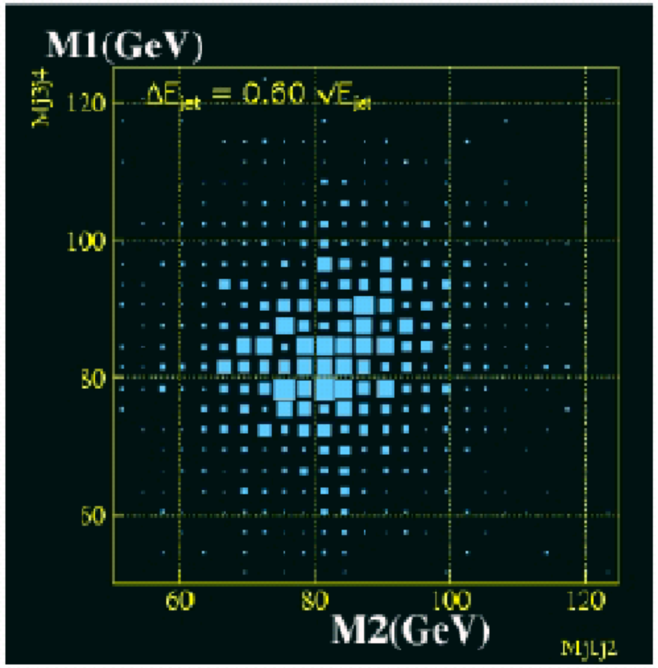
$\sigma_p/p^2 \sim 5 \times 10^{-5}$ is "necessary"

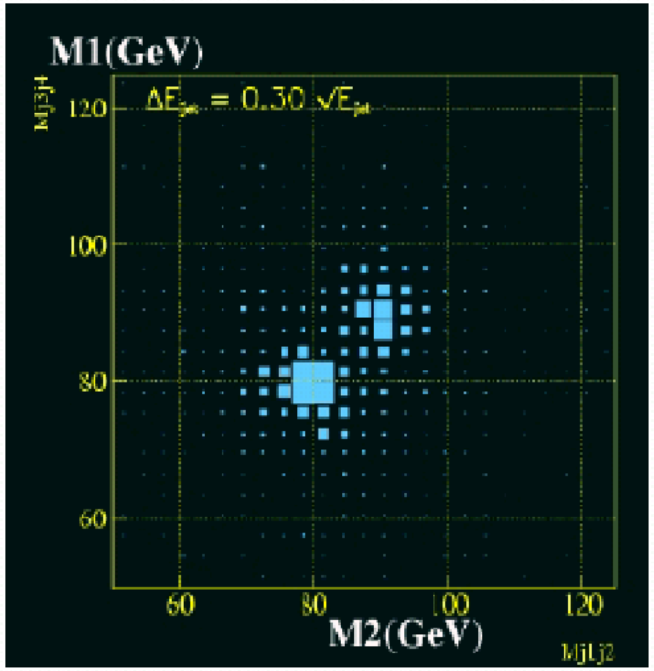
Detector Performance Goals

e.g: Separation of WW and ZZ

$$e^+e^- \rightarrow \nu\bar{\nu}W^+W^-, \nu\bar{\nu}ZZ\,, \quad W, Z \rightarrow \text{2jets}$$

$$\frac{\sigma_E}{E} = \frac{0.6}{\sqrt{E}} \qquad\qquad \frac{\sigma_E}{E} = \frac{0.3}{\sqrt{E}}$$

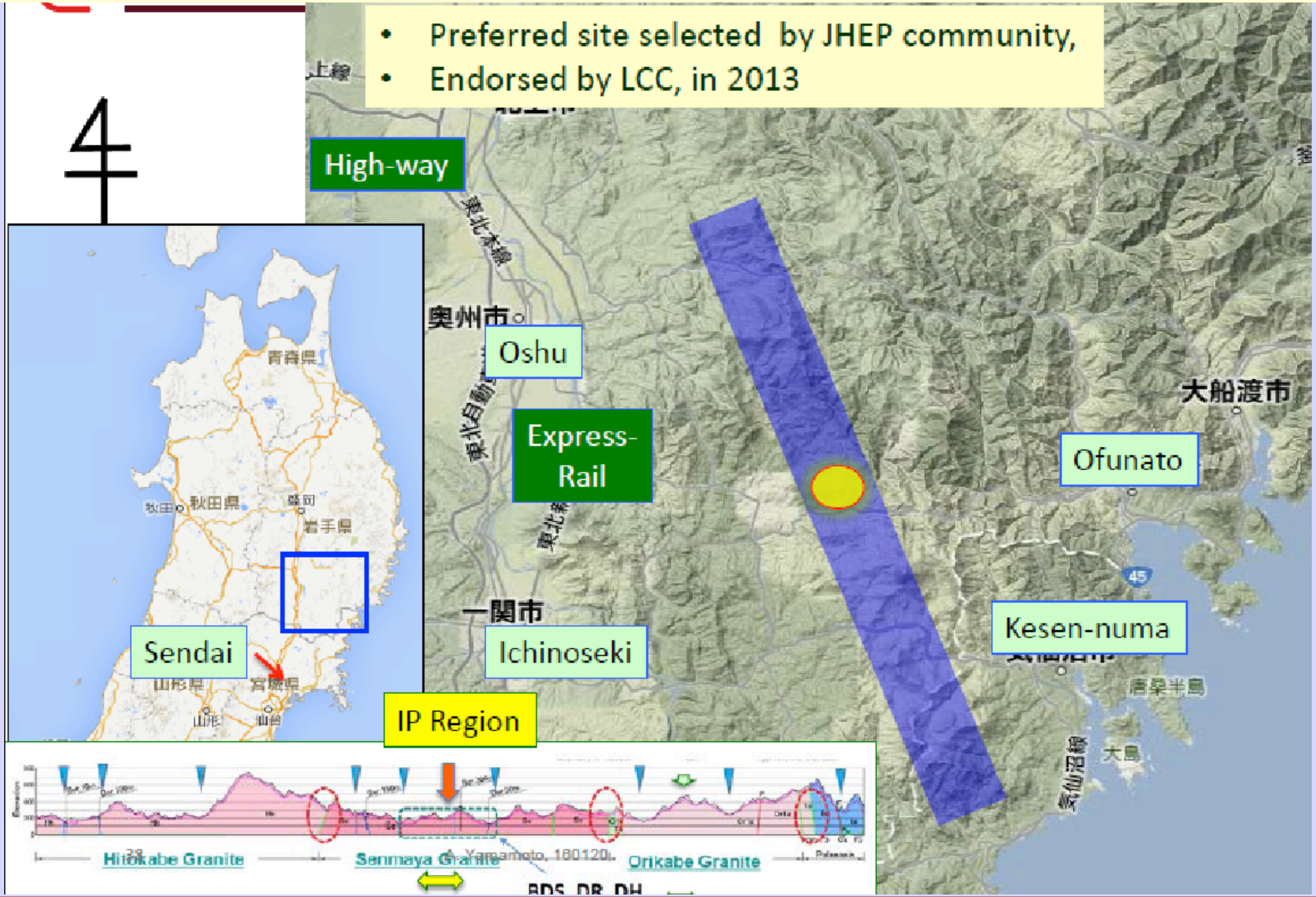




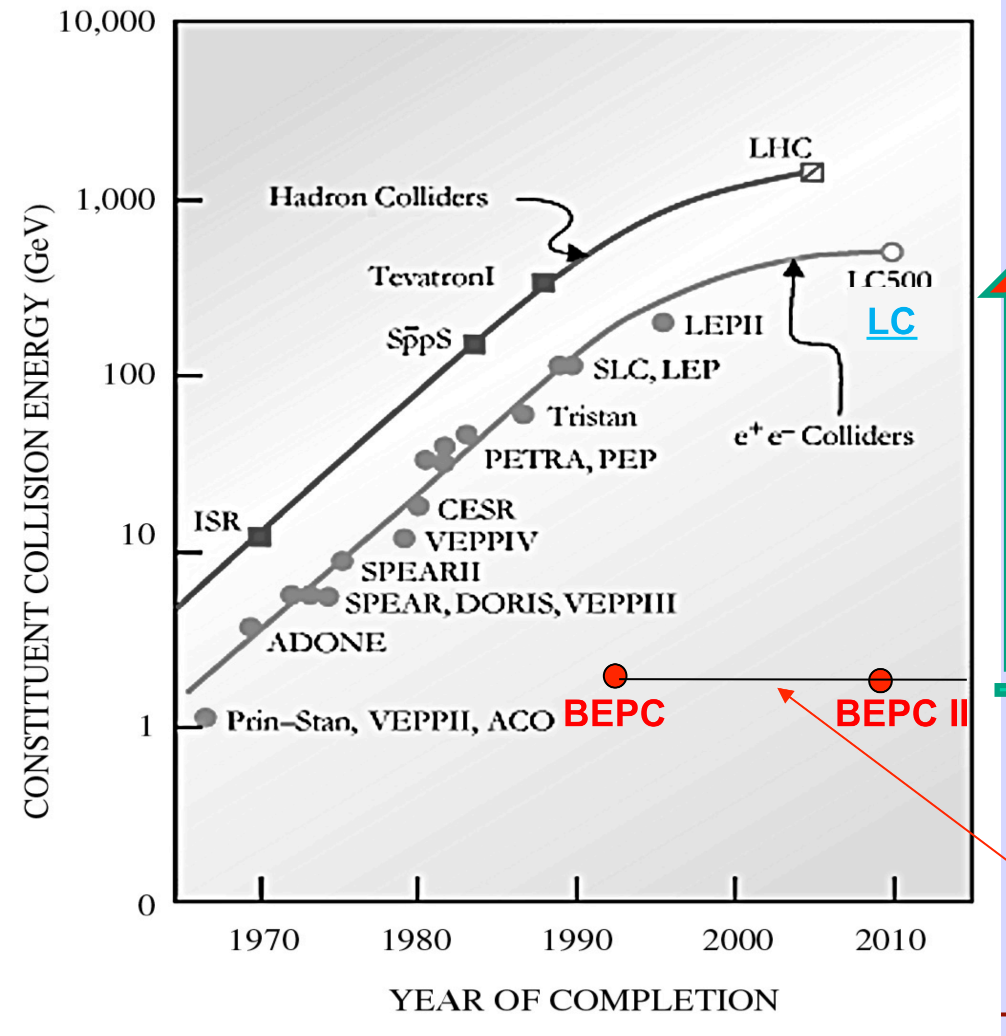
$\frac{\sigma_E}{E} \sim \frac{0.3}{\sqrt{E}}$ is 'needed'.

For jets !!!!

ILC Site in Japan
Kitakami – 500 km North of Tokyo



Chinese Future Accelerator



CEPC+SppC

CEPC: Ecm=240GeV e+e- Circular Collider

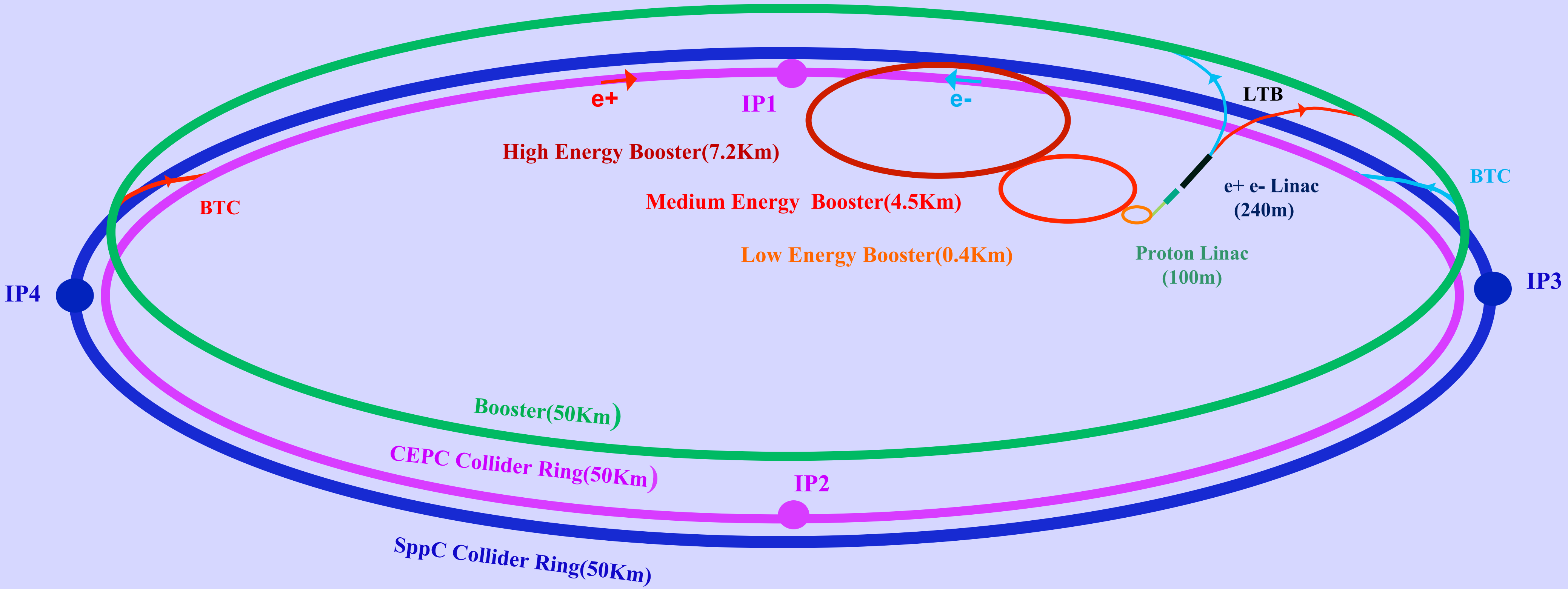
SppC: Ecm=50-100TeV pp Collider

CEPC+SppC will be constructed with international collaboration and participation

HIEPAF: High Intensity Electron Positron Accelerator Facility

History of BEPC and BEPC II

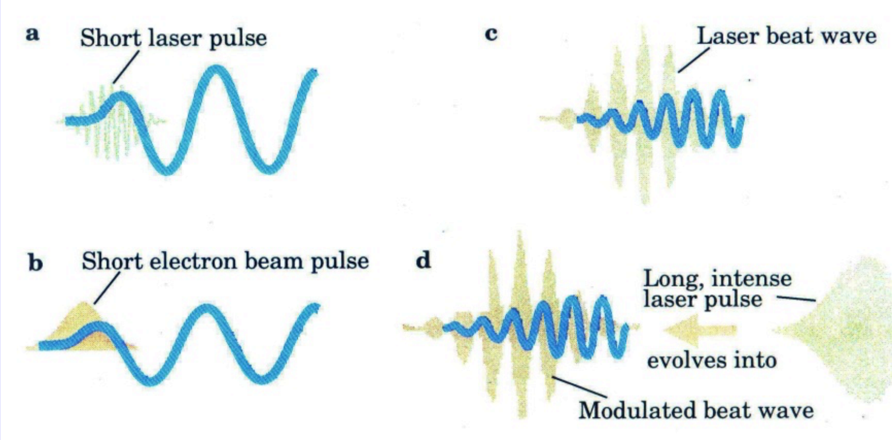
CEPC/SppC Layout



LTB : Linac to Booster

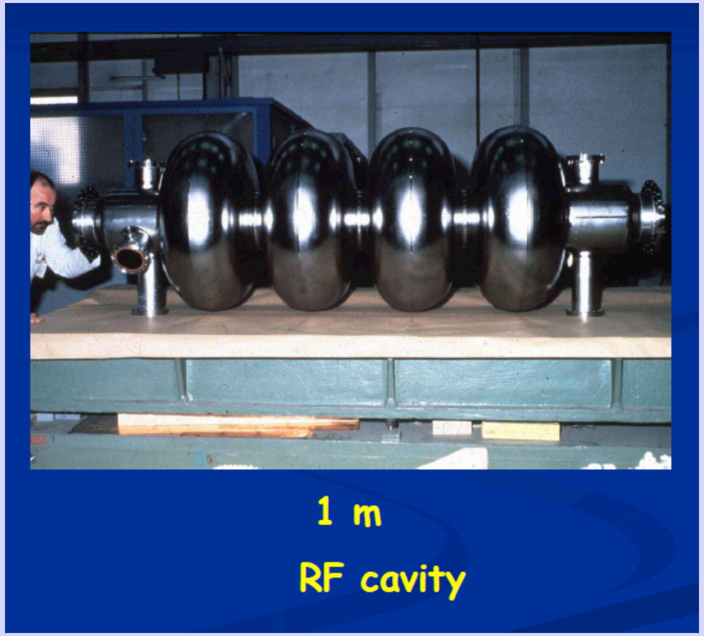
BTC : Booster to Collider Ring

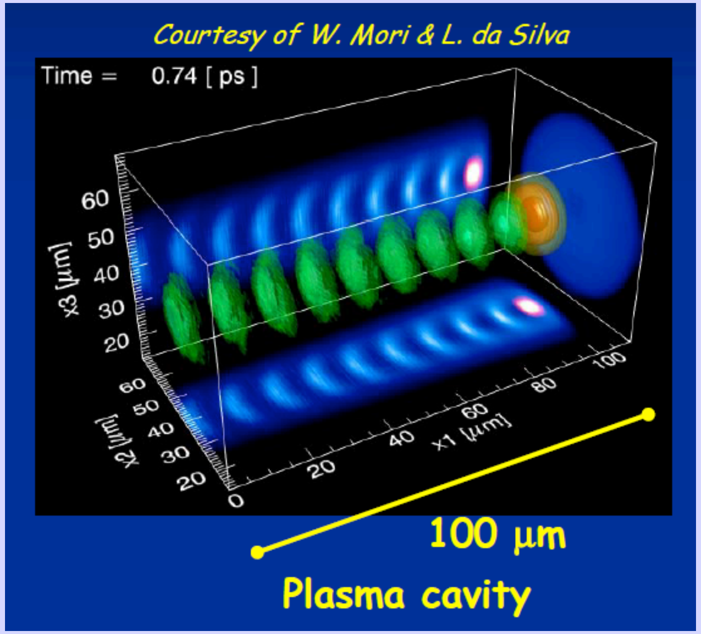
Accelerators of the Future ?



ELIMINATE MATERIALS !!

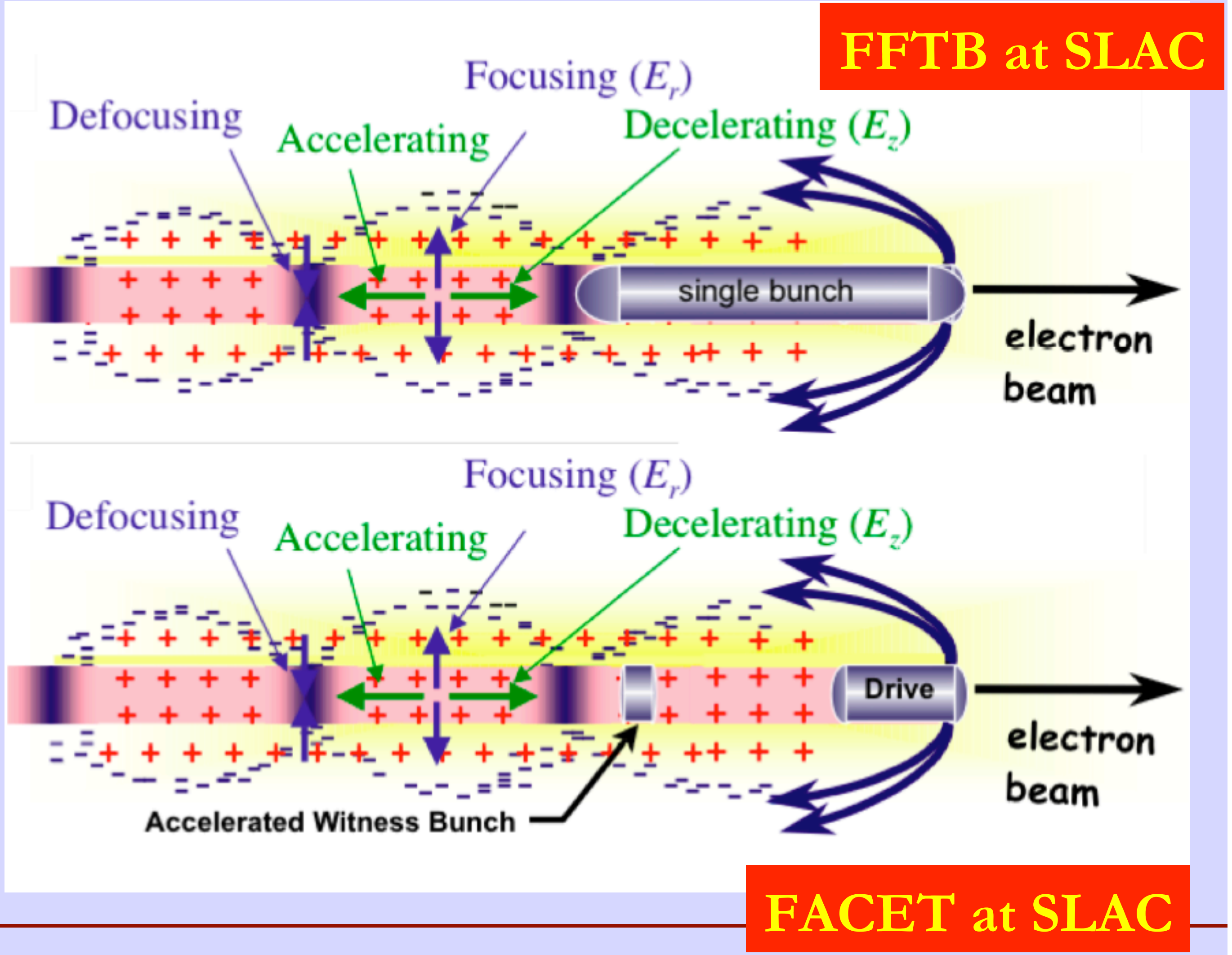
Plasma/Laser Wakefield Acceleration

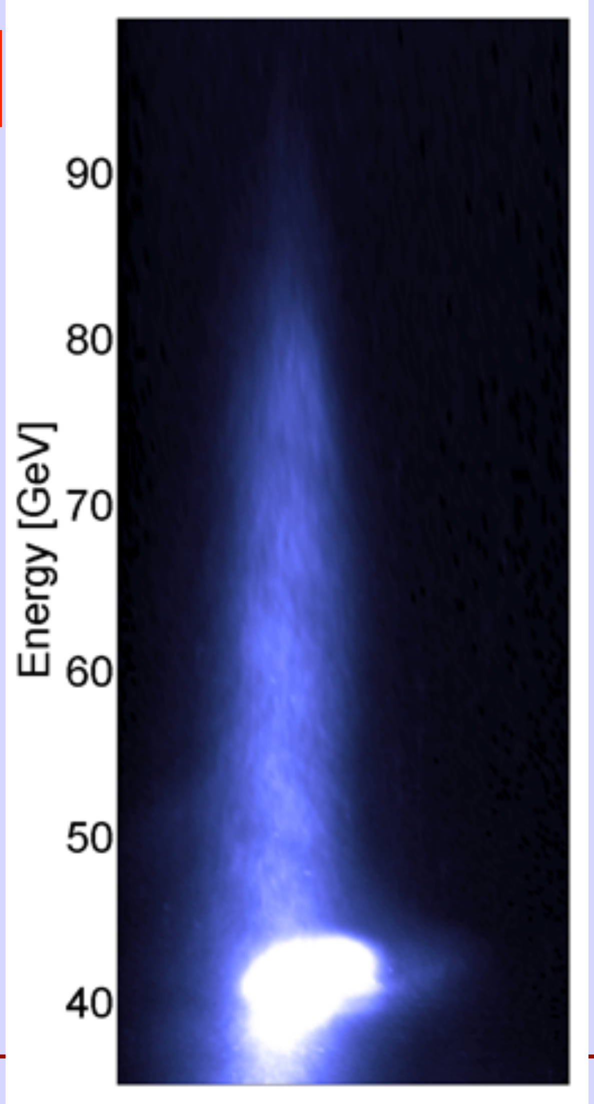




Compact Acceleration

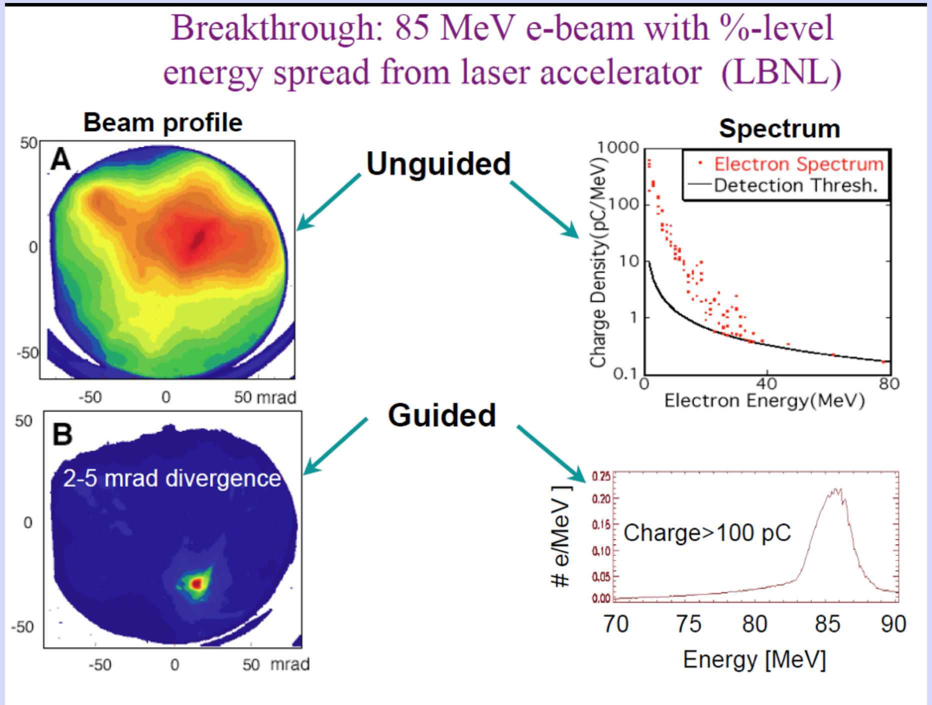
50 GeV/meter has been achieved



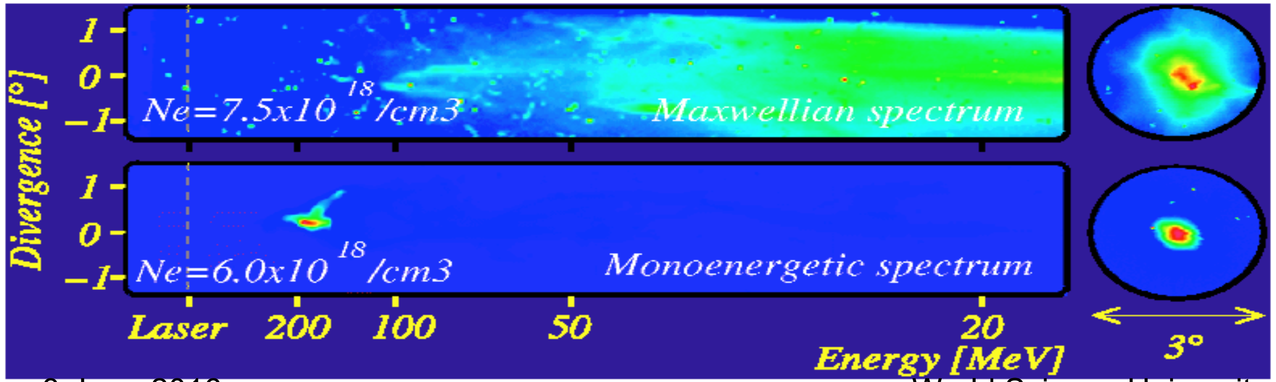


Controlling the Beams

LBNL



Reducing energy spread to ~ percent level



Reducing angular divergence (< 1 degree)

Conclusions

The International Linear Collider

- Strong Science Motivation: Higgs, Top physics ++
- Mature Technology; Well-reviewed Technical Design
- Japan to host ???   2025 +

Other Options

- CLIC -- ~ 2-3 Tev R&D? power consumption? 2030 +
- Muon Collider R&D??? 2035 +
- CEPC/SppC Large Ring in China 2035 or future high energy collider (CERN)

Long Range Possibilities

- Laser-driven or Beam-driven Plasma-Wakefield Accelerator