High Energy Frontier
Future High Energy Colliders

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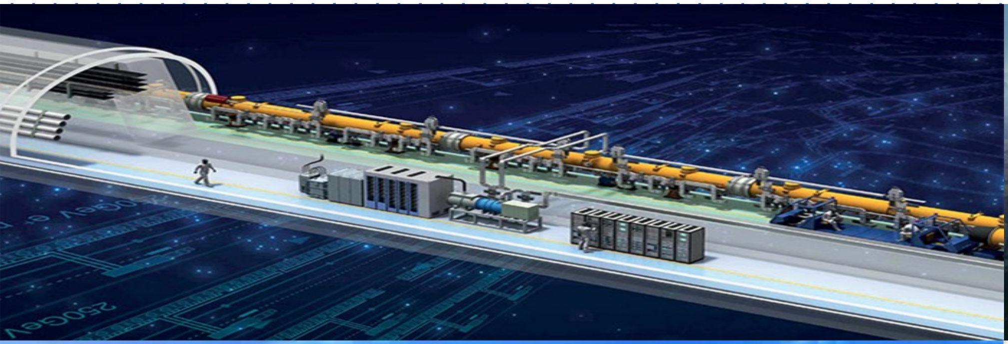
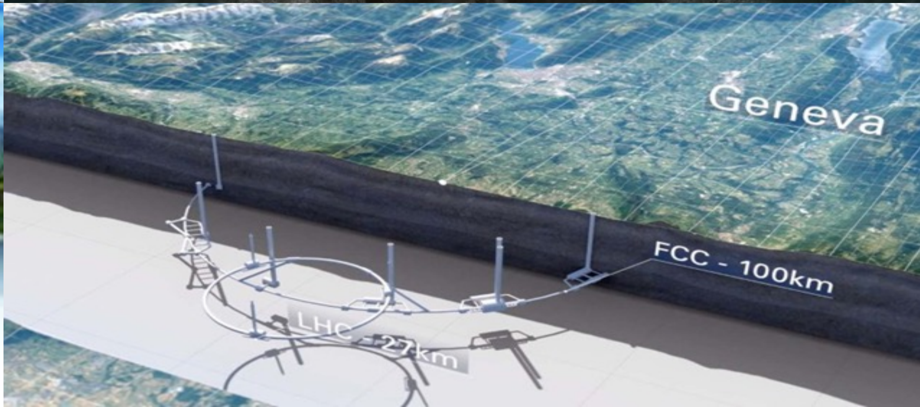




Outline

- **Introduction:**
  - particle physics
  - high energy particle colliders
  - important science questions,
  - discovery of the Higgs boson & the opportunities
- **Future High Energy Particle Physics Colliders**
- **Status and Development**
- **Innovations and Challenges**
- **Summary**

Introduction

particle physics

high energy particle colliders

important science questions

discovery of the Higgs boson & the opportunities

Big & Important Questions in Particle Physics

Challenges to Human

Constitutes of Matter
Evolution of the Universe

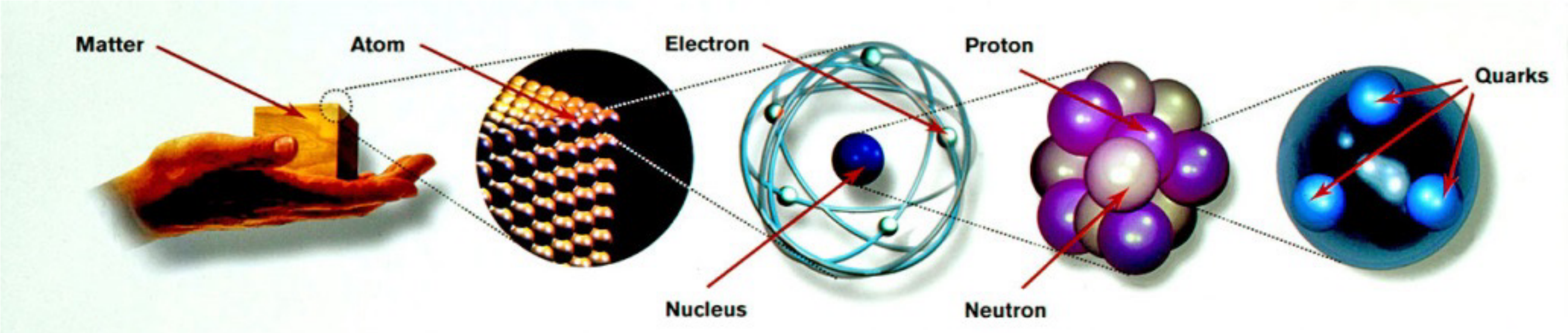
«Science» 125 Questions:
Where did the Big Bang Start?
What Is the Universe Made Of?
What are the smallest building blocks of matter?
What is dark matter?

Important Frontier Science Questions

- What is the origin of the flavor symmetry?
- Why the masses of the fundamental particles are so different?
- Why the vacuum of the Standard Model is unstable?
- Where is the mass of the Higgs from?
- Where are the new physics and particle beyond SM?
- Matter-antimatter asymmetry, dark matter, why?

Ask scientists!

Constitutes of Matter



Matter in fine details

Structure of Matter- Particle Physics

Fundamental building blocks: quarks, leptons, force mediators

generation / particle	I	II	III	gauge bosons
Quarks	u (0.005)	c (1.5)	t (180)	gluon 1
(mass / strength)	d (0.01)	s (0.2)	b (4.7)	γ 1/1,000
Leptons	e (.0005)	μ (0.106)	τ (1.777)	Z^0 **1/10,000**
(mass/ strength)	ν_e $<7\times10^{-9}$	ν_μ $<.0003$	ν_τ <0.03	$W^\pm$

3 generations of quarks & leptons
Bosons as force mediator

Remarkable symmetry

scale: proton mass ~ 1 GeV

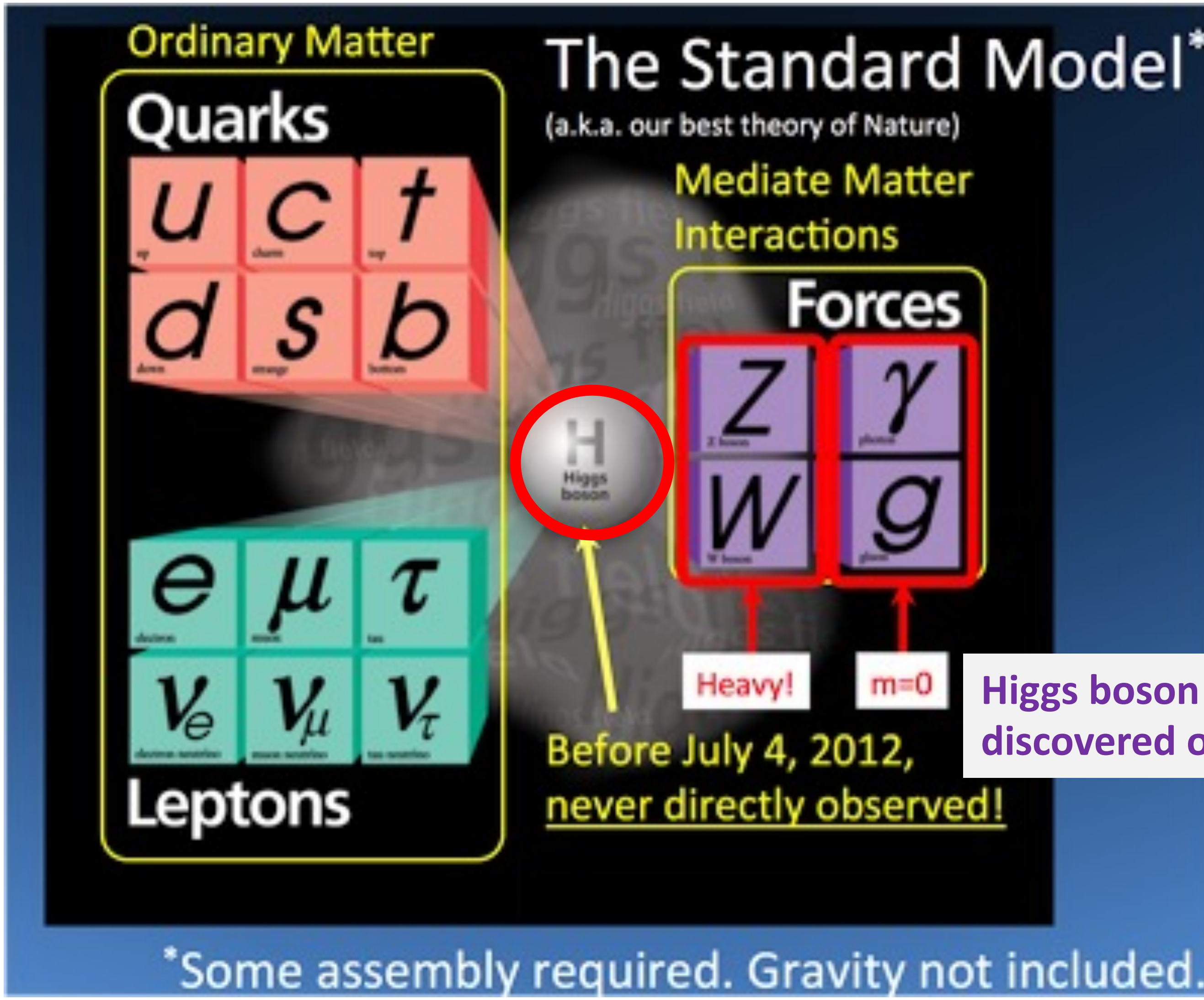
91 GeV

hugely different masses

80.4 GeV

But their masses are so different – a big problem for physicists

Why?



Higgs boson was discovered on 4.7.2012

The Higgs boson was proposed to explain the huge mass difference

H interacts with all fundamental particles with a mass

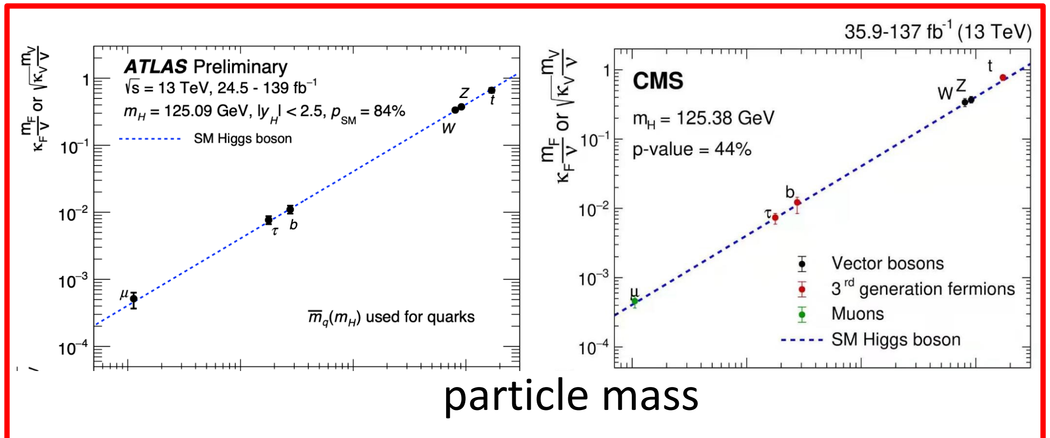
H – does it interact with dark matter? New particles, new world?

H – is it a path to a new world?

Structure of Matter- Particle Physics

The Large Hadron Collider(LHC) discovered the Higgs and made possible of many measurements

Coupling of to the Higgs : mass of final state particles

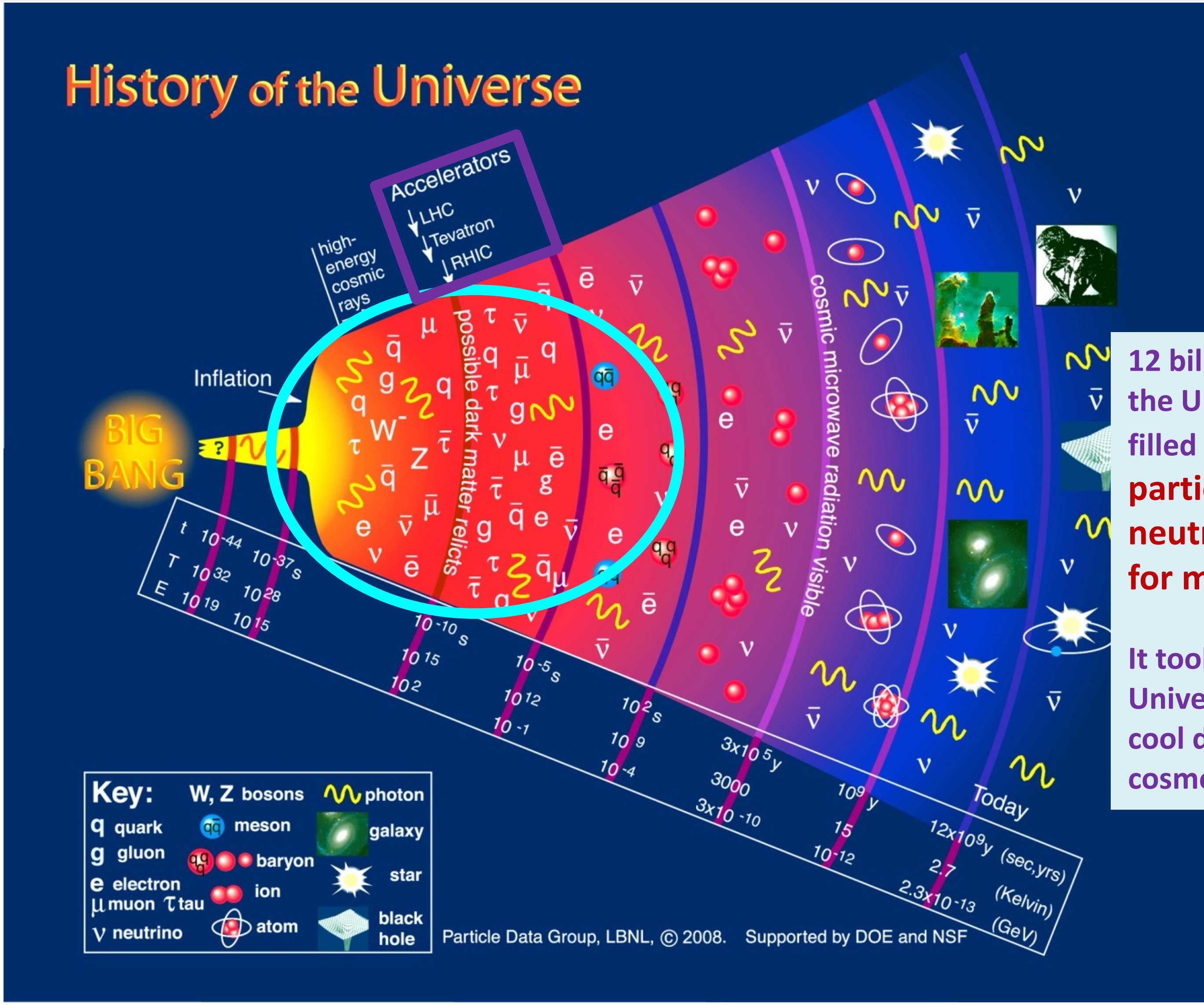


Highly consistent with the Standard Model of Particle Physics

→ origin of fermion mass indeed from the Higgs

more precise measurements will rely on future high energy electron accelerators

The Universe according to the Big Bang



12 billions years ago, the Universe was filled with **elementary particles: charged leptons, neutrinos, quarks, bosons for mediating interactions.**

It took 12 billions years for the Universe to expand and cool down to form the cosmos.

Big & Important Questions in Particle Physics

Challenges to Human

Constitutes of Matter
Evolution of the Universe

2021<Science» 125 Questions:
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What Is the Universe Made Of?
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Important Frontier Science Questions

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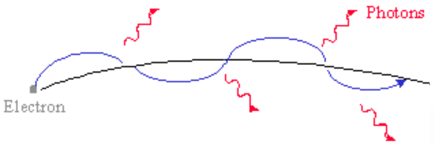
Breakthrough points:
Higgs (H) + Z, W bosons, top quark

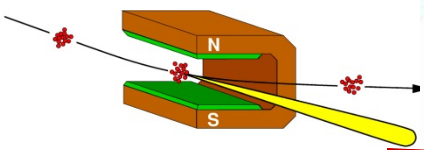
Need for high energy accelerator to produce H, Z, W, t

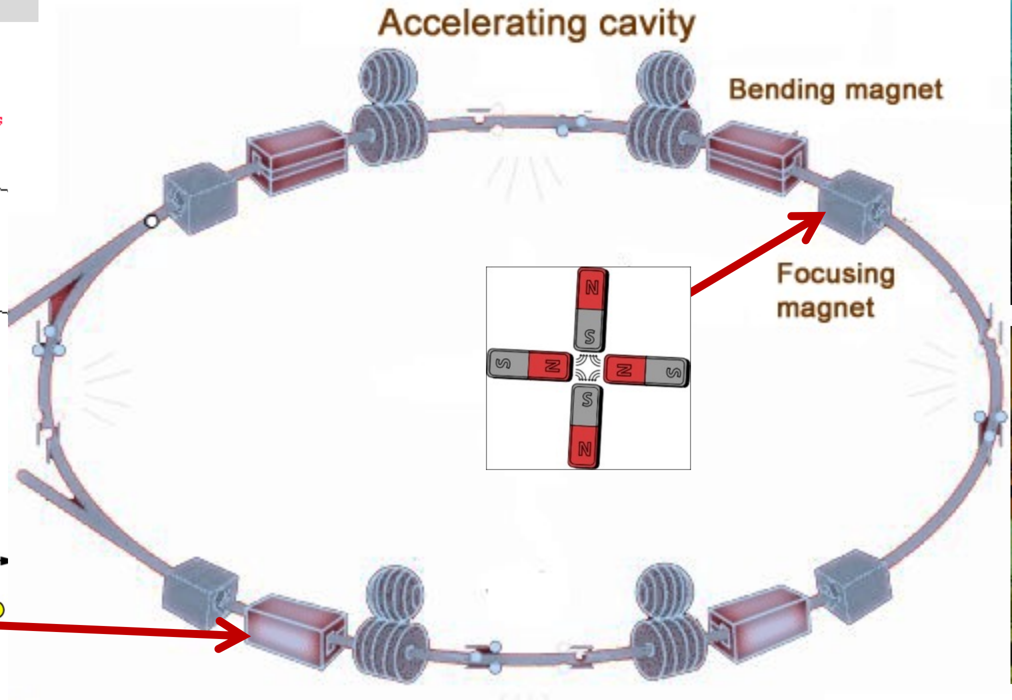
Ask scientists!

Circular Accelerator

synchrotron light







CERN LHC tunnel

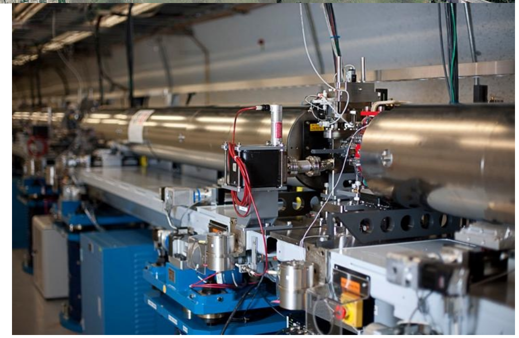
Can Store Beams
High Intensity
Limit on Energy

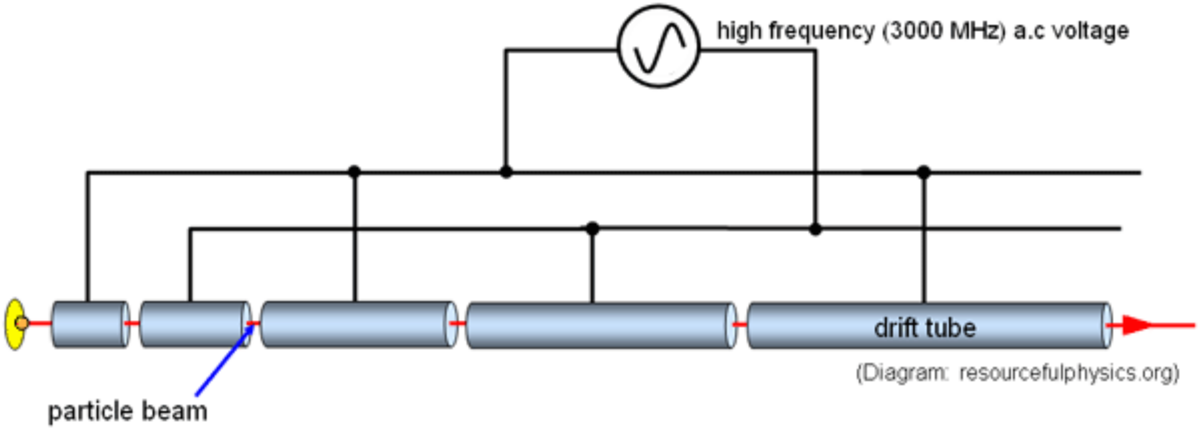
circumference=27km (LHC tunnel)
E=500GeV, I=10mA

$\Rightarrow$ P(power)=13 GW (e^+e^- collider)

Need much bigger tunnel

Linear Accelerator



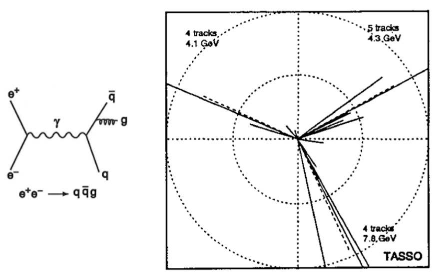


Reach High Energy
Can't Store Beam
Low Intensity

High Energy Accelerator and Major Discoveries

PETRA (Germany)

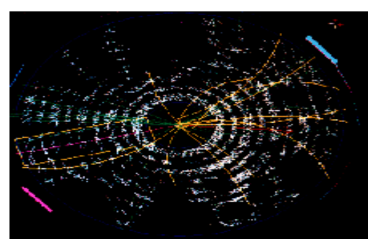
PETRA （1978-86）



Electron-positron energy ~46 GeV, discovery of the gluon jet

Tevatron (USA)

Tevatron (1987–2011)



Proton-proton collision ~1 TeV, discovery of the top quark

LEP， LHC (Europe)

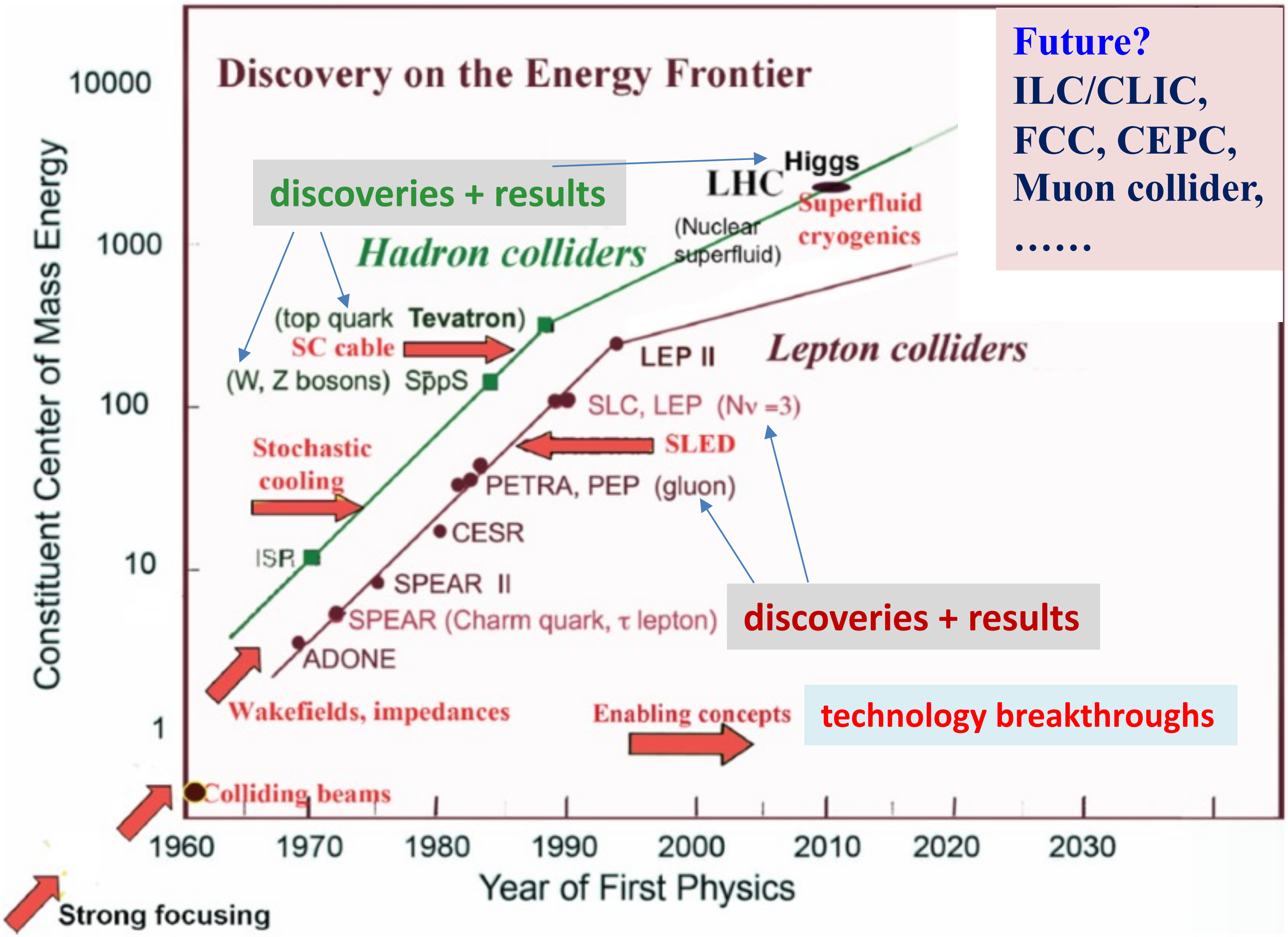
LHC tunnel

Proton-proton collision ~13 TeV, discovery of the Higgs boson

History of High Energy Accelerators

"New Technologies + High Energy + Advanced Instrumentation, etc.."

result in major scientific achievement

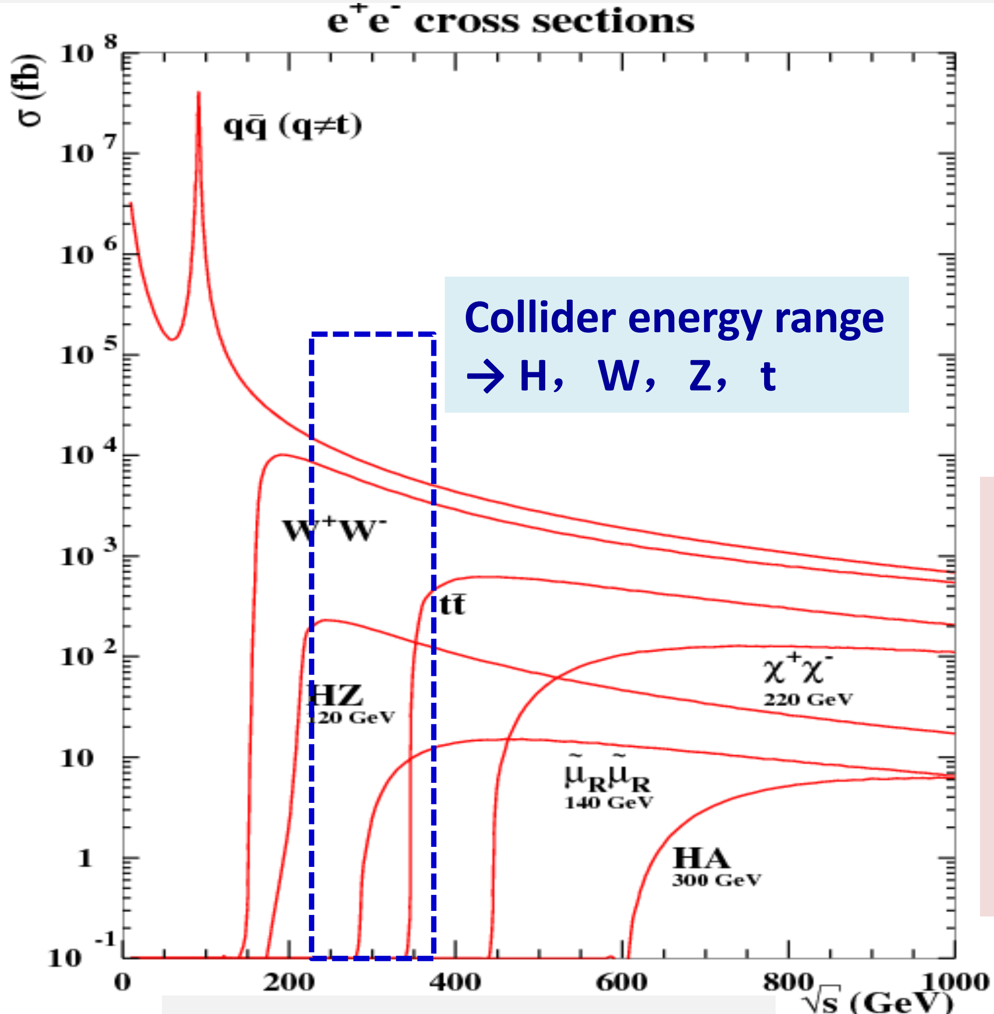


Winning Experience – Particle Physics

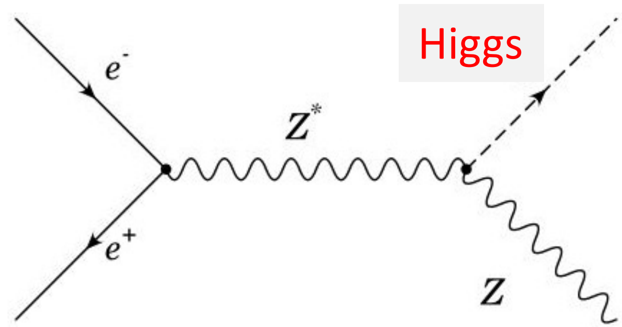
- Innovations in Technology and Design
- Effective Organization and Leadership
- Planning and Execution
- Deep and High Intensity Theoretical Development
- "Creative mind", Dedicated Professionals, a large set of very bright young scientists
- Strong support from government with sustained funding
- ……

High Energy e^+e^- Colliders

Physics Process - Scientific Goals



e+e- Collider Energy（GeV）



Scientific Research & Goals

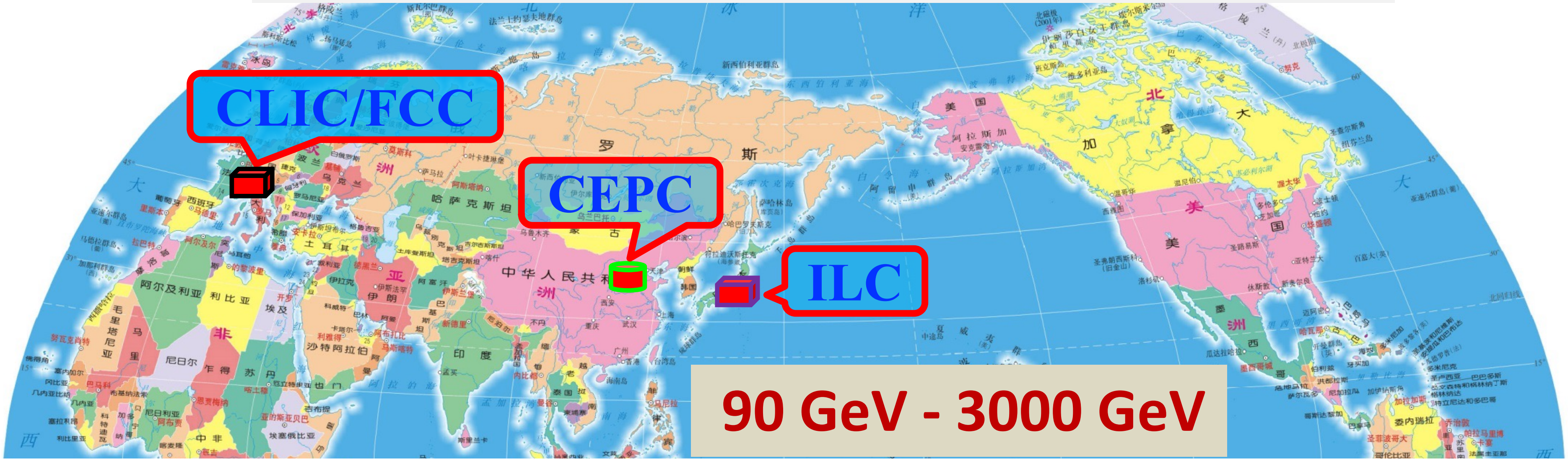
- Increase precision on H by X10
- Increase precision on W,Z by X10-100
- Search for new physics ~10 TeV

aim at major discoveries, deep understanding of the microscopic world, answer fundamental questions and …

Future High Energy Accelerators

Status and Development

Proposed High Energy Accelerators



3000 GeV *(CLIC)*

(+ BSM new physics, …)

250-500GeV 1TeV *(ILC)*

(Higgs, $t\bar{t}$, …)

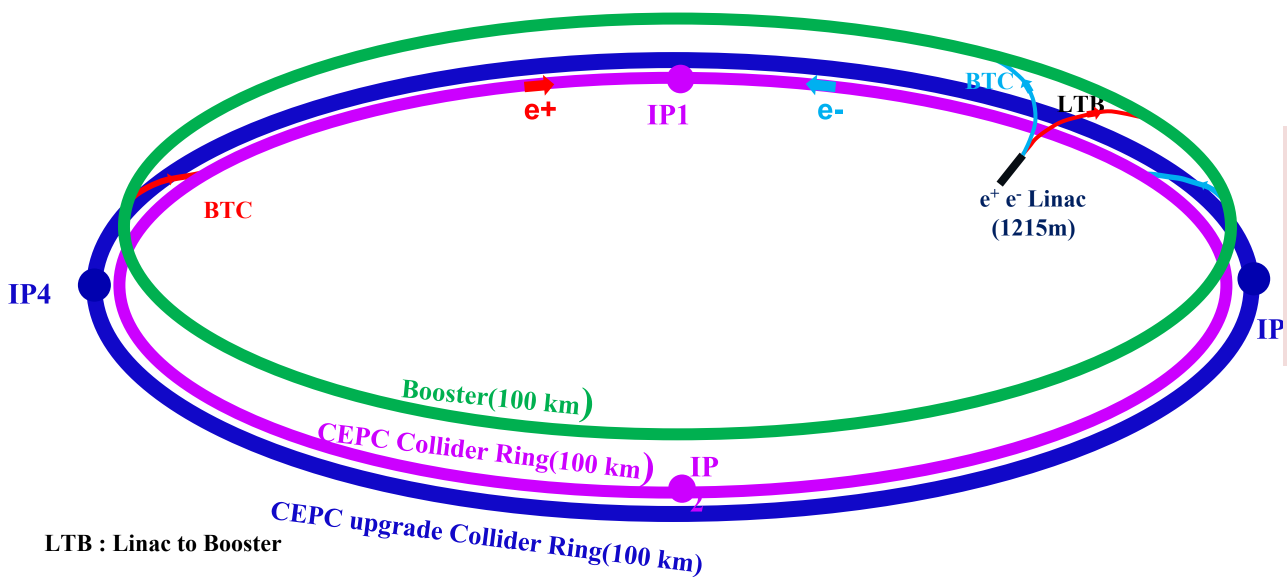
90-250GeV *(CEPC,FCC-ee)*

(H, W, Z, t,…)

Upgradable to proton-proton collider → 100 TeV!

Circular Electron-Positron Collider（CEPC）

- Circular Electron-Positron Collider（CEPC): circuference~100 km，Centre-of-mass energy 90-240 GeV，upgradable to 360 GeV （t quark)
- Goals to produce several 10^6 H, 10^8 W, 10^{12} Z bosons
- Proposed by Chinese physicists in Sept. 2012
- Continuation of expertise in electron accelerator
- Application: world's first γ synchrotron light source, (high energy ~ 300 MeV)，……



LTB : Linac to Booster

BTC : Booster to Collider Ring

- Frontier science
- Long lifetime
  CEPC + upgrade > 50 years
- Serves the world

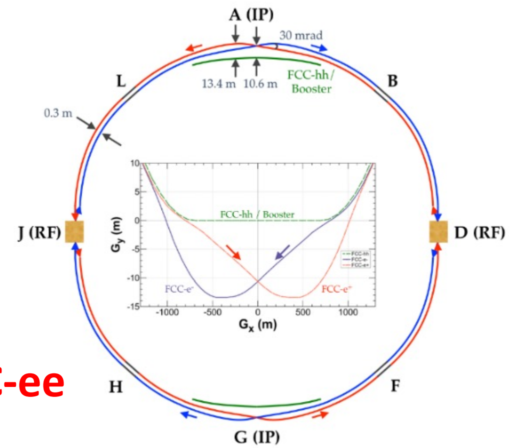
Future Circular Collider in Europe（FCC）

Comprehensive cost-effective program maximizing physics c

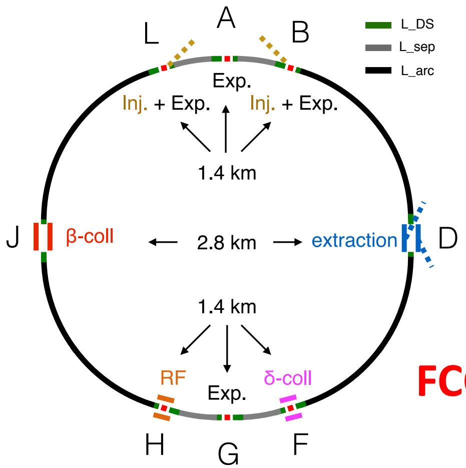
- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs fa luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at**
- Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP.

Phase-1： e+e- collider（FCC-ee）

Phase-2: proton-ptoron collider（FCC-hh）

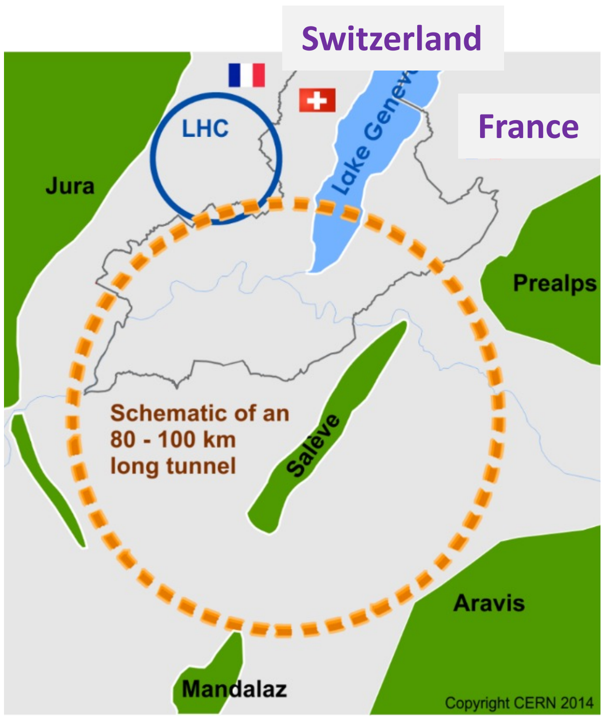


FCC-ee

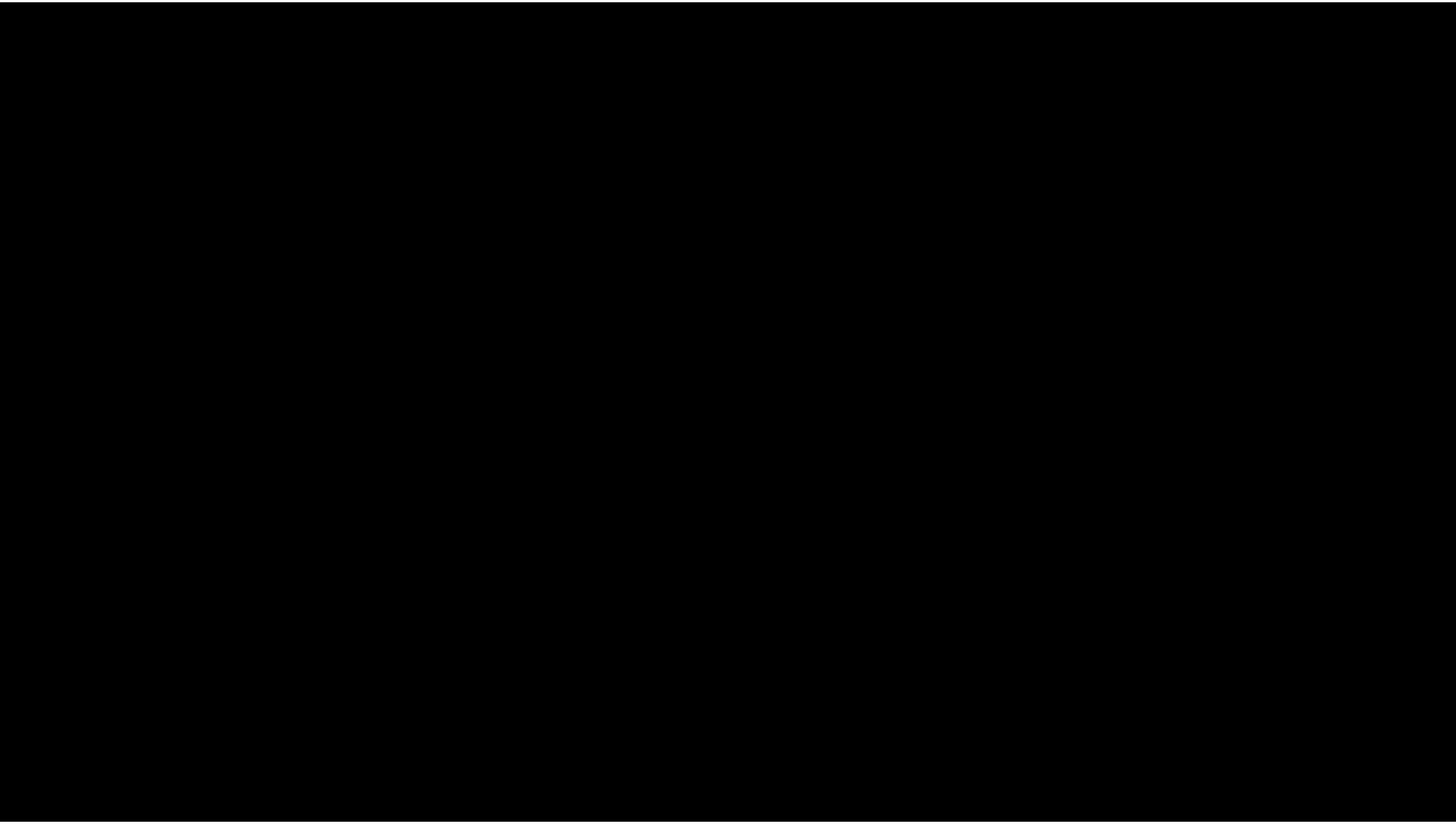


FCC-hh

collider schematic design



collider location



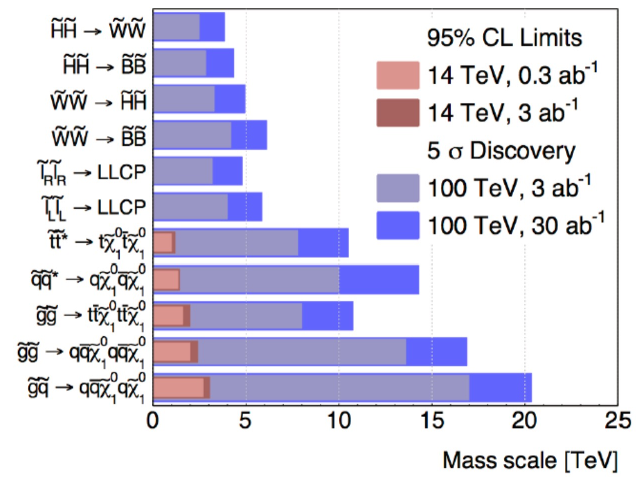
Future Circular Collider in Europe（FCC)

FCC Physics Program

e^+e^- collider (FCC-ee)
240/365 GeV (t quark)

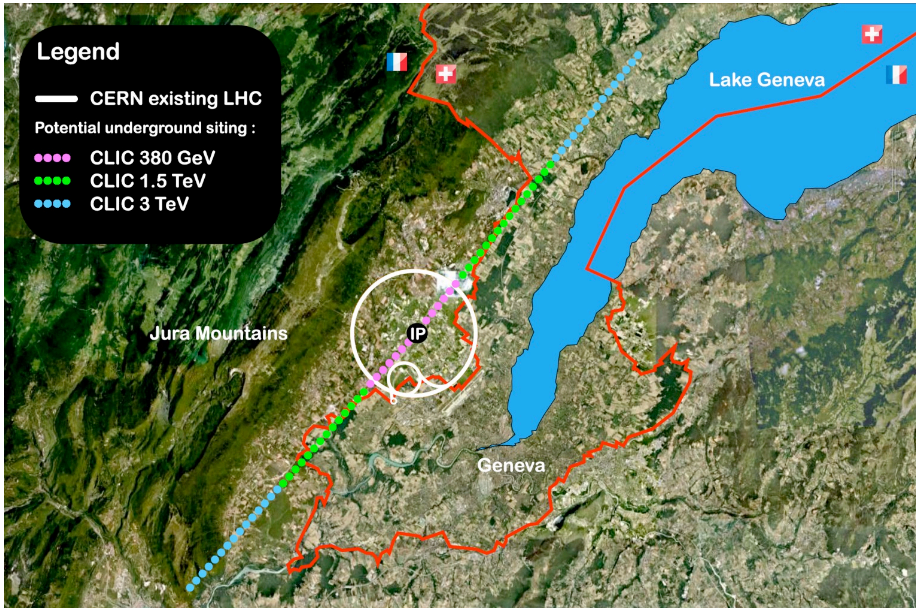
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau\tau$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invisible	< 0.3		< 0.6	

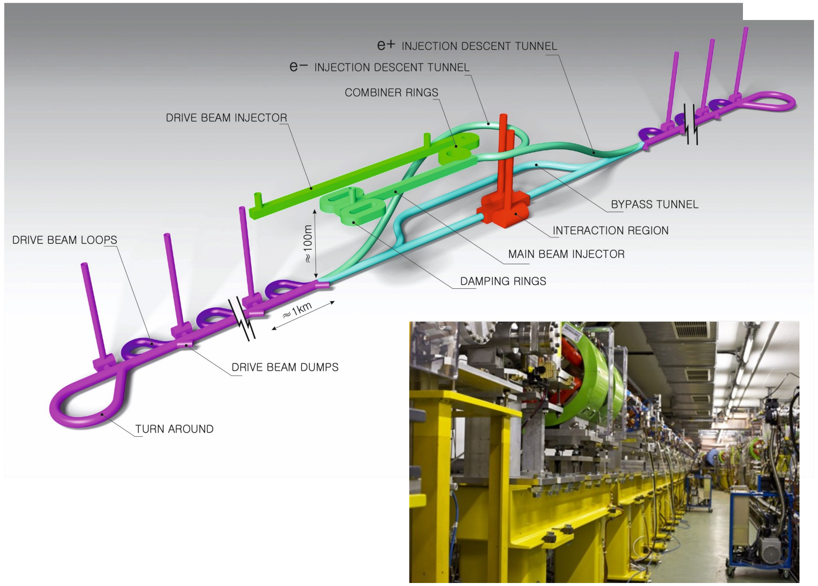
Proton-proton collider 100TeV

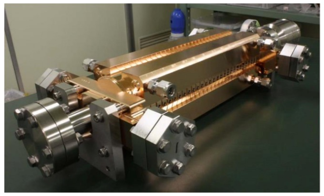


Extremely rich physics and discovery potential

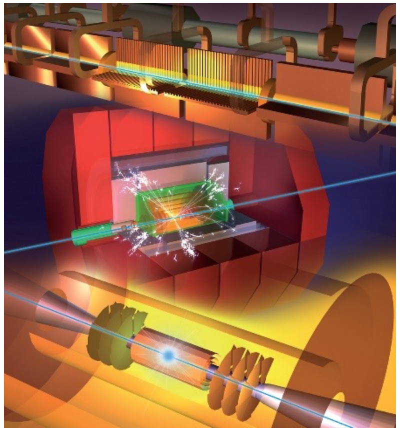
Compact Linear Collider in Europe (CLIC)







Accelerator Structure
12 GHz (L~25 cm)



detector

Compact Linear Collider in Europe (CLIC)

The Compact Linear Collider (CLIC)

- **Timeline:** at CERN (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged program with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

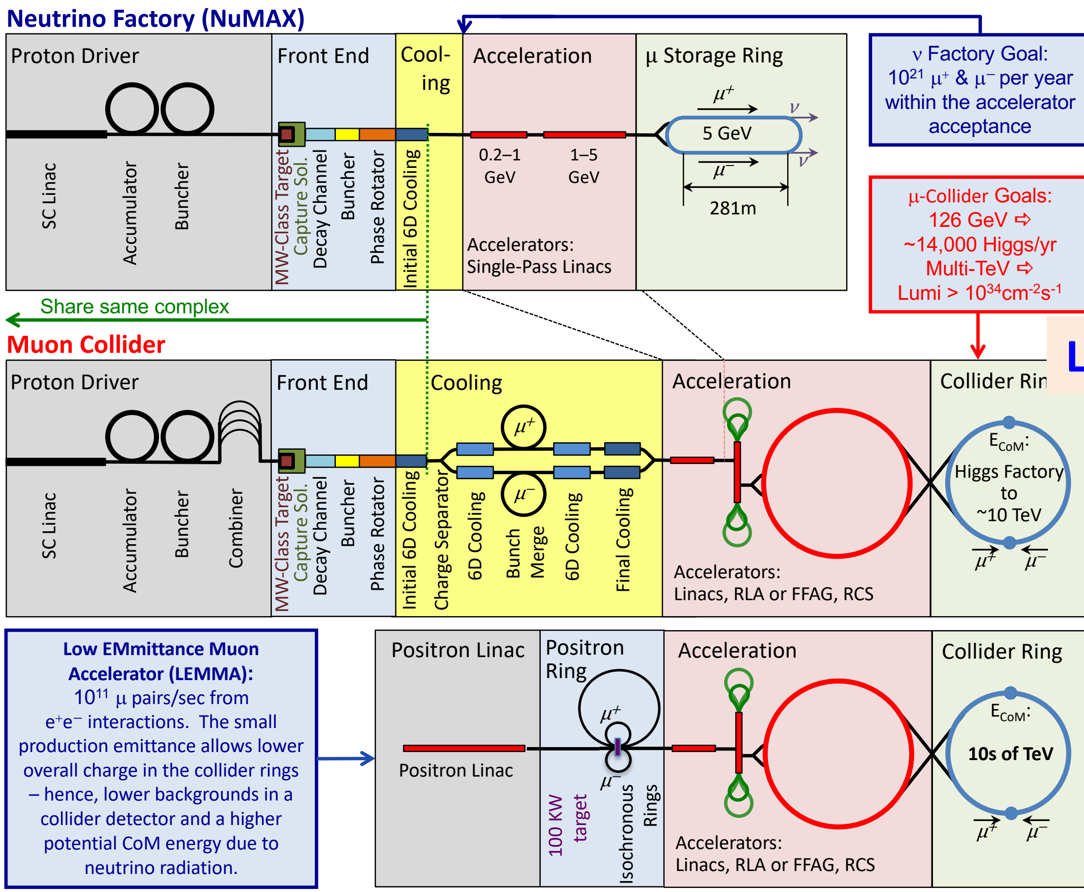
- CDR in 2012. Updated project overview documents in 2018 (Project Implementation Plan).

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

- Comprehensive **Detector and Physics** studies

Muon Collider (CERN)

New technology, to be fully developed



Muon collider based on proton driver

Broad Applications:

- Neutrino Factories
- Colliders from ~100 GeV to 10s of TeV scale
- Secondary Beams

Low radiation loss, high energy 10s TeV

- Proton-driver with ionization cooling
- Positron-driver with low emittance

Muon Accelerator Design Status

- Full conceptual designs for NFs
- Key feasibility tests from MAP/MICE completed successfully!
- Now ready for a more detailed collider conceptual design study

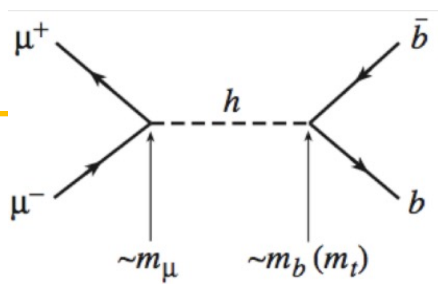
High level of complexity
Need CDR and technology development
Long way to go

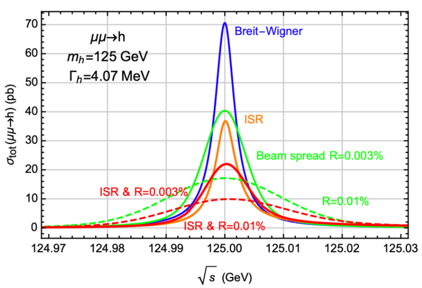
CLIC Physics Program

- **3 steps**: **380 GeV (updated from 350 GeV for ttbar coupling measurement), 1.5 TeV, 3.0 TeV.**
- **Physics**
  - **380 GeV run : Higgs measurement, top mass scan, top coupling measurement.**
    The precisions of Higgs parameters are 1-5% and can reach 1% or better combining 1.5/3 TeV runs
    Top mass measurement can reach tens of MeV
  - **1.5,3 TeV runs : Higgs self coupling, top-Yukawa coupling, search for BSM new physics.**
    Di-Higgs (Heavy Higgs), ttH
    SUSY, Z', etc.

Muon Collider Physics Program

- Larger mass of the muon allows a smaller foot print and higher energies compared to e^+e^- counterparts, although suffering from major challenges of finite lifetime and cooling.
- Physics:
  - **Higgs factory at ~125 GeV** : line-shape scan of the Higgs boson, simultaneous measurement of the Higgs boson mass, width and muon Yakawa at unprecedented precision.
  - **High Energy runs up to 100 TeV to probe** :
    Top Yukawa coupling, Multi-Higgs, possible new physics contributed to Muon g-2
    Muon has a structure
    Vector boson machine
    WIMP dark matter





New Strategy in Europe 2020

High-priority future initiatives

a) **An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.** Accomplishing these compelling goals will require innovation and cutting-edge technology:

b) **Innovative accelerator technology** underpins the physics reach of high-energy and high-intensity colliders. …. must **intensify accelerator R&D and sustain it** with adequate resources…… A **roadmap** should prioritise the technology, should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.

Europe's funding for future energy frontier collider projects (2021-2025):

FCC 20 MCHF/year

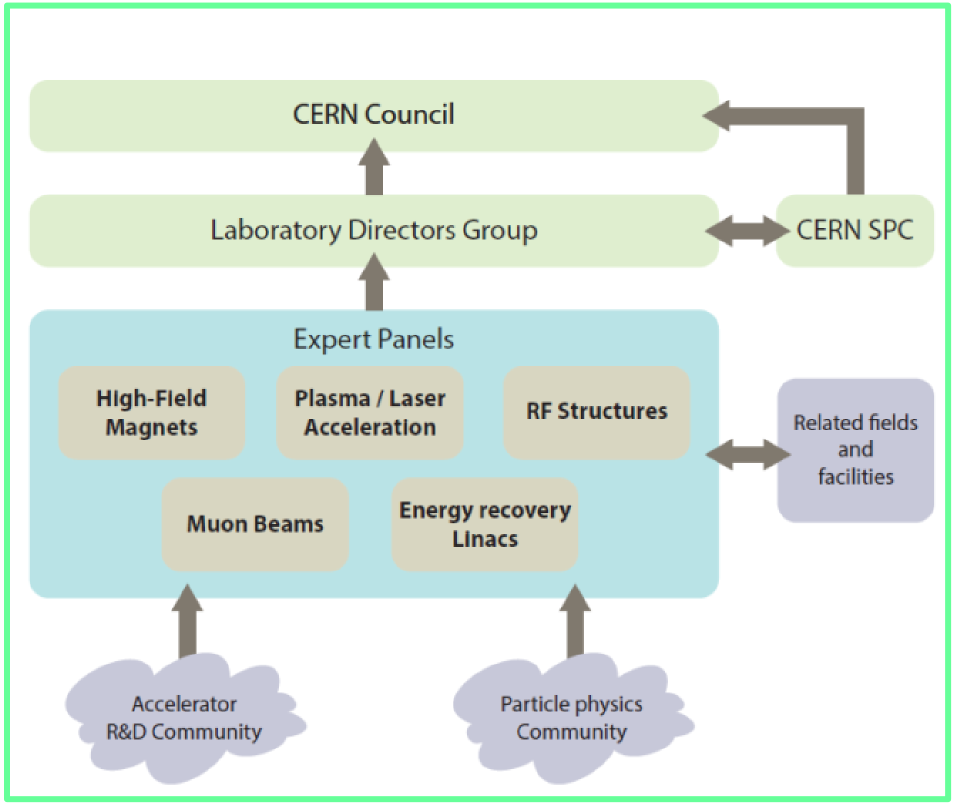
CLIC 5.5 MCHF/year

muon collider 2 MCHF/year

SC magnet 190 MCHF/10 years; **detector** 90 MCHF/11 years

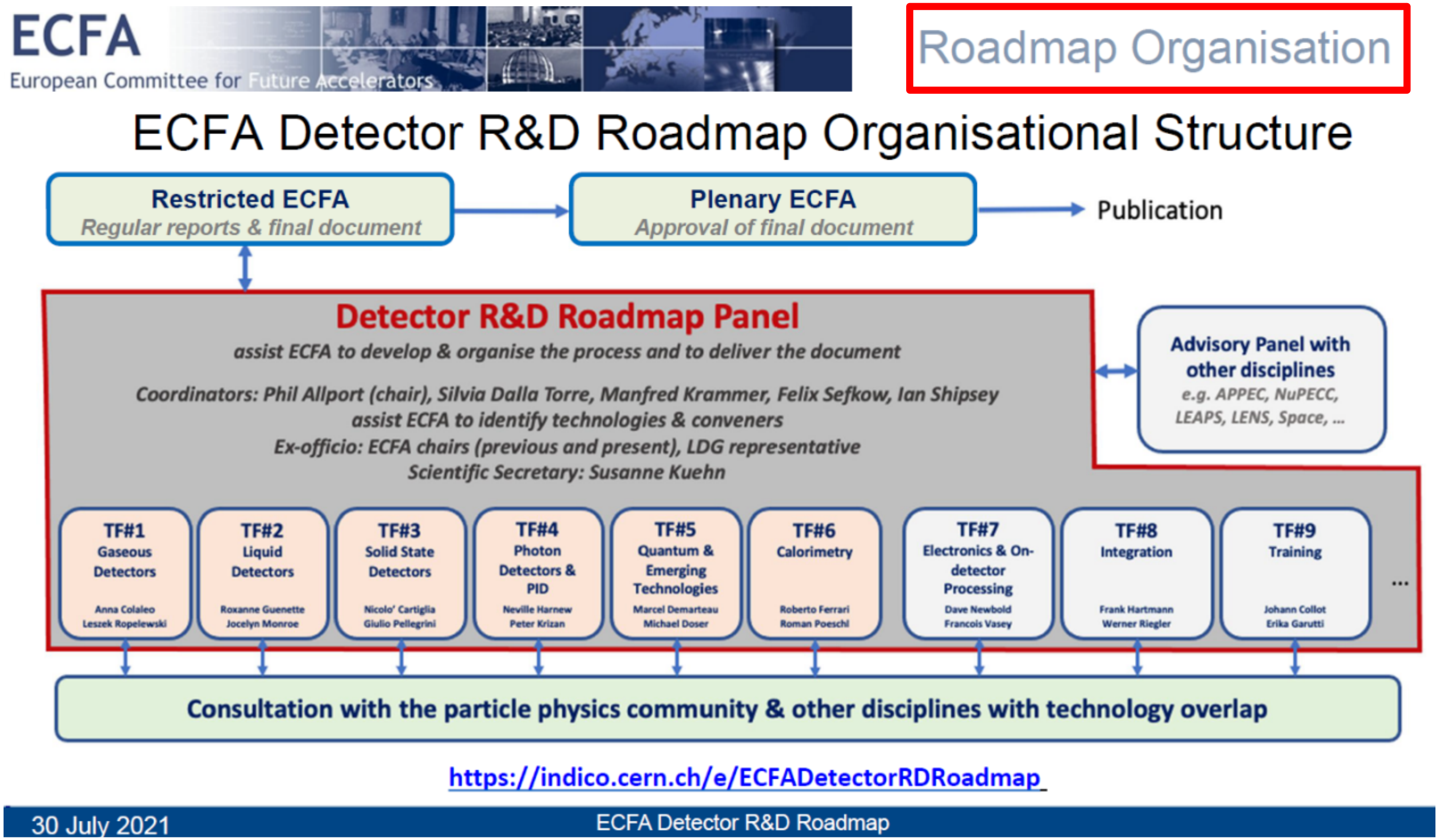
Feasibility and Engineering Design（2021-25） **100 MCHF**

European National Activities and CERN Roadmap



Dave Newbold @ EPS2021

European National Activities and CERN Roadmap



Phill Allport at EPS 2021

SNOWMASS 2021
US High Energy Physics Planning

① Define the most important questions for HEP & related fields
② Identify the most promising opportunities to address these questions in a global context

U.S. Strategic Planning Process for Particle Physics

~year-long process
Snowmass Community-Wide "Science" Study
Organized by Division of Particles and Fields (DPF) of APS

Input to P5

The Snowmass community planning exercise, that had been delayed since January 2021 due to the COVID-19 pandemic, resumed the full activity in September 2021

Snowmass Book + online document： October 31, 2022.

Japanese National HEP Strategy

High energy frontier focuses on the HL-LHC Experiment

Japan's Strategy for Energy Frontier

- **Current HE research concentrates on (HL-)LHC**

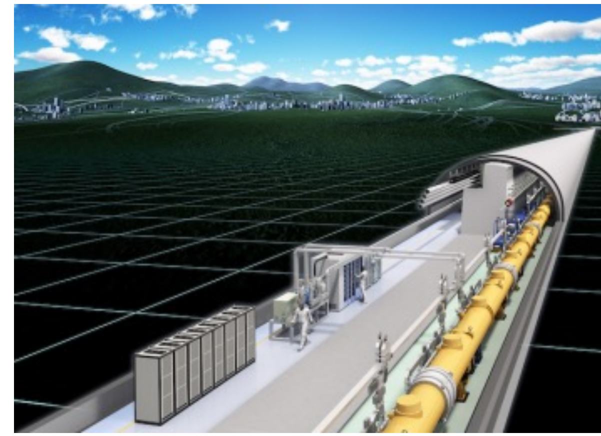
"… continuing studies of new physics should be pursued using the LHC and its upgrades."

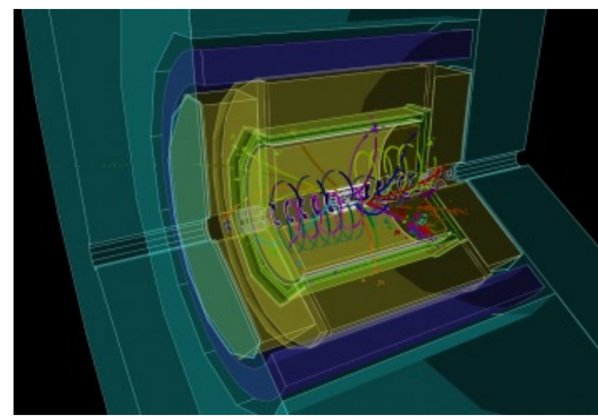
- **Future HE project in Japan is the ILC**

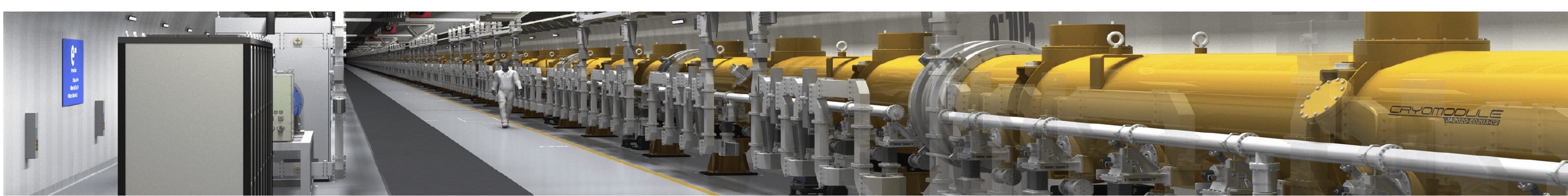
"… construction of the International Linear Collider with a collision energy of 250 GeV should start in Japan immediately without delay so as to guide the …. through the research of the Higgs particle ..

Future high energy frontier is the ILC

Final Report by the Committee on Future Projects in High Energy Physics, September 2017
http://www.jahep.org/files/20170906-en.pdf







Japanese National HEP Strategy

2020.08.02 **ICFA announces a new phase towards preparation for the International Linear Collider. ICFA approved the formation of the ILC International Development Team as the first step towards the preparatory phase of the ILC project, with a mandate to make preparations for the ILC Pre-Lab in Japan.**

2020.08.31 Snowmass2021 LOI "Update of the Japanese Strategy for Particle Physics"

2020.10.28 The **ILC Steering Panel** was established by the Japan High Energy Physics Committee (HEPC) of the Japan Association of High Energy Physicists (JAHEP). **"Leading the high energy physics community in Japan toward a timely realization of the ILC"**

2021.01.16 The JAHEP **ILC Steering Panel** released a report "**Recent Progress Towards the Realization of the ILC in Japan: Cooperative Efforts by Academia, Industry, and Local Region**".

2021.06.02 The ILC International Development Team has released "**ILC Preparatory Laboratory proposal**". http://www.jahep.org/files/input_JapanHEPC_20191213.pdf

Future High Energy Accelerators

Innovations and Challenges

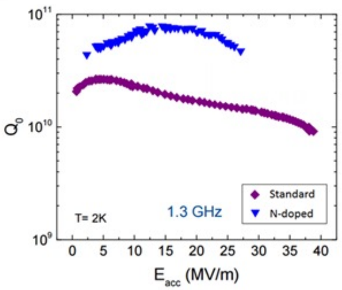
Innovations and Challenges

United States

Landscapes and national roadmaps

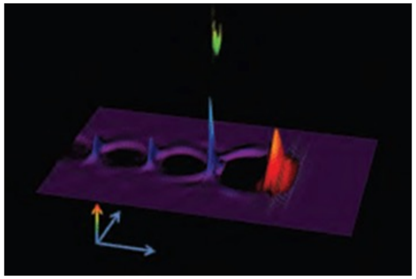
Innovations

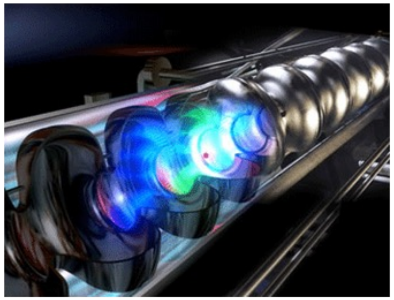
N_2 doping
High Q RF



Fermilab

laser-plasma accelerators





BELLA group
Berkeley Lab

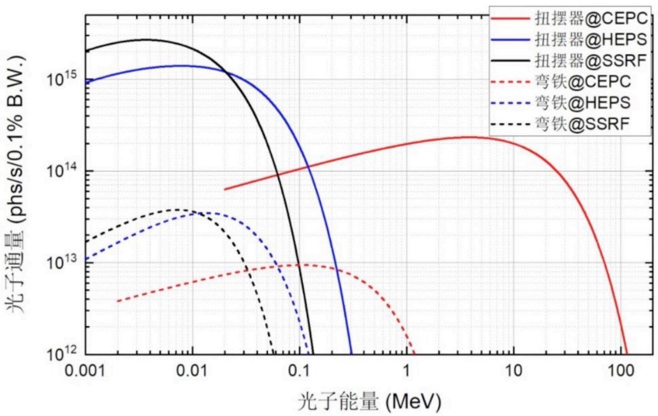
Quantum Computing - quantum support vector machine (QSVM), detects Higgs bosons at the LHC. The algorithm run both on quantum simulators and on physical quantum hardware (on Google Tensorflow Quantum, IBM Quantum and Amazon Braket, ~20 qubits and a 5K-event dataset,)

quantum algorithm for the parton shower by LBNL theorist PhysRevLett.126.062001

Innovations and Challenges

CEPC: World first high energy-high intensity γ synchrotron light source → new applications.

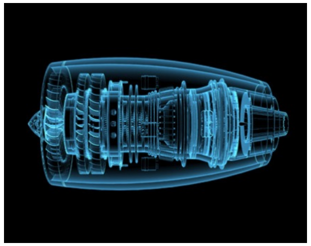
Potentially a broad range of important applications

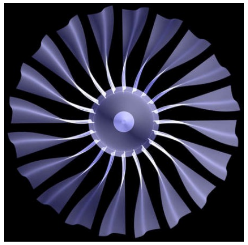


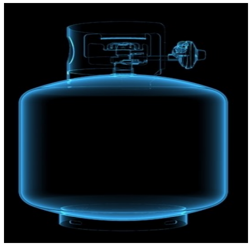
CEPC是最好的MeV高能同步辐射光源

Prof. Yifang Wang suggested this idea documented in CEPC CDR.

Structure Analysis - 1KHz penetration power







- Photo-nuclear physics
- cosmology
- γ transmutation
- Isotope production

……

Innovations and Challenges

Collaboration:

Continued collaboration and coordination among Europe, US and Asia

Shared R&D on critical technologies (nano beam, design and components,…)

Close organization association and consultation, with funding agency involvement

Europe and US have strong roles in the ILC

Cooperation with the FCC (ee,hh) group in key technologies

Push the field to find ways to probe the Universe and strive for discovery

Innovations and Challenges

EDITORIAL

NATURE REVIEWS | PHYSICS

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We believe that the case for big science enterprises, such as a future particle collider, is strong. What are the options? In a series of Comments we explore different projects: the Circular Electron Positron Collider, the Compact Linear Collider, the Future Circular Collider, the High-Luminosity Large Hadron Collider, the International Linear Collider and plasma wave accelerators.

It is too early to say which of these projects will go ahead and whether they will reach their goals, but it is clear that to discover new physics beyond the SM we need to throw in everything we have: large-scale high-energy particle accelerators, small-scale low-energy experiments and astrophysical observations. In science there is no final frontier, just many frontiers to unimaginable places. One ship at a time is not enough. We need a fleet of ships to explore all those strange new worlds.

Summary

- Particle Physics deals with a series of critically important science questions
- The Higgs boson serves as a rare window to the unseen side of the Universe
- High energy accelerators have played vital roles in history

  We have high hopes for future HE accelerators
- International collaboration & competition good for innovation and large projects
- High energy γ synchrotron light, development of accelerator-instrumentation technologies and application will benefit human being