THE FUTURE OF HIGH ENERGY ACCELERATORS

Future High Energy Accelerators for Particle Physics

Joachim Mnich
DESY

IPAC17, Copenhagen, May 2017

Outline

- High-energy physics and the need for accelerators/colliders
- LHC and HL-LHC
- Beyond the LHC: future hadron colliders
- Precision machines: future electron positron colliders
- Other ideas: neutrino beams, muon colliders, ...
- Some strategy considerations
- Conclusions

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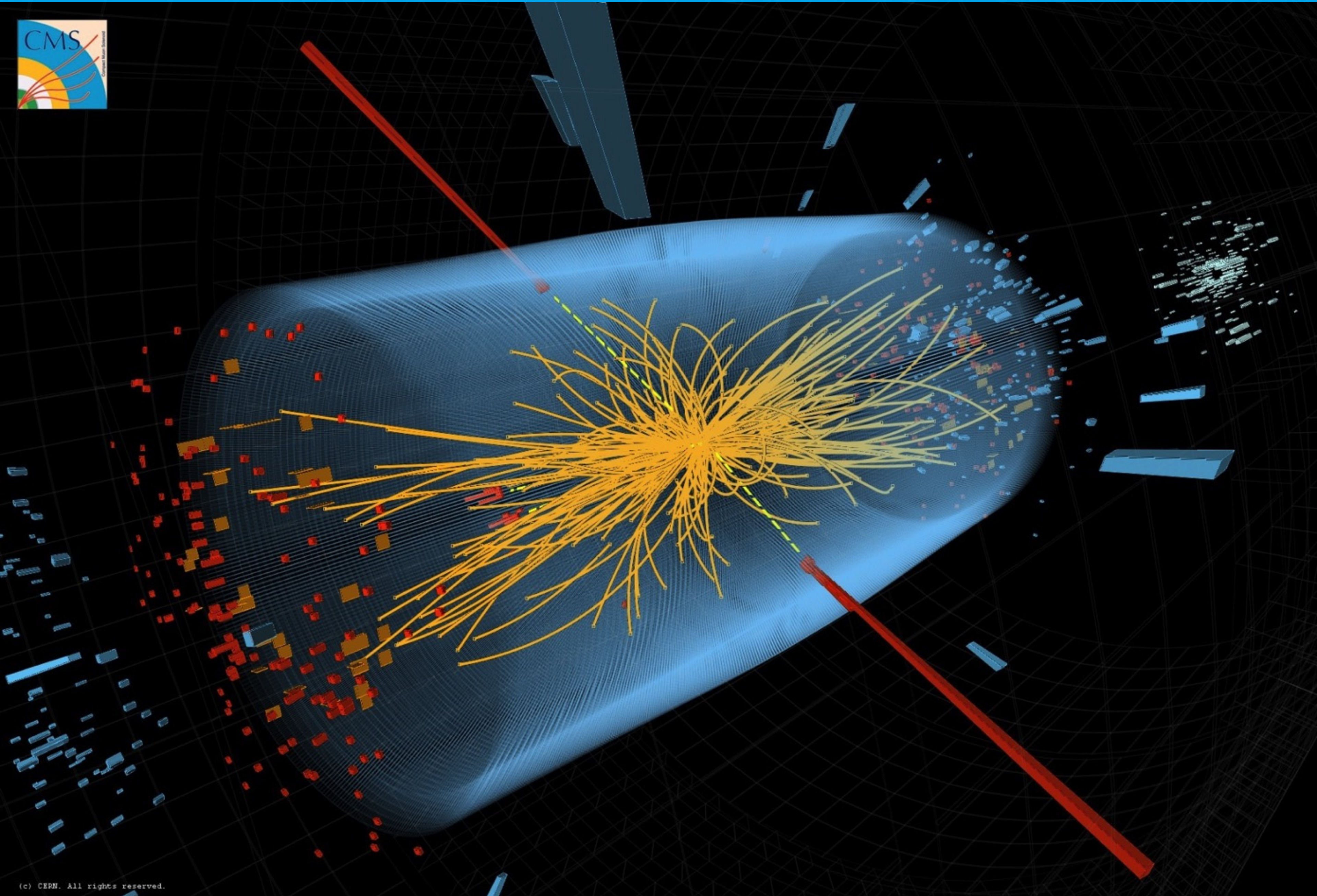
Observation of a Higgs Boson: A Centennial Discovery



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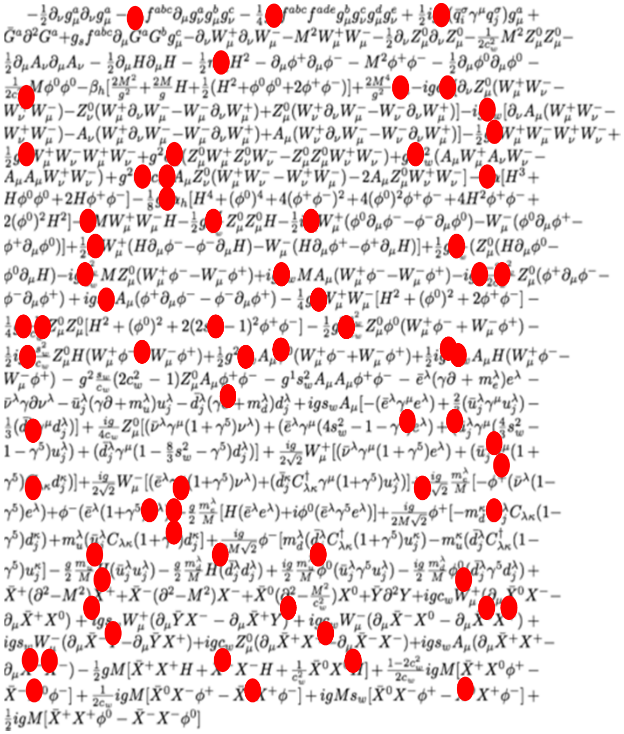
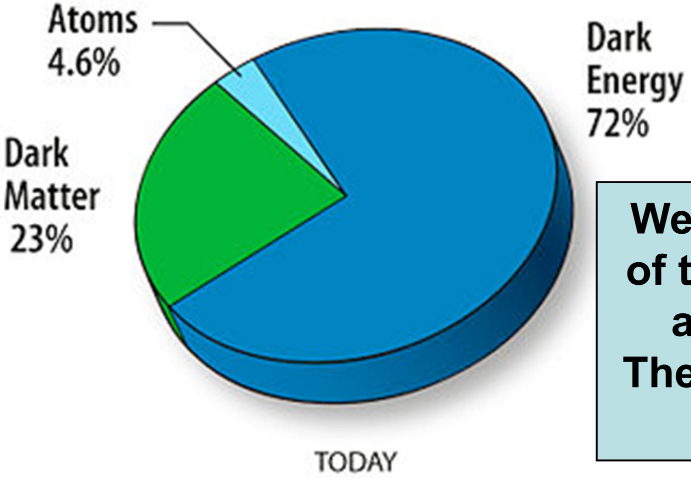
… but many fundamental questions remain open!

Higgs explains why particles have masses – but many parameters still unexplained!
The Standard Model is NOT the last answer.





We understand only 5% of the universe's energy and matter content!
There is dark matter and dark energy!

We don't understand why we exist at all! Matter-antimatter asymmetry, connection to cosmology.

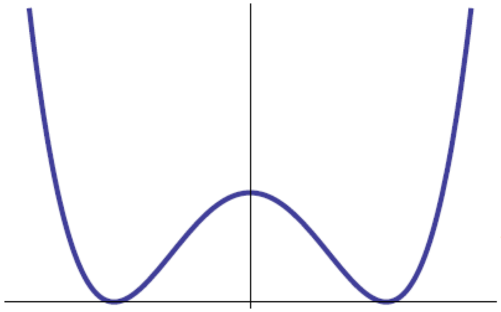
But ... we have a Higgs now!

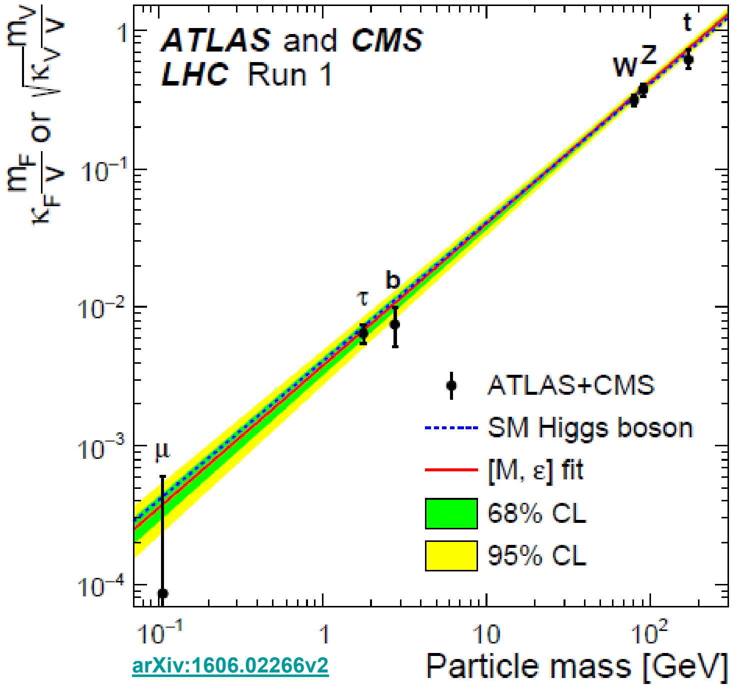
- Higgs mechanism seems to be at work and explains at least partially why fundamental particles have mass.
- The Higgs is different
  - it‘s not a quark or a lepton or a gauge boson – it‘s a new kind of fundamental particle;
  - there is a scalar field filling up the vacuum;
  - is it THE Higgs (of the SM) or just A Higgs (e.g. SUSY)?
- And why is the Higgs so light?
- We must measure the Higgs properties as precisely as possible
  - mass, couplings, spin, ...

Test of Higgs potential

$\lambda_{HHH} = \sqrt{2}\, M_H$

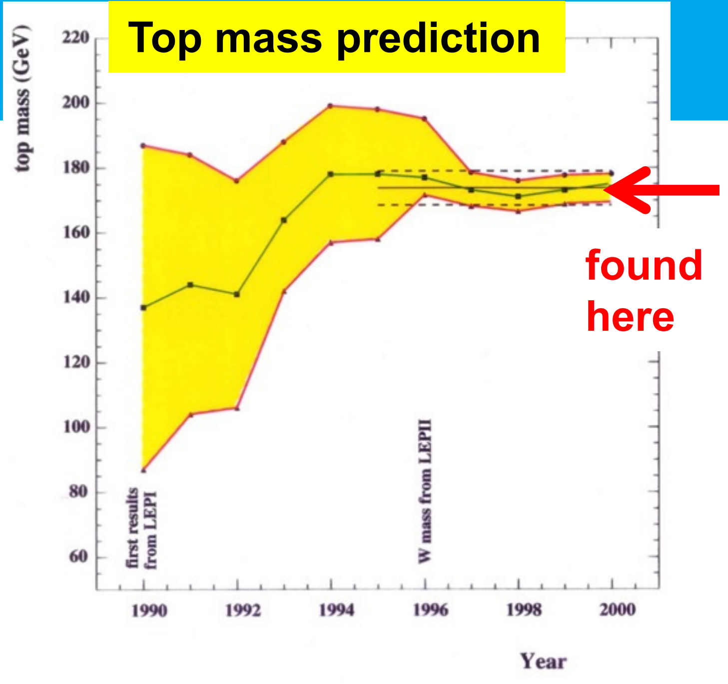
$$V(H) = \frac{1}{2} M_H^2 H^2 + \sqrt{2} M_H H^3 +$$





arXiv:1606.02266v2

Precision Measurements

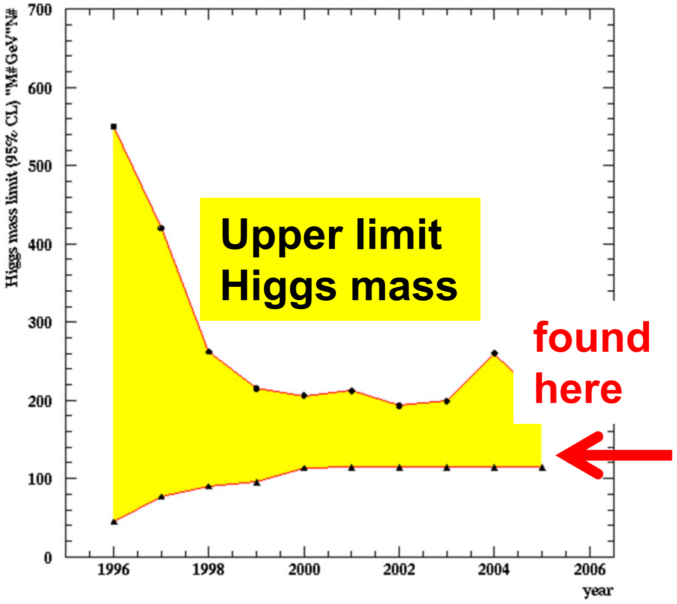

Top mass prediction

found here

> Looking back in history:

- W, Z bosons discovered in the 1980es at CERN in p anti-p collisions
- Precise determination of their properties, mainly in e^+e^- (LEP, SLC) in the 1990es
- Resulted in predictions for then unknown top quark and Higgs boson

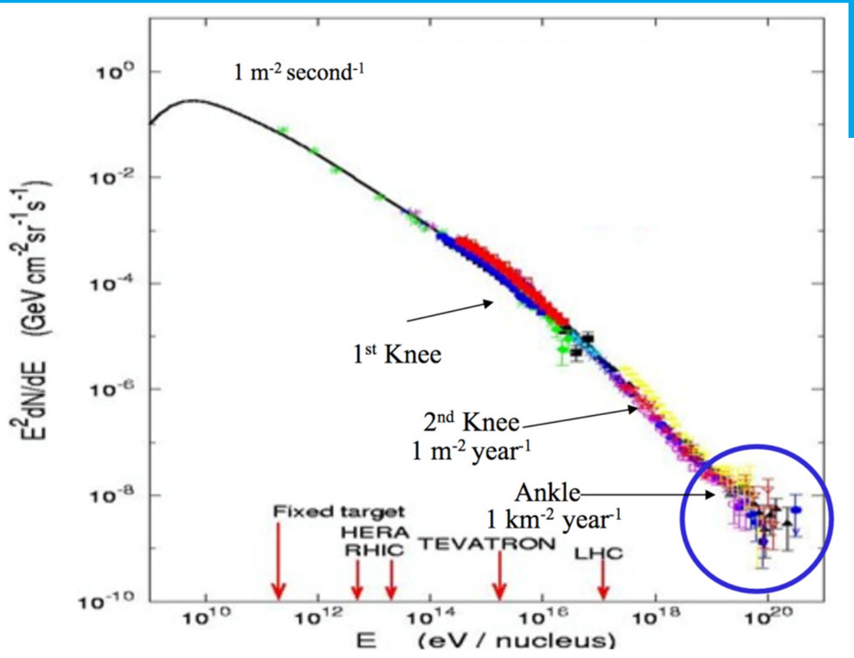
> New physics accesible through precision measurements of the Higgs?

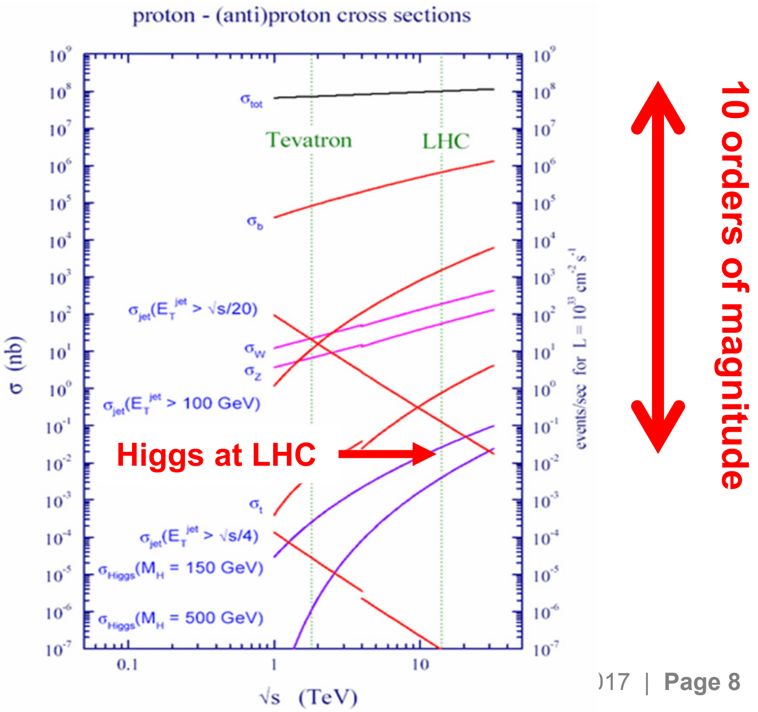

Upper limit Higgs mass

found here

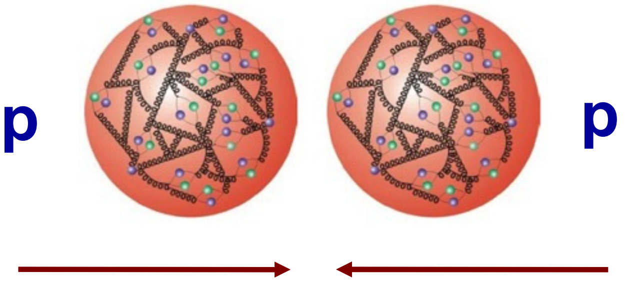
Why Man-Built Colliders?

- There are cosmic accelerators around, free of charge
  - energies up to 10^{20} GeV available
  - but center-of-mass energy matters! „only“ factor ≈ 30 beween LHC and highest energy cosmic rays.
- But also luminosity matters:
  - at highest energies only about 1 event per km^2 per year ...
  - ... compared 10^9 pp collisions per second at the LHC!
- Example Higgs production:
  - only 1 Higgs in 10^{10} pp collisions
  - Identification requires laboratory conditions
- For particle physics colliders like the LHC are THE tool to use.

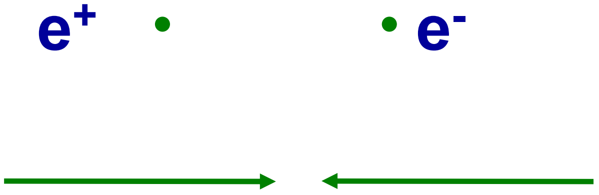




Hadron versus Lepton Colliders



- Proton-(anti-)proton colliders:
  - energy range high (limited by bending magnets power and ring radius)
  - composite particles, different (unknown) initial-state constituents and energies in each collision
  - complicated hadronic final states
- Discovery machines
  - only energy matters
- (Some) Precision measurement potential



- Electron-positron colliders:
  - energy range limited (by RF power)
  - point-like particles, well-defined initial-state quantum numbers and energies
  - simpler final states, well-defined missing energy
- Precision machines
  - sensitivity to new physics in quantum loop corrections!
- (Some) Discovery potential

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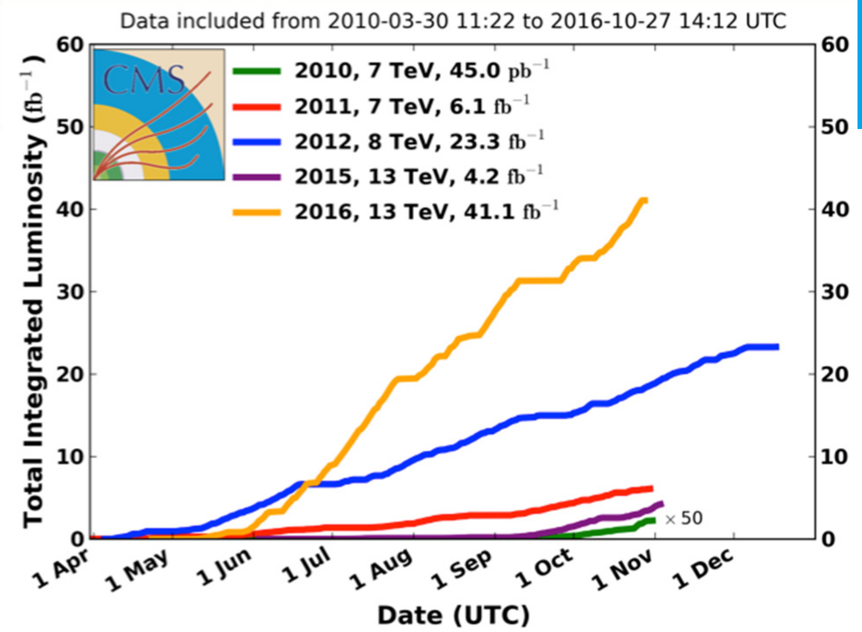
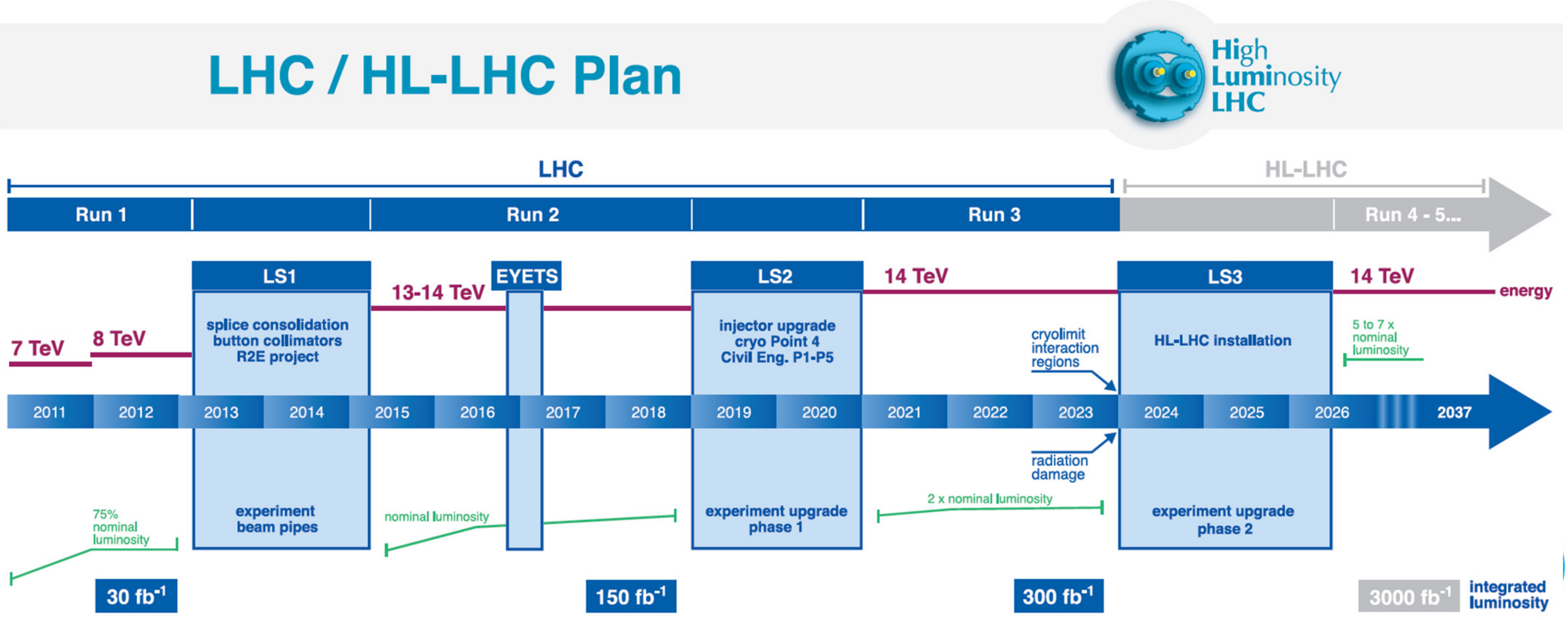
The Large Hadron Collider

- At least 20 years physics programme yet to come - we have only just begun:
  - very successful operation so far (2010-16) at 8-13 TeV; ~75 fb^{-1} per experiment.
  - only few percent of total luminosity:
    ≈ 75 fb^{-1} by end of 2016
    > 3000 fb^{-1} expected by 2035

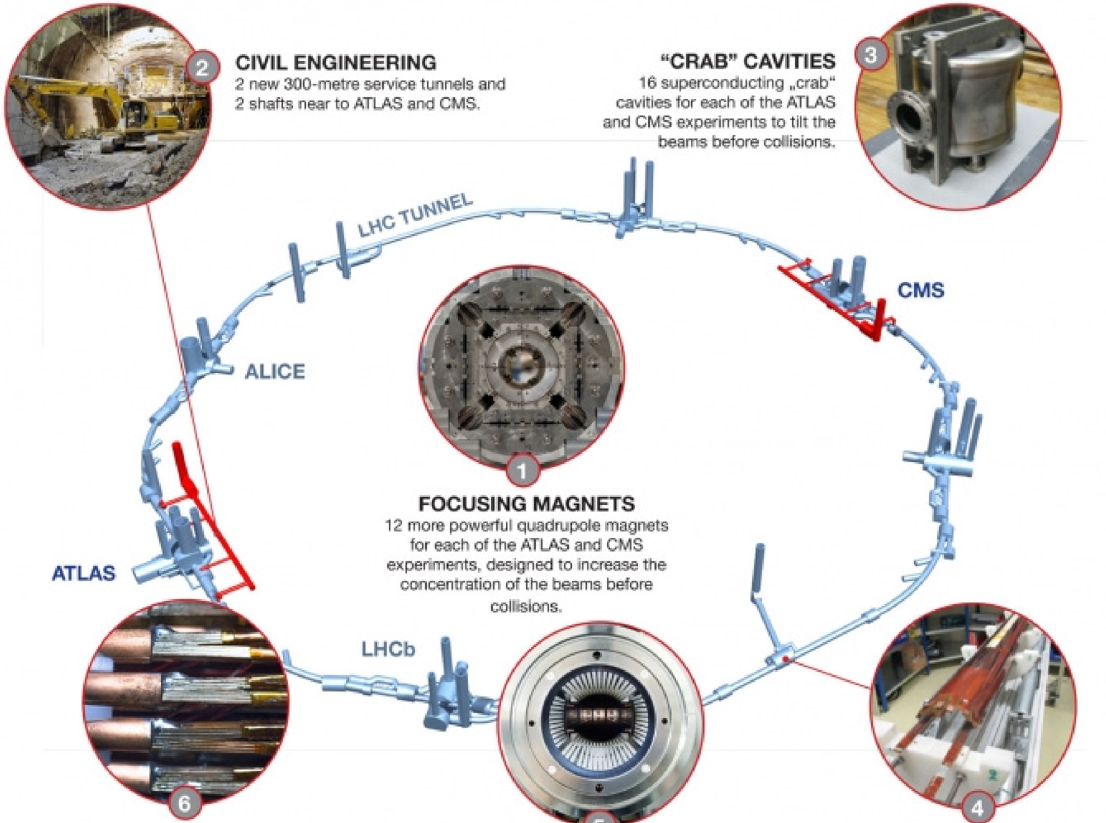




The High-Luminosity Large Hadron Collider

- Long shutdown from 2023-2025 with massive upgrades of LHC machine
  - HL-LHC with the goal of delivering 3000 fb^{-1} until 2035
  - development of new magnet technology for HL-LHC and beyond: Nb_3SN for magnets up to 12 T to replace some of the „old“ 8.33 T NbTi LHC magnets.
  - entails also major upgrade work to detectors to deal with rate and radiation.

HiLumi
HL-LHC PROJECT



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

“CRAB” CAVITIES
16 superconducting „crab“ cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

CERN Novembre 2015

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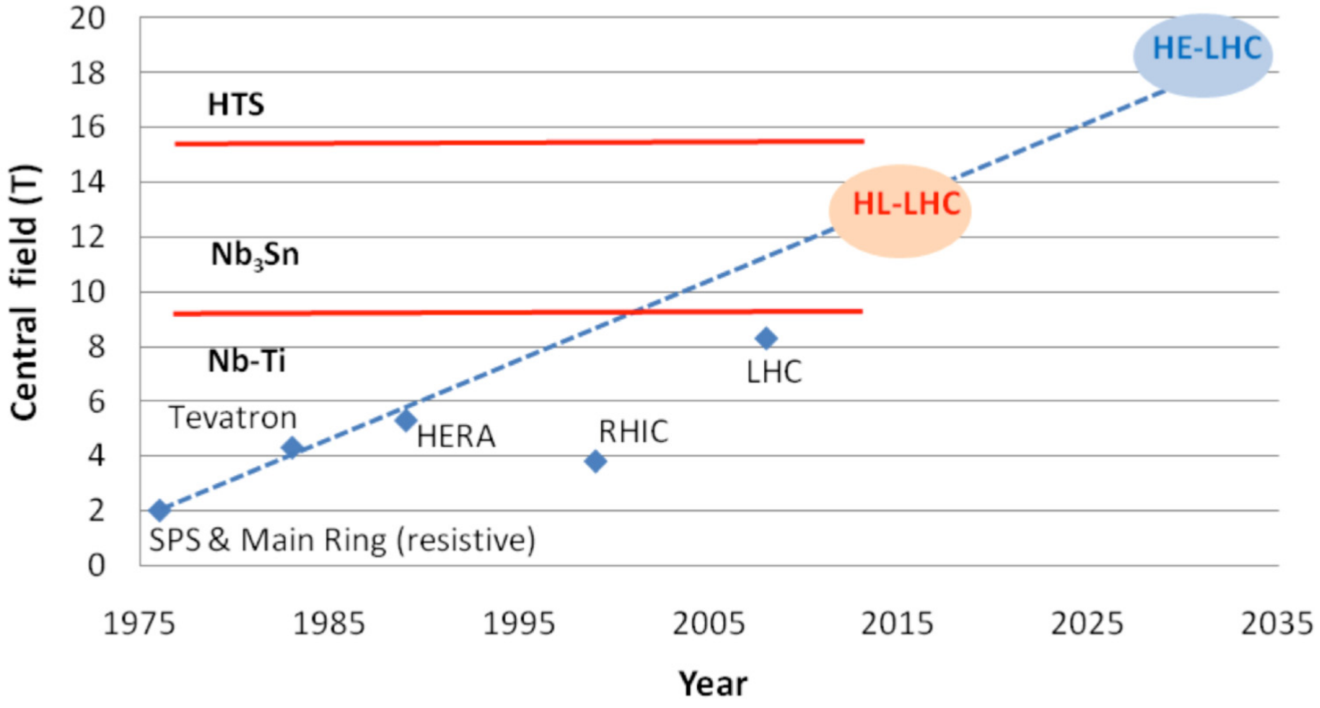
Hadron Collisions Beyond (HL-)LHC

- Energy matters – strong push towards higher-energy hadron colliders following the LHC.
  - note that many major HEP discoveries were made at hadron machines, i.e. bottom and top quark, W and Z bosons, tau neutrino, Higgs boson, ...
- Issue: magnet technology!
  - NbTi used for Tevatron, HERA, RHIC, LHC; need to move on to Nb3Sn, HTS, ...



FCC – Future Circular Collider @ CERN

> A circular tunnel @ Geneva

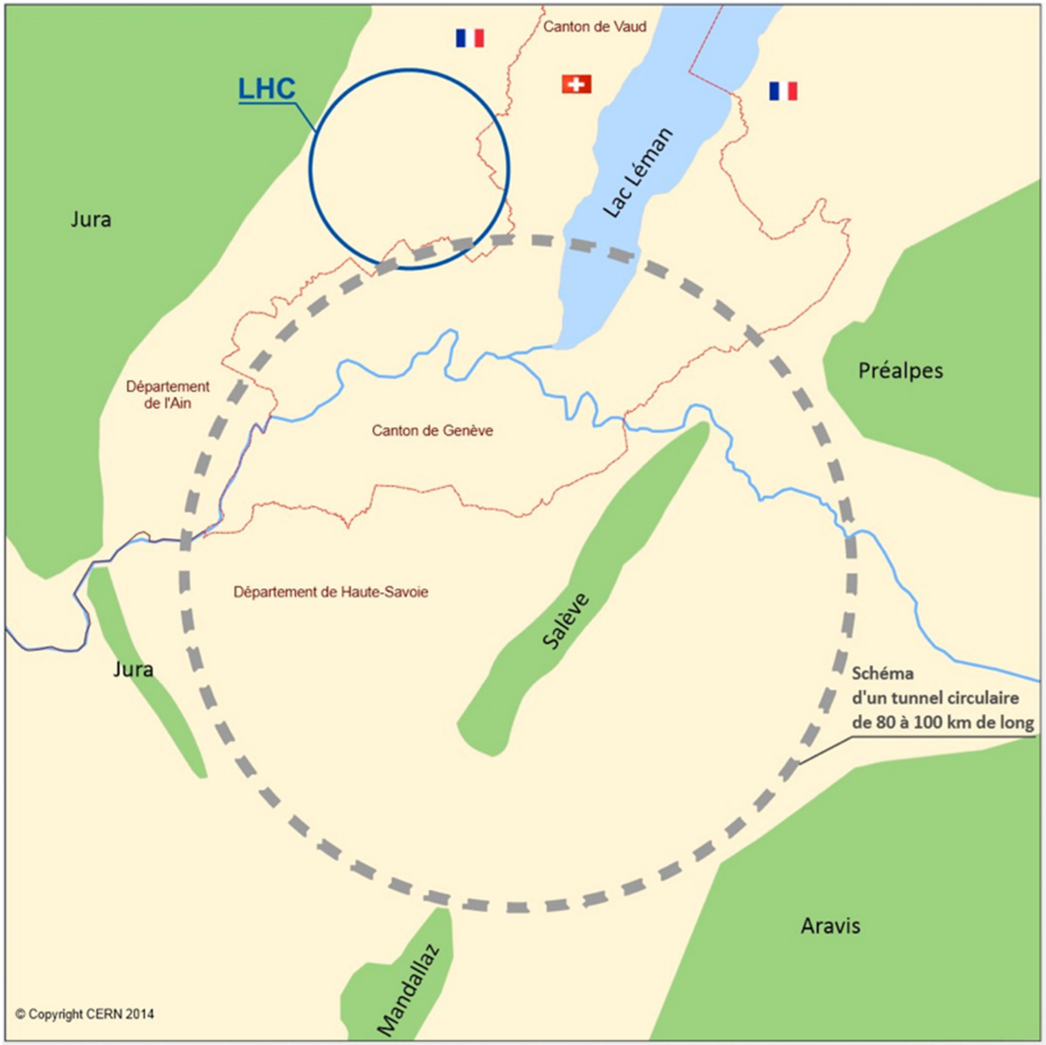
- for hadrons (and leptons before)
- „think big“ – in terms of magnet development and civil construction
- 100 km circumference, 100 TeV cms. energy
- CDR expected end 2018.

> Requirements:

- >16 T dipole magnets

> Part of the FCC study

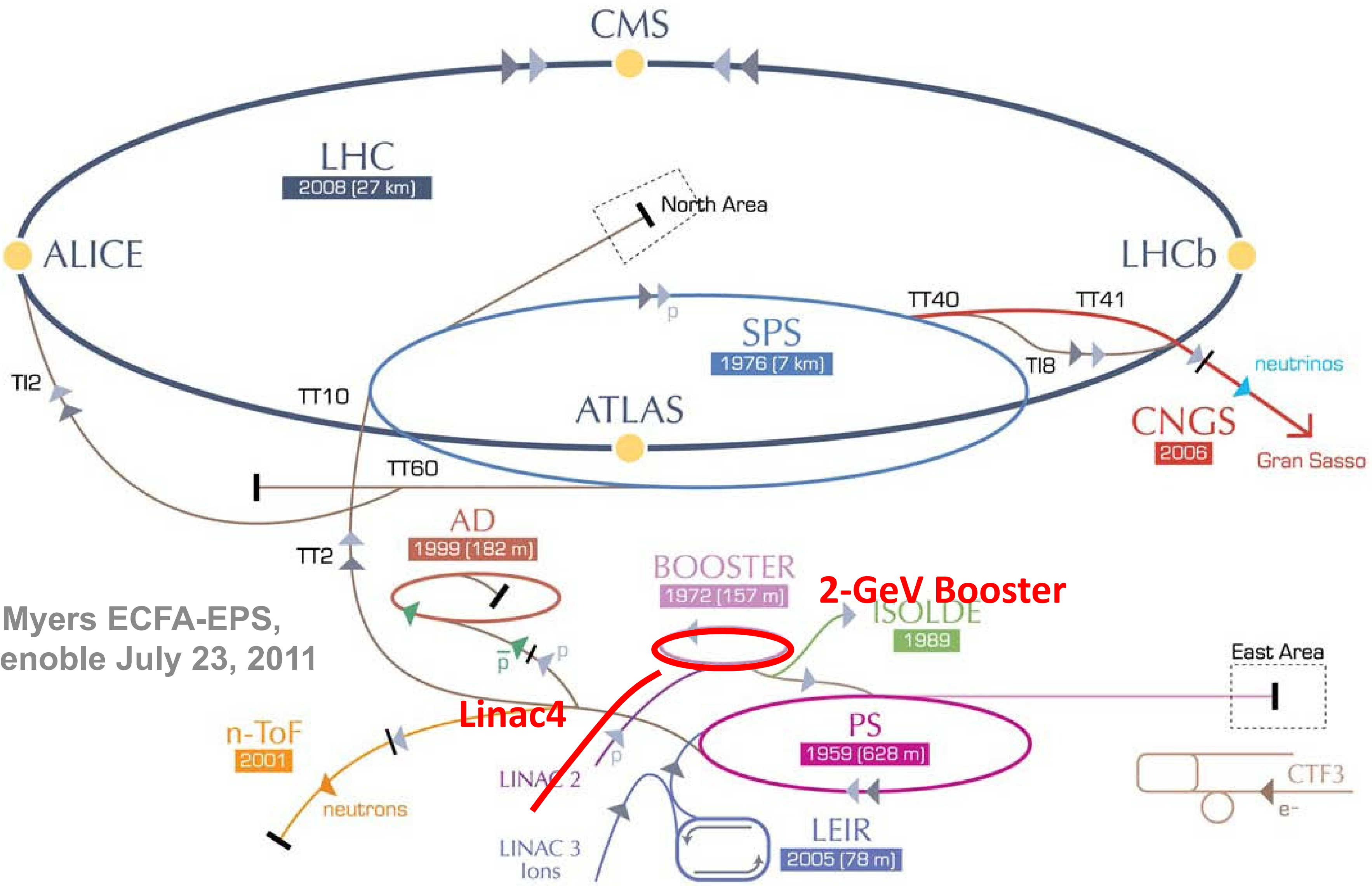
- high-Energy LHC (HE-LHC) new dipoles in LHC tunnel
- roughly twice LHC energy



FCC WEEK

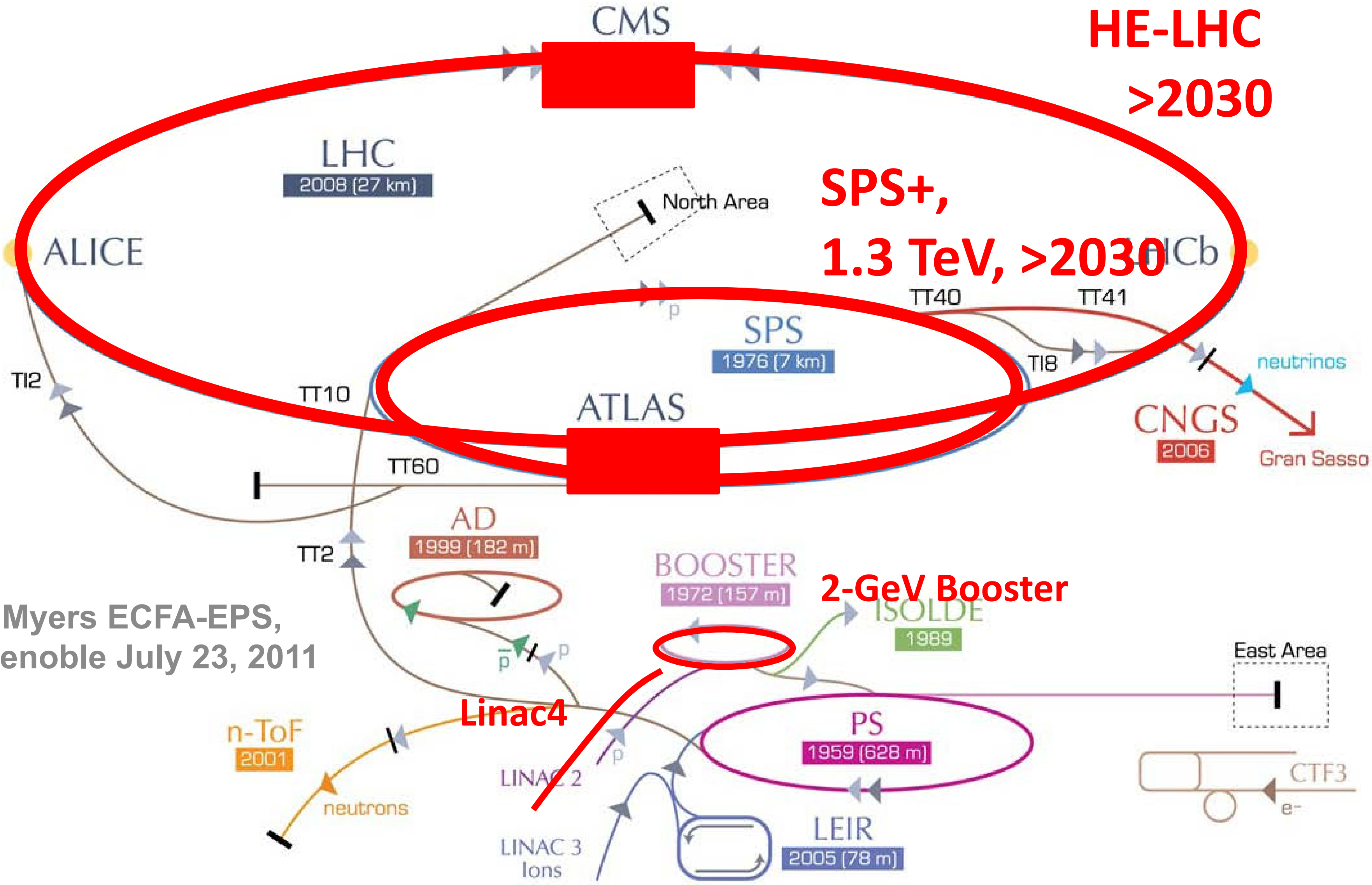

FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch
IEEE CSC
DPG
DESY

HE-LHC – LHC modifications



S. Myers ECFA-EPS, Grenoble July 23, 2011

HE-LHC – LHC modifications



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China CepC and SppC

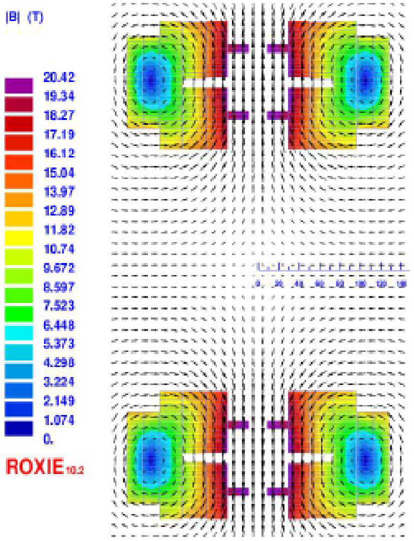
> Study for a O(100 km) tunnel
  - O(100 TeV) cms energy pp collider
  - preceeded by an e+e⁻ Higgs factory (CEPC, see below)

> Baseline Design
  - 12 T dipole iron-based HTS
  - cms energy ≈ 70 TeV

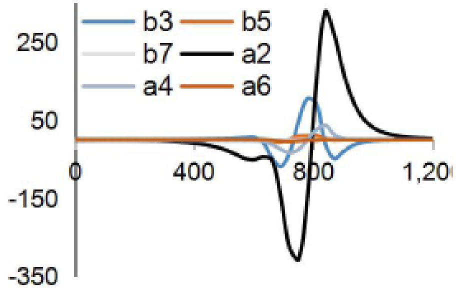
> Energy Upgrade
  - 20-24 T HTS dipoles
  - cms energy ≥ 125 TeV

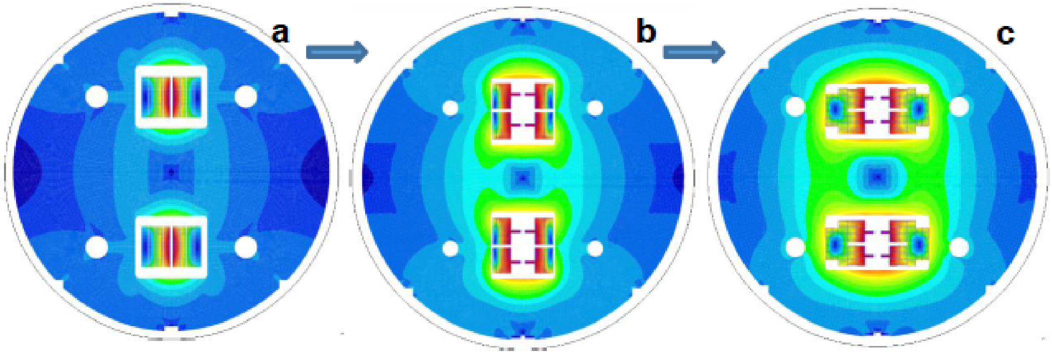
> Ambitious R&D for High Temperatur Superconductor

> CDR planned for end 2017



High order multiples along axis

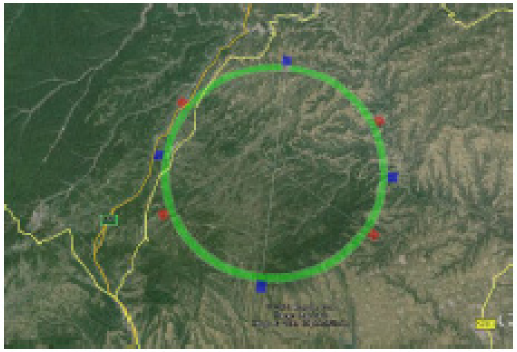




R&D steps for fabrication of the 20-T dipole magnet with common coil configuration
a. a 15-T sub-scale magnet; **b.** a 15-T dipole magnet with 2 apertures; **c.** a 20-T dipole magnet with 2 apertures and 10^{-4} field quality

CEPC/SppC

> **Sites under study:**



1) Qinhuangdao

(site technical exloring done)

2) Shanxi Province

(under site technical exploring, started from Jan. 2017)

3) Near Shenzhen and Hongkong

(site technical exloring done)

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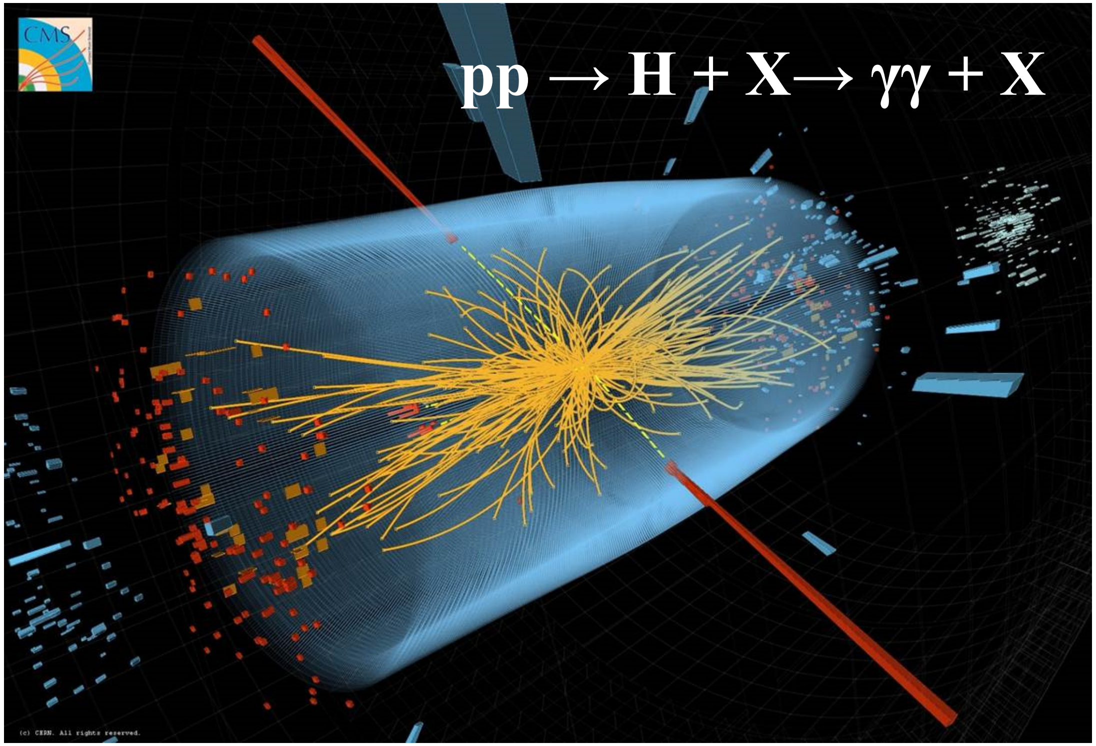
Higgs at the LHC and at an e^+e^- collider



Observed Higgs candidate at CMS

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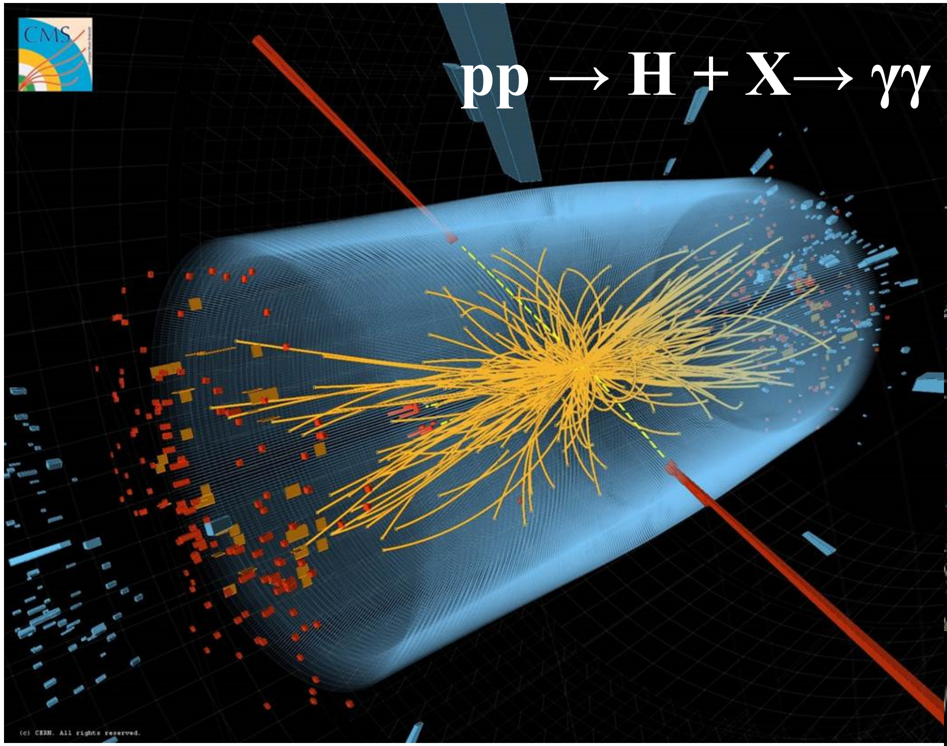
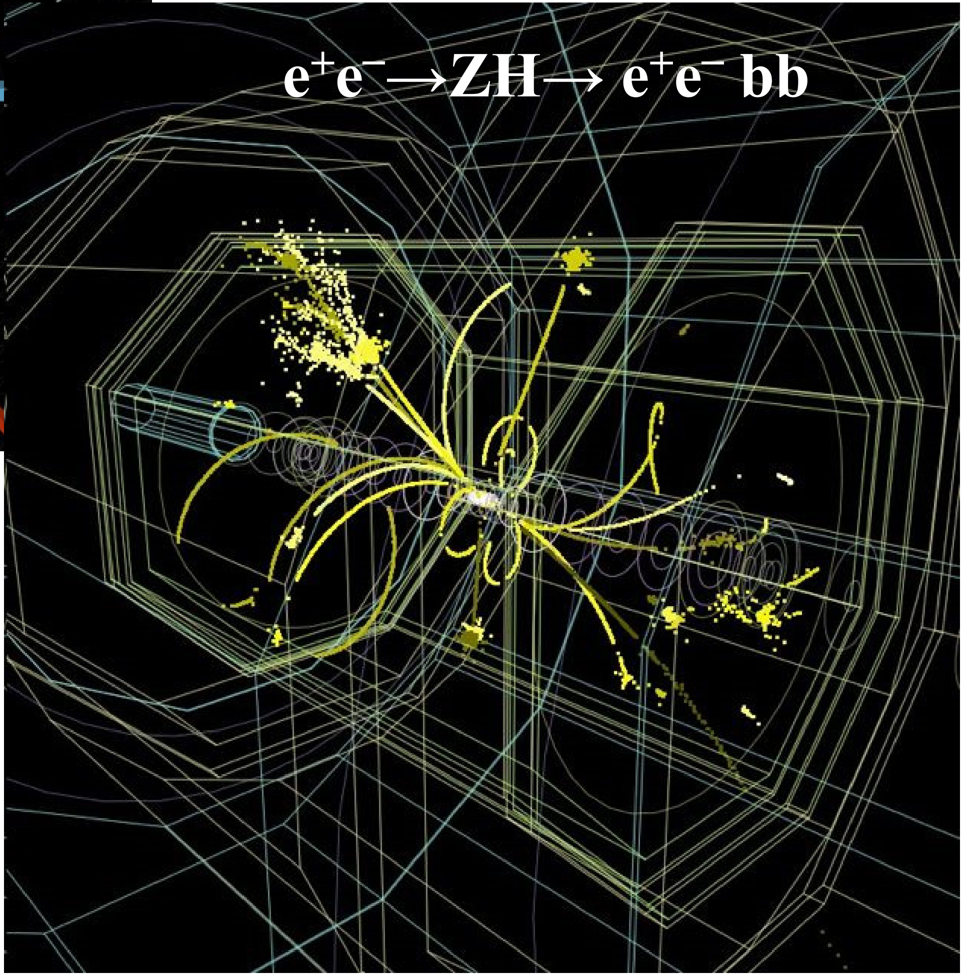
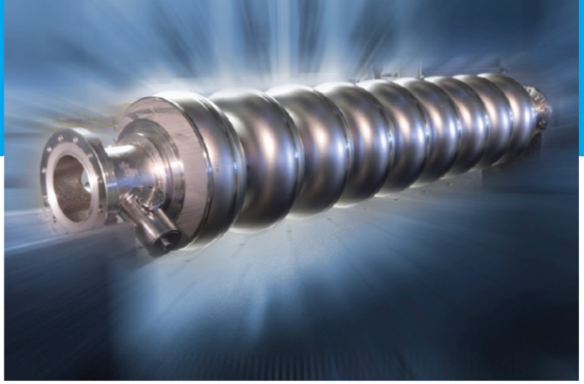


Observed Higgs candidate at CMS

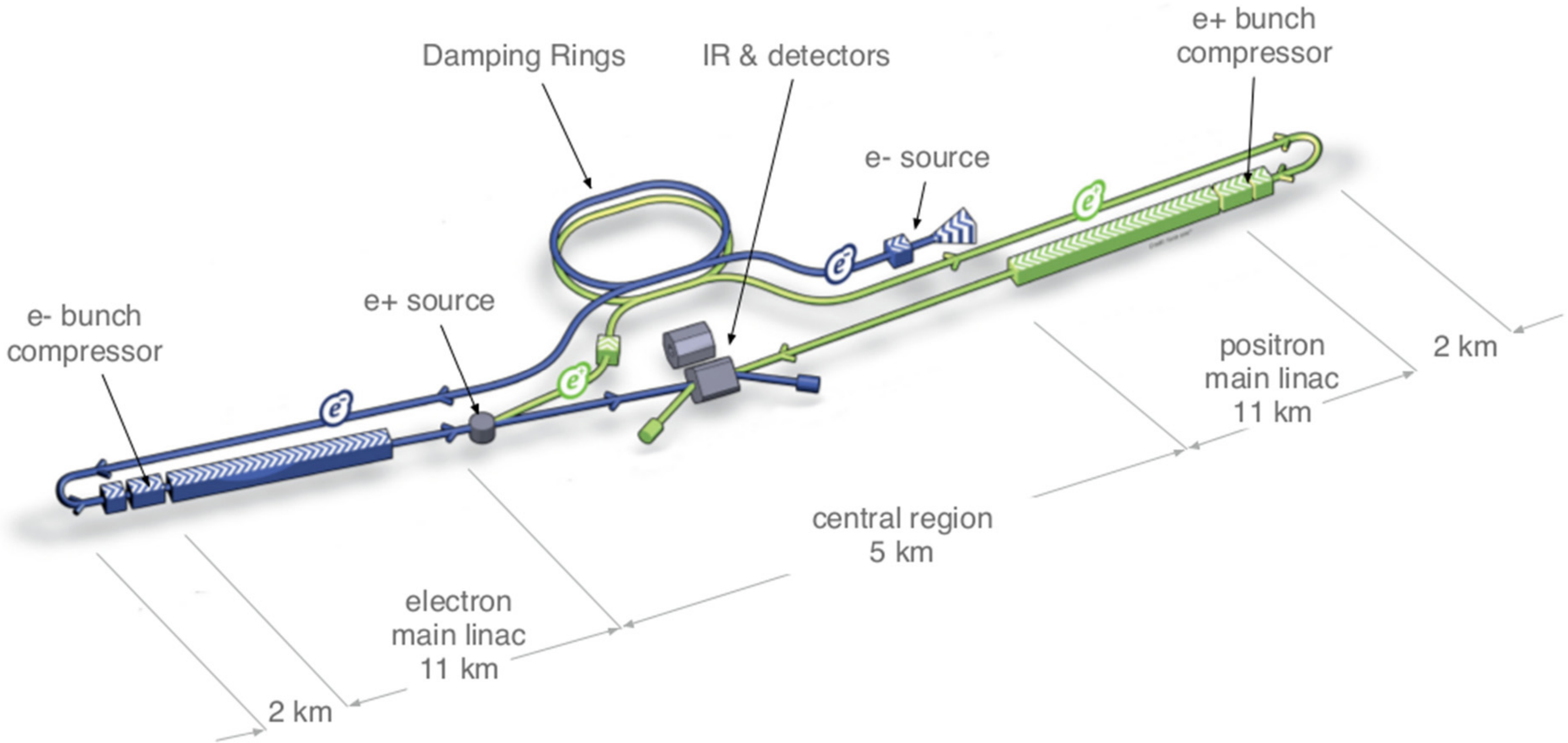
Simulated Higgs in ILD detector @ ILC



International Linear Collider (ILC)



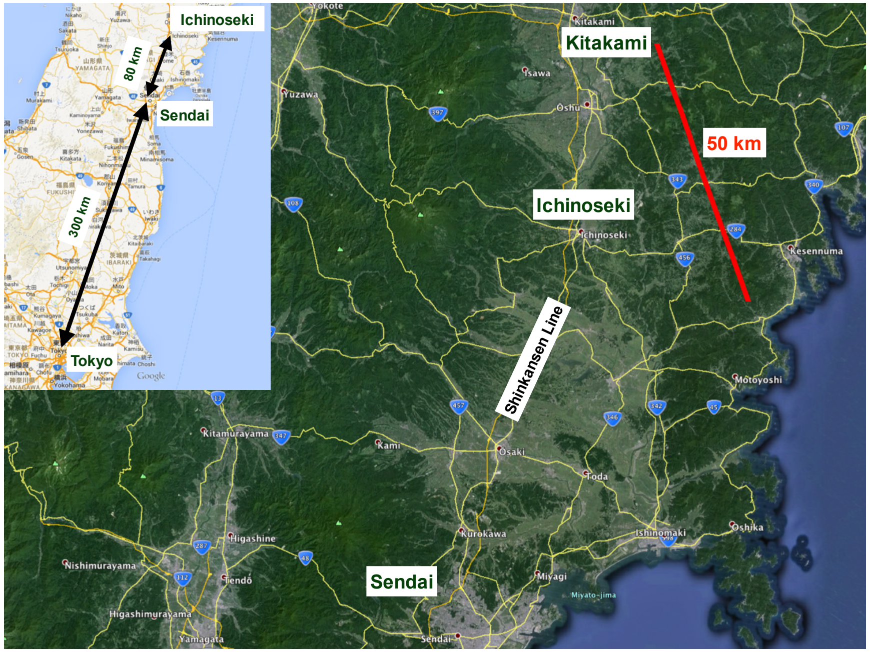
- Electron-Positron Collider
  - based on superconducting RF technology

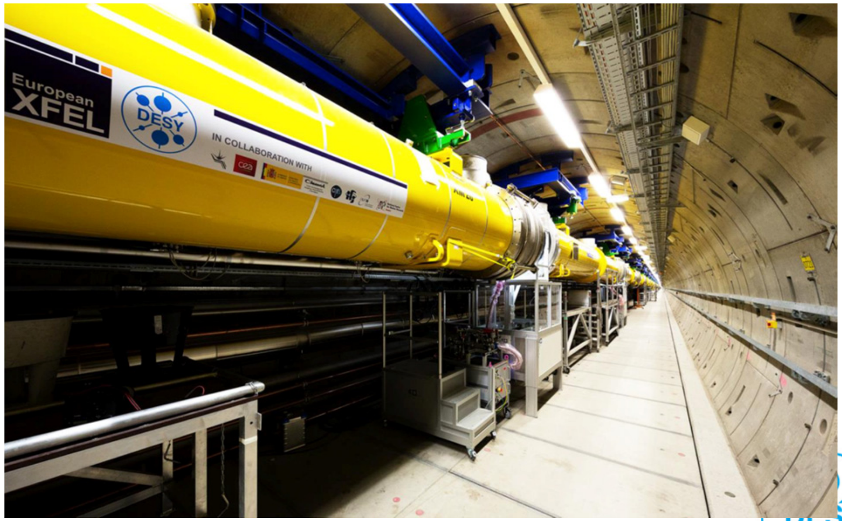


- Technical design report (TDR) submitted 2013
  - $\sqrt{s}$ = 250 – 500 GeV, upgrade for 1 TeV, acceleration gradient 35 MV/m

ILC Status

- Japan has expressed interest to host the ILC
  - top priority of Japanese particle physicist
  - worldwide support, e.g. ICFA
- Project under investigation by Japanese government
  - result expected in 2018
  - 90 Gev Giga-Z,
    250 GeV Higgs factory,
    ≈ 350 GeV at ttbar threshold and
    500 GeV for ttH and HH
- Project is technically mature
  - demonstrated by European XFEL





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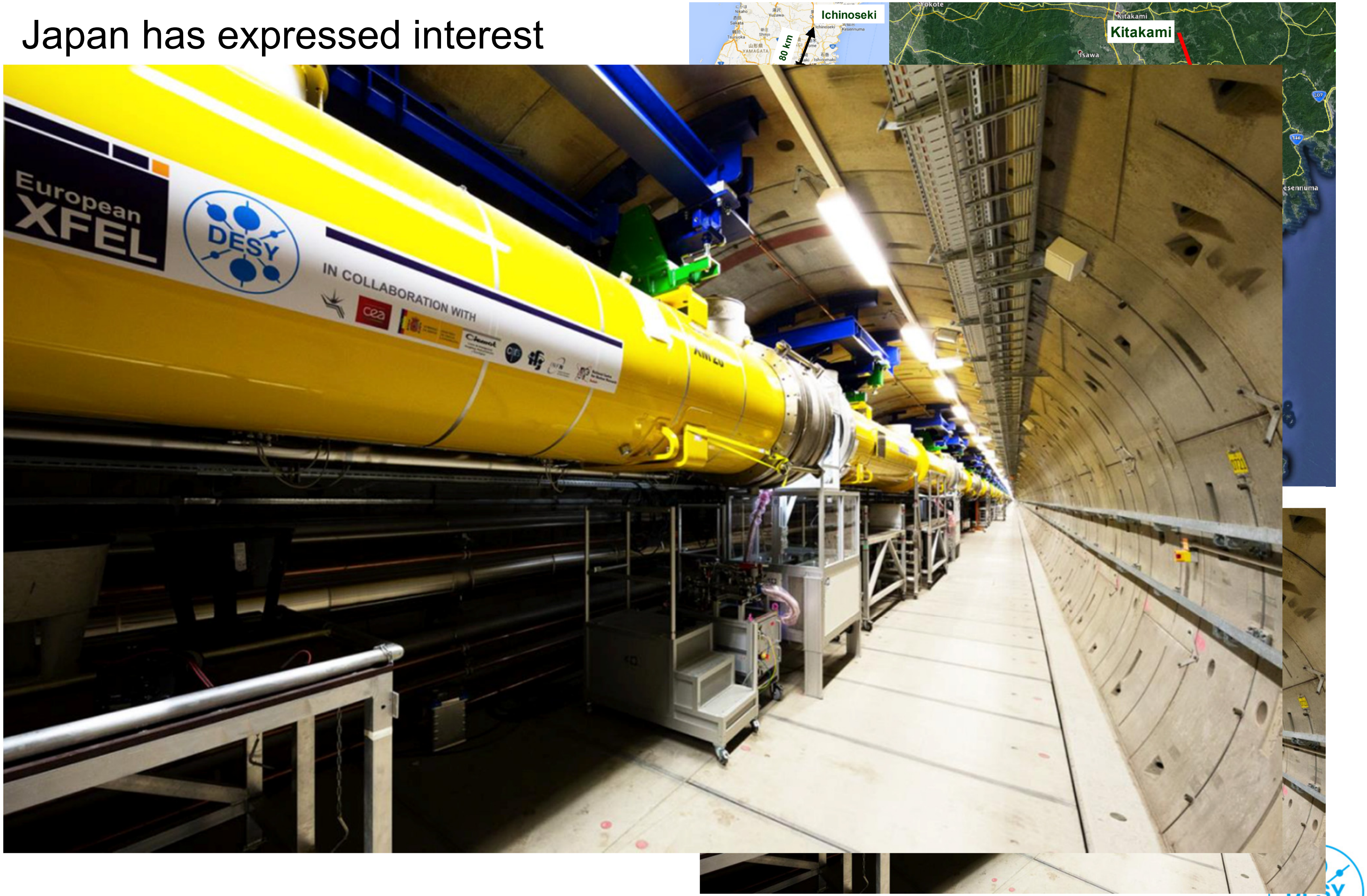
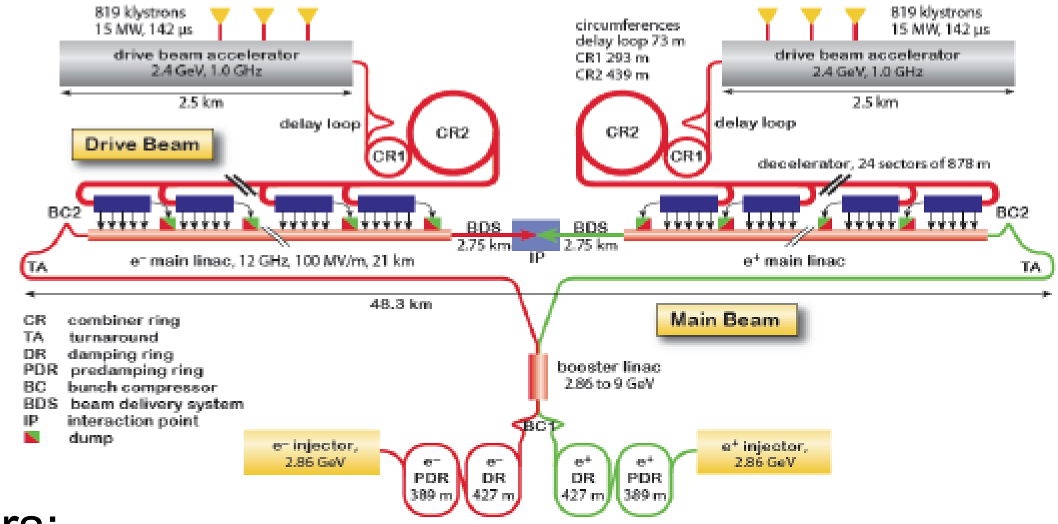


CLIC: A potential multi-TeV collider

- Novel two-beam acceleration concept
- 100 MV/m gradient seems feasible
    - cms energies up to 3 TeV
- But not yet at the same level of maturity as ILC technology
- General issue for linear colliders: power consumption:

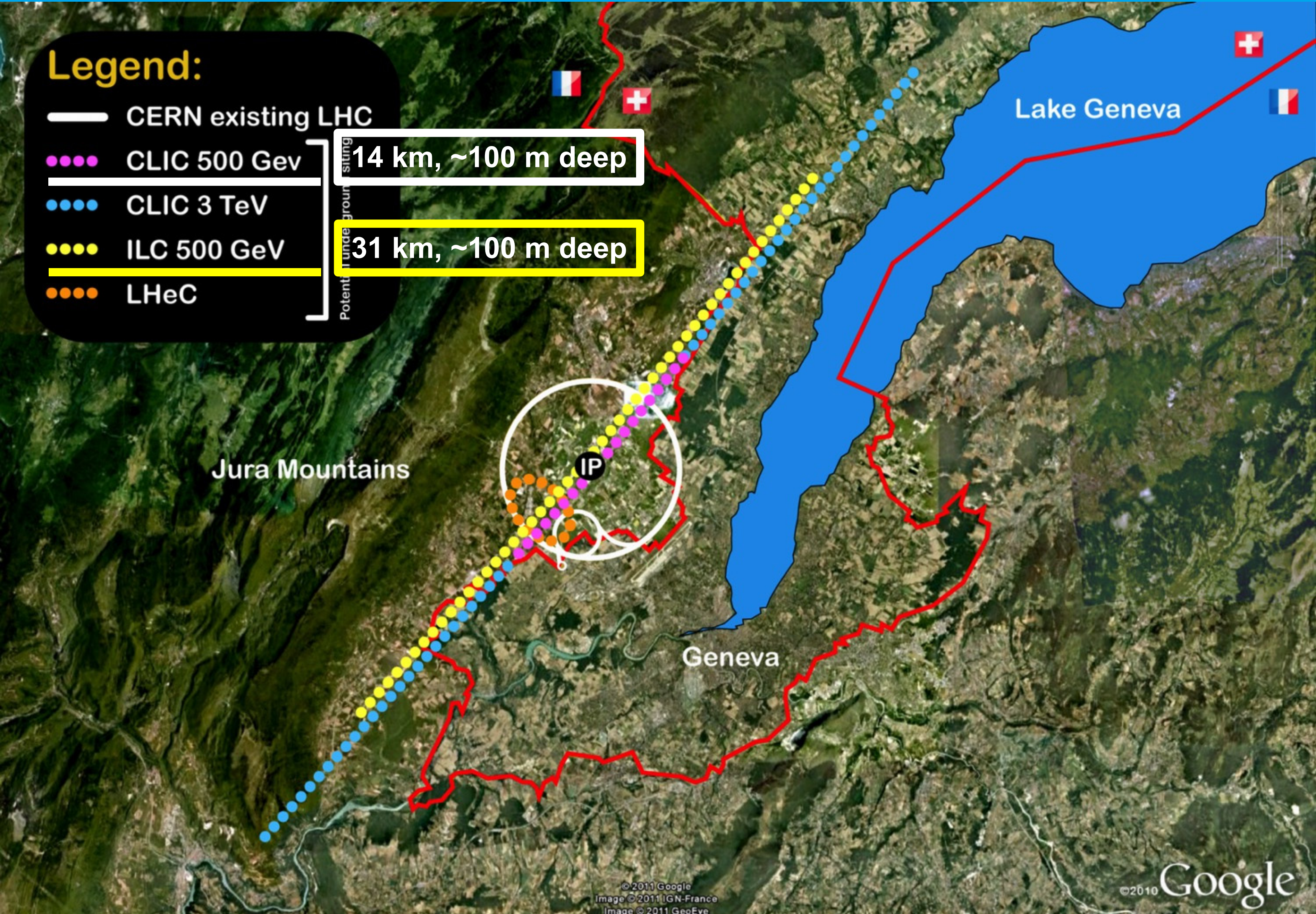
Overview of the CLIC layout at √s = 3 TeV



Project	√s/TeV	Power/MW
ILC	0.5	163
ILC	1	240
CLIC	1.5	364
CLIC	3	589

- CLIC R&D ongoing at CERN
    - gradient, stability, beam handling
    - 380 GeV start version
    - input to European strategy process

CLIC – Compact Linear Collider at CERN



Legend:

— CERN existing LHC

●●●● CLIC 500 Gev

●●●● CLIC 3 TeV

●●●● ILC 500 GeV

●●●● LHeC

14 km, ~100 m deep

31 km, ~100 m deep

Circular Electron-Positron Colliders

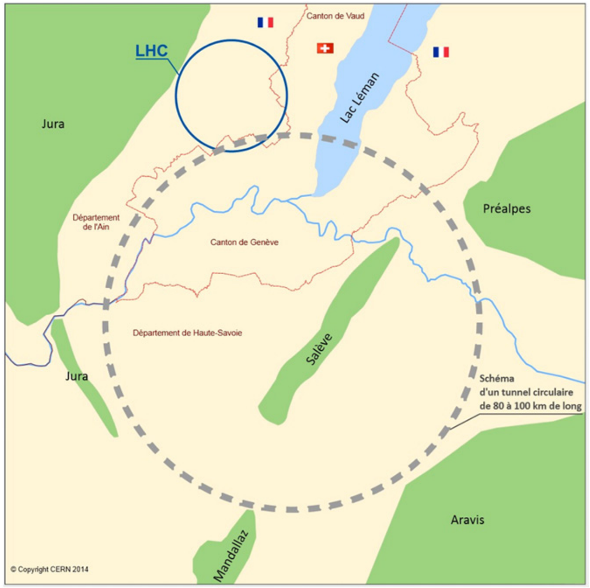
> FCC-ee:
- lepton option of FCC.
- beam energies up to the ttbar threshold, i.e. cms energy 350 GeV.
- various staging scenarios for Z, WW, H, ttbar thresholds

> CEPC:
- Higgs factory, i.e. cms energy 250 GeV.

> Circular: higher luminosity @250 GeV

> Linear: can reach higher energy

> Both projects are supposed to preceed the respective hadron collider



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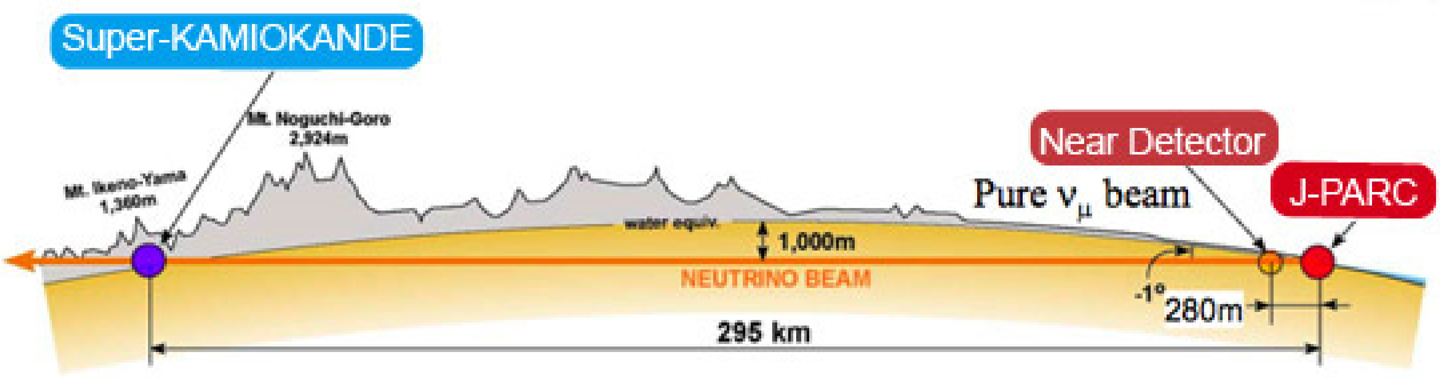
Neutrino Beams for High-Energy Physics

- Neutrino beams offer unique potential to address fundamental questions of HEP
  - CP violation and matter-antimatter asymmetry, SM parameters, CKM matrix, mass hierarchy and mass determination
  - numerous past and ongoing experiments,
- Most recent example: TK2 with SuperKamiokande
  - neutrino beams from J-PARC facility; mainly for study of muon-to-electron oscillation studies.



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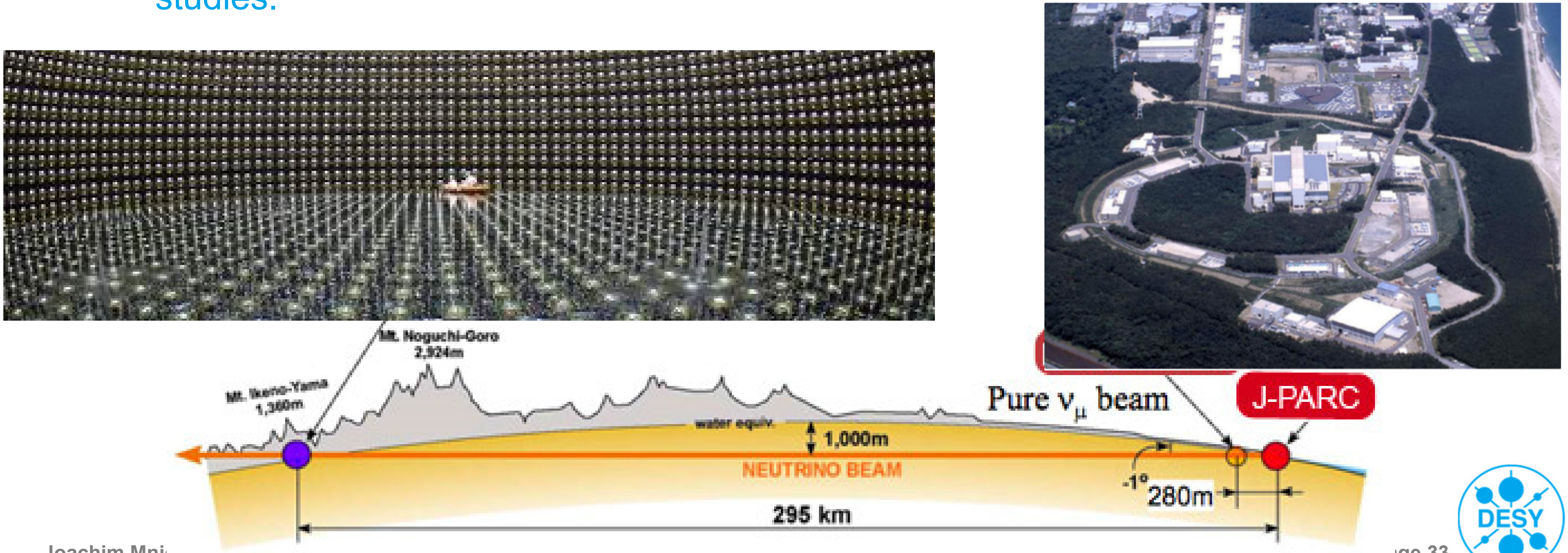

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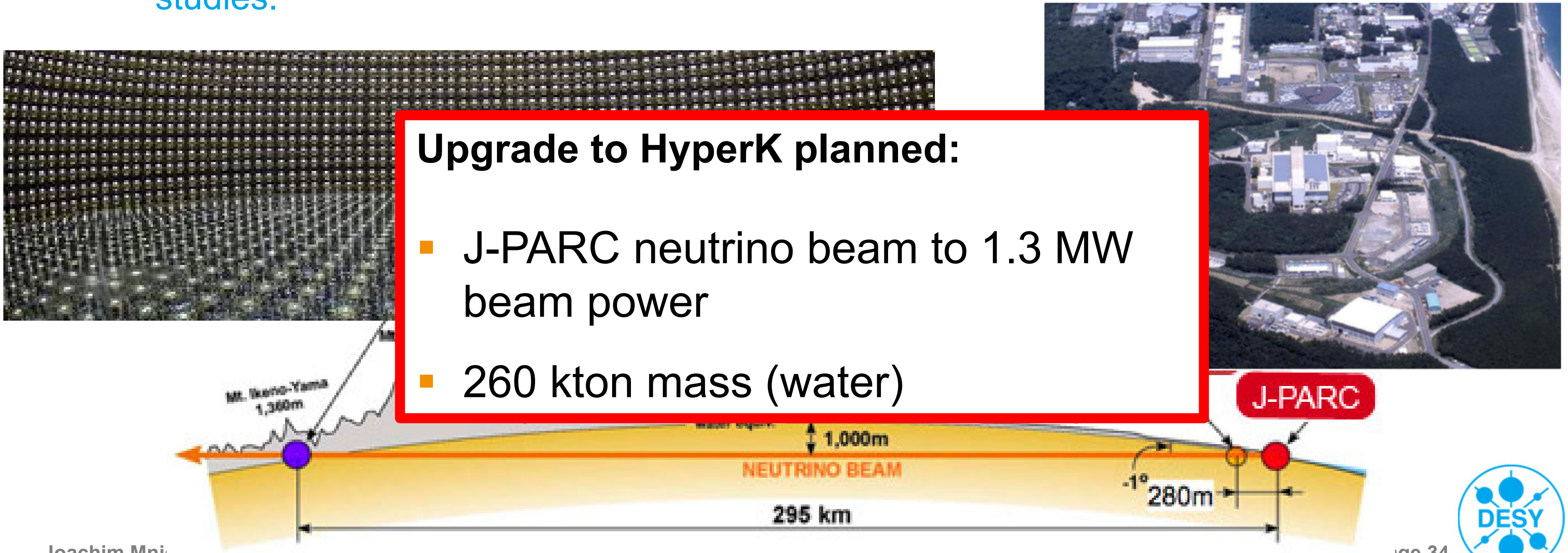
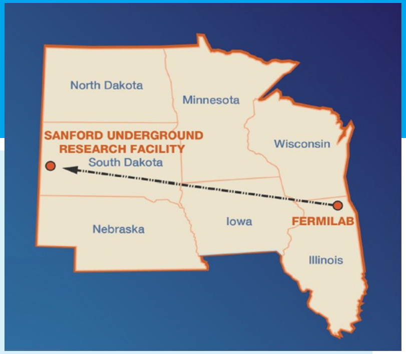


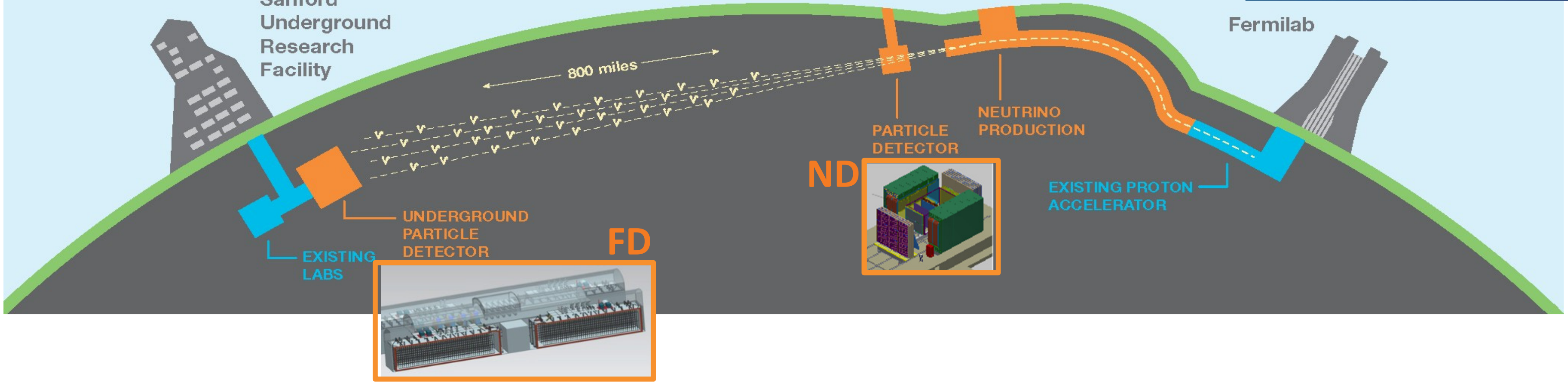
Upgrade to HyperK planned:

- J-PARC neutrino beam to 1.3 MW beam power
- 260 kton mass (water)

LBNF / DUNE

- Beam power 1.03 MW at 80 GeV; planned increase to 2 MW
- Compare $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$anti-ν_e





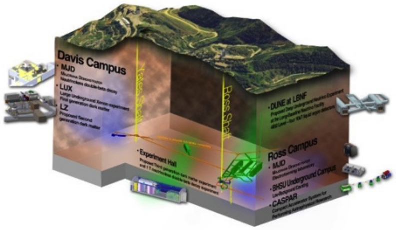
2017: begin far-site construction

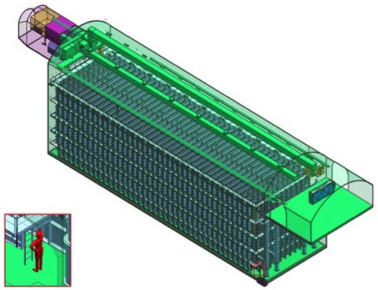
2018: proto-DUNEs at CERN

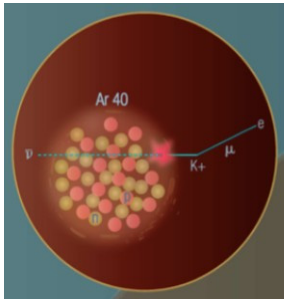
2021: far detector installation begins

2024: physics data begins (20 kt)

2026: neutrino beam available



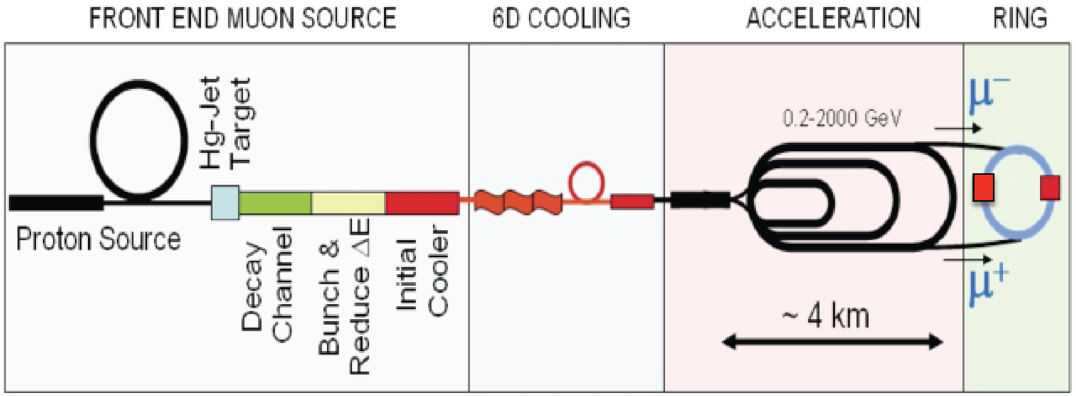


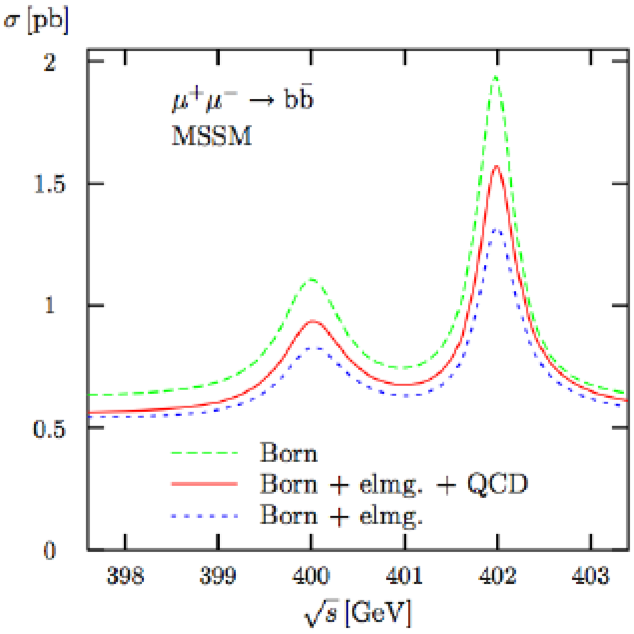


2017: form ND consortium

Far Future: Muon Collider

- Try to collide $\mu^+\mu^-$ rather than e^+e^-
- Advantages:
  - much smaller synchrotron losses: $\sim E^4/m^4r$
  - smaller facility size even for a multi-TeV machine
  - s-channel Higgs production: $\sim m^2$ factor 40000 enhancement wrt. e^+e^-
  - first stage could be a υ-factory
- Problems:
  - muons live only for 2.2 μs
  - need very intense proton source
  - muon cooling
  - high background from muon decays (neutrinos!) at high energy
  - …

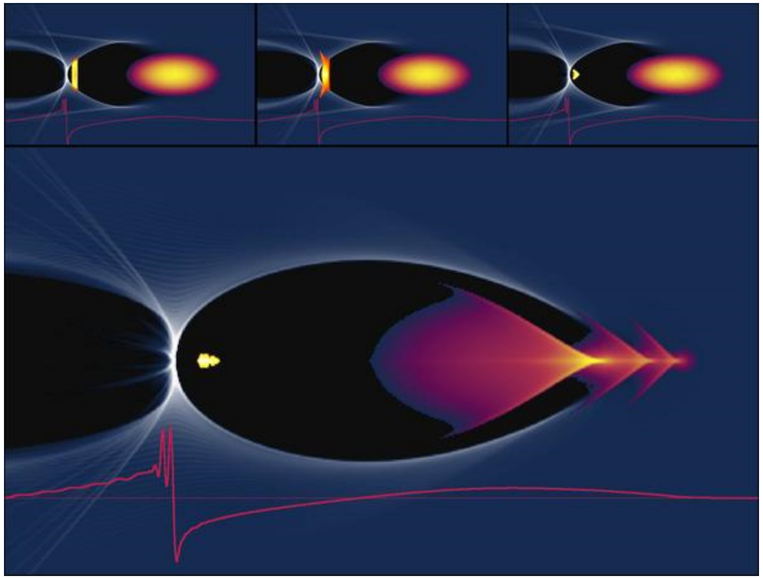


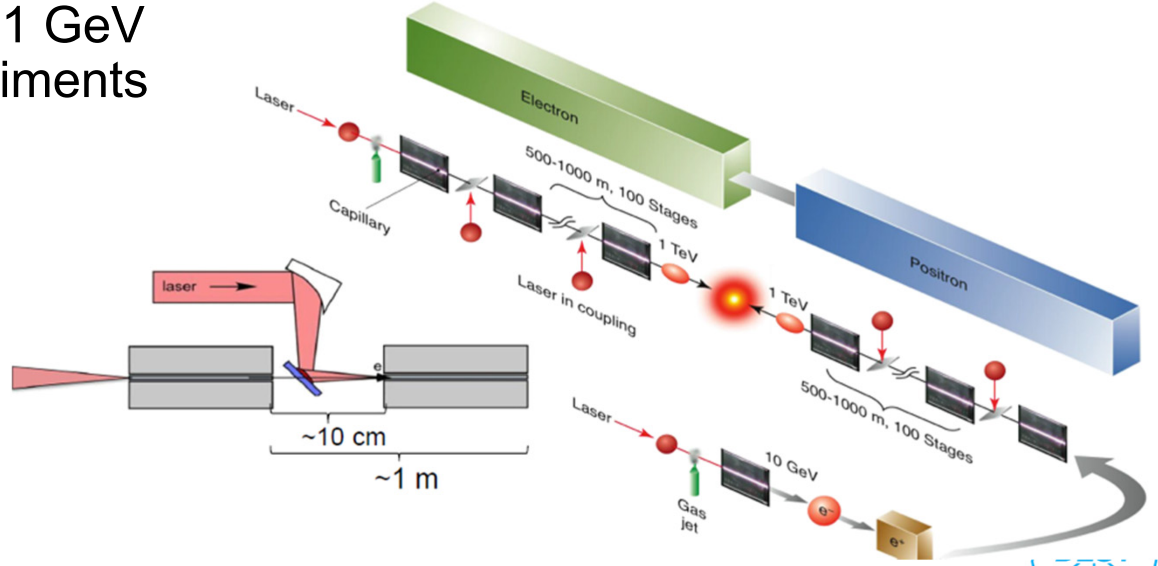


Example SUSY Higgs bosons

Far Future: Plasma Wakefield Collider

- How to achieve significantly higher gradients than 30 – 100 MV/m ?
  - Plasma Wakefield Acceleraion (PWA)
- Create very high electric field by pushing away electrons from atoms in a plasma
  - using very intense laser
  - or particle particle beams e.g. AWAKE at CERN
- Gradients of 10 GV/m with 1 GeV achieved in table top experiments
  - electrons accelerated from 40 to 80 GeV!
- But still many open issues
  - e.g. staging in a high energy linear collider





EuPRAXIA

NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

- 3 M€ awarded to 16 laboratories and universities from 5 EU member states within Horizon 2020.
- Joined by 22 associated partners with additional in-kind commitments.
- Goal: produce a CDR for the worldwide first high energy plasma-based accelerator that can provide industrial beam quality and user areas.
  - Important intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or the energy frontier.
- 14 work packages; 8 included in EU design study
  - E.g. “Physics and simulation”, “High-gradient laser plasma acceleration structure”, “Electron beam design”, etc.
  - Also application WPs: “FEL pilot application”, “HEP and other pilot applications”, …

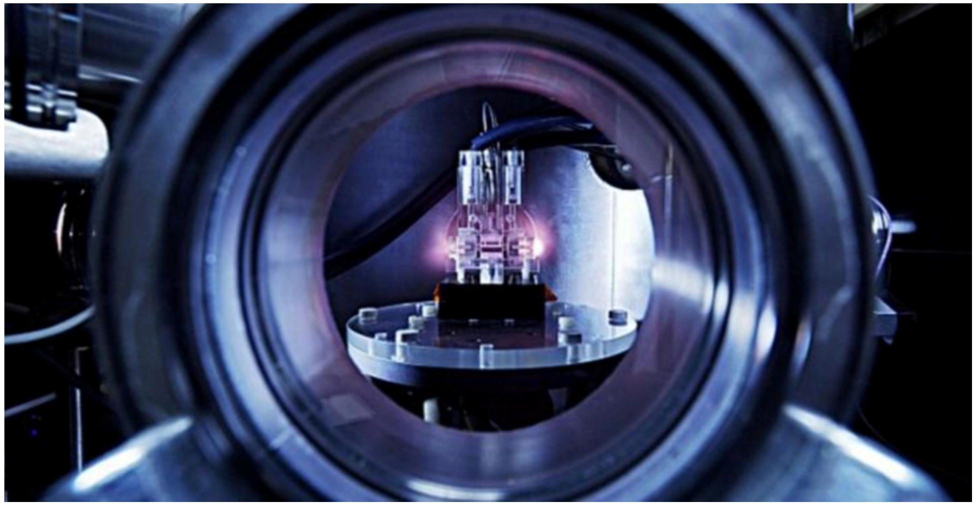


Image of plasma cell

Outline

- High-energy physics and the need for accelerators/colliders
- LHC and HL-LHC
- Beyond the LHC: future hadron colliders
- Precision machines: future electron positron colliders
- Other ideas: neutrino beams, muon colliders, ...
- Some strategy considerations
- Conclusions

HEP is a Global Endeavour

- New machines are multi-billion Dollar / Euro /CHF projects
  - there can only be one of a kind?!
  - need international consensus – a slow and careful political process!

- Last round of strategy discussions has concluded in 2012/13 in various regions of the world

- Important issues in European discussion:
  - High-Luminosity LHC is decided
  - High energy physics at CERN after LHC
    R&D and input from LHC needed.
  - LC project: European participation in ILC project in Japan; CLIC
  - Long-baseline neutrino programme.
  - and others

GLOBAL PARTICLE PHYSICS STRATEGY

Japan: Future HEP Projects

– „... Japan should take the leadership role in an early realisation of an e+e- linear collider.“

Update of European Strategy for by CERN Council (May 2013)

- **LHC, incl. HL-LHC**
- **accelerator R&D**
- **strong support for ILC**
- **long-baseline neutrino**
- **importance of theory**

European Strategy
for Particle Physics

USA: Snowmass conclusions and recommendations to P5 in line with worldwide strategy statements

- Different flavours in different regions of the world
- But looks like an emerging global, coherent strategy in particle physics
- Next update of European strategy 2020;
  US to follow 2-3 years after.

Conclusions

- High-energy accelerators are indispensable tools to address the most fundamental questions of nature
- The LHC is the current workhorse and immensely successful.
  - future defined until 2035 (HL-LHC programme)
- Numerous concepts and projects for both hadron and lepton collider projects around
  - also (accelerator-based) neutrino projects are important
- Next update of international strategy processes ahead of us
  - European strategy update 2020
  - important physics input from LHC
  - will guide the future
- Accelerator R&D is important for the future of particle physics!