Future of Particle Physics

Joachim Mnich

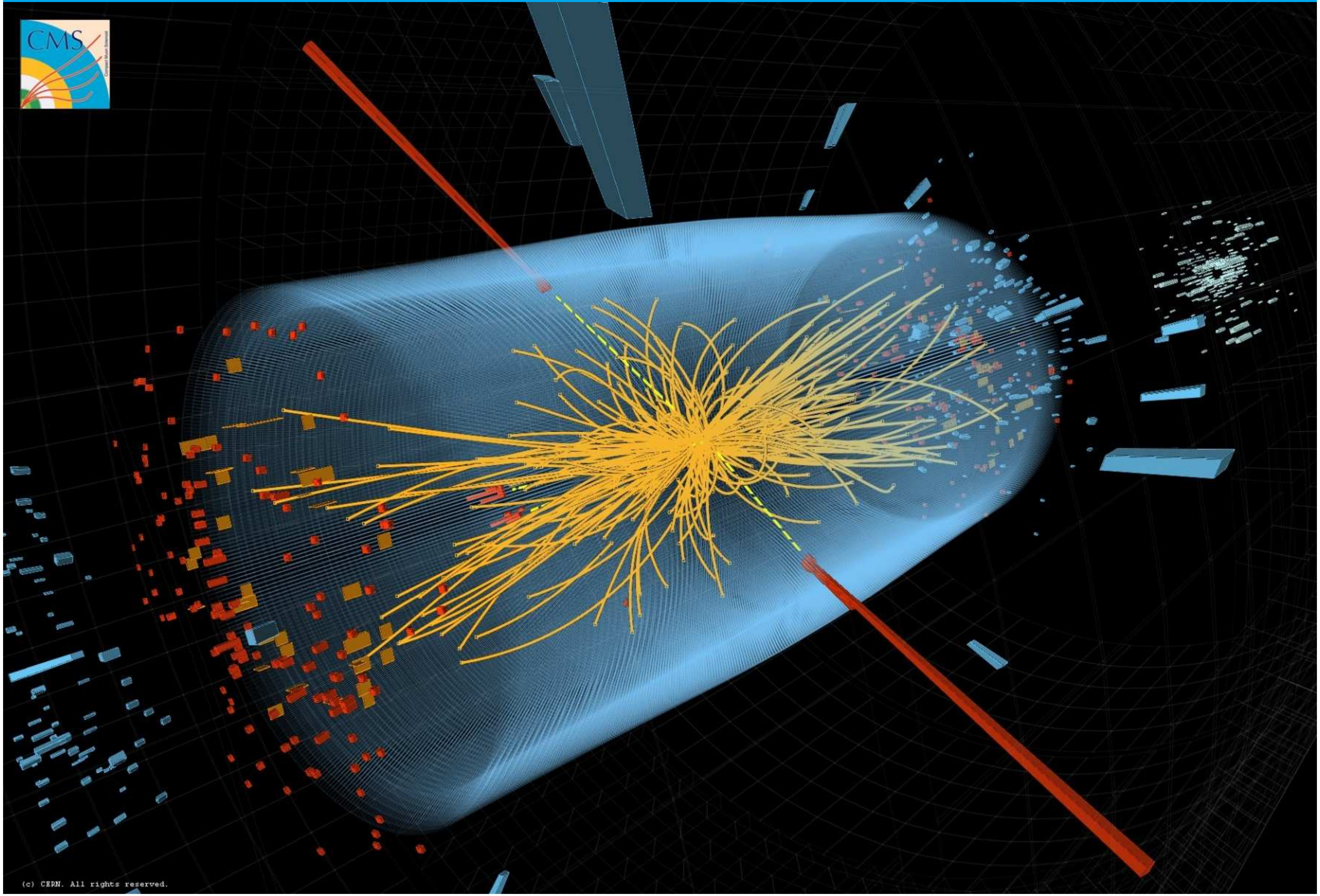
Trans-European School
of High Energy Physics

July 14, 201

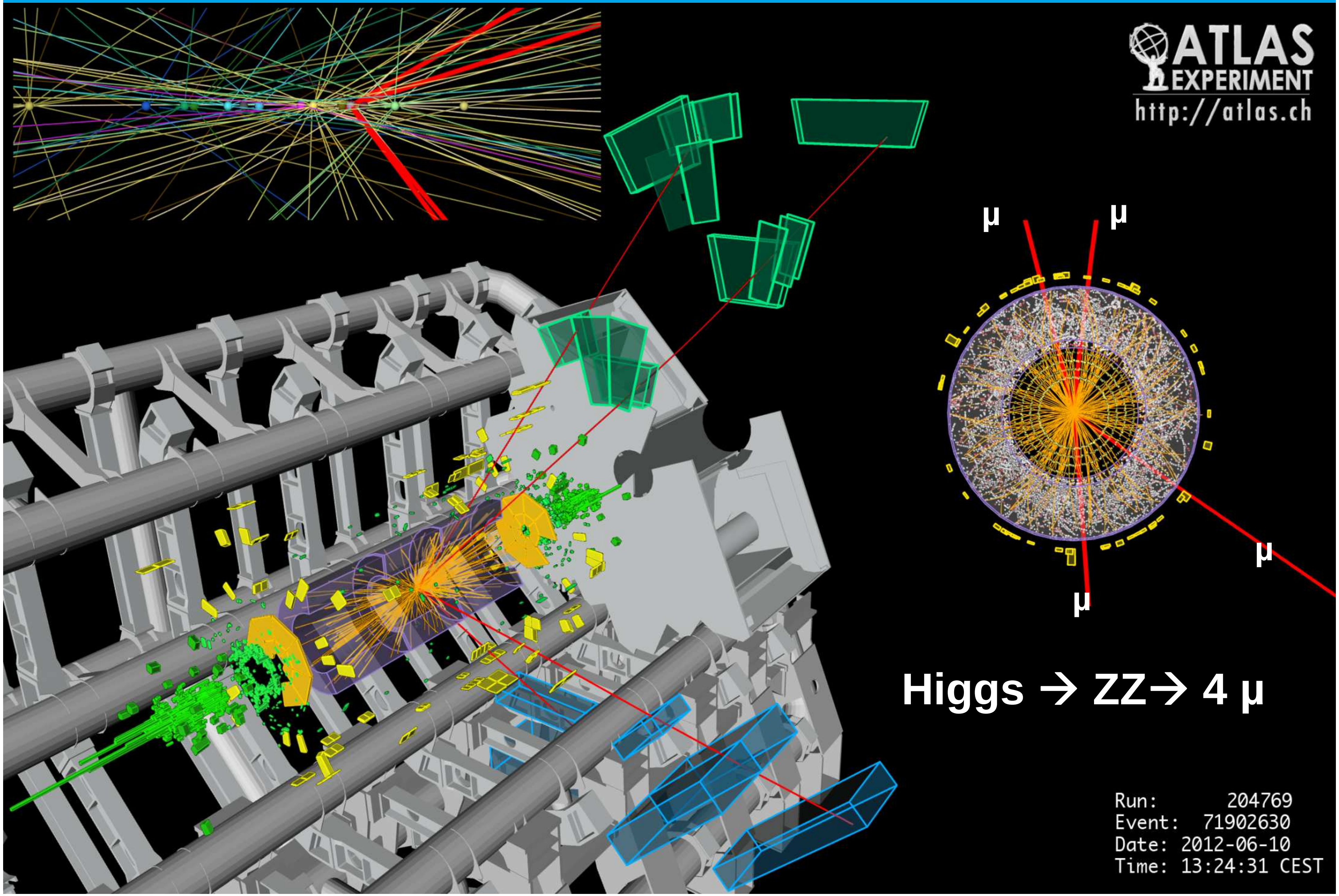
Disclaimer:
- **my personal view**
- **probably a bit biased**
- **but anyway…**

HELMHOLTZ
GEMEINSCHAFT

Observation of a Higgs Boson: A centennial discovery

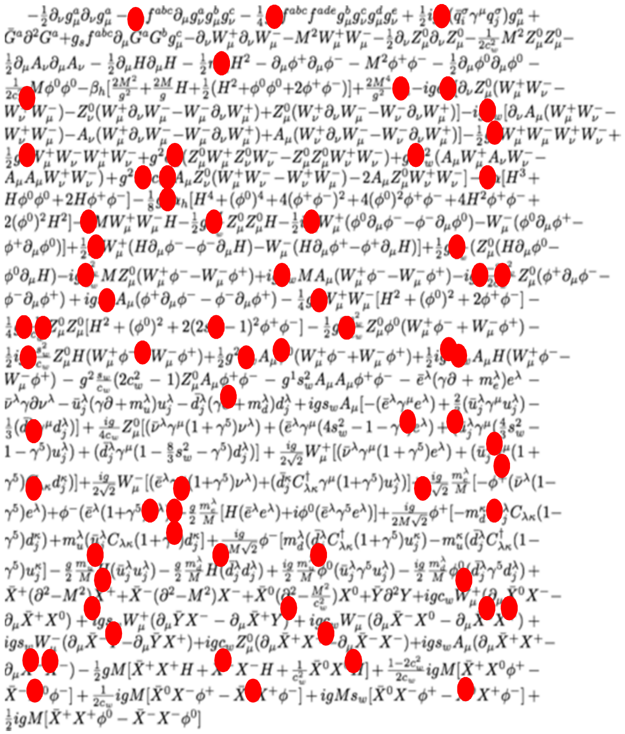


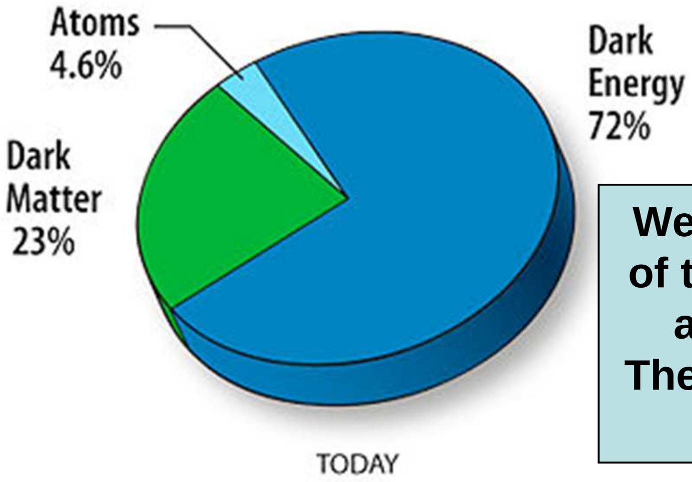
Observation of a Higgs Boson: A Centennial Discovery



… 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.

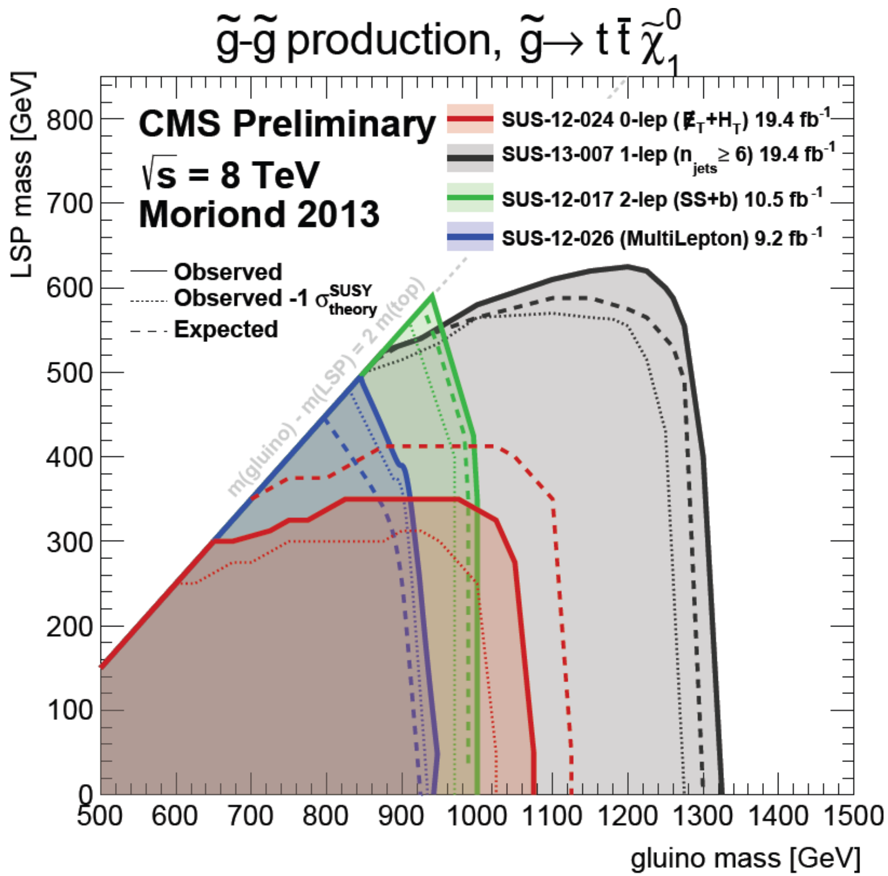
Theory

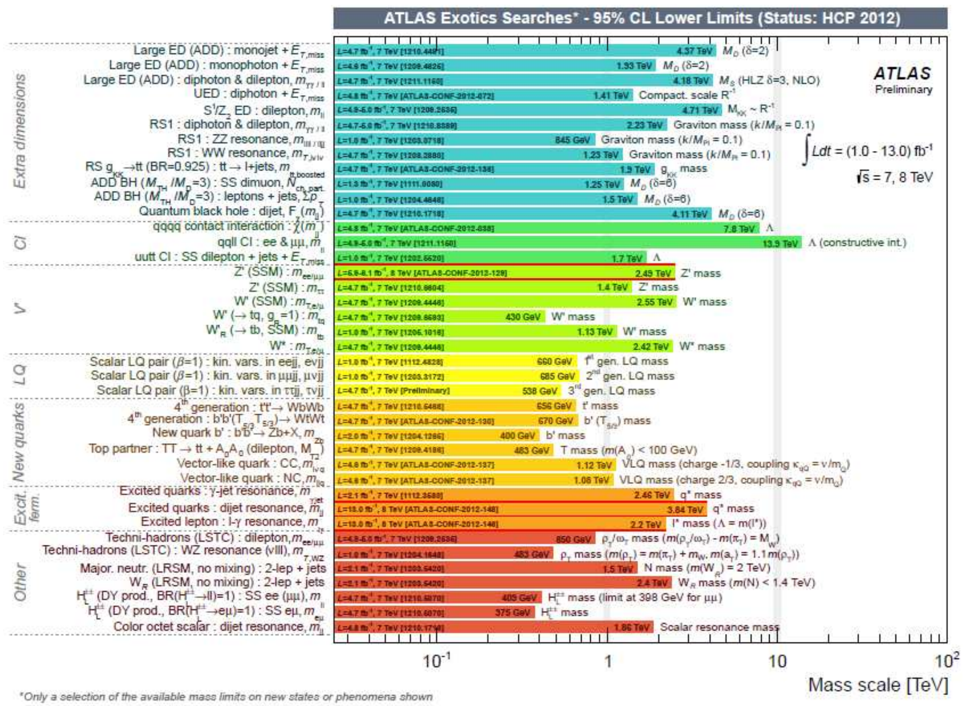
By Hitoshi Murayama

Theory and the LHC

> **LHC starts to challenge some theories**

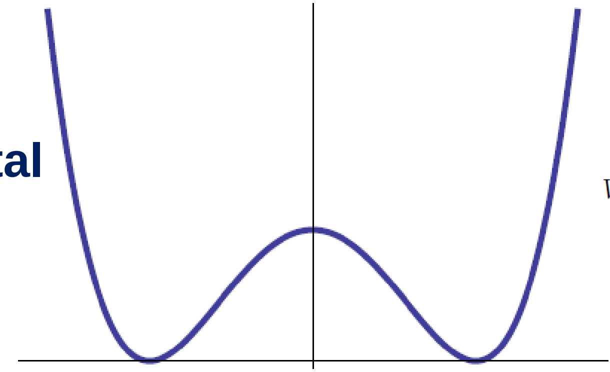
- **Supersymmetry: the air is getting thin for some minimal (simple) models**
- **Other theories: limits in the (multi)-TeV range**
- **Examples:**





But we have a Higgs now!

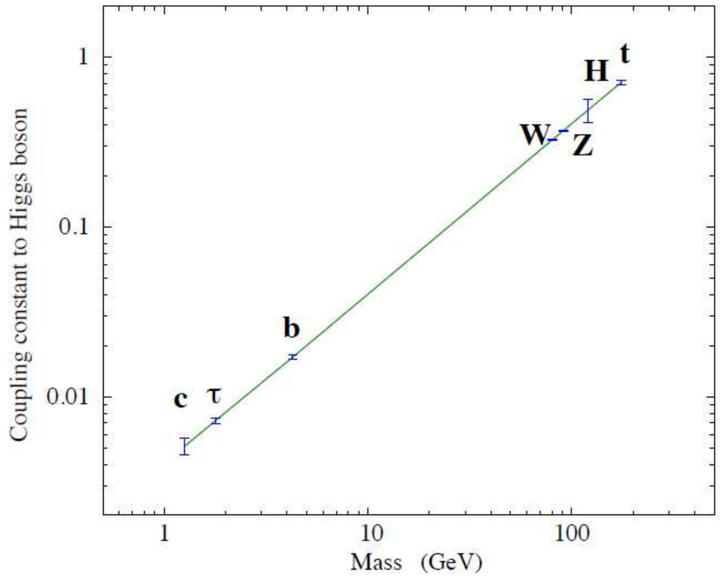
- **Higgs mechanism seems to be at work and explains at least partially why fundamental particles have mass**
  - **the Higgs is different:
    it's not a quark or a lepton
    or a gauge boson
    it's a new kind of fundamental particle**
  - **there is a scalar field filling up the vacuum**
  - **is it THE Higgs (of the SM) or just A Higgs (e.g. SUSY)?**



Test of Higgs potential

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

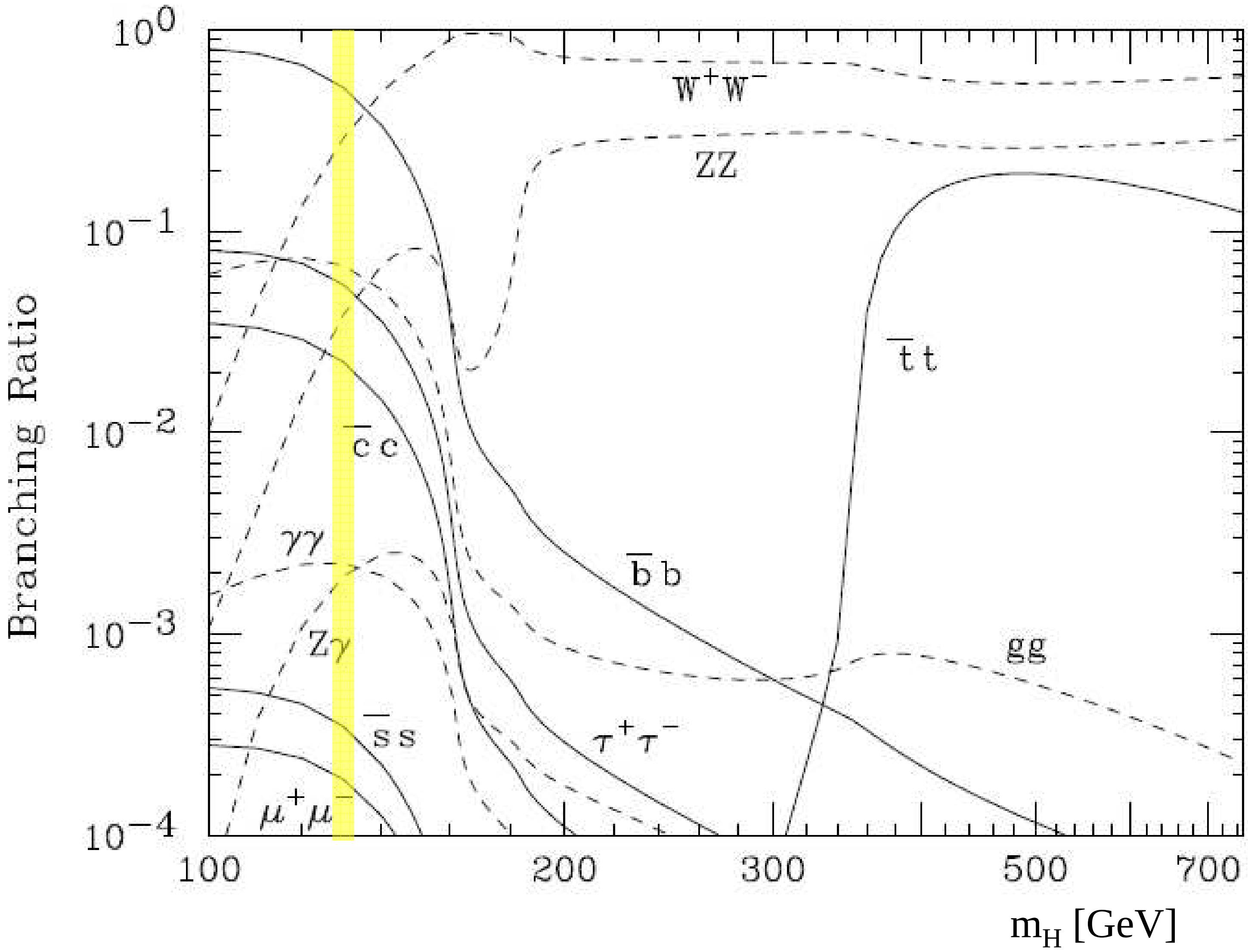
$$V(H) = \frac{1}{2} M_H^2 H^2 + \sqrt{2} M_H H^3 + \cdots$$



- **And why is the Higgs so light?**
- **Must measure its properties as precisely as possible**

Higgs Couplings

> $m_H \approx 125$ GeV is ideal because many Higgs decay modes are accesible



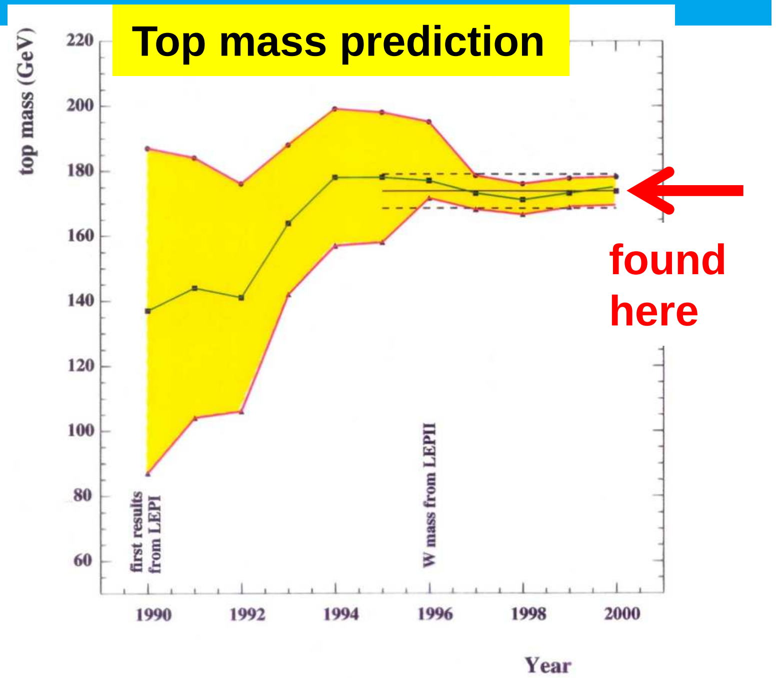
Precision Measurements

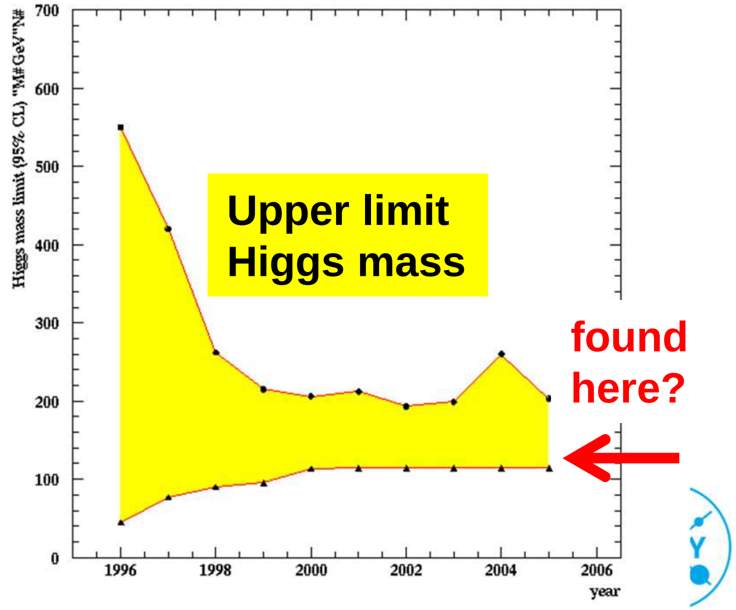
> **Precision measurements of Higgs properties**

- **Is it THE Higgs of the SM or just A Higgs boson, e.g. Supersymmetry?**

> **Looking back in history:**

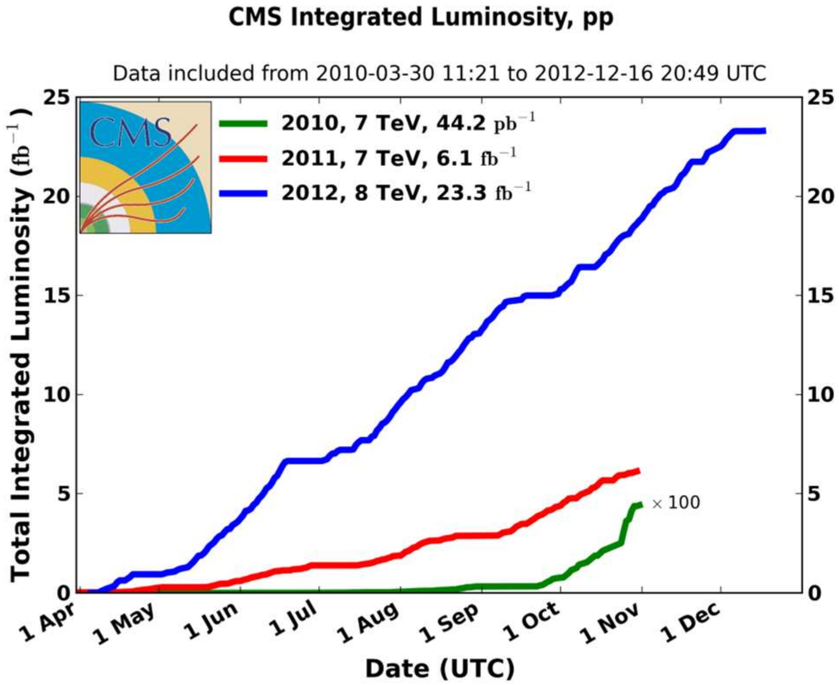
- **W, Z bosons discovered in the 1980ies at CERN in p anti-p collisions**
- **Precise determination of their properties, mainly in e^+e^- (LEP, SLC) in the 1990ies**
- **Resulted in predictions for then unknown top quark and Higgs boson**





The Large Hadron Collider

- **At least 20 years physics programme**
- **We just started:**
  - **very successful operation since 2010**
  - **so far just about half the maximum energy reached 8 TeV wrt. 14 TeV**
  - **and 1% of the luminosity**
    ≈ 30 fb^{-1} by end of 2012
    ≈ 3000 fb^{-1} expected by 2030
- **2013/14 shutdown preparation for run at full energy**
- **2015 ff LHC running at 13-14 TeV**
- **2022 ff High Luminosity LHC**
  - **increase luminosity beyond $10^{34}/cm^2/s$ by approx factor 5 to 10 to collect 3000 fb^{-1}**

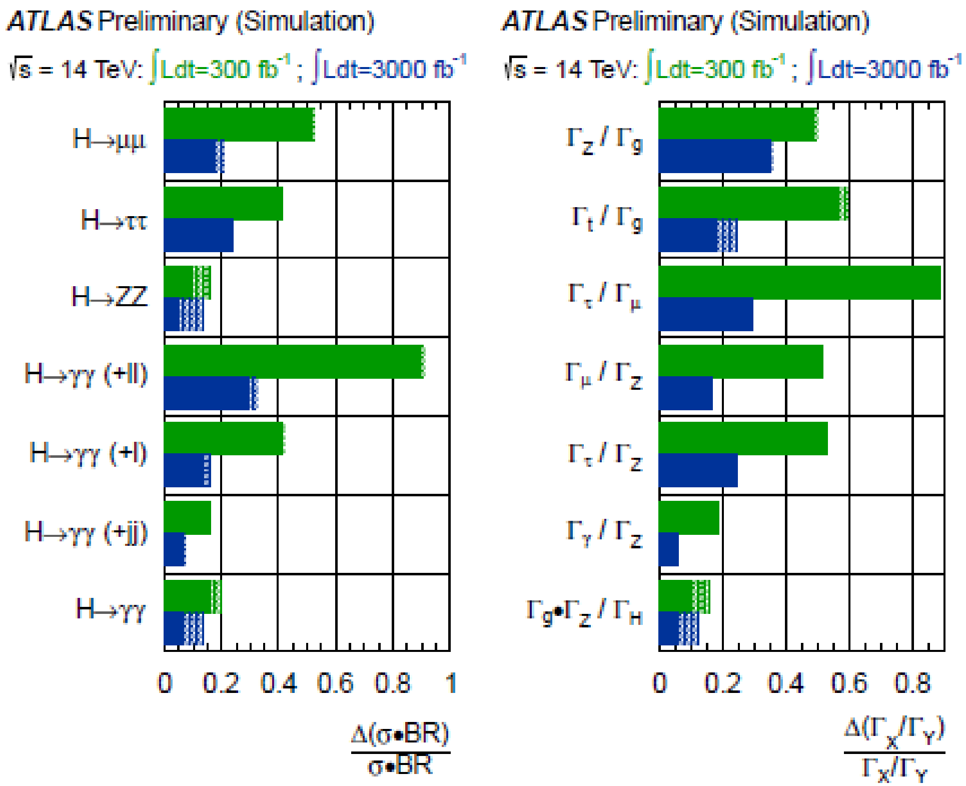


- **peak luminosity > 7.5 $10^{33}/cm^2/s$ achieved**
- **design goal exceeded (scaled to 14 TeV)**

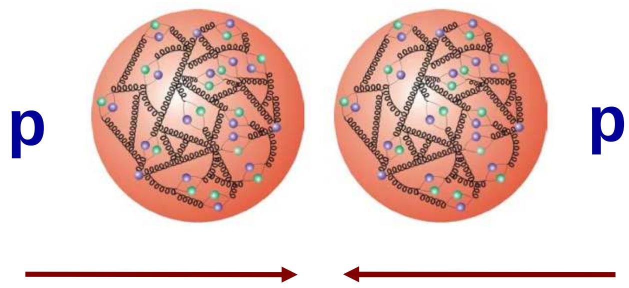
Higgs Physics at the LHC

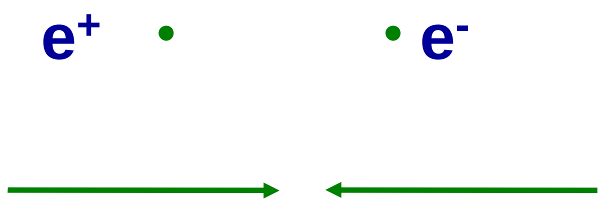
- **Among others studies of the Higgs boson will be in the focus**
  - **spin, CP eigenvalues, couplings, …**
  - **some sensitivity to spin & CP with 30 fb^{-1} at the end of 2012 achieved**

    Higgs-like → Higgs
- **But precision at LHC is limited:**
  - **branching ratios O(10%)**
  - **only ratios of couplings accessible**
- **However, more detailed studies required & ongoing**



Hadron and Lepton Colliders

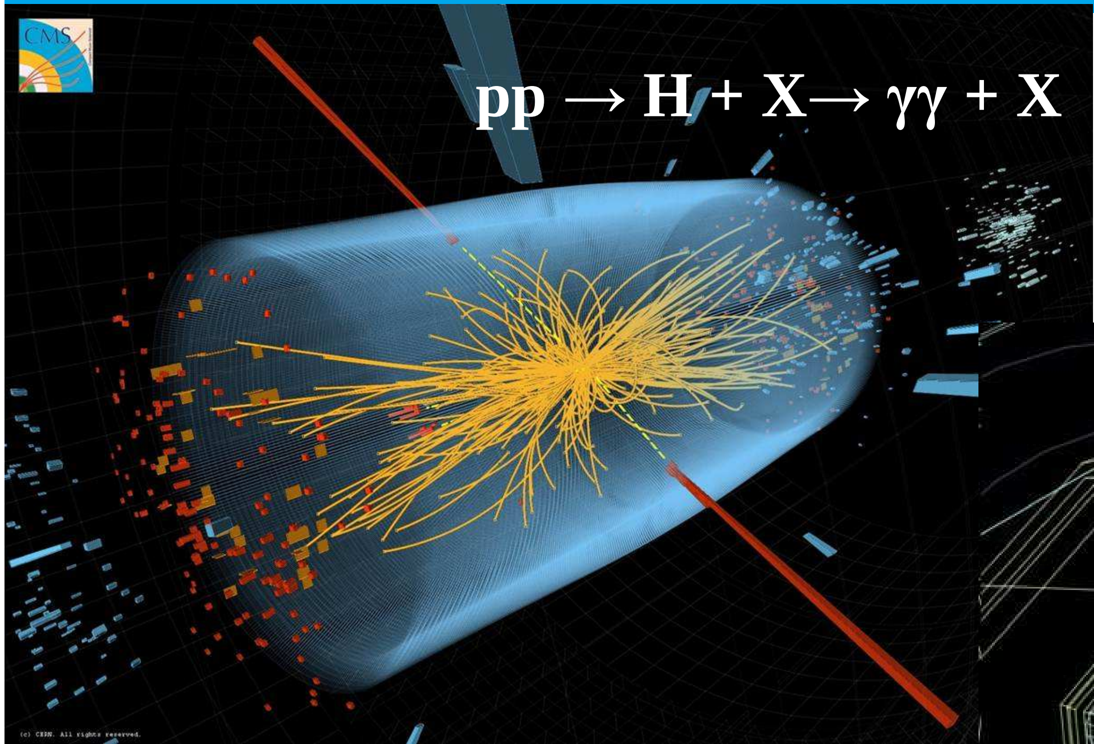




- **Proton (anti-) proton colliders:**
  - **energy range high (limited by bending magnets power)**
  - **composite particles, different initial state constituents and energies in each collision**
  - **difficult hadronic final states**
- **Discovery machines**
- **Precision measurement potential**

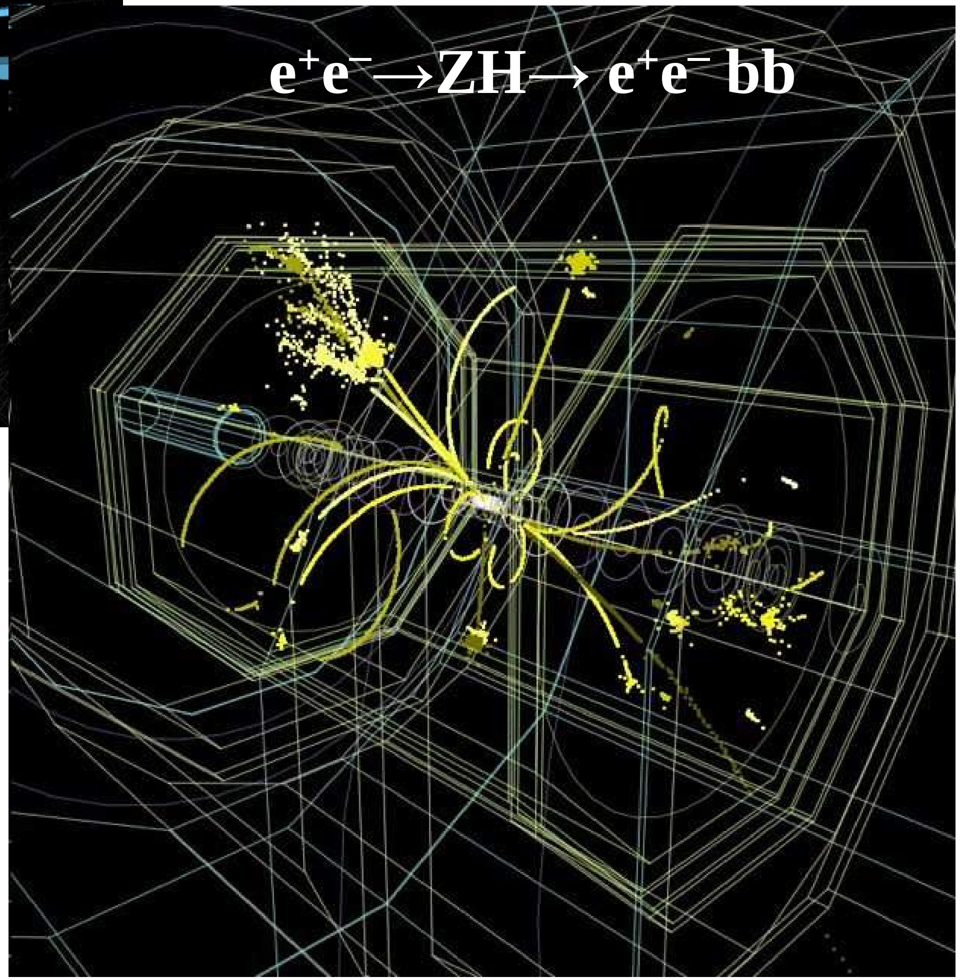
- **Electron positron colliders:**
  - **energy range limited (by RF power)**
  - **point-like particles, well defined initial state quantum numbers and energies**
  - **simpler final states**
- **Precision machines**
- **Discovery potential**

Higgs at LHC and e^+e^- collider



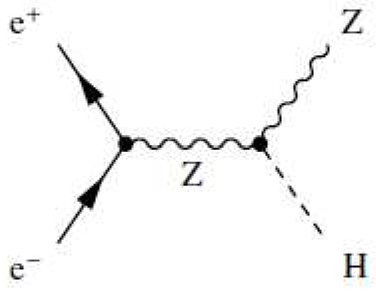
Observed Higgs candidate at CMS

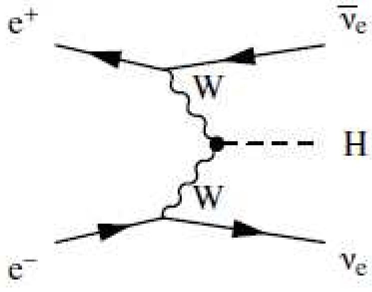
Simulated Higgs in ILD detector



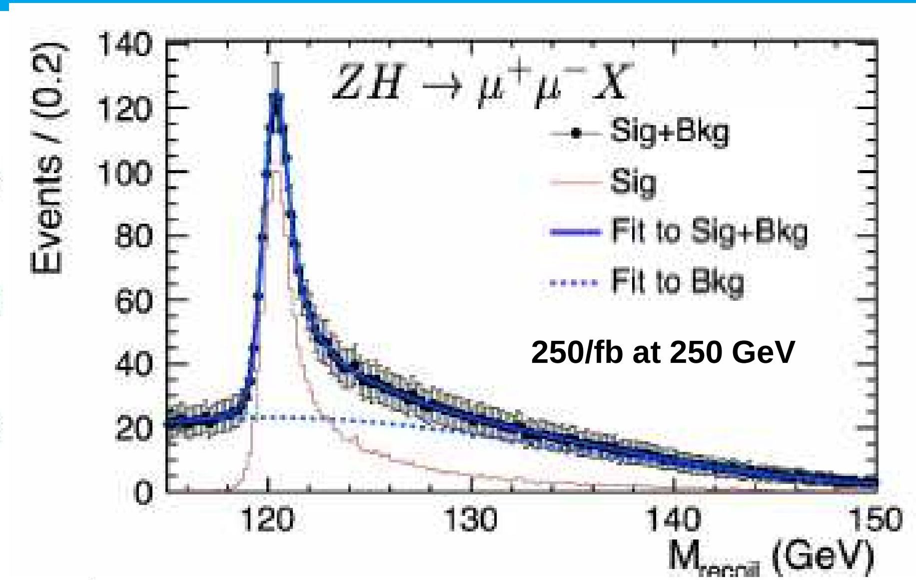
Higgs Factory

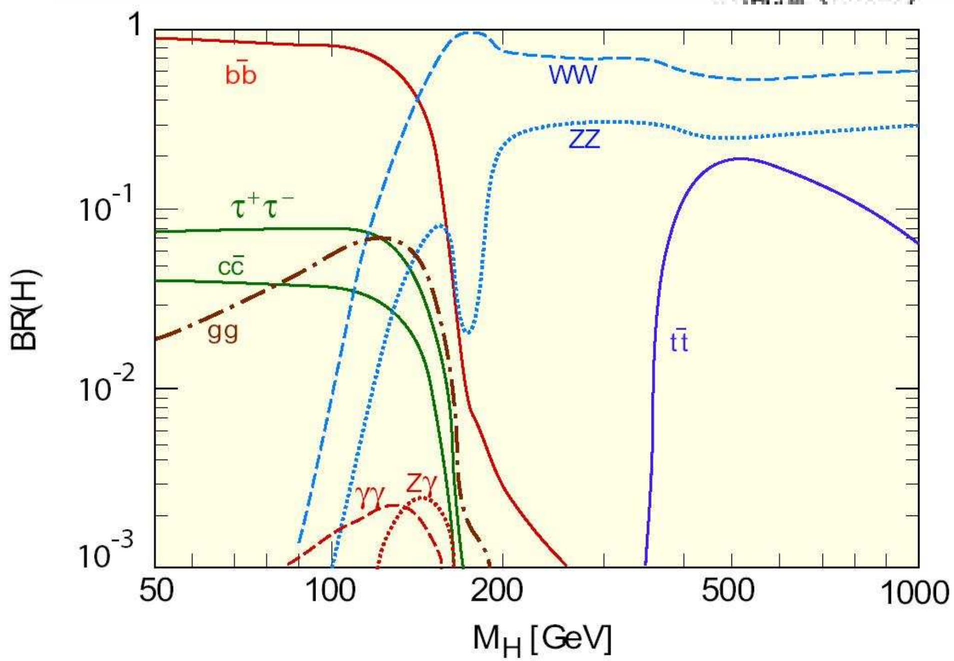
- **Higgs-Production in e^+e^-**





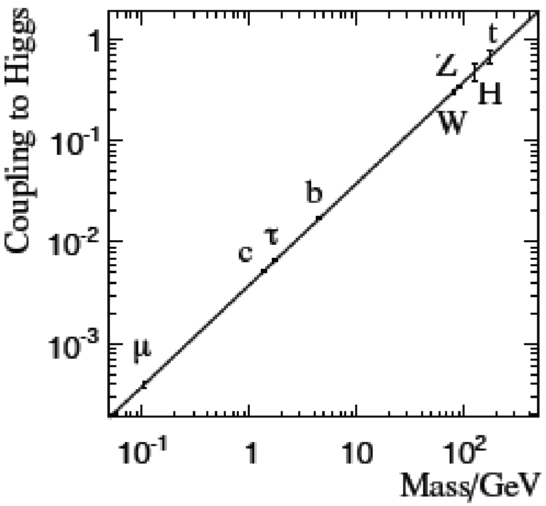
- **Higgs-Strahlung dominates at lower energies**
  - **max. cross section $\sqrt{s} \approx 250$ GeV**
  - **no assumption about Higgs identify Higgs through Z decay**
  - **very clean, model independent signal using the recoil method**
  - **$m_H \approx 125$ GeV is ideal because many decay modes are accessible**

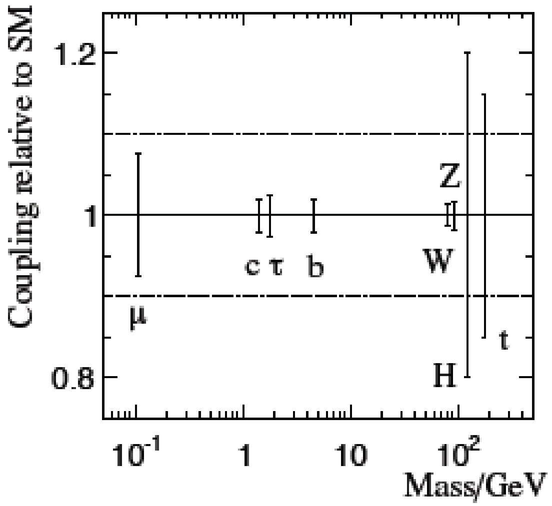




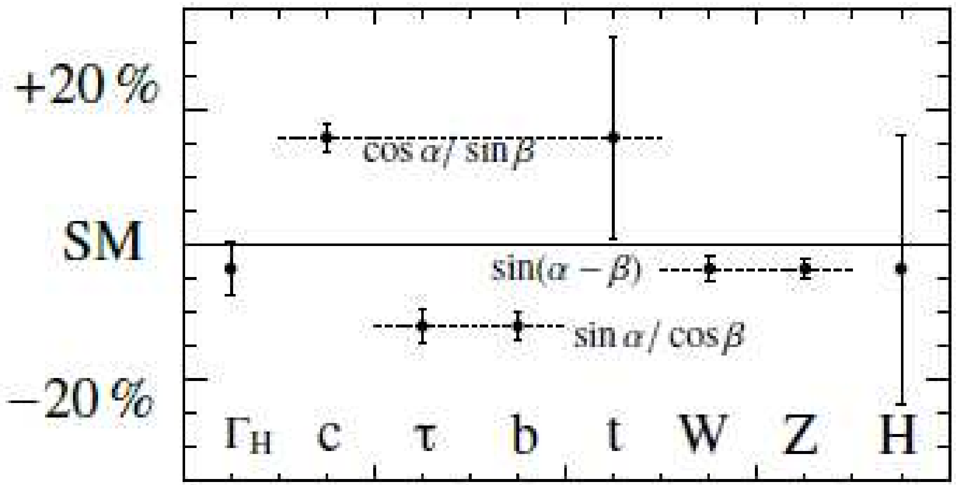
Precision at a Higgs Factory

- Absolute determination of Higgs (Yukawa)-couplings
- Precision O(1-2%) in some cases
  - example corresponds to 250 fb^{-1} at 250 GeV plus 500 fb^{-1} at 500 GeV
  - O(10 years) running time





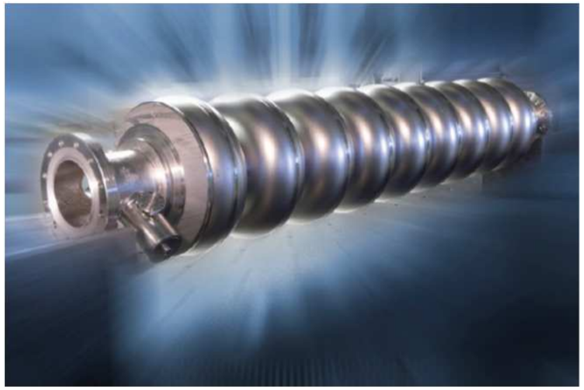
- Typical deviations from SM couplings in a Two-Higgs-Doublet model

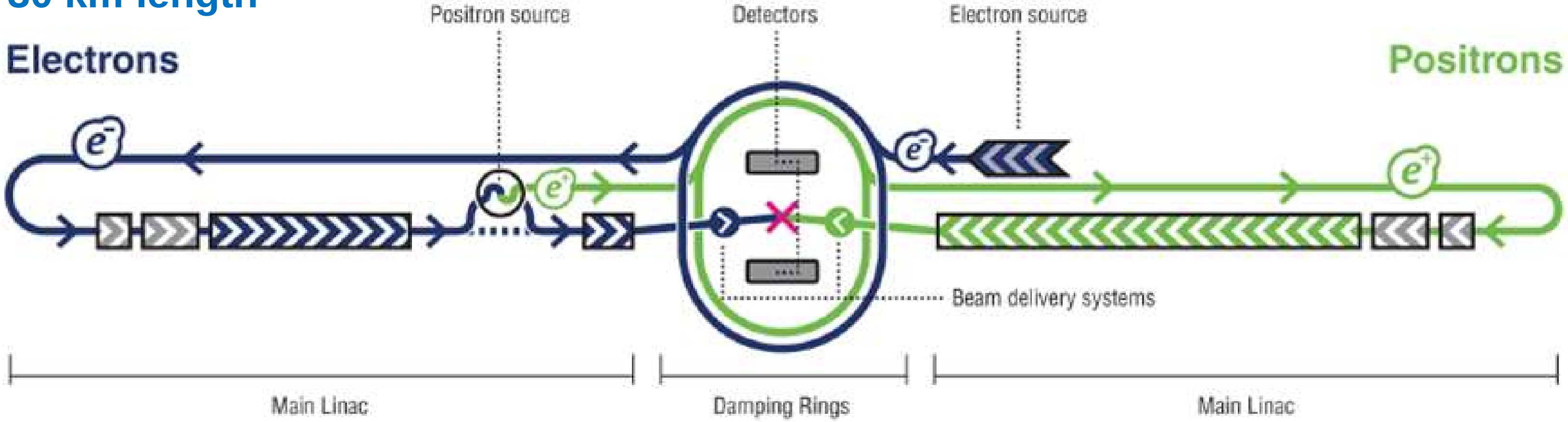


International Linear Collider (ILC)

> **Electron-Positron Collider**
  - **based on superconducting RF technology**
  - **developed at DESY and used for FLASH and XFEL**
  - **$\sqrt{s}$ = 250 – 500 GeV**
  - **acceleration gradient 35 MV/m**
  - **30 km length**

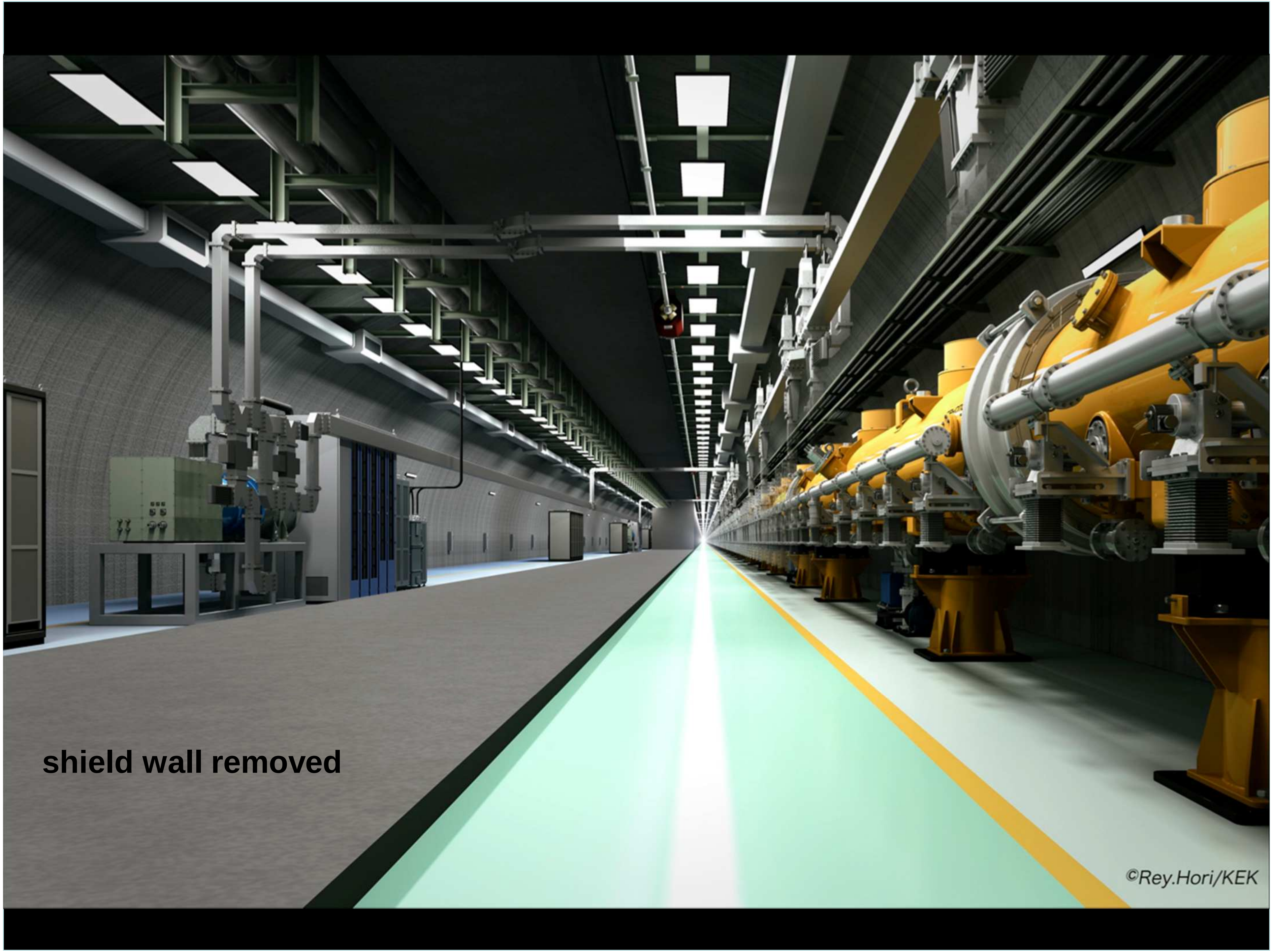
Elektron 250 GeV → ← **Positron 250 GeV**





Schematic layout of the ILC complex

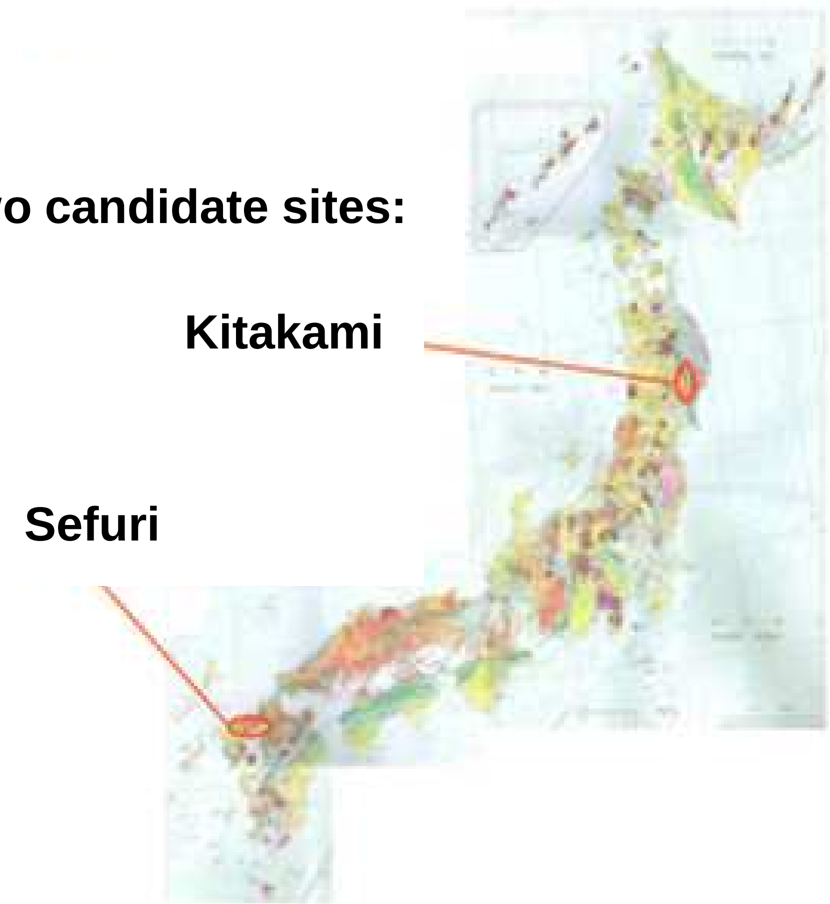
- **Technical Design Report submitted end of 2012**
- **Multi-billion € project…**


shield wall removed
©Rey.Hori/KEK

ILC Siting

- **ILC would be a global project**
  - **a new world-machine like the LHC**
- **Japan has expressed interest to host the ILC**
  - **top priority of Japanese particle physicist**
  - **support in Japanese politics, incl. significant financial contribution**
- **Possible staging scenario**
  - **250 GeV Higgs-factory**
  - **>≈ 350 GeV at tt-threshold**
  - **500 GeV**
- **This would define a physics programme for O(15 years)**

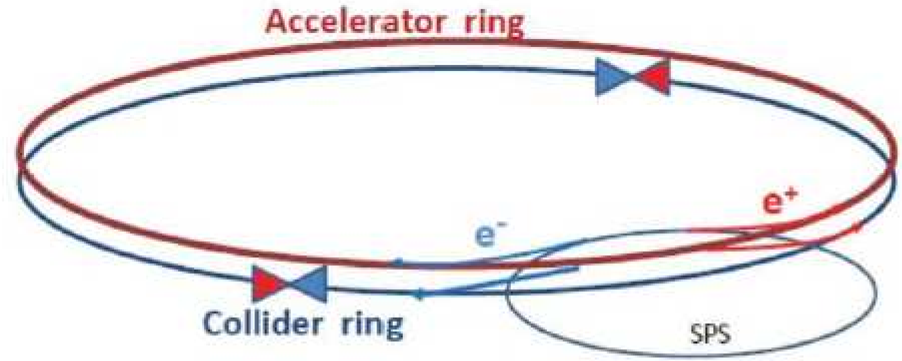
Two candidate sites:



Alternative Higgs Factory?

> **Circular e^+e^- collider**

- **e.g. LEP3**
  $\sqrt{s}$ = 240 GeV in the LHC tunnel
  (former LEP tunnel)



> **Main issue is synchrotron radiation**

- **grows as E^4**
- **mean loss ≈ 7 GeV per turn**
- **power loss ≈ 50 MW per beam**
- **beam life time ≈ 16 min**
  requires second ring for top up

> **Feasible?**

- **if yes probably only after the exploitation of LHC**

> **Dead end**

- **no energy increase, e.g. to reach top-pair threshold, possible**

> **BTW same holds for TLEP, a circular e^+e^- collider in a 80 km tunnel**

The High Energy Frontier

> **Physics beyond the SM**
  - **so far no clear indication from LHC except for the Higgs boson?**
  - **some limits exceed 1 TeV**

> **Too early to worry still large discovery potential**

> **But what could be the future after LHC?**

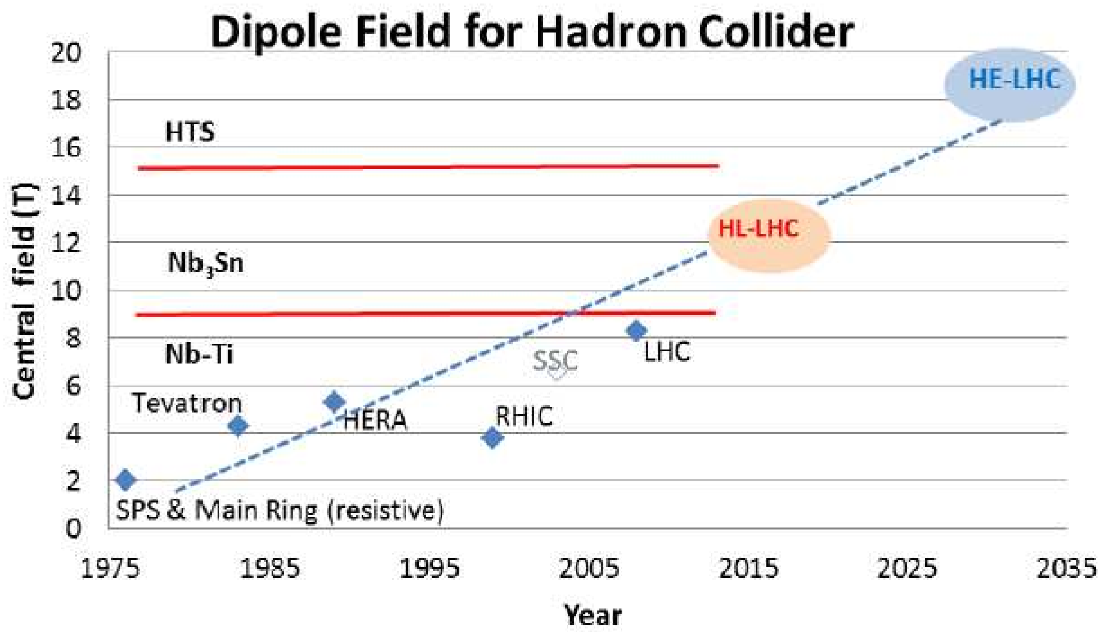
> **Precision measurements of Higgs properties and searches at 14 TeV LHC will guide us**

> **Key question:**

How to reach energies >> 10 TeV or > 1 TeV in case of e^+e^- ?

High Energy LHC

- LHC energy is limited by dipole field
  - 7 TeV beam energy correspond to 8.33 T field
  - close to the physical limit of NbTi superconductor
- High field magnets
  - Nb_3Sn: $B_{max} \approx 15$ T
    R&D programme on final focus magnets for HL-LHC used by ITER
  - High Temperature SC (HTS)
    $B_{max} \approx 20$ T
    requires a lot R&D
- **HE-LHC would be a completely new machine**



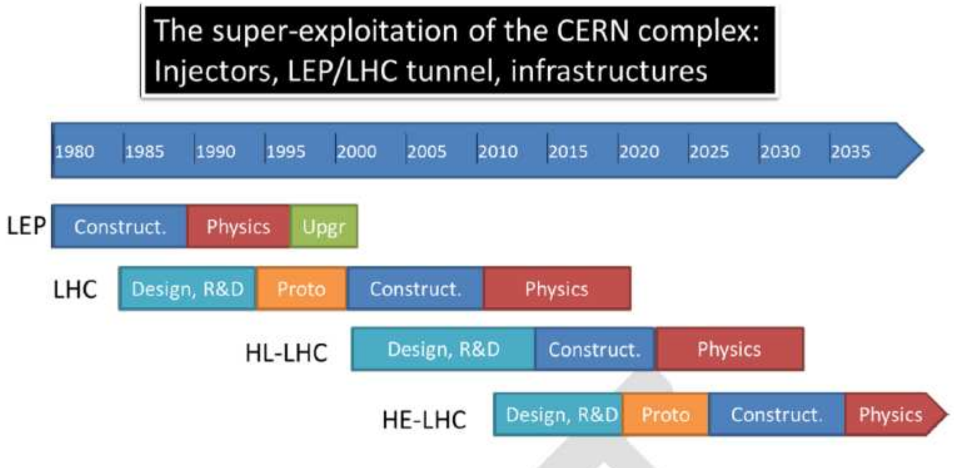
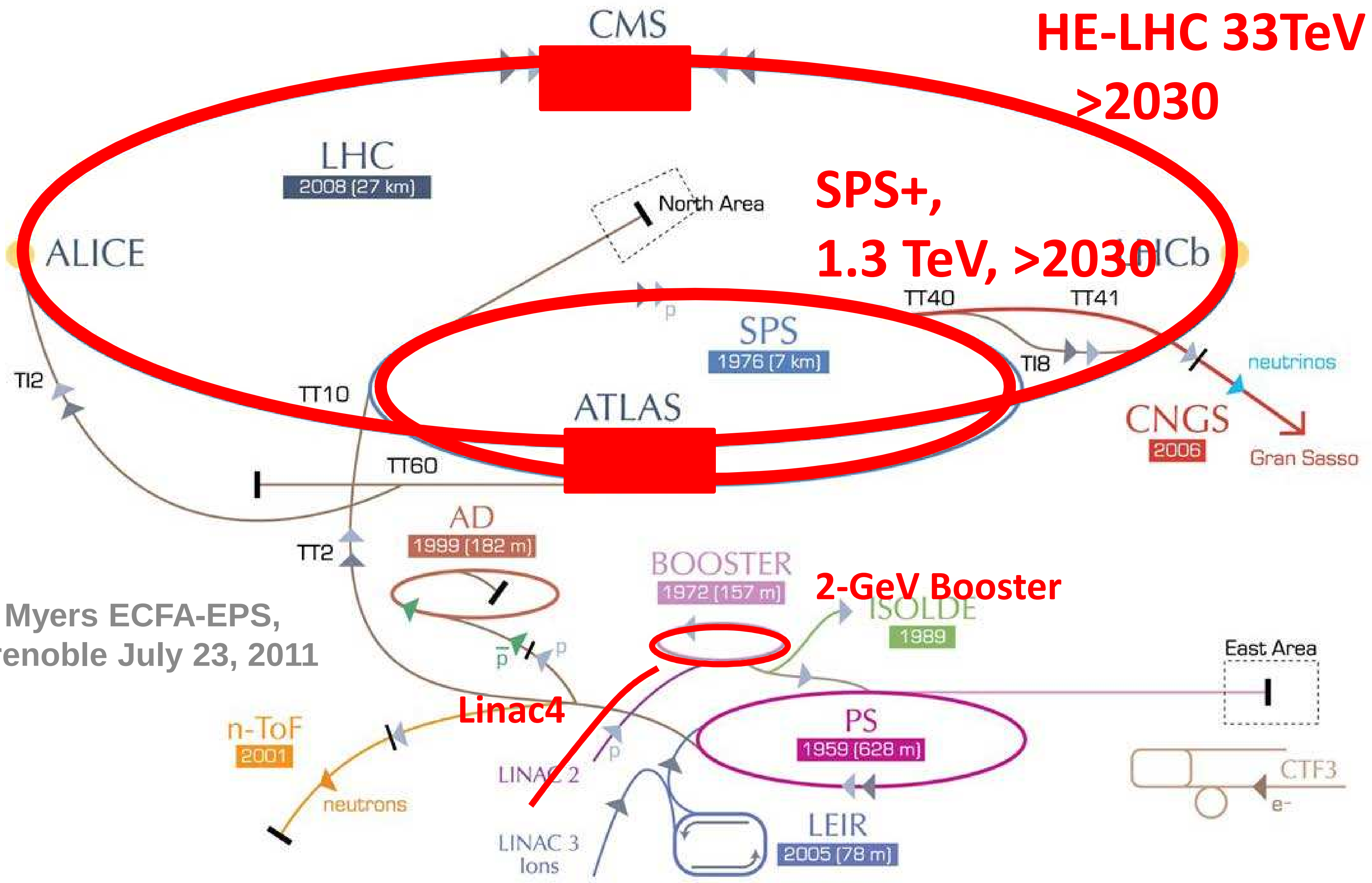


Figure 10. The possible timeline of LHC and its upgrades.

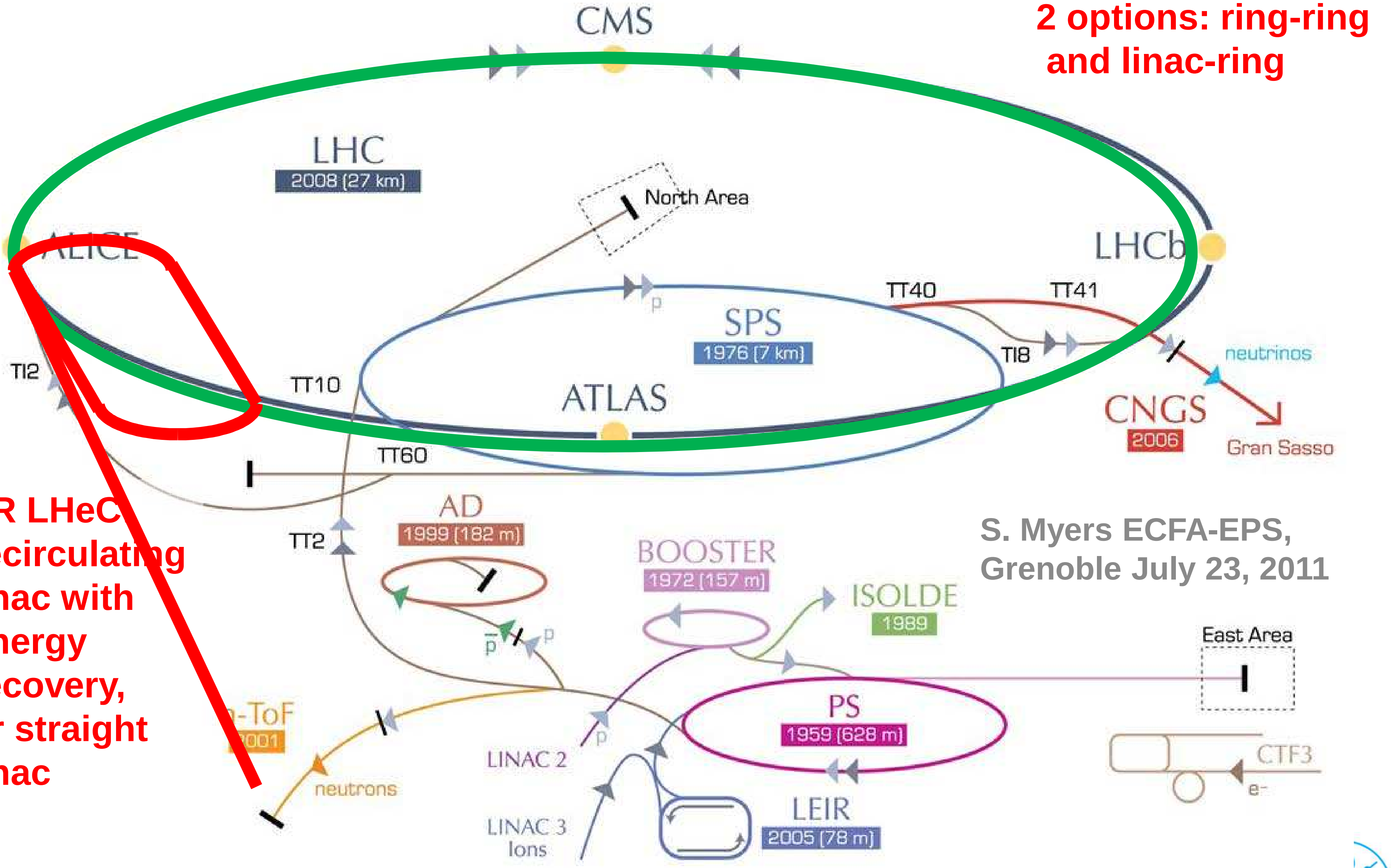
HE-LHC – LHC modifications



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

Super-HERA: LHeC

2 options: ring-ring and linac-ring



LR LHeC: recirculating linac with energy recovery, or straight linac

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

Beyond High Energy LHC

- **First studies on a new 80 km tunnel in the Geneva area**
  - **42 TeV   with 8.3 T using present LHC dipoles**
  - **80 TeV   with 15 T based on Nb_3Sn dipoles**
  - **100 TeV   with 20 T based on HTS dipoles**

see also TLEP

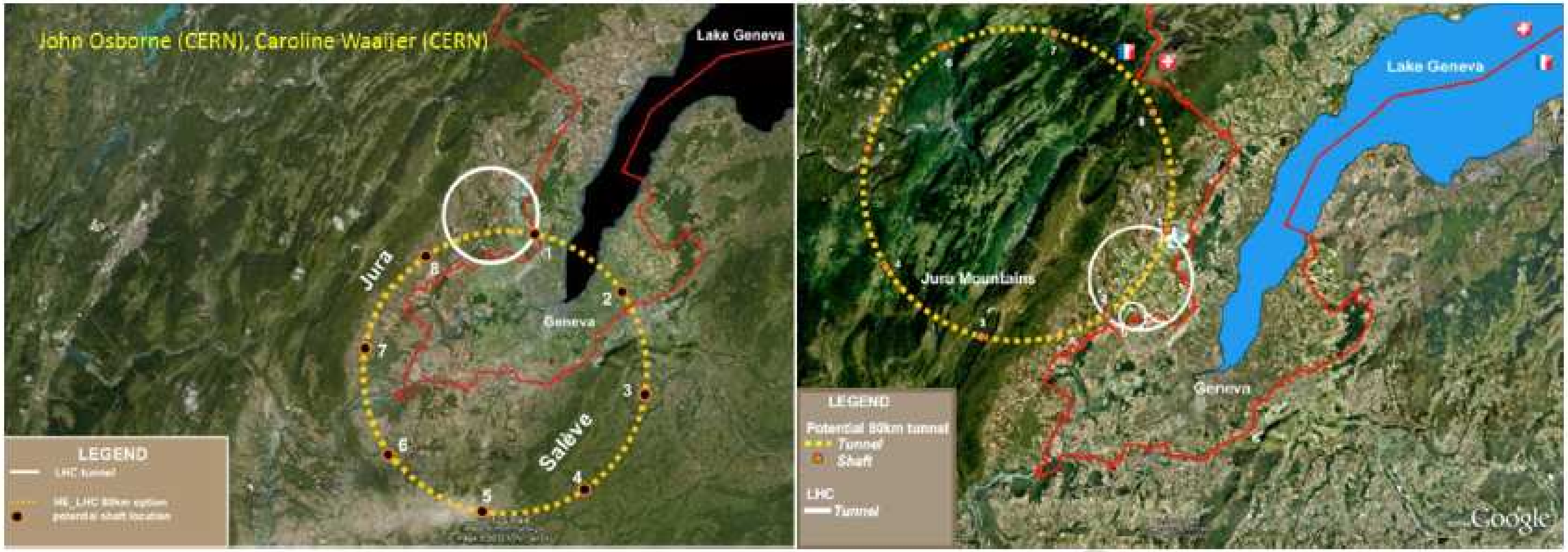


Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

Multi-TeV Electron-Positron Collider

> **Novel two-beam acceleration concept**

> **100 MV/m gradient seems feasible**

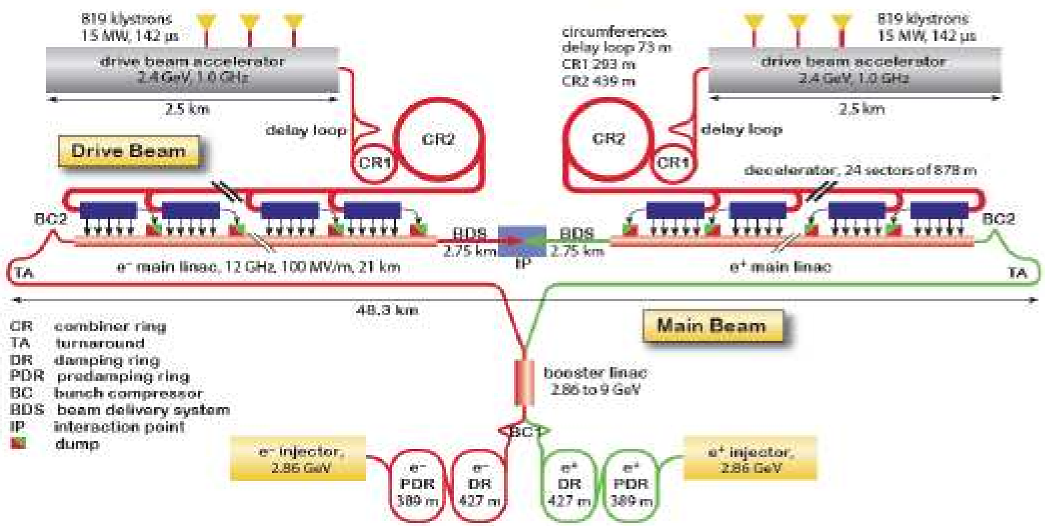
  - **cms energies up to 3 TeV**

> **But not yet at the same level of maturity as ILC technology**

> **General issue for linear colliders: power consumption**

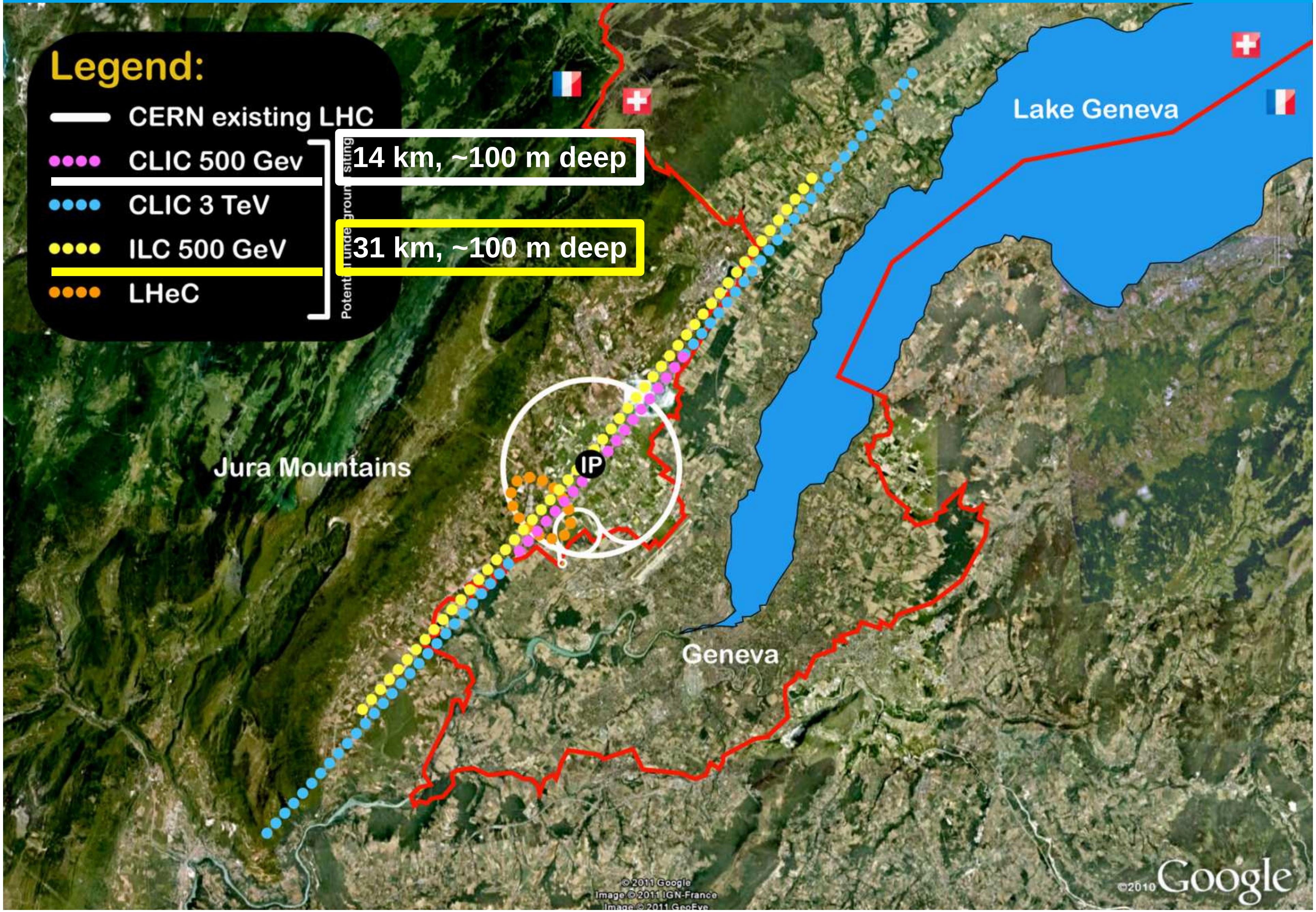
Project	√s/TeV	Power/MW
ILC	0.5	163
ILC	1	240
CLIC	1.5	364
CLIC	3	589

Overview of the CLIC layout at √s = 3 TeV



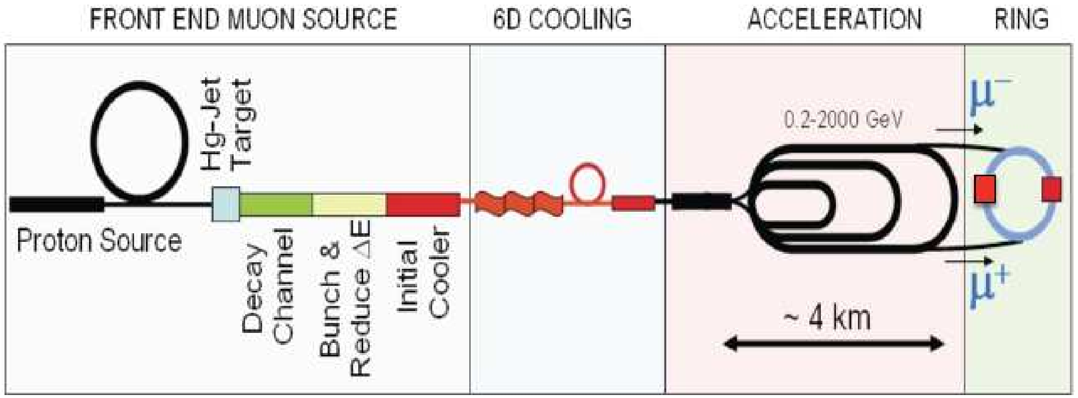
- **CLIC R&D ongoing at CERN**
  - **gradient**
  - **stability**
  - **beam handling**
  - **…**

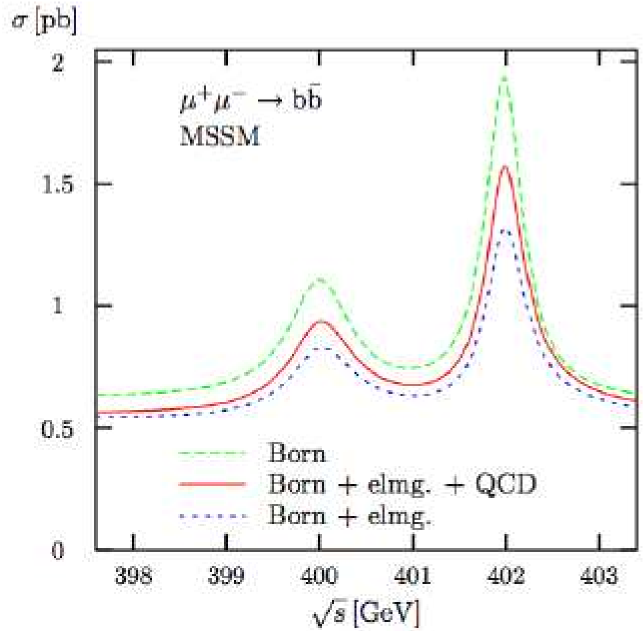
A Linear Collider at CERN



The far Future: Muon Collider

- **Try to collide μ⁺μ⁻ rather than e⁺e⁻**
- **Advantages:**
  - **much smaller synchrotron losses: ~E^4/m^4r**
  - **smaller facility size even for a multi-TeV machine**
  - **s-channel Higgs production: ~ 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**
  - **energy spread**
  - **high background from muon decays (neutrinos!) at high energy**
  - **...**





Example SUSY Higgs bosons

Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

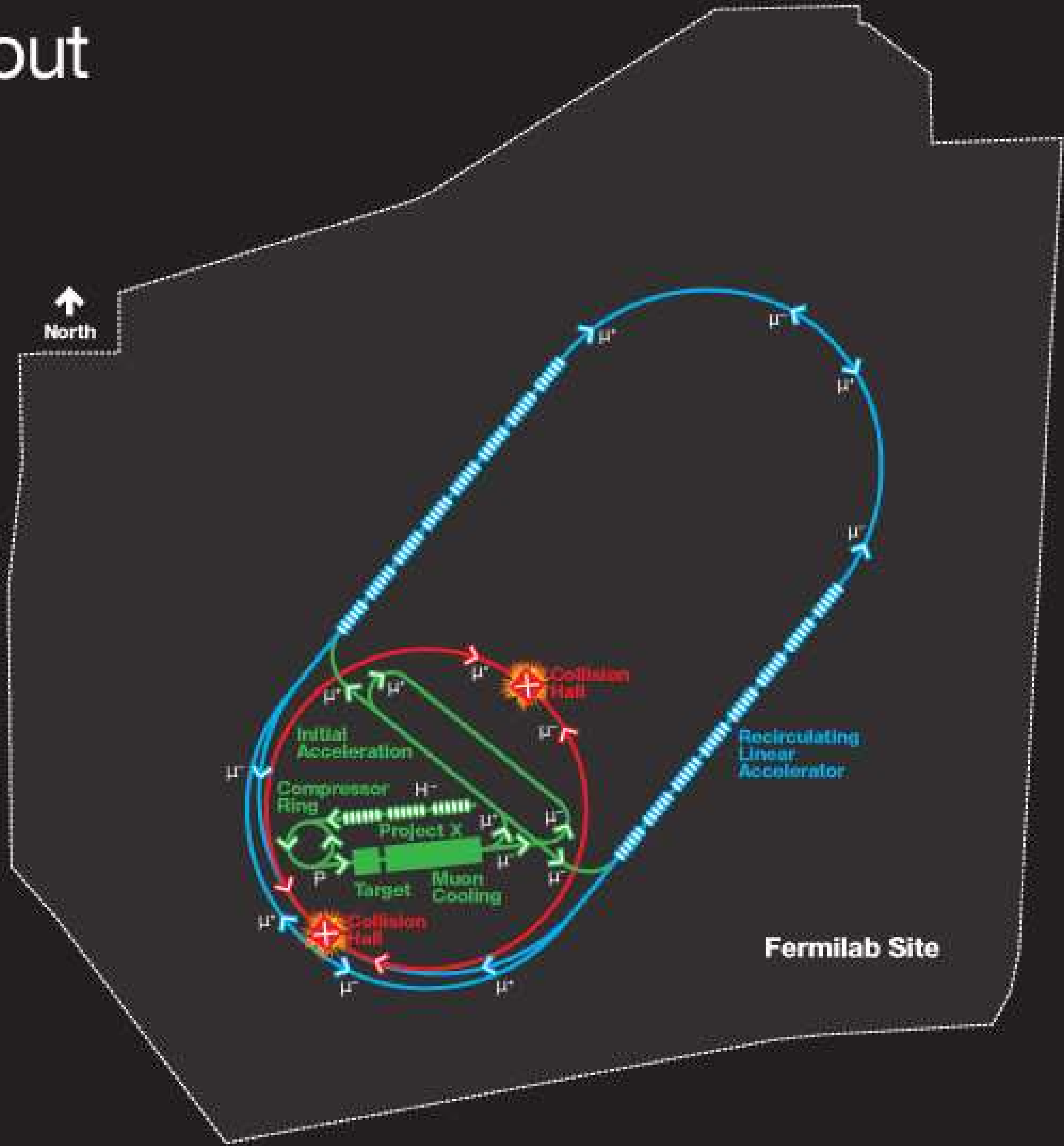
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

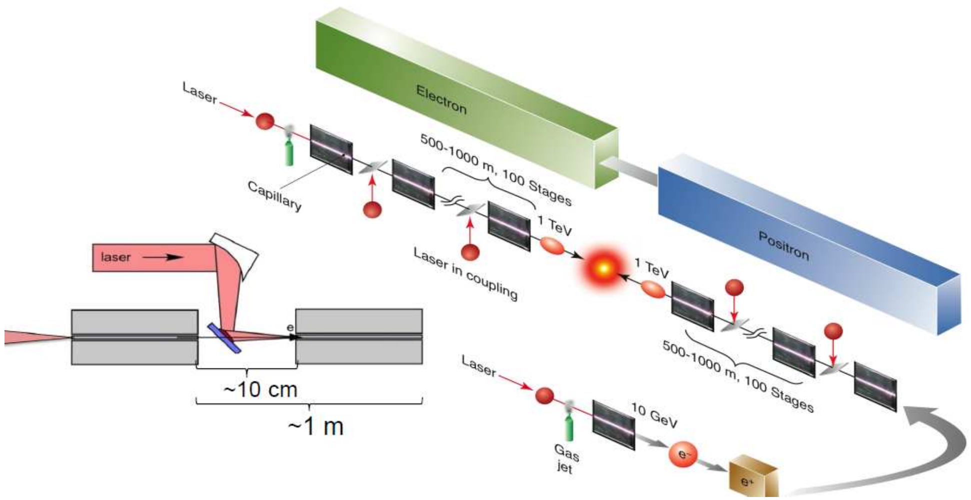
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.



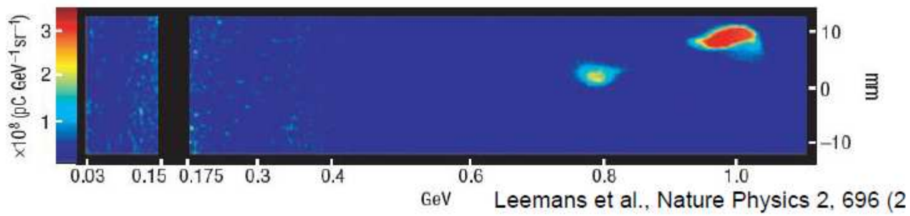
The far Future: Plasma Wakefield Acceleration

- How to achieve significantly higher acceleration gradients than 30 – 100 MV/m ?
- Plasma wakefield acceleration might be one day a solution



DESY has started a programme on PWA

- Create very high electric field by pushing away electrons from atoms in a plasma
  - using very intense laser
  - or particle particle beams
- Gradients of 10 GV/m and 1 GeV achieved in table top experiments



- Many open issues still to be resolved
  - small emittance beam
  - staging
  - …

Politics

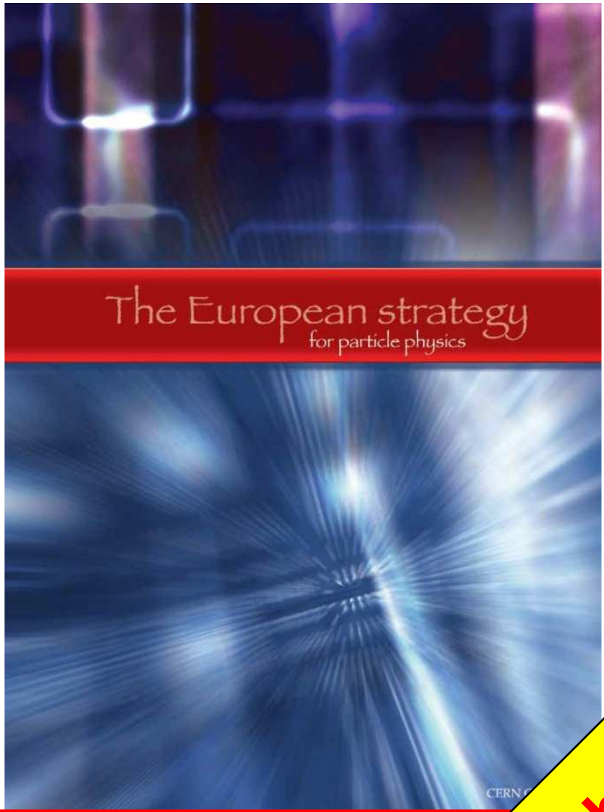
> Strategy discussions (have been) going on in various regions of the world

- Japan: concluded last year with ILC as top priority if a light Higgs is found
- Europe: 2013 update of the European Strategy (initiated by CERN Council)
- USA: Snowmass process, to be completed in 2013

> Important issues in European discussion:

- High-Luminosity LHC to be decided now
- European participation in an ILC project in Japan
- High Energy Physics at CERN after LHC
  R&D and input from LHC needed
- Large Baseline Neutrino programme: at CERN or outside Europe?

The European Strategy for Particle Physics 2006



Unanimously approved by th... Council at the special Sess... in Lisbon on 14 July 2006

http://council-strategygroup.web.cern.ch/council-strategygroup/Strategy_Statement.pdf

To be updated after O(5 years)

The European strategy *for particle physics*

Particle physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They w... easure the properties of the elementary constituents of matter and their ... ns with unprecedented accuracy, and they will uncover new phenomen... ggs boson or new forms of matter. Long-standing puzzles such a... ass, the matter-antimatter asymmetry of the Universe and the ... matter and energy that permeate the cosmos will soon bene... nts that new measurements will bring. Together, the results will h... mpact on the way we see our Universe; *European particle phys... ughly exploit its current exciting and diverse research programm... ion itself to stand ready to address the challenges that will emer... ion of the new frontier, and it should participate fully in an incre... venture.*

...s

...rticle physics is founded on strong national ...s, universities and laboratories and the CERN ...nization; *Europe should maintain and strengthen its central position in particle physics.*

2. Increased globalization, concentration and scale of particle physics make a well coordinated strategy in Europe paramount; *this strategy will be defined and updated by CERN Council as outlined below.*

Scientific activities

3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; *the hi... he physics potential of the LHC ... initial programme have to be s... riments can operate optimally ...* subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; *to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

LHC

4. In o... and lumi... gthen the ... inated progr... ology and ... o play a sig... ensity neutr... facility.

Accelerator R&D

5. It is fundamental to complement the results of the LHC with meas... 0.5 t... will ... front... activ... its d... decis... 2010.

Studies for Linear Collider

6. ...

Scientific case for υ-factory

7. A range of very important non-accelerator experiments take place at the overlap between particle and astroparticle physics exploring otherwise inaccessible phenomena; *Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest.*

Timeline Update European Strategy

> 2011/2012	Start of the process, set up Strategy Group, ESPG, working groups etc.
> Sep 2012	Open Symposium in Cracow input from the community
> Nov 2012	Plenary ECFA meeting: last chance for input
> 7. Dec 2012	ESPG prepares briefing book synthesis of Cracow
> 21. - 26. Jan 2013	ESG drafting session in Erice
> March 2013	Finalizing Update of Strategy by CERN Council
> May 2013	Formal adaption of Strategy by CERN Council special meeting in Brussel with EU commission

> For details see
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/ESG/welcome.html

Update European Strategy

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

High Luminosity LHC (HL-LHC)
Implicit approval!

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Accelerator R&D for future CERN project at the energy frontier

e) 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. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

Strong support for ILC in Japan

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.*

Long-baseline neutrino (in Japan or USA)

Summary

> **The Higgs-like boson found at LHC is a centennial discovery**

- **Opens a new window to understand the fundamental principles of the Universe**
- **LHC is only at the beginning of its scientific exploitation**
- **Determination of Higgs properties will be in the focus of particle physics**

> **Higgs factory**

- **Detailed concepts and technology ready for an e+e⁻ collider to do precision Higgs physics**
- **Scientific and political support for such a project is emerging**

> **The energy frontier**

- **LHC will remain the machine at energy frontier for the next 20 years**
- **Plans and ideas to go beyond LHC in energy or precision**
- **R&D on new technologies required (acceleration, magnet)**
- **LHC results, in particular at the full energy, will guide the way**

The Future of Particle Physics

- We are living in exciting times
  make use ot it!
  - Discovery of a Higgs boson
    the most important scientific discovery in 2012
  - Variety of future (global) projects under study
  - Worldwide effort to prioritize and decide

- A typical conversation with funding agencies in 2013:
  - Q: You found the Higgs. Is this the end of particle physics?
  - A: No! The best is yet to come!