# CERN: the next 60 years (the FCC study)

Michael Koratzinos, UNIGE and CERN

Picture courtesy: Jörg Wenninger

UNIVERSITÉ DE GENÈVE

3rd International Conference on New Frontiers in Physics 2014

# Acknowledgements

- I would like to thank
  - the pioneers of the Higgs factory: **Roy Aleksan, Alain Blondel, John Ellis, Patrick Janot, Frank Zimmermann**
  - The whole FCC community
  - In particular A. Blondel, F. Gianotti, M. Benedikt, F. Zimmermann, D. Schulte, L. Rossi, G. Kirby for the liberal use of material

Do not miss: S. Vlachos, "FCC-hh", this conference

Also see: G. Bruno, "CERN achievements in Relativistic Heavy Ion Collisions", this conference
A. Levy, "Overview of physics potential at CLIC", this conference
M. Bataglia, "WIMP Dark Matter at colliders from 14 to 100 TeV", this conference

# Before I start…

- This is a talk about the FCC project. I have no crystal ball about which projects will materialise the next 60 years.
- There are other excellent projects at CERN and outside that might well be the ones that get the go-ahead, depending on what Nature has in store for us: CLIC at CERN, the ILC in Japan, CEPC in China…

# Why?

**"…we chose these things not because they are easy, but because they are hard, because that goal will serve to measure and organize the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win"**: J.F. Kennedy, president of the US, 1962

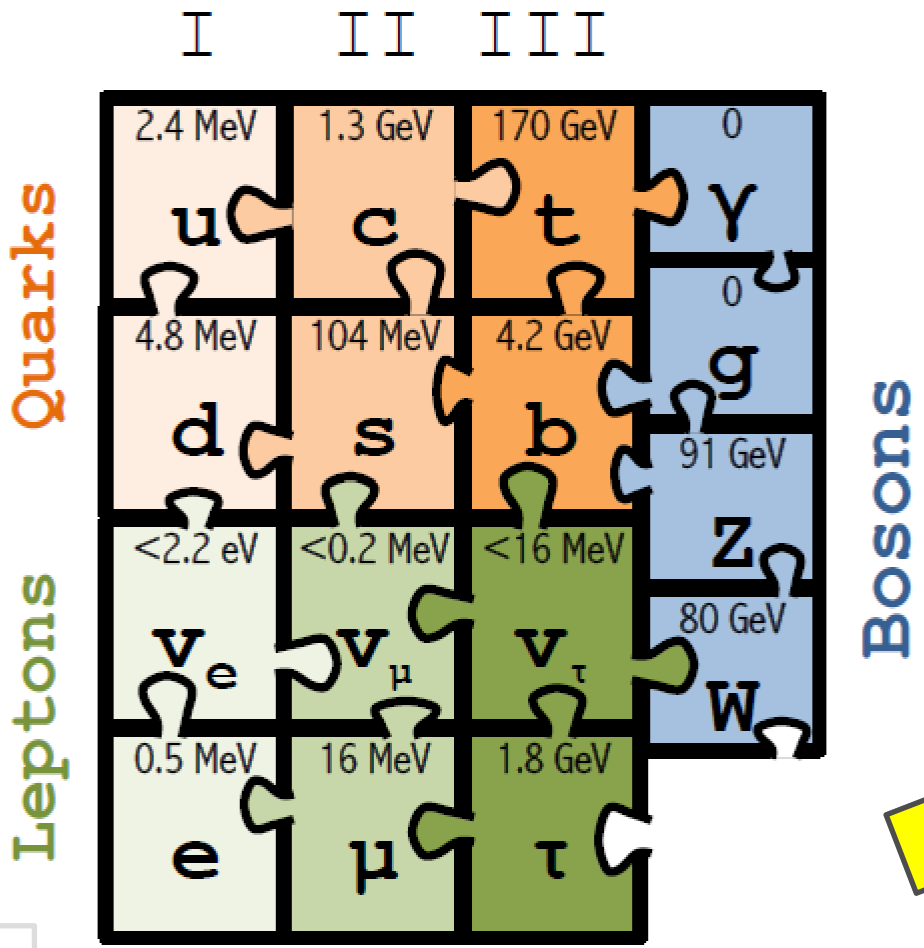
# CERN's 60$^{th}$ anniversary

- CERN deservedly celebrates 60 years of existence
- It has been a tremendous ride and its founding fathers would be very proud (major discoveries – neutral currents, W, Z, Higgs bosons, the establishment of the SM through LEP measurements, etc. , plus major technological achievements – SPS, ISR, LEP, LHC, etc.)
- This stellar performance makes the next 60 years even more difficult as expectations are, rightly, very high
- CERN cannot rest on its laurels. It needs to define a future which is
  - Ambitious
  - With excellent scientific value
  - Will make future generations of scientists dream

# The Standard Model – circa 1954

(empty)

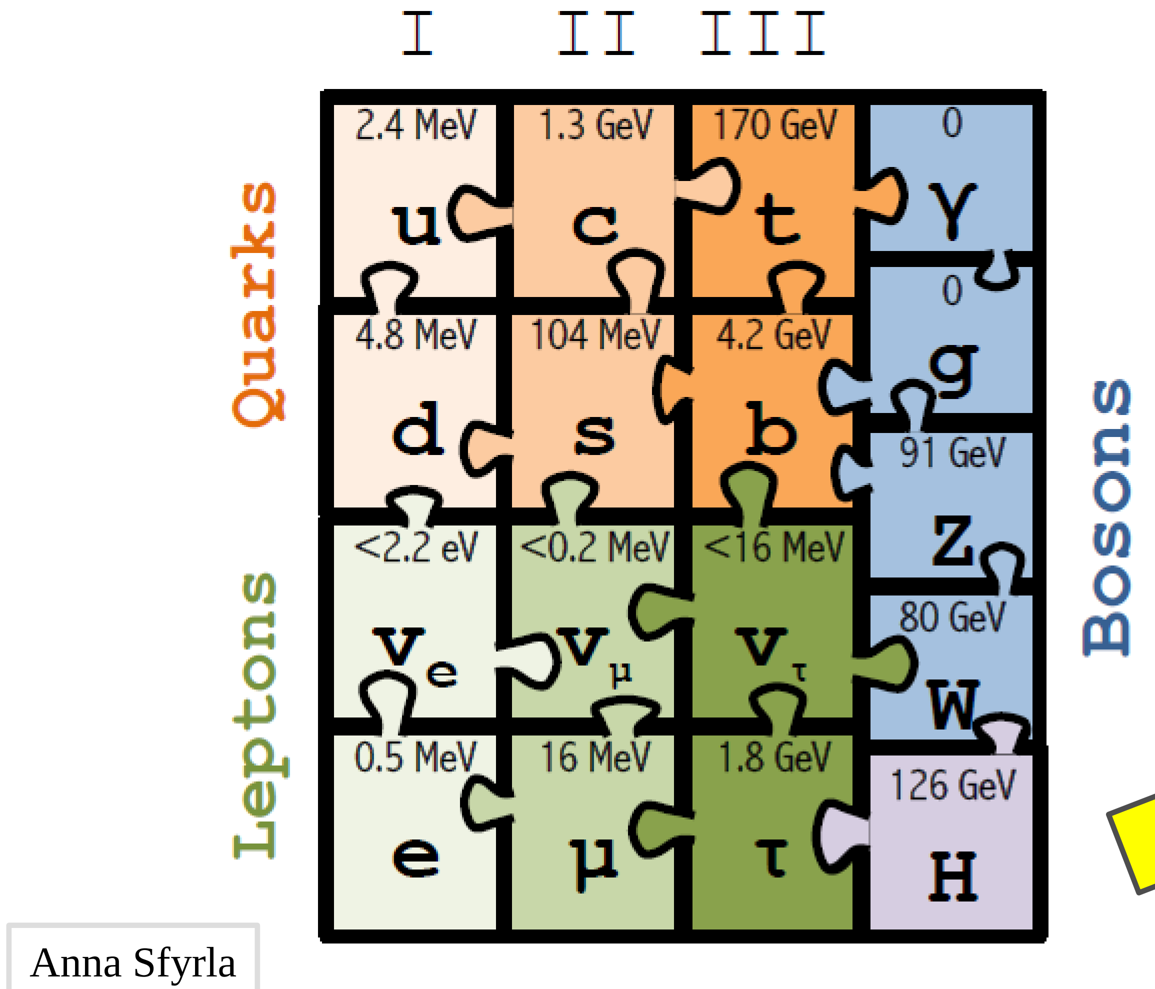
# The Standard Model – circa 2000




Nearly complete!

Anna Sfyrla

# The Standard Model – circa 2014




Completed!

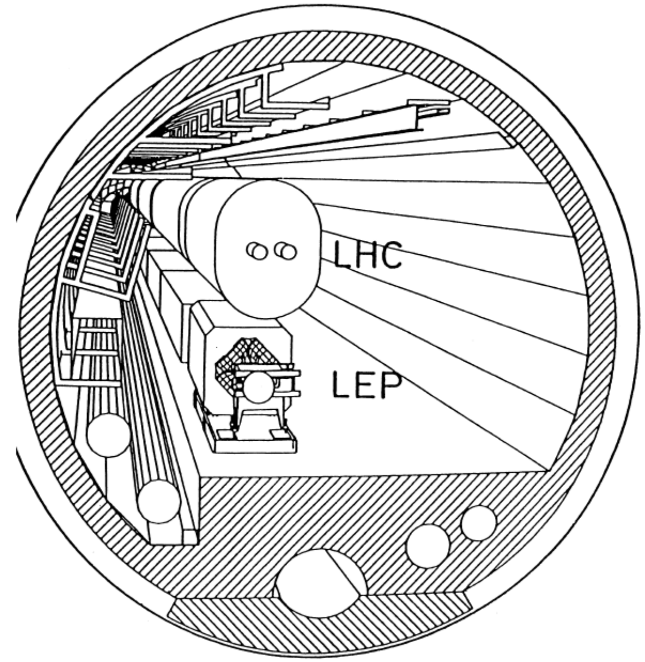
# The backdrop

- The Standard Model is complete, but it is not a complete theory
- Major problems:
  - What is the origin of lepton/baryon asymmetry?
  - What is the origin of dark matter?
  - What is the nature of neutrinos?
  - What is the solution to the hierarchy problem?
  - (plus even more profound questions)

# Is 60 years an exaggeration?

**The 27-km project: LEP and the LHC:**

- LEP first discussions: 1975-76, approved six years later (1981)
- LHC first discussions: 1977 (C. L. Smith, Nature 448, 281-284), approved 17 years later (1994).
- The LHC approved programme stretches to 2025 with the HL project stretching to 2035…




LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

ps

SCAN-0008106

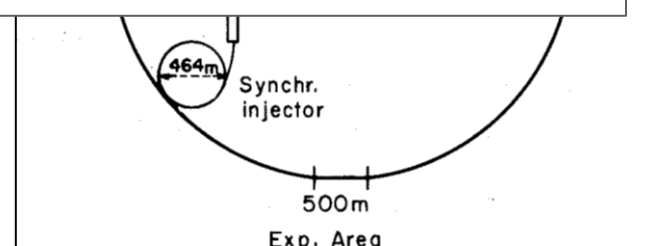
LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a



# The physics case – the experimentalist's point of view


Fabiola Gianotti

- "Regardless of the (outcome of the LHC), […] the directions for future high-Energy colliders are clear:
  - highest precision → to probe E scales potentially up to O(100) TeV and smallest couplings (e+e- collider)
  - highest energy → to explore directly new territories and get crucial information to interpret results from indirect probes (pp collider)"
- This calls for an approach similar to the LEP-LHC approach: a new tunnel than can host a variety of circular colliders (pp, ee, ep, …)

# The view of a theoretical physicist

Nima Arkani-Hamed

In my view, the scientific questions at stake in our field today are the most difficult + profound ones we have faced since the 1930's

The scale of our vision and ambition — both theoretically + experimentally — must be commensurate ... tasks at hand with the

Clearly, how to proceed will depend on first LHC13 results.

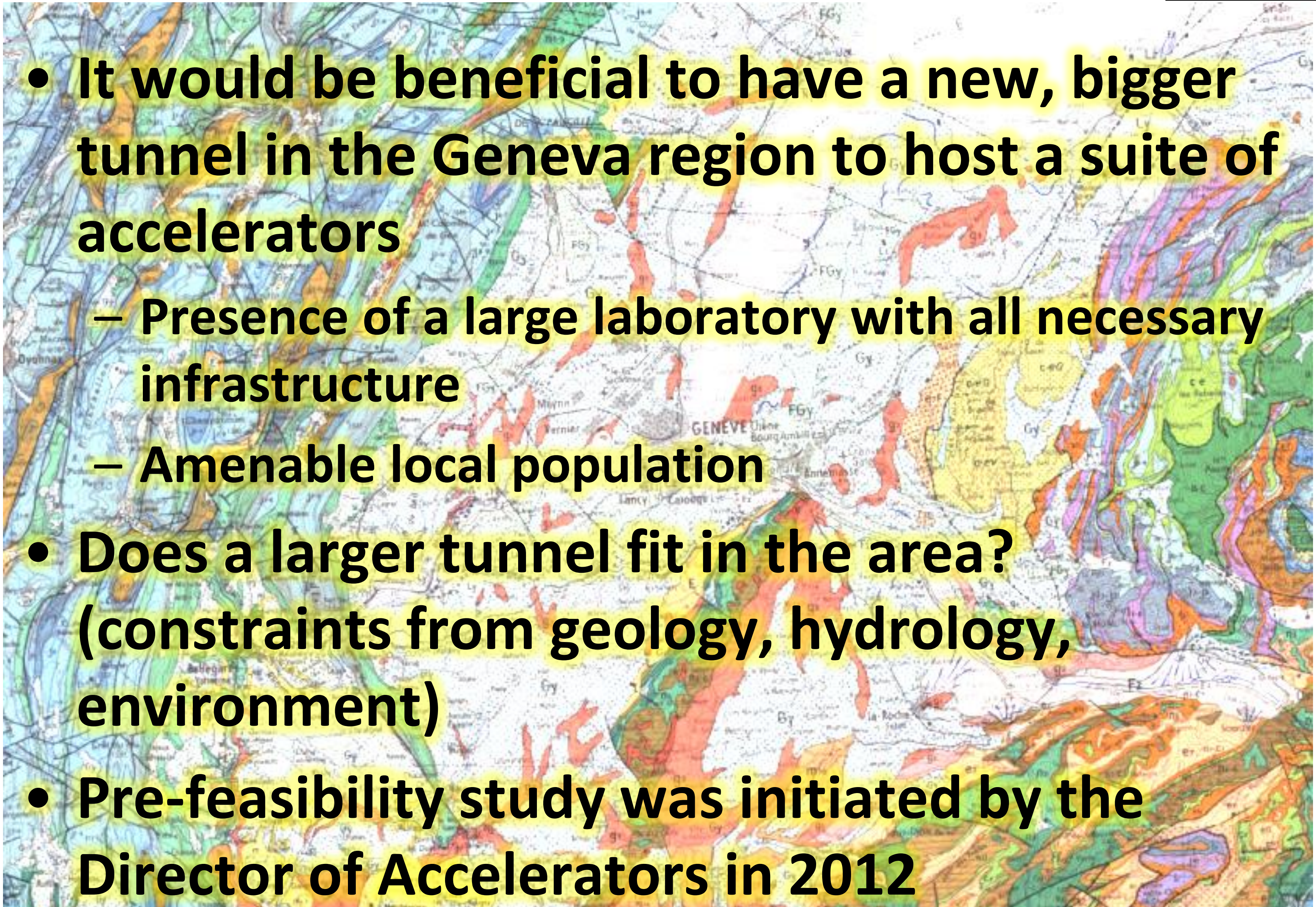
But in every scenario I can imagine, we will need the 100 TeV pp machine

* Circular $e^+e^-$ machine Higgs Factory plays very important, complementary role

Looking for $\frac{h^\dagger h (h Q b^c)}{\Lambda^2}$, $\frac{(h^\dagger D_\mu h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

# CERN's neighbourhood



- **It would be beneficial to have a new, bigger tunnel in the Geneva region to host a suite of accelerators**
  - **Presence of a large laboratory with all necessary infrastructure**
  - **Amenable local population**
- **Does a larger tunnel fit in the area? (constraints from geology, hydrology, environment)**
- **Pre-feasibility study was initiated by the Director of Accelerators in 2012**

# FCC study: a study born in 2013

The paper that started it all: arXiv:1112.2518 [hep-ex]

CERN-OPEN-2011-047
**12 December 2011**
Version 2.1

**A High Luminosity $e^+e^-$ Collider in the LHC tunnel to study the Higgs Boson**

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

First international discussions: HF2012 at Fermilab:
http://indico.fnal.gov/conferenceDisplay.py?confId=5775

Following a recommendation of the European Strategy report, in Fall 2013 CERN Management set up the FCC project, with the main goal of preparing a Conceptual Design Report by the time of the next European strategy update (~2018)

FCC kick-off meeting took place on 12-15 February 2014 at University of Geneva
http://indico.cern.ch/event/282344/timetable/#20140212.detailed
Very successful, almost 350 participants, strong international interest

Links established with similar studies in China and in the US, already a series of successful workshops

# Summary: European Strategy Update 2013
## *Design studies and R&D at the energy frontier*

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

**d) *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.***

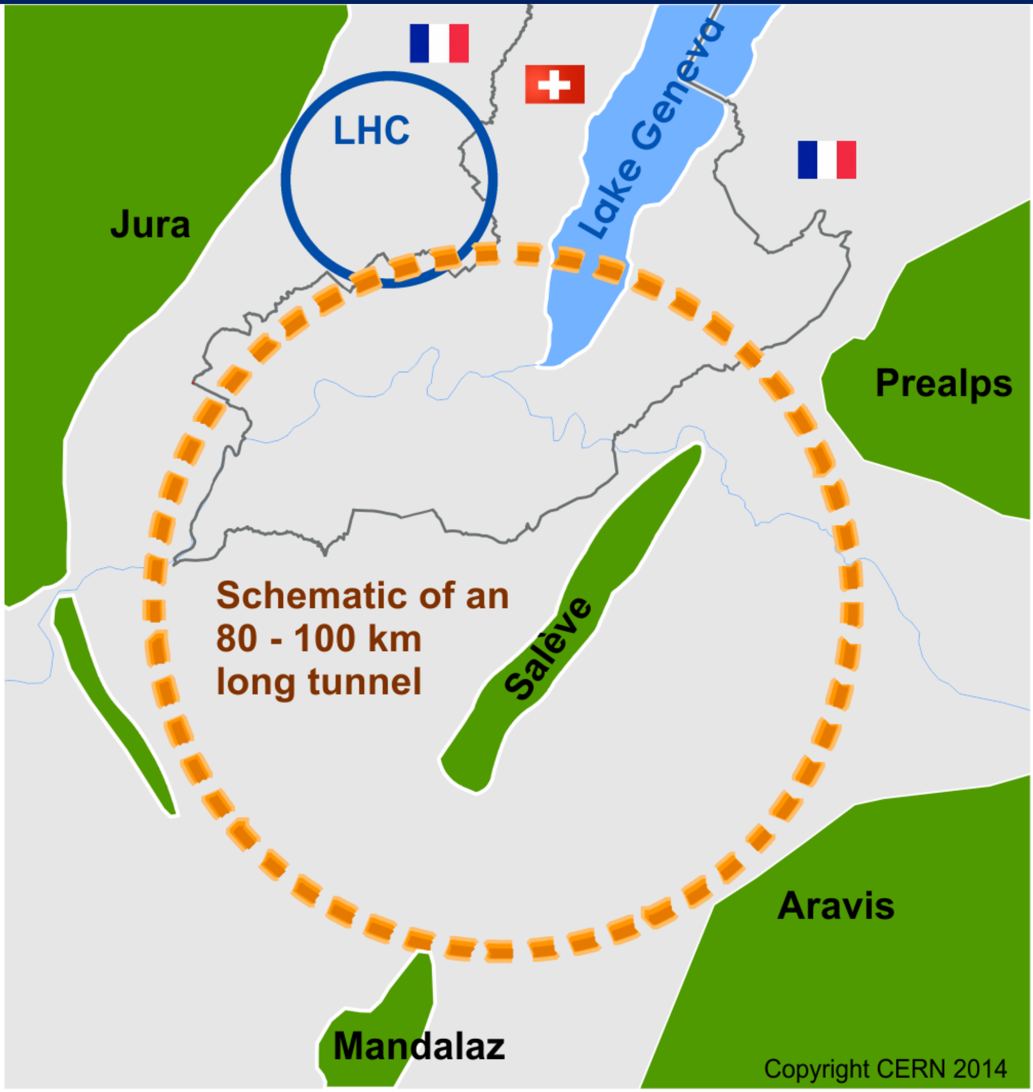
- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

# Future Circular Collider Study - SCOPE
# CDR and cost review for the next ESU (2018)

**Forming an international collaboration to study:**

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements
- **$e^+e^-$ collider (*FCC-ee*)** as potential intermediate step

  → Study Z, W, H, top
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



# FCC Kick-off Meeting

# FCC-hh

# The hadron collider: FCC-hh

The name of the game of a hadron machine is **energy reach.**

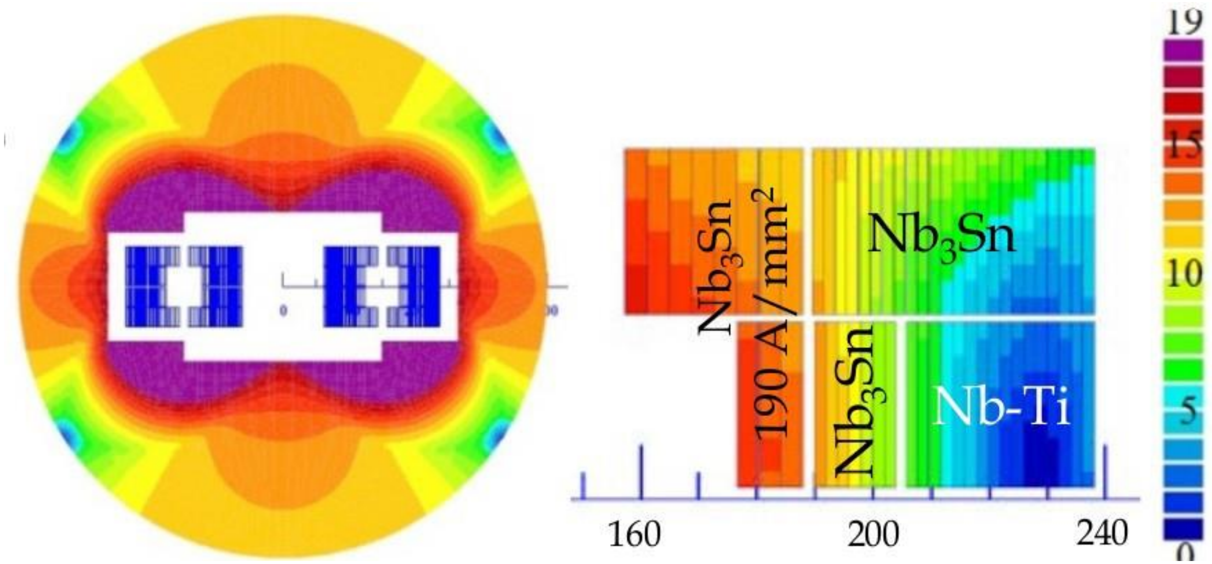
$$E \propto B_{dipole} \times \rho_{bending}$$

Luminosity is (to first order) less of a problem – simply run at a tolerable **pileup.**

To go to 100 TeV from the current 14 TeV of the LHC we need to increase the diameter by a factor of ~3-4 and the field from 8 T to 16-20 T

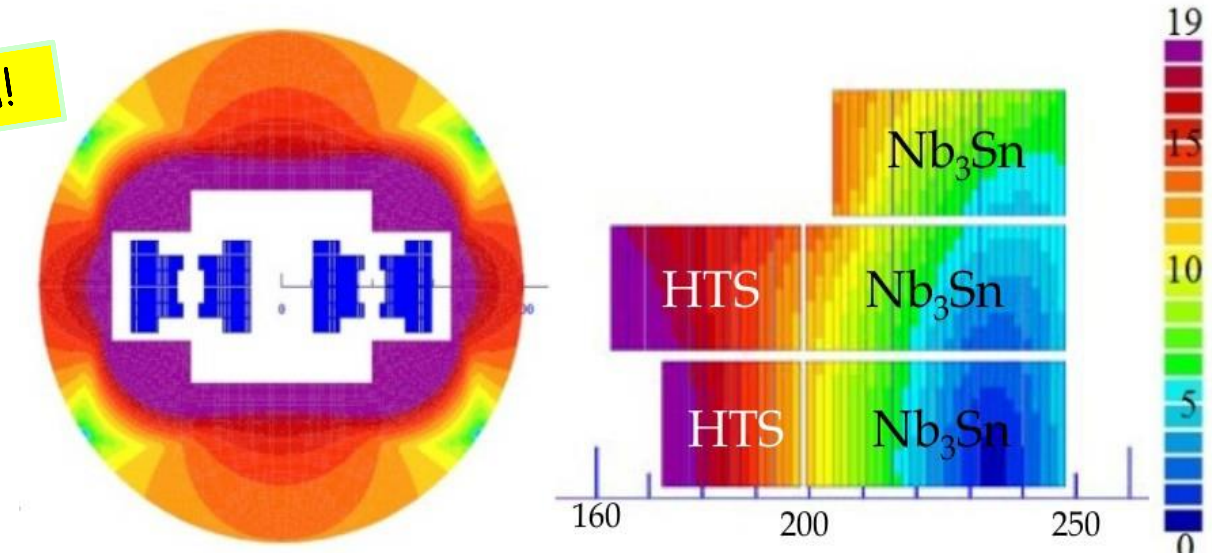
# High field dipole magnets

15 T with Nb3Sn and Nb-Ti (preliminary, project goal 16 T)




Quench protection!

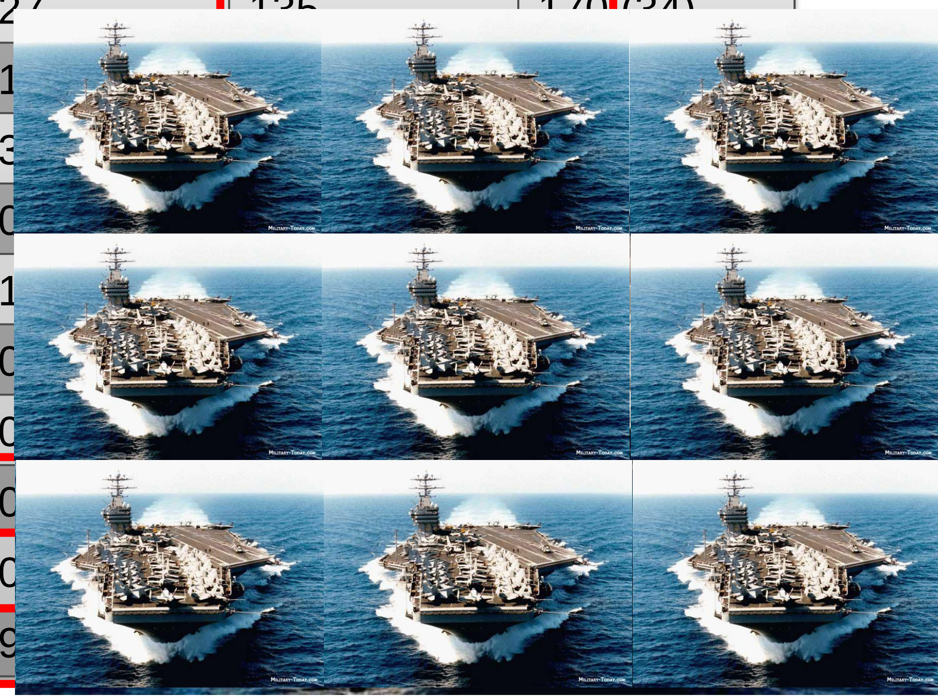
20 T with HTS and Nb3Sn



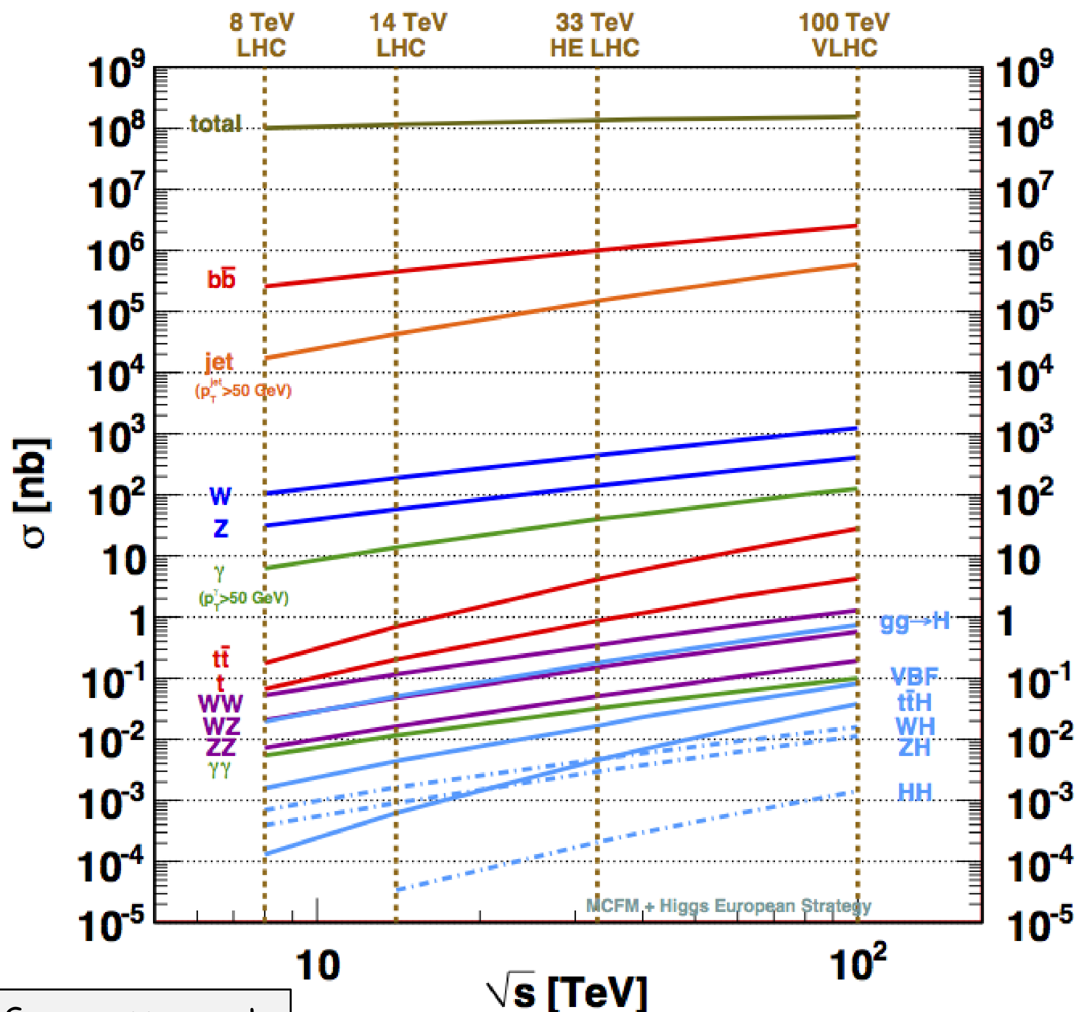

L. Rossi, E. Todesco, `Conceptual design of 20 T dipoles for High-Energy LHC', CERN Yellow Report 2011-003 13-9 (2011)

# FCC-hh: main parameters

| Parameter | LHC | HL-LHC | FCC-hh |
|---|---|---|---|
| c.m. energy [TeV] | 14 | 14 | 100 |
| dipole magnet field [T] | 8.33 | 8.33 | 16 (20) |
| circumference [km] | 27 | 27 | 100 (83) |
| luminosity [1034 cm-2s-1] | 1 | 5 | 5 [→20?] |
| bunch spacing [ns] | 25 | 25 | 25(5) |
| events / bunch crossing | 27 | 135 | 170 (34) |
| bunch population [$10^{11}$] | 1 | | |
| norm. transverse emitt. [mm] | 3 | | |
| IP beta-function [m] 0.55 | 0 | | |
| IP beam size [mm] | 1 | | |
| synchrotron rad. [W/m/aperture] | 0 | | |
| critical energy [keV] | 0 | | |
| total syncrotronrad. power [MW] | 0 | | |
| Total energy stored (beam) [GJ] | 0 | | |
| Total energy stored (magnets) [GJ] | 9 | | |



# Cross sections vs √s



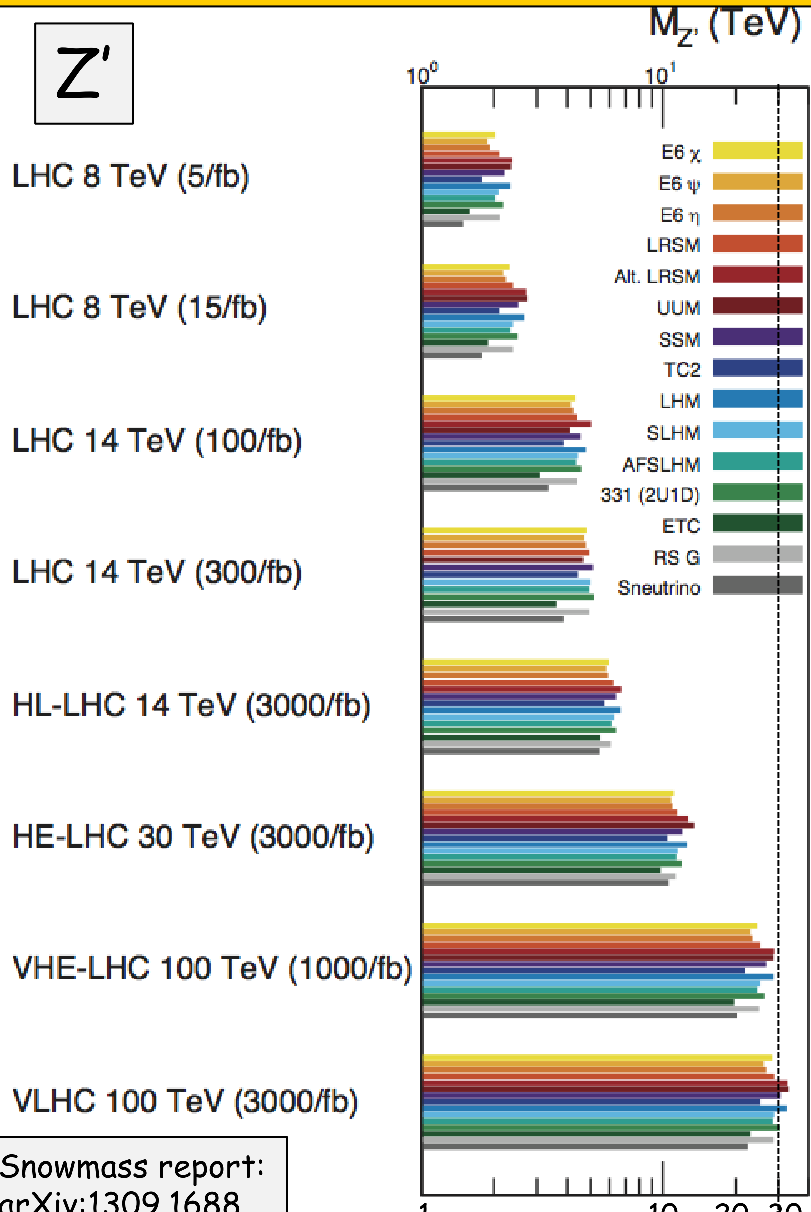

Snowmass report: arXiv:1310.5189

| Process | σ (100 TeV)/σ (14 TeV) |
|---|---|
| Total pp | 1.25 |
| W | ~7 |
| Z | ~7 |
| WW | ~10 |
| ZZ | ~10 |
| tt | ~30 |
| H | ~15 (ttH ~60) |
| HH | ~40 |
| stop (m=1 TeV) | $\sim 10^3$ |

→ With 10000/fb at $\sqrt{s}$=100 TeV expect: $10^{12}$ top, $10^{10}$ Higgs bosons, $10^8$ m=1 TeV stop pairs, …

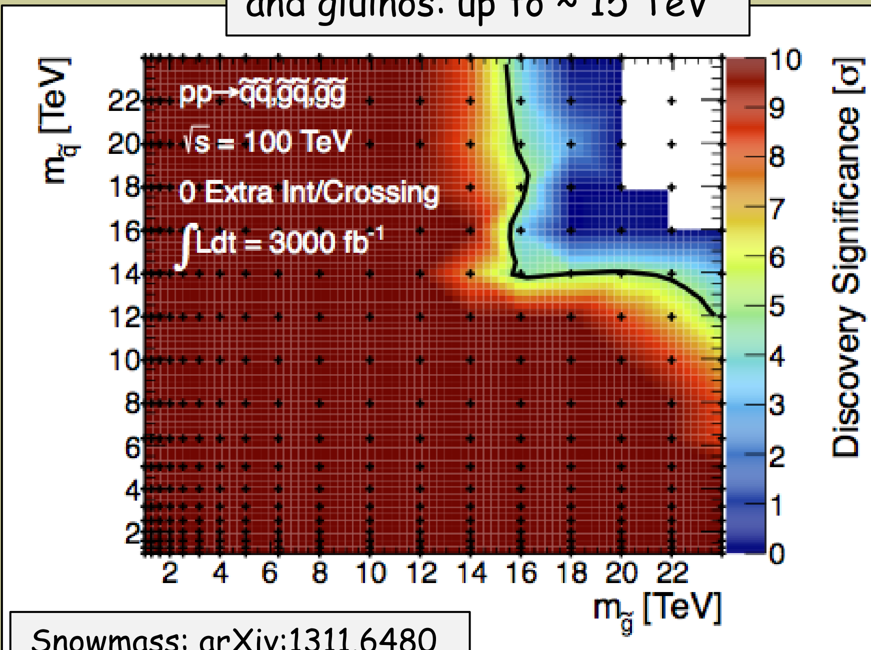
# A 100 TeV pp collider is the instrument to explore the O(10 TeV) E-scale directly

Z'



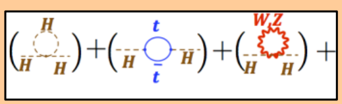

Snowmass report: arXiv:1309.1688

Discovery of squarks and gluinos: up to ~ 15 TeV




Snowmass: arXiv:1311.6480

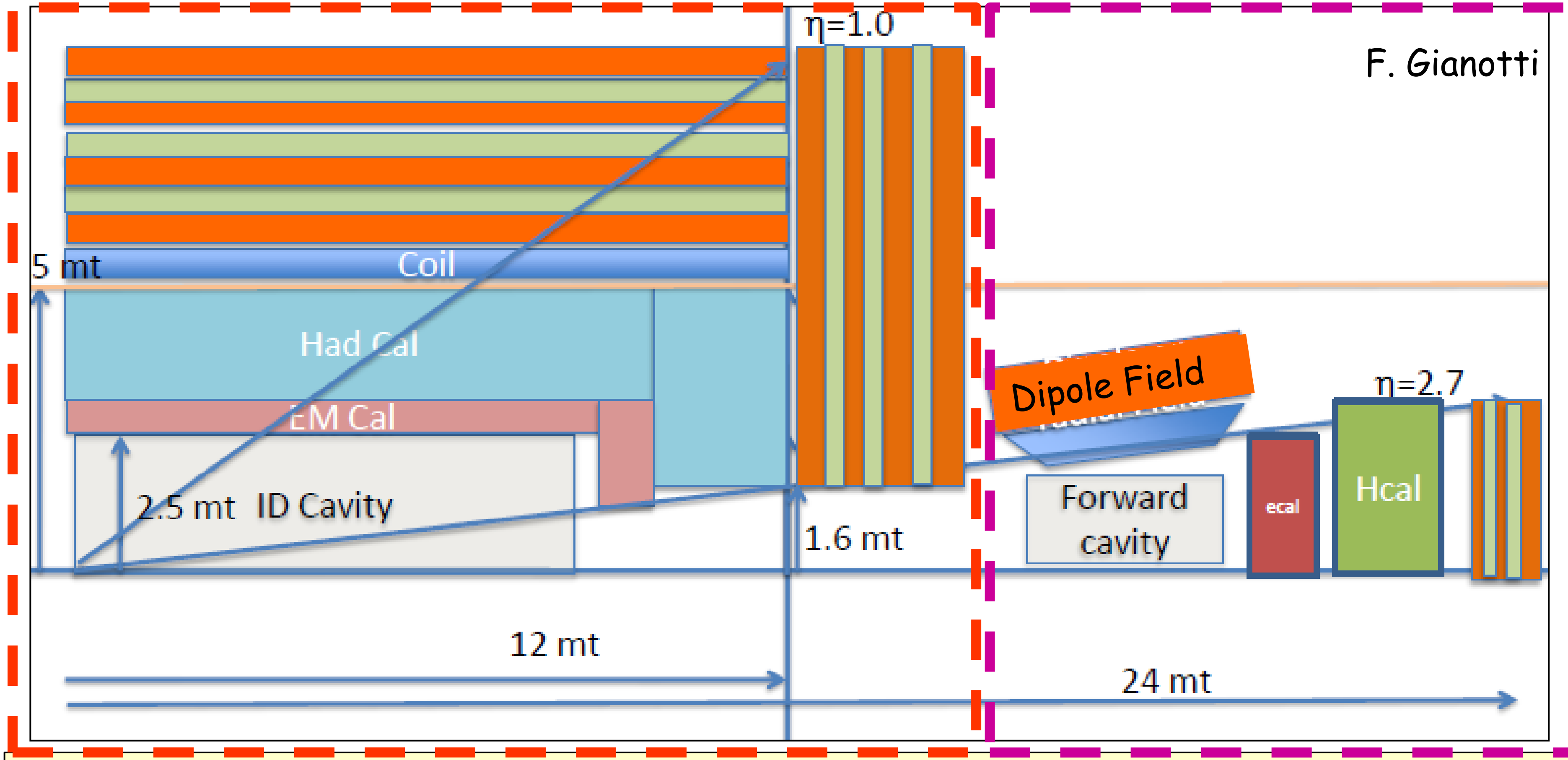
The naturalness problem:

$\Delta M_H^2 \sim$  $\cdots \sim \Lambda^2$



- ❑ Only Higgs and nothing else at ~O(1 TeV) → $10^{-2}$ fine-tuning
- ❑ Only Higgs and nothing else at ~O(10 TeV) → $10^{-4}$ fine-tuning

# First ideas about detector layout: a-la CMS + LHCb

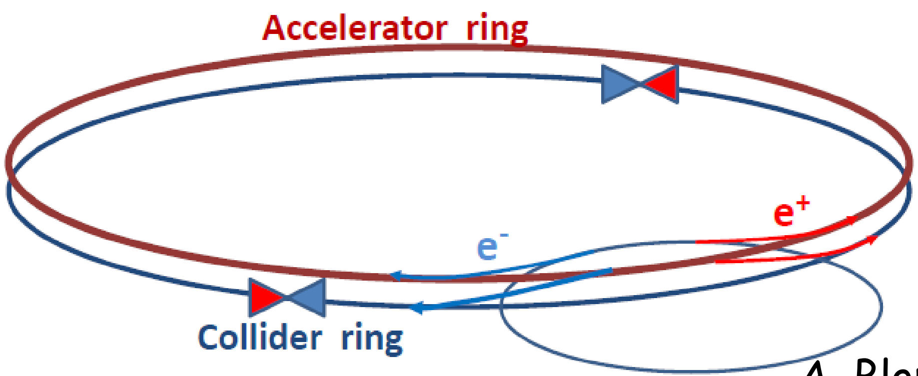



- Need $BL^2$ ~10 x ATLAS/CMS to achieve 10% muon momentum resolution at 10-20 TeV
- Solenoid: B=5T, $R_{in}$=5-6m, L=24m → size is x2 CMS. Stored energy: ~ 50 GJ
- > 5000 $m^3$ of Fe in return joke → alternative: thin (twin) lower-B solenoid at larger R to capture return flux of main solenoid
- Forward dipole à la LHCb: B~10 Tm
- Calorimetry: ≥ 12 λ for shower containment; W takes less space but requires 50ns integration for slow neutrons; speed advantageous for 5ns option (→ Si active medium ?)

# FCC-ee (*the project formerly known as TLEP*)

# The electron-positron collider: main design considerations

- Here the name of the game is **luminosity**
- The energy reach of circular colliders is rather limited due to synchrotron radiation issues.
- A circular collider of 80-100 kms would comfortably run at the t-tbar threshold ($E_{CM}$ 350GeV) but not too much higher
- A high luminosity circular collider is very efficient in ‘burning up’ the beams (beam lifetimes are a few minutes). This necessitates the use of continuous top-up injection




A. Blondel

Considerable experience in circular colliders ensures that their performance can be predicted with high reliability

# Luminosity of a circular lepton collider

$$\mathcal{L} = const \times \boxed{P_{tot}} \boxed{\frac{\rho}{{E_0}^3}} \boxed{\xi_y} \boxed{\frac{R_{hg}}{\beta_y^*}}$$

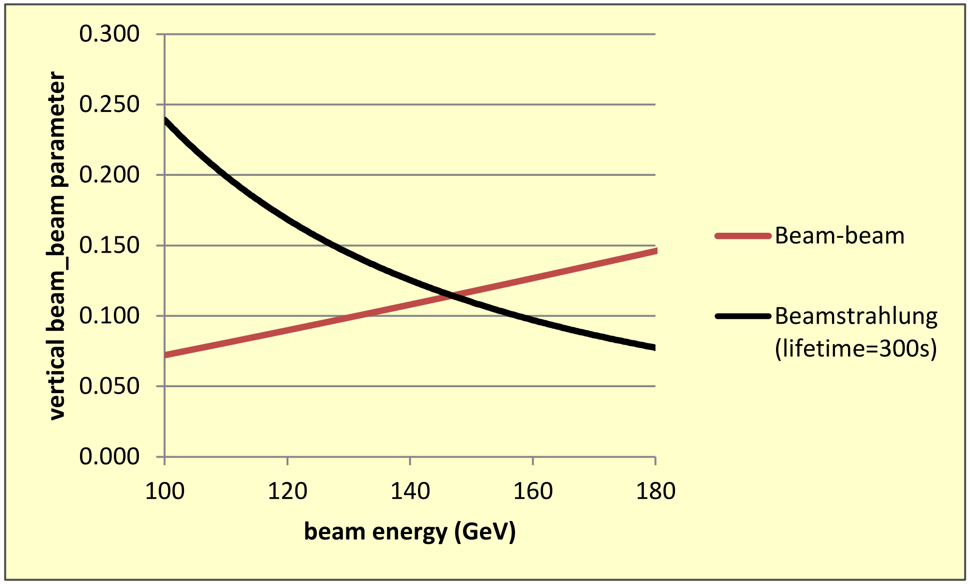
(head-on collisions)

The maximum luminosity is bound by the total power dissipated, the maximum achievable beam-beam parameter, the bending radius, the beam energy, the amount of vertical squeezing $\beta_y^*$ , and the hourglass effect, a geometrical factor (which is a function of $\sigma_z$ and $\beta_y^*$)

$$\mathcal{L} = 6.0 \times 10^{34} \left(\frac{P_{tot}}{50MW}\right)\left(\frac{\rho}{10km}\right)\left(\frac{120GeV}{E_0}\right)^3 \left(\frac{\xi_y}{0.1}\right)\left(\frac{R_{hg}}{0.83}\right)\left(\frac{1mm}{\beta_y^*}\right) cm^{-2}s^{-1}$$

# Two limits for the beam-beam parameter

- At low energies the beam-beam parameter $\xi$ saturates at the so-called beam-beam limit
- At high energies, the "beamstrahlung" limit arrives first




Parameters of FCC-ee-175

**Beamstrahlung**: is the synchrotron radiation emitted by an incoming electron in the collective electromagnetic field of the opposite bunch at an interaction point. The main effect at circular colliders at high energy is decreasing the beam lifetime.

# Main baseline parameters

- This is work in progress and rapidly evolving

| Parameter | Z | W | H | t | LEP2 |
|---|---|---|---|---|---|
| E (GeV) | 45 | 80 | 120 | 175 | 104 |
| I (mA) | 1400 | 152 | 30 | 7 | 4 |
| No. bunches | 16'700 | 4'490 | 1'330 | 98 | 4 |
| Power (MW/beam) | 50 | 50 | 50 | 50 | 11 |
| E loss/turn (GeV) | 0.03 | 0.33 | 1.67 | 7.55 | 3.34 |
| Total RF voltage(GV) | 2.5 | 4 | 5.5 | 11 | 3.5 |
| $\beta^*_{x/y}$ (mm) | 500 / 1 | 500 / 1 | 500 / 1 | 1000 / 1 | 1500 / 50 |
| $\varepsilon_x$ (nm) | 29 | 3.3 | 1 | 2 | 30-50 |
| $\varepsilon_y$ (pm) | 60 | 7 | 2 | 2 | ~250 |
| $\xi_y$ | 0.03 | 0.06 | 0.09 | 0.09 | 0.07 |
| **L ($10^{34}$ $cm^{-2}s^{-1}$)** | **28** | **12** | **6.0** | **1.8** | **0.012** |
| Number of IPs | 4 | 4 | 4 | 4 | 4 |
| Lumi lifetime (mins) | 213 | 52 | 21 | 24 | 310 |

# STATISTICS

($e^+e^- \rightarrow ZH$, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow ZH$,[$e^+e^- \rightarrow t\bar{t}$] )

| | TLEP-4 IP, per IP | statistics |
|---|---|---|
| **circumference** | 100 km | |
| **max beam energy** | 175 GeV | |
| **no. of IPs** | 4 | |
| **Luminosity/IP at 350 GeV c.m.** | $1.8\times10^{34}$ cm$^{-2}$s$^{-1}$ | $10^6$ $t\bar{t}$ pairs |
| **Luminosity/IP at 240 GeV c.m.** | $5.9\times10^{34}$ cm$^{-2}$s$^{-1}$ | 2 $10^6$ ZH evts |
| **Luminosity/IP at 160 GeV c.m.** | $1.2\times10^{35}$ cm$^{-2}$s$^{-1}$ | $10^8$ WW pairs |
| **Luminosity/IP at 90 GeV c.m.** | 2.8 $10^{35}$ cm$^{-2}$s$^{-1}$ | $10^{12}$ Z decays |

A real Z, W, H, t factory!

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# First look at the physics case of TLEP

PUBLISHED

The TLEP Design Study Working Group

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JHEP01(2014)164

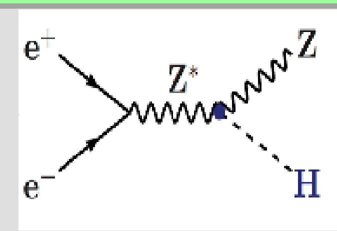
# Physics capabilities tea...


Crocodile in Crete, June 2014

Physics case published: [JHEP01 (2014) 164]

Main strength is the capability to study all known particles ...) with very high precision. For example: repeat the whole programme in a few minutes. Also sensitivity to very rare p... small couplings).

This represents a formidable challenge to theory: with statistical errors reduced by a factor of as much as 100 compared to LEP, theory needs to follow…




**2 $10^6$ ZH events in 5 years**

**«A tagged Higgs beam».**

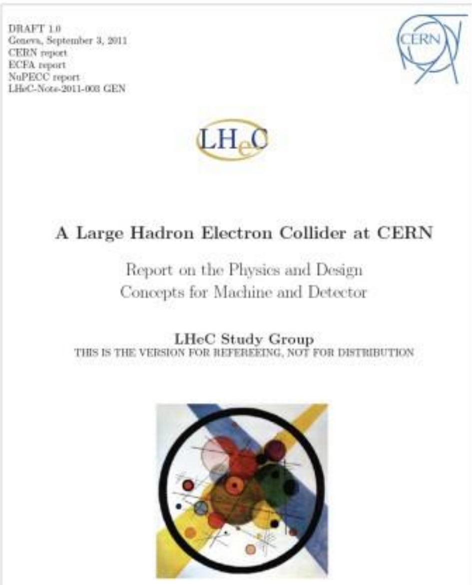
Example: invisible widths:

- Higgs $BR_{exotic}$ measured to 0.16% (4 IPs)
- Z invisible width ($\Delta N_\nu$ from LEP 0.008):
  - Z lineshape: $N_\nu$ measured to 0.0001 (stat)$\pm$0.004(syst)
  - tagged Z (1 year at ECM 160GeV plus data from 240 and 359GeV) $\Delta N_\nu$ =0.0008
  - Dedicated run at 105 GeV: $\Delta N_\nu$ =0.0004

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e,\mu}(SM)}$$

# Other possibilities

# FCC-he


DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

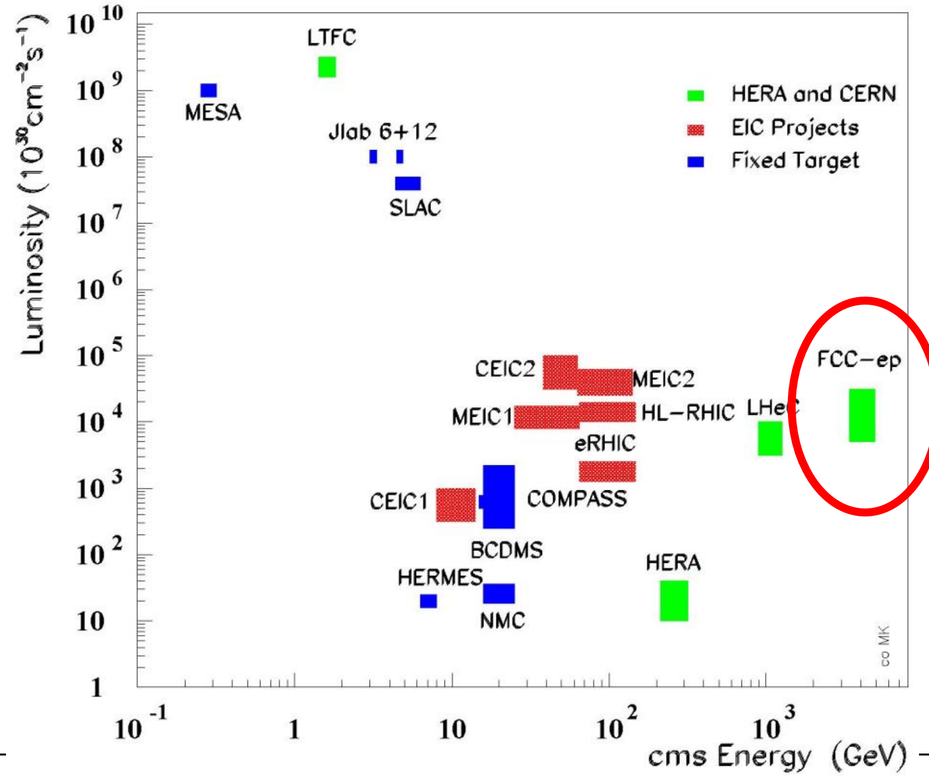
LHeC

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

- Based on LHeC – TDR published
- Two options:
  - (1) FCC-ee ring,
  - (2) ERL – energy recovery linac




M. Klein

# Ions at the FCC

- Centre-of-mass energy per nucleon-nucleon collision:

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}} \quad \Rightarrow \quad \begin{array}{l} \sqrt{s_{PbPb}} = 39\ TeV \\ \sqrt{s_{pPb}} = 63\ TeV \end{array} \quad \text{for} \quad \sqrt{s_{pp}} = 100\ TeV$$

- First (conservative) estimates of luminosity: x5 LHC (after LS2)
- Physics opportunities with heavy ion beams at the FCC (AA, pA) are investigated by a dedicated WG within the FCC-hh group: next WS in September at CERN (https://indico.cern.ch/event/331669)
- Main directions:
  - Quark-Gluon Plasma studies: larger size, higher temperature, new hard probes available (e.g. top quarks)
  - Saturation of small-x gluon densities (with pA): reach down to x~$10^{-6}$ (one order of magnitude small than at LHC)
  - Photon-induced collisions ($\gamma+\gamma$, $\gamma$+A): saturation and EW studies
- More details: https://indico.cern.ch/event/282344/session/16/contribution/109

Andrea Dainese

# The study

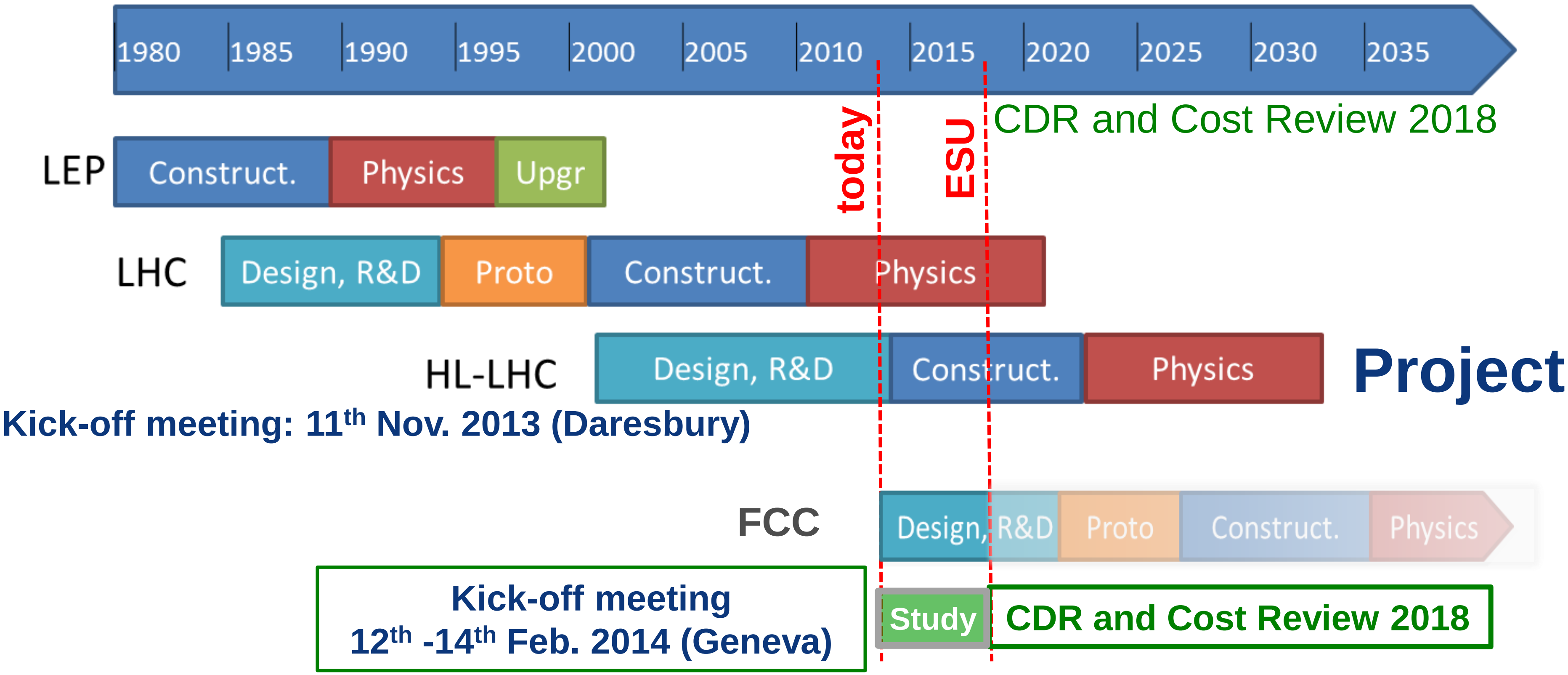
# FCC Coordination Team

**Future Circular Colliders - Conceptual Design Study**
**Study coordination, M. Benedikt, F. Zimmermann**

| Hadron collider | Hadron injectors | e+ e- collider and injectors | Infrastructure, cost estimates | Technology | Physics and experiments |
|---|---|---|---|---|---|
| **D. Schulte** | **B. Goddard** | **J. Wenninger** | **P. Lebrun** | High Field Magnets **L. Bottura** | Hadrons **A. Ball, F. Gianotti, M. Mangano** |
| | | | | Supercon-ducting RF **E. Jensen** | e+ e- **A. Blondel J. Ellis, P. Janot** |
| **e- p option** Integration aspects **O. Brüning** | | | | Cryogenics **L. Tavian** | |
| **Operation aspects,** energy efficiency, safety, environment **P. Collier** | | | | Specific Technologies **JM. Jimenez** | e- p **M. Klein** |

**Planning (Implementation roadmap, financial planning, reporting)**
**F. Sonnemann, J. Gutleber**

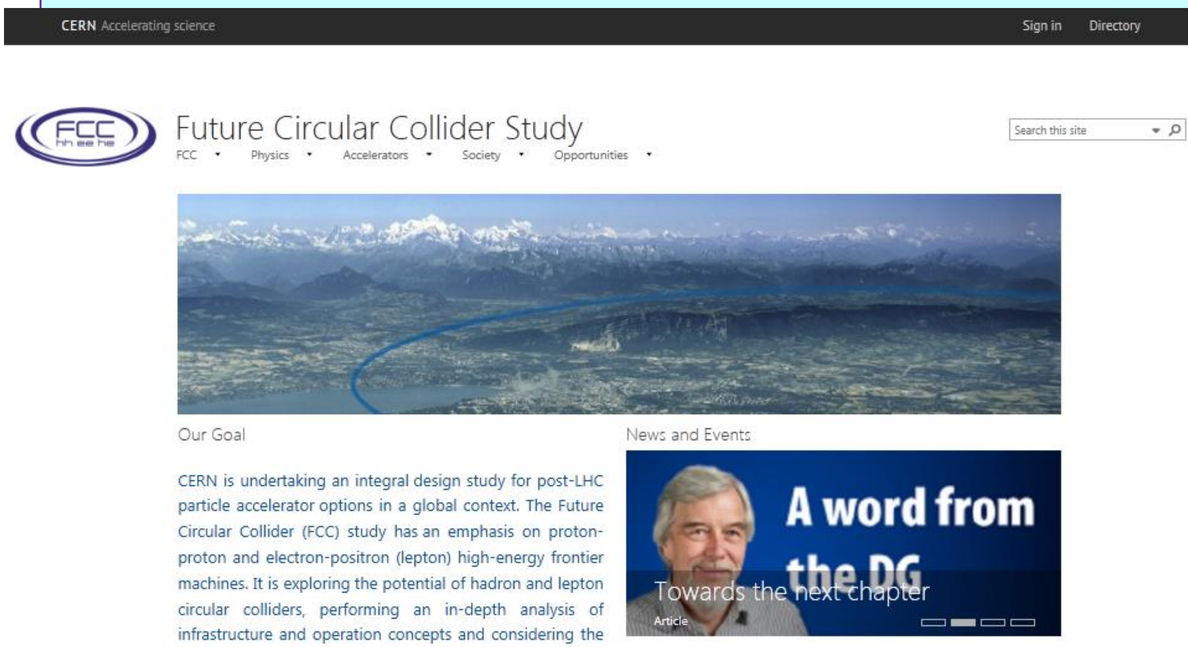
# CERN and FCC timelines




- LHC and HL-LHC operation until ~2035
- Must start now developing FCC concepts to be ready in time

# Join us!

- This programme stretches way into the future (provided that it gets the go-ahead)
- But you can help shape the future today by joining in one or more of the working groups




Public site: http://cern.ch/fcc
FCC collaboration site: http://cern.ch/fcc/collaboration
Indico site: http://indico.cern.ch/category/5153/

# Conclusions

- The FCC project might well shape the next 60 years of CERN
- It offers unique opportunities to further explore Nature…
  - …by increasing the Energy frontier (through the 100TeV hadron collider)
  - …and by changing the game of precision physics by offering unprecedented statistics at an $E_{CM}$ of 90 GeV (Z), 160 GeV (W), 240 GeV (ZH) and 350 GeV (tt) (with a high luminosity e+e- collider)

# Is history repeating itself…?

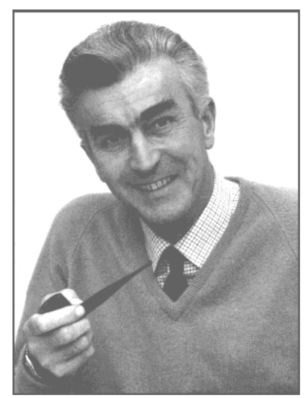
When **Lady Margaret Thatcher** visited CERN in 1982, she asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.***

Margaret Thatcher,
British PM 1979-90

Dr. Schopper's answer was ***there would be no bigger tunnel at CERN***.

Herwig Schopper
CERN DG 1981-88
built LEP

Lady Thatcher replied that she had obtained ***exactly the same answer from Sir John Adams when the SPS was built 10 years earlier***, and therefore she did not believe him.



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

## Was lady Thatcher right?

Herwig Schopper, private communication, 2013; curtesy F. Zimmermann

End

Thank you