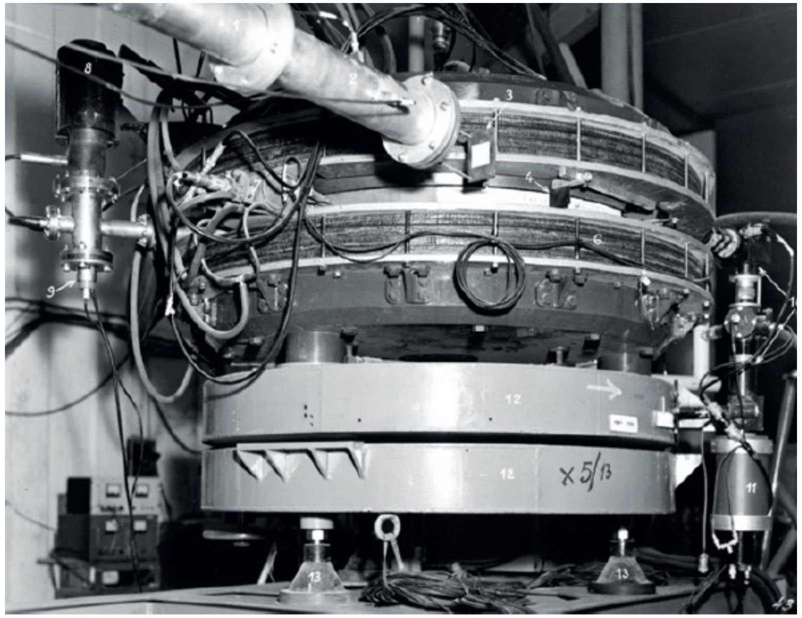
# The path toward future accelerators

P. Campana (INFN-LNF), ICFA chair

Vulcano Workshop, Ischia - May 31, 2024

# A 60-year long trip in Energy and Intensity



**AdA: Anello Di Accumulazione**
(1963)

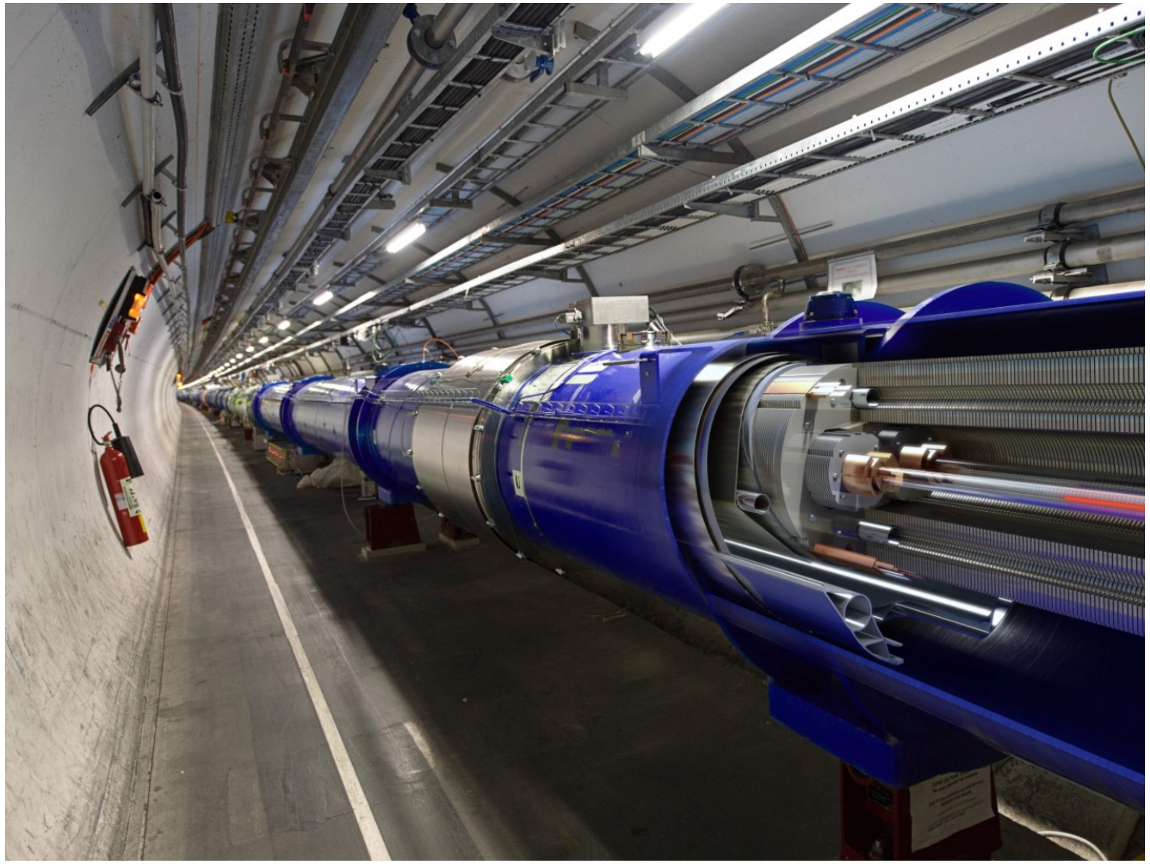
- 1,3m diameter, 250 MeV
- first electron-positron collisions
- Luminosity ~ $10^{25}$ $cm^{-2}s^{-1}$

E x 3 $10^4$

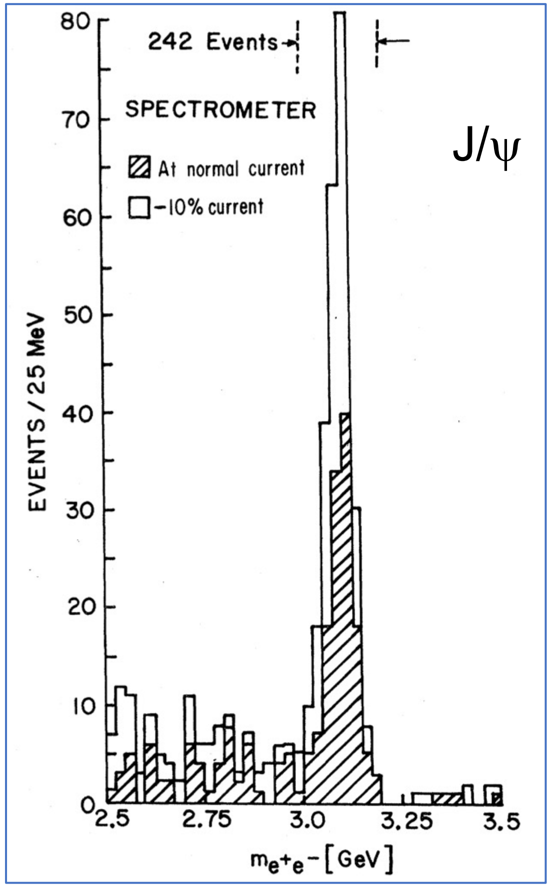
L x 2 $10^9$

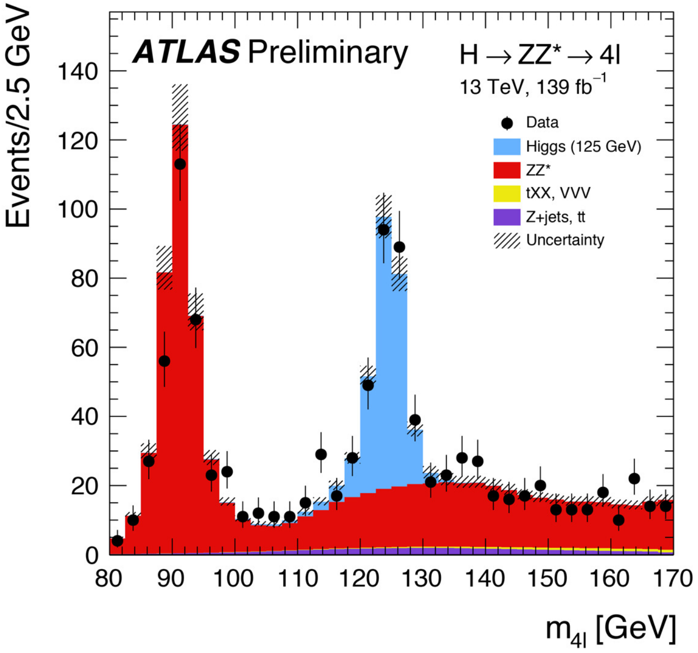
**LHC: Large Hadron Collider**

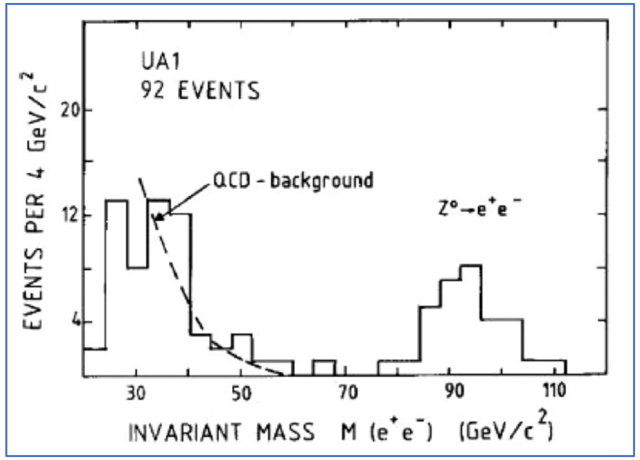
- Beam energy 6.8 TeV
- Luminosity ~ $2x10^{34}$ $cm^{-2}s^{-1}$

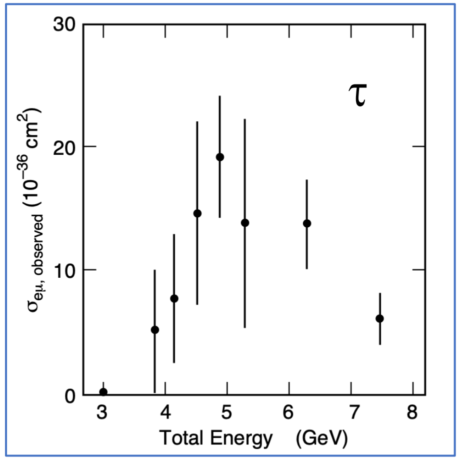


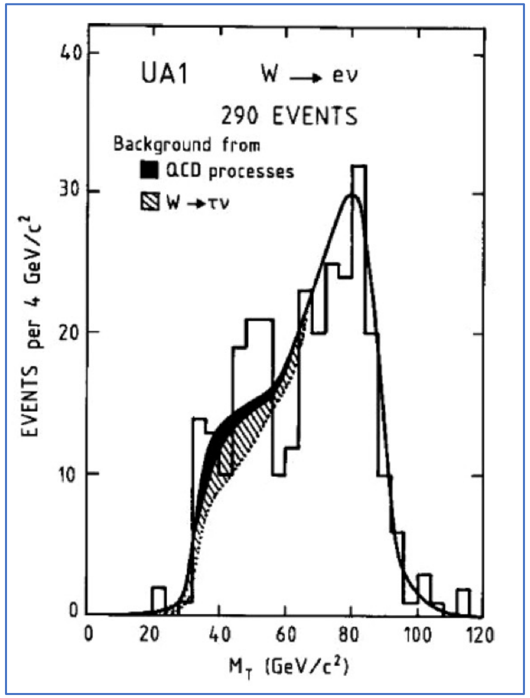
# 60 y of successful SM at accelerators

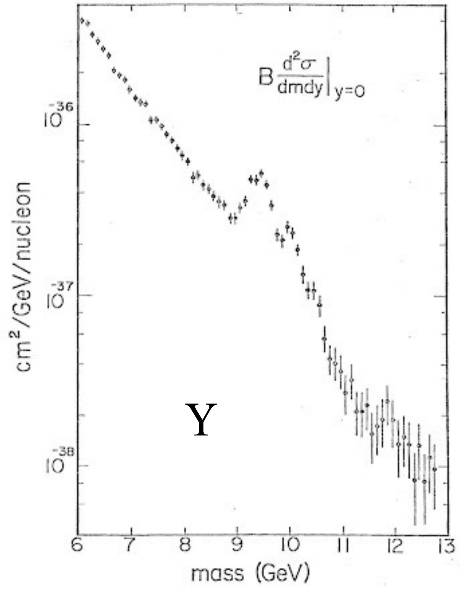


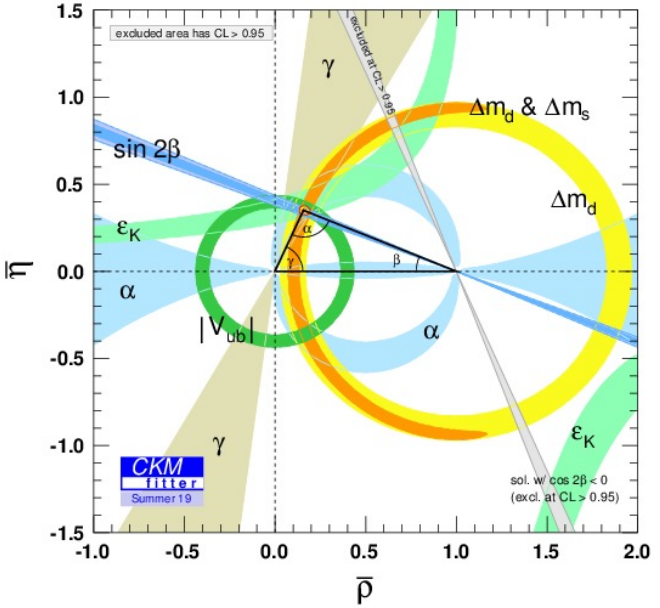



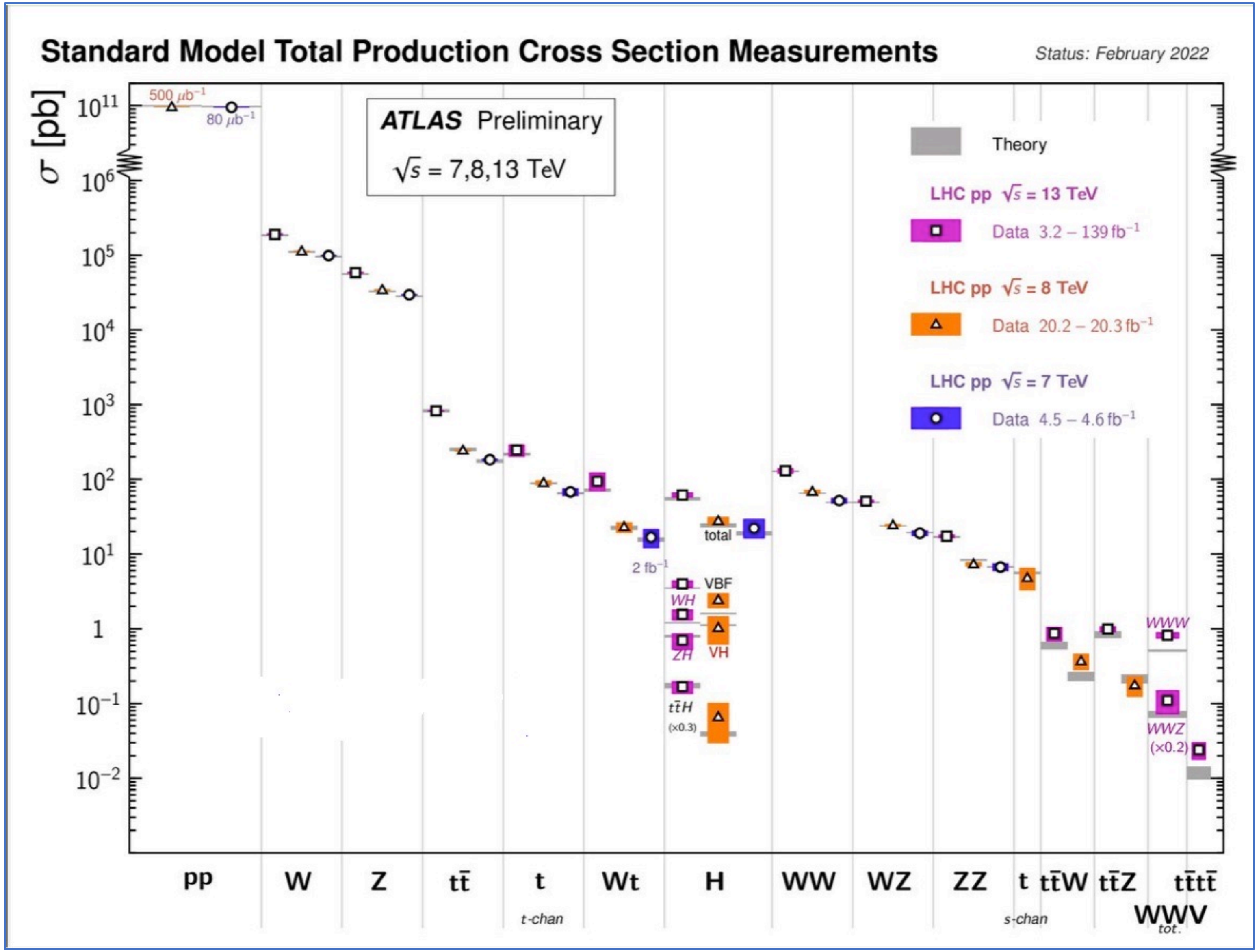



Despite an outstanding success of SM at LHC, we all know that SM is an approximate theory

We don’t (yet) have hints on:

- **Nature and masses of the neutrinos**
- **CP violation & baryogenesis**
- **The naturalness problem**
- **Origin of dark matter & dark energy**
- **Quarks & leptons mass scales**
- **The quantum gravity**



How to increase our know-how of microscopic word ?

Two options:

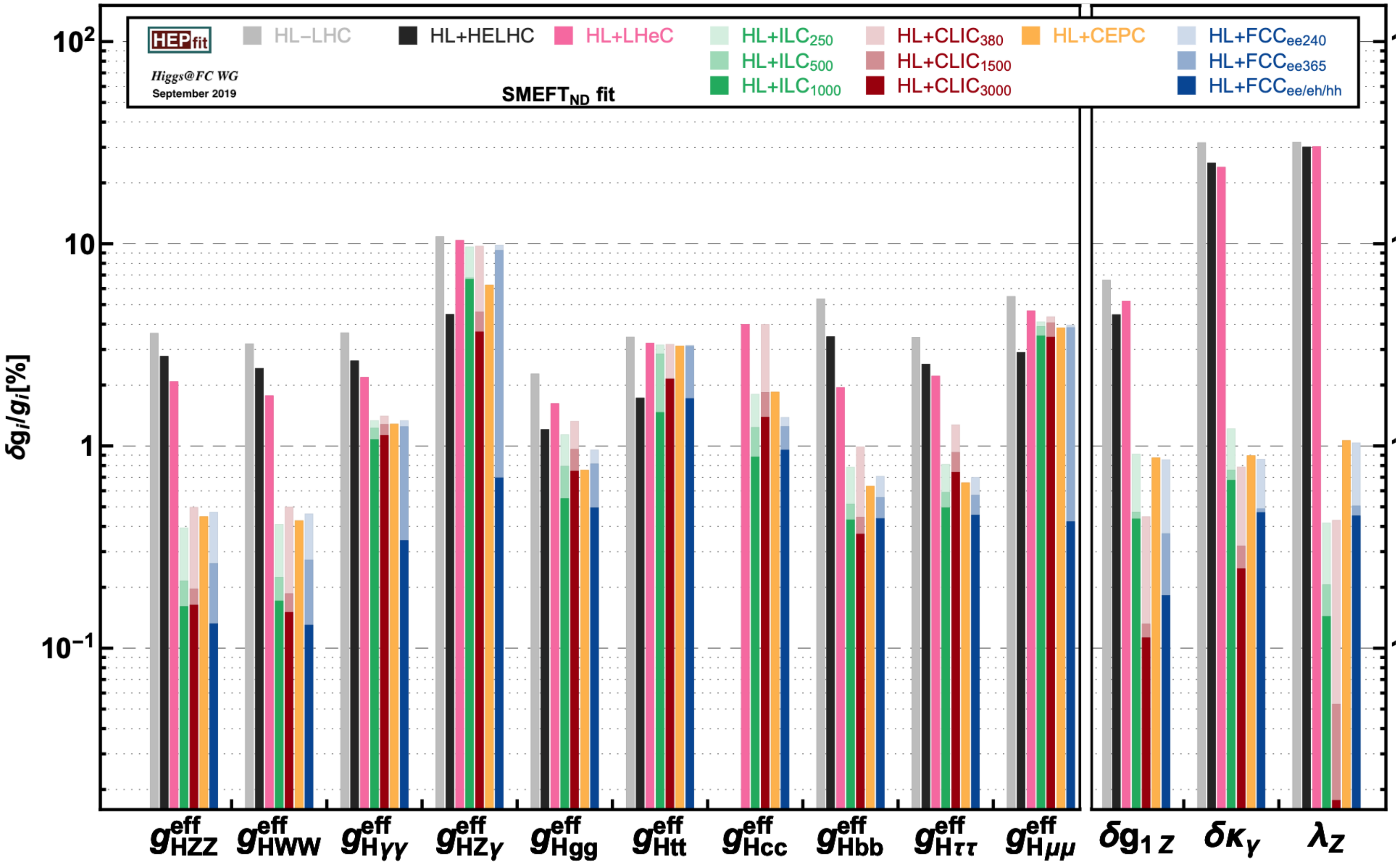
1) Performing a theoretical leap in our understanding of present misteries, with new interpretations of existing experimental data

2) Performing new (brilliant) experiments at existing accelerator facilities and/or repeating current experiments at new, more powerful colliding machines, exploring new regions in energy/intensity

Both goals are extremely challenging for theorists, experimentalists and accelerator people !

# Where to look for New Physics

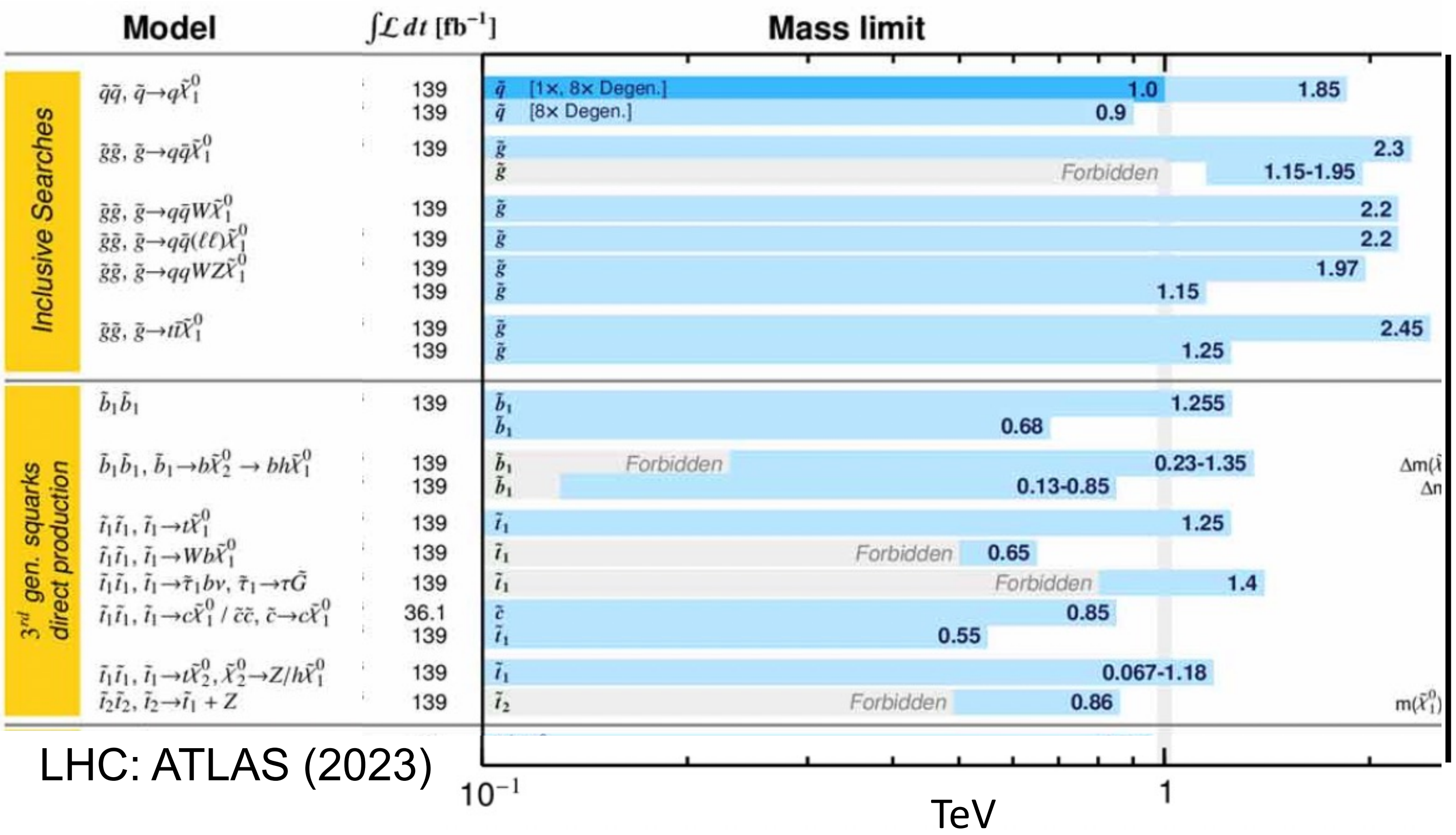
**Immediate goal**: study the unknown scalar field of Higgs Boson through its couplings



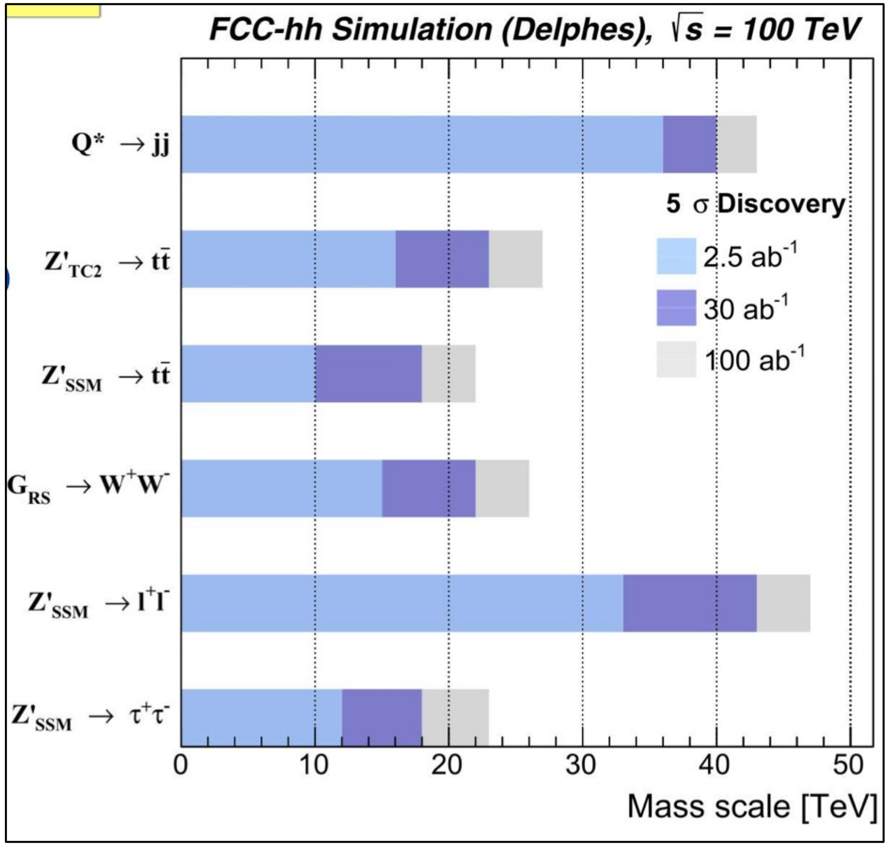

Combination of the future full data set available from HL-LHC with any of the foreseen Higgs factories (ILC, CLIC, FCC/CEPC) will bring up to a factor x 10 increase in knowledge of various Higgs couplings

Tool to find out new states/new couplings

**Alternate (longer term goal)**: direct searches for new states with O(100 TeV) c.m. energy circular hh colliders




LHC: ATLAS (2023)




New colliders in the range of >10 TeV/parton (FCC-hh, SPPC, μμ) can reach mass scales 20-40 TeV depending on model assumption

## Challenges for the next generation of HEP accelerators

- More powerful acceleration technologies (more MV/m or even GV/m, especially for e+/e-)

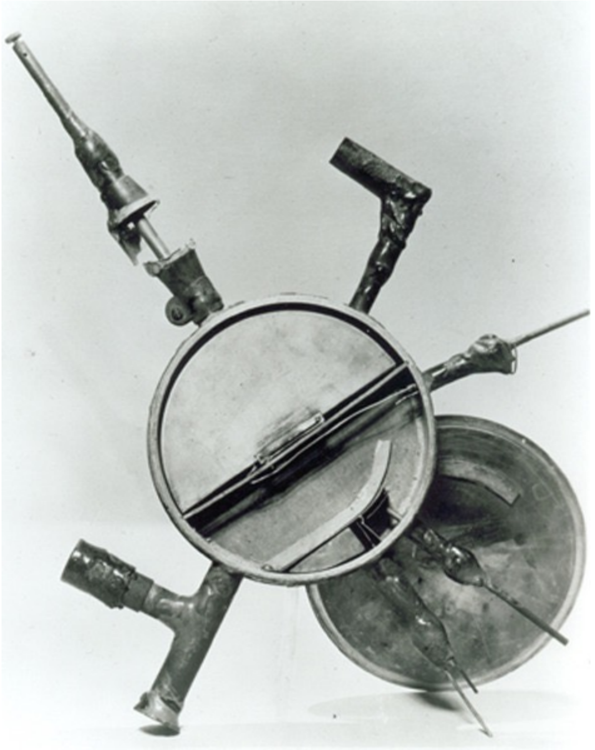
- High Field Magnets for increased bending power (transition from LTS to HTS ?)

- More powerful particles sources (e+ production is extremely demanding)

- Efficiency, sustainability and carbon footprint of new infrastructures

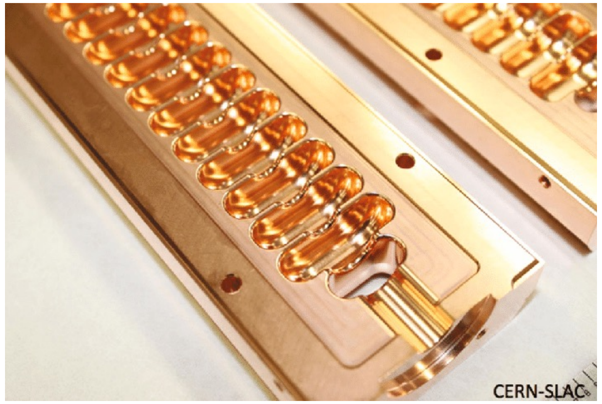
- Costs & Governance of global projects

- Sociology of HEP community



# Acceleration: more energy in less space, more efficiently

speaking mostly about e-/e+ LINACs



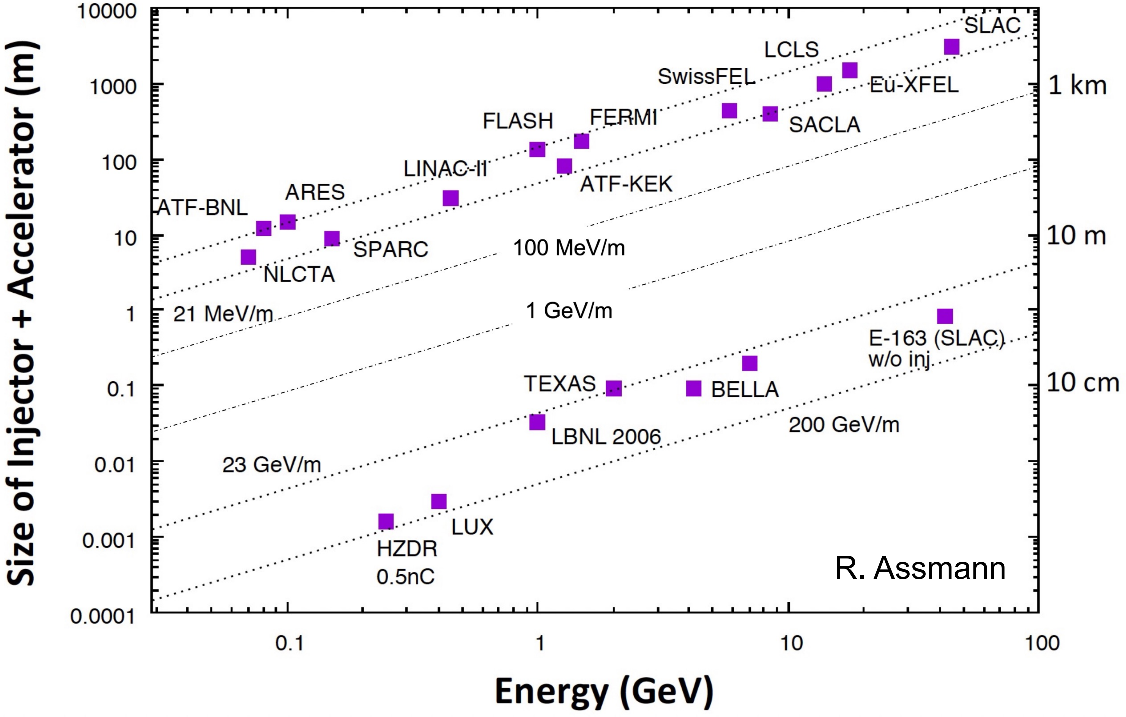

Several LINAC technologies (conventional):

- SRF: high currents, high Q, well established, low gain ~ 20-30 MV/m
  XFEL, LCLS II, CEBAF, …
- Normal conducting: based on bulk Cu cavities (S, C, X bands), higher gain ~ 70-100 MV/m
  SwissFEL, KEK, FERMI, DAFNE, MAX IV, …
  A lot of R&D (driven by CLIC), including
  that on high efficiency klystrons
  (next step: solid state tubes)

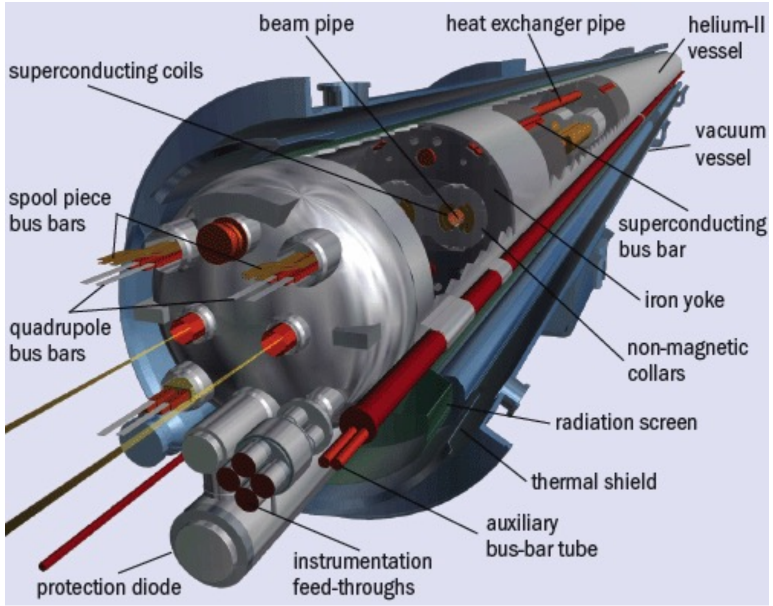
… and more advanced …

$C^3$ Copper Cool Technology, Cu cavities cooled at LN2 80 K, pushing the gain at ~150 MV/m

Plasma-based acceleration (beam or laser driven), > GV/m → see *M. Ferrario talk*
+ dielectric-based …

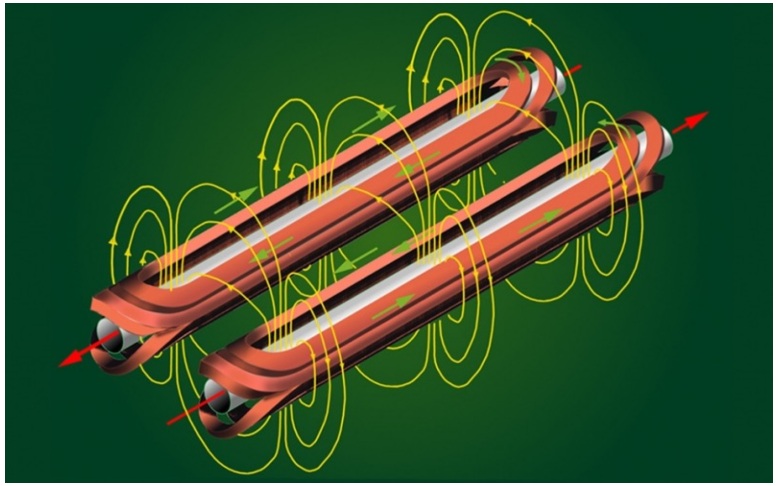


Bending: more curvature in less space, <u>more efficiently</u>
speaking mostly about pp Circular Colliders



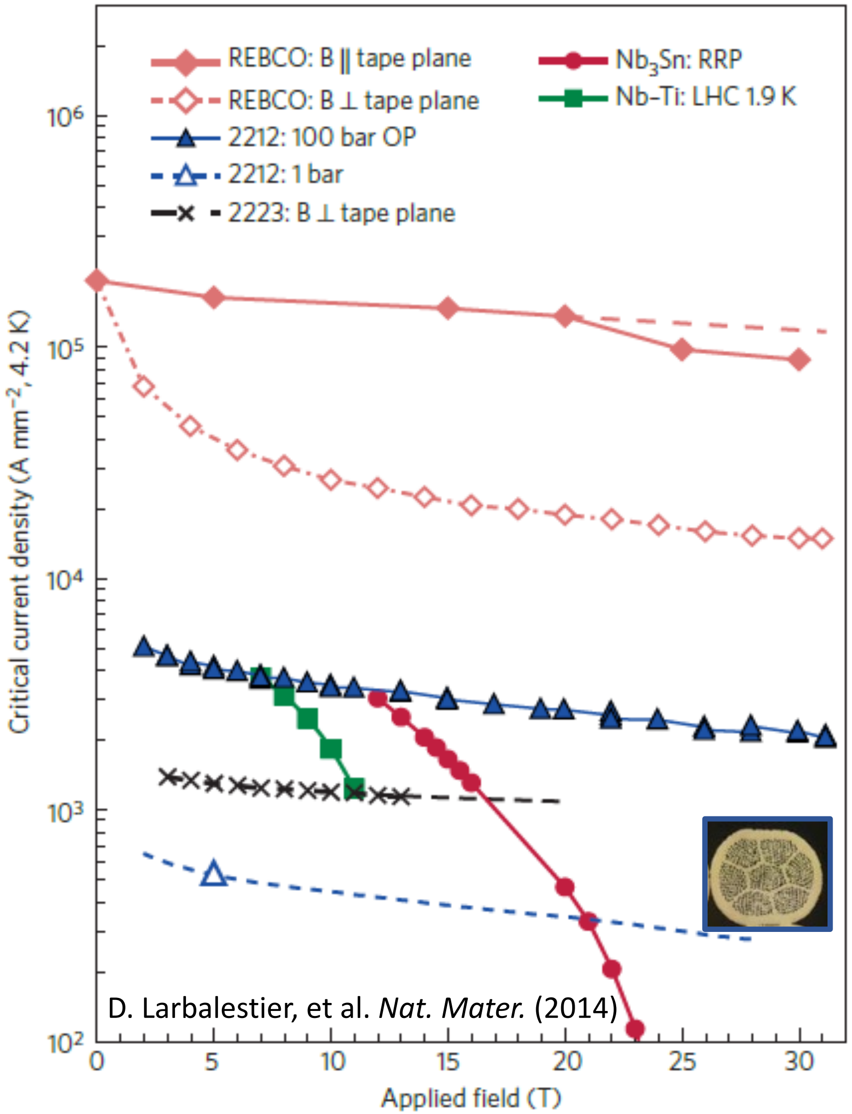

LHC technology: NbTi inherited from SSC, 15 y industrial R&D
- 1250 dipoles at 1.9 K, 8.3 T field
- 7 TeV/beam in the L=27 km LHC tunnel
- → 40 MW cryo power

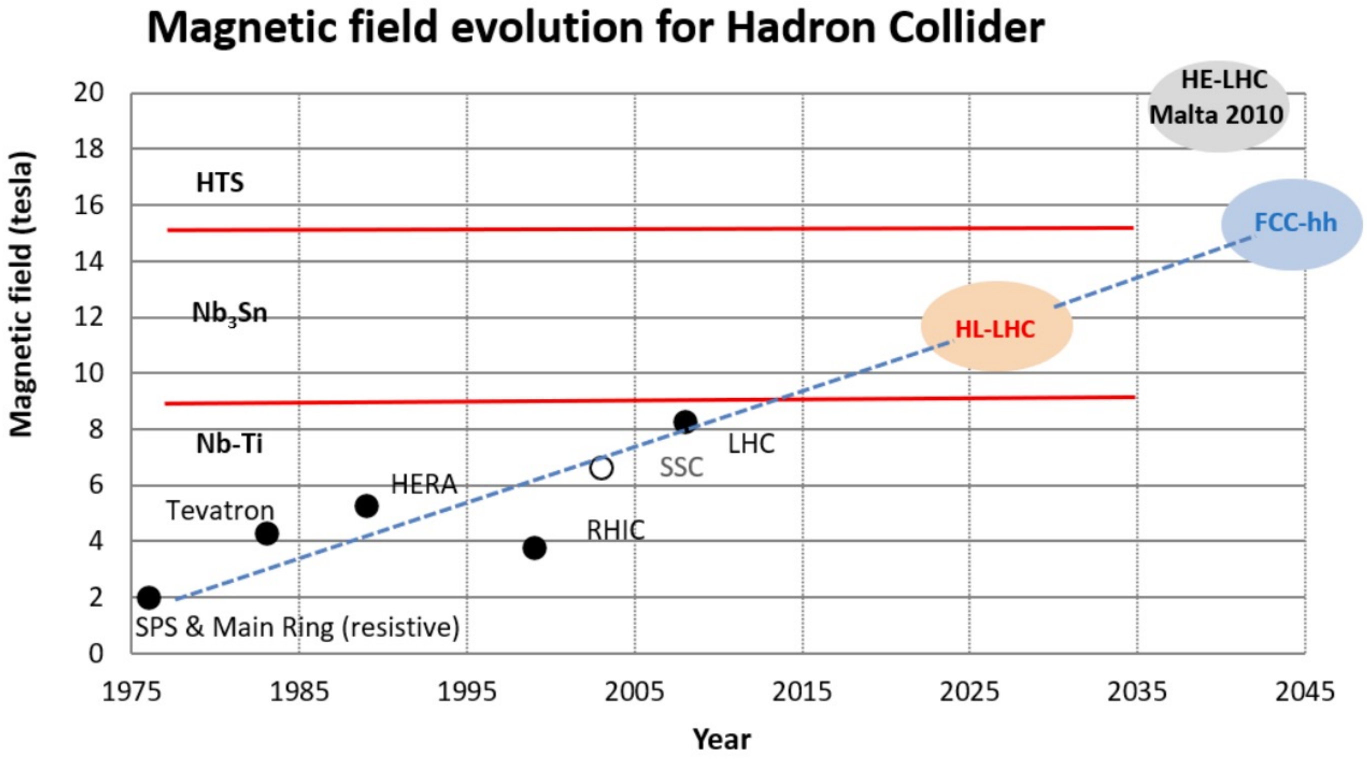
Which technologies for the next pp collider ?
- if we ask for ~50 TeV/beam in ~100 km, field must be **~16 T** or more
- → not reachable with NbTi, switch to $Nb_3Sn$ (brittle, difficult to manage)
  - but largely used for ITER, 700 t of cable (note: LHC strand was 1200 t)
  - 16 T is at the limit
- → other possibility, HTS alloys (REBCO, Bi-2212) with high Jc
  - still a "niche" market (expensive) but with fast expansion
  - interest by fusion programs (e.g. Commonwealth Fusion Systems)
  - smaller cryo-consumption (4-20 K), better stability
    - HTS @20 K ~ 1/10 cryo power needed
  - difficult to handle (cables are flat, not round)
  - theoretically can reach 20 T+



Strong R&D in the field by all world Labs

# Future for 20 T + (accelerator) magnets




L. Rossi, C. Senatore, https://doi.org/10.3390/ instruments5010008

- Mechanical stress limitation of superconductors
- Coils structural materials constrains
- Material tailored magnet designs

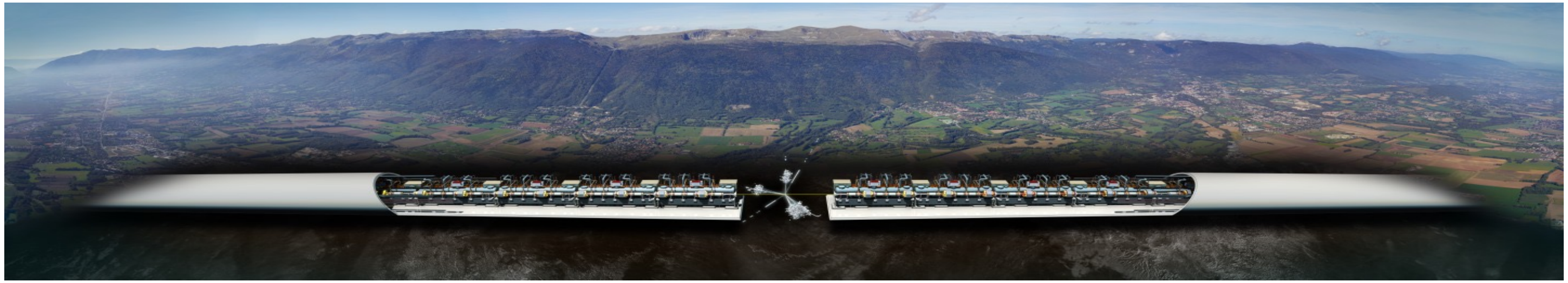
# Present status of HEP accelerators projects

Up to ~2040s, HL-LHC for an ultimate exploration of SM at c.m. parton energies ~ 4.5 TeV

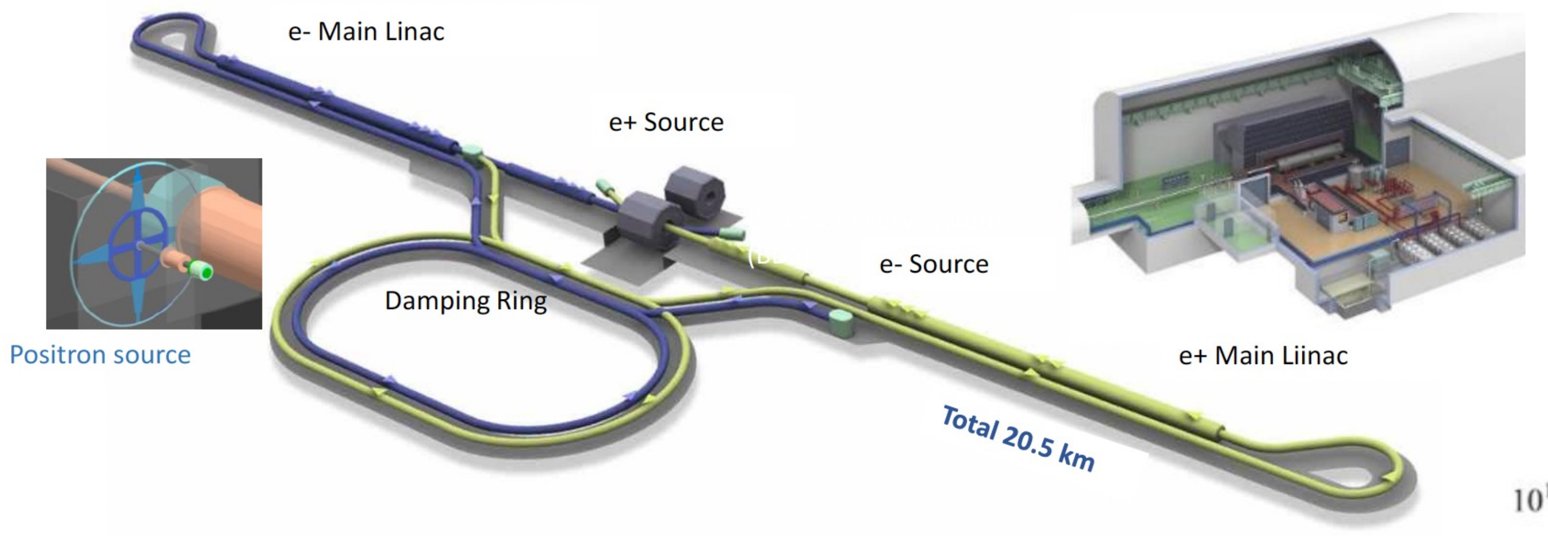
- e+e- Linear Colliders (phase 1): ILC & CLIC at E between ZZ and ttbar (200-350 GeV)
- e+e- Circular Colliders (FCC & CEPC) at E between ZZ and ttbar (200-350 GeV)

And at later times (technologically more challenging)

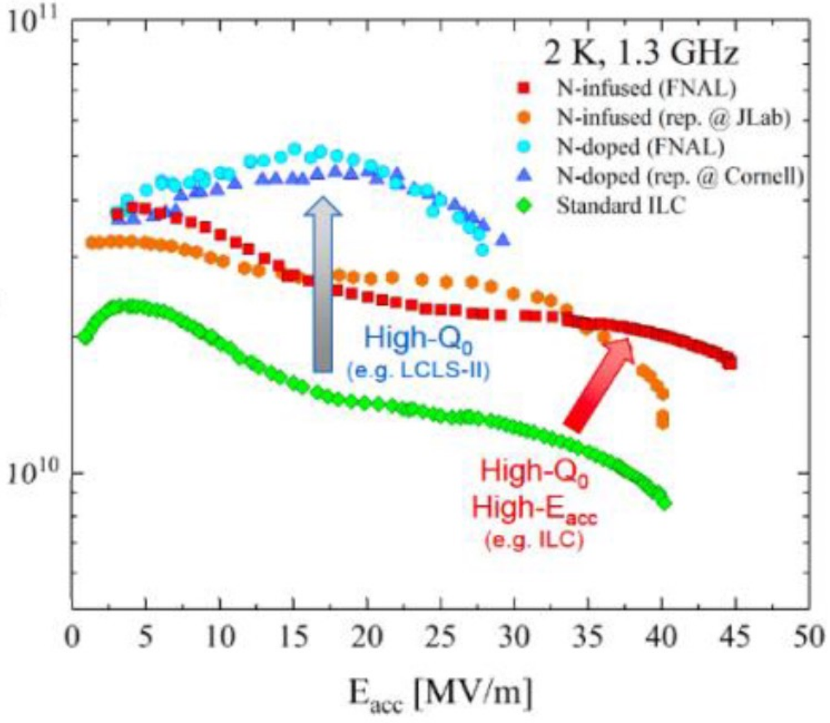
- hh Colliders (FCC & SPPC) at c.m. parton energies ~ 30 TeV
- e+e- LCs (phase 2) at 0.5-1.0 TEV (ILC), 1.5-3 TeV (CLIC) or plasma-based (HALHF)
- muon collider at c.m. energies 3-10 TeV



# 250GeV ILC – Japan



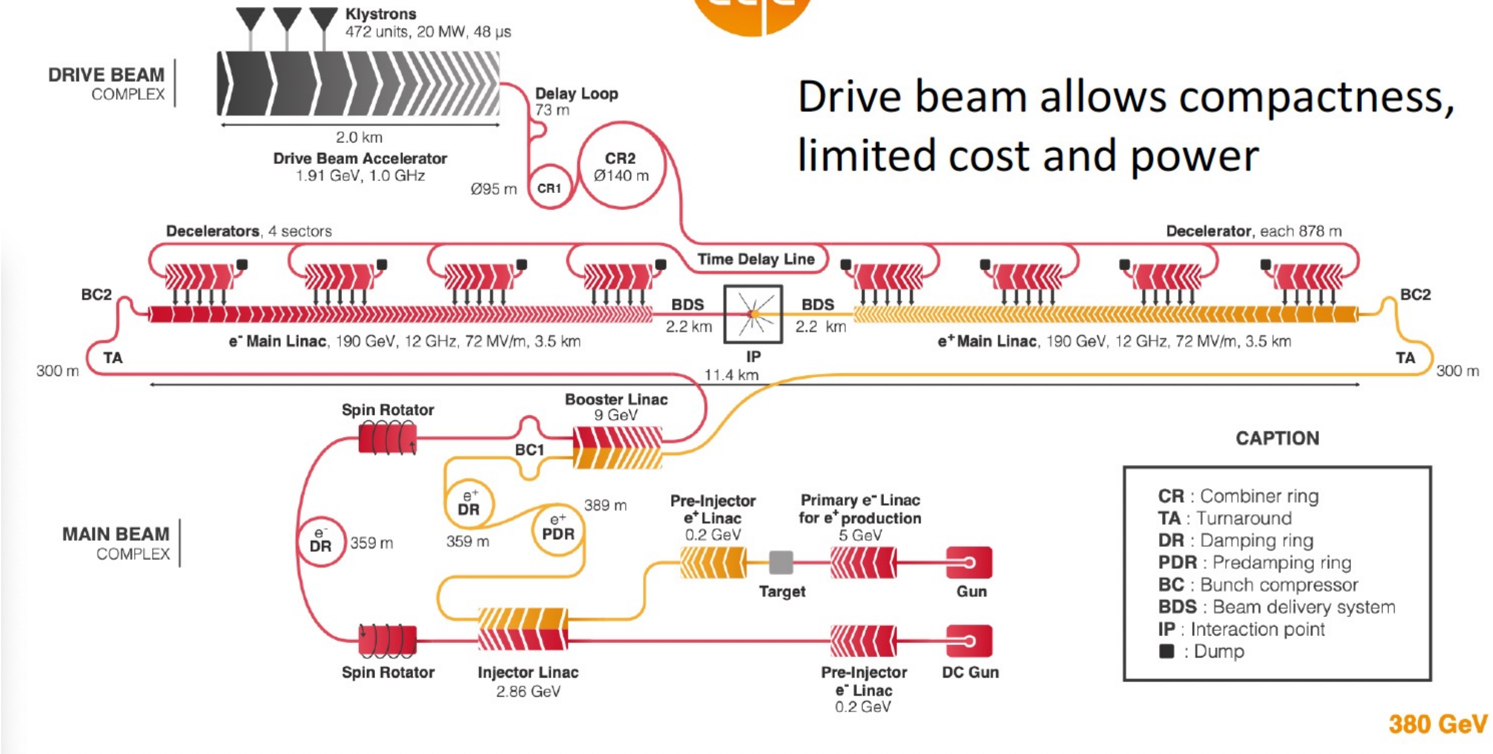

Recent developments on SRF gradient & Q factor (FNAL): more acceleration, more efficient



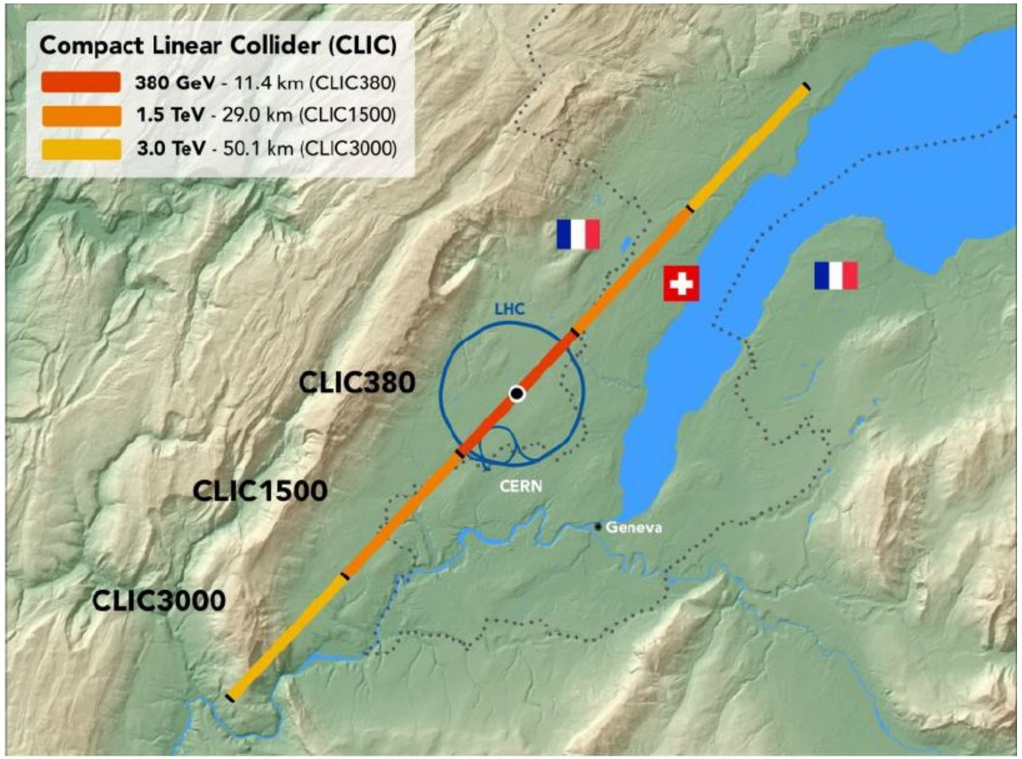

Superconducting RF technology: ~ 30 MV/m, 5 Hz
Baseline configuration: 250 GeV c.m. energy, L=20.5 km, P=110 MW, cost ~ 5 B$
Upgrade to 0.5 – 1.0 TeV

Possible location in Japan - TDR in 2013
Since then, long political negotiation (still on hold)

# CLIC




Drive beam allows compactness, limited cost and power




X-band normal conducting RF technology (12 GHz): ~ 70 MV/m, 50 Hz
Baseline configuration: 380 GeV c.m. energy, L=11.4 km, P=170 MW, cost ~ 6 BSF
Upgrade to 1.5 – 3 TeV

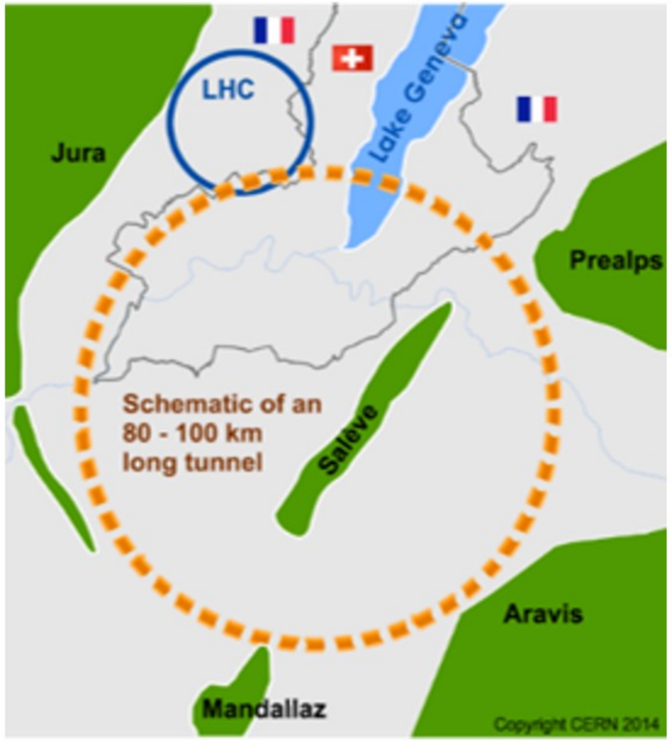
Possible location at CERN - TDR in 2018 – Project currently on hold

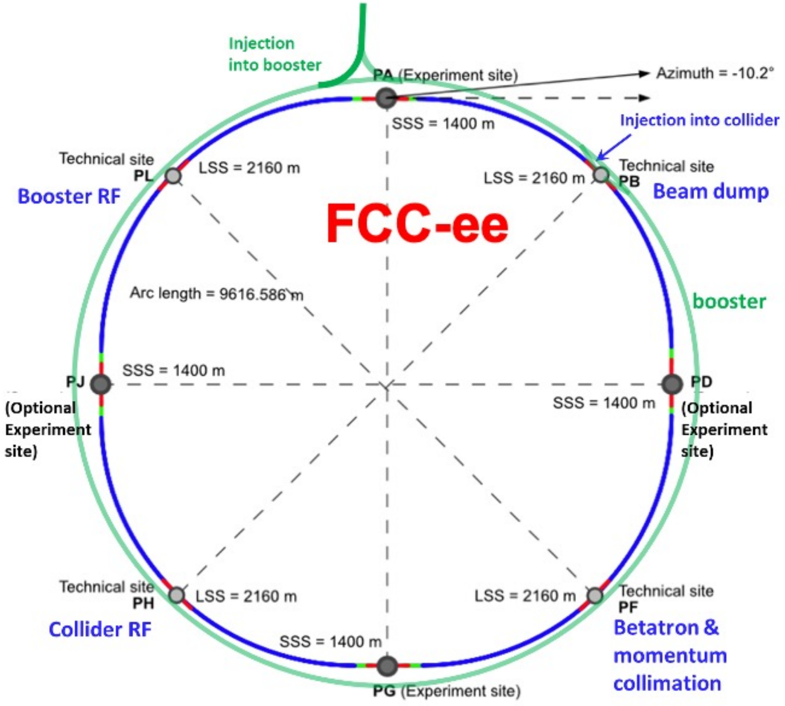
FUTURE CIRCULAR COLLIDER

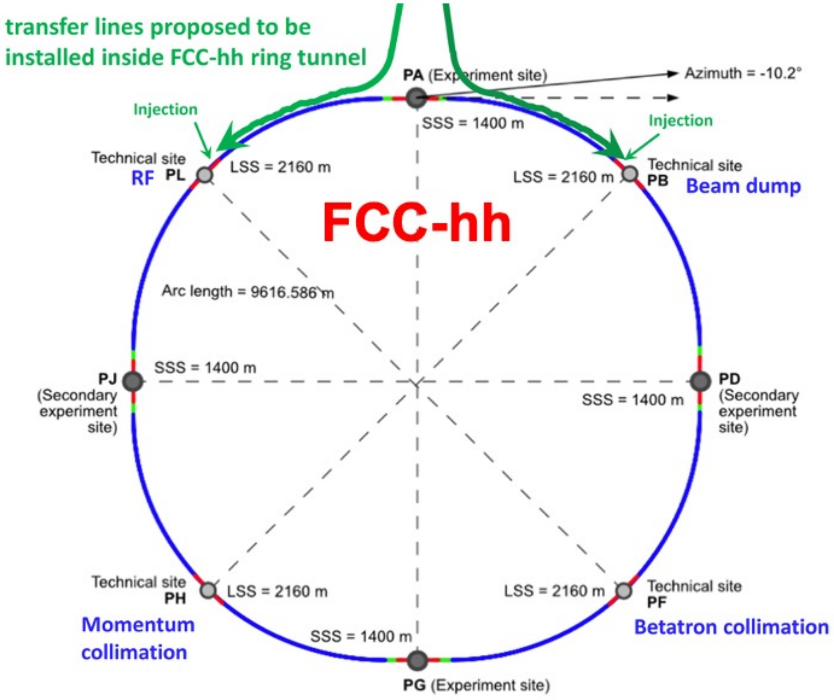
# FCC integrated program

## Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



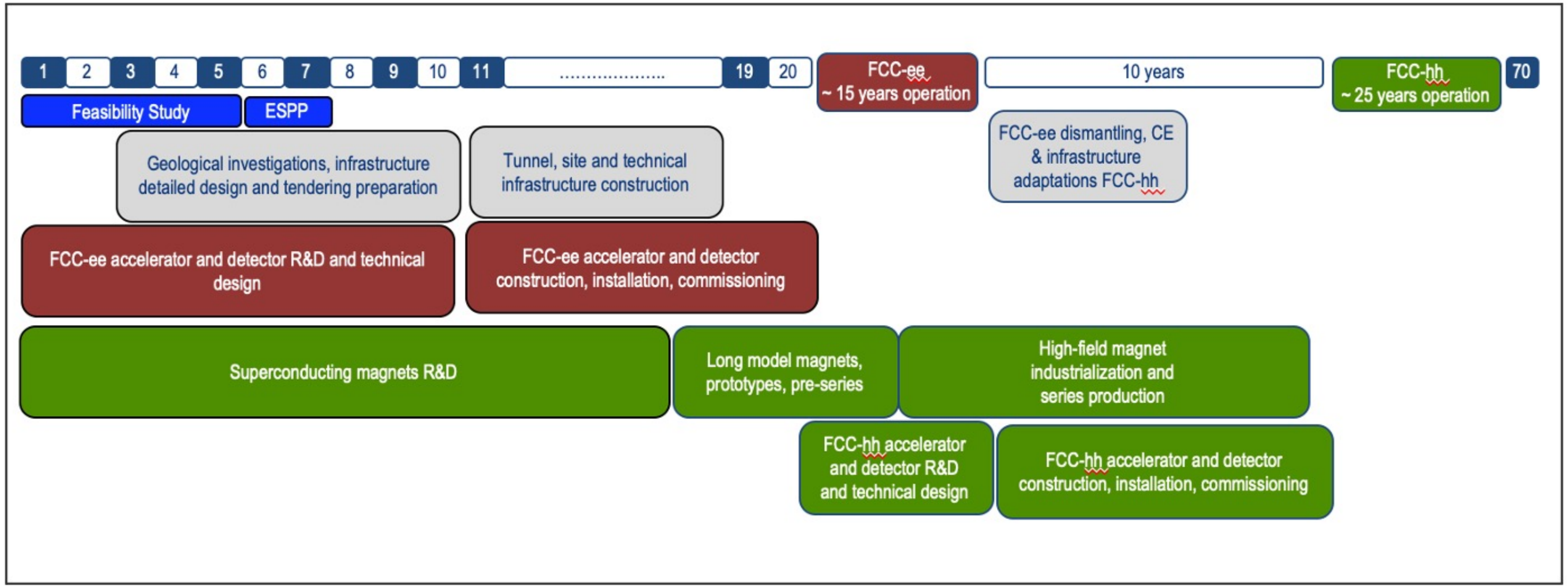






L=90 km, L=7 $10^{34}$ $cm^{-2}s^{-1}$ (@250 GeV) P~300 MW

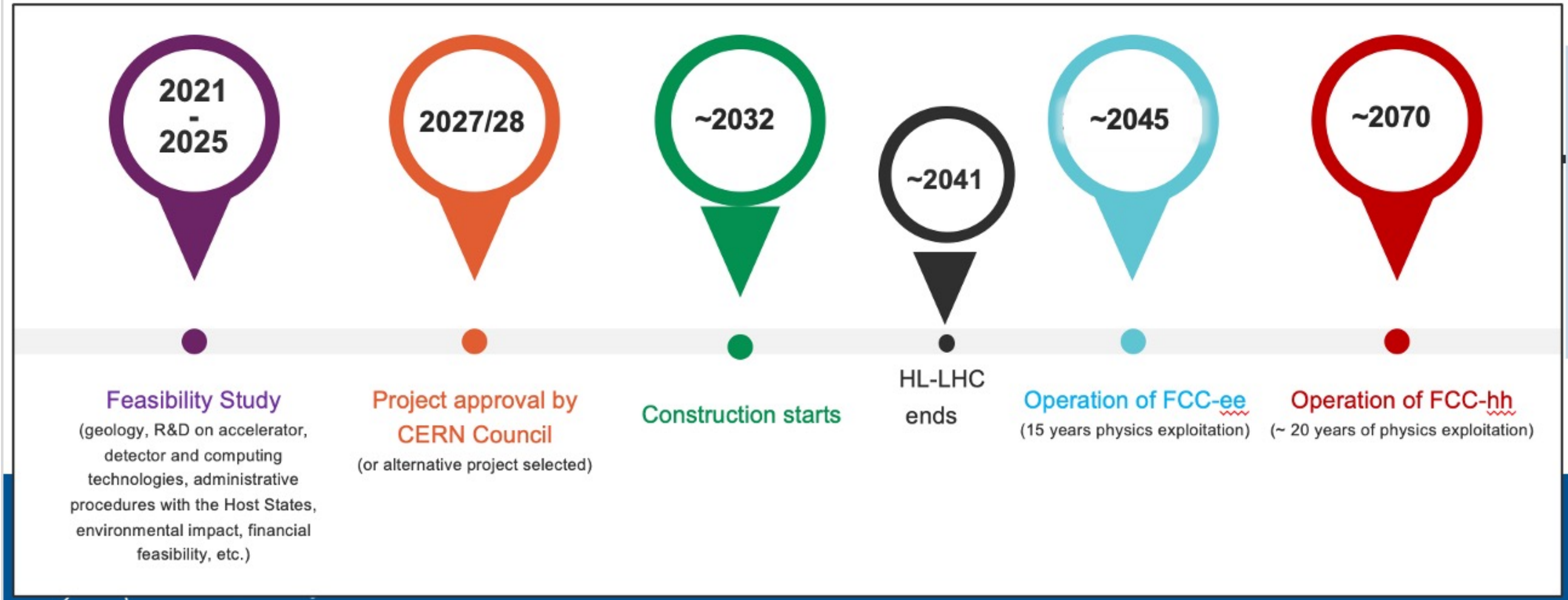
# FCC integrated program - timeline

FUTURE CIRCULAR COLLIDER




Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

Costs:
- FCC-ee 12.1 BSF
- FCC-hh +17 BSF (tentative, large uncertainty on dipole technology)

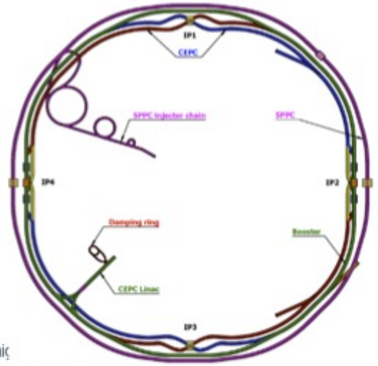


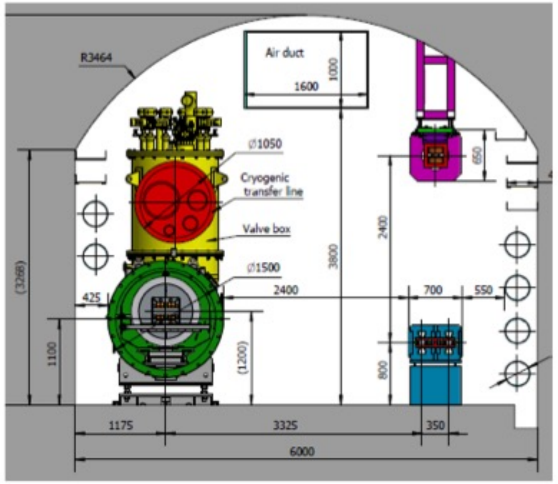

**Ambitious schedule** taking into account:
- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- **project preparatory phase with adequate resources immediately after Feasibility Study**

# CEPC Layout and Design Essentials

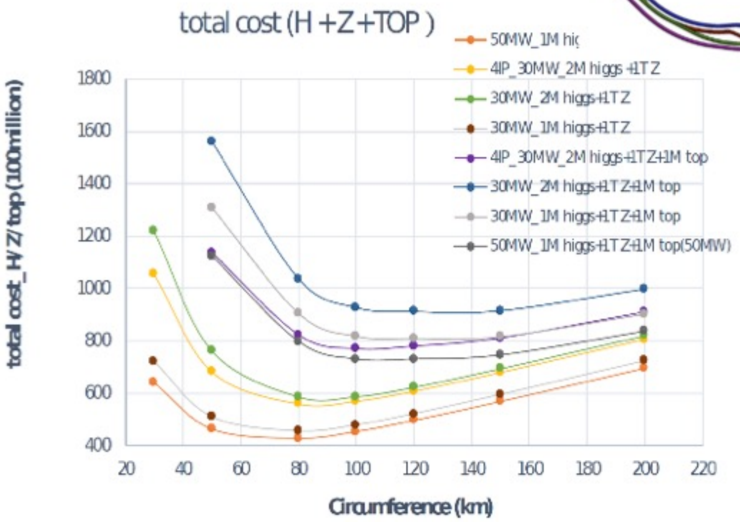
**Main Design considerations:**

- **100km circumference: Optimum total cost**
- **Shared tunnel: Compatible design for CEPC and SppC**
- **Switchable operation: Higgs, W/Z, top**






**Common tunnel for booster/collider & SppC**




**Cost optimization v.s. circumference**

D. Wang *et al* 2022 *JINST* **17** P10018

**Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar**

3

TDR prepared in 2023

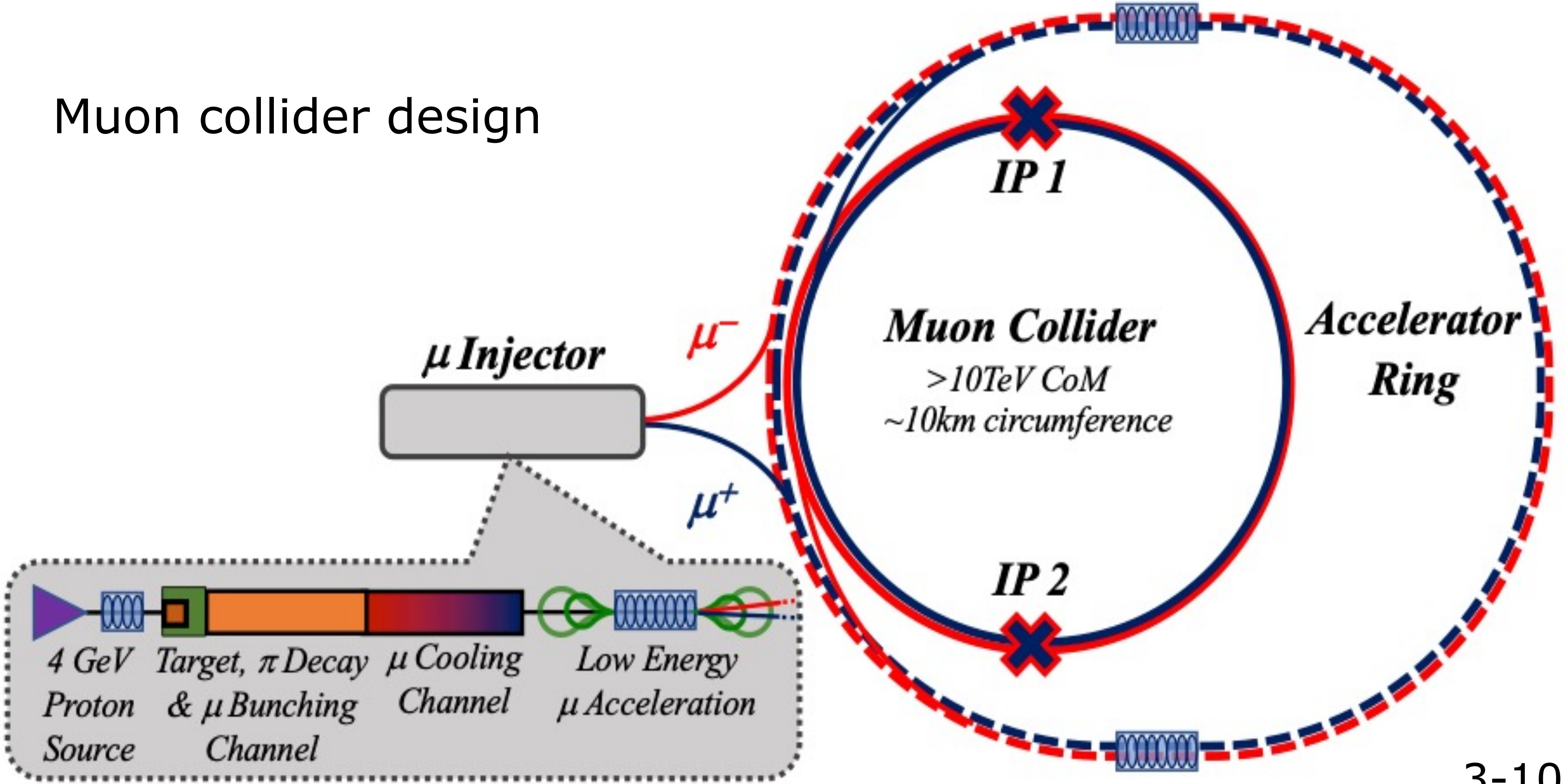
Submitted to Chinese Government for approval

Decision end of 2025 (quinquennial plan)
Start civil works 2027-8
First beams in 2036

L=8 $10^{34}$ $cm^{-2}s^{-1}$ (@250 GeV)

Cost ~ 5 BE

Muon collider design




International MUON Collider Collaboration

New strong interest in **high-energy, high-luminosity lepton collider**

- Combines **precision physics** and **discovery reach**
- Application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use

3-10 TeV program
Challenges:
- Dense neutrino flux (above tolerable limits for populated areas) to be mitigated
- Cooling channel (RFs in intense magnetic fields)
- Huge background at interaction region

# **HALHF**: A Hybrid, Asymmetric, Linear Higgs Factory

- Electrons (from PWFA): $E_e$ = 500 GeV
- Positrons (from RF accelerator): $E_p$ = 31 GeV

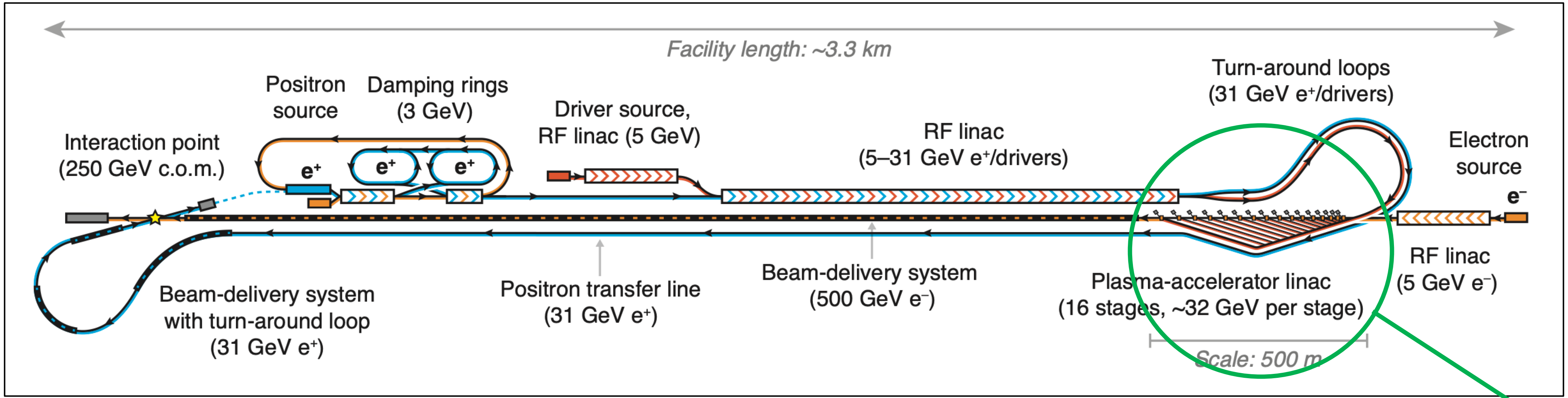
Overall footprint: ~3.3 km

- Length dominated by $e^-$ beam-delivery system
- Fits in most major particle-physics laboratories

**$\sqrt{s} \approx 250$ GeV**

Minimum for Higgs factory

e+ used (also) as driver for e- acceleration in plasma




Main challenges

- **Plasma-cell cooling** (*heat management will be challenging*)
- **Transverse instabilities** (*too large of an emittance growth*)
- **Beam ionisation** (*the beam density and hence peak E-field is too high*)
- **High-voltage and high-power linac** (*technically challenging*)

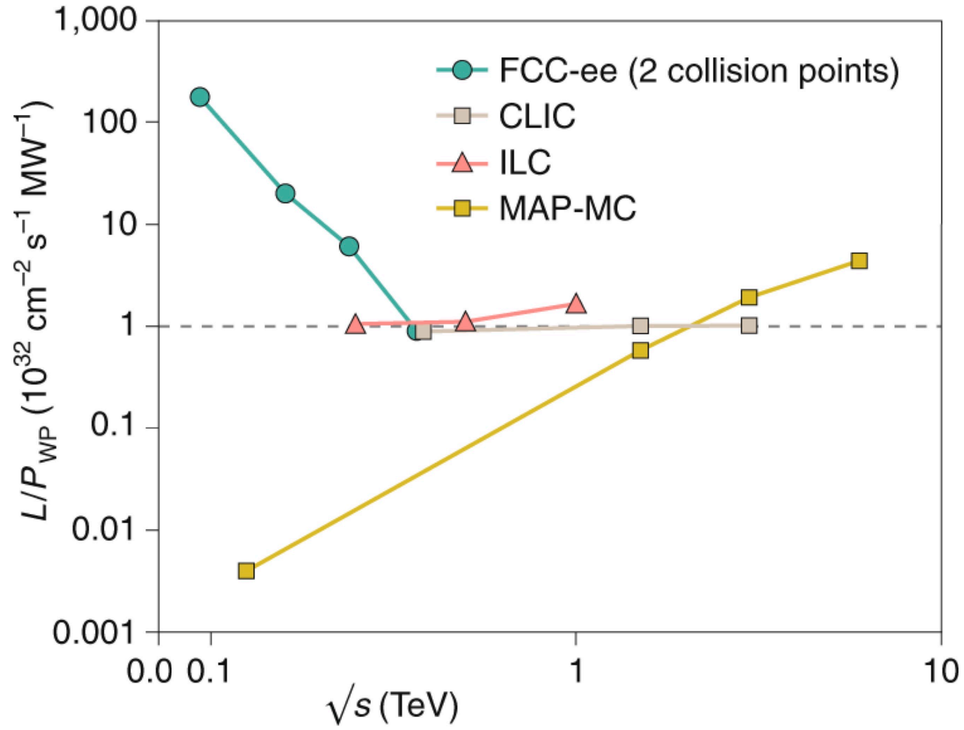
To be studied in detail at **EuPRAXIA** (M. Ferrario's talk)

# HEP colliders footprint and sustainability ("lifecycle analysis")

- All new projects and efforts needs to be analyzed in terms of total lifecycle energy consumption and CO2 emissions (carbon footprint). This is especially important for energy production projects!
- All future high energy collider proposals also need to be analyzed for total lifecycle energy consumption and CO2 emissions. Such analyses should play an important role in selecting the next high energy collider project.
- Some collider proposals (FCC, ILC, CLIC, CCC) have already prepared such lifecycle analyses. They cover or should cover construction of infrastructure, accelerators, and detectors, operation and appropriate decommissioning. (Recent report: M. Breidenbach et al., PRX Energy 2, 047001)

ILC/CLIC (@250 GeV) ~ 110-150 MW power
FCC-ee/CEPC ~ 300 MW
LHC reference: 120 MW
Possible mitigation with ERL techniques (R&D)

- More efficient power converters to DC and RF (incremental)
- More efficient refrigerators (limited by Carnot)
- Recovery of process heat using heat pump technology
- Energy efficient components (Superconducting technology, permanent magnets, HTS, …)
- Compact accelerators with high accelerating gradient (Wakefield Accelerators, …)
- Energy efficient accelerator concepts (Storage rings, Energy Recovery Accelerators, …)




T. Roser, ICFA Seminar 2023

# Governance/Social aspects of large projects

Dimensions of Research Infrastructures often go above national funding & know-how capacities

CERN (funded in 1954) is an IGO (Int. Gov. Org.), thet represents a well known benchmark. European-based governance, although LHC construction has been international, profiting of funds also from non member states (US, JPN, RUS, IND, etc…)

Depending on the chosen governance, projects can be Global, International, National with various levels of international collaboration and funding contributions.

Large time span (several decades) and dimension of projects are a deterrent for new generations, increasing the scarcity of brilliant minds in HEP at Universities and Research Institutions: mechanism already visible now

# World regions HEP strategies


Most notably DOE-NSF P5 and CERN ESPP strategy
P5 (just completed)

Highest priority was given by P5 to ongoing projects and their maximal science exploitation, such as HL-LHC, DUNE and PIP-II first phase, and the Rubin Observatory. In parallel, the community is encouraged to prepare a list of major projects to study fundamental matter and the universe, comprising CMB-S4, which looks back at the history of the universe, a second phase of DUNE, an offshore Higgs factory in collaboration with international partners, an ultimate experiment for dark matter direct detection, and the IceCube-Gen2 detector. The proposed portfolio includes an intense effort to implement theoretical, computational and technological resources vital to the achievement of the vision.

P5 strongly supports accelerator R&D to chart a path towards a 10 TeV parton centre-of-mass collider based on pp, muon, or potentially wakefield technologies. It also recommends to develop a plan that, under favourable funding conditions, could lead to the construction of a major HEP facility in the US, potentially in the form of a 10 TeV muon collider, to be hosted on the Fermilab premises.

CERN ESPP strategy by 2025, just starting. Collection of inputs from community.
Strategy process during 2025, focused on FCC-ee feasibility study.
Planning to decide on future activities/new projects at CERN

# Conclusions

HEP community is preparing since long time the next step for global/international Colliders program to become active when HL-LHC experimentation will end

Mostly oriented on Higgs boson couplings studies (+ Z & ttbar factories) first, and later, new high mass direct searches with hh colliders. More recently, new ambitious programs at the horizon (muon collider, linear plasma-based collider)

e+e- “feasible” (except for costs and civil engineering): no tec show stoppers
hh / $\mu\mu$ / HE plasma more challenging (e.g. HFM, b. cooling, etc…)

Construction and operation footprints and energy consumptions are of concern: a lot of activity in the field is ongoing

Project dimensions and timing pose severe questions on funding, governance and possible lack of appeal from youngest generations, **but …**


"To explain all nature is too difficult a task for any one man or even for any one age. Tis much better to do a little with certainty and leave the rest for others that come after than to explain all things by conjecture without making sure of any thing."

**Isaac Newton**