

# Circular Colliders

## *Present and Future*

Jon Butterworth

University College London

*WIN 2025*

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Leaning heavily on [European Strategy Inputs](#), including the *Future Colliders Comparative Evaluation - Working Group Report*

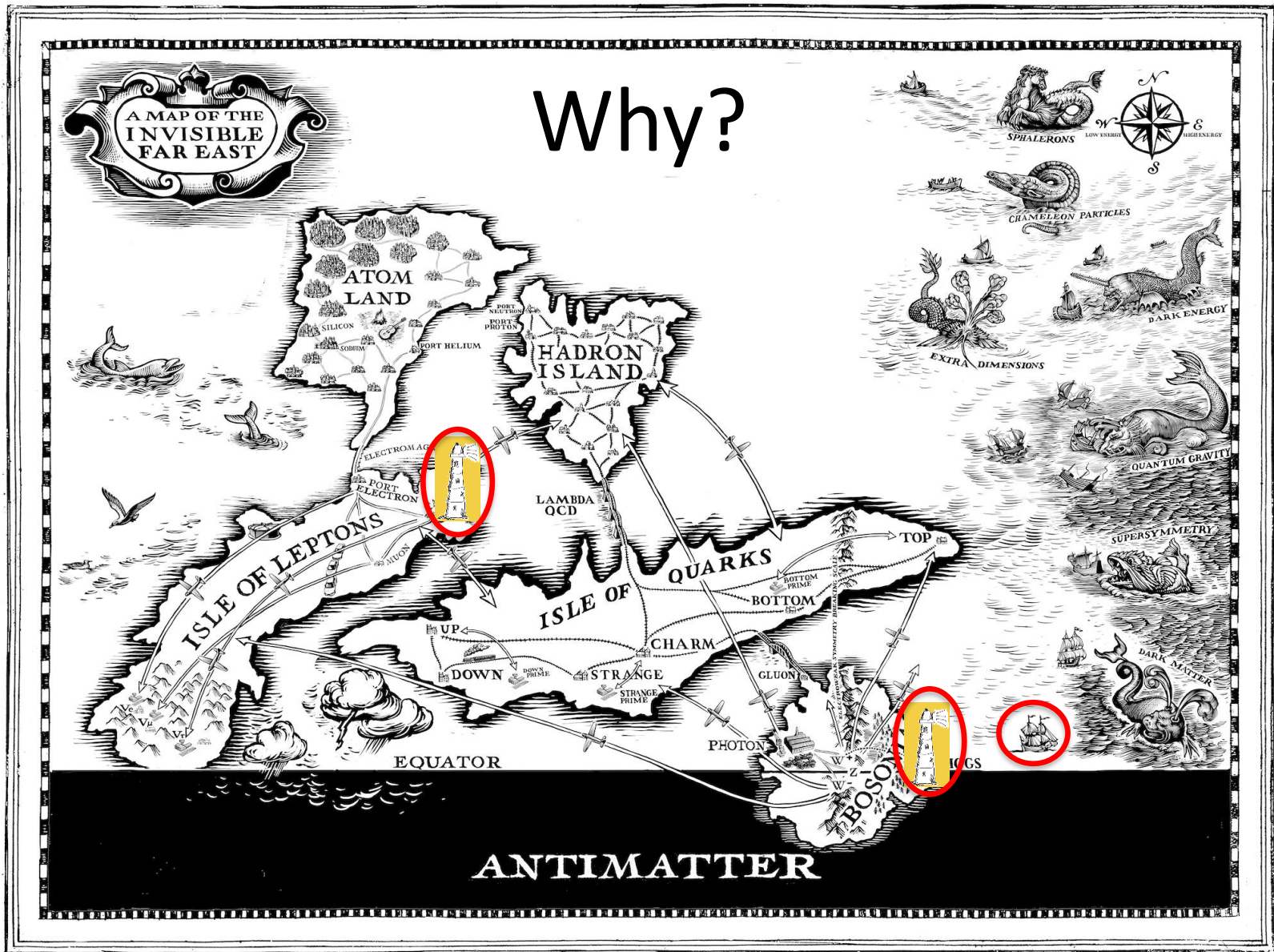
Necessarily “high level” (ie misses out a lot!).  
Will focus on physics capability and timescales.

# Outline

- This tunnel
  - Hadrons
  - Electrons
- New tunnels
  - Electrons
  - Hadrons
  - Muons



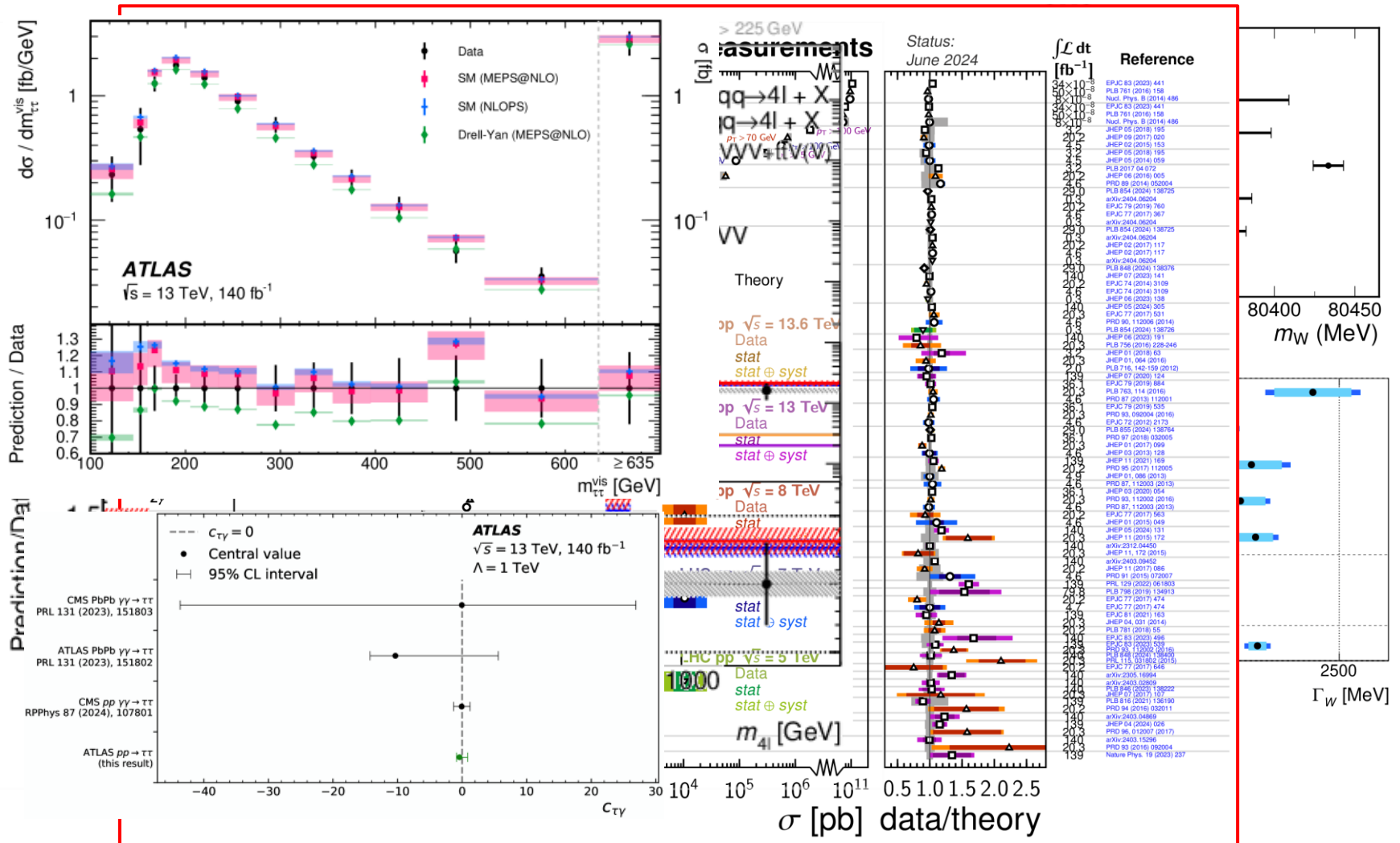
*Electroweak scale and above...*



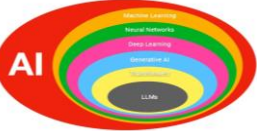
# Conventional Wisdom

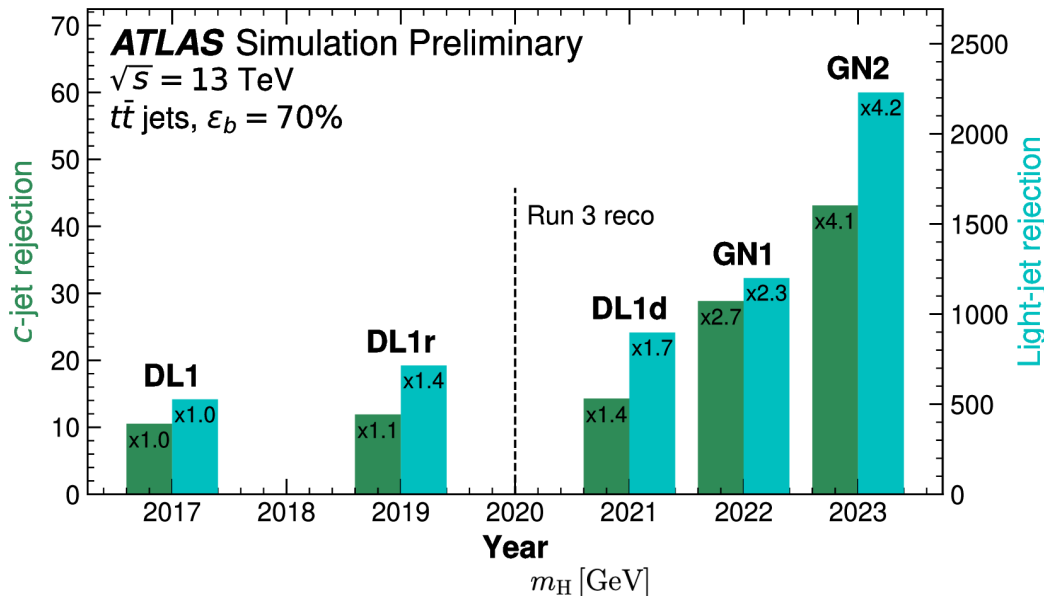
- Hadrons for exploration
- Leptons for precision
- Lepton-hadron for QCD
  
- $e^+e^-$  Higgs factory next (*c.f. ESPP 2020*)
- Hadrons in half a century or so
- ep ... not high priority
- Muons one day. Maybe.
  
- Circular colliders will reach the point of diminishing returns (synchrotron radiation, magnetic field strength)

# LHC: A precision Machine

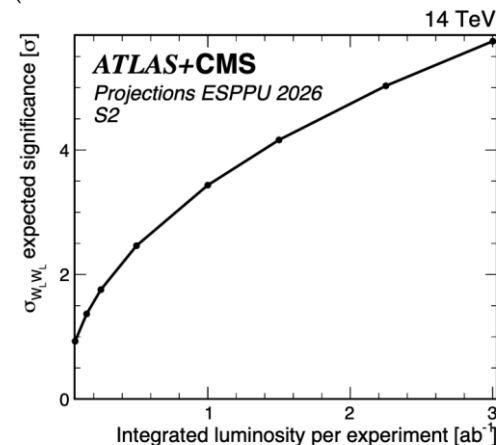
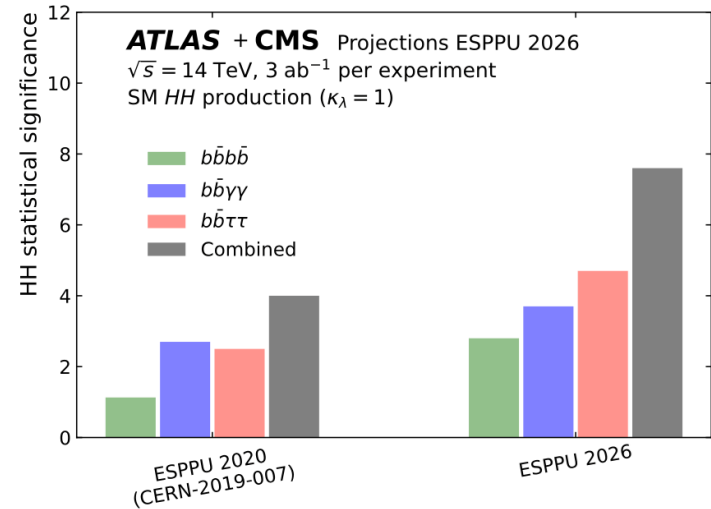


# HL-LHC: A precision machine

- Big - largely  improvements in performance
- 4-top cross section @ 6%
- CharmYukawa @ 1.5 x SM

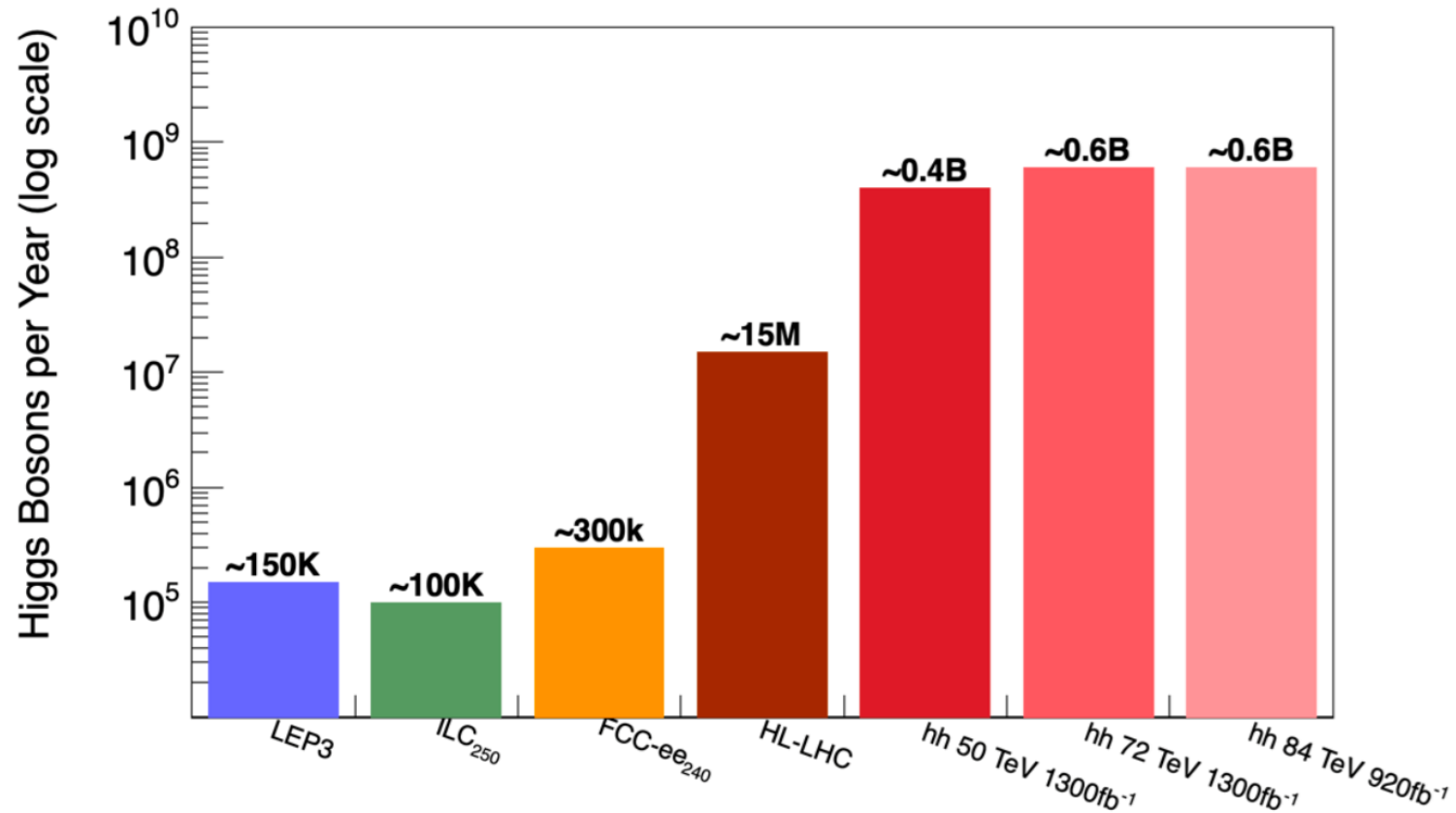


ATLAS & CMS, arXiv:2504.00672



# Higgs “Factories”?

Annual Higgs Boson Production by Collider



# LEP3

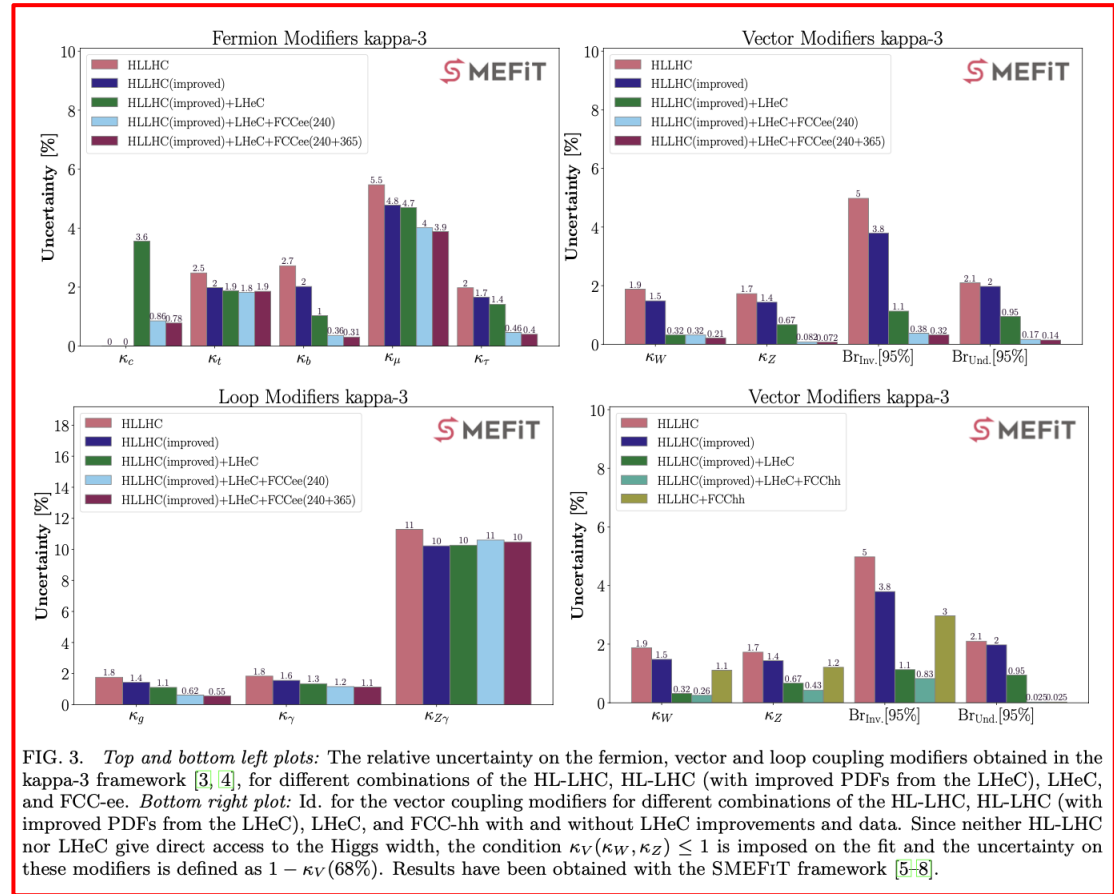
- New  $e^+e^-$  collider in the LEP/LHC tunnel
- CM energy range 91.2 – 230 GeV
  - Not possible to interleave low and high energy
- Two interaction points
- 2045 earliest start of operation
- Synchrotron power loss 50MW per beam
  - Consumption similar to FCC-ee
- Detailed accelerator design work required
- Current cost estimate 3.9BCHF
- Estimated precision mostly taken from FCC-ee (see next slides),
  - Scaling statistical uncertainty up by 1.9.
  - No top-antitop threshold running

# LHeC

- Electrons vs LHC protons
  - ERL 1/3 circumference of LHC tunnel
- Likely post-LHC running.
- Current cost estimate 2.4BCHF

*“... LEP3 or LHeC, would entail major infrastructure investments and operating costs and therefore delay the implementation of a next-generation collider by at least one to two decades. For this reason, they cannot be considered as “bridges”, but rather as alternative options to other proposed colliders”*

From FCCE Working Group Report



# HE-LHC

In currently proposed form, energy max 34 TeV, only achievable in the 2070s.

Current cost estimate 7.2 BCHF (excluding experiments)

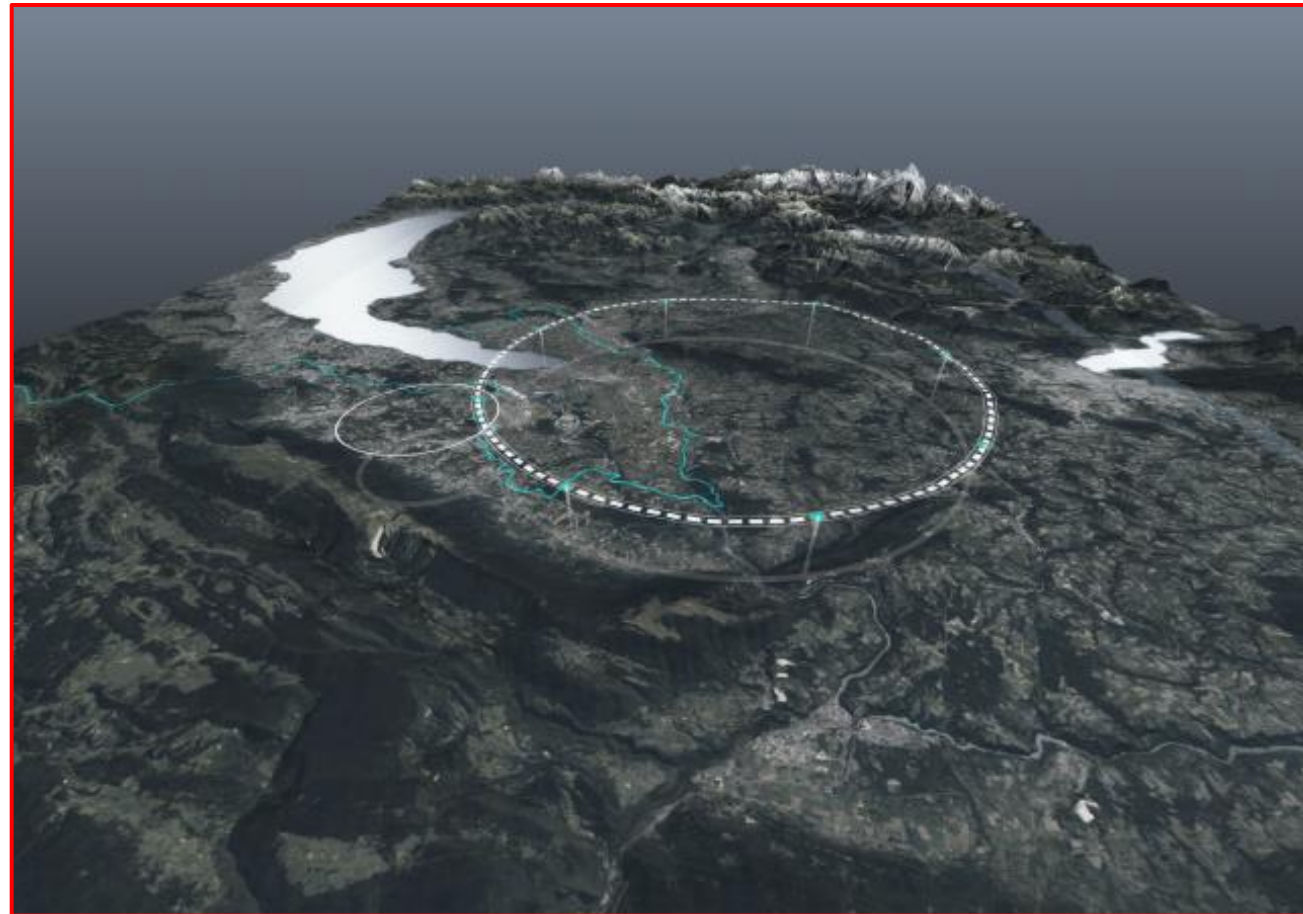
(24 TeV earlier?)

*“based on the current physics landscape emerging from the LHC and other results, the HE-LHC offers a very limited physics reach.”*

From FCCE Working Group Report

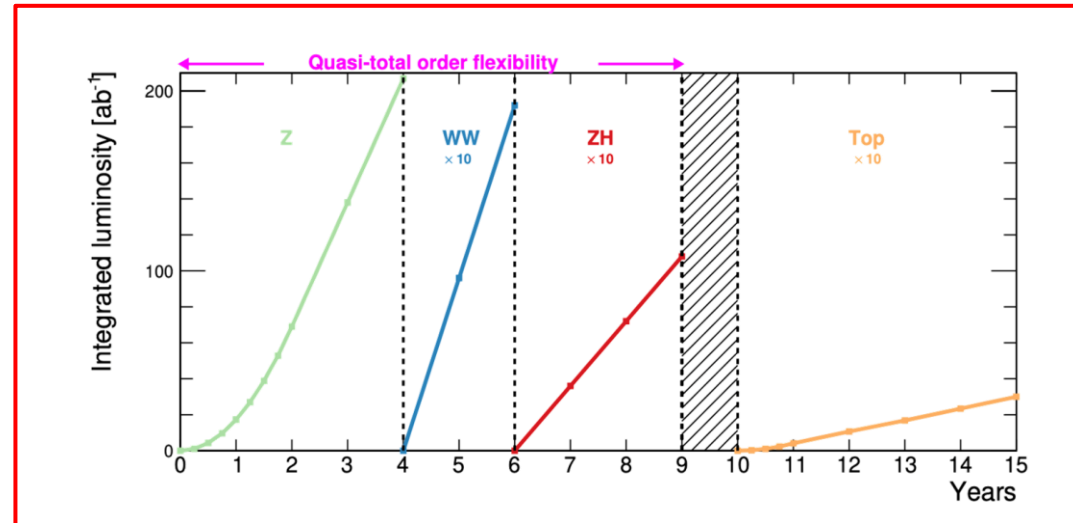
# A new tunnel

- FCC feasibility study
- 91km circumference
- Very significant civil engineering, geology, legal, safety, sustainability, societal preparation and studies undertaken already



# Electrons and positrons

- FCC-ee
  - Z-pole running 2048
  - then WW, Higgs, top
  - Four interaction points
  - Current cost estimate 15.3BCHF (inc 6BMCH tunnel)
- CEPC
  - Similar science case
  - Related technologies
  - (Different politics)





# Next-generation Hadron Collider

- The “ambition” Europe should have
  - *cf ESPP 2020.*
- Current FCC-hh baseline 85 TeV in 2074.
- Current cost estimate 19BCHF (post FCC-ee)
- Or 2055 if skip FCC-ee.
- Intermediate energy 50-70 TeV? Sooner?
- Relevant “detail”: Forward neutrino flux

Kappa [%]	2025 HL-LHC	2019 HL-LHC+FCC-ee	2019 HL-LHC+FCC-hh
$\kappa_W$	1.6	0.38	0.39
$\kappa_Z$	1.6	0.14	0.63
$\kappa_g$	2.4	0.88	0.74
$\kappa_\gamma$	1.8	1.2	0.56
$\kappa_{Z\gamma}$	6.8	10.	0.89
$\kappa_c$	–	1.3	–
$\kappa_t$	3.4	3.1	0.99
$\kappa_b$	3.6	0.59	0.99
$\kappa_\mu$	3.0	3.9	0.68
$\kappa_\tau$	1.9	0.61	0.9

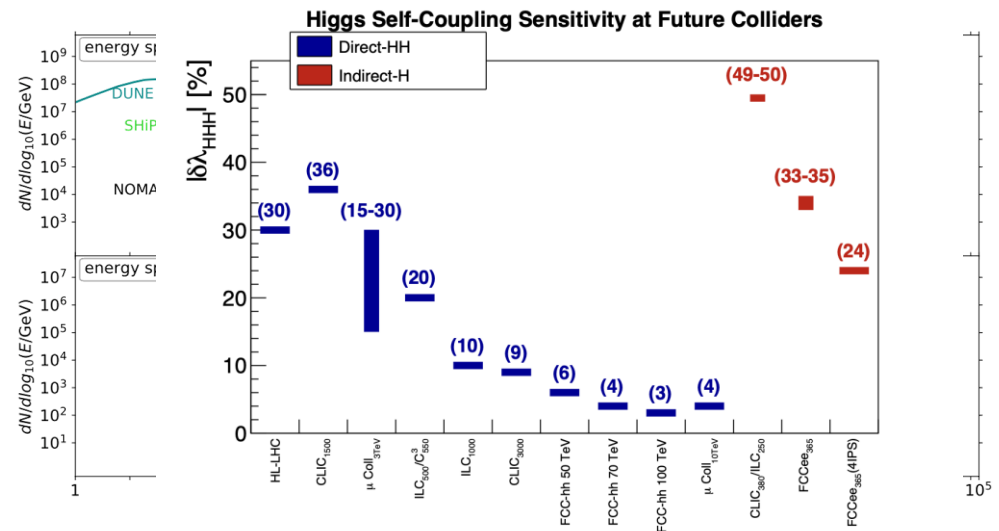


Fig. 45: The mu

# Muon collider

- Smaller tunnel etc ✓
- Neutrino background ×
- 125 GeV, 3 TeV, 10 TeV CoM energy studied at some level.
  - Main focus still on accelerator feasibility (see DS talk yesterday)
  - Energy spread a challenge for Higgs pole running
  - Staging/reuse of cooling and injection for energy upgrades
  - Current cost estimate 10-25BCHF
- At 10 TeV, electroweak bosons are “partons” inside the beam particle (e,  $\mu$  or p)
  - though the “remnant” will be very different!

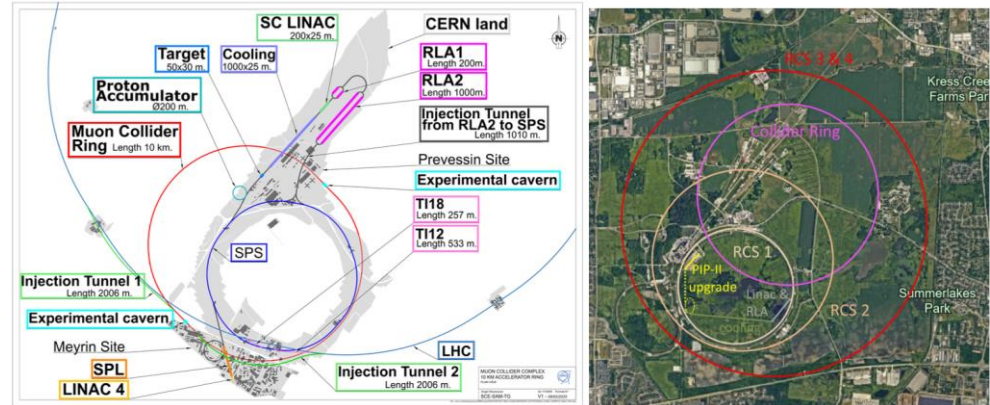
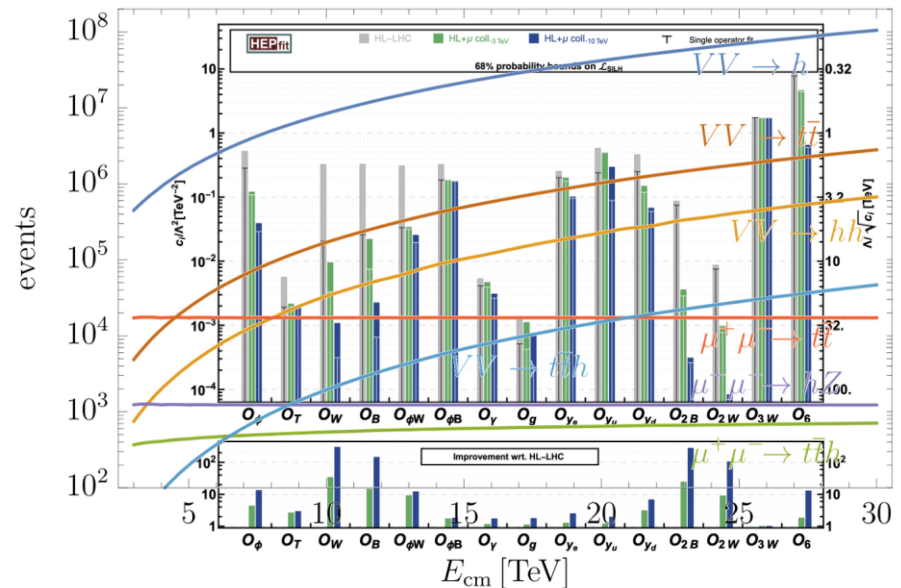


Fig. 6.a: Conceptual layout of the muon collider at CERN (left) and Fermilab (right).



# Conventional Wisdom

A black and white photograph of a man in a suit, looking slightly to the side with a thoughtful expression. The image has a halftone or dithered texture.

**BUT IT IS NOT THIS DAY.**

- Circular colliders will reach the point of diminishing returns (synchrotron radiation, magnetic field strength)  
**Well, that day may come...**