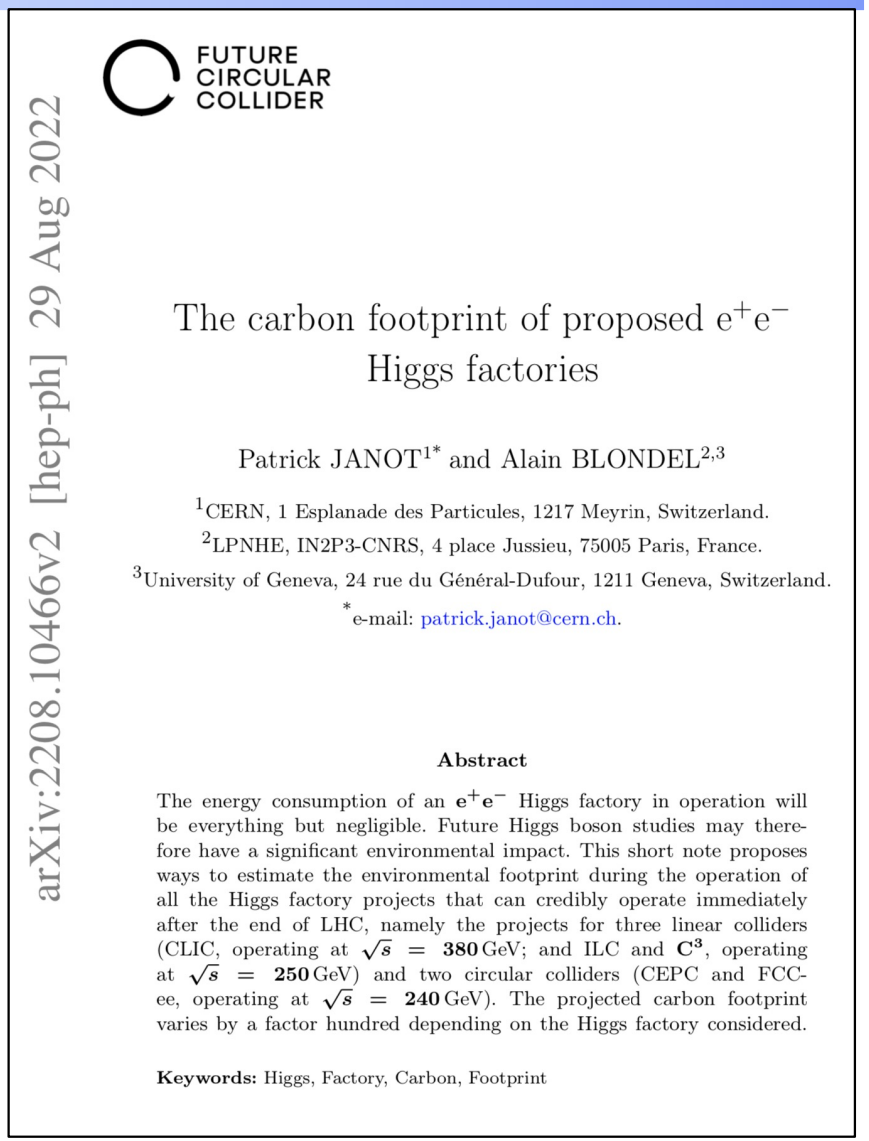
The carbon footprint of proposed e^+e^- Higgs factories

- **Presentation based on arXiv:2208.10466**
  - In the context of the FCC Feasibility Study
    - Contributed White Paper to Snowmass'21
- **Motivations**
  - We entered times of measurable climate change
    - Yielding a global warming of unprecedented rapidity
  - As a community, we must take stock of this situation
    - And show that environmental concerns are essential
      - ➔ E.g., in the choice of the next collider after LHC
  - As physicists, our most important criterion is at least to

Maximise the physics outcome for a given carbon footprint

(or to minimize the carbon footprint for a given physics outcome)



FUTURE CIRCULAR COLLIDER

The carbon footprint of proposed e^+e^- Higgs factories

Patrick JANOT[1*] and Alain BLONDEL[2,3]

[1]CERN, 1 Esplanade des Particules, 1217 Meyrin, Switzerland.
[2]LPNHE, IN2P3-CNRS, 4 place Jussieu, 75005 Paris, France.
[3]University of Geneva, 24 rue du Général-Dufour, 1211 Geneva, Switzerland.
[*]e-mail: patrick.janot@cern.ch.

Abstract

The energy consumption of an e^+e^- Higgs factory in operation will be everything but negligible. Future Higgs boson studies may therefore have a significant environmental impact. This short note proposes ways to estimate the environmental footprint during the operation of all the Higgs factory projects that can credibly operate immediately after the end of LHC, namely the projects for three linear colliders (CLIC, operating at $\sqrt{s} = 380$ GeV; and ILC and C^3, operating at $\sqrt{s} = 250$ GeV) and two circular colliders (CEPC and FCC-ee, operating at $\sqrt{s} = 240$ GeV). The projected carbon footprint varies by a factor hundred depending on the Higgs factory considered.

Keywords: Higgs, Factory, Carbon, Footprint

HEP strategy after ESU 2020 and Snowmass'21

- **European Strategy Update (January 2020)**
  - The highest priority next collider is an e^+e^- Higgs factory
    - Followed by a hadron collider with the highest achievable centre-of-mass energy
  - Vision endorsed by CERN Council in June 2020
    - FCC technical and financial Feasibility Study approved and funded in June 2021
      - ➔ With focus on the first step, i.e., the tunnel and the FCC-ee (which includes an e^+e^- Higgs factory)

- **Energy Frontier vision at the Snowmass'21 final community meeting (July 2022)**
  - Immediate future: HL-LHC
  - Intermediate future: an e^+e^- Higgs factory, based on
    - Either a linear collider (ILC in Japan, C^3 in the US, CLIC at CERN)
    - Or a circular collider (CEPC in China, FCC-ee at CERN)
  - Long-term future: a multi-TeV ($\mu\mu$ and/or pp) collider

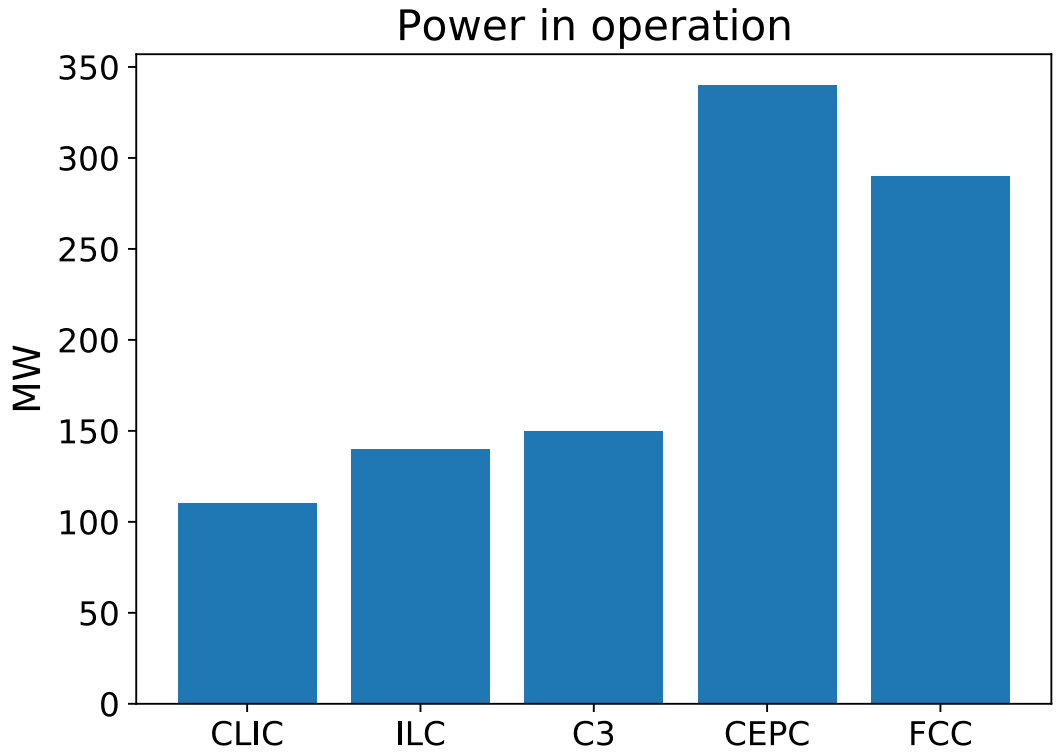
"Similar physics outcome"
(according to ESU'20 and Snowmass'21)

- **What is the carbon footprint of these Higgs factories for the same physics outcome?**

What you are usually shown

- **The power consumption of each collider (in MW) while in operation**
  - **Higgs factories displayed in the plot (as suggested by Snowmass'21)**
    - CLIC @ √s = 380 GeV
    - ILC @ √s = 250 GeV
    - C³ @ √s = 250 GeV
    - CEPC @ √s = 240 GeV
    - FCC-ee @ √s = 240 GeV
  - **Conclusion often drawn from the plot**

Linear colliders are less energy-hungry than circular colliders

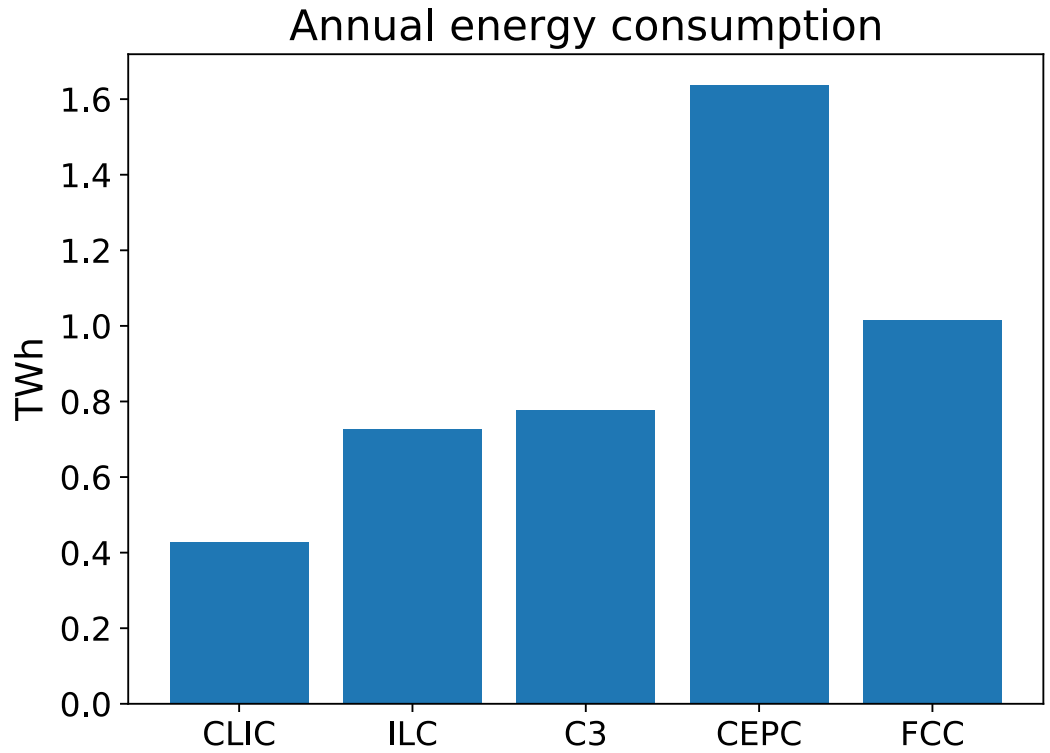


  - **True (even if linear colliders are also meant to operate at higher √s, with larger power)**
    - The power in operation is, however, only weakly linked to the collider carbon footprint

What you are less often shown

- **The annual energy consumption depends on WHEN the power is used**
  - **Integrated luminosity projections based on significantly different assumptions**
    - **Much longer physics runs for ILC/C³**

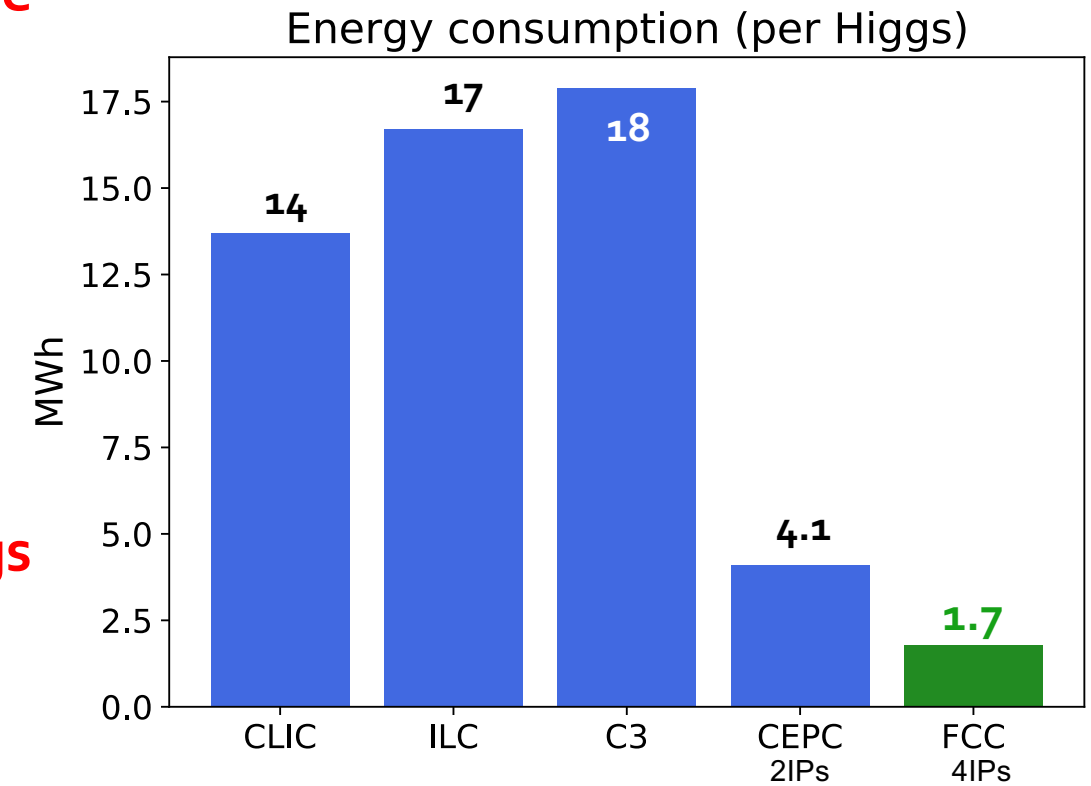
Higgs factory	CLIC	ILC	C³	CEPC	FCC-ee
$\sqrt{s}$ (GeV)	380	250	250	240	240
Instantaneous power P (MW)	110	140	150	340	290
Annual collision time T (10^7 s)	1.20	1.60	1.60	1.30	1.08
Operational efficiency ϵ (%)	75	75	75	60	75
Annual energy consumption E (TWh)	0.4	0.7	0.8	1.6	1.0



  - **Less physics days give much flexibility**
    - **To run only when electricity is available**
    - **To run only when electricity is carbon-free**
  - **Less physics days also reduce proportionally the annual energy consumption**
    - **The annual energy consumption is, however, only weakly related to the collider carbon footprint**

What you are rarely reminded

- A Higgs factory physics outcome is 100% correlated to the number of Higgs produced
- Circular colliders have a clear advantage here
  - Allow for a much larger collision rate
    - Beams are not lost at each crossing
  - Can operate four detectors simultaneously
    - ~550,000 Higgs/year with FCC-ee$_{240}$
    - ~ 50,000 Higgs/year with ILC$_{250}$
    - ~ 30,000 Higgs/year with CLIC$_{380}$
- If desired physics outcome requires 1M Higgs
  - Less than two years for FCC-ee (4 IPs)
  - Up to 20/30 years for ILC and CLIC



- Energy consumption / Higgs produced (or per physics outcome) is the proper estimator
  - Circular colliders are much less energy-hungry than linear colliders

Apparte: Is this a lot of energy ?

- **Yes, 1 TWh per year is significant energy consumption**
  - **But there is real value for mankind to do research as we do**
    - It is all the more important to maximise the corresponding physics outcome !
  - **Compared with other energy consumption / production per year**
    - CERN : 1.3 TWh
    - Geneva in 2019: 2.8 TWh
    - Dam in Verbois: 0.5 TWh ; Dam in Génissiat: 1.7 TWh
    - Nuclear plant in Bugey: 25 TWh
    - Largest solar panel farm (45 km2): 1 TWh
      - ➔ Would require a 500m-wide band of solar panel along the FCC ring
    - A 3MW wind turbine: 0.02 TWh
      - ➔ Would require 500 such turbines (one every 200m) along the FCC ring

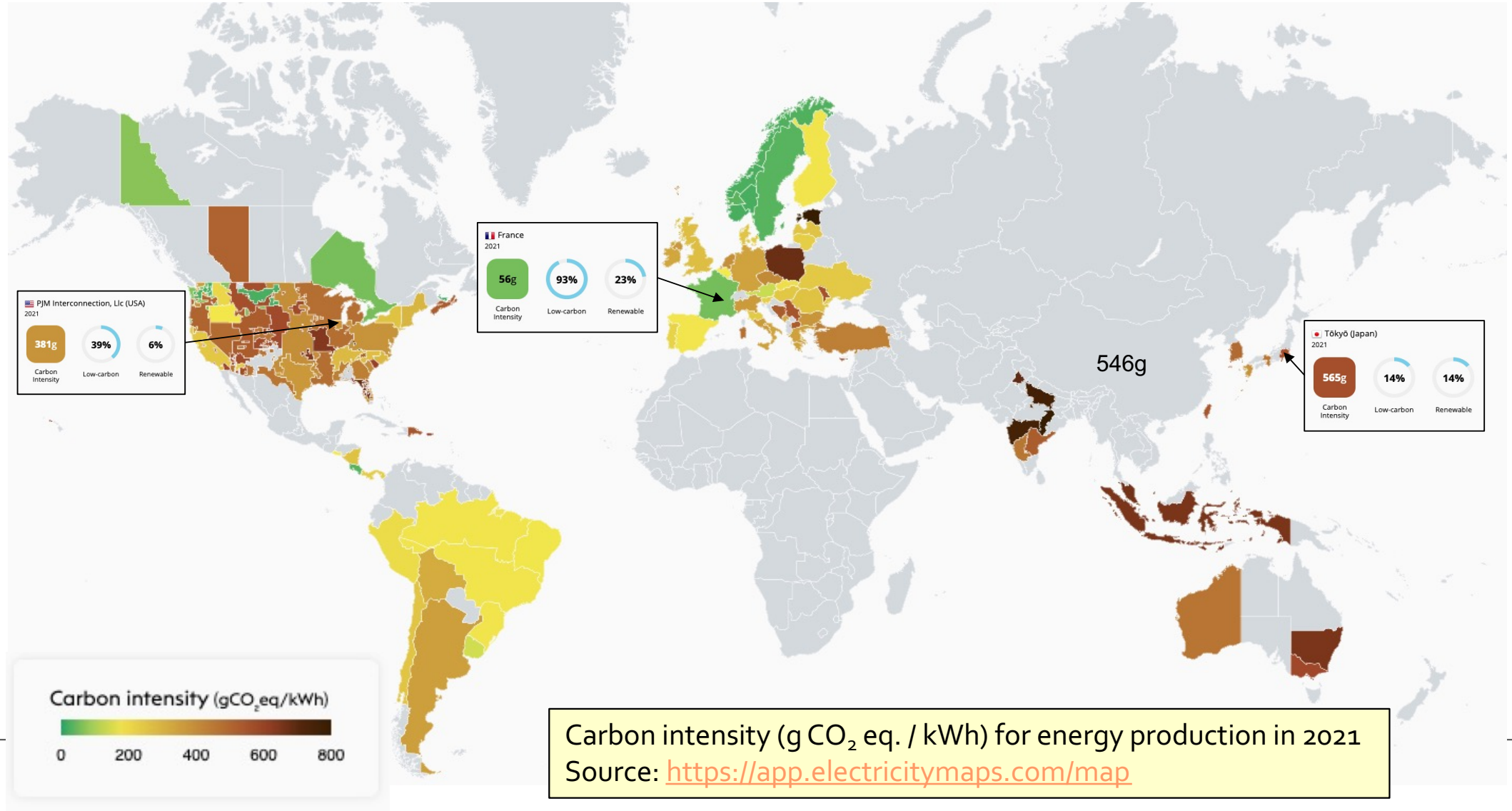
Highly variable sources
- Require larger peak energy
- Require energy storage

to run the collider 24h a day
→ Large investment
→ Environmental impact

  - **Our first responsibility, as particle physicists, is to do the maximum of science**
    - For the minimum environmental impact with the necessary energy consumption

What you are never told (until today)

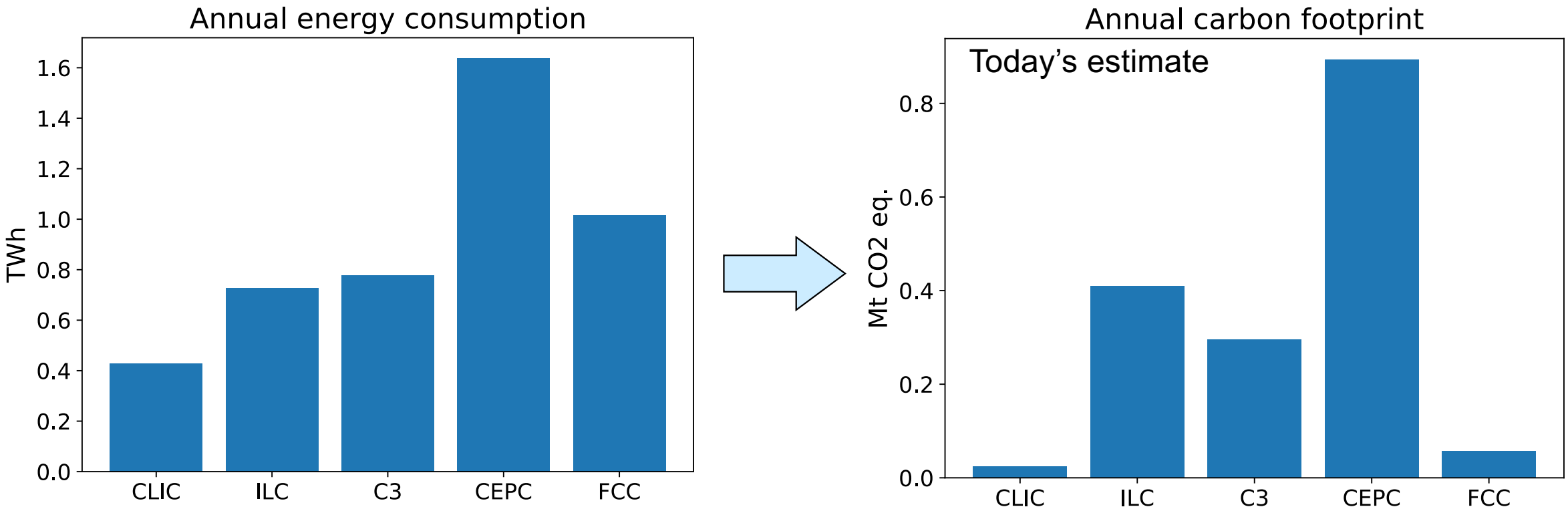
- **The environmental impact depends on WHERE the consumed energy is produced**



Carbon intensity (g CO_2 eq. / kWh) for energy production in 2021
Source: https://app.electricitymaps.com/map

Carbon footprint per year

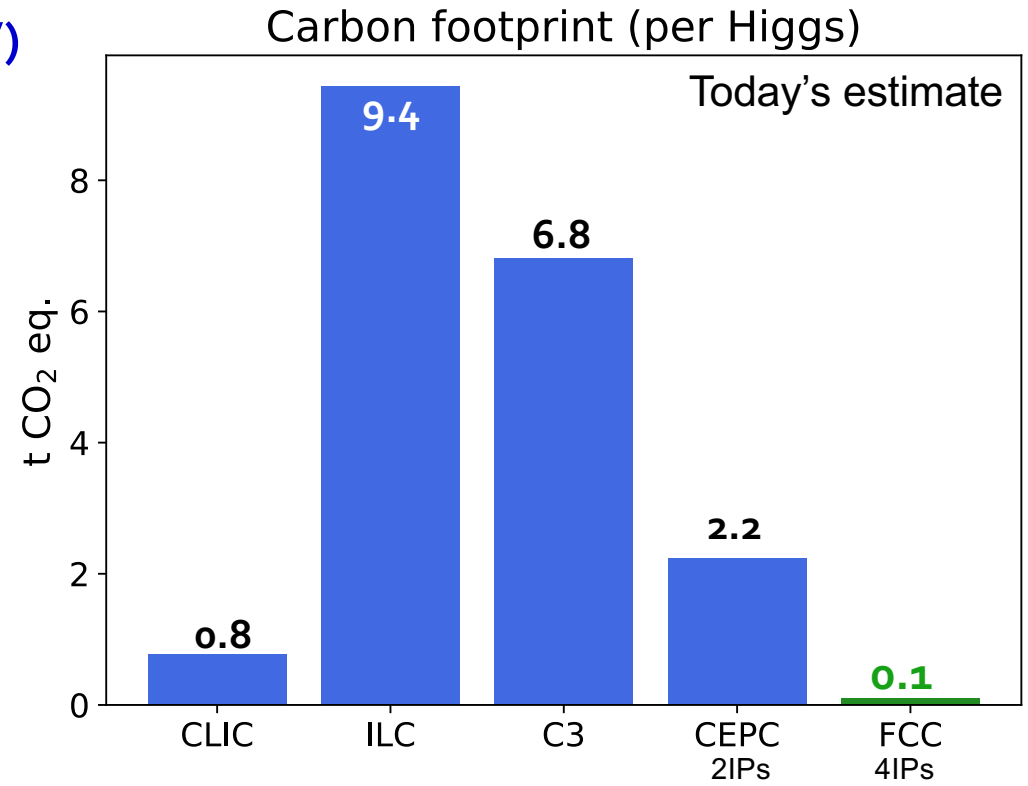
- **No surprise here: Higgs factories at CERN have a much smaller impact every year**



- **In addition, FCC-ee produces many more Higgs bosons every year than linear colliders**
  - **And therefore needs to run for a much shorter period for the same physics outcome**

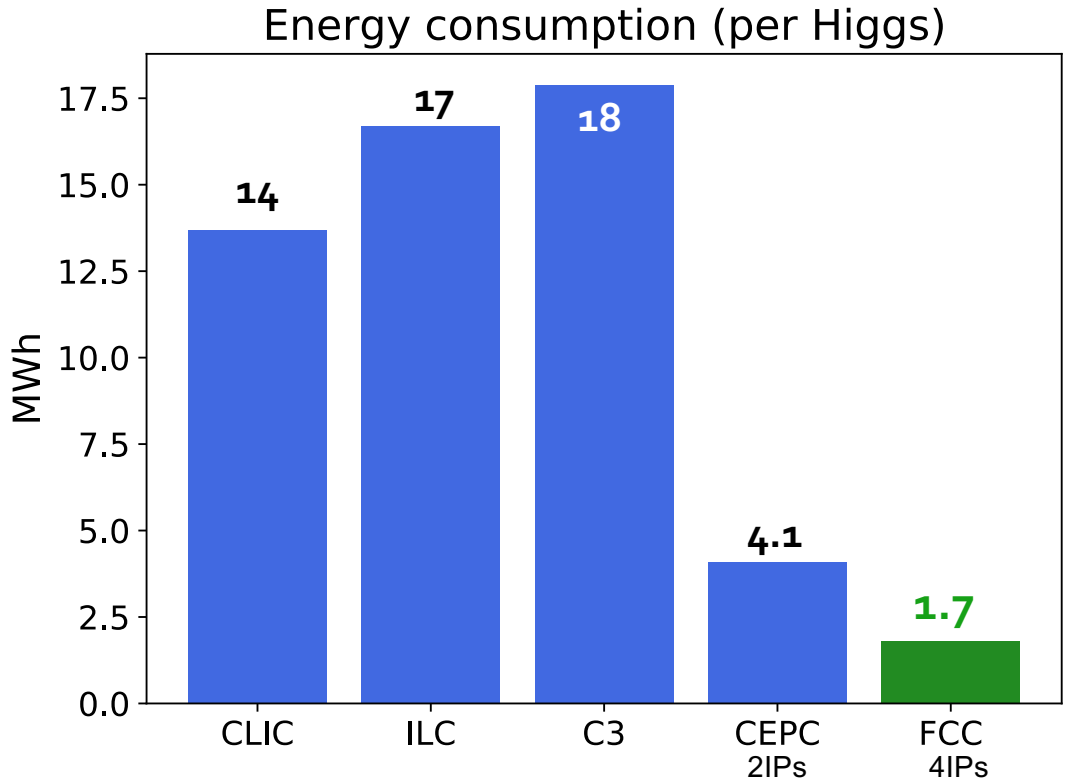
Carbon footprint per physics outcome

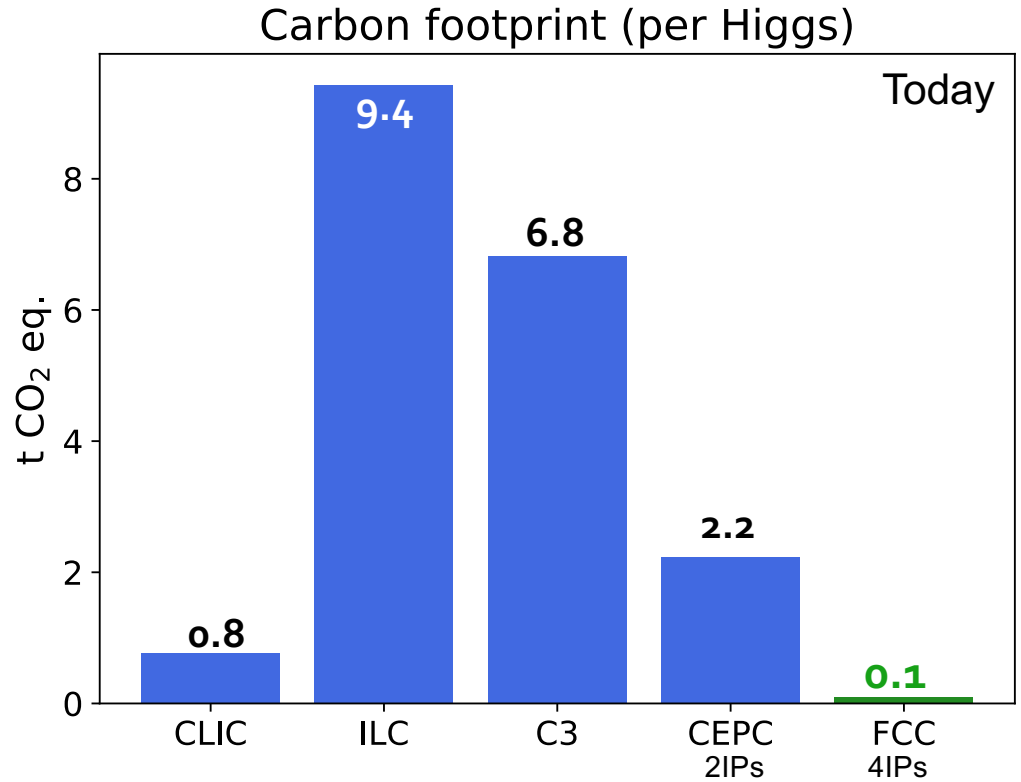
- **Today, FCC-ee would be the least disruptive it terms of environmental impact**
  - **When running as a Higgs factory ($\sqrt{s}$ = 240 GeV)**
    - **For a given physics outcome**
- **The carbon footprint is large, even for FCC-ee**
  - **Today, all developed countries are committed**
    - **To reduce carbon intensity by 40% in 10 years**
  - **What can we do at CERN ?**
    - **Develop energy efficiency technology**
      - ➔ **e.g., high-efficiency RF power sources**
    - **Recover dissipated power (heat)**
      - ➔ **To heat the neighbourhood (already with LHC)**
    - **Think of alternative ways of energy storage**
    - **Maximize synergies with developments towards carbon-free energy production**
      - ➔ **Nuclear fusion, solar and wind energy, etc.**
    - **Use electricity only when it is available and carbon-free: adapt power consumption with agility**
    - **Find ways of efficient international collaboration that minimizes airplane travel**
    - **Systematic use of electric vehicles; use bicycles to go to work; energy efficient buildings; etc.**



Conclusion

- **Higgs factory energy consumption and carbon footprint per physics outcome**





- **Suggestion: Always present our proposals not only in terms of cost and performance**
  - **But also in terms of carbon footprint / physics outcome (and use it for design and decision)**
    - **Because cost is mostly local, while carbon footprint affects everyone on the planet**