Landscape for the future colliders

-a personal view on the constraints and opportunities-

日本のコライダーの系譜と将来展望

KEK, Tsukuba, Japan, 3 March 2024

Tatsuya NAKADA
Laboratory for High Energy Physics
Institute of Physics
EPFL, Lausanne, Switzerland

Contents of this talk

- Current situation of physics
- Requirements for the next HEP machine
- Options for the next HEP machine
- Some comparison between circular and linear
- Aspect of international and global project
- Scope of linear colliders after initial Higgs factories and possibilities
- Personal view

Current situation of physics

- All the Standard Model (SM) particles were discovered.
- There exist concrete signs of physics beyond SM (BSM):
  - Nonzero neutrino masses
  - Existence of dark matter in the universe
  - Absence of antimatter in the universe
- There are also a little indication for BSM:
  - Deviation of μ(g–2) from the SM predictions
  - Flavour anomaly in semileptonic B meson decays
  - …
- Puzzling characteristics of SM
  - Mass hierarchy and flavour structure
  - Absence of CP violation in strong interactions
  - The value of the Higgs mass vis a vis that of top mass,
  - …
- NB: Majorana vs Dirac is one of the most important open questions for the neutrinos.

Current situation of physics

To conclude

- BSM must exist.
- The energy scale for BSM is an open question.

⇒"No-lose Theorem" (NLT) cannot be applied for motivating a new energy frontier discovery machine, unless it reaches up to the Plank scale: → difficult to justify a HE machine.

LHC (and B factories) was a unique example with NLT, thanks to the well established prediction for SM Higgs (and CP violation).

⇒New facilities for precision measurements can still be motivated, thanks to the quantum loop sensitive to high energy scales (within a "reasonable" cost).

e.g. μ, π, K, c, τ etc. at low energies and Z, W, H and t at high energies

H and t are least explored, followed by W and Z.

A general agreement on a Higgs Factory to be the next HEP machine.

Other subjects such as ν properties, search for feebly interacting particles, etc. remain to be important.

Requirements for the immediate next machine

- From pure physics point of view
  - Capable of H and t physics complementary to/beyond LHC and HL-LHC
  - Also capable of Z and W physics beyond currently known

    ⇒ an e^+e^- collider covering a region of 90-350 GeV centre of mass energy (cme)
- Somewhat physics related issues
  - It is good to start data taking with some overlap with the HL-LHC operation since the results might influence each other’s scientific programme.

    ⇒ A machine which can be built within the next 10~15 years.
  - Can be upgraded to probe higher energy scales, if compelling physics motivations.
  - Should not damage the diversity of particle physics activities.

    ⇒ A machine with a reasonable cost
- If you consider HEP sociology
  - Continuity in the HEP programme to sustain the community
- Society related issues have become increasingly important
  - Environmental impact, energy consumption, resource availability, attractivity in technology, impact on industries, spinoffs, …

Options for the "immediate" next machine

"Higgs Factory"; e^+e^- collider ($\sqrt{s}\approx 250$ GeV) with mature technology

- A circular collider (CC): e,g, FCC(CERN) and CECP(IHEP)
  - Double storage rings of 90-100 km circumference, $L\sim 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Also from Z with $L\sim 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ up to $t\bar{t}$ with $L\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Well established technology. Many CC's have been built, the highest $\sqrt{s}$, LEP @207 GeV, with 27 km circumference, the highest L achieved by SuperKEKB at 10 GeV, 3.8×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Upgrade path: installing pp collider $\sqrt{s}\approx 100$ TeV accessing 10 TeV physics
- A linear collider (LC): i.e. CLIC and ILC
  - Colliding e^+ e^- accelerated by lineacs, with a total length of up to 20 km depending on the acceleration gradient of the technology used, with $L\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - CLIC: normal conducting room temperature X-band Cu RF cavities, 72 MeV/m
  - ILC: super conducting L-band RF cavities (series production experience @European XFEL), 32 MeV/m
  - There has been only one LC built, SLAC Linear Collider 100 GeV with $L\sim 3\times10^{30}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (end of 90's)
  - Upgrade path: increasing $\sqrt{s}$ energy: multi-TeV to beyond, by improving the acceleration gradient, ultimately fully wake-field acceleration and extending the tunnel if needed. Large increase of luminosities is also an option.

Options for the "immediate" next machine

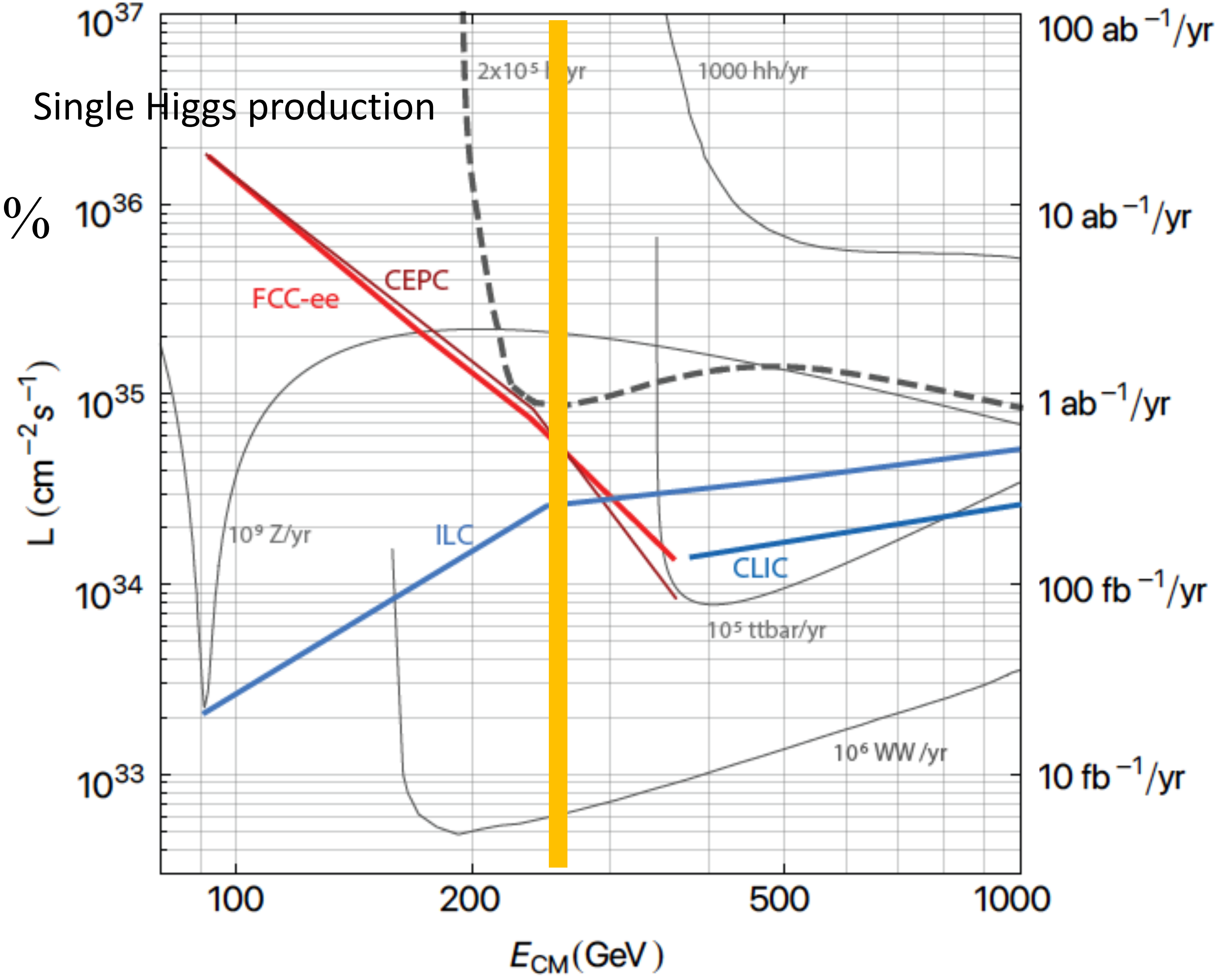
- From Snowmass 2021 report

ArXiv ePrint: 2208.06030

Higgs couplings with σ~a few %

Power consumption

- CC ~300 MW
- LC ~100 MW



Cost range of the machines and remarks

Cost range	Up to ~5 BCHF	5 to 10 BCHF	>10 BCHF
Example	HL-LHC, LHC	LC's	CC's
Remark	A CERN project with O(10%), contribution from the non-member states. It is primarily managed by CERN with limited participation in the decision making for those non-member states.	CLIC is conceived at CERN, being developed as an international collaboration where CERN plays a clear role of the host laboratory. ILC is a global project started by a merger of three regional projects, GLC (Asia), NLC (US) and Tesla (Germany), supported by the International Committee for Future Colliders (ICFA). Japanese HEP community proposed to host ILC in Japan as a global project. No decision taken.	CECP is primarily a Chinese project lead by IHEP. Several candidate sites being studied but none is at IHEP. Some R&D budget has been allocated and waiting for a decision by the Chinese government. FCCee is a project at CERN. An international collaboration has been formed where the top of the reporting line is still the CERN Council. Studies on technical and funding feasibility is ongoing with an expected completion by the end of 2025.

Some comparison between circular and linear

Machine	Circular collider	Linear Collider
Some advantages	Higher luminosity at 250 GeV and below • Excellent electroweak physics • Good sensitivities in rare phenomena in the Higgs decays	Longitudinal polarization and constant luminosities for above 250 GeV • Comparable sensitivities in the Higgs coupling measurements • Excellent top physics
Number of interaction points	Can have several interaction points	Only one interaction point
Footprint	90 to 100 km tunnel will result in larger environmental impact and cost for the civil engineering	Shorter tunnel, 20 km for ILC, will have additional advantages such as simplified logistics in the installation and maintenance.
Additional comments	Technical work is not as advanced as ILC, but technology of circular colliders is very well established	ILC has made quite through design studies, technically most mature. Thus, a possible scenario could be to start a linear collider with superconducting RF technology, which will be upgraded by the technologies for higher *L* or $\sqrt{s}$ but still require substantial R&D work.

Aspect of international and global project

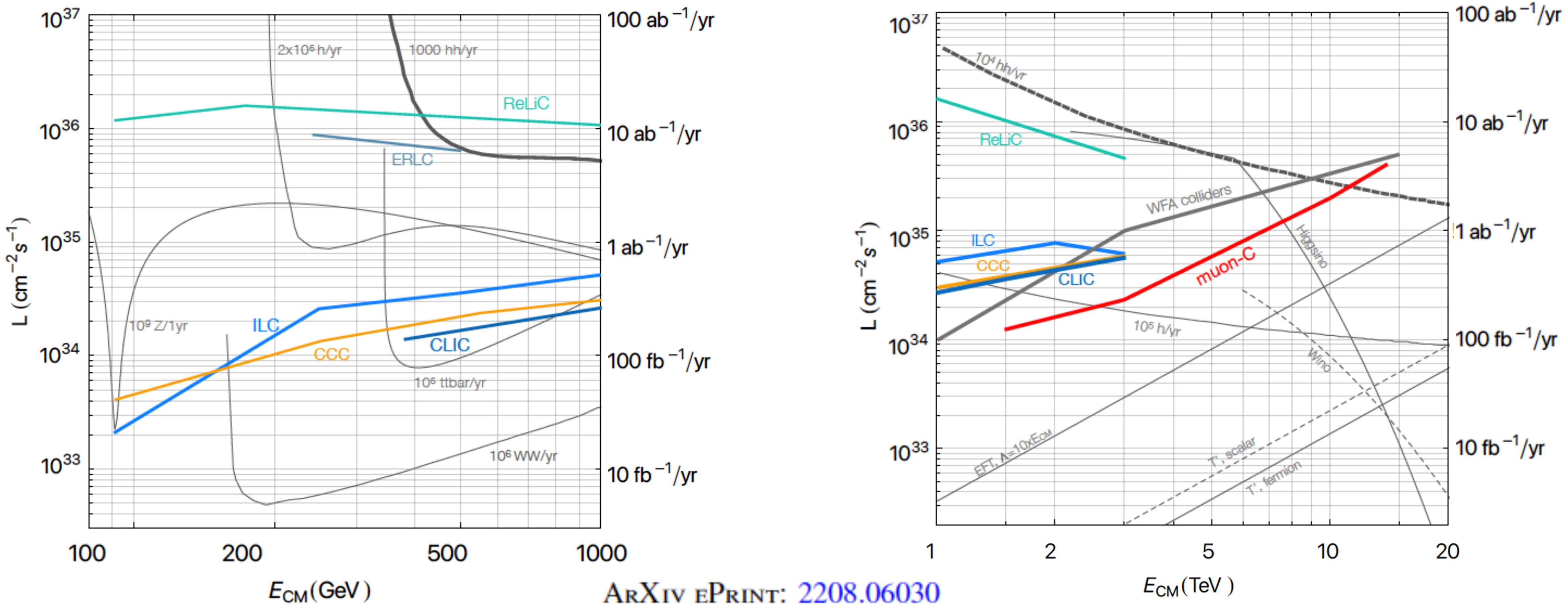
	International project	Global project
Conception	Conceived as a project of single laboratory, a national laboratory such as FNAL, IHEP, KEK etc., or an intergovernmental laboratory such as CERN and Dubna, acting as the host laboratory, who seeks contribution of other countries worldwide.	Initiated through discussion among partners interested in realising the project. It becomes a project of every partners.
Responsibility and decision making	The main responsibility is carried by the host laboratory with small participation in decision making by the partners.	The project is carried as a collaboration of partners with collective decision making and shared responsibilities.
Host and site	Host laboratory is predefined and site is decided by the host laboratory.	Decision on the host and site is a part of the decision process of a global project.
Funding	Mostly funded by the host with a small, 10 to 20%, contribution from outside.	Share of funding and responsibilities is a part of the decision process of a global project.
Remark	• Fast decision process • Limited scope of funding • Could be a large burden for the host laboratory and the country(region)	• Decision making could become a long process • Global resources become available • Global optimisation of science programme could be possible.

LC after initial Higgs factories

- Important benchmark physics goal now could be
  - Higgs self-coupling with σ~a few %
    - Very high luminosity at 500 GeV, cf. ILC500 ~20%
      ILC500 20% and CLIC3TeV 10%. Only FCC-hh or Munon collider 10TeV claim a similar sensitives.
  - Search for weakly coupled SUSY particles up to ~1 TeV (considered to be difficult with LHC or HL-LHC to reach this…),
    - A few TeV e^+e^- collider, e.g. CLIC3TeV
- But must be done in a socially responsible matter respect to, energy consumption (e.g. not much more than we spend now), environmental impact (e,g, civil construction, pollution, radiation, etc.) and cost.
- A natural extension of an e^+e^- LC Higgs factory, after exploitation of ~10 years, i.e. ~25 years from now….

LC after Higgs factories, possibilities…

- Ambitious ideas, which will win????
  - Energy Recovery Lineac for energy and e^+ recovery
  - High-rate collisions (up to ~MHz) for very high *L*
  - Travelling wave, NC high gradient, PWFA for high to very high $\sqrt{s}$



ArXiv ePrint: 2208.06030

Personal view

- The main objective of the next HEP machine will be the precision physics, primarily Higgs (and top).
- Considering that
  - A sign of new physics could come from elsewhere: e.g. flavour physics at low energy, neutrino properties, feeble interacting particles, etc.
  - Although we are sure of the existence of new physics, we have no idea the energy scale and type of new physics,

  our plan for the near-term future should not constrain the longer term.
- A linear e^+e^- Higgs factory based on the SRF technology, i.e. ILC, will provide a base for a flexible plan with a reasonable footprint and energy consumption, and is ready to proceed engineering design studies.
- Such a machine can be an infrastructure for a future path towards a very high energy and luminosity collider.