Particle Physics Outlook

-a personal view-

Asia-Europe-Pacific School of High-Energy Physics

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About myself

- Emeritus Professor at École Polytechnique Fédérale de Lausanne
- Experimental work, historically
  - Feasibility study of finding Υ(1S)→3g with DASP2 detector at DESY DORIS
  - Baryon production in hard and soft pp interactions at CERN ISR
  - QED correction for pionic atom experiment at SIN
  - CP violation in K^0 decays with CPLEAR experiment at CERN LEAR from the start
  - 👎 Proposal for a e^+e^- B factory at SIN/PSI 😟
  - 👎 Proposal for a e^+e^- B factory at CERN ISR 😔
  - 👎 Proposal for an internal gas-jet target b experiment, GAJET at LHC 😩
  - LHCb experiment from the start
  - Also helping a bit linear colliders, in particular ILC
- Some oof the past social/community work
  - European Committee for Future Accelerators
  - European Strategy for Particle Physics
  - CERN Scientific Policy Committee

Contents of this talk

- What is particle physics?
- Some history of the development: can we learn something from that?
- We have the Standard Model, but… Thinking needed…
- To conclude the current situation for the next step
- Requirements for the immediate next HEP machine
- Options for the immediate next HEP machine
- Cost range of those machines and remarks
- Some comparison between circular and linear
- A comment on international and global project
- Personal view
- Personal questions for discussion

What is “Particle Physics

Physics describing

- most fundamental building blocks of matter

- interactions between them

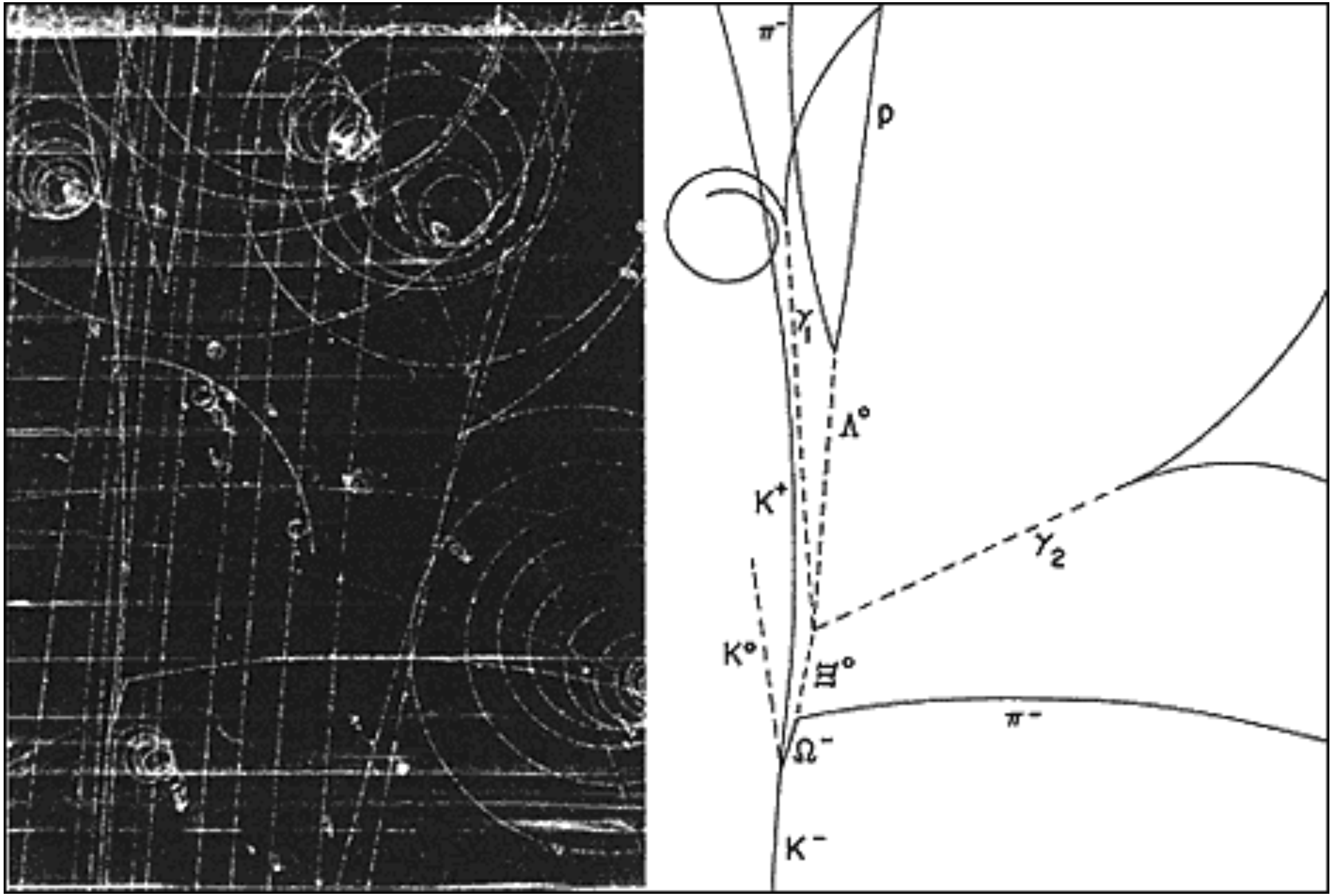
- and underlying dynamics

Some history for building blocks

Flavour of hadrons may go back to an idea of isospin (Heisenberg 32) as the first step? Discovery of pions and kaons in the cosmic rays in 30’s and 40’s:

- A concept of strangeness (Gell-Mann 56, Nishijima 55), as a quantum number
- Explosion of particles in 50’s and early 60’s, so called particle zoo, “thanks” to the accelerator experiments.
- Introduction of SU(3) flavour symmetry (Han-Nambu, Nishijima, Sakata, Zweig, and many others), resulting in the “quark” model (u,d,s) (Gell-Mann 64, Ne’eman 64)
- Discovery of Ω^-(sss) baryon at BNL (Barmes et al 64) postulated by the quark model

Discovery of Ω^-



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-However, it was not clear whether "quark" was just a mathematical representation or had physics existence. Scaling behaviour in the electron-nucleon deep inelastic experiments at SLAC (Bloom er al. 69), which could be explained by point-like constituent particle of nucleons (Feynman 69). Further electron and neutrino deep inelastic data brought us the understanding that quarks are constituents of nucleons and mesons with physical existence.-

Some history for building blocks

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Since then, experimental observations lead to further understanding of flavours

- K^0 mesons with two lifetimes (Lande et al. 56) ⇒ K^0-$\overline{K^0}$ mixing
- Supresion of $\Delta S = 1$ decays ⇒ Cabibbo mixing (63)
- small Δm_K and very suppressed $K_L \to \mu^+\mu^-$ ⇒ Glashow–Iliopoulos–Maiani mechanism (70)
- CP violation in K^0 decays (Christenson et al. 64) ⇒ three families of quarks (Kobayashi&Maskawa 73)
- Charm (Aubert et al. and Augustin et al., 74) and Beauty (Herb et al., 77) discovery
  NB: 4^{th} quark already considered in ~1964, even with the name "charm" (Gell-Mann, Tarjanne and Teplitz, Hara, Bjørken and Glashow), also ν_μ discovered in 1962 (Lederman, Schwartz and Steinberger)
- m_t much higher than anticipated in 80's: searched by PEP, PETRA, TRISTAN…

Was this top discovery?

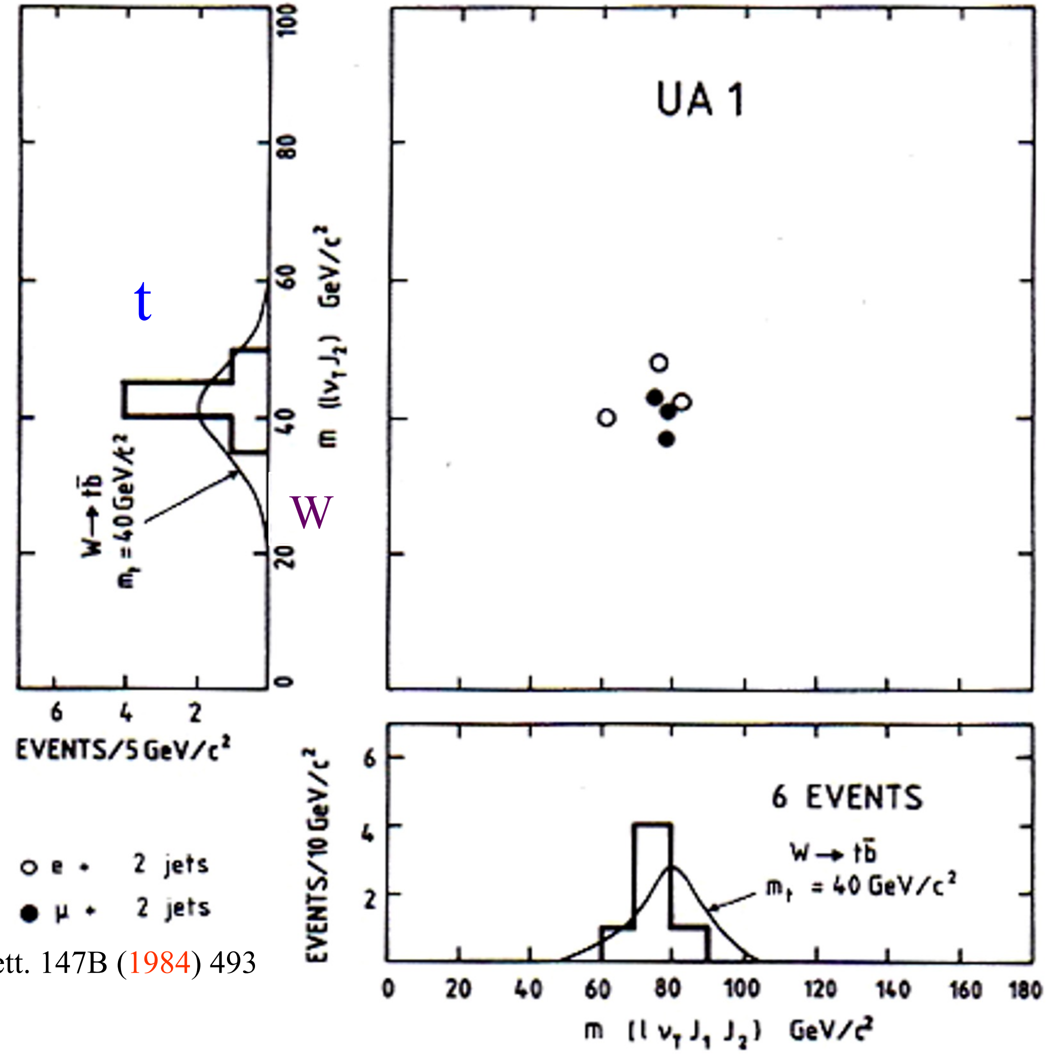
UA1, 1984

$p\bar{p} \rightarrow W^+ + X$

$\quad \rightarrow W^+ \rightarrow t\, b \rightarrow$ jet

$\qquad\qquad \rightarrow b l \nu \rightarrow$ jet

$m_t = 30 \sim 50\ \mathrm{GeV}/c^2$



Phys. Lett. 147B (1984) 493

Some history for interactions

Electroweak Theory developed in the beginning of 70's by Glashow, Salam, Weinberg and others postulating a neutral current in weak interactions mediated by neutral vector boson Z^0:

- Observation of a phenomena mediated by the neutral current by Gargamell bubble chamber at CERN, 1973
  $\nu_\mu/\nu_\mu + N \rightarrow \nu_\mu/\nu_\mu$ + hadrons: may call it an indirect discovery
- Discovery of the Z^0 boson created by the pp annihilation at by the SPPS collider at CERN, 1983 by UA1 and UA2 experiments: may call it a direct discovery

Followed by the precision measurements of Z^0 and $W^\pm$ properties and other electroweak parameters by LEP, Tevatron and others. This has become now a very well tested part of the SM. In turn, those measurements gave a prediction for m_t and m_H in the theoretical framework.

Some history for dynamics

Reconciliation of quantum mechanics and special relativity: two well tested fundamental theories:

- Dirac equation (28) postulated the existence of anti-particle, later confirmed by Anderson in cosmic rays (32)

Was this particle going up or down?

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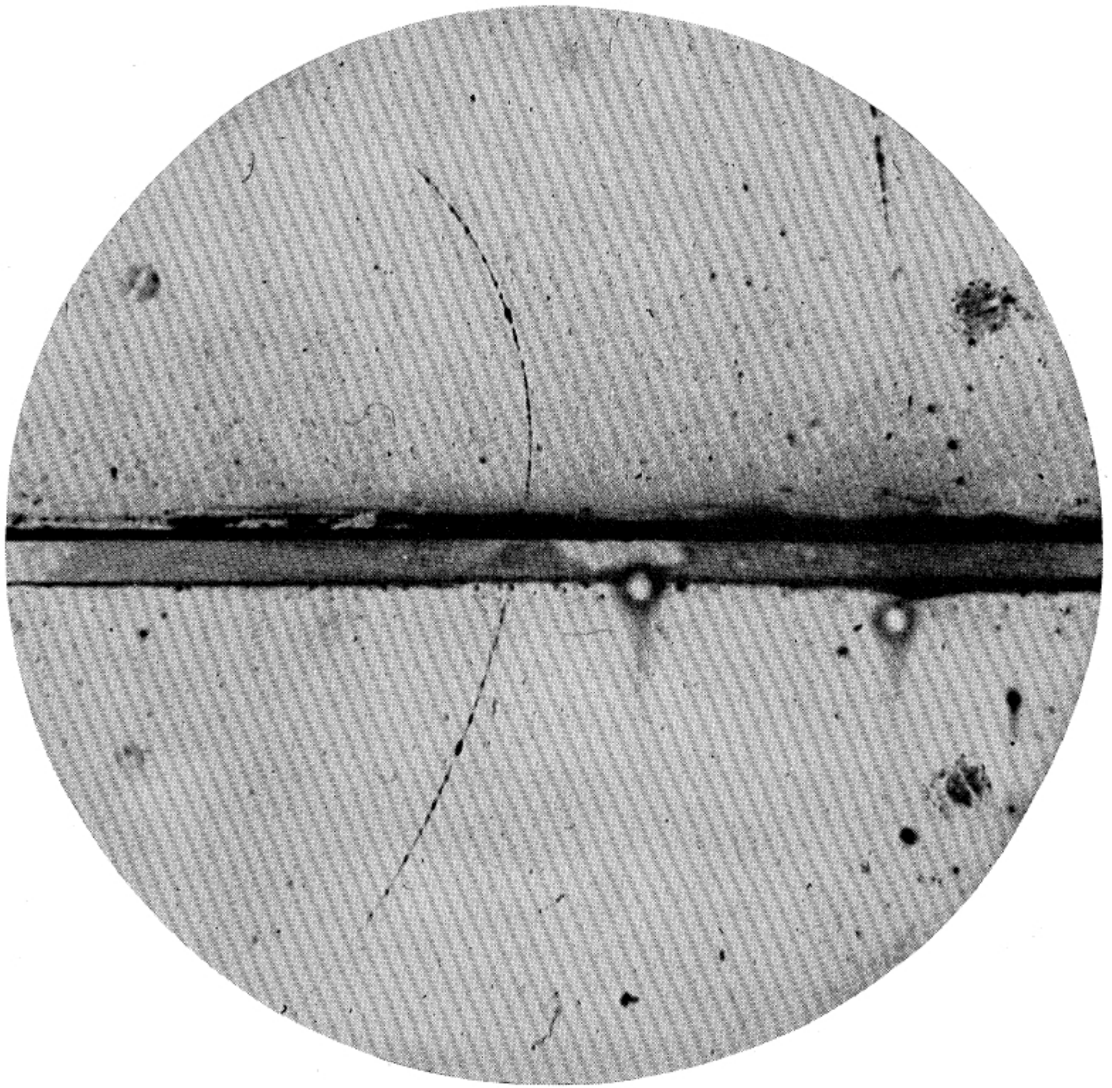

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Some history for dynamics

Reconciliation of quantum mechanics and special relativity: two well tested fundamental theories:

- Dirac equation (28) postulated the existence of anti-particle, later confirmed by Anderson in cosmic rays (32).

Followed by development of quantum electrodynamics, QED, particularly in 40's

- Particularly stimulated by the precision measurements in atomic transition energies, the Lamb shift, in the US after the war, while advancement was also made in parallel in Japan (for obvious reasons) till later 40's.
- Feynman, Schwinger, Tmonaga, and many others.

Continuously developed and established as Quantum Field Theory, one of the foundation of particle physics.

What can we learn from those histories?????

Current state of “Particle Physics

Physics describing

- most fundamental building blocks of matter
  Quarks and Leptons
- interactions between them
  Electromagnetic, weak and strong interactions mediated by photon, weak bosons and gluons, respectively
- and underlying dynamics
  Relativistic quantum field theory

Strongly driven by the concept of symmetries

- gauge symmetry
- space-time symmetry
- …

The Standard Model: $SU3_{colour} \times SU2_L \times U1$ with six quarks and six leptons

$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$ $u_R, d_R, c_R, s_R, t_R, b_R$ $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$ e_R, μ_R, τ_R g, $W^{\pm}, Z^0, \gamma$, H

$\times$3(colour)$\times$2(particle-antiparticle) $\times$2(particle-antiparticle) $\times$8(colour)

We have the Standard Model, but…

- All the Standard Model (SM) particles were discovered and quite well tested, but…
- 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 compelling evidence for BSM:
  - Deviation of $\mu(g-2)$ from the SM predictions
  - Flavour anomaly in semileptonic B meson decays
  - …

Thinking further

- All the Standard Model (SM) particles were discovered and quite well tested, but…
- There exist concrete signs of physics beyond SM (BSM):
  - Nonzero neutrino masses ⇒ Crucial questions is whether n is Majorana or not, i.e. $0\nu 2\beta$ decays
  - Existence of dark matter in the universe ⇒ Extend search with novel underground detectors
  - Absence of antimatter in the universe ⇒ Further search for sign of CP violation beyond SM
- There are also a little compelling evidence for BSM:
  - Deviation of $\mu(g-2)$ from the SM predictions ⇒ Better understanding of hadronic contributions
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  - …

This may mean…

- Three clear signs of new physics are not necessarily pointing the energy scale of BSM to be very close.

Thinking even further

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  - 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,
  - Too many (?) different symmetries …

Still…

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Thinking even more…

- Three clear signs of new physics are not necessarily pointing the energy scale of BSM to be very close.
- Many many ideas of BSM, but their parameter spaces are vast with little know quantalities: it is not easy to target a "favourable" scenario.

But also

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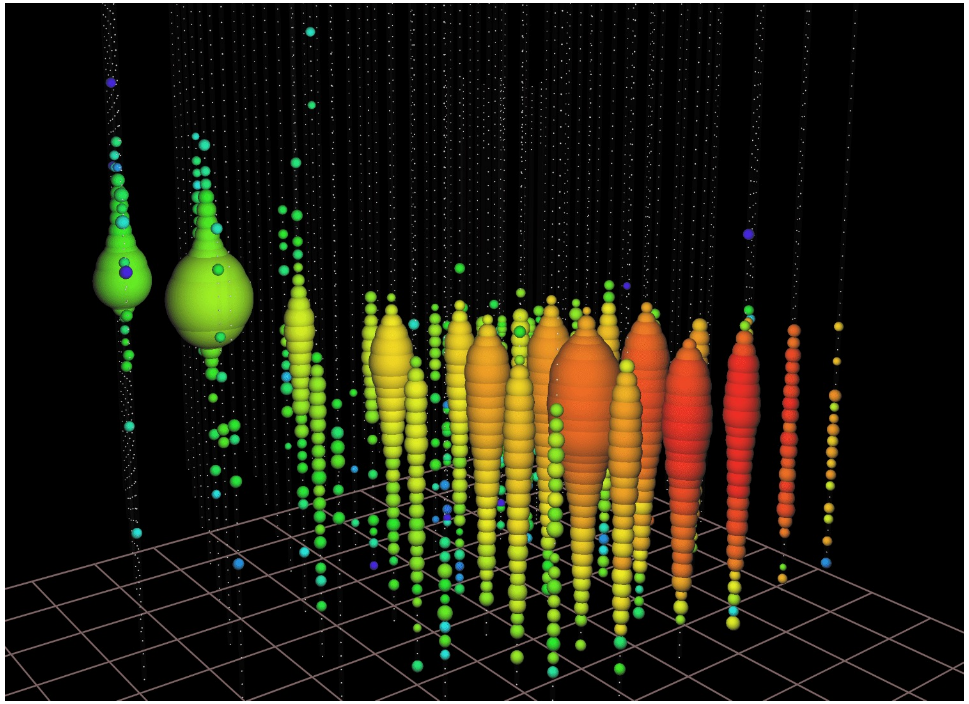
  - The value of the Higgs mass vis a vis that of top mass,
  - Too many (?) different symmetries …
- Quantum Field Theory has been long under scrutiny as not mathematically rigour. ⇒ Smart ideas, may be inclusion of gravity, may be solving everything at once?

Thinking even more…

- Three clear signs of new physics are not necessarily pointing the energy scale of BSM to be very close.
- Many many ideas of BSM, but their parameter spaces are vast with little know quantalities: it is not easy to target a "favourable" scenario.
- Further signs of BSM could appear in different places, i.e. at accelerators with different energies and non-accelerators experiments (including keep looking at objects from the sky).



SHiP

Search for Hidden Particles

To conclude the current situation for the next step

We know BSM must exist, but

neither the type nor energy scale of BSM is not yet known.

⇒"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 funding

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.

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

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

😃 A general agreement on a Higgs Factory to be the next HEP machine to gain a guidance for the further step through precision measurements.

🙁 Other research areas such as ν properties, search for feebly interacting particles, search for dark mutter below the neutrino floor and in much wider mass rages, etc. remain to be very important, if not become more.

😠 Resource requirement for those activities are also getting large, e.g. the next or next to next generation of $0\nu2\beta$ decay search. "Global" optimisation may become necessary…

Requirements for the next HEP machine

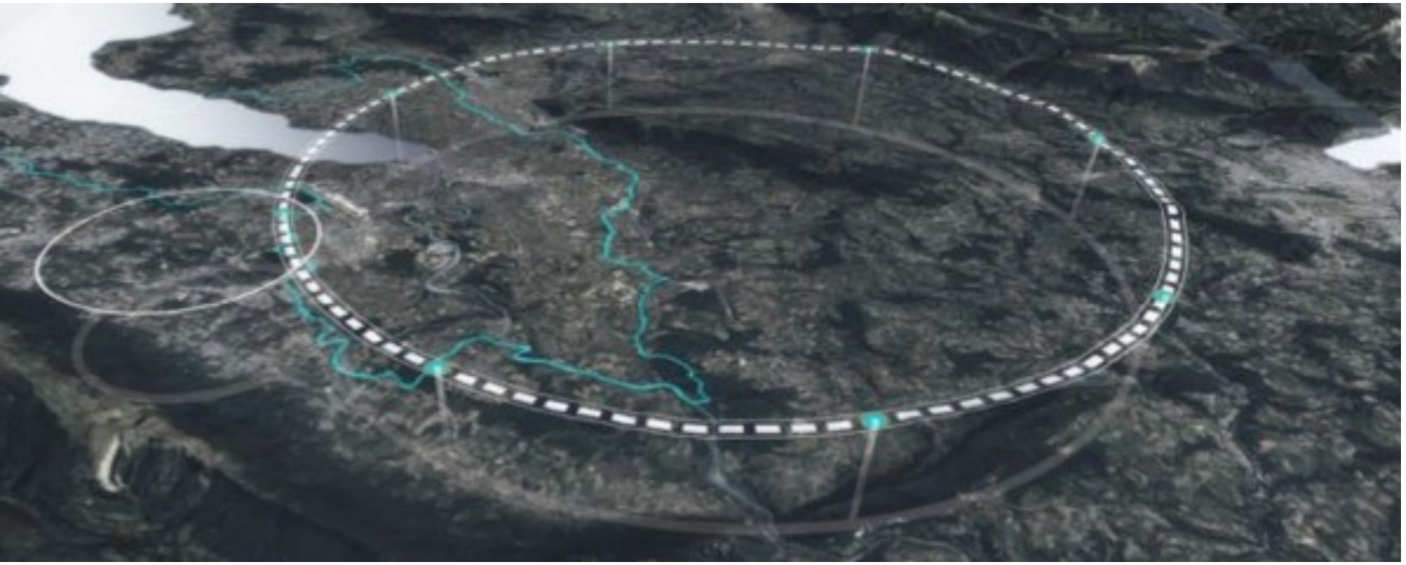
- From pure physics point
  - Capable of H and t physics complementary to/beyond LHC and HL-LHC
  - Capable of Z and W physics beyond currently known
    - ⇒ an e^+e^- collider covering a region of 90-350 GeV centre of mass energy (cme)
- Somewhat physics related issues could be
  - It would be good 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.
  - Flexible and can be upgraded to probe higher energy scales/luminosities if physics results motivates.
  - Should not damage the diversity of particle physics activities.
    - ⇒ A machine requiring a reasonable level of resources
- HEP sociology
  - Continuity in the HEP programme to sustain the community
- Other issues have become increasingly important
  - Environmental impact, energy consumption, resource availability, attractivity in technology, impact on industries, spinoffs, …

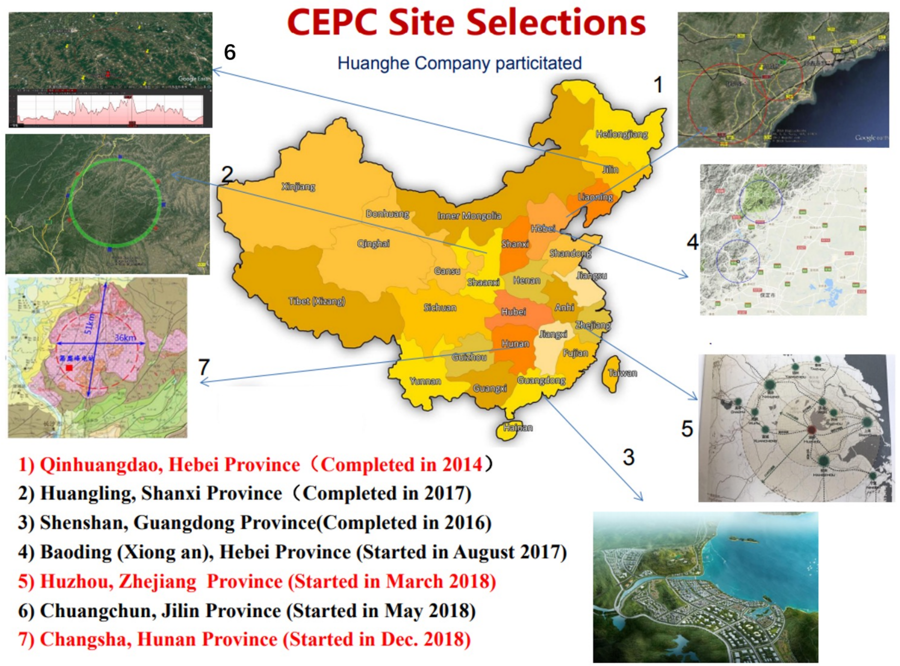
Options for the "immediate" next machine

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

- A circular collider (CC): e,g, FCC(CERN) and CEPC(IHEP)
  - Double storage rings of 90-100 km circumference, $L\sim 10^{35}\text{cm}^{-2}\text{s}^{-1}$
  - Also from Z with $L\sim 10^{36}\text{cm}^{-2}\text{s}^{-1}$ up to $t\bar{t}$ with $L\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - 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} $\text{cm}^{-2}\text{s}^{-1}$
  - Upgrade path: installing pp collider $\sqrt{s}\approx$100 TeV accessing 10 TeV physics

Just in case you have never heard about them





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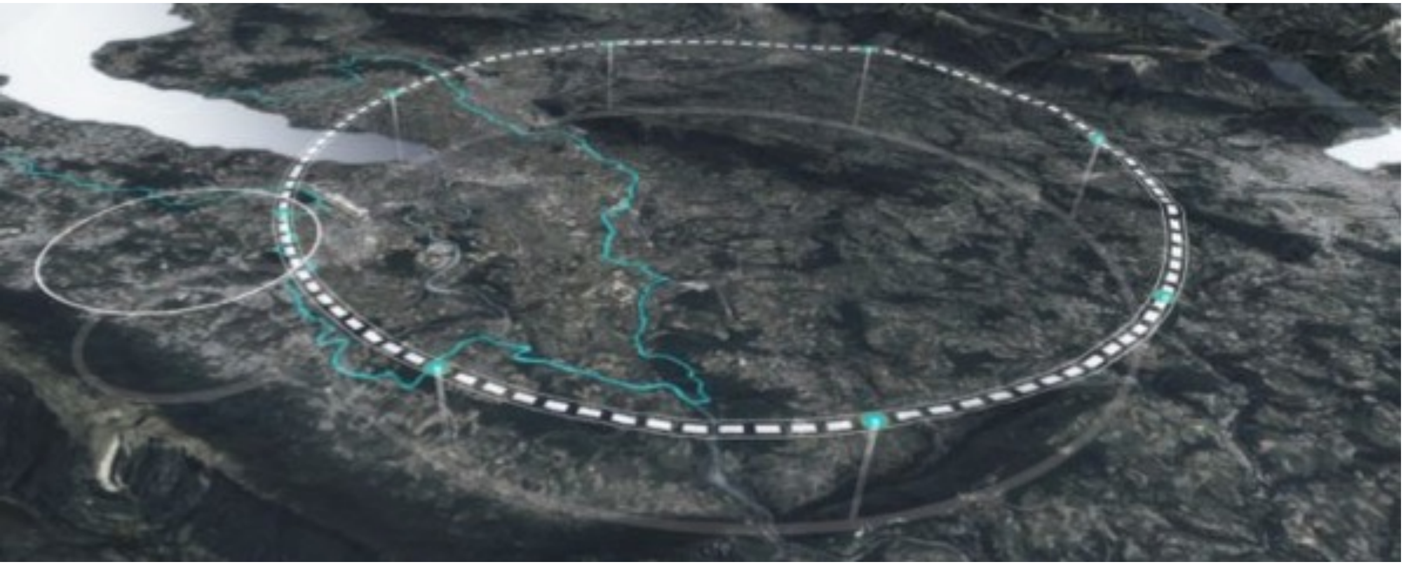
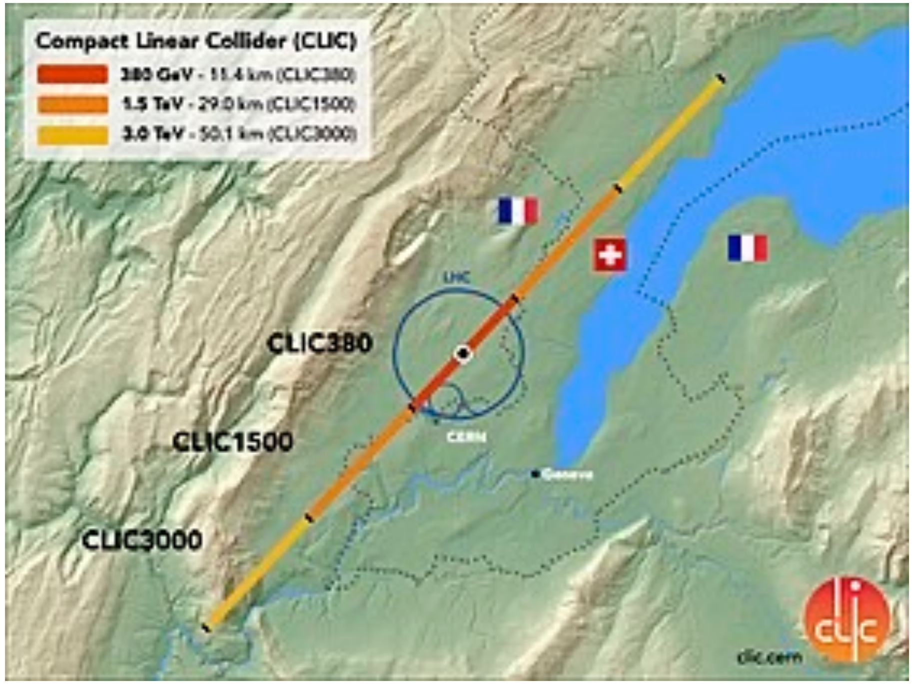
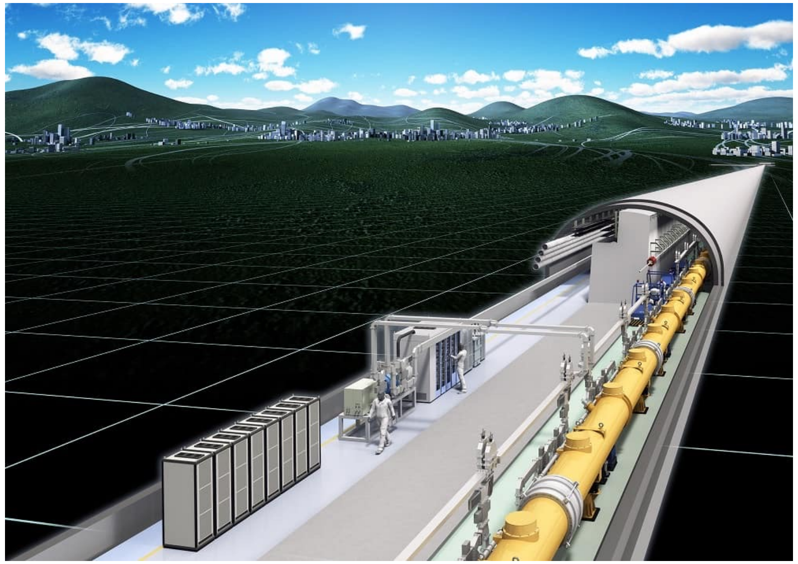
  - Upgrade path: installing pp collider $\sqrt{s}\approx 100$ TeV accessing 10 TeV physics
- A linear collider (LC): i.e. CLIC and ILC
  - Colliding $e^+\ e^-$ accelerated by lineacs, with a total length of up to 20 km depending on the acceleration gradient of the technology used, with $L\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 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 $L\sim 3\times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (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.

Just in case you have never heard about them





1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chuangchun, Jilin Province (Started in May 2018)
7) Changsha, Hunan Province (Started in Dec. 2018)



Options for the "immediate" next machine

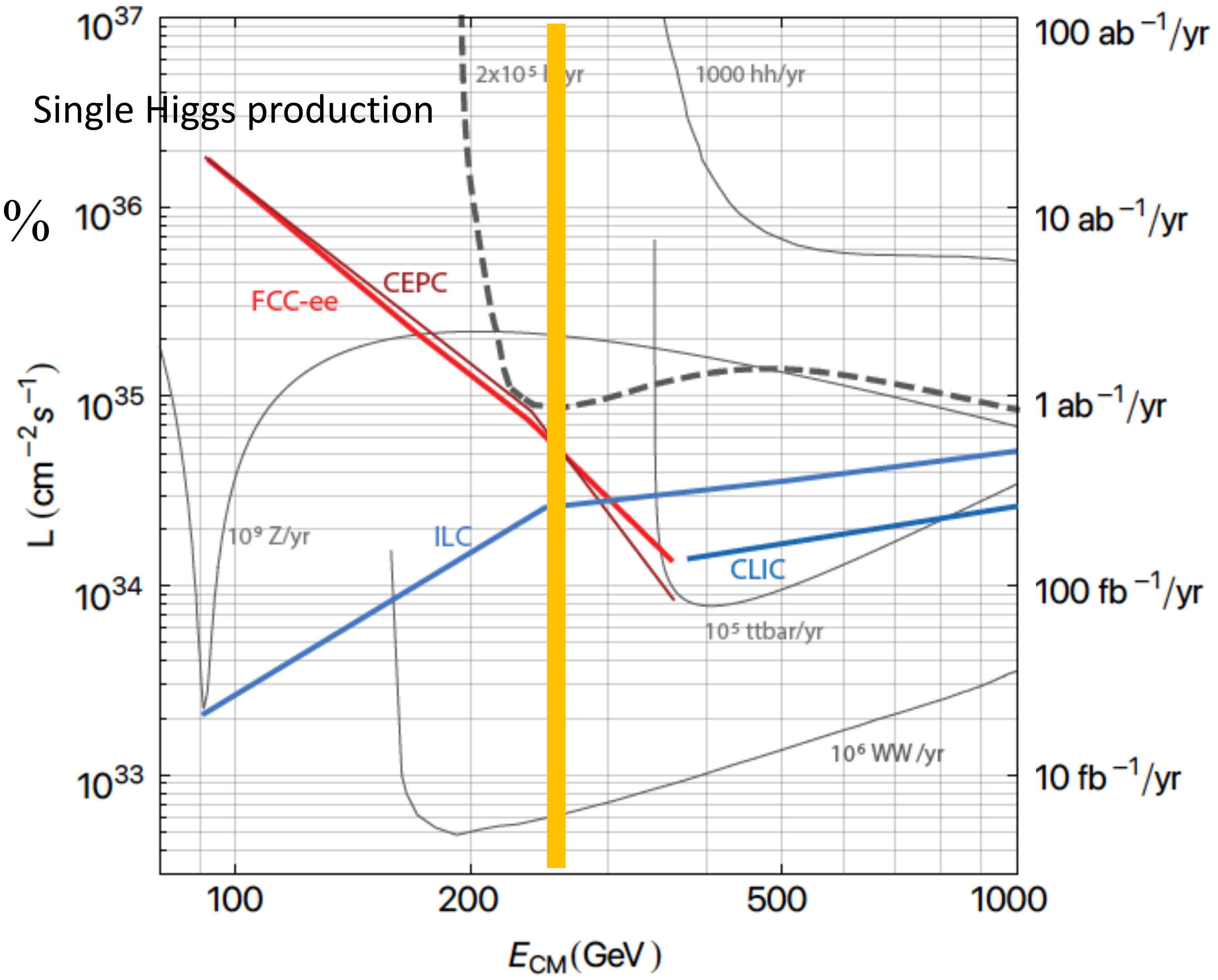
- From Snowmass 2021 report

ArXiv ePrint: 2208.06030

Higgs couplings with σ~a few %

Power consumption

  - CC ~300 MW
  - LC ~100 MW



Cost range of those machines and remarks

Cost range	Up to ~5 BCHF	5 to 10 BCHF	10 to 15 BCHF
Example	Don’t forget LHC&HL-LHC	CLIC, ILC, CEPC	FCCee
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 to be constructed at CERN. 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. CEPC is a Chinese project lead by IHEP. Several candidate sites being studied but none is at IHEP. Some R&D budget allocated and waiting for a decision by the Chinese government anticipated in 2026.	FCCee is the first phase of the FCC project at CERN with international participation for ongoing technical feasibility studies. Result of studies, together with financial feasibility, will be available for the update activities of the European Strategy for Particle Physics in 2025 and 2026.

Some comparison between circular and linear

Machine	Circular collider	Linear Collider
Some of the 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 with little penalty in luminosities.	Only one interaction point (or sharing luminosities)
Footprint	90 to 100 km tunnel will result in larger impact on environment, risk and cost for the civil engineering	Shorter tunnel of ~20 km will have additional advantages such as simplified logistics in the installation and maintenance.
Additional comments	Technology of e^+e^- circular colliders is very well established.	ILC has made quite through studies and technically most mature. An interesting scenario is to start a linear collider with superconducting RF technology, which will be upgraded later by technologies capable of much higher acceleration gradient and luminosities but still require R&D work.

FCC after initial Higgs factories, FCChh

😃 With an indication of 10 TeV energy scale for BSM, install a hadron collider in the same tunnel with very high field dipole magnets (14 to 20 T) reaching; pp, $\sqrt{s}$ = 80~116 TeV with $L \approx 5\text{–}30\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ with an option for ep and ion-ion collisions

- Accessing physics at 10 TeV energy scale
- Higgs self-coupling with σ ~ a few %
- Could be used with ions, a la LHC, or ep.

😟 Substantial work is needed to develop the dipole magnet. Given the number of magnets required, the process of magnet production to keep the production cost and time down will be non trivial. Cost of the machine will be well above 20BCHF. Power consumption >500 MW

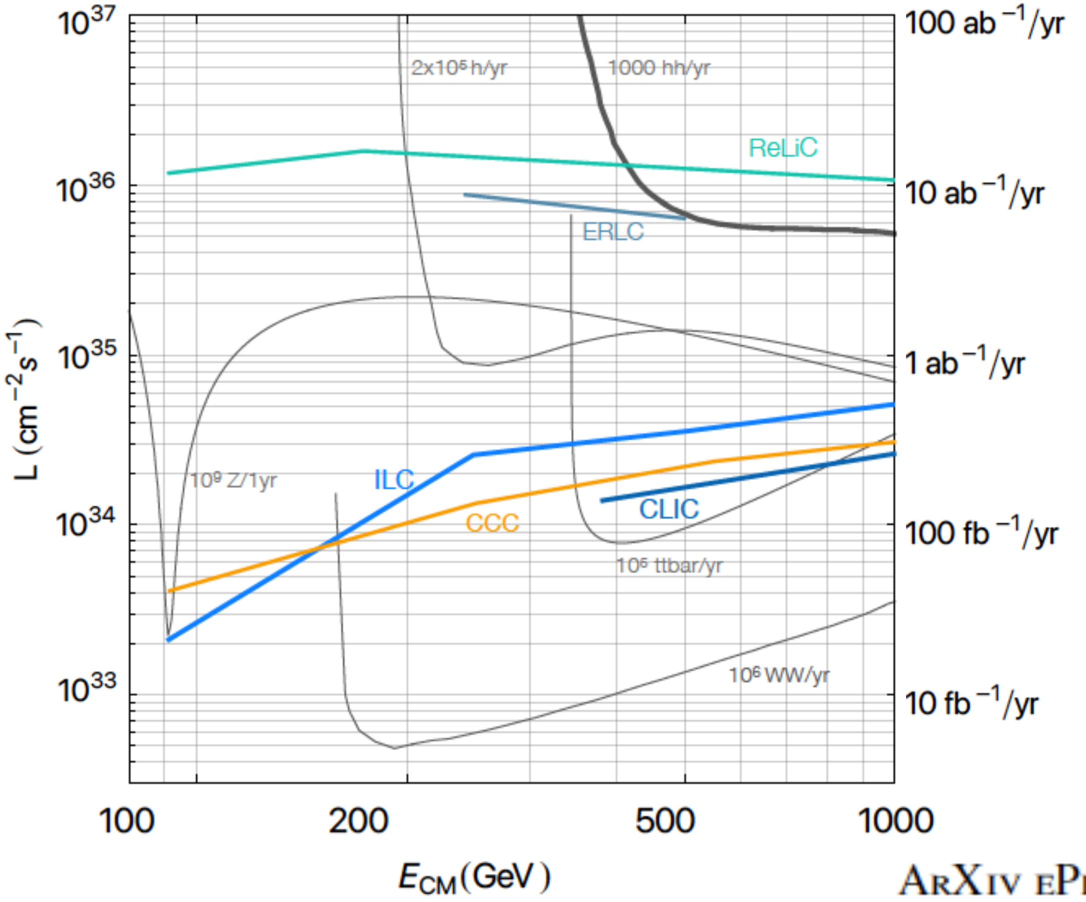
😠 A muon collider might become a viable alternative in that time scale.

LC after initial Higgs factories

- Important benchmark physics goal could be
  - Higgs self-coupling with σ~a few %
    - Very high luminosity at 500 GeV, cf. ILC500 ~20%
      CLIC3TeV 10%. Only FCC-hh or Munon collider 10TeV claim required 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 timescale for such an extension of an e^+e^- LC Higgs factory is 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 $\sqrt{s}$



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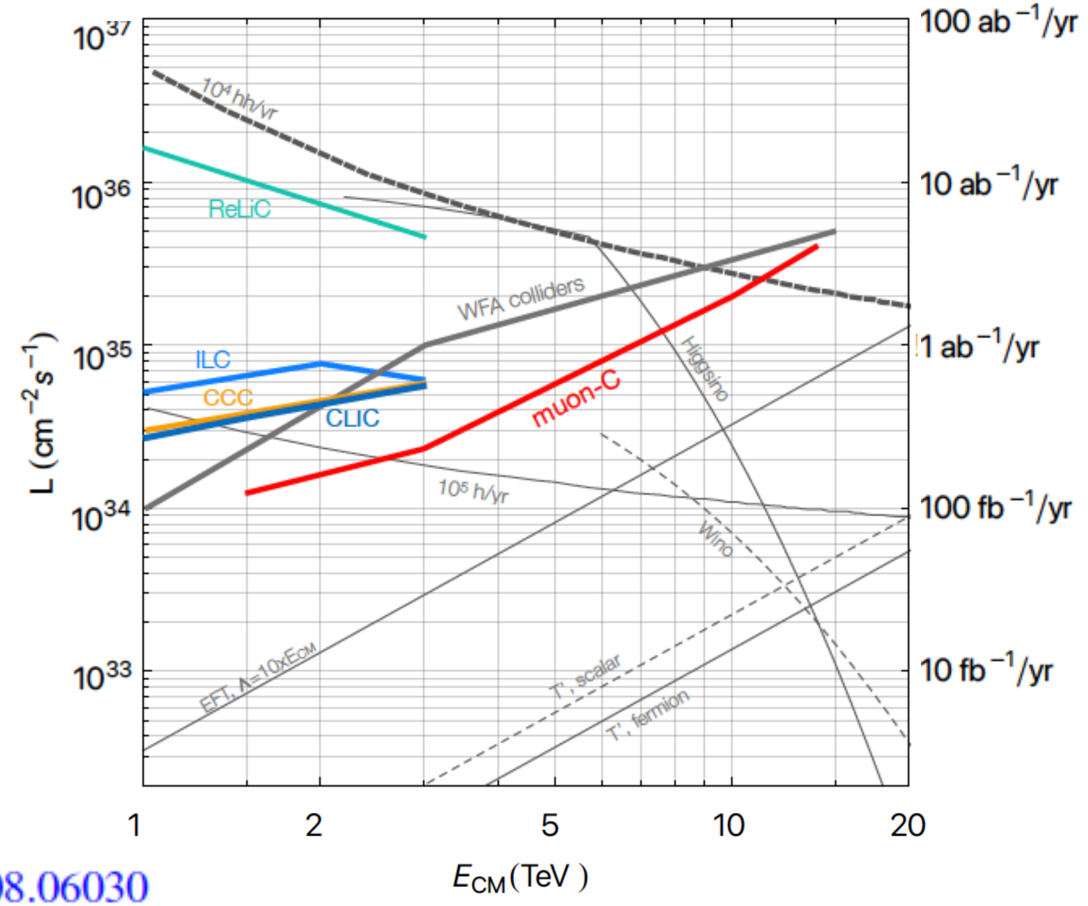

A comment on international and global project

	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.

Personal view

- Although existence of physics beyond the Standard Model is well established, the current knowledges do not tell its nature. Thus, we must continue testing its validity of the Standard Model at many fronts.
- Physics at higher energy scales have been successfully detected indirectly through precision measurements of rare phenomena, thanks to the quantum loop effect. Along this context, precision measurements of the Higgs properties are one of the most promising issue.
- An e^+e^- Higgs factory stands out as an obvious candidate for the next HEP machine. However,
  - it should be flexible and not constrain already the very long-term future at this stage.
  - it should not prevent considering medium scale infrastructure for well motivated projects. We should also note that underground experiments such as the next and next next generation of $0\nu\beta$ decay and dark matter search will require sizable resources.
- An e^+e^- Higgs factory will cost more than LHC even for a linear which is costed less than a circular collider. Is it realistic to construct a Higgs factory as an international project, a la LHC?
  😠The present world is different from the LHC era, which was already different from the LEP era.
- Shouldn't a path of global project be taken more seriously now? It is more complicated and may take some time to get started. But it has also an advantage to generate larger resources. In a longer term, e.g. for 10 TeV physics machine, this will be for sure needed.

⇒ An e^+e^- Higgs factory could be used as a pathfinder!!!

Personal questions for discussion

- How can we weigh among strengths in different physics capabilities in different projects?
- At LEP we had four and LHC two, so-called general purpose detectors. Do we really need more than one detector at the Higgs factory, working at the same machine, while we are using more and more sophisticated detector, simulation tool and analysis methods? Two completely separated date stream a solution?
- Sociological aspect is important for the community but can we defend it towards the outside?
- How important is the spinoff technology to defend the construction of a new collider?
- How can we transmit the "fascination" of precision measurements?
- Shouldn't a path of global project be taken more seriously now? It is more complicated and may take some time to get started. But it will bring us global resources and also provide a better optimisation of the global activities in the field. In a longer term, e.g. for 10 TeV physics machine, this will be for sure needed.