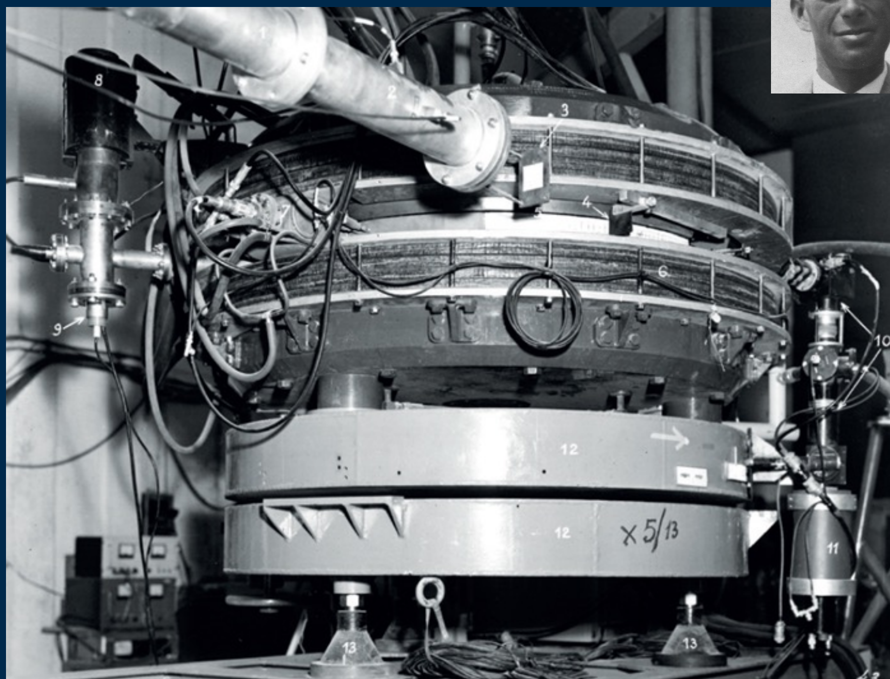
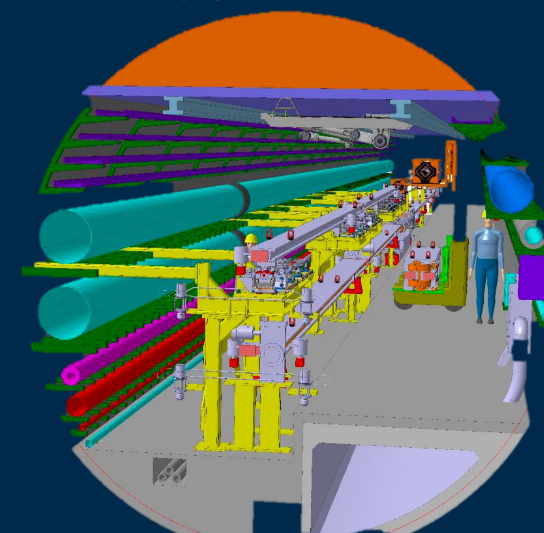
Institut national de physique nucléaire
et de physique des particules





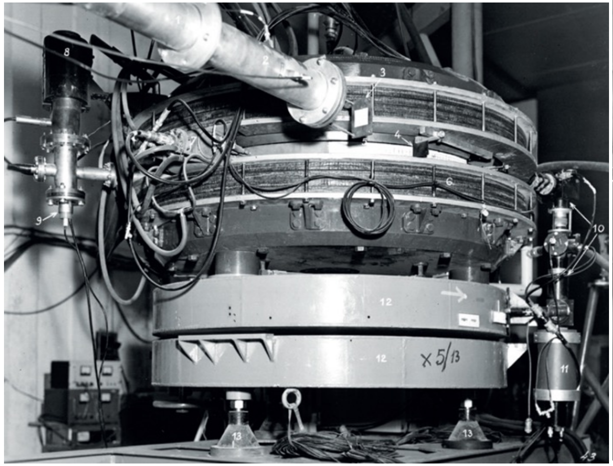
A portfolio of HEP colliders

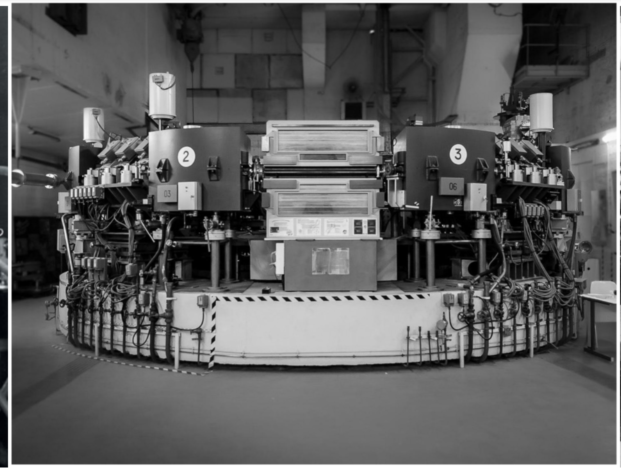
Ursula Bassler

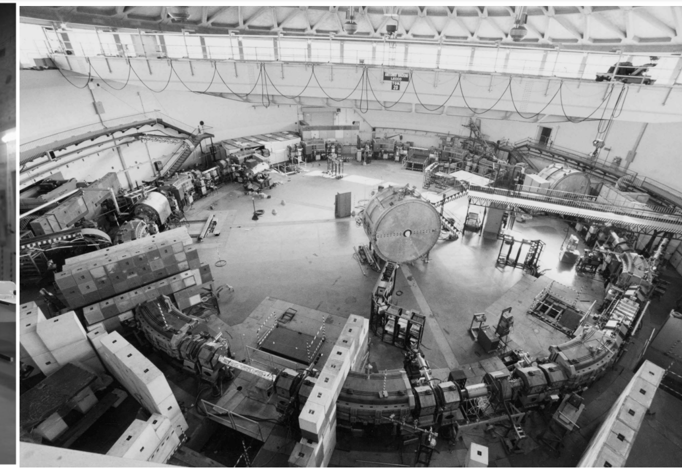
Scientific Director IN2P3

Community report on the Accelerator Roadmap, Frascati July 2023

AdA, ACO, ADONE: paving the way!







AdA: Anello Di Accumulazione
(1963)
- 1,3m diameter, 250 MeV
- first electron-positron collisions
- built in Frascati, shipped to Orsay

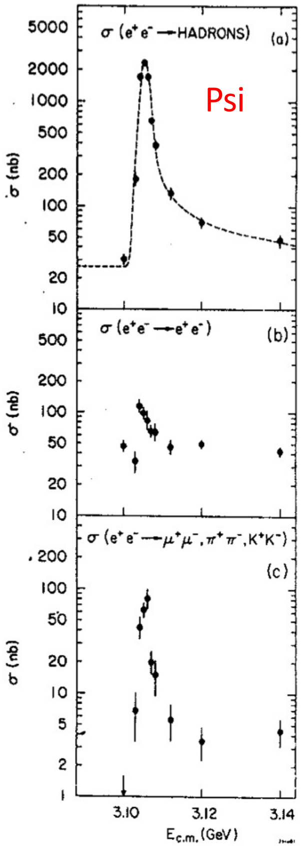
ACO: Anneau de collision Orsay
(1967)
- 7 m de diameter, 500 MeV
- Collisions used for physics, later synchrotron light source

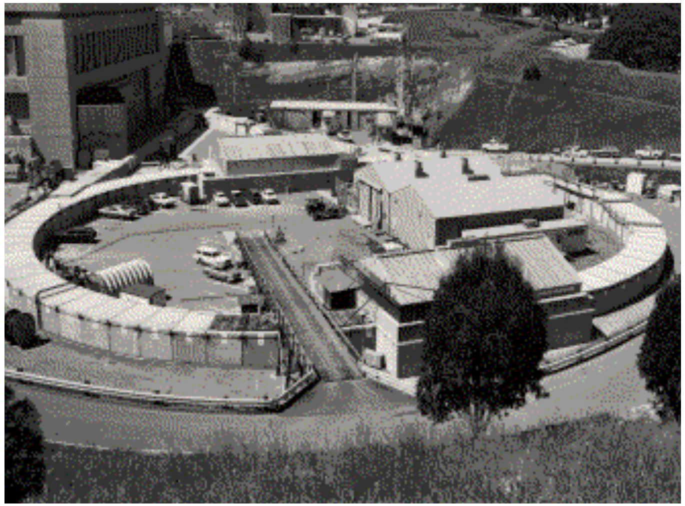
ADONE:
(1969)
- 33 m diameter, 1.5 GeV
- 24 years of operation: 22.000 hours of colliding beam

Work on e+e- colliders
also in Princeton/Stanford (O'Neil),
Novosibirsk (Budker)

Early e+/e- machines also in Novosibirsk (VEP-I, VEPP-2), Havard/MIT (CEA)

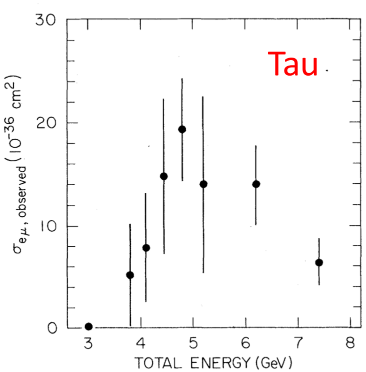
Major discoveries at e^+e^- colliders

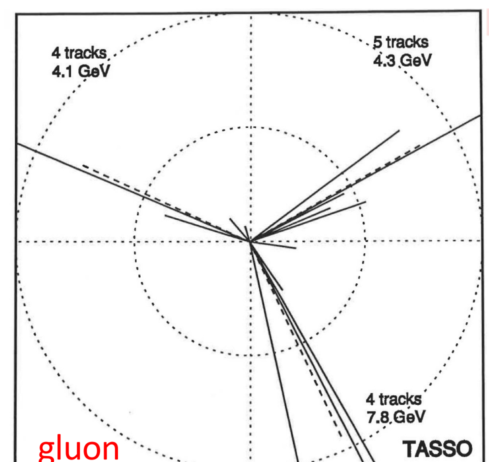




SPEAR 1972

- 80m diameter, 4 GeV
- Discoveries: Psi (1974), Tau (1976)





Petra 1978

- 2,3 km, 19 GeV
- Gluon discovery (1979)

The Electro-weak scale

LEP 1989:
- 27 km, 45 – 100 GeV
- More than 1400 publications!

SLC 1989 :
- 3,2 km, 50 GeV
- first linear collider!

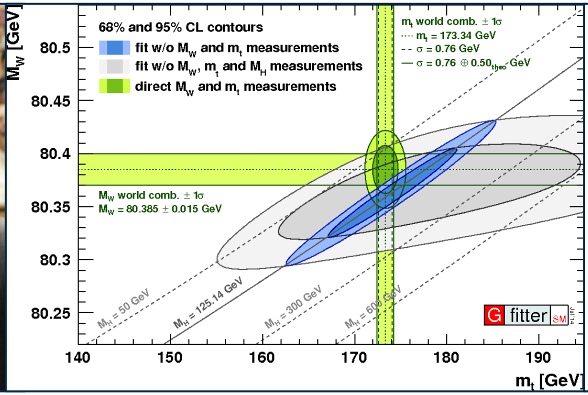
“An electron-positron Higgs factory is the highest-priority next collider."

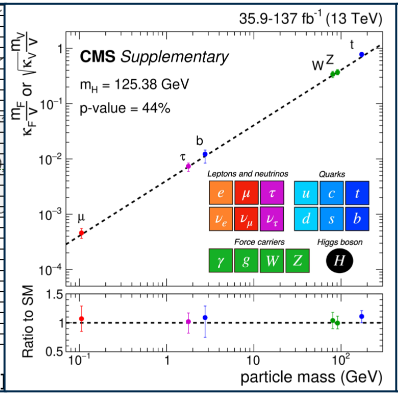
From Higgs discovery towards Higgs precision physics

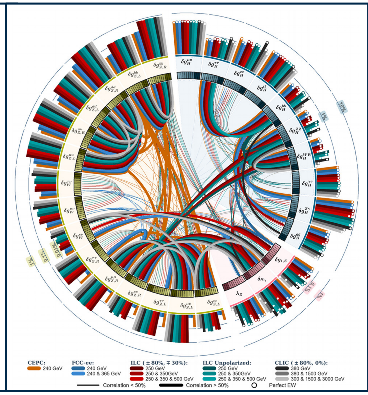
→ Explore a the totally new domain of physics of a scaler field

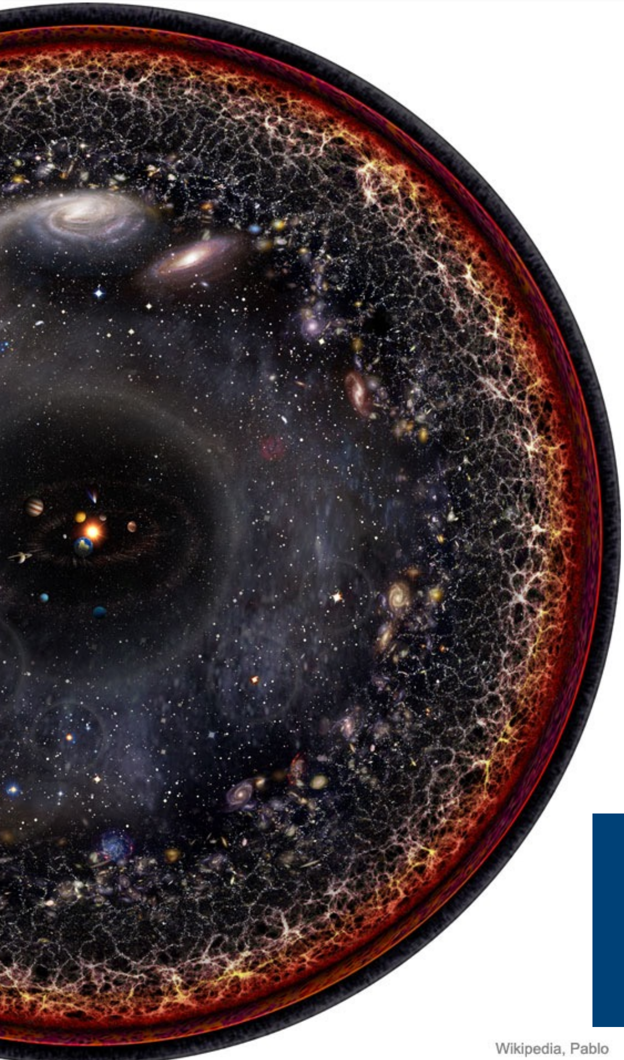
- Completion of the standard model: test of coherence → improve W/top mass
- Precise measurement of the coupling constants → aim: permille level!
- Measurement of the self-coupling: Determination of the Higgs potential
- Search for composite Higgs and additional particles in the Higgs sector

→Detailed study of the Higgs boson and the physics of scaler fields









Wikipedia, Pablo

Links between Particle Physics and Cosmology:

- **Dark Matter** : explanation from new particles?
- **Matter-Antimatter differences** :
  - Baryogenesis, leptogenesis?
  - Observation of Sphalerons?
- **Inflation** and scaler fields?
  - Evolution of Higgs potential in the early universe?
- **Unification** of forces?
- **Quantification** of Gravity?

→ No clear guidelines from theory

→ Higgs is not the only physics motivation: EW-precision measurements, flavor physics, BSM searches

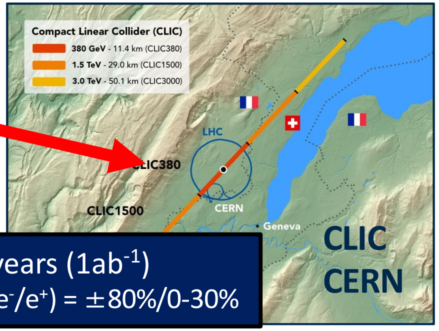
"For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest ***achievable*** *energy."*

Collider concepts at the ESPP

Normal conducting accelerator cavities 72-100MV/m and drive beam technology

Super conducting accelerator cavities 35-45 MV/m

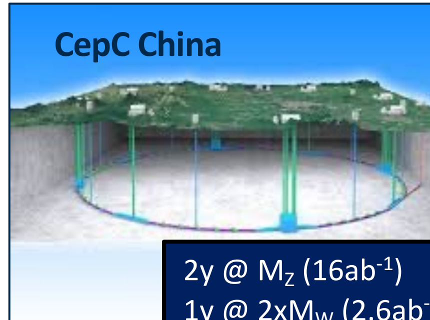
Linear colliders:
nm-beamsize



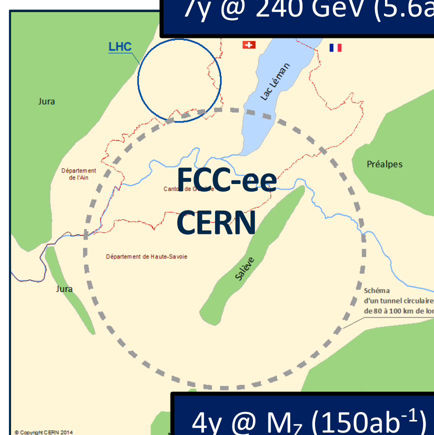
8 years ($1ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/0\text{-}30\%$

11.5 years ($2ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/\pm 30\%$

Circular collider:
synchrotron radiation



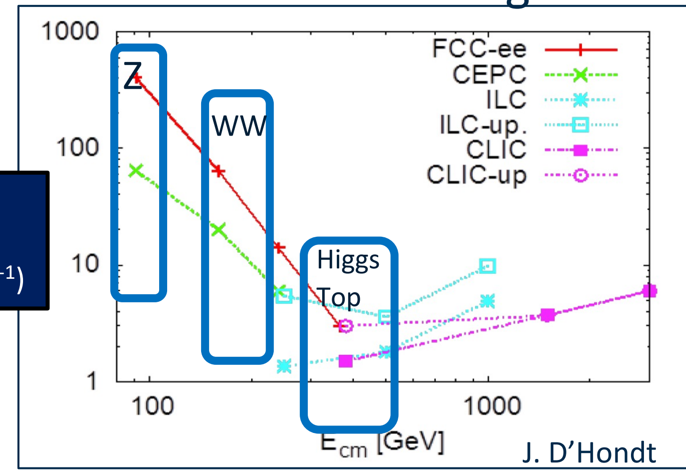
2y @ M_Z ($16ab^{-1}$)
1y @ $2xM_W$ ($2.6ab^{-1}$)
7y @ 240 GeV ($5.6ab^{-1}$)



4y @ M_Z ($150ab^{-1}$)
1-2y @ $2xM_W$ ($10ab^{-1}$)
3y @ 240 GeV ($5ab^{-1}$)
5y @ $2xm_t$ ($1.5ab^{-1}$)

4 possible colliders:

Linear or circular design



Differences :

- Energy reach
- Flavour physics
- Luminosity performance

➔ Precision frontier vs energy frontier

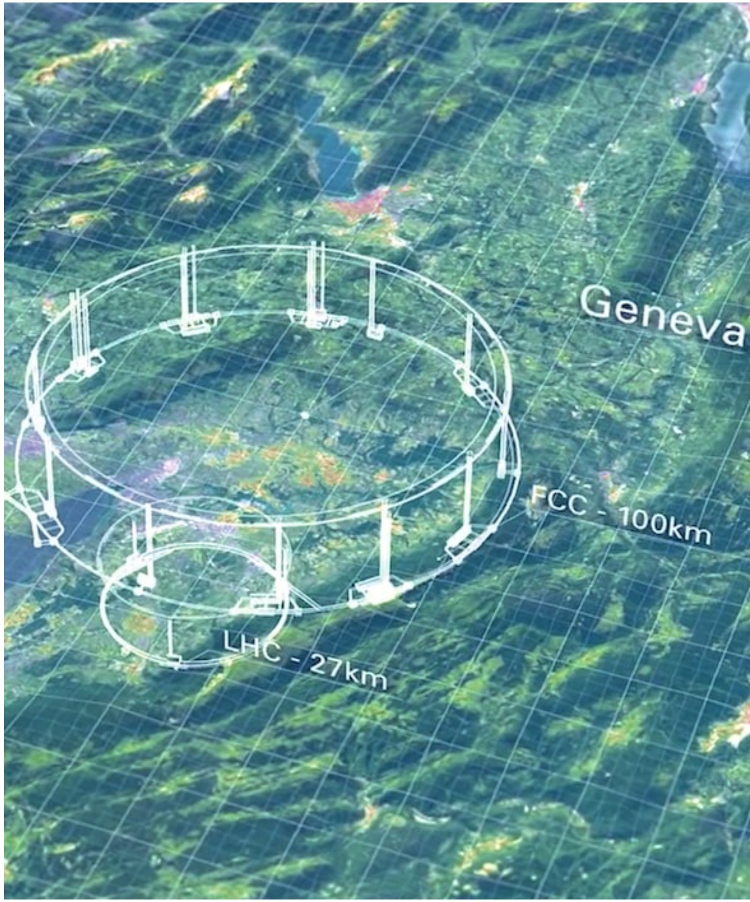
CNRS IN2P3 Les deux infinis

FCC-ee: Collaboration: FCC-week 2023 London
150 institutes, 32 compagnies, 34 countries

- Feasibility study updating 2919 CDR:
  - mid-term review end of 2023,
  - final report 2025:

  → Infrastructure and placement, Technical Infrastructure, Accelerator designs, Physics, Financing and Organization
- Cost estimation ≈11 G
- Additional contributions beyond CERN budget ≈20-50%
- Particular focus: environmental impact and local implementation

→ Input to the next European Strategy around 2026/2027



CepC: CEPC-week 2023 Edinburgh
Collaboration 221 institutes, 140 non-domestic (20 MoU), 70 compagnies

- CDR published 2018, TDR tbp 2023, EDR 2025
- Cost estimation ≈ 5 G
- International participation foreseen ≈15-20%
- Highest ranked HEP/NP project in strategy exercise of the Chinese Academy of Science :

→ Decision for possible construction start in 2027 at the next 5-year plan in 2025

Circular collider with Energy Recovery Linacs: CERC

V.Litvinenko et al (BNL - 2019)

« Squaring the circle » !

Linear collider: bunches collide only once

→ efficient collisions (collisions per beam particles)

→ higher luminosity

Storage ring collider: recovery of beam energy during deceleration

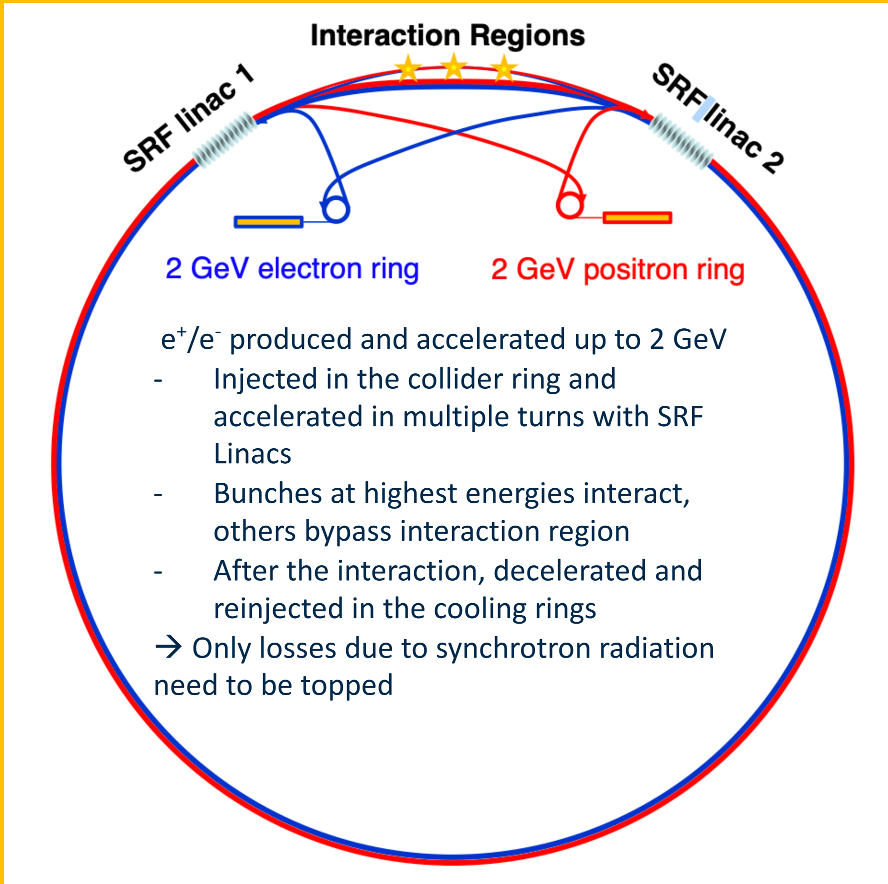
→ Recycling of beam energy and particles

Requires:

- R&D !

→ BNL-ERL, Cornell (Cbeta), HZB (berlinPro), IJClab (Perle)

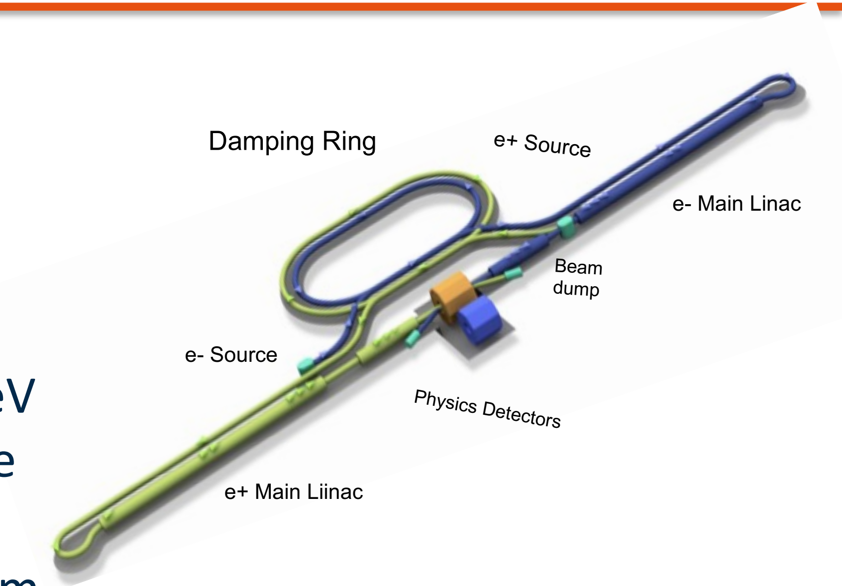
→ European Project iSAS accepted



Also linear collider concepts : Relic, ERLC

ILC: First LCWS 1991, Saariselka, Finland
- 3 linear collider concepts (JLC/GLC – Japan, NLC – SLAC, TESLA – DESY)

→ 2004 : ILC – choice of superconducting technology, setup by ICFA of GDE and FALC
- 2007: Reference design report 500 GeV-1 TeV
- 2013: TDR published, Japan proposed as site by Japanese HEP community
- 2020: setup of an International Develop team (IDT)→ 250 GeV ILC
- Studies for upgrades up to 3 TeV
- International Technology Network : KEK-CERN agreement 7/7/2023: cooperation with CERN and CERN as European hub → other collaborations looked for

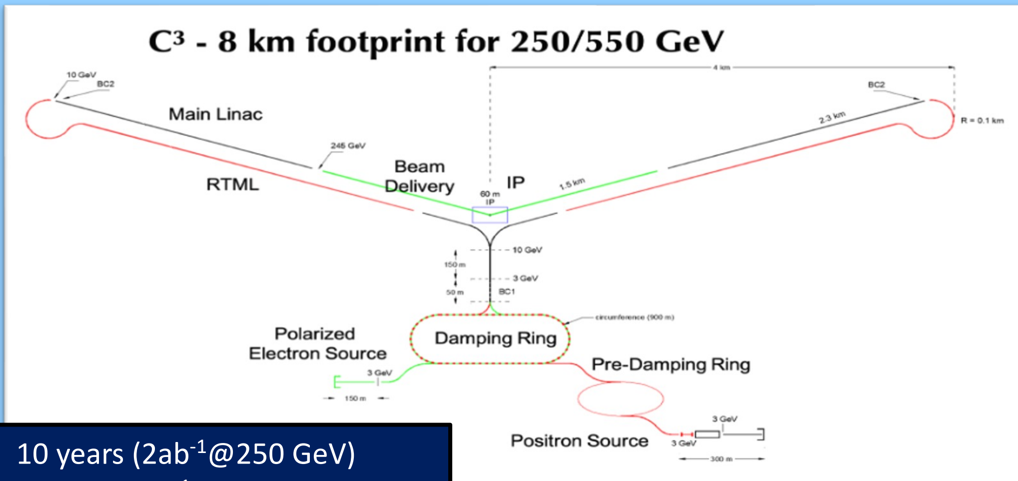


CLIC: two beam concept proposed in 1986

- CDR in 2012 focus on 3 TeV, update in 2018 with focus on 380 GeV

→ Project Readiness Report

- 50 institutes from 28 countries
- R&D on luminosity optimization and power efficiency
- X-band studies for use of small, compact Linacs for applications.



10 years ($2ab^{-1}$@250 GeV)
4 years ($4ab^{-1}$@550 GeV)

Higgs factory on FNAL site: ≈7km

C^3: Cool Copper Collider (SLAC/FNAL)

- new RF technology
- Cryogenic temperatures (liquid Nitrogen ~ 80K)
- High gradient: 70-120 MeV/m

→ improving efficiency and breakdown rate

- Scalable to multi-TeV operation

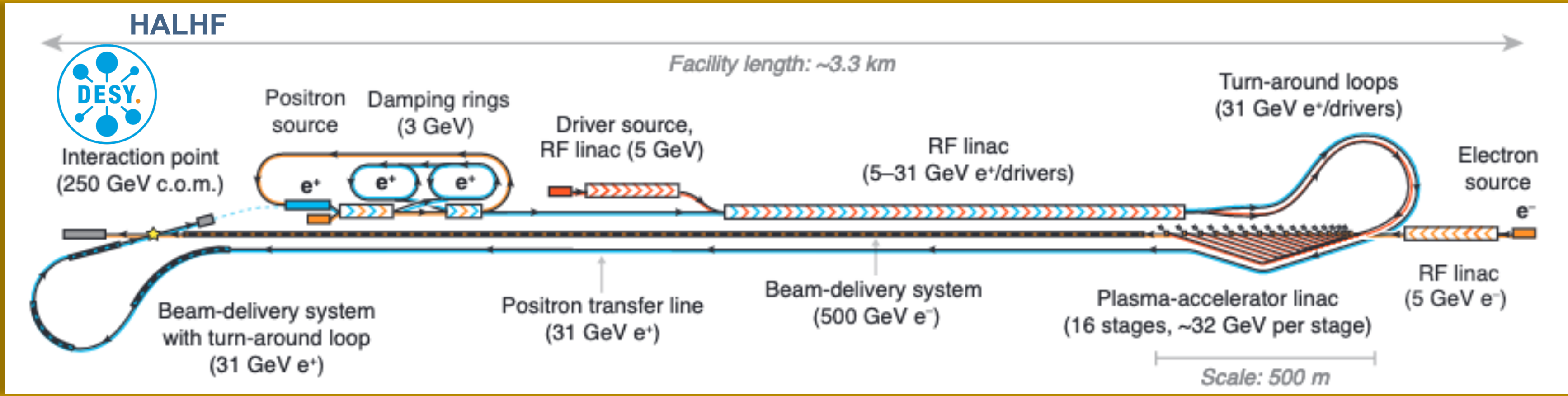
Presentation during US Snowmass process:

- Large portions of accelerator complex compatible between LC technologies
- Damping rings and injectors to be optimized with CLIC as baseline

Proposal for 5-year demonstrator development@ SLAC ➔ TDR:

3 C^3 cryomodules ≈120 M (Total Project cost+contingency)

→ **Evaluation during P5 process to be presented October 2023**



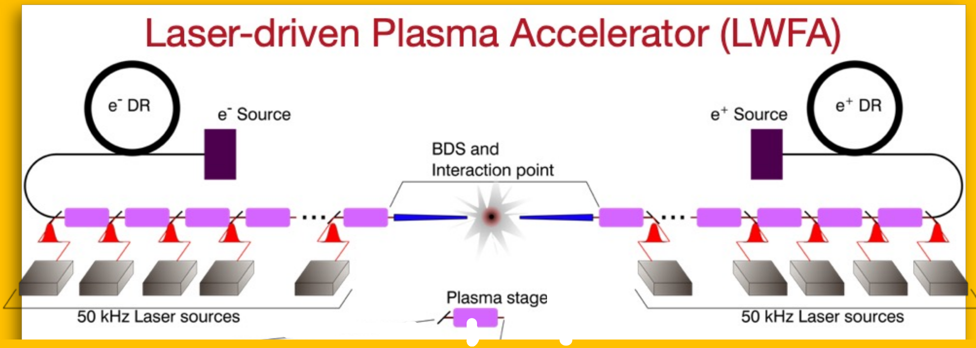
HALHF: Hybrid Asymmetic Linear Higgs Factory (DESY)

- PWFA e^- accelerator, low energy conventional e^+ accelerator
- Most innovative concept : small (3,3km) and cheap (≈ 1,5 G€) ➔ national facility
- (+) Efficient energy consumption (-) luminosity
- Towards higher energies: trade off between Linac length and boost
- Major R&D areas → 10% demonstrator?

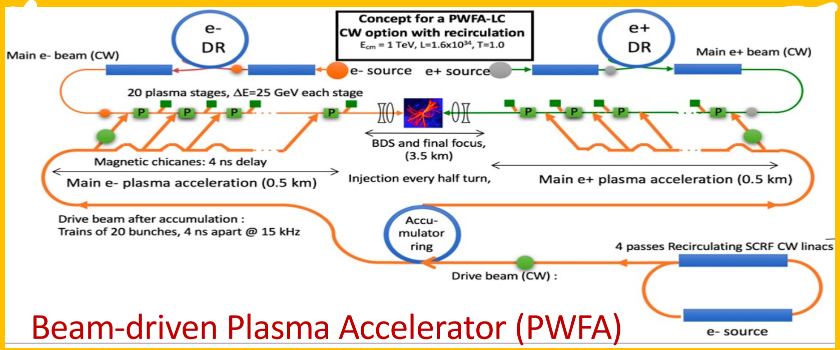
Plasma Wakefield accelerators towards 10 TeV scale

Impressive progress over the last years in Plasma Wakefield Acceleration !

Alegro: ICFA initiated international collaboration PWA



Schroeder et al. – LBNL



© Adli et al., Chen et al.

→ Ultra high gradients opens path to 10+ TeV colliders

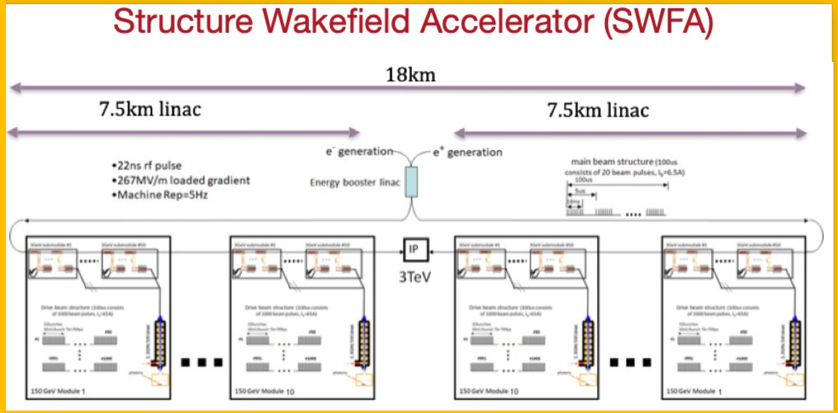
→ Main challenges:

staging of plasma modules, consistent high beam quality, emittance preservation, low energy spread, efficient energy transfer, high repetition rate, reduction of power consumption …

→ Possiblity of $\gamma\,\gamma$-collider → no positron source

Some facilities: BELLA (LBNL), FLASHForward (DESY), FACET-II (SLAC), AWA (ANL), AWAKE (CERN)

To come: EuPraxia (LNF)

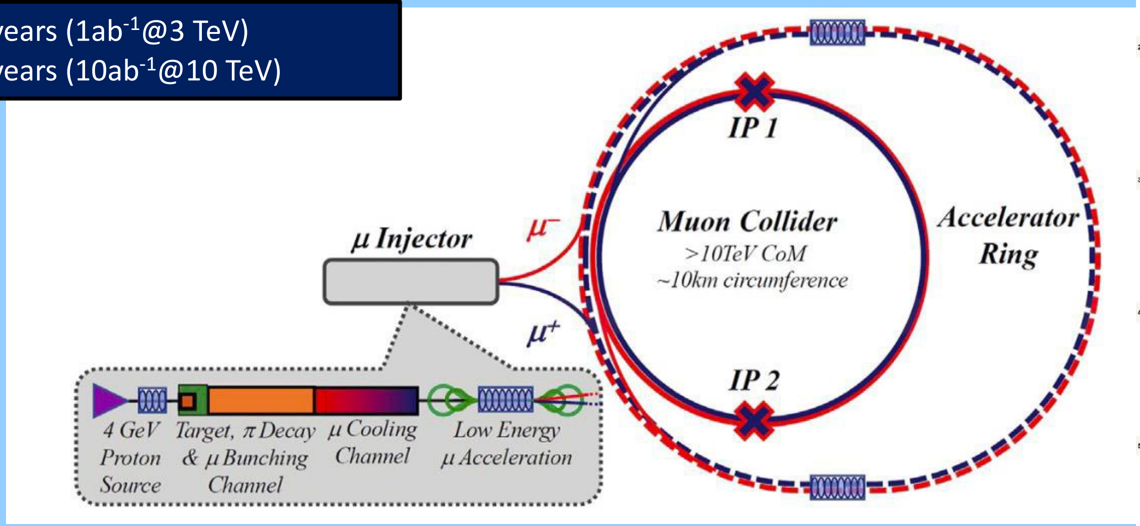


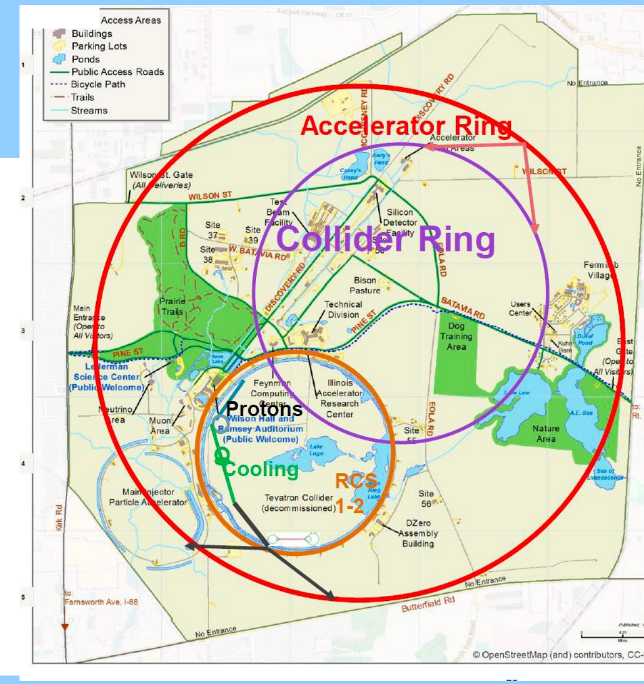
© C. Jing et al. ANL

Muon collider

Initial Concept of Muon Collider from 1983: Skrinsky et al, Neuffer et al.
- R&D activities in the mid-1990
2022: International Muon Collider Collaboration (IMCC) hosted at CERN

5 years ($1ab^{-1}$@3 TeV)
5 years ($10ab^{-1}$@10 TeV)





© Diktys Stratakis (FNAL)   Possible Fermilab implementation

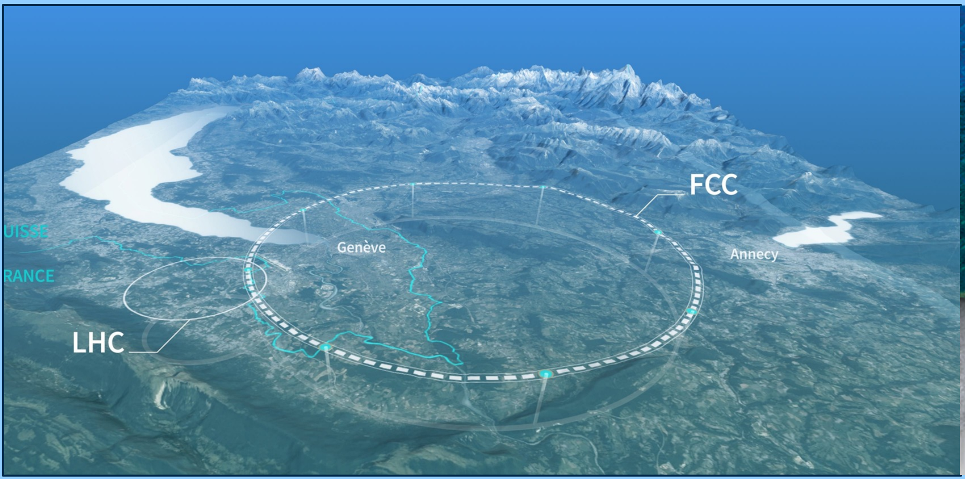
- Requiring high power proton source (1-4 MW) and suitable targets (C or W promising)

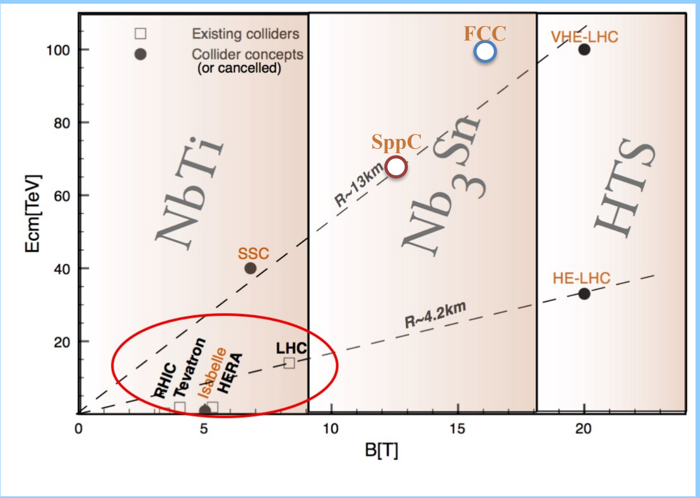
→ Synergies with proton accelerator developments for neutrinos experiments

- Cooling, high field magnets, neutrino flux mitigation (radiation protection)

→ Timescales : R&D phase (7 years), demonstrator phase (10 years) → TDR by 2030

100 TeV hadron colliders: FCC-hh, SppC





Hadron colliders may reach about 100 TeV or beyond

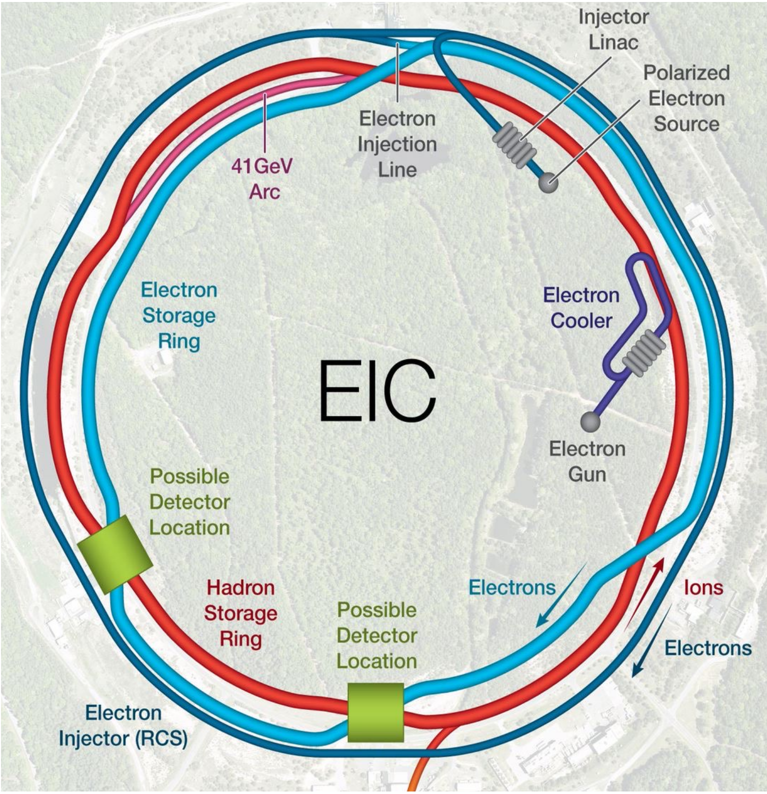
→ magnets drive:

- Physics/Energy reach
- Cost : about ≈ 70%

➔ Important place on the Roadmap for magnet development

➔ CERN led effort in Europe

Electron Ion Collider@BNL



Funding from nuclear physics:

- Nucleon spin
- Hadron masses

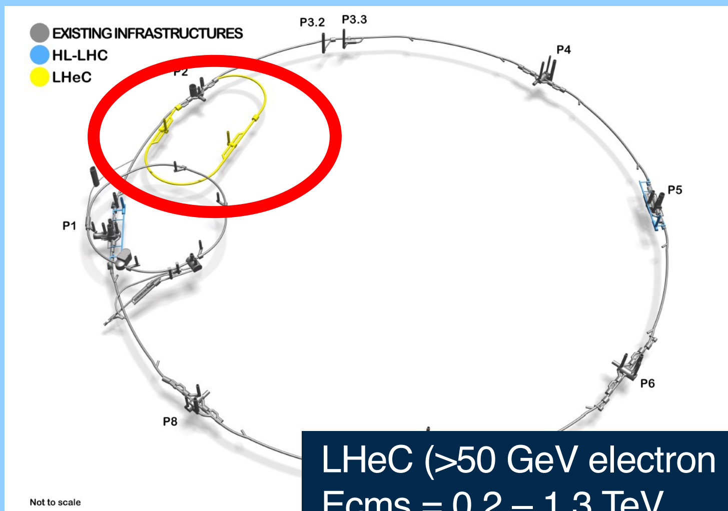
- Polarized electrons beams on protons and light ions

2025: TDR and construction start
2034: Begin of physics programme

Rich R&D and pre-production prototypes:

- Polarized electron source
- Fast kickers
- Polarimeters
- Cavities

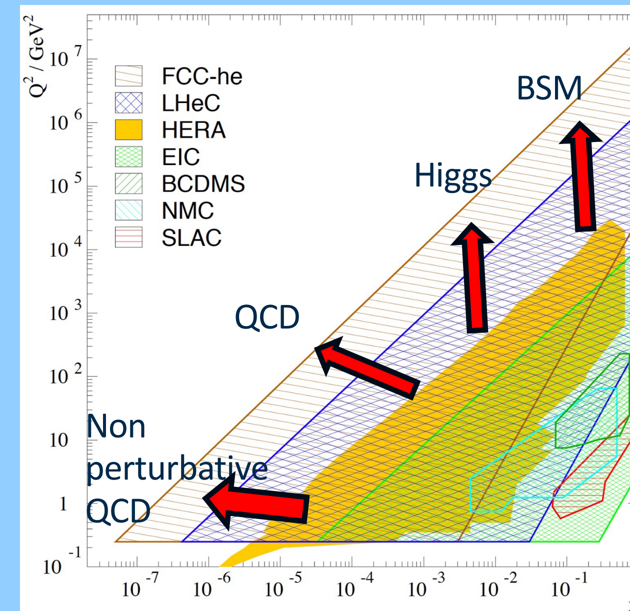
High energy ep collider

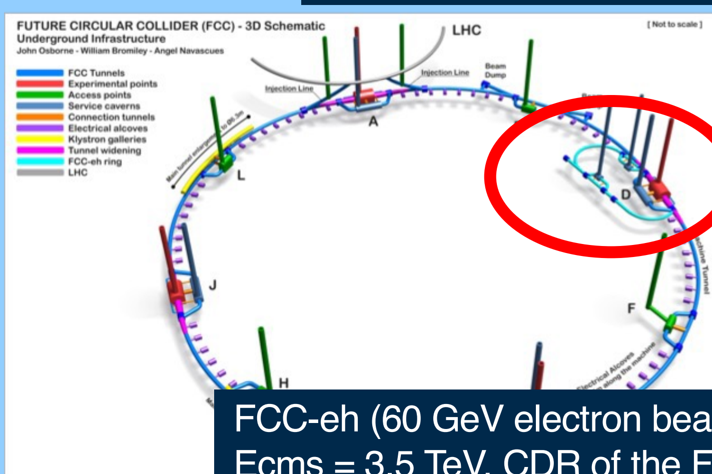


LHeC (>50 GeV electron beams)
Ecms = 0.2 – 1.3 TeV

HERA → pdf for LHC physics simulations

FCC-eh → tremendous improvement in pdf precision, but also contribute to Higgs measurements and BSM searches

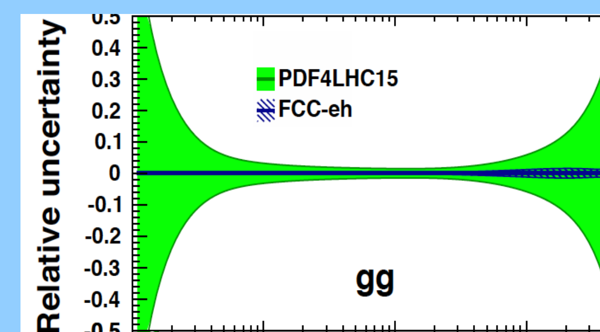




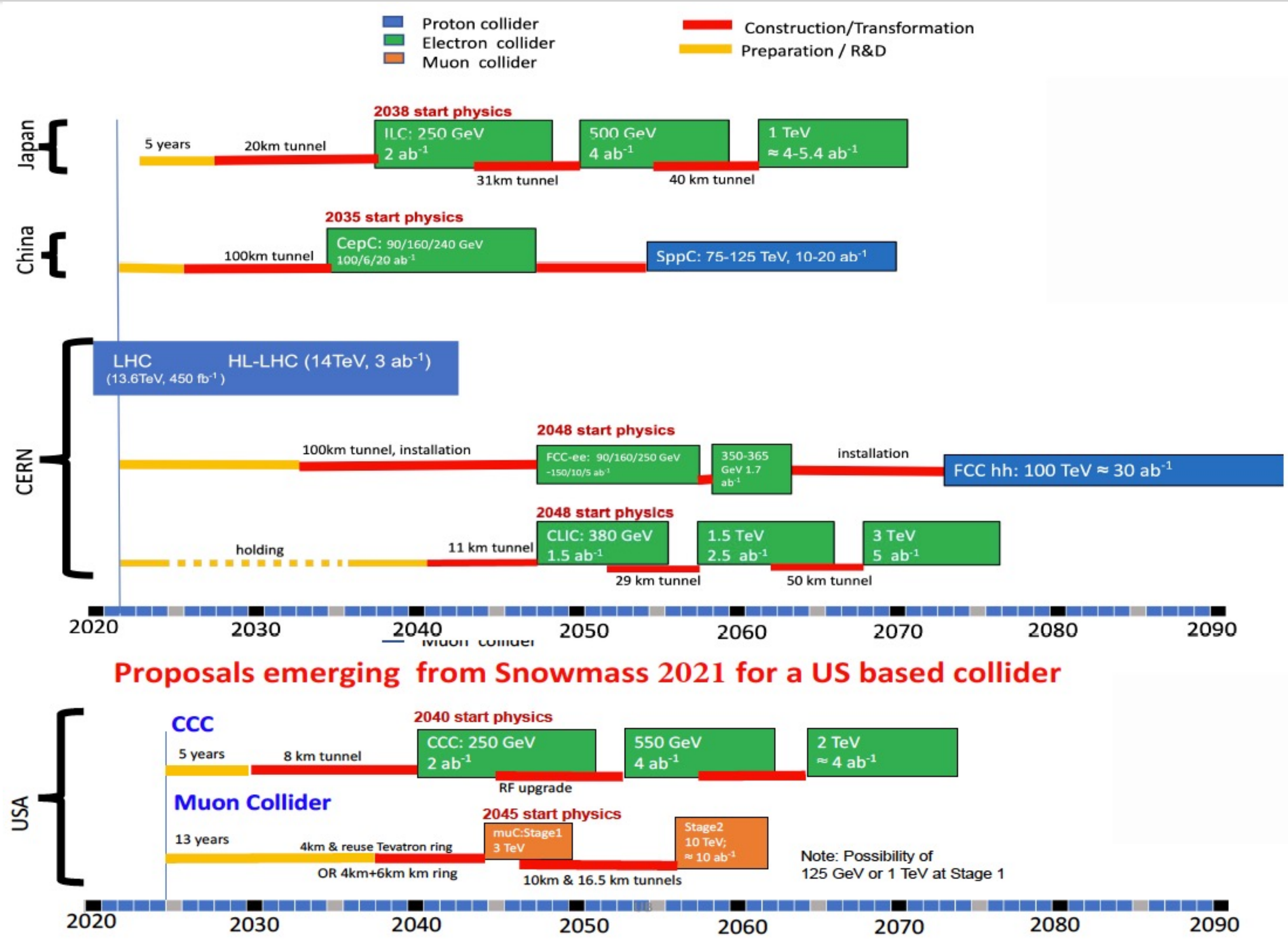
FCC-eh (60 GeV electron beams)
Ecms = 3.5 TeV, CDR of the FCC

ep-collisions in parallel with normal pp operation of hadron colliders

e-beam could be produced used ERLs !



Collider timescales after Snowmass 2021



Technical Risk table

© Snowmass 2023 : Collider implementation Task Force

Technical risk categories (darker blue is higher risk).

"Design status":
I - TDR complete
II - CDR complete
III - substantial documentation
IV - limited documentation and parameter table
V - parameter table

"Overall risk tier":
1 – lower overall technical risk
…
4 – multiple technologies require further R&D

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

Environmental impact

© Snowmass 2023 : Collider implementation Task Force

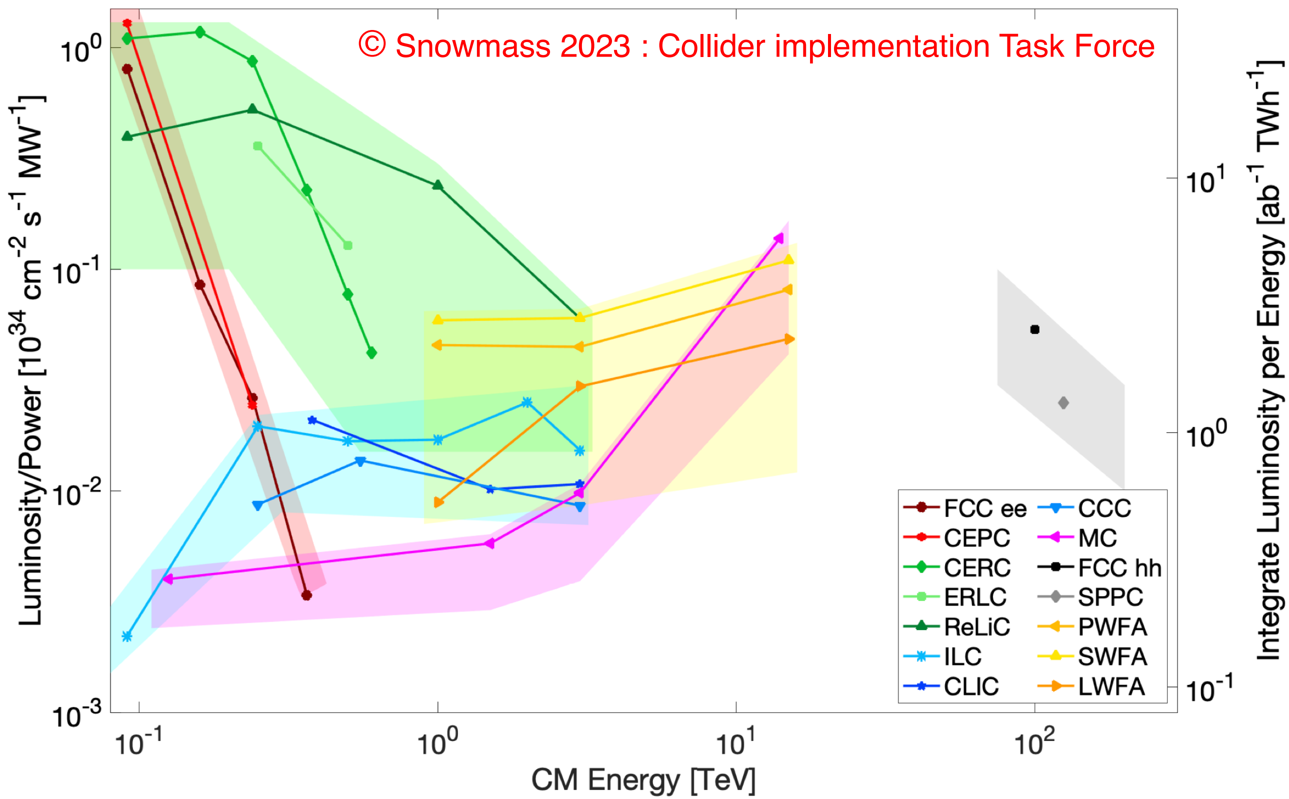
Power, complexity, environmental impact

Summary table of categories of electric power consumption, size, complexity and required radiation mitigation.

Darker blue means more impact.

Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	91 km	II	I
ReLiC (0.24 TeV)	315	20 km	II	I
ERLC (0.24 TeV)	250	30 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	0.3 km	I	II
ILC (3 TeV)	∼400	59 km	II	II
CLIC (3 TeV)	∼550	50.2 km	III	II
CCC (3 TeV)	∼700	26.8 km	II	II
ReLiC (3 TeV)	∼780	360 km	III	I
MC (3 TeV)	∼230	10-20 km	II	III
LWFA (3 TeV)	∼340	1.3 km (linac)	II	I
PWFA (3 TeV)	∼230	14 km	II	II
SWFA (3 TeV)	∼170	18 km	II	II
MC (14 TeV)	∼300	27 km	III	III
LWFA (15 TeV)	∼1030	6.6 km	III	I
PWFA (15 TeV)	∼620	14 km	III	II
SWFA (15 TeV)	∼450	90 km	III	II
FCC-hh (100 TeV)	∼560	91 km	II	III
SPPC (125 TeV)	∼400	100 km	II	III

Luminosity per power consumption



Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.

Luminosity is per IP and integrated luminosity assumes 10^7 sec/year

Data points are provided to the ITF by proponents of the respective machines.

The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts

CNRS IN2P3 Les deux infinis

- **Initiatives for future colliders** are generally taken by a major laboratory and since HERA with contributions from international partnets.
- For a **global initiative**, the field lacks the adequate coordination structure:
  - **CERN Council** includes government representatives and allows for shared governance and risk management, but is limited to the Member States
  - **ICFA** has a global representation but no forum for intergovernmental exchanges, binding exchanges.
  - Regional strategic exercises with cross-representation, but no "**global strategy**"
- **Is it necessary ? Or can we go without?**
  Depends on the funding options:
  - Predominant funding through the host laboratory carrying risks and having the final decision power:
    → **international** project (HERA, LHC…)
  - Shared funding, risk and decision taking
    → **global** project planning required (ITER, SKA…)
- Operations has so far been born by the host laboratory → may become a subject

Strategy outcomes

- **Higgs factory** is the highest priority physics case, yet we also need to do **EW** and **QCD** precision measurements, **flavor physics**, **BSM** searches….
- **Strategic exercises** in Europe, the US, etc… lead to a detailed comparison of currently studied collider concepts and initiated new ideas

→ The **variety** of the developments and the innovation in the field is impressive !

- Mandatory to address **environmental aspects** in technical developments

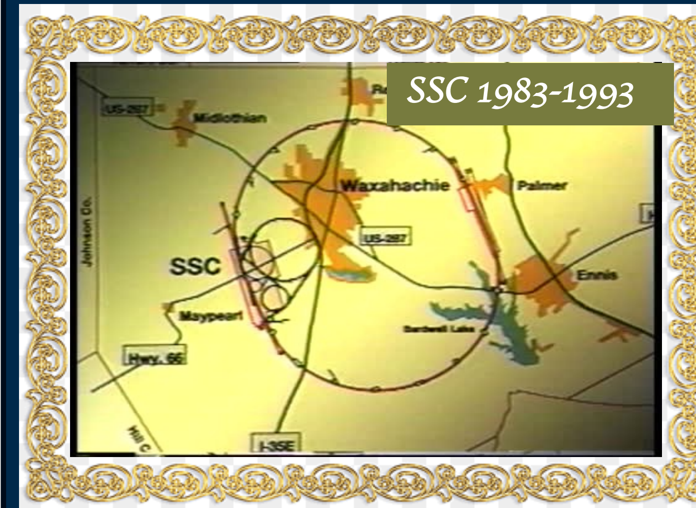
→ HTS materials, klystron efficiencies, ERL, AI for beam design and control…

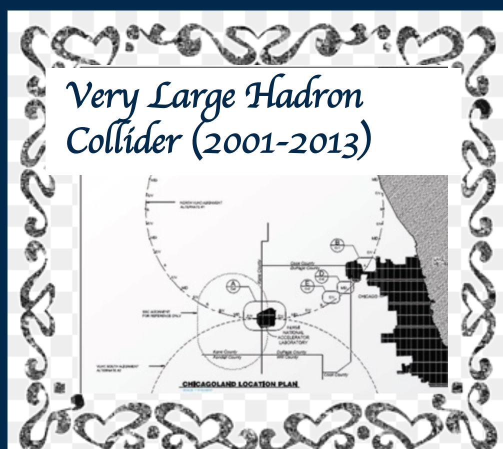
→ Major R&D efforts ineed to be understood globally

- **Collider concepts** are developed with different aims and time scales:
  - soon to be built Higgs factories
  - multi-TeV lepton colliders
  - 100 TeV hadron colliders

→ **Rich landscape for physics programs to come**

“The graveyard of Future Colliders Concepts”





A bouquet of Higgs factories