Prospects on future energy frontier colliders

Brief overview of talks and discussions in
CERN Council Open Symposium on the Update of
European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

Alexander Kupčo
Institute of Physics of Czech Academy of Sciences

Meeting of Particle Physics Czech and Slovak community

May 2019, Prague

EPPSU 2019 meeting

- https://cafpe.ugr.es/eppsu2019/
- Input for this talk
  - C. Biscardi: *Accelerator Summary +* talks in parallel sessions
  - F. Gianotti: *Implementation of the 2013 European Strategy Update*
  - G. Taylor: *Perspective on the European Strategy from Asia*
- *Submitted input documents*

European Strategy Update

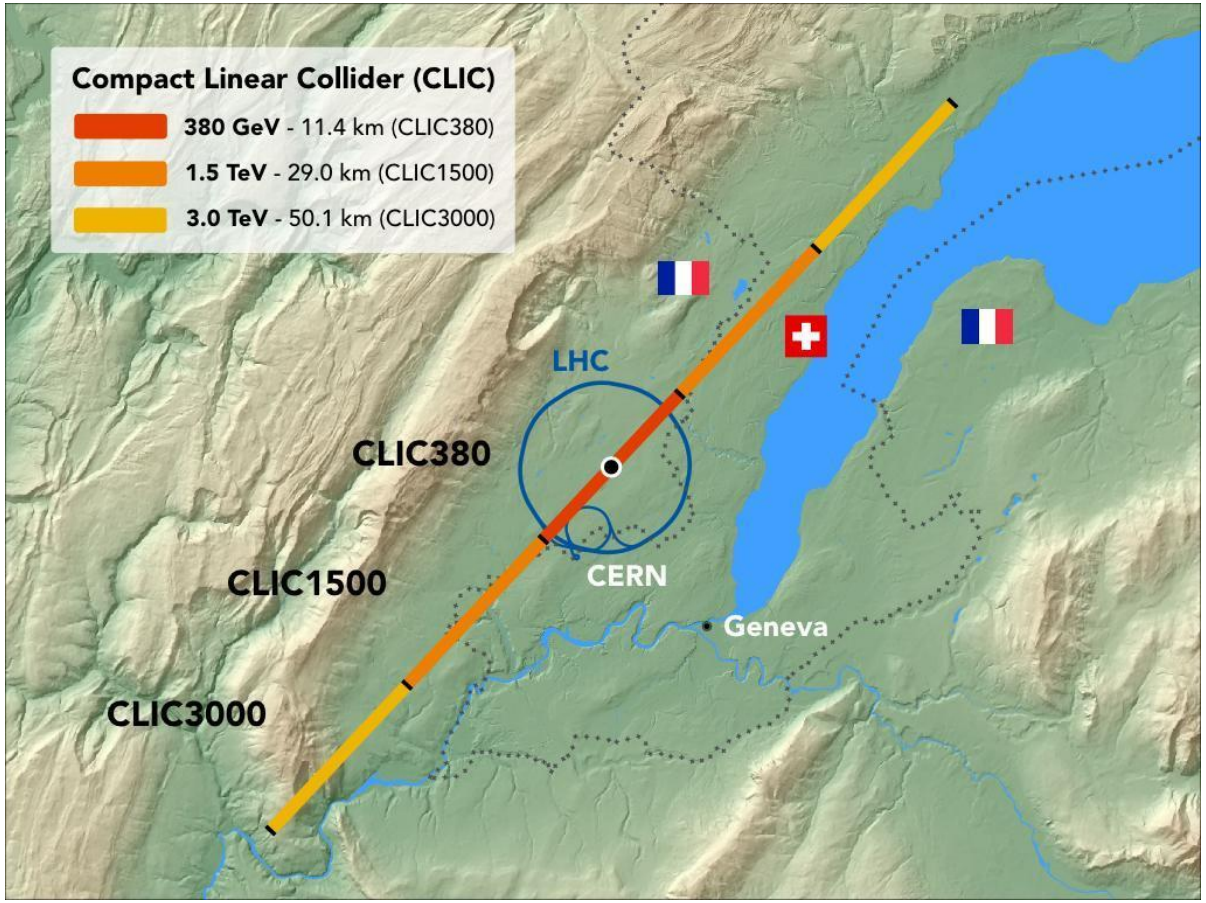
Accelerators summary

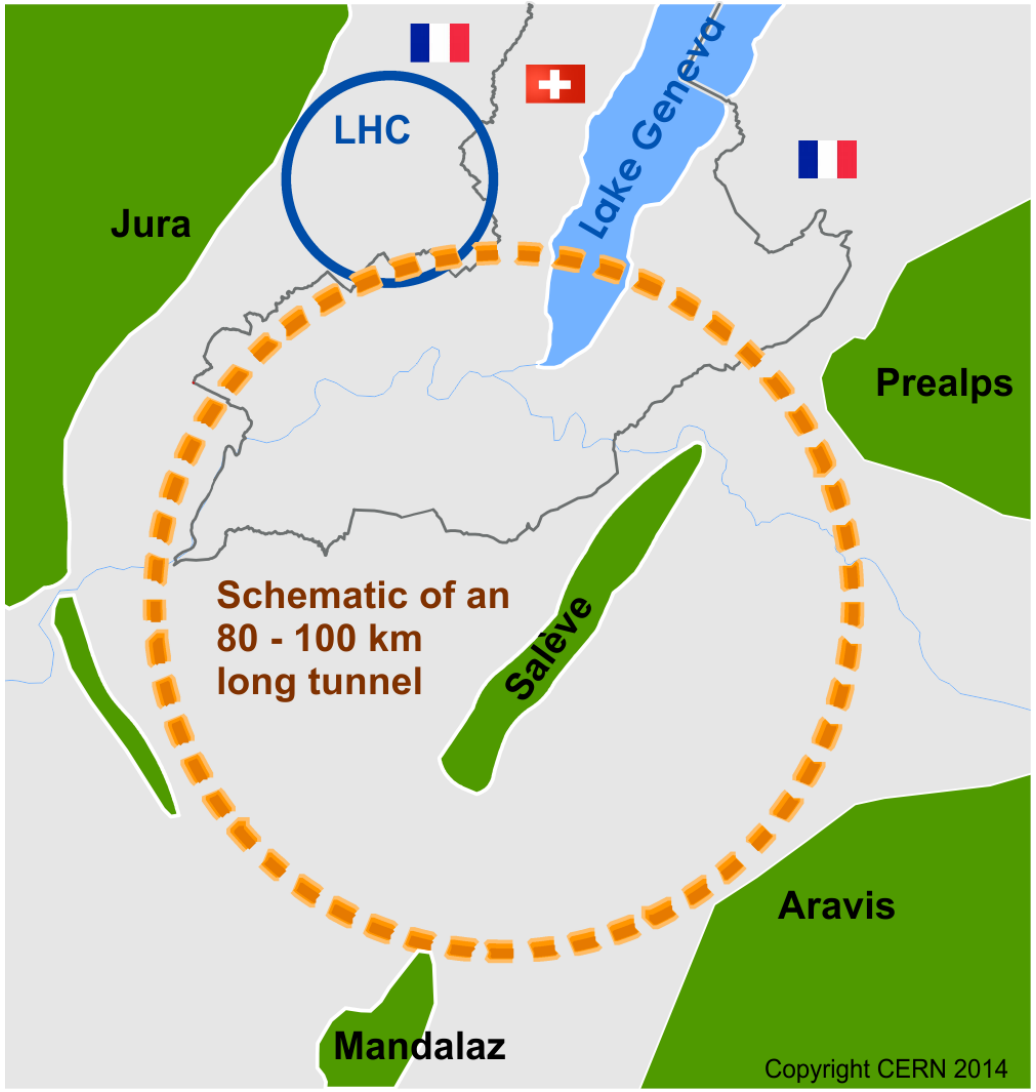
Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics

May 13-16, 2019, Granada, Spain

Q1: What is the best implementation for a Higgs factory?
Choice and challenges for accelerator technology: linear vs. circular?

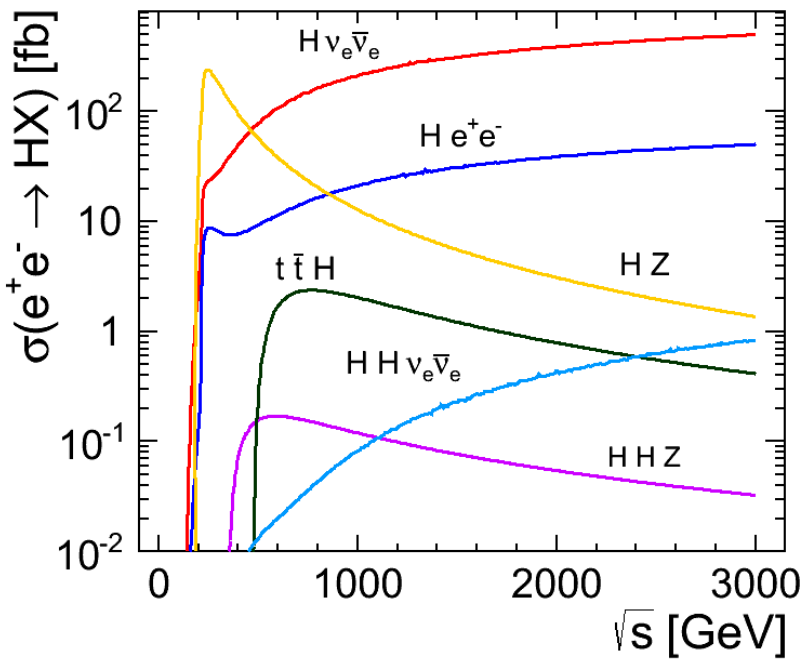




Higgs Factories

All new high-energy colliders are also higgs factories

- Cannot cover them all in detail, so focus on some



- Electron-positron colliders
  - Linear colliders
    - ILC and CLIC
  - Circular colliders
    - FCC-ee and CepC
    - (LEP 3)

One in Europe, one in Asia

- Hadron colliders
  - LHC, HL-LHC, HE-LHC, FCC-hh and SppC

Happens in any case

- Lepton-hadron colliders
  - LHeC and FCC-eh
- Muon colliders
- Plasma colliders
- LEP3 and "Low-field" magnets in FCC tunnel

Not mature enough at this moment
More R&D needed
Muon colliders could come in if we fail to have another higgs factory

Rationales

CLIC:
Ultimate goal: Achieve multi-TeV electron-positron collisions
- Linear collider with high gradient normal-conducting acceleration
- Overcome the challenges with technologies
- Now: do it in stages for physics and funding

ILC:
Ultimate goal: Reach energies of originally 0.5-1 TeV
- Use high gradient superconducting technology
- Now reduce cost to obtain funding

FCC-hh + FCC-ee
Push the energy frontier with protons
- Large ring with high field magnets

Use the FCC-hh tunnel for an electron-positron collider
- The layout and cost is not optimised for FCC-ee proper

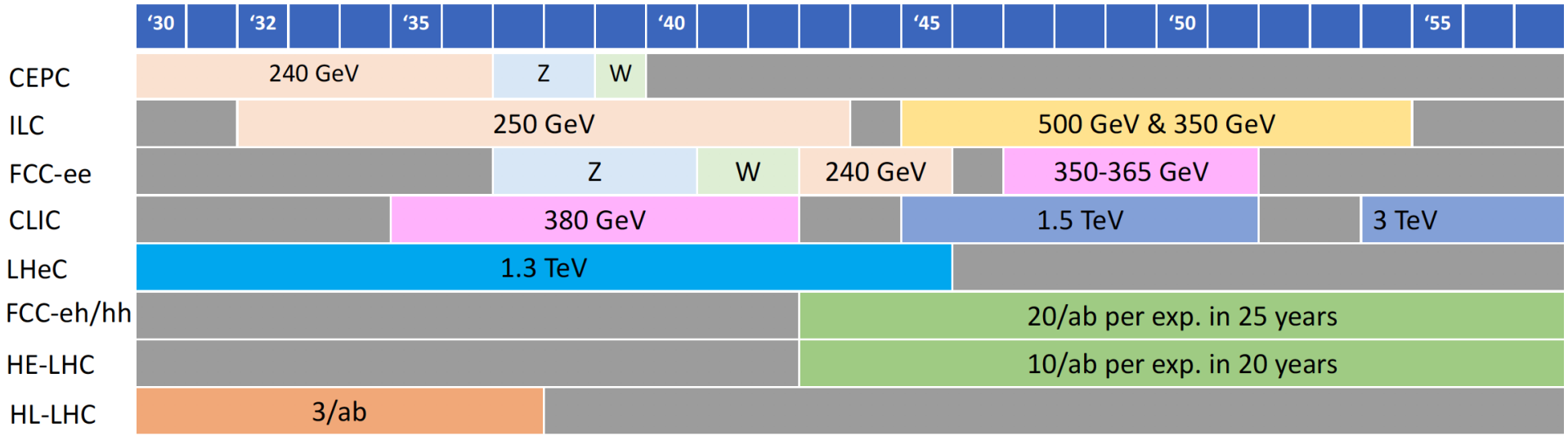
CEPC:
Build a higgs factory with limited energy with a tunnel that could house a hadron collider afterwards

LHeC:
Expand the LHC programme with limited cost

Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost	Annual energy consumption [TWh] CERN today: 1.2 TWh
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade	
		0.5	4	10	163 (204)	7.8 GILCU	
		1.0			300	?	
CLIC	ee	0.38	1	8	168	5.9 GCHF	0.8
		1.5	2.5	7	(370)	+5.1 GCHF	1.7
		3	5	8	(590)	+7.3 GCHF	2.8
CEPC	ee	0.091+0.16	16+2.6		149	5 G$	
		0.24	5.6	7	266		
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF	
		0.24	5	3	282		
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF	1.9
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF	
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)	4
HE-LHC	pp	27	20	20		7.2 GCHF	

Proposed Schedules



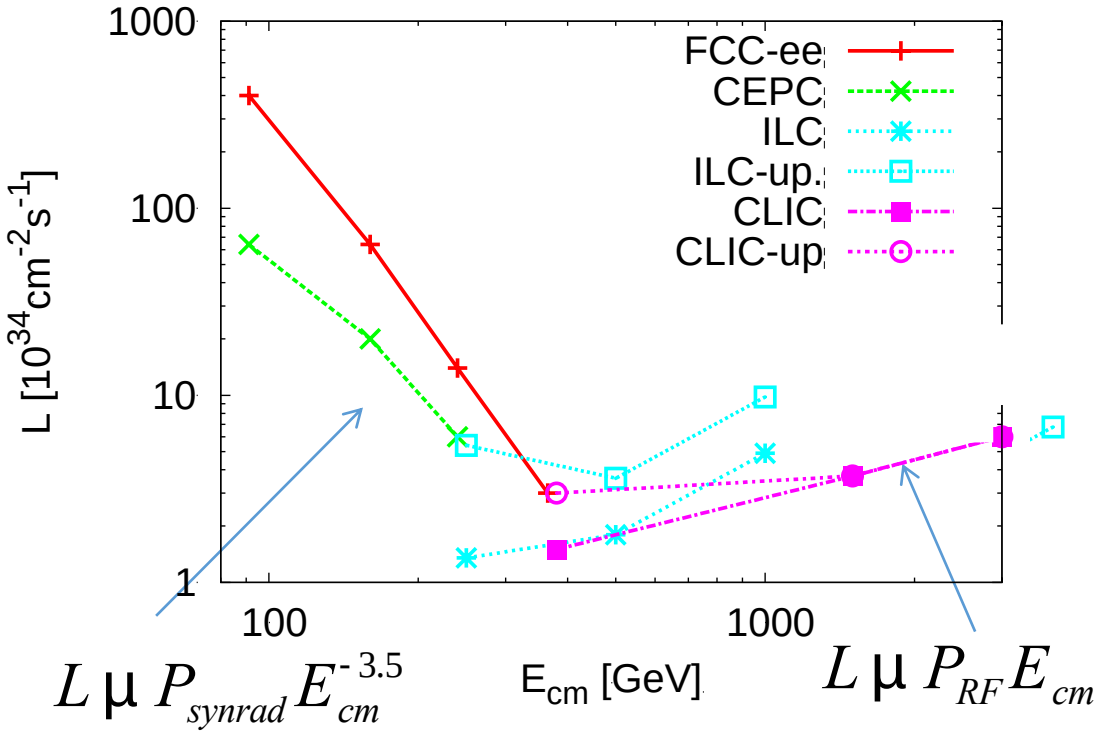
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC		

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Luminosity

Luminosity per facility



Energy dependence:

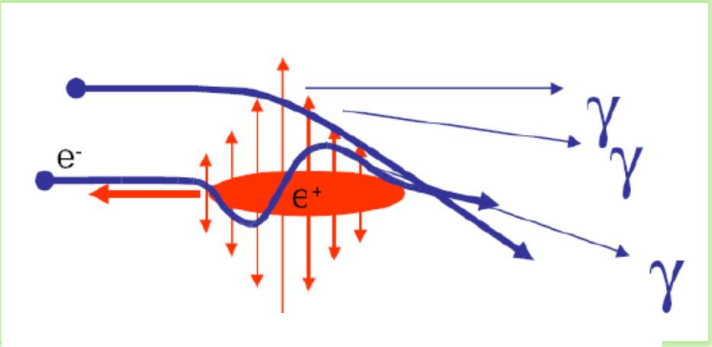
At low energies circular colliders trump
- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel
- Luminosity per beam power roughly constant

The typical higgs factory energies are close to the cross over in luminosity
Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung
- All included in the physics studies

The picture is much clearer at lower or higher energies

Luminosity Spectrum (Physics)



- $\delta E/E$ ~1.5% in ILC
- Grows with E: 40% of CLIC lumi 1% off

Luminosity Challenge

Luminosity cannot be fully demonstrated before the project implementation

- Luminosity is a feature of the facility not the individual technologies
- Have to rely on experiences, theory and simulations
- Foresee margins

FCC-ee and CEPC are based on experience from LEP, DAPHNE, KEKB, PEP II, superKEKB, …

- Gives confidence that we understand performance challenges
- New beam physics occurs in the designs,
    - e.g. beamstrahlung is unique feature of FCC-ee and CEPC
        - Identified and anticipated in the design, should be able to trust simulations
- The technologies required are improved versions of those from other facilities

Linear colliders are based on experiences from SLC, FELs, light sources, …

- Gives confidence that we understand the performance challenges
- Gives us confidence that we can do better than SLC
- Still performance goal more ambitious, e.g. beam size of nm scale
    - Creates additional challenges and requires additional technologies, e.g. stabilisation
- A part of the technologies are improved versions of those from other facilities
- Some had to be purpose-developed for linear colliders

All studies prioritised their work because of limited resources

- Depending on your preference you will see holes in any of them that you find are unacceptable
- Or you will be convinced that this very issue is a mere detail …

Conclusion

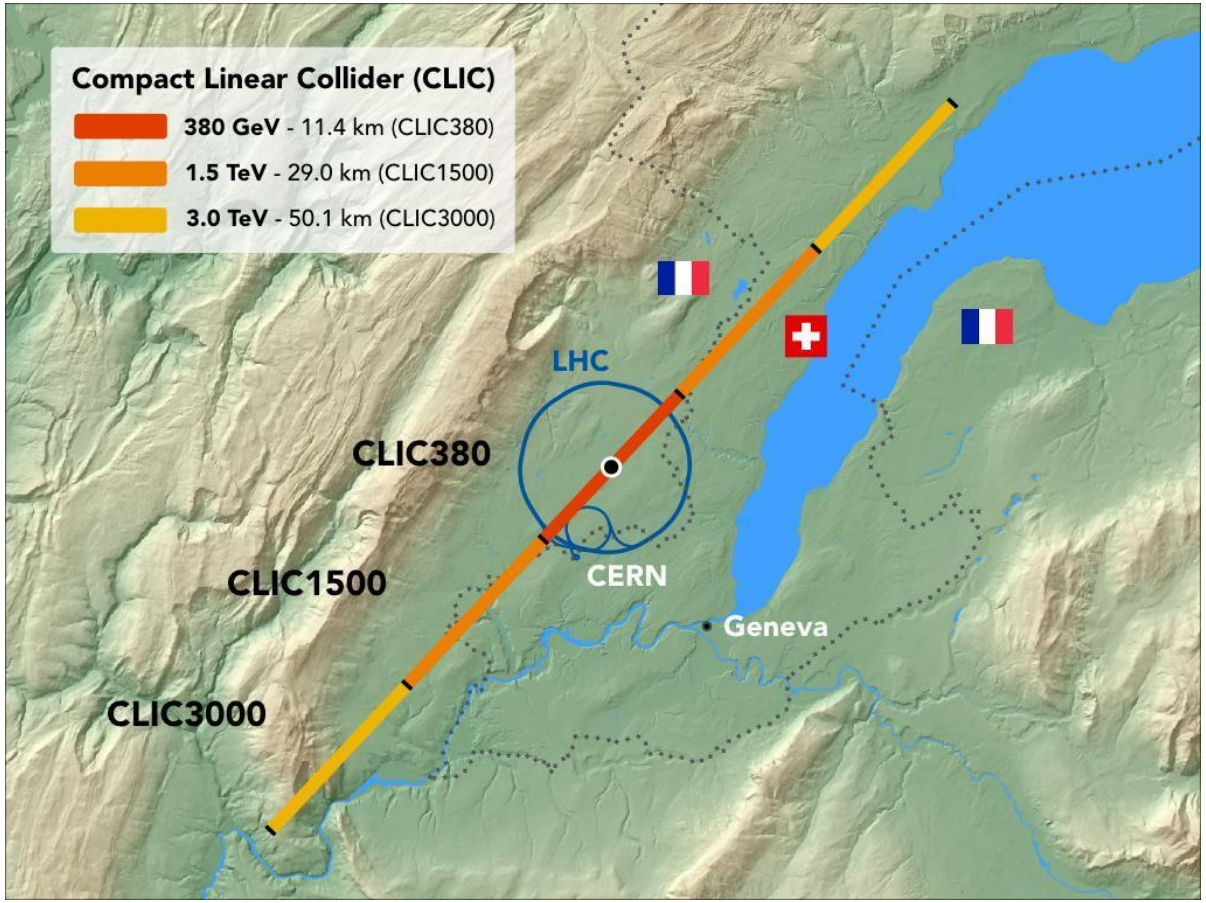
- Four main proposals for higgs factories exist
  - ILC, CLIC, FCC-ee and CEPC
  - FCC-hh and HE-LHC need time for technology development (see Yamamoto's talk)
  - LHeC would also produce some higgs
  - No clear proposal for options like LEP3 or low field magnets in FCC-tunnel
  - Muon and plasma-based colliders will need more time to become realistic alternatives

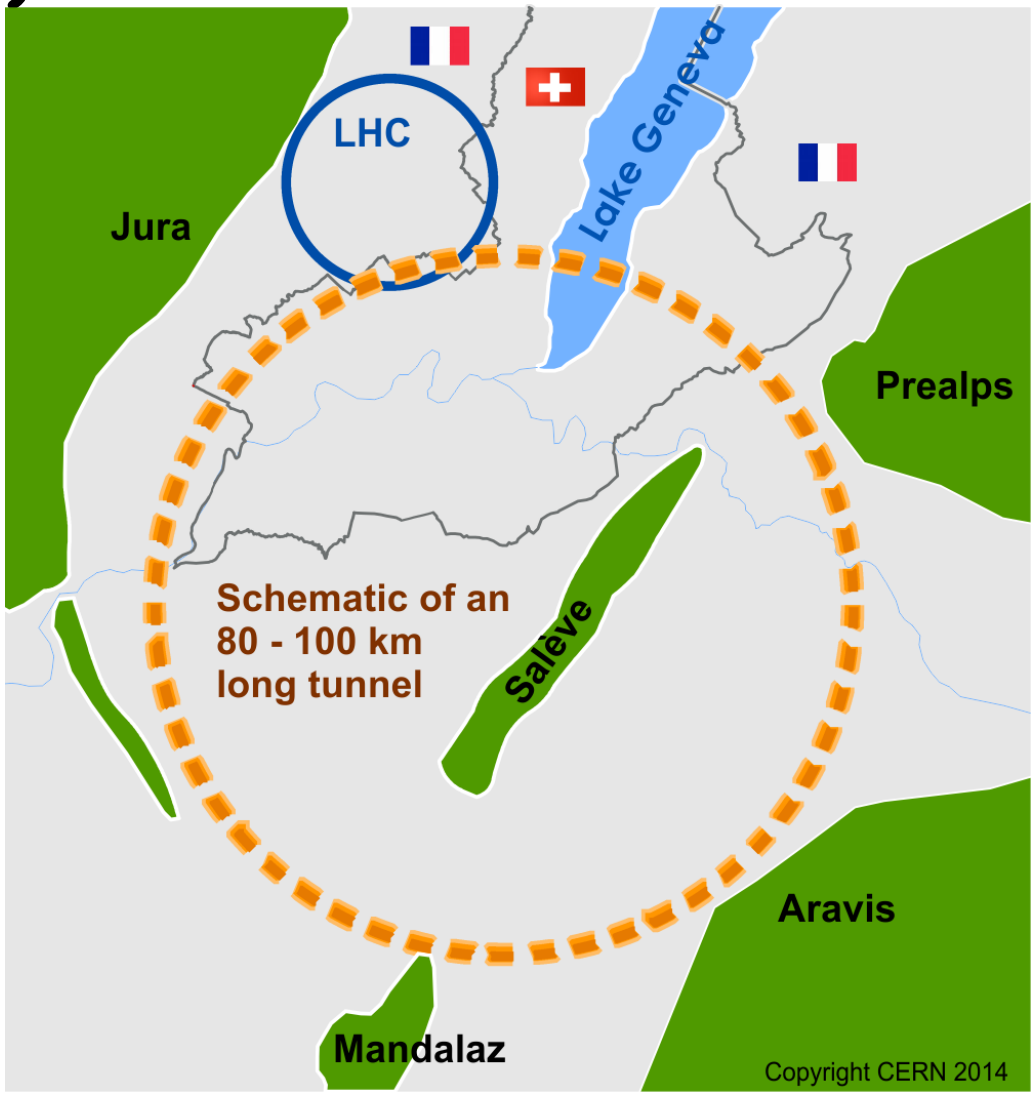
- No feasibility issue is known for any of the proposed higgs factories CLIC, ILC, FCC-ee and CEPC
  - More work has to be done for each of them to ensure performance goal is met
  - Should review in detail them before commitment is made
  - In all cases need several years before construction could start
  - Currently, technology can not help with the choice of the next project

- Cost are high in all
  - 5.9 GCHF for 380 GeV CLIC, 5.3 GILCU for ILC, 11.6 GCHF for FCC-ee, 5 G$ for CEPC

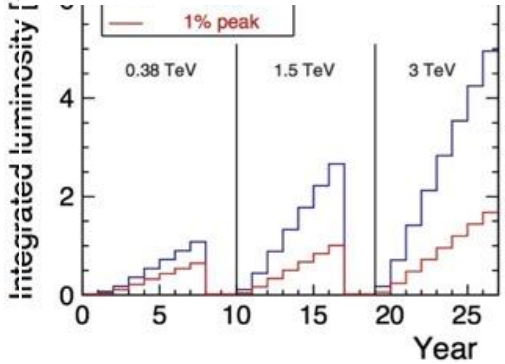
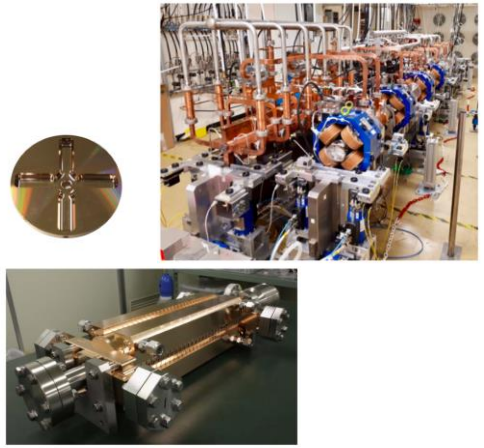
- Physics potential and strategy should be the governing principles

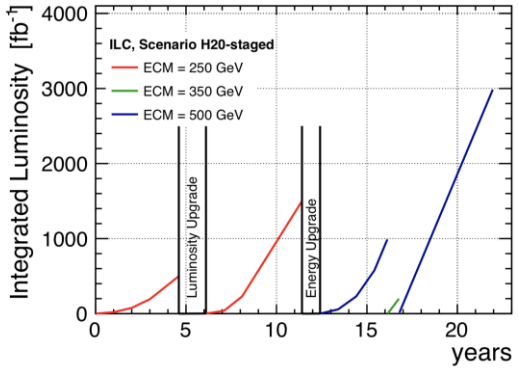
Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?



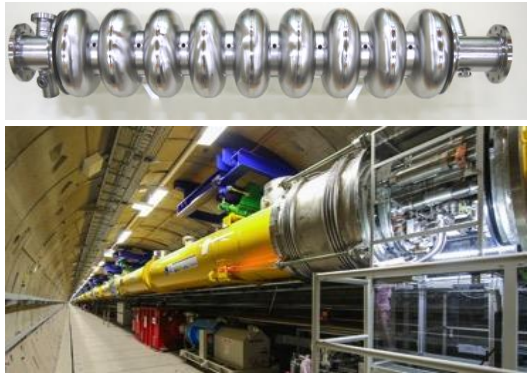


Overview of CLIC and ILC parameters

CLIC illustrations	CLIC parameters	ILC parameters
	E: 380, 1500, 3000 GeV (L: 11-50 km) Lum: 1.5-5.9 $10^{34\ -2}$ cm-2 s-1 * Prep. phase 2020-2025 Constr.+comm. 7y, ready before 2035 Cost: CLIC-380: 5.9 BCHF, Upgrades: deltas of 5 and 7 BCHF Power: ~ 170 MW – 580 MW**	E: 250, 500, 1000 GeV (L: 20-40 km) Lum: 1.35 (2.7) – 1.8(3.6) 10^{34} cm-2 s-1* Prep. phase 2020-2023(4) Constr.+comm. 9-10y, ready before 2035 Cost: ILC-250: 4.9-5.3 BILCU, ILC-500: 8 BILCU (2012 $) Power: ~ 130 – 300 MW
CLIC y: 75% of 180 days	NCRF X-band now established and industrially available, used in small systems and being introduced in larger ones, relevant reference experience with C-band for larger systems (Swissfel).	SCRF in extensive use in several FELs with parameters close to ILC parameters, the primary one being the E-XFEL at DESY. Technology optimization underway, linking to evolving SCRF R&D for grad. and Q.
	Nanobeam addressed in design & specifications, benchmarked simulations, low emittance ring progress, extensive prototype and method development (for alignment, stabilization, instrumentation, algorithms and feedback systems, system and facility tests : FACET, light-sources, FELs, ATF2) Extensive prototyping of all parts of these accelerators, for lab-test, use/test in test-facilities, light-sources or FELs (magnets, instrumentation, controls, vacuum, etc)	
	CERN hosted international project (follow LHC model)	Japan hosted international project, initial ideas about European capabilities available (link)

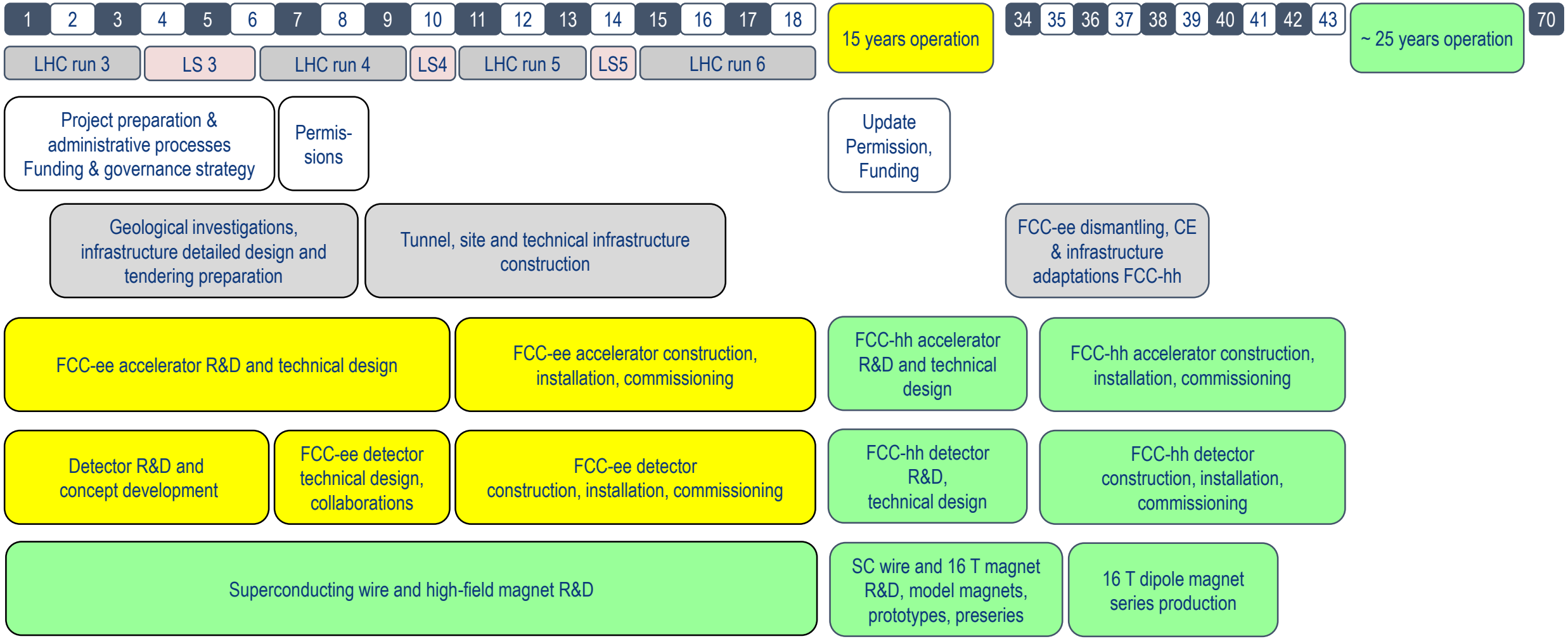


ILC y: 75% of 240 days



to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012

FCC integrated project technical schedule



FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

Consideration on timeline:
LHC possible because SSC developed the superconductor…

9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

1985 1987 1990 1994 2000 2006 2010

Only 2 y to make a short magnet «near to final». Conductor available(SSC)

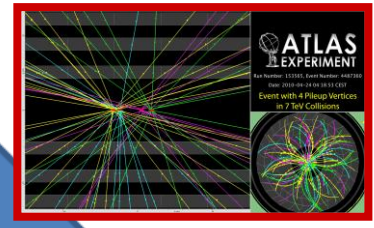
7 years from start R&D to 1st Industry proto

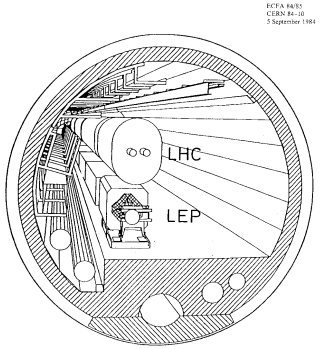
12 y from first working prototype to last magnet

Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up





LARGE HADRON COLLIDER
IN THE LEP TUNNEL

HE-LHC 27 TeV

- Needs some 1700 large magnets in Nb_3Sn (1200 dipole 15 m long) operating at 16 T. (same as FCC-hh)
- It needs a new generation of Nb_3Sn, beyond HiLumi (like FCC-hh): the 23 y timeline presented is realistic (21 for the magnets) but t_0 is probably 2025 or more because of SC development.
- **The set up of a SC Open Lab for fostering development of superconductors (F. Bordry and L. Bottura proposal) is critical for HEP HC progress.**
- A further upgrade to 42 TeV in HTS at 25 T possible to envisage for longer time. 24 T dipole is the long term goal also of the Chinese SppC. (Recently an HTS 32 T special solenoid and a commercial HTS 26 T NMR solenoid have been announced!)

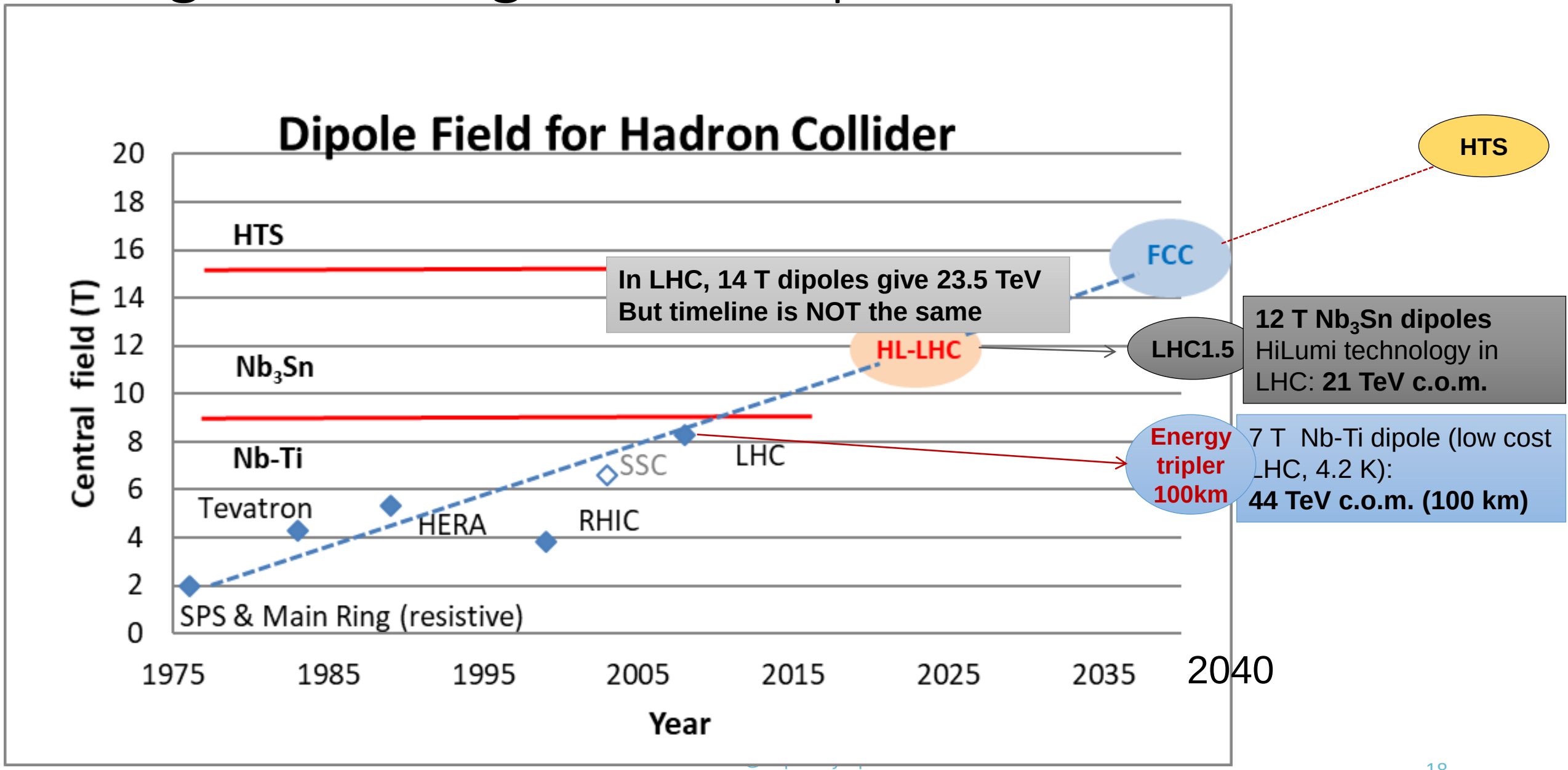
s.c. magnet technology

- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - **Nb_3Sn, 12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).
  - **NbTi , 8~9 T:** proven by LHC and **Nb_3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Intensify HTS accelerator magnet development

A. Yamamoto, 190512b

High field magnet development



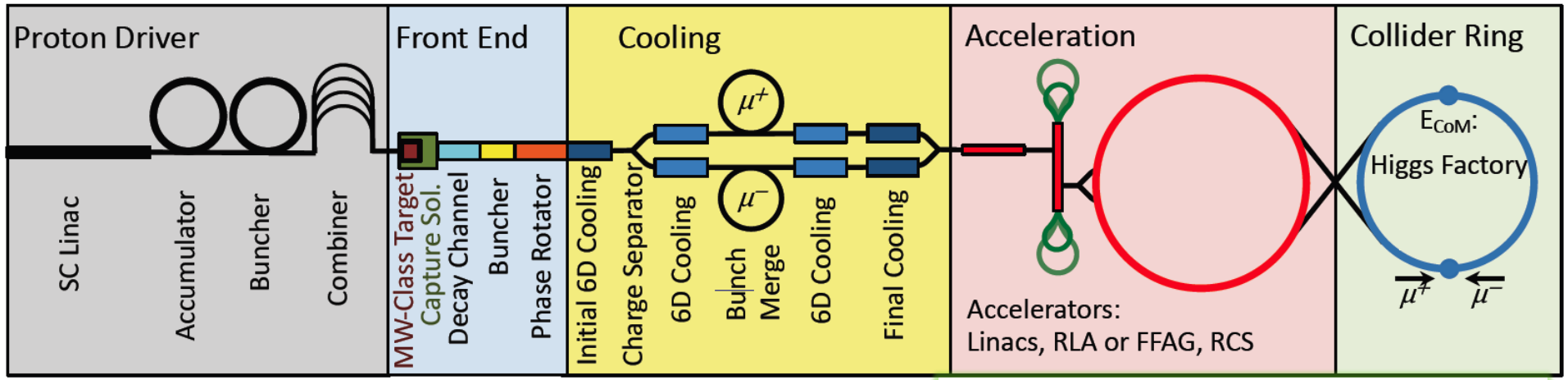
V. Shiltsev slide

Input #41 **Input #120** **Input #141**

$\mu+\mu-$ Higgs Factory

V. Barger, et al, *Physics Reports* 286, 1-51 (1997)

JINST Special Issue (*MUON*)



Key facts:

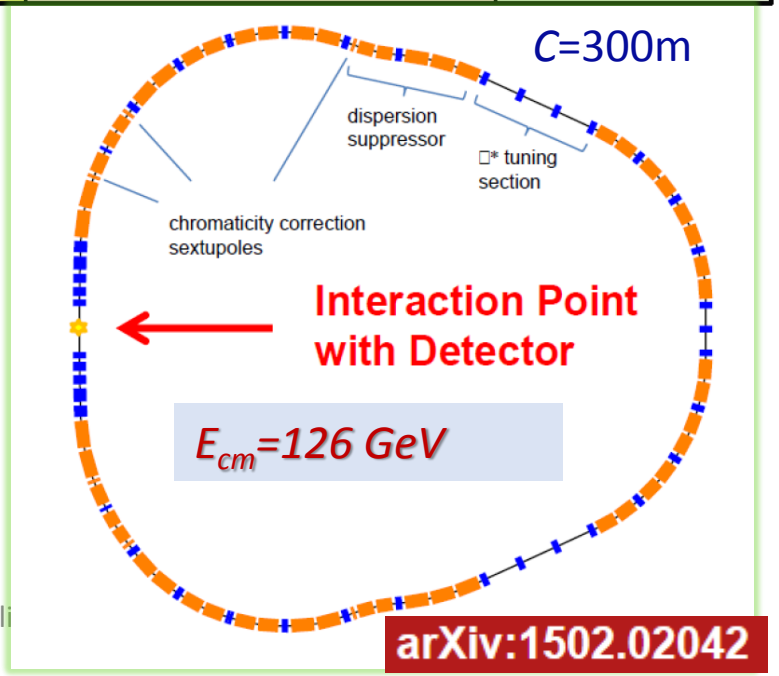
1/100 luminosity requirements (large cross-section in ***s***-channel)

Half the energy 2 x 63 GeV $\mu+\mu- \rightarrow H_0$

Small footprint (<10 km) and low cost

Small(est) energy spread ~3 MeV

Total site power ~200MW (tbd)



V. Shiltsev slide

High Energy μ+μ- Colliders

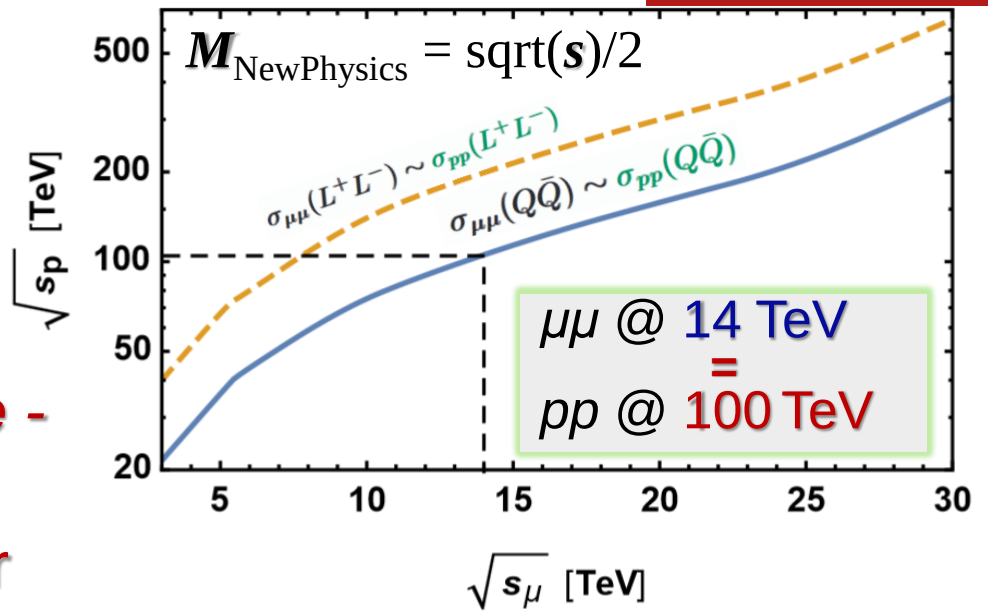
Input #120

JINST Special Issue (*MUON*)

arXiv:1901.06150

Advantages:

- ***μ***'s do not radiate / no beamstrahlung→ acce-leration in rings → *low cost & great power efficiency*
- ~ x7 energy reach vs *pp*



Offer *"moderately conservative - moderately innovative"* path **to cost affordable** energy frontier colliders:

- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like "strawman" parameter table*

Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA e^+-45 GeV + e^- at rest →μ^+-μ^- , design study of acceleration, detector background and neutrino radiation

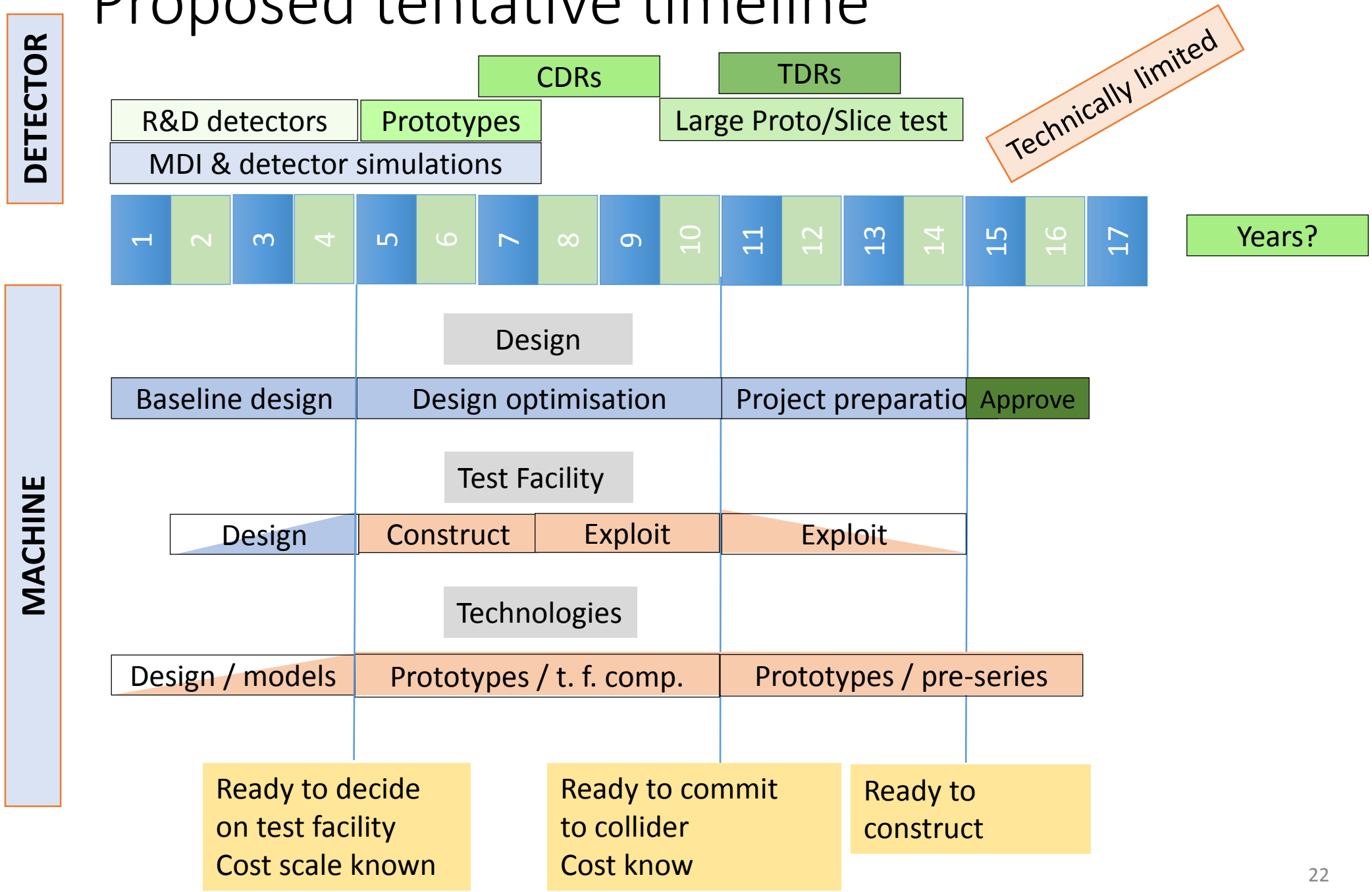
Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

Proposed tentative timeline



Q4: Energy management in the age of high-power accelerators?

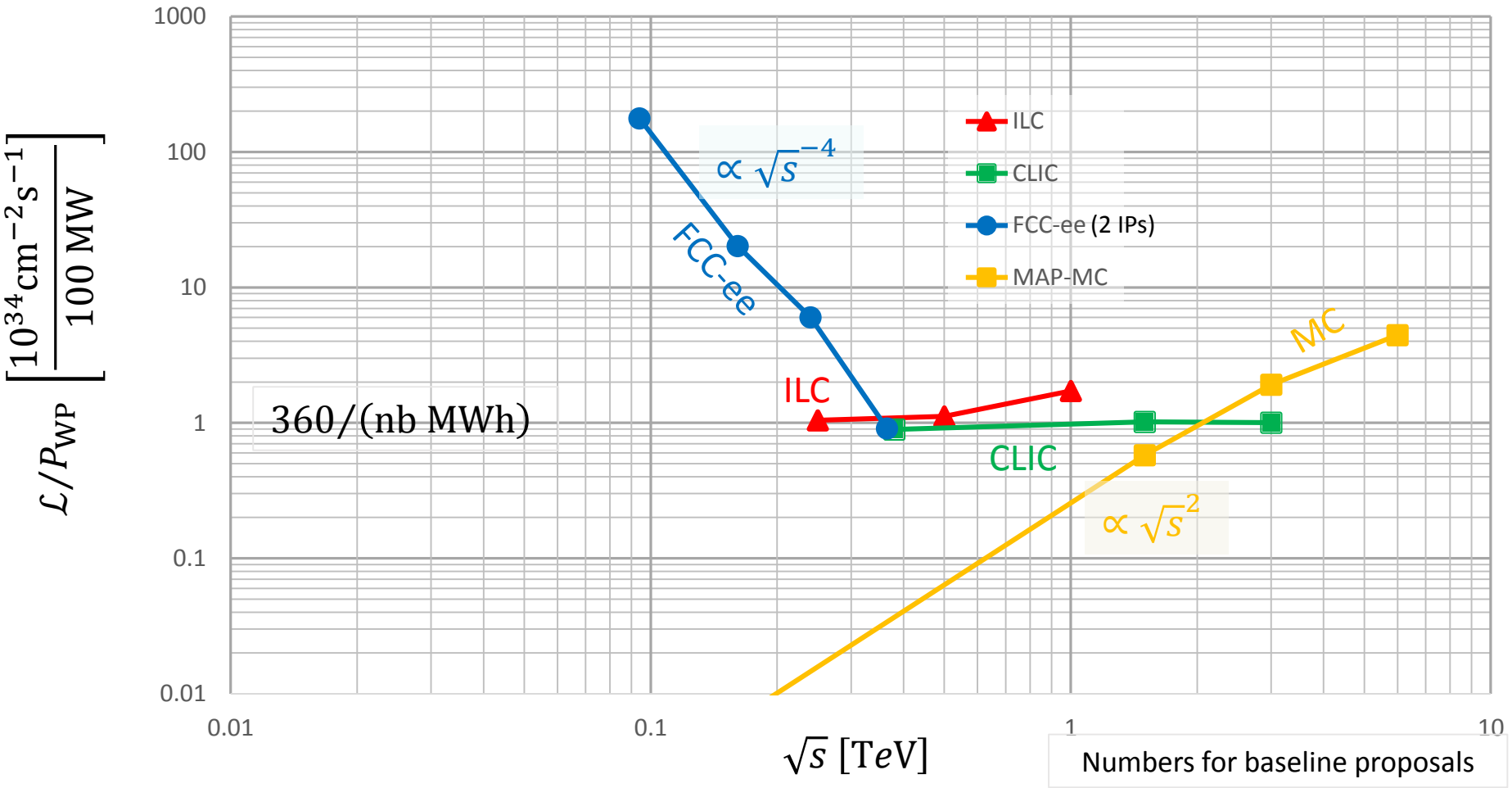
Energy Efficiency

- Energy efficiency is not an option, it is a must!
- Proposed HEP projects are using $\mathcal{O}(\mathrm{TWh/y})$, where energy efficiency and energy management must be addressed.
- Investing in dedicated R&D to improve energy efficiency pays off since savings can be significant.
- This R&D leads to technologies which serve the society at large.
- District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can be significantly be improved.

Figure of merit for proposed lepton colliders

Disclaimers:

1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



Numbers for baseline proposals

Recent Developments of ILC in Japan

- **KEK & Japanese HEP: Post-2012 Higgs ->**
  - ***ILC 250GeV Higgs factory in Japan, upgradable in energy.***
- **November 2017:**
  - ***LCB strong support***
  - ***Timely decision sought from Japanese Government***
- **July 2018:**
  - ***ILC Advisory panel of MEXT recommended the ILC proposal be reviewed by the SCJ.***
- **December 2018:**
  - ***SCJ released its report - some issues need addressing***
- **March 2019:**
  - ***MEXT presented its view to the LCB meeting in Tokyo***
  - ***ILC Federation of Diet Members message of support***
    - MEXT and KEK released their action plans.
  - ***ICFA made clear that other options being considered at EPPSU2019***

MEXT= Ministry of Education, Culture, Sports, Science & Technology in Japan

Science Council of Japan (SCJ), Master Plan

- SCJ represents all sciences but
  - *Not policy making nor budgetary authority*
- Large-scale project proposals sought every three years.
  - *recommends "priority programs" to MEXT*
  - *2017 round: 20 selected from 200 proposals*
- MEXT Minister: ILC be evaluated in this process to provide evidence of support by the broader academic community in Japan
  - *ILC proposal submitted with recommendation letter from Barry Barish*
  - *Results of this evaluation will be publicist February 2020 (informally late 2019?)*
- Active political work continues

CepC Path to Funding

- **"Chinese Initiated International Large Scientific Plan and Large Scientific Project" :**
  - ***By 2020 3-5 Projects will be selected for further development with some funding***
  - ***Following a small number of years (?), 1~2 projects selected for construction***
  - ***Should be complementary to other large national or multinational scientific projects.***
  - ***Be seen to be important to international scientific organizations' and laboratory scientific projects and activities.***
  - ***Process has commenced***

Yifang Wang, Jie Gao

Inputs from the communities

- R. Pöschl - Future colliders - Linear and circular
- M. Spiro (Amaldi, Llewellyn Smith, Maiani, Myers, Iliopoulos, 50+ signataru)
  - *A View on the European Strategy for Particle Physics (#81)*
  - *Worldwide, the particle physics and accelerator community is very actively working towards the next major facility. Based on the designs and performance of linear and circular e+e− colliders in the 90 (Z) to 365 (above top-antitop) GeV centre-of-mass energy range, we consider a circular collider at CERN to be the most attractive option. It is also an investment in the future for a possible later stage as a 100 TeV hadron collider.*

Inputs from the communities (cont.)

- A. Blondel, P. Janot: *Future strategies for the discovery and the precise measurement of the Higgs self coupling*
- Revision of 2013 European Strategy statement

  "energies of 500 GeV or higher could explore the Higgs properties further, for example the [Yukawa] coupling to the top quark, the [trilinear] self-coupling and the total width."
- Potential of FCC-ee at sqrt(s)=90, 240, 350, 365 GeV **without** 500 GeV
  - Higgs width with 1.3%
  - Top Yukawa coupling – 2.5% from HL-LHC, combination with FCC-ee breaks model dependence
  - HHH coupling
    - 30 years of ILC500 to reach 3 sigma, 15 years on FCC-ee - from single-Higgs x-section as function of s
    - 5sigma with 4 FCC-ee experiments – (needs much more time at 1TeV ILC)
  - Precision physics with Zs

  We conclude that 500 GeV is not a particularly useful energy for the lepton colliders under consideration, especially for the FCC-ee. A 5σ demonstration of the existence of the Higgs self-coupling is within reach at the energies foreseen for the FCC-ee, with a moderate change of configuration, which certainly deserves consideration.

Some points from the discussion sessions

- M. Spiro – strong support for FCC-ee followed by FCC-hh
- K. Jacobs – against FCC-ee, wants to go for FCC-hh directly and as soon as possible
- M. Mangano – we should not look at projects in Asia, on which Europe has little influence anyway
- Many others expressed the opinion that FCC is too large and long project at that we should go for linear e+e- accelerator
- Several strong open calls that CERN should play leading role in Einstein Telescope project