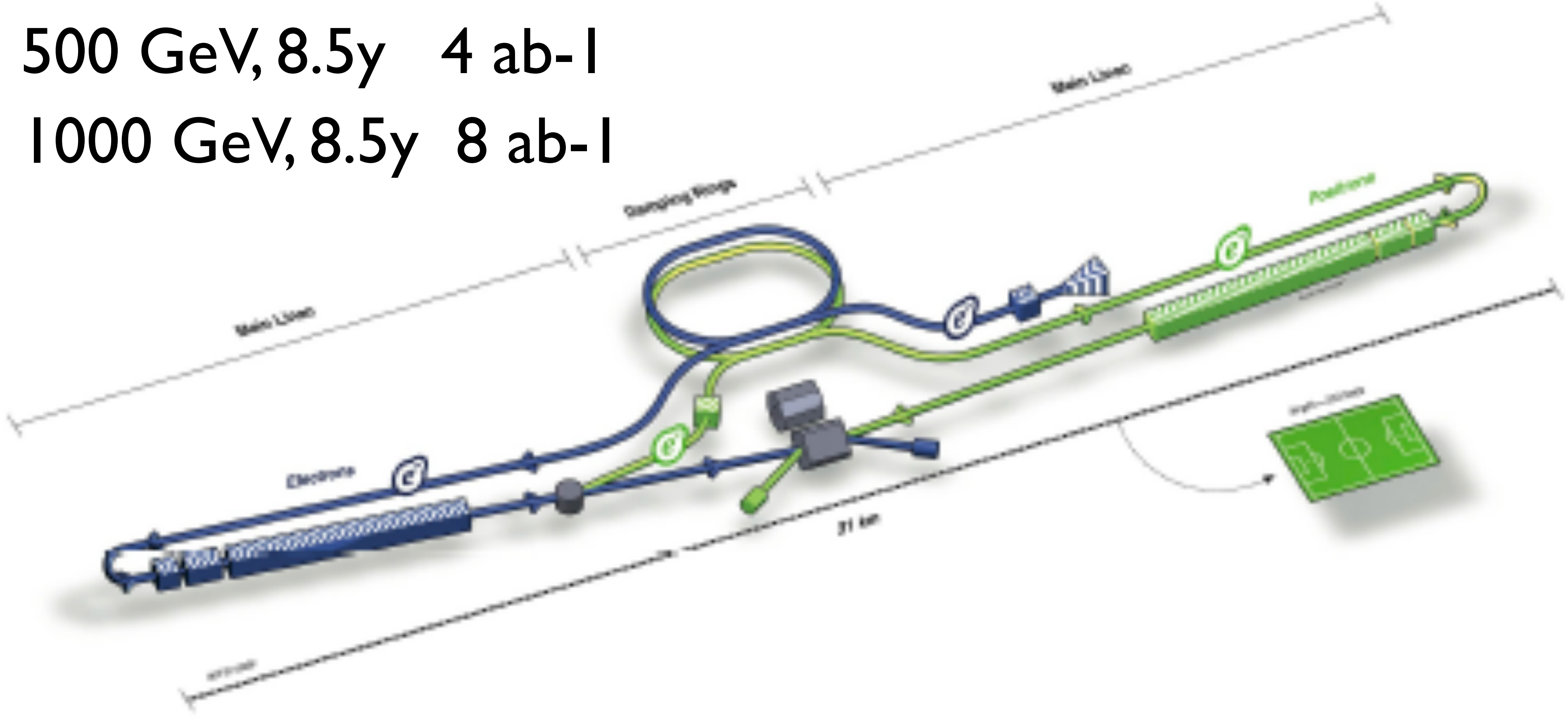
Large Projects

Pamela Ferrari, Clara Nellist, Tristan du Pree

Future e+e- Colliders in Asia

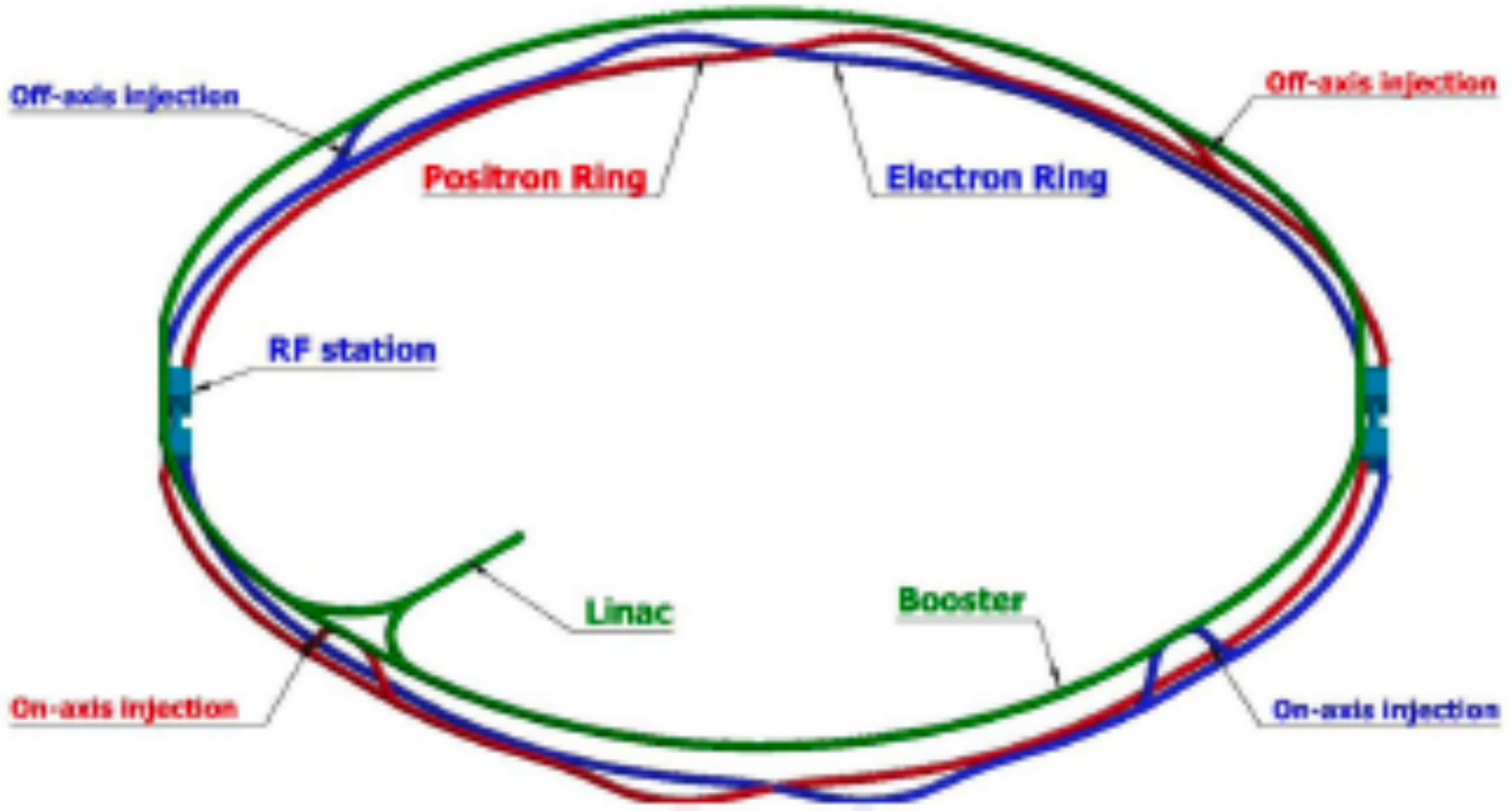
Linear e+e-

ILC Japan
250 GeV, 11y -> 2 ab-1
500 GeV, 8.5y 4 ab-1
1000 GeV, 8.5y 8 ab-1



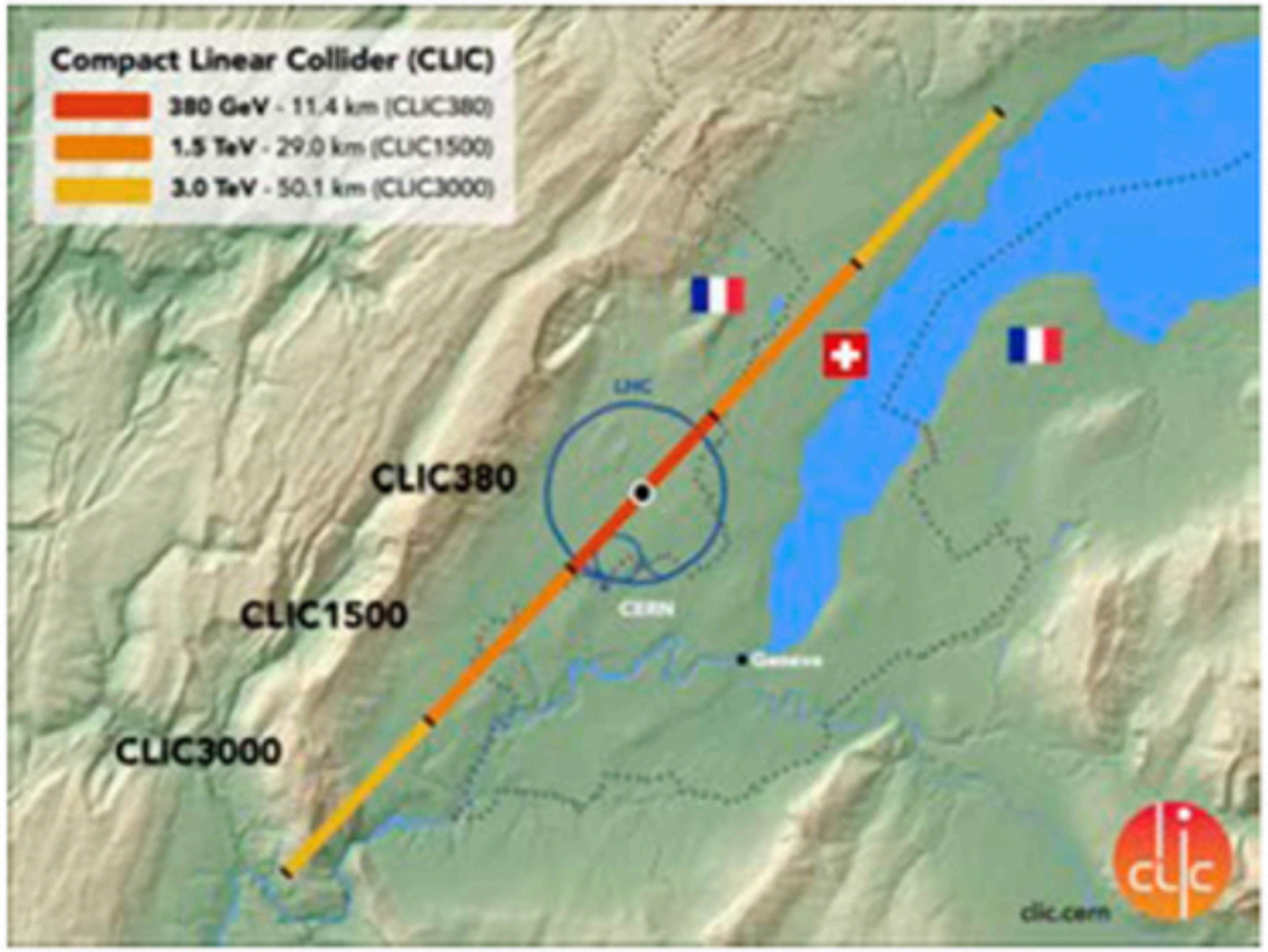
Circular e+e-

CEPC, China 100 Km tunnel
mZ, 2y -> 16 ab-1
2 mW, 1y 2.6 ab-1
240 GeV, 7y 5.6 ab-1

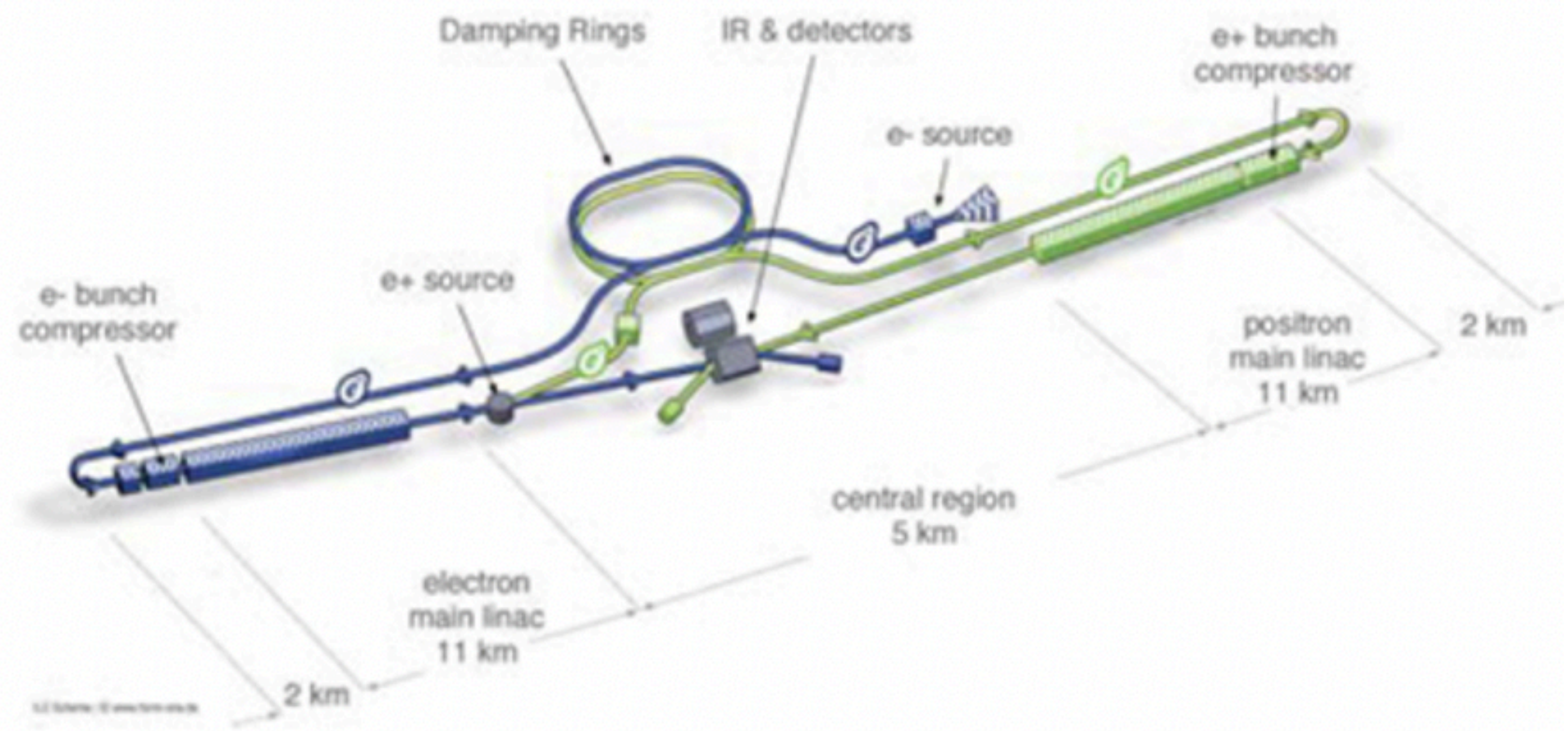


Future e+e- Linear Colliders in Europe

CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



Future e+e-Circular Colliders in Europe

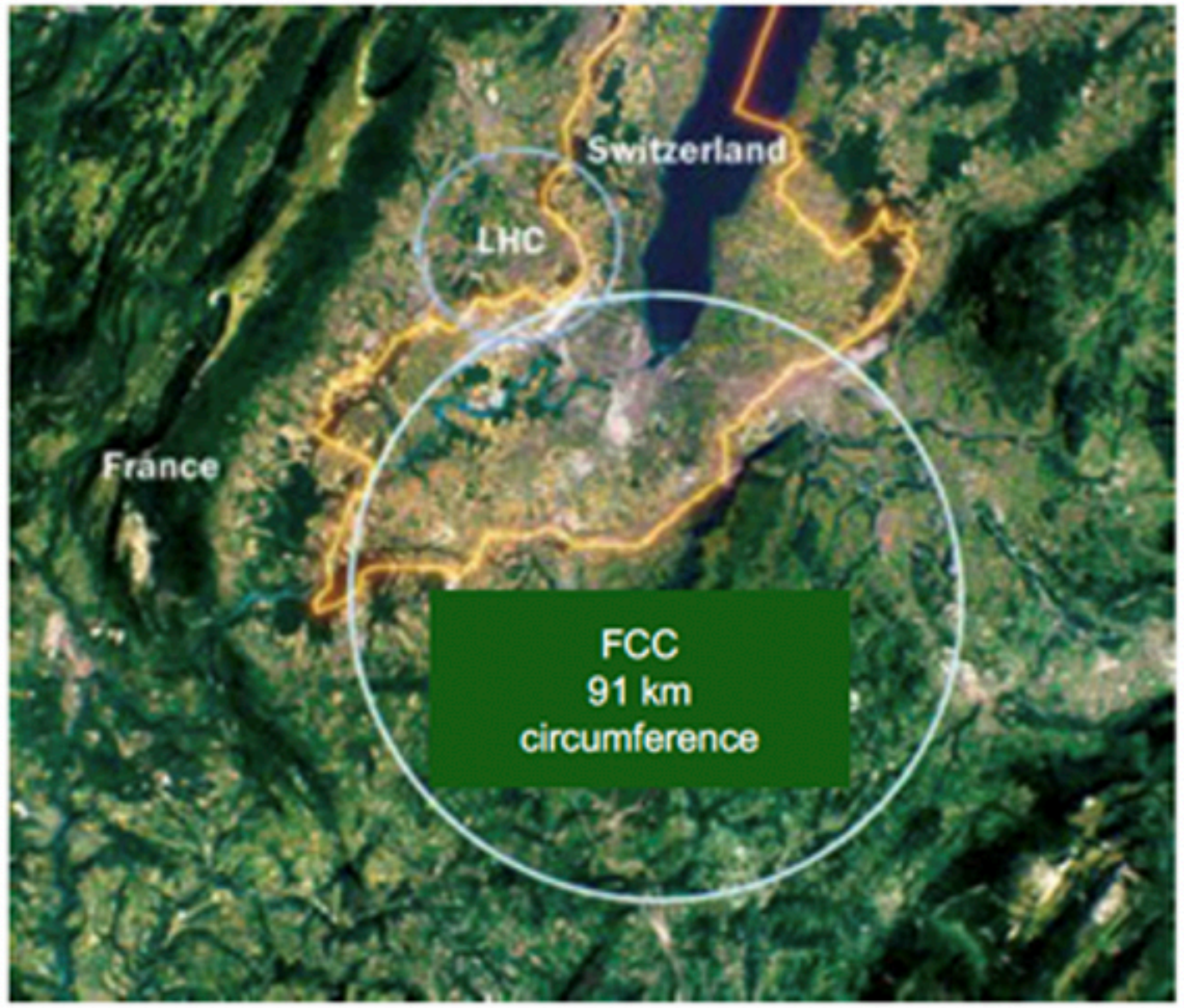
Plan B if there is not enough money for Fcc-ee or Linear collider:
2-4 experiments re-use LHC ones?

91 Km tunnel in Geneva, which could be used for a p-p machine

LEP3 (e^+e^-, circular, 91 – 230 GeV)

LEP3 e+e- machine in the LHC tunnel:
would need the LHC to be dismantled (few years delay)

FCC-ee (e^+e^-, circular, 91 – 365 GeV)



Future e+e- Colliders : Asia

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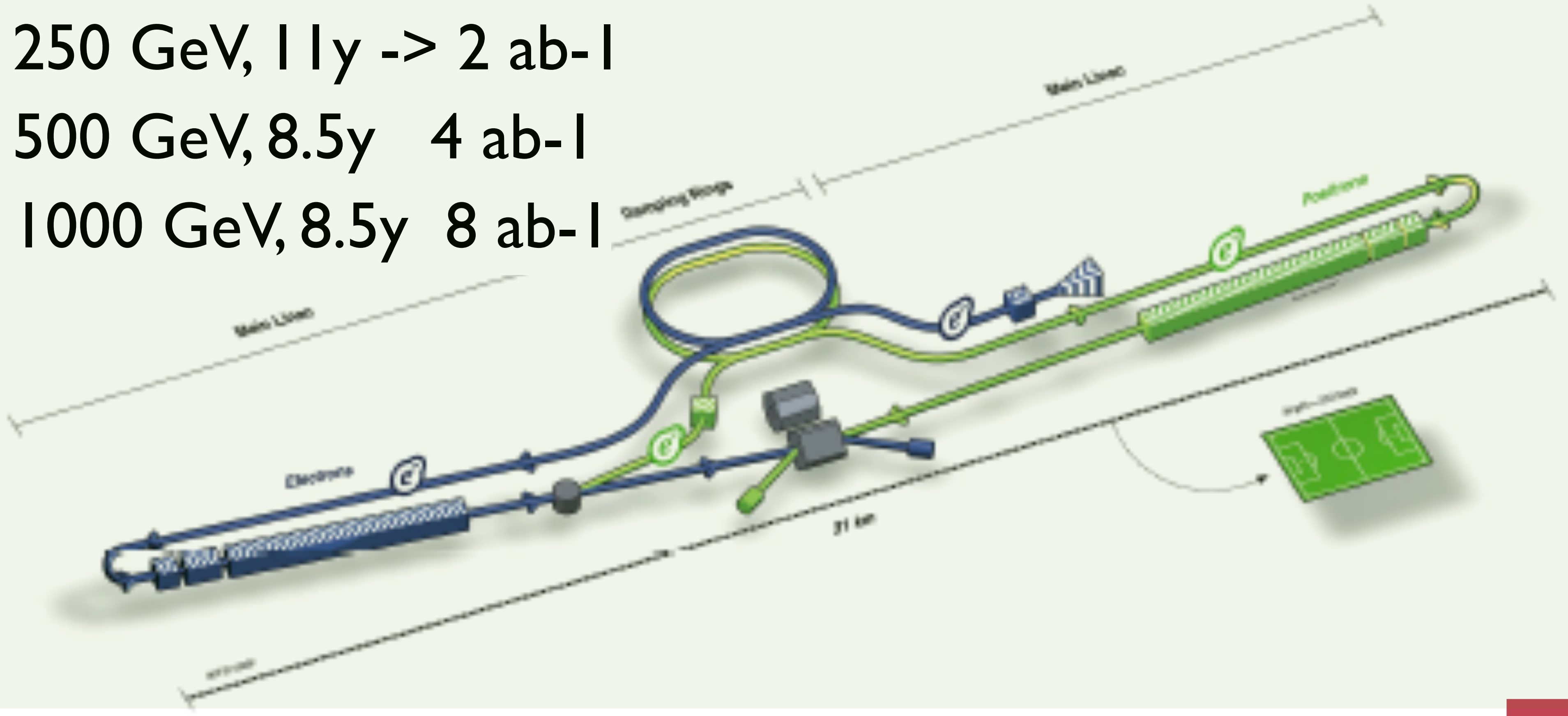

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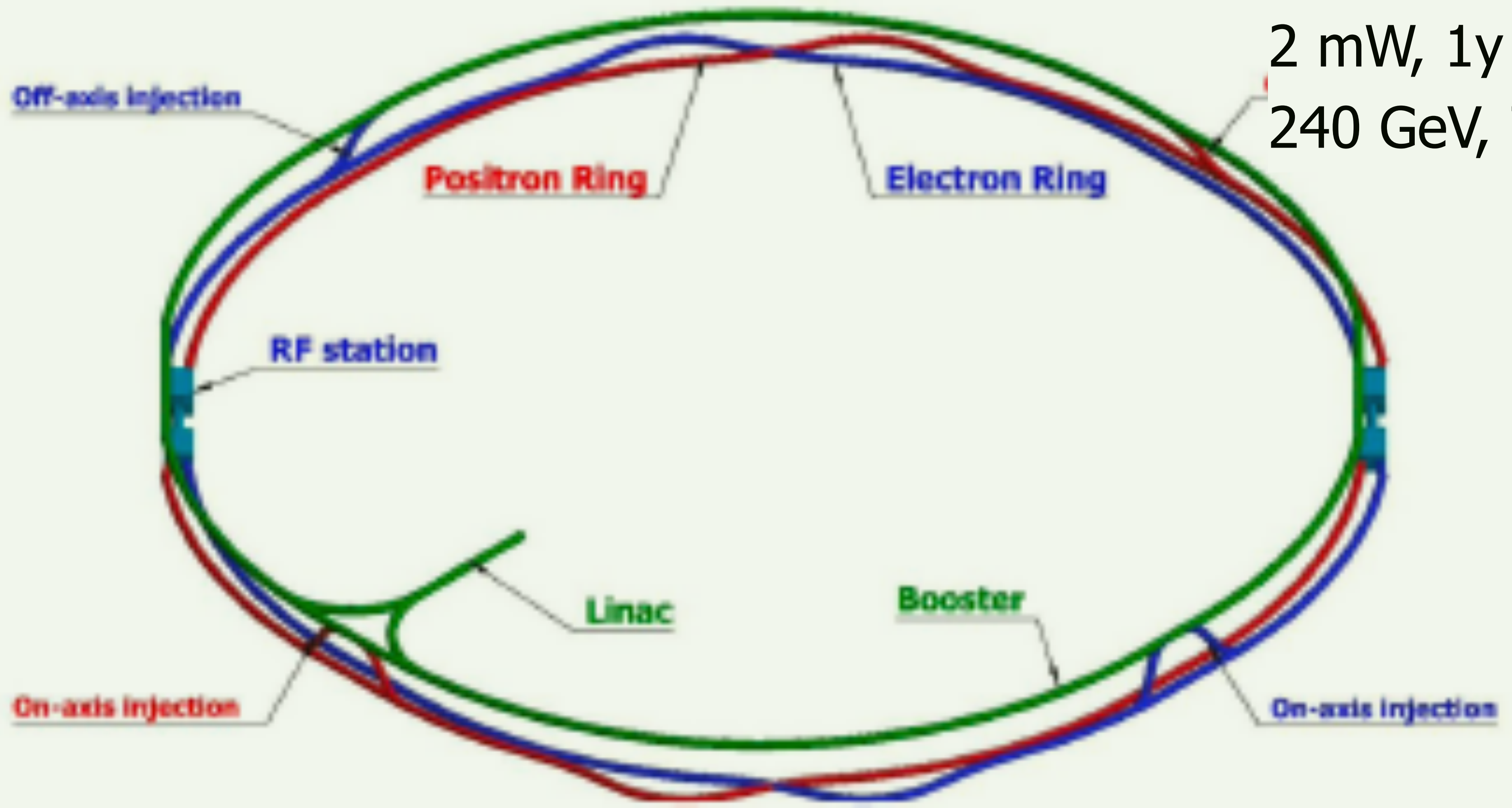
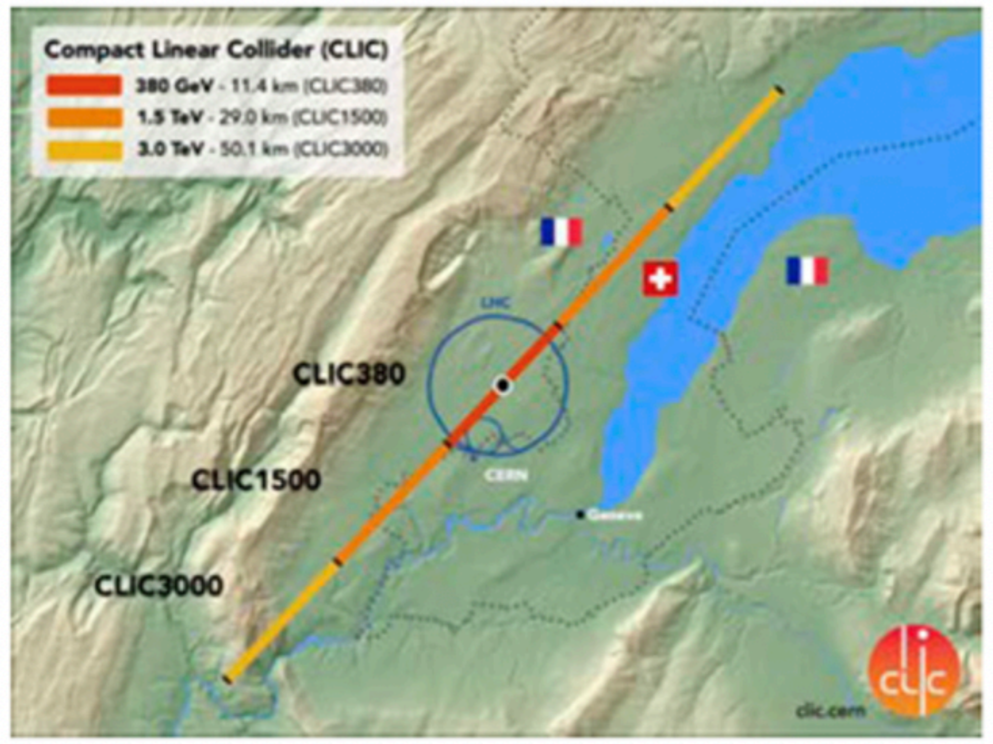
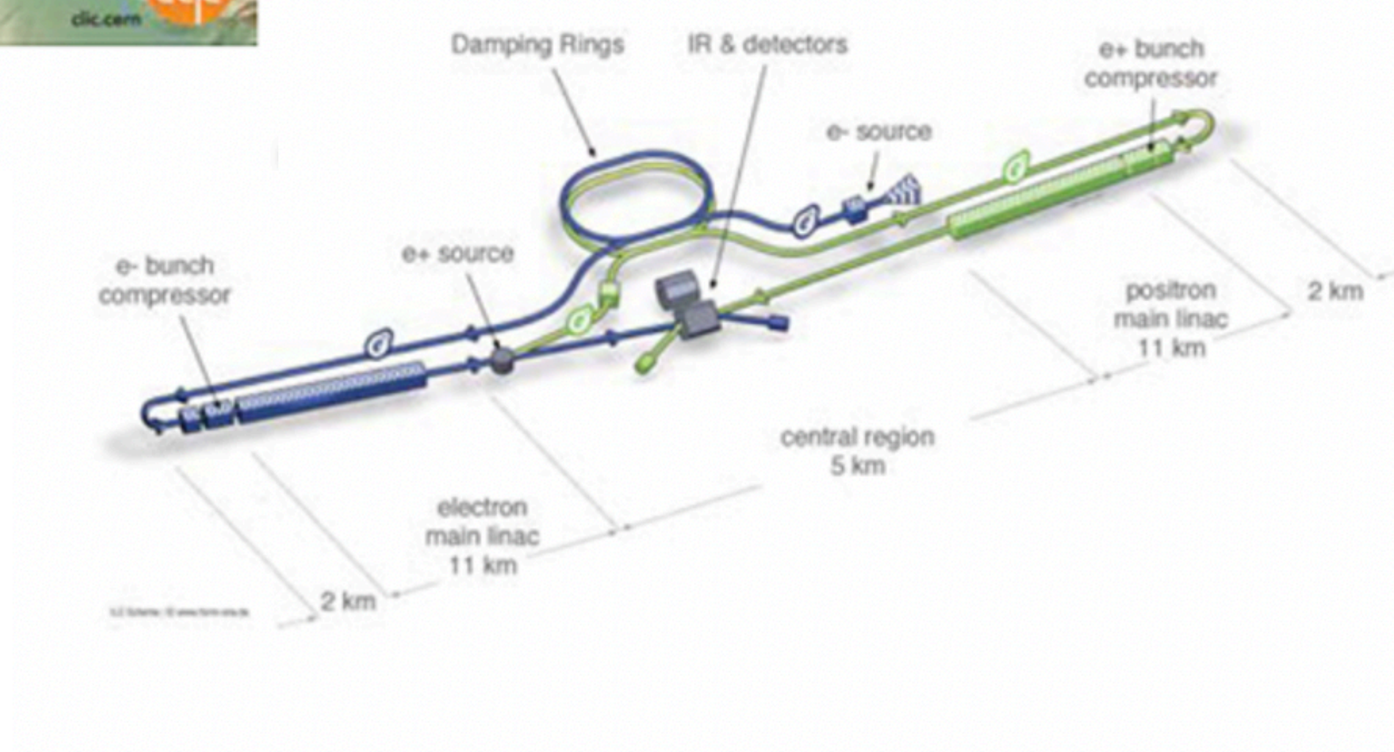


Europe

CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

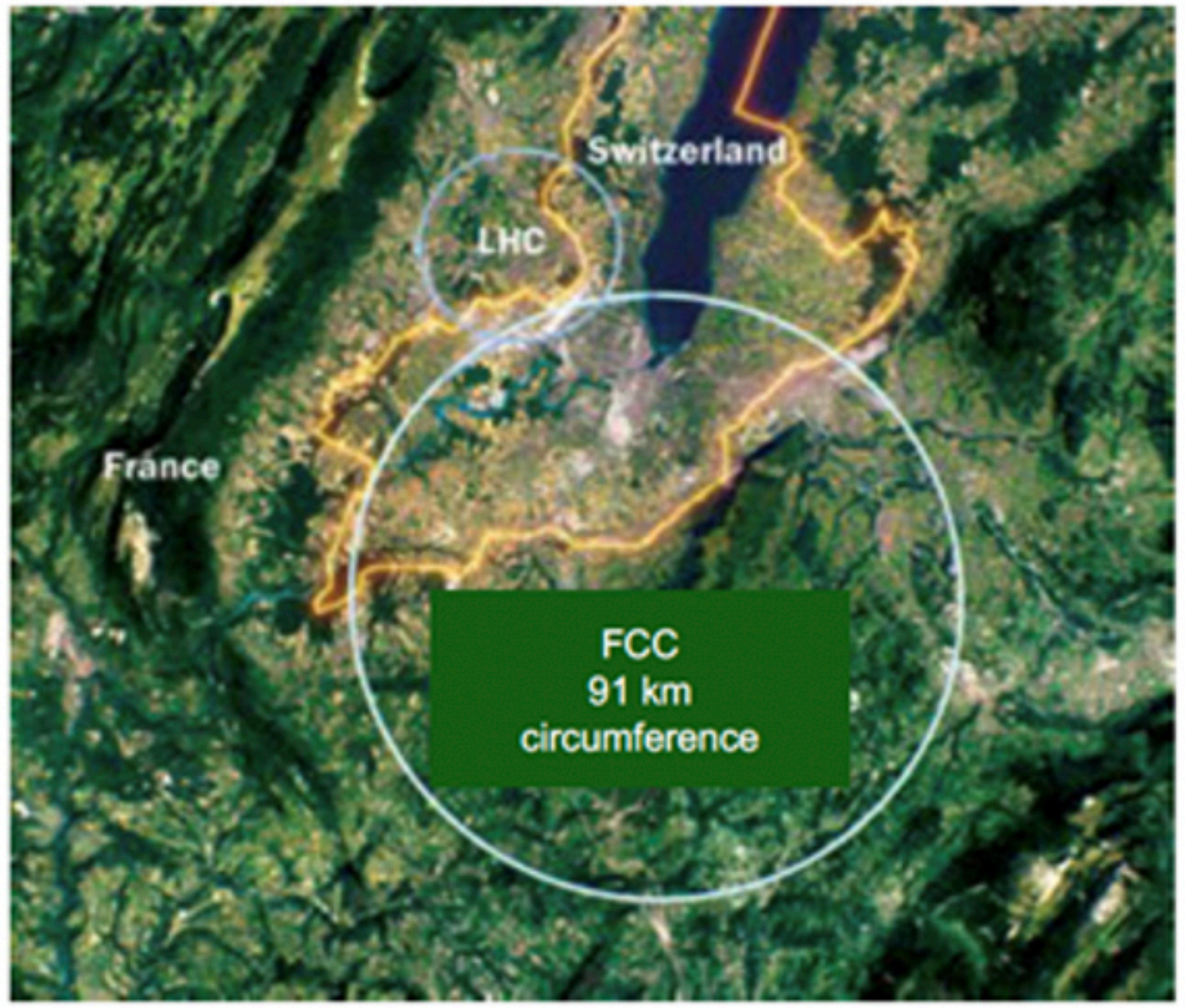


LCF (e^+e^-, linear, 91 – 240, 550 GeV)



LEP3 (e^+e^-, circular, 91 – 230 GeV)

FCC-ee (e^+e^-, circular, 91 – 365 GeV)



Do we need an e+e- machine?

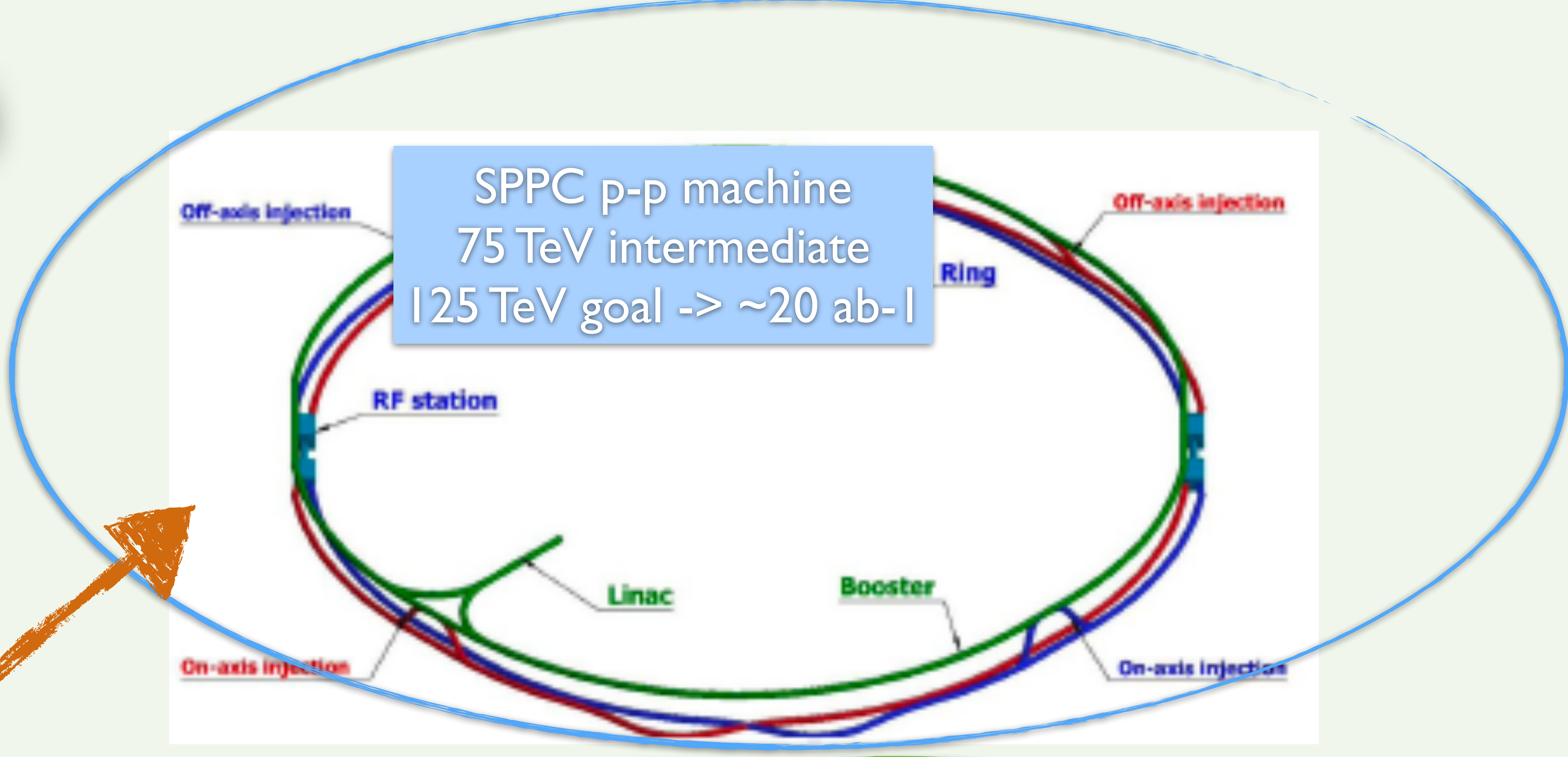
- e+e- Could measure directly and precisely measure certain Higgs couplings, Higgs width, BR to invisible and provide precision measurements as input to pp program that would increase the pp measurement precision

- The same is true for a muon collider that would profit of these measurements.

- What is a pity is that in Venice no studies were presented about the loss of precision if an e-e+ machine would not be build at all **(but it reasonable to think that it is < 10% percent level)**

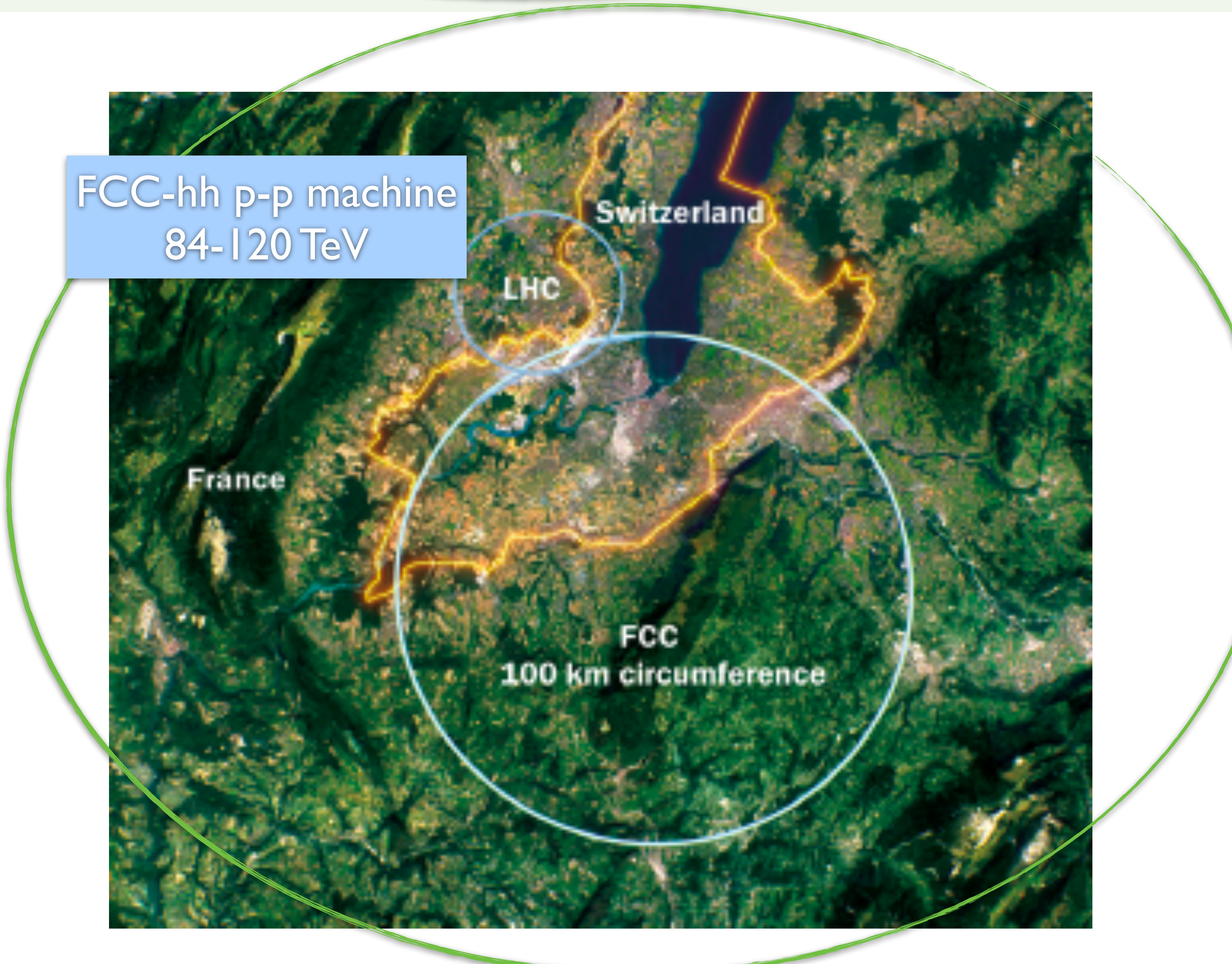
Hadron Colliders

in Asia



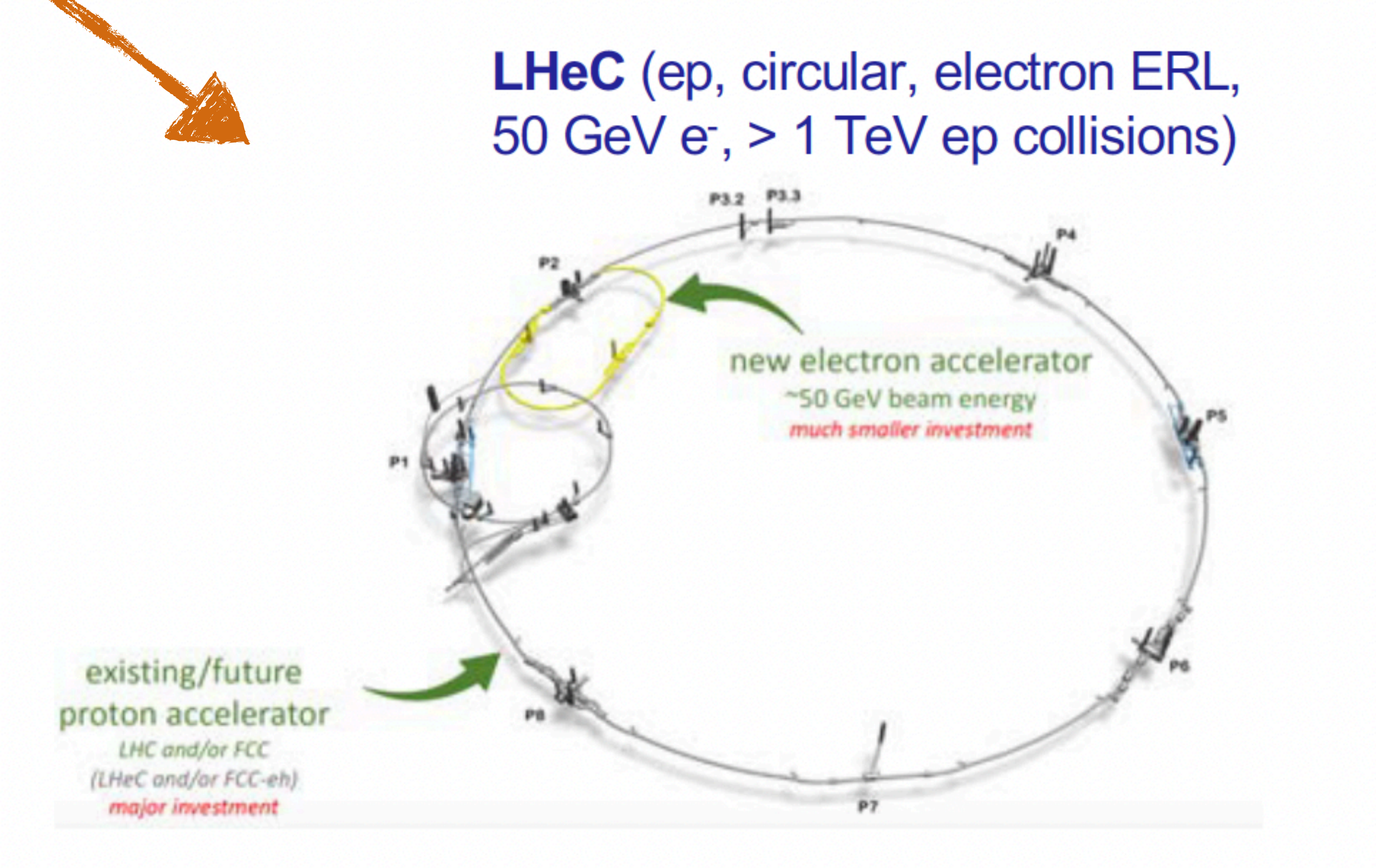
p-p machines in the ~100 km tunnels

in Europe



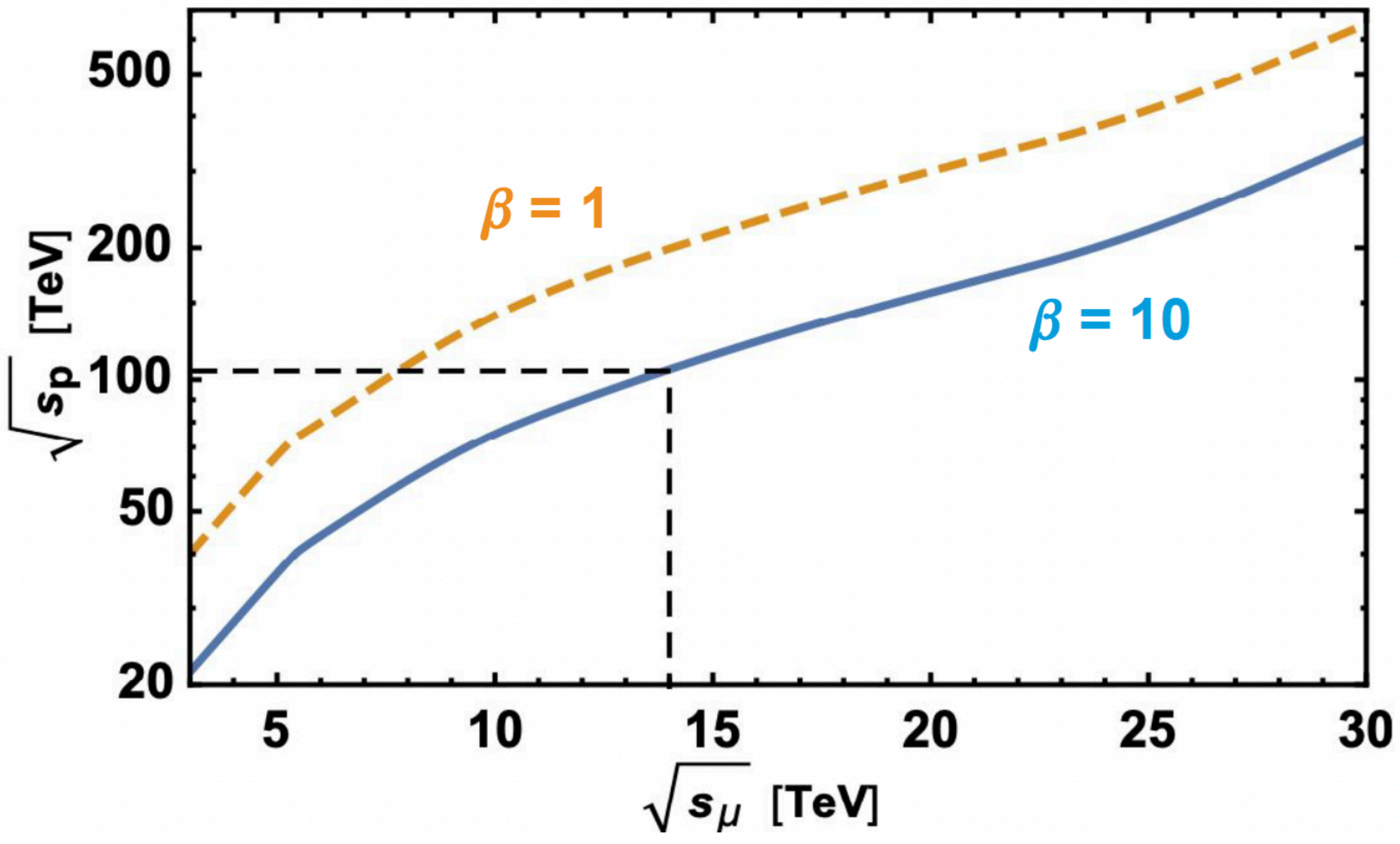
Do we need an e-p machine?

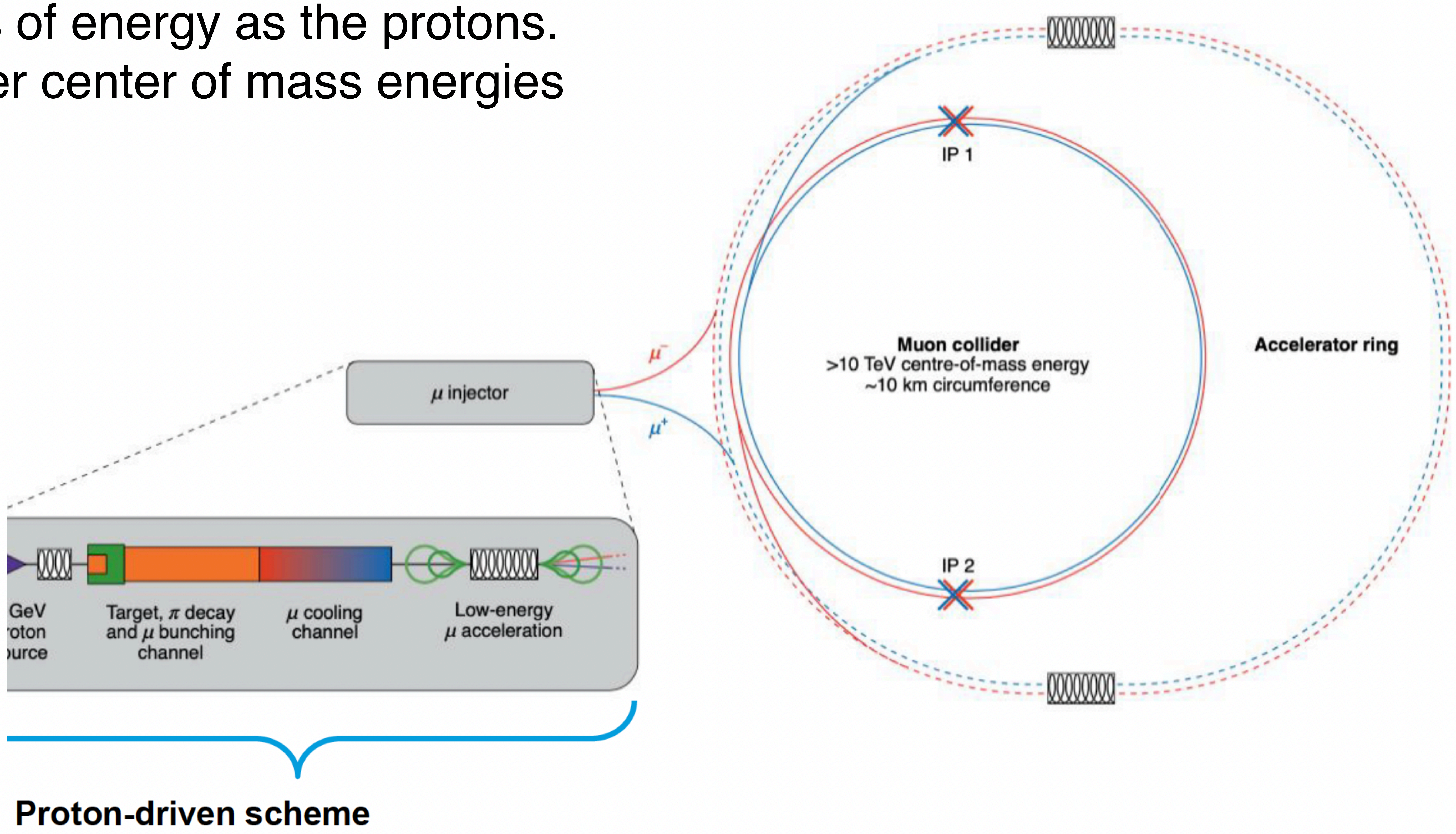
an electron proton accelerator ultra-precise PDFs + Higgs/EW inputs useful for both muon and p-p future colliders LHe-c, that could run in parallel to LHC, using its tunnel. No delay due to dismounting of LHC



Do we need a μ+μ- machine?

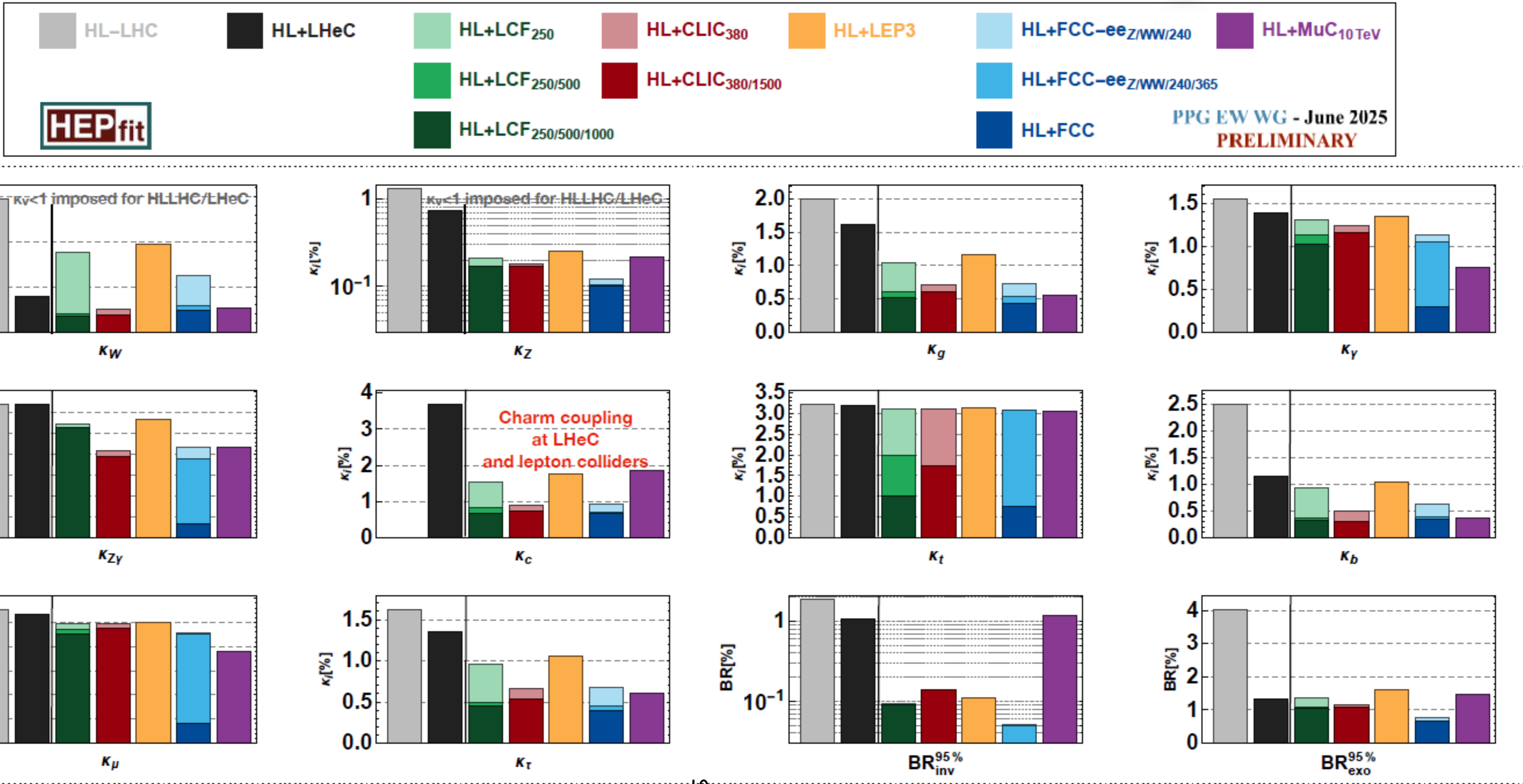
A muon Collider, is a new adventure. It combines the advantages of a hadron machine and a lepton machine.
The muon mass is 207 times the electron mass->Negligible synchrotron radiation emission
It does't have PDFs (substructure) and loss of energy as the protons.
It can probe precision physics at much lower center of mass energies
(10-30km)





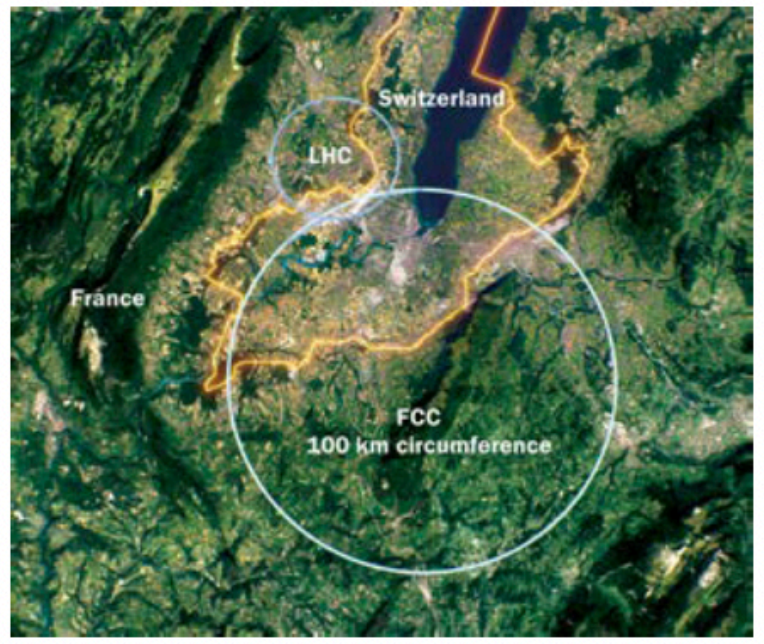
Challenge: muons have limited lifetime: 2.2 μs Technology challenge!

Kappa framework results LEP3 and LHeC are good..



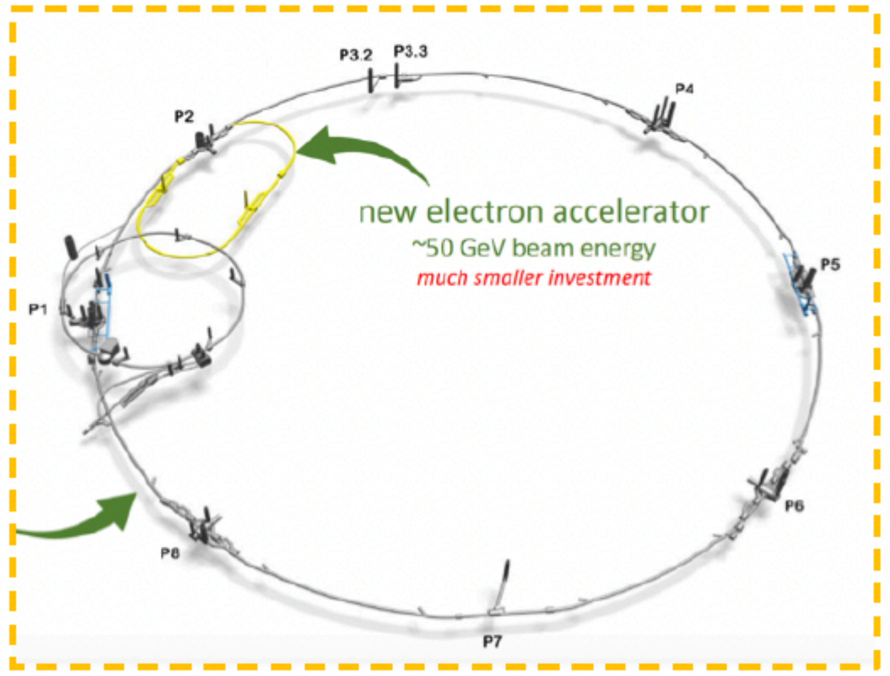
Potential for developement: future 10 TeV parton-scale collider options

FCC-ee



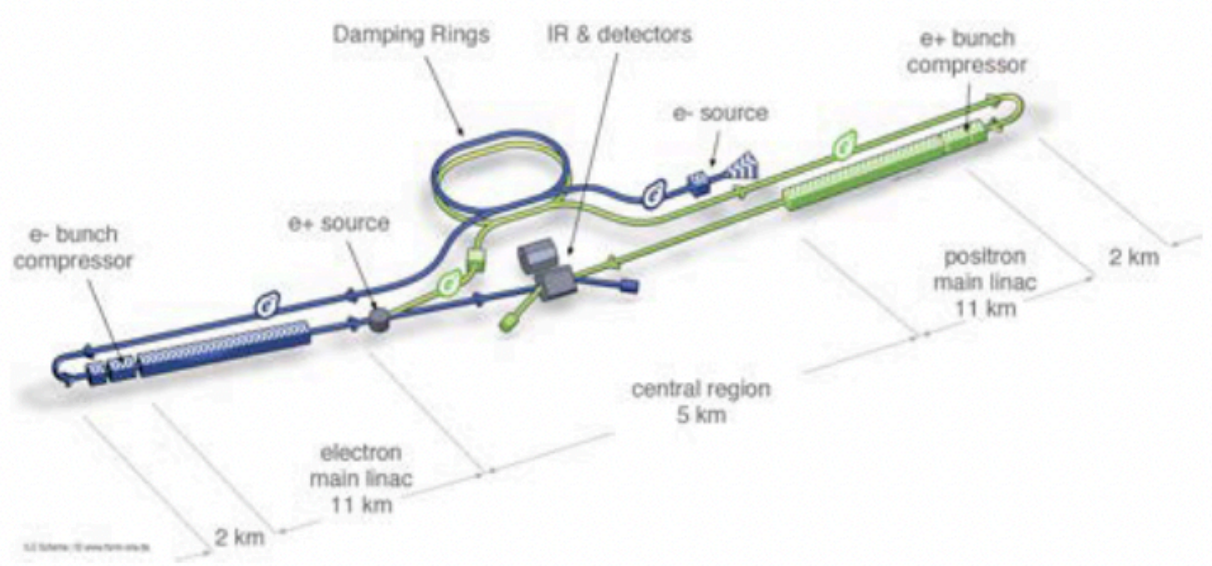
LEP3

LHeC

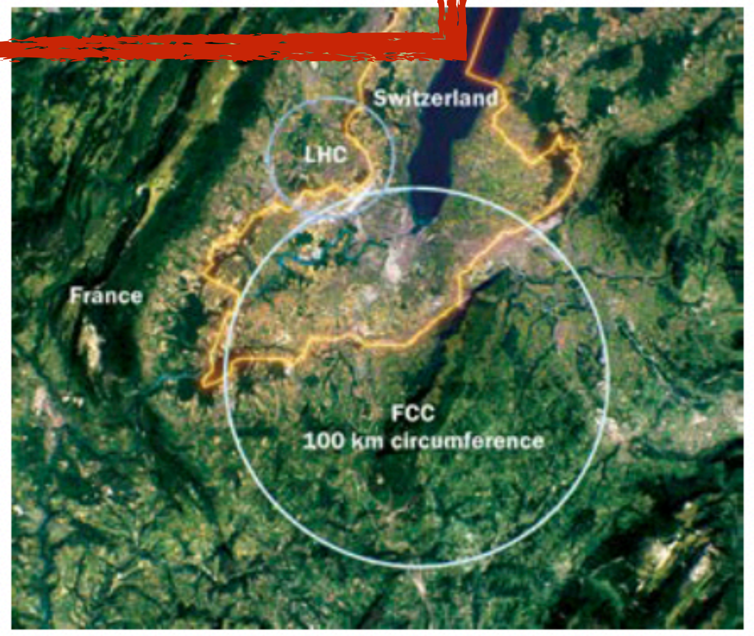


PERLE

LCF, CLIC

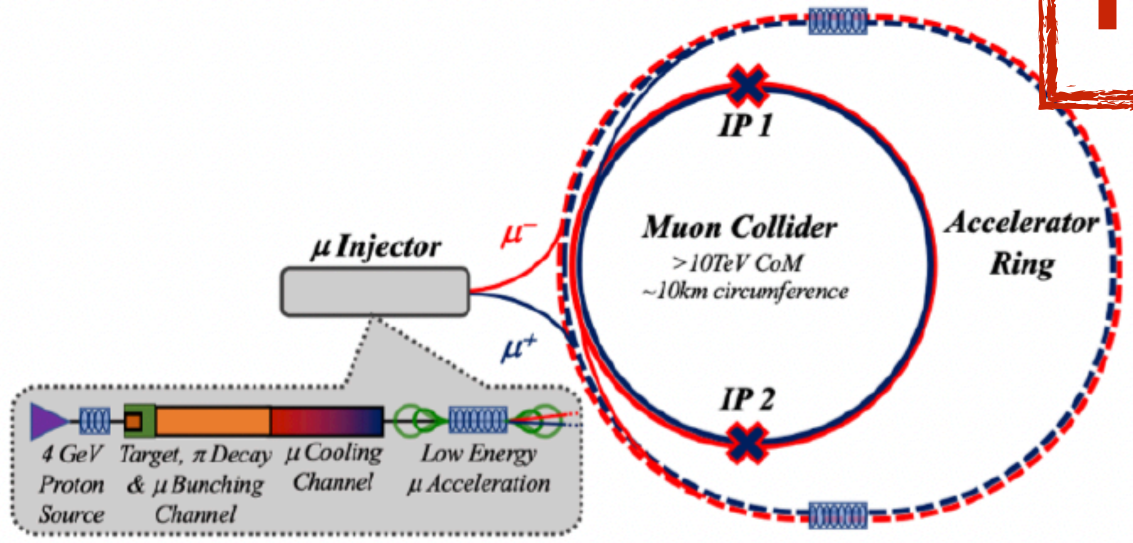


limited R&D



FCC-hh,
baseline 85 TeV (à 120 TeV)

NEED R&D



Muon Collider (3, 10 TeV)

e+e- with improved acceleration technologies
LCF, C3 (à 1 TeV), CLIC (1.5 TeV)
plasma acceleration for higher energies

How important is a high energy linear e+e- running?

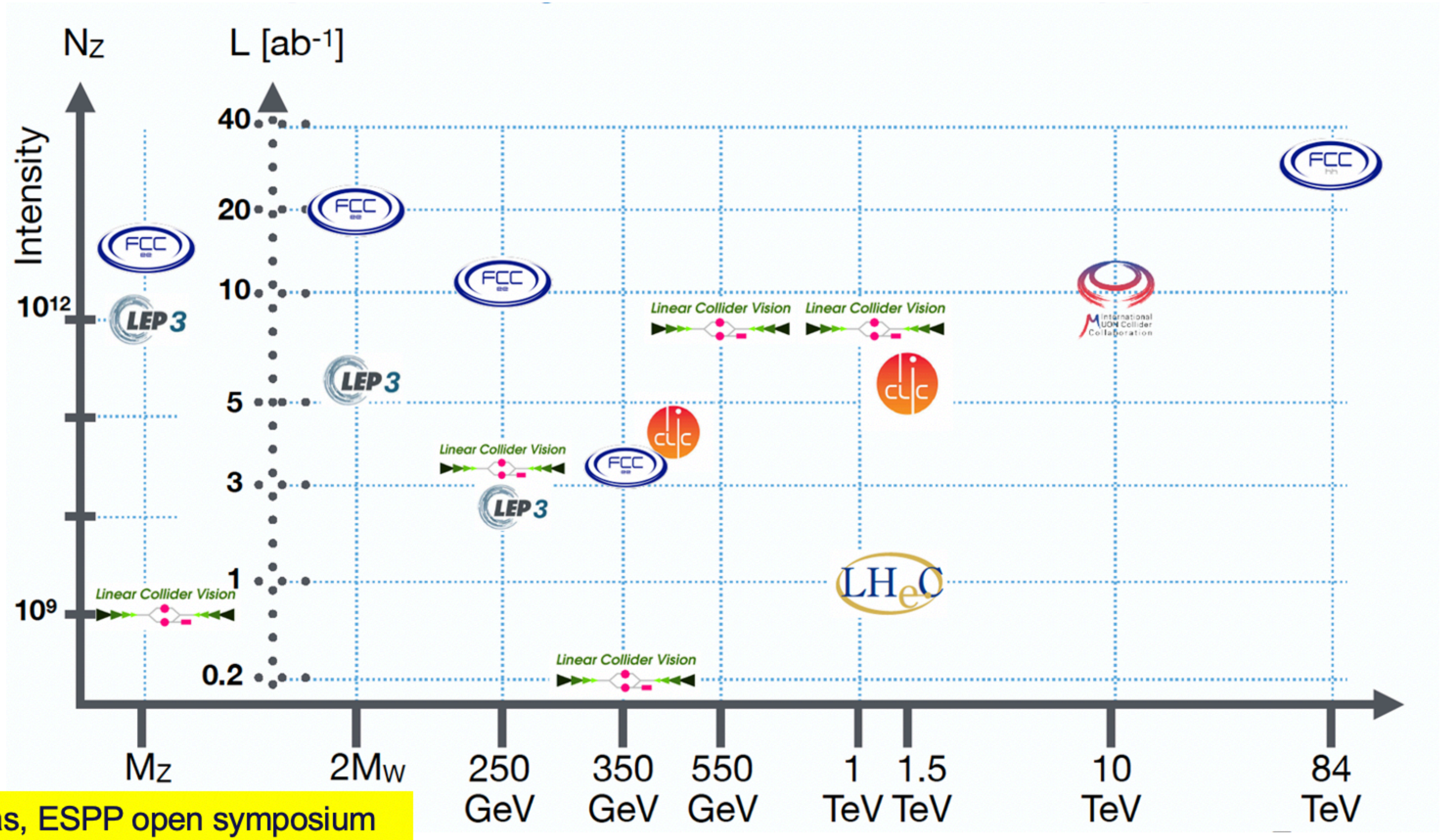
- LCF at 550 GeV

- CLIC at 550 GeV, 1.5 TeV (maybe 3 TeV in a second phase)

- Will 1.0, 1.5 or 3 TeV be enough to discover new particles or do we rather need a more powerful hadron machine?

- Will 1.0, 1.5 or 3 TeV it will bring sensitivity to the self coupling 10-20%, but the Fcc-hh or muon colliders would go to 4%

comparing future collider capabilities

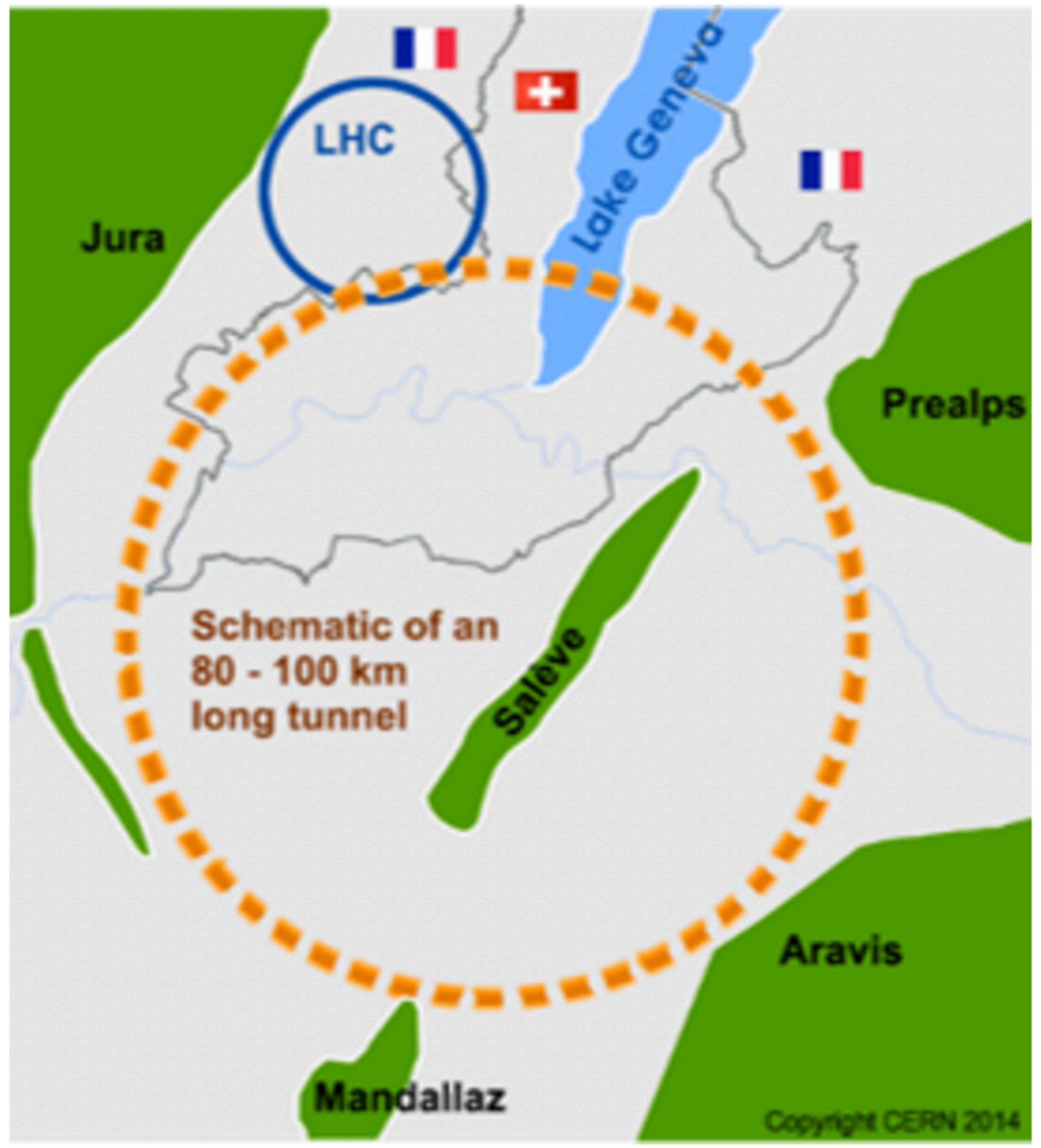


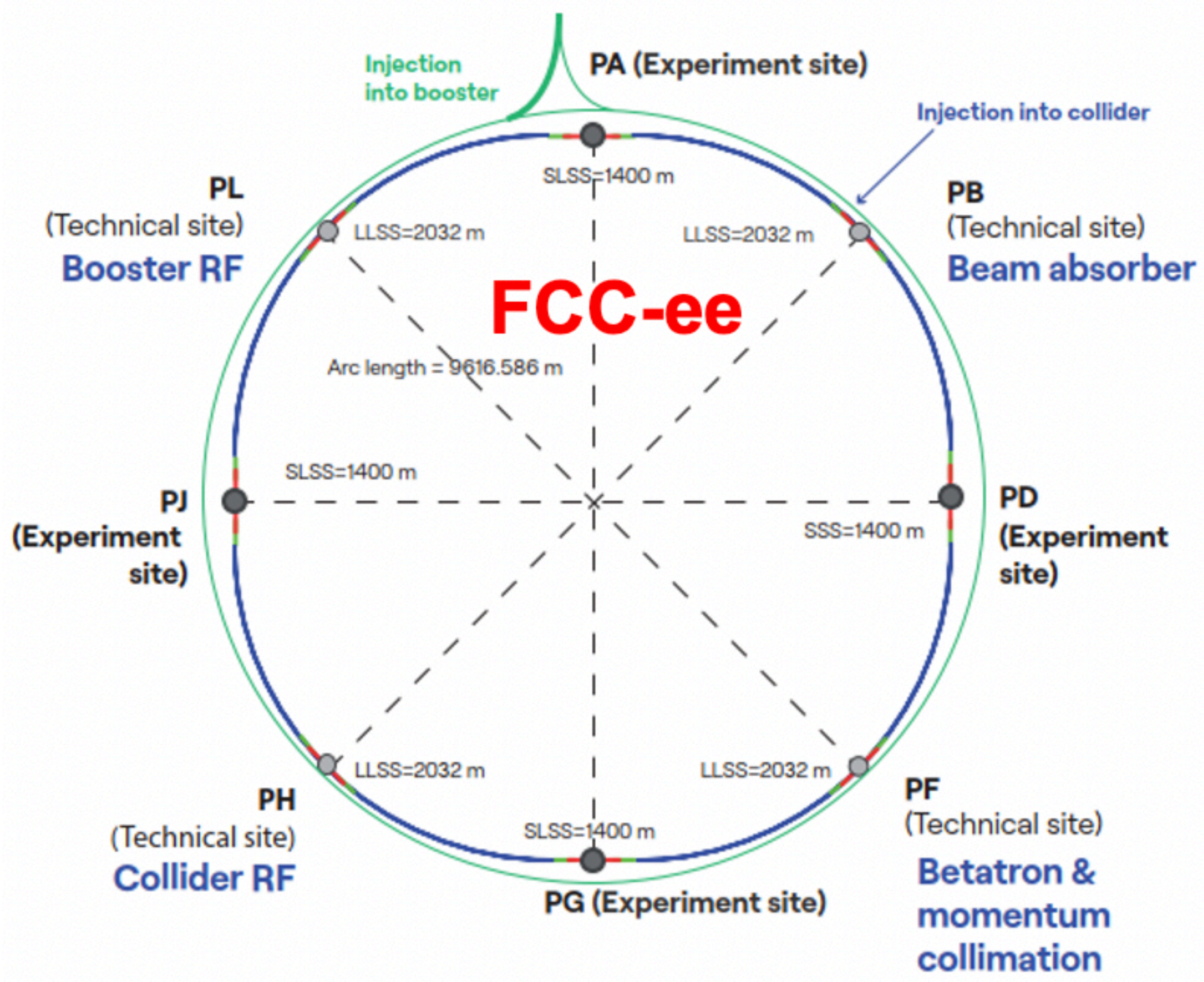
J. de Blas, ESPP open symposium

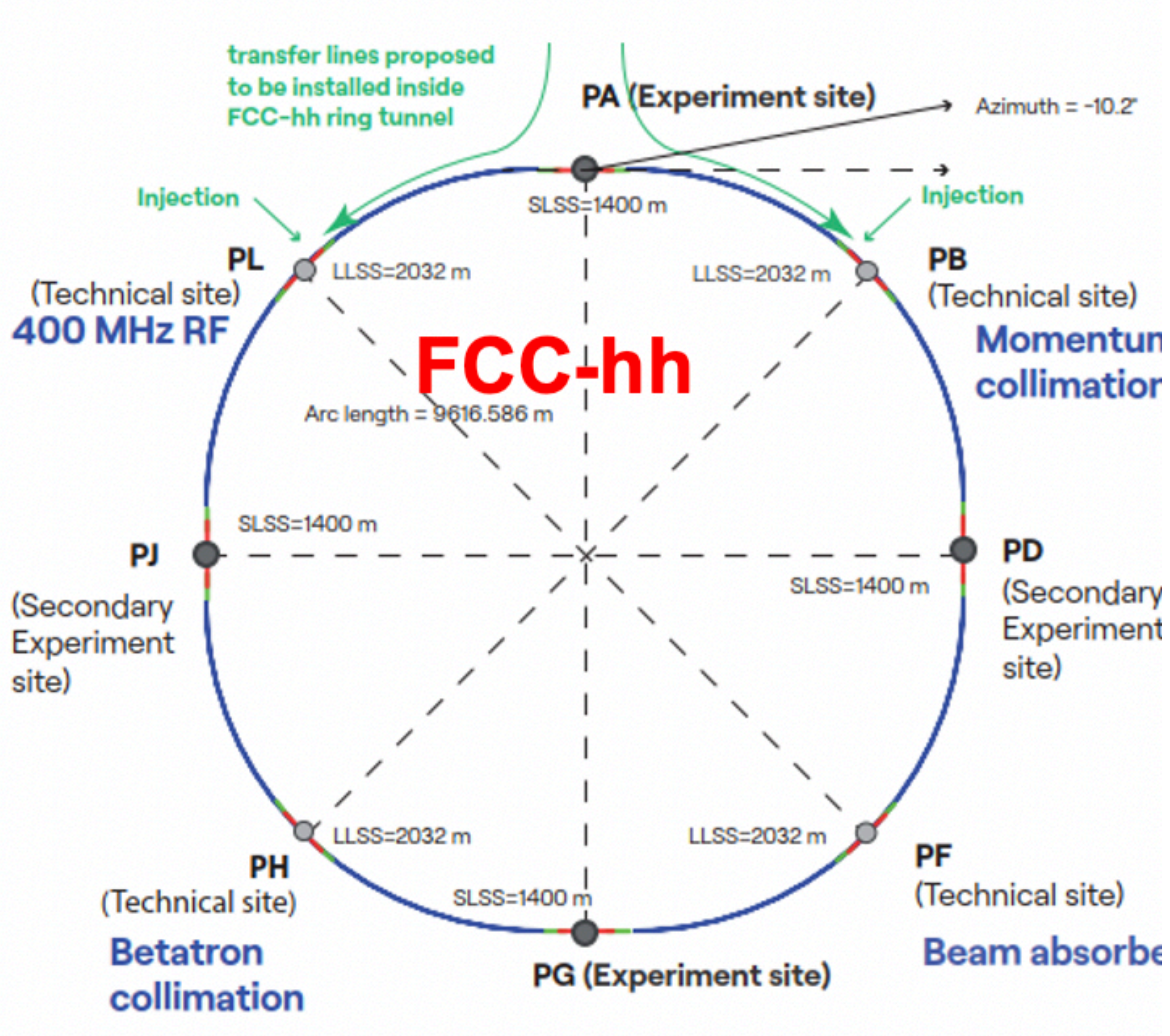
FCC integrated programme

stage 1: FCC-ee (Z, W, H, "tt") as Higgs factory, electroweak & top factory at highest luminosities
stage 2: FCC-hh (~84 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option

Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure







2020 - 2045 | 2046 - 2065 | 2070 - 2100

Building a viable financial path

Updated project cost for FCC-ee up to and including operation at ZH and 4 experiments
t-tbar upgrade requires additional 1.3 BCHF

Domain	Cost [MCHF]
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	**14 020**
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	**15 320**

F. Gianotti
ESU Venice

50% is there.
50% missing?
I interpret it as 7BCHF

Funding of FCC (or any other major future collider project) expected to come from two main sources:

- ❑ CERN Budget (i.e. revenues from Member and Associate Member States): would cover more than 50% of FCC investment cost
- ❑ External contributions:
  - additional voluntary contributions (in-cash or in-kind) from Member and Associate Member States
  - contributions from non-Member States
  - exploring possible contributions from the European Union in the next Multiannual Financial Framework (MFF 2028-2034)
  - exploring possible contributions of private donors (→ in Dec 2024, Council approved "*Policy for fundraising from private donors for scientific activities at CERN* ")

→ good progress over the past months

Several funding scenarios developed, based on different assumptions (e.g. constant or slightly increased CERN Budget)
→ ongoing discussions in Council

18

CEPC ee plan

Operation Plan

Starting with Higgs!!!

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30****	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30****	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30****	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30****	0.5	0.13	0.65	0.4×10^6

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

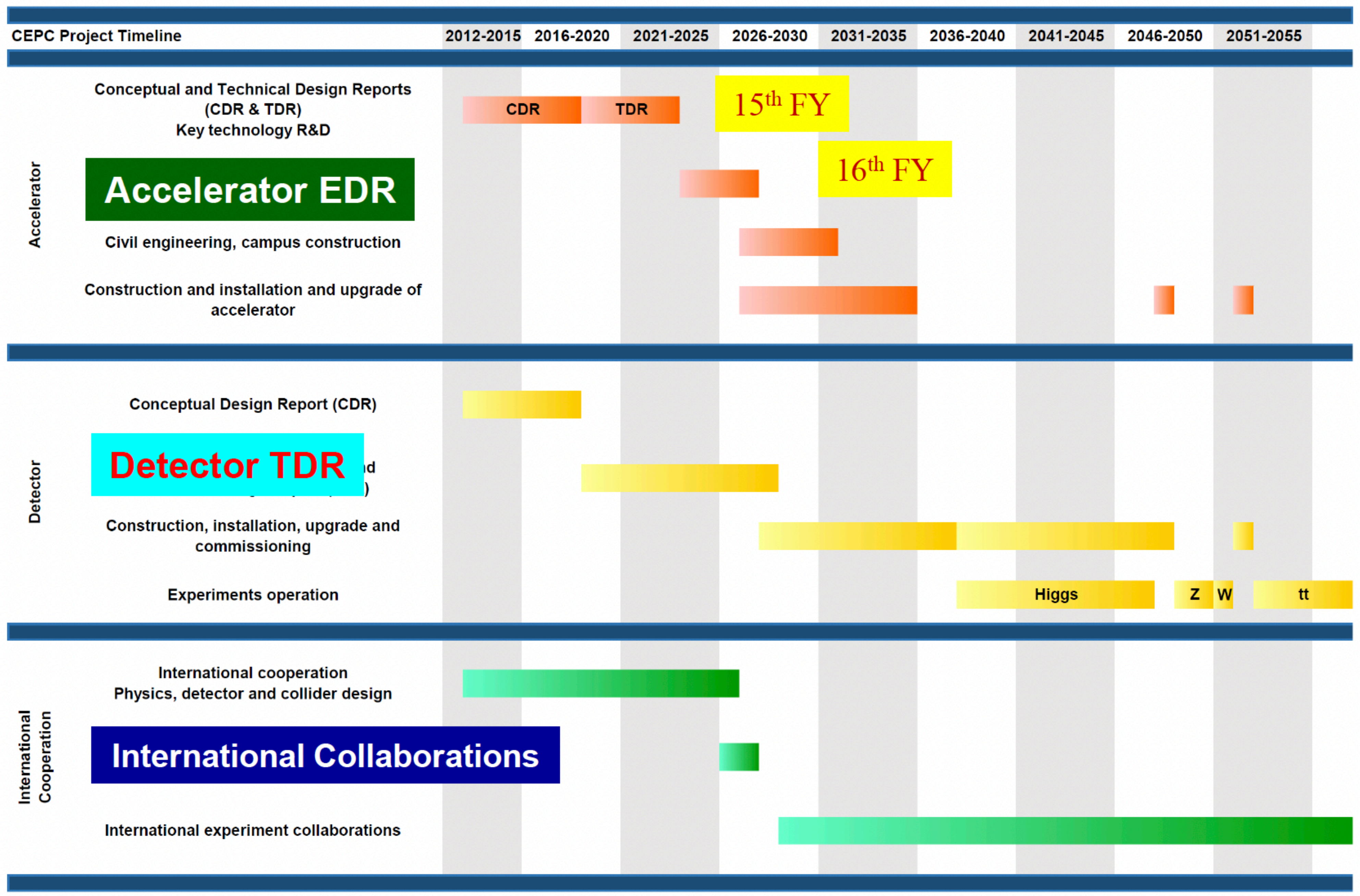
**** **30 MW leaves room for international in-kind contributions**

CEPC ee plan

- Schedule very fast, and not expensive thanks to automatic production of magnets and digging in granite (less concrete and left over from digging sold).
- Decision late 2026-or 2027.
- “They won’t built the machine if Europe builds Fcc-ee.” (quote from Venice)

CEPC Planning and Schedule

TDR (2023), EDR(2027), start of construction (~2027)



- CEPC plans to submit the proposal to the central government(NDRC) within the “15th five year plan”
- For this purpose, CAS organized studies and reviews
- CEPC was ranked by CAS as the No. 1 for HEP & NP, and No.2 for Basic Science
- We are waiting for the 2nd review by CAS later this year
- Waiting for the “call for proposals” by NDRC by the end of this year

Yifang Wang
ESU Venice

CEPC magnets development: interesting for hh collider

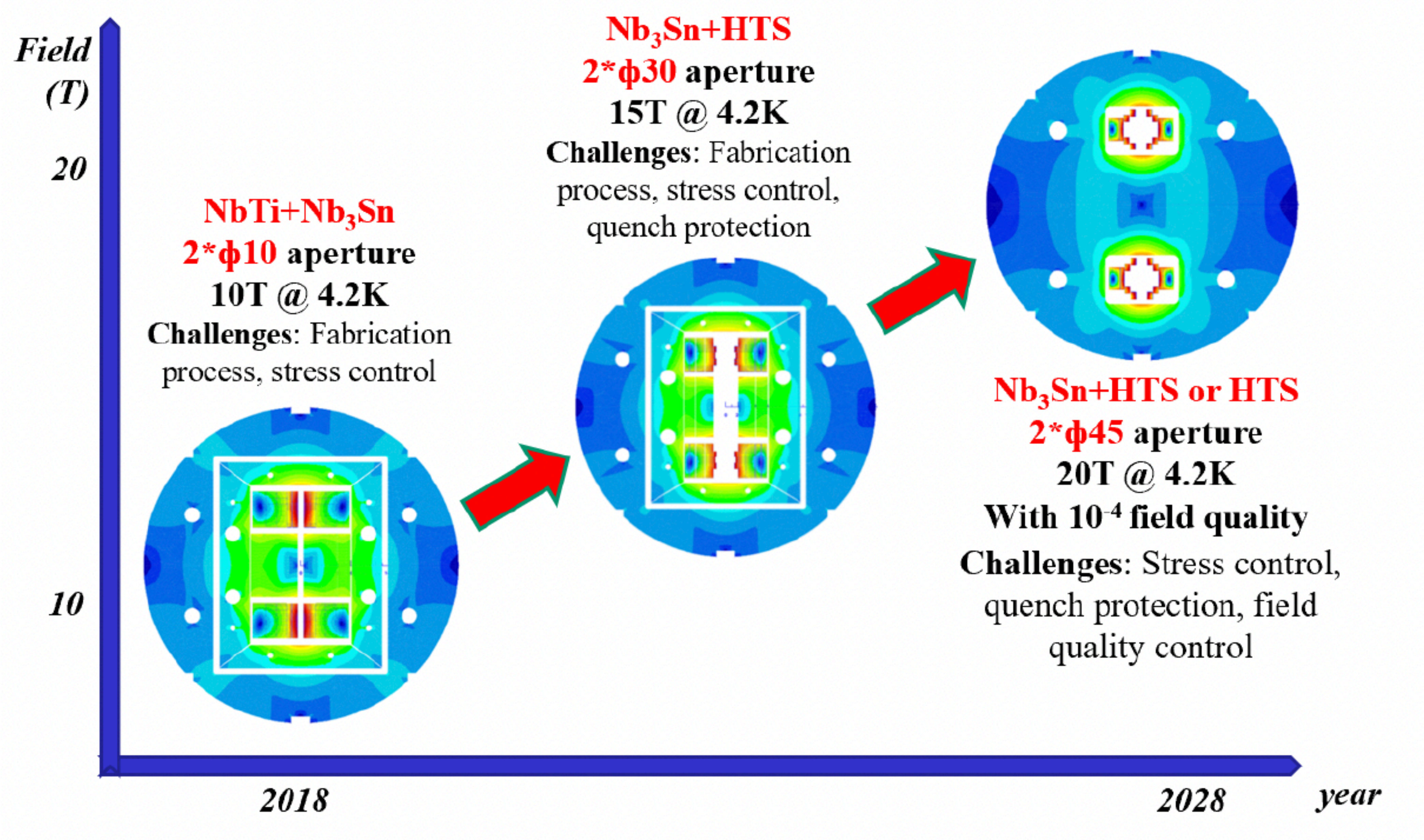
- the CEPC (and in particular its successor SppC) R&D includes intriguing developments in **iron-based high-temperature superconducting (IBS)** materials 4.2K that could be game-changers for future high-field magnets, potentially benefiting projects like FCC-hh (@2K)

- (IBS) are a relatively new class of high-temperature superconducting materials.

- IBS magnets promise fields exceeding 30 T, which would be unaffordablele or impractical with conventional NbTi or Nb_3Sn technologies.

- The cost profile of IBS materials is attractive as well — they don't require expensive rare-earth elements and can be fabricated with standard, scalable techniques.

- They could be realistically ready by 2045-2050, which could imply that if the CEPC-ee won't be built China could go for the hh option at that point..



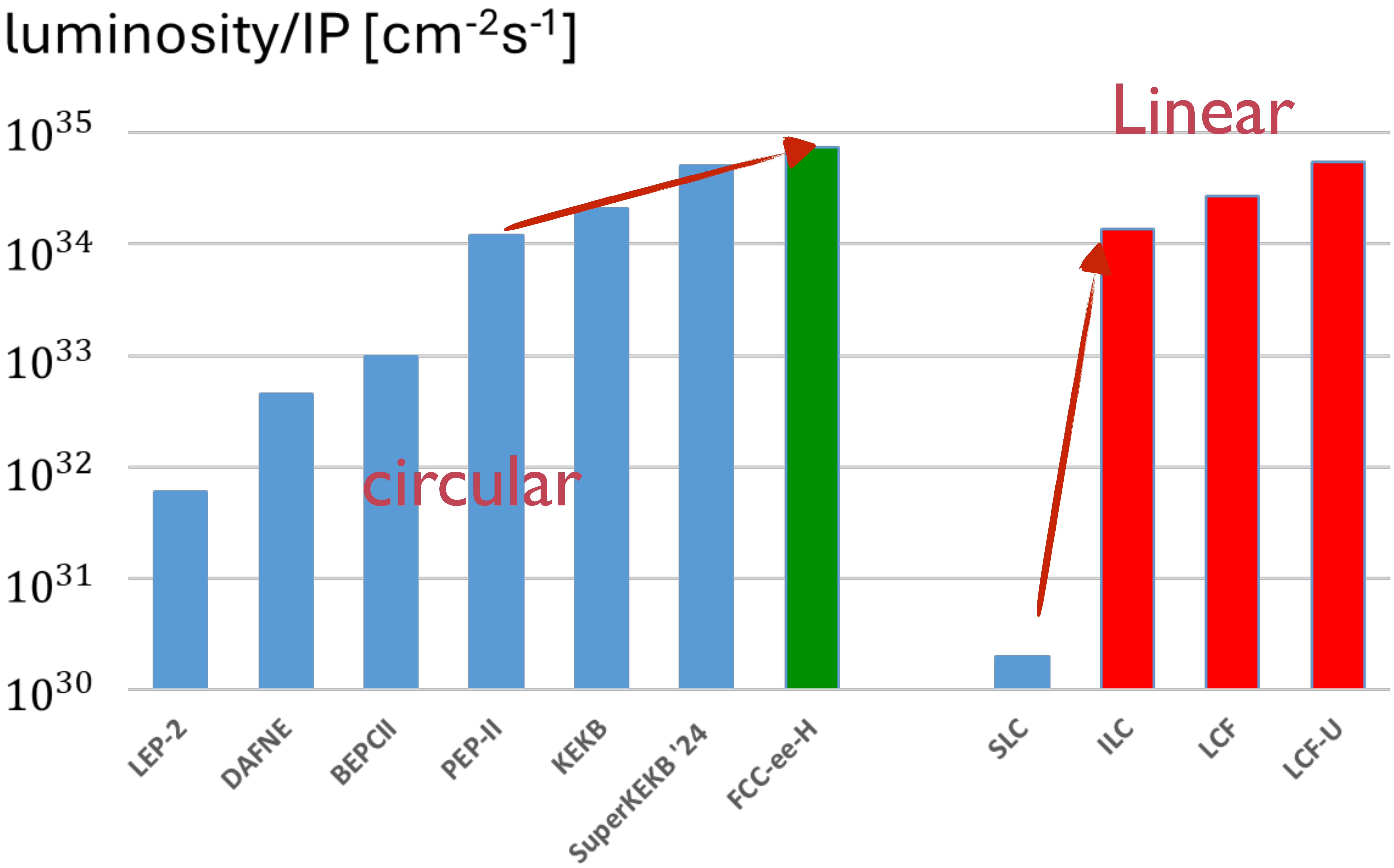
Future experiments

Future experiments

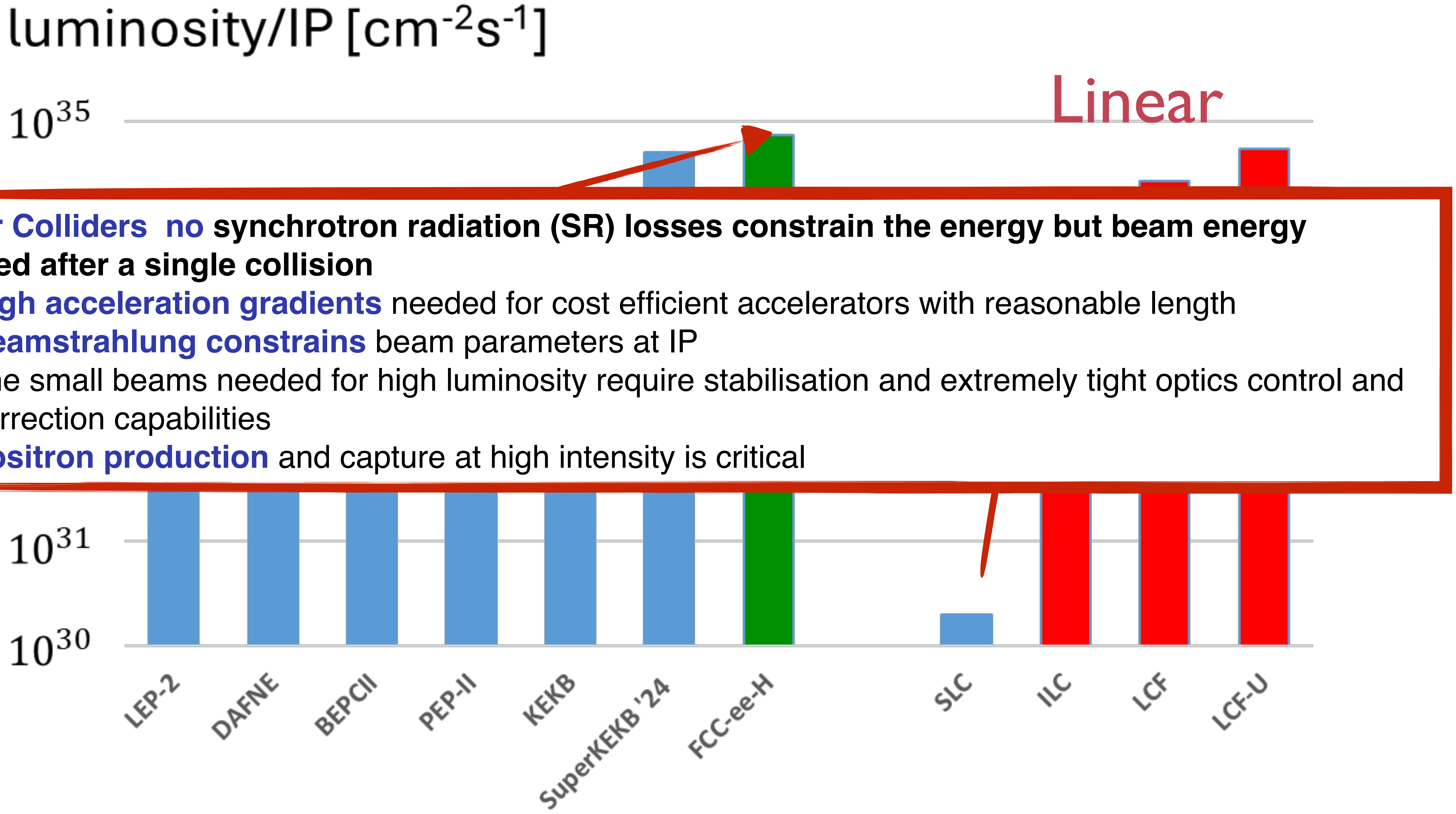
Future experiments

Future experiments

Linear versus Circular: luminosity step



Luminosity achieved in past colliders



Linear Colliders no synchrotron radiation (SR) losses constrain the energy but beam energy dumped after a single collision

- **High acceleration gradients** needed for cost efficient accelerators with reasonable length
- **Beamstrahlung constrains** beam parameters at IP
- The small beams needed for high luminosity require stabilisation and extremely tight optics control and correction capabilities
- **Positron production** and capture at high intensity is critical

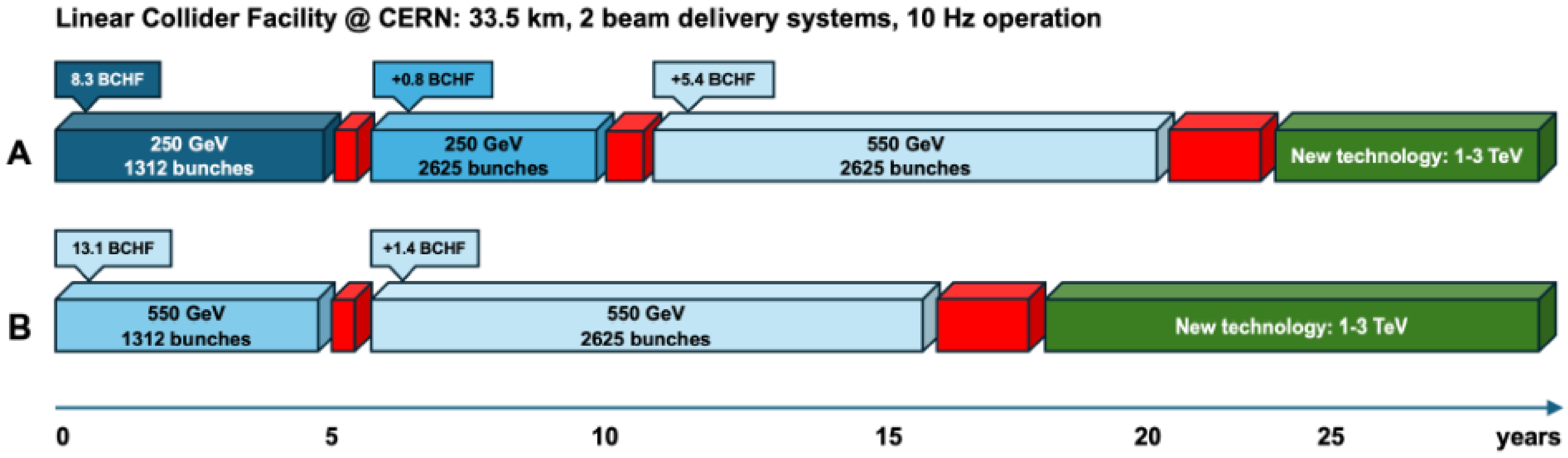
"Linear Collider at CERN LCF"

To go at >~550 GeV in the LCF, you need to either:

- **Build longer linacs (linear accelerators)** → more distance to accelerate the particles.
- **Use higher accelerating gradients** → more energy gain per meter.

Quantity	Symbol	Unit	Initial-250	Upgrades		Initial-550	Upgrade
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. Luminosity	$\mathscr{L}$	$(10^{34}\text{cm}^{-2}\text{s}^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert / \lvert P(e^+)\rvert$	(%)	80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Site AC power	P_{site}	MW	143	182	322	250	322
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Operation & maintenance		MCHF/y	170	196	342	291	342
Electricity		MCHF/y	66	77	142	115	142
Operating Personnel		FTE	640	640	850	850	850

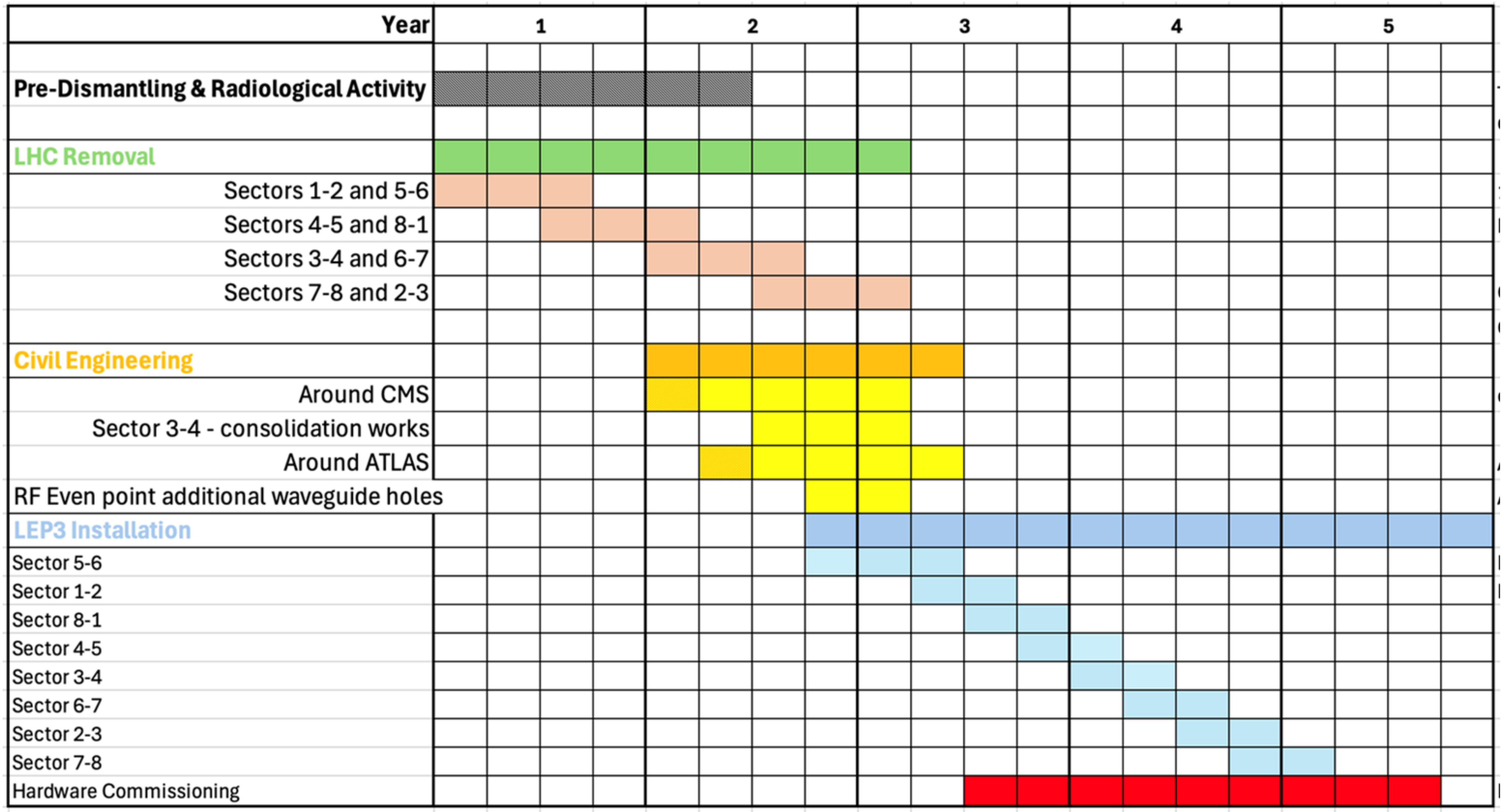
Table 1: Summary table of the LCF accelerator parameters in the initial 250 GeV configuration (4th column) and possible upgrades (first to 2625 bunches per train, then to 550 GeV), as well as a configuration for starting directly at 550 GeV with 1312 bunches (7th column) and its upgrade to 2625 bunches per train. All options based on a 33.5 km long facility.



LEP3

LEP 3: second cheapest option

- needs LHC to be dismantled to be installed (radiation levels have to decrease, needs a couple of years)
- technical design would need more studies (not complex) Re-uses LHC experiments.
- if the LHC is dismantled can we re-use it as an injector for the Fcc-hh? Is this important anyhow?



Overall not so shorter than Fcc-ee: One running scenario: **6 yrs at 230 GeV, 4 years around WW, 6 years around Z**
But the difference wrt to Fcc-ee, is that Fcc-hh could be built and even be running at the same time!
How much money would that imply?

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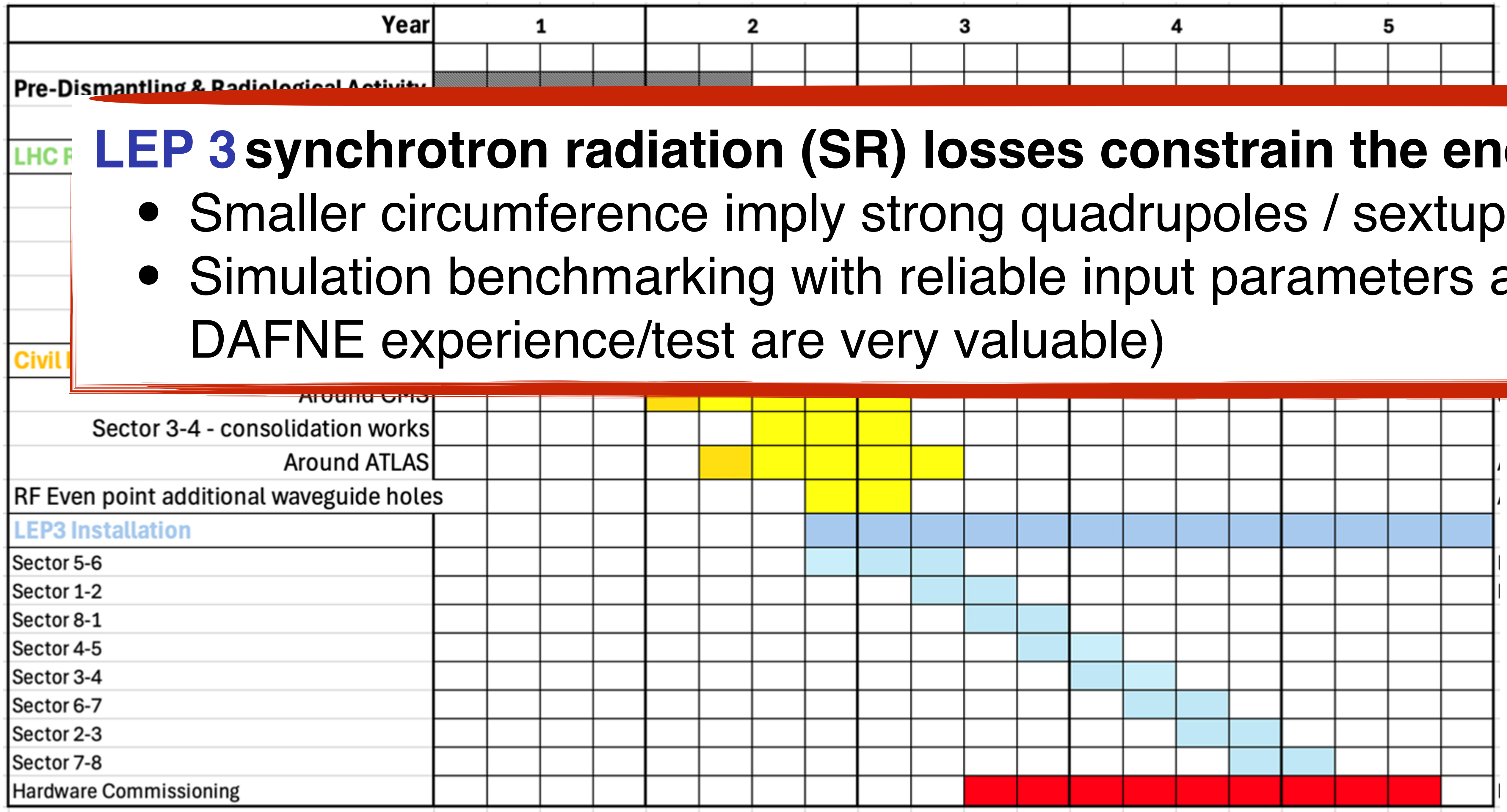


LEP 3 synchrotron radiation (SR) losses constrain the energy
- Smaller circumference imply strong quadrupoles / sextupoles to maintain luminosity (e.g. LEP3)
- Simulation benchmarking with reliable input parameters and diagnostics are required (SuperKEKB and DAFNE experience/test are very valuable)

Overall not so shorter than Fcc-ee: One running scenario: **<u>6 yrs at 230 GeV, 4 years around WW, 6 years around Z</u>**
But the difference wrt to Fcc-ee, is that Fcc-hh could be built and even be running at the same time!
(Please note that the LHC cannot be used as injector for the Fcc-hh in its present form,
so it does’t matter that it gets dismantled)

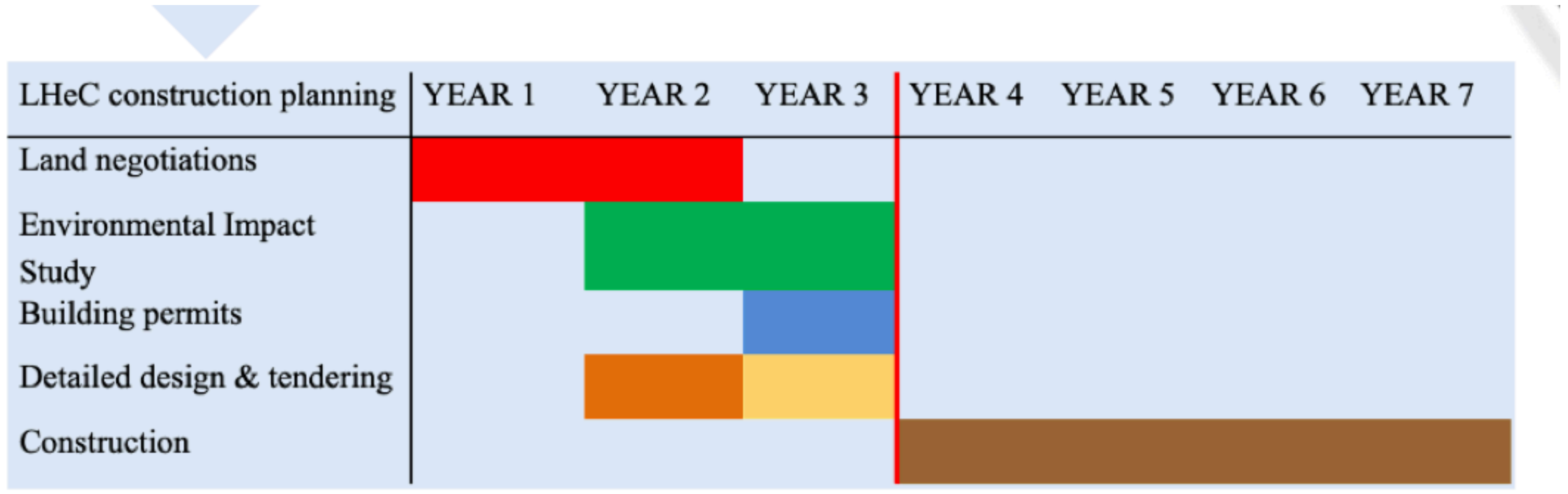
LHeC

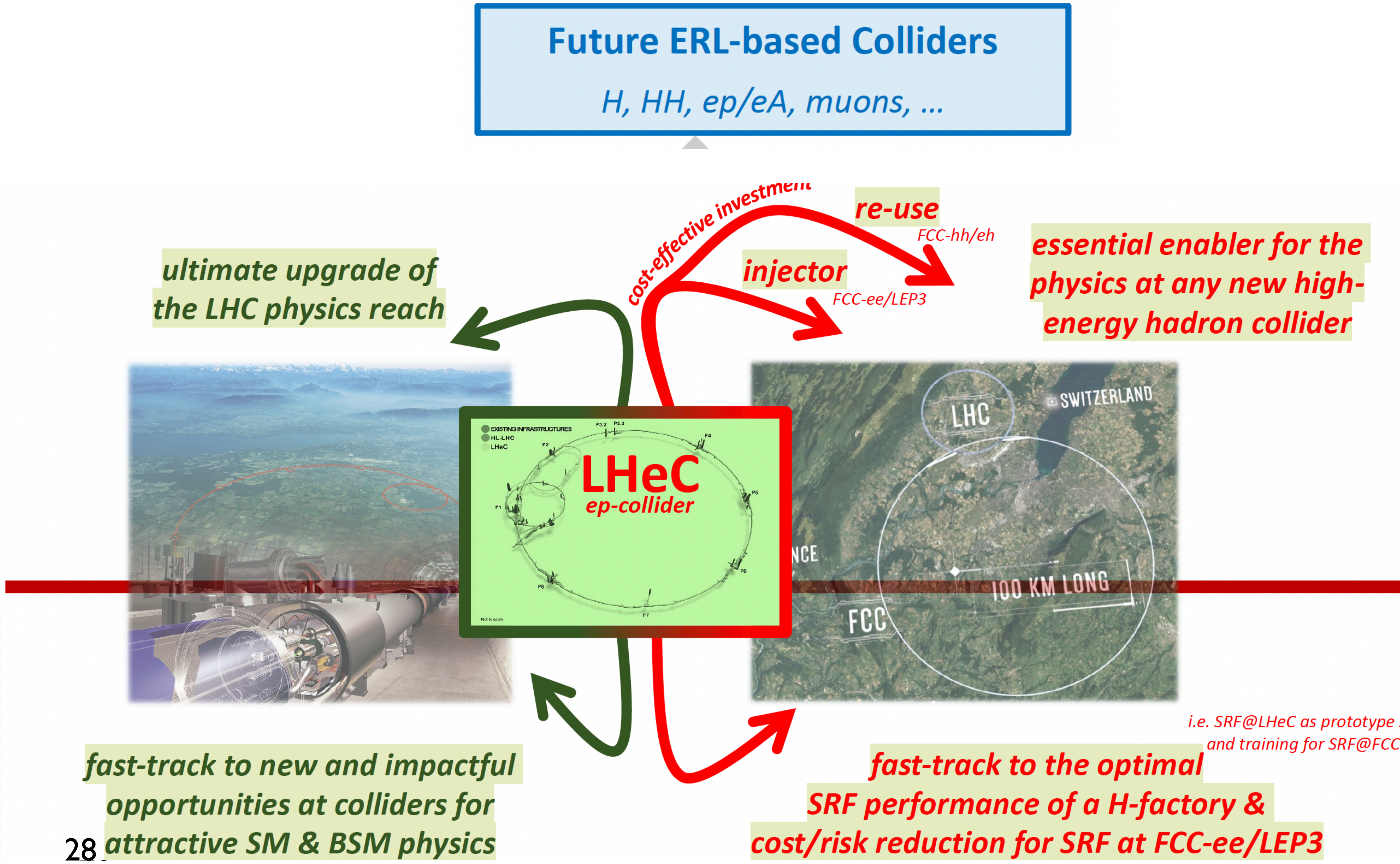
- LHeC: cheapest option, only one experiment, requires HL-LHC to run.
  Needs demonstrator for Electron Recovery Linac PERLE at IJCLab

- Start operation after or at the same time of HL-LHC (>2041), luminosity > 1034 cm-2s-1.
  6 years of operation: 1 ab-1 (e.g. 2043-2048).

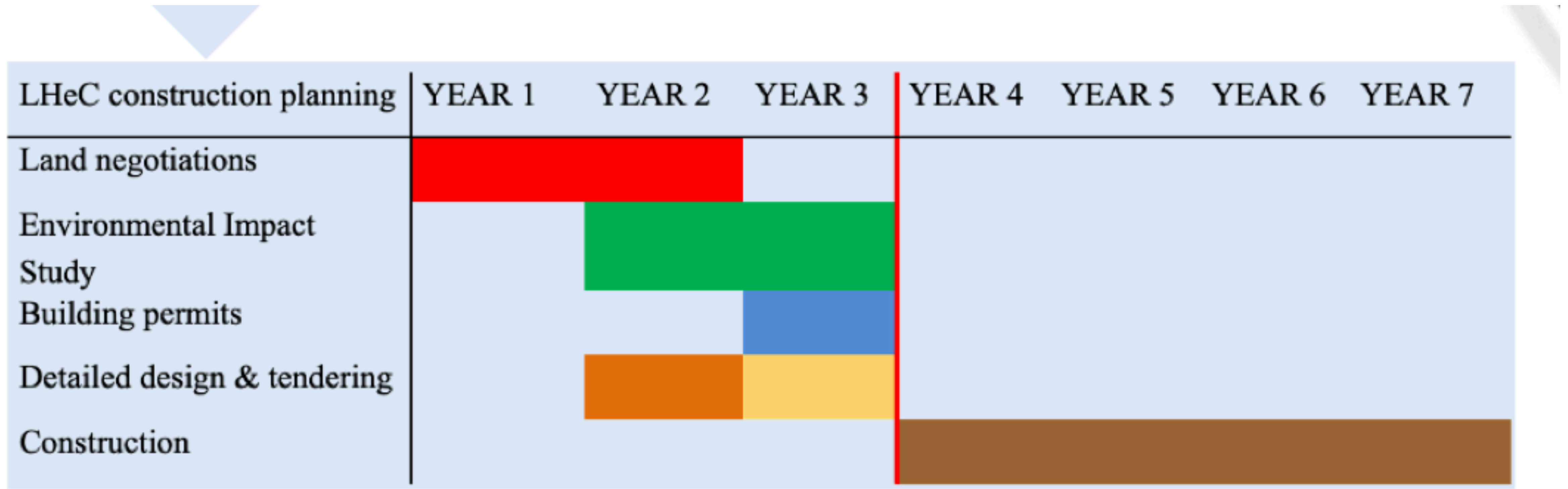
- Would also allow Fcc-hh to be constructed in parallel, running in parallel is a problem as there is no money to have both machines at the same time.

- **Could be a bridge both for Fcc-hh or before LEP3**
  The ring could be used for Muon Collider





LHeC



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Start operation after or at the same time of HL-LHC
(>204
6 yea

LHeC / Energy Recovery Linacs Allow high luminosity for ep collisions

- Very high currents; recirculation efficiency is critical
- R&D on superconducting linac technology:
- Comprehensive beam dynamics simulations needed to ensure performance

Woul
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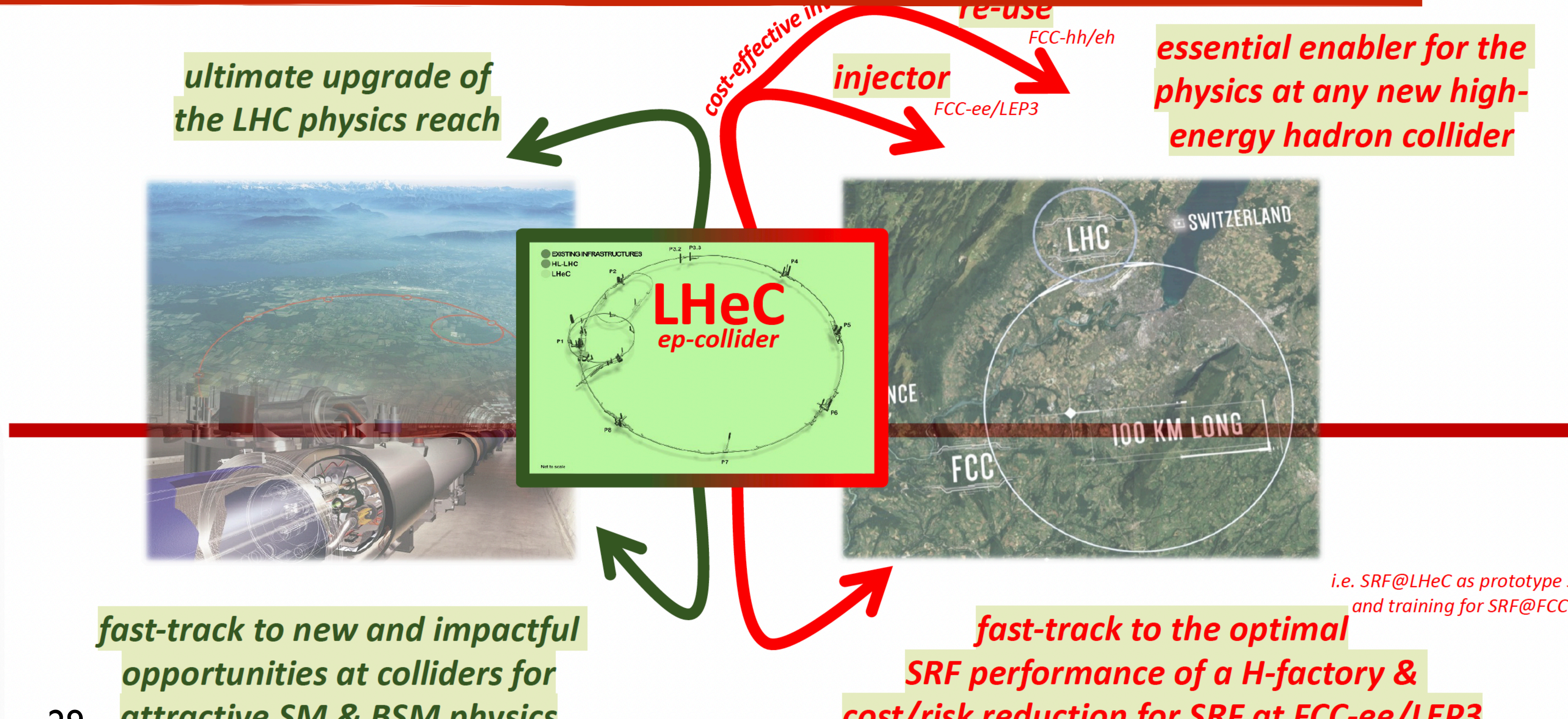
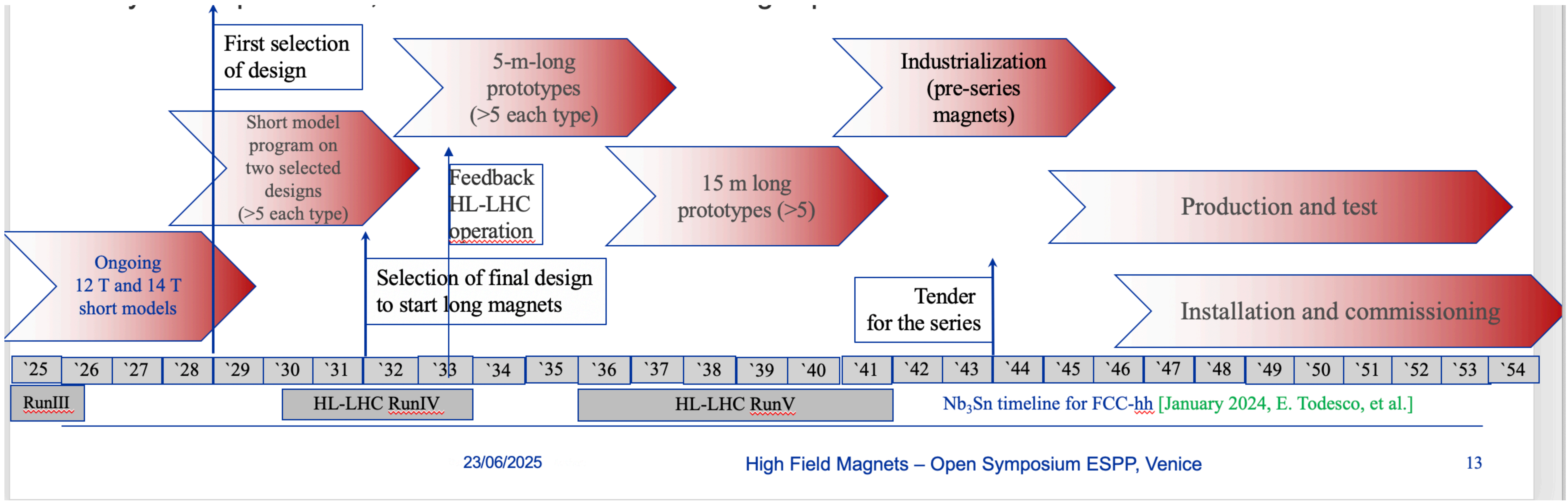


“Energy-frontier colliders”

Fcc-hh Magnet timeline

2024 LTS timeline

LTS= Low Temperature Superconducting magnets
With new design of FCC-hh
(85 TeV and 91 km ring)
There is a fast track for these magnets that could be ready by 2051



Fcc-hh Magnet timeline

New accelerated LTS timeline!!!!!

LTS= Low Temperature Superconducting magnets
With new design of FCC-hh
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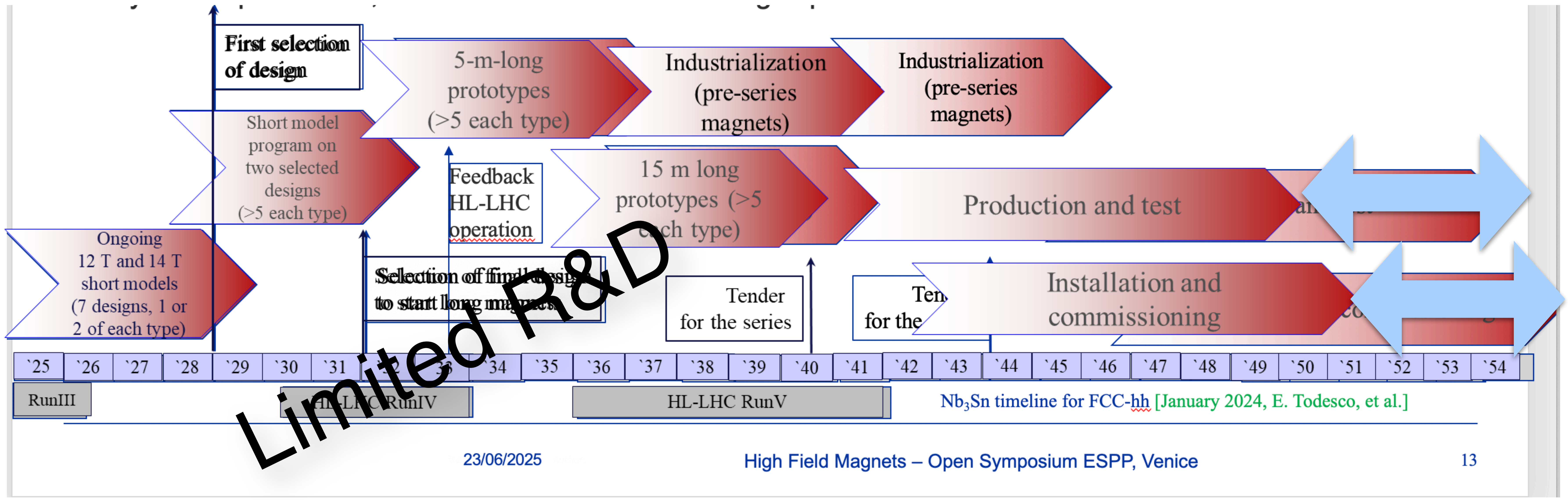
14 T Nb_3Sn targets:
select design by 2028/29, then scaling in length

TRL 7
in 2032-40



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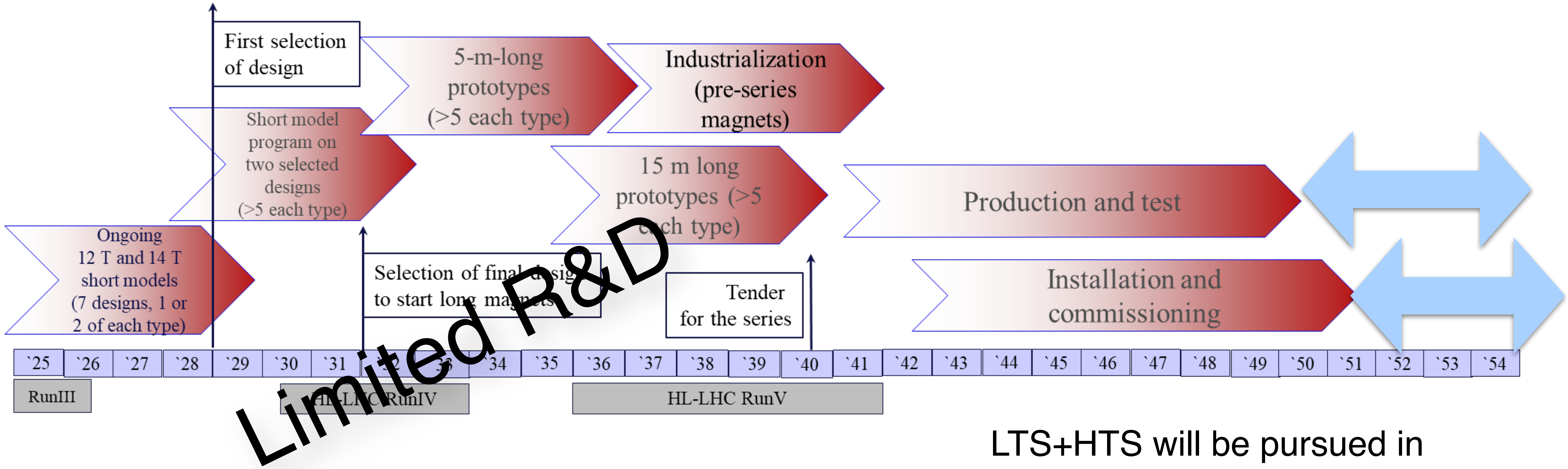
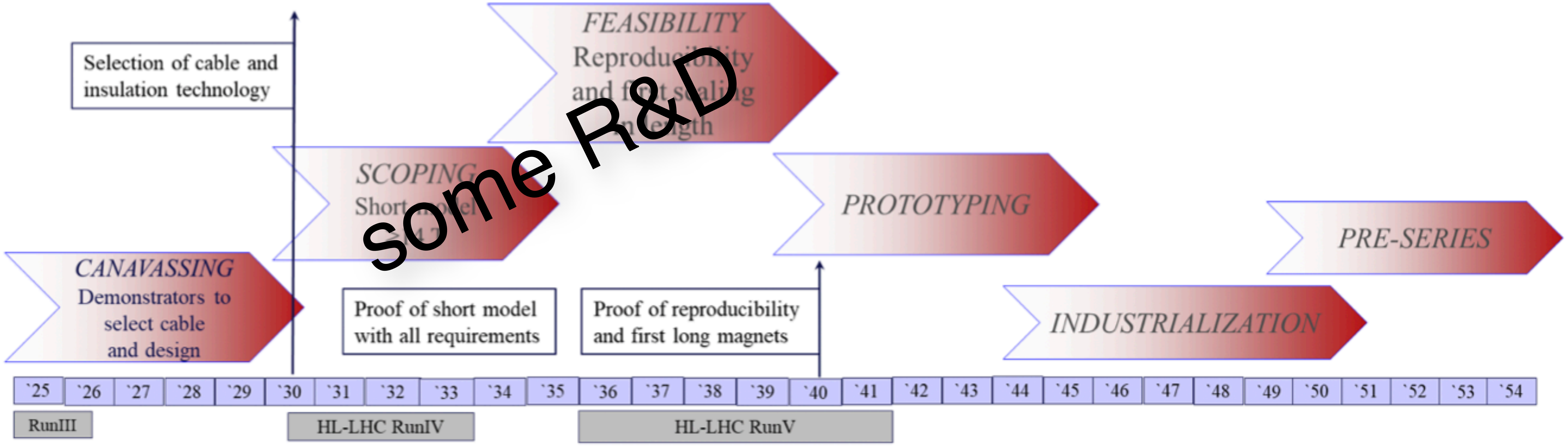


LTS+HTS will be pursued in parallel until 2035(HTS work at higher T)

HTS=High Temperature Superconducting magnets

HTS targets:
by 2035 short model dipole with all features (aperture, field ≥14T, field quality, protection, …)

TRL 7 in 2040-45



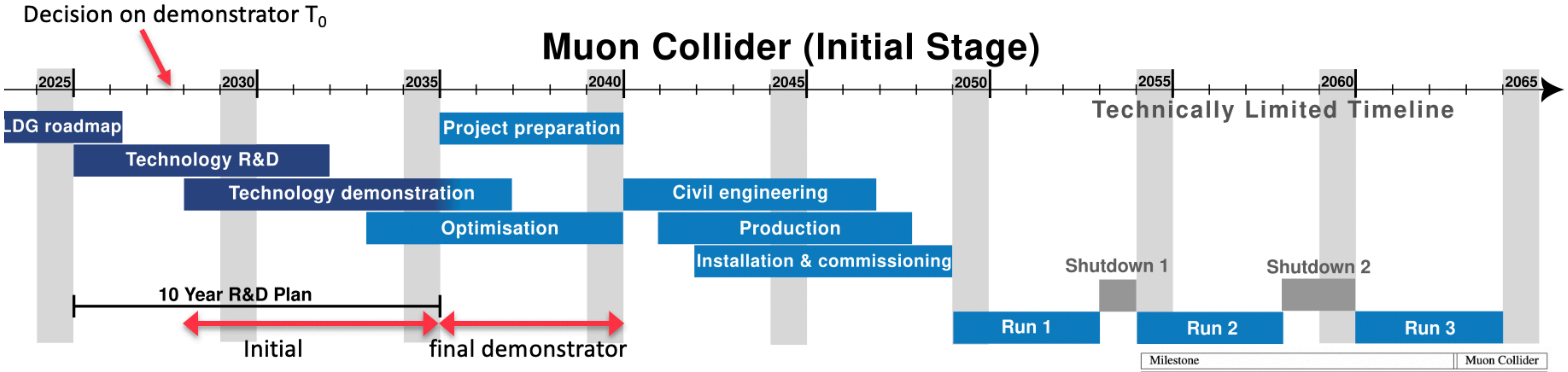
Fcc-hh possibly in stages? A bit of Science Fiction

- Fcc-hh based on 14 T Nb_3Sn magnets could start operation in ~2055 at ecm~85 TeV as a standalone project

- Fcc-hh 2nd stage could start in 2074 with HTS , a formidable machine !
  The HTS (at higher temperature 4.5 K or even 10K will reduce the electrical power required . Worldwide the development of such magnets is driven by other fields and application, so the cost for such magnets will most likely reduce

Muon Collider

Timeline and R&D Programme Proposal



Milestone	Muon Collider
Construction of RF test stands	2025 – 2028
Production of test cavities	2026 – 2039
Operation of test stands	2027 – 2040
Demonstration Phase	$T_0 - (T_0 + 7)$
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (5 cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	$T_1 - (T_1 + 5)$
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2 + 9)$
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	$T_2 + 10$

Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

- Assumes firm commitment to enable the muon collider as next flagship after HL-LHC
- R&D is fully successful
- No delays due to decision making

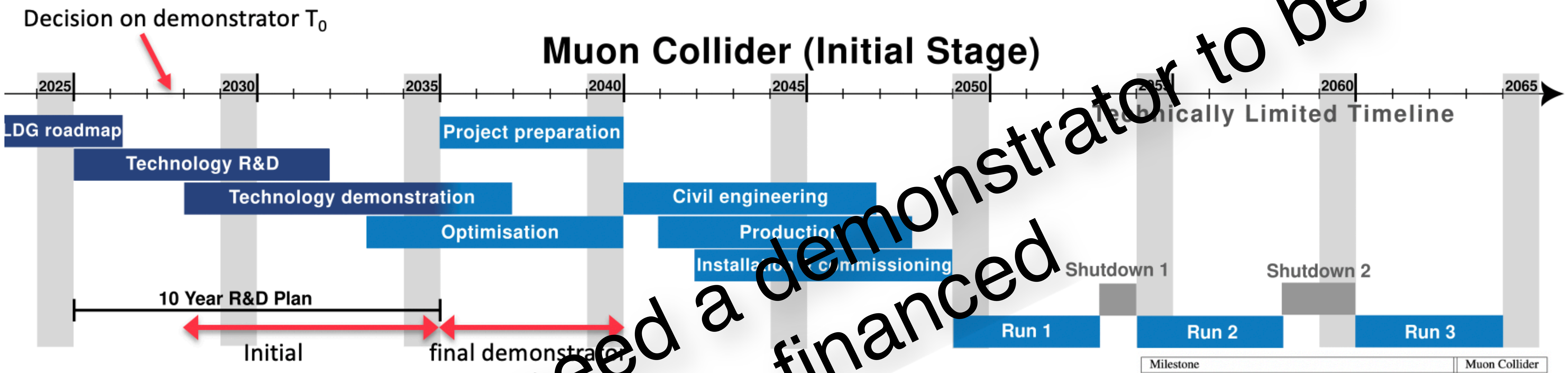
Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

https://indico.cern.ch/event/1439855/contributions/6542430/

Muon Collider

Timeline and R&D Programme Proposal



We need a demonstrator to be financed

Timeline is **driven by R&D**

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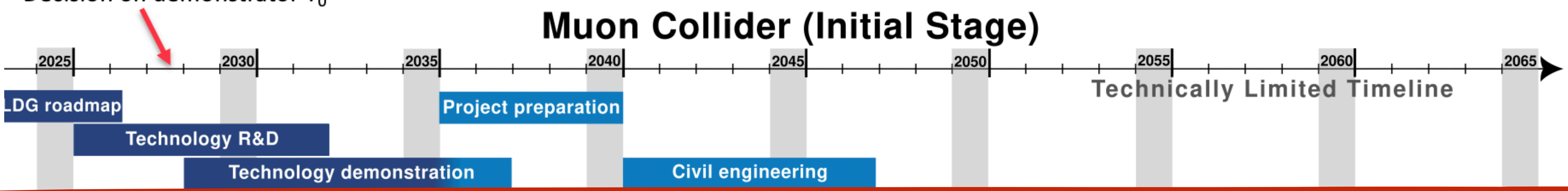

Technological challenge: Muon colliders provide a path towards high energy lepton collisions but are not at the level of maturity of the other proposals at present.

- Demonstration of the 6D-cooling technology is critical
- Technological challenges are associated with the various acceleration steps, in particular s.c. magnets, RF systems, fast cycling magnets
- Reliable start-to-end simulation tools need to be further developed to validate and optimise the overall performance
- Mitigation of neutrino flux and resulting secondary radiation remains a critical issue

- No delays due to decision making

Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

Main technologies R&D completion Industrialisation of key components Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2 + 9)$
Civil engineering TI installation Component construction Accelerator HW installation HW commissioning Beam commissioning	
Physics operation start	$T_2 + 10$

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cost estimates

Fcc-ee +Fcc-hh 33 (35) BCHF (experiments)
Fcc-hh 27 BCHF

project	scenario / energy / details	cost
FCC-ee	Z, WW, ZH, + 4 exp. CERN part	14.0 BCHF
	+ 4 exp. non CERN part	+1.3 BCHF
	+ upgrade to ttbar	+1.3 BCHF
FCC-hh	85 TeV pp, as second stage	+19.1 BCHF
FCC-hh	85 TeV pp, standalone	27.3 BCHF
LCF	250 GeV	8.5 BCHF
	550 GeV	+5.5 BCHF
CLIC	380 GeV	7.3 BCHF
	1500 GeV	+7,1 BCHF
LEP3	ZH at 230 GeV + 2 exp CERN part	3.9 BCHF
	+ 2 exp non CERN part	+0.9 (0.3) BCHF

project	scenario	cost
LHeC	9 km new tunnel, 50 GeV e^-	2 BCHF
Muon Collider	3.2 TeV at CERN	12.0 BCHF
	7.6 TeV at CERN	17.0 BCHF
	10 TeV green field	19 BCHF

F. Zimmerman @Higgs Hunting

Conclusion

- Fcc-ee+ (Fcc-hh) has a large support: but money is missing right now. Situation may be clearer shortly

- A cheaper option B should be identified and seriously studied. There are cheaper options, but they would require anyways additional money if we want to build the tunnel of Fcc-hh at the same time.
  In general we would need more insight on these options.

Back-up

Sustainability

	A	B	C	D	E	F	G
	Greenhouse gas emissions	of various projects					
	As compiled by the LDG WG on sustainable accelerators (soon on arXiv)						
		FCC-ee	CEPC	LHeC	LCF 250	LCF 550	
	Construction [kt CO2e]	530	1137		380	380	
	Detectors [kt CO2e]	142 - 186			94	94	
	Electricity [TWh/year]	1.2 - 1.9	1.3 - 2.2	1.1	0.8 - 1.0	1.4 - 1.8	
	Operation [kt CO2e/year]	18 - 40	16 - 27		13 - 15	23 - 28	
	LCF have data inclusing infrastructure and services, but most do do not. Hence I skip.						
	There is also data from C3 and CLIC, but that's on a longer timescale.						

@P. Koppenburg

“LCF option at CERN”

To go at >~550 GeV in the LCF, you need to either:

- **Build longer linacs (linear accelerators)** → more distance to accelerate the particles.
- **Use higher accelerating gradients** → more energy gain per meter.

“CLIC technology offers gradients 70–100 MV/m”

- **CLIC (Compact Linear Collider)** developed at CERN uses a different accelerator tech (two-beam acceleration).
- It can provide much higher accelerating gradients (70–100 megavolts per meter), compared to the superconducting RF tech of the ILC/LCF (~30–35 MV/m).
- This means you can reach higher energies with a **shorter machine**, but the technology is more complex.

“(Also: C3, HELEN …)”

- These are other **emerging accelerator concepts**:
  - **C^3 (Cool Copper Collider)** → uses cryogenically cooled copper RF structures, aiming at ~120 MV/m.
  - **HELEN** → another high-gradient linear accelerator R&D project.
- Both are being studied as alternatives to SRF or CLIC to make future colliders more compact and powerful.
-

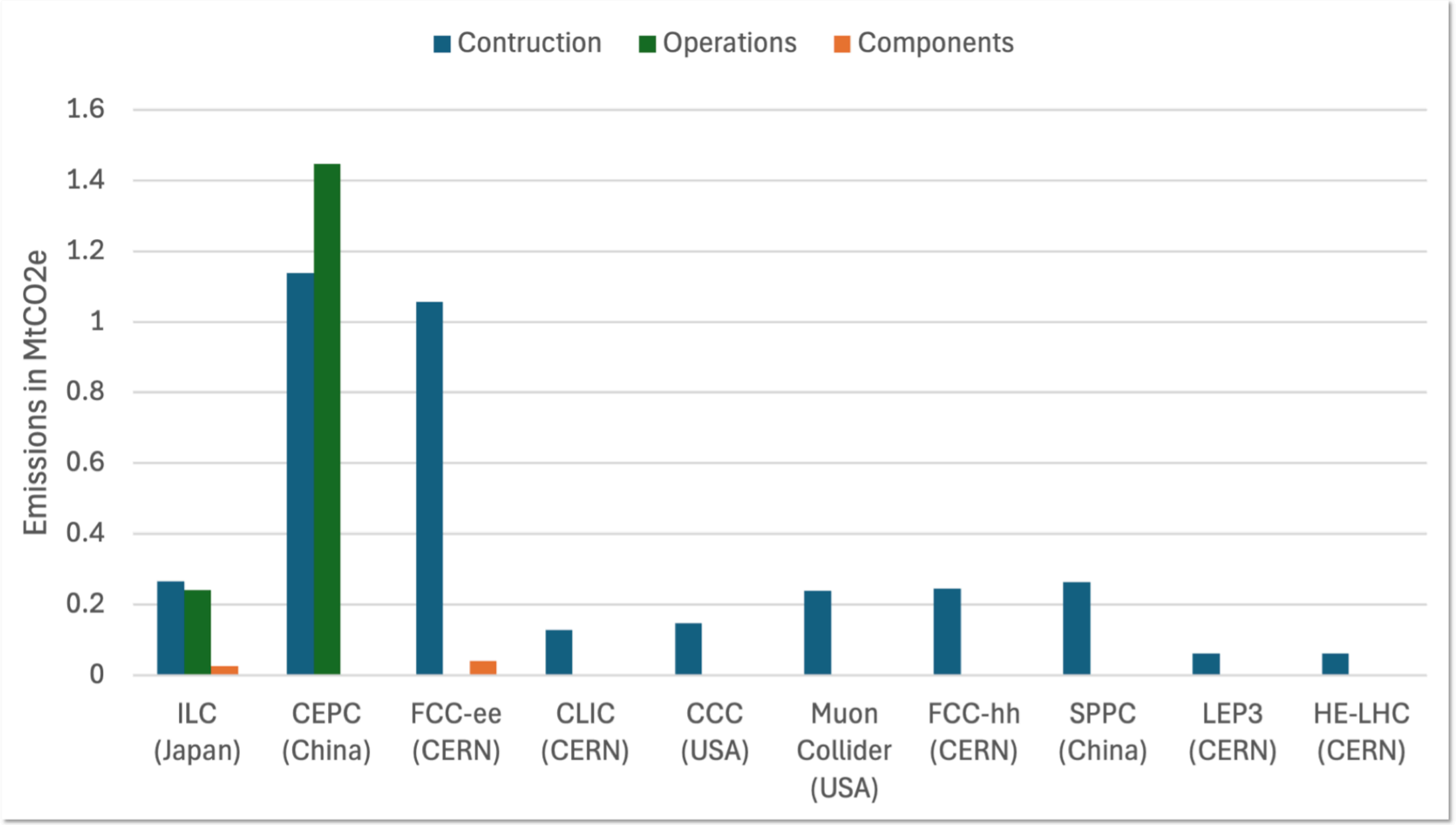
“Wakefield accelerators offer possibility of GV/m gradients”

- Plasma or dielectric **wakefield acceleration** is an advanced concept where particle bunches or lasers drive waves in plasma.
- These waves can accelerate particles at **gigavolts per meter (GV/m)** — far beyond conventional RF tech.
- Still experimental, but if successful, could shrink colliders by a factor of 10–100.

SUSTAINABILITY

Recent report

- arXiv:2411.03473



Fcc-hh design parameters

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

Final Words

Over the past years very significant progress has been made towards the realisation of the next flagship project at CERN

- FCC: Successful completion of the Feasibility Study; No technical showstoppers identified

- Overwhelming support for the integrated FCC-ee/hh programme by the HEP communities in the CERN Member and Associate Member states and beyond;

  The strong support is largely based on the superb physics potential and the long-term prospects (FCC-ee /hh)

- Discussions on the financial feasibility are ongoing (CERN management and Council)


Photo Trevor Sherwin

K.Jakobs Venice

Final Words

Discussions on the prioritisation of alternative options are ongoing

- Linear colliders (LCF, CLIC) present as well mature options for a Higgs factory at CERN
- LEP3 and LHeC could be considered as “intermediate” collider projects
- The differences in the physics potential (→ Physics Briefing Book), review of the technical readiness and the final input from the national HEP communities (due by 14 Nov.) will be important ingredients in the final recommendations by the European Strategy Group

What would be option B ? If A could not be financed?
If CEPC would be built rapidly?

LC 250 GeV, CLIC 380 GeV

- x4 ZH (x1000 Z-pole) less luminosity
- "only" two detectors
- Polarisation enhances sensitivity in some channels
- Less precision on Higgs couplings
- Less precision on EW observables
- No access to top, OK with CLIC 380 GeV
- No reach to 1^{st} generation couplings

+ LC 550 GeV and 1+ TeV

- Di-boson measurements at high energy
- Access to direct HH and ttH production
- Excellent top program with large energy span and polarisation
- No hadron option

LHeC

- Improved PDFs and strong coupling
- Excellent Higgs coupling on Hcc, Hbb, HWW
- Interesting top physics (i.e. via single top production)
- Competitive near-term W mass determination

LEP 3

- x4 less luminosity compared to FCCee
- Short-term energy changes w/reduced lumi
- Precision Higgs couplings, worse w.r.t. FCCee
- Systematics increase for EW measurements
- No high energy run
- Impacts Higgs width via lack of VBF H
- No top program

FCChh - direct

- Large luminosities and energy reach
- Excellent self-coupling sensitivity
- Excellent sensitivity to low BR Higgs couplings, if...
- Sensitivity to top operators, differential distribution
- Search for di-bosons, large BSM potential
- Reduced or no e+e- could affect Higgs results
- More studies needed to compare its full sensitivity

A number of open questions

- Can the technology challenges of the various colliders be mastered?

  * FCC-ee: very high luminosity (Super KEKb comparison)?

  * LCF: final focus & positron production (→ luminosity), polarisation?

  * CLIC: Final focus, acceleration gradients?
    What type of demonstrator would be needed?

- What R&D on accelerators should be pursued?
  High-field magnets? Muon Collider? Plasma? Energy recovery linacs?
  In general it is felt that we are too broad in the "accelerator roadmap"