Future Collider scenarios

a brief introduction to inform the discussion

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Nikhef

Nikhef Strategy Day

September 2025

Ambition for particle physics & collider options at CERN

- **Discoveries at the highest energies**

  → 10 TeV parton-scale energy
  - hadron collider, muon collider, plasma-based collider
    - FCC-hh ~100 TeV
    - μ-collider @ 3 or 10 TeV
    - *LC e^+e^- @ 10 TeV*

- **Discoveries through precision & high intensity**

  → energy scales up to 1 TeV
  - e^+e^- linear or circular collider, electron-hadron collider
    - FCC-ee 90-365 GeV
    - LCF 250-550 GeV
    - CLIC 380-1500 GeV
    - LEP3 90-230 GeV
    - LHeC 1200 GeV

Ambition for particle physics & collider options at CERN

Flavia

- **Discoveries at the highest energies**

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  directly to high-Λ

  - hadron collider, muon collider, plasma-based collider
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  - e^+e^- linear or circular collider, electron-hadron collider
    - FCC-ee 90-365 GeV
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    - LHeC 1200 GeV

Technical timelines for each collider option at CERN

- **FCC-ee** – earliest 2048
- **FCC-hh** with 14T to 85TeV – earliest 2051-2055 (short model Nb_3Sn)
- **FCC-hh** with 20T to 120TeV – earliest 2070 (HTS)

- **LCF/ILC** SCRF from 250GeV to 550GeV (29.5km) – earliest 2045
- **CLIC** NCRF from 380GeV to 1.5TeV (33.5km) – earliest 2045

- **MuColl** 7.6TeV – earliest 2048 (need an initial demonstrator project)

- **LEP3** after HL-LHC – earliest 2047
- **LHeC** after HL-LHC – earliest 2043

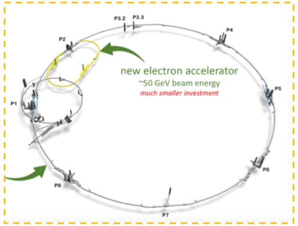
Taken from the slides of Karl Jakobs at the Open Symposium

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

FCC-ee

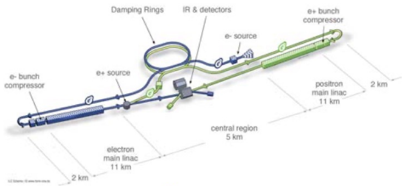
LEP3

LHeC



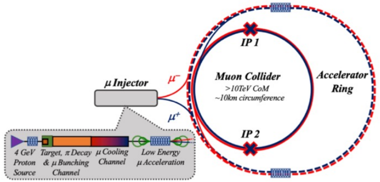
PERLE

LCF, CLIC



R&D

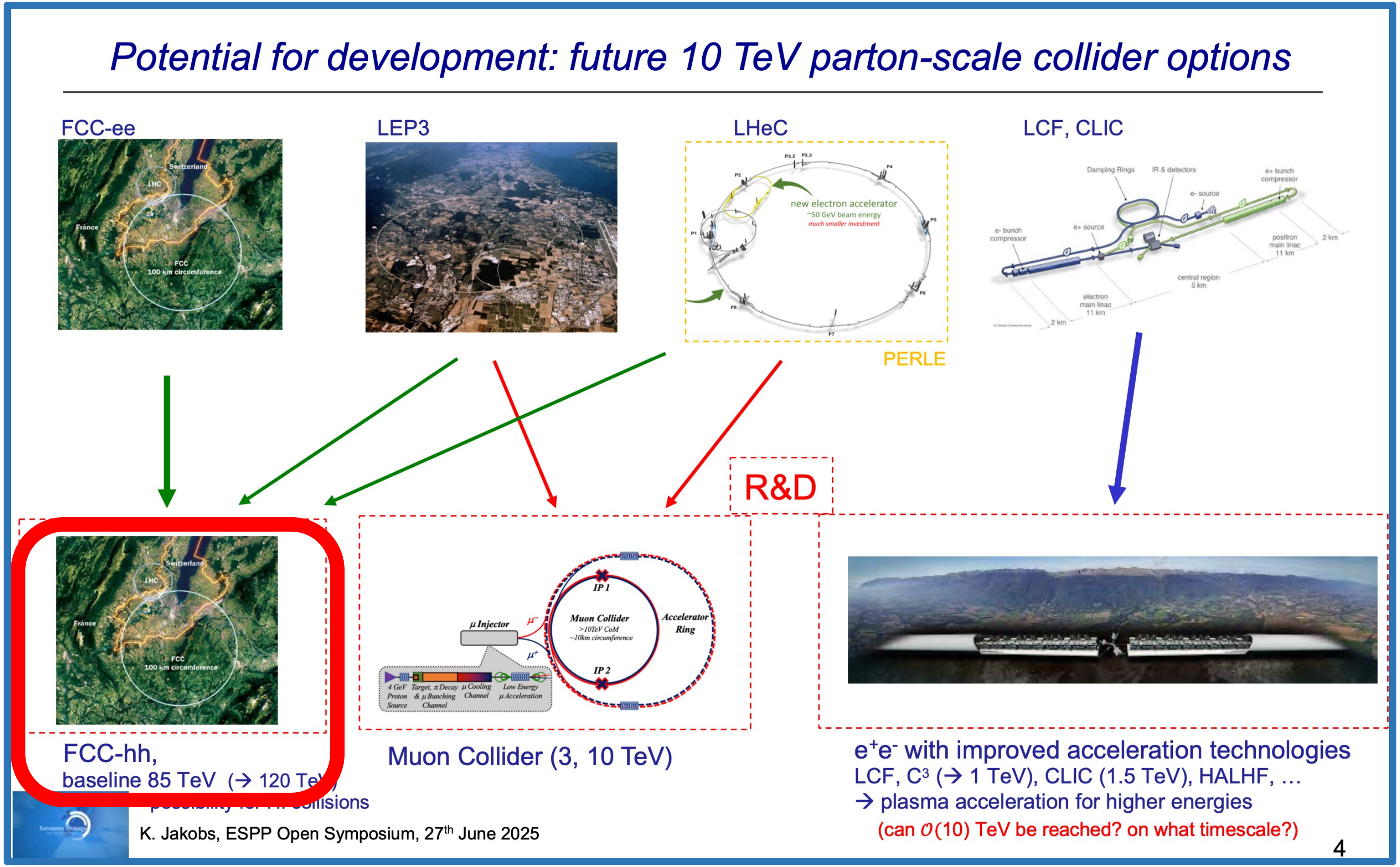
FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



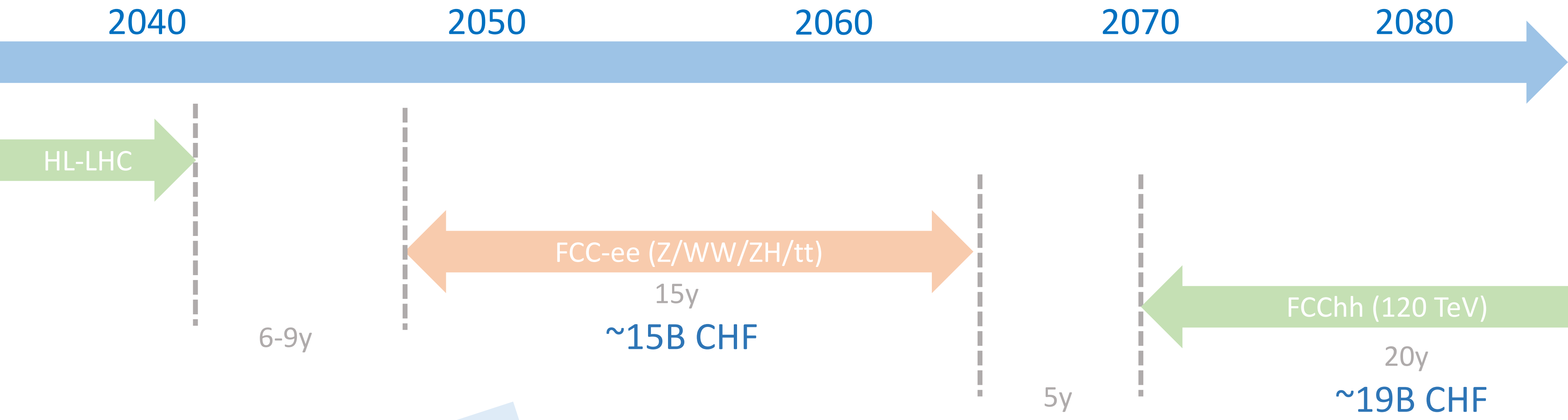
Muon Collider (3, 10 TeV)

e^+e^- with improved acceleration technologies
LCF, C³ (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

Taken from the slides of Karl Jakobs at the Open Symposium

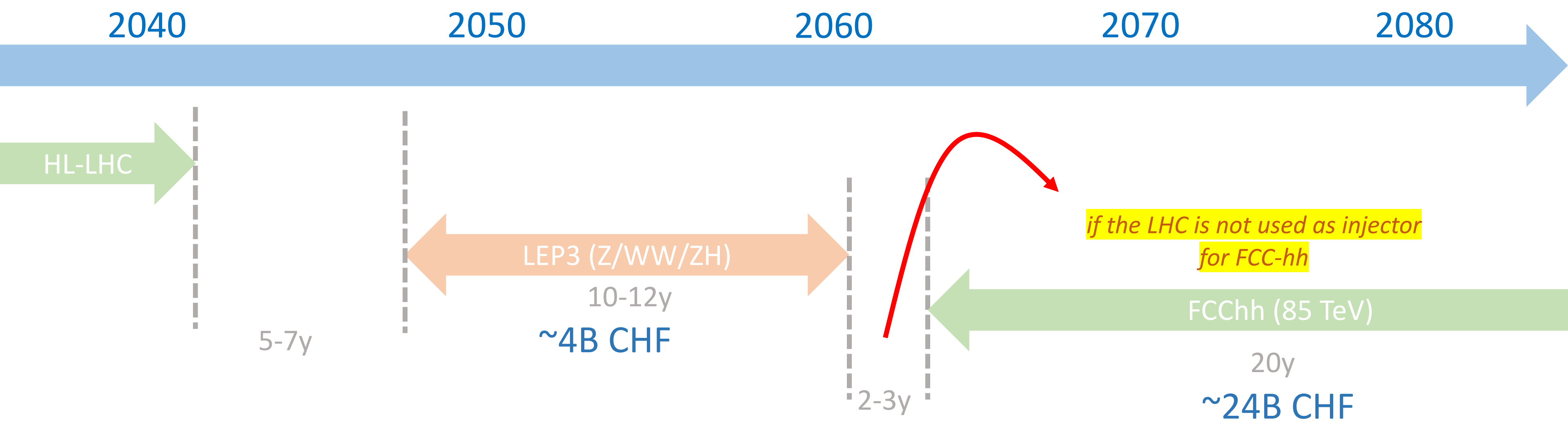


HL-LHC → FCC-ee → FCC-hh

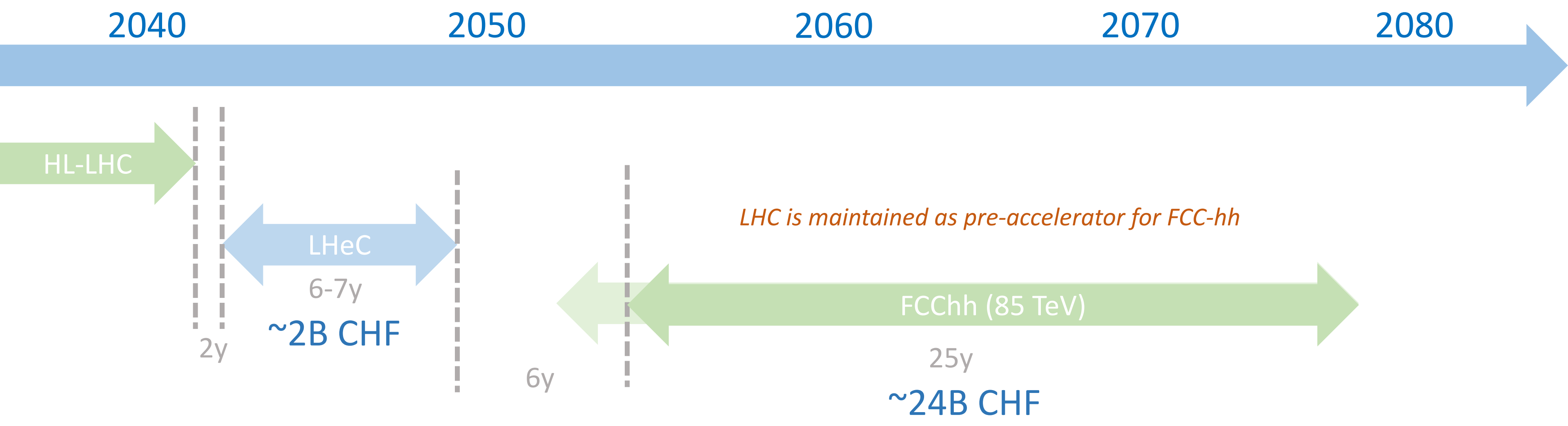


Emerging as Plan A

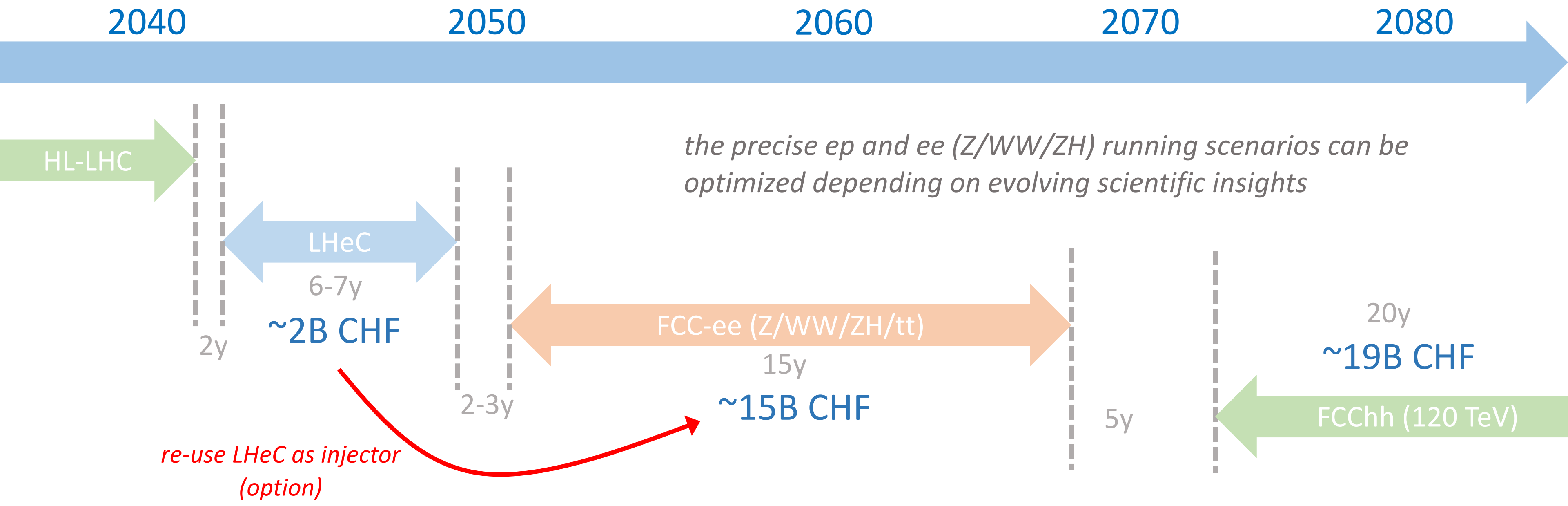
HL-LHC → LEP3 → FCC-hh



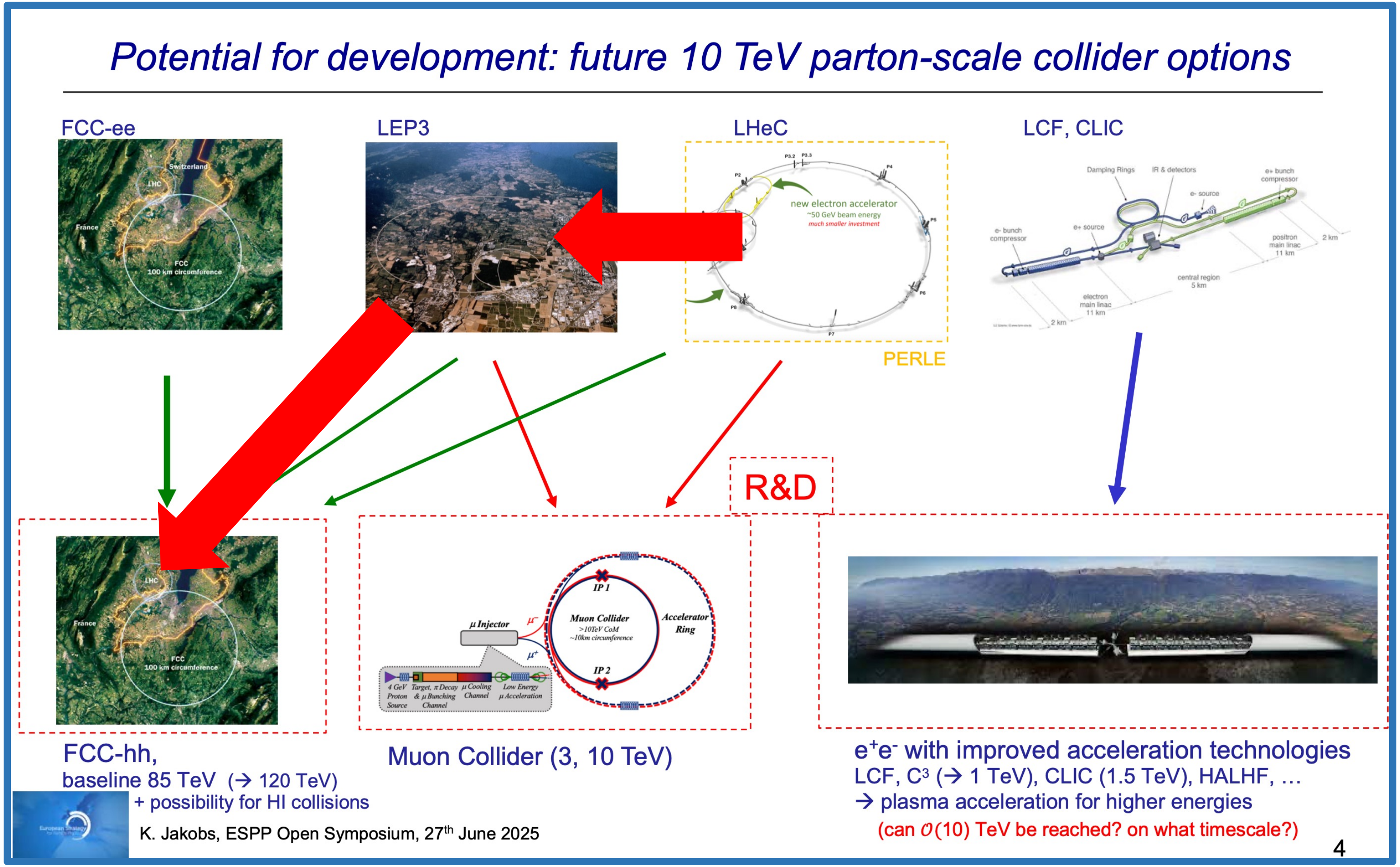
HL-LHC → LHeC → FCC-hh



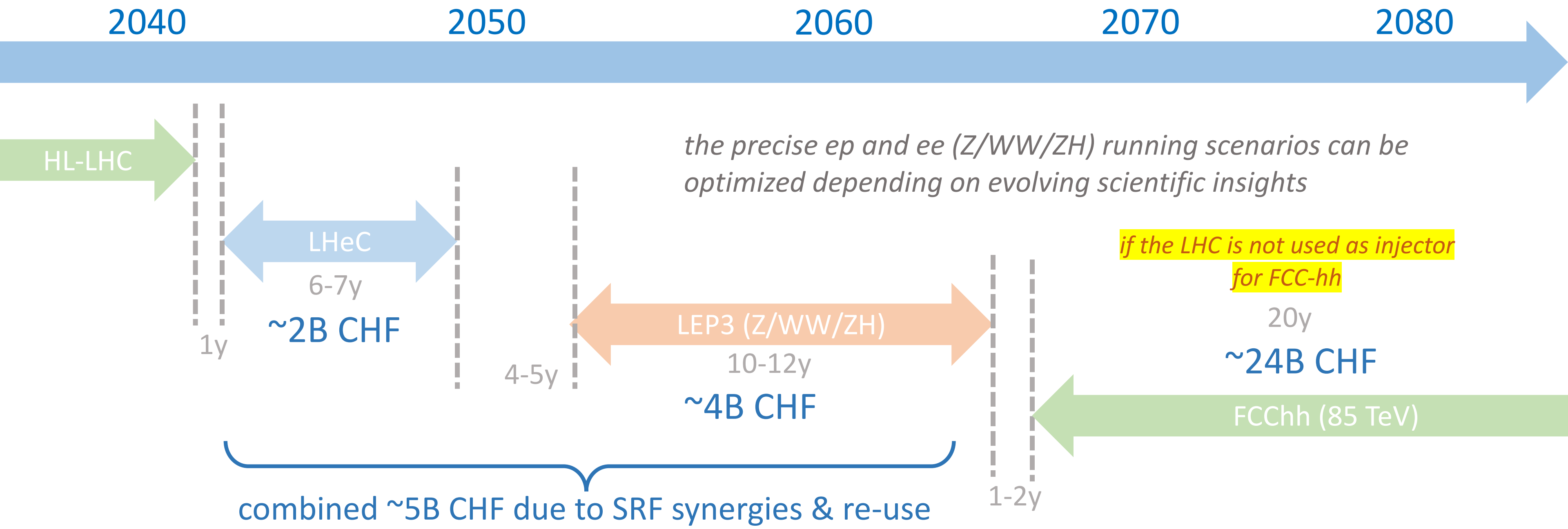
HL-LHC → LHeC → FCC-ee → FCC-hh



adapted from the slides of Karl Jakobs at the Open Symposium



HL-LHC → LHeC → LEP3 → FCC-hh



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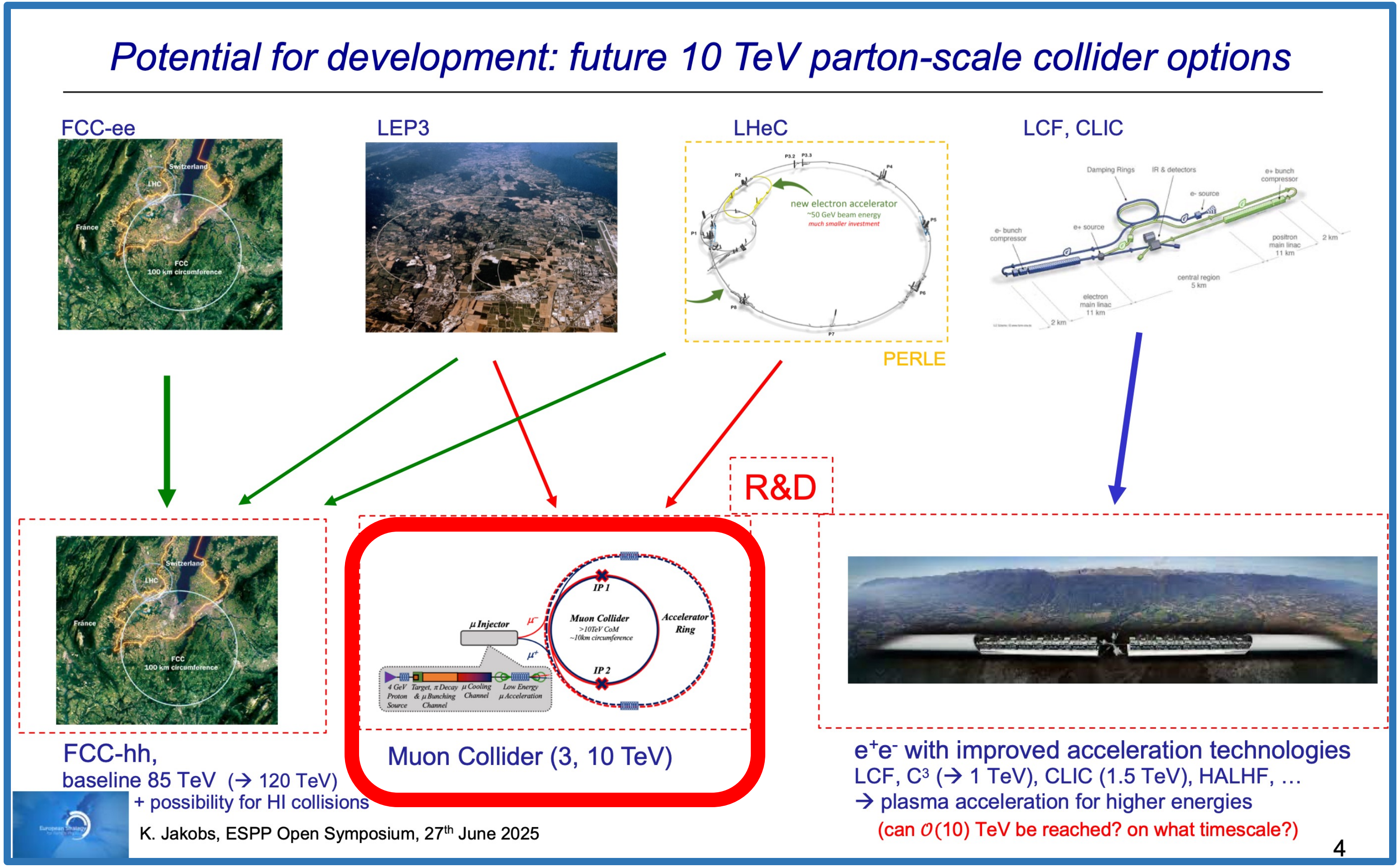
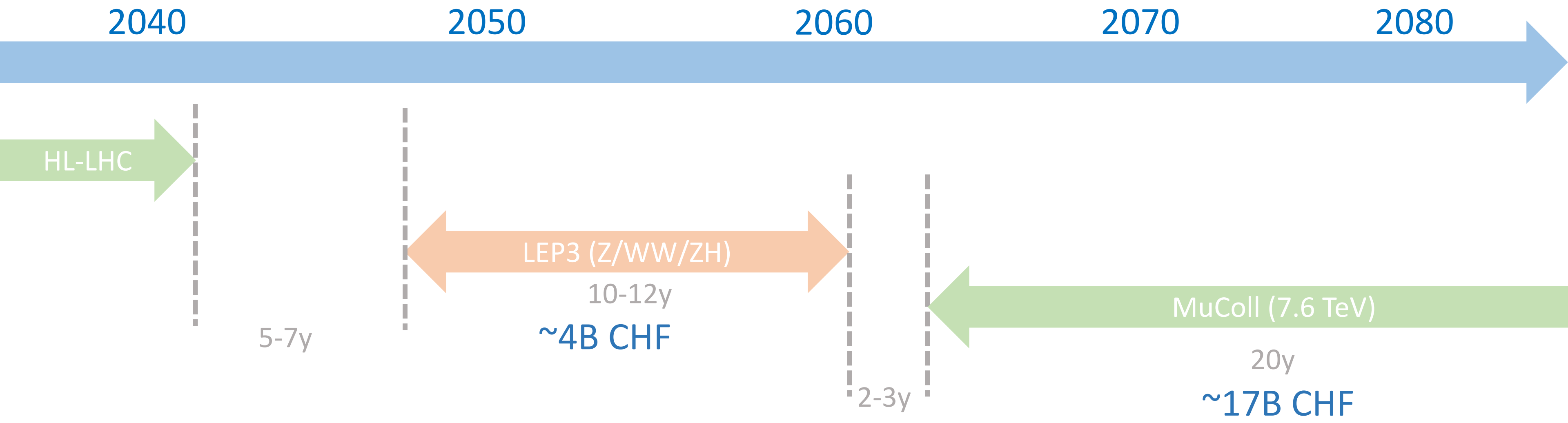


HL-LHC → LEP3 → μ-collider



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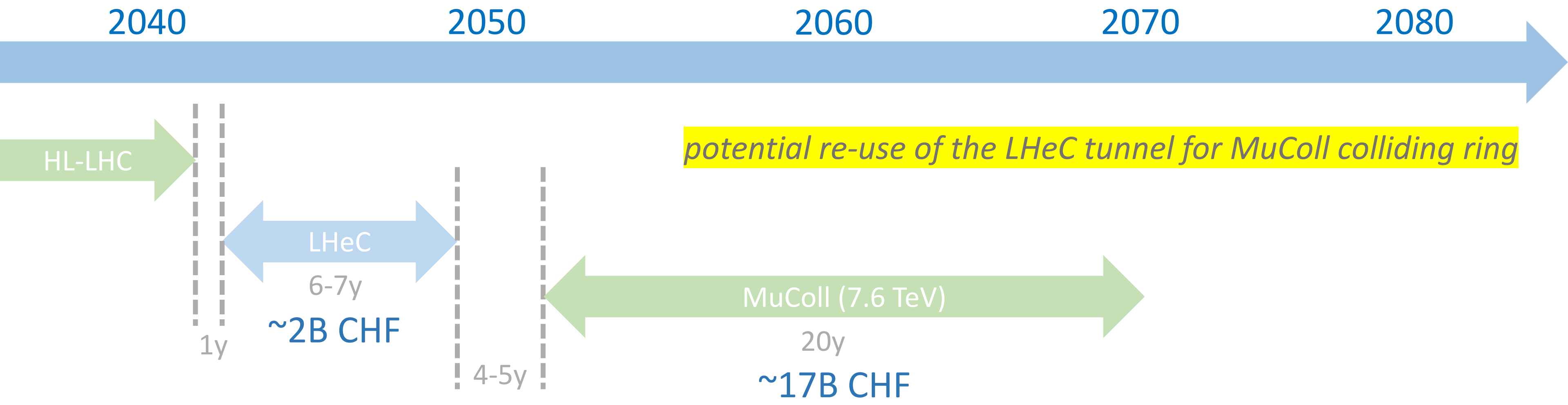

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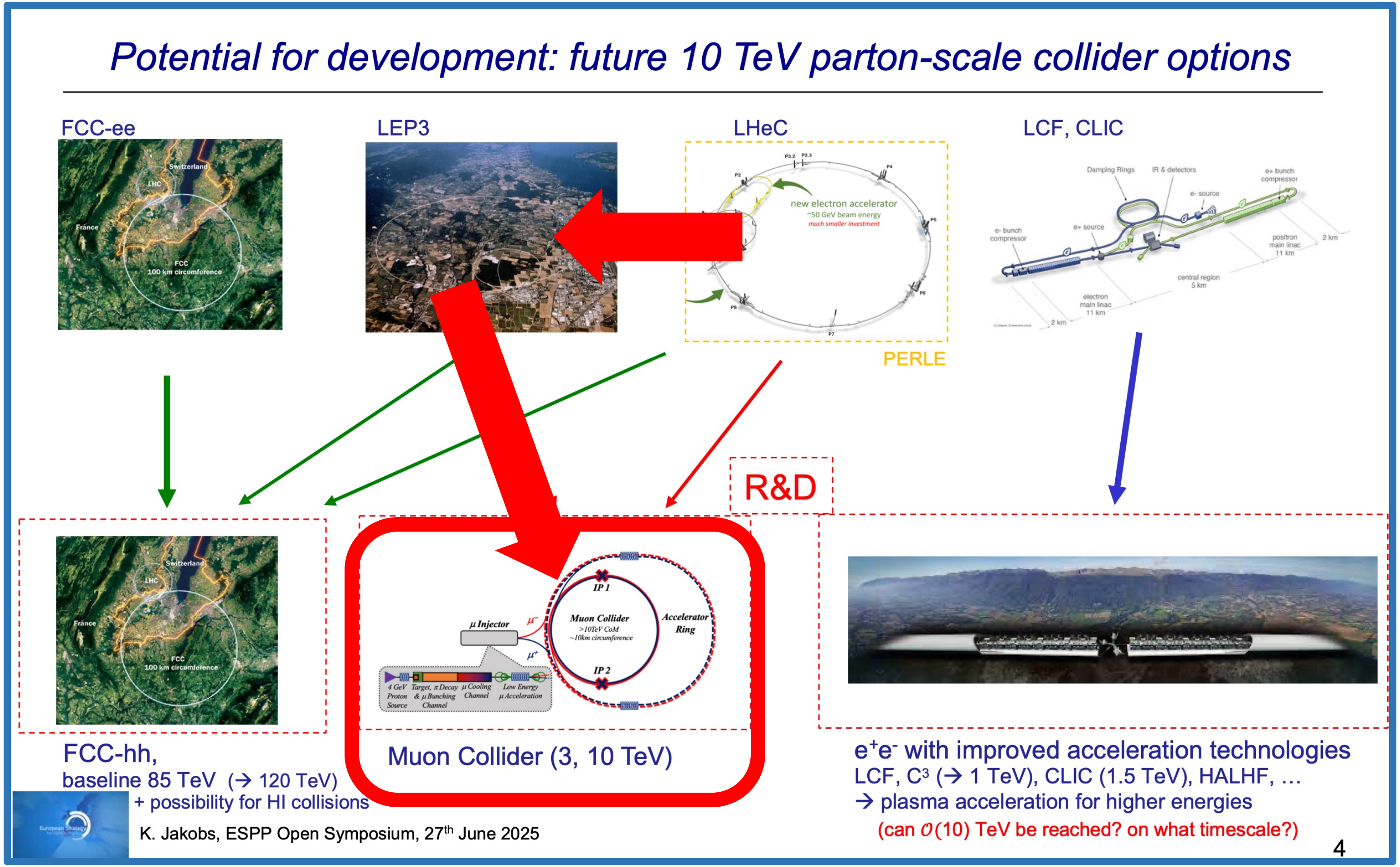
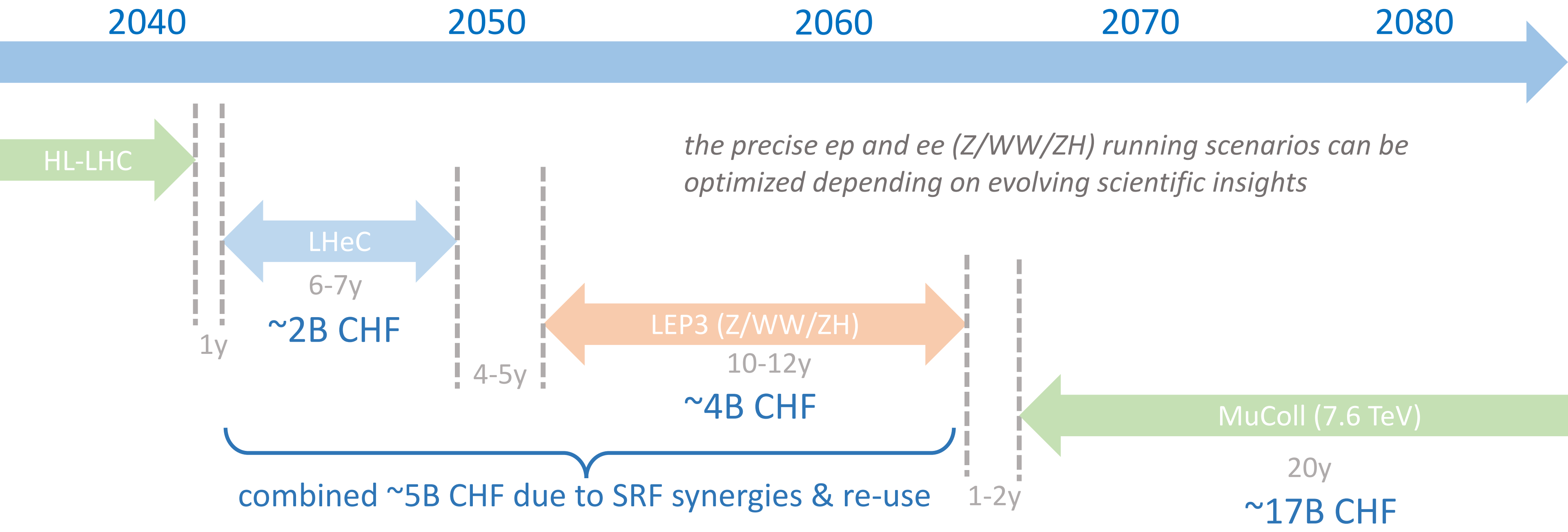


HL-LHC → LHeC → LEP3 → μ-collider



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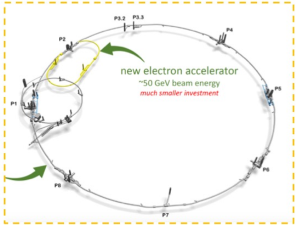
Potential for development: future 10 TeV parton-scale collider options

FCC-ee

LEP3

LHeC



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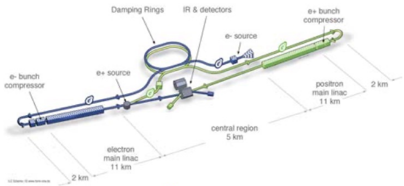

FCC-hh,
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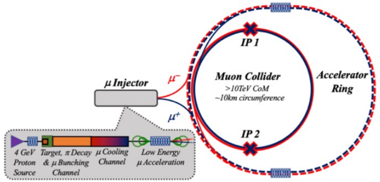

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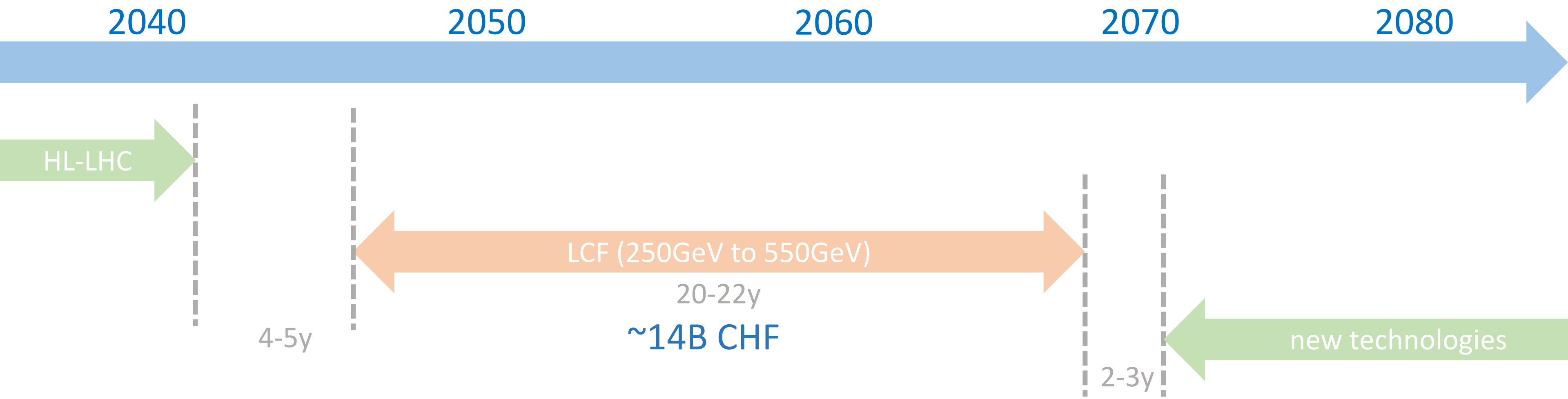
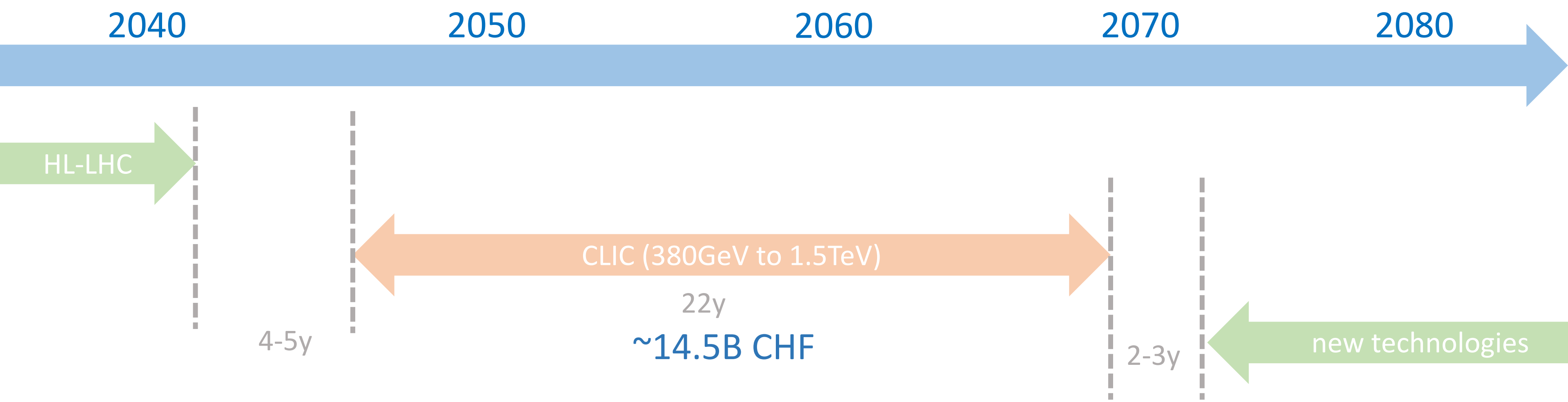
K. Jakobs, ESPP Open Symposium, 27th June 2025

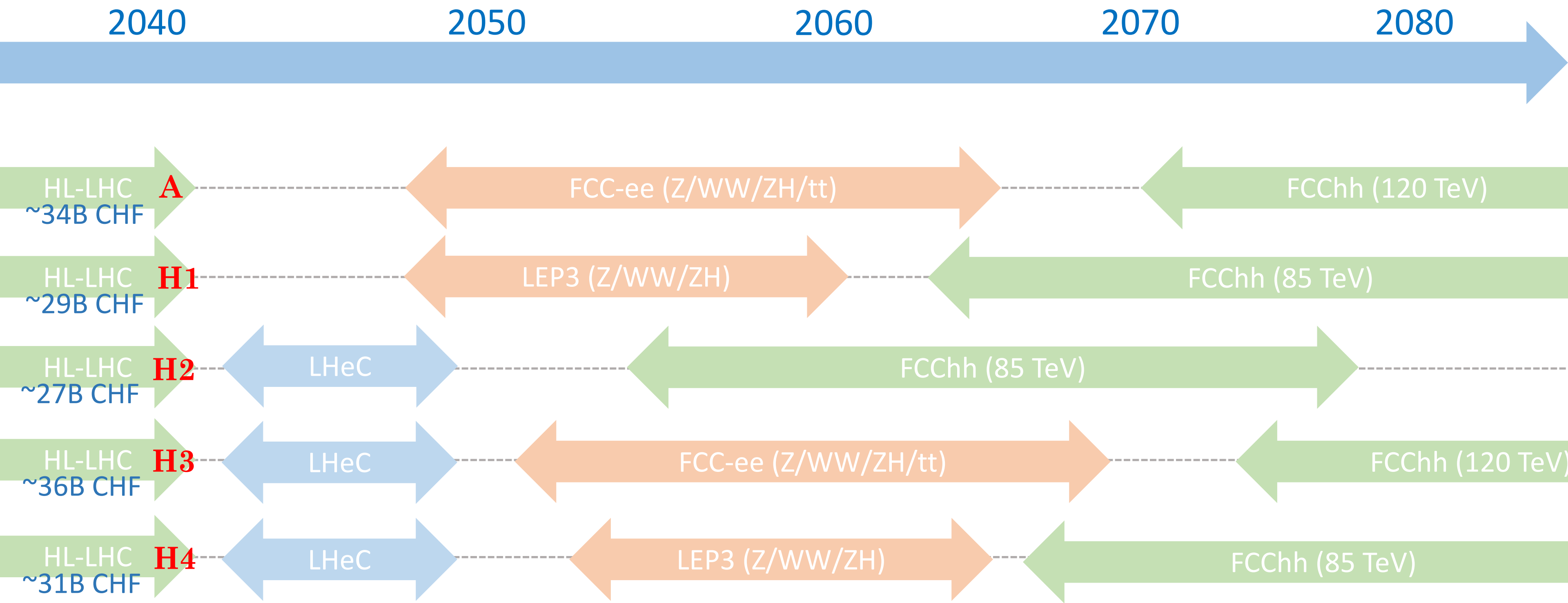
HL-LHC → LCF → Linear 10 TeV



HL-LHC → CLIC → Linear 10 TeV

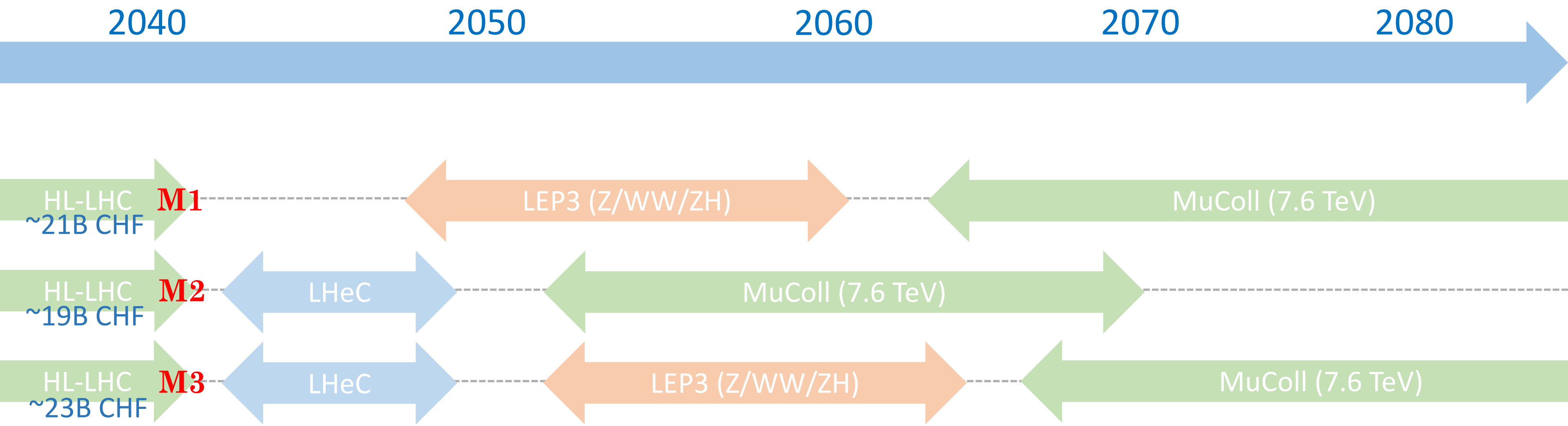


scenarios to FCChh



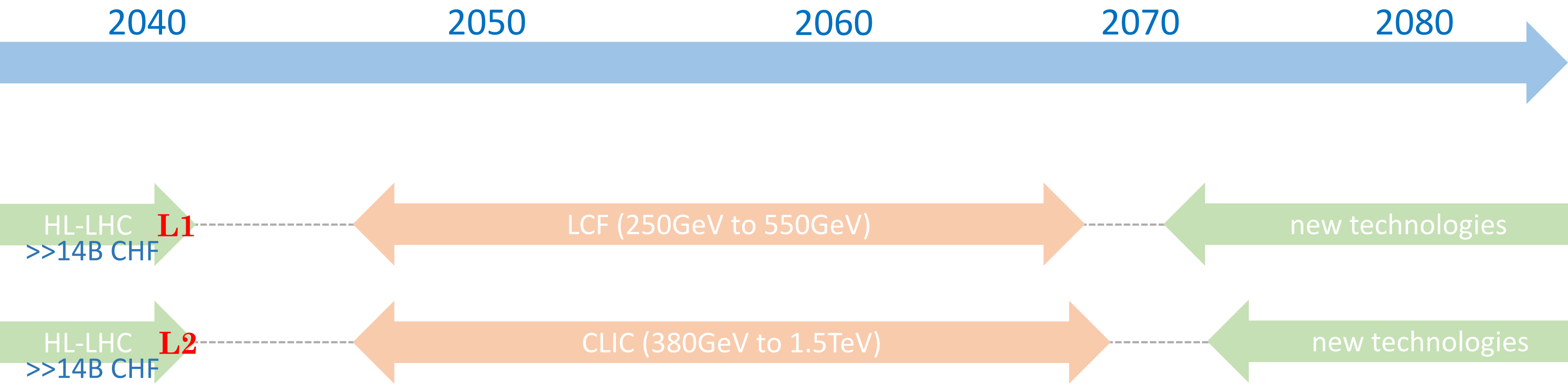
costs do not include HF magnet R&D

scenarios to MuColl



costs do not include a muon collider demonstrator

scenarios to LC @ 10 TeV



back-up

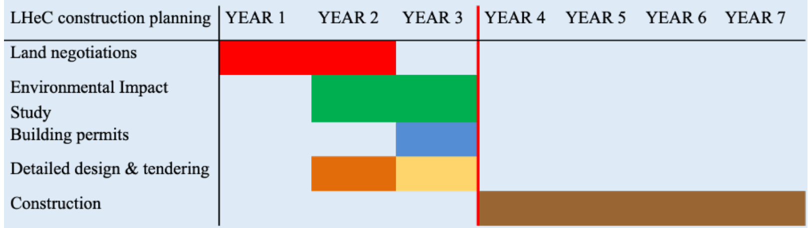
LHeC – baseline

LHeC – baseline high-lumi running in the 2040'ies

https://indico.cern.ch/e/LHeCFCCeh

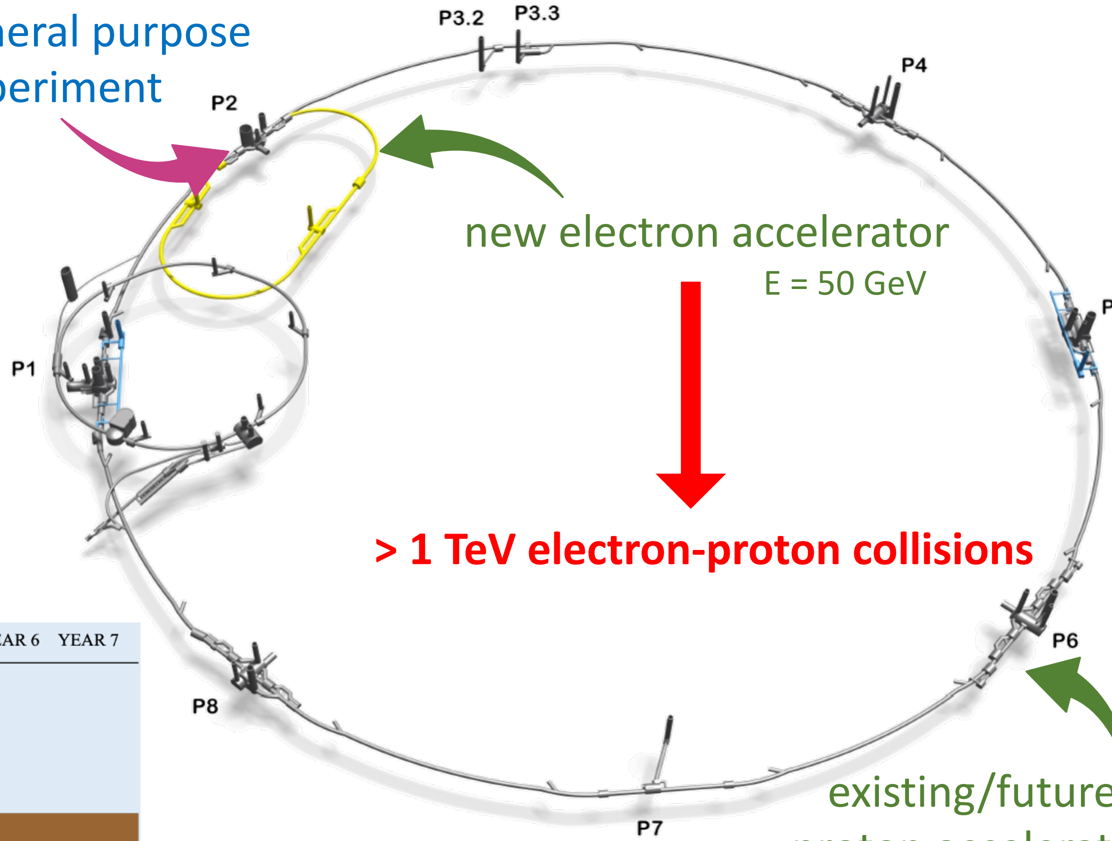
LHeC

802.5MHz, 20MV/m in CW, 6x25mA in SRF
ERL 3-turns, 50 GeV (1/3 of LHC circumference)
Start operation after HL-LHC (>2041)
Luminosity above 10^{34} $cm^{-2}s^{-1}$
6 years of operation, 1 ab^{-1} (e.g. 2043-2048)
120MW from HL-LHC + 100MW from e-beam



for example 2034 → 2041

one general purpose experiment



new electron accelerator
E = 50 GeV

> 1 TeV electron-proton collisions

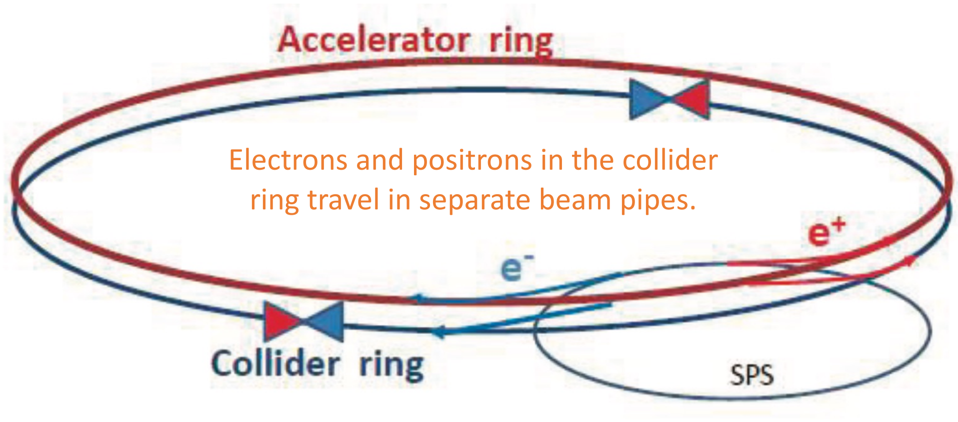
existing/future proton accelerator
E ≳ 7 TeV

LEP3 – baseline

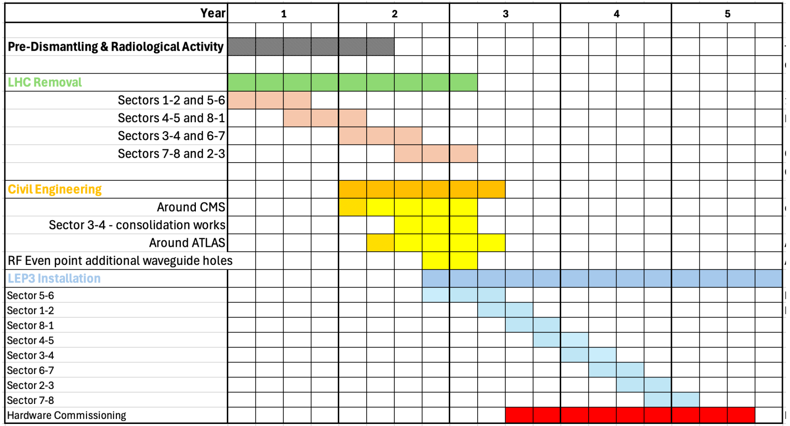
LEP3 – baseline Z/WW/ZH

(adapted from Jim Virdee's slides at the ESPP Open Symposium)

No. of IPs	2
Can't reach t-tbar threshold	
Energy for ZH	230 GeV
Fix SR power loss at 50 MW/beam	
SR energy loss/turn	~ 5.4 GeV
Total RF voltage installed	~ 6 GV
Crossing angle	30 mrad



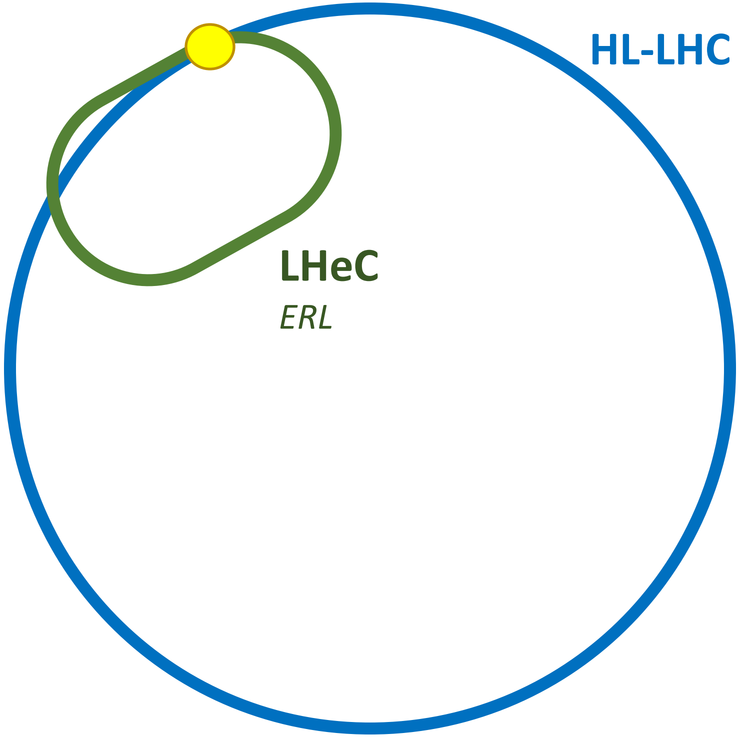
Running	Z	WW	ZH	Booster
Common RF for two beams	No	No	Yes	No
No. of Cryomodules	104	104	104	66
Frequency (MHz)	800	800	800	800
Cells/Cavity	1	4	4	6
Voltage/Cavity (MV)	2.4	14.4	14.4	22.7
Beam current (mA)	371	39	9	0.9
Power/cavity (kW)	240	240	240	20.1
Accelerating Gradient (MV/m)	12.9	19.3	19.3	20.3
Total Power Required (MW)	100	100	100	5.3
Total Required RF Voltage (MV)	1000	3000	6000	6000



LHeC → LEP3@230

- LHeC and LEP3 have a comparable number of cryomodules and thus comparable 800 MHz power system and distribution lines, i.e. very similar industrial contracts and the LHeC developments can directly lead into LEP3 orders / productions.
    - clear synergies that can be exploited for common design and optimization, e.g. cryomodules, power sources, cryogenic systems, beam diagnostics, magnets
    - opportunity to leverage the synergies between the SRF developments for LHeC, LEP3 and FCCee into a joined effort
    - efficient (re-)use of new technologies and infrastructure

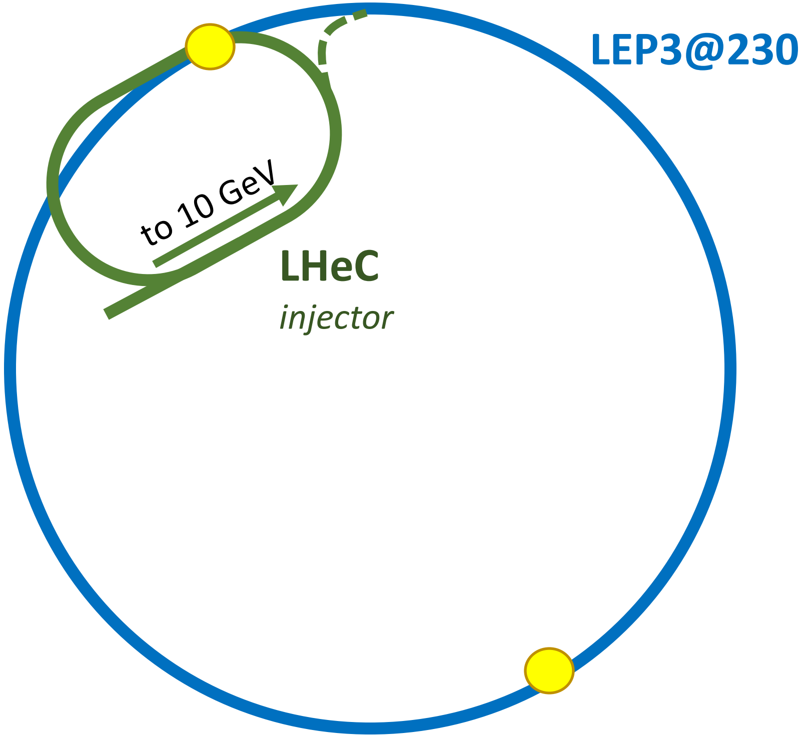
LHeC → LEP3@230



Two linacs of ~1km each in the LHeC each providing ~10 GeV acceleration to the electrons.

- the electron beam operates at a high beam-power of ~1 GW
- requirement to recover the energy with the ERL method

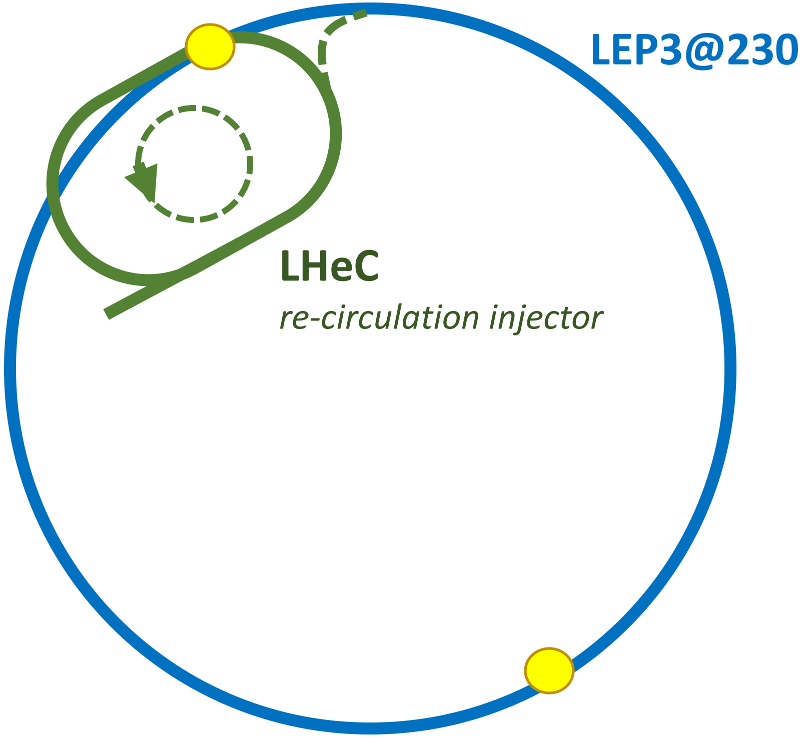
LHeC → LEP3@230



The current LEP3 design assumes an injection energy of 10 GeV which is equivalent to one of the LHeC linacs.

- one of the LHeC linacs can be the injector for LEP3

LHeC → LEP3@230



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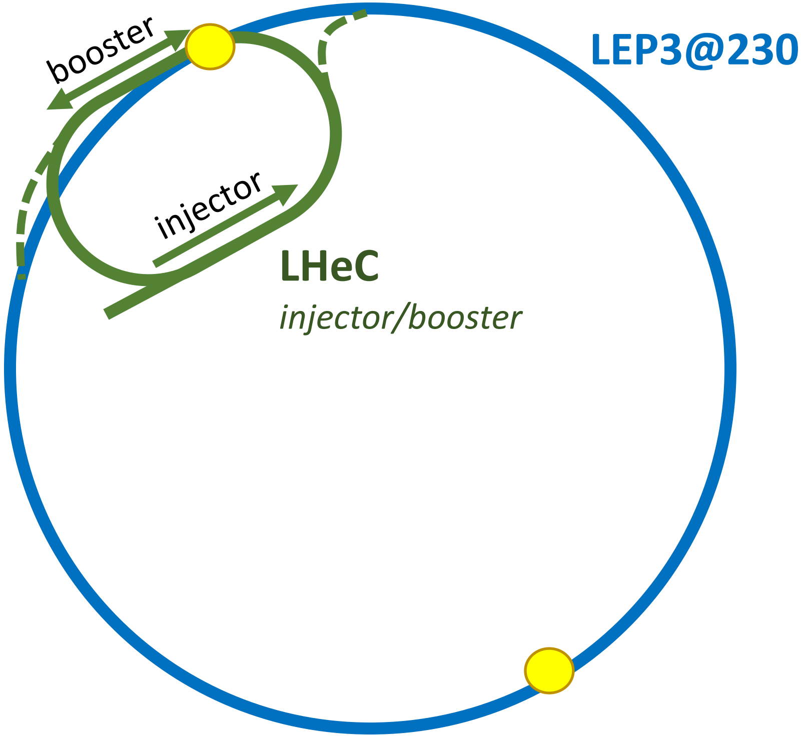
- one of the LHeC linacs can be the injector for LEP3

Using both LHeC linacs could easily increase the injection energy to 20 GeV, even without re-circulation.

- in re-circulation mode, the LHeC could even inject with direct top-up at the Z energy and possibility up to W production beam energies

LHeC → LEP3@230

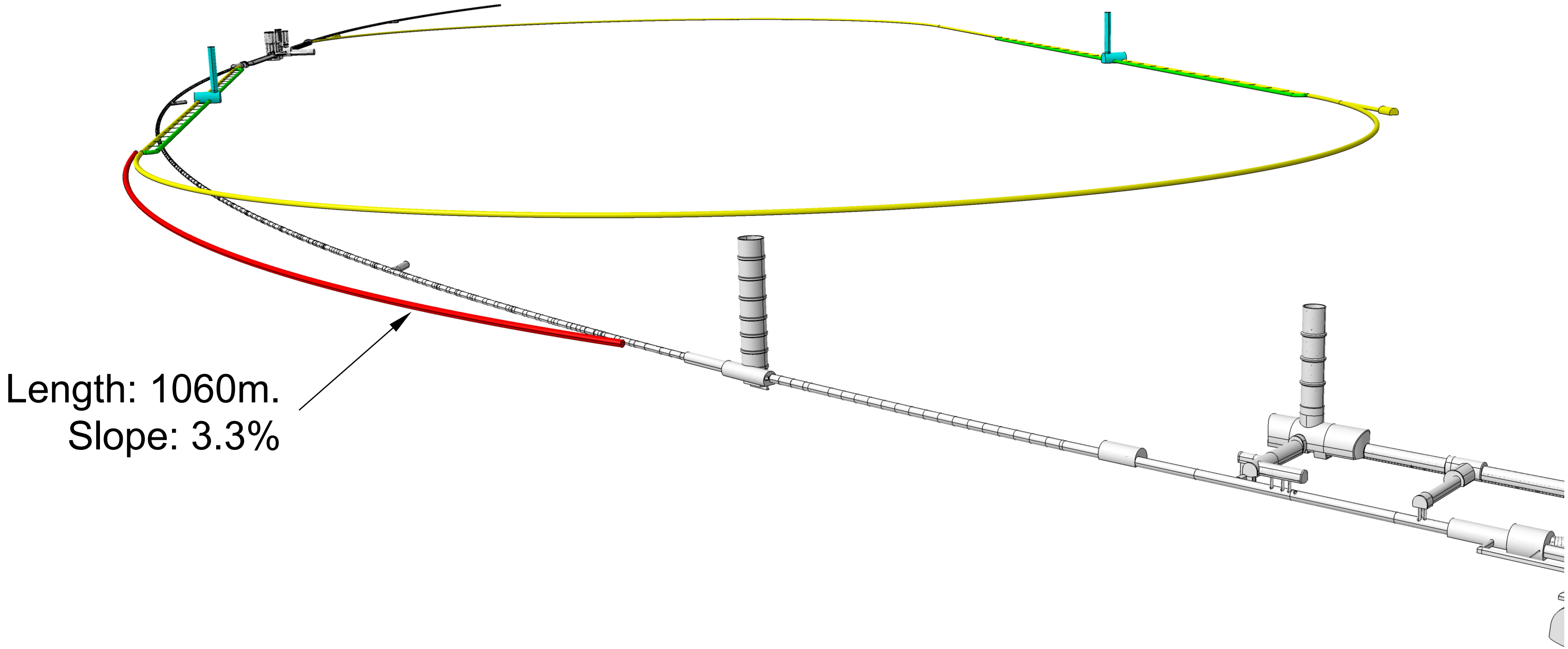


One could use one of the LHeC tunnel straight sections for the installation of the LEP3 booster ring RF (1 km straight section ➔ > 10 GeV potential for both electrons and positrons)

- one of the LHeC linacs as 10 GeV injector of electrons and positrons for LEP3
- one of the LHeC linacs can be used for the LEP3 booster

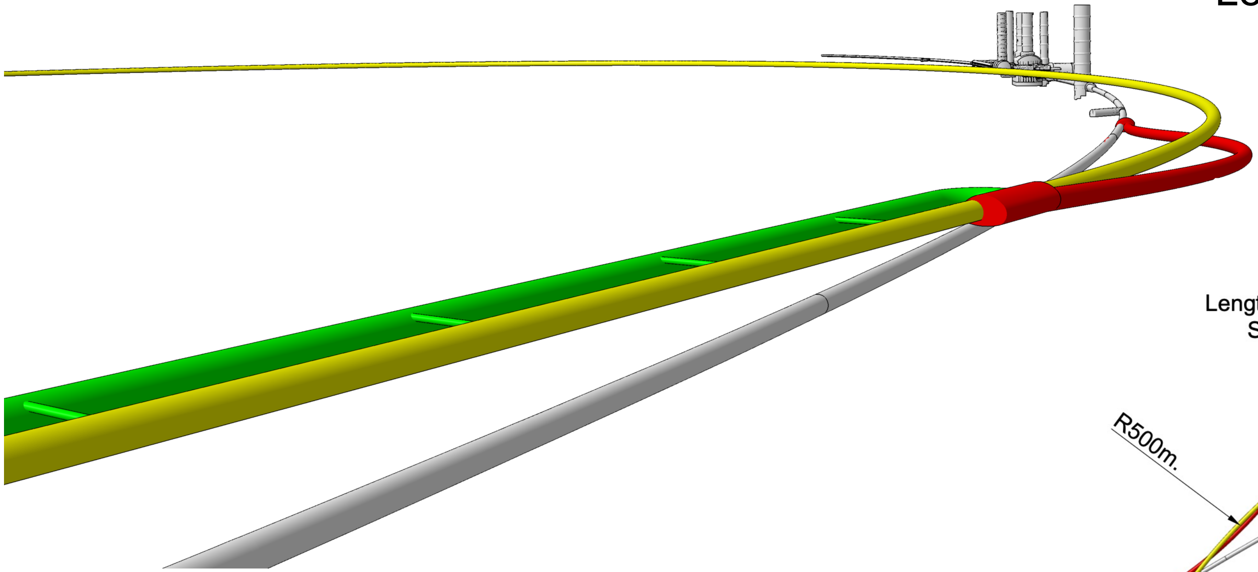
LHeC transfer line to LEP3

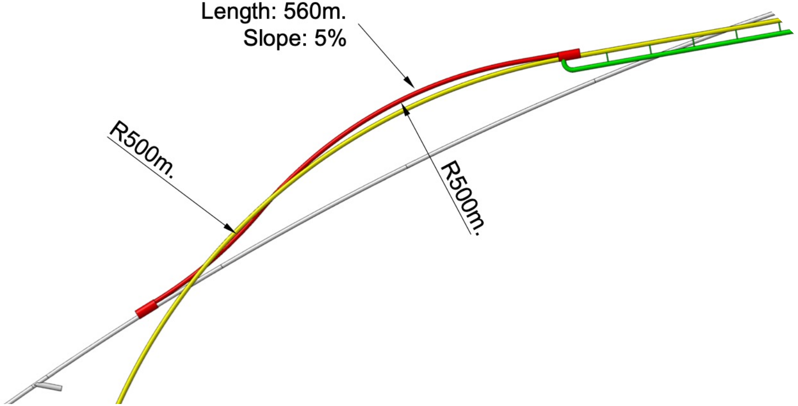
LHeC transfer line to LEP3



LHeC transfer line to LEP3

Length: 560m.
Slope: 5%





Cost of the combined LHeC + LEP3 scenario

- The capital investment for LHeC is ~2B CHF, standalone
- Most of this investment can be directly reused for the LEP3 injector

- The capital investment for LEP3 is ~4B CHF, standalone
- A significant part is for the SRF system and the injector

- Due to the synergies and the dual use, the combined capital investment for LHeC+LEP3 can be expected to be ~5B CHF

The combined LHeC + LEP3 scenario makes an interesting bridge to the FCChh:

1. FCChh starts ~2065: faster compared to FCCee route (independent tunnel ee vs pp),
2. Less expensive compared to FCCee (~5B CHF rather than ~10B CHF),
3. Brings interesting physics and flexibility to adapt (e.g. balancing pp/ep/ee runs, alternative high-energy options like the muon collider),
4. At all times, avoids long gaps between colliders at CERN.

Summary: SRF synergies & options to combine LHeC+LEP3

- The combined LHeC + LEP3 scenario provides excellent physics for a broad range of topics (QCD, EW, top, Higgs, BSM, flavour) and in the search for deviations from the SM the combination of pp+ep+ee physics allows to break degeneracies in global fits
- SRF developments for LHeC and LEP3 are synergistic, also with FCCee
- There is opportunity for a significant reuse of the LHeC capital investment in LEP3
- After the LHeC runs, the LEP3 injector will be fully commissioned from the start of the LEP3 run which would gain time to high performance which is essential for LEP3
- The final choice of the physics ep and ee runs can be decided in due time depending on the evolution of the science case

Strategy:

1. further the exploration & exploitation of the SRF synergies between FCCee, LHeC and LEP3, such that developments for FCCee can also be deployed for alternative options;
2. no choice required today among alternatives to FCC, only when it would not be feasible to implement the integrated FCC programme, the alternative routes to FCChh would be ready for a decision by ESPP2032 (i.e. LHeC-only, LEP3-only or combined LHeC+LEP3)