Overview of Future Collider Options

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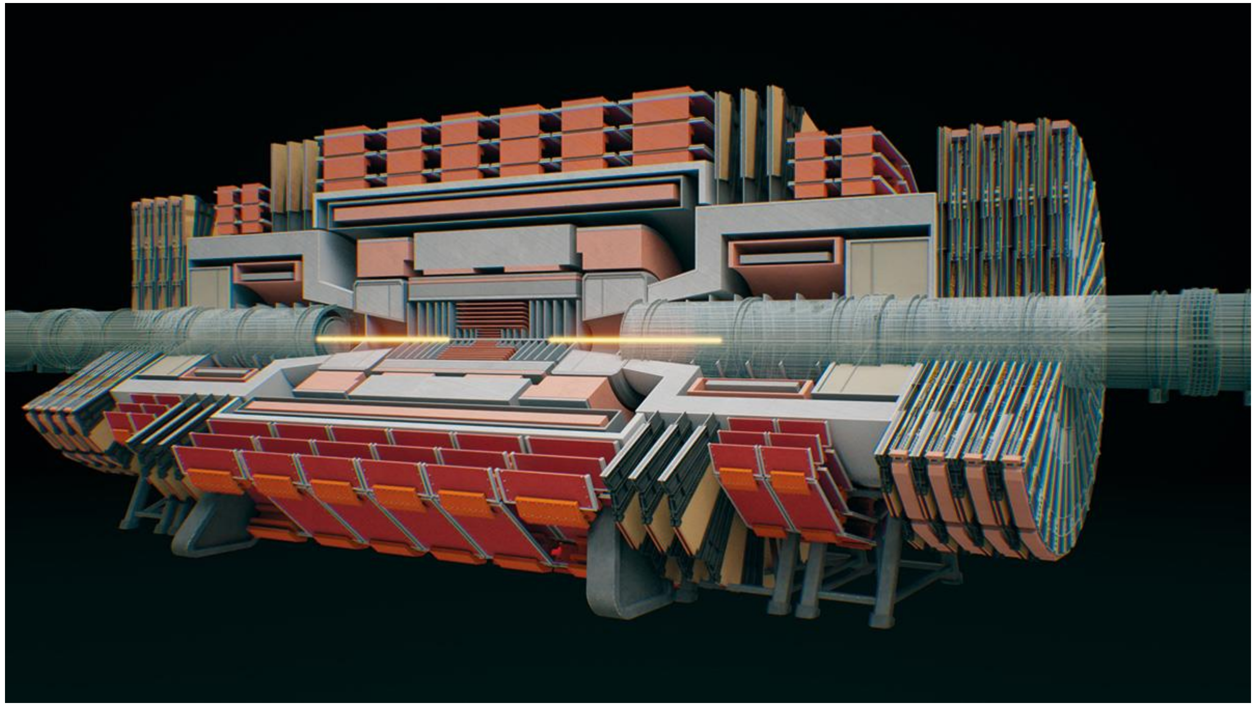
Nikhef Strategy Day

15th October 2024

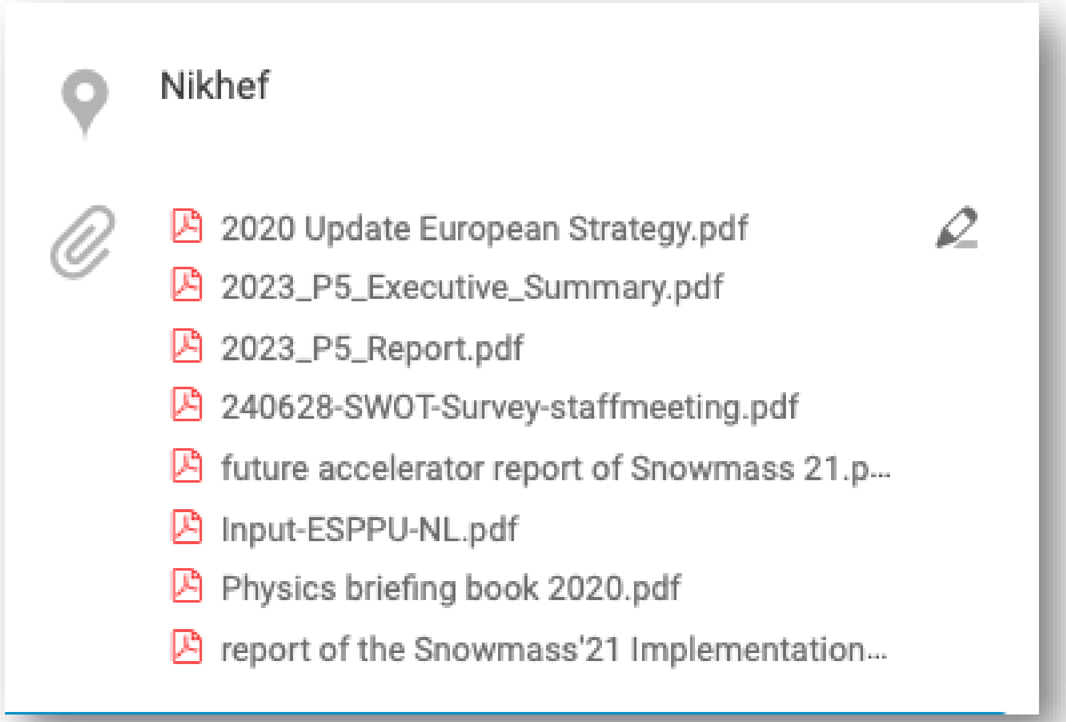
Overview:

- Where we are now?
- What physicists care about in a particle collider
- Future Colliders
  - Linear e+e- colliders
  - e+e- synchrotons
  - Hadron synchrotrons
  - Muon Collider
- Future R&D

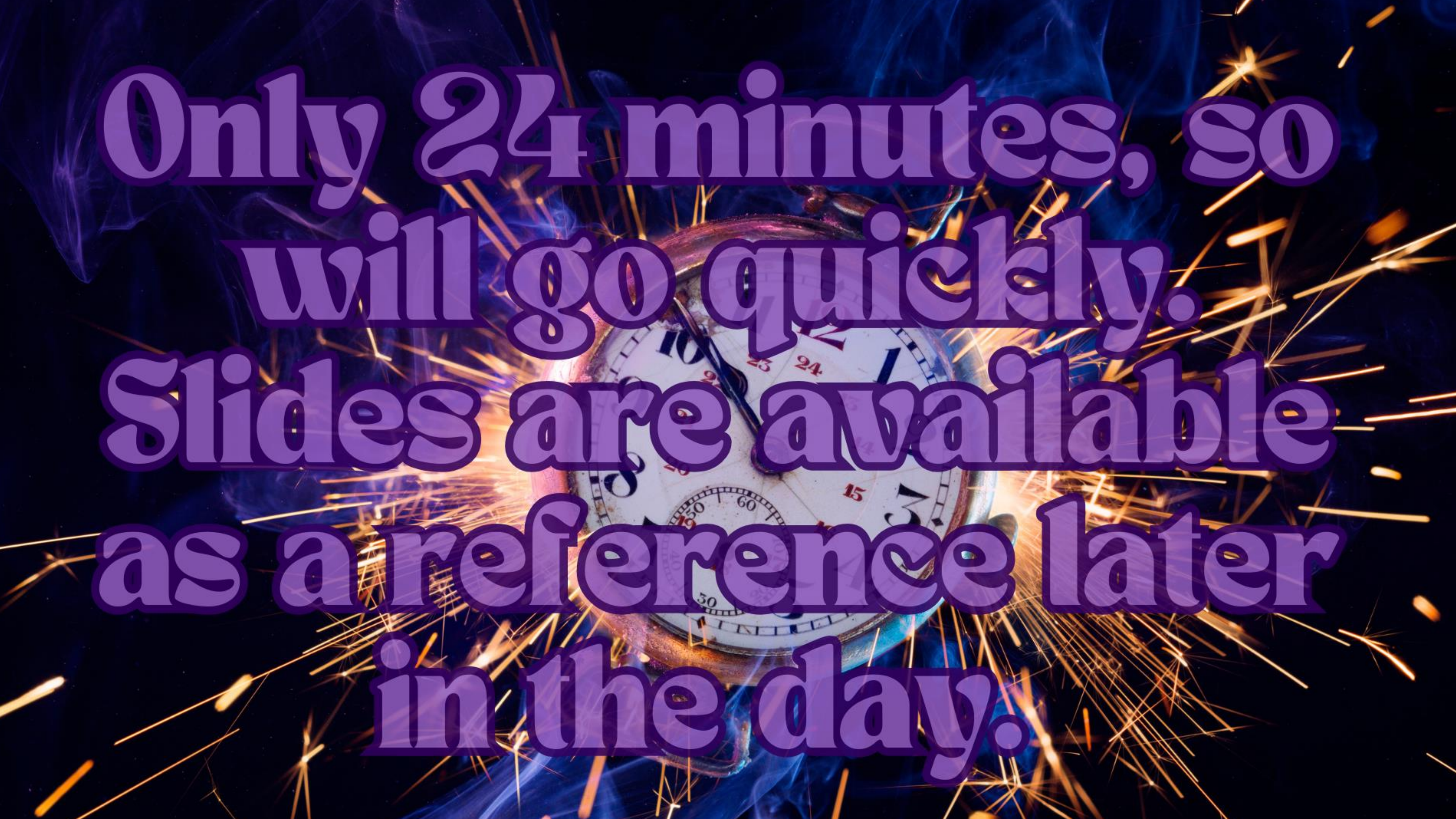


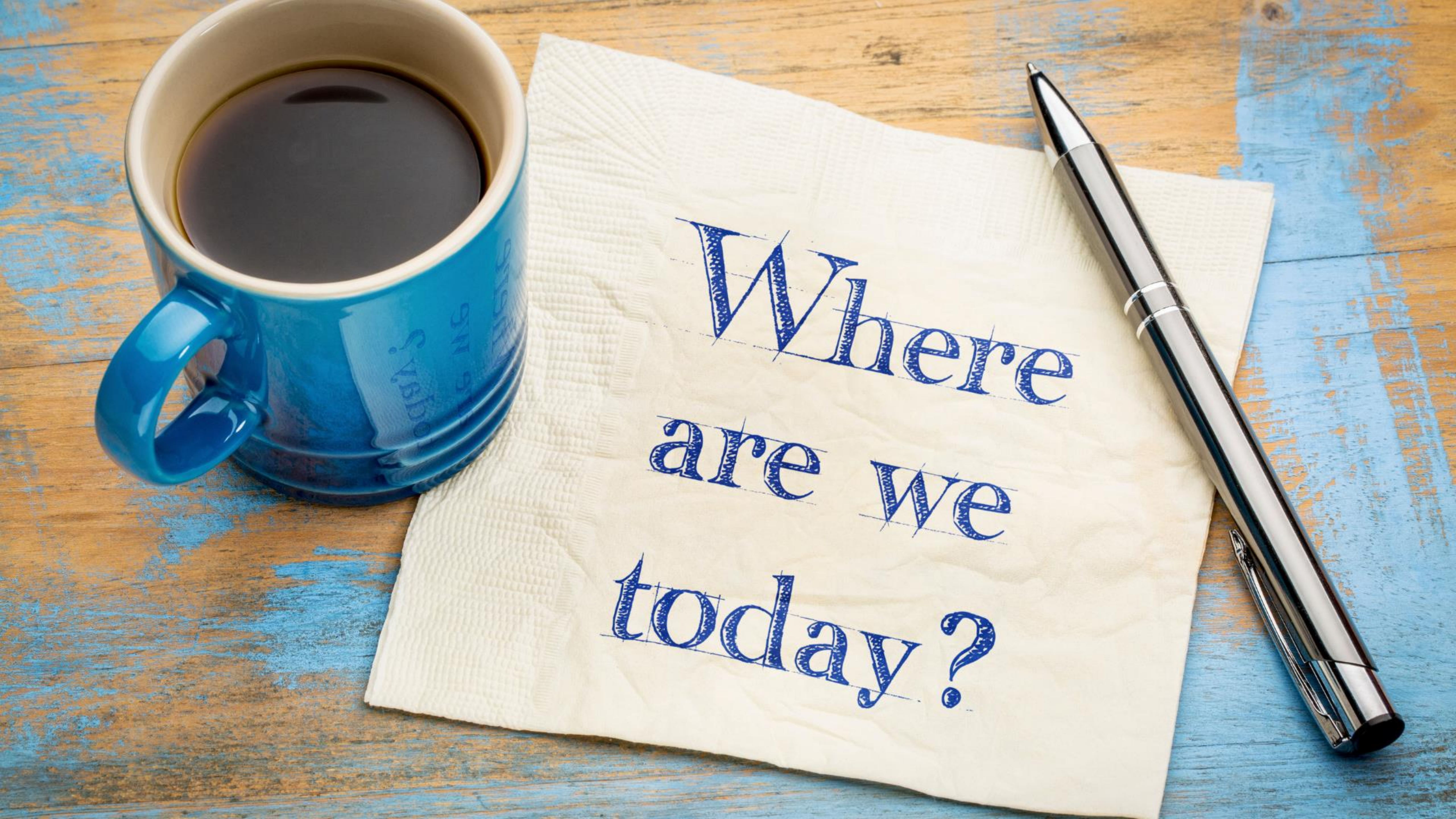
Credit: Polar Media

With thanks to E. Maclean for contributions to these slides
For more details: https://indico.nikhef.nl/event/4900/



https://indico.nikhef.nl/event/5729/


Only 24 minutes, so will go quickly.
Slides are available as a reference later in the day.


Where are we today?

The LHC was/is a long journey

60 year journey!

This is why we have to be thinking about the next collider already now

1984

Workshop to discuss various options for hadron collider in LEP tunnel

1992

ATLAS & CMS Collaborations submit letters of intent. ALICE and LHCb follow in 1993 and 1995

1994

- Superconducting magnets successfully achieves 8.73 T
- LHC construction approved!

1998

Construction begins on the Large Hadron Collider

2008

- First proton beams in the LHC
- Magnet incident

2009

First collisions in the LHC

2012

- Announcement of the Higgs discovery by ATLAS and CMS.
- Collision energy increase to 8 TeV

2015

Run 2: Collision energy increase to 13 TeV

2016

Weasel incident

2022

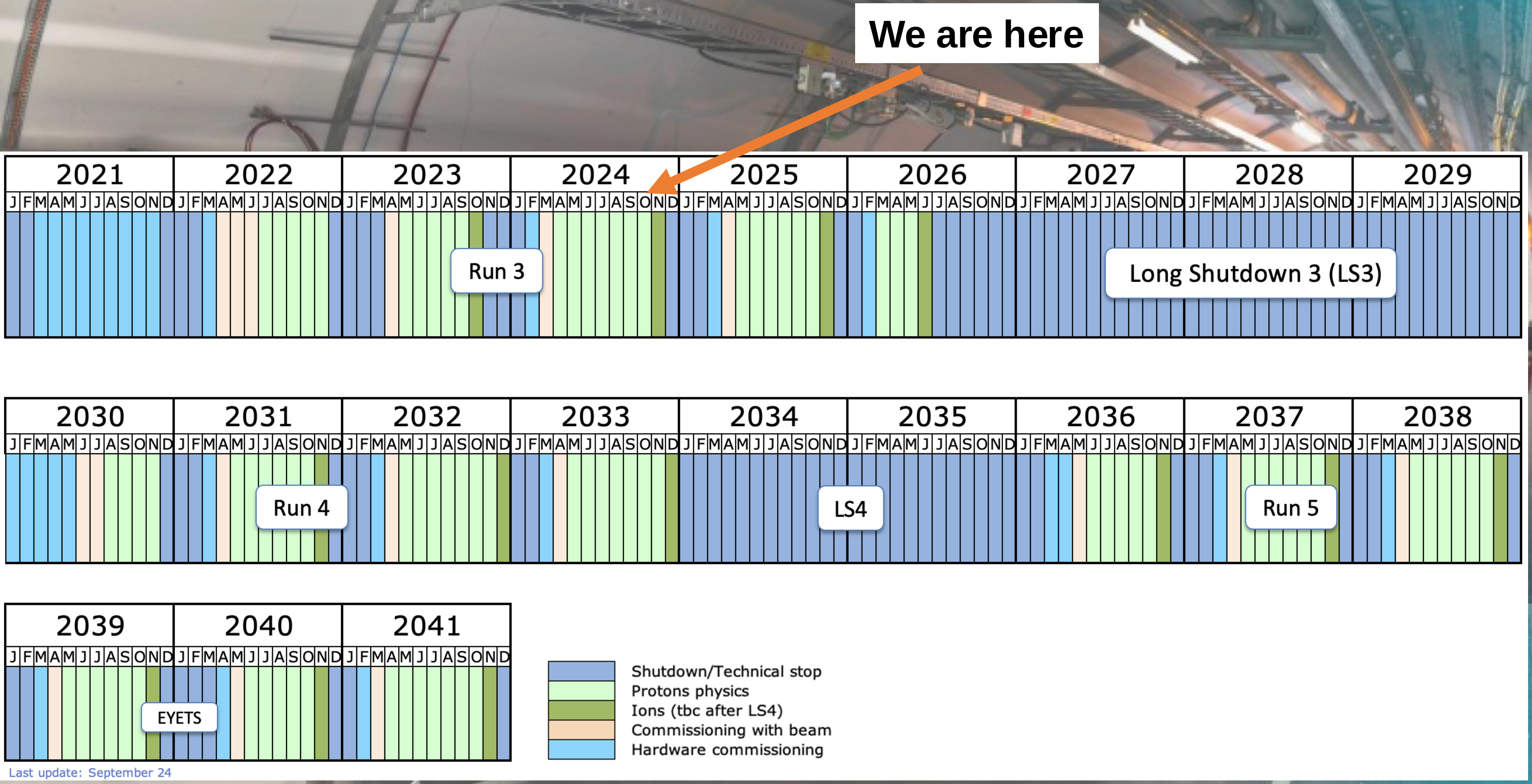
Run 3: Collision energy increase to 13.6 TeV

~2029

- Start of the High-Luminosity LHC

2040+

- LHC programme ends
- What’s next?

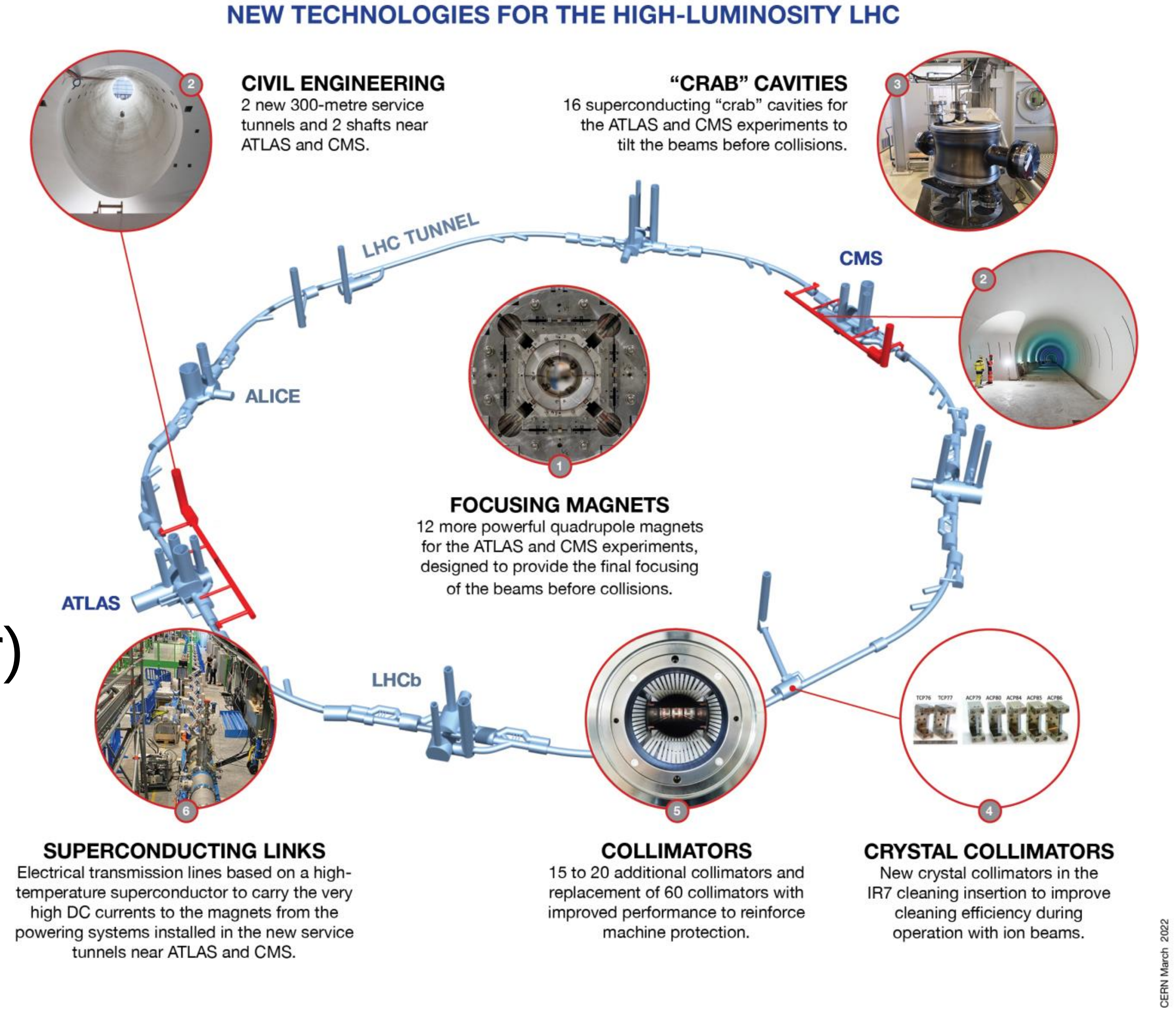


Have only taken ~ 10% of planned data so far

2028

A new LHC

Towards high luminosity with a new(er) collider



Energy

Sustainability

Power

What do physicicists care about in a collider?

Viability

Luminosity

Cost

Energy

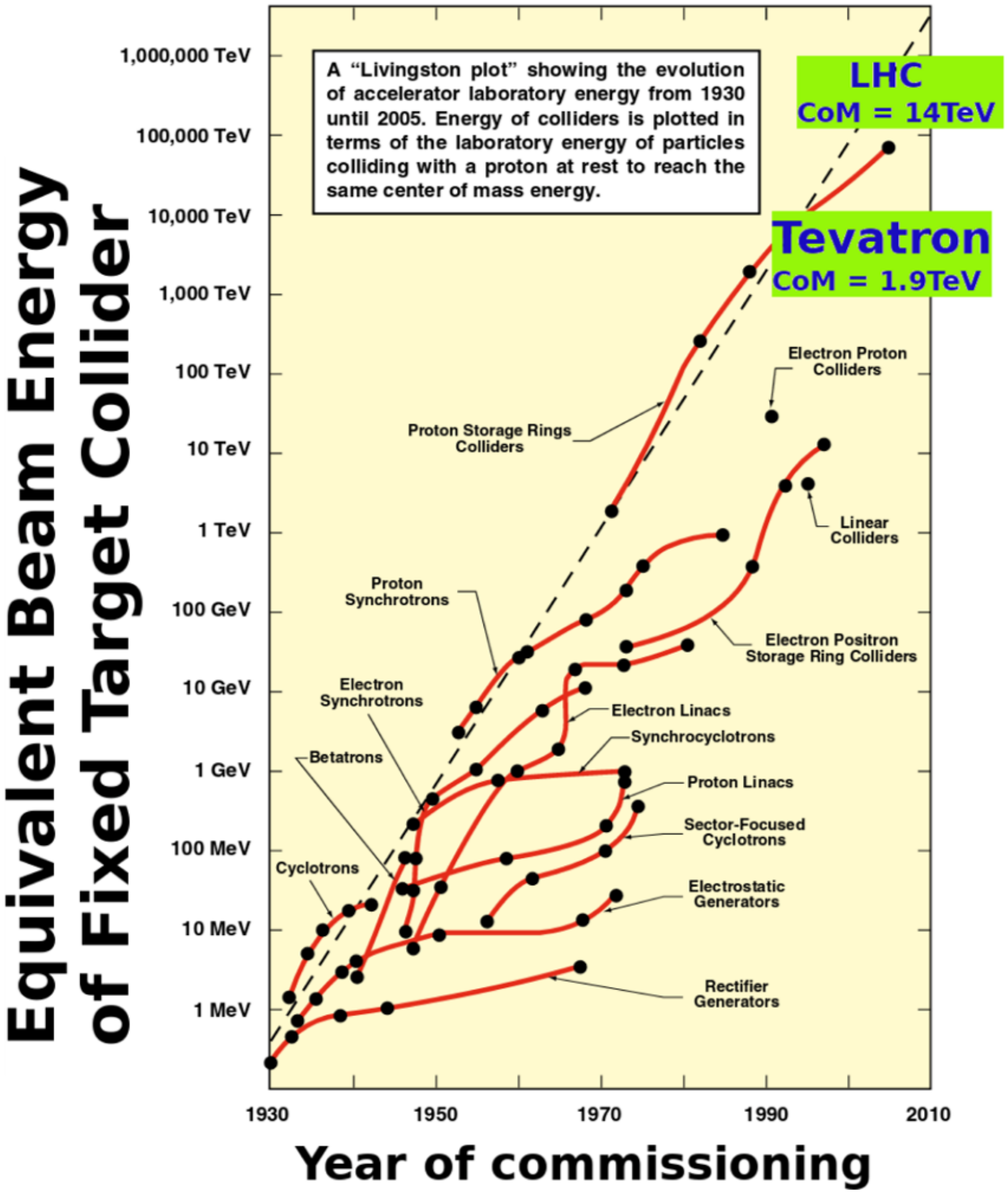
Fixed target: CoM energy

$$E_{CM} \approx \sqrt{2m_t E_b}$$

Collider CoM energy
(head-on, equal mass)

$$E_{CM} = 2E_b$$

From 2001 Snowmass AQccelerator R&D report,
Part I : Executive Summaries, eConf C010630, SLAC-R-599
http://www.slac.stanford.edu/econf/C010630/papers/MT1001.PDF

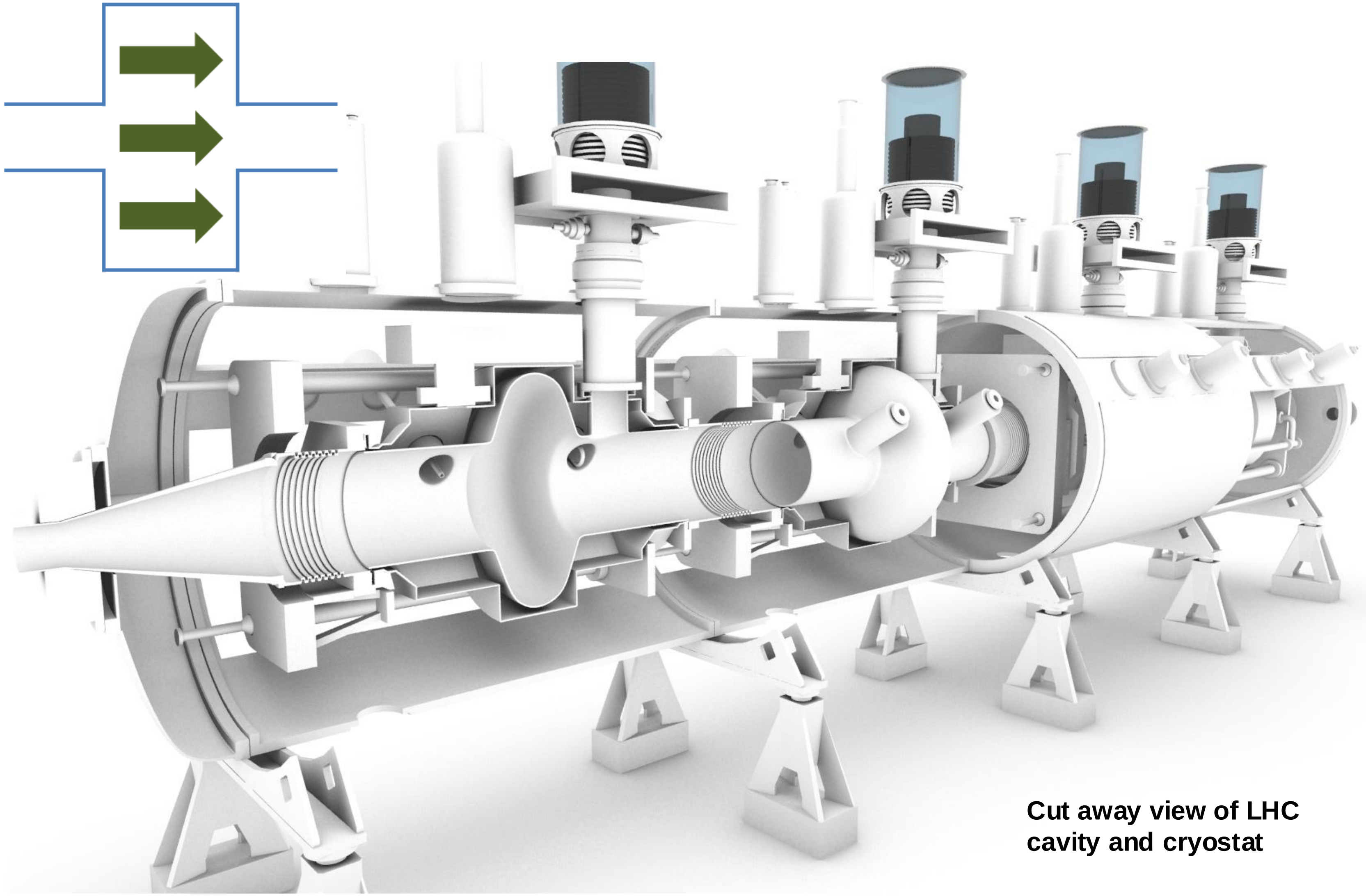


To reach LHC CoM collision energy with a fixed target experiment would require beam energy of 100,000 TeV

Still, even in a collider, we need to accelerate particles to very high energies.

To get high energy, we need to accelerate

Conventionally accelerate high-energy particle beams using *RF cavities*



Cut away view of LHC cavity and cryostat

- Some sort of conducting waveguide or cavity containing an oscillating EM field.
- Boundary conditions on the electric field, which force it to periodically point in the correct direction to accelerate.
- Only certain phases of the RF wave give acceleration => we collide bunches of high-energy particles.
- RF cavities are typically generated with klystrons.

Read more, here:
Steffen Döbert, CERN Accelerator School RF Power Systems, CLIC Drive Beam
https://cas.web.cern.ch/sites/default/files/lectures/zurich-2018/doebert2.pdf

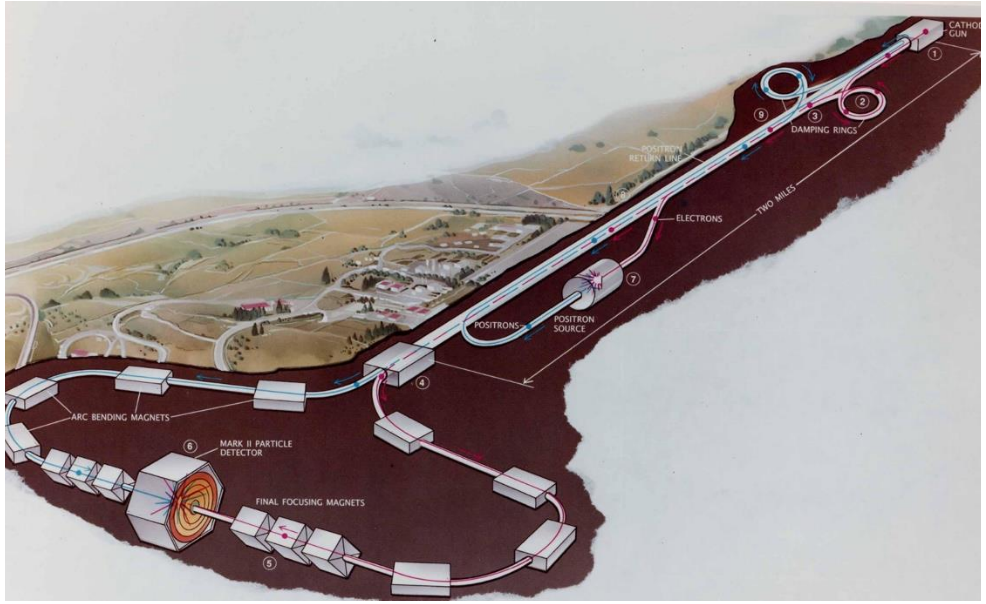
What limits the energy?

Acceleration generated by the RF cavities needs to be enough

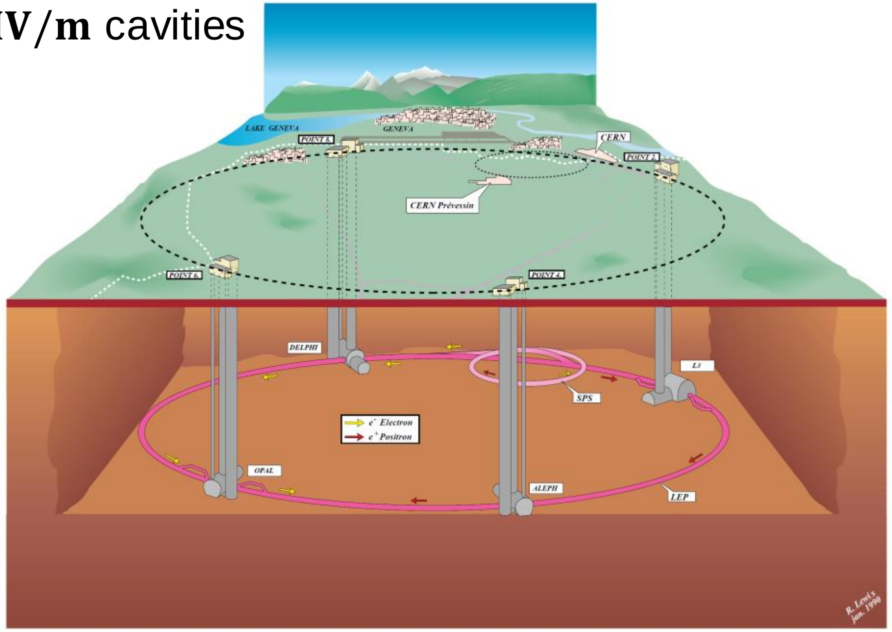
- **Defined by accelerating gradient of cavities $(\mathrm{MV/m})$ and total length of cavities**
  → Superconducting cavities limited by quench threshold of accelerating field on cavity walls.
  → Normal conducting limited by RF breakdown, can potentially deliver higher gradients

Linear accelerator/collider e.g. SLC @ $\approx 90\,\mathrm{GeV}$
→ A chain of RF cavities + some magnets
→ Needs to accelerate beam in single pass
→ SLC @ $\approx 90\,\mathrm{GeV}$: about **2.8km** of $\approx 21\ \mathrm{MV/m}$ cavities

Synchrotron collider e.g. LEP1 @ $\approx 91\,\mathrm{GeV}$
→ A ring of magnets + some RF cavities
→ Accelerates gradually over many turns, then maintain beam energy
→ LEP1 @ $\approx 91\,\mathrm{GeV}$: approximately **270m** of $\approx 1.47\ \mathrm{MV/m}$ cavities

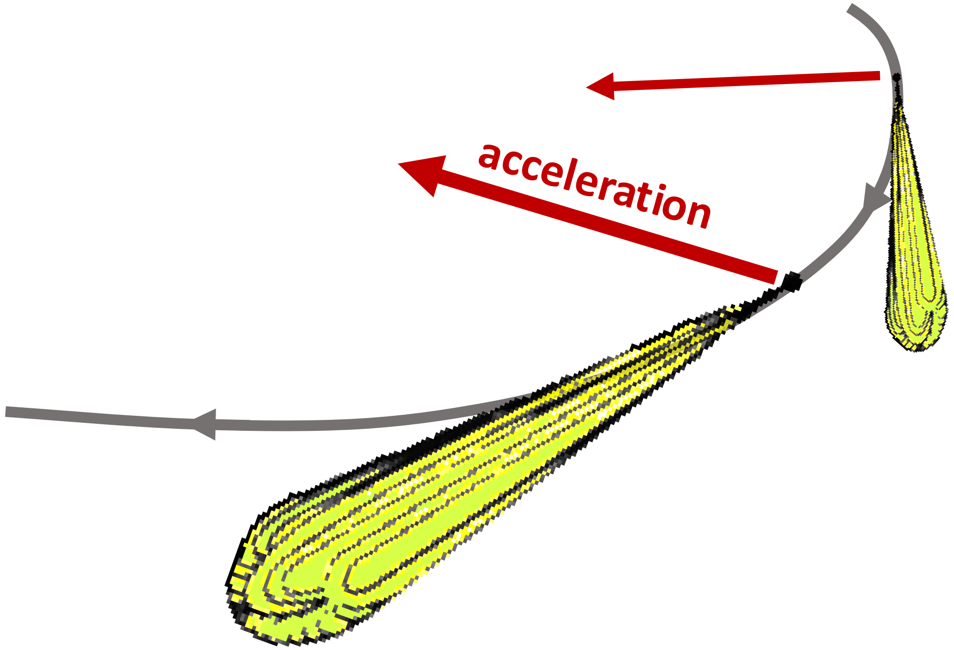


RF phase distribution systems at the SLC
https://www.slac.stanford.edu/pubs/slacpubs/4750/slac-pub-4893.pdf



LEP Technical design report:
https://cds.cern.ch/record/102083/files/cm-p00047694.pdf

When particles are deflected around an accelerator ring, they emit synchrotron radiation



Synchrotron light is one of the most important tools for scientific discovery at dedicated `light sources'

$$\Delta E/\mathrm{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$

For HEP synchrotron radiation is problematic as it carries away a portion of the particle's energy

- **This must be restored every turn by the RF cavities**
  → increases the electrical power consumption of the accelerator

$$\Delta E/\text{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$

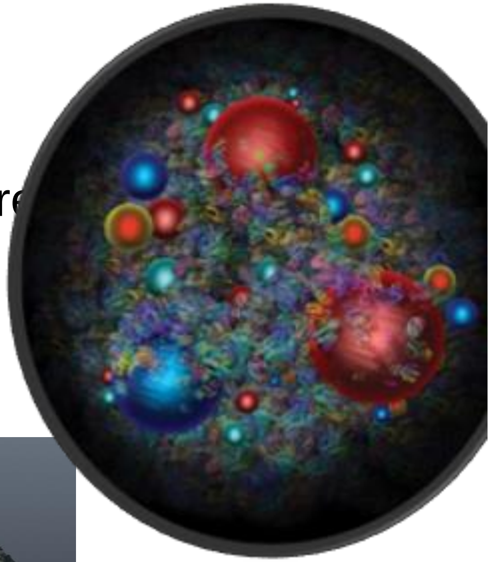
Collide more massive particles

- **LEP** (e) **energy loss:** $\sim 3\,\text{GeV/turn}$ (@ 101 GeV)
- **LHC** (p) **energy loss:** $\sim 5\,\text{keV/turn}$ (@ 6.5 TeV)

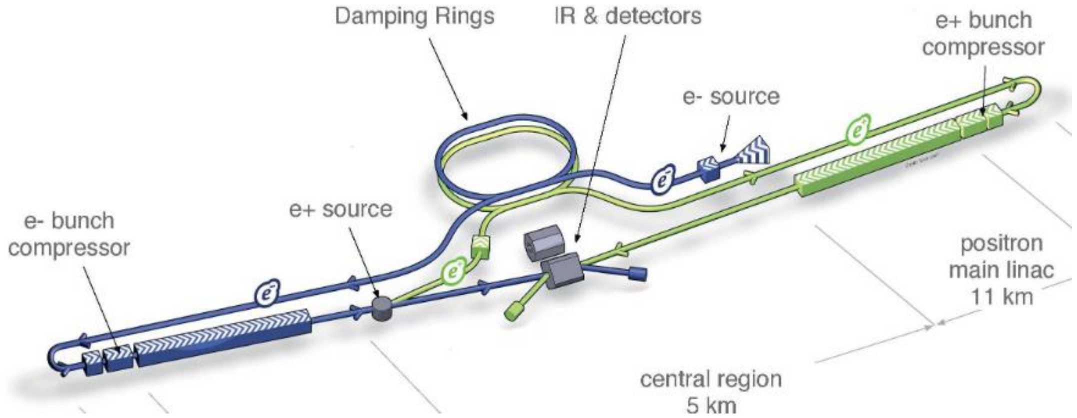
Electron 

Proton

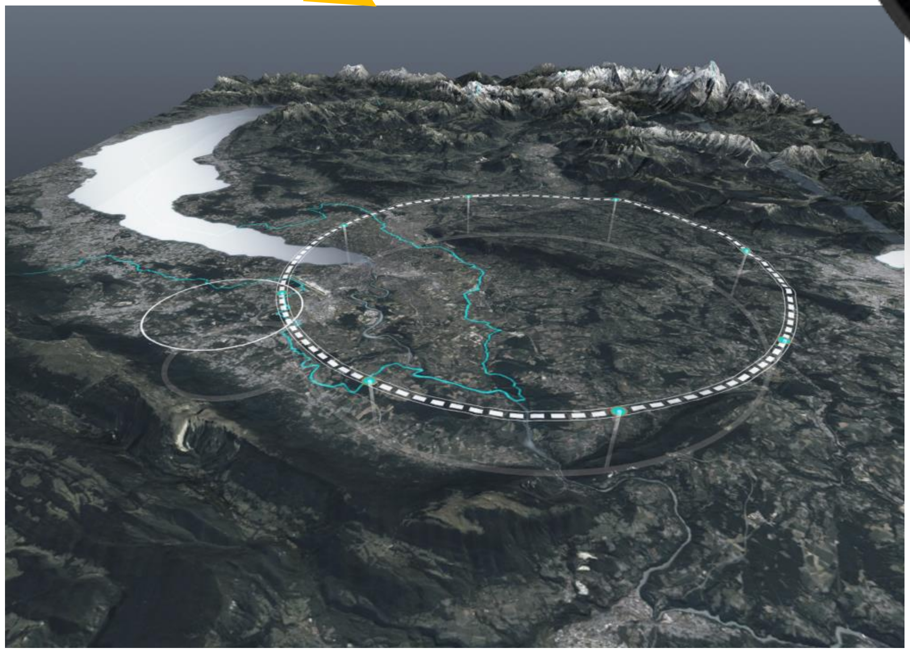
~2000 times more massive!



Linear collider



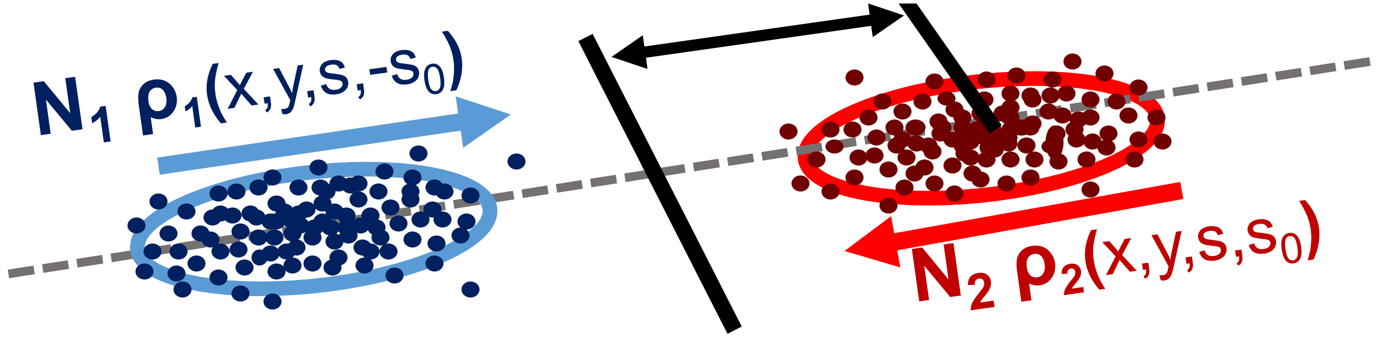
Increase circular collider circumference



Next up: luminosity

Why do we care about the luminosity?

$$\mathbf{R} = \mathbf{L} \times \sigma$$



- **R:** *Event Rate* $[\mathbf{s}^{-1}]$
- **σ:** *Cross Section* $[\mathbf{barn} = \mathbf{10^{-24} cm^2}]$
  property of the HEP interaction
- **L:** *Luminosity* **[inverse barn / s]**
  property of the collider

Can approximate luminosity as (head-on collisions of uncorrelated Gaussian profiles, same profile in each bunch)

$$L = \frac{f \, n_b \, N_1 N_2}{4\pi \, \sigma_x \, \sigma_y}$$

Repetition frequency (e.g. revolution freq. in circular collider) → f

Number of colliding bunches → n_b

Number of particles in the colliding bunches → N_1, N_2

Bunch size → $\sigma_x \, \sigma_y$

Particles need to survive acceleration & storage
→ Lots of effects in beam-dynamics can limit bunch intensity & survival

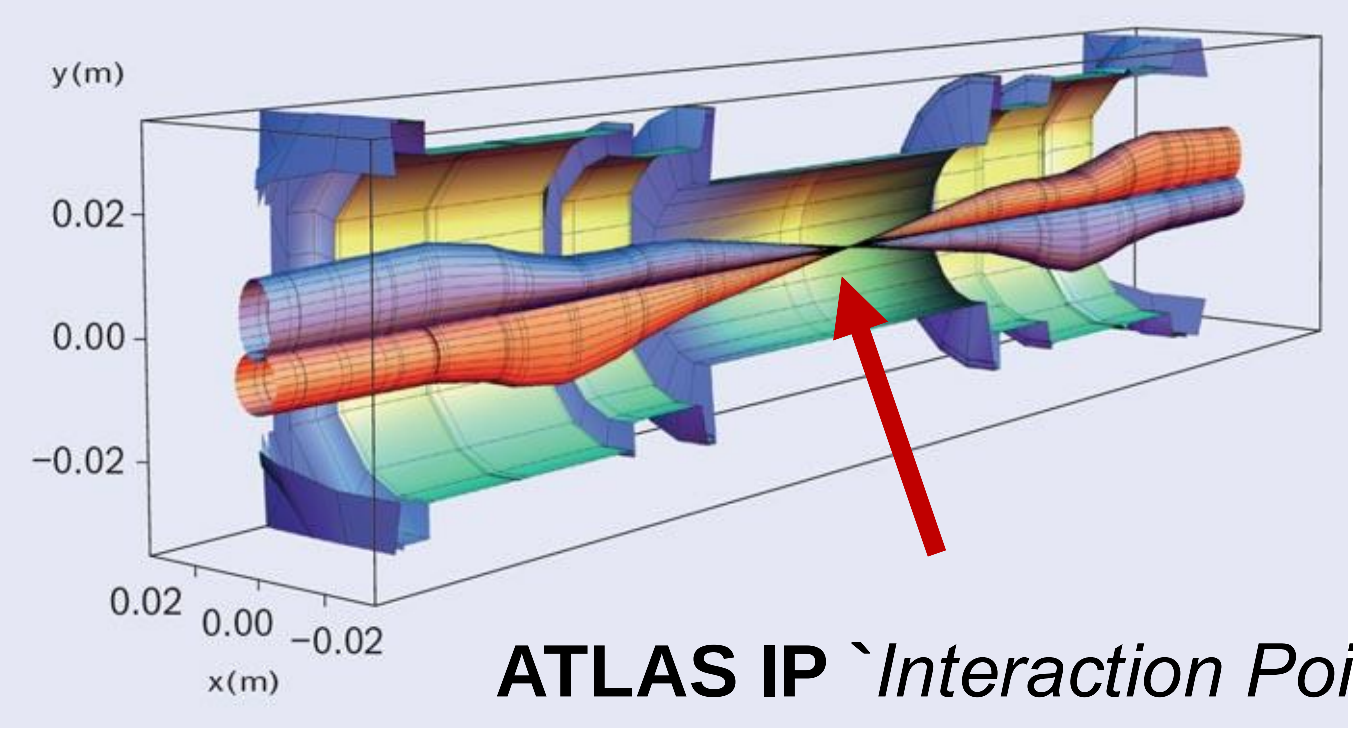
One way to increase the luminosity

$$L = \frac{f\, n_b N_1 N_2}{4\pi \boxed{\sigma_x \sigma_y}}$$

To produce high luminosity squeeze beams at the interaction points down to a small size with quadrupole magnets

LHC beam sizes at collision:

$$\sigma = \mathbf{10\mu m - 20\mu m}$$



ATLAS IP `*Interaction Point'*

Also, can **maximise the frequency** of bunch collisions and **create particles for collision more quickl**y

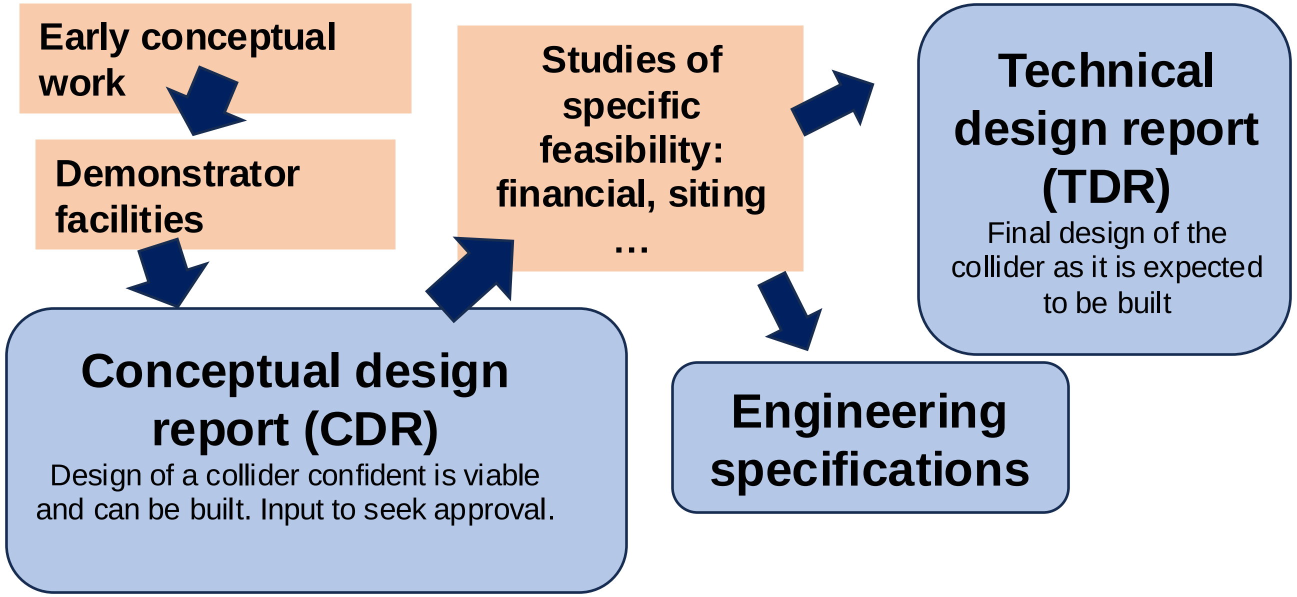
$\bar{p}$ production rate was primary limitation to Tevatron luminosity


Viability

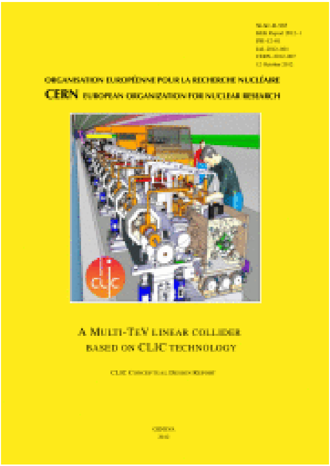
Viability: *if we're going to build a new accelerator need to be confident it will work when we turn it on*

→ Various usual milestones in an accelerator's development

(not strict or to be taken completely literally)



e.g. CLIC CDR: 3 volumes ≈1000 pages



Not always easy to compare project viability…

→ Recent snowmass exercise made a nice review of status/risk of various projects…

2023, JINST 18 P0501 *On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force*
https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

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

Cost

Cost/Power

Any future accelerator will represent a considerable financial investment

Exercise <u>extreme caution</u> comparing construction/power/running-cost estimates

→ Uncertainty heavily influenced by project maturity

→ Many estimates are out-of-date: inflation/labour cost, technological/industrial improvements

At CERN industrial return of member states vs contributions monitored & procurement rules favour poorly balanced members

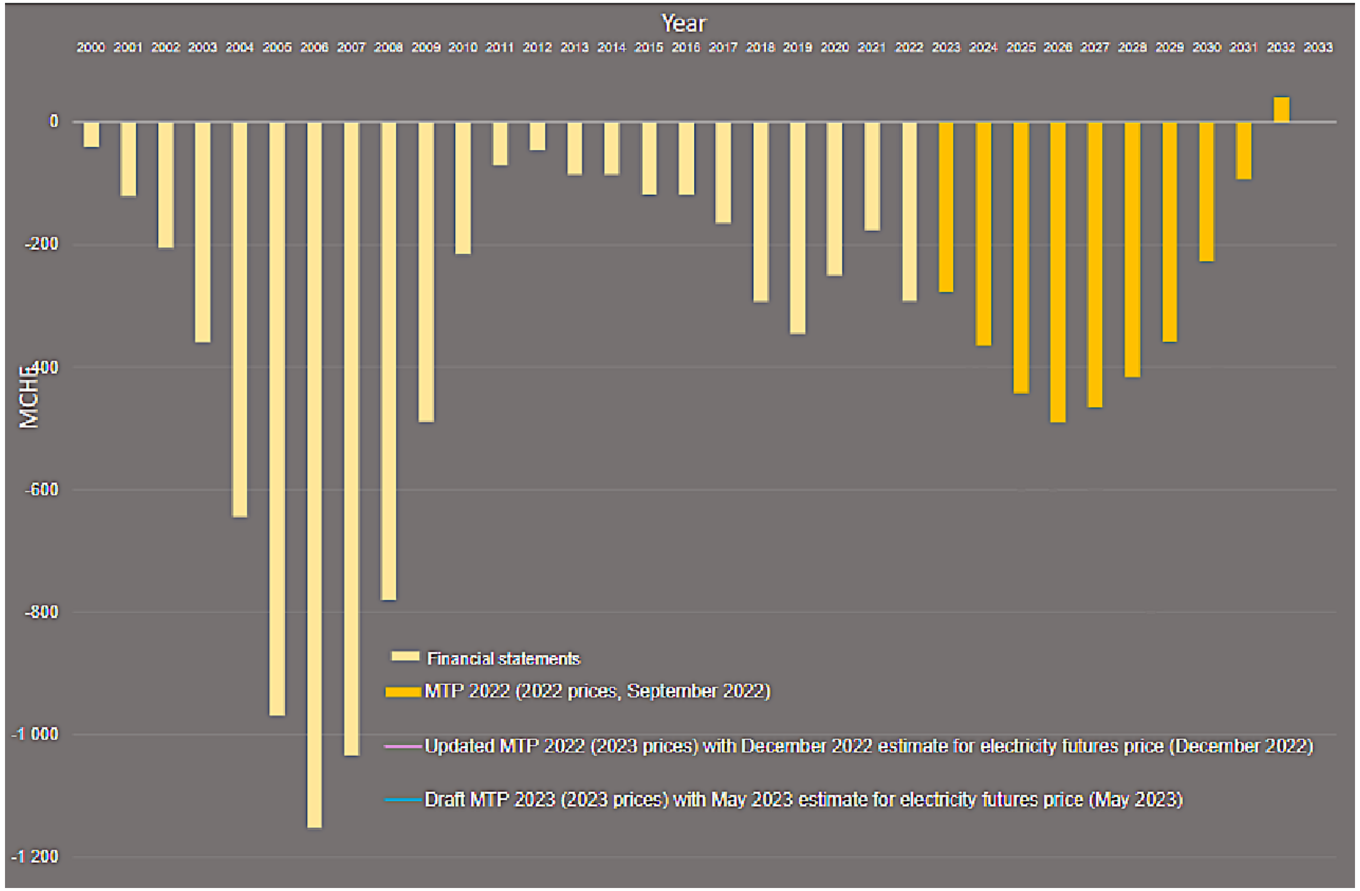
CERN relatively unique NGO/Lab in that it can take loans to fund development of future: helps limit up-front cost to member states. Subject to council.

Some financial support for future projects could come from non-member states (for example specific in-kind contributions e.g. some LHC magnets constructed by US**)**

Various financial figures of merit that can be considered

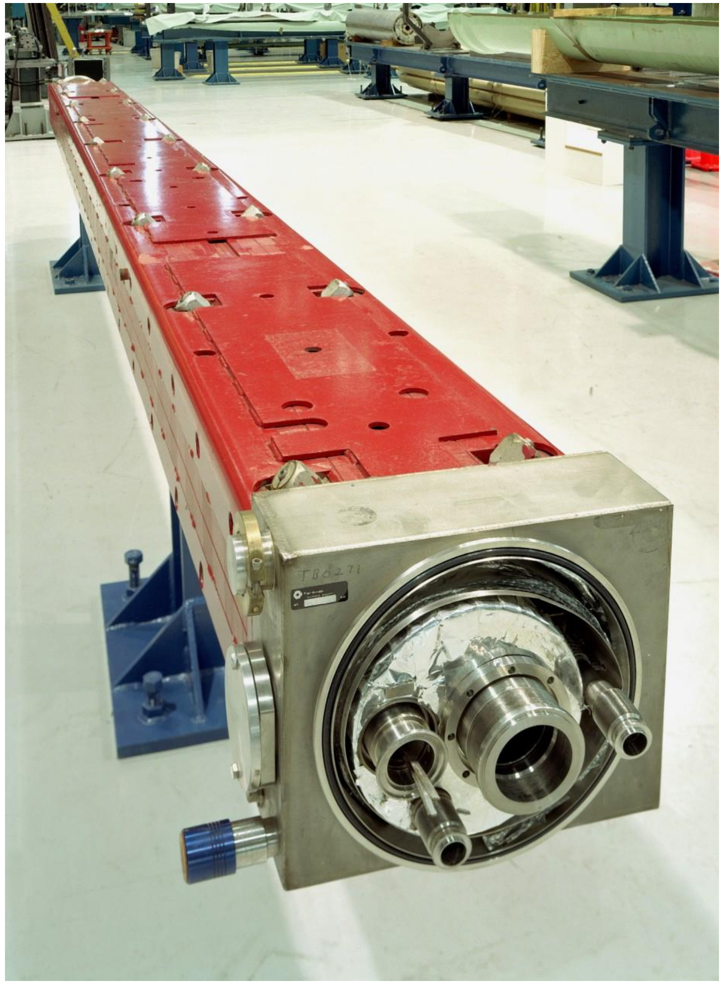
- **Capital construction cost , power requirements, but also:**

$$\frac{\text{Luminosity}}{\$} \quad \& \quad \frac{\text{Luminosity}}{\text{TWh}}$$



F.Sonnemann, FCC week 2023 *Funding options and integration of the FCC ee construction and operation in CERN's financial plan* https://indico.cern.ch/event/1202105/contributions/5431438/

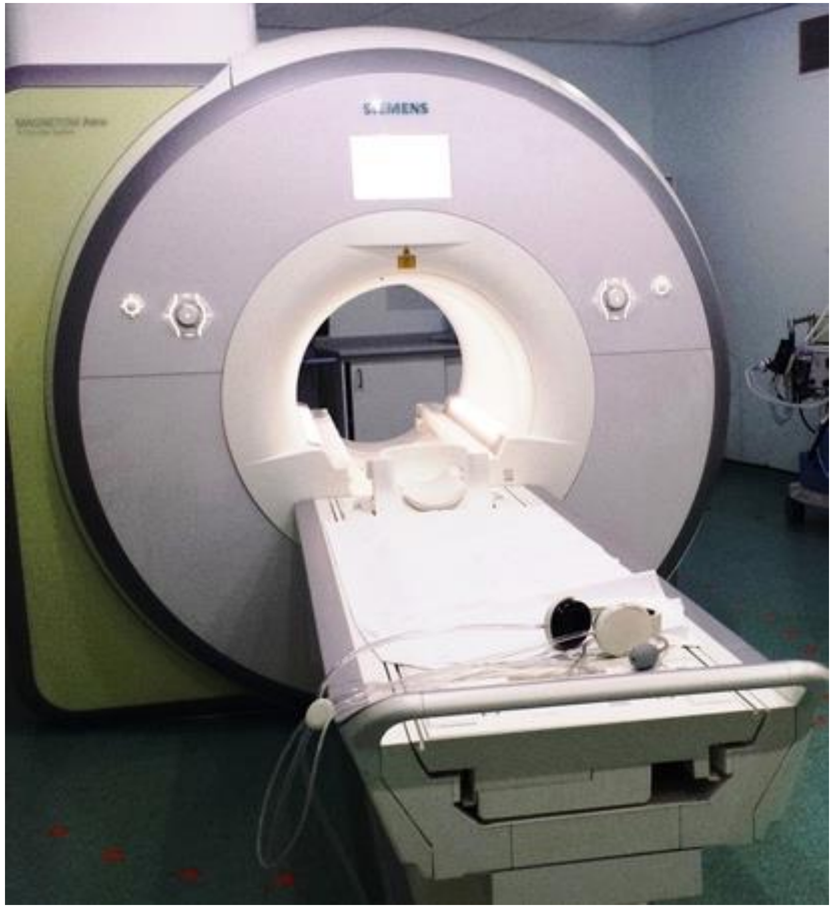
Large scale procurement in accelerator projects can act as a stimulus to relevant high-tech industries



When Tevatron was being built it accounted for around 90% of world procurement of NbTi superconducting cable

Generally credited with stimulating industrial capacity for superconducting magnets, contributing to wide-spread availability of e.g. MRI machines

- Accelerator R&D for major HEP projects often benefits society as a whole



Sustainability

Sustainability

≈90% of CERN power comes from France non-fossil fuel sources, majority nuclear

- Helps partially decouple power requirements of future project from CO_2
- Still important to seek energy savings and sustainability improvements wherever possible, and ensure future power supplies are sustainable!

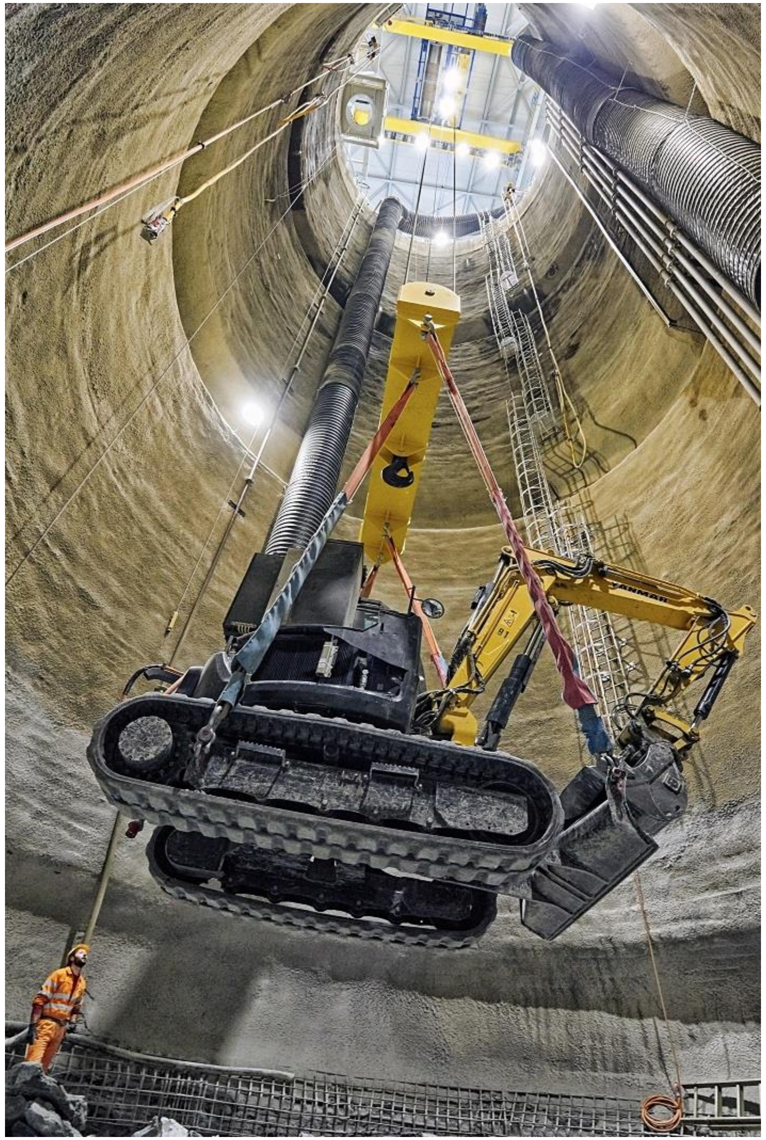
Concrete used in civil engineering is expected to dominate CO_2 footprint of future project proposals (production inherently produces CO_2 via calcination of limestone)

$$CaCO_3 \rightarrow CaO + CO_2$$

Various EU projects underway to help support low carbon footprint concrete

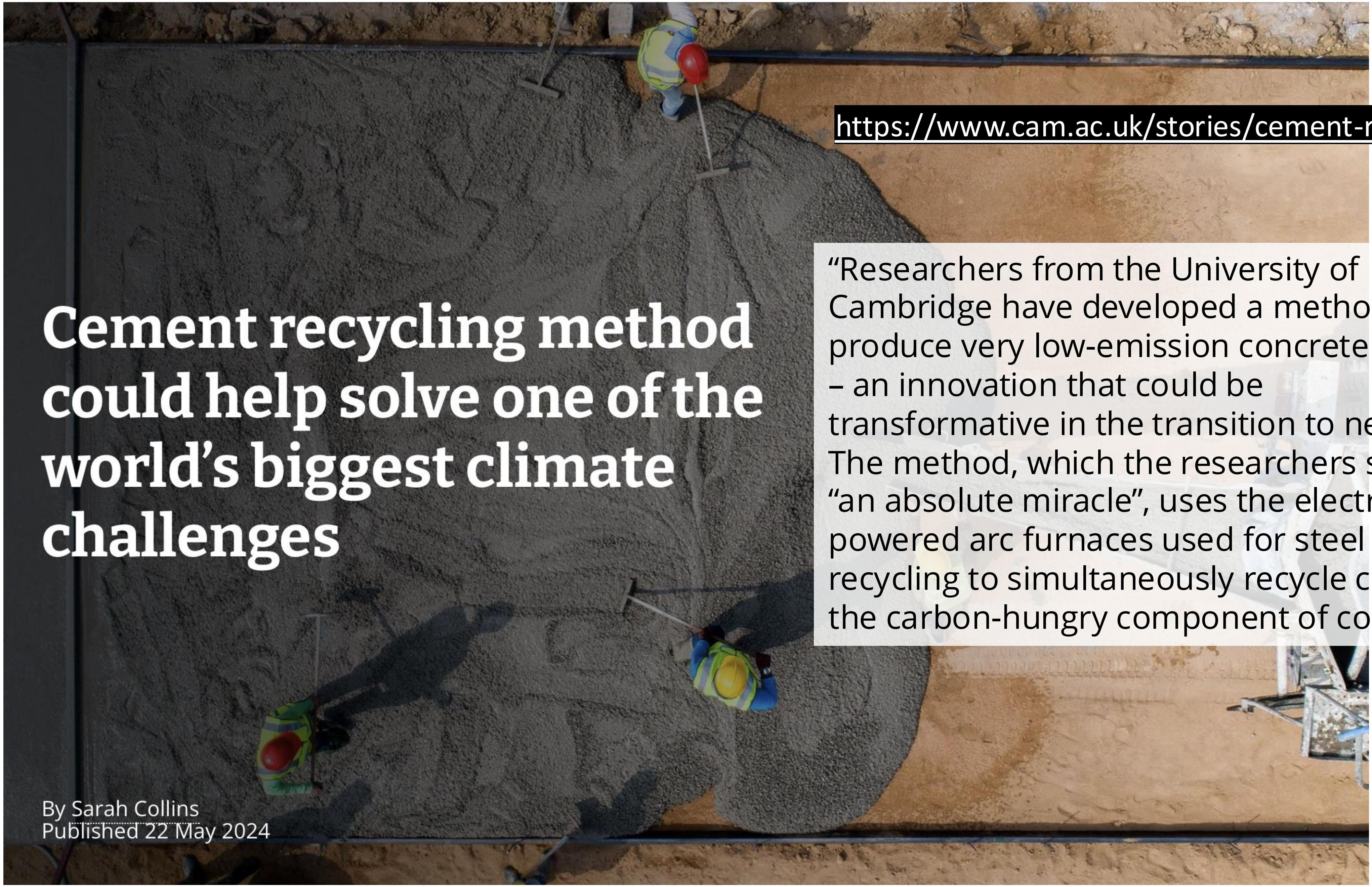
Reusability of civil engineering and upgrade paths is also important

Civil engineering work underway for the HL-LHC



Civil engineering work underway for the HL-LHC

UNIVERSITY OF CAMBRIDGE



https://www.cam.ac.uk/stories/cement-recyclinga

"Researchers from the University of Cambridge have developed a method to produce very low-emission concrete at scale – an innovation that could be transformative in the transition to net zero. The method, which the researchers say is "an absolute miracle", uses the electrically-powered arc furnaces used for steel recycling to simultaneously recycle cement, the carbon-hungry component of concrete."

Future colliders?

Future colliders?

Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

Hadron synchrotron

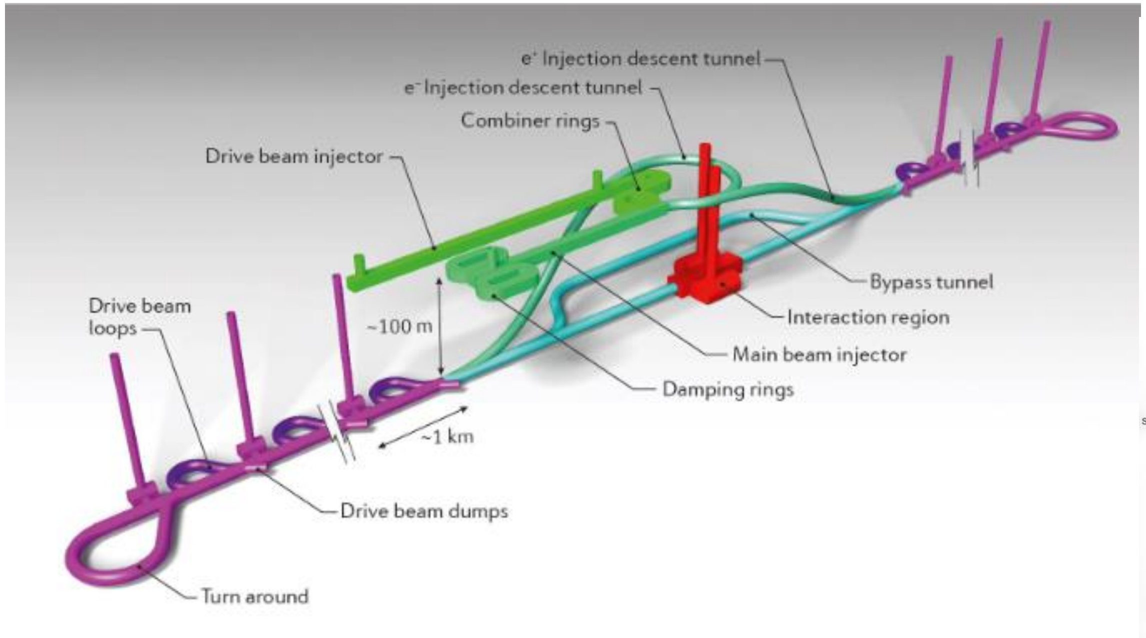
- FCChh
- SPPS

Muon Collider

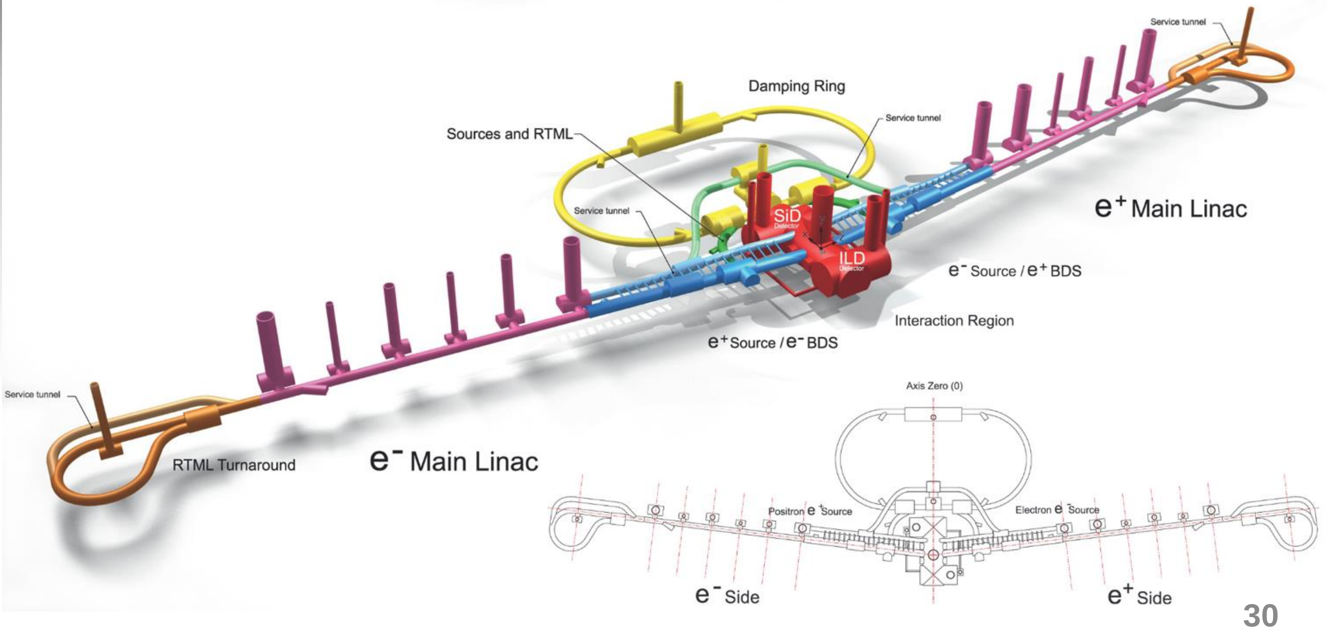
Linear e^+e^- collider

Two main proposals

Compact Linear Collider (CLIC) @ CERN



International Linear Collider (ILC) @ Japan



Linear e^+e^- collider

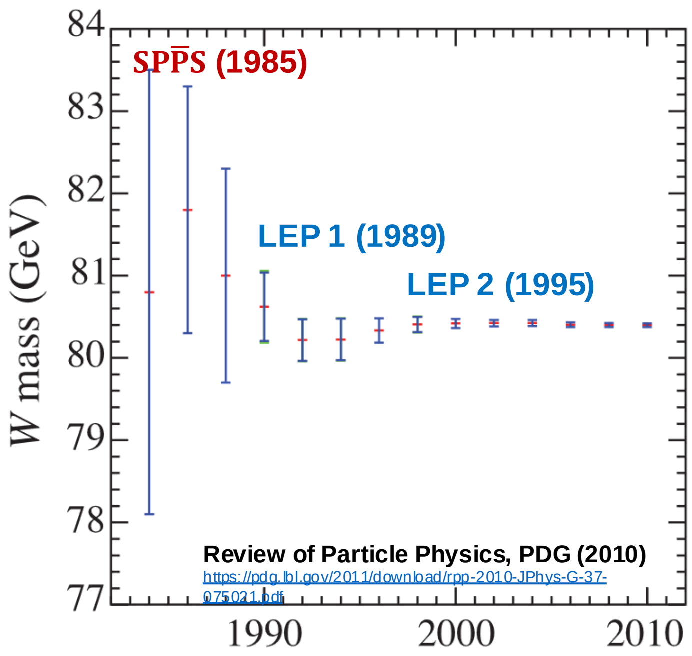
- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

a pathway to highest energy e^+e^- collisions

Why an e^+e^- linear collider?

Hadron machines like LHC collide composite particles

- Don't precisely know energy of constituents involved
- Probe large energy spread → great for discovery, harder for precision



Review of Particle Physics, PDG (2010)
https://pdg.lbl.gov/2011/download/rpp-2010-JPhys-G-37-075021.pdf

Fundamental particles => know well the collision energy

- Can be beneficial for precision studies
- E.g. can precisely scan energy of collider over a resonance

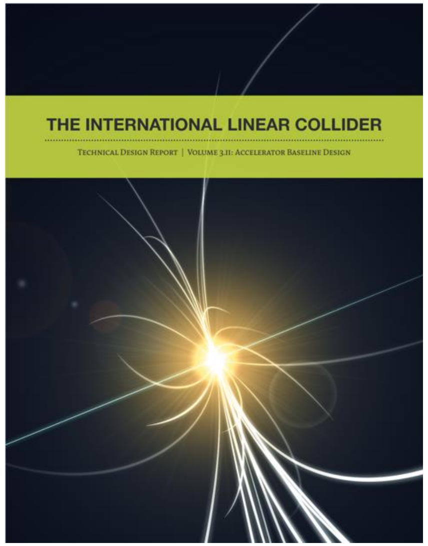
Energy reach of circular e^+e^- machines limited by synchrotron radiation

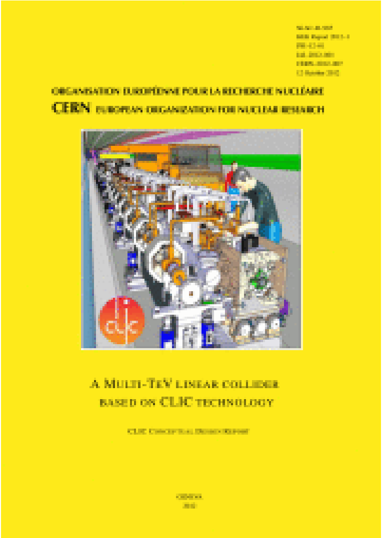
- Linear collider energy not subject to this restriction
- Linear collider offers potential for highest possible energy e^+e^- collisions

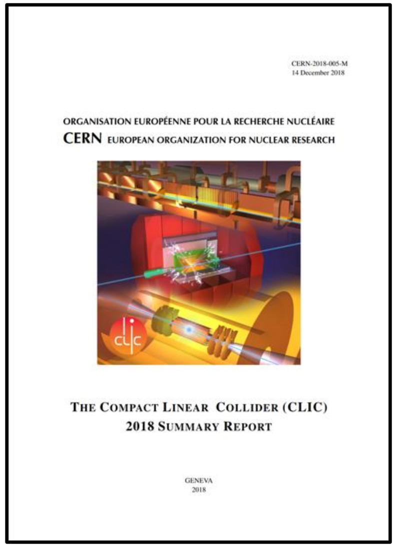
Both CLIC and ILC are extremely mature projects

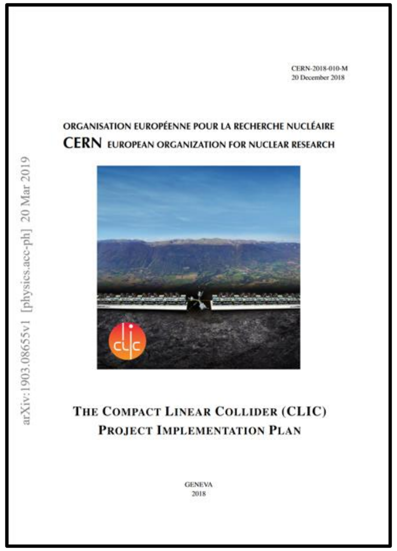
- **R&D for the CLIC / ILC projects began in 1985 / early 1990s!**
- **Multiple dedicated test facilities built & operated to demonstrate key technologies: CTF1** (1994), **CTF2** (1996), **CTF3** (2001-2016), **ATF** (1995), **ATF2** (2009)
- **ILC produced Technical Design report in 2013** https://cds.cern.ch/record/1601969/files/ILCTDR-VOLUME_3-PART_II.pdf
- **CLIC Conceptual Design Report published 2012 (focused on 3TeV collider viability)** http://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
- **Following discovery of Higgs CLIC published strategy update in 2018 (focused on initial staging from 380GeV) plus an implementation plan**
  https://arxiv.org/pdf/1812.06018.pdf , https://arxiv.org/pdf/1903.08655.pdf
- **Most recent CLIC update in 2022 for submission to US Snowmass** https://arxiv.org/pdf/2203.09186.pdf

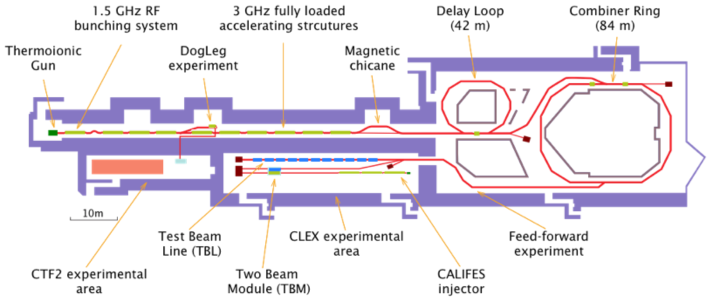
(lowest possible risk classification in 2021 Snowmass)

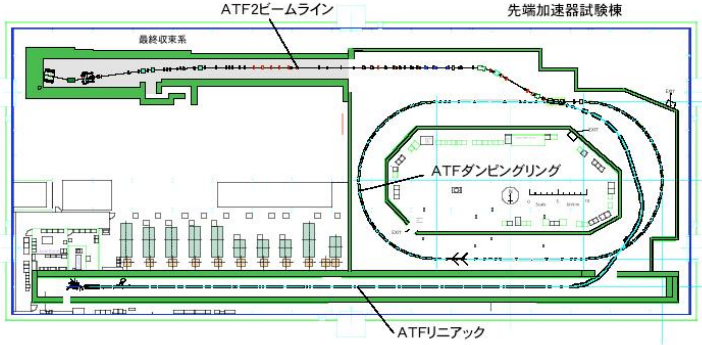












Both linear colliders with staged increase in C.O.M energy achieved by increasing length of tunnel → more RF cavities

- To reach 3TeV in 50km CLIC requires extremely high ($\approx 100\mathrm{MV/m}$) accelerating gradient.

CLIC

$\leq 380\mathrm{GeV}$ **(11.4km)**

$\leq 1.5\mathrm{TeV}$ **(29.0km)**

$\leq 3.0\mathrm{TeV}$ **(50.1km)**

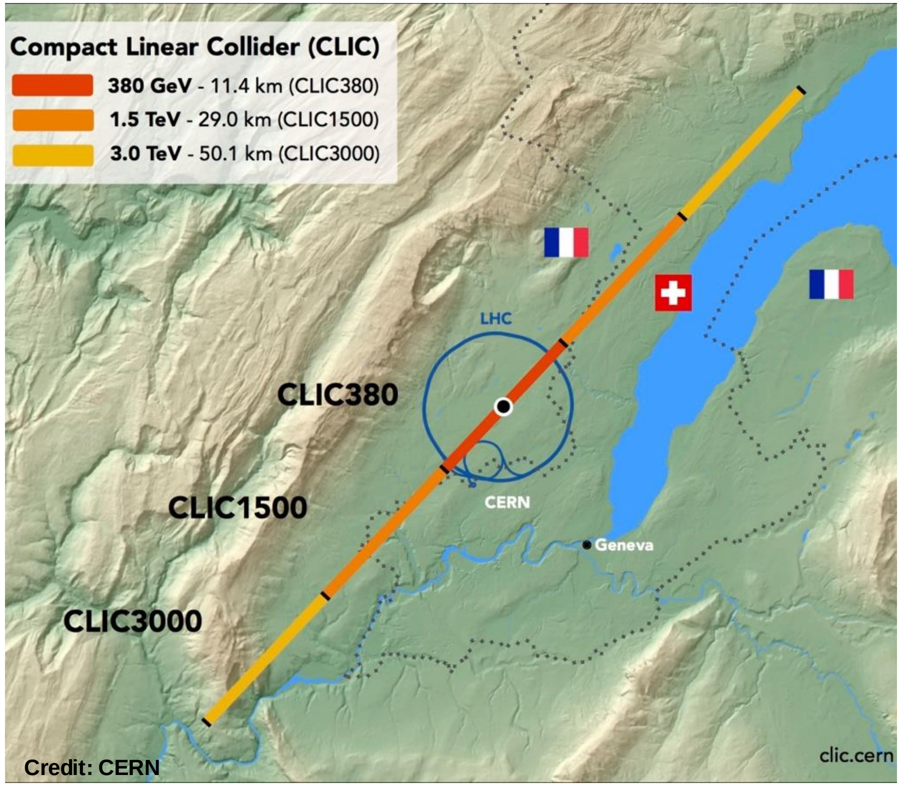
ILC

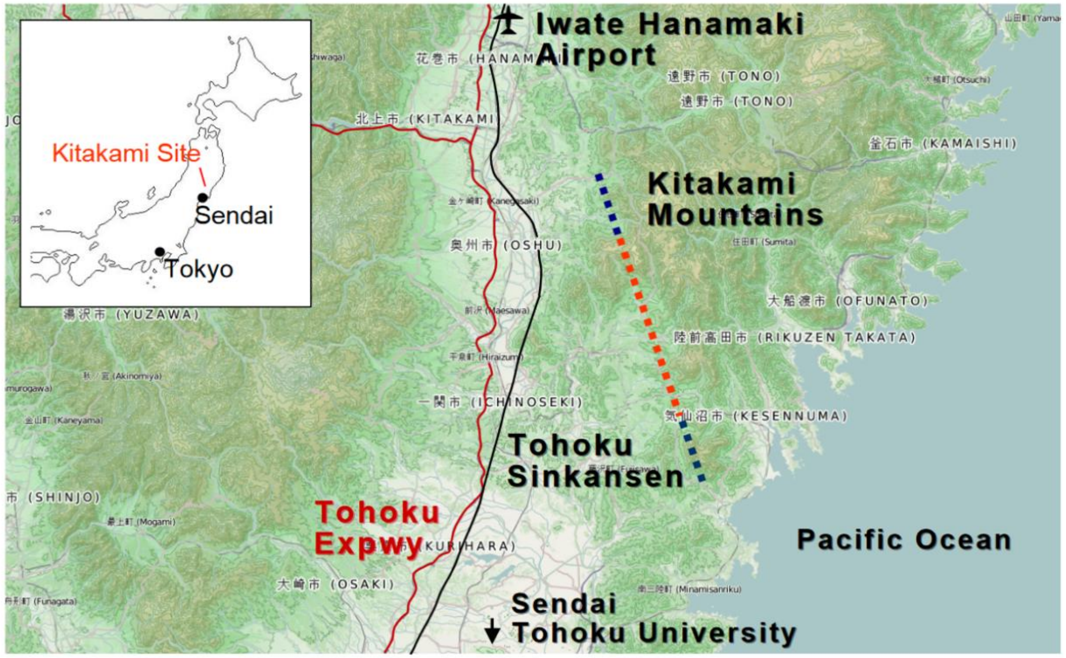
$\leq 250\mathrm{GeV}$ **(20.5km)**

$\leq 500\mathrm{GeV}$ **(31km)**

$\leq 1.0\mathrm{TeV}$ **(40km)**

ILC requires lower accelerating gradient ($\approx 31.5\mathrm{MV/m}$). Uses conventional superconducting RF cavities powered by Klystrons

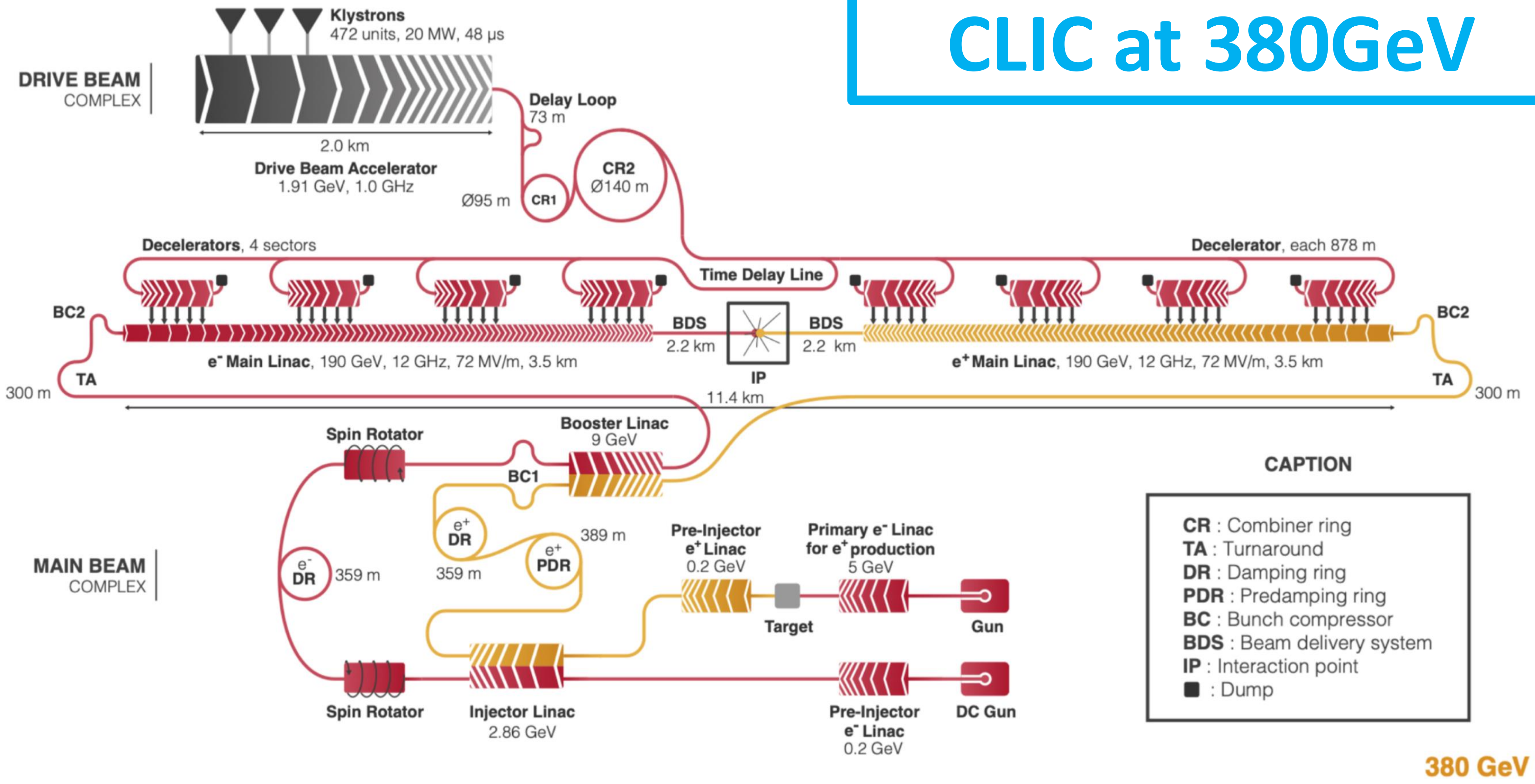




0 10 20 30km

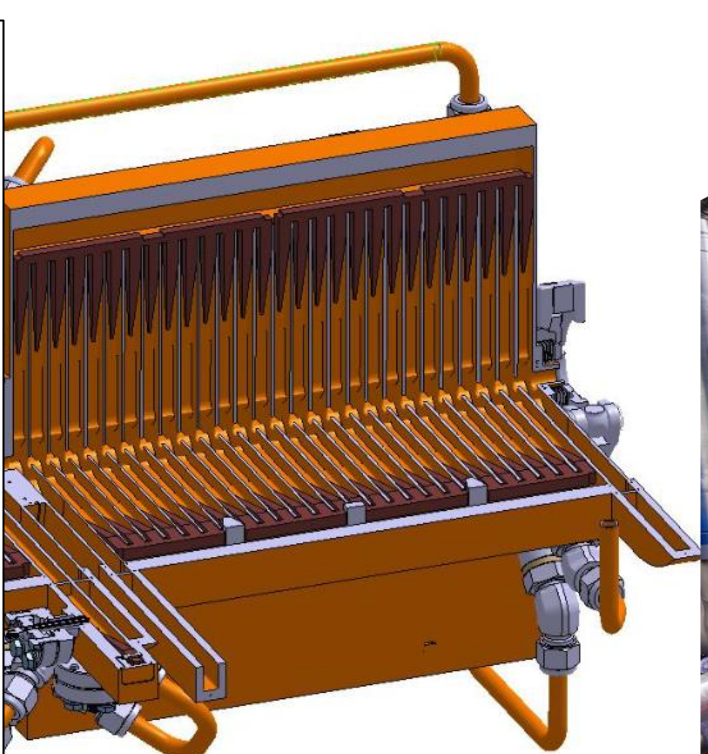
LEGEND :
ILC 500GeV ≈30km
ILC 1TeV ≈50km

CLIC at 380GeV



To reach multi-TeV scale energy in acceptable tunnel CLIC project developed novel high-gradient cavities (100MV/m) capable of accelerating high-current high-quality electron beams

→ Already delivering societal impact



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journal homepage: www.thegreenjournal.com

Flash irradiation

Irradiation in a flash: Unique sparing of memory in mice after whole brain irradiation with dose rates above 100 Gy/s

Pierre Montay-Gruel [a,b,1], Kristoffer Petersson [c,1], Maud Jaccard [c], Gaël Boivin [a], Jean-François Germond [c], Benoit Petit [a], Raphaël Doenlen [d], Vincent Favaudon [b], François Bochud [c], Claude Bailat [c], Jean Bourhis [a,1], Marie-Catherine Vozenin [a,*,1]

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ABSTRACT

This study shows for the first time that normal brain tissue toxicities after WBI can be reduced with increased dose rate. Spatial memory is preserved after WBI with mean dose rates above 100 Gy/s, whereas 10 Gy WBI at a conventional radiotherapy dose rate (0.1 Gy/s) totally impairs spatial memory.

Our recent publications have shown that irradiation at an ultra-high dose rate was able to protect normal tissue from radiation-induced toxicity. When compared to radiotherapy delivered at conventional dose rates (1–4 Gy/min), this so called "Flash" radiotherapy (>40 Gy/s; Flash-RT) was shown to enhance the differential effect between normal tissue and tumor in lung models [1,2] and consequently allowed for dose escalation. The biological interest of Flash-RT seems to rely essentially on a specific, yet undefined, response occurring in normal cells and tissues. We initially hypothesized that the protective effect of Flash was related to the high dose rate delivery, in other words related to the very short time of exposure. In order to further explore Flash-RT and to validate its protective effect on normal tissues, we decided to extend our observation from the lung to other organs. We decided to investigate brain response to Flash-RT as it is a well-defined and robust model in radiobiology [3–5].

When dealing with unexpected biological results, such as the ones previously described with Flash-RT, accurate dosimetry of the delivered irradiation is essential. However, dosimetry at (an ultra-)high dose rate in high dose-per-pulse beams is non-trivial as current radiotherapy dosimetry protocols are not designed for such conditions and because the detectors available for online measurements (i.e. ionization chambers, diodes, and diamond detectors) start to saturate when the dose rate/dose-per-pulse is increased beyond what is used in conventional radiotherapy [6–8]. Therefore, we needed to rely on dosimeters that had been previously validated to function accurately at more extreme irradiation conditions, i.e. mainly passive dosimeters. Among these options, we selected thermo-luminescent dosimeter (TLD) chips because of their small size ($3.2 \times 3.2 \times 0.9\ mm^3$) so that they could be used for measuring dose in the brain of mice. By positioning the TLD inside the skull of a sacrificed mouse, we were able to validate the dose delivered to the brain during whole brain irradiation (WBI).

Brain injuries after WBI at sub-lethal doses delivered at conventional radiotherapy dose rates are well described [5,9,10]. They include functional alterations, neuronal [11], glial [12,13] and vasculature toxicities [14,15]. Cognitive impairments are the most described functional defects observed in mice and humans following WBI [4,16]. They are caused by an alteration of hippocampal neurogenesis, which can occur as early as one month post 10 Gy single fraction WBI [17]. These cognitive impairments can be evaluated using the "Novel Object Recognition test" [18] on WBI murine models [19]. Therefore, we used this assay to investigate the functional effect of Flash-RT on the normal brain of irradiated mice.

Using a combination of accurate dosimetry measurements and robust biological tests, we first aimed to investigate the potential neuroprotective effect of Flash-RT and indeed found memory preservation in mice after 10 Gy WBI with Flash-RT (delivered in

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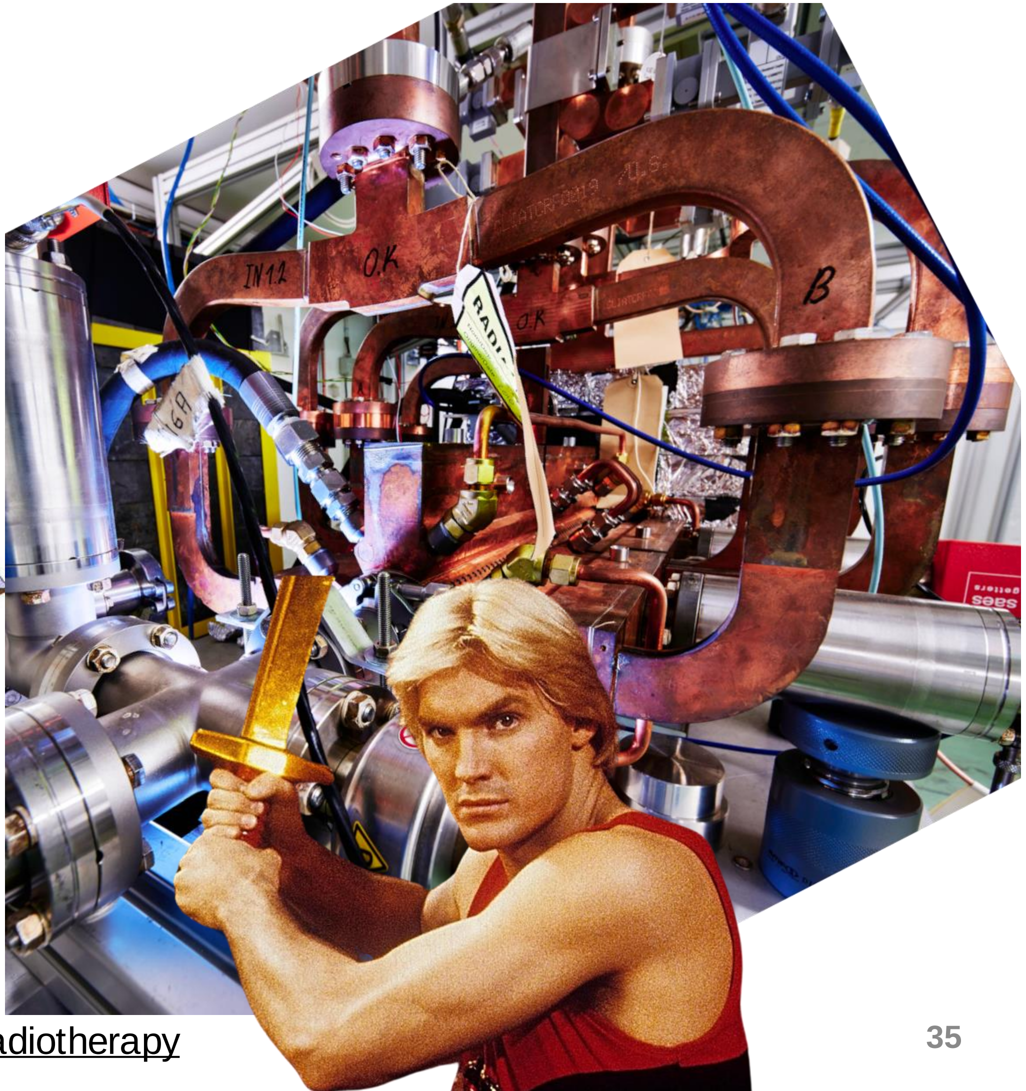
E-mail address: marie-catherine.vozenin@chuv.ch (M.-C. Vozenin).

[1] Equal contribution.

http://dx.doi.org/10.1016/j.radonc.2017.05.003

Flash



Ah ahhhh

https://kt.cern/flash-radiotherapy

CLIC stats

Most recent cost estimates for 380GeV option in from 2018
→ NOT ADJUSTED FOR INFLATION OR LABOUR COST CHANGED
→ Approximately 6000-7000 MCHF for stage 1

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	10^9	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

Upgrades to stage 1→2 & 2→3 estimated at approximately 5000 MCHF & 7000 MCHF

→ NOT ADJUSTED FOR INFLATION OR LABOUR COST

Power estimates from most recent (2022) snowmass summary report

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

Collision energy [GeV]	Annual Energy Consumption [TWh]
380	0.6
1500	1.8
3000	2.8

Future colliders?

Linear e^+e^- collider
- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron
- FCCee
- CEPC

Hadron synchrotron
- FCChh
- SPPS

Muon Collider

Synchrotron colliders: a pathway to luminosity frontier
e^+e^- collisions at high energy

Why an e^+e^- circular collider?

LHC discovered Higgs at relatively low mass, but no major hints of new physics at the TeV scale (so far!)

Circular e^+e^- provides potential for high-precision studies at high-luminosity in energy range of known interest

- One of highest priorities from European Strategy Review was precision study of Higgs

Offers natural upgrade path to hadron-hadron collider which would facilitate high-luminosity exploration over largest energy spread of future options

Circular e^+e^- machines can support the most HEP experiments of any future collider option

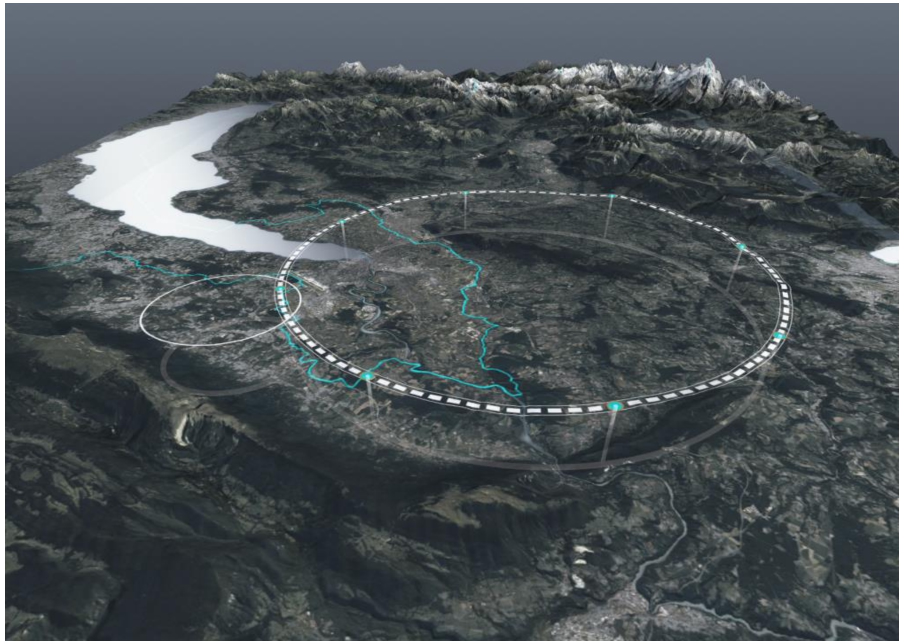
- Up to 4 experimental insertions on the same collider ring

Synchrotron colliders: a pathway to luminosity frontier

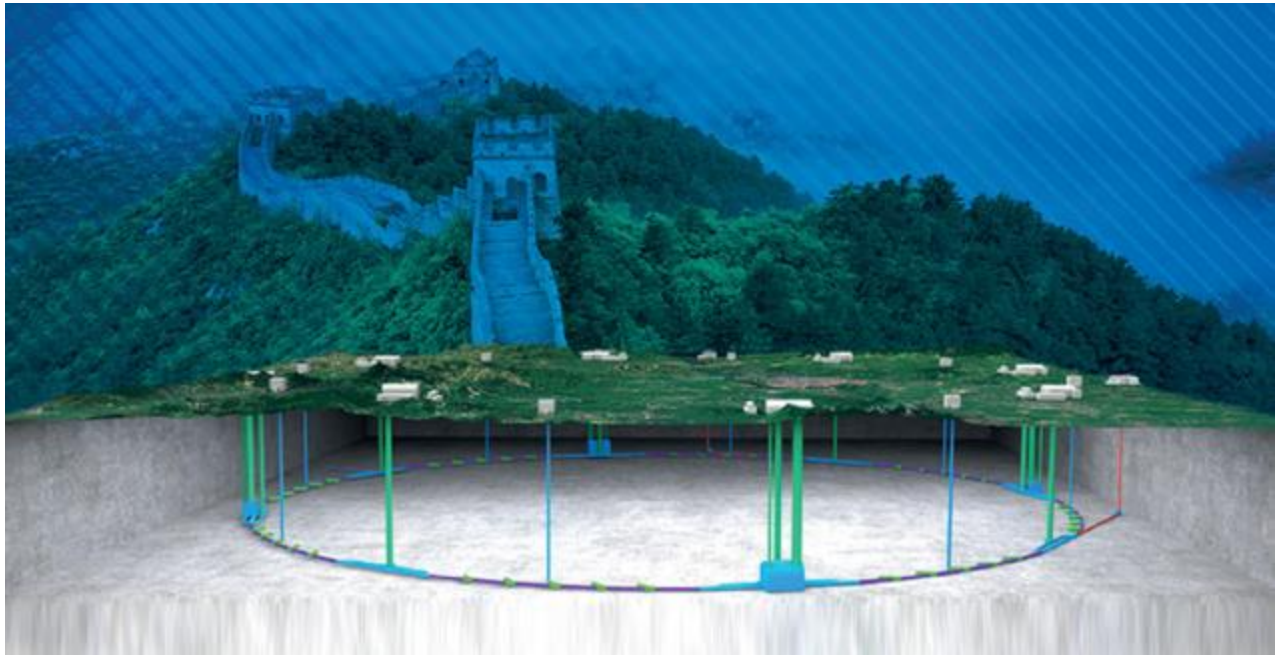
e^+e^- collisions at high energy

Two main proposals

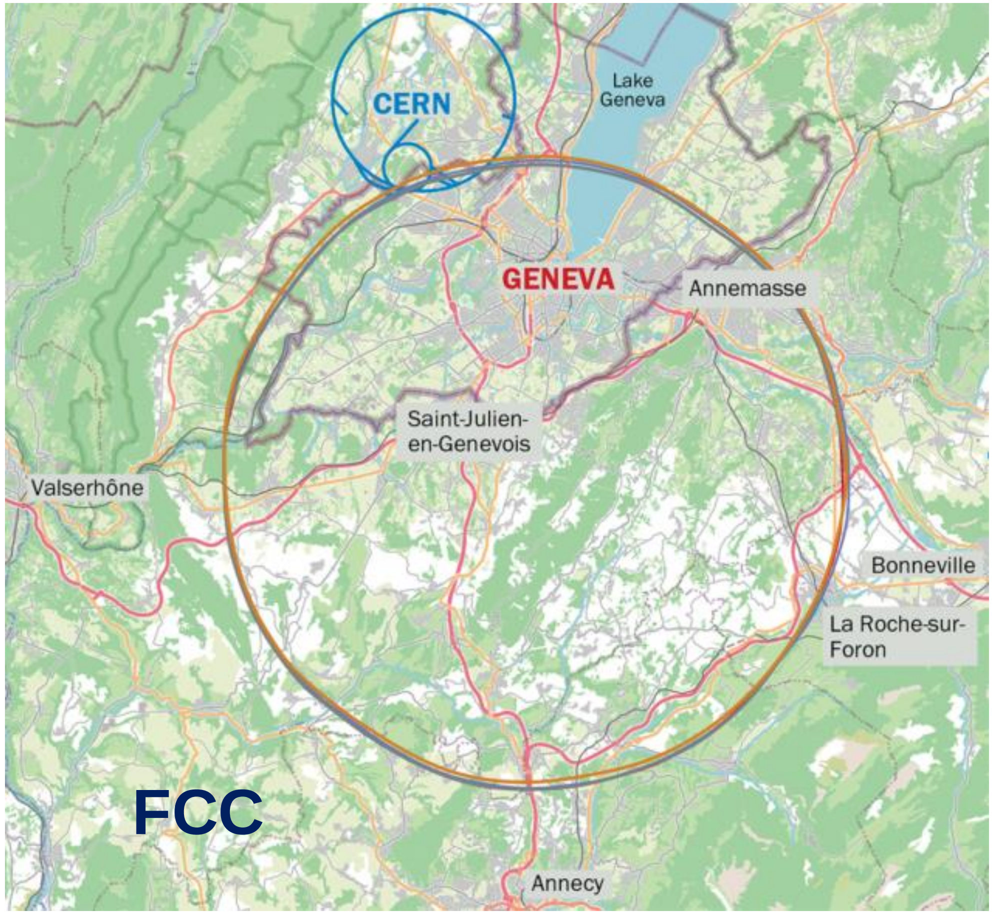
Future Circular Collider (FCCee) @ CERN



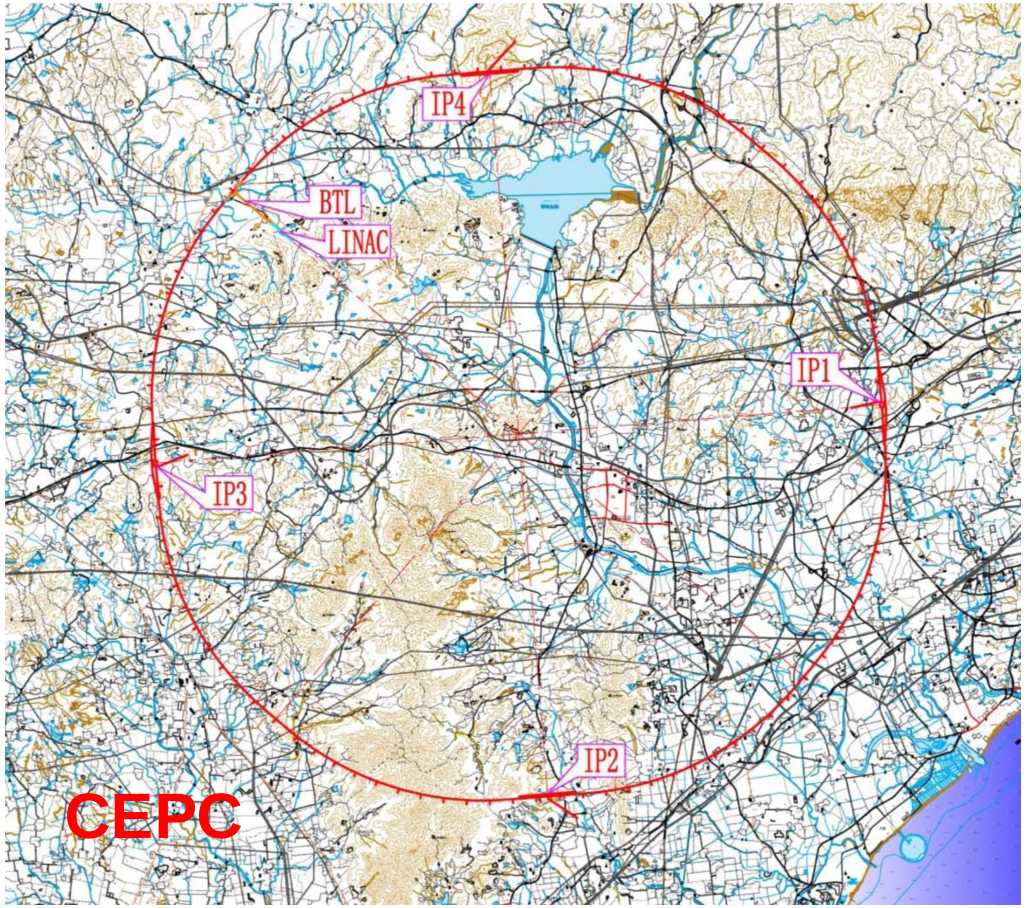
Circular Electron Positron Collider (CEPC) @ China



FCC: 90.6km ring building on existing CERN infrastructure
Similar CoM energy range 90 - 365
Similar Luminosities / IP
FCC hosts 4 experimental insertions



CEPC: 100km greenfield site with larger tunnel aperture
Similar CoM energy range 90 - 365
Similar Luminosities / IP
CEPC hosts 2 experimental insertions

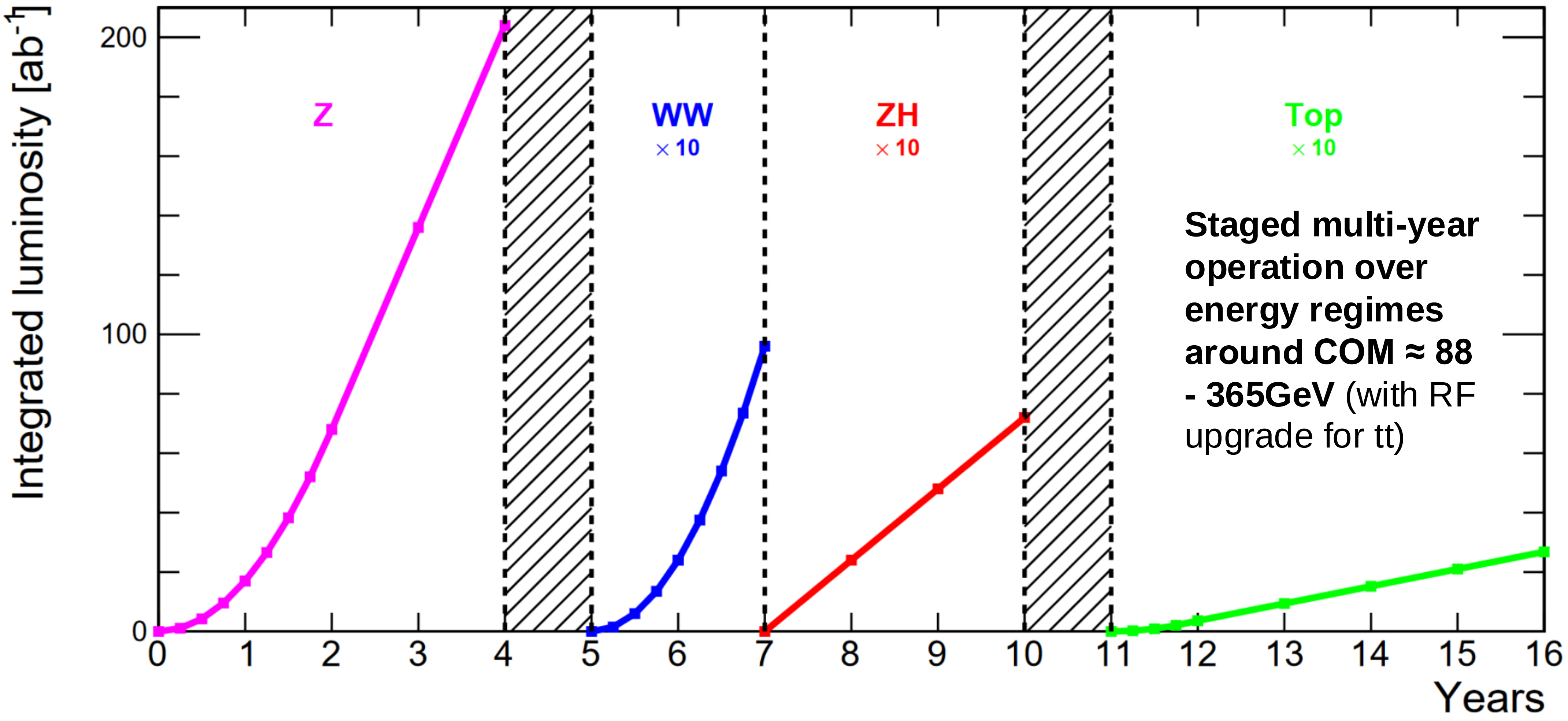


Both FCCee and CEPC are very mature projects

(FCCee = lowest risk classification in 2021 Snowmass, CEPC not reviewed)

- **FCC CDR published in 2018** https://fcc-cdr.web.cern.ch/
- **Detailed feasibility and implementation study ongoing**
  → mid term report released in Feb
  → final results of Feasibility Study expected in 2025
- **Viability as a design constraint**
  → design building on significant body of global experience from previous colliders and light source community to achieve ambitious but low risk baseline.
- **No purpose build demonstrators for FCCee/CEPC but significant cross-over work with e.g. superKEK, LightSources**
- **CEPC published CDR in 2018**
  http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
- **CEPC published TDR in Dec 2023**
  http://cepc.ihep.ac.cn/CEPC_tdr.pdf

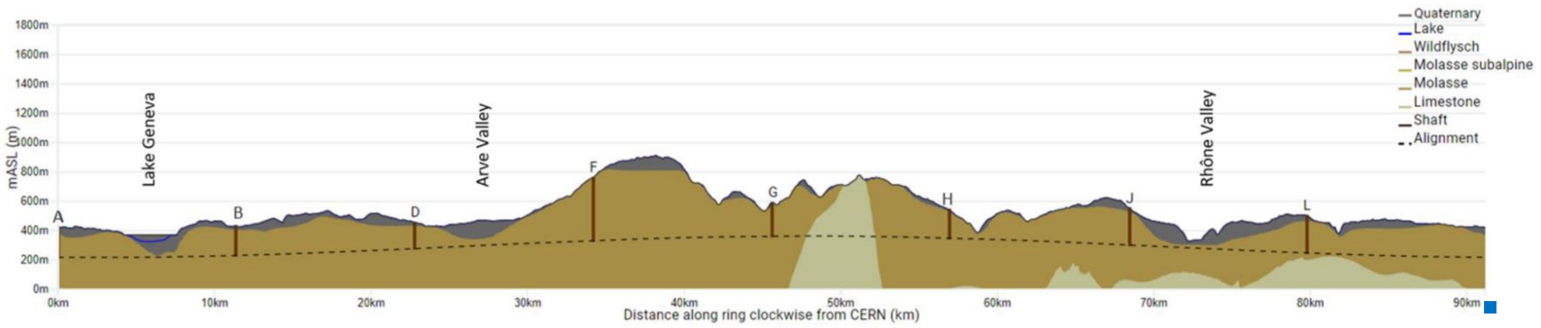
Likely operational scenario for FCCee

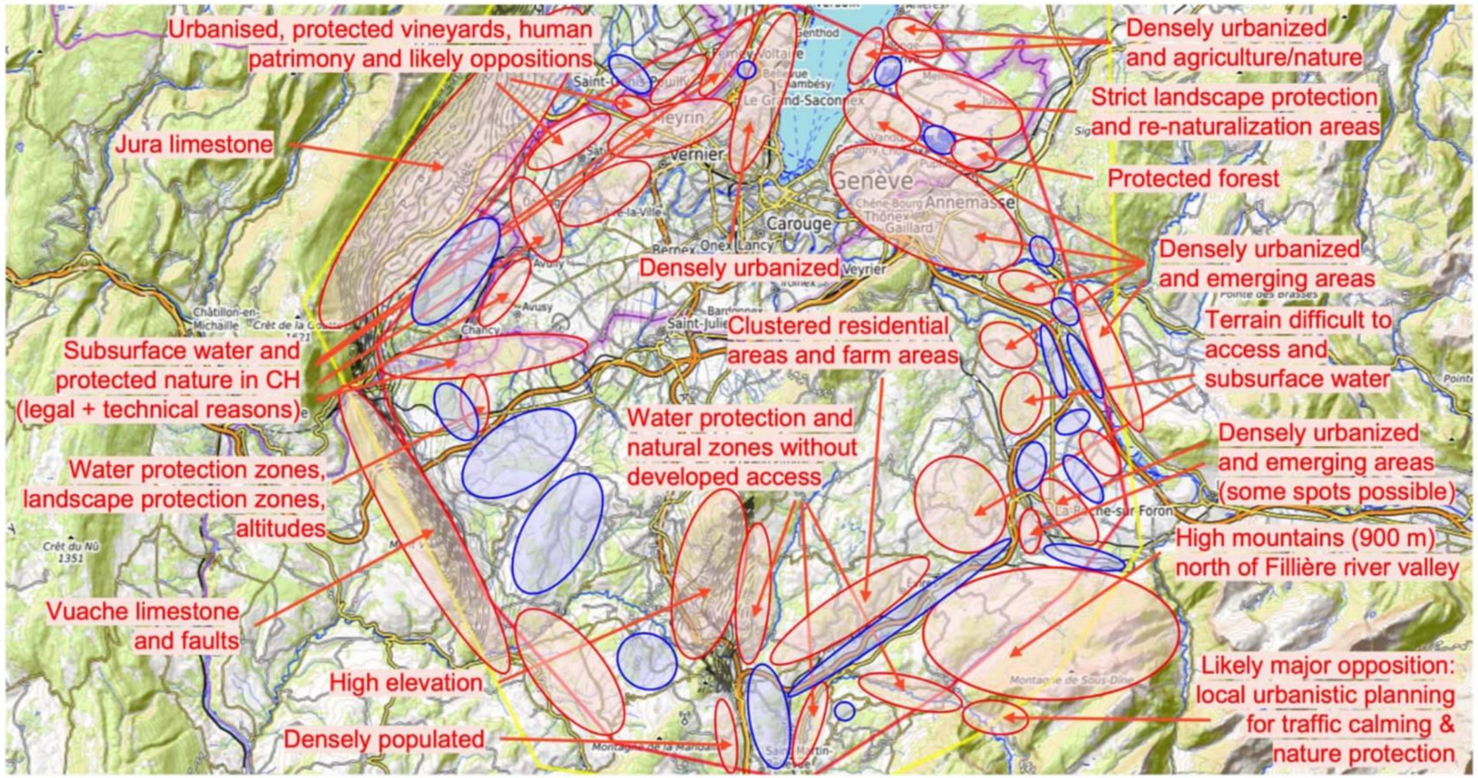


Staged multi-year operation over energy regimes around COM ≈ 88 - 365GeV (with RF upgrade for tt)

Why 91km for the FCC?

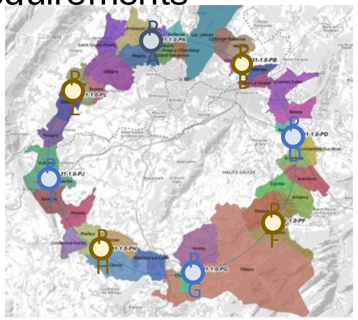
→ challenging to find suitable site without compromising performance





J.Gutleber Reference implementation scenario & work with the host states, FCC week 2023, https://indico.cern.ch/event/1202105/contributions/5423506/

- **Developing from existing CERN site allows FCCee and FCChh to utilize existing infrastructure: accelerator, electrical, cryogenic…**
  → substantial cost savings vs greenfield
  → one of the key issues with SSC project in US
- **Geology:**
  → geometry limited by nearby mountain ranges
  → avoid tunnelling too deep for access shafts
  → avoid extensive regions of e.g. limestone
  → remain in shallow region of lake Geneva
- **Social / legal / practical**
  → many protected areas where civil construction not permitted
  → highly urbanized areas
  → viability of access + new infrastructure
  → minimize new infrastructure requirements e.g. new road construction…



What does FCCee expect to achieve? (subject to ongoing optimization, precise numbers will vary)

Latest cost estimates put construction of the accelerator around 12.5 billion CHF (≈1/2 of that civil engineering) **+ 1.5 billion CHF for tt energy upgrade**

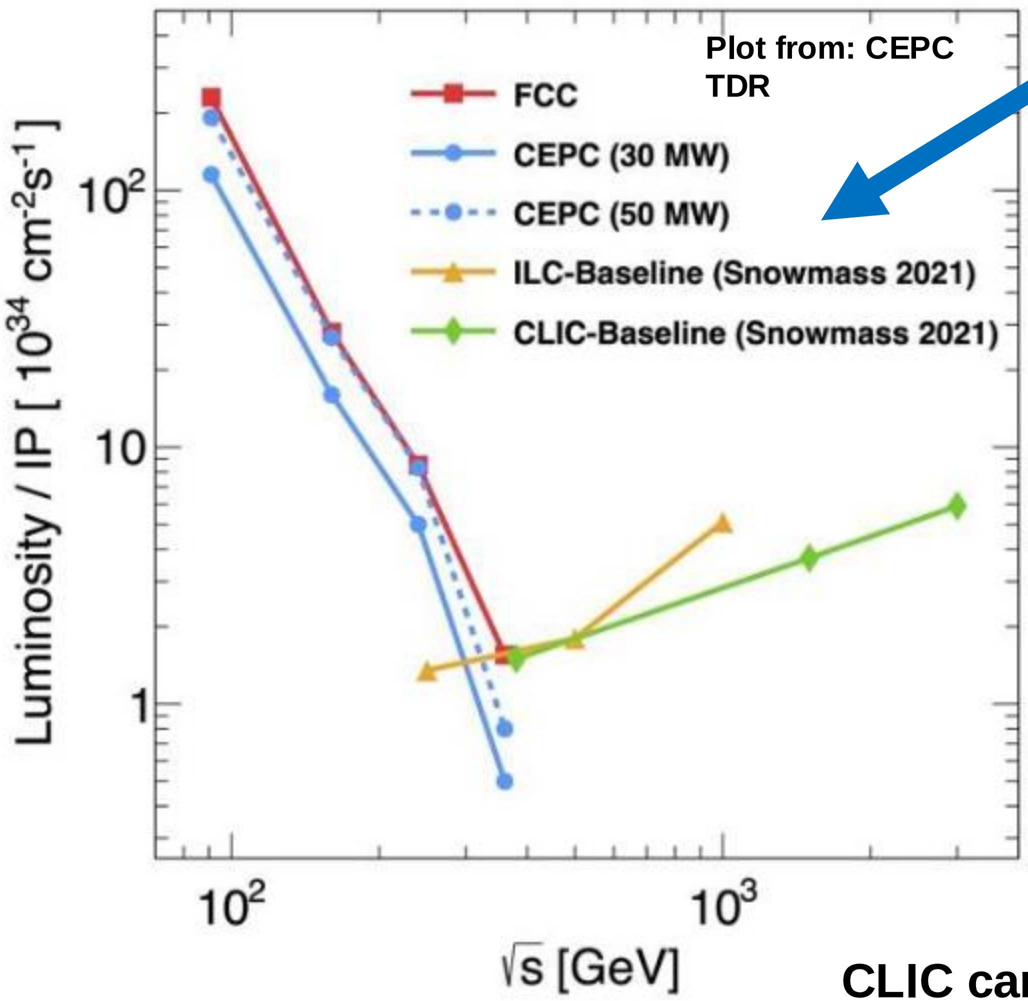
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

M.Benadikt, FCC week 2023 https://indico.cern.ch/event/1202105/contributions/5423504/attachments/2659109/4606291/230605_FCC-FS-Status_ap.pdf

Huge luminosity, particularly at lower energy e.g. : `TeraZ program' → produce 5e12 Z in 4year run – LEP every few minutes!

2 orders of magnitude more luminosity than LHC or any previous collider!

Some comparisons



FCC luminosity decreases with collision energy:

→ Trade-off between energy / luminosity / cost to replenish energy loss from synchrotron radiation

→ Operation plan is to reduce number of bunches in ring at higher energy to run at approximately constant total SR power

Luminosity per IP of FCCee breaks even with CLIC around the tt. → FCC has 4 IPs vs CLIC single IP (note, may move to 2 now)

Even per-IP get significantly higher FCCee luminosity at ZH!

FCCee may cost more to construct than CLIC (latest CLIC estimates are from 2018)

→ **but Luminosity-per-CHF expected to be better for FCCee**

CLIC can be upgraded to higher lepton collision energy than FCCee

Future colliders?

Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

Hadron synchrotron

- FCChh
- SPPS

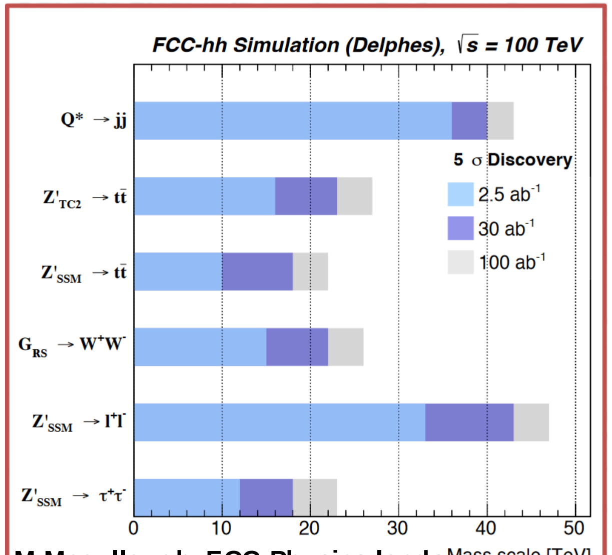
Muon Collider

Synchrotron colliders: a pathway to hadron-hadron collisions at the highest energies

Why a pp **circular collider?**

LHC has so far found no major hints of new physics. Don't know at what energy this might appear

Circular pp collider is natural upgrade path to FCCee: allows highest possible beam energy of all future proposals at high-luminosity



M.Mccullough, FCC Physics landscape, Chamonix'24

Circular pp collider gives broadest possible discovery potential with full integrated lumi
→ Up to 40TeV **scale reach**

Circular pp **machines can support most experiments of any high-energy option**
- **Up to 4 experiments**

Re-uses FCCee tunnel and infrastructure. Potential upgrade paths in same facility
→ 150TeV with higher magnets
→ Lepton hadron upgrade option

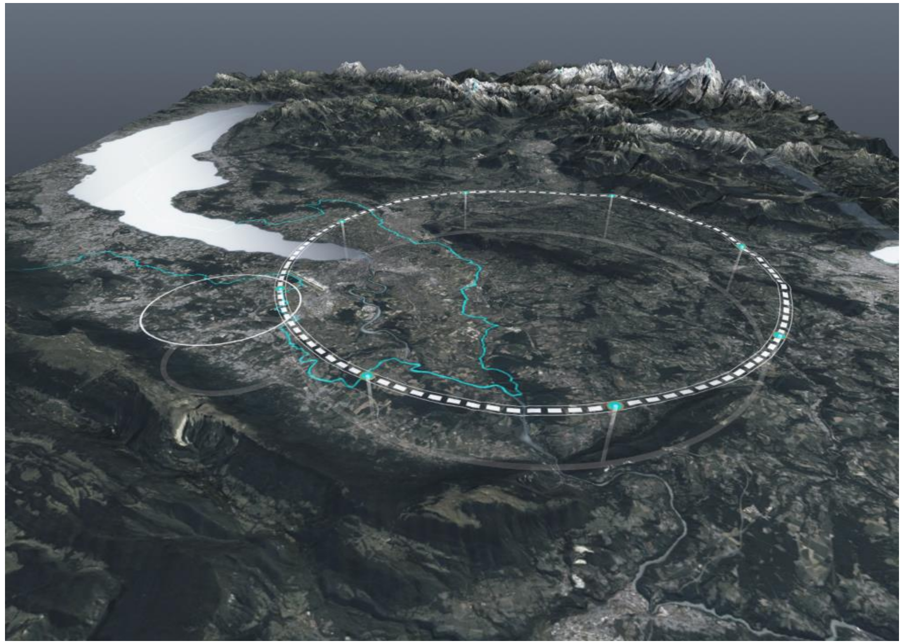
Diverse collider program option → not only proton, also heavy ions at high-energy

FCC CDR, https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

Synchrotron colliders: a pathway to hadron-hadron collisions at the highest energies

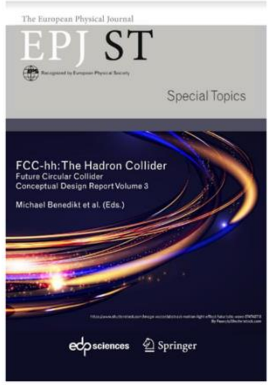
Two main proposals

Future Circular Collider (FCChh) @ CERN
→ FCCee upgrade



Super Protron Proton Collider (SppC) @ China
→ CEPC upgrade

FCChh and SppC are less mature projects than electron/positron equivalents



But also expected to begin operation on much longer timeline

→ plenty of time for R&D!

- **Project design and integration with lepton colliders are well documented**
  → e.g. FCC-hh CDR published in 2018 https://fcc-cdr.web.cern.ch/
- **No dedicated demonstrator facility required** → LHC as FCChh/SppC demonstrator
- **Collider and lattice designs well advanced and compatible with FCCee and FCChh performance goals**
- **Snowmass'21 exercise listed FCC-hh risk as ¾, probably two main considerations:**
  → FCChh project reliance on prior construction of FCCee
  → reflects that FCChh targets R&D for high-field superconducting magnets, beyond what is already achieved today

What does FCChh expect to achieve? (subject to ongoing optimization, precise numbers will vary)

	LHC	HL-LHC	FCC-hh initial	FCC-hh target
Physics performance and beam parameters				
Peak luminosity[1] (10^{34} cm^{-2}s^{-1})	1.0	5.0	5.0	<30.0
Optimum average integrated lumi/day (fb^{-1})	0.47	2.8	2.2	8
Assumed turnaround time (h)			5	4
Target turnaround time (h)			2	2
Peak no. of inelastic events/crossing	27	135 (lev)	171	1026
Total/inelastic cross section σ proton (mbarn)	111/85		153/108	
Luminous region RMS length (cm)			5.7	5.7
Distance IP to first quadrupole, L* (m)	23		40	40
Beam parameters				
Number of bunches n	2808		10 400	
Bunch spacing (ns)	25	25	25	
Bunch population $N(10^{11})$	1.15	2.2	1.0	
Nominal transverse normalised emittance (μm)	3.75	2.5	2.2	2.2
Number of IPs contributing to ΔQ	3	2	2+2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.011	0.03
Beam current (A)	0.584	1.12	0.5	
RMS bunch length[2] (cm)	7.55		8	
IP beta function (m)	0.55	0.15 (min)	1.1	0.3
RMS IP spot size (μm)	16.7	7.1 (min)	6.8	3.5
Full crossing angle (μrad)	285	590	104	200[3]

Lifetime target of 30ab^{-1} !

Hard to precisely estimate cost of a project so far from start date, while key R&D is ongoing…

FCChh CDR (2018) estimated cost of upgrade from FCCee to FCChh as ~$\mathbf{17bCHF}$

What R&D is needed for FCChh?
→ high-field superconducting magnets!

FCChh will also be first pp collider where synchrotron radiation plays a significant role

Both Nb3Sn and HTS options face practical challenges for magnet construction

- Nb3Sn more brittle than NbTi – coils need to handle stress and forces generated in construction / operation
- HTS cable geometries can differ from historical SC cables used in accelerators. Needs novel designs!
- **R&D on coil material goes hand-in-hand with R&D on magnet design and incorporation**
- **Operation in 2070s gives plenty of time for technologies to mature and industrialize**

- **FCC would be large scale procurement of such technologies – clear potential for societal cross-over**

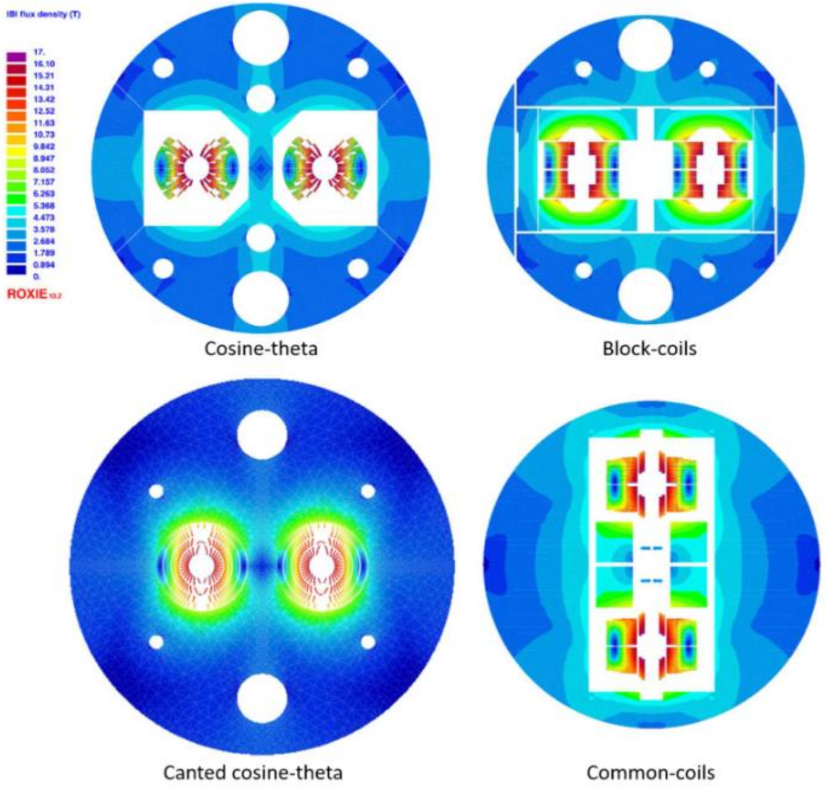


Fig. 3.7. Electromagnetic cross sections of the 16 T dipole design variants.

FCChh will use the existing LHC injector chain as an FCC injector
→ various configuration being studied

Future colliders?

Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

Hadron synchrotron

- FCChh
- SPPS

Muon Collider

Muon colliders: a new approach to HEP accelerators, and a pathway to lepton-lepton collisions at the highest energies

Why a μμ collider?

electron/positron colliders are limited at high-energy by SR power and beamstrahlung

SR emission scales strongly with particle mass: a muon collider at the 10TeV scale would not be limited by SR, allowing precision lepton-lepton measurements at high-energy

Beamstrahlung emission scales strongly with particle mass. Even at high-energy muon-muon collisions would not suffer from beamstrahlung induced energy spread. Potential for fine resolution measurements of particle width if low momentum spread beams can be created

Muons collide at the beam energy, unlike parton collisions in HH machines. Could reach comparable energy scale at lower beam-energy / smaller machine

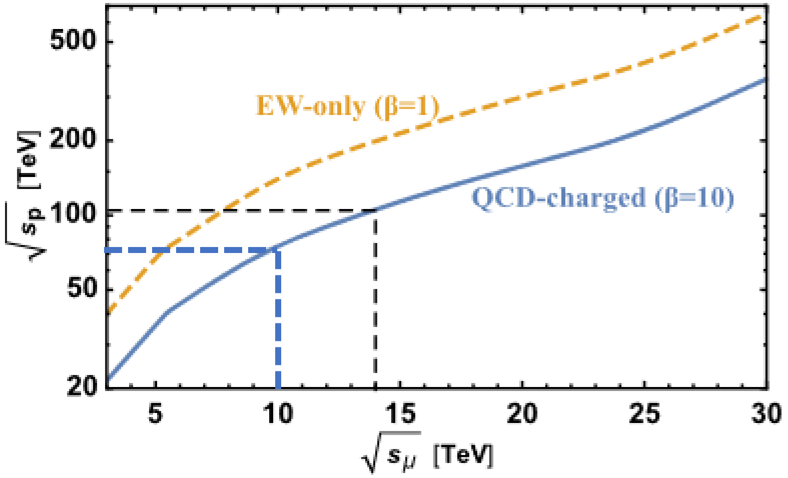
Muon colliders gained significant attention in recent months following US Particle Physics Project Prioritization Panel (P5)

Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design

Why 10TeV?

- **Fits inside the existing Fermilab site!**
- **10TeV muon collisions could approach comparable energy scale as 100TeV pp machine (assuming equivalent collider performance)**



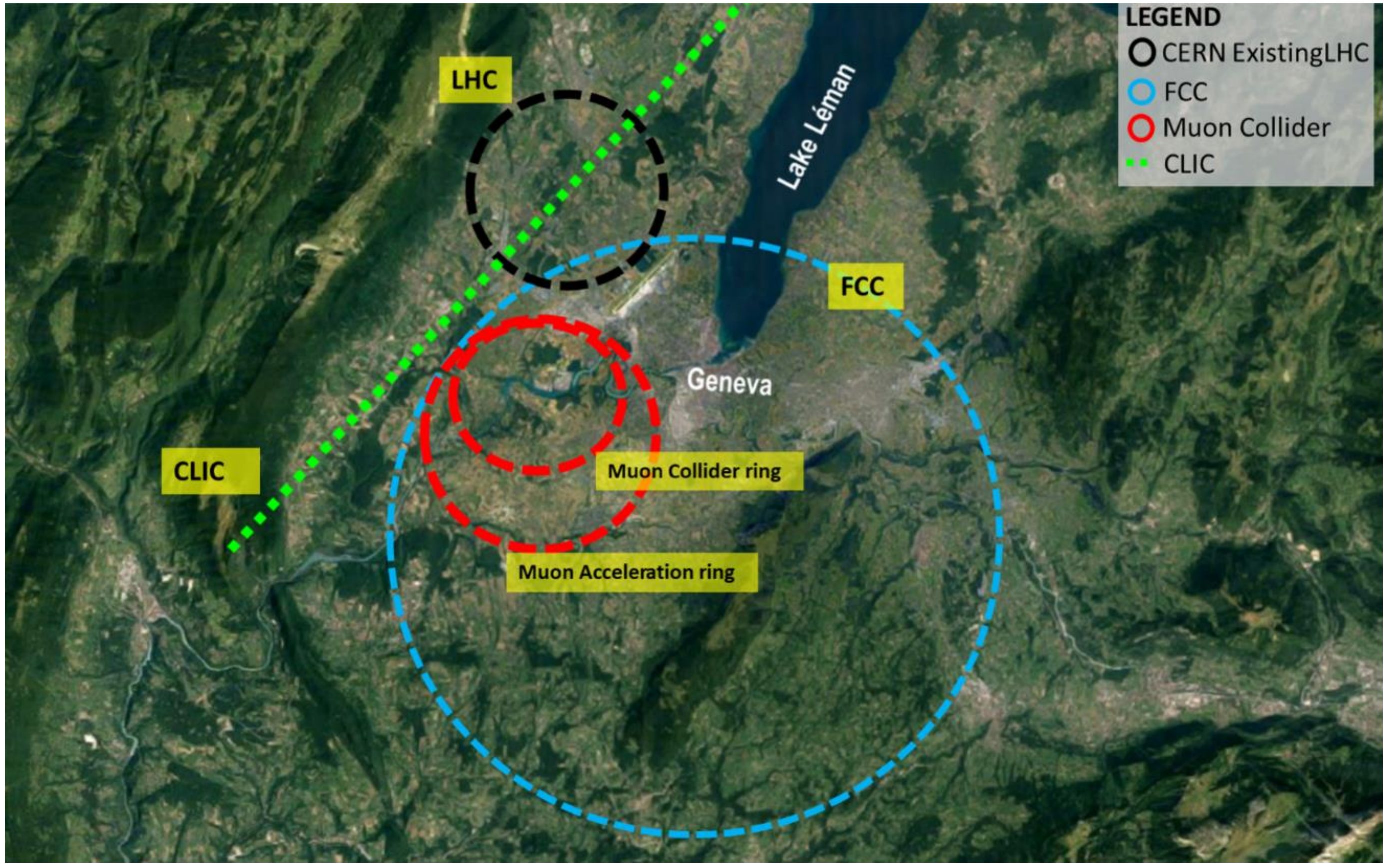
Towards a muon collider
https://link.springer.com/article/10.1140/epjc/s10052-023-11889-x

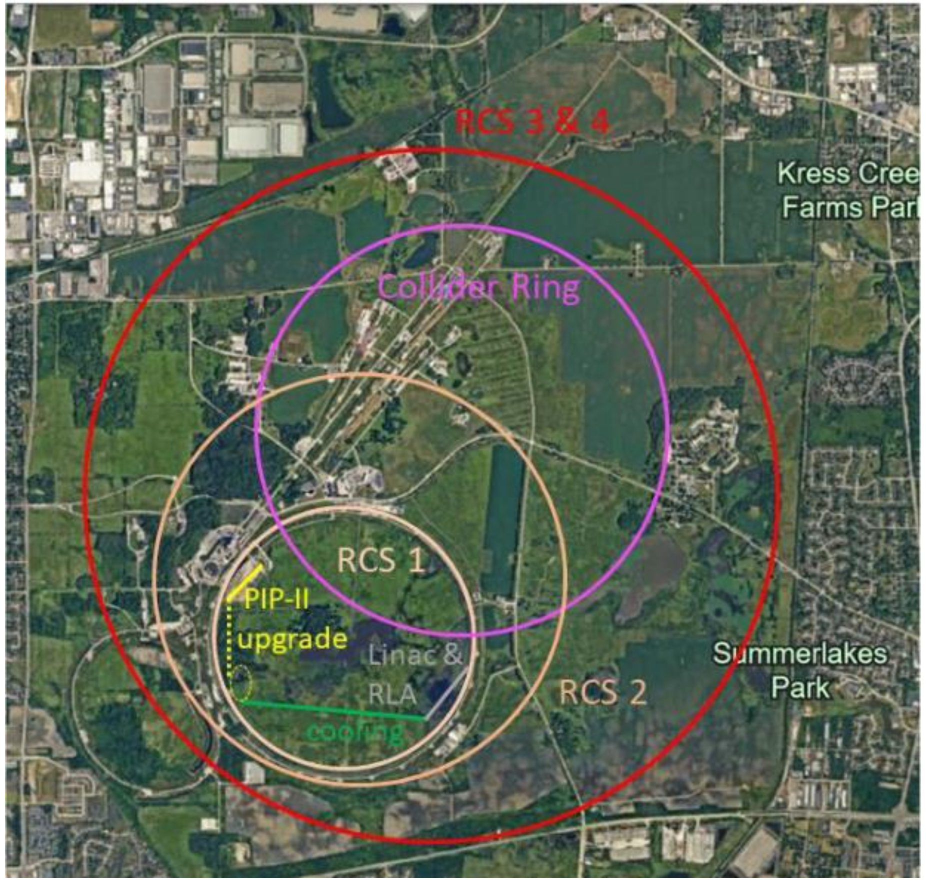
No definitive muon collider proposals yet, but large collaborations

International MUON Collider Collaboration

https://muoncollider.web.cern.ch/

In general designs expected to support 1 or 2 HEP experiments at ≈10TeV



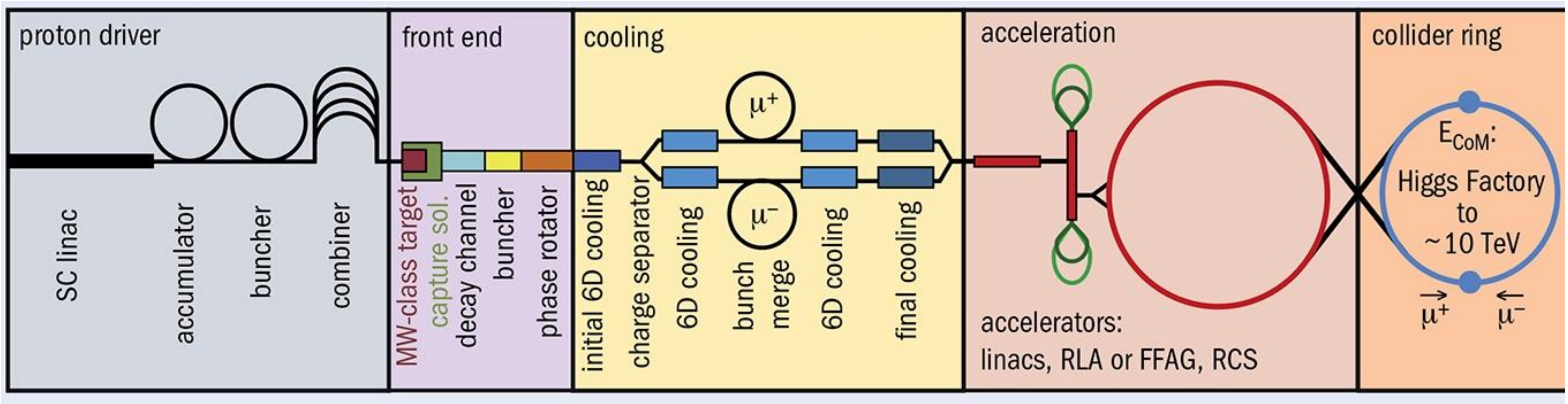


Muon collider offers some very exciting opportunities!
→ But is also the least mature of the main future project proposals

- No Conceptual design report published: however, there is a nice review article prepared by IMC which does good job of outlining baseline options
- No muon collider demonstrator facility exists yet, likely some will be needed and R&D towards this was one of P5 key recommendations, **aiming to determine the feasibility of a muon collider**
- Snowmass 2021 exercise ranked Muon collider on any energy scale as 3 / 4 risk. Comparable to FCChh. → likely reflecting that multiple core technologies will require some significant R&D to be ready
- Lots of active research, and lots of synergy with other projects

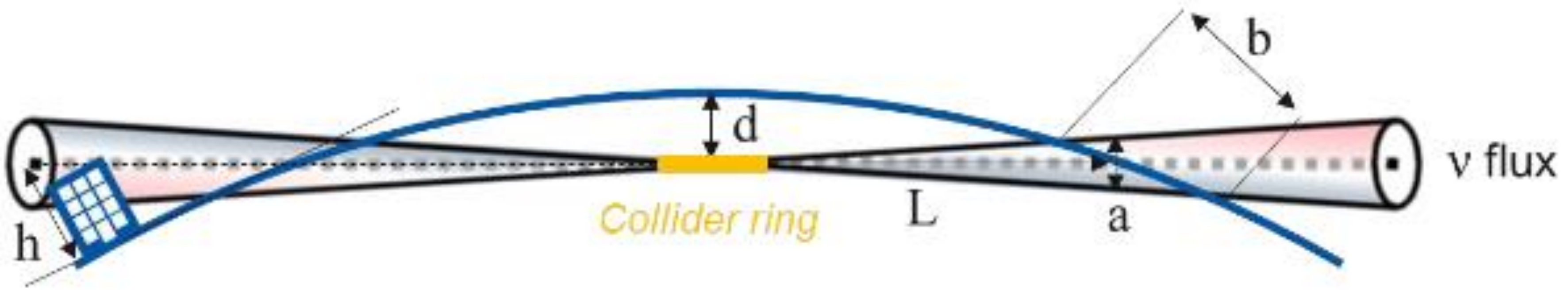
https://indico.cern.ch/event/1325963/overview

Towards a muon collider https://link.springer.com/article/10.1140/epjc/s10052-023-11889-x


proton driver
front end
cooling
acceleration
collider ring
SC linac
accumulator
buncher
combiner
MW-class target
capture sol.
decay channel
buncher
phase rotator
initial 6D cooling
charge separator
6D cooling
μ+
μ−
bunch merge
6D cooling
final cooling
accelerators:
linacs, RLA or FFAG, RCS
E_CoM:
Higgs Factory
to
~10 TeV
μ+
μ−

Challenges -> Opportunities for innovation

- **Muon beams are created indirectly from decay of pions**
- **Muon beams need to be cooled to small emittance in order to generate decent luminosity**
- **Use ionization cooling to rapidly cool muon beams: demonstrated by MICE collaboration**
- **Muons have a short lifetime even at 10TeV (≈0.1s)**
  - **Need to be accelerated to top energy in as short a time as possible**
  - **Decay while stored in accelerator**
  - **Decay products induce a heat load on the magnet cryo** (500W/m/beam)
  - **Need to include significant shielding to magnet design to limit heat load and radiation damage to magnets**
  - **Neutrinos produced in the decay escape the collider tunnel and generate radiation does at surface**
    - **Require negligible impact on public (10 μSv/year)**



Muon colliders exciting proposal with lots of potential advantages, but also significant R&D challenges which need to be overcome.

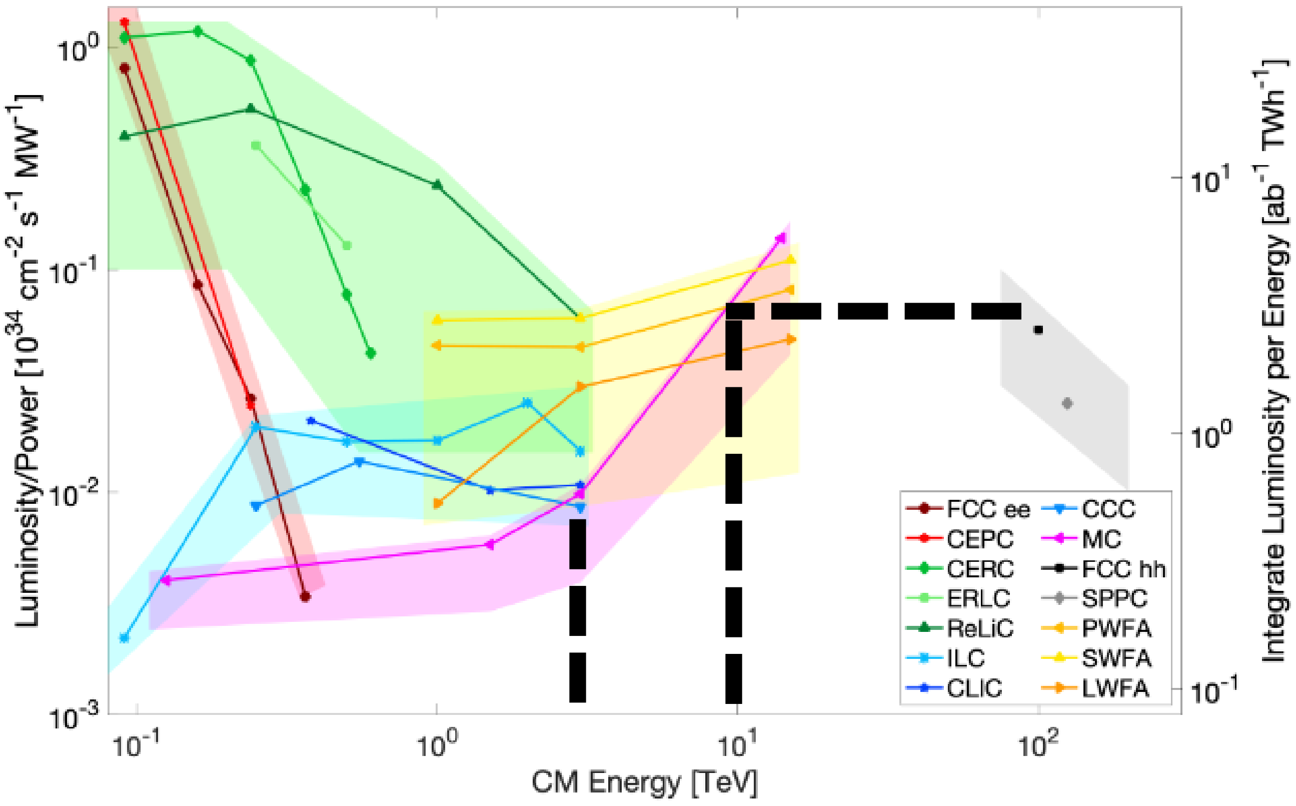
Many of these challenges are synergistic with other projects or very valuable in their own right! High-field magnets, rapid cycling magnets, intense muon sources…

Hard to estimate cost and power consumption for project at such and early stage. Snowmass included some estimates

At 10TeV Luminosity per power consumption looks similar for FCChh and MuColl

At 3TeV Luminsoity / power consumption similar between MuColl and CLIC

At lower energy muons decay too fast to achieve good Lumi/power



2023, JINST 18 P0501 *On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force*
https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

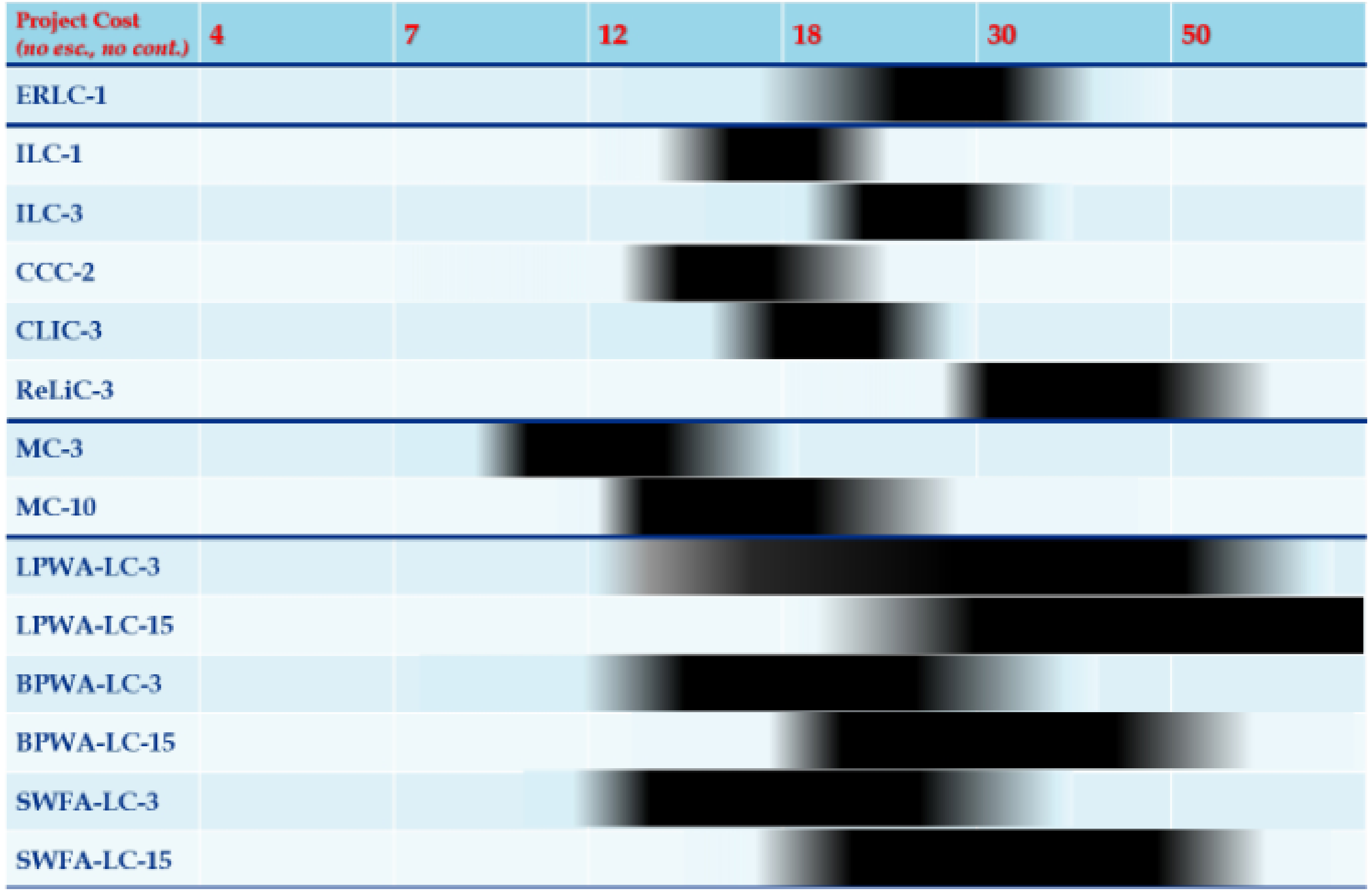
Muon colliders exciting proposal with lots of potential advantages, but also significant R&D challenges which need to be overcome.

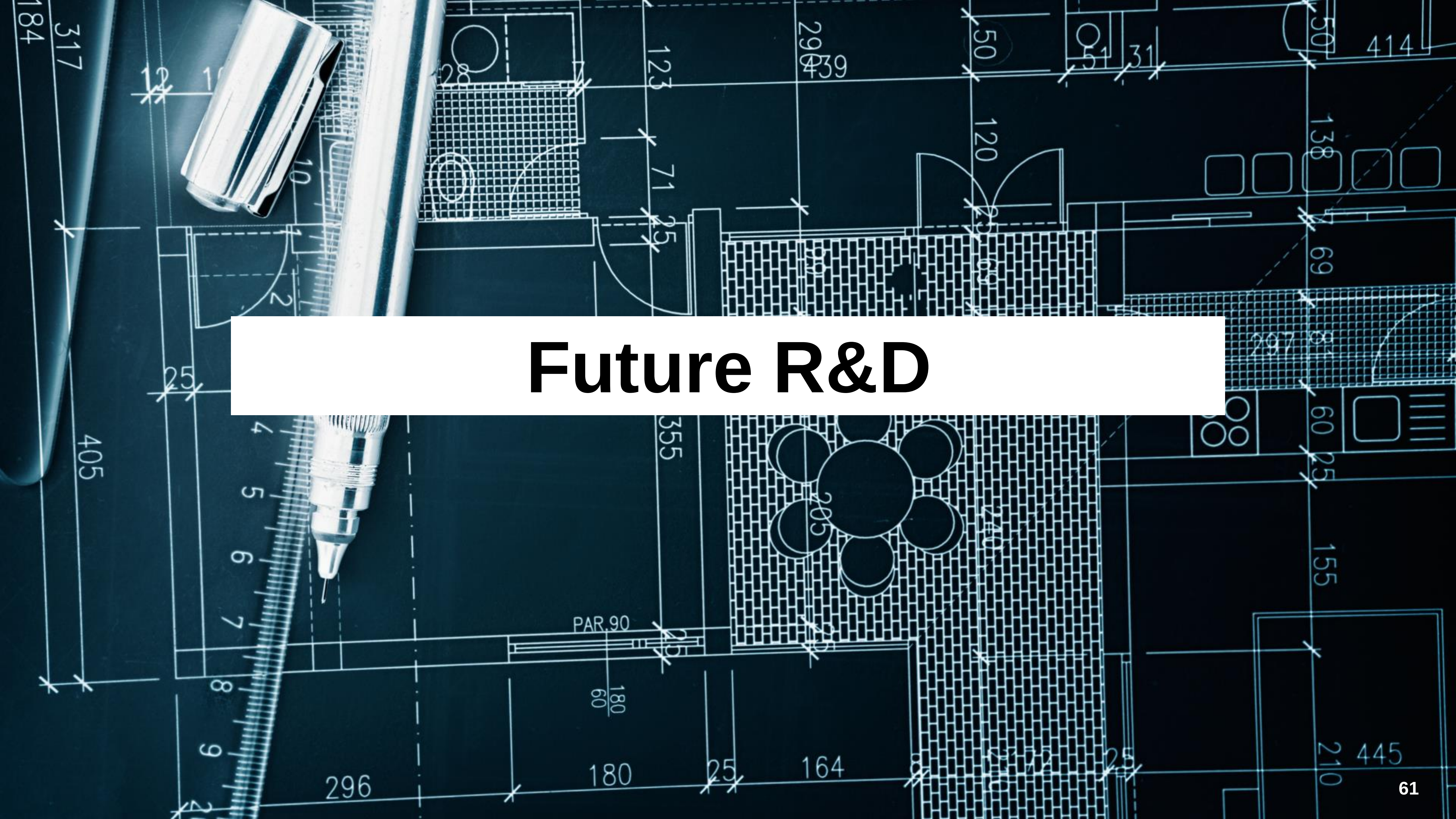
Many of these challenges are synergistic with other projects or very valuable in their own right! High-field magnets, rapid cycling magnets, intense muon sources…

On greenfield site 10TeV muon collider would require

35km accelerator + 10km collider + ~km low energy rings

One possibility could be to re-use LHC tunnel, but viability not yet studied in detail by Muon collaboration

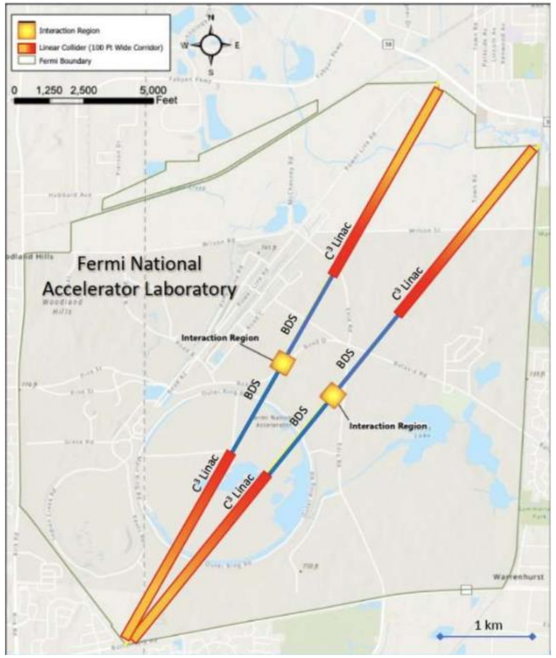




Future R&D

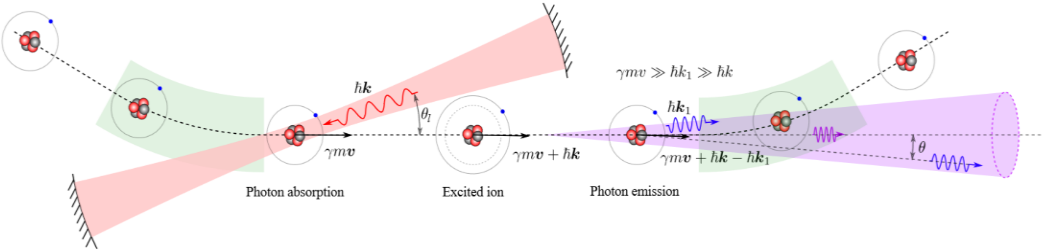
Cooled Copper Collider (C^3)

Can improve the performance of high-frequency normal conducting cavities (like CLIC) by chilling the copper
→ Allows to reach higher accelerating gradients: e.g. C3 at 120MV/m vs CLIC at 100MV/m.
→ Can make Higgs factory in more compact tunnel able to fit on FermiLab site!

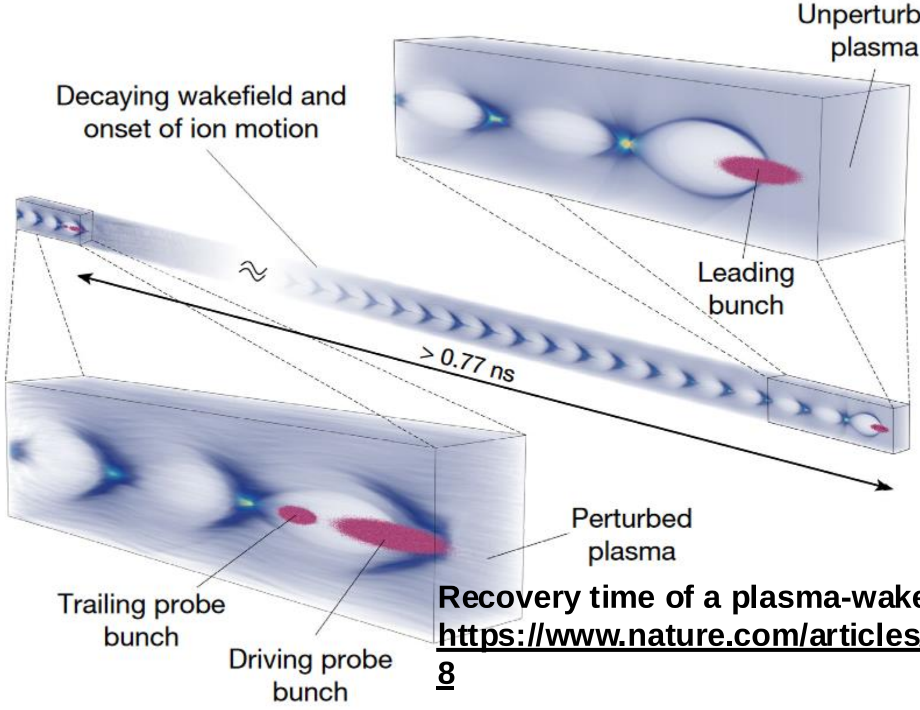


Gamma factory

Create intense beam of polarized high-energy photons using partially stripped ions in LHC or FCChh



Plasma Wakefield acceleration (PWA)

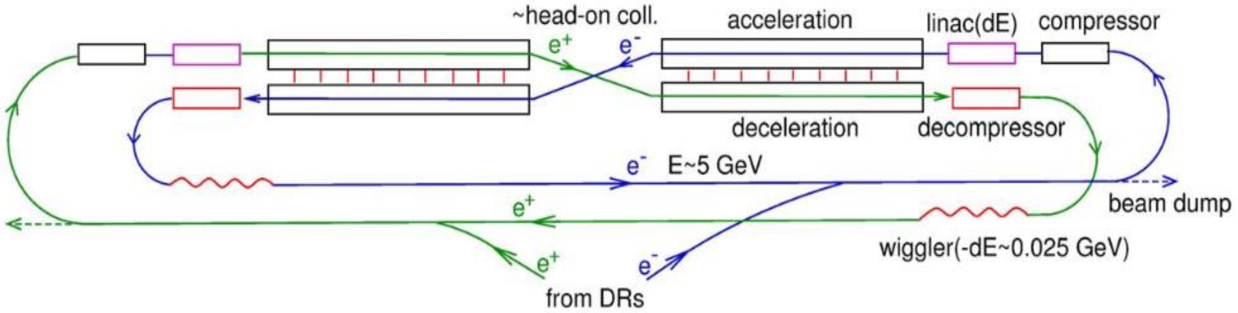


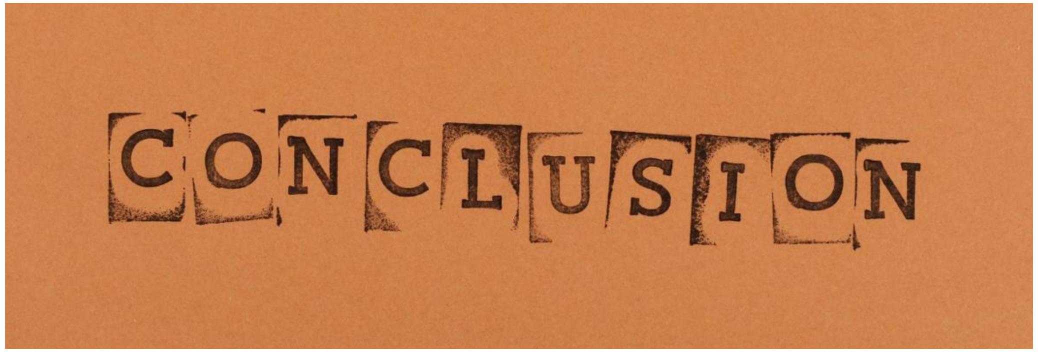
Recovery time of a plasma-wakefield accelerator
https://www.nature.com/articles/s41586-021-04348-8

Energy-Recovering LINAC collider

Power to accelerate ingoing bunch provided by deceleration of outgoing bunch from the IP

Could hypothetically significantly improve luminosity/power of FCC and CLIC/ILC designs





We have a 'future collider' coming up soon – the HL-LHC!

Lots of truly exciting options on the table for future collider programs in Europe and globally!

Several leading candidates for the next big European project, all involve lots of exciting R&D with clear societal benefit. Lots of promising future technologies to be explored!

Any choice will be a trade-off between luminosity, energy, upgradeability, running cost, construction cost, and risk.

Discussions are on-going, so now is the time to be getting involved.

thank you!

With thanks to E. Maclean for contributions to these slides

Backup

Here’s one I prepared earlier