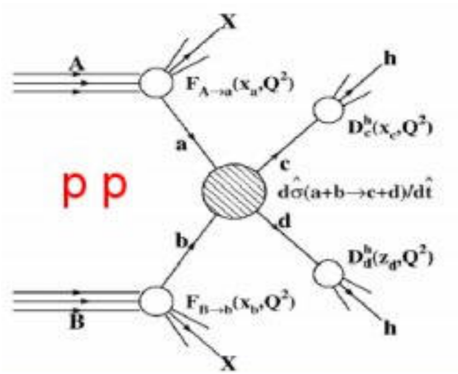
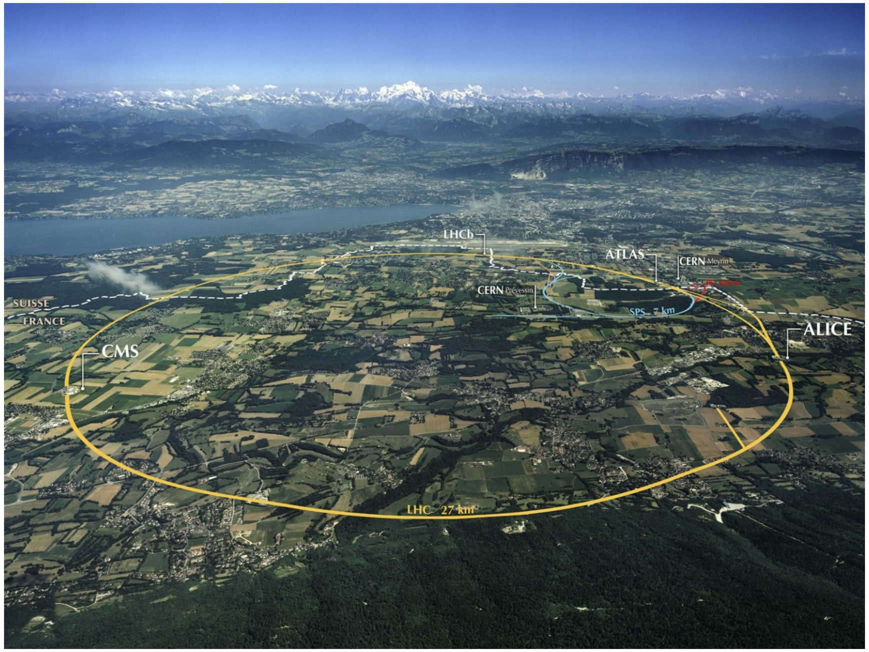
Muon Collider

Daniel Schulte for the International Muon Collider Collaboration

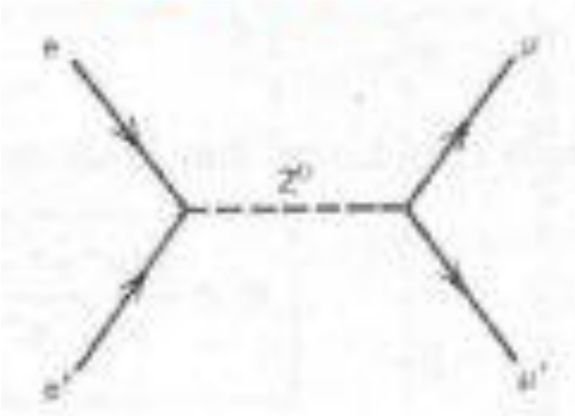
Collider Choices

- **Hadron collisions**: compound particles
  - Example **LHC** with 14 TeV in proton-proton collisions
  - Protons are mix of quarks, anti-quarks and gluons
  - Very complex to extract physics
  - But can reach high energies

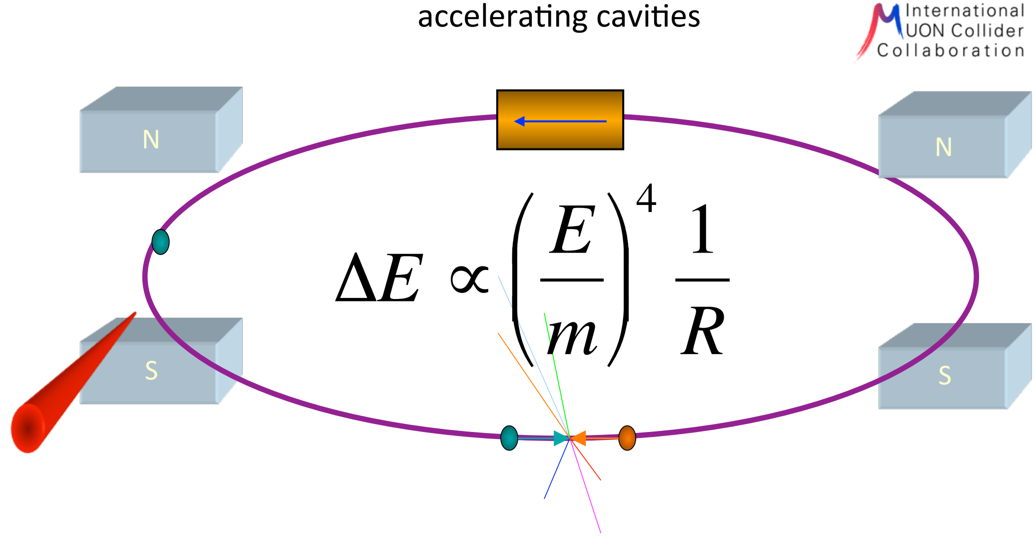




- **Lepton collisions**: elementary particles
  - **LEP** reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - Lepton collisions $\Rightarrow$ precision measurements
  - Hard to reach high energies



Energy Limit

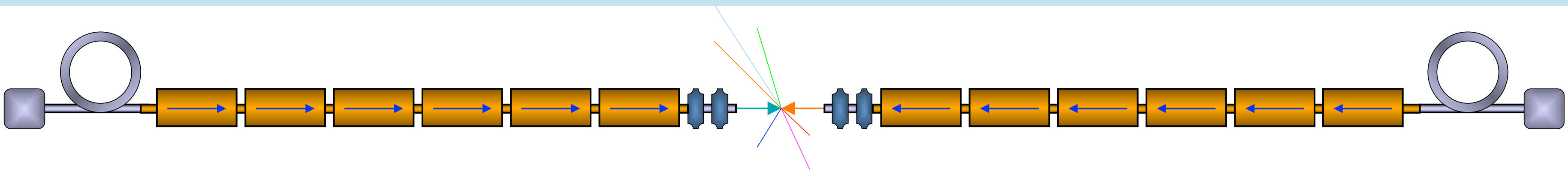


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation

Hence **proton rings** are energy frontier
Magnet limited

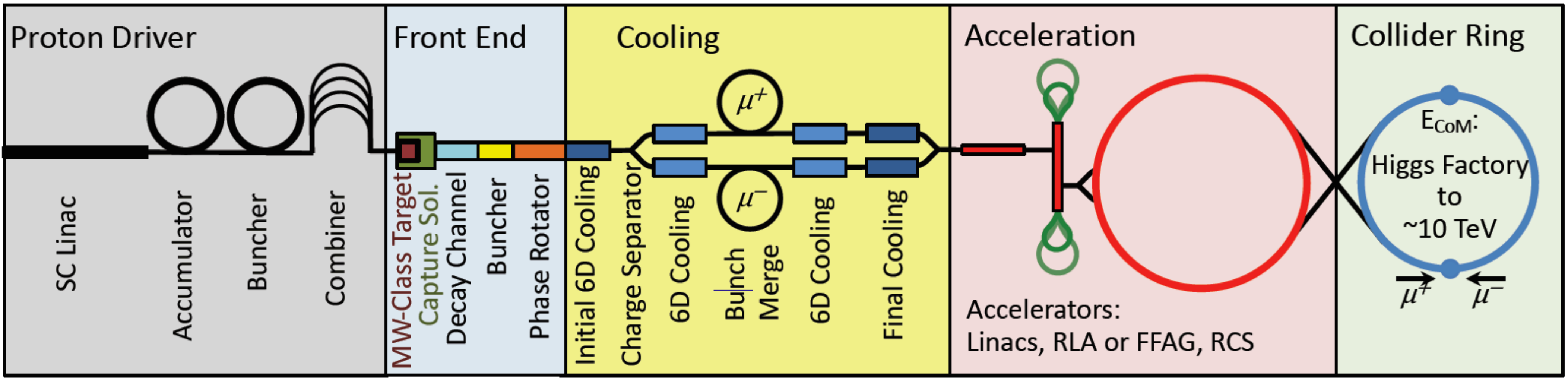
Electron-positron linear colliders avoid synchrotron radiation, but are **single pass**
Typically cost proportional to energy and power proportional to luminosity, **RF limited**



Novel approach: **muon collider**
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs (increases with energy)

Therefore part of European Accelerator R&D Roadmap
Magnet limited, but need O(0.1 x proton energy)

Proton-driven Muon Collider Concept



Produce short, intense proton bunch

Protons in target produce pions which decay into muons muons are captured

Muons are cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$

International Muon Collider Collaboration

Objective:

In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

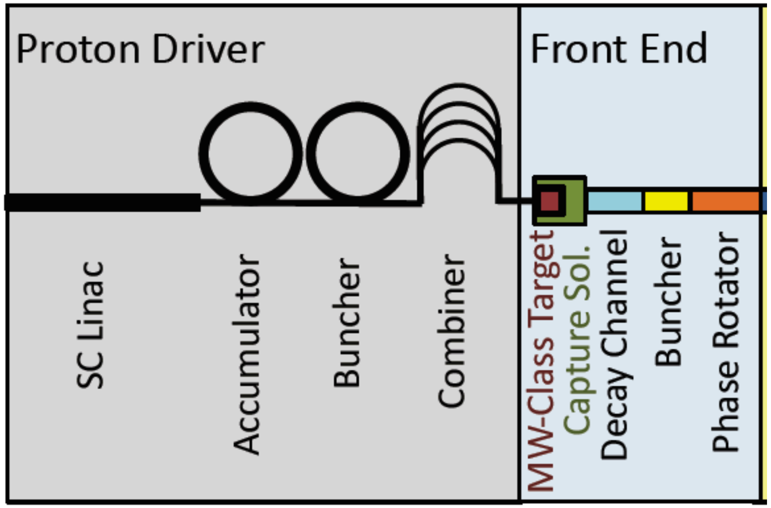
It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Scope:

- Focus on two energy ranges:
  - **10+ TeV**, as long-term direction, **the reason to chose muon colliders**
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Part of the Accelerator R&D Roadmap that has been approved by Council
Funding still to be developed

Muon Production



2 MW proton beam

5 bunches per second
400 kJ each

Protons produce (many) pions in the target

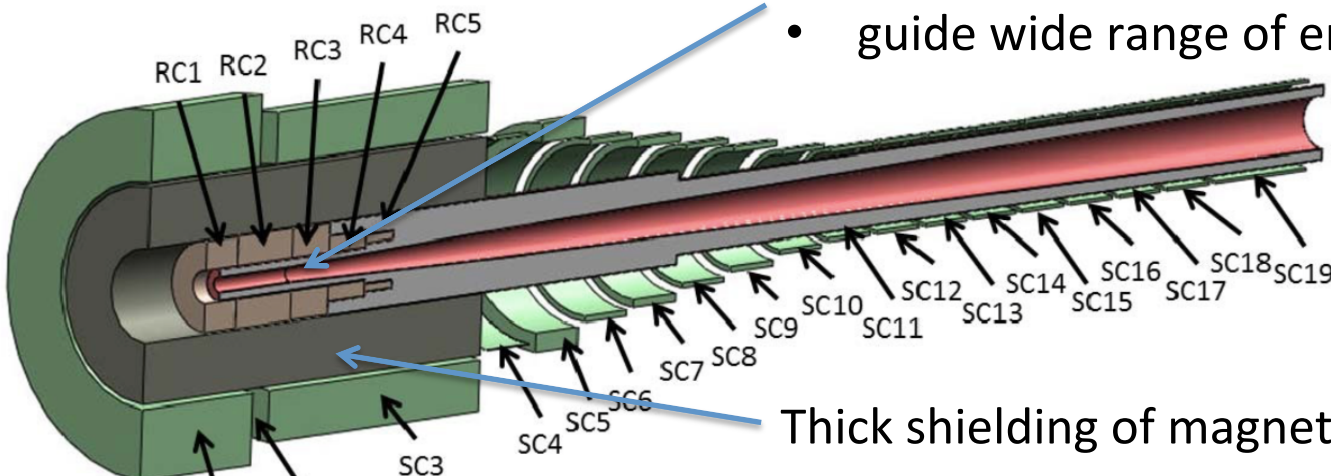
$$p + N \rightarrow \pi + X$$

Charged pions decay to muns

$$\pi^{+} \rightarrow \mu^{+} + \nu$$
$$\pi^{-} \rightarrow \mu^{-} + \nu$$

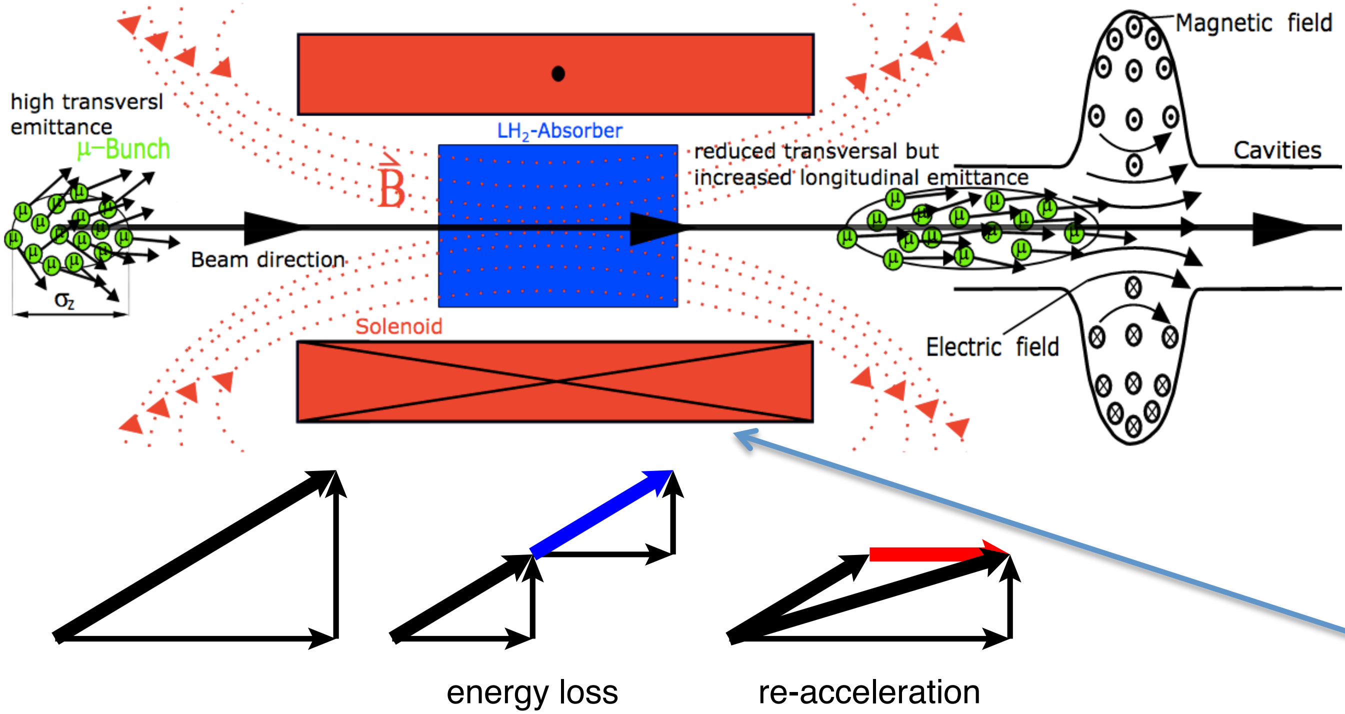
Collect and bunch them

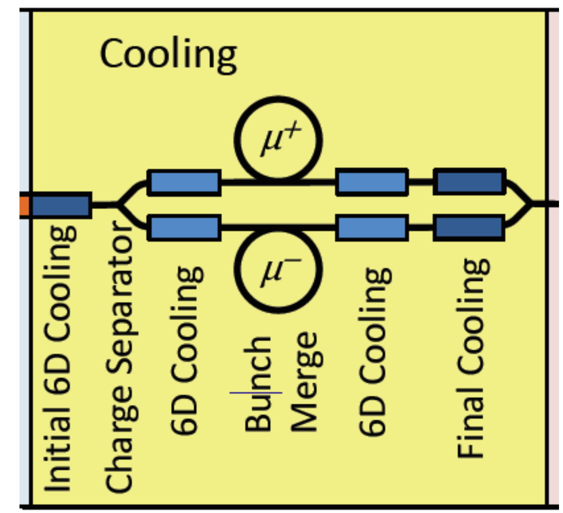
Target is in 20 T solenoid
- keeps pion phase space small
- guide wide range of energies



Thick shielding of magnet

Cooling Concept





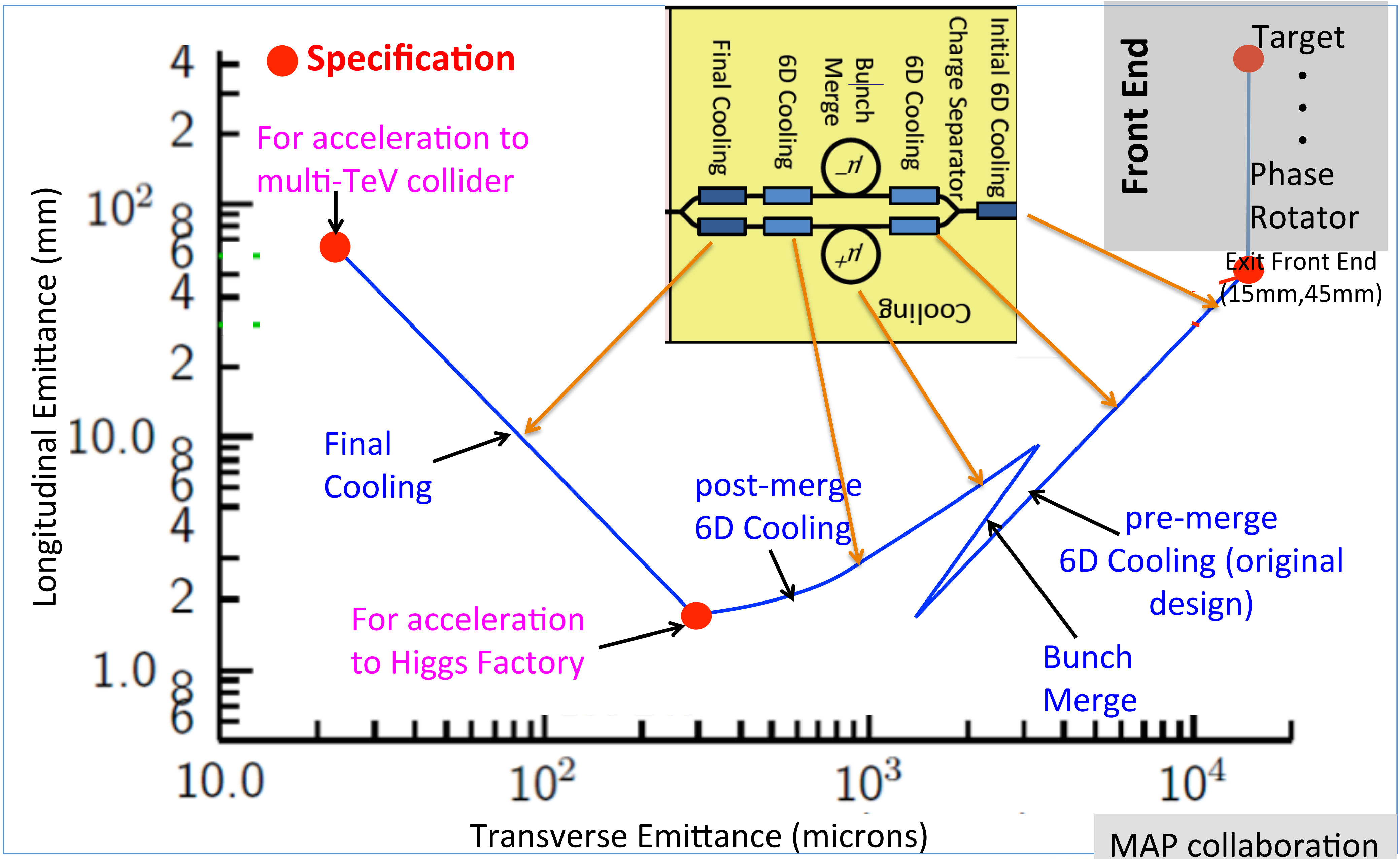
High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

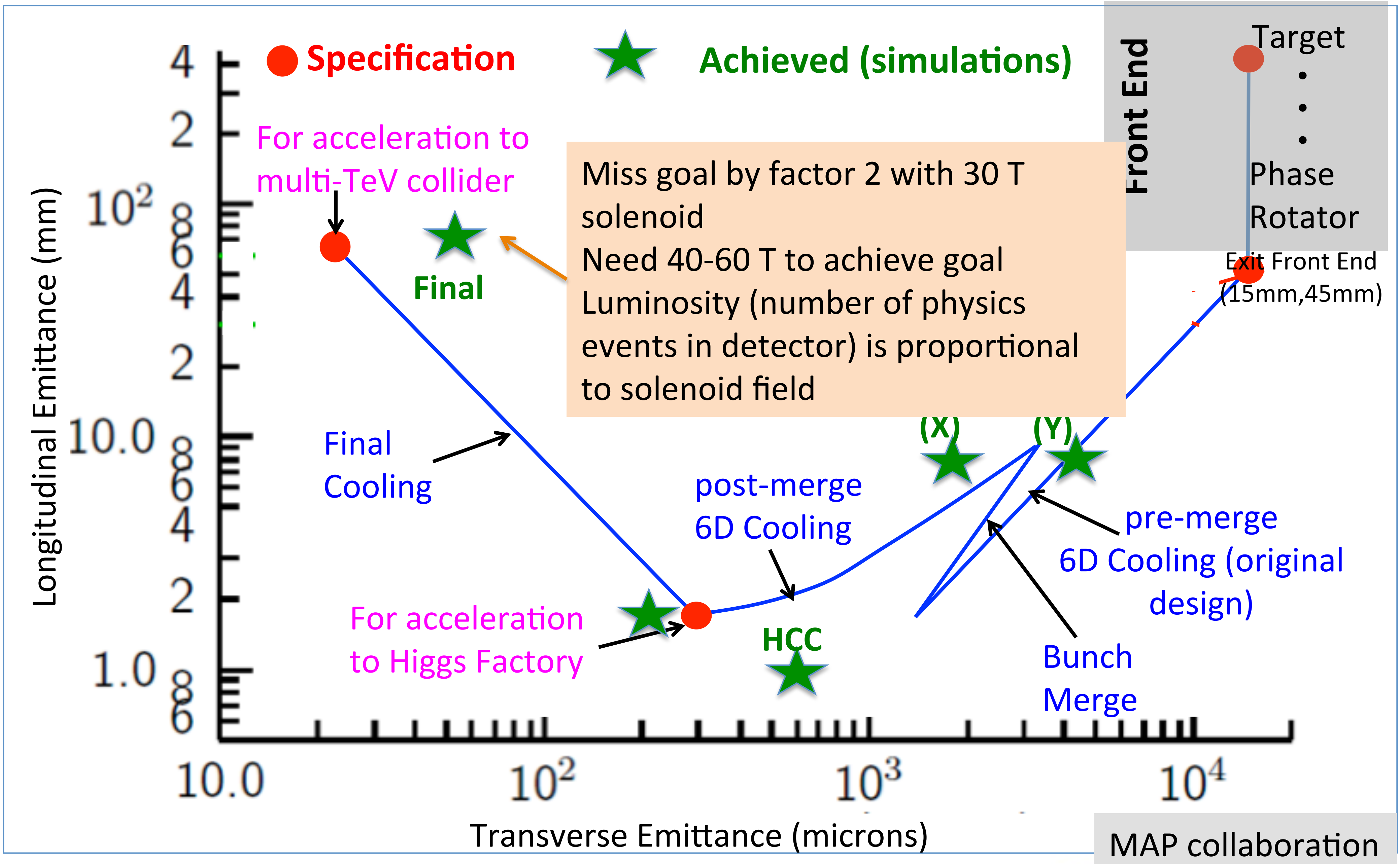
Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = \boxed{-\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E}} \boxed{+\frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}}$$

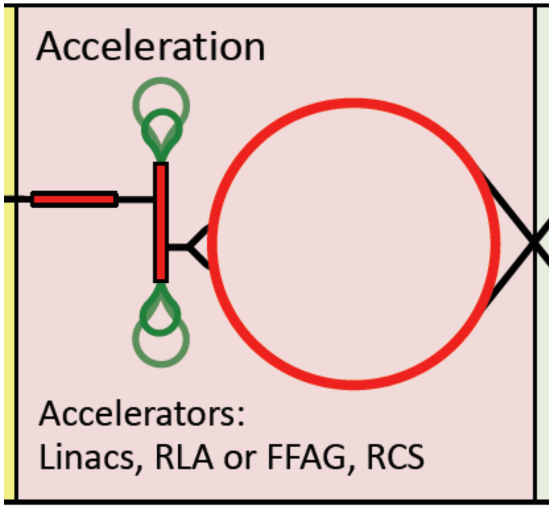
Cooling: The Emittance Path



Cooling: The Emittance Path



Acceleration

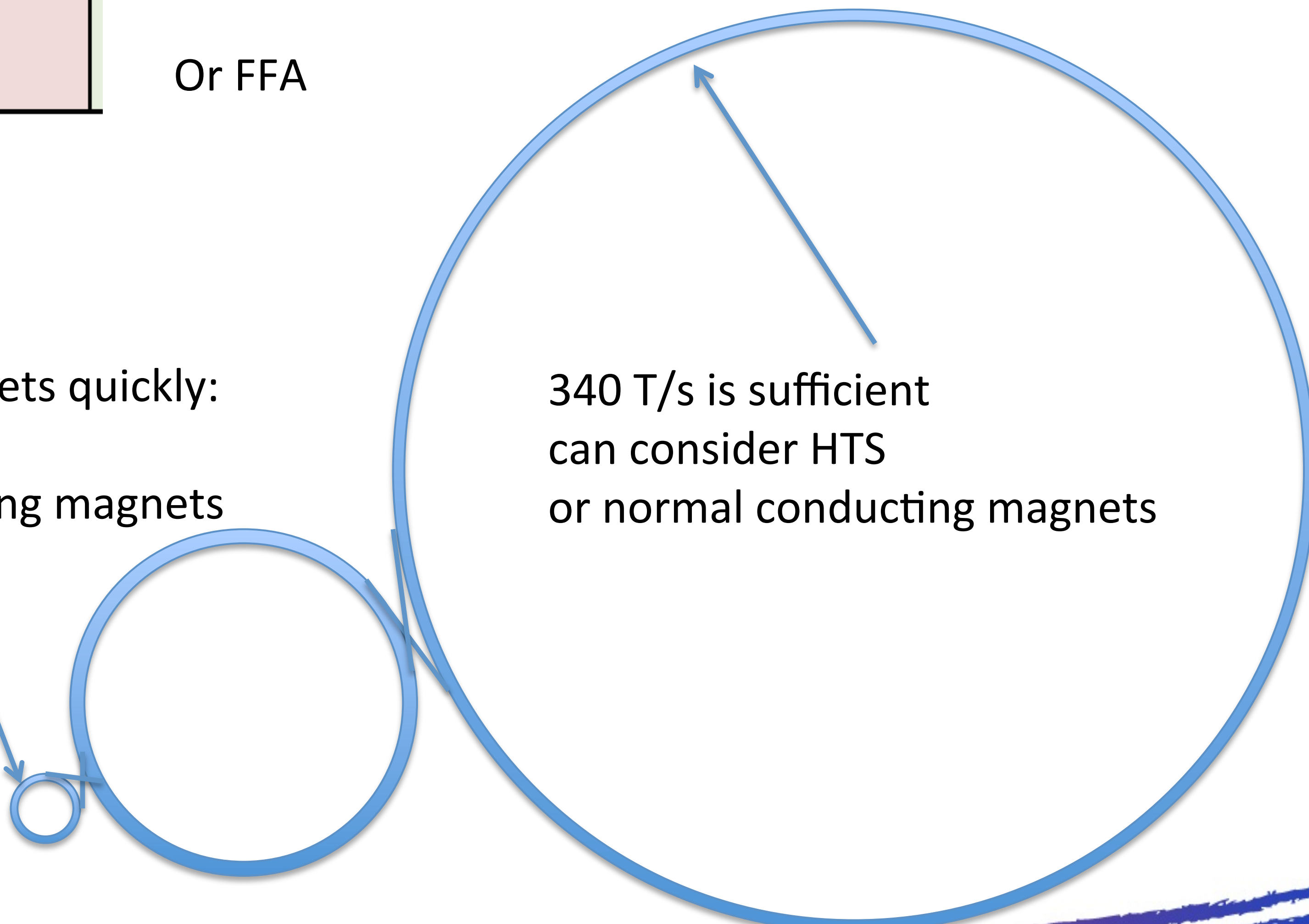


Sequence of
- linac, two recirculating linacs
- 2-4 rings (baseline: pulsed synchrotron, alternative: FFA)

Pulsed synchrotron: NC magnets ramping from -2 to 2 T
or HTS with larger range if possible

Or FFA

Need to ramp magnets quickly:
- ideally 10 kT/s
- normal-conducting magnets



340 T/s is sufficient
can consider HTS
or normal conducting magnets

Timeline

Initial design phase 2021-2025

Establish whether investment into full CDR and demonstrator is scientifically justified.

Provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.

Identify an R&D path toward the collider, considering High-field Magnet and RF Roadmap results.

Conceptual design phase 2026-

Develop concept and technology to be ready to commit

Verify performance of all key components. In particular, build cooling cell string and test with beam. Build and test magnet models and RF components. Start building industrial base for production. Develop site and infrastructure. Determine cost, power, construction schedule. Optimise design.

Technical design phase

Prepare approval and project implementation

Prepare industrial production of components, e.g. build magnet prototypes and pre-series with industry. Prepare site for construction. Refine cost, power and construction schedule.

Strategy decision (2026)

Define performance goals and timeline for muon collider

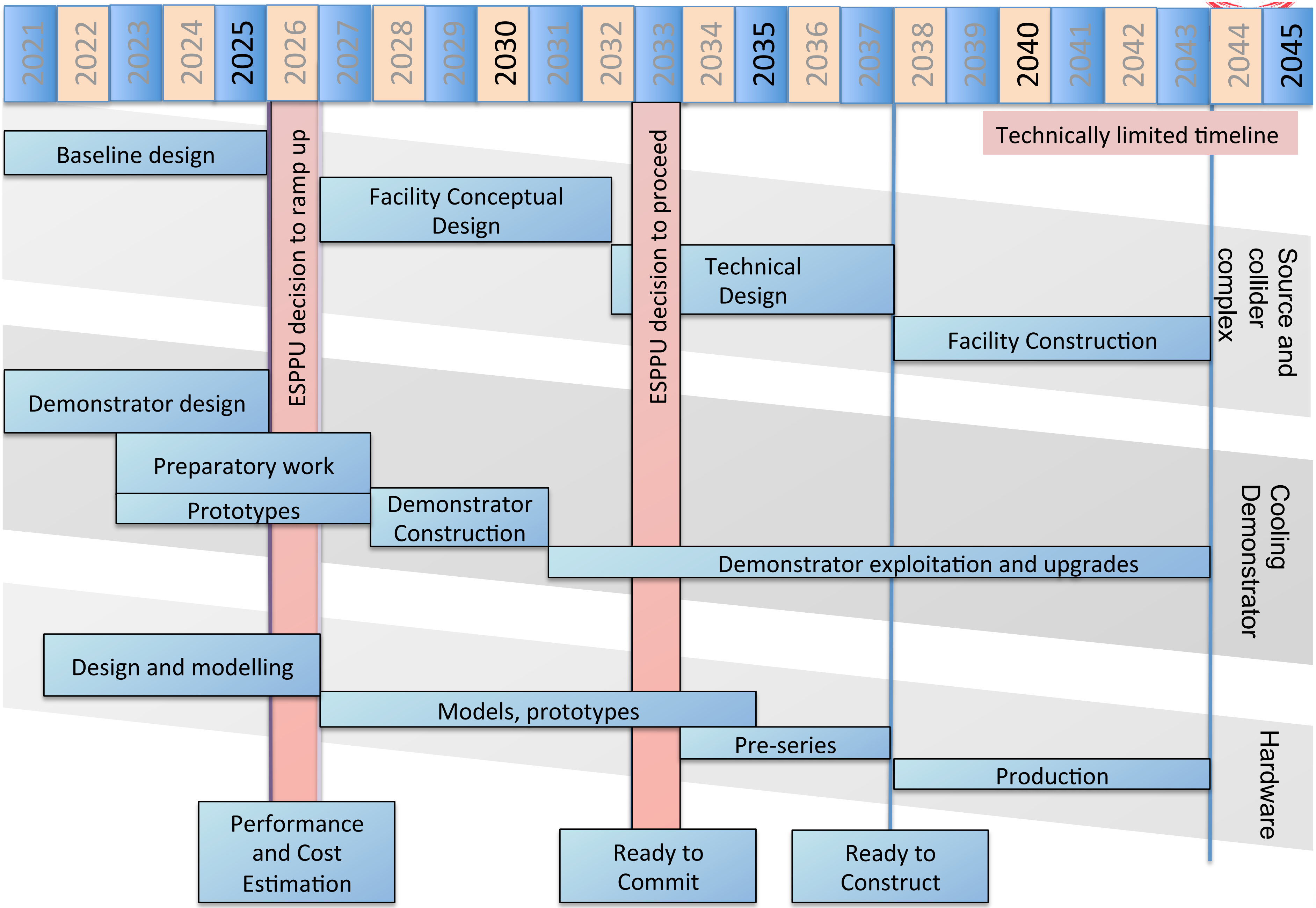
Potentially ramp up of muon collider effort

Decision to move to technical design

Pre-commitment to project

Project Approval

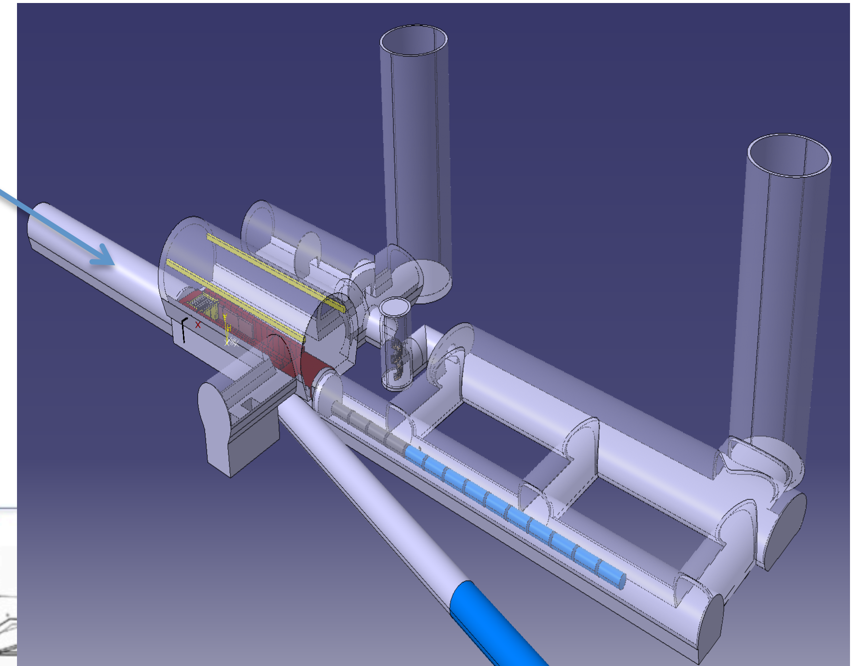
Tentative Target for Aggressive Timeline



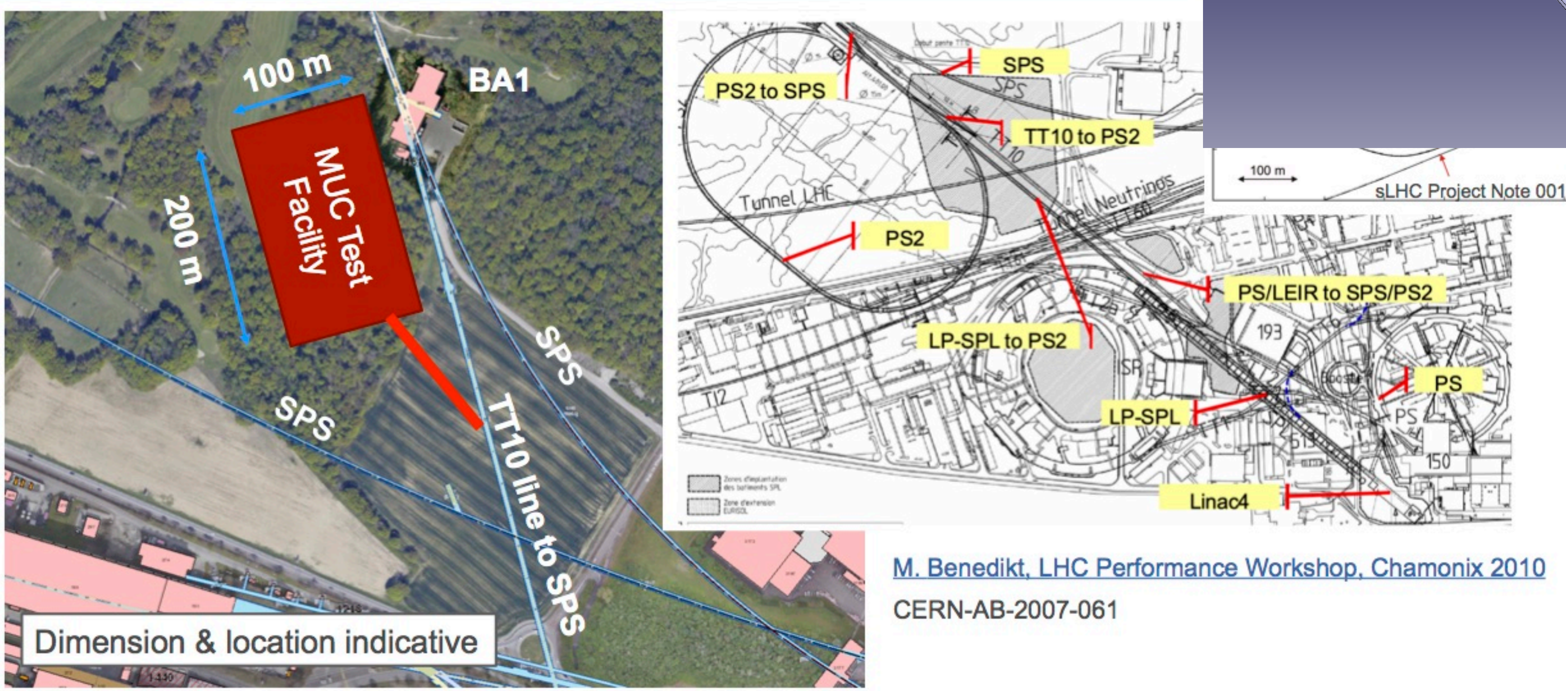
Demonstrator Facility

Are planning a demonstrator facility with muon production target and cooling stations

Suitable site on CERN land exists that can use existing proton infrastructure



Possibility around TT10



M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

EU Design Study

HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept development
Expected EU contribution: 1-3 MEUR
Total budget 21.8 MEUR
Type of Action: Research and Innovation Actions

Develop a conceptual design for the collider

HORIZON-INFRA-2022-TECH-01-01:
Expected EU contribution: 5-10 MEUR
Total budget 110 MEUR
Type of Action: Research and Innovation Actions

Develop technologies for at least three infrastructures of European interest.
European Spallation Source (ESS), CERN proton complex, ISIS in UK, European Magnetic Field Laboratory (EMFL)

Conclusion

The muon is a unique promising option at highest lepton energies

- Part of the European Accelerator R&D Roadmap
- Starting global collaboration

Need ambitious magnet technology

- solenoids (unique for accelerators)
    - high-field larger aperture for target
    - in tight integration with RF in
    - highest field, small aperture solenoids
- fast-ramping superconducting dipoles as improvement
- superconducting accelerator magnets (dipoles, quadrupoles etc.)

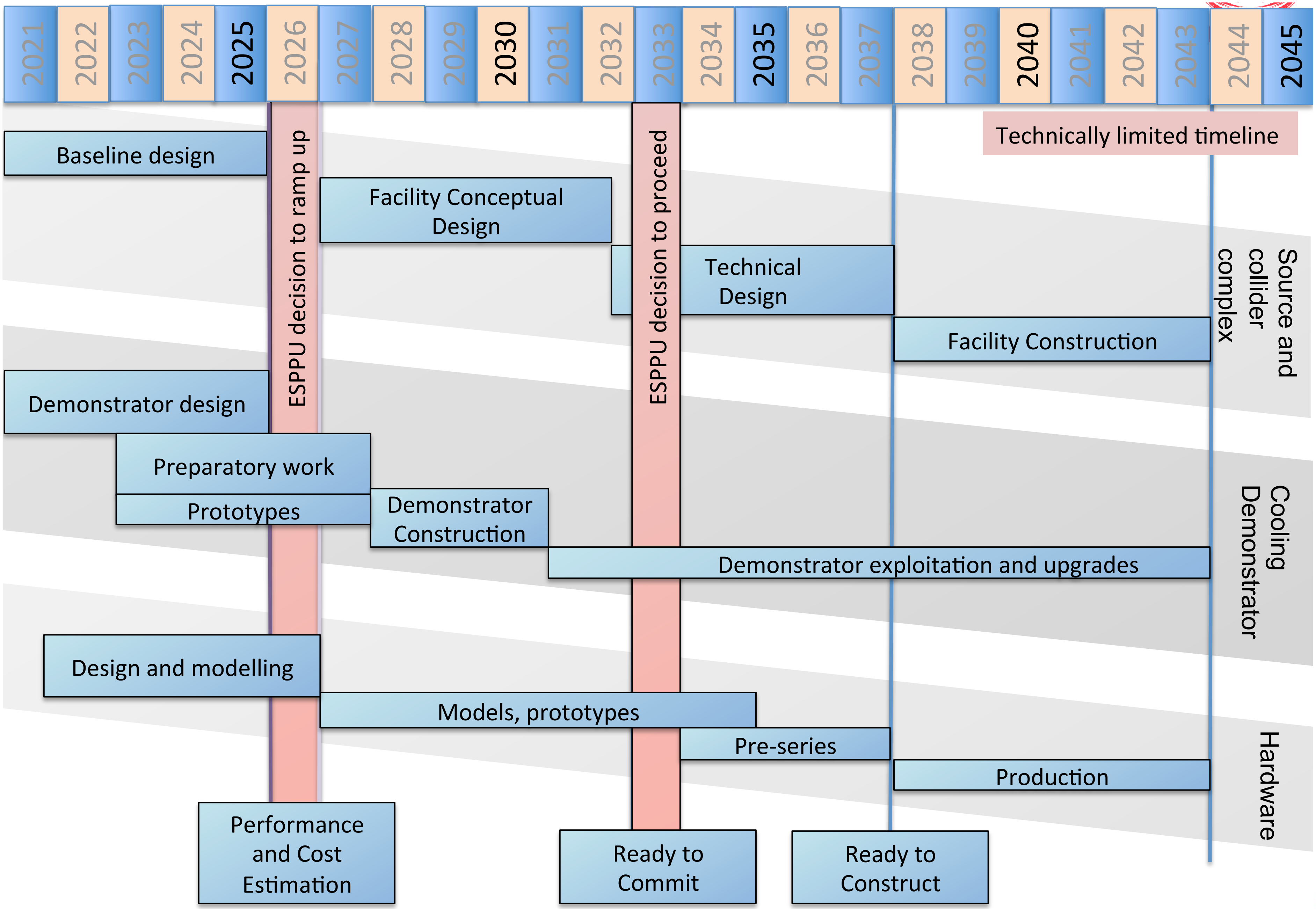
Prepare workplan, also for EU-co-funded studies

Web page: http://muoncollider.web.cern.ch

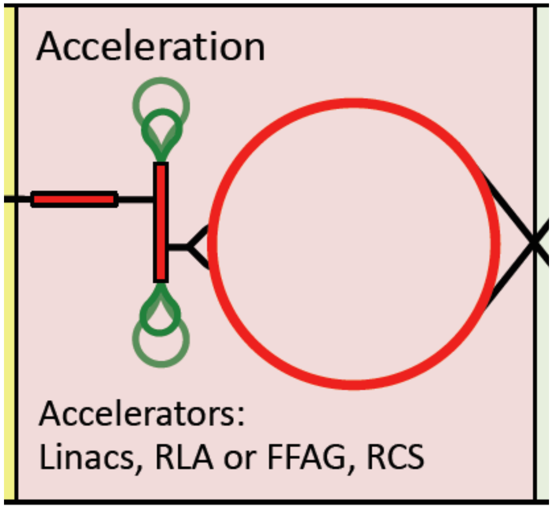
Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch
go to https://e-groups.cern.ch and search for groups with "muoncollider" to subscribe

Reserve

Tentative Target for Aggressive Timeline



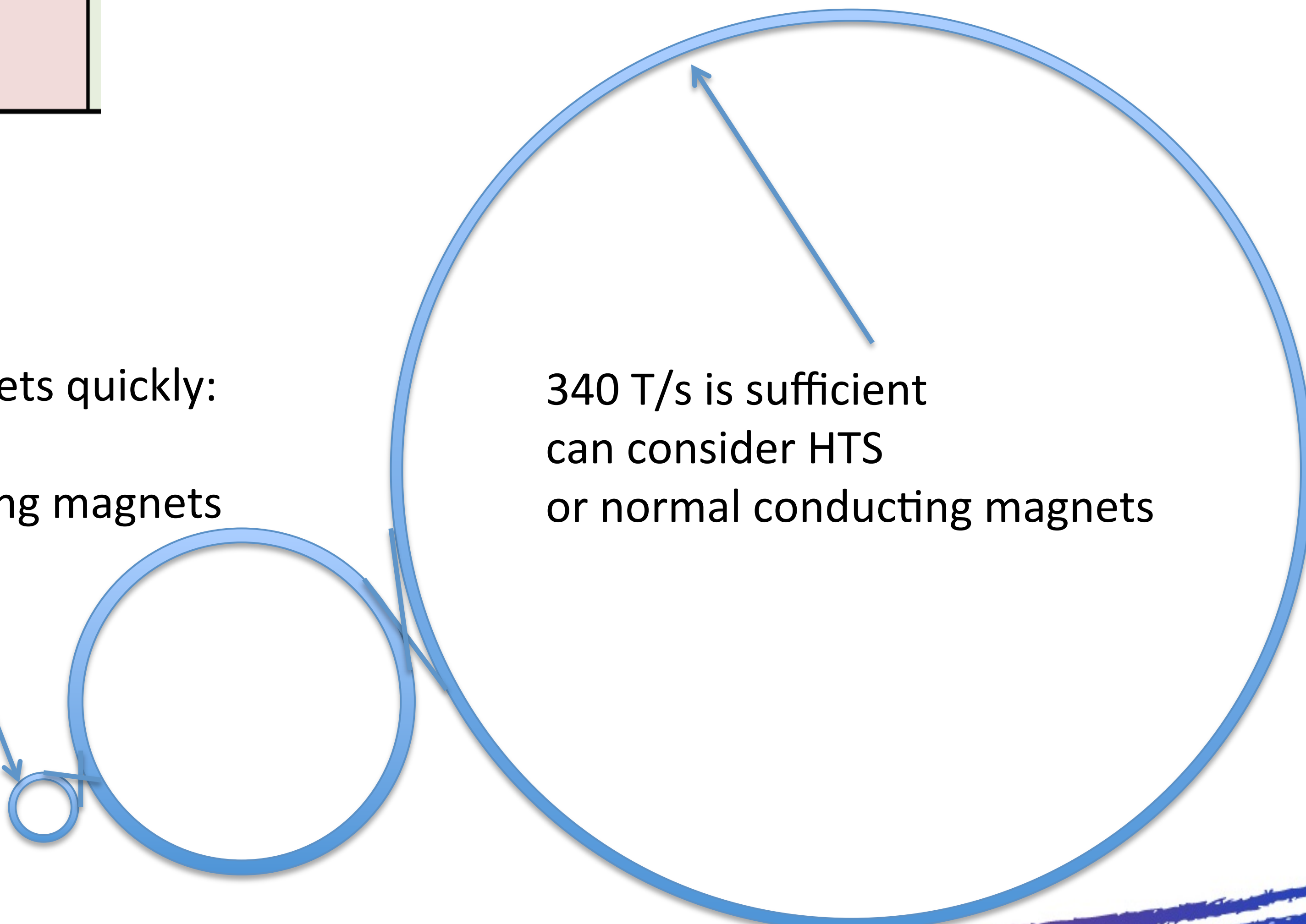
Acceleration



Sequence of
- linac
- two recirculating linacs
- two to four rings (baseline: pulsed synchrotron, alternative: FFA)

Need to ramp magnets quickly:
- ideally 10 kT/s
- normal-conducting magnets

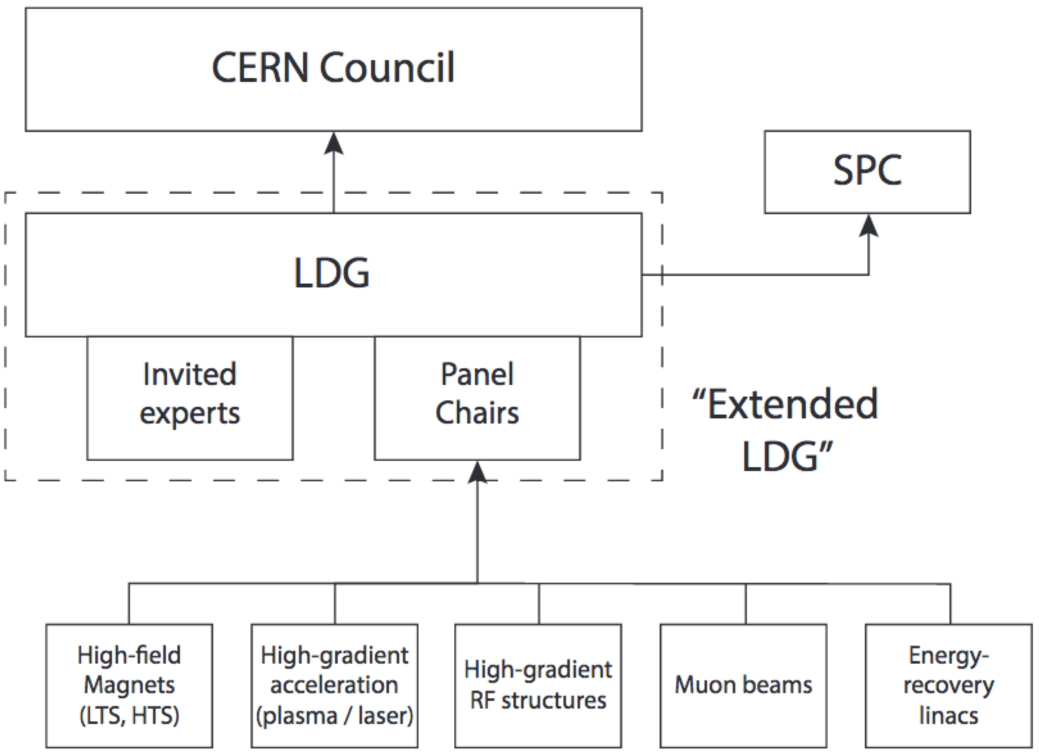
340 T/s is sufficient
can consider HTS
or normal conducting magnets



European Accelerator R&D Roadmap

CERN Council charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap** by end of 2021

- Includes the muon collider
- Describes the required R&D and resources
- Will now need to be turned into a resource-loaded work programme



Similar strategy process in the US is also showing interest in the muon collider
Also discussions with Canadian and Japanese partners

LDG initiated International Muon Collider Collaboration, hosted by CERN

Luminosity Goals

International MUON Collider Collaboration

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Goals from physics

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

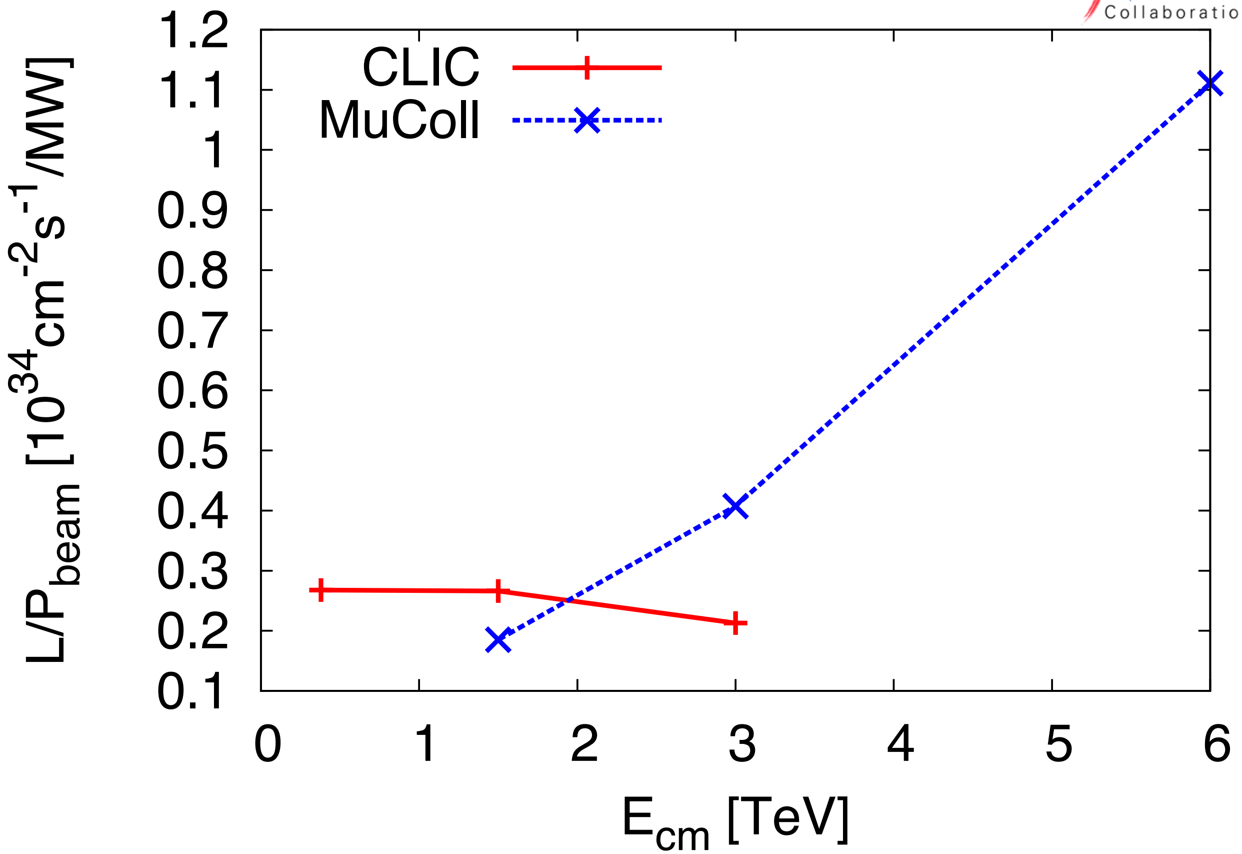
Would need only 5 years to reach integrated luminosity
But probably will back-off a bit
FCC-hh takes 25 years

Scaling to High Energy

In linear colliders, the luminosity per beam power is about constant
- have pushed technologies for decades

In muon collider, luminosity can increase linearly with energy

Muon collider can accelerate beams in several passes
⇒ efficient use of RF systems and power



Muon collider promising for **high energy**
Collaboration focuses on
- **10+ TeV** to reach well beyond other lepton colliders
- **3 TeV** as initial stage with technologies available in 20 years
- consider synergies (e.g. on-resonance higgs factory, neutrino facility)

EU Design Study

HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept development
Expected EU contribution: 1-3 MEUR
Total budget 21.8 MEUR
Type of Action: Research and Innovation Actions

Expected Outcome:

Projects are expected to contribute to all the following expected outcomes:

- sound science cases for new research infrastructures, including expected scientific breakthrough, gap analysis and feasibility/design studies to support planning and decision making at the national level (e.g. funding bodies, governments) and at European level (e.g. ESFRI);
- a better alignment of the development of the research infrastructure landscape with the advancement of excellent science and frontier research;
- new services and access opportunities available to the research community, allowing to better tackle scientific and societal challenges.

EU Design Study

HORIZON-INFRA-2022-TECH-01-01:
Expected EU contribution: 5-10 MEUR
Total budget 110 MEUR
Type of Action: Research and Innovation Actions

Expected Outcome: Project results are expected to contribute to several of the following expected outcomes:

- enhanced scientific competitiveness of European research infrastructures foundations for the development of innovative companies;
- increase of the technological level of industries through the co-development of advanced technologies for research infrastructures and creation of potential new markets;
- integration of research infrastructures into local, regional and global innovation systems.