# Muon Collider Collaboration

Daniel Schulte for the forming international muon collider collaboration

# Lepton Physics at High Energy

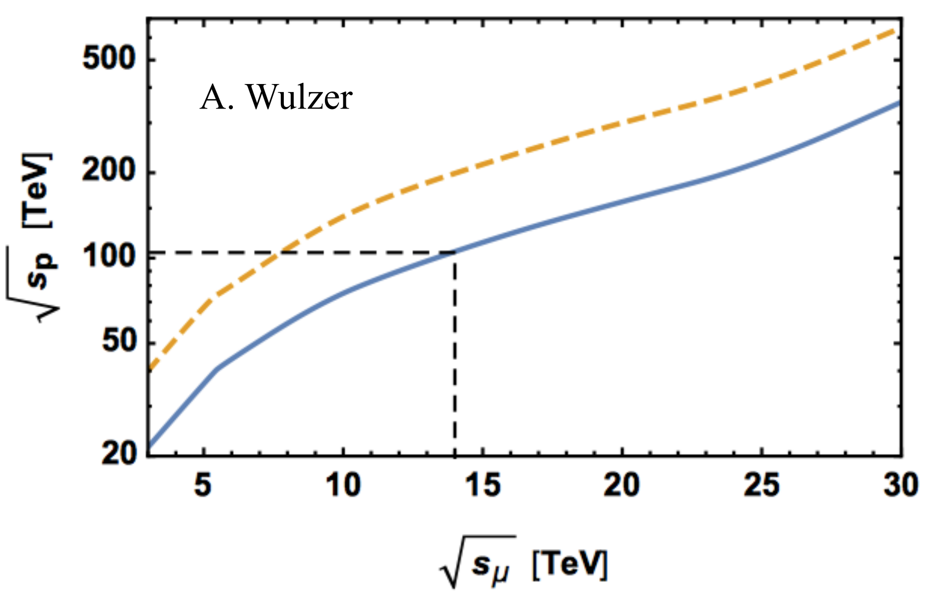
High energy lepton colliders are precision and discovery machines

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao
Muon Collider - Preparatory Meeting

Precision potential

Measure $k_4$ to some 10%
With 14 TeV, 20 $ab^{-1}$



Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions for production of heavy particle pairs

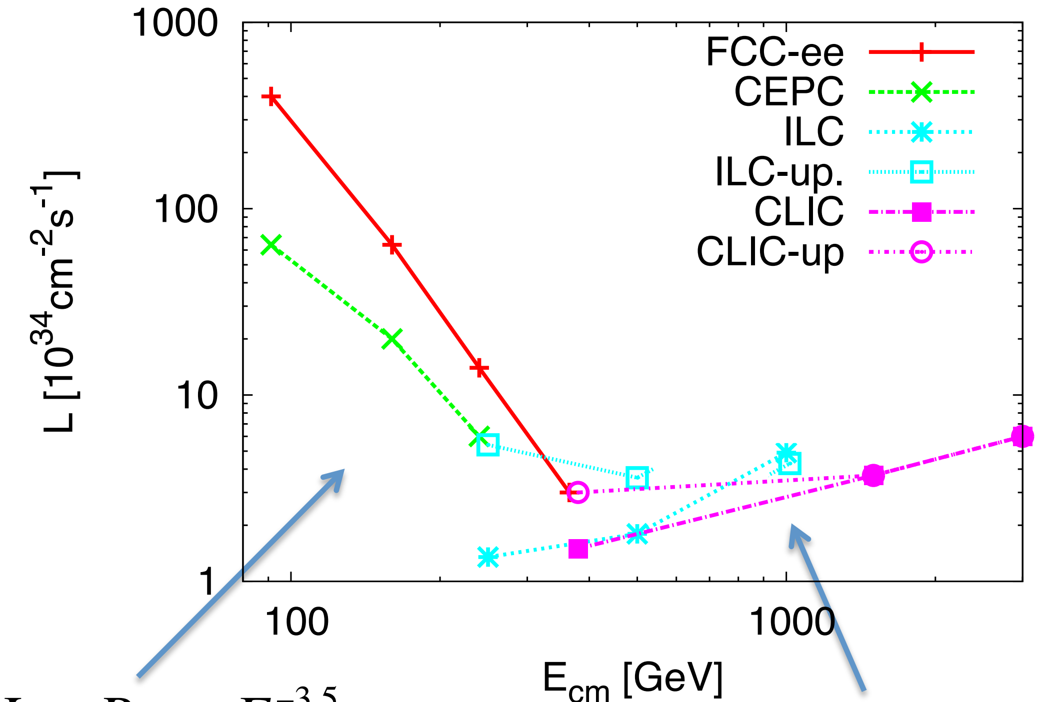
**Luminosity goal**

(Factor O(3) less than CLIC at 3 TeV)
$4\times10^{35}$ $cm^{-2}s^{-1}$ at 14 TeV

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left( \frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

# Proposed Lepton Colliders (Granada)

**Luminosity per facility**



$$L \propto P_{synrad} E_{cm}^{-3.5}$$

$$L \propto P_{RF}$$

$$\boxed{L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left( \frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}} \right)^2 2 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy

- Power 590 MW
  - Part in luminosity, a part in energy

- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

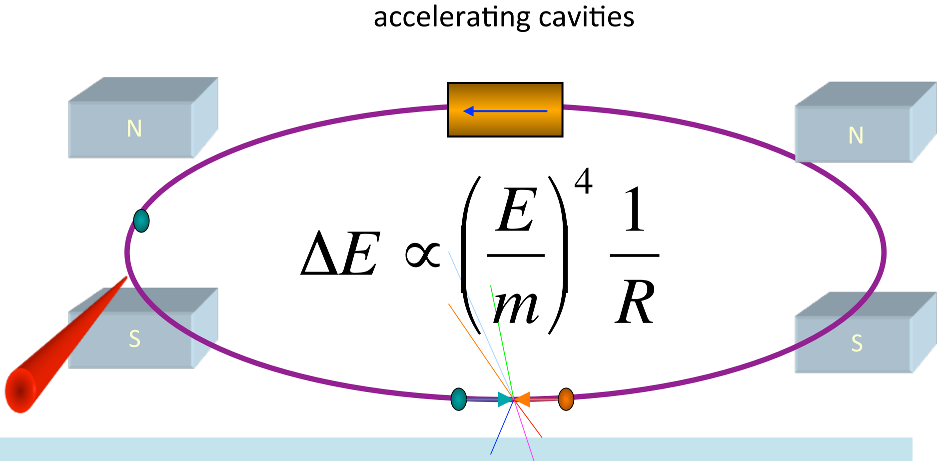
Cost roughly is linear with energy

Power consumption roughly goes with the square of energy

# Energy Limit

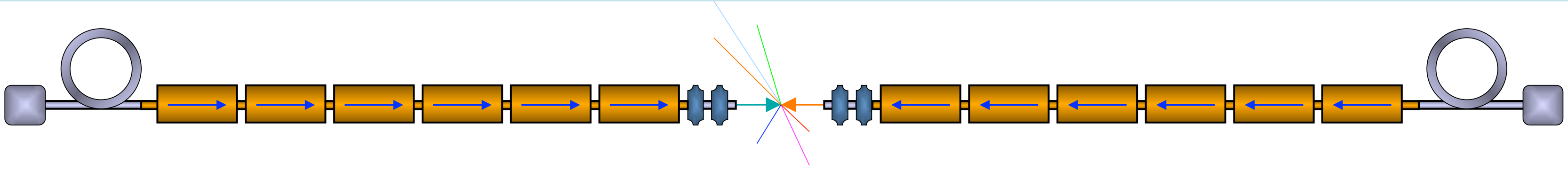
**Electron-positron rings** are **multi-pass** colliders limited by synchrotron radiation

Hence **proton rings** are energy frontier



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

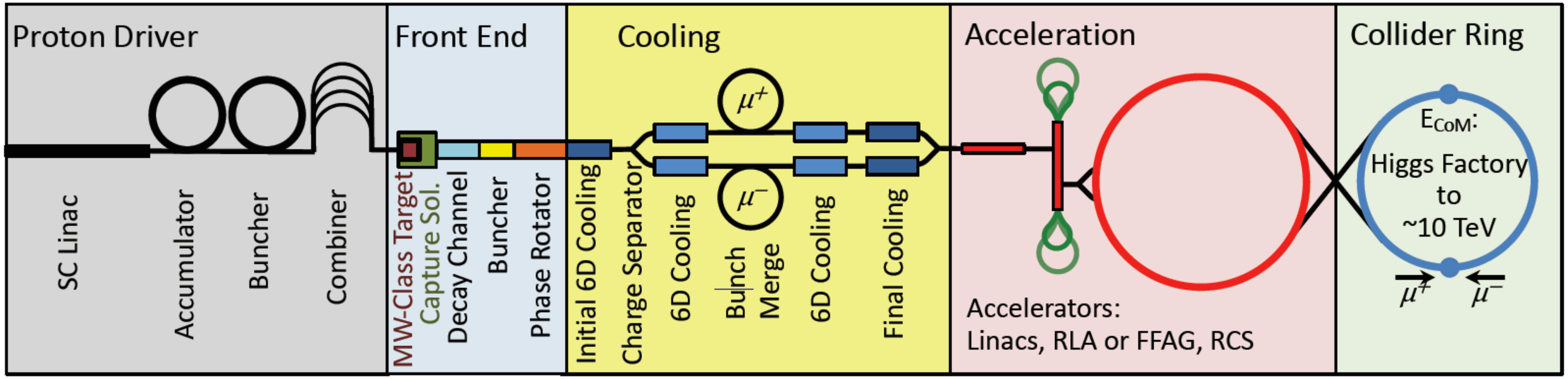
**Electron-positron linear colliders** avoid synchrotron radiation, but **single pass**
Typically cost proportional to energy and power proportional to luminosity,
e.g. CLIC at 14 TeV O(60 GCHF) and O(1.7-2.8 GW)



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
Proportional to energy

# Proton-driven Muon Collider Concept

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

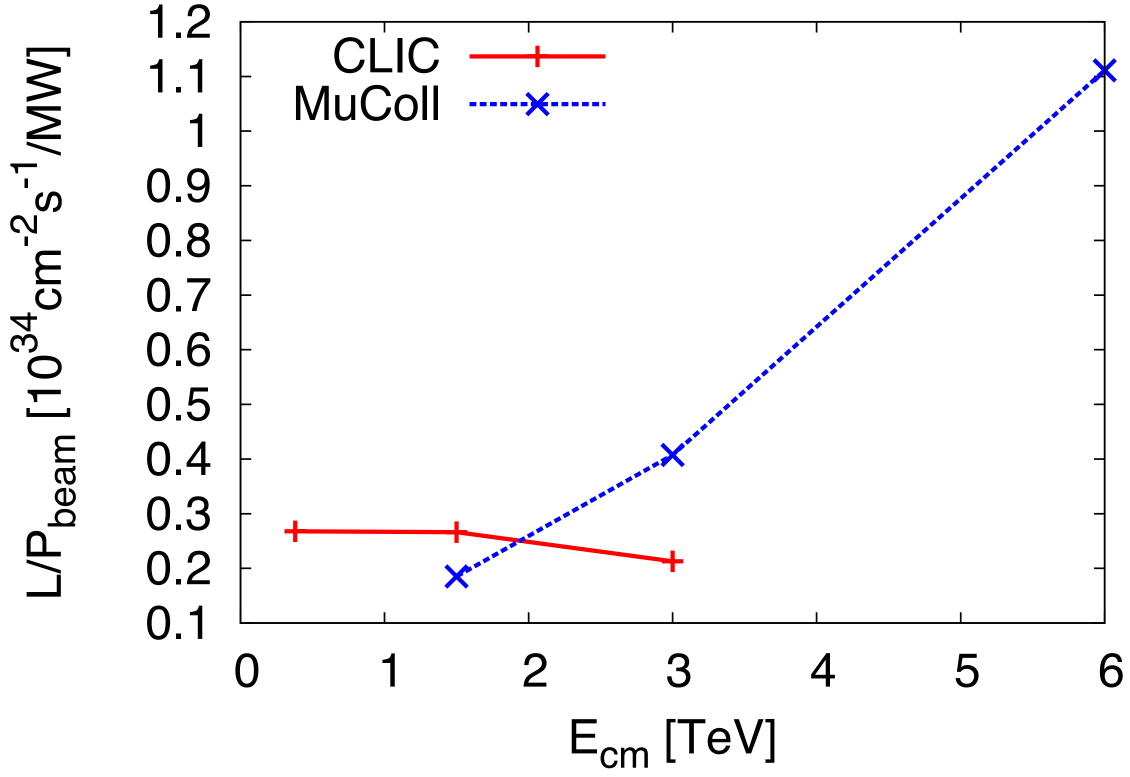
Collision

No CDR exists, no coherent baseline of machine
No cost estimate
Need to extend to higher energies (10+ TeV)
But did not find something that does not work

# Luminosity MAP vs. CLIC

In linear colliders, the luminosity per beam power is about constant

In muon collider, luminosity can increase linearly with energy



A linear collider is single-pass so need full voltage in main linac

Muon collider is multi-pass so have lower voltage

But have to carefully verify this

Overall muon colliders have the potential for high energies

May overcome the energy limitations of linear colliders

**European Strategy advised to consider muon collider**

# Muon Collider Collaboration: Objective and Scope

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.

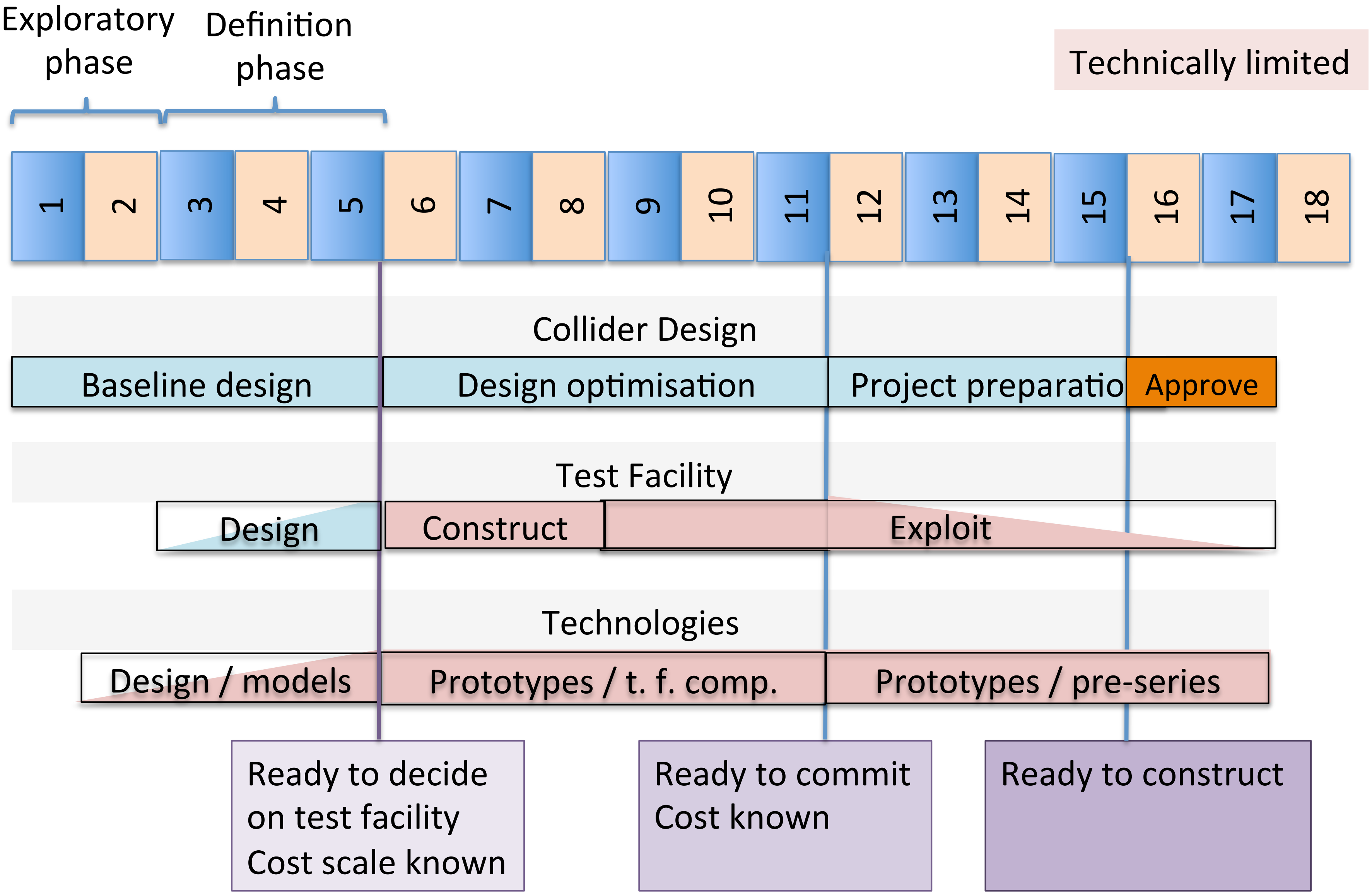
Deliverable:

Report assessing muon collider potential and describing R&D path to CDR

Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

# Potential Long-Term Timeline



Ready to decide
on test facility
Cost scale known

Ready to commit
Cost known

Ready to construct

# European Roadmap on Accelerator R&D

LDG has been charged by Council to deliver an Accelerator R&D Roadmap for Europe by the end of the 2021

LDG created panels to provide the input for the Roadmap, one for muon beams

The extended LDG will deliver a report to council:

- The scientific drivers for R&D, and the progress needed to enable future facilities
- The current state-of-the-art, and the further steps to be taken over the next decade
- Potential deliverables and demonstrators for the next decade
- A prioritised work plan, taking into account the capabilities and interests of stakeholders
- A range of scenarios for engagement, ranging from ‘minimal investment’ to ‘maximum possible rate of progress’, with a first estimate of resources and timeline.

# Luminosity Goals

Target integrated luminosities

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

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

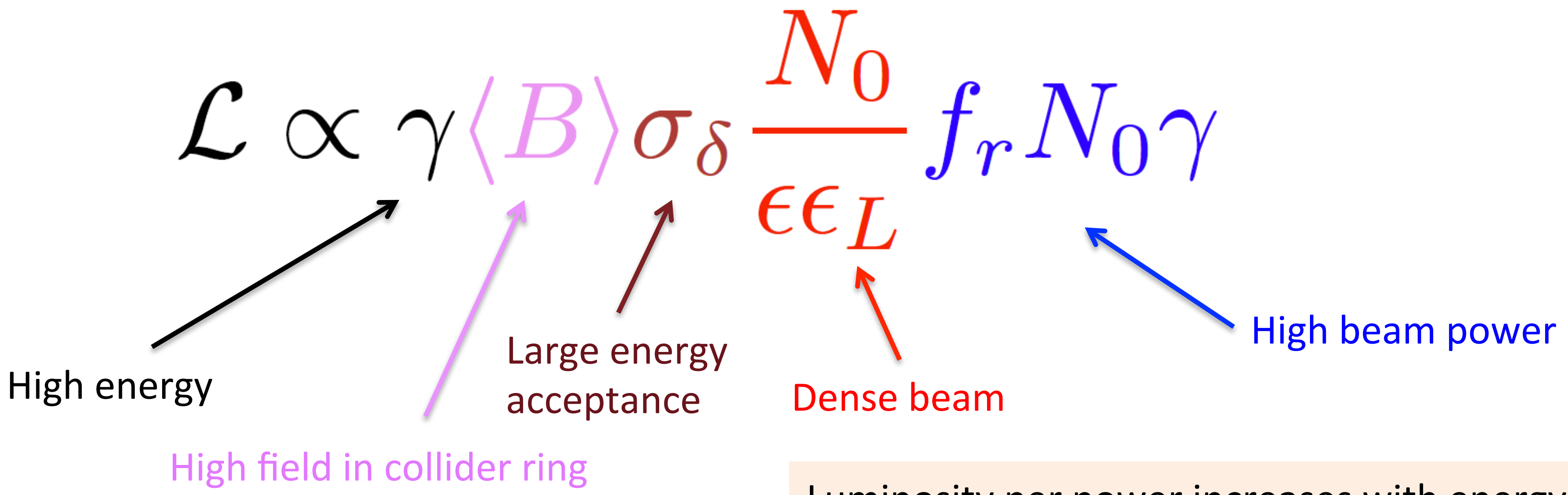
Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV |
|---|---|---|---|---|
| L | $10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ | 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 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_E / E$ | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | mm | 5 | 1.5 | 1.07 |
| $\beta$ | mm | 5 | 1.5 | 1.07 |
| $\varepsilon$ | µm | 25 | 25 | 25 |
| $\sigma_{x,y}$ | µm | 3.0 | 0.9 | 0.63 |

# Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design



$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left(\frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}}\right)^2 2 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Luminosity per power increases with energy
Provided all technical limits can be solved

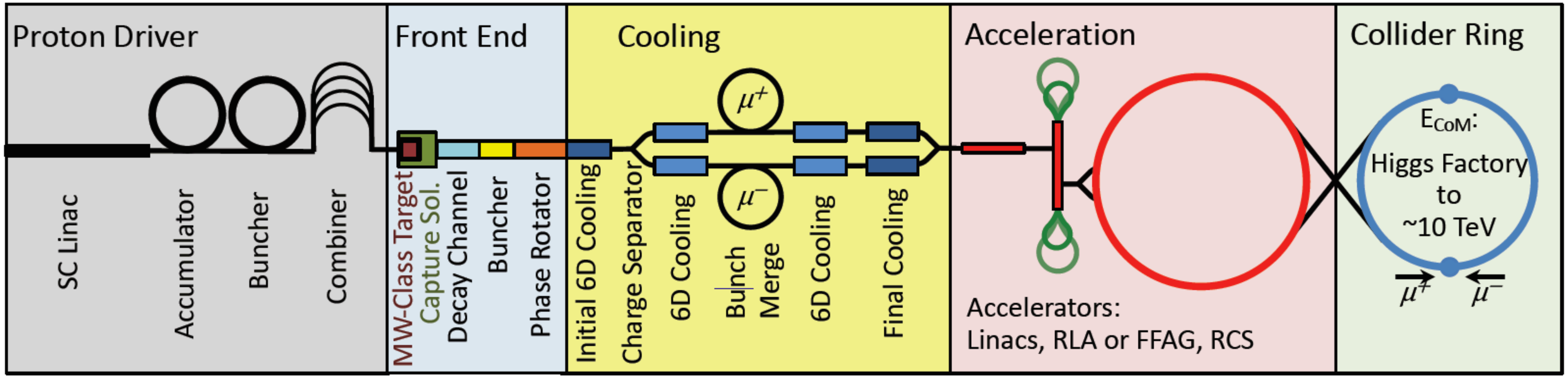
Constant current for required luminosity

Better scaling than linear colliders

# Exploratory Phase – Key Topics

- Physics potential evaluation
- Impact on the environment
  - The **neutrino radiation** and its impact on the site. This is known to require mitigation strategies for the highest energies.
  - Power consumption (accelerating RF, magnet systems, cooling)
- The impact of **machine induced background** on the detector, as it might limit the physics reach.
- **High-energy systems** that might limit energy reach or performance
  - Acceleration systems, beam quality preservation, final focus
- **High-quality beam production**, preservation and use
  - Target and target area
  - Cooling, in particular final cooling stage that does not yet reach goal
  - Proton complex

# Overall Considerations



These systems will drive the beam quality

Currently assume that we use the same production complex at all energies

We assume that we will got to the limit of technologies

But there are still ideas that need to be explored for further improvement

These systems will be the cost and power consumption drivers
(for 10 TeV accelerator ring could be LHC size, collider ring is half LHC size)

They will limit the energy reach

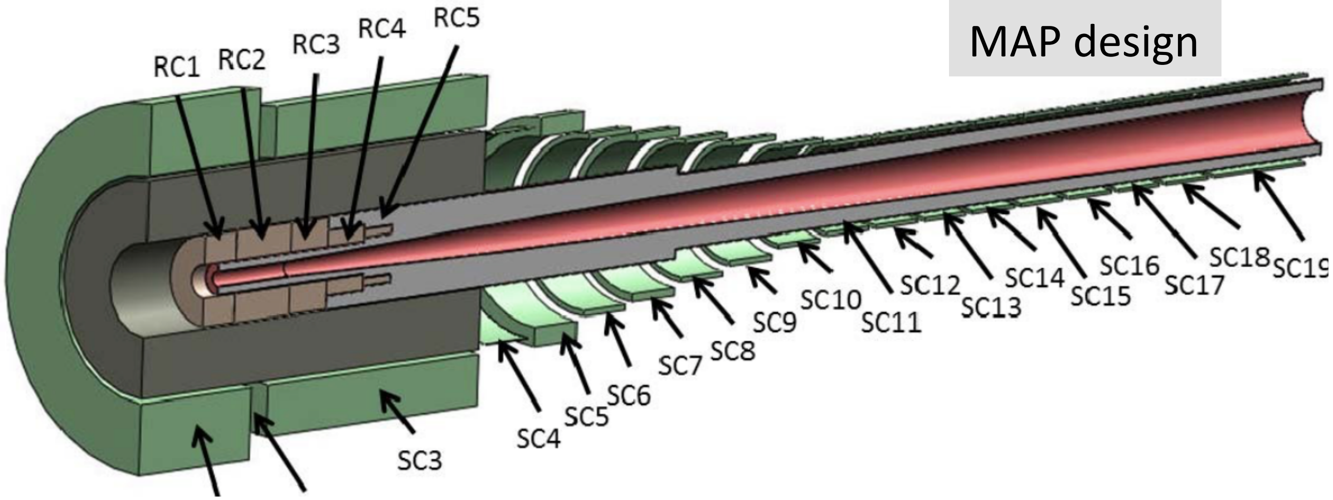
Can imagine to implement accelerator for 3 TeV in the LHC tunnel or a smaller new one

# Source

**Intense proton beam** is challenging

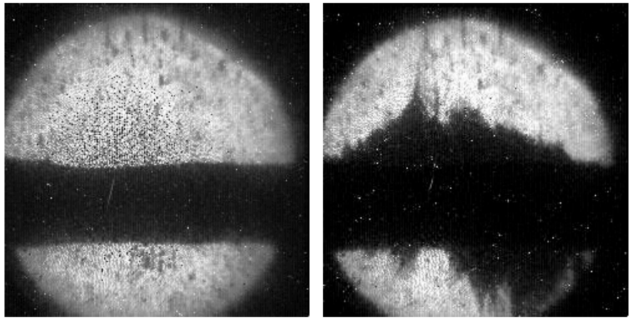
Need to make choices for the **target**

**Ambitious high-field solenoid**


MAP design

Target has to withstand **strong shock**

- liquid mercury target successfully tested at CERN (MERIT)
- but solid target better for safety
- or beads
- or …



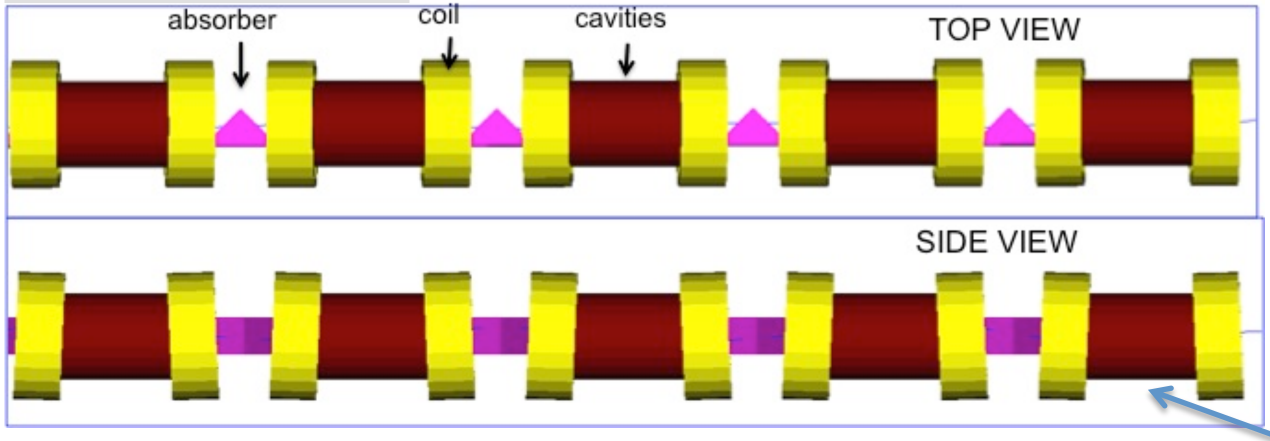
Important power of proton driver O(1.3 MW)

- radiation in solenoid
- need to cool
- need to take care of debris for downstream systems

What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

# Cooling Concept

MAP collaboration

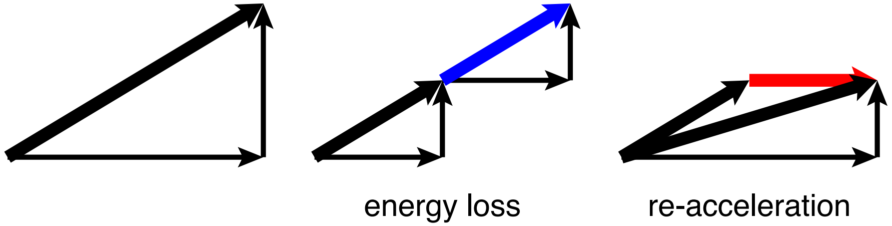


Superconducting solenoids

High-field normal conducting RF

Liquid hydrogen targets

Compact design

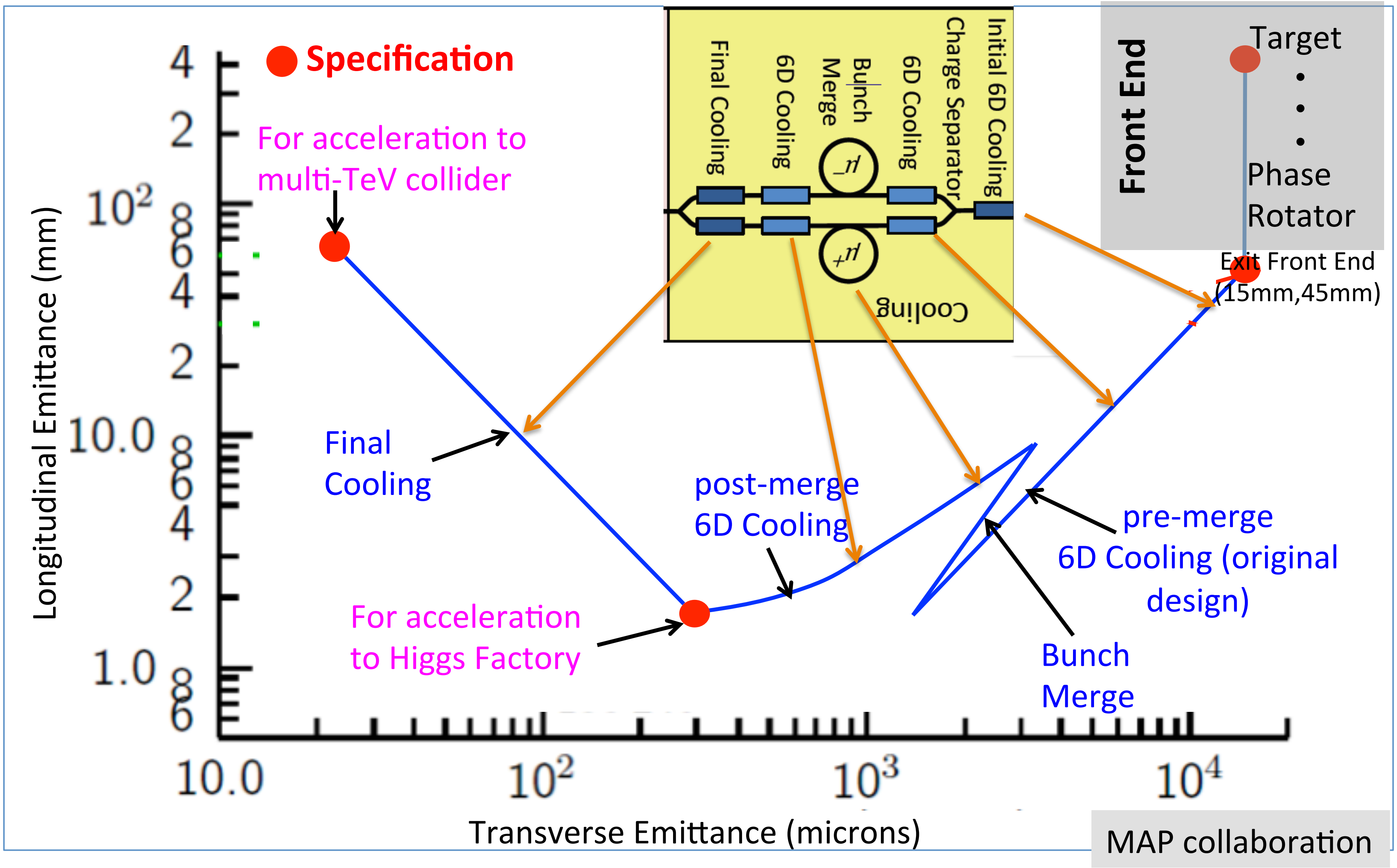


Maximise gradient in a magnetic field to limit muon decay

Minimise betafunction with strongest solenoids

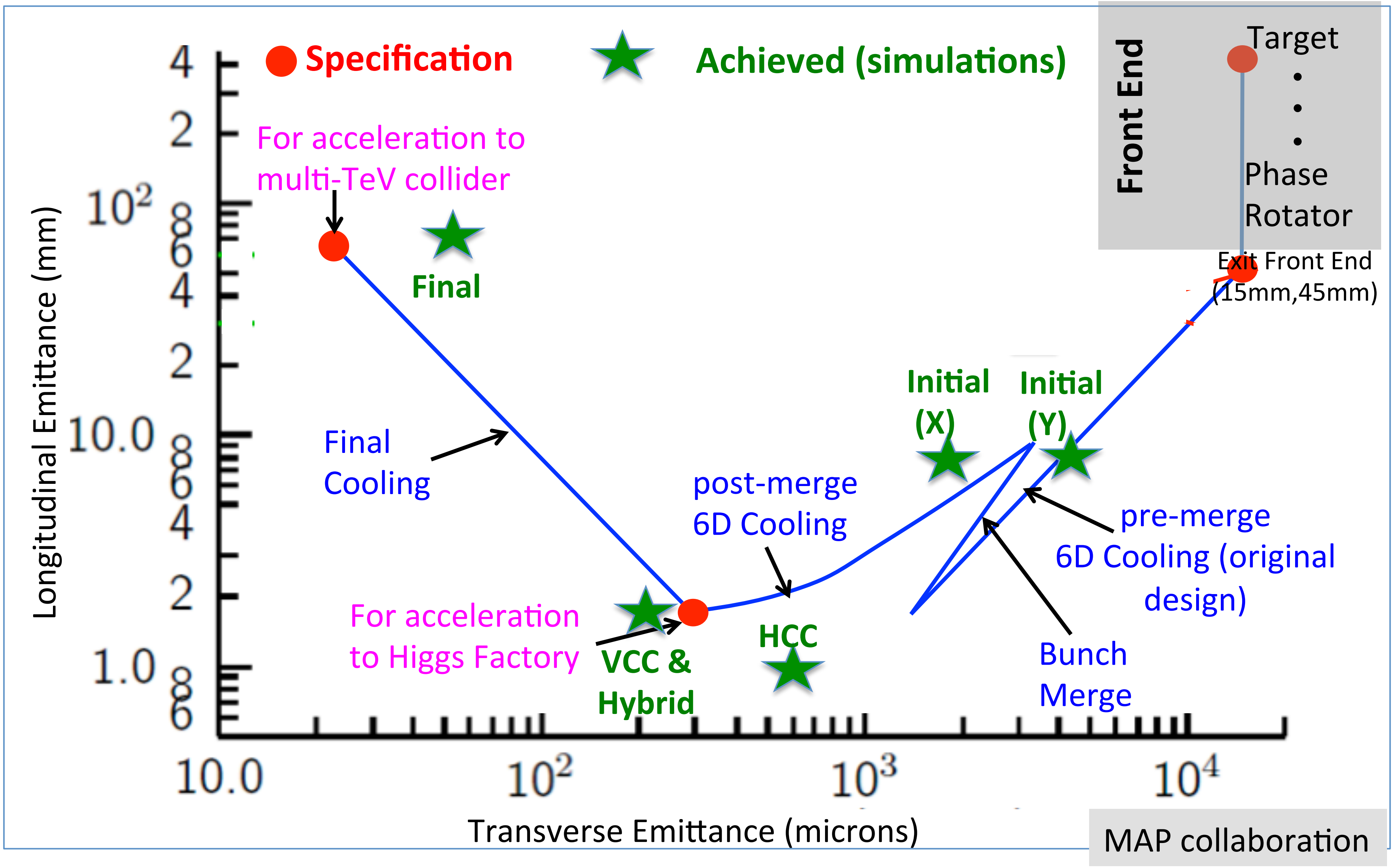
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

# Cooling: The Emittance Path

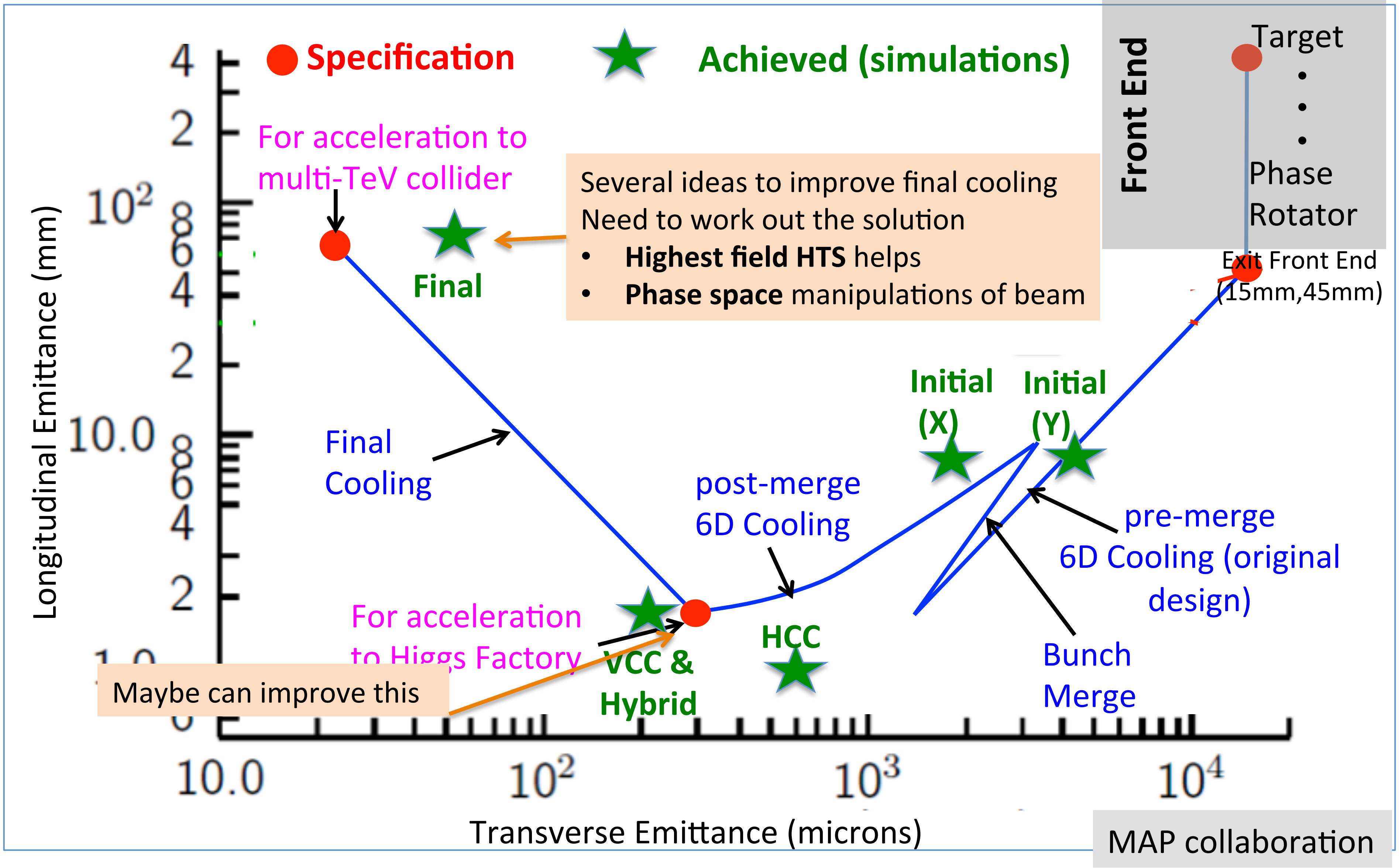


MAP collaboration

# Cooling: The Emittance Path



# Cooling: The Emittance Path



Several ideas to improve final cooling
Need to work out the solution

- **Highest field HTS** helps
- **Phase space** manipulations of beam

Maybe can improve this

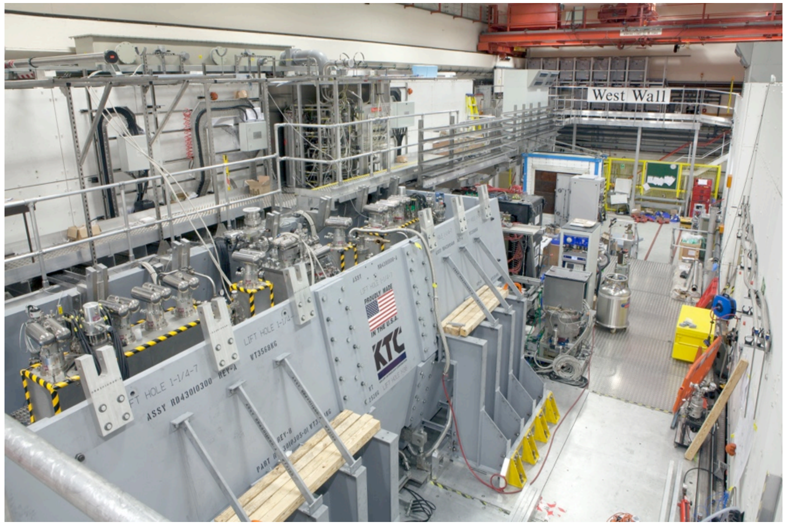
MAP collaboration

# Design Status

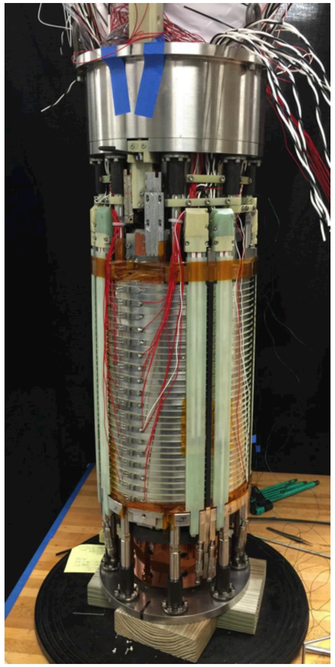
Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

But no CDR, no integrated design, no reliable cost estimate
More work to be done, e.g. substantial, 6D cooling

MICE (UK)

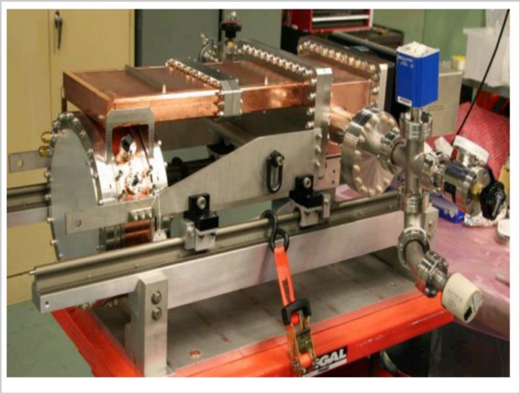


**FNAL**
Breakthrough in HTS cables



**NHFML**
32 T solenoid with low-temperature HTS

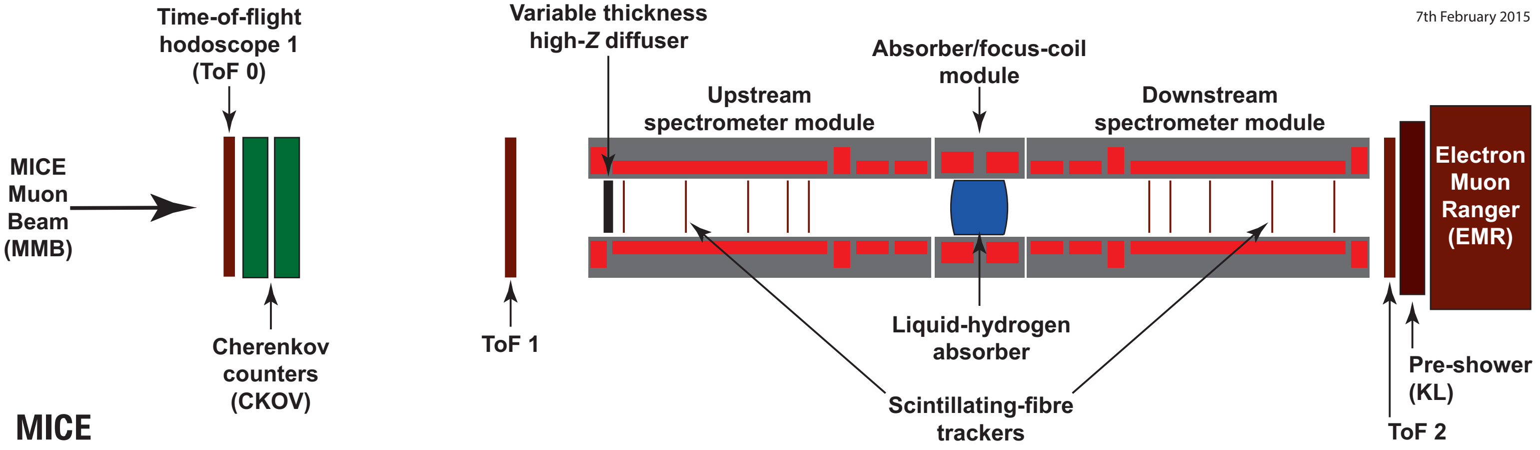
**MuCool**: >50 MV/m in 5 T field

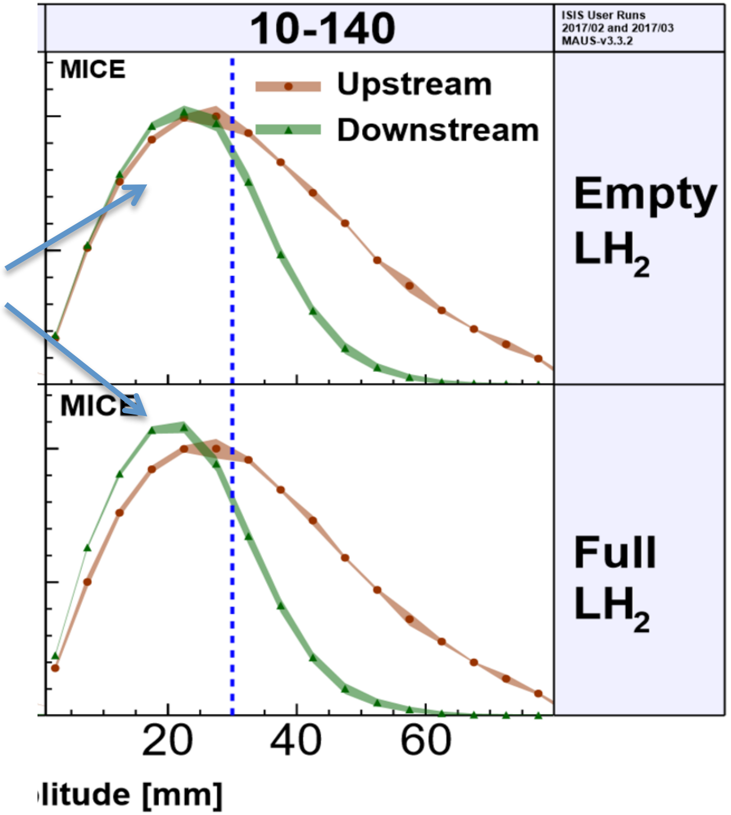


**FNAL**
12 T/s HTS
0.6 T max

Mark Palmer

# MICE (in the UK)





ature volume 578,
ages 53-59 (2020)

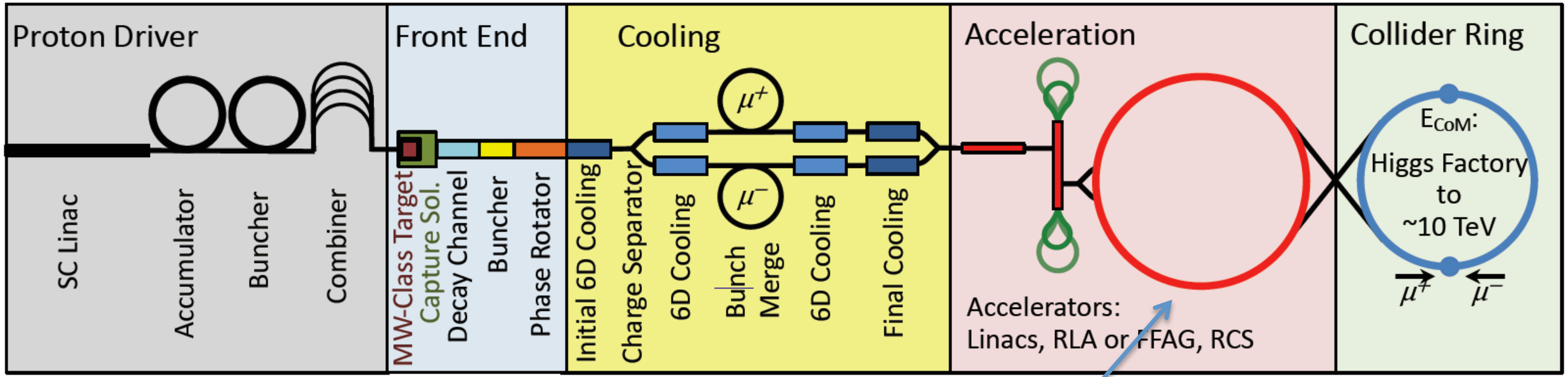
More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

# Beam Acceleration



Larger than collider ring

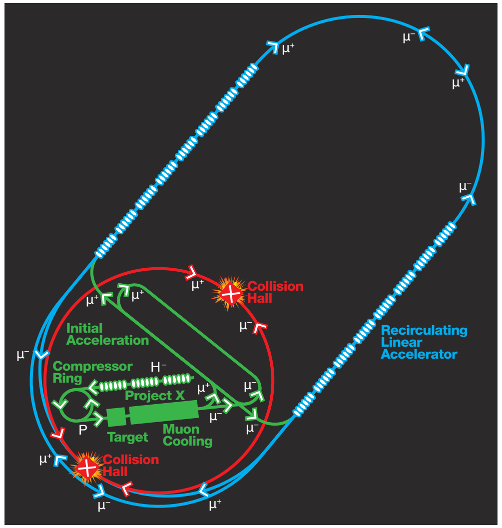
An important cost driver

Important for power consumption

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAGs (static superconducting magnets)
- Rapid cycling synchrotrons (pulse magnets)



# High-energy Acceleration

Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- Could use combination of static and ramping magnets
- Possible circumference
- 14-26.7 km at 3 TeV
- O(30 km) for 10 and 14 TeV

**Fast-pulsing magnets** (O(ms) ramps))

Field defines size of accelerator ring

- normal-conducting
- HTS is interesting

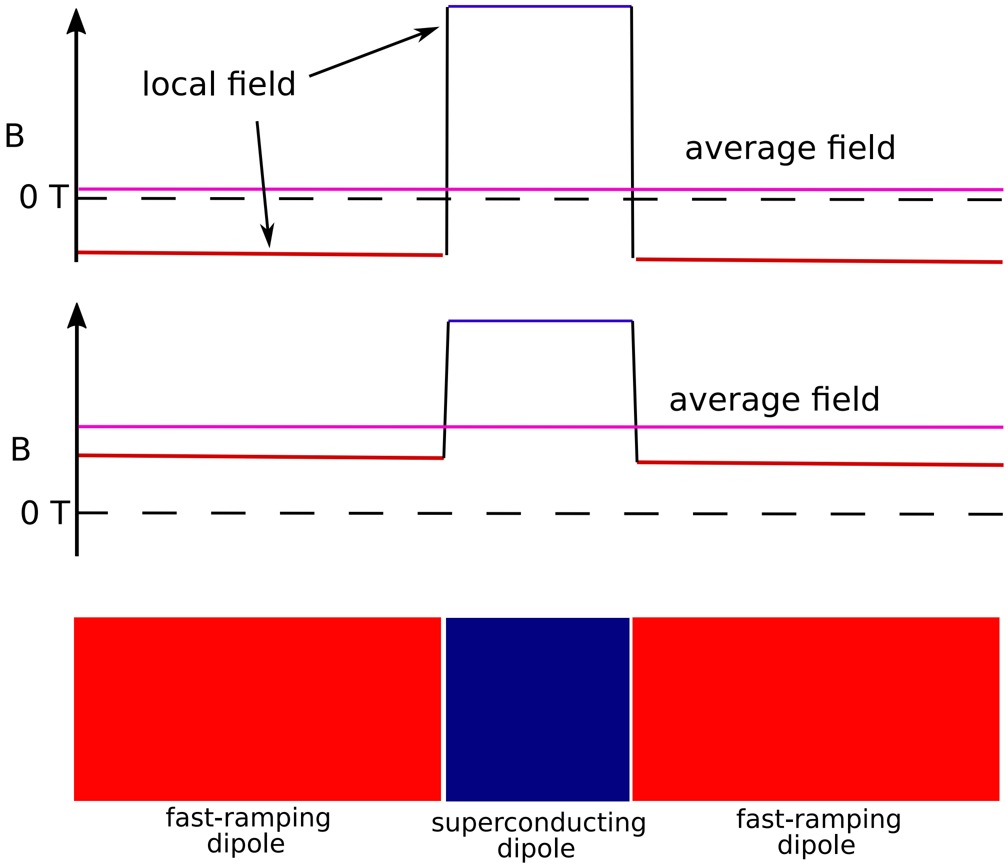
Important energy in fast pulsing magnets

- O(200 MJ) @ 14 TeV
- need **very efficient energy recovery**

FFAG

Challenging lattice design for large bandwidth and limited cost

High field magnets



**RF challenge**:

High efficiency for power consumption

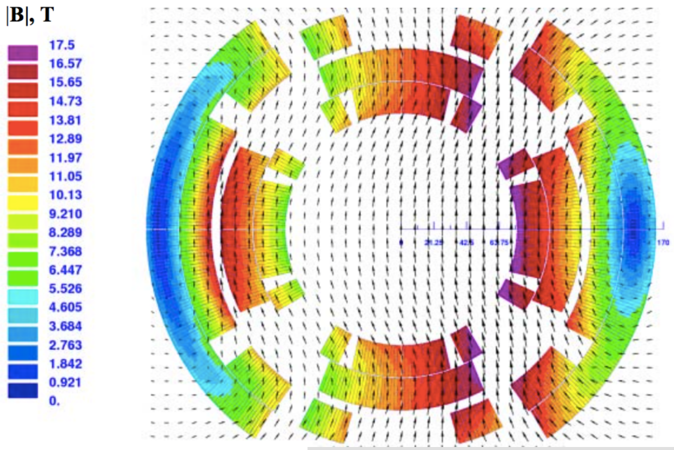
High-charge, single-bunch beam (10 x HL-LHC)

Maintain small longitudinal emittance

# Collider Ring

**High field dipoles** to minimise collider ring size and maximise luminosity
4.5 km at 3 TeV, 10/14 at 10/14 TeV

Combined function magnet design



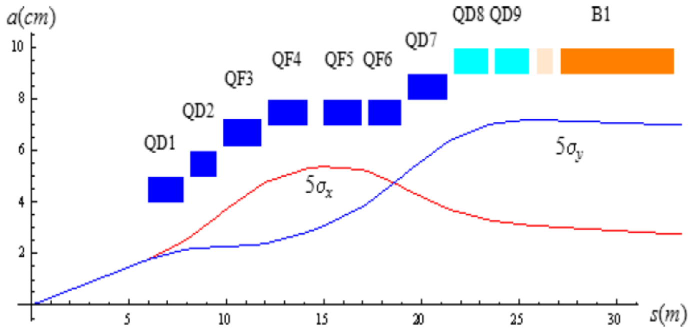
V.V. Kashikhin et al.

Need to protect from O(400 W/m) **beam loss**

- 1/3 of beam energy
- large aperture and shielding
    - 150 mm in MAP at 3 TeV, 30-50 mm shielding
- open mid-plane magnets
- efficient cooling

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy
Divergence independent of energy
Challenging triplet design

$$\beta \propto \frac{1}{\gamma}$$



Maintaining very short bunch (1 mm) in large ring

- Careful control of longitudinal motion
- Beam dynamics of frozen beam

# Tentative Detector Performance Specification

10+ TeV collider enters uncharted territory

Need to establish physics case and detector feasibility

**Established tentative detector performance specifications** in form of DELPHES card (thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor, A. Sailer, D. Lucchesi, N. Pastrone M. Pierini, F. Maltoni, A. Wulzer et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

- For use by physics potential studies
  - Are the performances sufficient or too good?
- For detector studies to work towards
  - make sure technologies are reasonable
  - ensure background is OK
- Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies/design will now have to verify/ensure that this is realistic considering background and technologies

# Detector

Detector is based on CLIC detector

Nozzles added to protect from beam-induced background (BIB)

Each beam contains one bunch crossing every 15 µs (3 TeV) or 47 µs (14 TeV)

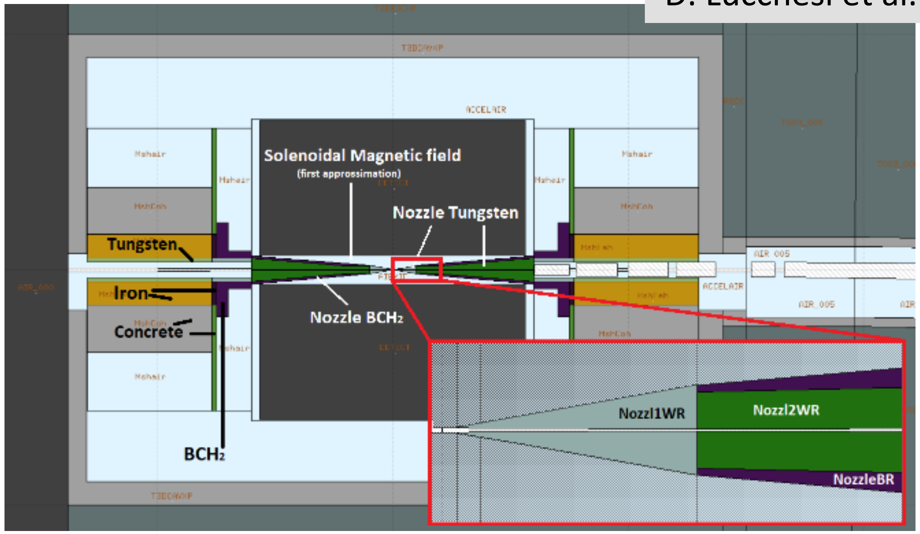
Muon decay rate at 3 TeV:
200,000 $bx^{-1}$ $m^{-1}$

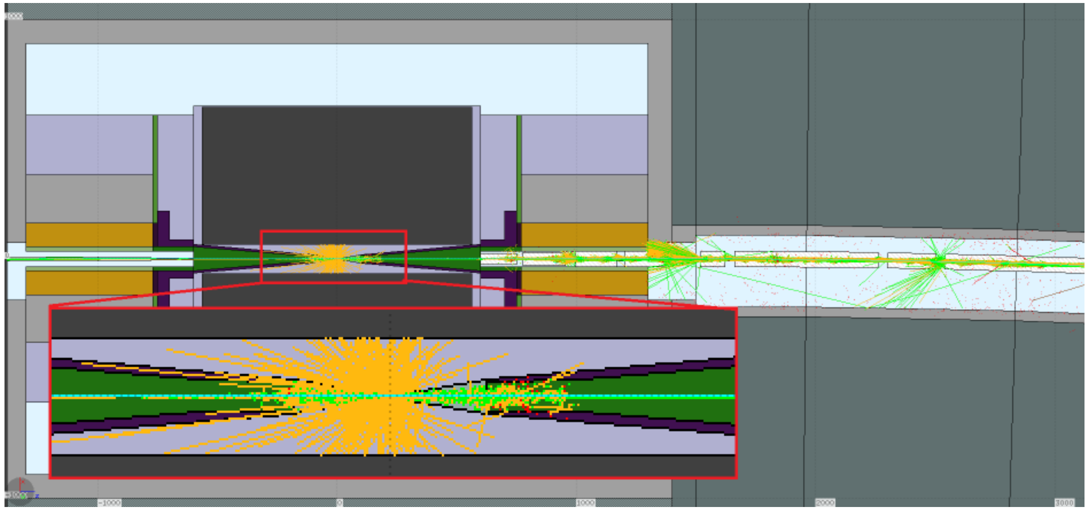
Rate decreases with energy but energy in each decays increases

Simulations for 1.5 TeV with LineBuilder and FLUKA comparing to previous MAP results (MARS)

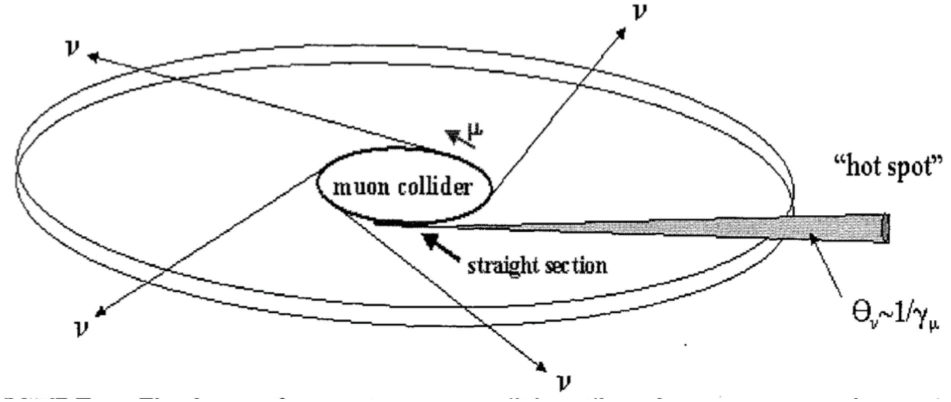
Will study higher energies as machine designs become available

D. Lucchesi et al.





# Neutrino Radiation



Neutrinos from decaying muons can produce showers just when they exit the earth

Due to narrow neutrino beam, radiation can become relevant

Particularly high in direction of the straights
- maybe buy the land concerned
- to be worked out with civil engineers

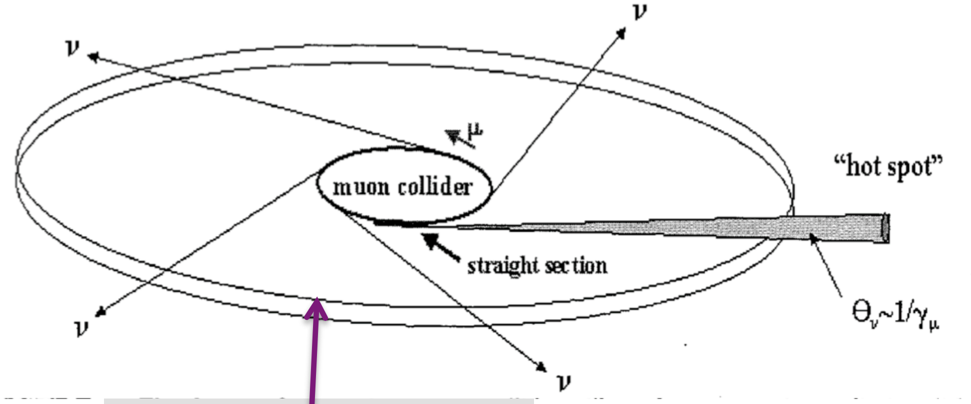
Arcs remain important limit

Dose increases with energy x luminosity, i.e. proportional to $E^3$

B. King

$$D_{arc} \approx 0.41\,\mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{B}$$

# Arc Estimates



Formulae by B. King

Tricks

$$\frac{D}{\int\mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\,\frac{\epsilon_T\epsilon_L}{N_0}\,\frac{1}{\sigma_\delta}$$

Higher field, shorter gaps in collider

Deeper tunnel

Denser beam

Larger energy spread acceptance

More efficient physics
More years of running

Typical legal limit 1 mSv/year

MAP goal < 0.1 mSv/year

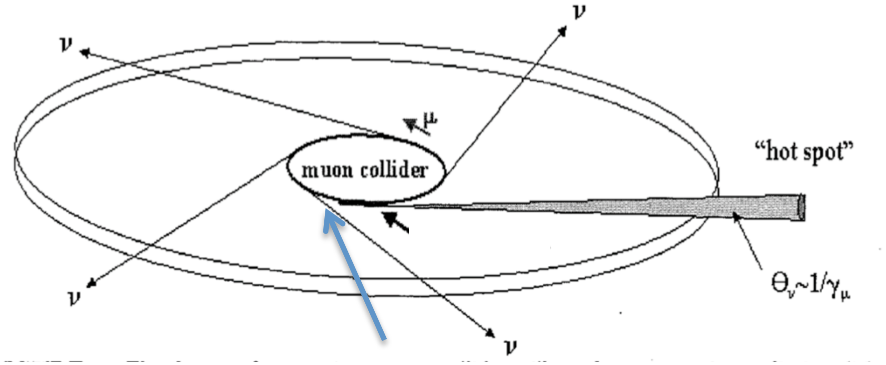
Our tentative goal < 10 µSv/year
No legal procedure needed

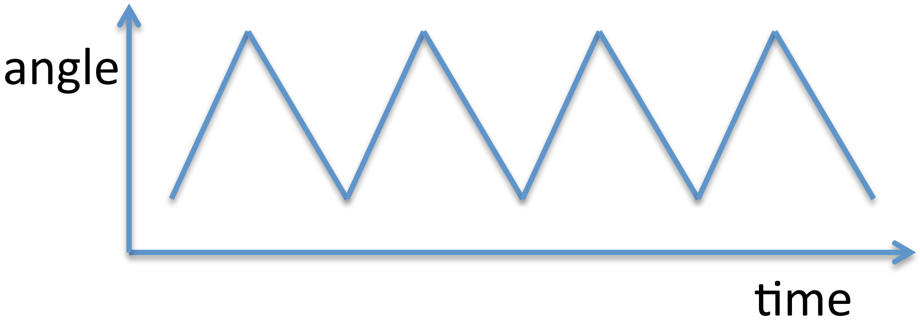
LHC achieved < 5 µSv/year

For our parameters and d = 500 m
10 TeV : 100 µSv/year
14 TeV : 280 µSv/year

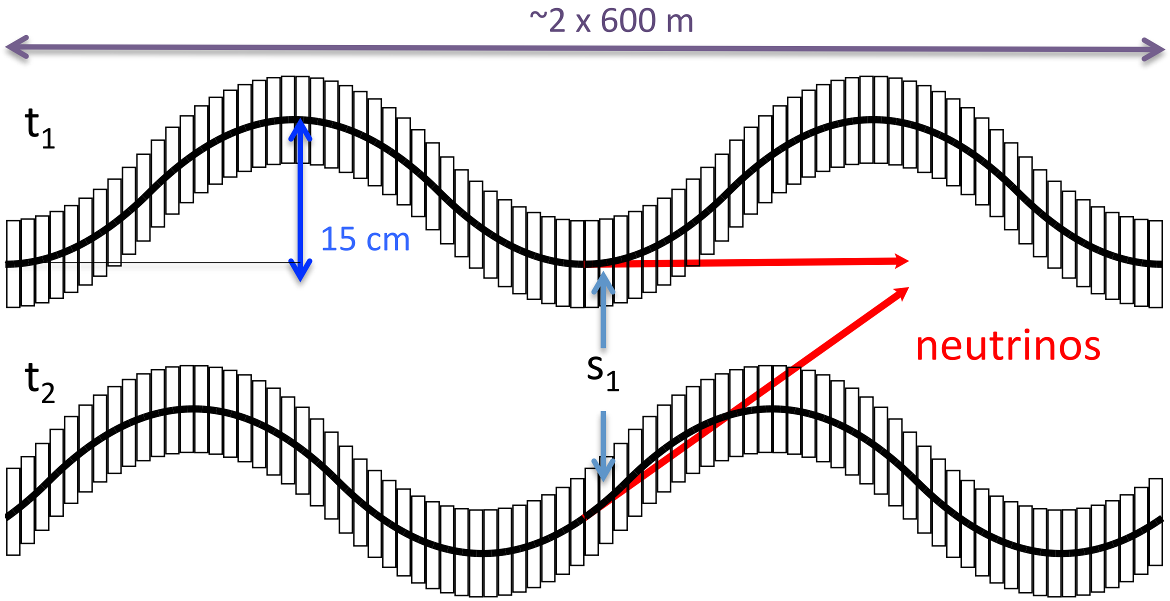
With 20 cm gap between 15 T magnets
<B> = 10.5 T
10 TeV : 340 µSv/year
14 TeV : 940 µSv/year

# Neutrino Radiation Mitigation





Move collider ring components, e.g. vertical bending with 1% of main field

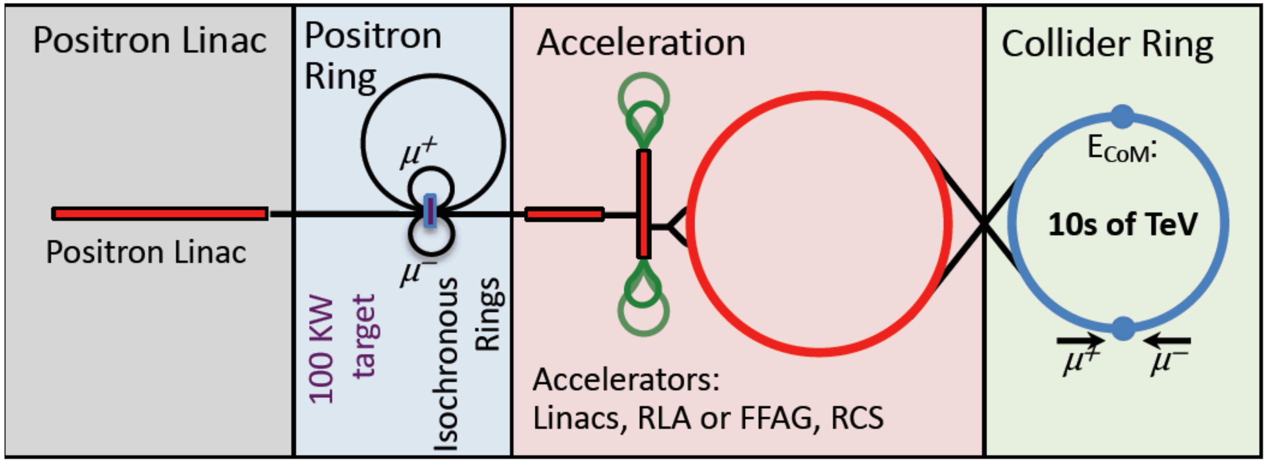


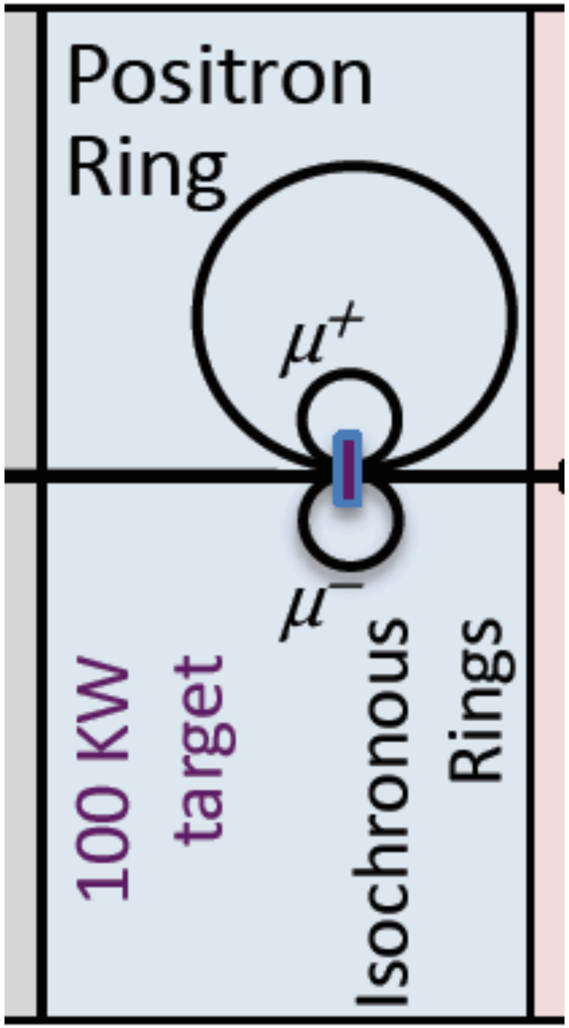
Opening angle ± 1 mradian

Even at 14 TeV
200 m deep tunnel would stay
below 5 μSv/year

Need to study impact on beam and operation, e.g. dispersion control

# Alternative: The LEMMA Scheme





45 GeV positrons to produce muon pairs
Accumulate muons from several passages

Low-emittance muon beam can reduce radiation

Less mature than proton-driven scheme
Large positron current required
Target is challenging
Large positron production rate [O($10^{17}$/s)]
Currently do not reach luminosity goal

# Conclusion

The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility
- Ensure that BIB is not an obstacle
- Through European Roadmap for Accelerator R&D

Workshop on the muon collider testing opportunities (with physics case):
https://indico.cern.ch/event/1009746/ .

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

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
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