# Prospects on Muon Colliders

Daniel Schulte for the forming international muon collider collaboration

# Context

Muon collider has in the past been studied in the US (MAP)

- effort largely ceased after last P5 process
- some effort mainly in the UK on MICE
- some, mainly in Italy, on LEMMA on alternative muon source

For the European Strategy the Laboratory Directors Group (LDG) established a muon collider working group to provide input on the muon collider

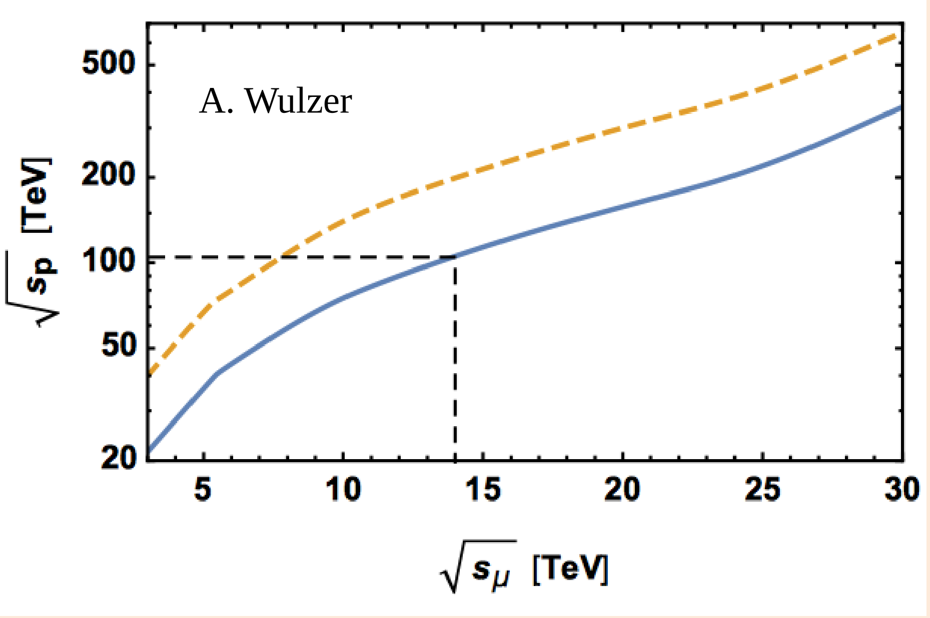
- LDG represents: CERN, DESY, INFN, STFC, IRFU (CEA), CIEMAT, NIKHEF, LNGS, IJCLab (CNRS), PSI
- Group has been chaired by N. Pastrone
- Proposed to the European Strategy Process to form an international collaboration to study the muon collider

# 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

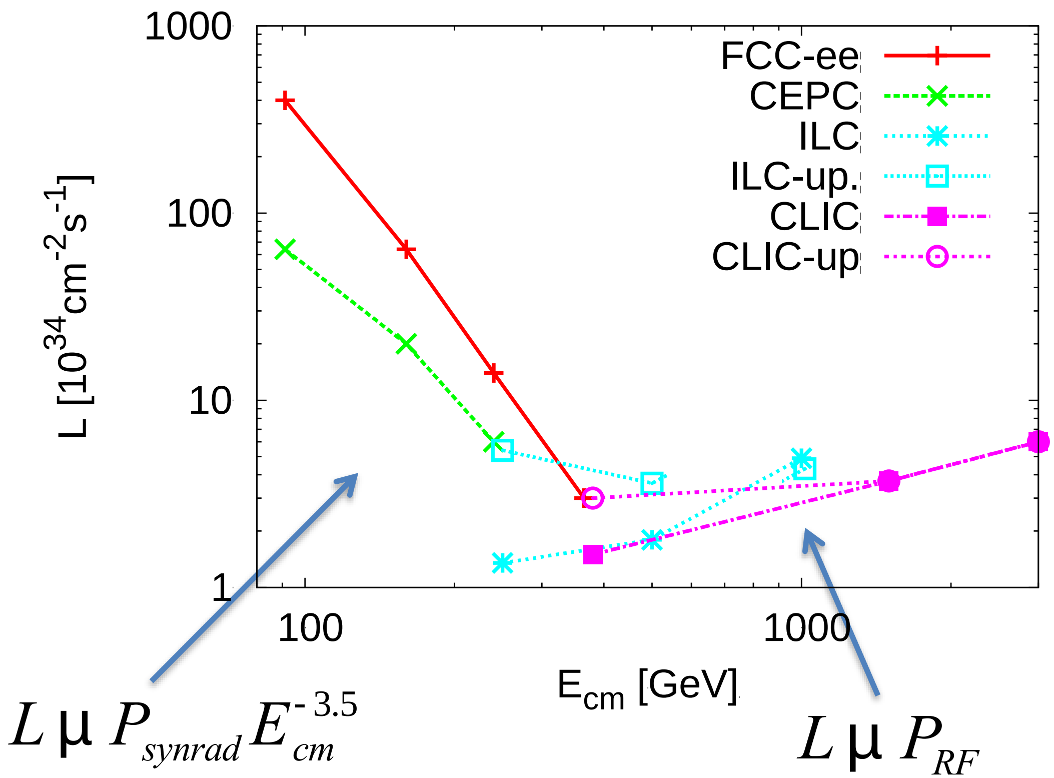
## Luminosity goal

(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**




Maximum proposed energy CLIC 3 TeV

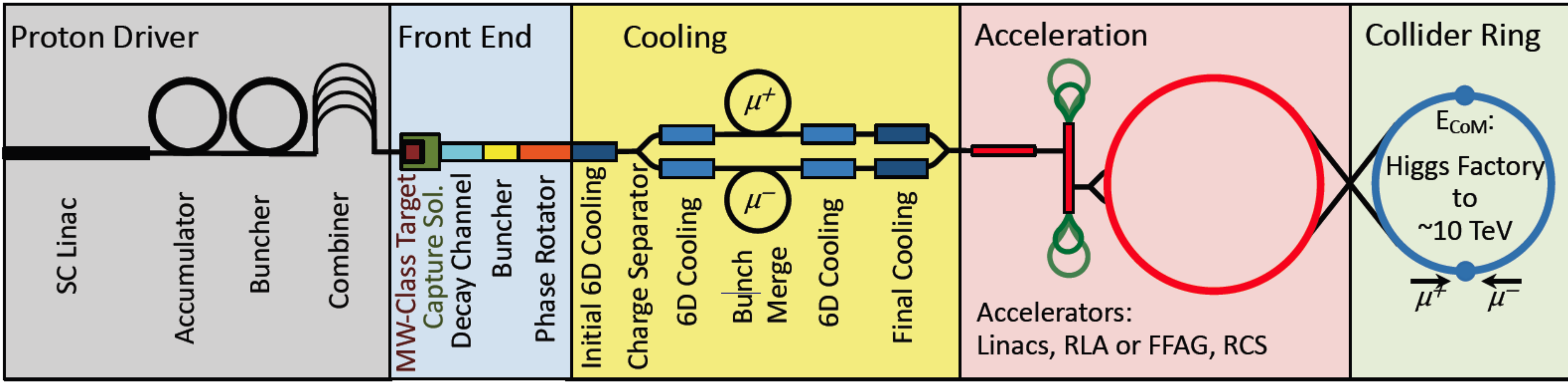
- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy
But cost and power are a concern
Single pass collider needs high voltage and beam current

**Muon colliders** have suppressed synchrotron radiation
Can use the advantages of rings
Ring size defined by maximum magnet field and ring size
**But lifetime at rest only 2.2 μs**

# 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

# Target Parameter Examples

From the MAP collaboration:
Proton source

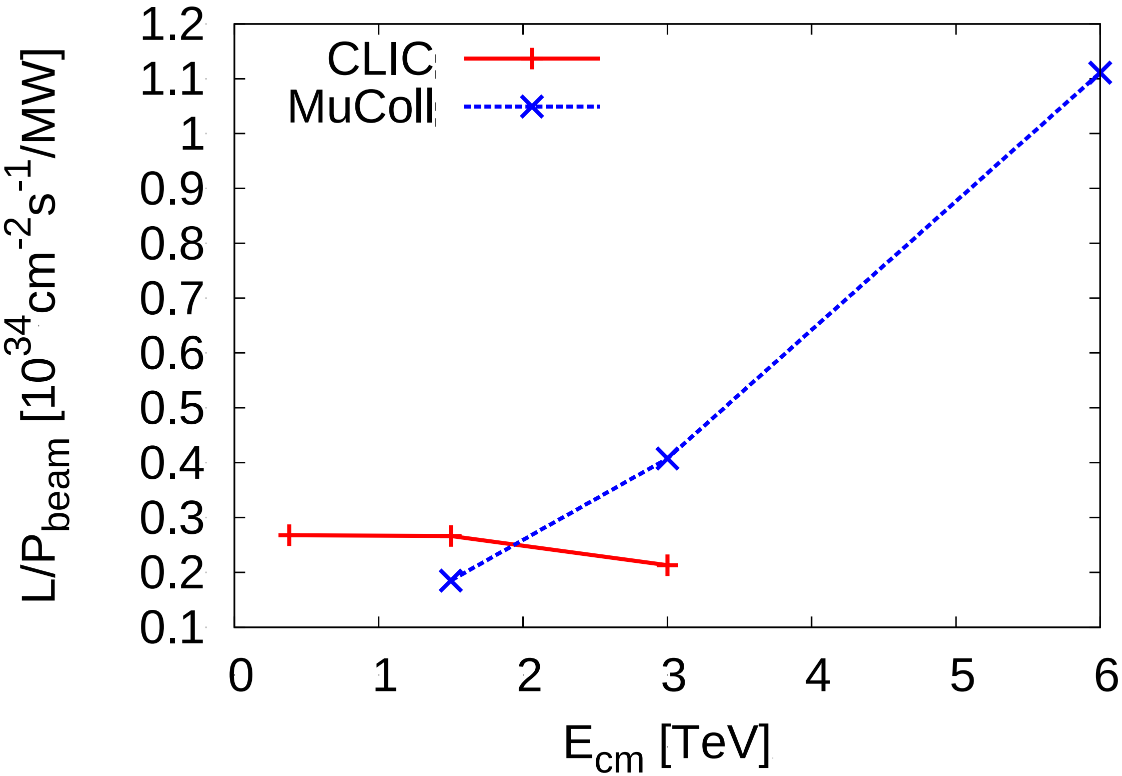
| Muon Collider Parameters | | | | | |
|---|---|---|---|---|---|
| | | Higgs | | | |
| ***Parameter*** | ***Units*** | *Production Operation* | | | *Accounts for Site Radiation Mitigation* |
| CoM Energy | TeV | **0.126** | **1.5** | **3.0** | **6.0** |
| Avg. Luminosity | $10^{34}cm^{-2}s^{-1}$ | 0.008 | 1.25 | 4.4 | 12 |
| Beam Energy Spread | % | 0.004 | 0.1 | 0.1 | 0.1 |
| Higgs Production/$10^7$sec | | 13,500 | 37,500 | 200,000 | 820,000 |
| Circumference | km | 0.3 | 2.5 | 4.5 | 6 |
| No. of IPs | | 1 | 2 | 2 | 2 |
| Repetition Rate | Hz | 15 | 15 | 12 | 6 |
| b* | cm | 1.7 | 1 (0.5-2) | 0.5 (0.3-3) | 0.25 |
| No. muons/bunch | $10^{12}$ | 4 | 2 | 2 | 2 |
| Norm. Trans. Emittance, $e_{TN}$ | p mm-rad | 0.2 | 0.025 | 0.025 | 0.025 |
| Norm. Long. Emittance, $e_{LN}$ | p mm-rad | 1.5 | 70 | 70 | 70 |
| Bunch Length, $s_s$ | cm | 6.3 | 1 | 0.5 | 0.2 |
| Proton Driver Power | MW | 4 | 4 | 4 | 1.6 |
| Wall Plug Power | MW | 200 | 216 | 230 | 270 |

Even at 6 TeV above target luminosity with reasonable power consumption
But have to confirm power consumption estimates

# Comparison MAP vs. CLIC

In linear collider, 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

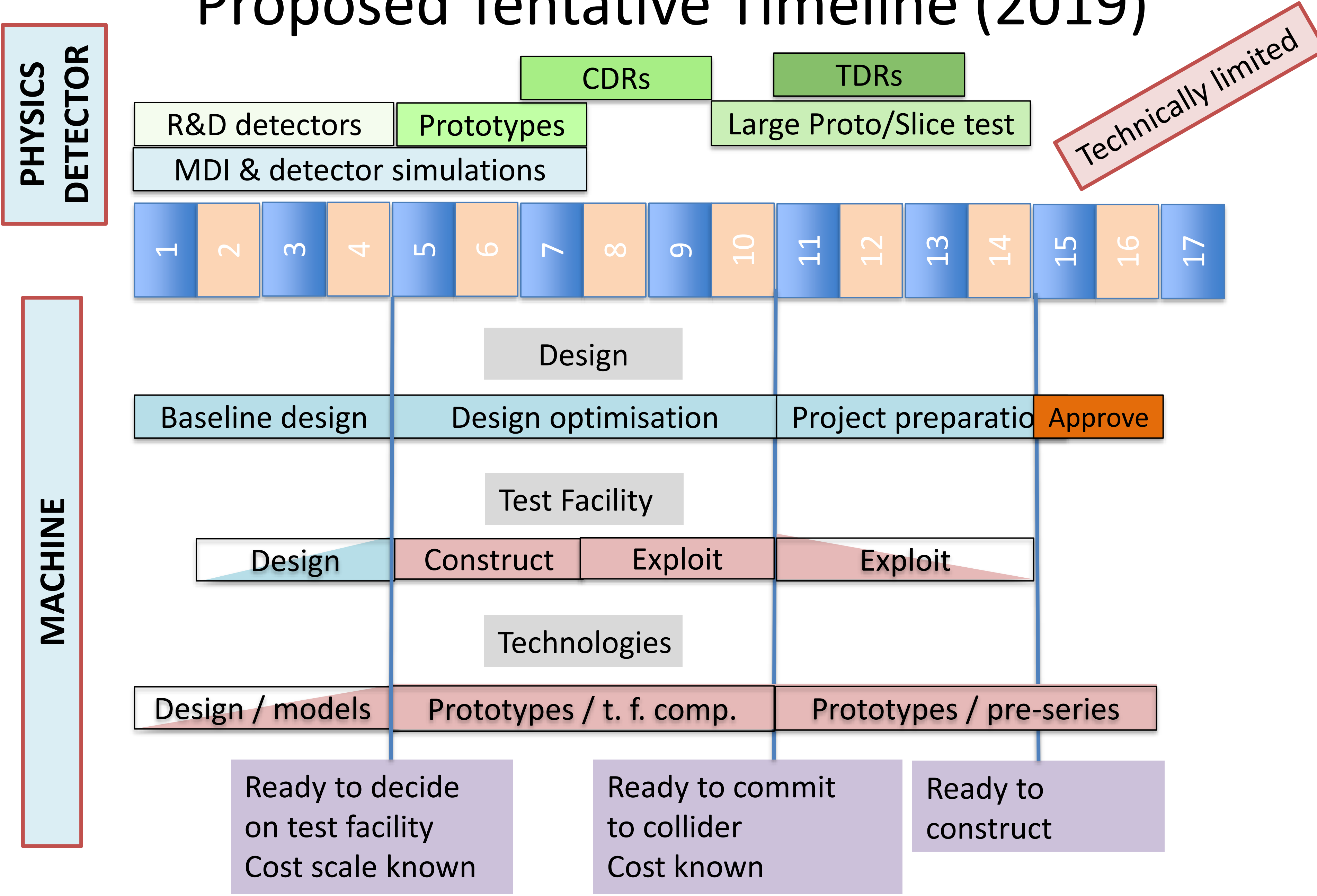
But have to carefully verify this

Overall muon colliders have the potential for high energies

May overcome the energy limitations of linear colliders

**The working group concluded that an Interantional collaboraiton should be formed to study the muon collider**

# Proposed Tentative Timeline (2019)



# European Strategy

From the deliberation document of the European Strategy Update:

**High-priority future initiatives**

[..]In addition to the high field magnets the accelerator R&D roadmap could contain:

[..] an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of $e^+e^-$ -colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

**To start implementing this the Laboratory Directors Group has established an international muon collider collaboration on July 2nd 2020**

- Covering physics, detector and machine
- Now are in the process of getting organised
- Had first meeting July 3rd 2020 (270 participants)
- International design study
  - participation of US and IHEP

# Initial Collaboration Goal

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 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:
  - 3 TeV, well above higgs factory, if possible with technology ready for construction in 10-20 years
  - 10+ TeV, well above normal-conducting linear colliders, with more advanced technology
- Explore synergy with other options (neutrino/higgs factory)
- Define R&D path and design demonstrator

# Initial Collaboration Goal

Objective:

In time for the next European St
study aims to establish whether
demonstrator is justified. It will
supported performance expecta ks
as well as cost and power consu
R&D path to demonstrate the fe

Scope:

- Focus on two energy ranges:
  - 3 TeV, well above higgs facto
    construction in 10-20 years
  - 10+ TeV, well above normal-
    advanced technology
- Explore synergy with other o
- Define R&D path and design

Next European Strategy Update likely means 5 years before submission

Envisage to split this into
2 years exploration phase
3+ years definition phase

We need to make sure that this timescale is sufficient for other regions

**An important milestone is set by the current Snowmass process**

- What do we need to provide and how can we exploit this to the benefit of the muon collider?

# Tentative Target Parameters

| 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 |
| $\varepsilon_L$ | 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 |

Based on MAP source and concept

The same source for all energies

Achieves physics goal of

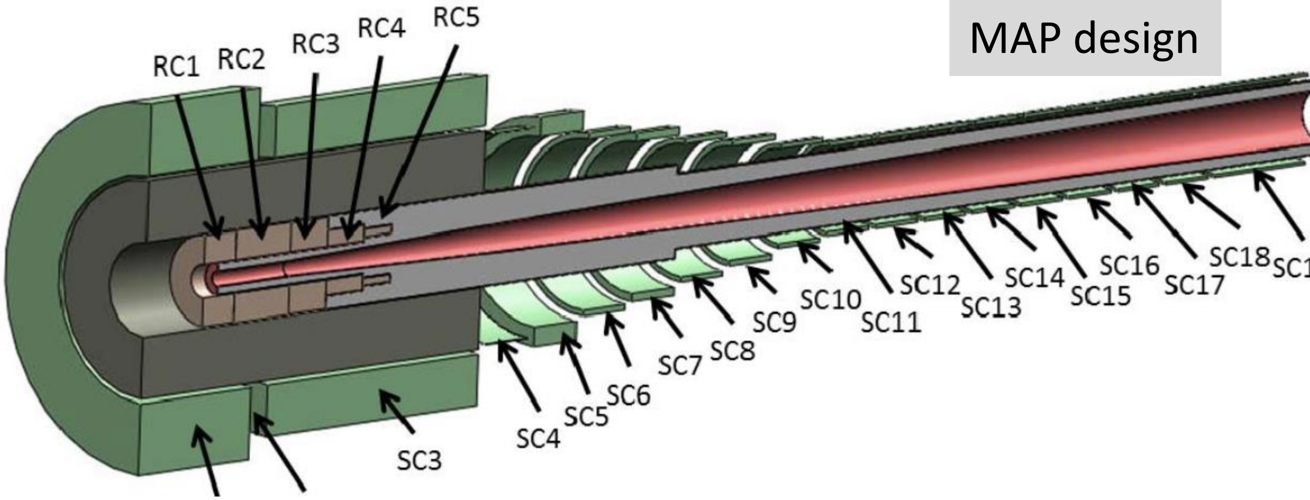
$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left( \frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}} \right)^2 2 \cdot 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

# Source

**Intense proton beam** is challenging

Need to make choices for the **target**

**Ambitious high-field solenoid**




High power target (8 required) has been demonstrated

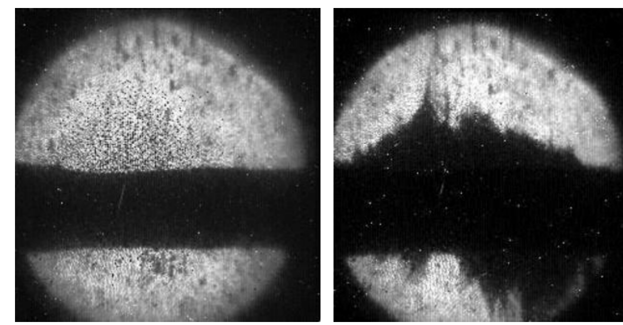
Target has to withstand **strong shock**

Maximum of $30 \times 10^{12}$ protons with 24 GeV

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

But radiation issues?

Maybe can use solid target



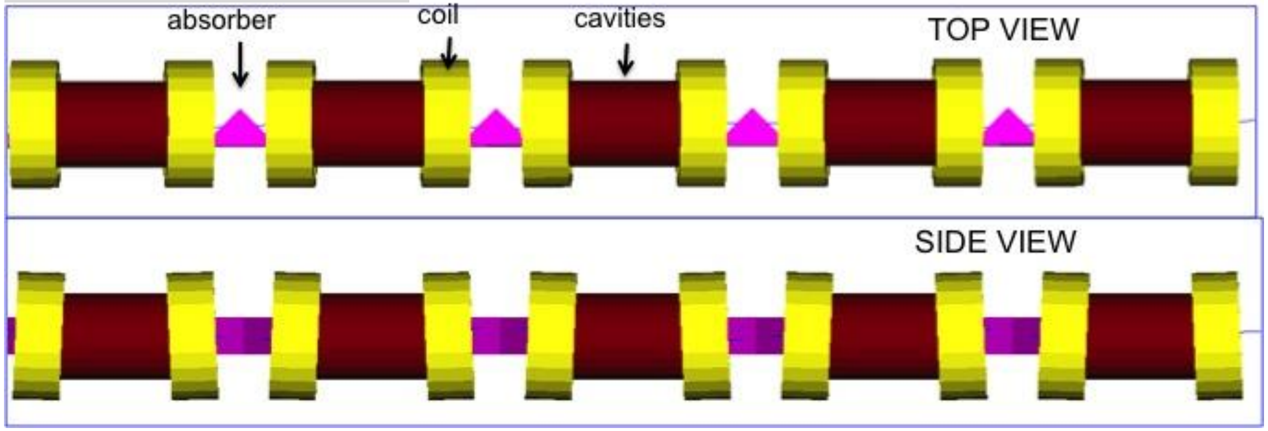
Important power of proton driver O(MW)
need to take care of debris for downstream systems
need to cool

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

# Cooling Concept

See previous presentation by J. Pasternak

MAP collaboration

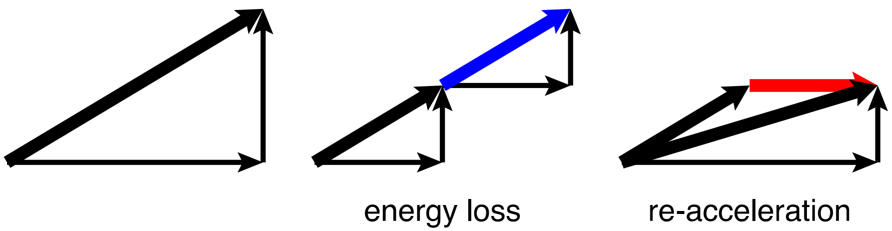



Superconducting solenoids

High-field normal conducting RF

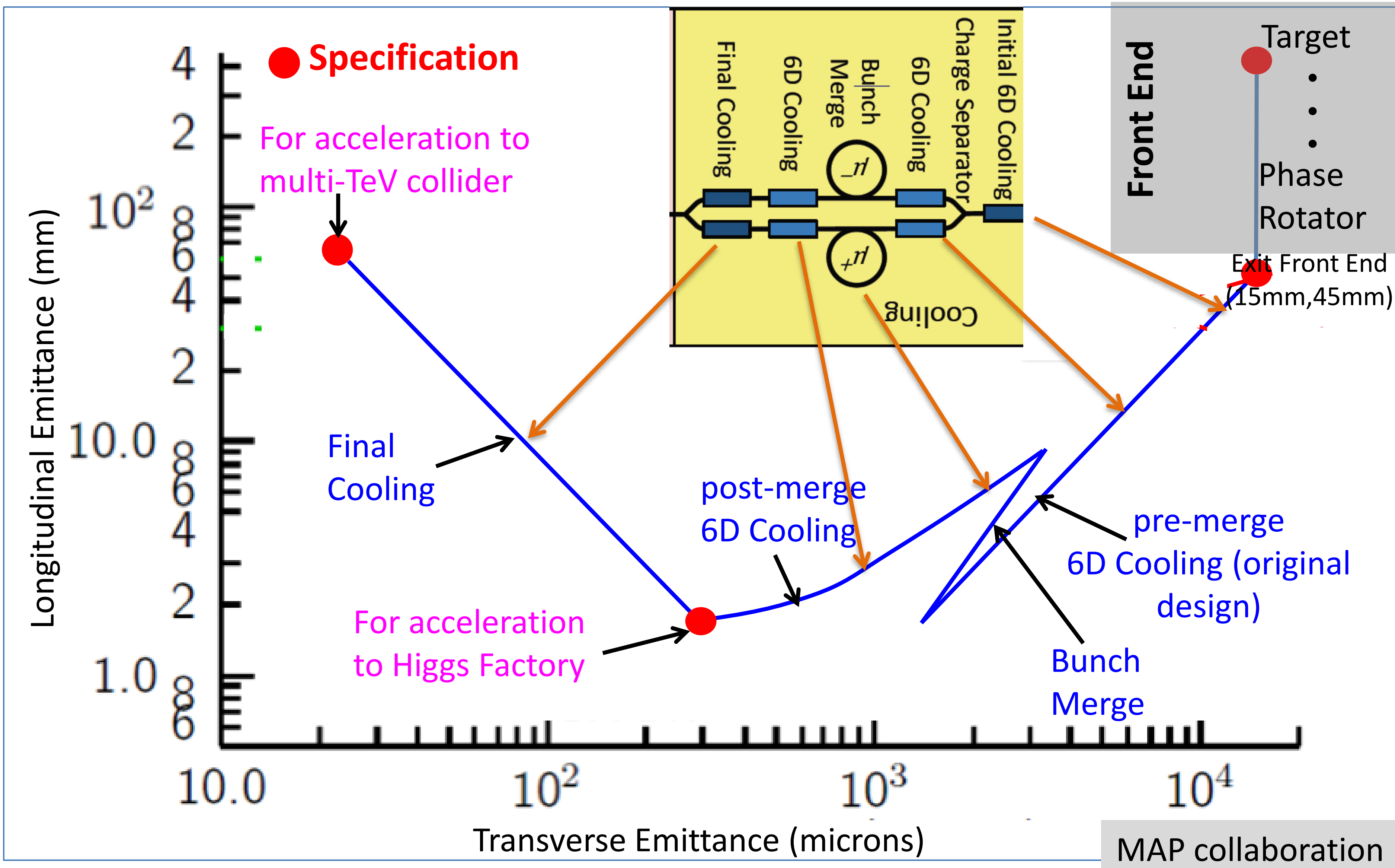
Liquid hydrogen targets

Compact design

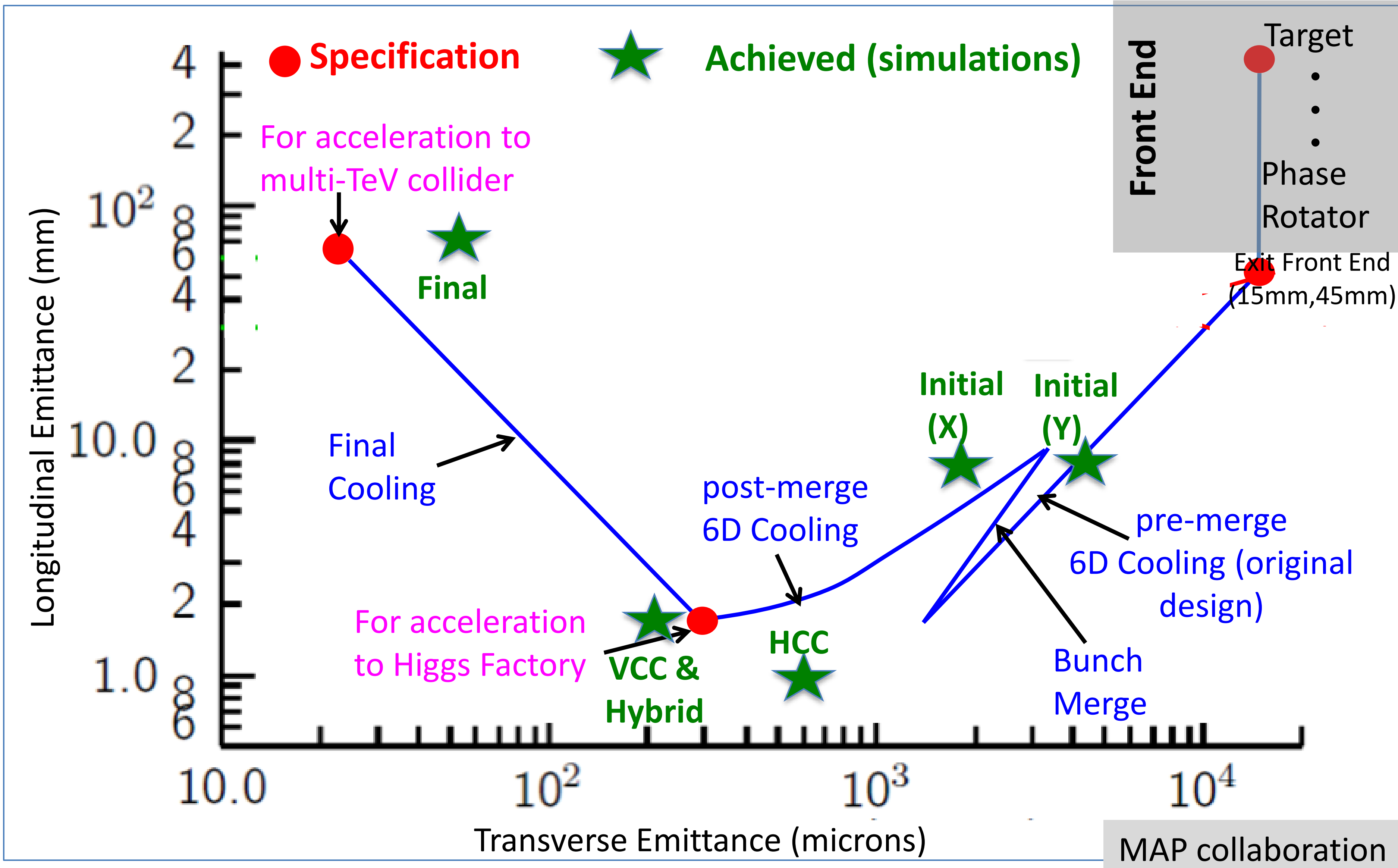



$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

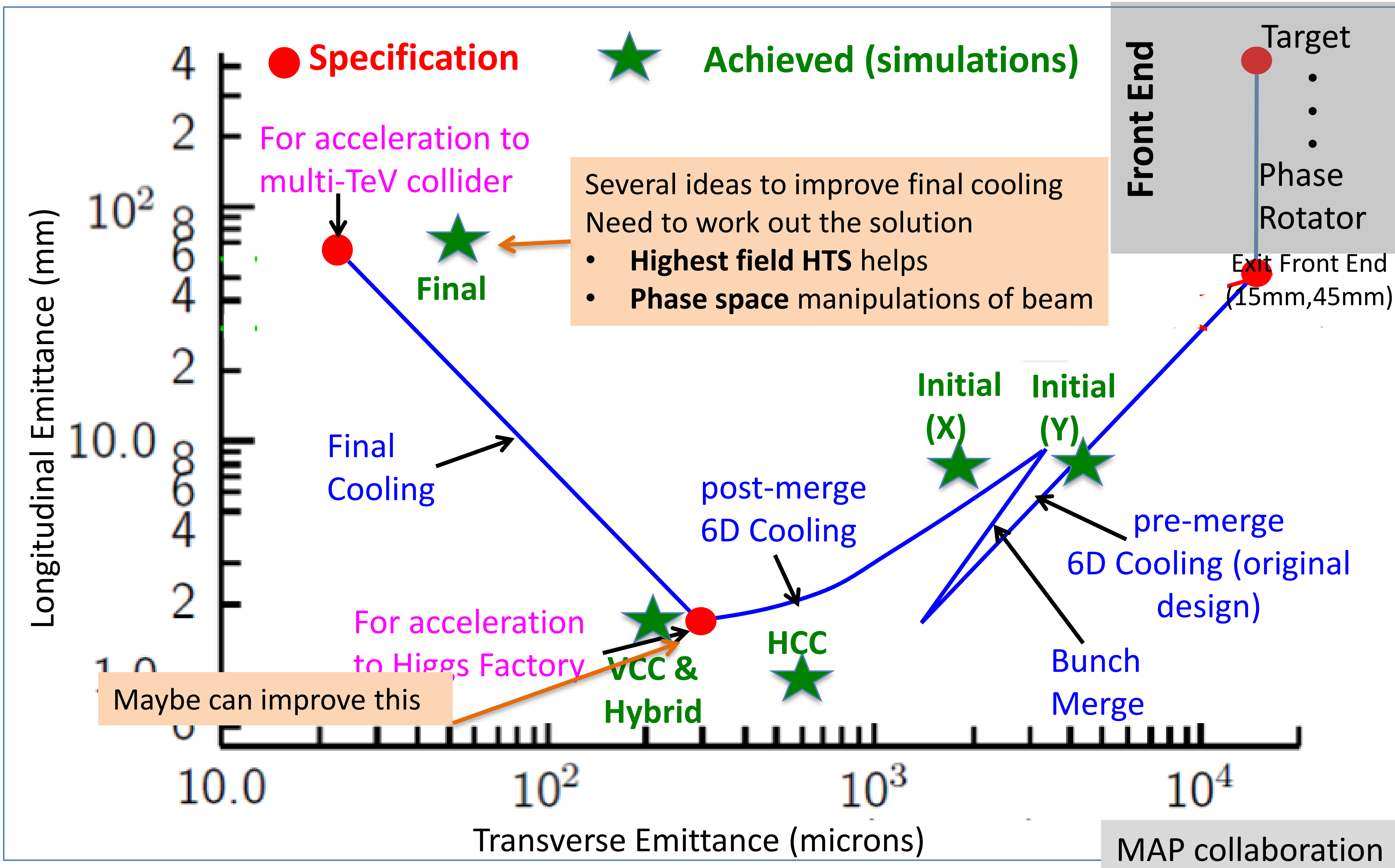
# Cooling: The Emittance Path



# Cooling: The Emittance Path



# Cooling: The Emittance Path



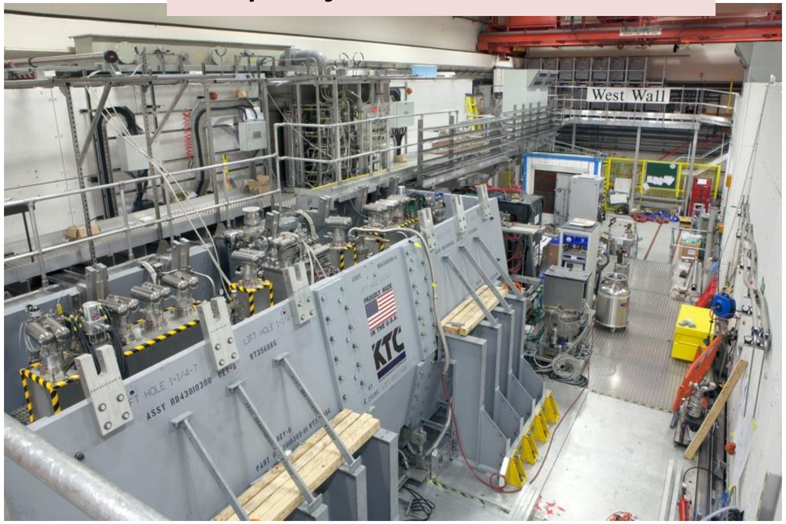
# Design Status

As you just heard in detail

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

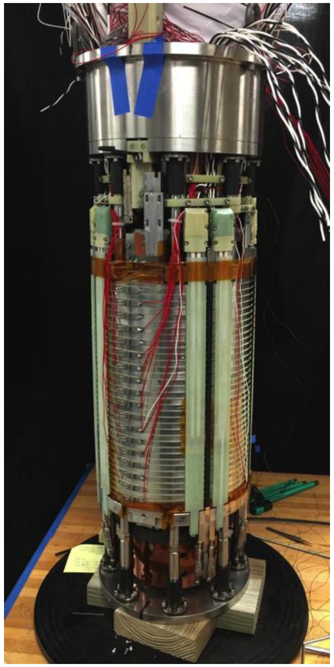
But no CDR, no integrated design, no reliable cost estimate
More work to be done, e.g. substantial, 6D cooling

MICE (UK)

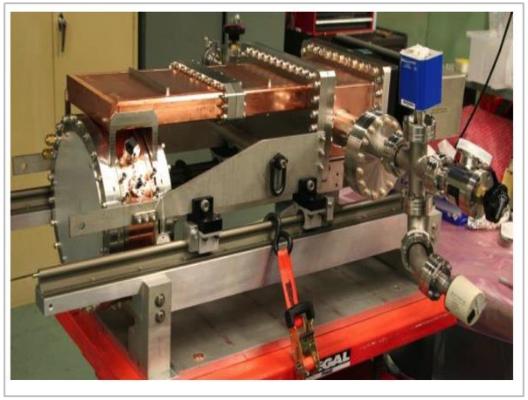



**FNAL**
Breakthrough in HTS cables

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



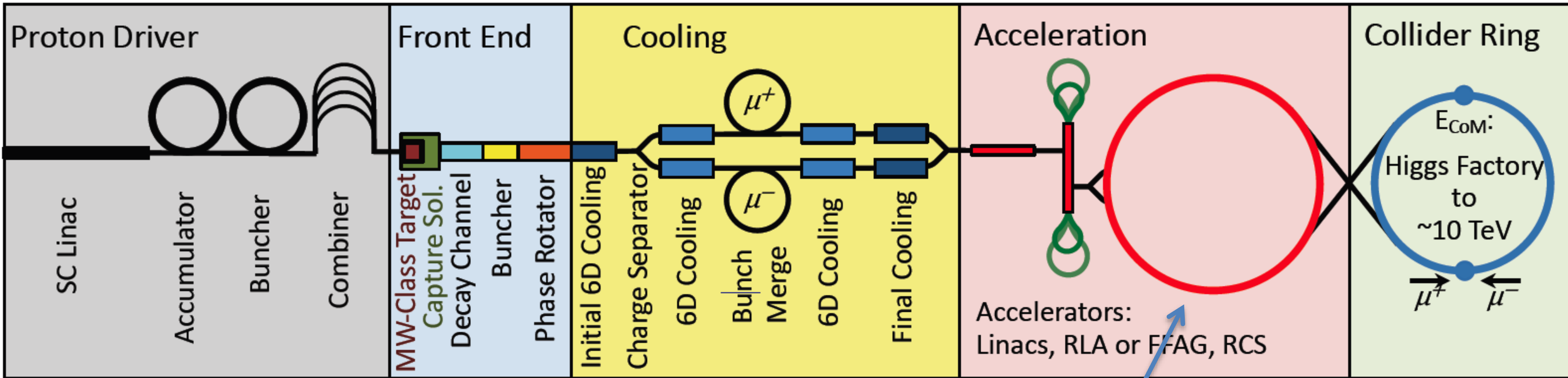
**MuCool**: >50 MV/m in 5 T field



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

Mark Palmer

# Beam Acceleration




An important cost driver

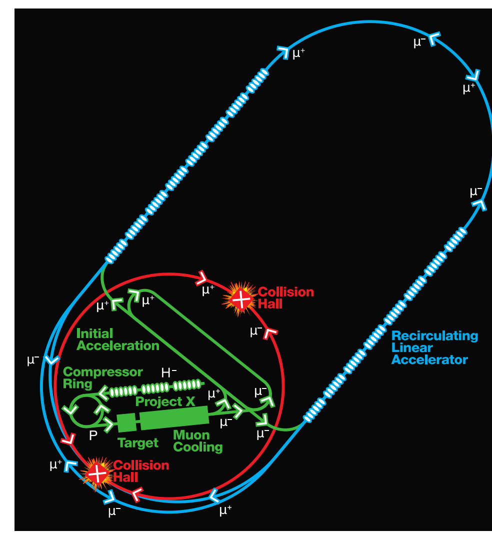
Important for power consumption

Much larger than collider ring

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAGs
- Rapid cycling synchrotrons

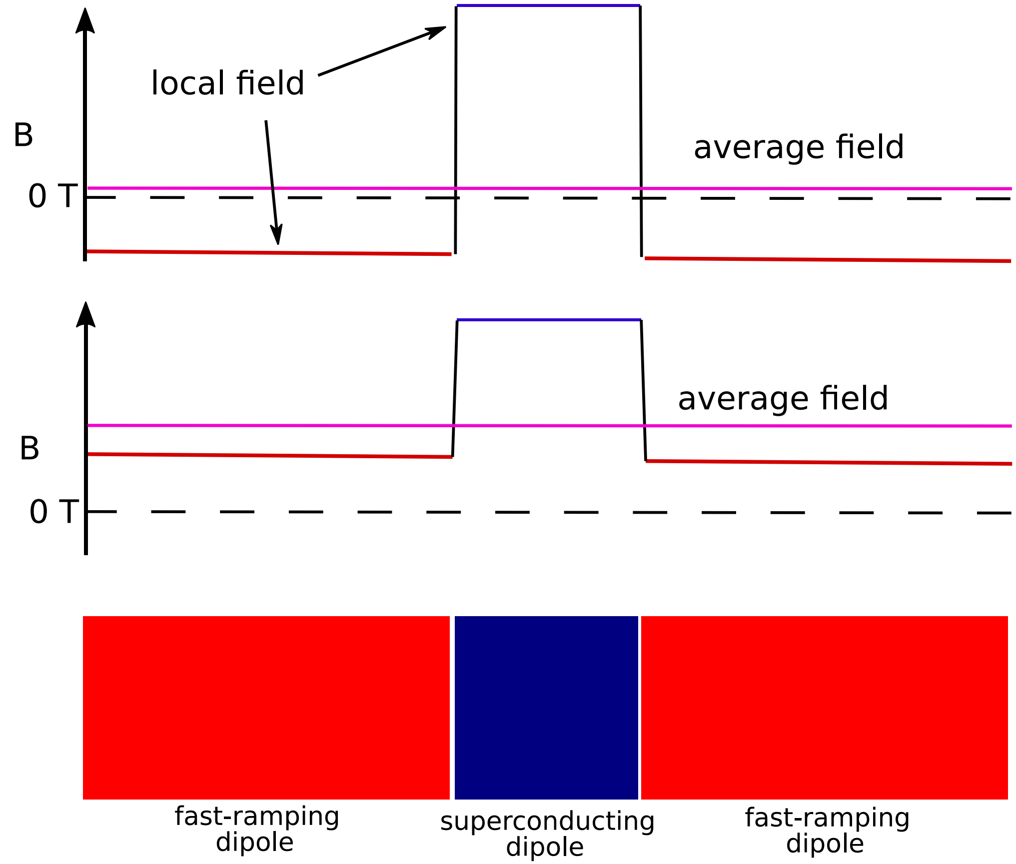


# High-energy Acceleration

Rapid cycling synchrotron (RCS)
- Inject beam at low energy and ramp magnets to follow beam energy
- Could use combination of static superconducting and ramping normal-conducting magnets

**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

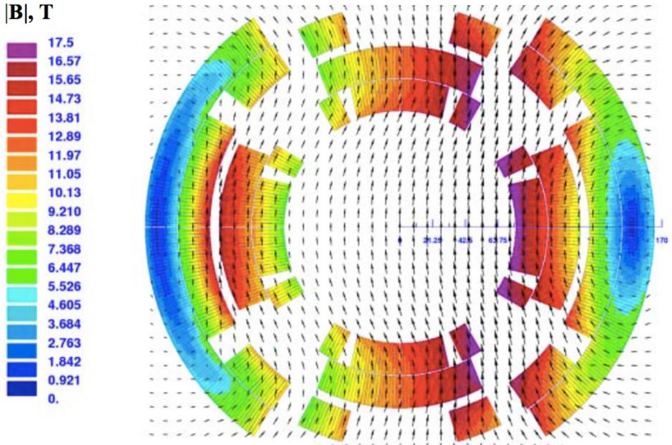
# Collider Ring

**High field dipoles** to minimise collider ring size and maximise luminosity

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

Combined function magnet design




V.V. Kashikhin et al.

Need **combined function magnets**

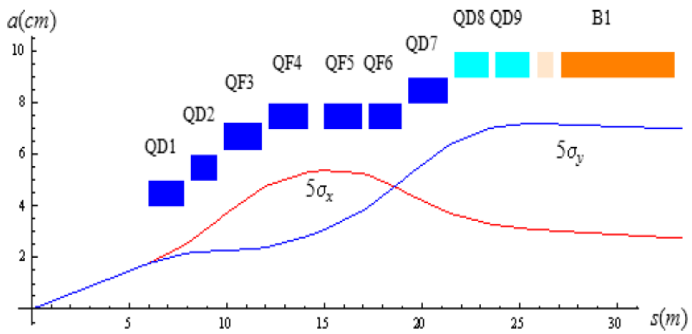
Strong focusing at IP to maximise luminosity

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

# MDI

See next presentation by F. Collamati

At 14 TeV:
40,000 muons decay per m and bunch crossing
At 3 TeV:
200,000 muons per m and bunch crossing

Beamline and detector are shielded

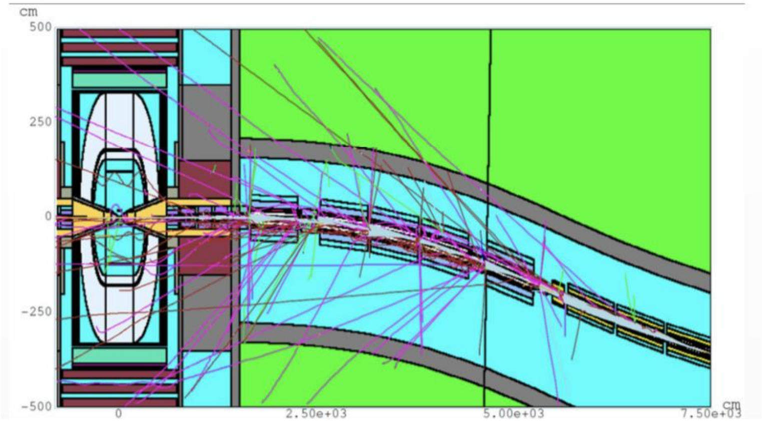
Simulations at 1.5 TeV centre-of-mass show this might be fine

Important effort required to study and mitigate impact of muon decays

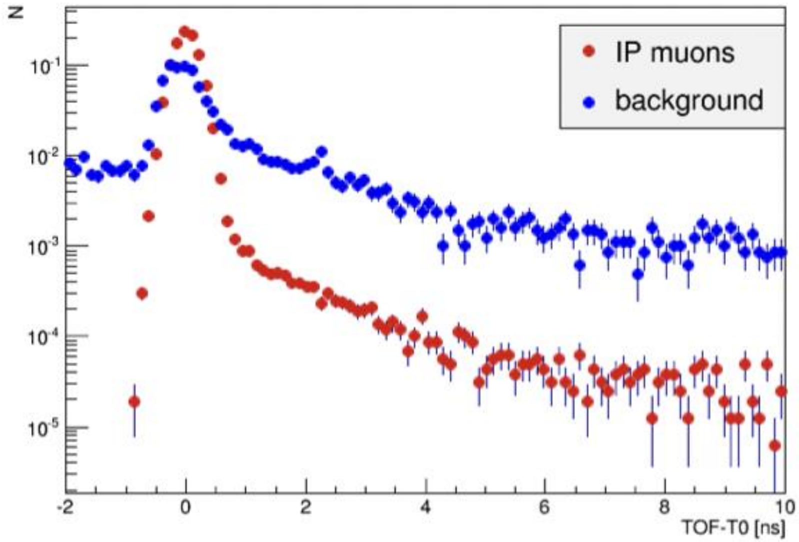
Detector must be designed for robustness
- effective masking
- high granularity
- fast timing
- clever algorithms

Detailed design of machine is required for this

D. Lucchesi et al.




Significant difference in arrival time

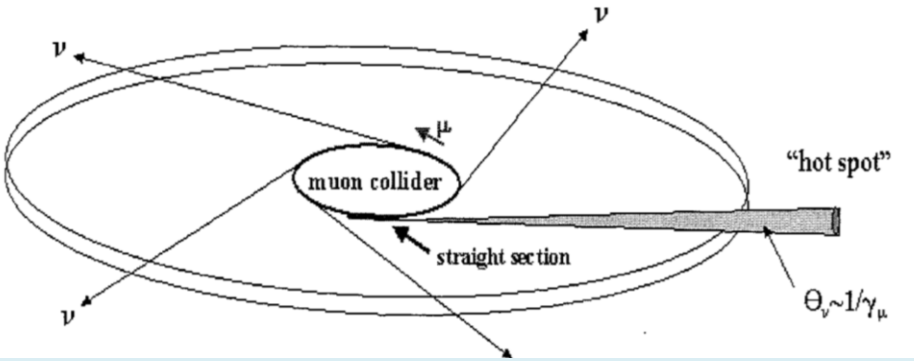


# Site Considerations

Could we reuse LHC tunnel?

- 14 TeV accelerator or combined accelerator/collider ring (V. Shiltsev, D. Neuffer)
- 3 TeV accelerator using more conventional technology
  - with new collider ring of 4.5 km optimised for luminosity

Limit can come from neutrino radiation
Decaying muons produce two neutrinos, which can produce showers just when they exit the earth
Minimise this as much as possible



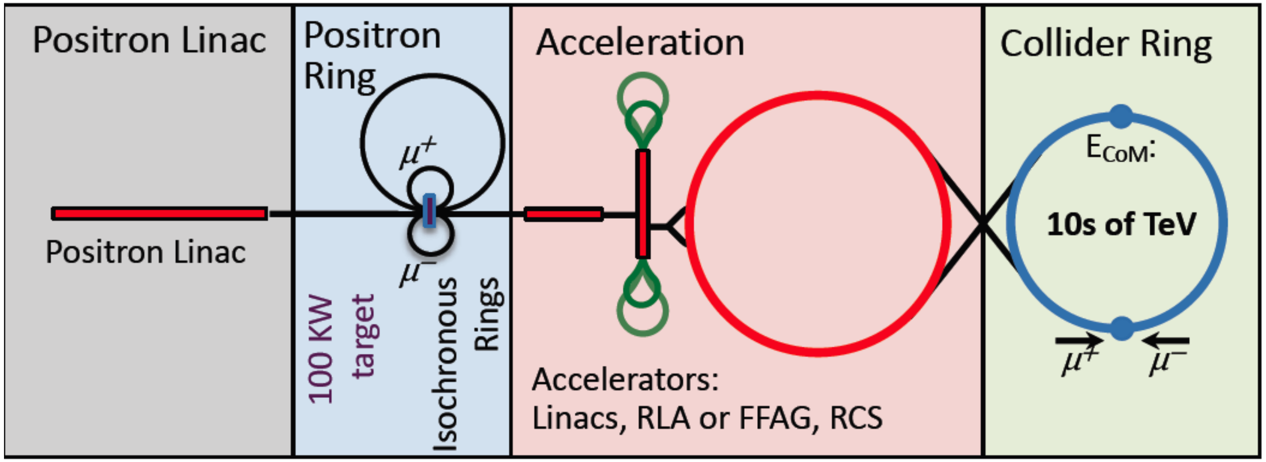

Potential mitigation by

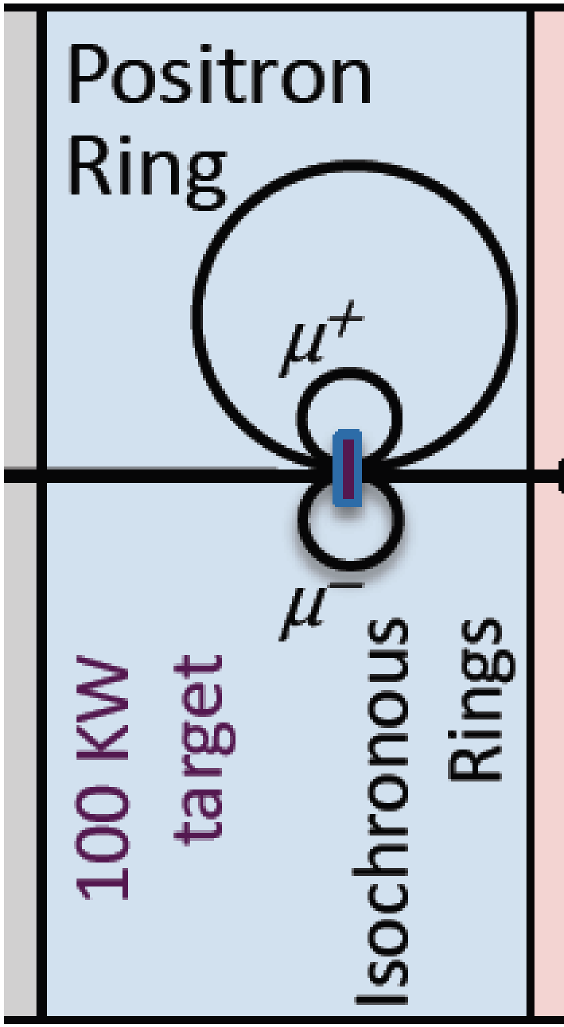
- Owning the land in direction of experimental insertion
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
- Some gymnastics with beam in straights to make it point in different directions
- Maximise luminosity per beam current
- …

Gut feeling based on some calculations, need serious review:

- LHC tunnel could work for 3 TeV accelerator
- Have to do more work for other options

# Alternative: The LEMMA Scheme




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

Low-emittance muon beam can reduce radiation

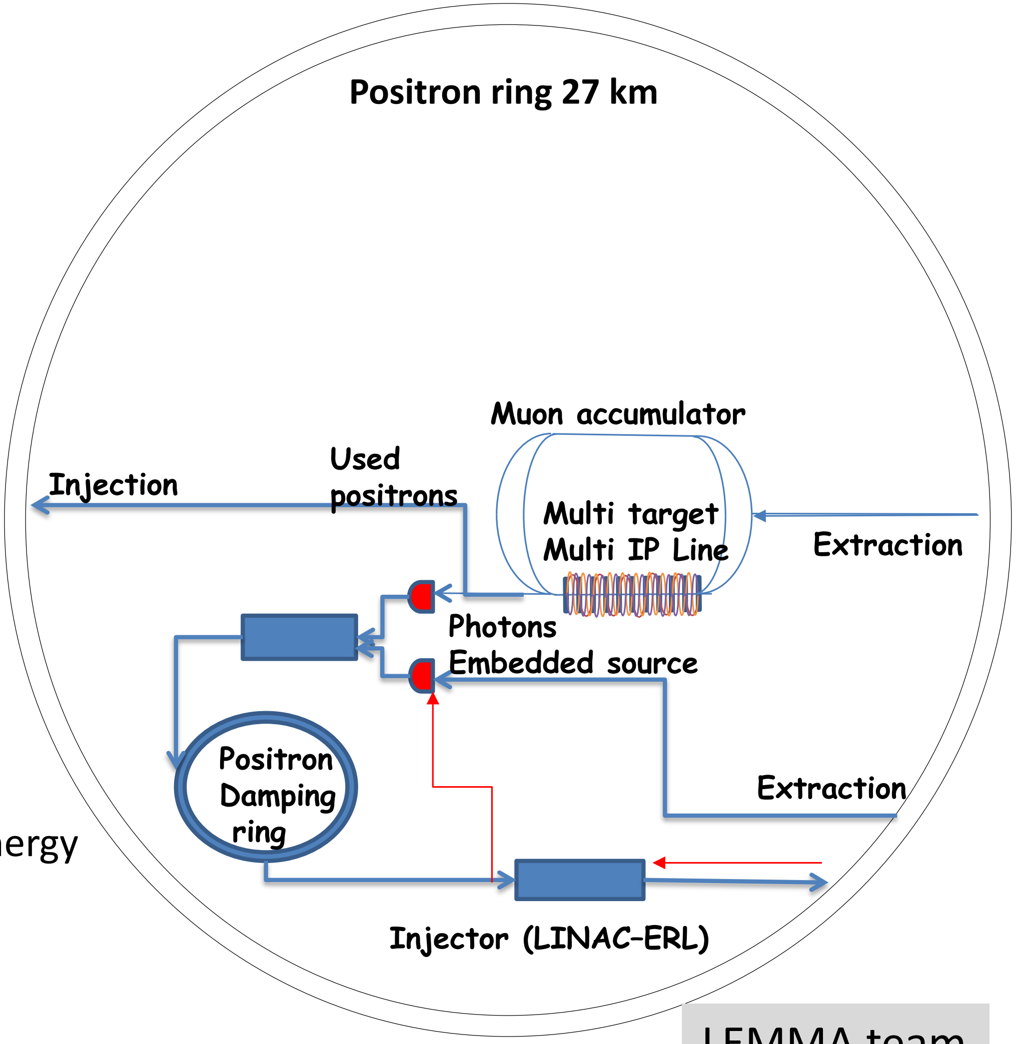
Less mature than proton-driven scheme
Large positron current required
Target is challenging
Large positron production rate [$O(10^{17}/s)$]
Currently do not reach luminosity goal

# Ongoing LEMMA Effort

Ongoing effort to address identified challenges

- Positron production
  - Rotating target (like ILC)
  - Use of positron beam for production
- Positron ring challenge
  - larger ring, pulsed ring, lower energy accumulator ring
- Large emittance from target
  - use sequence of thin targets, $H_2$ targets, …
  - Increased muon bunch charge, e.g. better capturing, …
  - muon cooling (crystals, stochastic, …)
- Difficulty of combining muon bunches at high energy
  - Increasing charge at the source (producing bunches in pulsed fashion)
  - increase muons per positron bunch

More detailed studies needed to understand what does work and how well




LEMMA team

# Path Forward

We will need you

Highest priority is to form the collaboration

- All partners taking ownership
  - define the work programme
  - find resources
  - start to work

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

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

- Will upload information

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