Muon Collider Collaboration

Daniel Schulte for the forming international muon collider collaboration

Introduction

Muon collider had been studied mainly in the US (MAP), effort reduced after P5

Other activities mainly in UK (demonstration of ionisation cooling) and at INFN (alternative muon production scheme)

The Laboratory Directors Group (LDG) appointed a working group (chair N. Pastrone) to review the muon collider for the European Strategy Update

- The report was favorable

The updated strategy recommends R&D on muon beams

The LDG initiated an international muon collider collaboration

- kick-off meeting July 3rd, 272 participants

CERN will host the study, we are finalising a Memorandum of Cooperation

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.

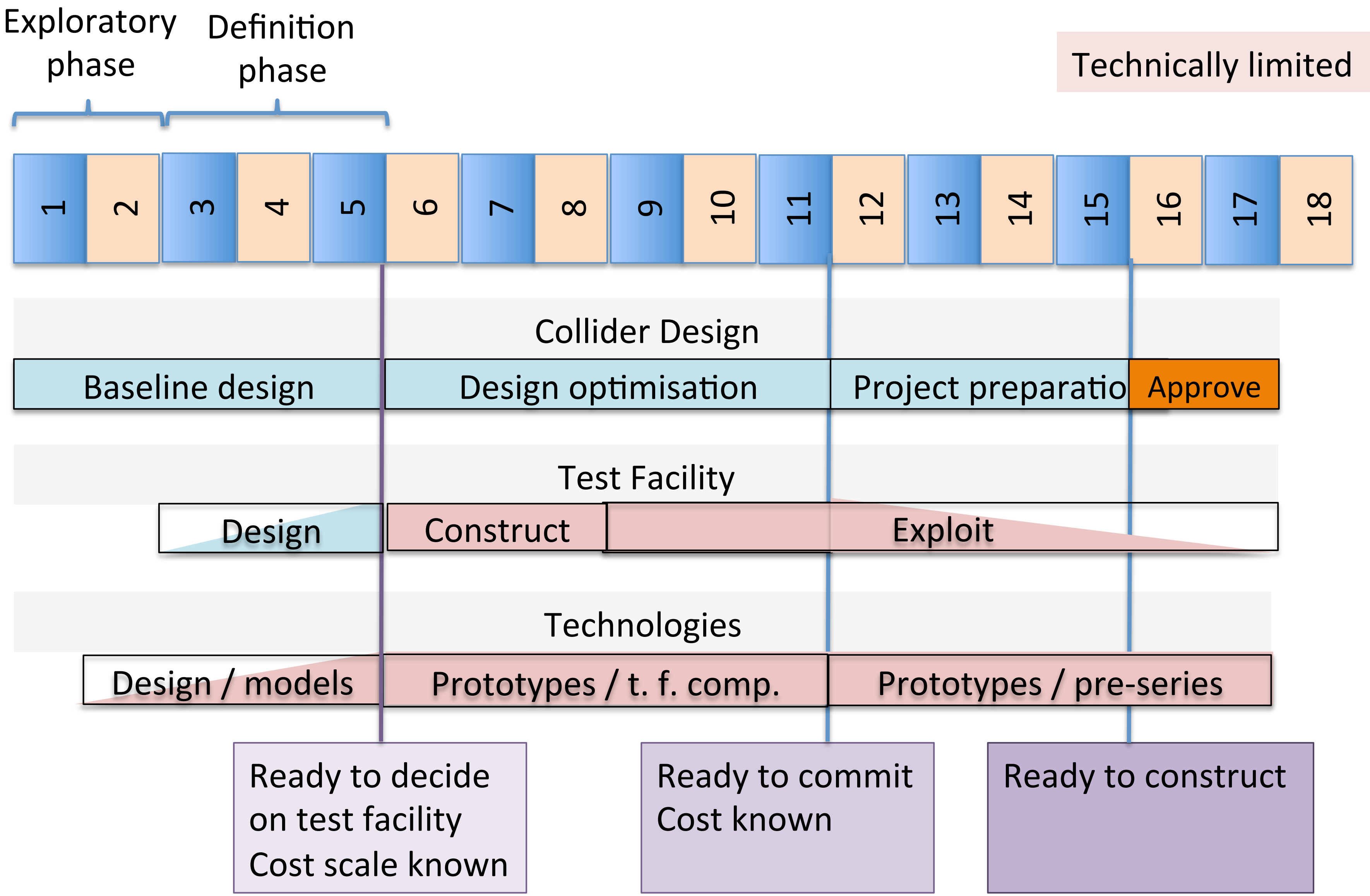
Deliverable:

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

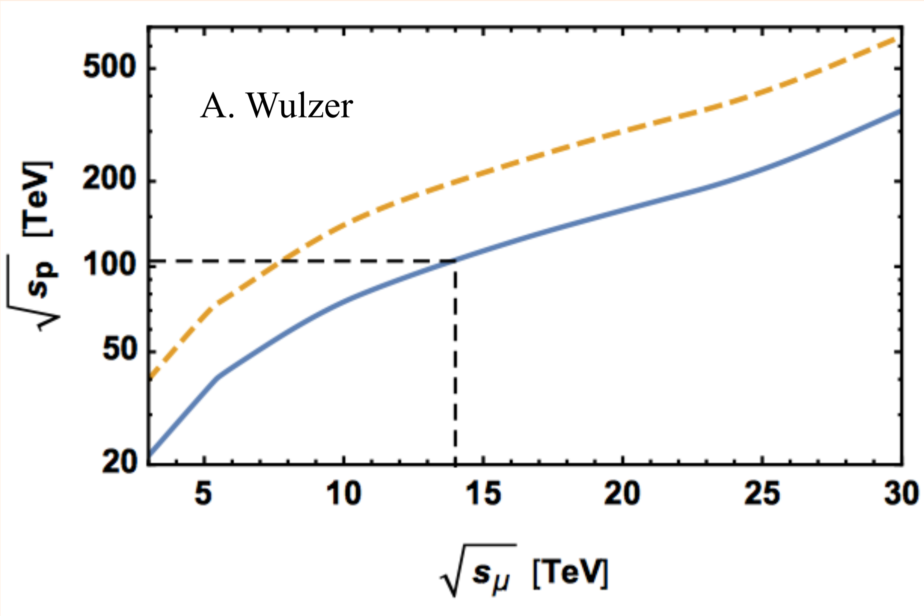


Lepton Physics at High Energy

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

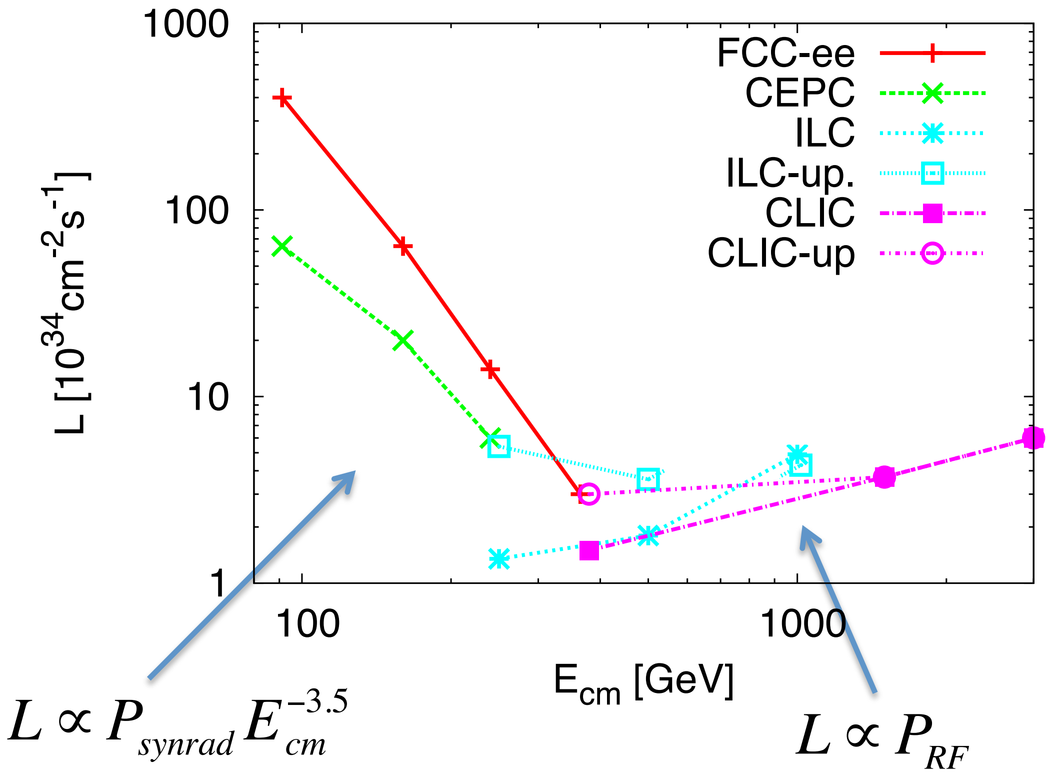
Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
$4 \times 10^{35}\ cm^{-2}s^{-1}$ 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 (ESU)

Luminosity per facility



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

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)

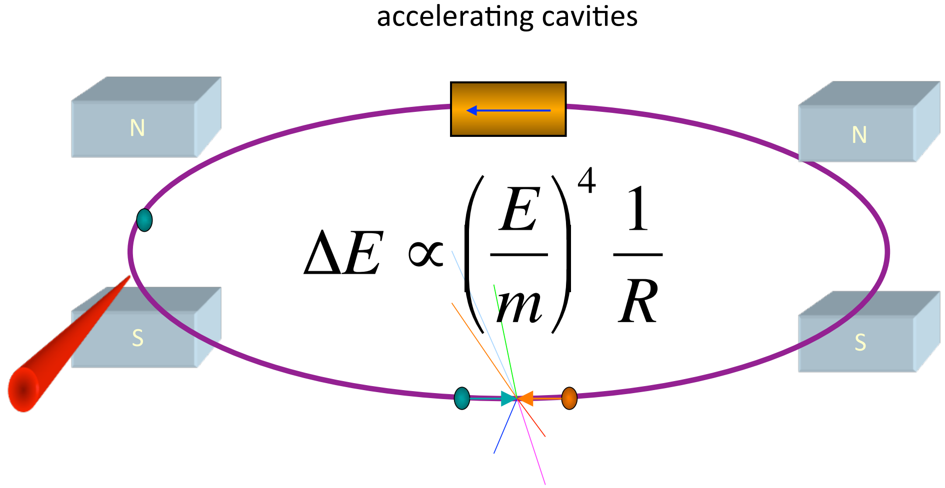
Technically possible to go higher in energy

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

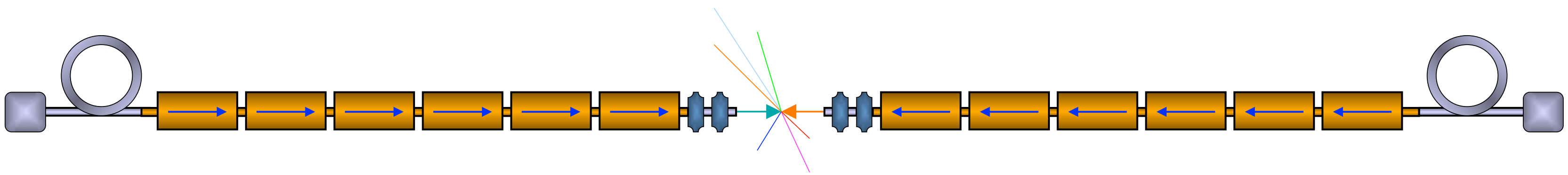
Strong dependence on particle mass

Hence **proton rings** are energy frontier

Electron-positron linear colliders avoid synchrotron radiation, but **single pass**

Energy challenge
Need full voltage in main linac which is costly

Luminosity challenge
Need very small beam size at collision is required, leads to strong beam-beam effects, requires extremely tight tolerances



Linear Collider Cost

CLIC cost at 3 TeV is about 18 GCHF

CLIC additional cost at 14 TeV: around 40-50 GHCF

- upgrade 1.5 to 3 TeV about 8 GCHF
- (14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = **59 GCHF**
- some cost reduction due to large-scale production
- upgrade could be performed in affordable steps but might have limited interest in each step

Plasma technology might potentially lead to a cheaper accelerator once it is mature

- much higher gradients
- but many issues to be solved

Linear Collider Luminosity

For constant technology

- keep bunch charge and length constant

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

- emittances and betafunctions are constant
  - same beam quality and same focusing
  - these are not directly linked to the acceleration technology
    - emittance is determined by damping rings
    - and degradation during acceleration
    - betafunction is quality of the focusing system
  - actually becomes harder at higher energies
    - more emittance degradation
    - harder to focus beam because of synchrotron radiation in focusing system
    - actually already visible at CLIC at 3 TeV

$\Rightarrow$ **Luminosity per beam power independent of energy**

Linear Collider Luminosity

CLIC requires about 300 MW of wall plug power for the RF to produce 28 MW of beam power and 300 about MW for other systems (e.g. magnets)

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

For CLIC about **190 MW beam power** to reach 40 x 10^{34}cm^{-2}s$^{\wedge-1}$ at 14 TeV

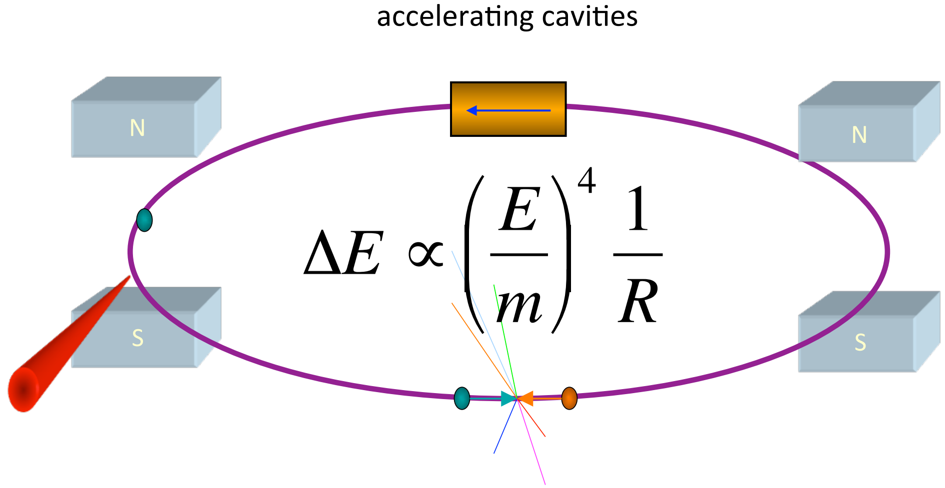
If we consider only luminosity above 99% of nominal centre-of-mass energy, we need about **570 MW beam power**

Efficiency from wall plug power into RF systems to beam power is O(10%)

- so **O(2-6 GW)** of **total power** consumption

Need to add the other systems (which also will increase compared to 300 MW)

Muon Collider Idea



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

Muons are much heavier than electrons
⇒ strongly suppressed synchrotron radiation
⇒ can use a ring and profit from multi-pass

Less RF voltage required
Can collider beams repeatedly

But muon lifetime is limited to 2.2 μs at rest

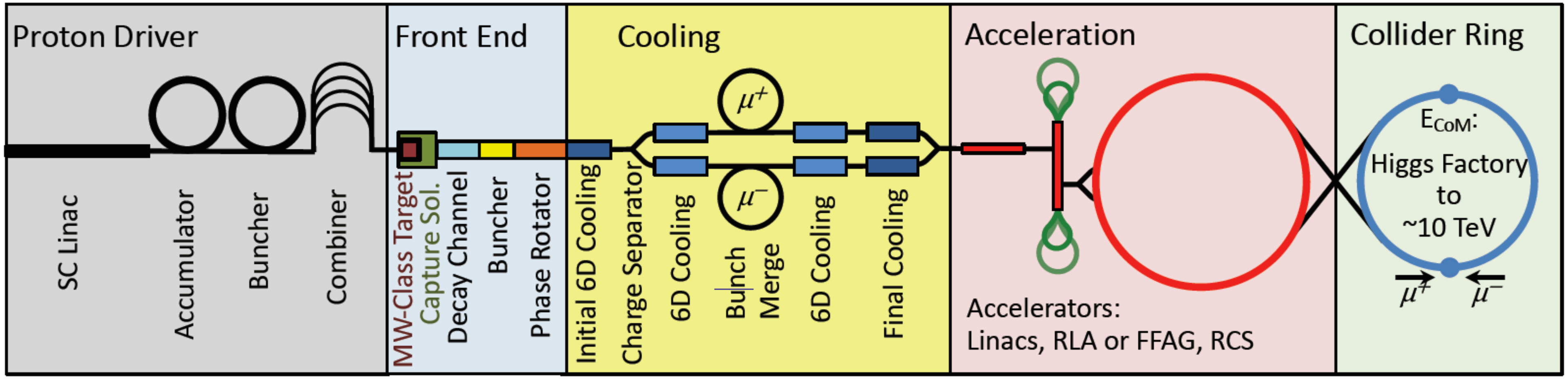
⇒ need to rapidly accelerate to increase lifetime

⇒ can only obtain limited number of collisions

⇒ need to deal with decay products (electrons/positrons and neutrinos)

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

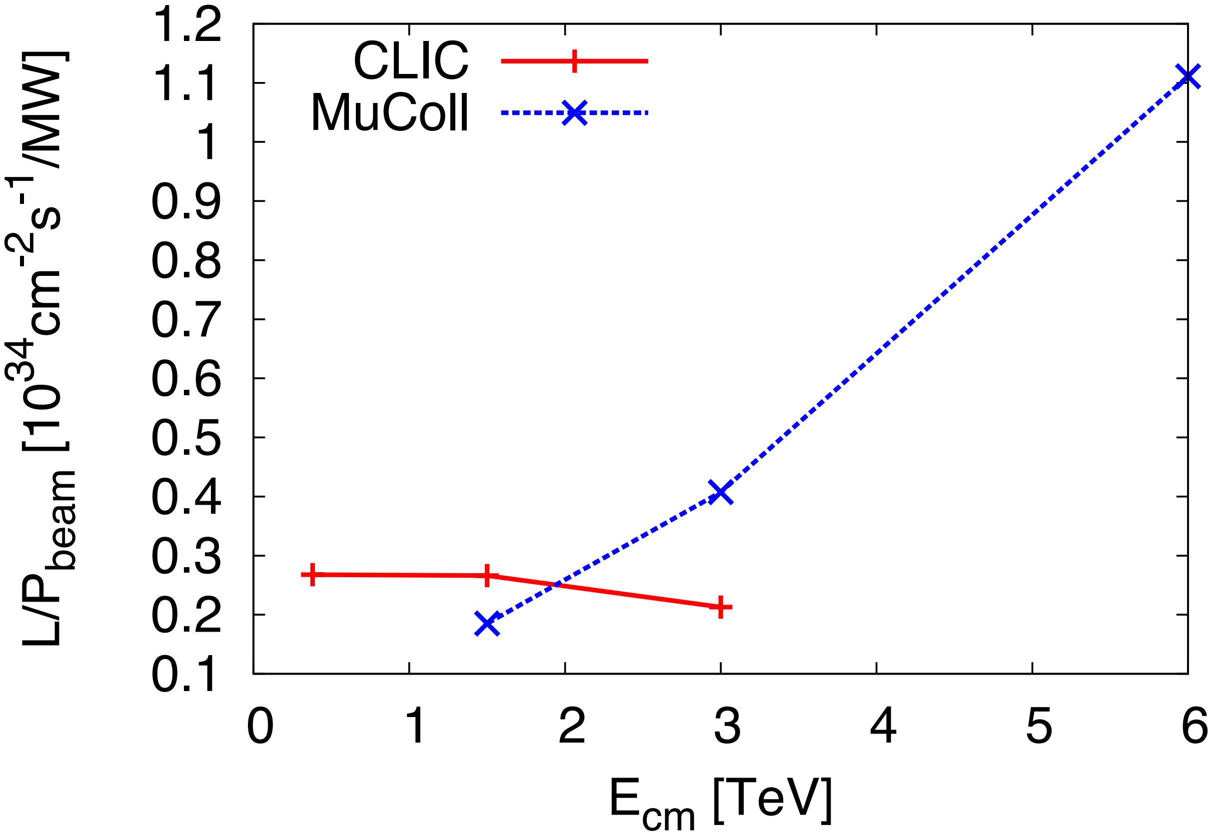
No CDR exists, no coherent baseline of machine
No cost estimate
Need to extend to higher energies (10+ TeV)
But did not find something that does not work

Comparing Luminosity in MAP vs. CLIC

Luminosity per beam power increases with energy in a muon collider

Overall muon colliders have the potential for high energies

May overcome the luminosity limitations of linear colliders



European Strategy advised to consider muon collider

Luminosity Goals

Target integrated luminosities

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

Target Parameter Scaling

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
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$\sigma_{x,y}$	µm	3.0	0.9	0.63

Scaled from MAP parameters

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

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

Betafunction decreases

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

Muon Collider Luminosity Drivers

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

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

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)

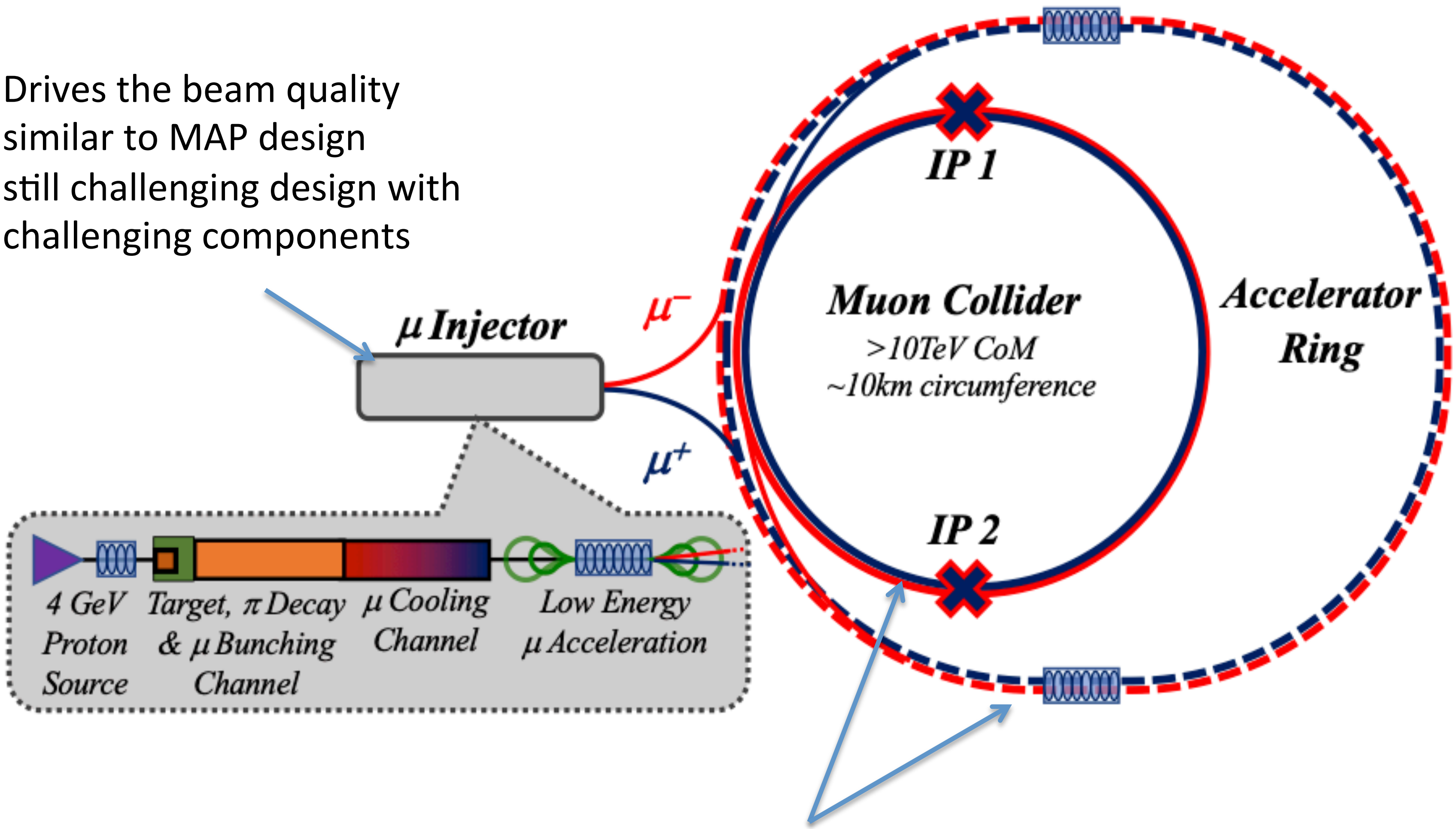
- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **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

Drives the beam quality
similar to MAP design
still challenging design with
challenging components



Cost and power consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts beam quality
Drives neutrino radiation and beam induced background

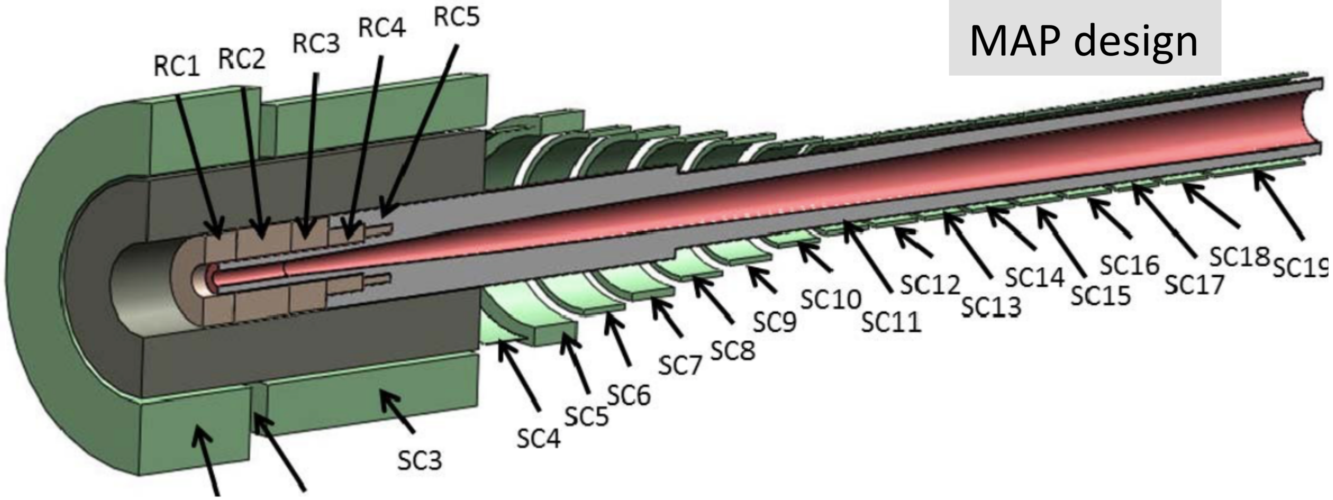
Source

Intense proton beam is challenging

Need to make choices for the **target**

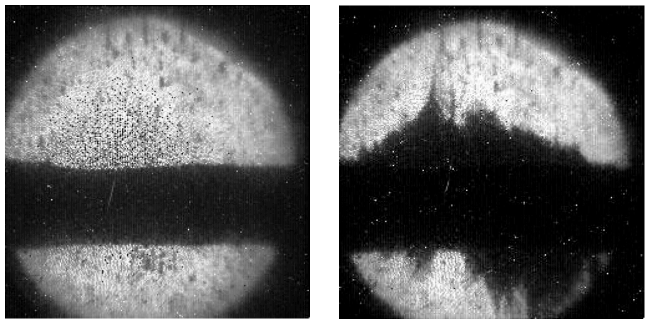
Ambitious high-field solenoid

MAP design



Target has to withstand **stress**

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

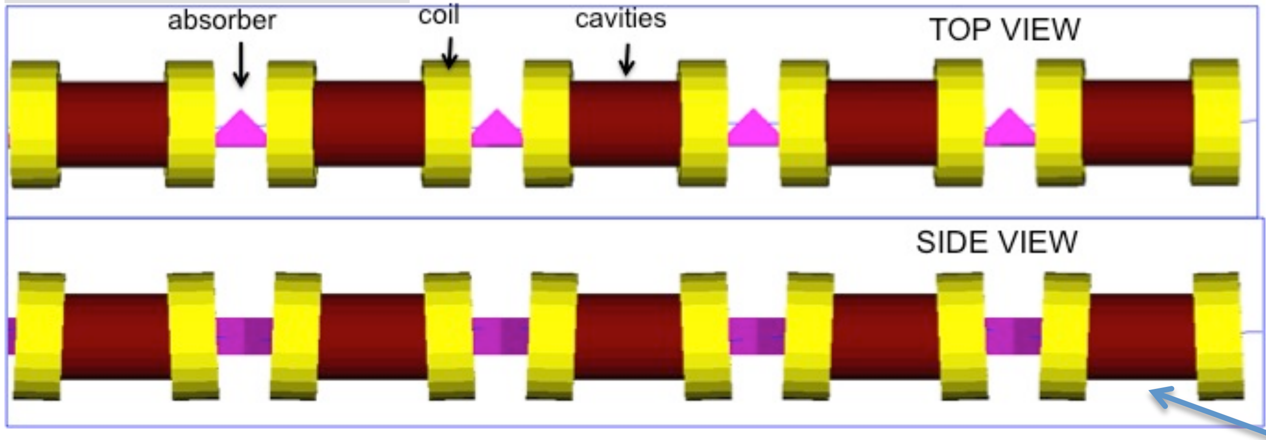


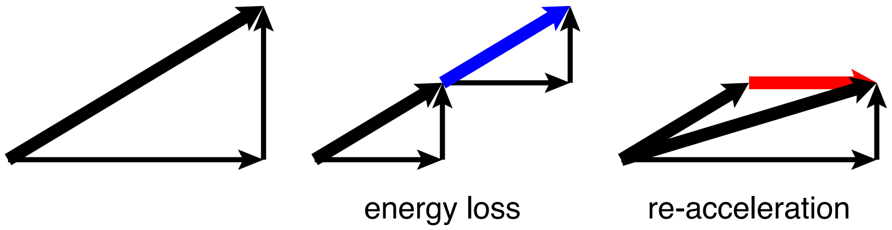
Important power of proton driver O(1.3 MW)

- **radiation in solenoid**
- need to cool
- **radiation in downstream systems**
- power level considered feasibility but not a huge margin

Cooling Concept

MAP collaboration





Superconducting solenoids

High-field normal conducting RF

Liquid hydrogen targets

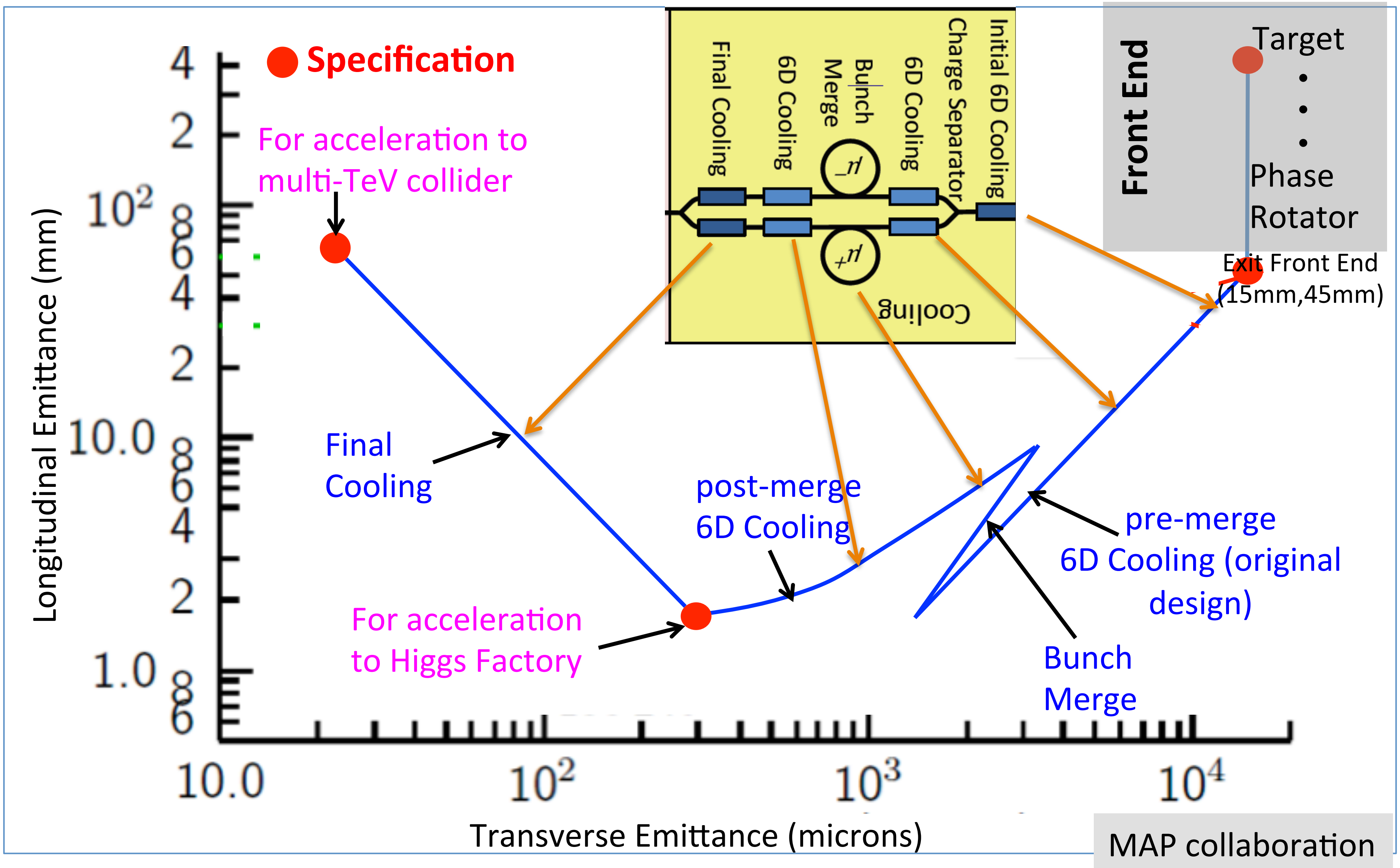
Compact design

Limit muon decay, cavities with **very gradient in a magnetic field**

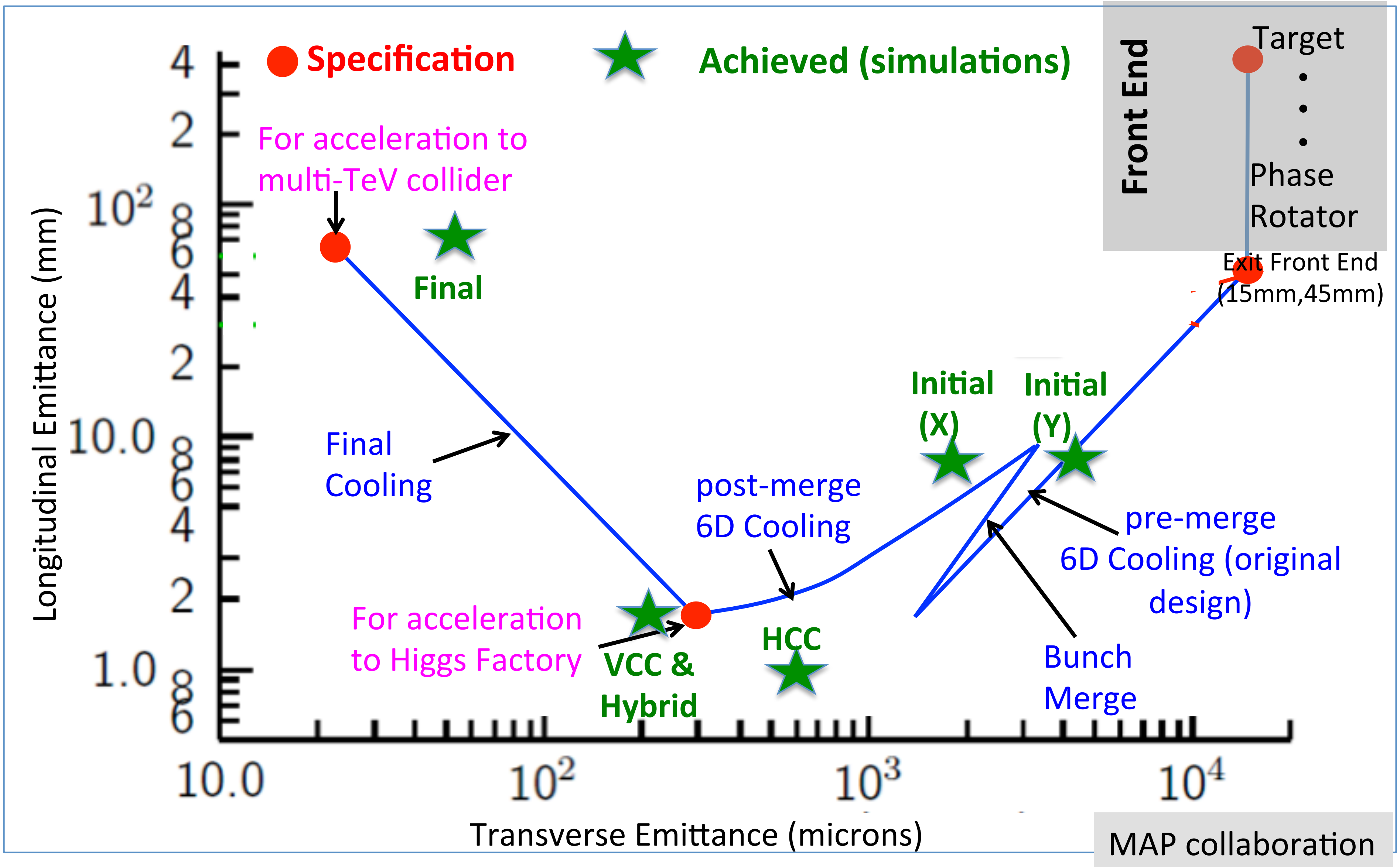
Minimise betafunction with **strongest solenoids**

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

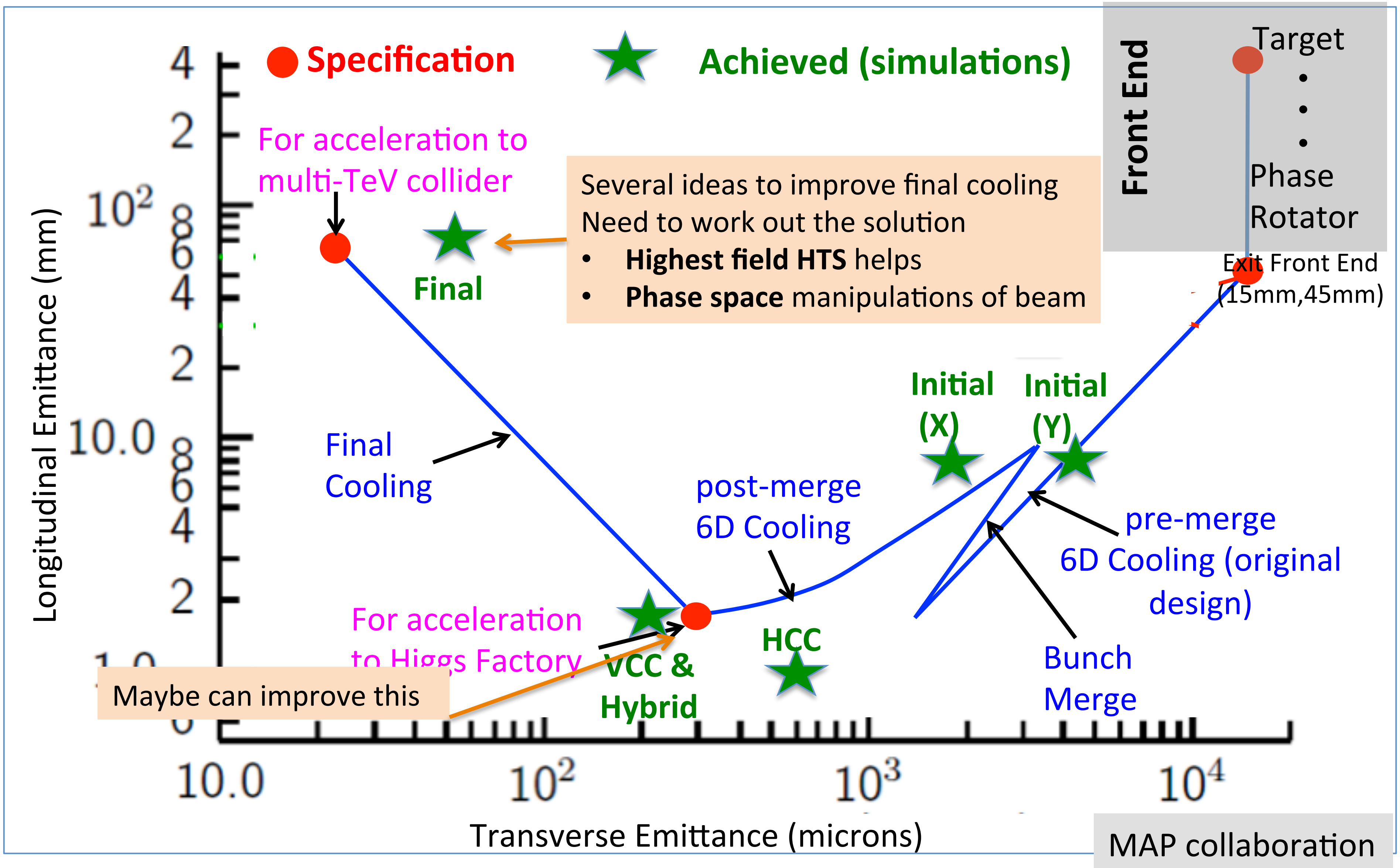
Cooling: The Emittance Path



Cooling: The Emittance Path



Cooling: The Emittance Path



Cooling Challenges and Status

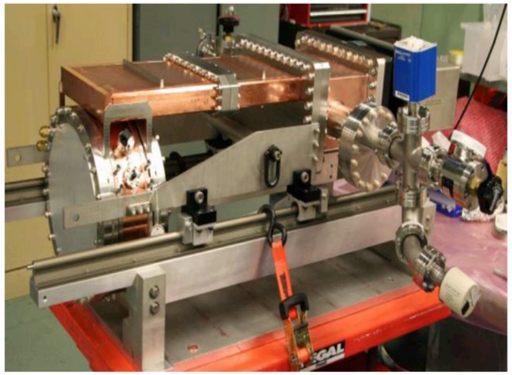
Cavities with very **high accelerating gradient in strong magnetic** field

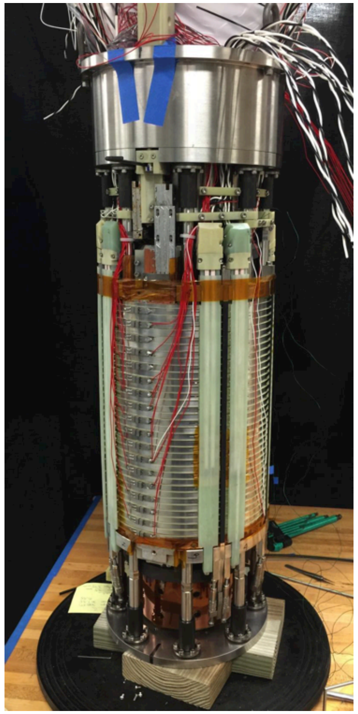
Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps

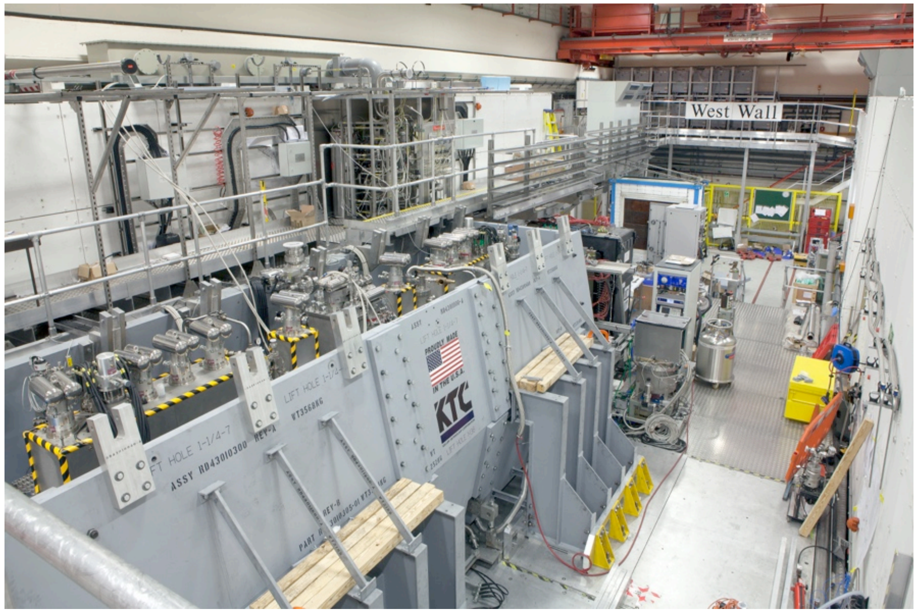




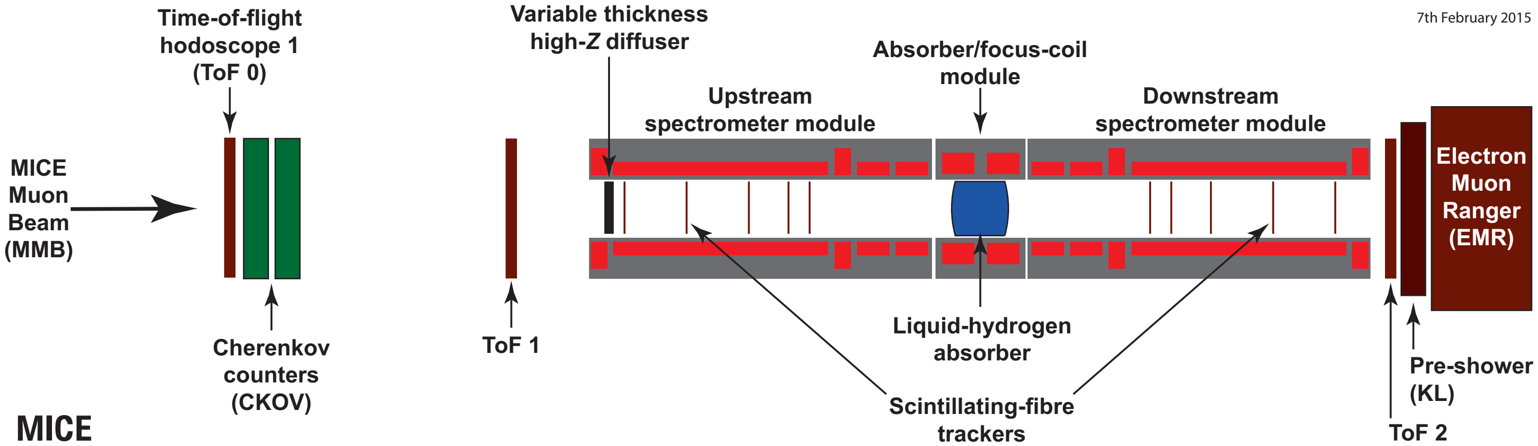
NHFML
32 T solenoid with low-temperature HTS

We would like to push even further

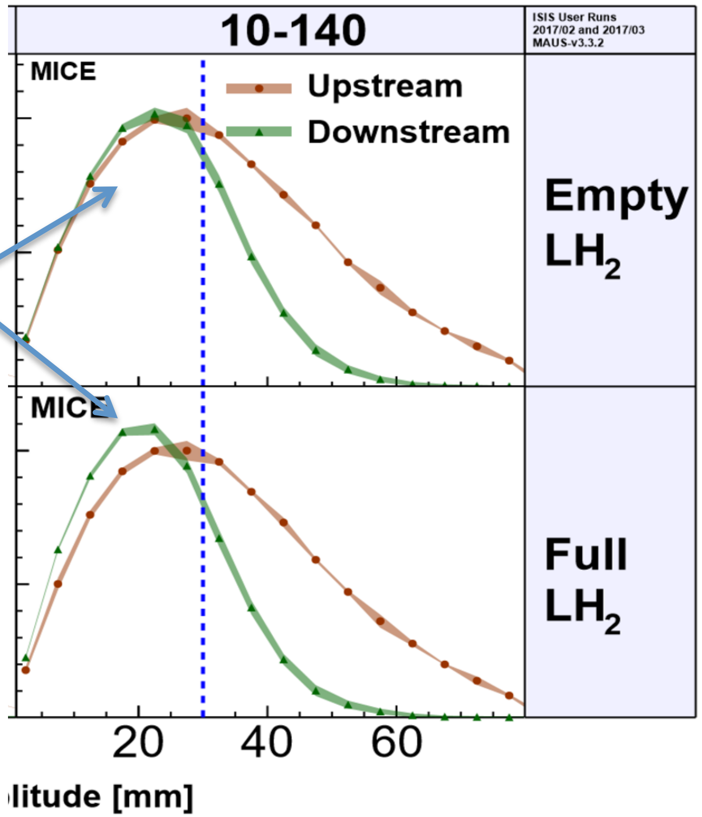
MICE (UK)



MICE (in the UK)



More particles at smaller amplitude after absorber is put in place



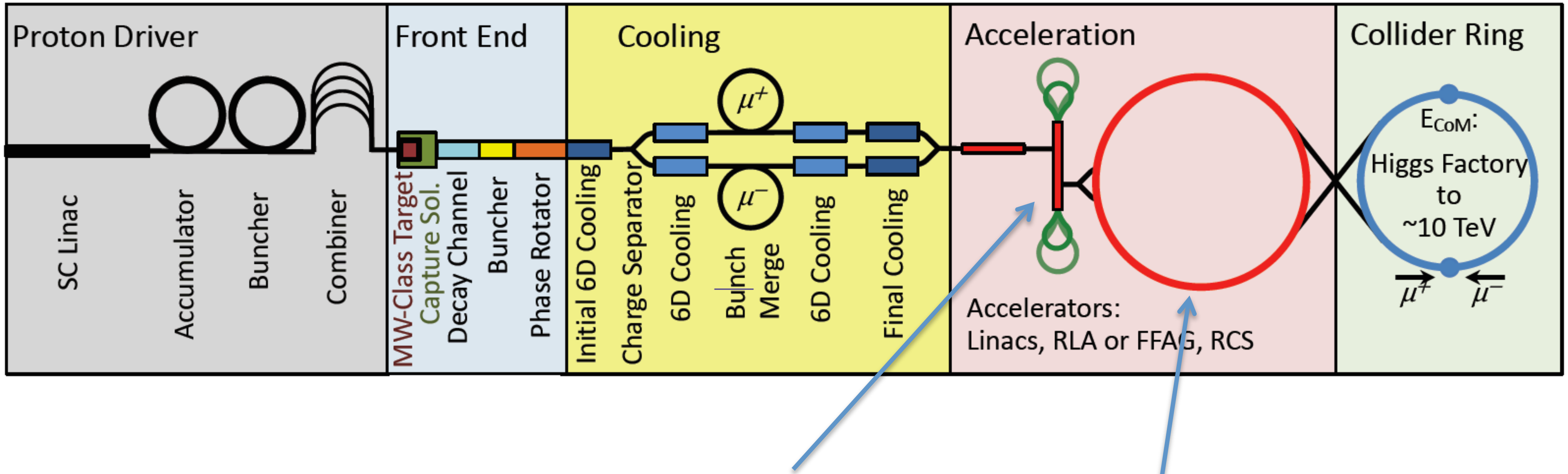
Principle of ionisation cooling has been demonstrated

Nature volume 578, pages 53-59 (2020)

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

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

Beam Acceleration



Initially use

- Linacs
- Recirculating linacs

Trade-off between cost and muon survival

Final acceleration

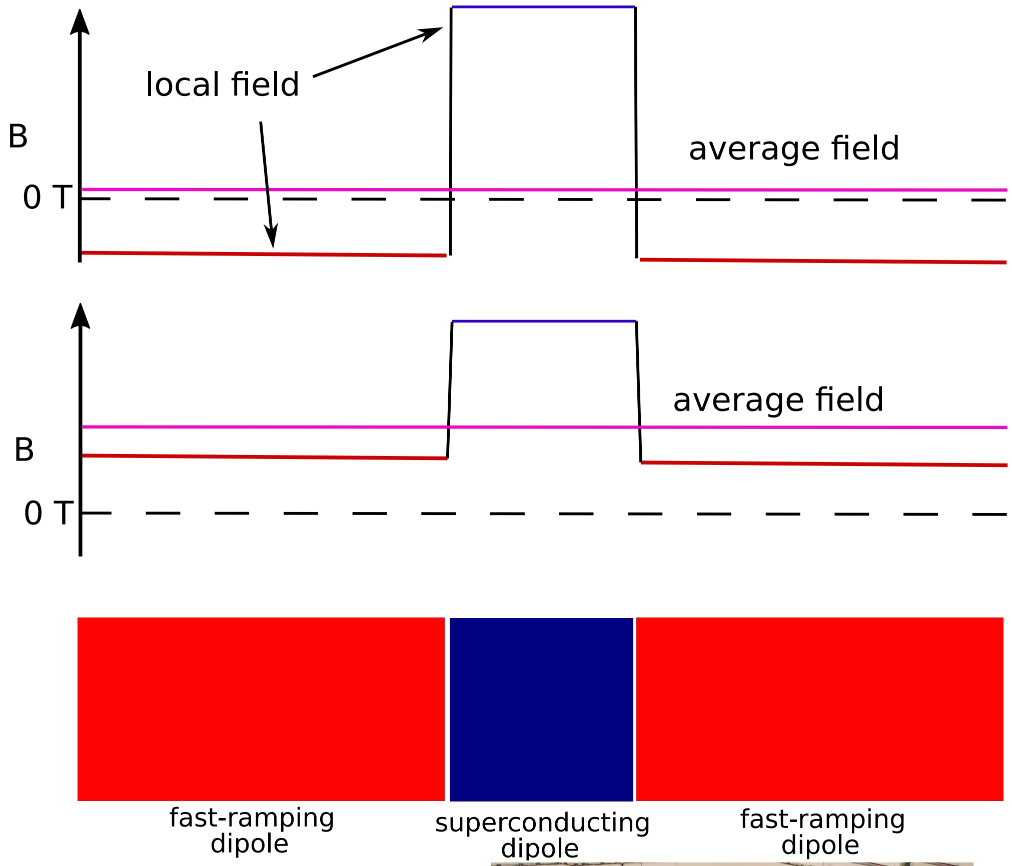
- FFAG (static superconducting magnets)
- or RCS (rapid cycling synchrotron)

High-energy Acceleration

Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- 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))



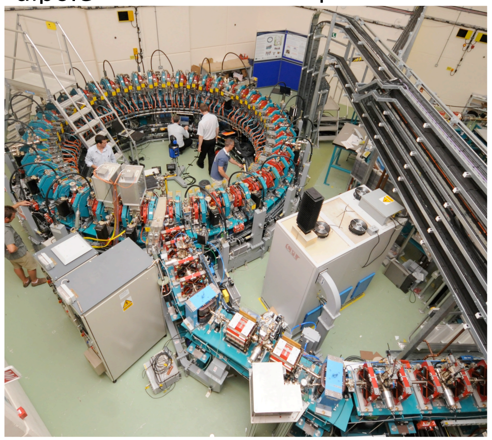
FFAG

Lattice with high-field magnets that are static and accommodates different energies at different location in the magnets

- Challenging lattice design for large bandwidth and limited cost
- Complex high field magnets
- Challenging beam dynamics

EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



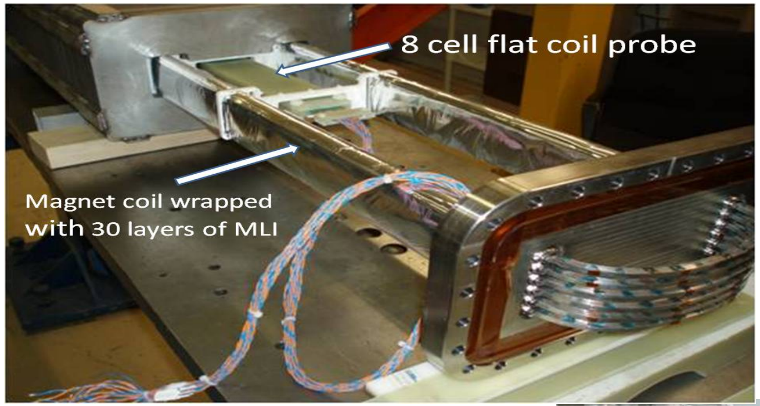
RCS

In hybrid design, need 5 km of 2 T of **fast-ramping, normal-conducting magnets** per TeV beam energy

O(30 km) for 1.5-5/7 TeV
- two rings in same tunnel
- or **higher field HTS ramping magnets**

Started to work on **power converters** (efficient recovery of energy in ramping magnets, O(200 MJ) at 14 TeV

Acceleration 0.3 to 1.5 TeV				
Length	km	13.8	26.7	26.7
8 T dipole	km	2.36	2.36	-
L_{ramp}	km	6.3	15.8	18.2
B_{ramp}	T	-2 / 2	-1 / 1	0.34 / 1.7



Test of **fast-ramping normal-conducting magnet** design

FNAL
12 T/s HTS
0.6 T max

Need to push in field and speed

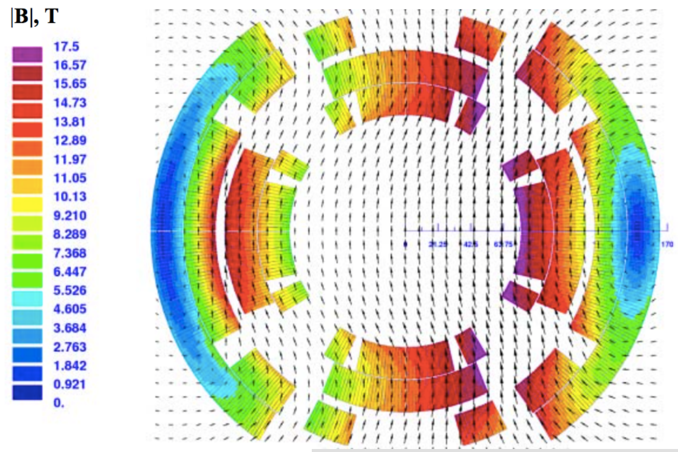
RF challenge (also for FFA):
High efficiency for power consumption
High-charge, single-bunch beam (10 x HL-LHC)
Maintain small longitudinal emittance

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

Need to protect from O(500 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

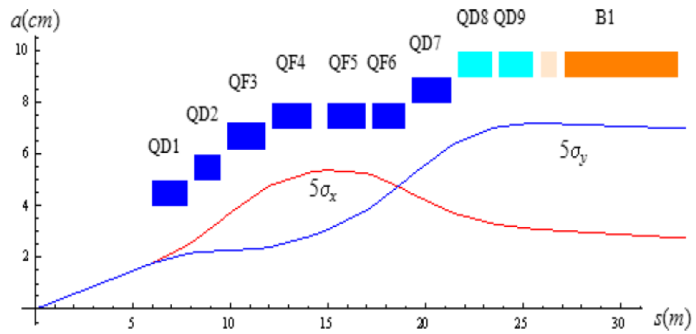
Combined function magnet design



V.V. Kashikhin et al.

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

Technology

Important progress on high-field magnets for many projects, HL-LHC, FCC, …

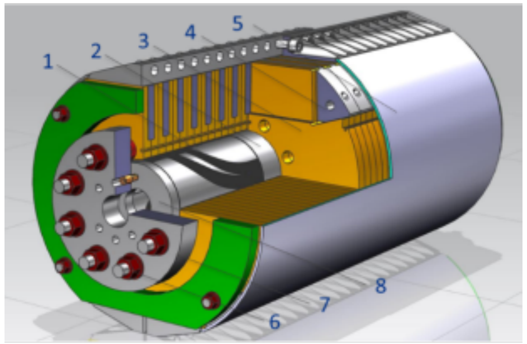
General development of superconducting magnets with advanced technologies (Nb_3Sn and HTS) in all regions

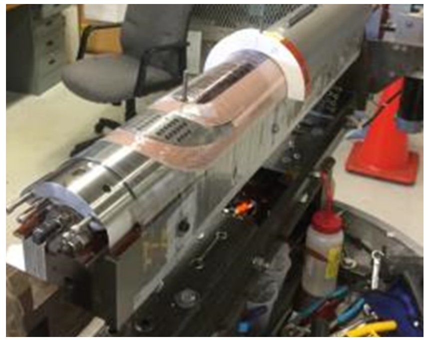
For the first energy stage could stay with more conventional performance
and use more advanced technologies for high-energy upgrades

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab
50 Years of Discovery

15 T dipole demonstrator
60-mm aperture
4-layer graded coil





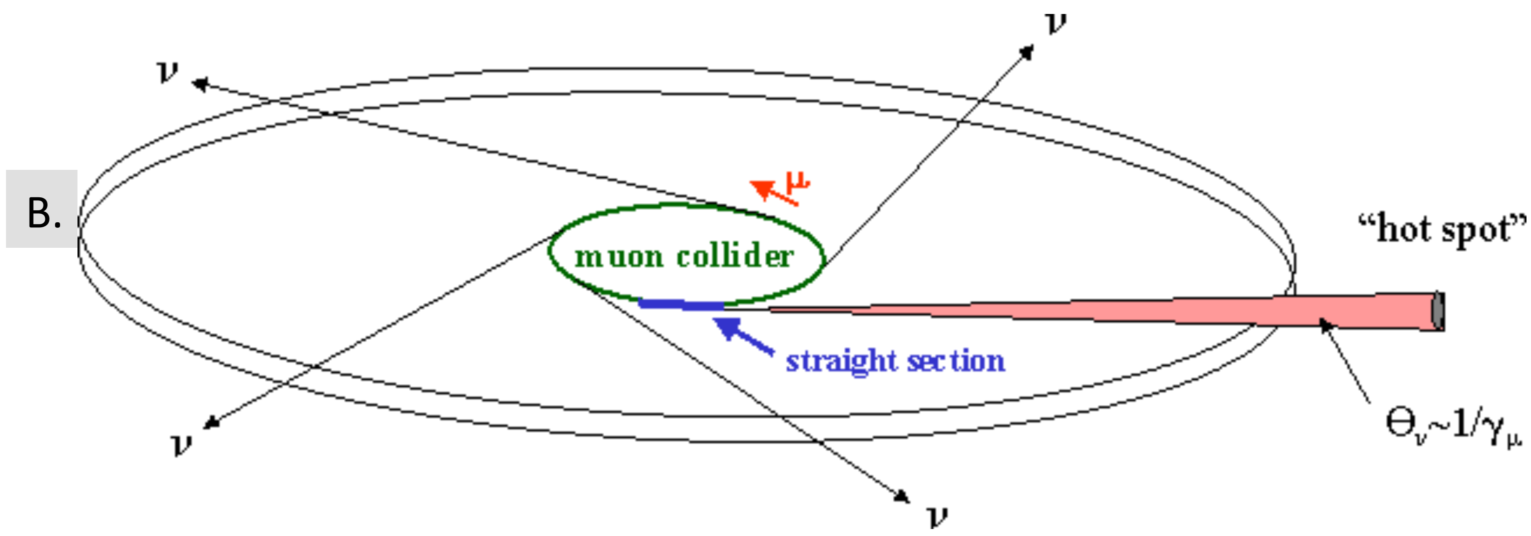
Development of conductors (FCC)

Participants

Switzerland: CERN
Japan: KEK, FURUKAWA ELECTRIC, JASTEC
Russia: BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM, TVEL
Korea: KISWIRE
China: Western Superconducting Technologies Co., Ltd.
Austria: TU WIEN
Germany: TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
Italy: Columbus Superconductors
Finland/USA: LUVATA SPECIAL PRODUCTS
Italy: SPIN
Switzerland: UNIVERSITÉ DE GENÈVE

7 companies, two universities and two national research institutes

Neutrino Radiation



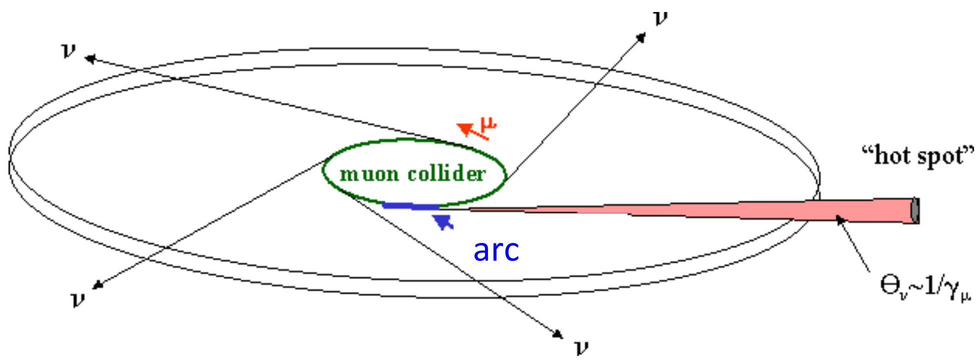
Neutrinos can produce showers just when they exit the earth

Due to narrow neutrino beam, radiation can become relevant
Particularly high in direction of the straights

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

Arcs



Tricks

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

More efficient physics
More years of running

Higher field, shorter gaps in collider

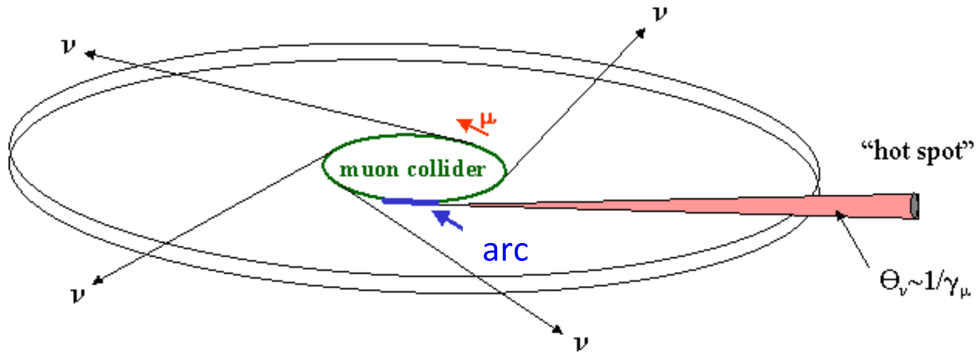
Deeper tunnel

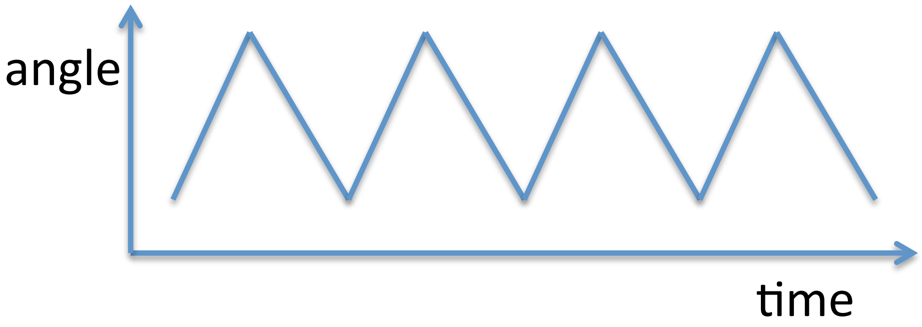
Denser beam

Larger energy spread acceptance

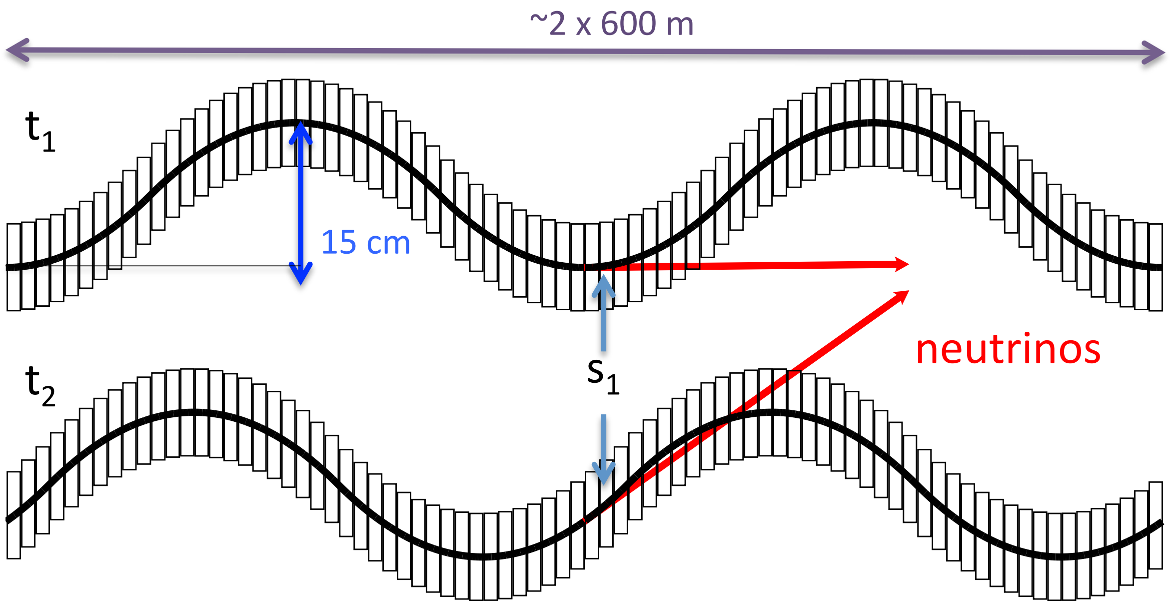
Typical legal limit 1 mSv/year MAP goal < 0.1 mSv/year No legal procedure < 10 μSv/year LHC achieved < 5 μSv/year	Mitigate radiation to a level as low as reasonably possible Similar to LHC

Neutrino Radiation Mitigation





Mokhov, Ginneken: move beam in collider aperture
Investigate: 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 be comparable to LHC case

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

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)

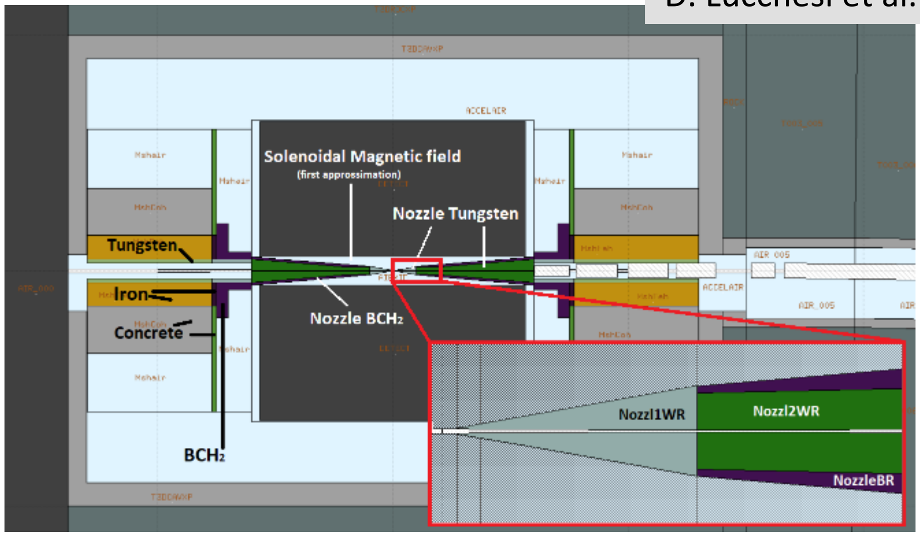
Muon decay rate at 3 TeV: 200,000 bx^{-1} m^{-1}

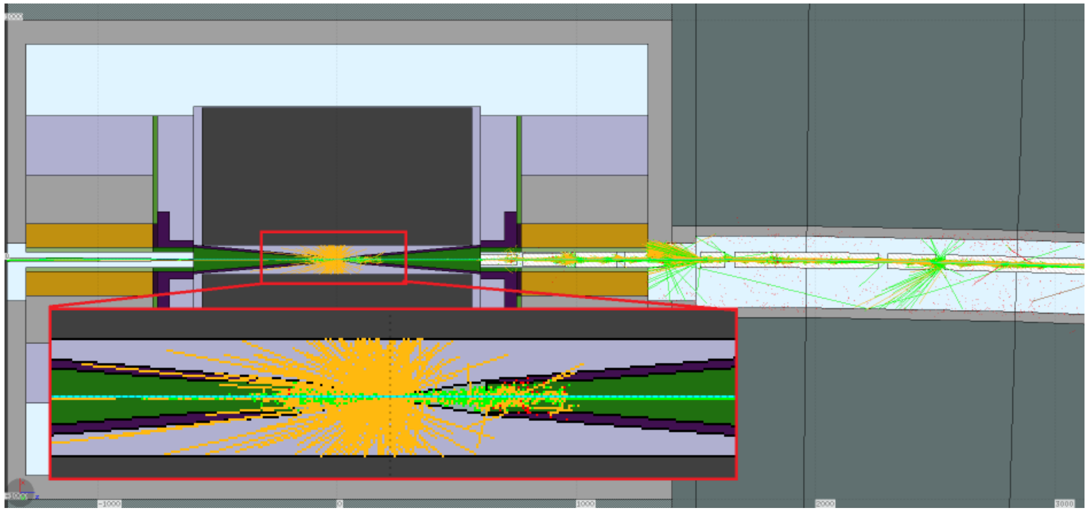
Rate decreases with energy but energy in each decays increases

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

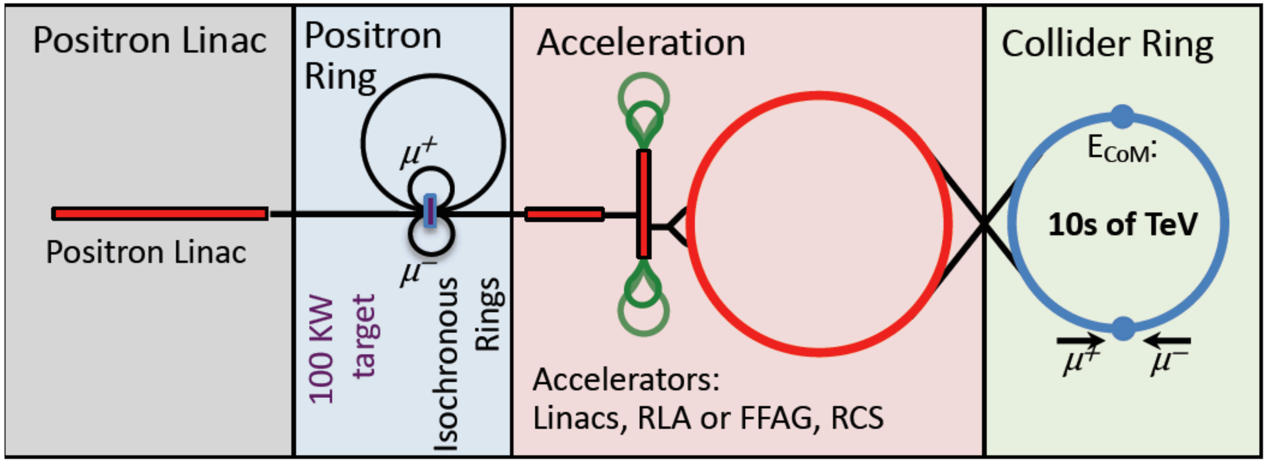
Will study higher energies as machine designs become available

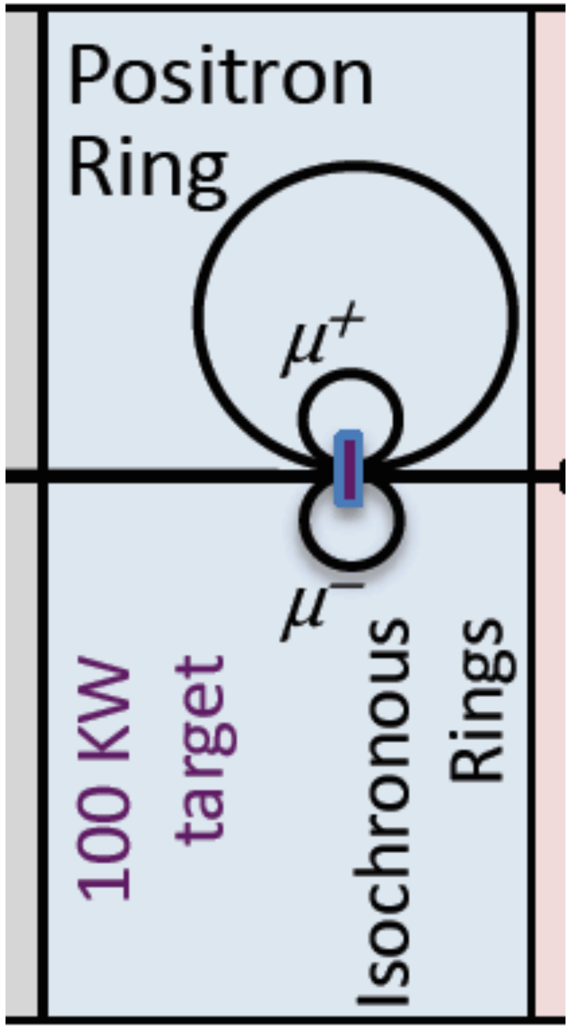
D. Lucchesi et al.





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

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

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.

LDG created panels to provide the input for the Roadmap

Muon Beam Panel

Members: Daniel Schulte (CERN), Mark Palmer (BNL), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)

Foresee three community meetings

- First in May, date to be defined
- Please contribute

Will profit from workshop on the muon collider testing opportunities (with physics potential of test facility):

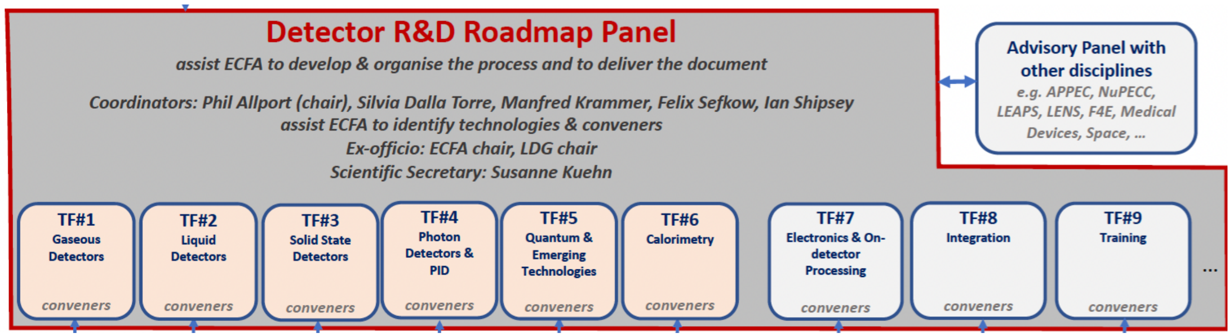
https://indico.cern.ch/event/1009746/ .

Report ready in September, given to Council in December

Detector Technologies

Will rely largely on European Detector R&D Roadmap (ECFA)

- Will provide link persons to relevant working groups



Currently consider the following most important (N. Pastrone)

- solid state tracking
- calorimetry
- emerging technologies
- electronics and in detector processing

Will also include other regions

Physics potential studies and machine background studies will verify if performances similar to CLIC and FCC-hh are sufficient

US Snowmass/P5

Submitted a number of proposals for white papers

- physics potential
- detector
- accelerator

Growing interest in the community

Aiming to coordinate the regional efforts

International Muon Collider Collaboration (corresponding author: D. Schulte)
Muon Collider Facility (c.a.: D. Schulte)
Muon Collider Physics Potential (c.a.: A. Wulzer)
Machine Detector Interface Studies at a Muon Collider (c.a.: D. Lucchesi)
Muon Collider experiment: requirements for new detector R&D and reconstruction tools (c.a.: N. Pastrone)
A Proton-Based Muon Source for a Collider at CERN (c.a.: Chr. Rogers)
Issues and Mitigations for Advanced Muon Ionization Cooling (c.a.: Chr. Rogers)
LEMMA: a positron driven muon source for a muon collider (c.a.: M.E. Biagini)
Applications of Vertical Excursion FFAs(vFFA)and Novel Optics (c.a.: Sh. Machida)

Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to "standard" future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

Our plans for Snowmass21:

https://indico.cern.ch/event/944012/contributions/3989516/attachments/2091456/3518021/Physics_SnowMass_LoI.pdf

Letter of Interest: Muon Collider Physics Potential

D. Buttazzo, R. Capedevilla, M. Chiesa, A. Costantini, D. Curtin, R. Franceschini, T. Han, B. Heinemann, C. Helsens, Y. Kahn, G. Krnjaic, I. Low, Z. Liu, F. Maltoni, B. Mele, F. Meloni, M. Moretti, G. Ortona, F. Piccinini, M. Pierini, R. Rattazzi, M. Selvaggi, M. Vos, L.T. Wang, **A. Wulzer**, M. Zanetti, J. Zurita

On behalf of the forming muon collider international collaboration [1]

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{\rm CM} = 3, 10, 14$, and the more speculative $E_{\rm CM} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\rm CM}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.

Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

And we are not alone

MUON COLLIDER: A WINDOW TO NEW PHYSICS

Douglas Berry[1], Kevin Black[2], Anadi Canepa[1], Swapan Chattopadhyay[1,3], Matteo Cremonesi[1], Sridhara Dasu[2], Dmitri Denisov[4], Karri Di Petrillo[1], Melissa Franklin[5], Zoltan Gecse[1], Allison Hall[1], Ulrich Heintz[6], Christian Herwig[1], James Hirschauer[1], Tova Holmes[7], Andrew Ivanov[8], Bodhitha Jayatilaka[1], Sergo Jindariani[1], Young-Kee Kim[9], Jacobo Konigsberg[10], Lawrence Lee[5], Miaoyuan Liu[11], Zhen Liu[12], Chang-Seong Moon[13], Meenakshi Narain[6], Scarlet Norberg[14], Isobel Ojalvo[15], Katherine Pachal[16], Simone Pagan Griso[17], Kevin Pedro[1], Alexx Perloff[18], Elodie Resseguie[17], Stefan Spanier[7], Maximilian Swiatlowski[19], Ann Miao Wang[5], Lian-Tao Wang[9], Xing Wang[20], Hannsjörg Weber[1*], David Yu[6]

[1] *Fermi National Accelerator Laboratory*, [2] *University of Wisconsin, Madison*, [3] *Northern Illinois University*, [4] *Brookhaven National Laboratory*, [5] *Harvard University*, [6] *Brown University*, [7] *University of Tennessee, Knoxville*, [8] *Kansas State University*, [9] *University of Chicago*, [10] *University of Florida*, [11] *Purdue University*, [12] *University of Maryland*, [13] *Kyungpook National University*, [14] *University of Puerto Rico, Mayagüez*, [15] *Princeton University*, [16] *Duke University*, [17] *Lawrence Berkeley National Laboratory*, [18] *University of Colorado, Boulder*, [19] *TRIUMF* [20] *University of California, San Diego*

Beyond the Standard Model with High-Energy Lepton Colliders

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Tianji Cai[1], Junyi Cheng[1], Tim Cohen[3], Nathaniel Craig[1], JiJi Fan[4], Isabel Garcia Garcia[5], Seth Koren[6,1], Giacomo Koszegi[1], Zhen Liu[7], Kunfeng Lyu[8], Amara McCune[1], Patrick Meade[9], Isobel Ojalvo[10], Umut Oktem[1], Matthew Reece[11], Raman Sundrum[7], Dave Sutherland[12], Timothy Trott[1], Chris Tully[10], Ken Van Tilburg[5], Lian-Tao Wang[6], and Menghang Wang[1]

Electroweak multiplets at the Muon Collider

R. Capdevilla, D.Curtin, Y. Kahn, G. Krnjaic, F. Meloni, J. Zurita

August 2020

Letter of Interest: EW effects in very high-energy phenomena

C. ARINA, G. CUOMO, T. HAN, Y.MA, F. MALTONI, A. MANOHAR, S. PRESTEL, R. RUIZ, L. VECCHI, R. VERHEYEN, B. WEBBER, W. WAALEWIJN, A. WULZER, K. XIE

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

HIGGS AND ELECTROWEAK PHYSICS AT THE MUON COLLIDER: AIMING FOR PRECISION AT THE HIGHEST ENERGIES

Aram Apyan[1], Jeff Berryhill[1], Pushpa Bhat[1], Kevin Black[2], Elizabeth Brost[3], Anadi Canepa[1], Sridhara Dasu[2], Dmitri Denisov[3], Karri DiPetrillo[1], Zoltan Gesce[1], Tao Hann[4], Ulrich Heintz[5], Rachel Hyneman[6], Young-Kee Kim[7], Da Liu[8], Mia Liu[9], Zhen Liu[10], Ian Low[11,12], Sergo Jindariani[1], Chang-Seong Moon[13], Isobel Ojalvo[14], Meenakshi Narain[5], Maximilian Swiatlowski[15*], Marco Valente[15], Lian-Tao Wang[7], Xing Wang[16], Hannsjörg Weber[1], David Yu[5]

Muon Collider: Study of Higgs couplings and self-couplings precision

C. Aimè[a], F. Balli[b], N. Bartosik[c], L. Buonincontri[d], M. Casarsa[e], M. Chiesa[f], F. Collamati[g], C. Curatolo[d], D.Lucchesi[d], B. Mele[g], F. Maltoni[h], B. Mansoulié[b], A. Nisati[g], N. Pastrone[c], F. Piccinini[i], C. Riccardi[a], P. Sala[l], P. Salvini[i], L. Sestini[m], I. Vai[a], D. Zuliani[d]

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

A great challenge but also a great opportunity

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
…

Reserve

Memorandum of Cooperation

Basically ready, waiting for final polishing

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

High-energy Frontier Proposals

European Strategy Process just finished

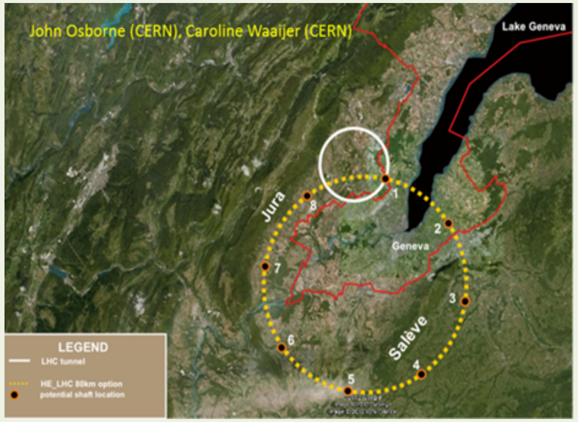
Four main high-energy facilities proposed
- two at CERN
- two in Asia

FCC (Future Circular Collider):

FCC-hh
- pp collider with 100 TeV cms
- ion option

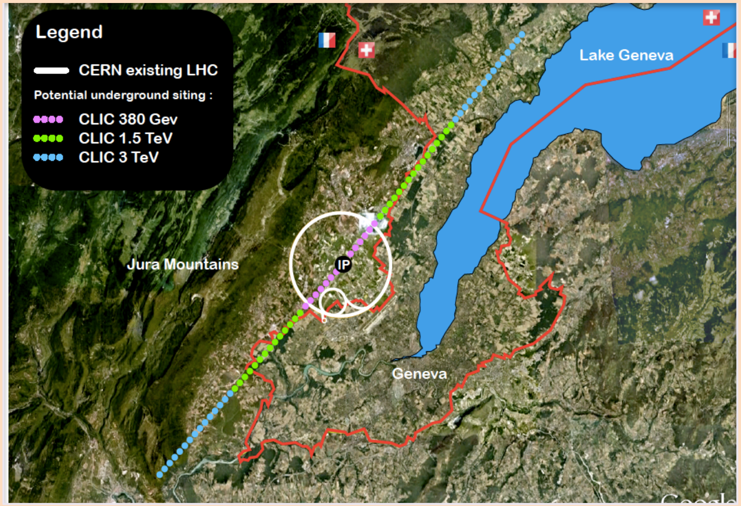
FCC-ee
- Potential e^+e^- first stage

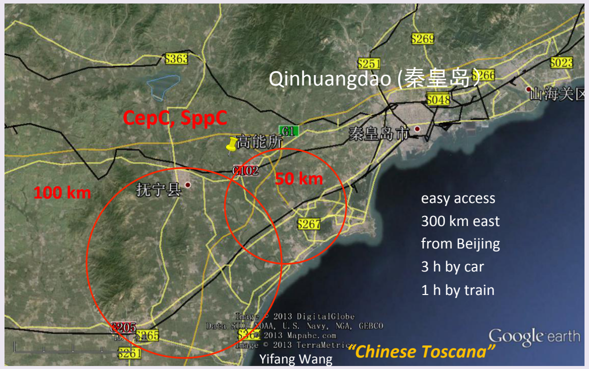
FCC-eh
- additional option



ILC
- 250 GeV electron-positron linear collider
- Japan might host
- limited in energy reach

CLIC
- 380 GeV, 1.5 TeV and 3 TeV electron positron collider





CEPC / SppC

CEPC
- e^+e^- collider 90-240 GeV

SppC
- 75-150 TeV hadron collider later in the same tunnel

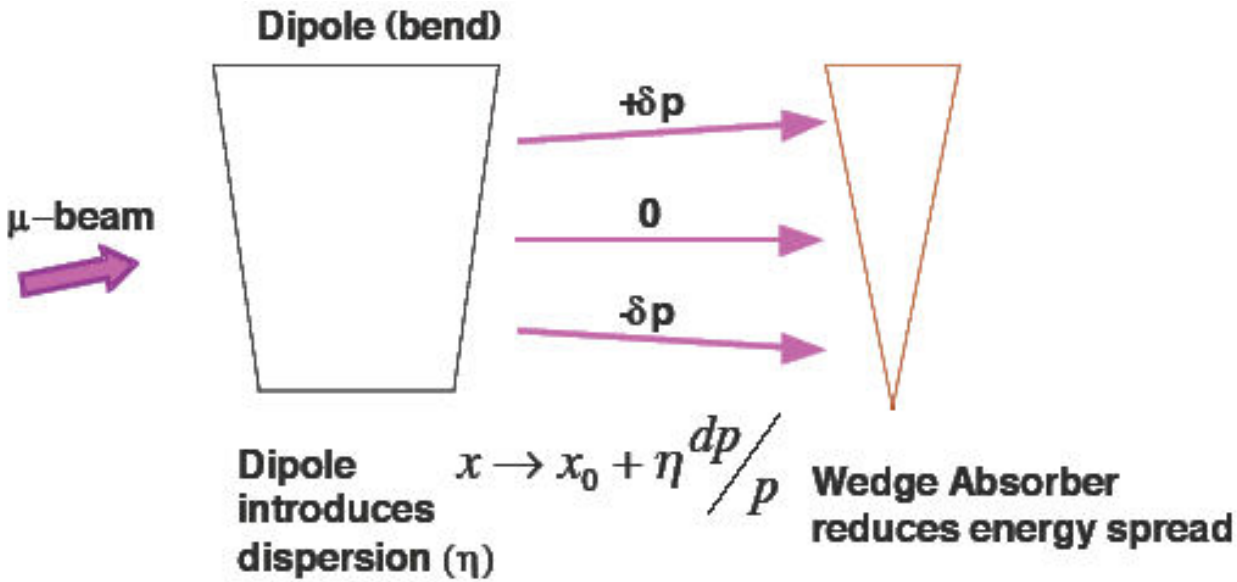
Proposed Projects (ESU)

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Longitudinal Cooling/Emittance Exchange

Combined with transverse cooling at beginning

Several options considered



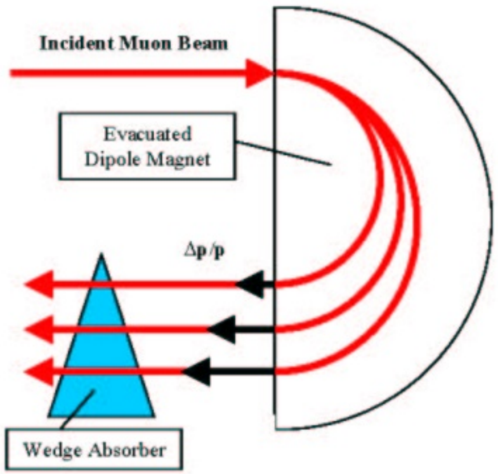


Figure 1. Use of a Wedge Absorber for Emittance Exchange

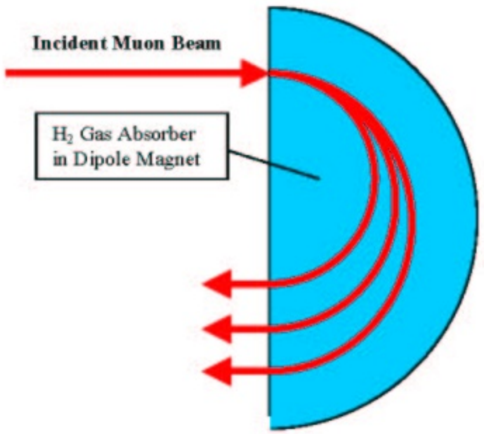


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Allows 6-D cooling

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Direct search of heavy particles	High energy measurements	High rate Higgs production
SUSY-inspired, WIMP, VBF production, 2->1	difermion, diboson, EFT, Higgs compositeness	Higgs single and self-couplings, rare Higgs decays, exotic decays

Few Preliminary Results

A. Wulzer et al.

Higgs 3-linear coupling: **δκλ=(5%, 3.8%, 1.6%) for E = (10, 14, 30) TeV**

[2008.12204; 2005.10289; Buttazzo, Franceschini, Wulzer, to appear]

[FCC reach is from 3.5 to 8.1% depending on systematics assumptions]

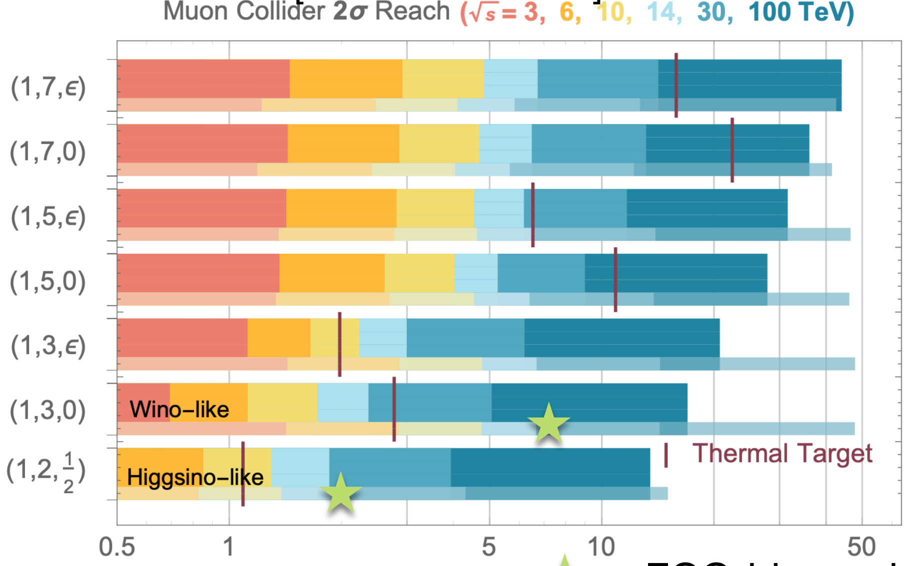
Higgs compositeness scale: **(38, 53, 115) TeV for E = (10, 14, 30) TeV**

[Buttazzo, Franceschini, Wulzer, to appear]

[other F.C.: from 20 to 40 TeV depending on model]

WIMP DM

[arXiv:2009.11287]



Scalar Singlet