Muon Collider Collaboration

D. 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 (MICE: demonstration of ionisation cooling, EMMA: FFA) 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 very 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 initially host the study and preparing a Memorandum of Understanding

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

Memorandum of Understanding

Basically ready, waiting for final approval of DG

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

Overall Context

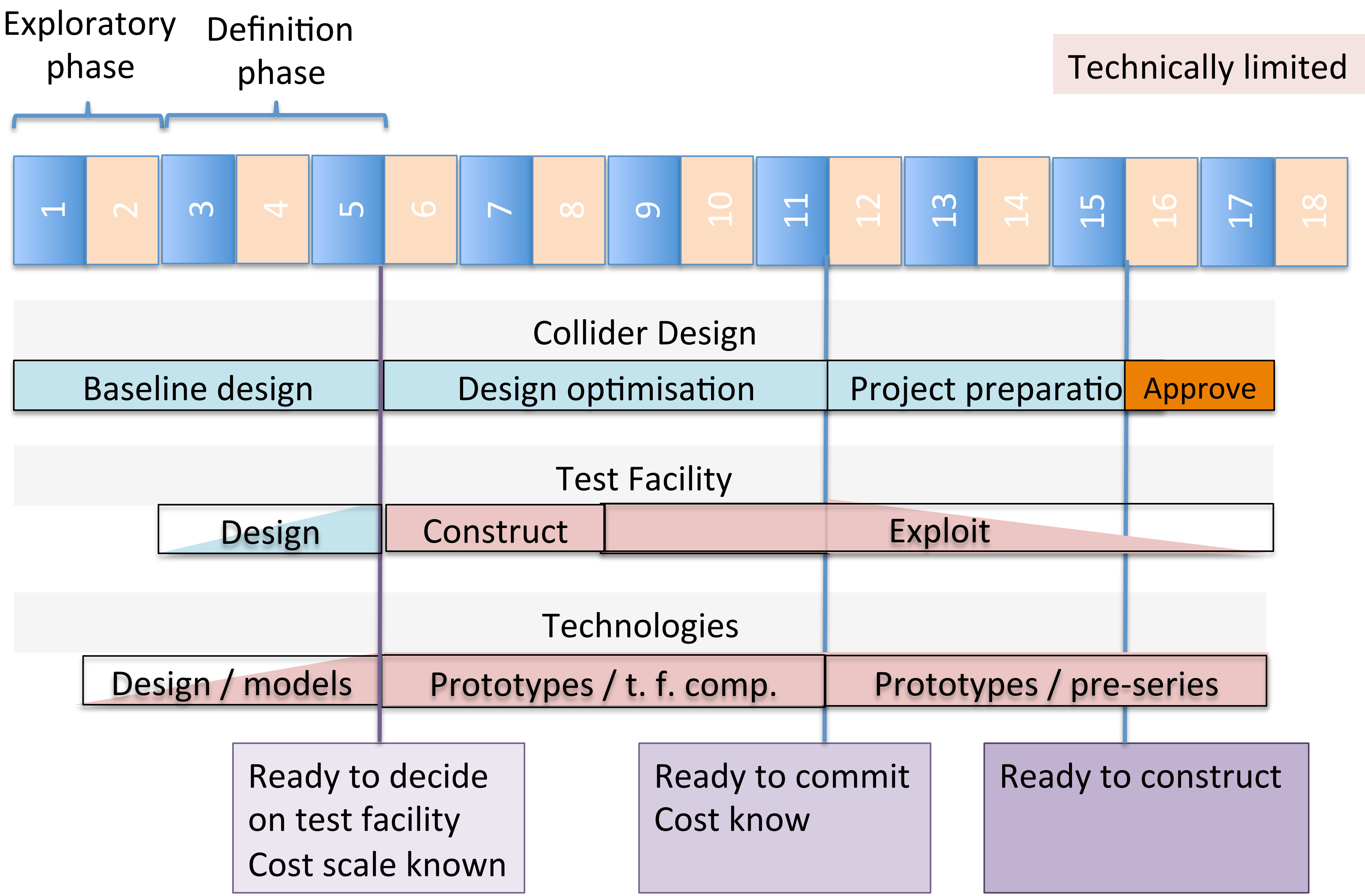
Two main strategic processes are ongoing

- Definition of European **Accelerator R&D Roadmap** by LDG
  - Define scope of muon collider study until September 2021
- **Snowmass/P5** process in the US
  - Input until June 2021, decisions in 2022
    - will have to prepare white papers
  - Submitted several Letters Of Interest from the collaboration:

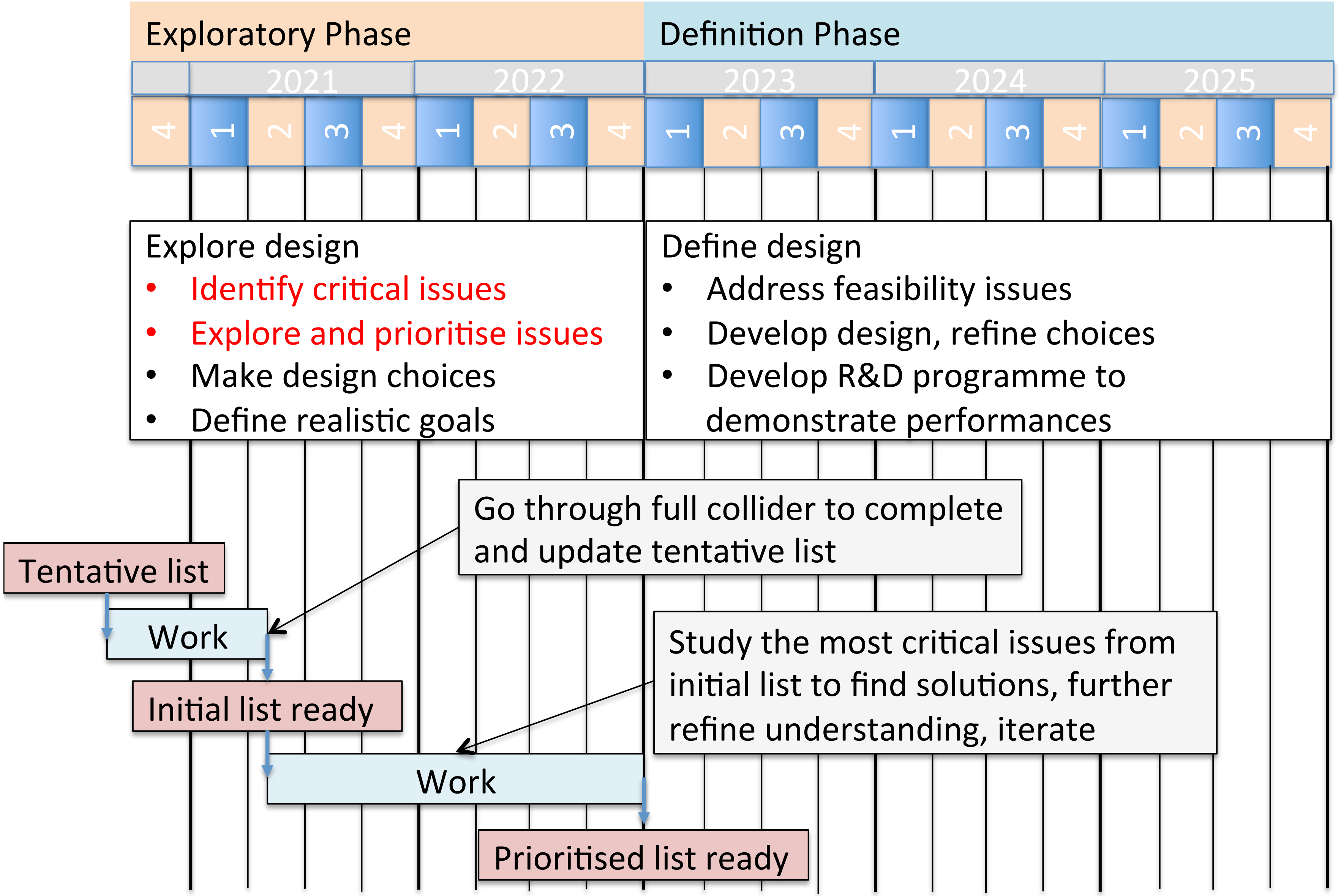
    International Muon Collider Collaboration (corresponding author: D. Schulte)
    Muon Collider Facility (c.a.: D. Schulte)
    Muon Collider Physics Potential (c.a.: A. Wulzer)
    Machine Detector Interface Studies at a Muon Collider (c.a.: D. Lucchesi)
    Muon Collider experiment: requirements for 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)

  - In addition, others refer to the muon collider, e.g. technologies, physics, …

Updated Timeline



Tentative Roadmap



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

Comment on Resources

MUST in IFAST (WP 5.1, N. Pastrone)

- *INFN, CERN, CEA, CNRS, KIT, PSI, UKRI,* 300 kEUR request from EU

aMUSE contains relevant workpackages "Muon beams" and "Tools" (D. Lucchesi)

- uniPD, LIP, INFN, PSI, HZDR, Mainz, UniRM, TUD, Krakow, BNL, FNAL, integrated 117 pm over 4 years

Proposal to BMBF for funding of magnet and RF work (T. Arnd, U. van Rienen)

- KTI, Darmstadt University, Rostock University (9 py total)

JAI students worked on rapid cycling synchrotron as project (E. Tsesmelis)

Medium term plan at CERN has dedicated budget line

- Per year 5 FTE staff, 6 fellows, 4 students, 1 associate, 5 x 2 MCHF

Interest expressed in many institutes

- CEA, CNRS (IJClab), INFN, University of Chicago, IFIC, Jefferson Lab, Spanish Network, KIT, Darmstadt University, University of Rostock, Helmholz-Zentrum Dresden-Rossendorf, Sofia University, Lund University, Uppsala University, Oslo University, LBL, EPSL, PSI, ESS, University of Mississippi, NIKHEF, HEPHY, FNAL, SLAC, …

Actual work already ongoing (mainly volunteers)

Key Initial Steps

Define tentative collider energy and luminosity goals

Define tentative detector performance specifications to be able to launch physics potential studies

Start verification of detector performance

- beam-induced background conditions
- technologies

Start verification of accelerator performance, affordability and siting

- also estimate (and mitigate if possible) beam-induced background

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

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

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

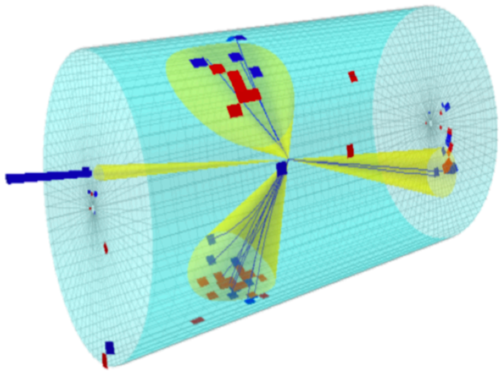
Detector simulation studies/design will now have to verify/ensure that this is realistic considering background and technologies

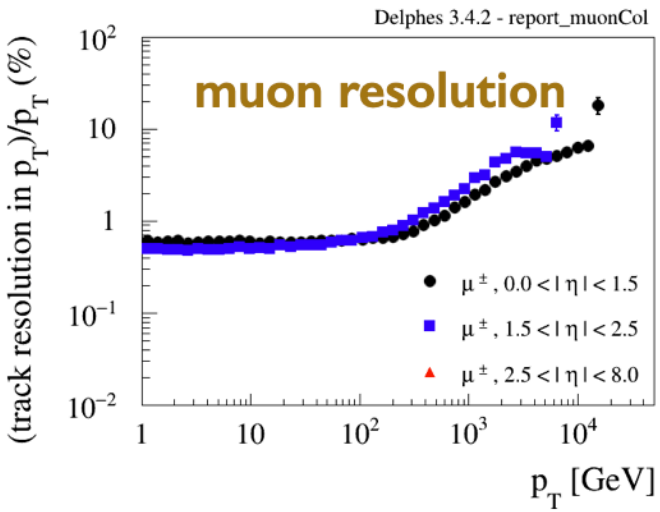
Note: Delphes Simulation

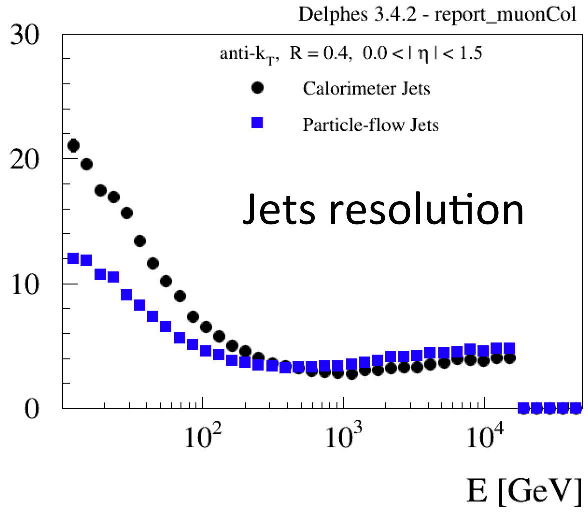
M. Selvaggi

Delphes is a modular framework that simulates the response of a **multipurpose detector** in a parameterised way

- allows to easily scan key detector parameters
- perform preliminary key physics benchmark studies







Muon Collider aims at reconstructing **physics object** momenta **up to 15 TeV**

- Baseline concept is **hybrid** between **FCC-hh** and **CLIC**

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**.

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

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]

Few Preliminary Results

A. Wulzer et al.

Higgs 3-linear coupling: **$\delta\kappa_\lambda$=(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]

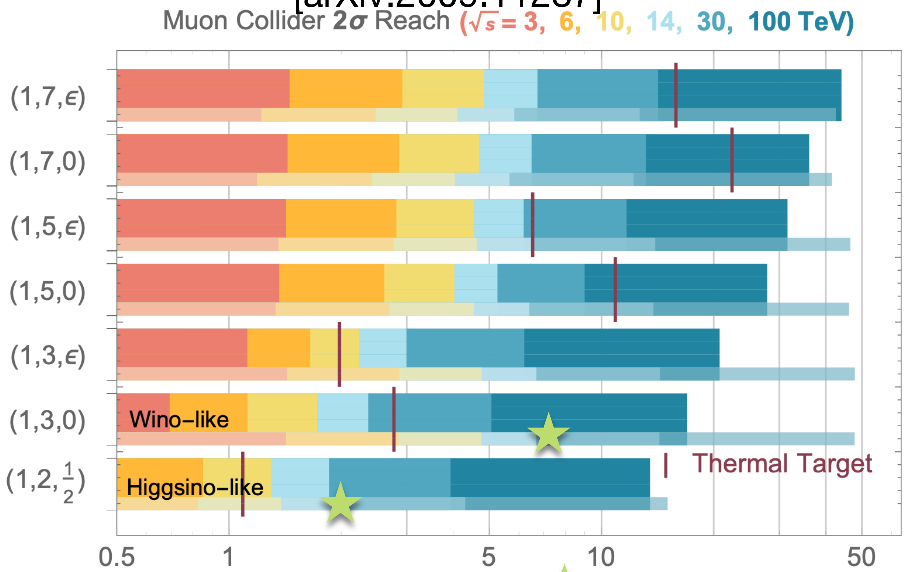
Higgs compositeness scale: **(38, 53, 115) TeV for E = (10, 14, 30) TeV**

[Buttazzo, Franceschini, Wulzer, to appear]

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

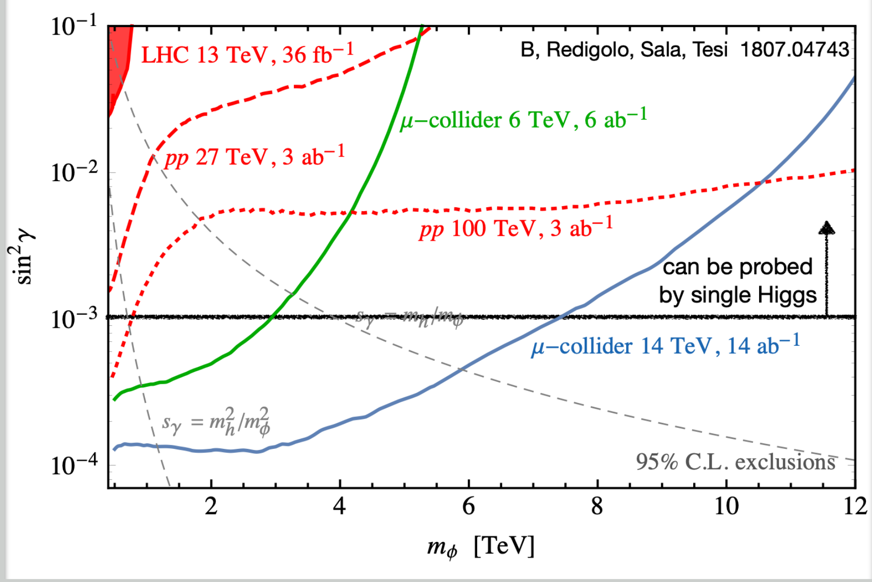
WIMP DM

[arXiv:2009.11287]



= FCC-hh reach

Scalar Singlet



Detector Studies

Verify/ensure that target performance can be reached

Detector simulation infrastructure is mostly in place (D. Lucchesi et al., S. Jindariani et al.)

Background data for 125 GeV and 1.5 TeV available, hope to have 3 TeV in time for Snowmass

Are working to develop higher energy lattice but will take time

Try to characterise background to identify mitigation strategy

Consider snapshot DELPHES card for CLIC-like detector and reconstruction to see how far we have to go to reach tentative performance

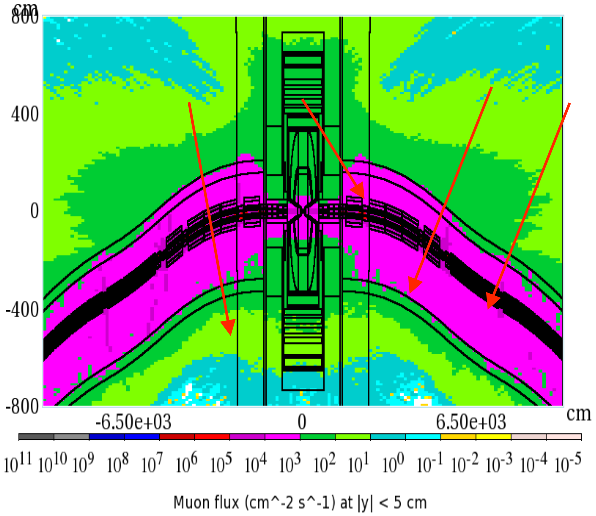
Detector Simulations

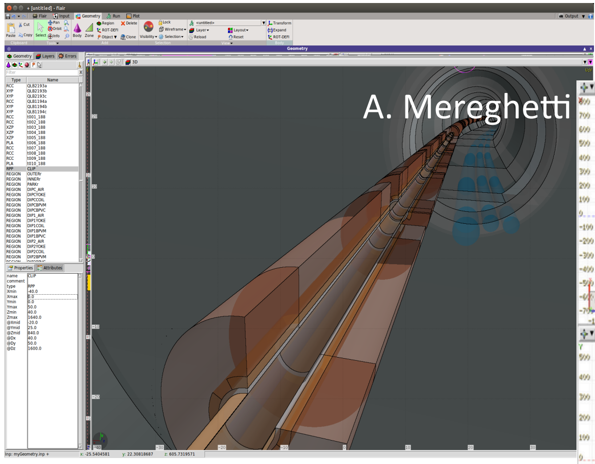
D. Lucchesi et al.

BIB available for $\sqrt{s}$=1.5 TeV and $\sqrt{s}$=125 GeV

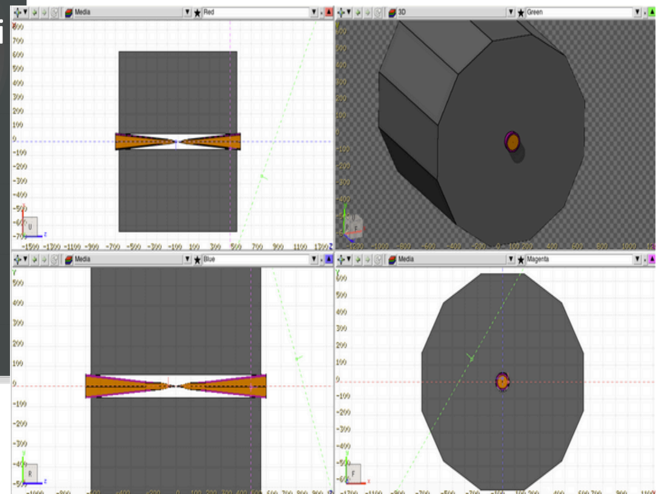
Prepare a new tool based on Fluka to generate new BIB:

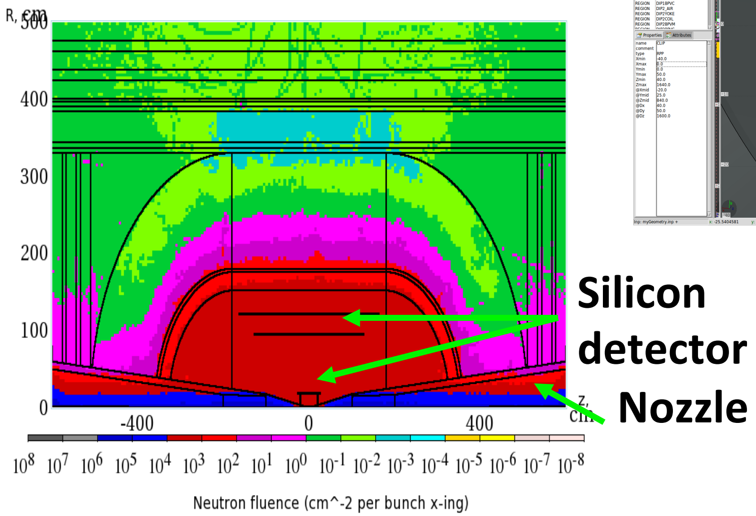
- at different $\sqrt{s}$
- Modifying the detector and the interaction region

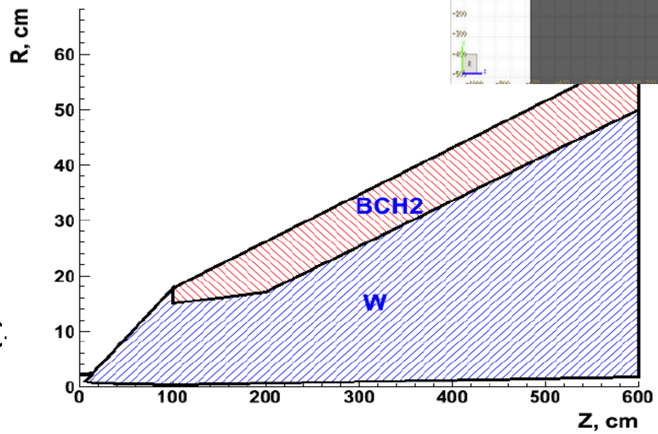




F. Collamati, C. Curatolo



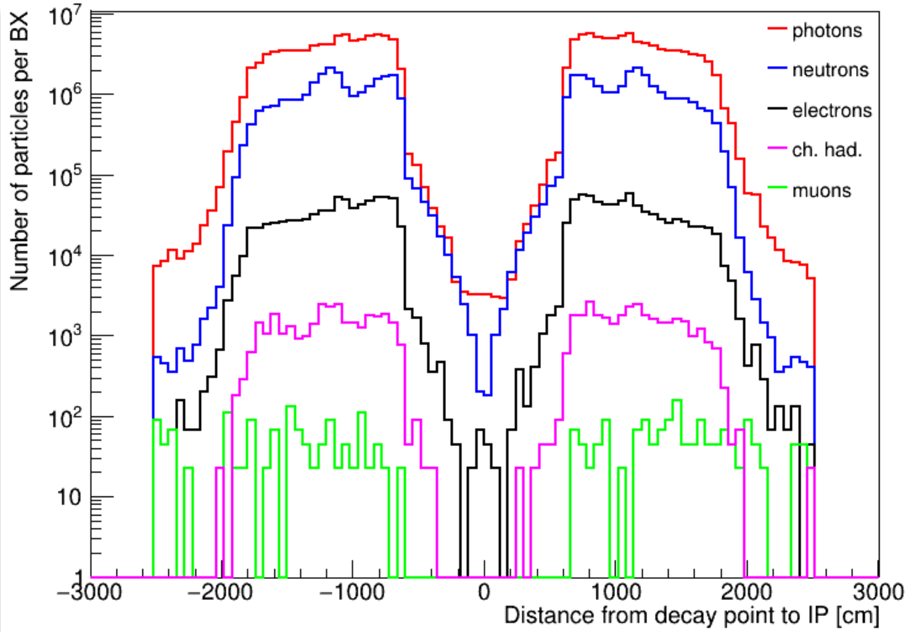




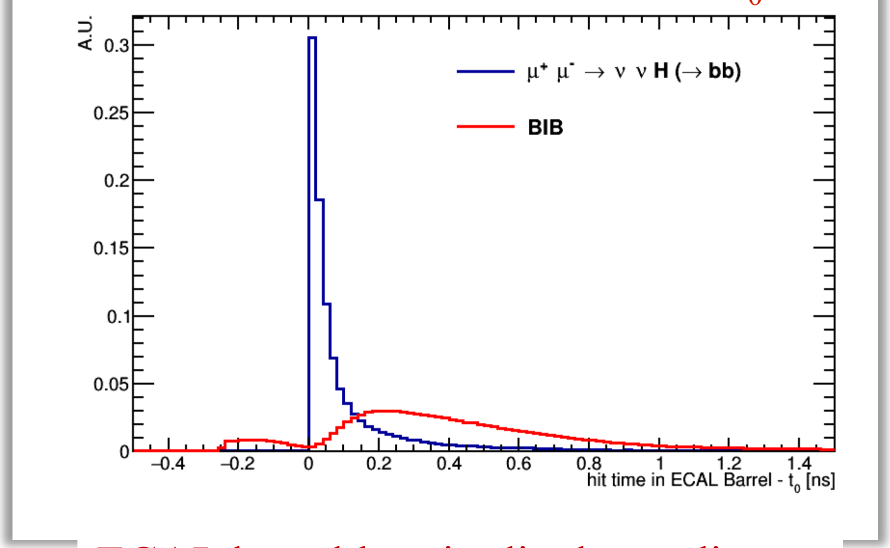
N. Mokhov et al. Fermilab-Conf-11-094-APC

Beam-induced Background

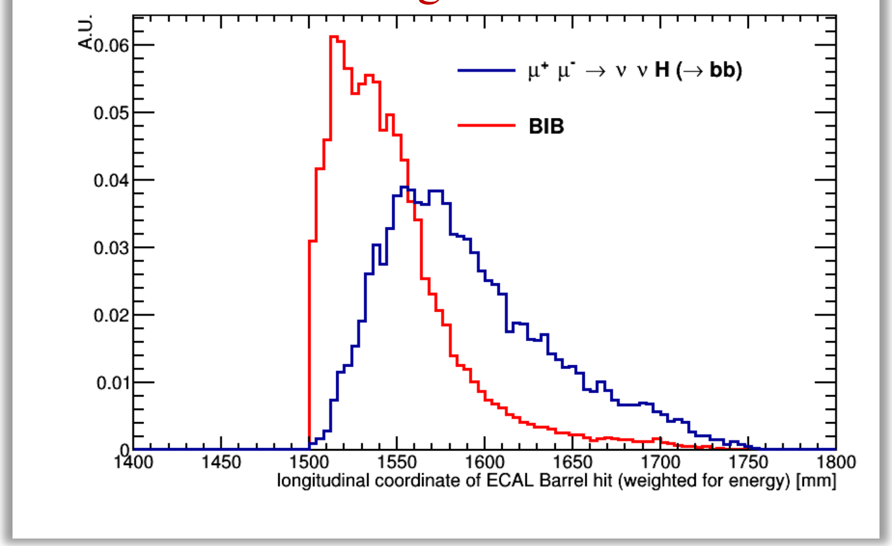
D. Lucchesi et al.



ECAL barrel hit arrival time – t_0



ECAL barrel longitudinal coordinate



Event Full Simulation ⇒ no issues

Event track reconstruction:

- It takes a long time to do it with full BIB
- Reduce the combinatorial:
  - cutting harder on timing
  - exploit double layer to remove tracks not coming from primary interaction

Jet Reconstruction:

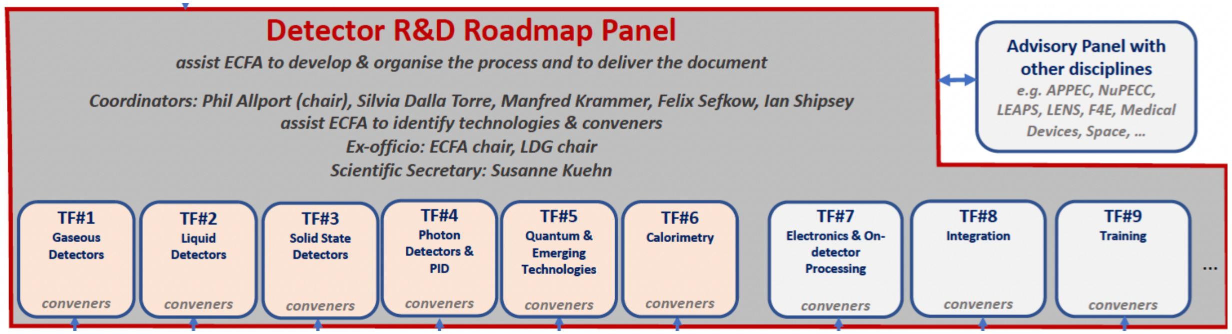
- Subtract "average" BIB energy
- Optimize ParticleFlow algorithm

Jet b-tag: to be optimized

Detector Technologies

Will rely largely on European Detector R&D Roadmap

- 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

Ongoing Accelerator Work

Muon collider is new in Europe

- Have to get up to speed

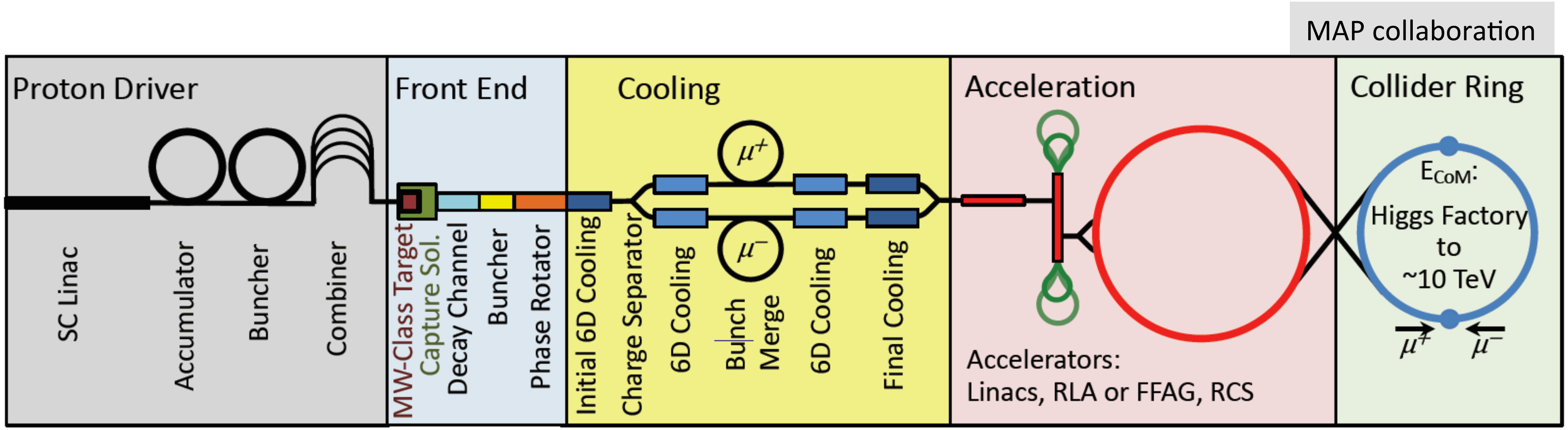
Together with US colleges are starting to take (shared) ownership of design

- Detailed presentations and discussions in serious of Design Meetings
- Transfer of lattice decks
- As new partners are forming own opinions
- Identifying issues that have been neglected
- Already part of generating the critical issues list
- Understanding the challenges and the resource needs

An important phase, excellent time to identified overlooked issues because of fresh view

Also have to find consensus on sometimes diverging opinions or define way to arrive at agreement

Muon Collider Baseline Concept



Proton Driver and Front End, Cooling and First part of Acceleration have same challenge level as in MAP designs

Final cooling misses transverse emittance target by factor 2

Still a **challenging design** with **challenging components**

Started to review to complete R&D item list and prepare priority

Accelerator ring, collider ring, interaction region, MDI, neutrino radiation become **more challenging with energy**
Also will drive cost and power

They will **limit energy reach**

Challenging design with **challenging components**

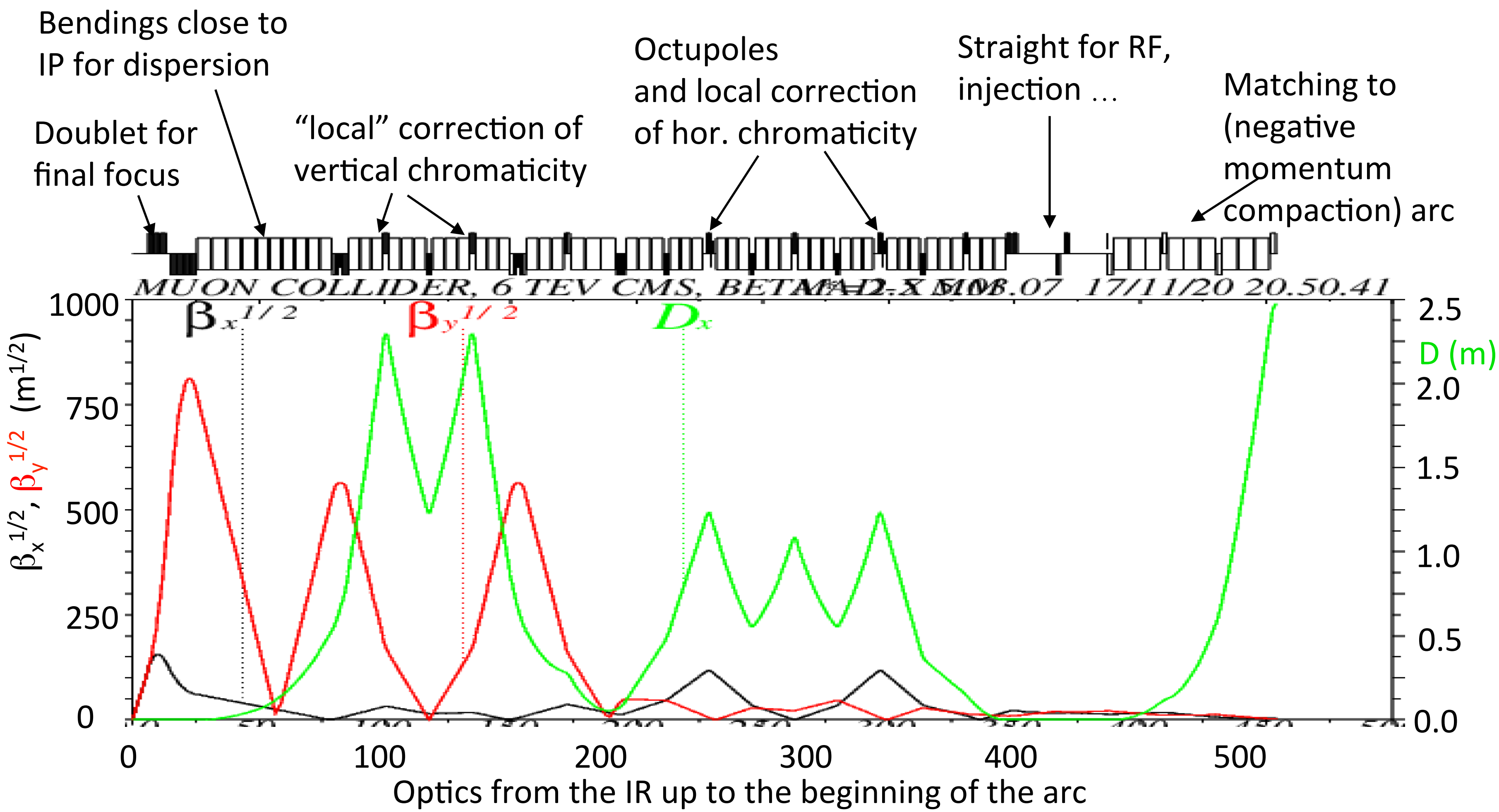
Interaction Region (IR)

Very challenging design

- Typical design example to be used as starting point for our design

Chr. Carli

6 TeV design by M-H. Wang, Y. Nosochkov, Y. Cai and M. Palmer

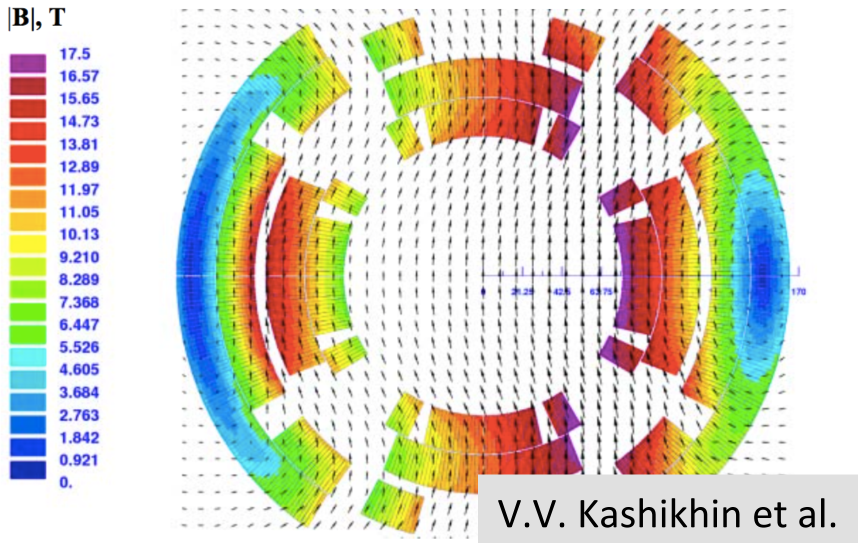


Collider Ring

Challenging optics (short bunch, long ring, minimal RF)
Important **collective effects** (beam-beam etc.)

High-field, large aperture dipoles to minimise collider ring size and maximise luminosity

Combined function magnet design



Combined function magnets replace quadrupoles to avoid straights

O(400 W/m) **beam loss**

- 5 MW total at 10 TeV
- Need to shield magnets
    - MAP at 3 TeV: 30-50 mm shielding
- Large apertures
    - MAP at 3 TeV: 150 mm

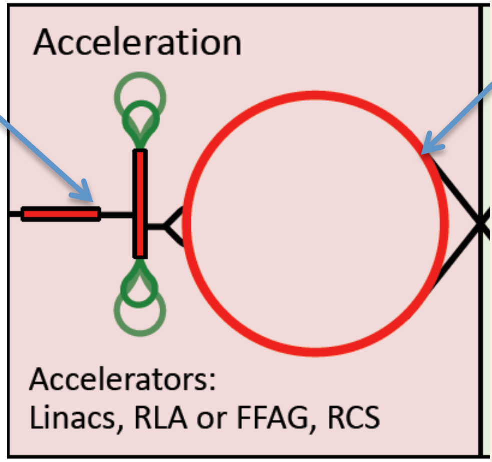
Will consider different technology options at different energies (NbTi, Nb_3Sn, HTS)
Balance performance, cost and timescale

Muon Acceleration

Design of initial acceleration (A. Bogacz) looks very solid

Does not change with collider energy

Main question is if we can further optimise



Accelerator ring is cost driver

Changes with collider energy

- potential energy limit

Two options are considered (presented by S. Berg, S. Machida, D. Summers)

- RCS (Rapid Cycling Synchrotron) with fast-ramping magnets
- FFAG with static magnets and special optics

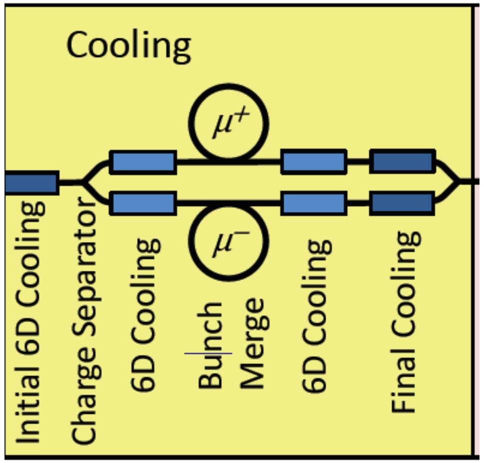
Optics design (Interest: RCS: A. Chance, CEA, FFAG: S. Machida, Rutherford Lab)

Fast-pulsing magnets (normal-conducting or HTS (Interest: L. Rossi, INFN))

Efficient energy recovery of fast pulsing magnets (Interest: CERN)

Efficient superconducting RF for short, intense bunches (Interest: U. van Rienen, Rostock, A. Grudiev, CERN)

Muon Cooling



Presentations: Chr. Rogers, D. Neuffer, D. Bowring, P. Jurj, D. Summers

6D cooling can probably be better than foreseen

- Review integration aspects (supercondcuting magnet coils next to normal-conducting RF)
- Optimise the design

Final cooling misses target transverse emittance by factor 2

- Higher field solenoids should help (>> 30 T), KTI proposal to BMFT (T. Arndt)
- Equilibrium emittance proportional to 1/B

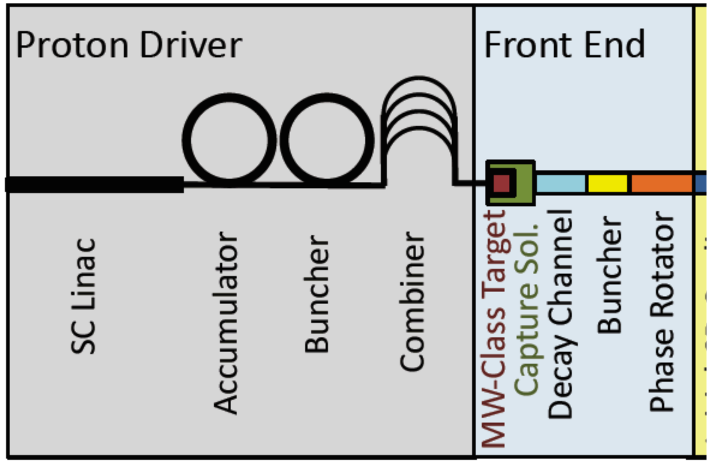
Chopping and recombining bunch as alternative to final cooling suggested (D. Summers)

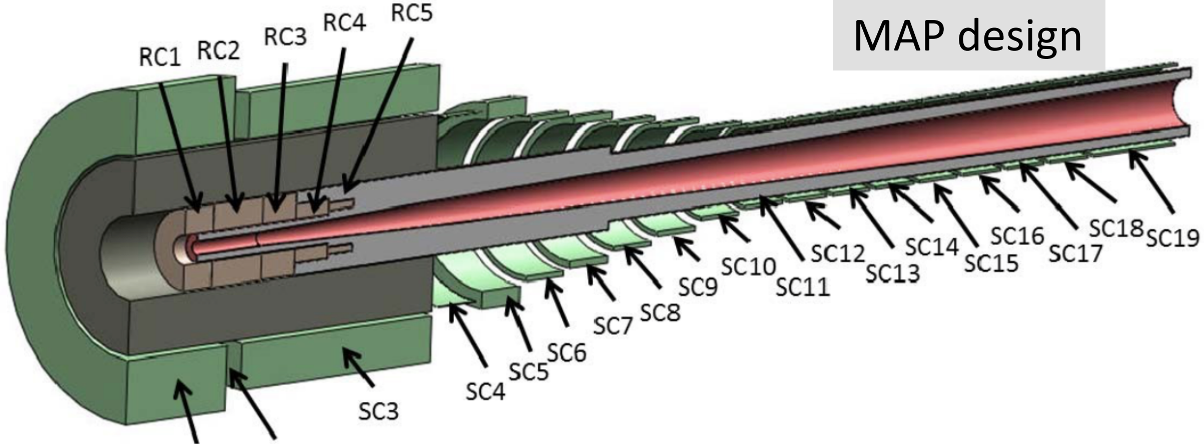
- To be reviewed

Experimentally proven RF gradients are higher than in design

- More muons will survive
- Can have more cooling
- Maybe can reuse some CLIC drive beam hardware for tests of RF

Proton Complex and Front-end





Intense proton beam is challenging

Need to make choices for the **target**

Ambitious **high-field solenoid**

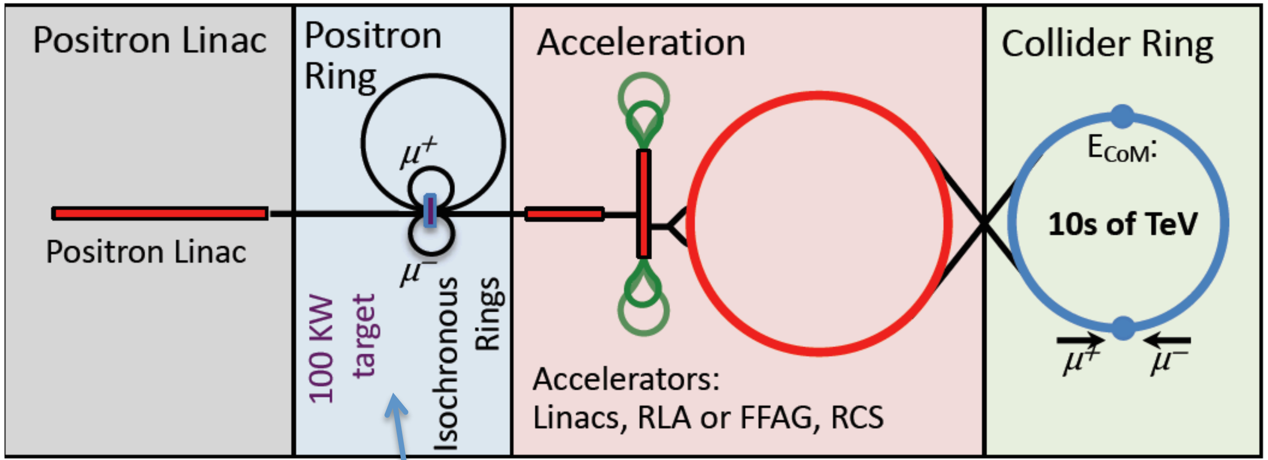
Radiation in magnet

Downstream radiation from MW proton beam

Need to quantify challenges

Will launch activity soon

Alternative: The LEMMA Scheme



M. Antonelli, M. Boscolo et al.

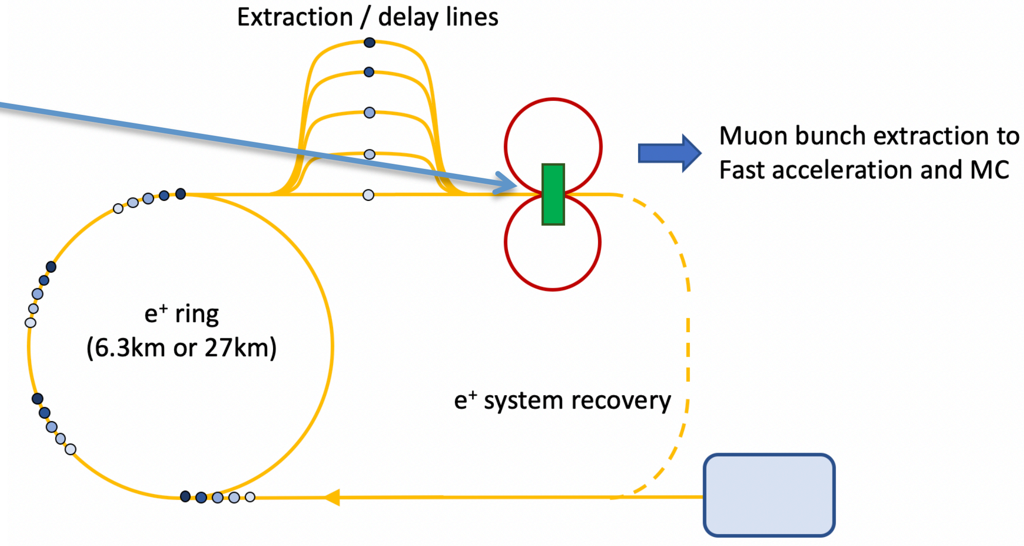
Less mature than proton scheme (less resources)

Progress in design but no parameter set for collider

45 GeV positrons to produce muon
Accumulate muons from several passages

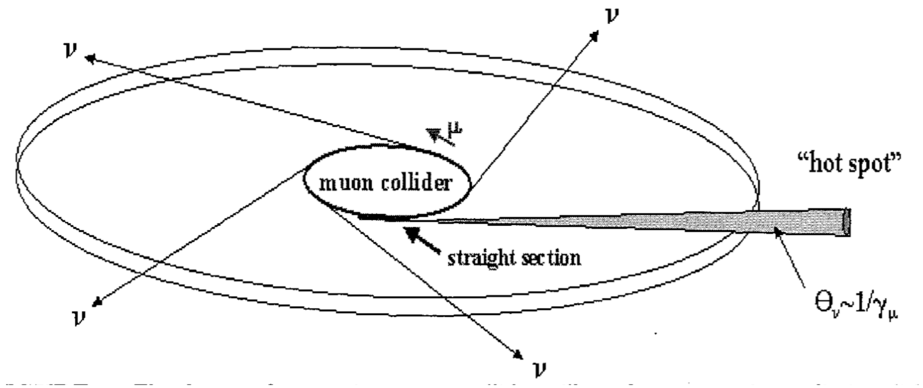
Goal: produce low emittance muon beam, no cooling required

Challenge to get enough charge into the bunch



Will try to put together **target parameter list** based on fundamental limitations (e.g. target and collider ring) to identify potential and R&D issues

Neutrino Radiation and Site Considerations



Tentative considerations on reuse of LHC tunnel:

- Too long for 3 TeV collider (need 4.5-6 km)
- 14 TeV collider ring suffers from neutrino radiation
- Use for 3 TeV accelerator ring appears possible

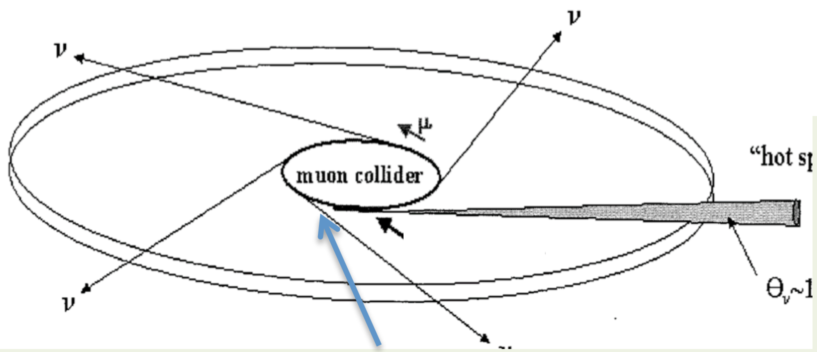
Neutrino radiation from collider ring is key for site and layout

- At 3 TeV 40 m deep tunnel arcs stay below 10% of legal limit, have to own land in direction of straights
- At 14 TeV with 500 m deep tunnel arc stays below legal limit

Want to minimise radiation as much as possible
CERN civil engineering will develop tool to optimise orientation of collider ring (J. Osborn)
Discussion started with neutrino experts on potential use of neutrinos in deirection of long straight (A. De Roeck et al.)
Development of lattice is starting
Discussion with HSE-RS (radiation safety) started
Consider mitigation techniques, even challenging ones

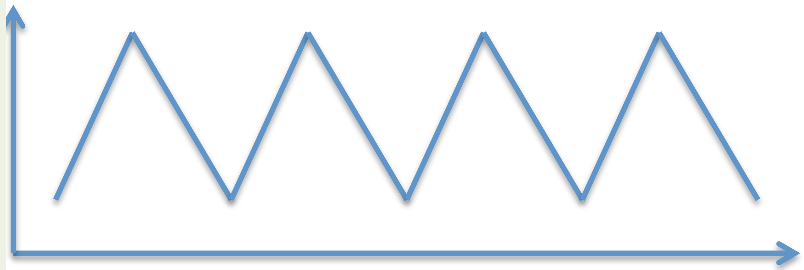
Example Neutrino Radiation Mitigation

Mitigation by varying beam orbit in collider is limited and costly (more space in magnets needed)

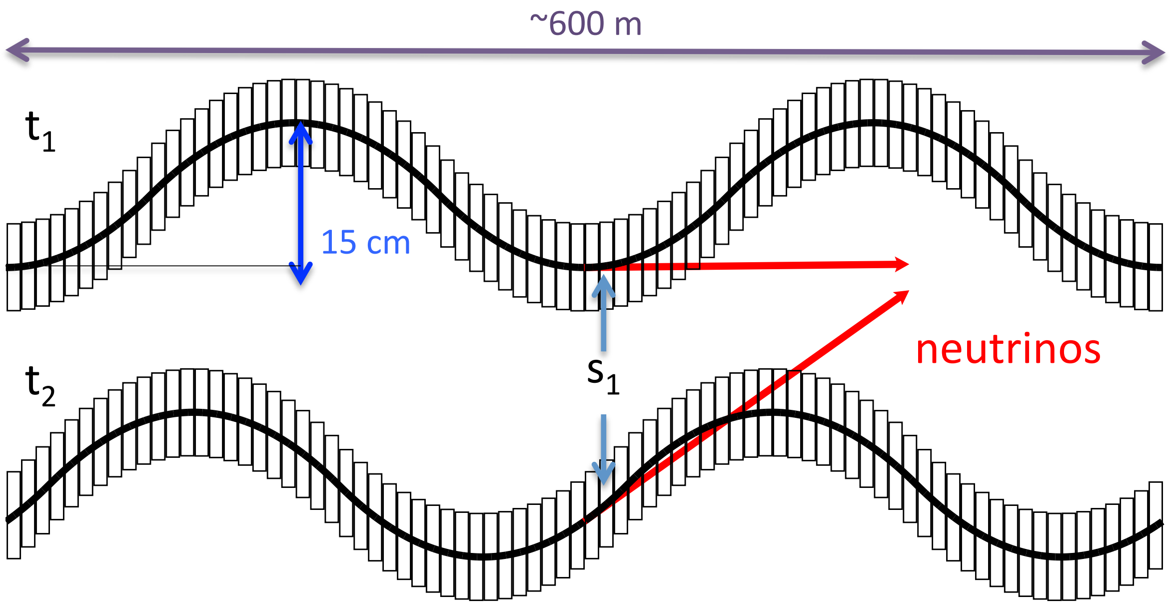


Relevant length of arc at s_1 is O(10 cm)

Vary vertical beam angle at s_1 in time



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



Opening angle ± 1 mradian

O(100) larger than decay cone
⇒ gain O(100) in radiation

In straights, additional improvement in horizontal

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

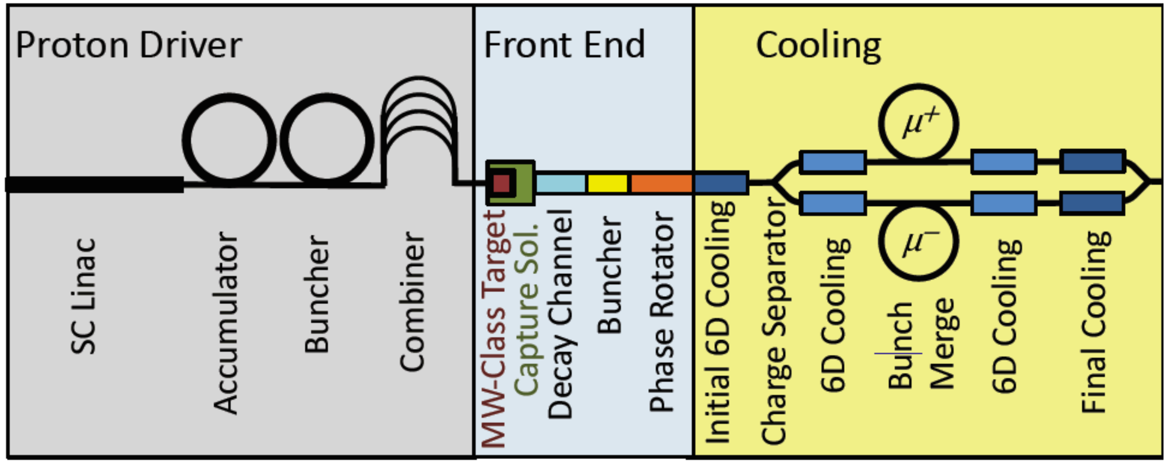
Demonstrator and Neutrinos

Need to develop R&D programme for implementation after next ESU

Key will be demonstrator facility to produce useful muon beam

Risk not being that cheap

Can this be combined with a neutrino facility such as NuSTORM?



Will explore synergies

Also explore if the neutrinos from the straights of the collider could be used for physics
First suggestion (A. De Roeck, E. Tsesmelis)
Deep-sea installations in Mediterranean (KM3NeT-Fr, KM3NeT-It, KM3NeT-Gr)
But could be too deep, maybe interesting for test facility

Ideas are very welcome

Conclusion

Started to address the R&D on muon collider as requested by European Strategy

Formal collaboration at any moment

Actual work started with meetings on design and specialised topics

- Accelerator design
- Physics and detectors

Topical meetings

- Physics potential, Detector simulations, Muon cooling

Will have project meeting with everyone

- Every few months, half day long

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

- Find meeting link in menu "Organisation"

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

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

Reserve

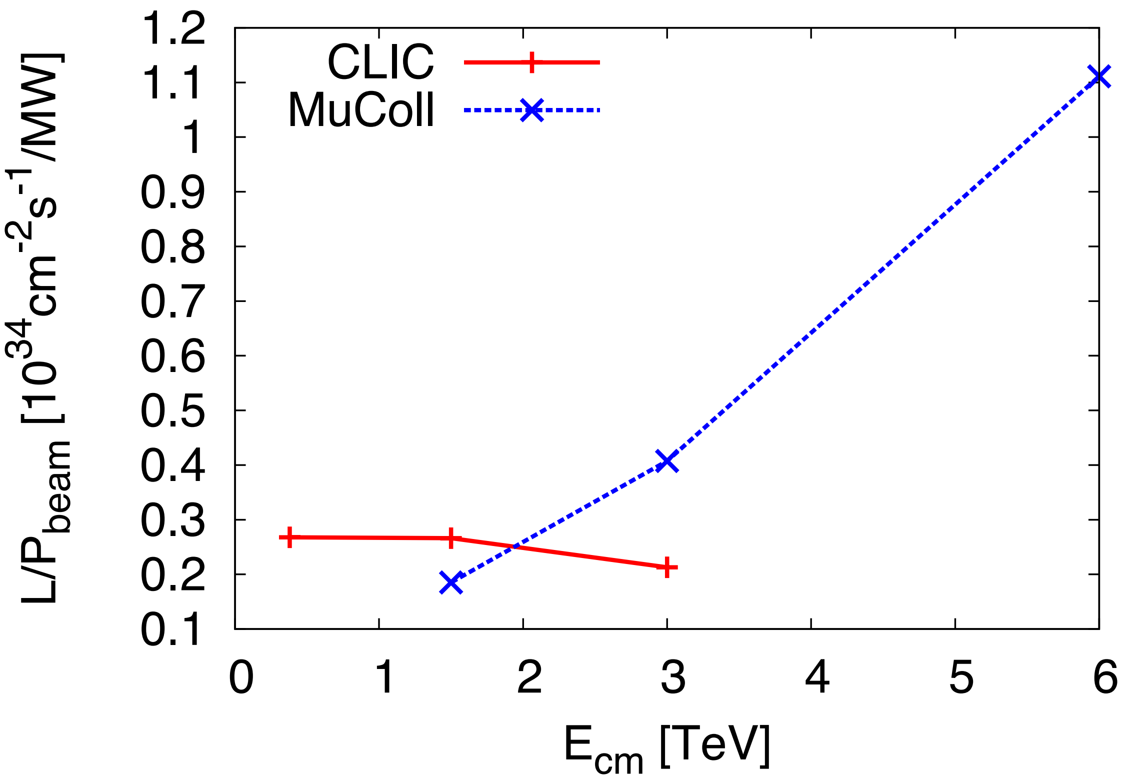
Critical Issues Include:

- **Advanced detector concepts and technologies**, requiring excellent timing, granularity and resolution, able to reject the background induced by the muon beams.
- **Advanced accelerator design** and beam dynamics for high luminosity and power efficiency.
- **Robust targets and shielding** for muon production and cooling as well as collider and detector component shielding and possibly beam collimation.
- **High field, robust and cost-effective superconducting magnets** for the muon production, cooling, acceleration and collision. High-temperature super-conductors would be an ideal option.
- **High-gradient and robust normal-conducting RF** to minimise muon losses during cooling.
- High rate **positron production** source and high current positron ring (LEMMA).
- **Fast ramping normal-conducting, superferric or superconducting magnets** that can be used in a rapid cycling synchrotron to accelerate the muons and efficient power converters.
- **Efficient, high-gradient superconducting RF** to minimise power consumption and muon losses during acceleration.
- **Efficient cryogenics systems** to minimise the power consumption of the superconducting components and minimise the impact of beam losses.
- Other accelerator technologies including high-performance, compact **vacuum systems** to minimise magnet aperture and cost as well as fast, robust, **high-resolution instrumentation**.

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

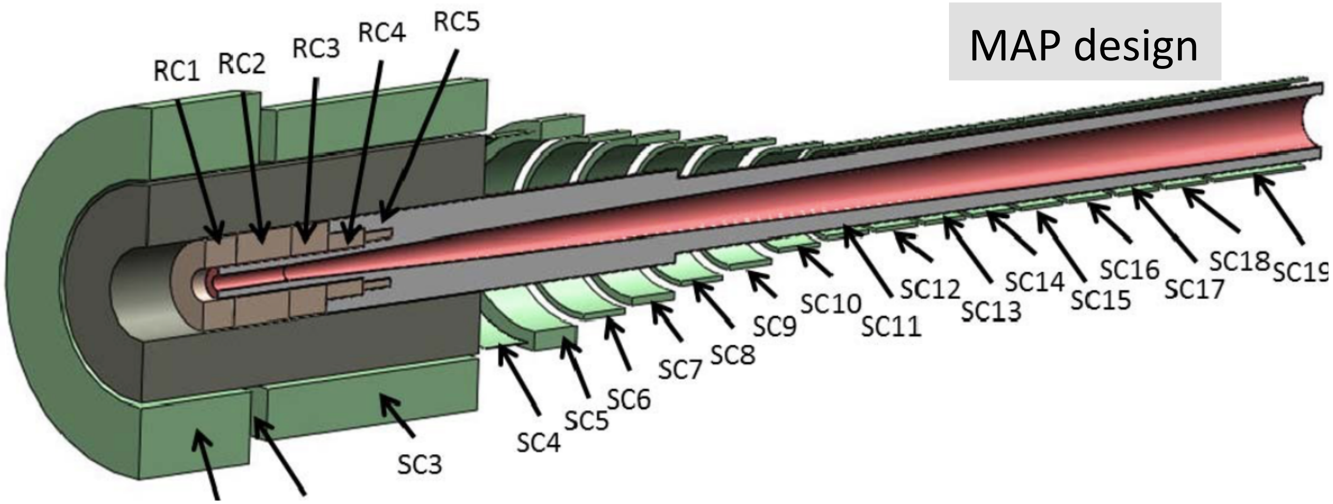
The working group concluded that an International collaboration should be formed to study the muon collider

Source

Intense proton beam is challenging

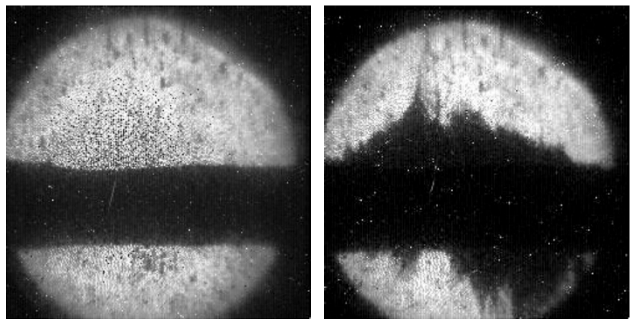
Need to make choices for the **target**

Ambitious high-field solenoid



Target has to withstand **strong shock**

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



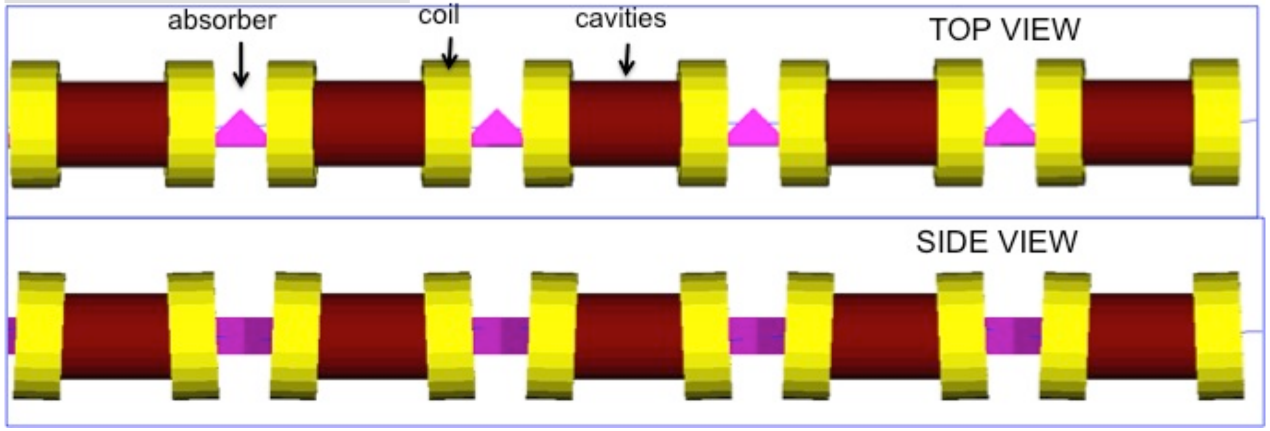
Important power of proton driver O(MW)
need to take care of debris for downstream systems
need to cool

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

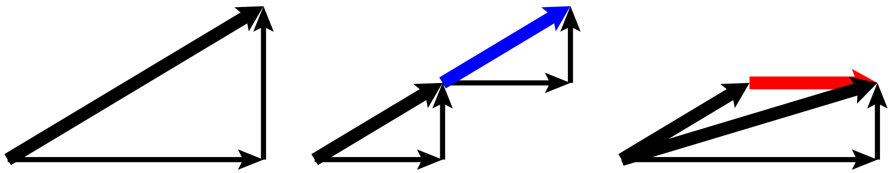
Cooling Concept

See previous presentation by J. Pasternak

MAP collaboration

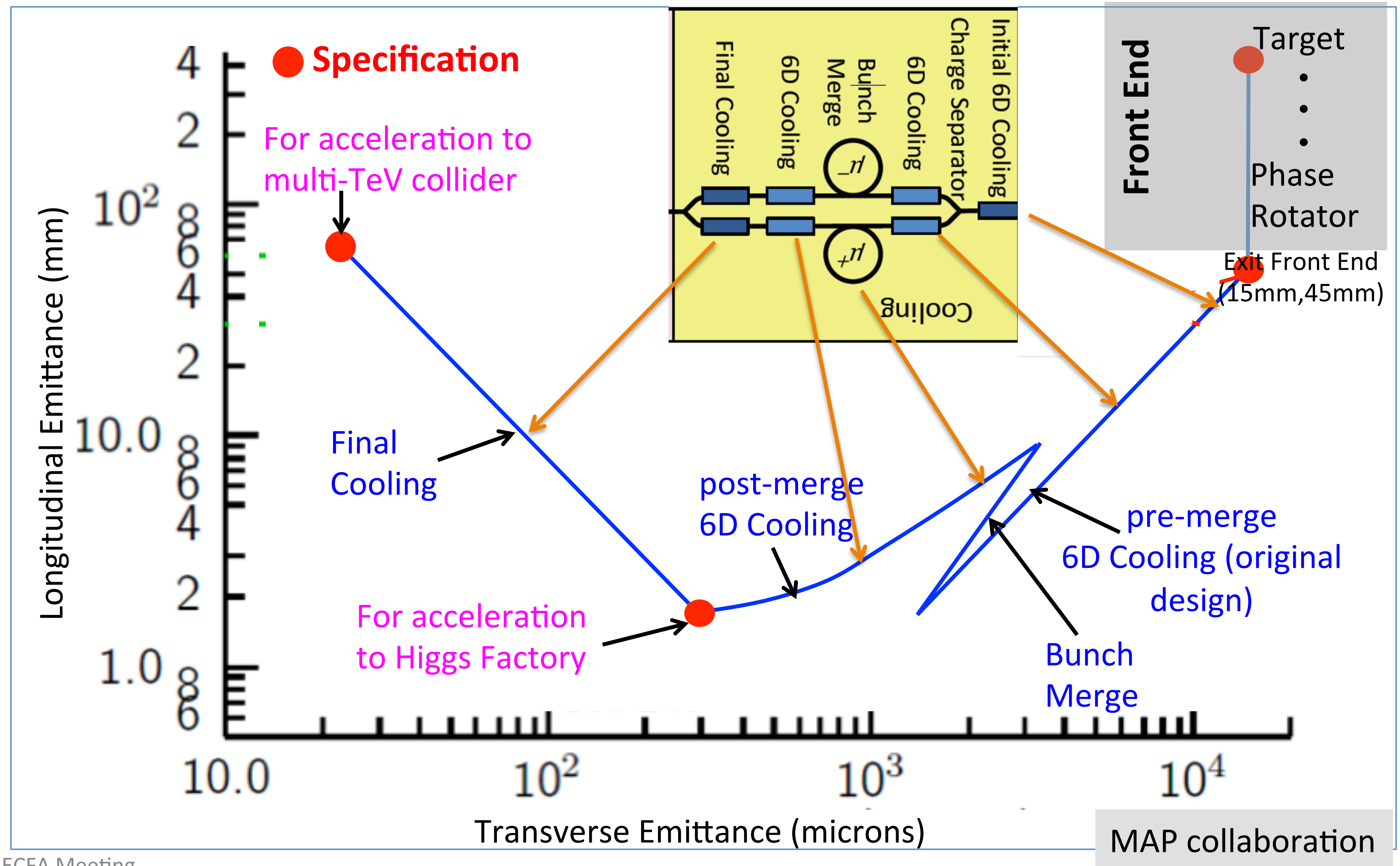


- Superconducting solenoids
- High-field normal conducting RF
- Liquid hydrogen targets
- Compact design

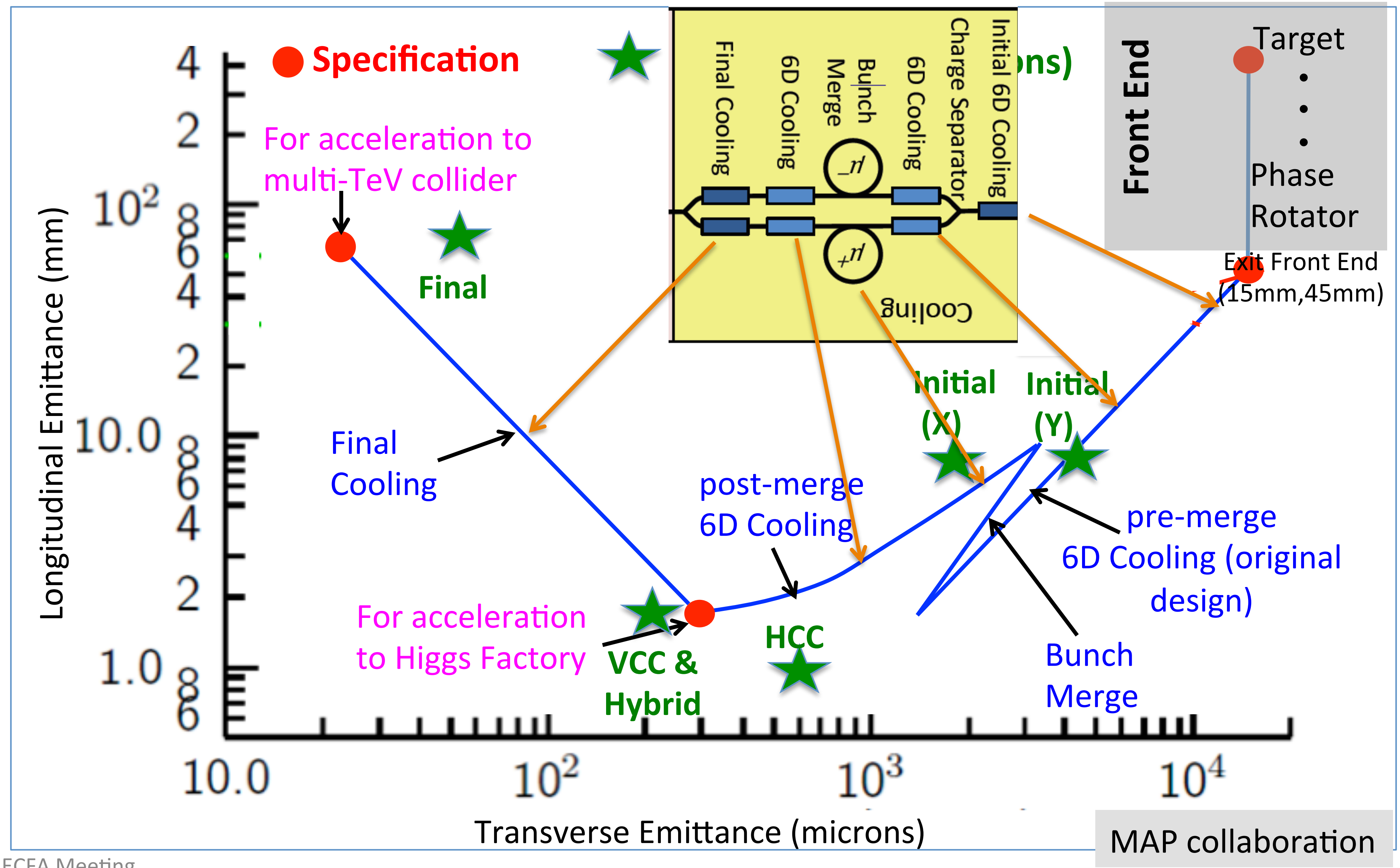


$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

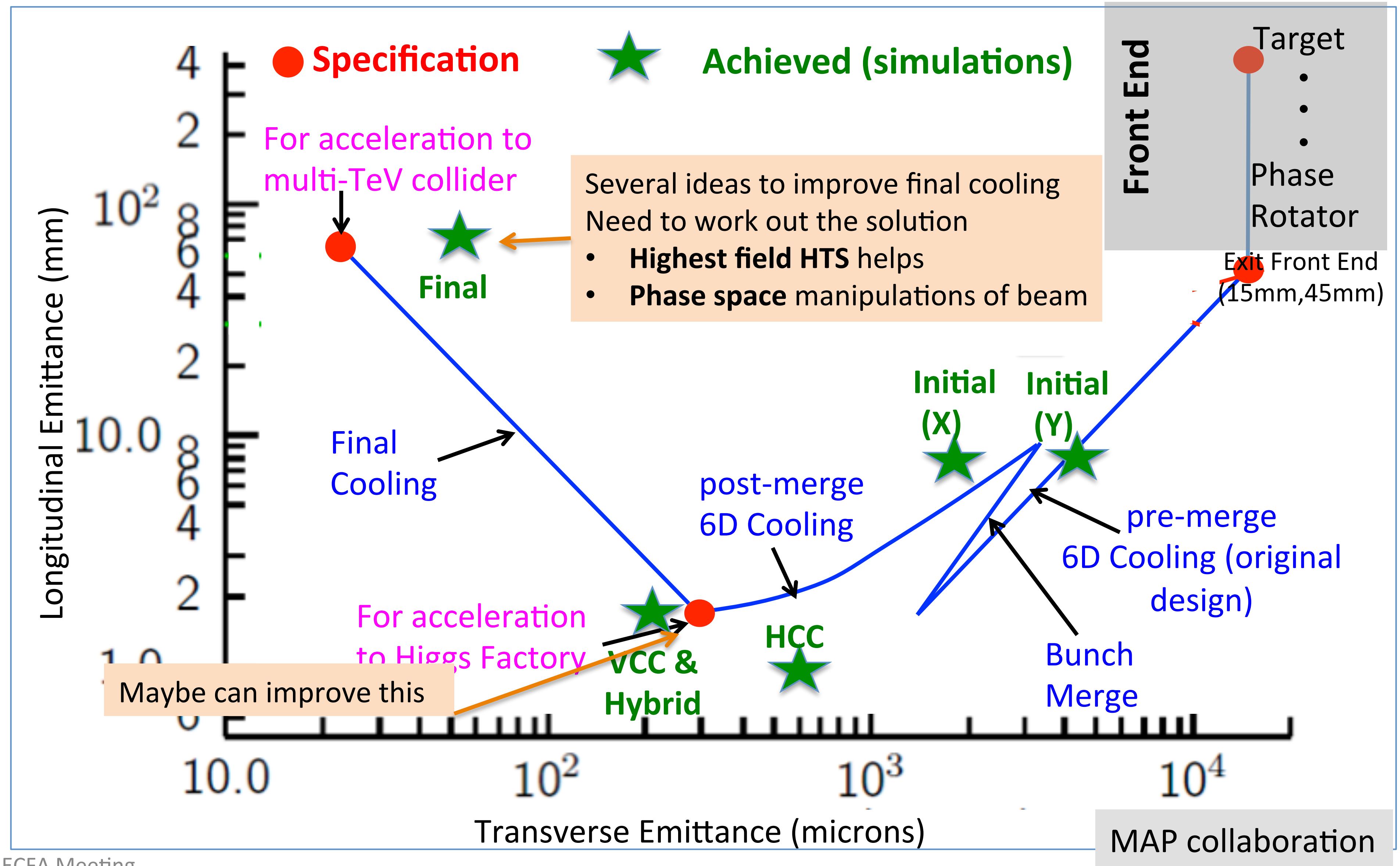
Cooling: The Emittance Path



Cooling: The Emittance Path



Cooling: The Emittance Path



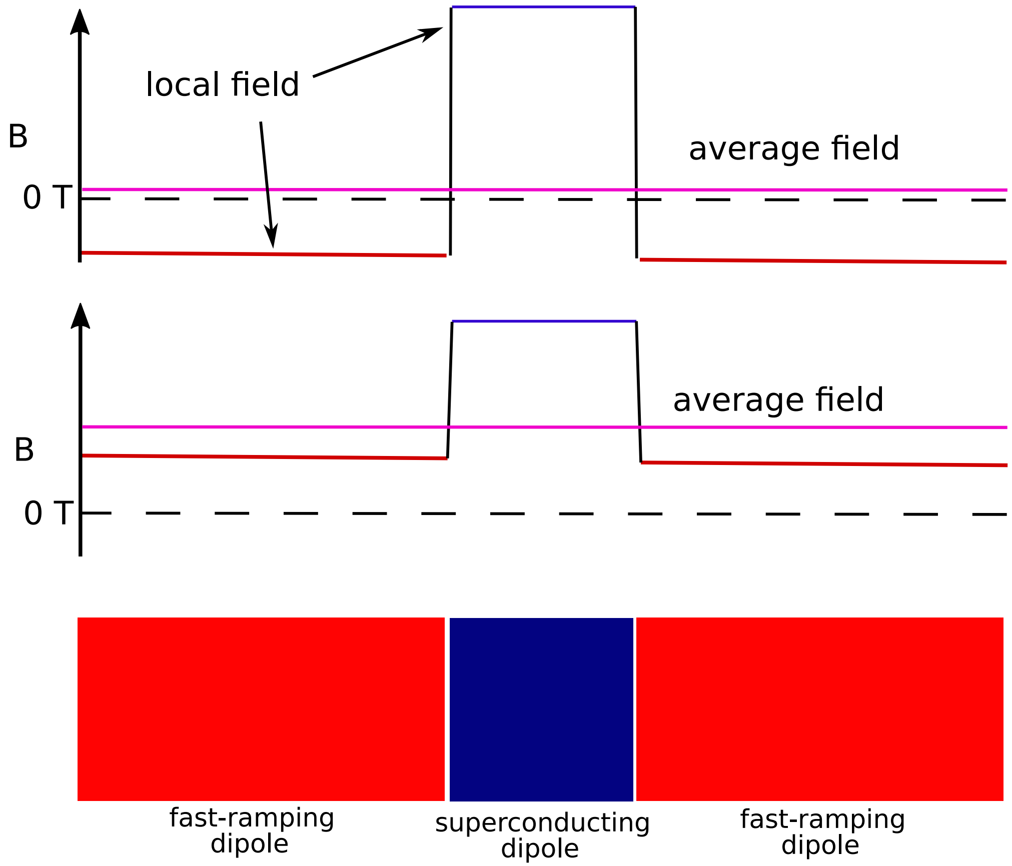
High-energy Acceleration

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

RF Challenge

Acceleration and collider ring RF

14 TeV: 1 mm long bunch with 0.1 % energy spread in collider ring

Almost same longitudinal emittance as after muon cooling

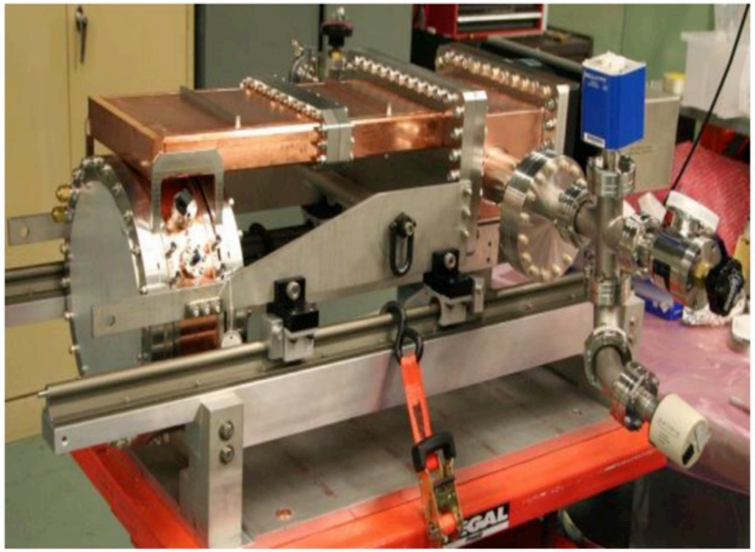
High bunch charge of 2×10^{12} muons

Start with long bunch that is subsequently compressed

Need concept of longitudinal dynamics all along the accelerator

Challenging to maintain emittance

MuCool: >50 MV/m in 5 T field



Muon cooling RF

Proof of principle in US (gas-filled copper and vacuum beryllium cavities)

Other RF

e.g. proton complex RF

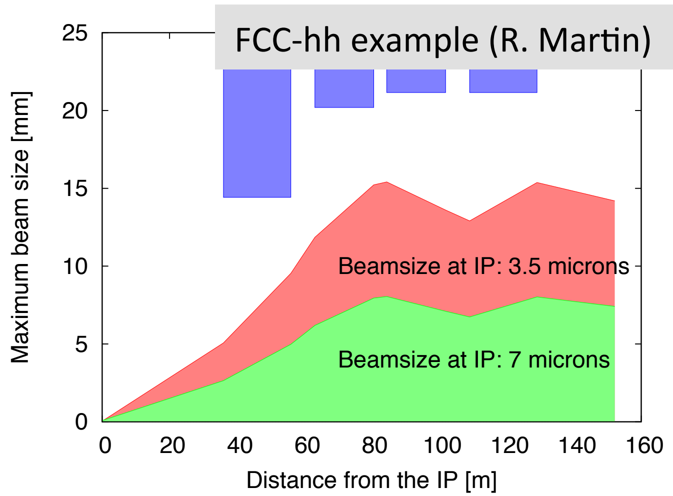
making contact, may need more effort later

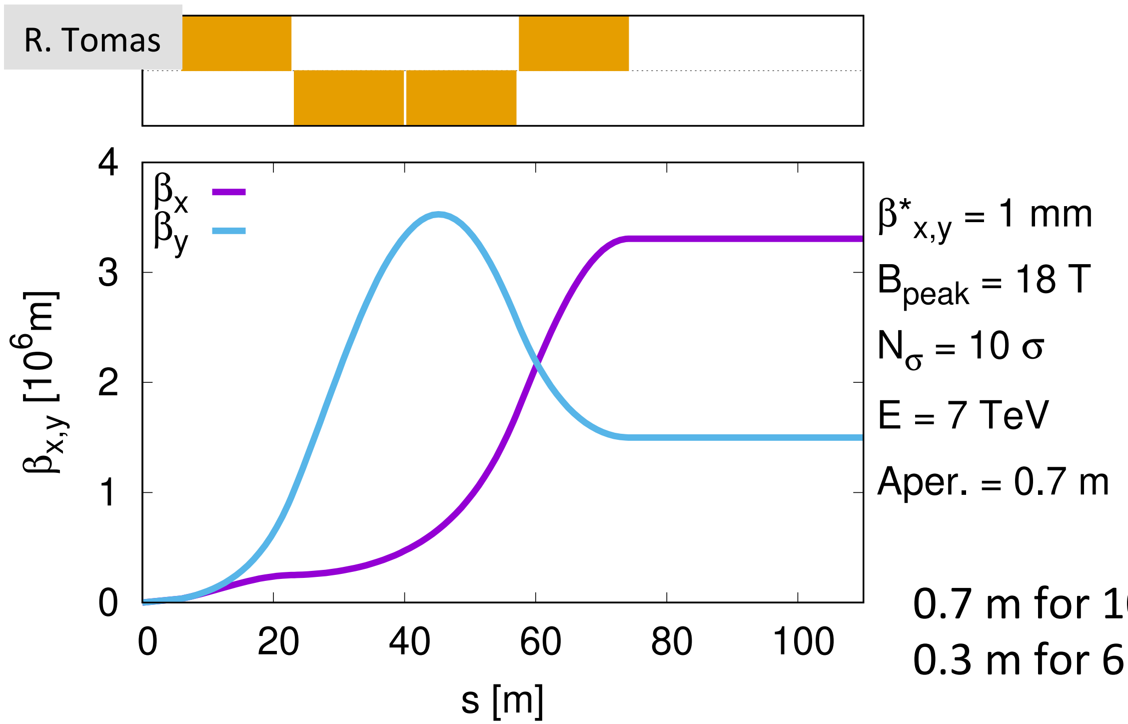
Final Focus

Need smaller betafunctions at higher energy
Or smaller longitudinal emittance / larger energy acceptance

$$\beta^* \propto \frac{1}{E}$$

And focusing of higher energy beam is more difficult





0.7 m for 10 σ
0.3 m for 6 σ

First look from Rogelio Tomas on final triplet at 14 TeV (L* = 6 m):

Challenging system
Need to add shielding

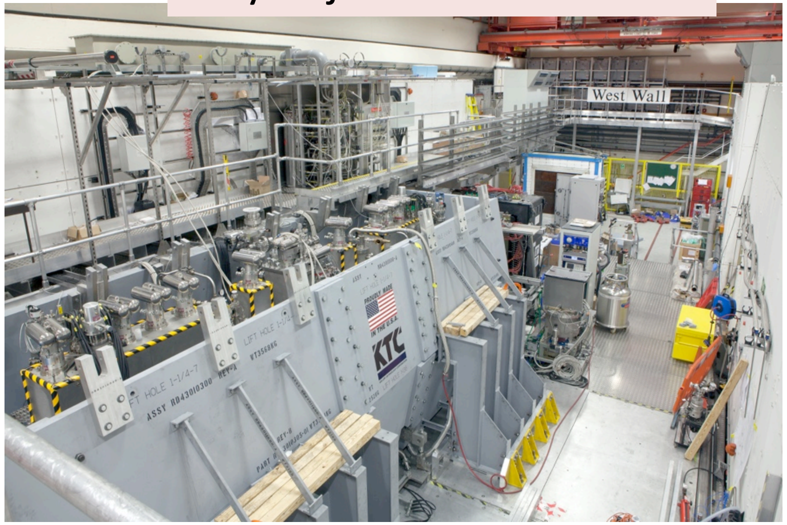
Design Status

As you just heard in detail

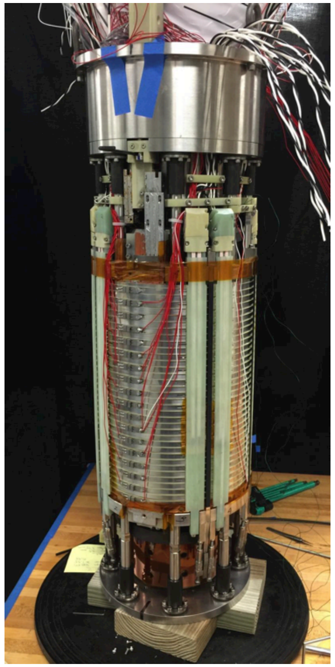
Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

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

MICE (UK)

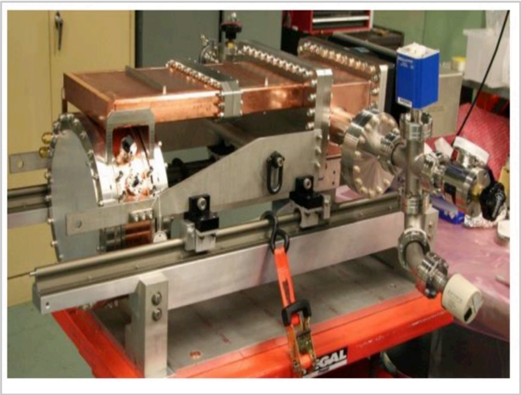


FNAL
Breakthrough in HTS cables



NHFML
32 T solenoid with low-temperature HTS

MuCool: >50 MV/m in 5 T field



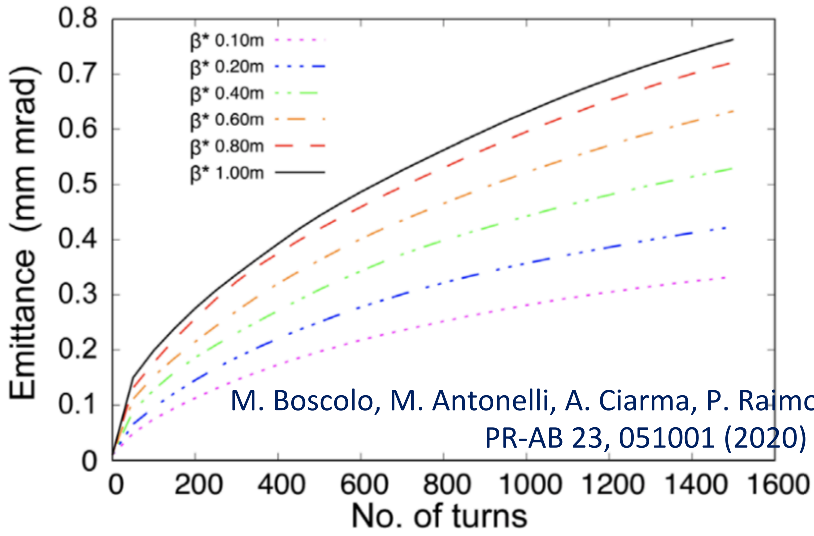
FNAL
12 T/s HTS
0.6 T max

Mark Palmer

The LEMMA Scheme

Progress in design

- Fluid targets
- Combination of bunches into single bunch
- Novel design of muon accumulator rings with very large energy acceptance [-10%; +15%]
- Sequence of targets to keep beta-function small



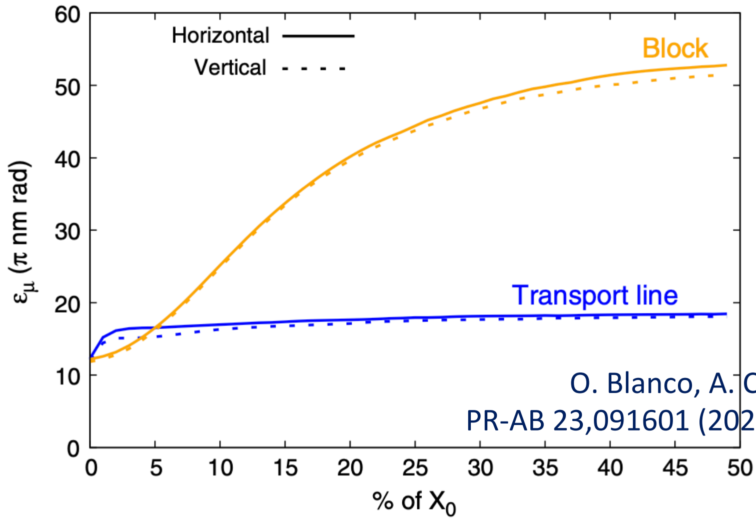
M. Boscolo, M. Antonelli, A. Ciarma, P. Raimondi
PR-AB 23, 051001 (2020) link

However, emittance are not so small:

- 1 - 20 μm (normalised)

Will assess LEMMA based on first principles

- target and collider ring
- to develop target parameters
- to judge feasibility
- to devise a strategy of how to continue



O. Blanco, A. Ciarma
PR-AB 23,091601 (2020) link

Physics and Detector Studies

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 et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

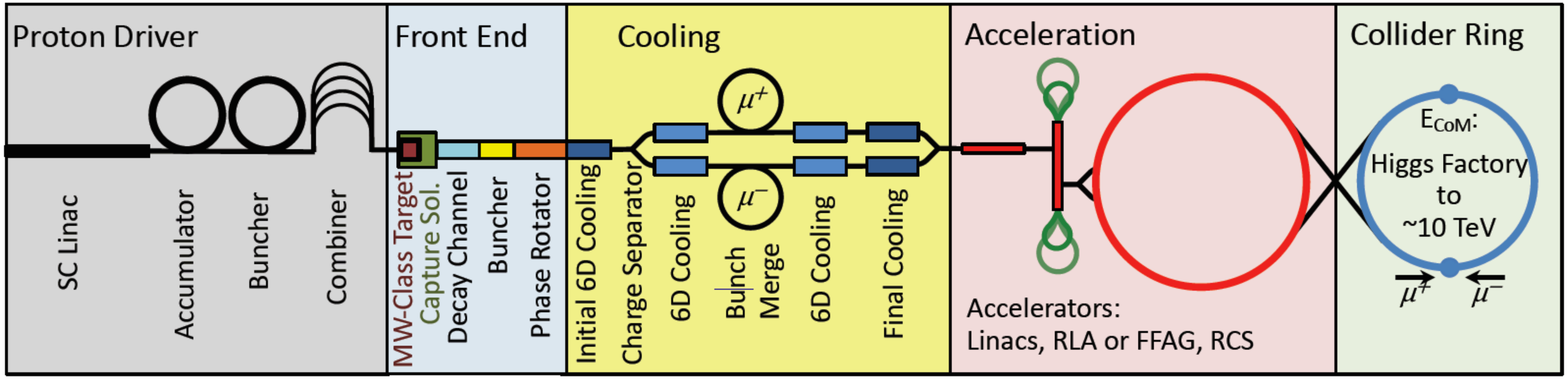
- For use by physics potential studies
  - Are the performances sufficient or too good?
- For detector studies to work towards
  - make sure technologies are reasonable
  - ensure background is OK
- Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies

- Currently at 1.5 TeV and 125 GeV (because we have background data)
- To understand background characteristics
  - develop mitigation strategy (e.g. origin of tracks for rejection, timing)
- To check how far we have to go to arrive at target performance
  - Snapshot DELPHES card to motivate further R&D
- Note: reconstruction tailored to beam-induced background might become important

Muon Collider Baseline 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