Muon Colliders

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Many thanks to Mark Palmer, Vladimir Shiltsev and the MAP and LEMMA teams
Also to Christian Carli, Alexej Grudiev, Alessandra Lombardi, Gijs De Rijk, Mauricio Vretenar, …

Muon Collider Working Group

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Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France,
Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland,
Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN

appointed by CERN Laboratory Directors Group in September 2017

to prepare the Input Document to the European Strategy Update

"Muon Colliders," arXiv:1901.06150

de facto it is the seed for a renewed international effort

Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018

Università di Padova - Orto Botanico

https://indico.cern.ch/event/719240/overview

Preparatory meeting to review progress for the ESPPU Simposium

April 10-11, 2019

CERN – Council Room

https://indico.cern.ch/event/801616

Scope of the Working Group

- The working group performed a first, high-level review of the two muon collider possible schemes: one based on protons to produce muons and one on positrons, as content of the submitted input document

- The focus has been on the positron-based scheme, which it was really promising but it has been found to require consolidation

- This year a more in depth investigation can provide a better assessment for the European Strategy Process about the potential value of the technology for a collider and the R&D programme that would be required. Dedicated work is being carried out on a positron driven new scheme

Note:

- Not ready to draft a CDR
- To pursue the promising muon collider option, a strong R&D effort should be supported to take ownership of a conceptual design or develop a better one

Findings

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project.

A set of recommendations at the end will allow to make the muon collider technology mature enough to be favorably considered as a candidate for ehigh-energy facilities in the future.

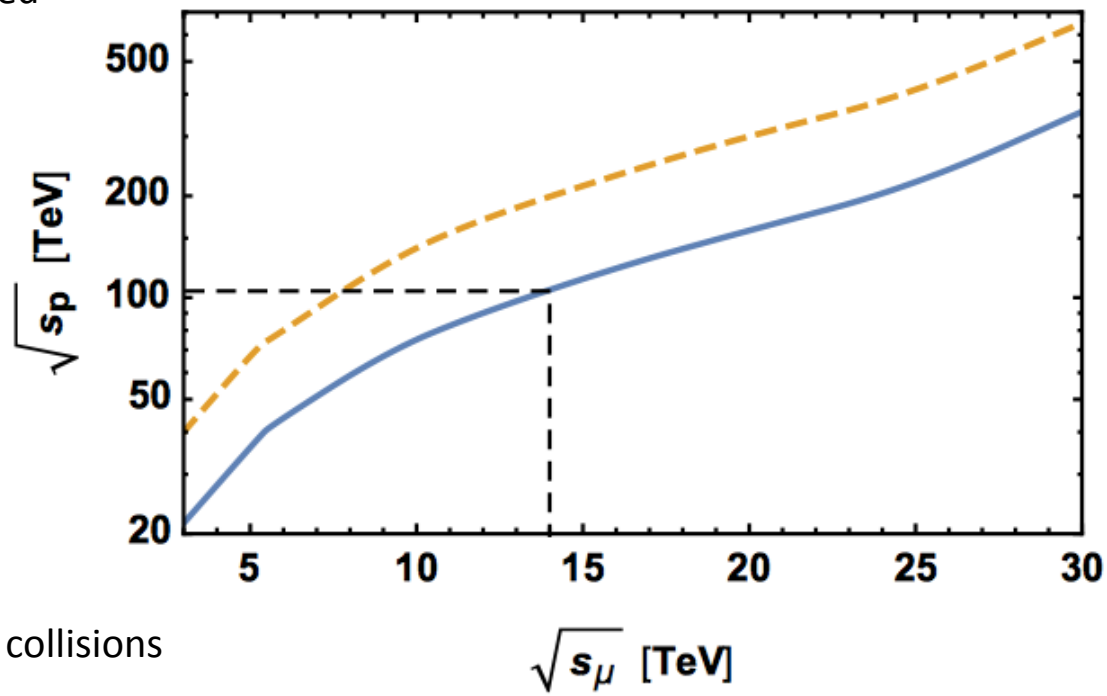
Motivation

Lepton colliders offer the potential of precision measurements

- Well defined initial conditions
- Low background levels
- …

At high energies they are efficient discovery machines

- Full collision energy available for particle production
- But sufficient luminosity is required



14 TeV lepton collisions
Are comparable to 100 TeV proton collisions

Luminosity Goal

To investigate s-channel processes, luminosities have to increase quadratically with energy

- From the physics a luminosity goal is defined as

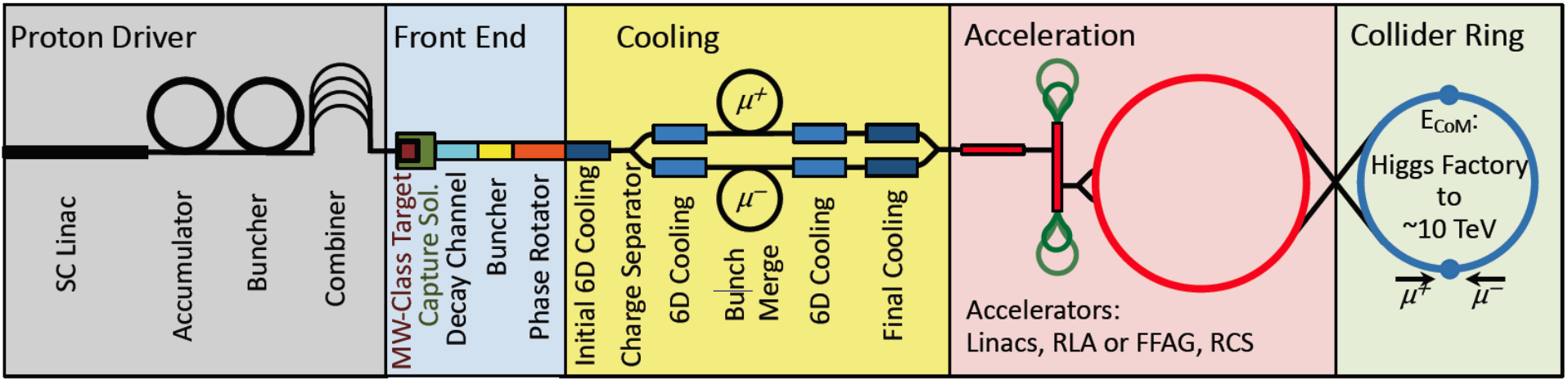
$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s}_\mu}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

The main difficulty of electron-positron colliders is to provide the luminosity at high energies

- Circular collider radiate dramatically at high energy
- Linear colliders can provide linear increase of luminosity for constant beam current
- Or a constant luminosity per beam power

A muon collider might break this limit and provide a luminosity that increases linearly with energy for constant beam power

Proton-driven Muon Collider Concept



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

Collider Parameter Examples

From the MAP collaboration: Proton source

Muon Collider Parameters					
		Higgs	**Multi-TeV**		
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/10^7sec		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

Key to Luminosity

Integrated luminosity of one bunch

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

High bunch charge

High energy

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

High beam power

High field in collider ring

Small emittance

For constant longitudinal emittance

Win luminosity per power as the energy increases

In linear colliders, luminosity per power tends to be energy independent

- except if one changes technology (very short bunches, smaller vertical emittance)

In circular electron-positron colliders luminosity drops rapidly with energy (power ≈3.5)

Key to Luminosity

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

$$\sum_{i=0}^{\infty} \left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2 \propto N_0^2 B$$

$$\Delta \int \mathcal{L} \propto \frac{B N_0^2}{4\pi\epsilon\beta/\gamma}$$

$$\beta \approx \sigma_z$$

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

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

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

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

Note: this might be limited by technology

$$\Delta \int \mathcal{L} \propto B \frac{N_0^2 \gamma^2}{\epsilon}$$

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

Collider Parameter Examples

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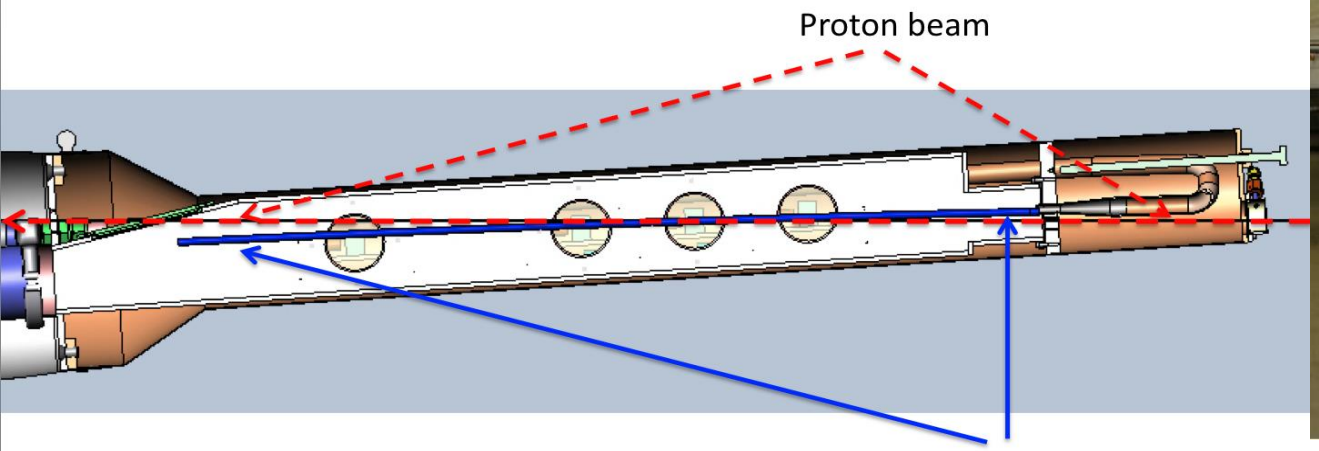
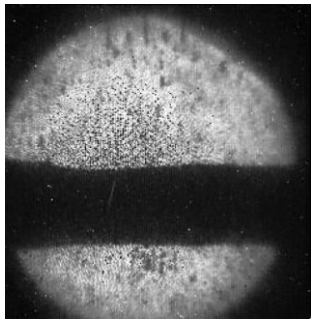
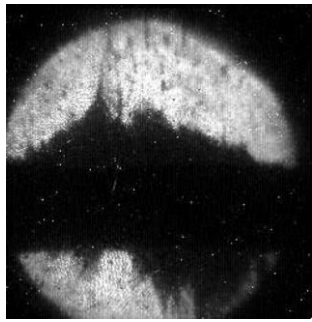
Source

Protons → Target → Pions → Muons



MERIT experiment at CERN





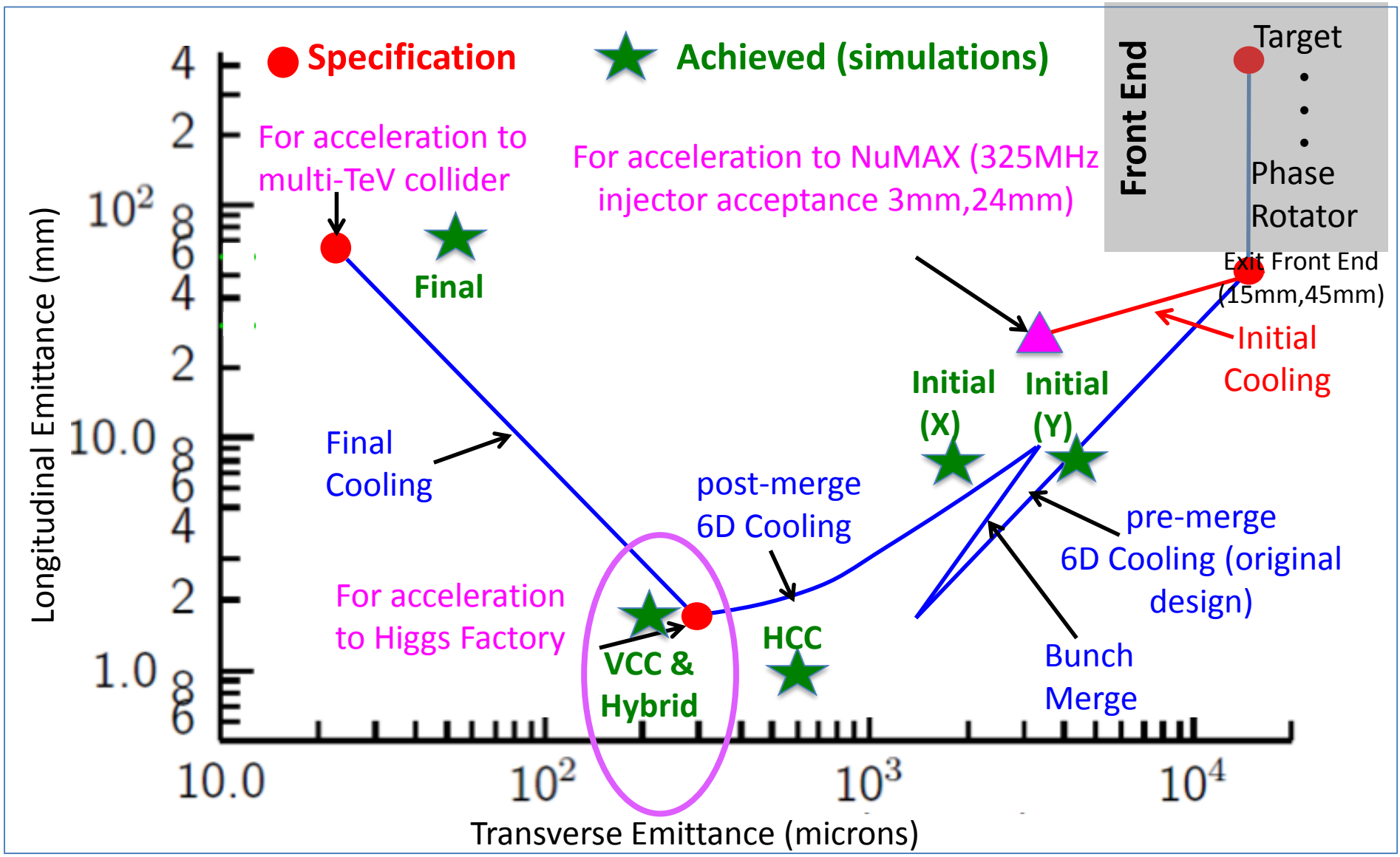
High power target (8 MW vs. 2-4 MW required) has been demonstrated

Maximum of 30×10^{12} protons with 24 GeV

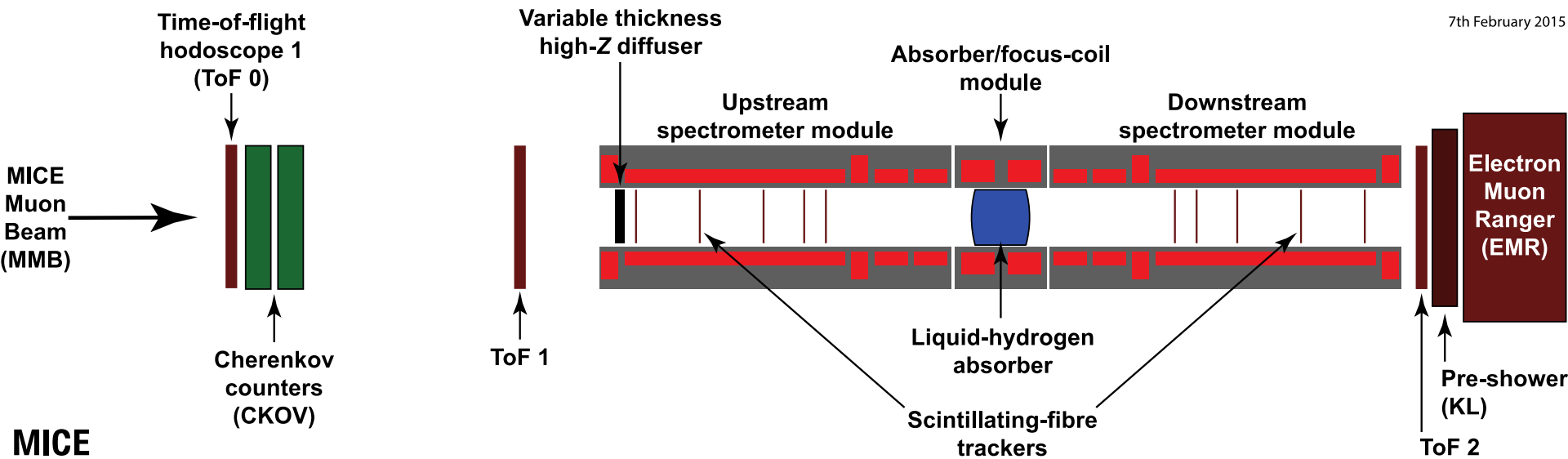
But radiation issues?

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

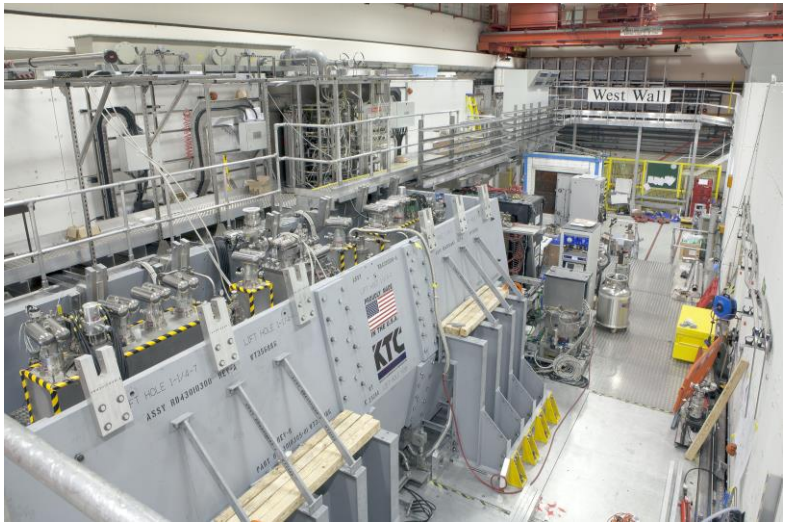
Cooling: The Emittance Path



Cooling and MICE



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

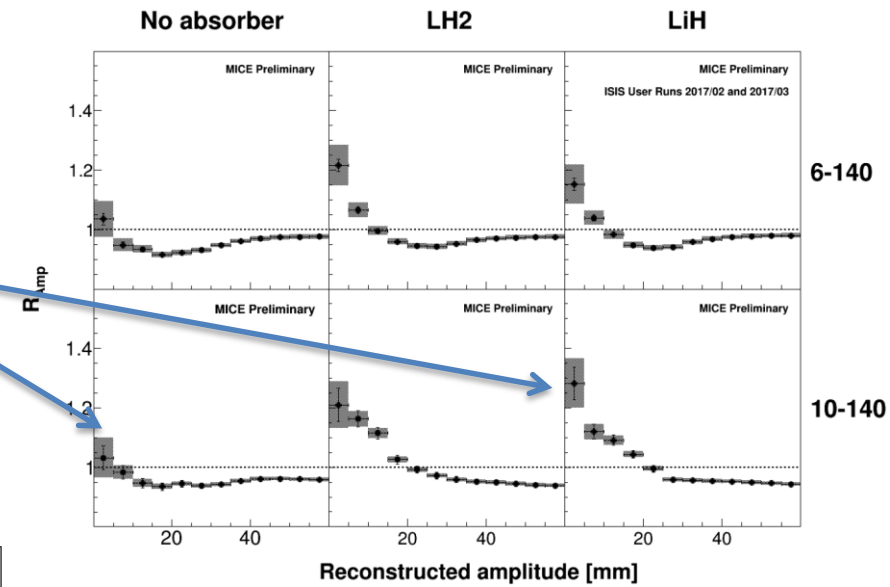


MICE allows to address 4D cooling with low muon flux rate

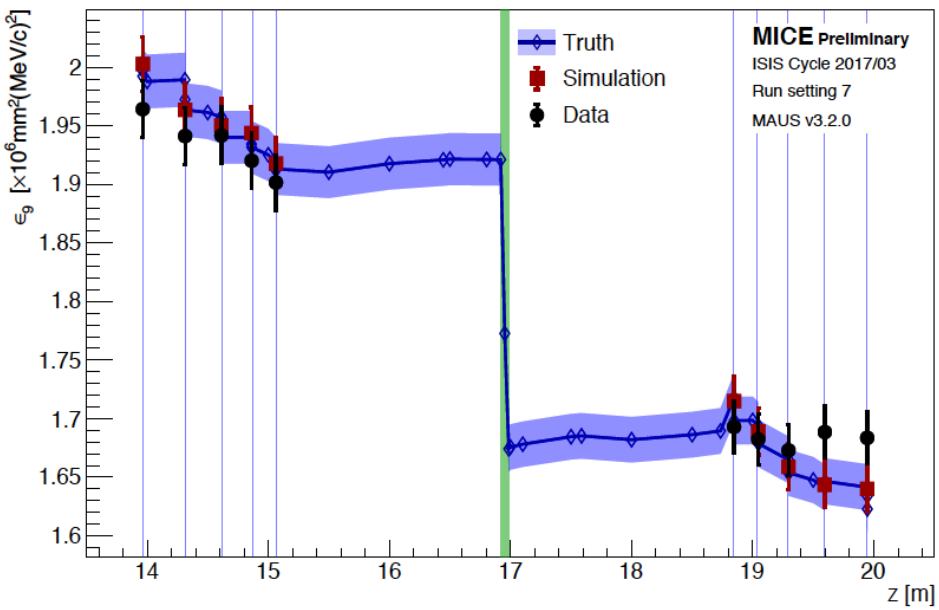
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance

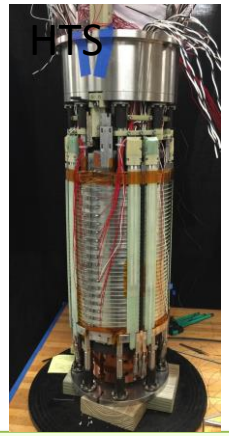


But still some way to go
- 6D cooling
- Stages
- Small emittances

Other Tests

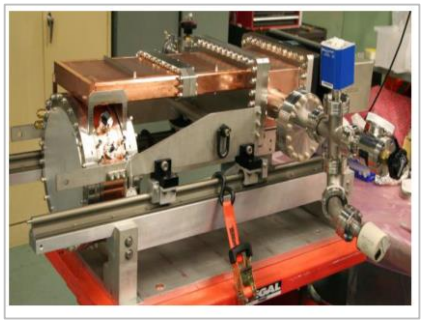
FNAL
Breakthrough in HTS cables

NHFML
32 T solenoid with low-temperature HTS



FNAL
12 T/s HTS
0.6 T max

MuCool: >50MV/m in 5 T field



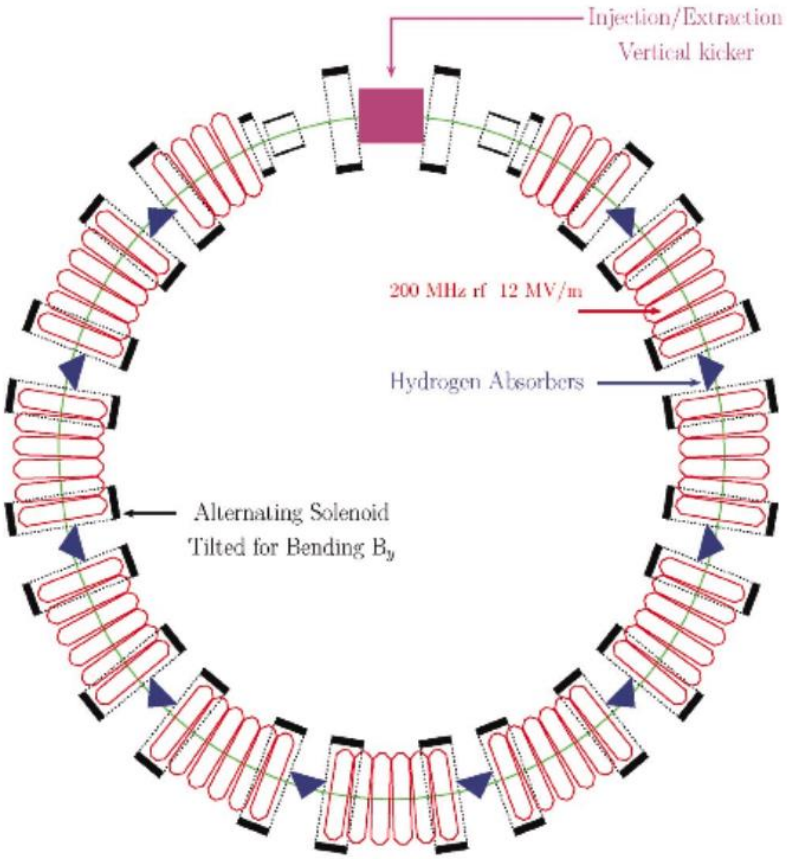
Mark Palmer

- ✓ 6D Ionization Cooling Designs
  - Designs in hand that meet performance targets in simulations with stochastic effects
  - Ready to move to engineering design and prototyping
  - Able to reach target performance with Nb_3Sn conductors (NO HTS)
- ✓ RF operation in magnetic field (MTA program)
  - Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
  - Vacuum cavity performance now consistent with models
  - MICE Test Cavity significantly exceeds specified operating requirements in magnetic field
- ✓ MICE Experiment data now in hand
- ✓ Final Cooling Designs
  - Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
  - Alternative options under study

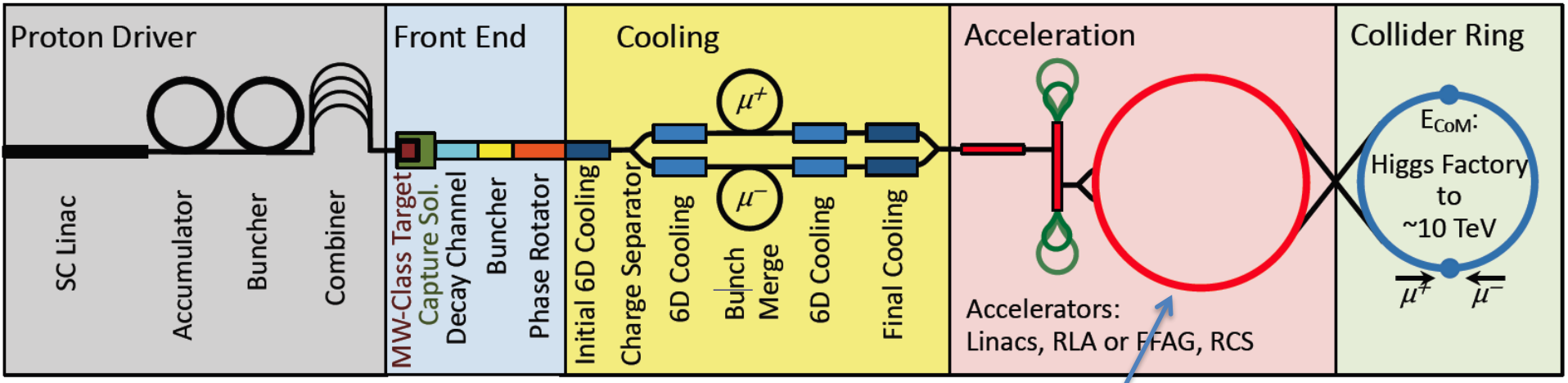
Test Facility Example

Carlo Rubbia: The experimental realization of the presently described μ+μ- Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the Ho, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.

Initial Cooling Experiment
Use 100 ns ESS pre-pulse with 3×10^{11} protons
Yields 3×10^{7} μ^- and 6×10^{7} μ^+ around 250 MeV



Beam Acceleration



Had some difficulty finding detailed information

Much larger than collider ring

A trade-off between cost and muon survival

An important cost driver

- Following V. Shiltsev, acceleration and collider ring are roughly equal and almost the full collider cost

Important for efficiency

Potential Approaches

Acceleration is important for cost and power consumption
No conceptual baseline design yet
But different options considered
A whole chain is needed from source to full energy

Recirculating linacs

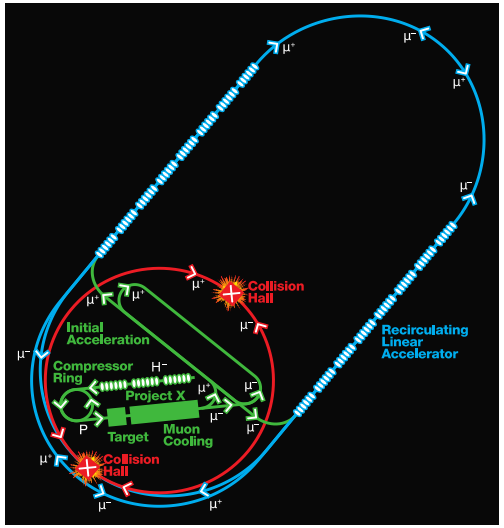
- Fast acceleration but typically only a few passages through RF, hence high RF cost

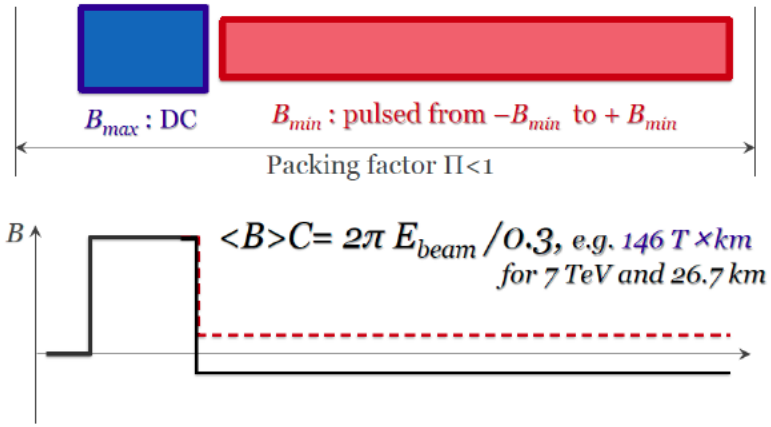
FFAGs

- Static magnets, but only limited increase in energy possible

Rapid cycling synchrotron (RCS)

- Potentially larger acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets



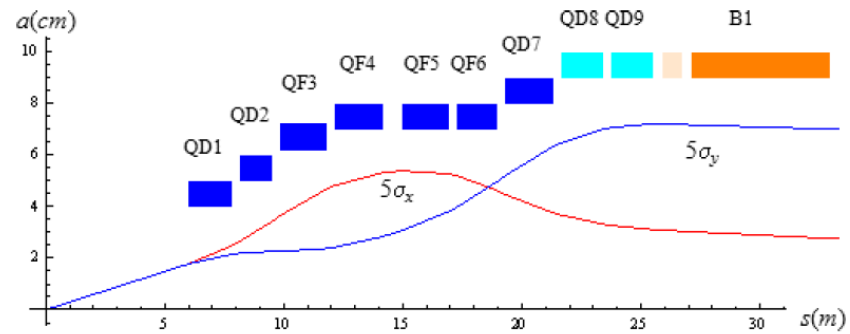


Challenge to achieve a combination of high efficiency, low cost and good beam quality

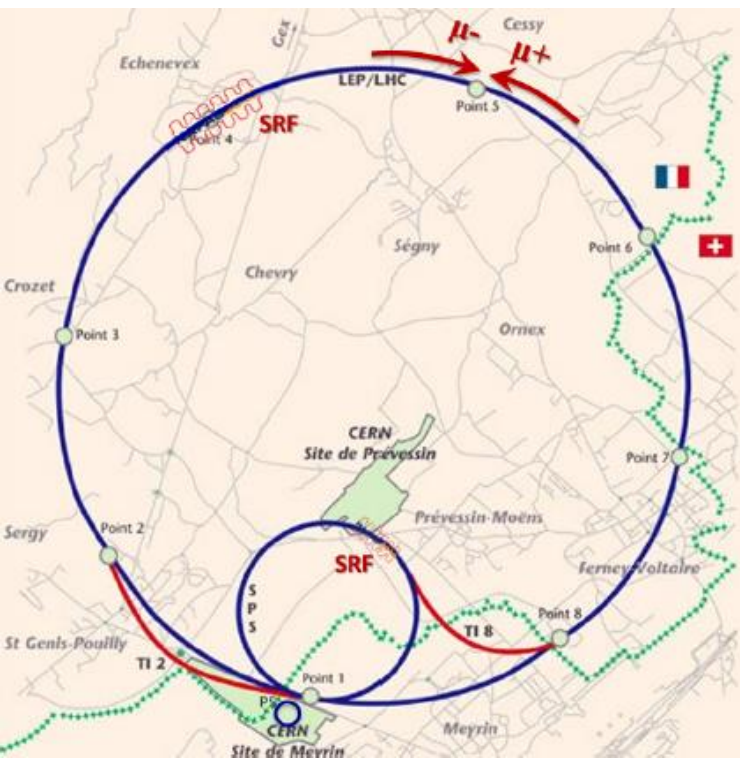
Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

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



High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



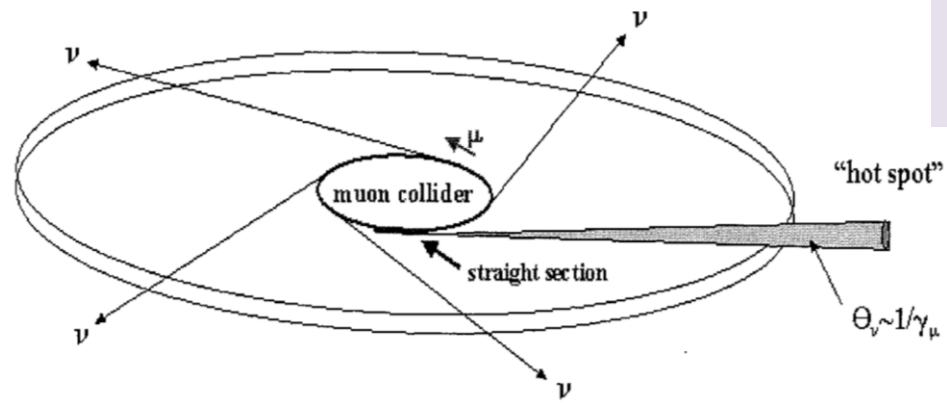
Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

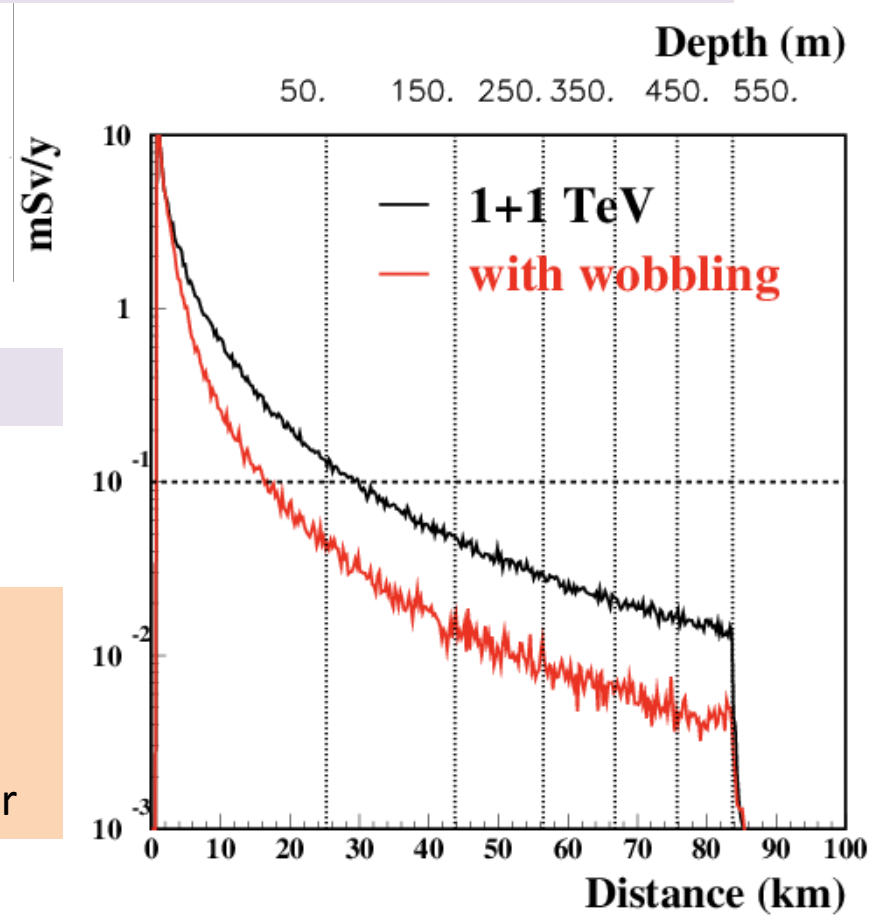
Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

Beam induced background studies
neutrino radiation hazard



The source, ring or section, is placed at the fixed depth of 550 m.



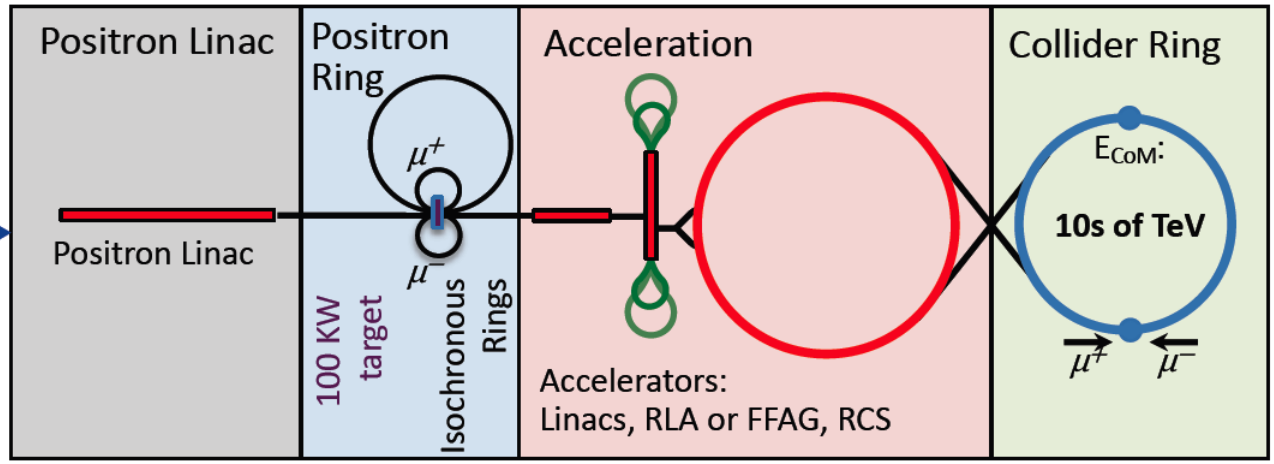
Ambient dose assuming 1.2×10^{21} decays/year

Need to study for higher energies (scaling E^3)

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator

The LEMMA Scheme

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 μm in proton scheme)

- No cooling required, use lower muon current

- Positron beam (45 GeV, 3×10^{11} particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons (4.5×10^{7})
- Every 0.5 ms, the muon bunches are extracted and accelerated
- They are combined in the collider ring, where they collide

Key Issues

Small efficiency of converting positrons to muon pairs

- Muon pair production is only small fraction of overall cross section (O(10^{-5}))
- Most positrons lost with no muon produced
- Have to produce many positrons (difficult)
- O(100MW) synchrotron radiation
- High heat load and stress in target (also difficult)

$$e^+e^- \to \mu^+\mu^-$$ O(1μb)

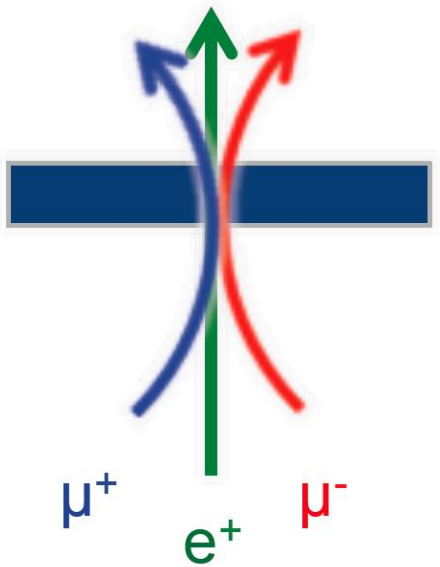
$$e^+e^- \to e^+e^-\gamma$$

O(100mb), $E_\gamma \geq 0.01\ E_p$

Two additional severe issues were identified

– The multiple scattering of the muons in the target
  - Theoretical best emittance of 600 nm instead of assumed 40 nm
  - Reduction of luminosity by factor 15

– Small bunches were accelerated and later merged but no design exists for the merger
  - The combination factor is proportional to beam energy
  - If the combination does not work, loose a large factor of luminosity



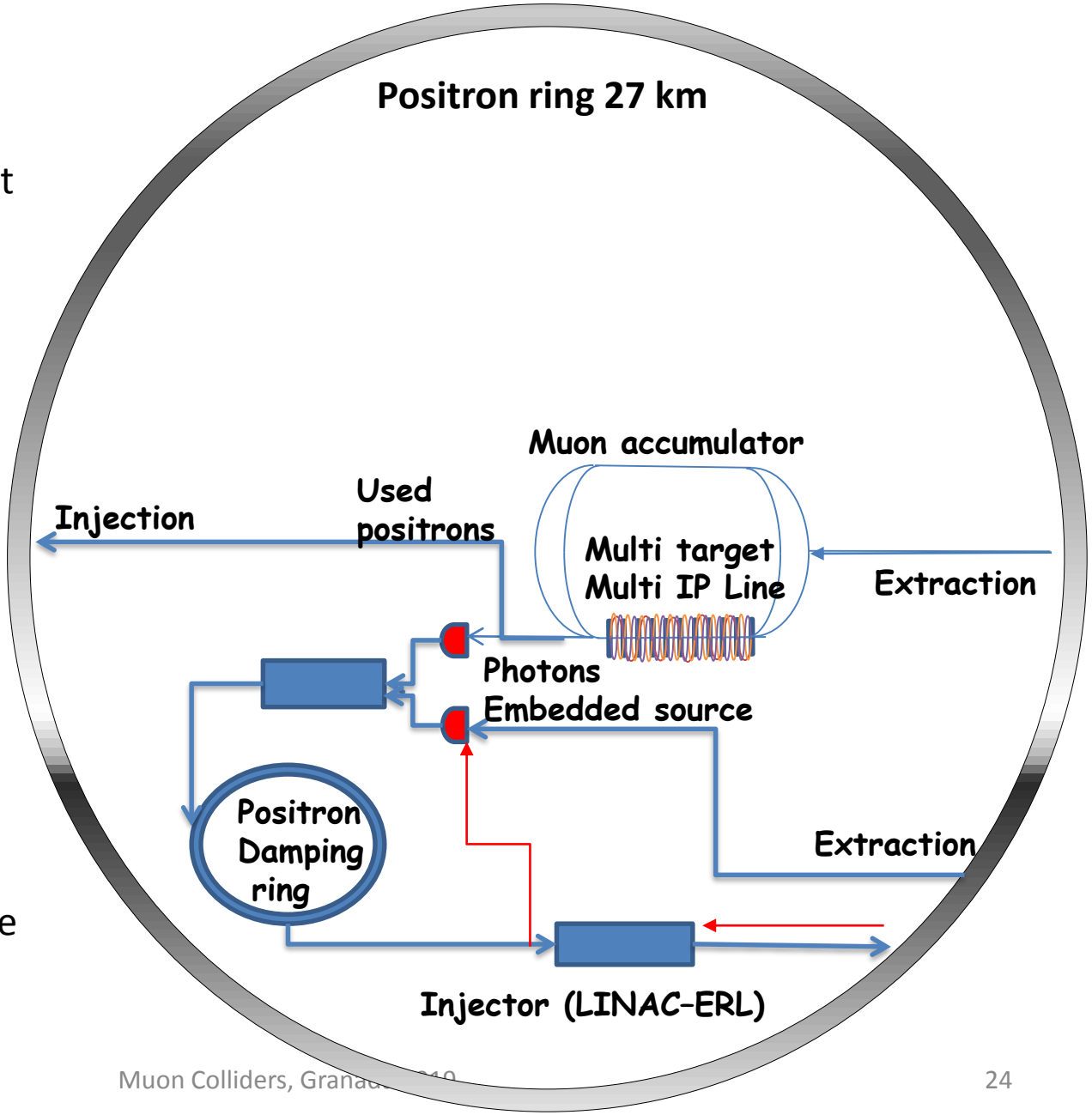
Working on a better design but have to wait and see the outcome

Ongoing LEMMA Effort

Address found issues

- Large emittance from target
  - use sequence of thin targets
- Difficulty of combining bunches at high energy
  - producing bunches in pulses fashion
- Positron ring challenge
  - larger ring
- Positron production
  - Improved concepts

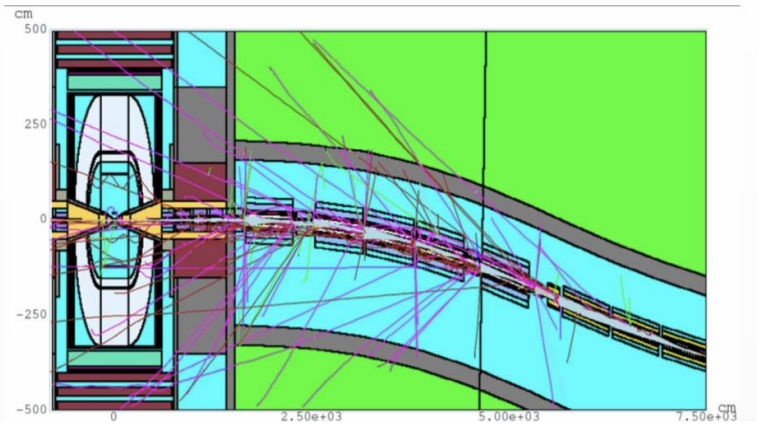
Did not yet reach competitive performance
- but work is ongoing



Beam induced background studies

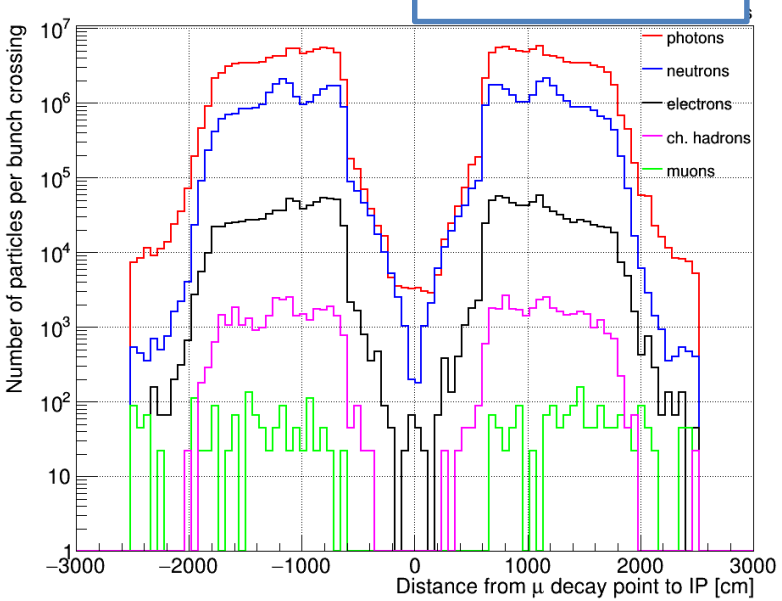
on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

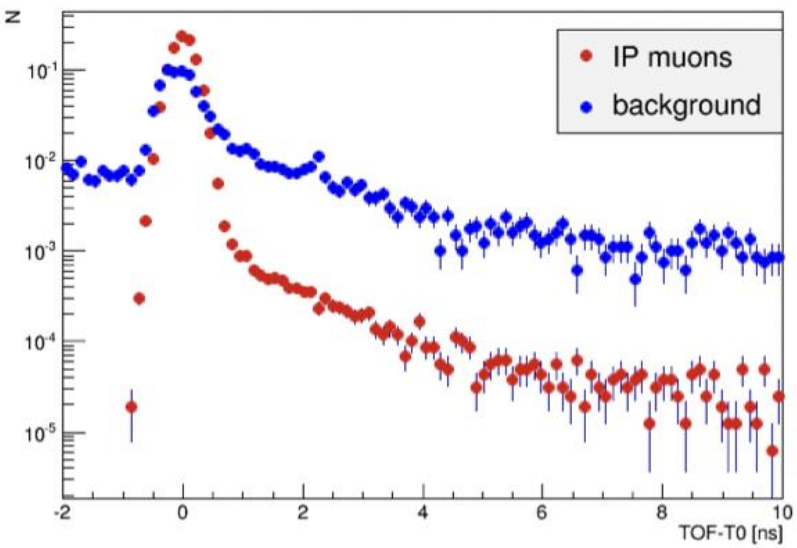


MARS15 simulation in a range of ±100 m around the interaction point

750 GeV beam



Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

Conclusion

We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source

Recommendations

Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update. As demonstrated in past experiences, the resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort.
For example, the MAP program required an yearly average of about 10M$ and 20 FTE staff/faculty in the 3-year period 2012-2014.
Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, ...
Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.
Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

Proposed tentative timeline