Muon Collider Strategy

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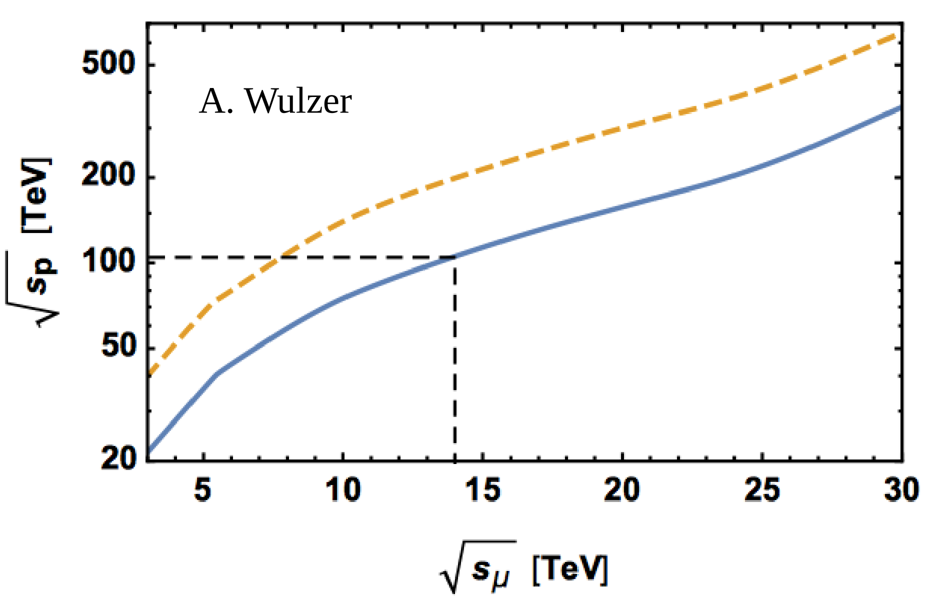
Motivation

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 s-channel physics target

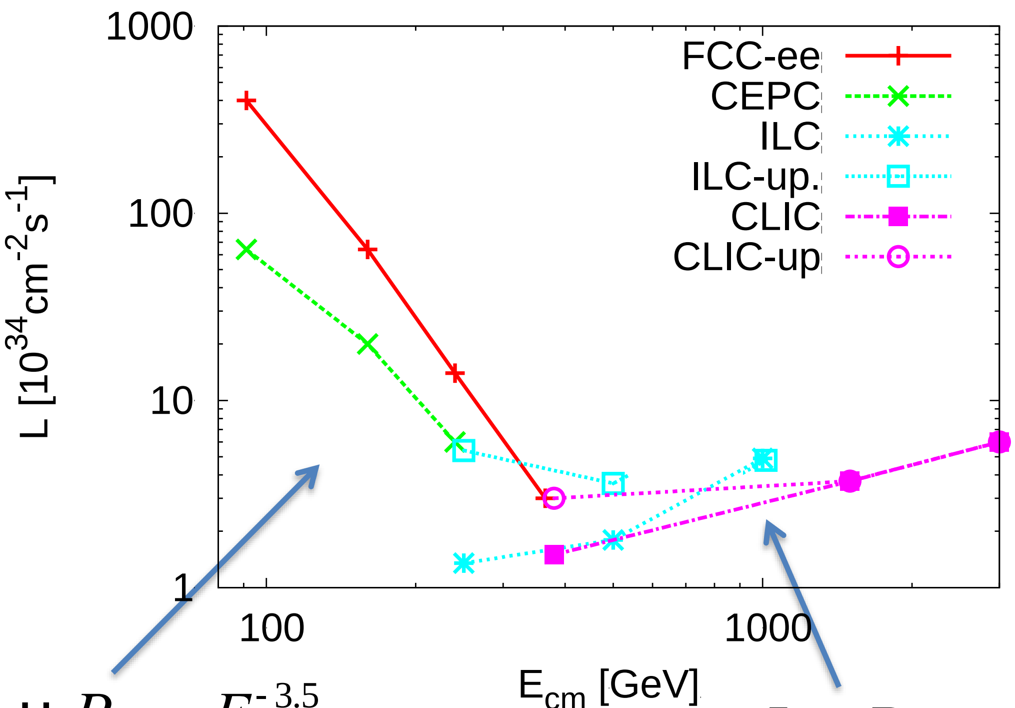
Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
4×10^{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 (Granada)

Luminosity per facility



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

$L \propto P_{RF}$

CLIC can reach 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)

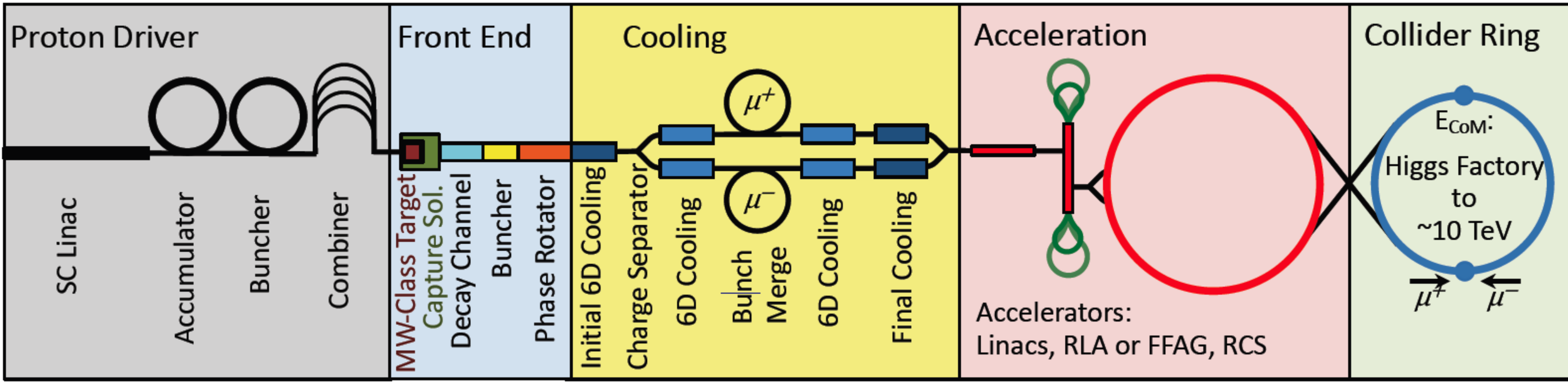
Technically possible to go higher in energy

But is it affordable?

R&D required towards higher energies (or improvement of 3 TeV)

- Reduction of cost per GeV (improved NC acceleration, novel acceleration technologies
- Improved power consumption (higher RF to beam efficiency, higher beam quality)

Proton-driven Muon Collider Concept (US)



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

Did find holes in the design
but nothing that does not work
No CDR exists, no coherent baseline of machine
No reliable cost estimate

Target Parameter Examples

From the MAP collaboration:
Proton source

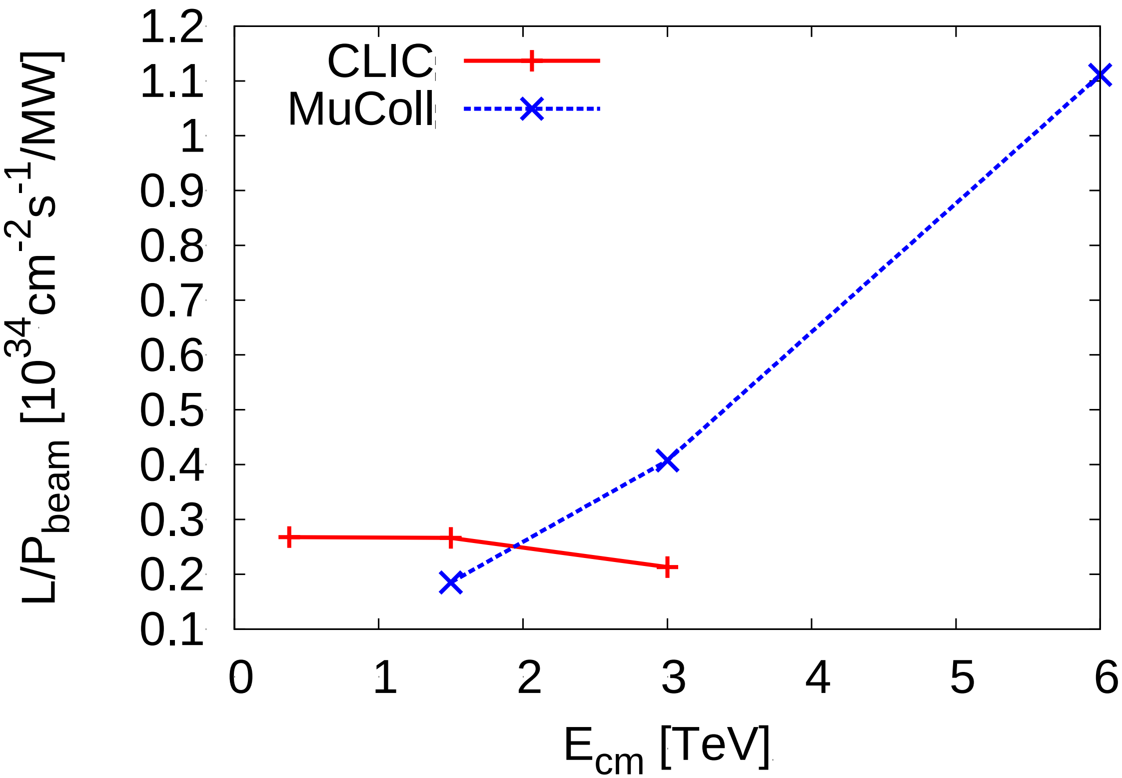
Muon Collider Parameters					
		Higgs			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	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

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

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

⇒ Proton-based muon collider promising at high energies

Key Parameters

From the MAP collaboration:
Proton source

Parameter	Unit	1.5 TeV	3 TeV	6 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.25	4.4	12
N	10^{12}	2	2	2
f_r	Hz	15	12	6
P_{beam}	MW	6.75	10.8	10.8
<B>	T	6.3	7	10.5
ε_L	MeV m	7.4	7.4	7.4
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)
β	mm	10	5	2.5
ε	μm	25	25	25
$\sigma_{x,y}$	μm	5.9	3.0	1.5

Muon Collider Luminosity Scaling

Key assumptions:
Emittances are preserved from source to collision
Higher energy allows shorter bunches and hence smaller betafunctions

$$\mathcal{L} \propto B \frac{N_0}{\epsilon \epsilon_L} \gamma f_r N_0 \gamma$$

High field in collider ring

Dense beam

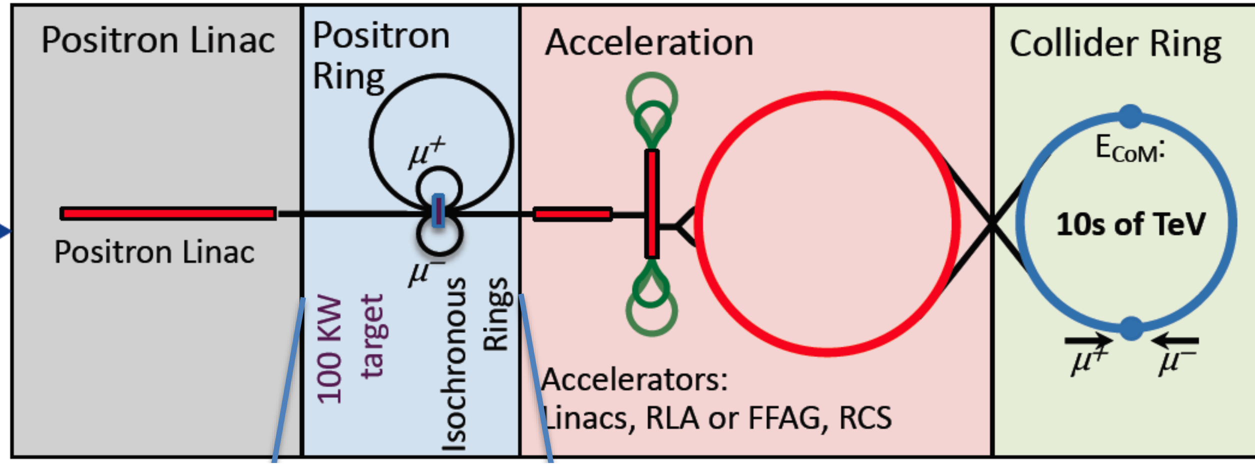
High energy

High beam power

For mostly unchanged technologies:
Luminosity per power naturally increases with energy
(Provided we can focus the beam accordingly, …)
Better scaling than other options to high energies

The LEMMA Scheme (2018)

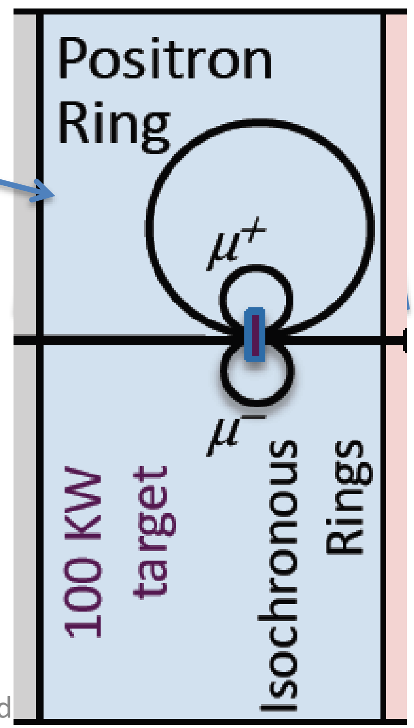
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:

Produce muon beam with low emittance using a positron beam

No cooling required



In design of 2018 two important issues were found

- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing

⇒ Updates this workshop

Muon current 10^{11} s^{-1} is 300 times lower compared to 3 x 10^{13} s^{-1} for proton driver

Emittance O(10^{-3}) smaller than in proton scheme, 40 ns vs. 25 μm

Review 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 (2018)

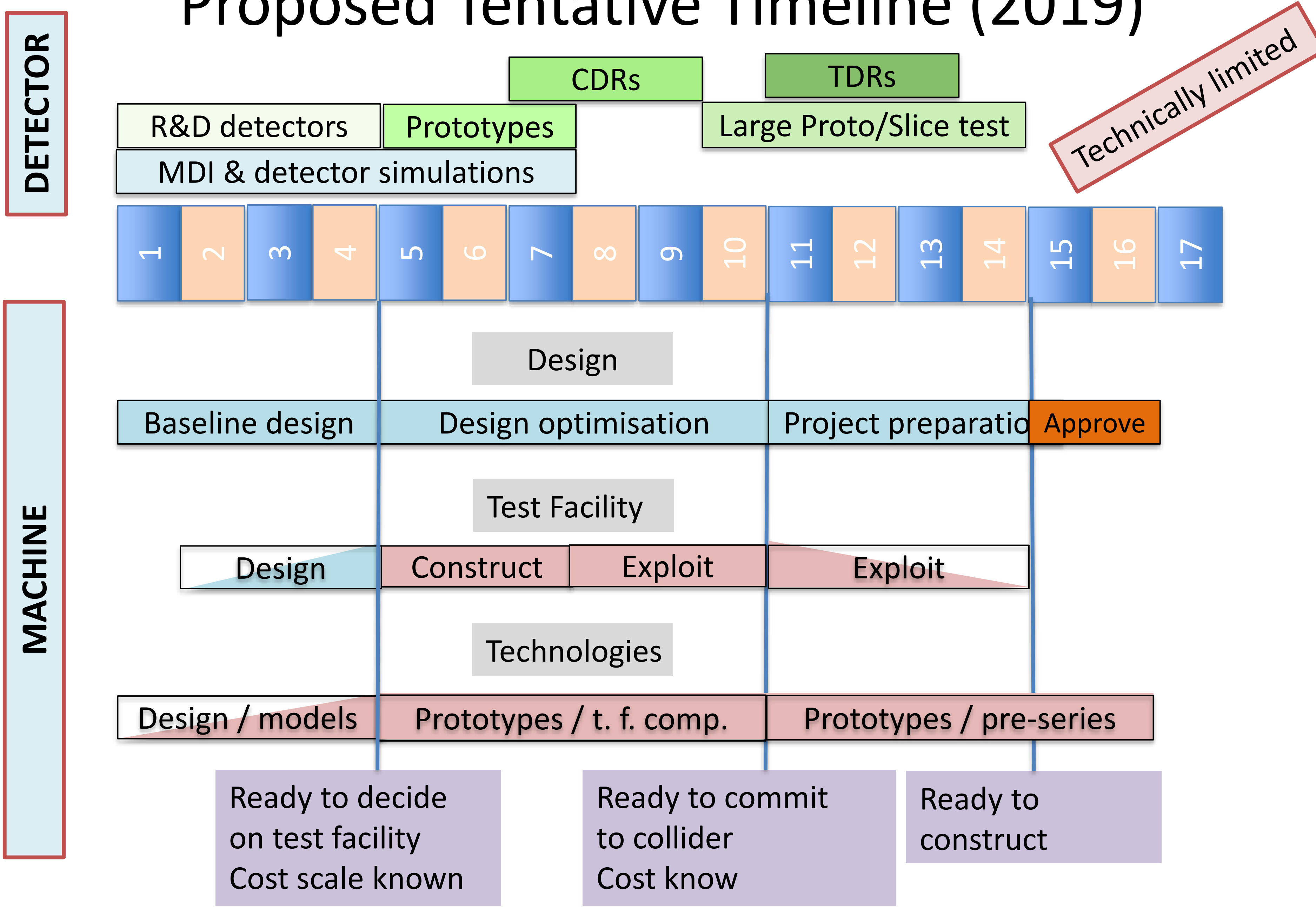
Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure.

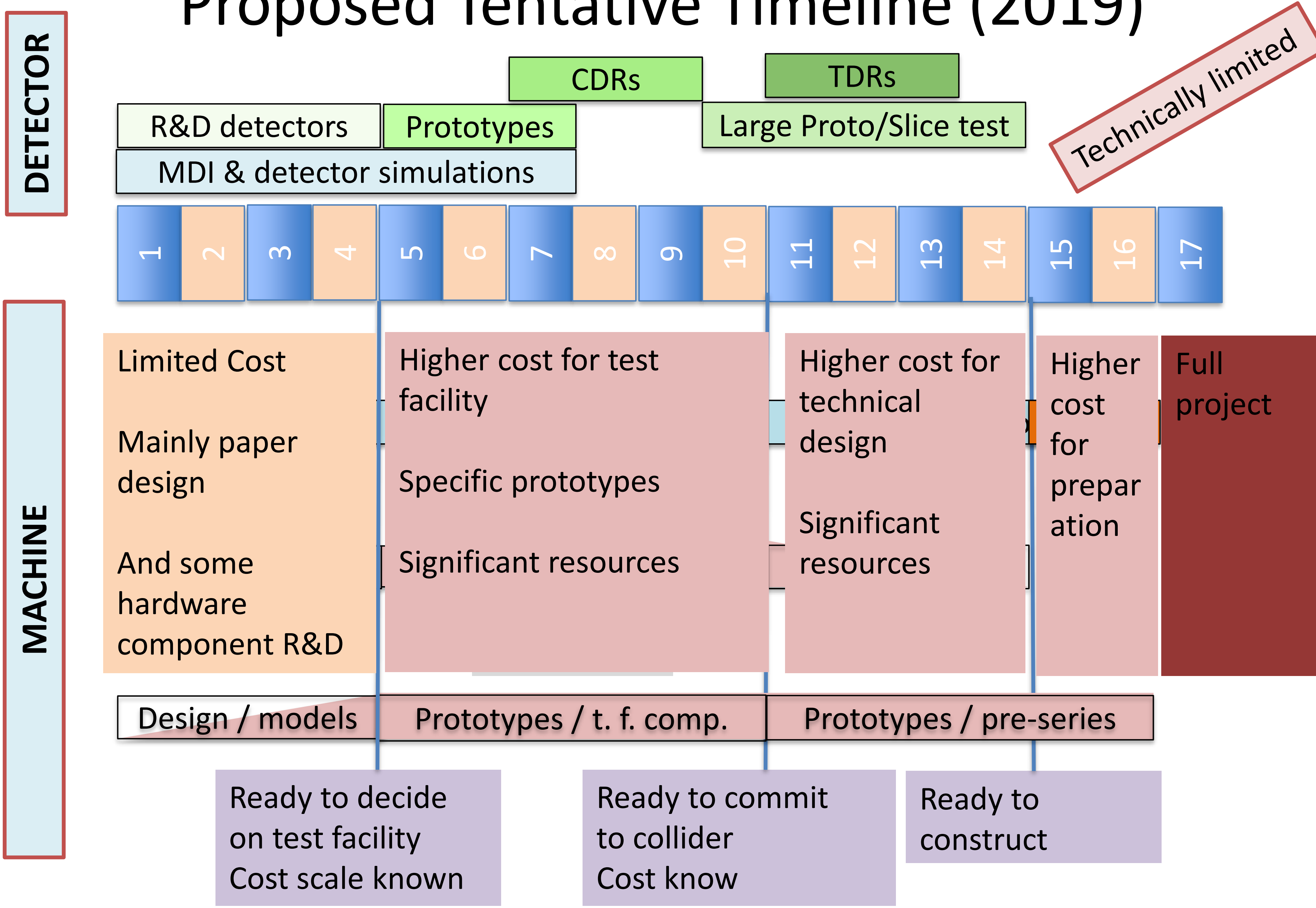
Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

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 (2019)



Proposed Tentative Timeline (2019)



Baseline

- Define energy stages (to be discussed at this workshop)
  - O(TeV) to match CLIC, come after Higgs-factory
    - Realistic design development / later feasibility demonstration for CDR
    - For implementation at CERN
  - 14 TeV to match FCC-hh discovery potential
    - To guide choices
    - Provide evidence for feasibility, maybe cost frame
  - Even higher energies?
- Put together coherent sets of parameters and layouts
  - Understand parameter choices and drivers, technological challenges
  - Includes both, MAP and LEMMA, scheme
- Define key R&D list (some items already collected)
  - So identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Prime examples
    - Background in experiments
    - Radiation to the public

One Potential Ingredient: ARIES2

- Proposed network-like activity
  - MUST: MUon collider STudy network
- Goal is to foster preparation of an organised study if the European Strategy so recommends
  - Start identification of feasibility issues
  - Identify resources required to address most critical issues
  - Prepare engagement of collaboration
- Support communication of a muon collider study
  - Organise workshops and meeting for the study
- Will discuss at this workshop
  - Welcome to join

Potential Key R&D Items

- Integrated design (to make sure things fit)
  - E.g. lose 90% of muons before collision, can this be reduced?
  - Important cross effects, e.g. beam emittance
- **Neutrino radiation (critical limit at highest energies)**
  - **How can it be reduced? (Better cooling, orbit variations, high energy at other site?,…)**
  - What can be defended to the public?
- **Experimental conditions (obvious, isn't it?)**
- **Beam production and cooling (critical parameter driver)**
  - **Emittance drives design, lower emittance: less radiation to public, detector, …; less power; less risk**
  - Proton beam production / compression
  - Paper design of cooling does not reach full performance
  - **Many key components: robust targets, RF with gas, high-field solenoids**
  - Take full advantage of MICE (data, installation)
  - **Likely will find need new facility to improve test compared to MICE**
  - **Anticipated to be core of new testing programme**
    - **6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, …**
    - **Parametric cooling to be tested**
    - **Likely the core of the experimental programme**

Potential Key R&D Items, cont.

- Acceleration complex design (important cost driver)
  - Is it affordable (cost and power)?
  - **Fast ramping magnets (for RCS), magnet powering scheme**
  - High-field superconducting magnets
  - Beamline design
  - Collimation
  - …
- Collider ring design (important parameter and cost driver)
  - Is it affordable (cost)?
  - **High field superconducting magnets, minimal gap, radiation hard**
  - **Improved lattice design beyond 3 TeV**
  - Injection, safety concept
- Reuse of existing infrastructure (potential cost saving)
  - Proton facilities
  - Tunnels (maybe more for acceleration than for collision)
- **LEMMA concept and new ideas (would be breakthrough for parameters)**
  - **Consolidation**
  - **Alternative low-emittance sources**
  - **Could define the source test facility**

Key Accelerator Technologies

- High-field, robust collider magnets with minimum gap
  - Dipoles, solenoids, …
- Efficient fast ramping magnets with efficient energy recovery
  - For the beam acceleration
- Efficient cryogenics, vacuum and shielding systems
  - Significant beam loss
- Robust targets and beam cleaning
- High field cavities
  - In a solenoid for the cooling system
- Efficient RF power production
- Civil engineering
- Other systems
  - E.g. instrumentation
  - …
- Beamdynamics and accelerator design
  - Start-to-end design and simulations, source design, …

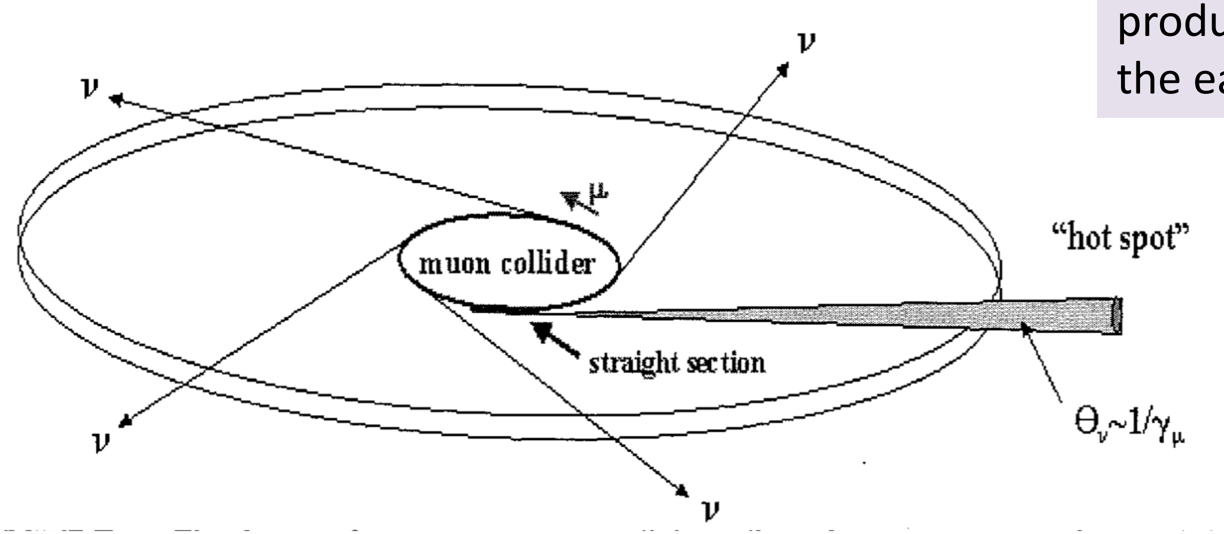
How Could 14 TeV Look Like?

Up to 6 TeV from the MAP collaboration: Proton source

Parameter	Unit	1.5 TeV	3 TeV	6 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.25	4.4	12	40
N	10^{12}	2	2	2	2
f_r	Hz	15	12	6	3.7
P_{beam}	MW	6.75	10.8	10.8	15.4
<B>	T	6.3	7	10.5	10.5
ε_L	MeV m	7.4	7.4	7.4	7.4
σ_E / E	%	0.1	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)	1.07
β	mm	10	5	2.5	1.07
ε	µm	25	25	25	25
$\sigma_{x,y}$	µm	5.9	3.0	1.5	0.63

At 6 TeV MAP design consistent with FNAL site
Radiation at 14 TeV is ~8 times higher than at 6 TeV

Neutrino Radiation Hazard



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

Potential mitigation by

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

Becomes more important at higher energies (scaling E^3)

US study concluded that 6 TeV parameters are OK

But our 14 TeV would have ~8-times the radiation

Muon Collider Luminosity Scaling

Scaling of radiation in arcs with parameters

Note: in addition to scaling need to develop design

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

Assume only E and Luminosity change
8 times more radiation than at 6 TeV

Other parameters are kept constant

D: radiation dose
E: beam energy
B: Magnetic field
d: depth underground

Scaling indicates 8 times worse than 6 TeV

Muon Collider Luminosity Scaling

Check:
Derive constants from B. Kings formulae and MAP choices one finds:

$$\frac{D}{\int \mathcal{L}} = \frac{0.8mSv}{4ab^{-1}}$$

$$a \approx 4 \times 10^{-4} \frac{mSv}{ab^{-1}} \frac{1}{eV^{-2}m}$$

E = 7 TeV
MAP-type beam
B = 10.5 T
L = 0.2 m
d = 500 m

Muon Collider Luminosity Scaling

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

How to gain a factor 8 in radiation?
Seems hard but not impossible

Muon Collider Luminosity Scaling

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

Higher field in collider ring
And shorter gaps

Deeper tunnel

Denser beam

Larger energy
spread acceptance

How to gain a factor 8 in radiation?
Seems hard but not impossible

Muon Collider Luminosity Scaling

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

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

How to gain a factor 8 in radiation?
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Muon Collider Luminosity Scaling

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

More efficient physics
More years of running

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

How to gain a factor 8 in radiation?
Seems hard but not impossible

Muon Collider Luminosity Scaling

Tricks
e.g. beam wiggling, dumping the beam, …

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

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

More efficient physics
More years of running

How to gain a factor 8 in radiation?
Seems hard but not impossible

Some Tools to Reduce Radiation

- Shorter gaps between magnets
  - e.g. 7 cm halves radiation
- More brilliant beams
  - Halving emittance halves radiation
- Wiggling the beam
  - O(8 sigma) starts to help (for 100 m beta-function)
- Dumping the beam before fully decayed
  - Fractional saving
- Cutting large amplitude muons
  - Does not help
- Spread out programme over more years
- Add the two detectors
- …

Conclusion

- Have a tentative plan for the future
  - In case muon collider R&D is proposed by the European Strategy
  - But need people and money
  - Try to obtain network-like activity (via ARIES2)
- Need to develop baseline
  - For both approaches important gaps exist
  - Need to bring knowledge to life again
  - And address holes
  - For LEMMA consolidation is attempted
- Need to address neutrino radiation
  - Confirm results from US study
  - Lower radiation at 14 TeV
  - Strong point of the LEMMA scheme
- Need to develop experimental R&D plan
  - Key is likely test facility for muon generation
  - Will depend on progress of baseline design

Reserve

Findings of Muon Collider Working Group

A first, high-level review of the two schemes with proton-based (MAP) and positron-based (LEMMA):

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

First focus promising positron-based scheme, but identified need for consolidation

No showstopper found for proton scheme, but much more detailed understanding is required to judge performance, cost and power. No CDR exists.

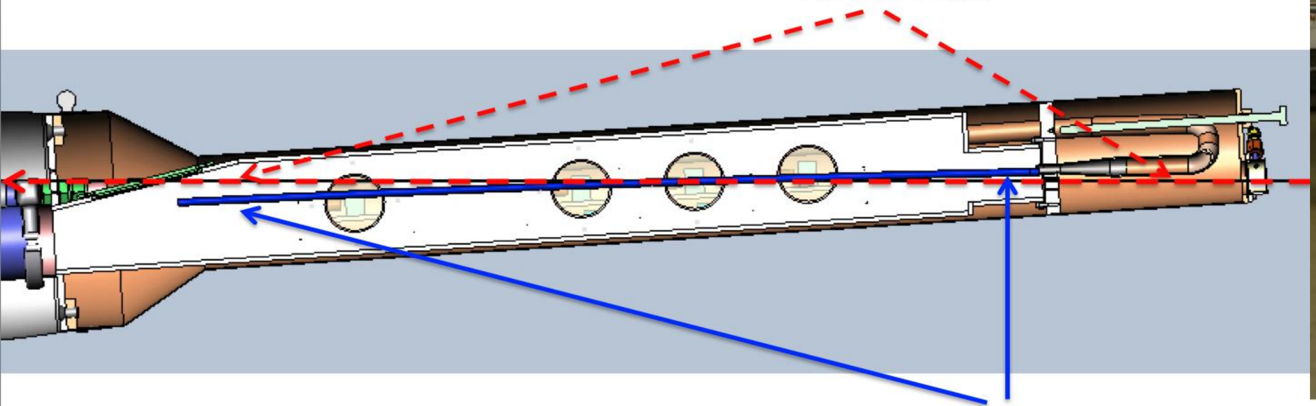
Important progress of the technologies, addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest (e.g. LHC).

Documents: see first slide of the reserve

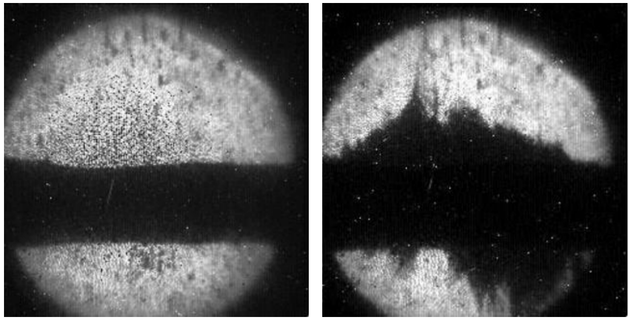
Source

Protons → Target → Pions → Muons



MERIT experiment at CERN

High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated



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

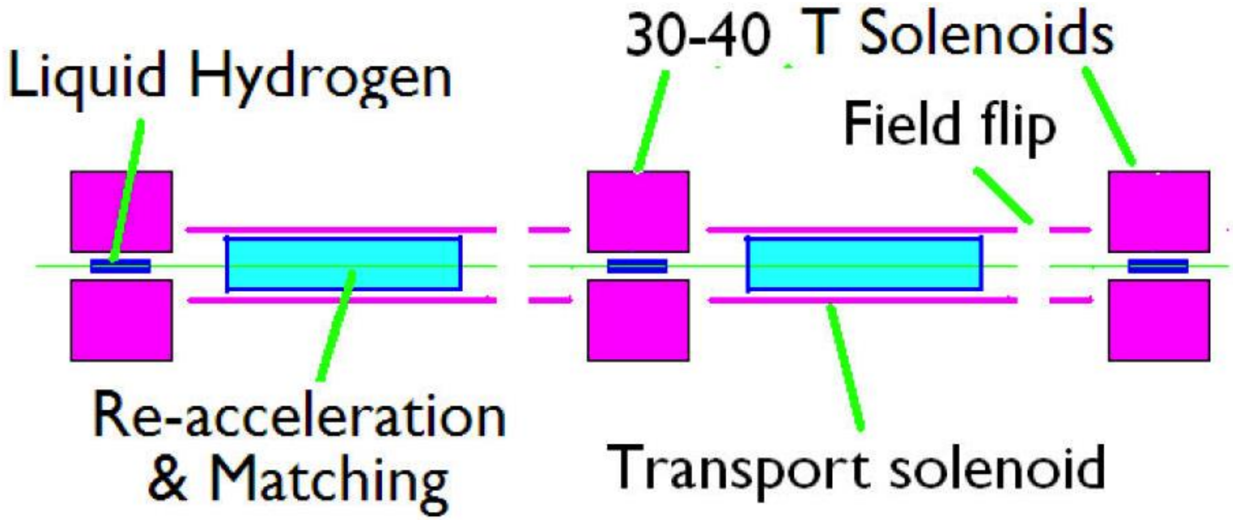
- 9×10^{12} muons (loose 90%)

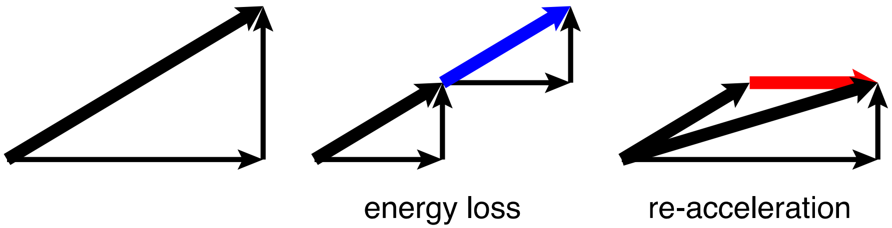
But radiation issues?

Maybe can use solid target

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

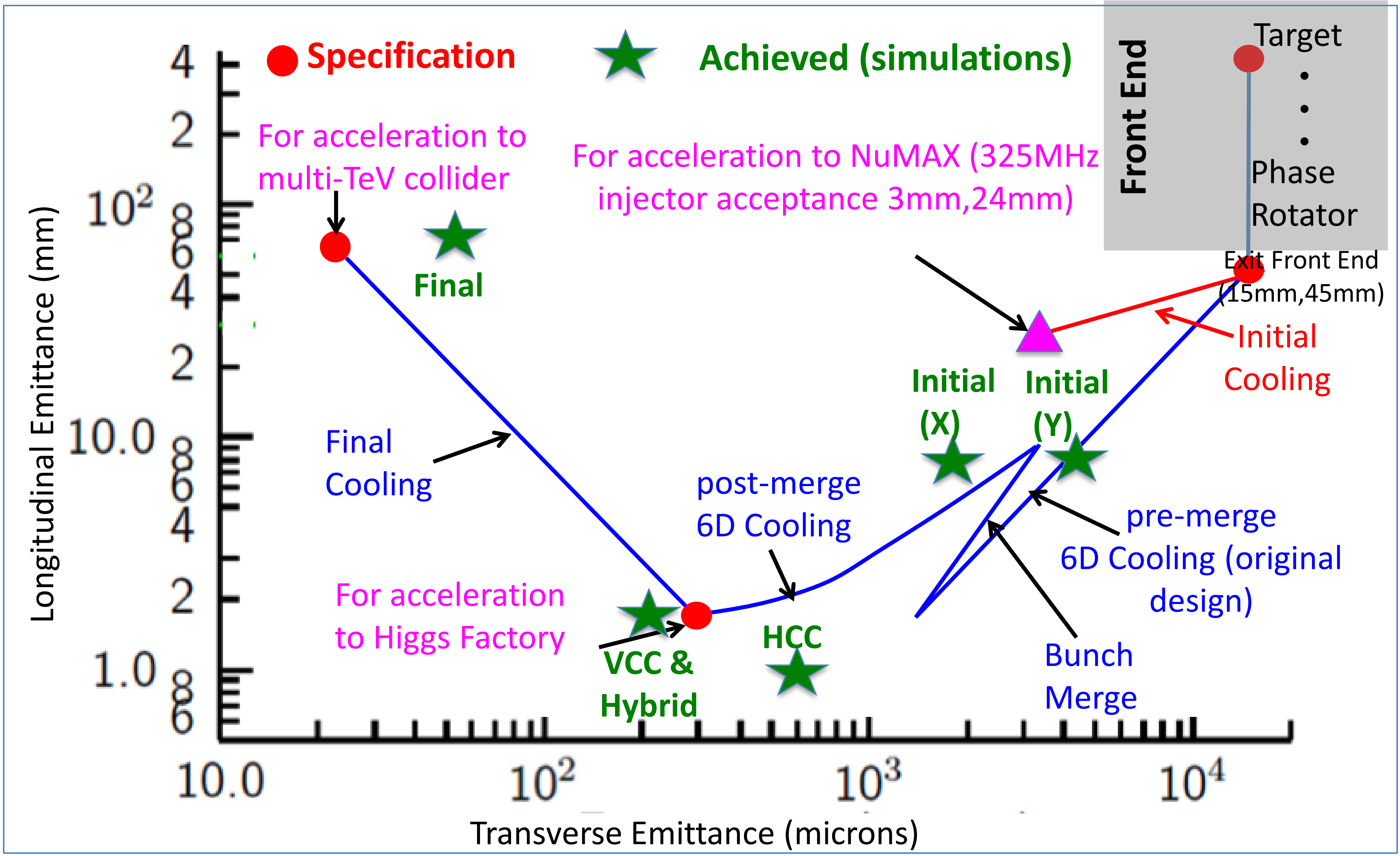
Transverse Cooling Concept



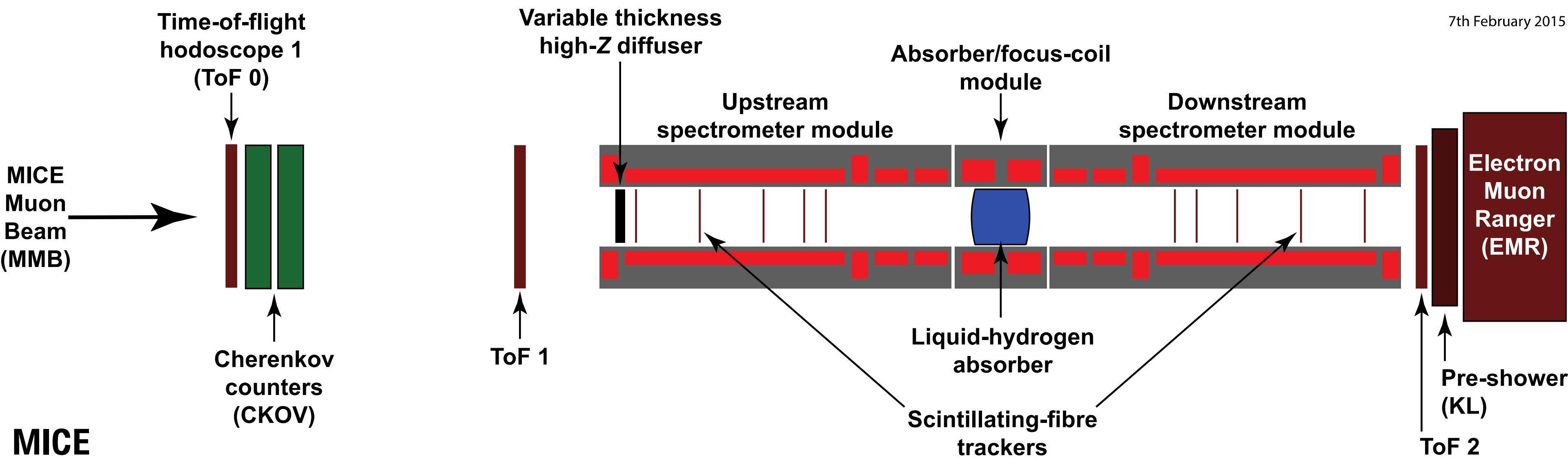


$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Cooling: The Emittance Path



Cooling and MICE



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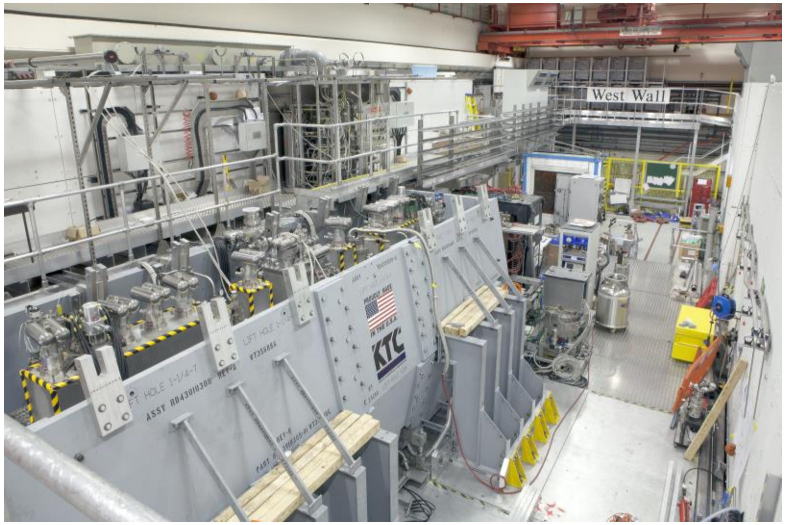
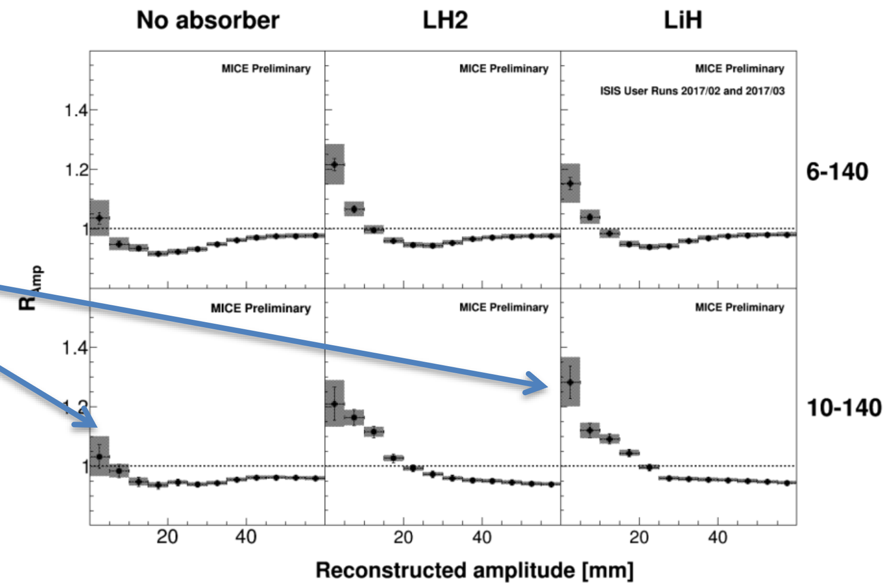


MICE allows to address 4D cooling with low muon flux rate

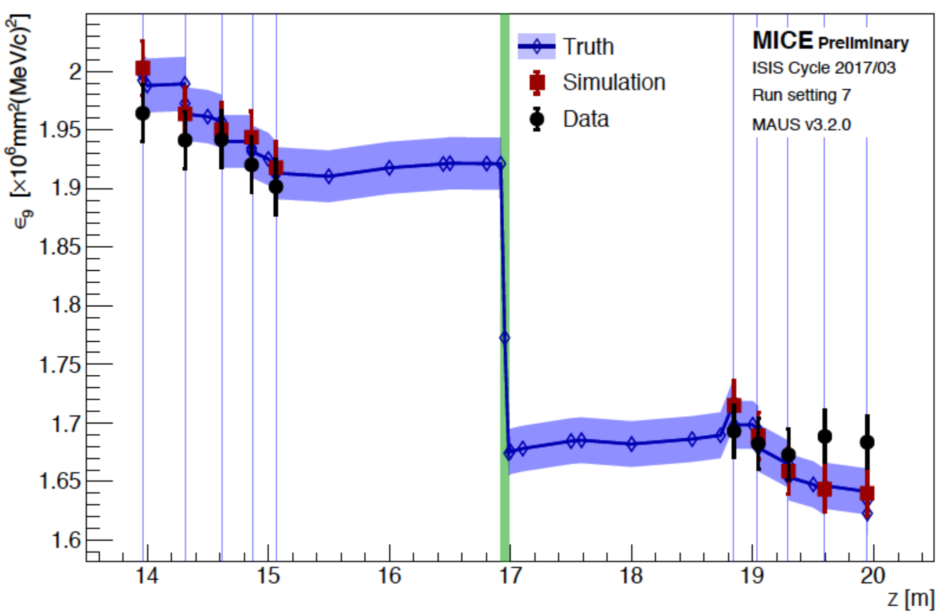
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance



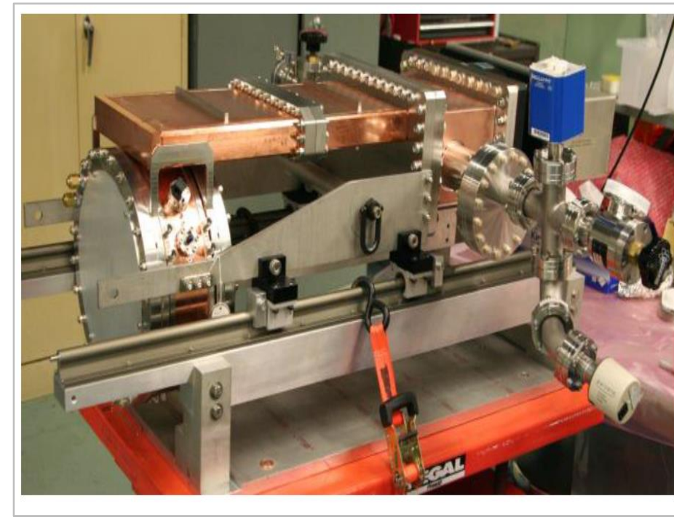
But still some way to go
- 6D cooling
- Stages
- Small emittances

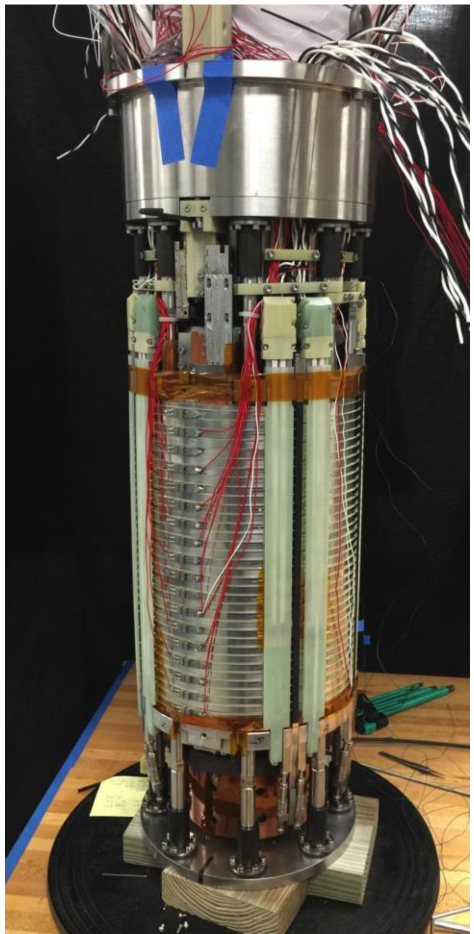
Other Tests

FNAL
Breakthrough in
HTS cables

A number of key components has been developed

MuCool: >50 MV/m in 5 T field



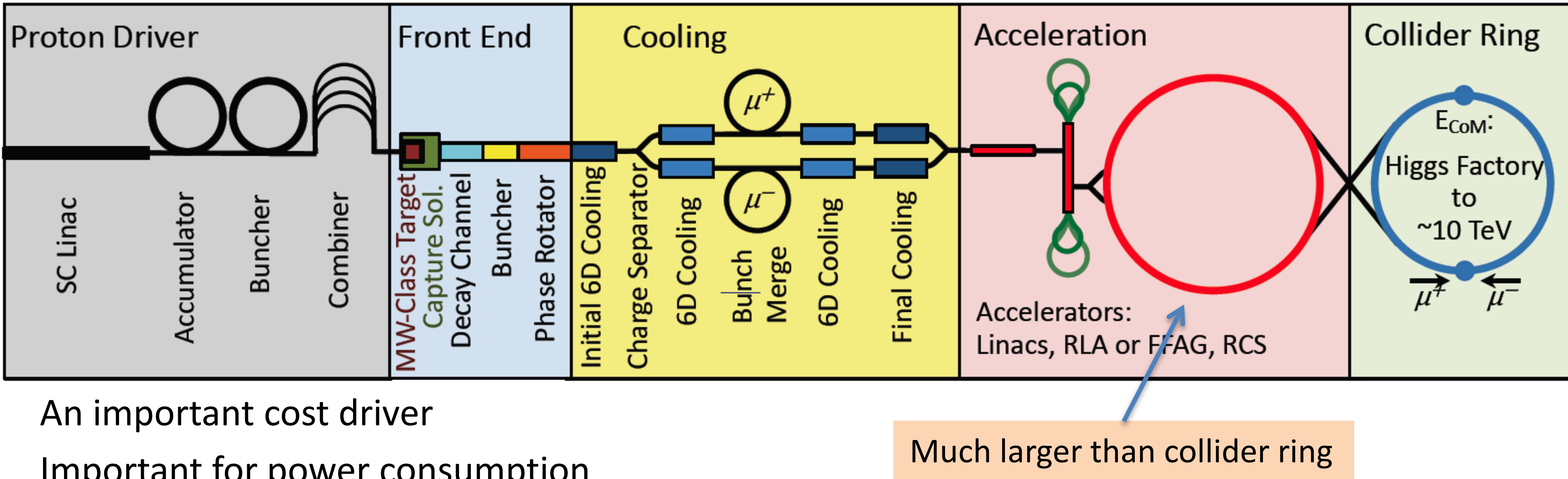


NHFML
32 T solenoid with
low-temperature
HTS

FNAL
12 T/s HTS
0.6 T max

Mark Palmer

Beam Acceleration



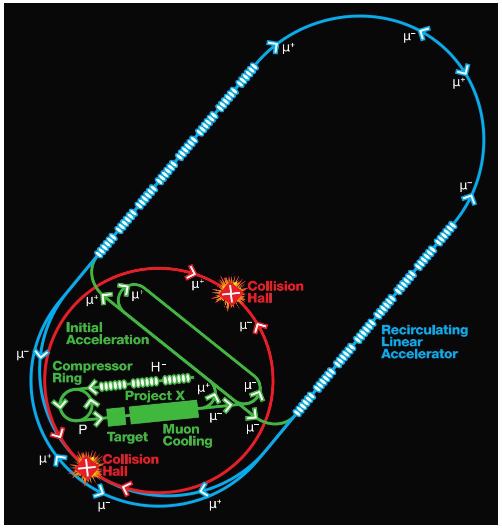
An important cost driver

Important for power consumption

A trade-off between cost and muon survival

Not detailed design, several approaches considered

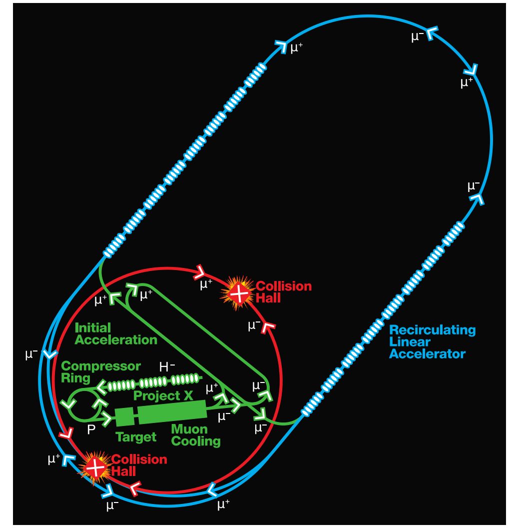
- Linacs
- Recirculating linacs
- FFAGs
- Rapid cycling synchrotrons



Challenge is large bunch charge but single bunch

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

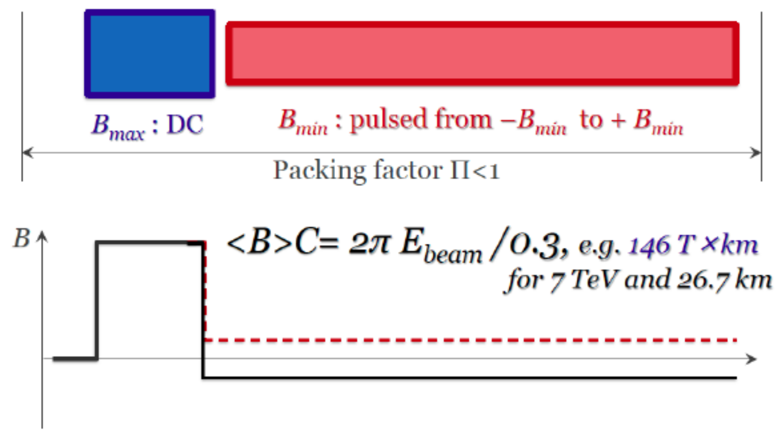


Recirculating linacs

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

Rapid cycling synchrotron (RCS)

- Potentially important 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
- Efficient energy storage is required



FFAGs

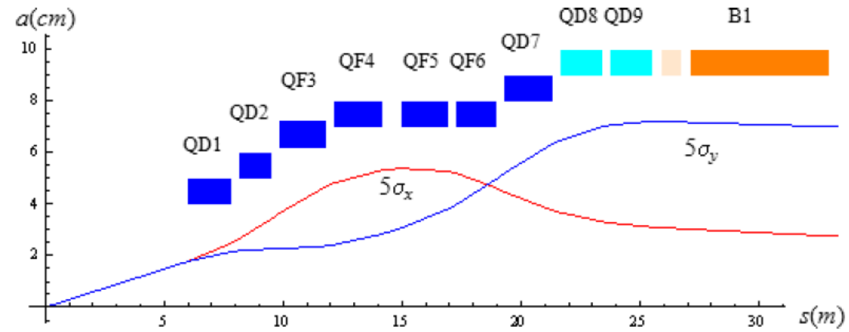
- Static high field magnets, can reach factor up to 4 increase in energy, needs design work

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

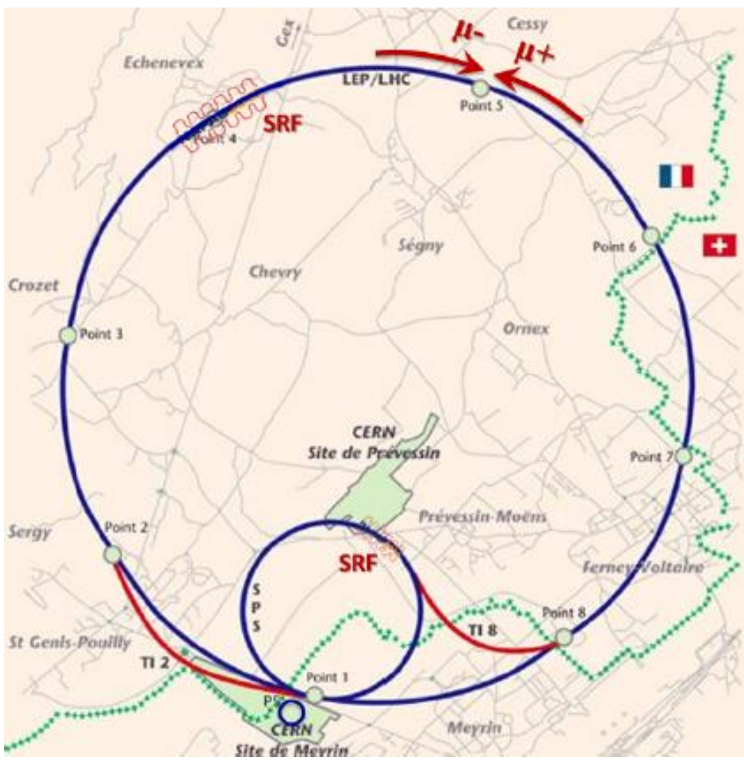
Collider Ring

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

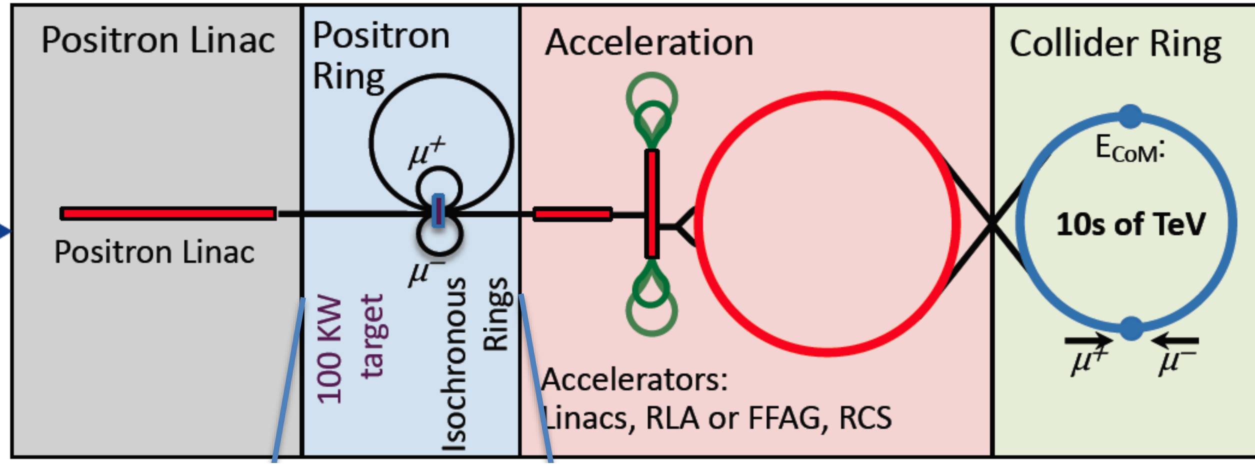
Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

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

The LEMMA Scheme

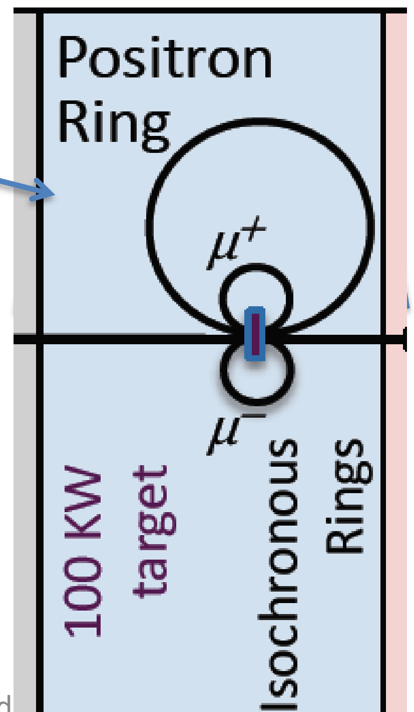
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:

Produce muon beam with low emittance using a positron beam

No cooling required



Muon current 10^{11} s^{-1} is 300 times lower compared to 3 x 10^{13} s^{-1} for proton driver

Emittance O(10^{-3}) smaller than in proton scheme, 40 ns vs. 25 μm

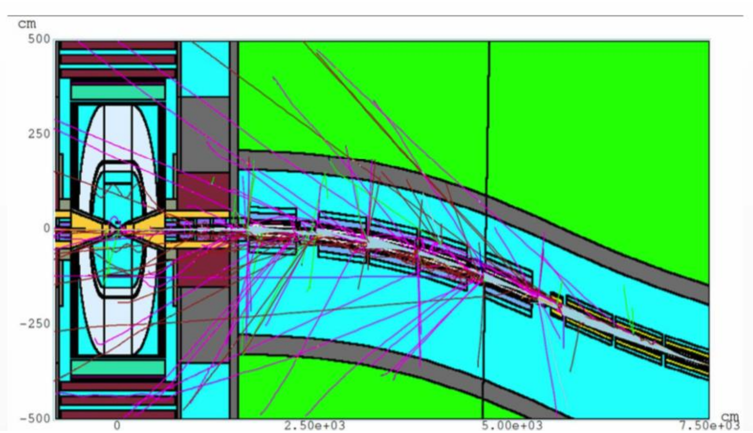
In design of 2018 two important issues were found

- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing
⇒ Nadia's talk

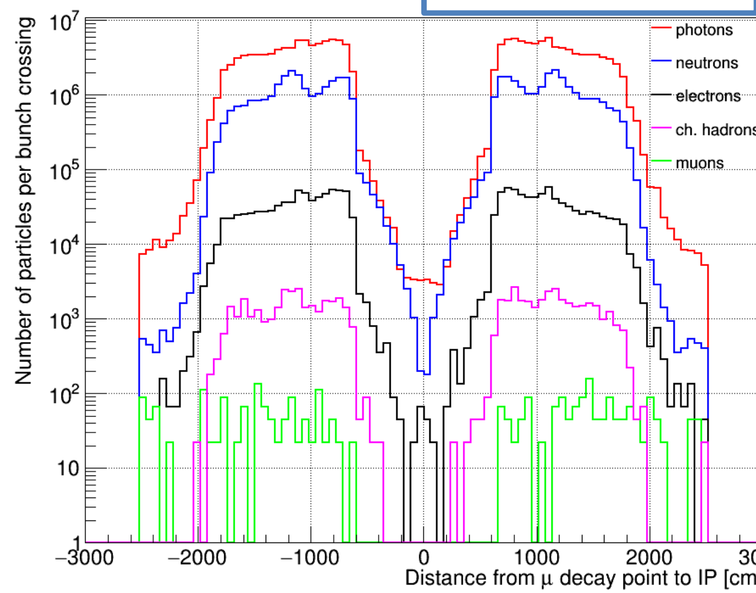
Beam induced background studies on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

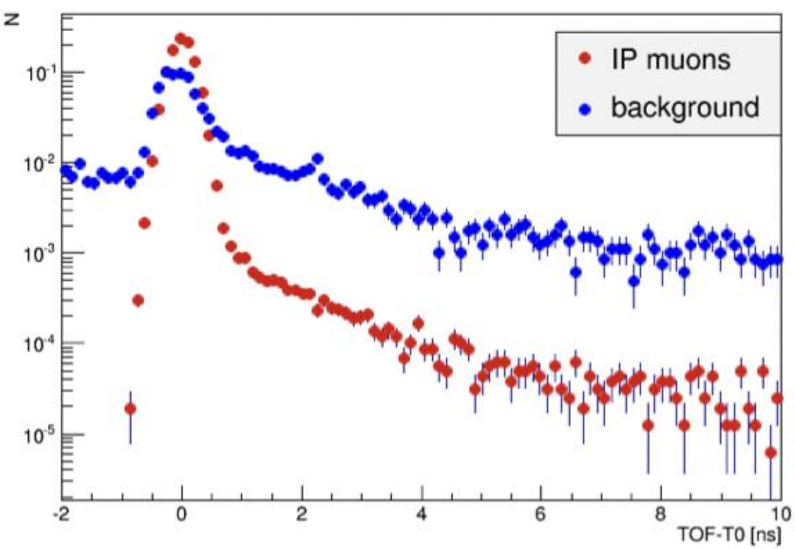


MARS15 simulation in a range of ±100 m around the interaction point

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

Muon Collider Working Group

Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy,
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 Symposium

April 10-11, 2019
CERN – Council Room
https://indico.cern.ch/event/801616

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.

Scope of the Working Group

- Performed a first, high-level review of the two muon collider schemes: one based on protons to produce muons (MAP) and one on positrons (LEMMA)

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

- The proton scheme
- 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.

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

For constant longitudinal emittance

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

High field in collider ring

Small emittance

High beam power

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

Integrated luminosity of two colliding bunches with charge N_0

Reduced charges as function of turn

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

Size of the ring scales as

Hence

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

Key to Luminosity

$$\Delta \int \mathcal{L} \propto \frac{BN_0^2}{4\pi\epsilon\beta/\gamma}$$

Geometric emittance shrinks with energy
Assumption: normalised emittance is preserved

Key to Luminosity

Assumption:
Longitudinal emittance is preserved

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

Collider ring can tolerate the same relative energy spread

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

Hence bunch length can shrink

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

Hence beta-function can shrink (provided we have a technical solution)

$$\beta \approx \sigma_z \qquad \beta \propto \frac{1}{\gamma}$$

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

Key to Luminosity

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

↓

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

Key Challenges

- Neutrino radiation
  - What can be defended to the public?
  - How can it be reduced?
- Experimental conditions
- Beam production and cooling
  - No paper design with full performance
  - Improve test compared to MICE
    - 6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, …
- Acceleration complex design
  - Is it affordable (cost and power)?
  - Fast ramping magnets
  - High field superconducting magnets
  - Beamline design
  - Collimation
  - …
- Collider ring design
  - Is it affordable?
  - High field magnet design
  - Improved lattice design beyond 3 TeV required
  - Injection, safety concept

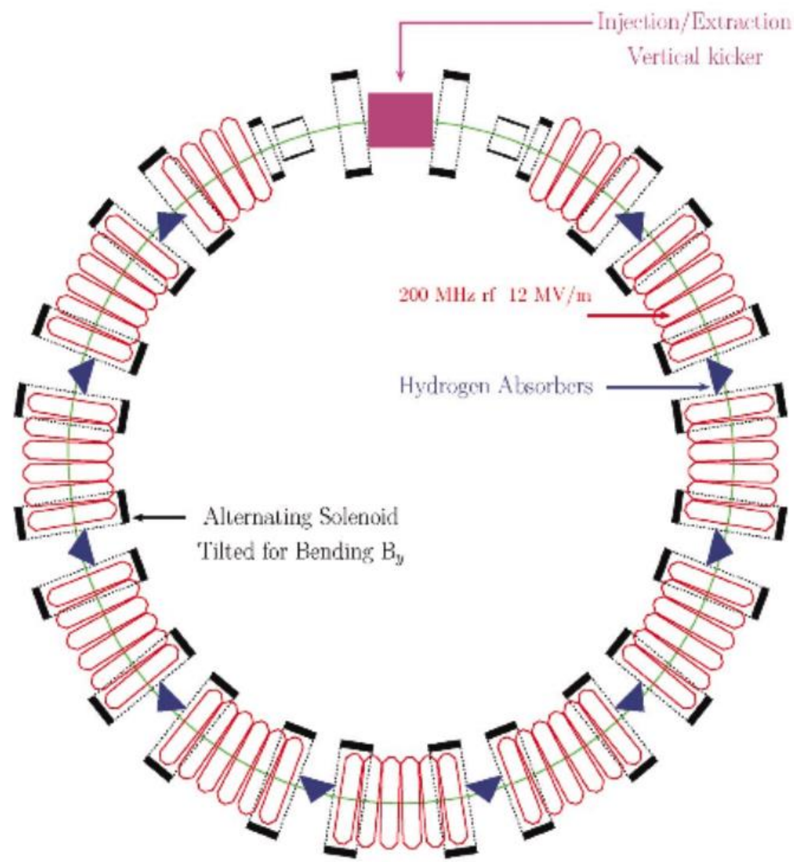
- Reuse of existing infrastructure
  - Proton facilities
  - Tunnels (maybe more for acceleration than collision)

- LEMMA concept
  - Consolidation
  - Alternative low-emittance sources

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



Linear Collider Scaling with Energy

Normalised emittances always used

$$\mathcal{L} \propto H_D \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\epsilon_y \beta_y}} \frac{R+1}{R} \frac{\eta P_{wall}}{mc^2}$$

Beamstrahlung limited by physics requirements

Beam quality and focusing design

RF-to-beam efficiency
Power consumption

At high energy

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

For unchanged technologies:
Luminosity per power remains constant with energy
Provided we can focus the beam accordingly

$R=\sigma_x/\sigma_y$

Muon Collider Luminosity Scaling

Key assumptions:
Emittance are preserved from source to collision
Higher energy allows shorter bunches and hence smaller betafunctions

$$\mathcal{L} \propto B \frac{N_0}{\epsilon \epsilon_L} \gamma f_r N_0 \gamma$$

High field in collider ring

Dense beam

High energy

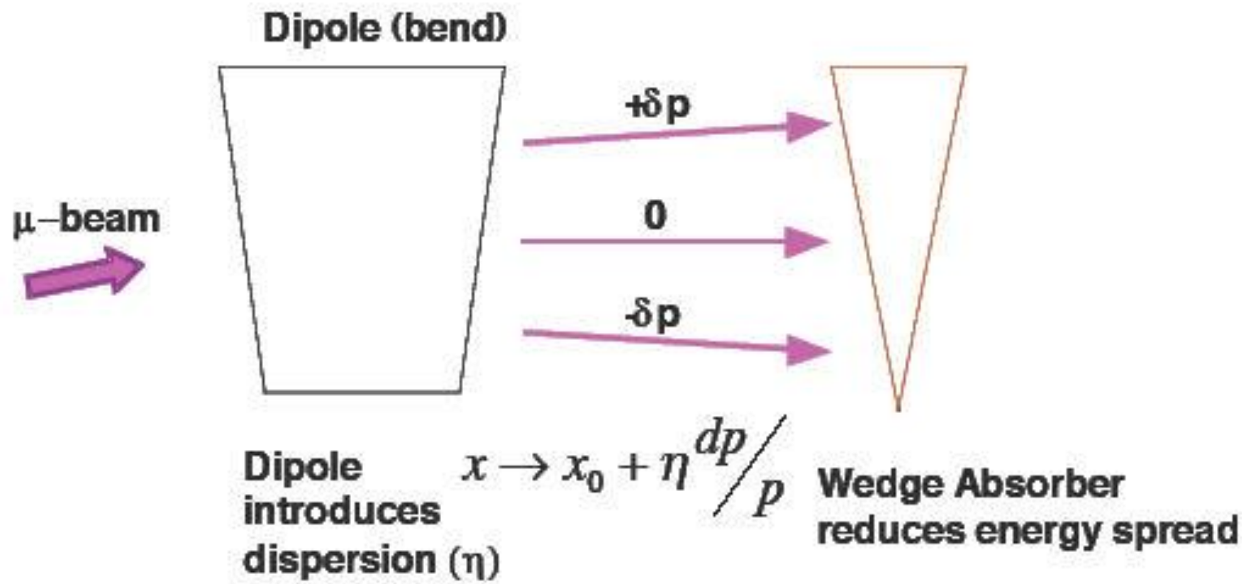
High beam power

For mostly unchanged technologies:
Luminosity per power naturally increases with energy
Provided we can focus the beam accordingly

Longitudinal Cooling/Emittance Exchange

Combined with transverse cooling at beginning

Several options considered



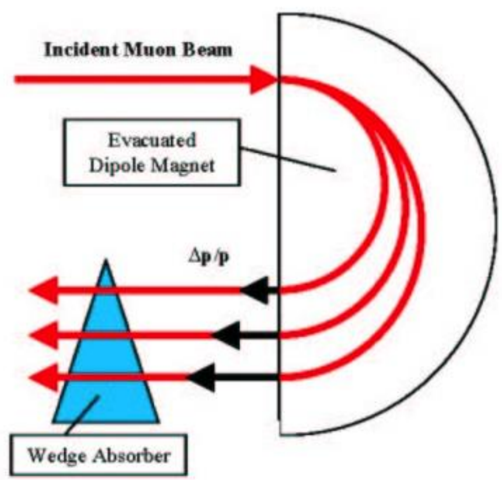


Figure 1. Use of a Wedge Absorber for Emittance Exchange

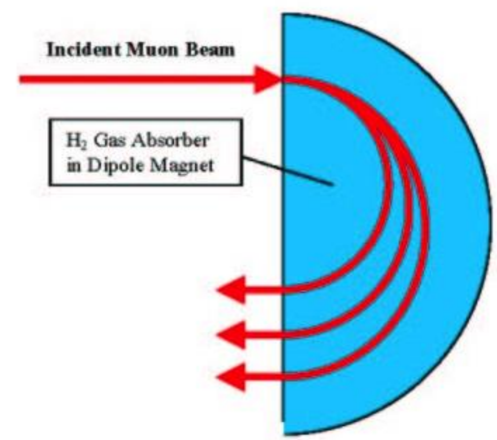


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Allows 6-D cooling

The LEMMA Scheme

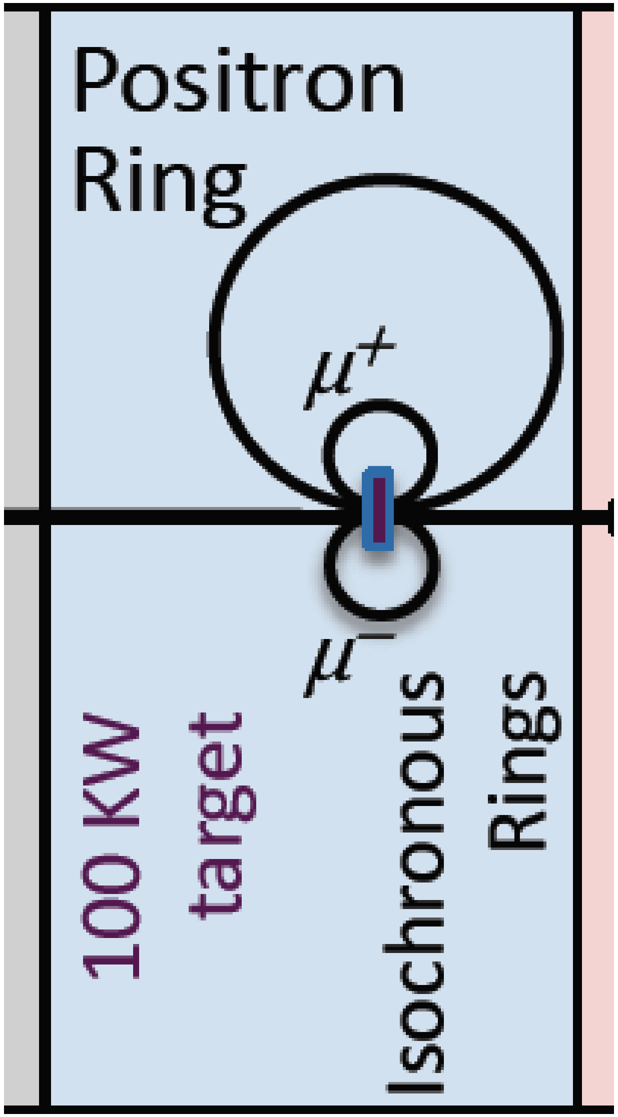
Key concept (original numbers in brackets)

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

Muon current 10^{11} s^{-1} is 300 times lower compared to 3×10^{13} s^{-1} for proton driver



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)

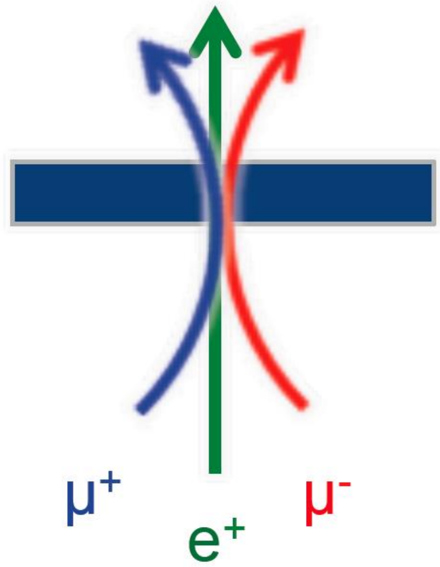
$$e^+e^- \rightarrow \mu^+\mu^- \quad O(1\mu b)$$

$$e^+e^- \rightarrow e^+e^-\gamma$$

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

Two additional severe issues were identified in the review

- 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

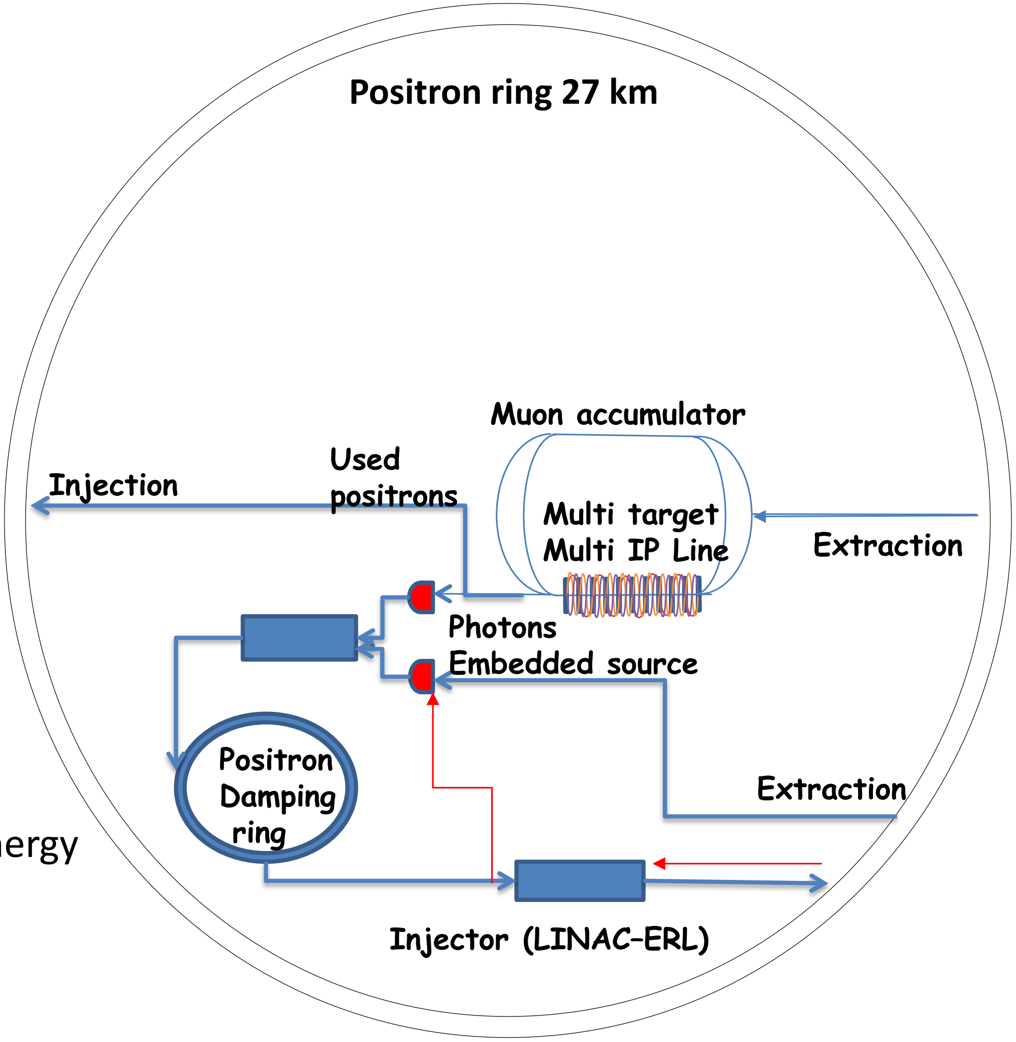
Ongoing effort to address identified challenges

- Positron production
  - Rotating target (like ILC)
  - Use of positron beam for production

- Positron ring challenge
  - larger ring, pulsed ring, lower energy accumulator ring

- Large emittance from target
  - use sequence of thin targets, H_2 targets, …
  - Increased muon bunch charge, e.g. better capturing, …
  - muon cooling (crystals, stochastic, …)

- Difficulty of combining muon bunches at high energy
  - Increasing charge at the source (producing bunches in pulsed fashion)
  - increase muons per positron bunch



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

Note: Total Power Consumption

Power consumption estimates are based on a table calculated by R. Palmer
- Leaves out a number of components, e.g. magnets
- Quote: “These numbers are preliminary, with large uncertainties”

J.-P. Delahaye added a constant value

Table 2. Estimated collider wall power requirements for 1.5 TeV center of mass; this does not include detectors, buildings, air conditioning, etc. ‘PS’ refers to Power Supplies, ‘4 K’ and ‘20 K’ refer to cryogenic power to cool elements to these temperatures.

	Length	Static	Dynamic	—	—	—	Total
		4° K	rf	PS	4° K	20° K	
	m	MW	MW	MW	MW	MW	MW
Proton driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merging	222	0.6	7.2		6.8	6.1	20.7
Merging	115	0.2	1.4				1.6
6D cooling after merging	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC rf acceleration	104	0.1	4.1				4.2
SC rf linac	140	0.1	3.4				3.5
SC rf RLAs	10,400	9.1	19.5				28.6
SC rf RCSs	12,566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Total	26	24.6	52.5	18.0	21.7	8.8	145.6

Need to have conceptual start-to-end design to estimate power correctly
Efficiency of wall plug to beam is not very different from CLIC