Muon Colliders

Daniel Schulte
European Strategy for Particle Physics

Recently a process has updated the European Strategy for Particle Physics
• Many studies prepared proposals (end of 2018)

A working group had been set up to evaluate muon collider for the strategy process
• chaired by Nadia Pastrone
• We provided input for the European Strategy
• In the past muon collider had been studied in the US (also UK contributions and others): the MAP study
  • But US strategy had no ambition for the energy frontier
• Also some activities existed, mainly in Italy, on an alternative scheme
• But no concerted study effort

The working group recommended to further explore the muon collider option since it has a unique potential for high energies

Friday June 19, 2020 Council approved the European Strategy Update
• it recommends that an international collaboration be formed to study the muon collider
Recommendations

**High-priority future initiatives**

a) [..]

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

[..]

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

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

European Strategy Process just finished

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

FCC (Future Circular Collider):
FCC-hh
• pp collider with 100 TeV cms
• ion option
FCC-ee
• Potential $e^+e^-$ first stage
FCC-eh
• additional option

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

CEPC / SppC
CEPC
• $e^+e^-$ collider 90-240 GeV
SppC
• 75-150 TeV hadron collider later in the same tunnel

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

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Muon Colliders, KIT/BESSY, June 2020
## Proposed Projects

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<td>580 (550)</td>
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Motivation for High Energy Lepton Physics

High energy lepton colliders are precision and discovery machines

Luminosity goal (for s-channel physics)

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

FCC-hh reaches 100 TeV

So there should be interest in a 14 TeV lepton collider with \( L = 4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)
Proposed Lepton Colliders (Granada)

Maximum proposed energy CLIC 3 TeV
- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)
Technically possible to go higher in energy

But cost and power

Extrapolated CLIC cost 59 GCHF
upgrade from 1.5 to 3 TeV is 8 GCHF
(14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = 59 GCHF

Extrapolated CLIC power consumption 1700 - 2800 MW
300 MW + 300 MW x 14 TeV / 3 TeV or even 600 MW x 14 TeV / 3 TeV
Another factor 1.5 to reach luminosity target
Energy Limit

Electron-positron rings are multi-pass colliders limited by synchrotron radiation.

That is why proton rings are energy frontier.

Electron-positron linear colliders avoid synchrotron radiation.
But are single pass is acceleration and collision.
This limits energy and luminosity.

Novel approach: muon collider
Large mass suppresses synchrotron radiation => multi-pass
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs
Proton-driven Muon Collider Concept (MAP)

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

Did find that design is not complete but did not find that does not work

No CDR exists, no coherent baseline of machine
No reliable cost estimate

From the MAP collaboration: Proton source (M. Palmer et al.)

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The luminosity per beam power is about constant in linear colliders

- Except if we can also change beam quality at production and focusing
- However, already worked on this for decades
- Using CLIC parameters

Novel technologies such as plasma acceleration make this even harder

A muon collider could potentially increase luminosity per beam power with energy
## Tentative Target Parameters

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<th>Unit</th>
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<td>$\sigma_{x,y}$</td>
<td>$\mu$m</td>
<td>3.0</td>
<td>0.9</td>
<td>0.63</td>
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Scaled from MAP parameters

- Emittance is constant: $\sigma_E \sigma_z = \text{const}$
- Collider ring acceptance is constant: $\frac{\sigma_E}{E} = \text{const}$
- Bunch length decreases: $\sigma_z \propto \frac{1}{\gamma}$
- Betafunction decreases

\[ \mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma \]
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Beam power of CLIC is 28 MW @ 3 TeV, 130 MW @ 14 TeV

Scaled from MAP parameters

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma \delta \frac{N_0}{\varepsilon \varepsilon_L} f_r N_0 \gamma$$
Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design
Applies to MAP scheme

\[ L \propto \gamma \langle B \rangle \sigma \delta \frac{N_0}{\epsilon L} f_r N_0 \gamma \]

High energy
Large energy acceptance
Dense beam
High beam power

Luminosity per power increases with energy
Provided all technical limits can be solved

Constant current for required luminosity

Better scaling than linear colliders

\[ L \gtrsim \frac{5 \text{ years}}{\text{time}} \left( \frac{\sqrt{s_\mu}}{10 \text{ TeV}} \right)^2 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]
High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

Maximum of $30 \times 10^{12}$ protons with 24 GeV yielded $9 \times 10^{13}$ muons (would like to double)

But radiation issues?
Maybe can use solid target

Example for capture solenoid
- Aperture 1.2 m and 15-20 T
- GJ stored energy
Cooling: The Emittance Path

- **Specification**
  - For acceleration to multi-TeV collider

- **Achieved (simulations)**
  - For acceleration to NuMAX (325MHz injector acceptance 3mm, 24mm)

Graph:
- **Final Cooling**
  - For acceleration to Higgs Factory

- **Initial (X)**
  - VCC & Hybrid

- **Initial (Y)**
  - HCC

- **Post-merge 6D Cooling**

- **Pre-merge 6D Cooling (original design)**

- **Bunch Merge**

- **Exit Front End (15mm, 45mm)**

- **Target**
  - Phase Rotator

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Transverse Cooling Concept

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

Example: final cooling solenoids \(>30\) T aperture 25 mm
Higher field means better emittance and more luminosity
MICE (in the UK)

Principle of ionisation cooling has been demonstrated

Noticeable reduction of 9% emittance
Principle of ionisation cooling has been demonstrated

Noticeable reduction of 9% emittance

Will need some better test facility
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

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**Example Acceleration**

**Rapid cycling synchrotron (RCS)**

- Inject beam at low energy and ramp magnets to follow beam energy
- Potentially important acceleration range at affordable cost

- Could use combination of static superconducting and ramping normal-conducting magnets
- First the normal magnets have opposite field
- Then they are ramped to add to static field

- Important energy in fast pulsing magnets
  - $O(40 \text{ MJ})$ @ 3 TeV
  - $O(200 \text{ MJ})$ @ 14 TeV

- Efficient energy recovery and storage is required
  - Concepts exist and have been used at much smaller scale
Collider Ring

High field dipoles to minimise collider ring size and maximise luminosity

Decaying muons impact accelerator components, detector and public

- The latter becomes much worse with energy
- Minimise distances with no bending

Protect dipole magnets and experiments from electrons / positrons from muon decay

E.g. remove part of coil in midplane

- But reduces field
Neutrino Radiation Hazard

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

Particularly bad in direction of straights
Mitigated by owning the land at exit
But also an issue in the arcs

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

US study concluded that 6 TeV parameters are OK

Reasonable goal is 0.1 mSv/ year, but to be verified

For 1.5 + 1.5 TeV 40 m depth is required
LHC effective depth is 23 m in worst direction

For 7 + 7 TeV 500 m depth requires factor 8 improvement
Mitigation Approaches

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

- Higher field in collider ring
- And shorter gaps
- Deeper tunnel
- Denser beam
- Larger energy spread acceptance
- Source design
- Civil engineering
- Magnet design
- Lattice design work
- More efficient physics
- More years of running

Tricks
e.g. beam wiggling, dumping the beam, …
Collider Ring (MAP Example)

O(400 W/m) beam loss (1/3 of beam energy)

Tungsten shielding 50 mm and 30 mm
1.5 mW/g but 10 W/m

Efficient cooling of magnet and shield needed

Study at high energy essential
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

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

Challenging system
Need to add shielding
RF and Optics Challenge

Longitudinal motion in collider ring
• average lifetime is O(3000) turns
• want short bunches O(1mm) @ 14 TeV
• significant energy spread O(10^{-3})
• large ring (14 km @ 14 TeV)
• Need very small momentum compaction

Almost completely suppress motion for
• i.e. 2.5 x 10^{-8} @ 14 TeV
• 5 x 10^{-6} @ 3 TeV

\[ \alpha \ll \frac{\epsilon_L m_\mu c}{\sigma_\delta^2 E^2 \tau c} \]

Or need enough RF voltage
• e.g. 4 GV @ 14 TeV, \( \alpha = 10^{-6} \), \( f_{RF} = 1 \text{ GHz} \)
• e.g. 86 MV @ 3 TeV, \( \alpha = 10^{-5} \), \( f_{RF} = 1 \text{ GHz} \)

\[ U = \frac{\sigma_\delta^4}{\epsilon_L^2} \frac{E^4 \alpha c \lambda_{RF}}{0.3\langle B \rangle} \]

Need to minimise momentum compaction
Proposal to combine last accelerator ring and collider ring (D. Neuffer / V. Shiltsev)

- Might reduce cost
- But creates many specific challenges
  - Would have to ramp final focus system
  - or find a bypass
  - ...

- This would be largest tunnel
Design Status

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

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

MICE (UK)

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

Low emittance muon beam
But very large positron current required
Target is challenging
Need large positron production rate \([O(10^{17}/s)]\)
Currently do not reach luminosity goal
Proposed Tentative Timeline (2019)

- **Design**
  - Baseline design
  - Design optimisation
  - Project preparation
  - Approve

- **Test Facility**
  - Design
  - Construct
  - Exploit
  - Exploit

- **Technologies**
  - Design / models
  - Prototypes / t. f. comp.
  - Prototypes / pre-series

- **Detector**
  - R&D detectors
  - Prototypes
  - MDI & detector simulations
  - Large Proto/Slice test

- **MACHINE**
  - R&D detectors
  - Prototypes

- Ready to decide on test facility
  - Cost scale known

- Ready to commit to collider
  - Cost known

- Ready to construct

Technically limited
Proposed Tentative Timeline (2019)

- **Design**
  - Baseline design
  - Design/ models
  - Ready to decide on test facility
  - Cost scale known

- **Construct**
  - Exploit
  - Design
  - Prototypes
  - Ready to commit to collider
  - Cost known

- **Test Facility**
  - Facility
  - Prototypes
  - Ready to construct

- **Facility**
  - Technologies
  - Prototypes
  - Full project
  - Higher cost for technical design
  - Significant resources

- **Tentative**
  - Timeline
  - (2019)

- **Limited Cost**
  - Mainly paper design
  - And some hardware component R&D

- **Higher cost for test facility**
  - Specific prototypes
  - Significant resources

- **Higher cost for technical design**
  - Full project
  - Higher cost for preparation

- **Full project**
  - Limited Cost

- **Mainly paper design**
  - And some hardware component R&D

- **Significant resources**

- **Full project**
  - Higher cost for preparation

- **Technical limited**

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Tentative Considerations on Baseline

• Stage with energy of $O(1.5 + 1.5 = 3 \text{ TeV})$
  – To come after higgs factory and matching highest CLIC energy
  – Using the high-energy strength of muon colliders
  – Realistic design for implementation at CERN, with cost power and risk scale
  – If successful, feasibility demonstration for CDR

• Explore 14 TeV as further step
  – To match FCC-hh discovery potential
  – Mainly exploration of parameters to guide choices
  – Provide evidence for feasibility, maybe cost frame

• Exploration of synergies
  – Higgs factory
  – Neutrino factory
Objective for First Period

• Important resources for R&D are required to make the muon collider mature enough that we can commit to it

• Goal is to establish until the next European Strategy Update that this effort is worthwhile, i.e.
  – A muon collider addresses the needs of the physics community
  – It appears feasible
    • Risks, performances, cost, power consumption are expected to be acceptable
  – Provide R&D plan to bring the technology to sufficient maturity for commitment
    • with estimated cost
Conclusion

Muon colliders are a promising option for the high-energy frontier

Important work to demonstrate feasibility and performance

Combination of challenges from proton colliders and electron machines

Strong support by European Strategy for Particle Physics

Hopefully strong support in Germany

Collaboration is forming

Meeting (remote) on July 3 14:00-18:00

• web page (agenda being prepared) [https://indico.cern.ch/event/930508/](https://indico.cern.ch/event/930508/)
• purpose is to start collecting statements of intent to collaborate
  • collaboration will be on best-effort basis
  • indication of fields of interest
  • obviously, no moral commitment possible now since every one needs to find resources
Reserve
Linear Collider Scaling with Energy

\[ \mathcal{L} \propto H_D \left( \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \right) \frac{1}{\sqrt{\epsilon_y/\beta_y}} \left( \frac{R + 1}{R} \right) \frac{\eta P_{wall}}{mc^2} \]

- 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

\[ R = \frac{\sigma_x}{\sigma_y} \]
Other Options

Variations of the muon sources were suggested
• E.g. use of channeling in crystals
• Use of gamma factory to produce muons
• Use of gamma factory to produce positrons for LEMMA
But all at a very tentative level for now

Also suggested were use of LHC and FCC tunnel for the collider ring
• Obviously something that needs to be explored
• Come back to this later

Combination of final accelerator stage and collider ring
• Could maybe save some cost
• But likely will compromise performance
• And generate its own challenges
• So trade-off has to be understood

Also some other ideas
• But too early to
Other Tests

MuCool: >50 MV/m in 5 T field

A number of key components has been developed

FNAL
Breakthrough in HTS cables

NHFML
32 T solenoid with low-temperature HTS

FNAL
12 T/s HTS 0.6 T max

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

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

arXiv:1905.03725
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.

<table>
<thead>
<tr>
<th>Length</th>
<th>Static 4° K</th>
<th>Dynamic rf</th>
<th>—</th>
<th>—</th>
<th>—</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton driver (SC linac)</td>
<td>16</td>
<td>15.0</td>
<td>6.8</td>
<td>6.1</td>
<td>20.7</td>
<td>(20)</td>
</tr>
<tr>
<td>Target and taper</td>
<td>95</td>
<td>0.1</td>
<td>0.8</td>
<td>4.5</td>
<td>5.4</td>
<td>15.4</td>
</tr>
<tr>
<td>Decay and phase rot</td>
<td>14</td>
<td>115</td>
<td>222</td>
<td>222</td>
<td>428</td>
<td>20.7</td>
</tr>
<tr>
<td>Charge separation</td>
<td>14</td>
<td>6D cooling</td>
<td>78</td>
<td>78</td>
<td>12,566</td>
<td></td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>Merging</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>Final 4D cooling</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>NC rf acceleration</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>SC rf linac</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>SC rf RLAs</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Merging</td>
<td>14</td>
<td>SC rf RCSs</td>
<td>14</td>
<td>15</td>
<td>78</td>
<td>20.7</td>
</tr>
<tr>
<td>Collider ring</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
</tr>
</tbody>
</table>

Loss of stored energy in magnets is not considered ⇒ Should review design more
Note: Stacking

Can increase relevant beam density by stacking $n$ bunches side by side in phase space

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

Could combine bunches in transverse phase space
Theoretically, $\epsilon_x \epsilon_y$ scales with number of bunches
Charge also scales with number of bunches
Hence

$$
\frac{N}{\epsilon} \approx \sqrt{n} \frac{N_0}{\epsilon_0}
$$

But difficult to do...

Particularly interesting for LEMMA with high rate of bunches
But only with square root of combination factor
Rough Estimate for CLIC

CLIC additional cost at 14 TeV: 40-50 GHCF ?
• upgrade 1.5 to 3 TeV about 8 GCHF
• some cost reduction due to large-scale production
• \((14\ \text{TeV} - 3\ \text{TeV}) / 1.5 \ \text{TeV} \times 8 \ \text{GCHF} = 59 \ \text{GCHF}\)

Power consumption: 1700 to 2800 MW ?
• Same beam current leads to 130 MW beam power
• \(300 \ \text{MW} + 300 \ \text{MW} \times 14 \ \text{TeV} / 3 \ \text{TeV} = 1700 \ \text{MW}\)
• \(600 \ \text{MW} \times 14 \ \text{TeV} / 3 \ \text{TeV} = 2800 \ \text{MW}\)

Luminosity \(2.8 \times 10^{35} \ \text{cm}^{-2}\text{s}^{-1}\) ?
• same repetition rate, same quality of focusing (hard)
• luminosity scales linearly with energy for constant beam current
• \(6 \times 10^{34} \ \text{cm}^{-2}\text{s}^{-1} \times 14 \ \text{TeV} / 3 \ \text{TeV} = 28 \times 10^{34} \ \text{cm}^{-2}\text{s}^{-1}\)

Luminosity is a bit marginal (could be fixed by higher rate)
Cost and power consumption are very high
Transverse Cooling Concept

\[ \frac{d\epsilon_{\perp}}{ds} = \frac{1}{(v/c)^2} \frac{dE}{ds} \frac{\epsilon_{\perp}}{E} + \frac{1}{2} \left( \frac{14 \text{ MeV}}{E} \right)^2 \frac{\beta\gamma}{L_R} \]
Longitudinal Cooling/Emittance Exchange

- Combined with transverse cooling at beginning
- Several options considered

Equation: \[ x \rightarrow x_0 + \eta \frac{dp}{p} \]

Dipole introduces dispersion (\( \eta \))

Wedge Absorber reduces energy spread

Allows 6-D cooling
Cooling and MICE

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

\[
\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2} \frac{dE}{ds} \frac{\epsilon_\perp}{E} + \frac{1}{2} \frac{1}{(v/c)^3} \left( \frac{14 \text{ MeV}}{E} \right)^2 \frac{\beta \gamma}{L_R}
\]
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
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, 3x10^{11} particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons (4.5x10^7)
- 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 x 10^{13} s^{-1} for proton driver
Key Issues

Need $10^{11}$ muons per s

Small cross section for muon production $O(10^{-7})$ per passage

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

⇒ Need to pass $10^{18}$ positrons per s

Large fraction of positrons is lost
• Mainly due to bremsstrahlung

\[ e^+ e^- \rightarrow e^+ e^- \gamma \quad O(100mb), E_\gamma \geq 0.01 E_p \]

⇒ Need to produce $10^{16}$ positrons per s ($O(10^7)$ per muon)

High current generates heat load and stress in target (also difficult)

Circulating current produces $O(100MW)$ synchrotron radiation
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 they were merged into the same phase space
    – No design exists for the merger
  • The combination factor is proportional to beam energy
    • Lifetime at high energy is larger
    • Extract muons at 22 GeV after one lifetime from accumulator
    • But they survive E/22 GeV times longer in collider
  • 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, H₂ 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