Novel ideas for further studies in Europe
Low Emittance Muon Collider (LEemma)
M. Antonelli (INFN-LNF)
For the LEMMA team
Outline

• Introduction
• Positron driven source
• LEMMA scheme
• Status
• Further studies on key topics
• Conclusion
Proton Driver

SC Linac
Accumulator
Buncher
Combiner

Front End

MW-Class Target Capture Sol.
Decay Channel
Buncher
Phase Rotator

Cooling

Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling

Acceleration

Closer Ring

E_{CoM}:
Higgs Factory
to
\sim 10 \text{ TeV}

\mu^+ \quad \mu^-

New tunnels and/or new high field magnets (e.g. HTS) and/or new acceleration could provide large benefits to both options

Low EMMittance Muon Accelerator (LEMMMA):
10^{11} \propto \text{pairs/sec from } e^+ e^- \text{ 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.}

Not really a fair comparison: MAP studies much more advanced
LEMMMA much simpler in principle but still many key aspects to be fully studied (this talk)
MICE selected Result

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
Muon production

from proton on target: \( p + \text{target} \rightarrow \pi/K \rightarrow \mu \)
typically \( P_\mu \approx 100 \text{ MeV/c} \) (\( \pi, K \) rest frame)
whatever is the boost \( P_T \) will stay in Lab frame \( \rightarrow \)
very high emittance at production point \( \rightarrow \) cooling needed!

from direct \( \mu \) pair production:
Muons produced from \( e^+e^- \rightarrow \mu^+\mu^- \) at \( \sqrt{s} \) around the \( \mu^+\mu^- \) threshold
(\( \sqrt{s} \approx 0.212 \text{ GeV} \)) in asymmetric collisions (to collect \( \mu^+ \) and \( \mu^- \))

NIM A Reviewer: “A major advantage of this proposal is the lack of cooling of the muons.... the idea presented in this paper may truly revolutionise the design of muon colliders ... “
Advantages:

1. **Low emittance possible:** $\theta_\mu$ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$; $\theta_\mu$ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low $\nu$ radiation (easier experimental conditions, can go up in energy)
3. **Reduced losses from decay:** muons can be produced with a relatively high boost in asymmetric collisions
4. **Energy spread:** muon energy spread **also small at threshold**, it gets larger as $\sqrt{s}$ increases

Disadvantages:

- **Rate:** much smaller cross section wrt protons ($\approx$ mb)
  \[ \sigma(e^+e^-\rightarrow\mu^+\mu^-) \approx 1 \mu b \text{ at most} \]
Possible implementation

• **Low energy collider with e⁺/e⁻ beam (e⁺ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity ≈ 10^{40} is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 needed to obtain a reasonable conversion efficiency to muons)

• **Electrons at rest (seems more feasible):**
  3. e⁺ on plasma target
  4. **e⁺ on standard target** (eventually crystals in channeling)
    ▪ Need Positrons of ≈ 45 GeV
    ▪ γ(µ)≈200 and µ laboratory lifetime of about 500 µs

Ideally muons will *copy* the positron beam
Contribution to $\mu$ beam size due to finite target length

**Diagram Explanation**

- **e+ beam on target**: Electron beam incident on a target.
- **If L was a drift**: Electron drift along the target.
- **Muons produced uniformly along target**: Muons produced uniformly along the target, with infinitely many drifts $[0,L]$.

**Formula**

$$\theta_{\mu}^{\text{max}} = \frac{4m_e}{s} \sqrt{\frac{s}{4} - m_{\mu}^2}$$

**Graphs**

- **Energy vs. Muon Production Angle**
- **Muon Beam at the Exit**

**Text**

- The emittance contributions due to muon production angle: $\varepsilon_{\mu} = x x'_{\text{max}}/12 = L (\theta_{\mu}^{\text{max}})^2/12$
- $\varepsilon_{\mu}$ completely determined by $L$ and $s$ - by target thickness and c.o.m. energy.
Criteria for target design

Luminosity is proportional to $N_\mu^2 \frac{1}{\varepsilon_\mu}$

optimal target: minimizes $\mu$ emittance with highest $\mu$ rate

- **Heavy materials, thin target**
  - to minimize $\varepsilon_\mu$: thin target ($\varepsilon_\mu \ll L$) with high density $\rho$
  - Copper: MS and $\mu^+\mu^-$ production give about same contribution to $\varepsilon_\mu$
  - BUT high $e^+$ loss (Bremsstrahlung is dominant) so
    $$\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \Rightarrow$$
    $$\frac{N(\mu^+\mu^-)/N(e^+)}{\sigma_\mu/[(Z+1)\sigma(\text{Bhabha})]} \approx 10^{-7}$$

- **Very light materials, thick target**
  - maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$ (enters quad) $\Rightarrow$ $H_2$
  - Even for liquid targets $O(1m)$ needed $\Rightarrow \varepsilon_\mu \ll L$ increase

- **Not too heavy materials (Li, Be, C)**
  - Allow low $\varepsilon_\mu$ with small $e^+$ loss
    $$\frac{N(\mu^+\mu^-)/N(e^+)}{\approx 10^{-6}}$$
Possible schemes for muon production

Multi-pass scheme

Single-pass scheme

Muons acceleration

Recovery system or secondary e+ source

Ramping e+ storage ring or recirculating linac

Multi-pass scheme

**Goal:**

\[ @T \approx 10^{11} \mu/s \]

Efficiency \( \approx 10^{-7} \) (with Be 3mm)\( \rightarrow \) 10\(^{18} \) e\(^+\)/s needed \( @T \rightarrow \) e\(^+\) “stored” beam with T

need the largest possible lifetime to minimize positron source rate

LHeC like e\(^+\) source required rate with lifetime(e\(^+\)) \( \approx 250 \) turns [i.e. 25% momentum aperture \( \rightarrow n(\mu)/n(e^+ \text{ source}) \approx 10^{-5} \)]

- Low emittance and high momentum acceptance 45 GeV e\(^+\) ring
- O(100 kW) class target in the e\(^+\) ring for \( \mu^+ \) \( \mu^- \) production
- High rate positron source
- High momentum acceptance muon accumulator rings
Low emittance 45 GeV positron ring

cell

circumference 6.3/27 km: 197 m x 32 cells

Table e+ ring parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.7 nm</th>
<th>6 nm</th>
<th>10 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [km]</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>N. cells</td>
<td>64</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>I_b [A]</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>N_part /bunch</td>
<td>5x10^{11}</td>
<td>5x10^{11}</td>
<td>5x10^{11}</td>
</tr>
<tr>
<td>N. bunches</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>E_loss/turn [GeV]</td>
<td>0.12</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>Nat. $\sigma_z$ [mm]</td>
<td>1.9</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>2.9x10^{-5}</td>
<td>1x10^{-4}</td>
<td>1.1x10^{-4}</td>
</tr>
<tr>
<td>Energy spread</td>
<td>7x10^{-4}</td>
<td>7x10^{-4}</td>
<td>9x10^{-4}</td>
</tr>
<tr>
<td>$\tau_{x,y}$ [ms]</td>
<td>68</td>
<td>66</td>
<td>42</td>
</tr>
<tr>
<td>Energy acceptance [%]</td>
<td>± 8</td>
<td>± 6</td>
<td>± 2</td>
</tr>
<tr>
<td>SR power [MW]</td>
<td>106</td>
<td>109</td>
<td>170</td>
</tr>
</tbody>
</table>

Physical aperture=5 cm constant

no errors

Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies
Beam dynamics $e^+$ beam in ring-with-target


$e^+$ emittance growth controlled with proper $\beta$ and D values @ target

After 40 turns $\sigma'_{MS} = 25$ $\mu$rad
Comments on multi-pass scheme

CONS

- High power on target
- Low number of muons per bunch: do not have a realistic scheme for recombination at high energy
- Muon beam almost in CW, not compatible with acceleration by synchrotron
- The same is true for positron beam replacement (source + acceleration + injection)

PROS

✓ muon emittance is small
Single-pass scheme

- positron beam passes only once through a ~X0
- **More muons** produced per bunch
- **Power can be distributed** over a long target

- Full preliminary accelerator complex description including all subsystems in [arXiv:1905.05747: e⁺ sources, e⁺ rings, compressor linac, target system...]
  - State of the art and future R&D
Target issues

3e11 e+ @45GeV
10 x 0.1X_0 of Be

Most of the muons are produced in the first 3 targets = 0.3X_0

Target material plays a crucial role
Thermo-mechanical issues

• Aim at bunch \((5\times10^{11} \text{ e}^+)\) transverse size on the 10-20 \(\mu\text{m}\) scale: rescaled from test at HiRadMat \((5\times10^{13} \text{p on 100}\mu\text{m})\) with Be-based targets and C-based (HL-LHC)

• Detailed simulation of thermo-mechanical stresses dynamics
  • FLUKA + FTDT/Ansys Autodyn) with CERN EN-STI)

• Multiple target system

• Experimental tests:
  • DAFNE linac
  • DAFNE TF available if approved
Thermal Study

Not rotating target

$5 \times 10^{11} \text{ e}^+ \text{ on Be target}$

FDTD model

$100 \mu \text{m} \times 50 = 5 \text{ mm}$

C : $R=5 \text{ mm}$, $L=1 \text{ mm}$

Be : $R=5 \text{ cm}$, $L=3 \text{ mm}$

Time (s)

Temperature increase (K)

ILC($e^+$ prod.) like target

- Radius 50 cm
- $N \sim 2000 \text{ rpm}$
- Wheel rim speed 100 m/s
- Wheel diameter $\sim 1 \text{ m}$

Much lighter for LEMMA

- No bunch pileup
- Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB)
Considerations on $\mu$ accumulation

Accumulation must be performed in $\tau_{lab} \sim 500\mu s$

Ring must be as short as possible with the largest possible $E$ acceptance

Number of muons increased by using a thick target

- drift contribution on beamsize ($\propto L_T$)
- MS contribution on emittance ($\propto \sqrt{X_0 N_T}$)

Possible solutions:

- Multiple IP
- Spaghetti/film-like targets or channeling in crystals

Proc. of IPAC18, Vancouver, MOPMF087
Luminosity of $\mu^+\mu^-$ Collider vs $e^+$ beam energy

Optimal working point for $\varepsilon(e^+) \approx \varepsilon(\text{MS}) \approx \varepsilon(\text{rad}) \approx \varepsilon(\text{prod}) \approx \varepsilon(\text{AR})$

and sustainable beam spot on target $\varepsilon(\text{prod})$ and $\mu$ intensity $\propto$ positron beam energy:

Need of high energy acceptance $\mu$ ring
First accumulator $\mu$ ring design
Multiple IP, multiple targets

Targets separated by a transport line where magnets are common to the three beams (e+, μ+ and μ−), focusing the beams at each IP to achieve the production of new muons with minimal growth to the final beam emittance.

lattice design:
- Lenght < 5 m
- magnet gradient at 200 T/m
- aperture radius 1 cm

Two triplets are used to focus the beams on both transverse planes, and they are put in asymmetry in order to partially cancel chromaticity at 45 GeV as in the apochromatic design

Still work to be done to benefit from this option
Positron source requirements

Positron source rate is independent on the scheme (multi- or single-pass)
Main dependences on target material and recovery system energy acceptance

Single-pass scheme

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</thead>
<tbody>
<tr>
<td>5</td>
<td>4,89E+15</td>
<td>41,43</td>
<td>4,99E+15</td>
<td>42,28</td>
<td>4,82E+15</td>
<td>40,9</td>
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<tr>
<td>10</td>
<td>4,11E+15</td>
<td>34,88</td>
<td>4,22E+15</td>
<td>35,79</td>
<td>4,06E+15</td>
<td>34,4</td>
</tr>
<tr>
<td>20</td>
<td>3,22E+15</td>
<td>27,33</td>
<td>3,33E+15</td>
<td>28,24</td>
<td>3,23E+15</td>
<td>27,4</td>
</tr>
</tbody>
</table>

To evaluate the number of positrons per second required from the source we assume to have 1500 bunches with $5 \times 10^{11}$ e$^+$/bunch on target at 10Hz (total of $7.5 \times 10^{15}$ e$^+$/sec)

This is a key issue to be studied

Summary of e$^+$ sources projects (all very aggressive):

Embedded positron source

Positron source extending the target complex? Possibility to use the γ’s from the μ production target to produce e+

- e+ 45 GeV
- Dipole magnet
- Thin light target (eventually crystal in channeling)
- Thick heavy target

γ’s angular distribution at the target exit

N(e+e−)/N(e+) [%]

Focusing based on AMD under study promising preliminary results on collection efficiency

Produce a fraction of e+ of the incoming positron beam

3 mm Be [Geant4]
Conclusion

Studies for a low emittance muon source are promising.
We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept.

Some of the key challenges:
- High rate positron source
- High momentum acceptance muon accumulator rings
- High power target

Most of them are in common with other accelerator projects.
R&D on high rate positron source

- R&D on this topic can take advantage of significant synergies with future collider studies as FCC-ee, ILC and CLIC.
- The required intensity for LEMMA is strongly related to the beam lifetime, determined by the momentum acceptance and the target material.
- So, also optics and beam dynamics optimization is necessary.

### e\(^+\) production rates achieved (SLC) or needed

<table>
<thead>
<tr>
<th></th>
<th>S-KEKB</th>
<th>SLC</th>
<th>CLIC (3 TeV)</th>
<th>ILC (H)</th>
<th>FCC-ee (Z)</th>
<th>LEMMA(Be)</th>
<th>LEMMA(LH2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^{14}) e(^+) / s</td>
<td>0.025</td>
<td>0.06</td>
<td>1.1</td>
<td>2</td>
<td>0.05</td>
<td>100</td>
<td>40</td>
</tr>
</tbody>
</table>

Present: 3 mm Be, 40 turns lifetime(DP/P<6%), ΔN/N=2.5%, P= 247 MW
35 mm LH2, 100 turns lifetime(DP/P<6%), ΔN/N=1%, P= 98 MW

Goal: 3 mm Be, 240 turns lifetime(DP/P<25%), ΔN/N=0.4%, P=39 MW
35 mm LH2, 625 turns lifetime(DP/P<25%), ΔN/N=0.1%, P= 16 MW
Low EMittance Muon Accelerator team

D. Alesini, M. Antonelli, M.E. Biagini, M. Boscolo, O. R. Blanco-García, A. Ciarma, R. Cimino, M. Iafrati, A. Giribono, S. Guiducci, L. Pellegrino, M. Rotondo, C. Vaccarezza, A. Variola†, INFN-LNF, 00044 Frascati, Italy
A. Allegri, F. Anulli, M. Bause, F. Collamati, G. Cavoto, G. Cesarini, F. Iacoangeli, R. Li Voti, INFN-Roma, 00185 Roma, Italy
A. Bacci, I. Drebot, INFN-MI, 20133 Milano, Italy
P. Raimondi, S. Liuzzo, ESRF, 38043 Grenoble, France
I. Chaikovska, R. Chehab, IN2P3-LAL, 91440 Orsay, France
N. Amapane, N. Bartosik, C. Bino, A. Cappati, G. Cotto, N. Pastrone, M. Pelliccioni, O. Sans Planell INFN-TO, 10125 Torino, Italy
M. Casarza, E. Vallazza, INFN-TS, 34127, Trieste, Italy
G. Ballerini, C. Brizzolari, V. Mascagna, M. Prest, M. Soldani, Insubria University, 22100 Como, Italy
A. Bertolin, C. Curatolo, F. Gonella, A. Lorenzon, D. Lucchesi, M. Morandin, J. Pazzini, R. Rossin, L. Sestini, S. Ventura, M. Zanetti, Padova University, 35121 Padova, Italy and INFN-PD, Padova, Italy
F. Carra, P. Sievers, CERN, CH-1211 Geneva 23, Switzerland
L. Keller, SLAC National Accelerator Laboratory, 94025 Menlo Park, CA, US
L. Peroni, M. Scapin, Politecnico di Torino, 10129 Torino, Italy
Criteria for target design

Number of $\mu^+\mu^-$ pairs produced per $e^+e^-$ interaction is given by

$$N(\mu^+\mu^-) = \sigma(e^+e \rightarrow \mu^+\mu^-)N(e^+)\rho(e^-)L$$

- $N(e^+)$ number of $e^+$
- $\rho(e^-)$ target electron density
- $L$ target length

To maximise $N(\mu^+\mu^-)$:
- $N(e^+)$ max rate limit set by $e^+$ source
- $\rho(e^-)L$ max occurs for $L$ or $\rho$ values giving total $e^+$ beam loss
  - **$e^-$ dominated target:** radiative Bhabha is the dominant $e^+$ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency
    $$N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \rightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, $X_0$ and electron density will matter
    $$N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \rightarrow \mu^+\mu^-)/\sigma_{brem}$$