Outline

- Muon collider (MC) characteristics:
  - Concept and advantages
  - Radiation effect challenges

- Interaction region: machine detector interface (MDI)
  - Beam induced background (BIB): halo, muon decay and incoherent pair production by muons
  - Secondary electron/positron trajectories

- 1.5 TeV results:
  - Precedent work in the MAP collaboration
  - Comparison between MARS and FLUKA

- 10 TeV results:
  - Muon decay as main source of background and comparison with other machines
  - Incoherent pair production as a non negligible BIB
  - Lattice design influence on BIB
  - Toward a 10 TeV nozzle design

- Conclusions
Muon collider: concept and motivations

Among various particles accelerated in colliders, muons have already been under consideration for a long time [1]. Very promising results were achieved in the contest of the MAP collaboration [2-3]. The following work is in the context and on behalf of the International Muon Collider Collaboration (IMCC).

Why?

- A multi-TeV muon collider could investigate Higgs properties with an unprecedented precision. [2]
- With $\sqrt{s} = 10$ TeV we can explore new physics at high energies. [2]

With a muon collider the luminosity per beam power increases with the collider energy!
Muons are unstable particles, with a rest lifetime of $\tau = 2.197 \, \mu s$. They decay spontaneously into electron and positrons (depending on the muon original charge), which are the main contributors to the secondary radiation field.

- **Superconducting magnets**: Secondary electrons impact on the beam chamber. Their energy induce **heat up** and long term radiation **damage** in the superconducting coils.

- **MDI**: The secondary field is a source of **background** to the experiment and induce radiation **damage** to the **detectors**.

- **Neutrino radiation**: High energy **neutrinos** from the muon decay interact with the rock delivering **dose** to the **environment**.
Interaction region: MDI

- MDI is a difficult challenge for the muon collider. First studies were done by the MAP collaboration (energies up to 6 TeV). So far, no studies were performed for a 10 TeV collider.
- Objectives of the new studies within the IMCC:
  - Devise a conceptual IP design achieving background levels compatible with detector operation, both in terms of physics performance and acceptable cumulative radiation damage.
  - The focus energies are 3 TeV and 10 TeV.
- Starting from the geometry of the nozzle devised by the MAP collaboration [5], first MDI studies for colliders up to 10 TeV have been conducted.

Parameters table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3 TeV</th>
<th>10 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>10^{34} cm^2 s^{-1}</td>
<td>1.8</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>N</td>
<td>10^{12}</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>f_r</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>P_{beam}</td>
<td>MW</td>
<td>5.3</td>
<td>14.4</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>km</td>
<td>4.5</td>
<td>10</td>
<td>14</td>
</tr>
</tbody>
</table>

Comparison: CLIC at 3 TeV: 28 MW

Geometry of the MDI

- Nozzle:
  - Outer boron layer to stop neutrons
  - Tungsten core for the electromagnetic showers

Interaction point

Beam line
MDI: radiation sources

- **Main** source of detector background for all collider energy options.
- Main responsible for heat and radiation effects in the accelerator components.

- Potential contribution to the BIB and damage on accelerator components.
- Levels of acceptable halo losses to be defined. *(halo cleaning)*

- **Muon decay** around the ring
- Incoherent $e^-/e^+$ pair production during bunch crossing in IP
- Beam-halo losses at aperture bottlenecks

- Potential problem for the detector background.
- Proven not to be an issue for low energy colliders, providing a solenoid field of $\sim 1$ T. [5].
- Under study in the 10 TeV collider.

Neutron fluence

Effects

Secondaries will interact with the **machine components** and with the detectors. In figure, a thick nozzle shielding protects the detector area by the strong fluences arising from the muon decay.

Photon fluence
In the context of the MAP collaboration, the muon collider detector background and Machine-detector interface has been thoroughly studied [5-8].

They observed that most background particles are generated in the last 25 m straight section, except muons that can be produced further away.

The MAP collaboration optimized nozzles for colliders up to 1.5 TeV (with MARS code).

Recent FLUKA results are in a good agreement with the past studies.

<table>
<thead>
<tr>
<th>Particle ($E_{th}$)</th>
<th>MARS15</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon (100 keV)</td>
<td>8.6 $10^7$</td>
<td>5 $10^7$</td>
</tr>
<tr>
<td>Neutron (1 meV)</td>
<td>7.6 $10^7$</td>
<td>1.1 $10^8$</td>
</tr>
<tr>
<td>Electron/positron (100 keV)</td>
<td>7.5 $10^5$</td>
<td>8.5 $10^5$</td>
</tr>
<tr>
<td>Ch. Hadron (100 keV)</td>
<td>3.1 $10^4$</td>
<td>1.7 $10^4$</td>
</tr>
<tr>
<td>Muon (100 keV)</td>
<td>1.5 $10^3$</td>
<td>1 $10^3$</td>
</tr>
</tbody>
</table>
1.5 TeV: results

- From the MAP collaboration, the results at 1.5 TeV are reported. In the former case, a comparison with FLUKA code shows a good agreement for all the particle spectra.

**1.5 TeV geometry and comparison with MARS from [13]**

- Radiation maps: $2 \times 10^{12}$ m/bunch, C=2.5 km, 5 Hz rate, 200 days/y
- Preliminary simulations show comparable BIB also with 3 TeV colliders.
- Radiation levels similar to HL-LHC (TID $\sim 10^{-3}$ Grad/y on tracker and $\sim 10^{-4}$ Grad/y ECA)
10 TeV: BIB from muon decay

- The 10 TeV geometry has to be extended to fully collect the BIB from decay position further away from the IP.
- The total number of particles entering into the detector is not significantly worse than the lower energy results!

**Counts per position of decay**

Decays after L' give a negligible contribution to the BIB

**Total particle number: comparison with different collider energies**

<table>
<thead>
<tr>
<th>Collider energy</th>
<th>1.5 TeV</th>
<th>3 TeV</th>
<th>10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>7.1E+7</td>
<td>9.6E+7</td>
<td>1.16E+8</td>
</tr>
<tr>
<td>Neutron</td>
<td>4.7E+7</td>
<td>5.8E+7</td>
<td>8.88E+7</td>
</tr>
<tr>
<td>e^+/e^-</td>
<td>7.1E+5</td>
<td>9.3E+5</td>
<td>9.49E+5</td>
</tr>
<tr>
<td>Ch. hadrons</td>
<td>1.7E+4</td>
<td>2.0E+4</td>
<td>3.37E+4</td>
</tr>
<tr>
<td>Muons</td>
<td>3.1E+3</td>
<td>3.3E+3</td>
<td>2.99E+3</td>
</tr>
</tbody>
</table>

Non optimized [14-15]
10 TeV: BIB from incoherent pair production

- At very high beam energies, beam-beam effects are not negligible. The most important phenomenon is due to the **incoherent beam-beam pair production** $\mu^+\mu^-\rightarrow\mu^+\mu^-e^+e^-$.  
  - The incoherent pair production $e^+/e^-$ are provided by D. Schulte and are obtained by a Guinea-Pig simulation.
- The **total number** of crossing is much lower than the muon **decay** case.
- The produced electrons are **energetic** and they **impact** directly on the **detectors**, since are generated in the IP, hence they might be dangerous despite the low total number.

**Longitudinal distribution of impacts**

Particle current (5T)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Current [cm²/2passage]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>$2.2\times10^4$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$8.2\times10^4$</td>
</tr>
<tr>
<td>$e^+$</td>
<td>$6.4\times10^4$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$1.7\times10^6$</td>
</tr>
</tbody>
</table>

**Electron energy spectrum**

Much harder spectrum!
A first attempt to reduce the BIB is conducted working on the lattice just before the IP. In principle, having a dipolar component in the lattice is beneficial, since all the low energy electrons are forced to impact on the magnet sides.

We considered three possibilities (from K. Skoufaris and C. Carli) for the lattice in the final focusing:

- Only quadrupoles, with no dipoles and no dipole component (pure).
- Combined function magnets, where there are no dipole magnet, but each quadrupole contains a 2T dipolar component (combined).
- Having both dipoles and quadrupoles in the final triplet, but without exploiting combined function magnets. In this case we “separate” the dipolar component in short 10 T dipole magnets (separated).
The contribution of different decay position to the BIB for a positive muon beams is reported. As expected, the further away the decay occurs, the less background will arrive to the detector area.

The overall capability to suppress BIB with lattice design choices does not seem to provide optimistic results. Even if we reduce slightly the BIB from far away, other optimization means have to be found.

With a dipole component in the final focusing, small reduction far away from IP
Current nozzle optimization: nozzle shape

- Considering the particle fluences in the **nozzle**, a tentative nozzle geometry reshaping has been conducted.

  - Lateral tungsten shaven off from the lateral side. The photon fluence is already small, the EM shower development is forward peaked.

  - Tungsten layer after the boron one. Smallest thickness: ~1 cm

  - More boron after the inner ‘bottleneck’
Conclusions

- **Muons decay** induces an intense secondary radiation field in all component of the muon collider. A detailed design is vital to mitigate the phenomenon.
- The situation with the **high energy option** (10 TeV) is *not significantly worse* in comparison with the 3 TeV collider.
- Different lattices do not significantly alter the BIB from muon decay in close proximity with the final focusing, while changing the nozzle shape alter the background profile in a more substantial way.
- At 10 TeV the incoherent pair production from muon is a non negligible source of radiation, while with lower energies this phenomenon is mitigated by the solenoidal magnetic field.

**Next steps:**
- Continue the optimization of the nozzle design at different energies
- Detectors response and radiation damage shall be studied

Preliminary detector design taken in collaboration with INFN from the CLIC layout
Thank you for the attention!
References

Muon collider: advantages

- The muon mass: 105.7 MeV/c². Synchrotron radiation (SR) is not a limiting factor.
- Energy emitted by SR per unit length:

  \[
  P = \begin{cases} 
  10^{-6} & \text{for Muons} \\
  10^{-4} & \text{for Electrons}
  \end{cases}
  \]

  \[E \text{ [GeV]}\]

  - Muons emit \((m_\mu/m_e)^4 = 1.6 \cdot 10^9\) less synchrotron radiation than electrons.

- Lepton collisions:
  - Muons, as leptons, are elementary particles, and they allow collision where the entire center of mass energy is involved (in proton collision the energy is shared among constituents).
  - Same performance of proton colliders, but with much lower center of mass energy! [2]

\* of the primary muon beam
Muon collider: radiation challenges

- **Muons** are unstable particles, with a rest lifetime of $\tau = 2.197 \mu s$. They decay spontaneously into electron and positrons (depending on the muon original charge).

**Neutrinos**: they hardly interact with the accelerator component, therefore little concern for the beam-machine interaction. The only concern is due to dose delivered to the environment outside the surface.

**$e^-/e^+$**: they carry around 1/3 of the original muon energy and they are responsible for the heat load and the radiation damage of the accelerator components.

Original muon: thanks to the Lorentz boost, it will survive for $\gamma \tau$. In any case, the muon production/acceleration/collision must be extremely fast.
e$^+$/e$^-$ impact on aperture: qualitative view

- Final focusing fields induce peaks in the azimuthal distribution of the e$^+$/e$^-$ impact position.
- (but!) The azimuthal dependence is diluted to negligible levels by the W nozzle.

Fluence of secondary electrons from the $\mu^-$ decay at -19 m from the IP.
Higgs factory

125 GeV: Higgs’ factory [11,12]
1.5 TeV spectra
Current nozzle optimization: angle tip

- Considering the aperture of the nozzle, various angles have been tested. The scope of the optimization of these parameters is not to reduce the overall number of particles going into the detectors, but to reduce their peaks.
- The results show a clear advantage to reduce the tip angle down to very small values.

Starting from 2.5 deg, we modify this angle.

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**Photon per crossing position**

- 20deg: 1.36e+08 (5.1%)
- 2p5deg: 1.04e+08 (2.2%)
- 1p5deg: 9.38e+07 (1.5%)
- 10deg: 1.23e+08 (2.6%)
- 5deg: 1.16e+08 (2.0%)

**Neutron per crossing position**

- 20deg: 7.9e+07 (3.7%)
- 2p5deg: 7.99e+07 (2.5%)
- 1p5deg: 7.88e+07 (1.9%)
- 10deg: 7.87e+07 (2.9%)
- 5deg: 8.25e+07 (2.1%)