Workshop on Muon Driven Colliders
SnowMass Muon Collider Forum

January 27, 2022

Machine Detector Interface
status and plans

Nadia Pastrone

most recent reports from past/on-going studies at:
https://indico.cern.ch/category/14577/ Community Meetings @ EU R&D Roadmap
https://indico.cern.ch/category/14574/ MDI Working Group meetings
https://indico.fnal.gov/category/1267/ SnowMass Muon Collider Forum

Machine Detector Interface (MDI) Working Group
Donatella Lucchesi (University of Padova/INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL)
MDI @ $\sqrt{s} = 125$ GeV

Not discussed here
Accelerator R&D Roadmap

Bright Muon Beams and Muon Colliders


Associated members: A. Grudiev, R. Losito, D. Lucchesi

International Design Study Collaboration GOAL

In time for the next European Strategy for Particle Physics Update, aim to establish whether the investment into a full CDR and a demonstrator is scientifically justified.

The Panel endorsed this ambition and concludes that:

- the MC presents enormous potential for fundamental physics research at the energy frontier
- it is the future direction toward high-energy, high-luminosity lepton collider
- it can be an option as next project after HL-LHC (i.e. operation mid-2040s)
- at this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies
- it identified important R&D challenges

The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045.

ESPP Accelerator R&D Roadmap

**Baseline facility**

- **Focus on two energy ranges:**
  - **3 TeV** technology ready for construction in 10-20 years
  - **10+ TeV** with more advanced technology

**Proton driver production**

**Baseline @ International Design Study**

Re-starting from well established MAP studies

**Assumption/IP**

\[ \mathcal{L} = \left( \frac{E_{CM}}{10 \text{TeV}} \right)^2 \times 10 \text{ ab}^{-1} \]

- @ 3 TeV \( 1 \text{ ab}^{-1} / 5 \text{ years} \)
- @ 10 TeV \( 10 \text{ ab}^{-1} / 5 \text{ y} \)
- @ 14 TeV \( 20 \text{ ab}^{-1} / 5 \text{ y} \)

**Cost and power** consumption drivers, limit energy reach

- e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

**Beam induced background**

Drives **beam quality:**

- challenging design and components

**Accelerator Ring**

- **Muon Collider**
  - >10 TeV CoM
  - ~10 km circumference
  - **IP 1**
  - **IP 2**

**Dense neutrino flux mitigation and site**

10+ TeV to explore!
Table 5.1: Tentative parameters for a muon collider at different energies, based on the MAP design with modifications. These values are only to give a first, rough indication. The study will develop coherent parameter sets of its own. For comparison, the CLIC parameters at 3 TeV are also given. Due to beamstrahlung only 1/3 of the CLIC luminosity is delivered above 99% of the nominal centre-of-mass energy ($L_{t,\infty}$). The CLIC emittances are at the end of the linac and the beam size is given for both the horizontal and vertical planes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Target value</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$E_{cm}$</td>
<td>TeV</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^{34}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>1.8</td>
<td>20</td>
</tr>
<tr>
<td>Luminosity above 0.99 $\sqrt{s}$</td>
<td>$\mathcal{L}_{0.01}$</td>
<td>$10^{34}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>1.8</td>
<td>20</td>
</tr>
<tr>
<td>Collider circumference</td>
<td>$C_{coll}$</td>
<td>km</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>Muons/bunch</td>
<td>$N$</td>
<td>$10^{12}$</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_r$</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Beam power</td>
<td>$P_{coll}$</td>
<td>MW</td>
<td>5.3</td>
<td>14.4</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>$\epsilon_L$</td>
<td>MeVm</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>$\epsilon$</td>
<td>$\mu$m</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$n_b$</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of IPs</td>
<td>$n_{IP}$</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>IP relative energy spread</td>
<td>$\delta_E$</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>IP bunch length</td>
<td>$\sigma_z$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>IP beta-function</td>
<td>$\beta$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>IP beam size</td>
<td>$\sigma$</td>
<td>$\mu$m</td>
<td>3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Key Challenge Areas

• **Physics potential** evaluation, including **detector concept and technologies**

• Impact on the environment
  – **Neutrino flux mitigation** and its impact on the site (first concept exists)
  – **Machine Induced Background** impact the detector, and might limit physics

• **High-energy systems** after the cooling (acceleration, collision, ...)
  – Fast-ramping magnet systems
  – High-field magnets (in particular for 10+ TeV)

• **High-quality muon beam production**
  – Special RF and high peak power
  – Superconducting solenoids
  – Cooling string demonstration (cell engineering design, demonstrator design)

• **Full accelerator chain**
  – e.g. proton complex with H- source, compressor ring  ➔ test of target material

High energy complex requires known components  ➔ synergies with other future colliders
MDI WG Summary

Can base the new studies on the valuable experience gained within MAP (N. Mokhov et al.)

- Study the beam-induced background and identify mitigation strategies
- Develop a (conceptual) interaction region (IR) design that yields background levels compatible with detector operation, i.e. show that
  - the desired physics performance can be reached
  - the cumulative radiation damage in the detector remains acceptable
- Address different centre-of-mass energies, with particular attention to:
  - 3TeV
  - 10TeV (IR design to be scaled up further to 14TeV if needed)

✓ By end of 2022, aim to have a first level IR optimization
  - 3 TeV option: start optimizing the IR design starting from MAP layout
  - 10 TeV option: obtain a first IR design, first quantification of background
✓ By 2025, aim to have a mature IR design
  - Demonstrate feasibility of reaching detector performance goals for both collider options
✓ Meetings with common discussions inviting contact persons from other WPs
✓ Interface with Snowmass is important
Muon decay around the ring
Major contribution comes from decays in IR
Bethe-Heitler muons also from further away

Incoherent $e^-/e^+$ pair production during bunch crossing in IP
$e^-/e^+$ trajectories influenced by solenoid field
can impact on nozzle and detector vacuum chamber

Beam-halo losses at aperture bottlenecks

Certainly a main background source for all collider options

Was found not to be an issue at energy of $\sqrt{s}=2$ TeV* (with a solenoid field of a few T)
Nevertheless to be studied for the $\sqrt{s}=10+$ TeV collider option

Halo losses near detector can yield non-negligible background contribution
Acceptable halo loss levels to be defined (halo cleaning)
Links with other accelerator WPs

List of topics is not complete (and not all have same priority)

Strong ties needed with:
- High-energy complex Magnets
- Beam dynamics
- Radiation protection

MDI WP depends on resource allocation in other WPs to address the different topics

- Iterate on lattice design, converge on L*
- Explore background mitigation techniques (e.g. combined-function magnets, chicanes, sweeping magnets)
- Estimate achievable magnet apertures
- Integrate shielding/masks (synergies with heat load/radiation damage studies for magnets)
- Quantify affordable minimum beam clearance
- Model beam halo
- Define requirements for halo cleaning system for background reduction (in addition to injection scraping)
- Quantify impact of neutrino hazard mitigation techniques (e.g. movers) on detector background
Links with detector community

List of topics is not complete!

- Iteration concerning detector envelope (compromise between shielding requirements and detector acceptance)
- Define metric for envelope optimization
- Define (simple) figure-of-merit for first shielding optimization
- Later full detector simulation
- Develop active background mitigation techniques, for example:
  - Time gates
  - Smart shielding (instrumented)
  - Directional suppression (e.g. BH muons)

The MDI work shall help to define the detector specs
<table>
<thead>
<tr>
<th></th>
<th>Task description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Study beam-induced <strong>background characteristics</strong> using the MAP $\sqrt{s}$=3 TeV interaction region design</td>
</tr>
<tr>
<td><strong>By 2022</strong></td>
<td>Define a <strong>metric</strong> for the determination of the <strong>shape and dimensions of the shielding</strong> inserted in the detector (nozzle)</td>
</tr>
<tr>
<td><strong>By 2022</strong></td>
<td>Explore <strong>further shielding strategies</strong> (e.g. asymmetric nozzle, optimization of interaction region active elements together with detector modifications)</td>
</tr>
<tr>
<td><strong>By 2025</strong></td>
<td>Provide estimates of the <strong>long-term radiation damage</strong> in the detector</td>
</tr>
<tr>
<td><strong>Concurrently with other tasks</strong></td>
<td>Adapt experiment design and propose new detector technologies</td>
</tr>
</tbody>
</table>

**TOTAL 15 FTEy/5 years**
Lattice challenges

- Low $\beta^*$ (few mm):
  - Strong IR quadrupoles and large $\hat{\beta}$:
    * large chromaticity;
    * large sensitivity to misalignments and field errors.
- Small circumference, particularly important for short living particles!
- High density: $N \approx 2 \times 10^{12}$ per bunch.
- Neutrinos hotspots limit the length of field-free regions at beam energy $\gtrsim 1.5$ TeV
- Protection of magnets and detectors.
- $\sigma_\epsilon \leq \beta^*$ to avoid hour-glass effect.

- Expected large momentum spread ($\approx 0.1\%$) requires
  - small $|\alpha_p|$ ($\approx 1 \times 10^{-5}$) over the momentum range to achieve short bunches with reasonable RF voltage;
  - sufficient Dynamic Aperture ($\gtrsim 3\sigma$) in presence of strong sextupoles and large $dp/p$.
Interaction Region @ $\sqrt{s} = 1.5$ and $3$ TeV

Muon Collider Lattice Concepts
Y. Alexahin et al 2018 JINST 13 P11002

<table>
<thead>
<tr>
<th>Name</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$Q_3$, $Q_4$</th>
<th>$Q_5$</th>
<th>$B_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{c_{\text{int}}}$ (cm)</td>
<td>4</td>
<td>5.5</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$R_{c_{\text{out}}}$ (cm)</td>
<td>8</td>
<td>9.5</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$R_{i_{\text{out}}}$ (cm)</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Length (m)</td>
<td>1.5</td>
<td>1.76</td>
<td>1.7</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

The machine elements, MDI and interaction region must be properly designed and optimized @ each collider energy

Final Focus quadrupoles

$\sqrt{s} = 1.5$ TeV

in cyan: defocusing quadrupoles with up to 2 T dipole component

$\sqrt{s} = 3$ TeV
Preliminary IR design @ $\sqrt{s} = 6$ TeV

assumed available $Nb_3$Sn magnet technology

Muon Collider Lattice Concepts
Y. Alexahin et al 2018 JINST 13 P11002

Design goals:
- $\beta^* = 3$ mm
- 10 m distance from IP to the first quad
- $\geq 3$ T dipole component in quads (not Q1) to sweep away charged secondaries
- magnet inner bore radius constrained by $IR > 5\sigma_{\perp}^{\text{max}} + 3$ cm $\Rightarrow$ good field quality
- magnets cut in pieces shorter than 6 m to insert protecting masks

Final Focus quadrupoles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
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<tbody>
<tr>
<td>ID (mm)</td>
<td>160</td>
<td>200</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>$G$ (T/m)</td>
<td>200</td>
<td>-125</td>
<td>-100</td>
<td>103</td>
<td>-78</td>
</tr>
<tr>
<td>$B_{\text{dipole}}$ (T)</td>
<td>0</td>
<td>3.5</td>
<td>4.0</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$L$ (m)</td>
<td>5.3</td>
<td>3.0</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
</tr>
</tbody>
</table>

in cyan: defocusing quadrupoles with up to 5 T dipole component
Preliminary IR design @ $\sqrt{s} = 10$ TeV

Kyriacos Skoufaris - Christian Carli (CERN)

Design requirements:

✓ the ring length should be as small as possible
  • to reach design luminosity with given $\beta^*$ and intensity
  • use of the maximum allowed magnetic field for all the lattice magnets, 20T for the final focusing quads and 16T for the rest of the magnets

✓ to mitigate Neutrino radiation issue (avoid local high doses)
  • extensive use of dipoles and combined function magnets (dipole+multipoles), with only exception the final focusing quads and the magnets in the straight section
  • the free space between magnets is 0.3m

✓ good control of the lattice optics, errors, fringe field and the particle dynamics needed
  • the chromatic phenomena such as linear/non-linear chromaticity, Montague functions, second order dispersion and higher order momentum compaction should be compensate/controlled

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>10TeV com mc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle energy</td>
<td>$E$</td>
<td>GeV</td>
<td>5000</td>
</tr>
<tr>
<td>Particle momentum</td>
<td>$P_0$</td>
<td>GeV $c^{-1}$</td>
<td>5000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>20</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$N_p$</td>
<td>$10^{12}$ ppb</td>
<td>1.8</td>
</tr>
<tr>
<td>Transverse normalized rms emittance</td>
<td>$\varepsilon_{nx} = \varepsilon_{ny}$</td>
<td>$\mu$m</td>
<td>25</td>
</tr>
<tr>
<td>Longitudinal emittance ($4\pi \sigma_E \sigma_T$)</td>
<td>$\varepsilon_t$</td>
<td>eVs</td>
<td>0.314</td>
</tr>
<tr>
<td>Rms bunch length</td>
<td>$\sigma_z$</td>
<td>mm</td>
<td>1.48</td>
</tr>
<tr>
<td>Relative rms energy spread</td>
<td>$\delta$</td>
<td>%</td>
<td>0.1</td>
</tr>
<tr>
<td>Beta function at IP</td>
<td>$\beta_x^* = \beta_y^*$</td>
<td>mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Beam power with 10 Hz repetition rate</td>
<td>$P_{\text{beam}}$</td>
<td>MW</td>
<td>14.4</td>
</tr>
</tbody>
</table>
**FF scheme with CCS @ $\sqrt{s} = 10$ TeV**

- The interaction region (IR) consists of the final focusing (FF) quadrupole triplet and the chromatic correction scheme (CCS)
- Strong chromatic effects from FF quads with strength depending on particle energy is compensated in CCS by dipole-sextupoles and dipole-quadrupole combined function magnets
- The magnetic field at the FF quads is close to 20T and for the rest elements in the CCS is close to the 16T (maximum allowed one)

This is a first version without dipolar magnetic fields to understand BIB
Options if only 16T magnets available

Interaction region – FF scheme

Reduction of the com energy to 8TeV

Reduction of the beam envelope to 4σ+1.5cm

Increase of the β* by a factor \((10/7)^2\)
Beam Induced Background @ 1.5 TeV

N.V. Mokhov - S.I. Striganov (FNAL)

Detector Backgrounds at Muon Colliders

Physics Procedia 37 (2012), 2015

0.75 TeV muon $\rightarrow$ decay length $4.7 \times 10^6$ m
2 $\times 10^{12}$ muons/bunch $\rightarrow$ $4.28 \times 10^5$ decays per meter of the lattice in a single pass
1000-turn stores with 15 stores per second
$\rightarrow$ $1.28 \times 10^{10}$ decays/meter/sec for two 0.75-TeV muon beams
components and in the walls of the tunnel produce a high flux of secondary particles (see figure 1).

As it was shown in the recent study [1], the appropriately designed interaction region and machine detector interface (including shielding nozzles, figure 2 and figure 3) can provide the reduction of muon beam background by more than three orders of magnitude for a muon collider with a collision energy of 1.5 TeV.

Figure 1. A MARS15 model of the Interaction Region (IR) and detector with particle tracks.

Figure 2. The shielding nozzle, general RZ view (W — tungsten, BCH2 – borated polyethylene).

Figure 3. The shielding nozzle, zoom in near IP (Be — beryllium).

The amount of MARS15 simulated data was limited to 4.6% of the \( \mu^+\mu^- \) decays on the 26 m beam length yielding total of \( 1.46 \times 10^6 \) background particles per bunch crossing (BX).

The corresponding statistical weight (\( \sim 22.3 \)) was taken into account in the following ILCRoot simulation. For each particle output by MARS15, 22 or 23 particles were generated by choosing a new azimuthal angle at random. This provided a total of \( 3.24 \times 10^8 \) particles entering the detector in the ILCroot simulation. The most abundant background consists of photons and neutrons.

Table 1 lists these background yields together with kinetic energy thresholds used in the MARS15 simulation for different types of particles.

muon beams @ 0.75 TeV with \( 2 \times 10^{12} \) muons/bunch ➔ 4\( \times 10^5 \) muon decays/m single bx.
Machine Detector Interface @ 1.5 – 3 TeV

Simulation tool: LineBuilder + FLUKA
Data analysis: Python

\( 750 \text{ GeV muon beam travels half ring to IP} \)

\( \sqrt{s} = 3 \text{ TeV} \)
Beam Induced Background distributions

Advanced assessment of beam-induced background at a muon collider

F. Collamati et al 2021 JINST 16 P11009
Advanced assessment of beam-induced background at a muon collider

F. Collamati et al 2021 JINST 16 P11009

First interaction

- Nozzle1WR: 70.8%
- Nozzle1WL: 27.3%
- Other: 1.8%

Particle exit

- Nozzle1WR: 42.7%
- Nozzle1WL: 30.3%
- NozzleBL: 11.9%
- NozzleBR: 6.1%
- Other: 6.1%
Comparisons of BIB at different energies

Massimo Casarsa et al. (INFN ++) 

three colliders operating at: 
125 GeV  1.5 TeV  3 TeV 

a single $\mu^-$ beam arriving from the right 

BIB samples not uniform: some generated with MARS15, some with FLUKA 

results at 3 TeV are very preliminary: there is still no optimized MID and ideal beam 

<table>
<thead>
<tr>
<th>beam energy (GeV)</th>
<th>63</th>
<th>750</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>average inst. lum. [cm$^2$ s$^{-1}$]</td>
<td>$0.008 \times 10^{34}$</td>
<td>$1.25 \times 10^{34}$</td>
<td>$4.6 \times 10^{34}$</td>
</tr>
<tr>
<td>number of muons/bunch</td>
<td>$4 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
</tr>
<tr>
<td>number of bunches</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>15</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>$\beta^*$ [cm]</td>
<td>1.7</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>normalized $\varepsilon_x$ [m m rad]</td>
<td>0.2</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>normalized $\varepsilon_y$ [m m rad]</td>
<td>1.5</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>bunch length [cm]</td>
<td>6.3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>bunch size at IP [\mu m]</td>
<td>75</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>momentum spread [%]</td>
<td>0.004</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Both MARS15 and FLUKA simulate the interaction of the muon decay products with the machine elements and transport the BIB particles up to the detector envelop 

IP optimized for a 125-GeV $\mu$ collider 

IP optimized for a 1.5-TeV $\mu$ collider
Muon Decay point

Time of arrival

Mars15

62.5-GeV \( \mu^- \) beam

Mars15

750-GeV \( \mu^- \) beam

Fluka

1500-GeV \( \mu^- \) beam

C. Curatolo

Muon Decay point

Time of arrival

Fluka

1500-GeV \( \mu^- \) beam

C. Curatolo
# BIB yields

<table>
<thead>
<tr>
<th></th>
<th>MARS15</th>
<th>MARS15</th>
<th>FLUKA</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>62.5</td>
<td>750</td>
<td>750</td>
<td>1500</td>
</tr>
<tr>
<td>μ decay length [m]</td>
<td>$3.9 \times 10^5$</td>
<td>$46.7 \times 10^5$</td>
<td>$46.7 \times 10^5$</td>
<td>$93.5 \times 10^6$</td>
</tr>
<tr>
<td>μ decays/m per beam (for 2x10^{12} μ/bunch)</td>
<td>$51.3 \times 10^5$</td>
<td>$4.3 \times 10^5$</td>
<td>$4.3 \times 10^5$</td>
<td>$2.1 \times 10^5$</td>
</tr>
<tr>
<td>simulation z range [m]</td>
<td>[-10, 30]</td>
<td>[-1, 25]</td>
<td>[0, 100]</td>
<td>[0, 100]</td>
</tr>
<tr>
<td>photons/BX (E_y &gt; 0.1 MeV)</td>
<td>$170 \times 10^6$</td>
<td>$86 \times 10^6$</td>
<td>$51 \times 10^6$</td>
<td>$70 \times 10^6$</td>
</tr>
<tr>
<td>neutrons/BX (E_n &gt; 1 meV)</td>
<td>$65 \times 10^6$</td>
<td>$76 \times 10^6$</td>
<td>$110 \times 10^6$</td>
<td>$91 \times 10^6$</td>
</tr>
<tr>
<td>e^±/BX (E_e &gt; 0.1 MeV)</td>
<td>$1.3 \times 10^6$</td>
<td>$0.75 \times 10^6$</td>
<td>$0.86 \times 10^6$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>charged hadrons/BX (E_h &gt; 0.1 MeV)</td>
<td>$0.011 \times 10^6$</td>
<td>$0.032 \times 10^6$</td>
<td>$0.017 \times 10^6$</td>
<td>$0.020 \times 10^6$</td>
</tr>
<tr>
<td>muons/BX (E_h &gt; 0.1 MeV)</td>
<td>$0.0012 \times 10^6$</td>
<td>$0.0015 \times 10^6$</td>
<td>$0.0031 \times 10^6$</td>
<td>$0.0033 \times 10^6$</td>
</tr>
</tbody>
</table>
The quantities are normalized to the single passage, assuming a bunch containing $2 \cdot 10^{12}$ muons.

**Electron, positrons and photons** cutoffs are at **100 keV**. SR photons are produced down to 100 keV. **Neutrons** are simulated down to thermal energies ($\sim$meV) (less than 10% will have energies below $10^{-5}$ GeV). **Photonuclear** reactions are activated at all energy ranges. Muon pair production by photons and bremsstrahlung by muons are activated.

**BIB** mainly due to **decays** which happens **around** the **beam core**. Decays further away in the transverse plane give less contribution.

The **tunnel** simulated length is ±35 m. Only pure quadrupole magnets are present in the lattice. The **detector area** is modeled as a **blackbox**, and the particle crossing its surface are scored. It is considered as the region outside of the nozzle (and the beryllium chamber) inside two planes at ±6m. In the nozzle, there is a solenoidal magnetic field of 5 T.
The **longitudinal decay position** is a very important indicator to understand the contribution of decays at large distances.

- Most of the particles come from the region where there is the largest variation of the beam size.
- Secondary muons and charged hadrons are not yet included. (The number of counts is still not enough for a satisfactory statistics)
- The main contributions are always due to decays happening near to the ideal trajectory.

### Normalization of the number of crossing for each probability to decay at a certain distance from the beam core

<table>
<thead>
<tr>
<th>Interval</th>
<th>Crossing per decay in interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s \in (0, 1)$</td>
<td>$1.98 \times 10^8$</td>
</tr>
<tr>
<td>$s \in (1, 1.4)$</td>
<td>$1.19 \times 10^8$</td>
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<tr>
<td>$s \in (1.4, 2.2)$</td>
<td>$8.17 \times 10^7$</td>
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<tr>
<td>$s \in (2.2, 3.2)$</td>
<td>$5.97 \times 10^7$</td>
</tr>
<tr>
<td>$s \in (3.2, 5)$</td>
<td>$1.37 \times 10^8$</td>
</tr>
</tbody>
</table>
- Both the photons and the neutrons show the same behavior. Far away from the IP, only the muons decaying around the beam core give a significant contribution.
- Near to the beginning of the nozzle, the tails become more important since the corresponding secondary electrons have to travel for less distance in the materials.
Detector studies @ $\sqrt{s} = 1.5$ TeV

- CLIC Detector technologies adopted with important tracker modifications to cope with BIB
- Detector design optimization at $\sqrt{s} = 1.5$ (3) TeV

**Full simulation available on public repository**

Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25µm$^2$
- 4+4 double-sensor disks 25x25µm$^2$

Inner Tracker (IT)
- 3 barrel layers 50x50µm$^2$
- 7+7 disks

Outer Tracker (OT)
- 3 barrel layers 50x50µm$^2$
- 4+4 disks

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm$^2$

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm$^2$

- To be improved
- Tuned at higher $\sqrt{s}$

B = 3.57 T to be studied and tuned

Quite advanced conceptual design for Higgs factory, 1.5 TeV and 3 TeV
Properties of BIB contribution

BIB has several characteristic features → crucial for its effective suppression

1. **Predominantly very soft particles** \( (p \ll 250 \text{ MeV}) \) except for neutrons
   fairly uniform distribution in the detector → no isolated signal-like deposits
   ↓ conceptually different from pile-up contributions at the LHC

2. **Significant spread in time** (few ns + long tails up to a few µs)
   \( \mu^+\mu^- \) collision time spread: 30ps (defined by the muon-beam properties)
   ↓ strong handle on the BIB → requires state-of-the-art timing detectors

3. **Large spread of the origin along the beam**
   different azimuthal angle wrt the detector surface
   + affecting the time of flight to the detector
   ↓ relevant for position-sensitive detectors

An overview of the main optimisation steps and their impact presented in a [recent paper](#)
Tracker detector requirements

- Timing window applied to reduce out-of-time BIB’s hits
- Granularity optimized to ensure $\lesssim 1\%$ occupancy
- BIB suppression based on cluster shape
- If primary vertex could be known before $\Rightarrow$ effective angular matching of hit doublets
- To be tuned in presence of secondary vertices or long-lived particles

Reconstruction of tracks suffers from large combinatorial background
- need suppression of BIB hits + efficient tracking strategies/algorithms
Calorimeters

BIB deposits large amount of energy in both ECAL and HCAL.

Timing and longitudinal measurements play a key role in the BIB suppression.

Remaining BIB is removed by subtraction.

Step 3: final jet clustering using calorimeter clusters and tracks with PandoraPFA and kT (R=0.5).

Preliminary
**Experiment design steps forward**

- Beam Induced Background requires an optimized interaction region design to mitigate the unique harsh environment limiting detector acceptance
  - Luminosity measure proposed via $\mu \mu \rightarrow \mu \mu$ scattering ($m_{\mu\mu} \sim \sqrt{s}$)

- A baseline detector for full simulation studies @ 3 TeV is available to be optimized

- New design and studies still missing @ 10+ TeV
  - ECFA Roadmap Detector R&D

- Tracker design and Tracking: biggest challenge is pattern recognition
- Calorimeter: huge diffuse background
- Muons: no major problems seen
A few comments and next steps

• Is a Muon Collider a more affordable alternative to hadron and lepton colliders both at the energy frontier?

First MDI Kick-off meeting @ November 2021

→ first lattice and MDI studies @ 10 TeV by CERN
Next tomorrow https://indico.cern.ch/event/1121610/

NEXT STEPS:

• Optimize the nozzle geometry with systematic design process @ 3 and 10 TeV
• Produce Fluence and TID maps to address proper detector R&Ds

Many thanks to all the community who contributed!!!
extras
High-priority future initiatives [...] 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.
<table>
<thead>
<tr>
<th>Label</th>
<th>Begin</th>
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<th>Description</th>
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Community Meeting WG

**Radio-Frequency (RF):** Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK)

**Magnets:** Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL)

**High-Energy Complex (HEC):** Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL)

**Muon Production and Cooling (MPC):** Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL)

**Proton Complex (PC):** Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS)

**Beam Dynamics (BD):** Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL)

**Radiation Protection (RP):** Claudia Ahdida (CERN)

**Parameters, Power and Cost (PPC):** Daniel Schulte (CERN), Mark Palmer (BNL), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP)

**Machine Detector Interface (MDI):** Donatella Lucchesi (University of Padova and INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL)

**Synergy:** Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK)

**Test Facility (TF):** Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (Uppsala University)

**Physics & Detector:**
Donatella Lucchesi *(Univ. Padova - INFN)*

**WG 1: Physics Potential:** Andrea Wulzer (EPFL&CERN) et al.

**WG 2: Detector performance (with several focus areas)**

**WG 3: Detector R&D and Software & Computing development**