Stato degli studi di fisica e rivelatore con la full simulation

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Riunione Referee RD_MUCOL – 25 luglio 2025

Physics and detector studies at $\sqrt{s}$ = 3 TeV

arXiv:2405.19314

- From now on, all activities of the Detector & Physics Group will be focused on the preparation for the update of the European Strategy for Particle Physics.

- The studies at 3 TeV have been finalized:
  - summary paper on the Higgs physics results with full simulation submitted to EPJC and under peer review.

$\sqrt{s}$ = 3 TeV, 1 ab^{-1}	channel	σ_{eff} [fb]	ϵ_{sel} [%]	N_{evt}	$\Delta\sigma_H/\sigma_H$ [%]
$H \to b\bar{b}$	S: $b\bar{b}$	308	19.3	59500	0.75
	B: $\mu^+\mu^- \to q_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	584	11.2	65400	
$H \to WW^*$	S: $q\bar{q}'\mu\nu_\mu$	17.3	14.1	2430	2.9
	B: $\mu^+\mu^- \to q\bar{q}'\mu\nu_\mu$	5020	0.05	2600	
$H \to \gamma\gamma$	S: $\gamma\gamma$	0.91	43.9	396	7.6
	B: $\mu^+\mu^- \to \gamma\gamma\nu_\mu\bar{\nu}_\mu$	82.0	1.1	442	
	$\mu^+\mu^- \to \ell^+\ell^-\gamma$ ($\ell = e, \mu$)	159	0.06	31	
	$\mu^+\mu^- \to \ell^+\ell^-\gamma\gamma$ ($\ell = e, \mu$)	4.41	0.3	11	
$H \to ZZ^*$	S: $q\bar{q}\mu^+\mu^-$	0.35	15.9	55	17
	B: $\mu^+\mu^- \to q\bar{q}\mu^+\mu^-$	5.67	0.69	39	
$H \to \mu^+\mu^-$	S: $\mu^+\mu^-$	0.12	21.6	26	38
	B: $\mu^+\mu^- \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$	11.1	5.74	637	
	$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$	297.4	0.16	476	
$HH \to b\bar{b}b\bar{b}$	S: $b\bar{b}b\bar{b}$	0.28	27.5	77	33
	B: $\mu^+\mu^- \to q_h\bar{q}_hq_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	4.1	17.7	724	
	$\mu^+\mu^- \to H(b\bar{b})q_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	2.8	24.7	698	

Preprint submitted to The European Physical Journal C

Higgs Physics at a $\sqrt{s}$ = 3 TeV Muon Collider with detailed detector simulation

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Abstract

The Muon Collider is one of the most promising future collider facilities with the potential to reach multi-TeV center-of-mass energy and high luminosity. Due to the significant Higgs boson production

1

Activities at √s = 10 TeV

- Machine-detector interface:
  - nozzle optimization for a 10 TeV collider.
- Dominant machine-induced backgrounds at 10 TeV:
  - from muon decays;
  - from incoherent e^+e^- pair production.
- Definition of a 10 TeV detector concept for the ESPP studies:
  - guidelines from lessons learned from 3 TeV studies (summarized in a review on Annu. Rec. Nucl. Part.).
- Physics studies for the ESPP update:
  - revision of the reconstruction algorithms for the main physics objects;
  - definition of the physics benchmarks to study.

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ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Experimentation at a Muon Collider

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Keywords

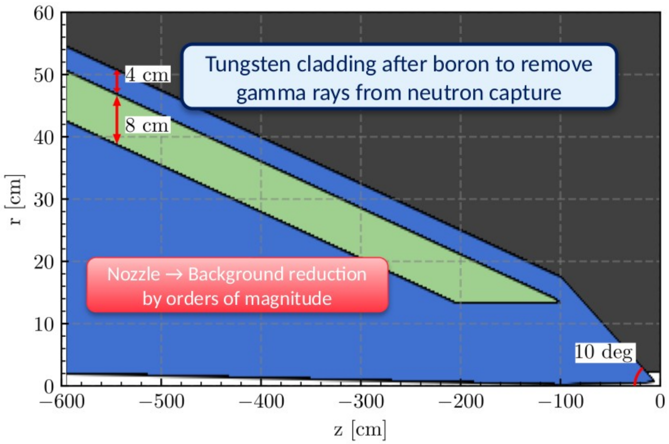
muon collider, detector, multi-TeV muon collisions, Higgs boson, new physics

Abstract

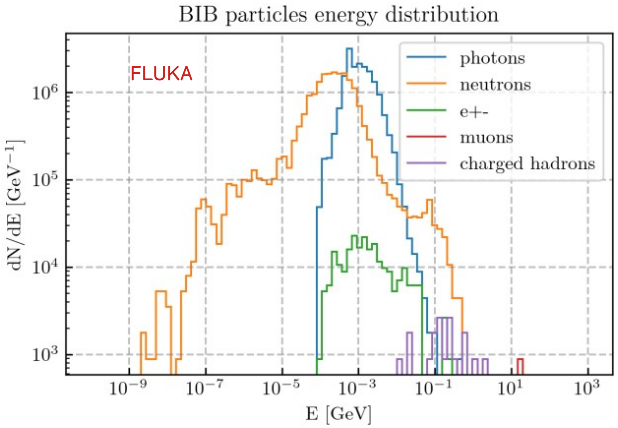
Experimental activities involving multi-TeV muon collisions are a relatively recent endeavor. The community has limited experience in designing detectors for lepton interactions at center-of-mass energies of 10 TeV and beyond. This review provides a short overview of the machine characteristics and outlines potential sources of beam-induced background that could affect the detector performance. The strategy for mitigating the effects of the beam-induced background on the detector at $\sqrt{s} = 3$ TeV is discussed with a focus on the machine–detector interface, detector design, and implementation of reconstruction algorithms. The physics potential at this center-of-mass energy is evaluated using a detailed detector simulation that incorporates the effects of the beam-induced background. This evaluation concerns the Higgs boson couplings and the Higgs field potential sensitivity, which then are used to obtain confidence on the expectations at 10 TeV. The physics and detector requirements for an experiment at $\sqrt{s} = 10$ TeV, outlined here, form the foundation for the initial detector concept at that center-of-mass energy.

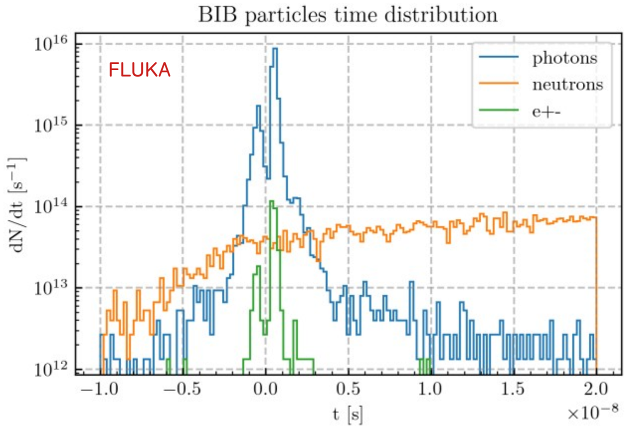
10 TeV nozzle and beam-induced bkg

new nozzle design with realistic material density



D. Calzolari (PD/CERN)





- Background from muon decays (BIB):
  - soft-momentum particles, mostly out of time w.r.t. the bunch crossing.
- Background in the detector mainly determined by the shape and material of the shields (nozzles).

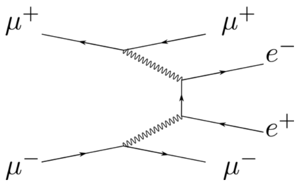
Ongoing generation of a high-statistics sample with the new nozzles.

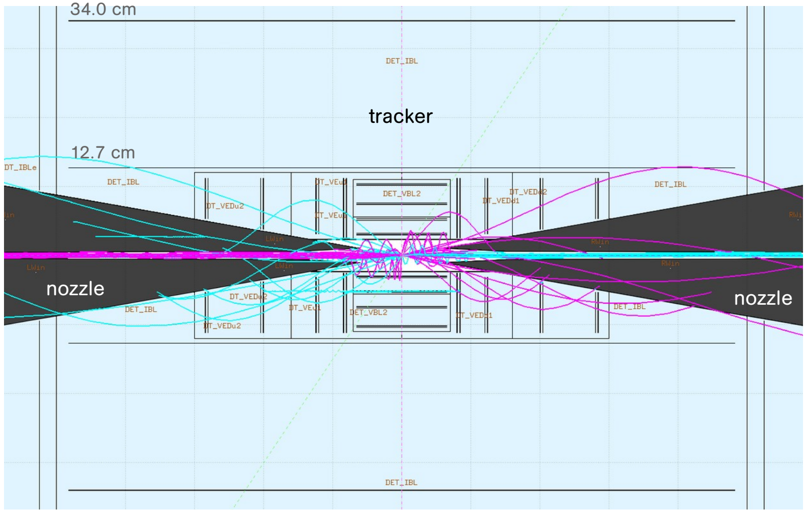
MAP's 1.5 TeV nozzle — new 10 TeV nozzle

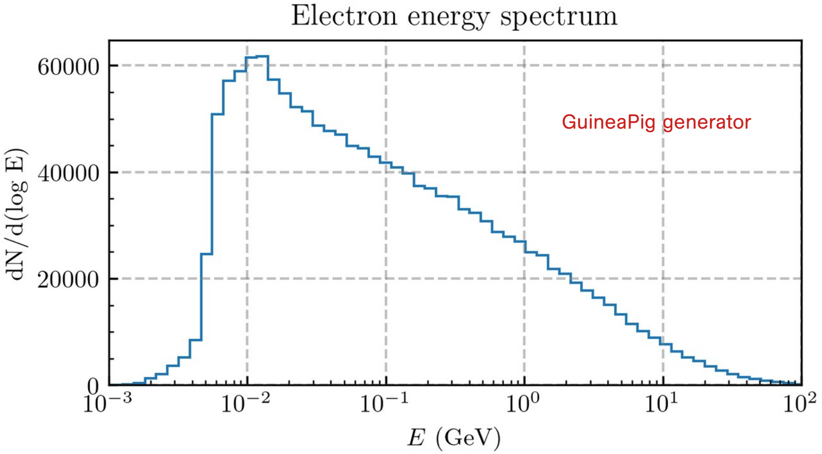
Collider energy	1.5 TeV	3 TeV	10 TeV (v 0.8)	10 TeV (EU24*)
Photons	7.1E+07	9.6E+07	1.6E+08	9.9E+07
Neutron	4.7E+07	5.8E+07	1.4E+08	1.1E+08
e+/e-	7.1E+05	9.3E+05	8.9E+05	1.2E+06
Ch. hadrons	1.7E+04	2.0E+04	5.2E+04	4.2E+04

Incoherent e⁺e⁻ pair production

D. Calzolari (PD/CERN)







- Background from incoherent e⁺e⁻ pairs produced at bunch crossing:
  - relatively high-energy e$^{\pm}$, which enter the detector at the interaction point in time with the bunch crossing;
  - affects mainly the vertex detector and the inner tracker layers.
- The solenoidal B field helps in confining most of the e$^{\pm}$ in the innermost region close to the beampipe.

10 TeV	BIB	e⁺e⁻ pairs
Photons	9.9E+07	4.0E+06
Neutron	1.1E+08	1.3E+05
e+/e-	1.2E+06	2.1E+05

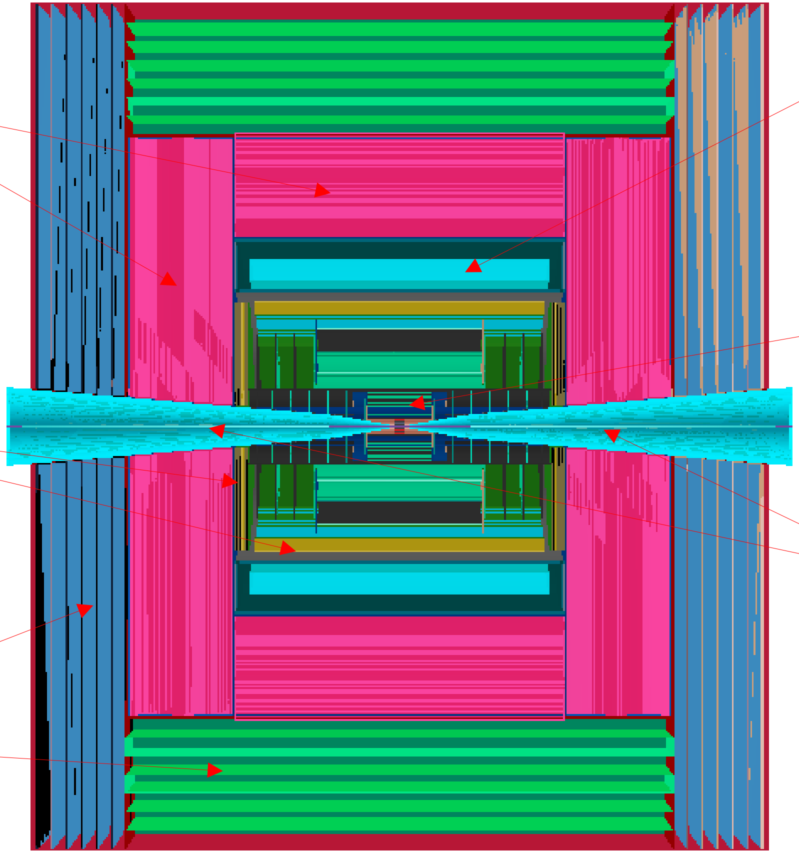
Driving factors for a muon collider detector

- The requirements for the detector specifications from physics are similar to those of other multi-TeV machines to reconstruct:
  - boosted low-p_T physics objects from Standard Model processes;
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
- Constraints from the machine design: final focusing quadrupoles at ± 6 m from the interaction point.
- Machine background conditions.

Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background.

Detector concept for 10 TeV collisions

The MUSIC detector (MUon Smasher for Interesting Collisions).



PD: P. Andreetto, A. Gianelle, C. Giraldin, D. Lucchesi, L. Palombini, L. Sestini, D. Zuliani
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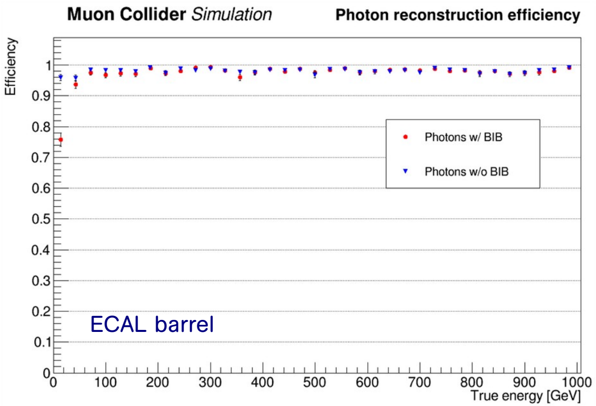
Tracking system

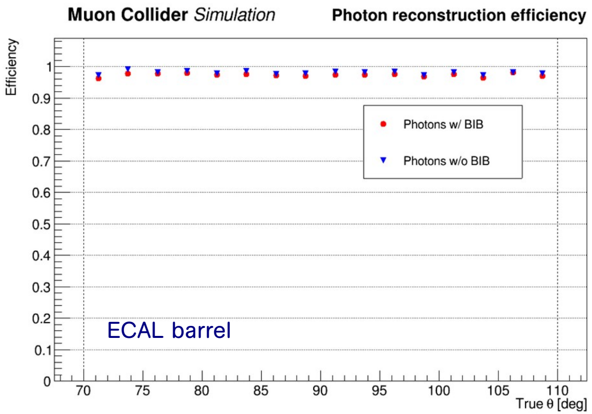
see Donatella's presentation

Electromagnetic calorimeter

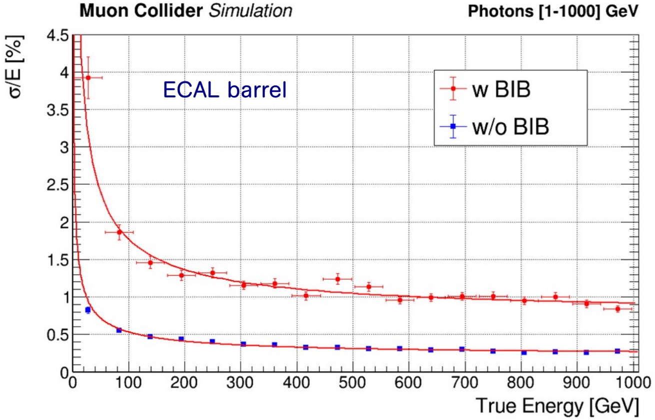
- Estimated a flux of 300 particles per cm^2 through the ECAL surface at every bunch crossing: ~96% photons with an average energy of 1.7 MeV and ~4% neutrons.
- Semi-homogeneous electromagnetic crystal calorimeter with longitudinal segmentation (CRILIN):
  - lead fluorite (PbF_2) crystals: very good timing (<100 ps), radiation hardness, affordable cost;
  - crystal layout: 6 layers of 10x10x40-mm^3 crystal matrices (~26.5 X_0).
- CRILIN calorimeter fully integrated in the muon collider software framework.

photon reconstruction efficiency





photon energy resolution



Hadronic calorimeter and muon system

- For the scope of the studies for the ESPP update, minimal changes in the hadronic calorimeter and muon system from those used in the 3 TeV detector.

- Hadronic calorimeter:
  - increased depth to better contain higher-energy showers;
  - steel absorber replaced with iron in order to use the HCAL absorber as return yoke for the magnetic field flux → we are in contact with the detector-magnet experts of INFN-Genova to determine the necessary amount of iron and an adequate support structure to sustain the stress forces.

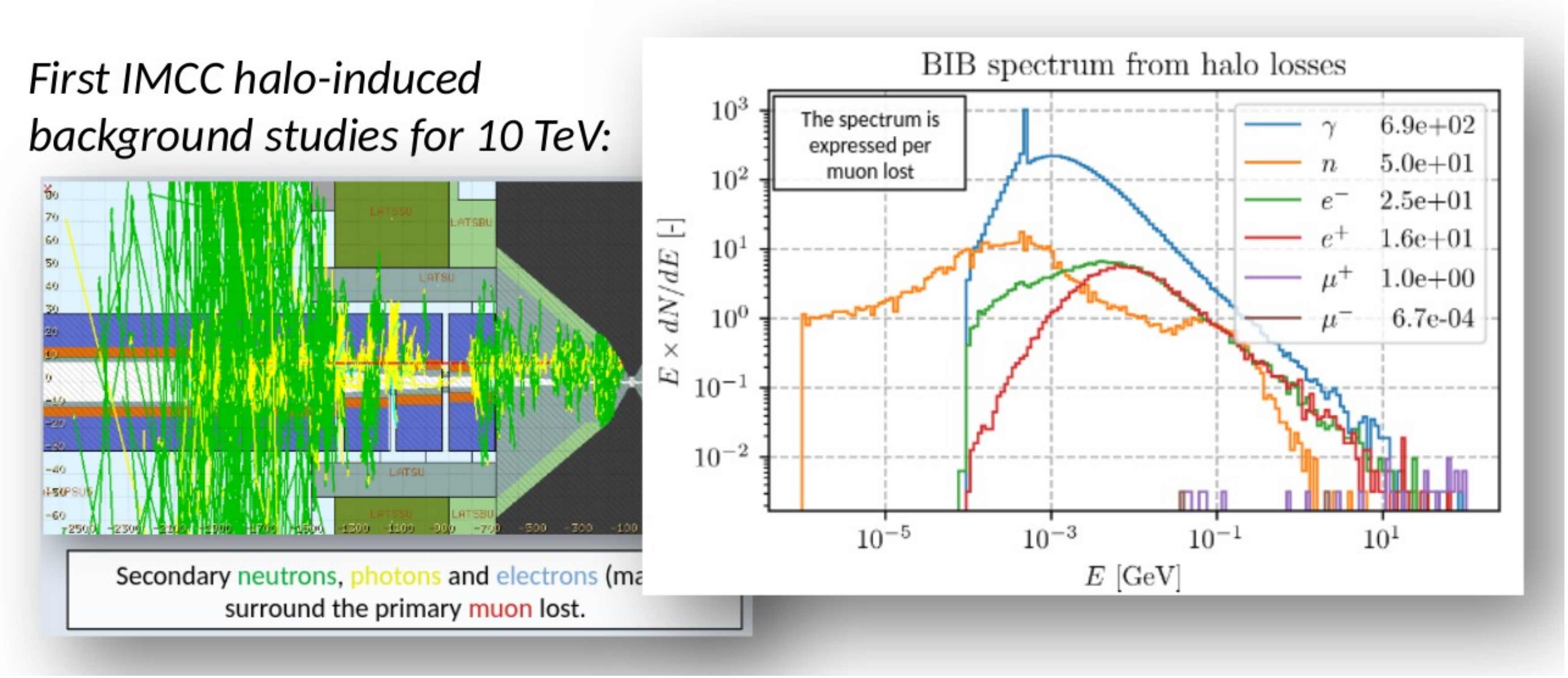
- Muon detectors:
  - removed the iron of the old return yoke and switched off the magnetic field
    → information of muon detectors not integrated with tracking, used just to tag muons;
  - reconstruction and identification of very high-momentum muons will likely rely on global algorithms that exploit information from all the subdetectors.

Planned physics studies for the ESPP update

- The detector performance at 10 TeV will be assessed on a set of benchmark physics processes, representative of the muon collider physics program:
  - featuring low- and high-p_T physics objects in the final state;
  - studied with a detailed detector simulation that includes the machine backgrounds from muon decay and incoherent e^+e^- pair production.
- Physics benchmarks to be studied (assuming $\sqrt{s}$ = 10 TeV and 10 ab^{-1}):
  - double Higgs boson production to estimate the sensitivity to the trilinear self-coupling: $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}W^+W^-$.
  - production of a new heavy state $Z' \to e^+e^-$ to estimate the mass reach in direct and indirect searches.

Backup

First look at the muon beam halo losses



D. Calzolari, "Machine-detector interface design for a 10-TeV muon collider", ICHEP2024