$H \rightarrow \mu\mu$ at a 3 TeV Muon Collider

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Introduction

The discovery of the Higgs boson at the CERN Large Hadron Collider (LHC), in 2012 [1] [2], opened a new era of research in particle physics, aimed at measuring its properties. In particular, the measurement of the Higgs boson couplings provides a strong test of the Standard Model (SM) and a direct probe to possible new physics beyond the SM. So far, only the couplings of the Higgs boson to the vector bosons and the third-generation fermions of the SM have been measured, which turned out to be in agreement with the predictions of the SM [3] [4]. On the other hand, the couplings to the first and second-generation fermions of the SM and the Higgs self-couplings are still to be observed. In addition, all the searches for new physics carried out at the LHC so far, suggest the absence of new physics signal on the TeV scale.
Whether it is to carry out precision measurements or to explore the new energy frontier in the multi-TeV energy scale, hardly within the reaches of the LHC, the construction of a new collider will be required [5].
The muon collider, among the projects currently under study for the next generation of particle accelerators, represents a unique machine, which has the capability to provide leptonic collisions at energies of several TeV [6]. The huge physical potential held by the multi-TeV energy scale will enable a novel research programme ranging from high precision measurements of known SM processes to high-sensitivity searches for the exploration of new physics beyond the SM. A multi-TeV muon collider will produce huge samples of Higgs bosons that will allow the determination of the Higgs boson properties with unprecedented precision, including its couplings to the lighter sectors of the SM and its trilinear and quartic self-couplings.

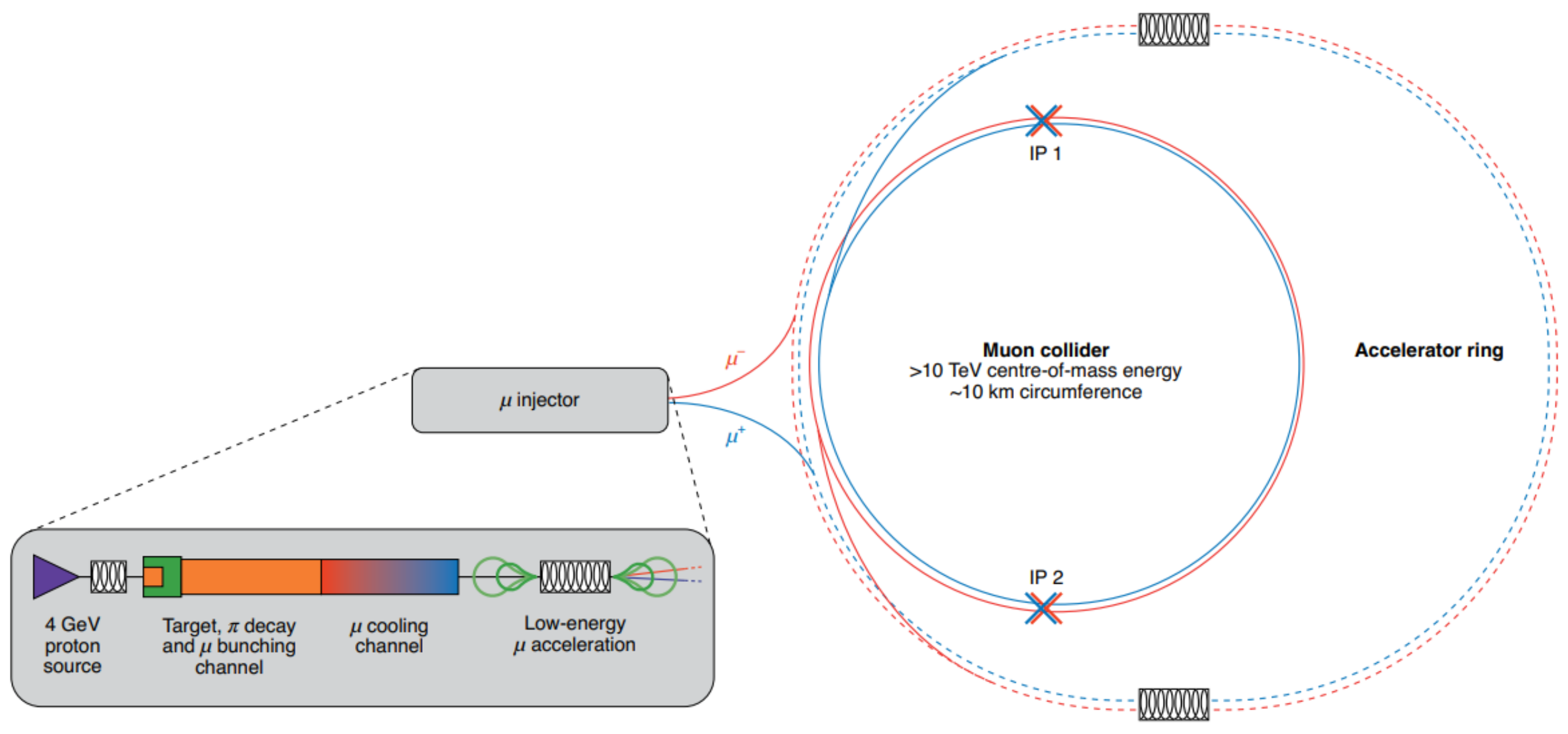

Figure 1. Schematic layout of a 10-TeV muon collider complex [7]. The muon injector system includes the proton driver, a high power target system with capture solenoid for the pions generated by the proton interactions with the target, a pion decay channel where muons are collected and subsequently bunched together, a muon ionization cooling channel that provides cooling for both positive and negative muon beams, and a low energy muon accelerator stage. From the injector, each species of muon beam is transferred into a high energy accelerator complex that can take the beams to the multi-TeV energies required. Finally, the beams will be transferred to a smaller collider ring whose circumference is optimized for luminosity performance.

Event selection

The analysis is carried out assuming an integrated luminosity of $\boldsymbol{L_{int} = 1\ ab^{-1}}$.

A preselection is performed before the event classification. The event preselection has the purpose of suppressing the low-energy part of the background in the phase-space regions where little to no signal is present, and It is implemented with the application of the following requirements:

- Two opposite-charge muons in each event.
- Di-muon system invariant mass in the range 105-145 GeV.
- Single muon polar angle in the range 10-170 degrees.
- Single muon transverse momentum greater than 5 GeV.
- Di-muon system transverse momentum greater than 30 GeV.
- Scalar sum of the two muons transverse momentum greater than 50 GeV.

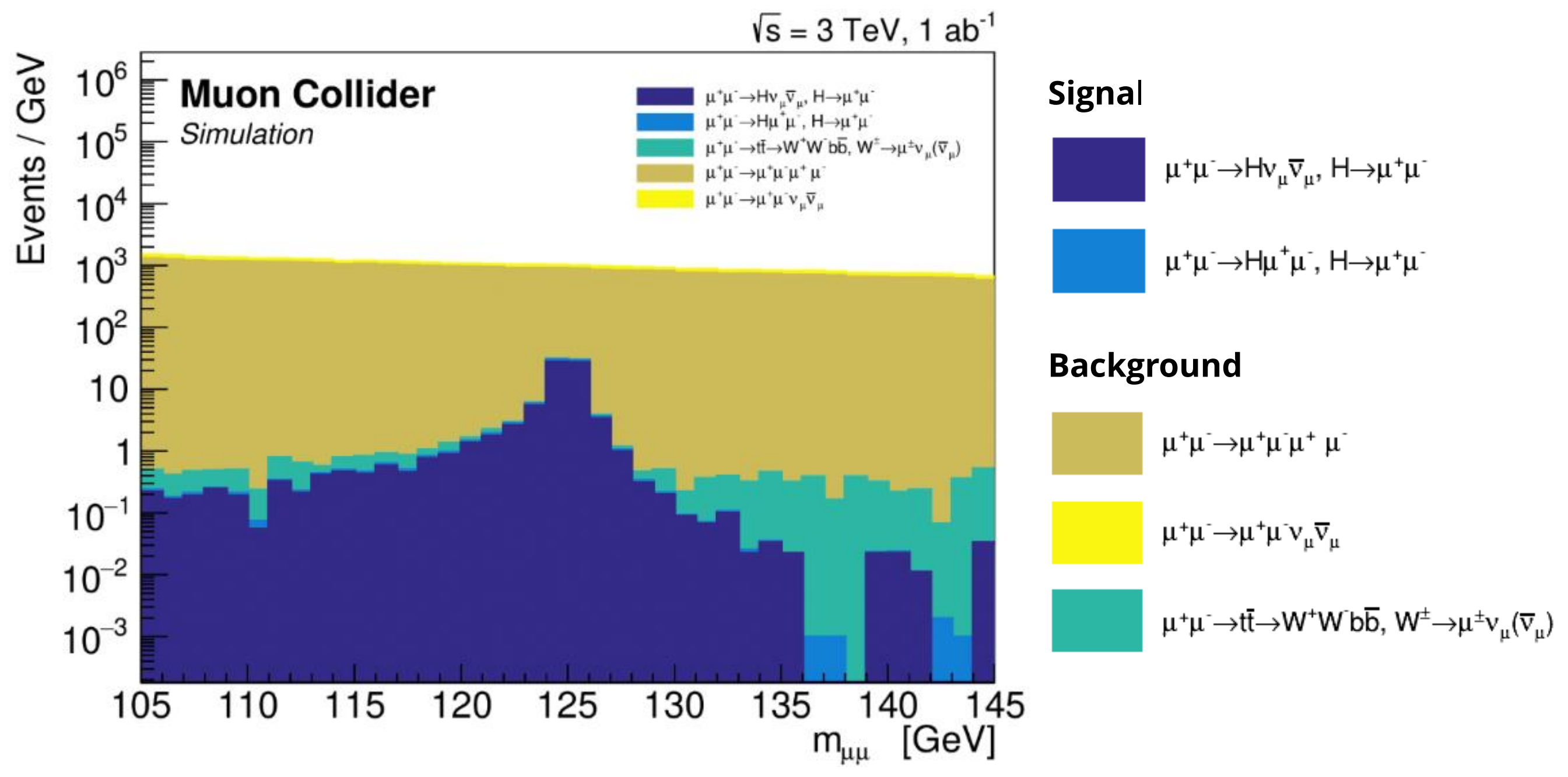

Figure 2. Stack of the di-muon system invariant mass distributions of the preselected signal and background events in the invariant mass range from 105 to 145 GeV.

The event classification is carried out with the use of two multivariate classifiers based on a boosted decision tree (BDT).
Each one of the two classifiers is trained independently to discriminate between the whole signal contribution and one of the two main background contributions:

- The "**BDT1**" is trained to discriminate between the signal and the $\mu^+\mu^- \rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$ background
- The "**BDT2**" is trained to discriminate between the signal and the $\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ background

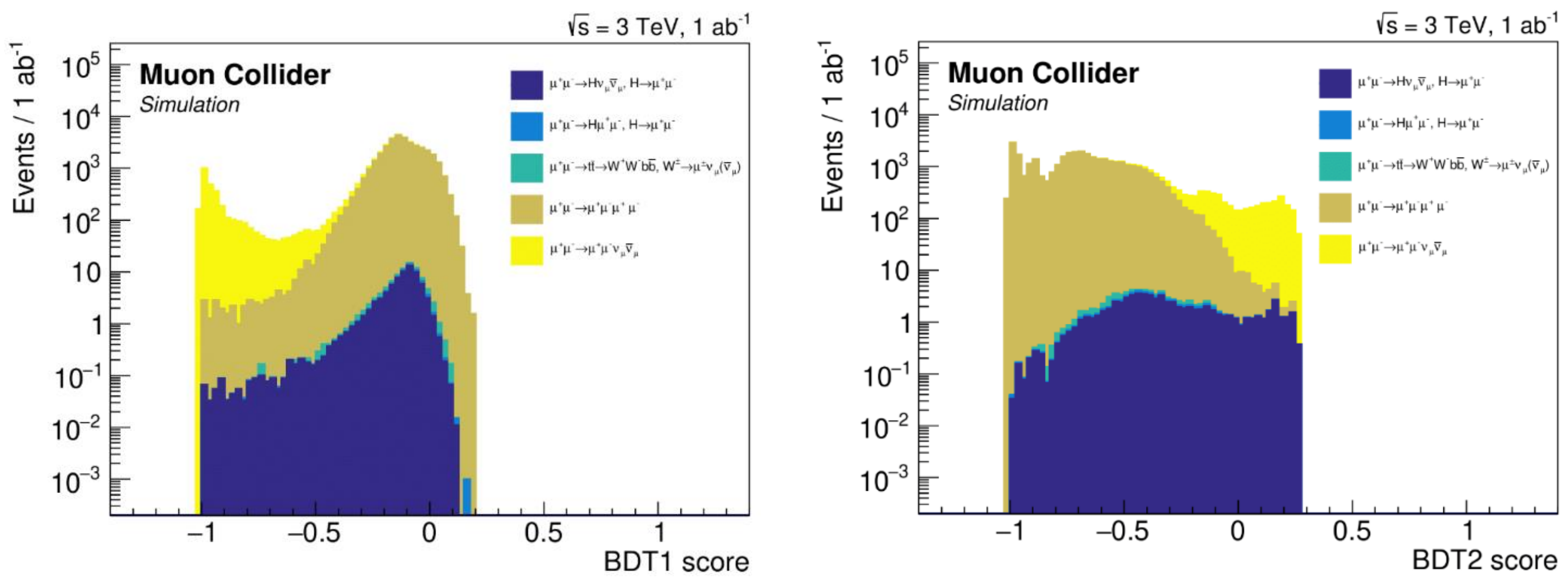

Figure 3. Stacks of the BDT1 (left) and BDT2 (right) scores distributions obtained with the application of the trained classifiers to the samples used for the analysis. The training and testing of the classifiers are performed using a fraction of the samples which is reserved for this purpose only and it is not used in the analysis.

The event selection is performed with the implementation of a double cut on the classification scores obtained with the two BDT classifiers, which are applied separately to all the samples, according to the following procedure:

- The positions of the two cuts, one for each classifier, are optimized simultaneously such that they maximize the overall signal significance, defined as $\boldsymbol{S/\sqrt{S+B}}$, where S and B are the total signal and background contributions respectively.
- The classification scores are evaluated for each single event using both the BDT1 and BDT2 classifiers.
- The event is taken as a signal event if the BDT1 score satisfies the cut chosen for the BDT1 classifier or if the BDT2 score satisfies the cut chosen for the BDT2 classifier, i.e. if the event is successfully discriminated against at least one of the two main backgrounds.

Process	Expected events with $105 < m_{\mu\mu} < 145$ GeV (*)
$\mu^+\mu^- \rightarrow H\nu_\mu\bar{\nu}_\mu,\ H \rightarrow \mu^+\mu^-$	24.2
$\mu^+\mu^- \rightarrow H\mu^+\mu^-,\ H \rightarrow \mu^+\mu^-$	1.6
$\mu^+\mu^- \rightarrow \mu^+\mu^-\nu\bar{\nu}_\mu$	636.5
$\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$	476.4
$\mu^+\mu^- \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b},\ W^\pm \rightarrow \mu^\pm\nu_\mu(\bar{\nu}_\mu)$	1.1

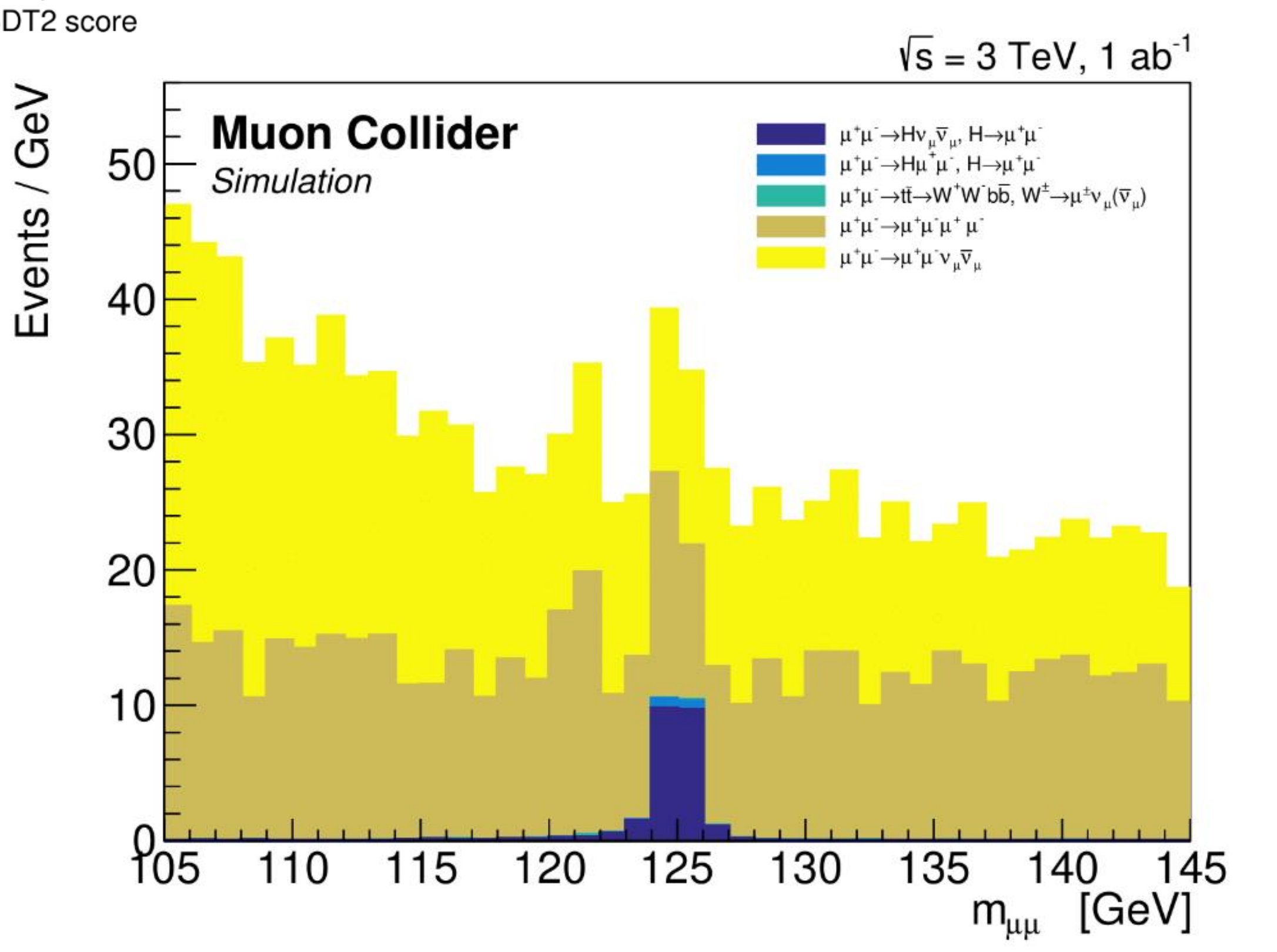

Figure 5. Expected number of events in the invariant mass range from 105 to 145 GeV of the di-muon system invariant mass distribution of the selected signal and background events.

Signal extraction

The quantity $\boldsymbol{\sigma_H \times BR(H \rightarrow \mu\mu)}$ is determined from:

$$\boldsymbol{\sigma_H \times BR(H \rightarrow \mu\mu) = \frac{N_S}{L_{int} \cdot \varepsilon_S}}$$

where N_S is the number of signal events in the invariant mass range from 105 to 145 GeV, L_{int} the integrated luminosity of the experiment and ε_S the total signal counting efficiency. The uncertainty on $\sigma_H \times BR(H \rightarrow \mu\mu)$ is expected to be dominated by the statistical uncertainty on N_S, which can therefore be taken as an estimate of the sensitivity of the measurement.

The number of signal events N_S is extracted with an extended maximum likelihood fit to the di-muon system invariant mass with the function:

$$\boldsymbol{f(m_{\mu\mu}) = N_S \cdot f_S(m_{\mu\mu}) + N_B \cdot f_B(m_{\mu\mu})}$$

where N_S and N_B are the free parameters of the fit (N_B is the number of background events) and f_S and f_B are the signal and background probability density functions. The two probability functions are modeled separately with an unbinned maximum likelihood fit to the di-muon invariant mass distribution of the total selected signal and background events.

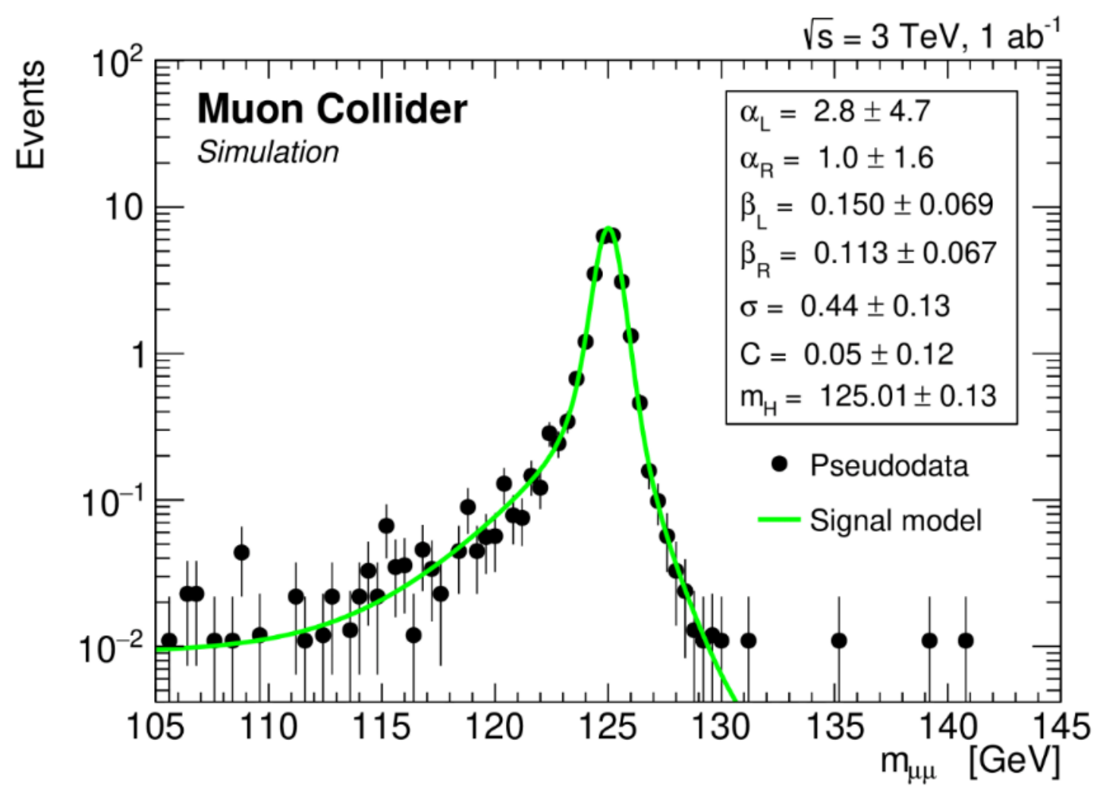

Figure 6. The signal probability density function is modeled with a fit to the di-muon invariant mass distribution using a function that is the linear combination of a gaussian function with exponential tails and a gaussian function with asymptotically constant tails.

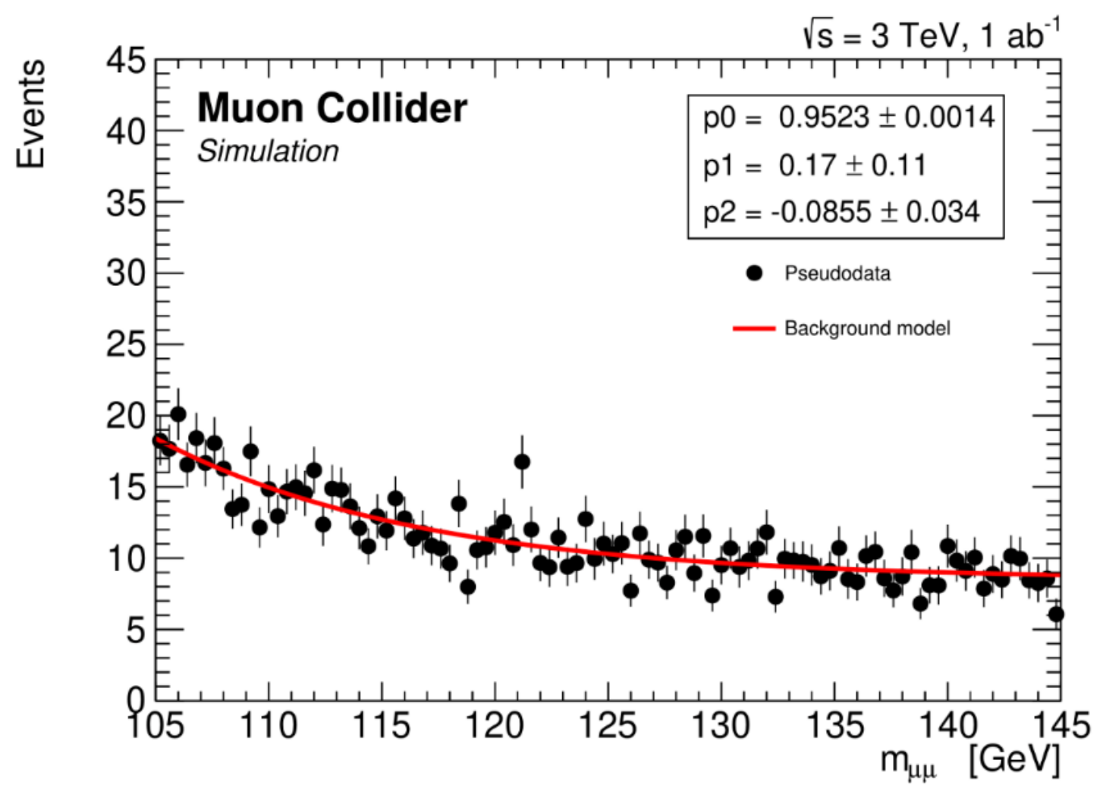

Figure 7. The background probability density function is modeled with a fit to the di-muon invariant mass using a function that is the linear combination of an exponential and a constant term.

Results

The statistical uncertainty on the number of signal events is estimated as the root mean square of the distribution of 10000 values of N_S that are extracted from the di-muon invariant mass distribution by performing 10000 pseudo-experiments.

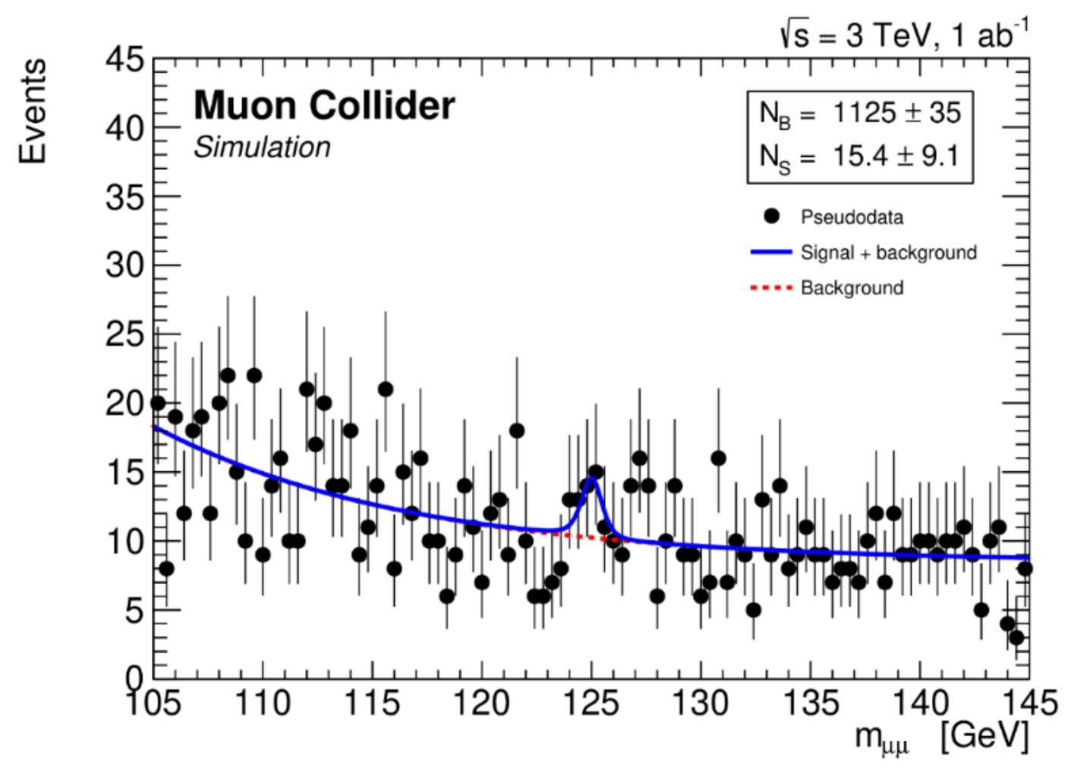

Figure 8. Example of the fitted di-muon invariant mass distribution for one of the pseudo-experiments. For each pseudo-experiment, the number of signal and background events are randomly generated according to a Poisson distribution, and the di-muon invariant mass values are randomly generated from the probability density functions f_s and f_B.

As a result, for a 3 TeV muon collider, the expected number of signal events in the di-muon invariant mass range from 105 to 145 GeV is expected to be

$$\boldsymbol{\langle N_S \rangle = 25.8 \pm 9.9}$$

for a dataset corresponding to an integrated luminosity of $1\ \mathrm{ab}^{-1}$. The relative uncertainty on $\langle N_S \rangle$ is estimated to be 38% and it is taken as the estimate of the sensitivity for the measurement of $\sigma_H \times BR(H \rightarrow \mu\mu)$.

$$\boxed{\boldsymbol{\frac{\sigma_{N_S}}{\langle N_S \rangle} = 38\%}}$$

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