Muon Collider: Study of methods for the luminosity measurement

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Abstract

The renewed interest for the muon collider, in particular in the multi-TeV energy range is posing several unprecedented challenges to the HEP community. Among them there are the interaction region and the detector designs that have to cope with the very high fluxes of particles coming from the muon beams decays. In order to mitigate the effect of the beam-induced background on the detector performance an ad-hoc shielding structure has been designed whose side effect is to limits the detector acceptance in the forward regions and makes difficult to determine the integrated luminosity with the standard methods adopted by the LHC experiments [1].

In this letter we propose to study an alternative way to determine such a fundamental parameter, which **is** mandatory for almost all physics measurements.

State-of-the-art

The muon collider facility, from muon generation to the beam collision, requires several technological advancements whose development will start during the Snowmass process. In order to achieve the target performance luminosity, muon beams of the order of $2 \cdot 10^{12}$ muons per bunch are necessary, which generate, in the case of 750-GeV beams, about $4.28 \cdot 10^{5}$ decays per meter of the lattice in a single pass, The Machine Detector Interface (MDI) was properly designed to mitigate the effect of the high fluxes of particles in the detector. Sophisticated tungsten nozzles with a borated polyethylene cladding, iron, and concrete shielding which extends from 6 to 600 cm on both sides around the interaction region (IR) for $\sqrt{s} = 1.5$TeV, were optimized by the MAP collaboration [2]. This structure forces the design of the inner tracker and, in particular, of the forward regions of the detector that cannot host instrumentation or a subdetector dedicated to the luminosity measurement.

On the other hand, the precise determination of the integrated luminosity target uncertainty is of crucial importance for any physics cross section measurement, as its precision directly translates to the precision of the cross section measurement and often is the dominant uncertainty.
If we have two beams with N_1 and N_2 being the average number of particles per bunch in the two beams, the luminosity is defined by

$$L = \frac{N_1 \cdot N_2 \cdot f \cdot n_b}{A_{eff}}$$

Where n_b is the number of colliding bunches, f is the revolution frequency in the collider and A_{eff} is the effective area of the luminous region. The quantities f and n_b are known since they are parameters of the machine, while the effective values of N_1 and N_2 target performanc at the interaction point and A_{eff} should be measured.
The area of the luminous region, if the distribution of particle density in the bunches is Gaussian, can be written as $A_{eff} = 4\pi \cdot \sigma_x \cdot \sigma_y$ where σ_x and σ_y are the Gaussian widths of the transverse bunch density distributions. A_{eff} is usually obtained by using the so called "van der Meer" scan method [3] and it is used to calibrate the luminometers. Luminometers are dedicated detectors, constituted by, e.g., crystals and diamonds in CMS, Cherenkov detectors in ATLAS, which are placed in proximity of the beam pipe and used to determine the actual value of N_1-N_2 A_{eff}at the experiment.
At a muon collider these methods cannot be used due to the presence of the nozzle.
Experiments taking data at the flavor factories like KLOE, Babar, Belle, BES and, recently, Belle2 and BESIII, measure the integrated luminosity by counting the number of events, N, of a process whose cross-section is theoretically known with high precision, σ_{th},

$$N = L \cdot \sigma_{th}$$

The physics process mostly used is the well-known quantum electrodynamics Bhabha scattering, $e^+e^- \rightarrow e^+e^- \, (n\gamma)$, where $(n\gamma)$ here involves initial-state radiation and final-state radiation. In order to avoid the forward region which often is not instrumented, events at at large angle with respect to the beamline are selected [4], see [5] for a recent review on the theoretical status.

Proposed activities

At a muon collider, given the peculiar structure of the MDI, a similar method can be used to measure the luminosity. We propose to study the feasibility of the reconstruction of $\mu^+\mu^- \rightarrow \mu^+\mu^-$ events at large angle with respect to the beam line to get $L = \frac{N}{\sigma_{th}}$. Here N is the number of di-muon events, and σ_{th} is the theoretical muon Bhabha cross section. It is important to evaluate the number of reconstructable events at large angle and the precision with which the theoretical cross section has to be known. The studies can be organized as follow:

- Produce a sample of $\mu^+\mu^- \rightarrow \mu^+\mu^-$ events at $\sqrt{s} = 1.5$TeV, $\sqrt{s} = 3.0$ TeV and $\sqrt{s} = 10$ TeV by using a tree-level Monte Carlo generator and study the reconstruction efficiency at large angle by using the full detector simulation and identify additional kinematical requirements that can help the obtain a more precise theoretical prediction.
- Perform the same studies with Mu-BabaYaga event generator [5].
- Evaluate the theoretical precision on the Bhabha cross section.
- Determine the expected precision on the luminosity.

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