Luminosity measurement at Muon Collider

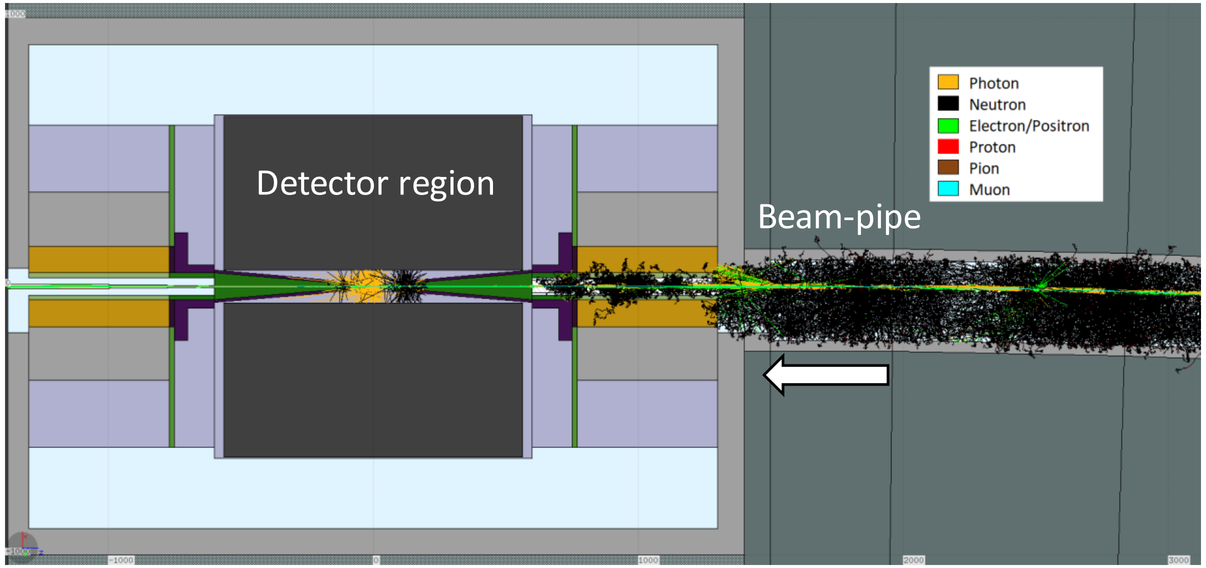
D.Lucchesi[1,2], L.Buonincontri[2,1], L.Sestini[2], U.Dosselli[2], C.Giraldin
[1]*Università degli studi di Padova*, [2]*INFN-Padova*

Muon Collider

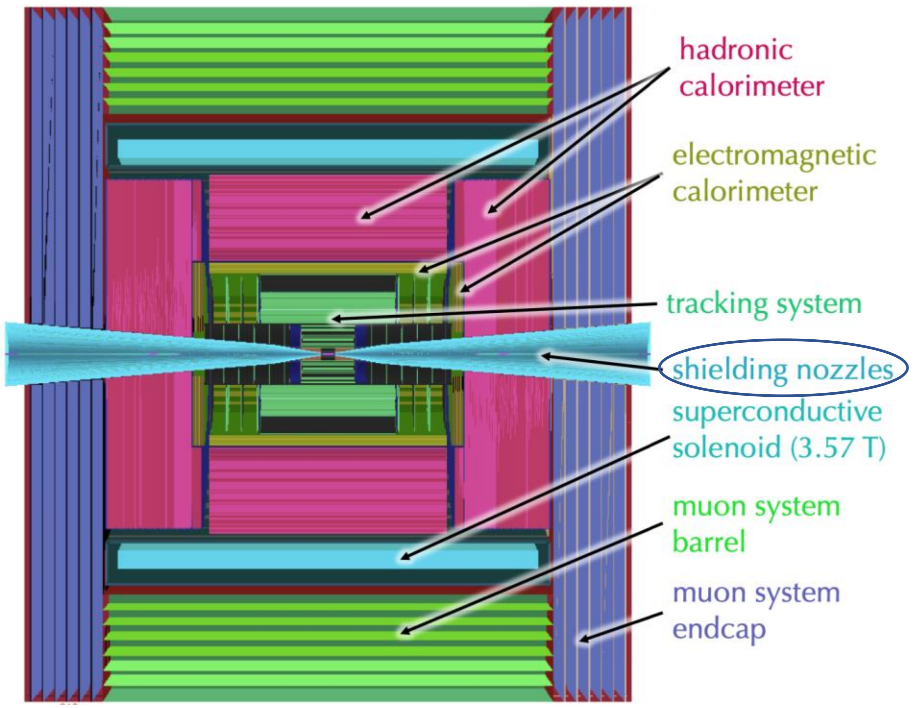
- A Muon Collider is one of the future particle accelerator projects with great physics potential since it could collide beams of $\mu^+\mu^-$ at very high center of mass energy (multi-TeV).

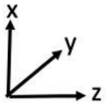
- **Advantages:** muons are elementary particles, then all the beam energy is available for collisions and the energy loss due to beamstrahlung and synchrotron radiation is negligible.

- **Challenges:** the Beam-Induced Background (BIB)[1] is produced by the very high fluxes of particles coming from the muons decay (τ_μ=2.2 μs at rest) along the beam pipe.



- Detector design is deeply linked to the presence of the BIB: two tungsten cone-shaped shields (nozzles) are inserted to mitigate BIB effects[2].





[1]: F.Collamati et al. "Advanced assessment of Beam Induced Background at a Muon Collider" arXiv:2105.09116.
[2]: N.V. Mokhov, S.I. Striganov e I.S. Tropin. "Reducing Backgrounds in the Higgs Factory Muon Collider Detector". In: (2014), pp. 1081–1083. doi: 10.18429/JACoW-IPAC2014-TUPRO029.

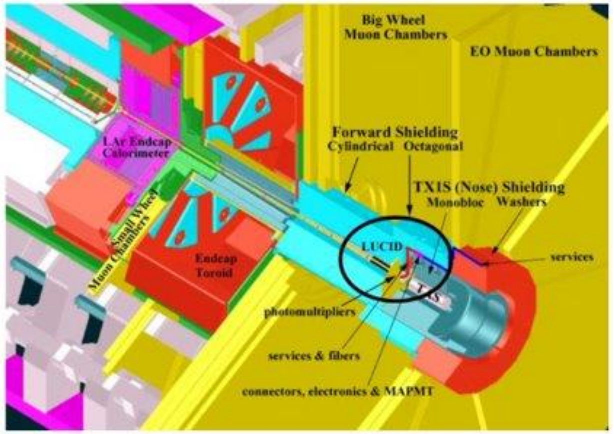
What's the problem with measuring luminosity?

- Luminosity can be estimated directly from the knowledge of the parameters of the colliding beams, through luminometers placed in the forward region of the detector in combination with Van der Meer's method:

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

- N_b: number of bunch.
- $N_{1,2}$: average number of particle per bunch.
- f: revolution frequency in the collier.
- A_{eff}: effective area.

- The presence of the two nozzles does not allow proper instumentation of the forward regions. Van der Meer's scan could not be practicable at Muon Collider.



(ATLAS experiment)
from https://project-atlas-lucid.web.cern.ch/taskforce/main.html#part7

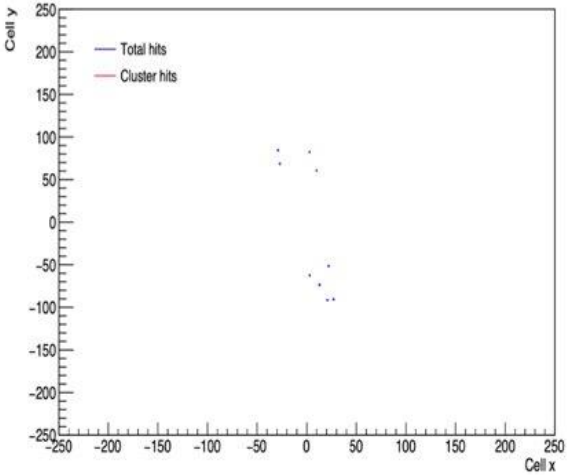
Measurement of luminosity at Muon Collider

- Some $e^+ e^-$ experiments (Belle2, BES) measure the integrated luminosity, L_{int}, by counting the number of Bhabha scattering ($e^-e^+ \rightarrow e^-e^+$) events ($N_{ev}$), whose cross section ($\sigma$) is theoretically known with high precision (0.1% at √s=1-10 GeV and large angle [3]).

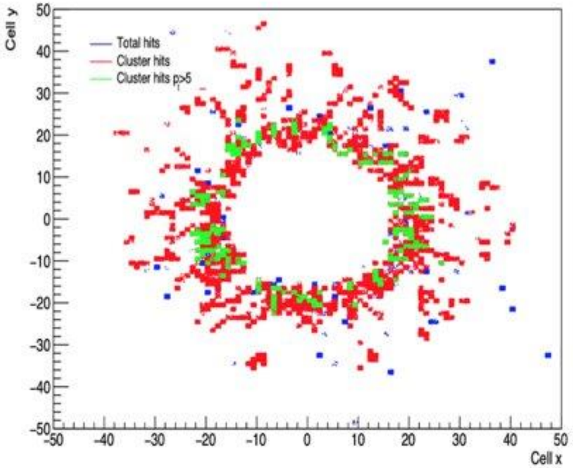
$$L_{int} = \frac{N_{ev}}{\epsilon \cdot \sigma}$$

- Muon-Bhabha scattering process $\mu^-\mu^+ \rightarrow \mu^-\mu^+$ at large emission angles is used at Muon Collider, to deal with:
  - the presence of the nozzle (|η|<2.44).
  - the distribution of the BIB at the muon detector. No clusters due to BIB are reconstructed in the central barrel region.
- Selected central angular region between 30° and 150°.

BIB hits on muon detector barrel



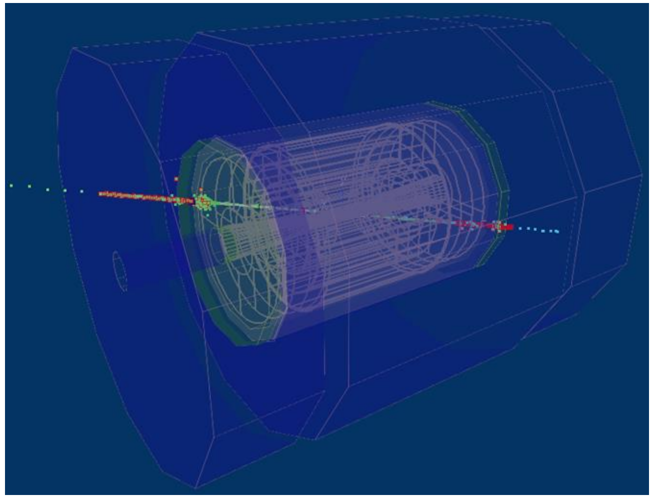
BIB hits on muon detector endcap



[3]: C. M. Carloni Calame et al. “NNLO massive corrections to Bhabha scattering and theoretical precision of BabaYaga@NLO”. In: Nucl. Phys. B Proc. Suppl. 225-227 (2012). A cura di Alexander Bondar e Simon Eidelman, pp. 293–297. doi: 10.1016/j.nuclphysbps.2012.02.061.

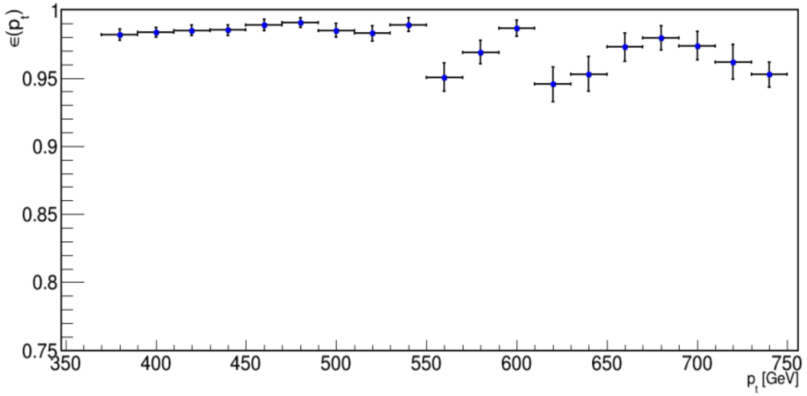
Large angle μ-bhabha events

- Simulation of a Bhabha process: $\mu^-\mu^+ \rightarrow \mu^-\mu^+$ at large emission angle. The pair of $\mu^+ \mu^-$ is emitted back to back with the same energy and momentum.



- Cuts to select μ-Bhabha events with a large emission angle (30°<θ<150°), tuned on a 100000 μ-Bhabha sample, at √s=1.5 TeV, generated with Pythia Monte Carlo:
  - p_t >130 GeV.
  - Angle between muons direction pair Δθ>3.08 rad.
  - Invariant mass 1440 GeV<$M_{\mu\mu}$<1560 GeV .
  - Clusters on the muon detector.

- Reconstruction efficiency values of the large angle μ-Bhabha process as a function of pt. Total reconstruction efficiency: **ε_{tot}=0.953±0.003**.

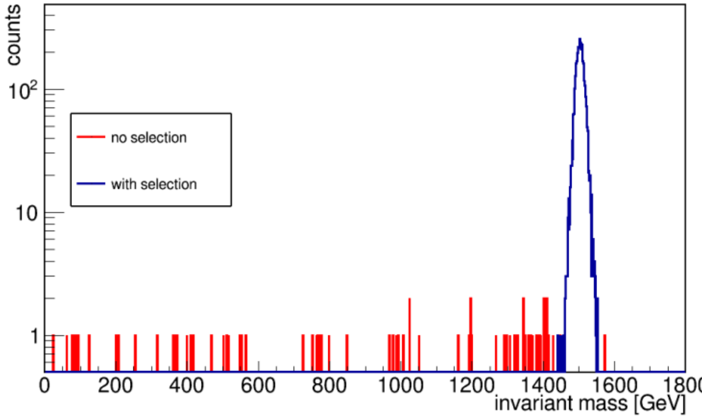


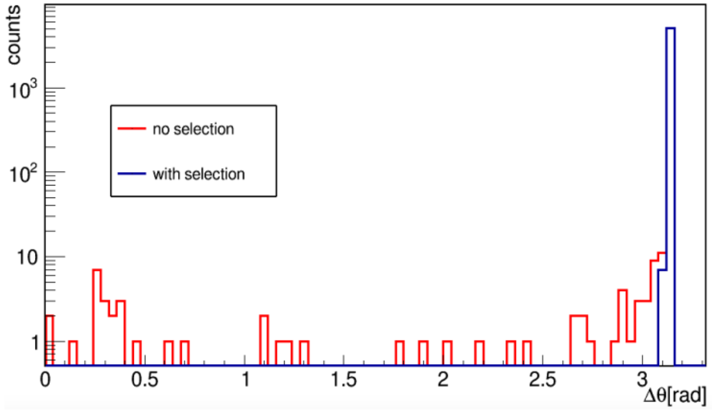
Simulation analysis

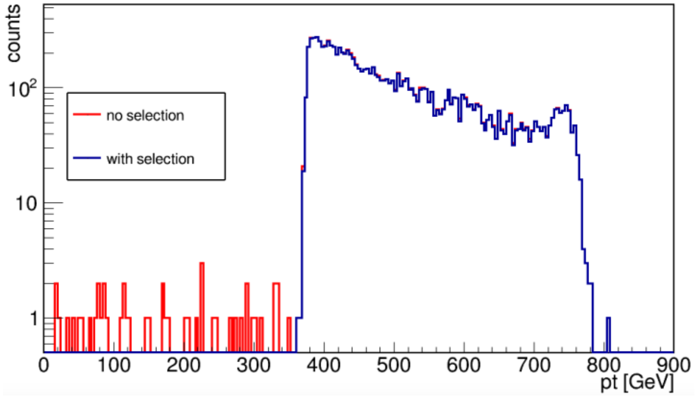
- Application of selection cuts to a sample of 100000 events $\mu^-\mu^+ \rightarrow \mu^-\mu^+$ at √s=1.5 TeV (Pythia Monte Carlo).

- μ-Bhabha events at 30°<θ<150° are selected among all the physics background processes included in the sample.

- Number of large angle μ-Bhabha events: **N_{ev}=5080**.







Results

- 5080 events are expected at a √s=1.5 TeV in $\Delta t=2.58\times10^5$s with a integrated luminosity of 3.23 fb^{-1} according to PYTHIA. Therefore, in one year of data taking (10^7s), **N_{ev}=196594** μ-Bhabha events at large emission angle are expected.

- The uncertainty on the integrated luminosity measurement has two contributions: the statistical uncertainty ($\Delta N_{ev}/N_{ev}$) and the theoretical uncertainty of the cross section ($\Delta\sigma_B/\sigma_B$):

$$\frac{\Delta L_{int}}{L_{int}} = \sqrt{\frac{\Delta N_{ev}{}^2}{N_{ev}{}^2} + \frac{\Delta\sigma_B{}^2}{\sigma_B{}^2}} = \left(\frac{\Delta N_{ev}}{N_{ev}}\right) \oplus \left(\frac{\Delta\sigma_B}{\sigma_B}\right)$$

- Statistical uncertainty in one year of data taking:

$$\frac{\Delta N_{ev}}{N_{ev}} = \frac{1}{\sqrt{N_{ev}}} = 0.002$$

Conclusions and next steps

- With the proposed method for the integrated luminosity measurement, based on the counting of large angle muon-Bhabha events, a statistical uncertainty on the luminosity of 0.2 % in one year of data taking is expected.
- This work represents the first study on the possibility of using a method based on the muon Bhabha process to overcome the difficulties in measuring the luminosity of the Muon Collider. The obtained results, referred to √s=1.5 TeV, are encouraging in order to determine luminosity with a reasonable precision.

- To obtain a complete estimate of the uncertainty on integrated luminosity, it is necessary to know the error on the theoretical cross section of the muon Bhabha process at large emission angle and at high energies, the order of TeV. Currently these values are not available.
- To complete this study it will be necessary re-perform this analysis at energies of √s=3 TeV and √s=10 TeV.