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Introduction to Muon Collider physics, detector and beam-induced background

MC/Simulation Framework Tutorial: Muon Collider

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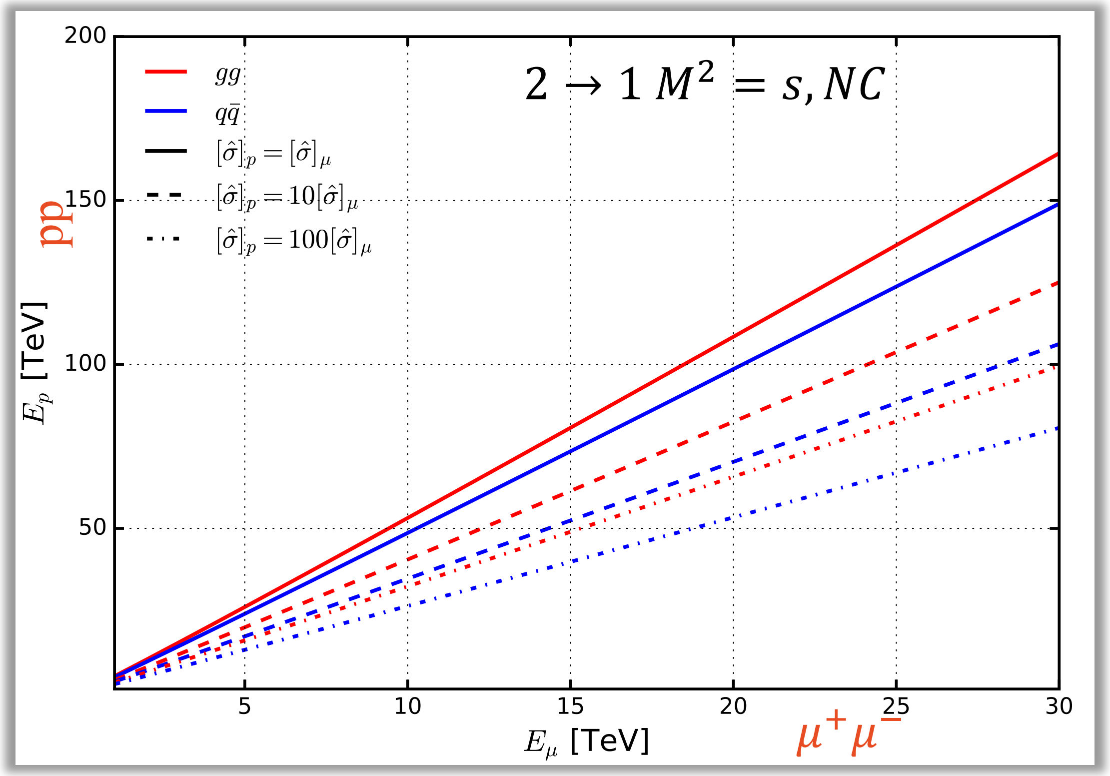
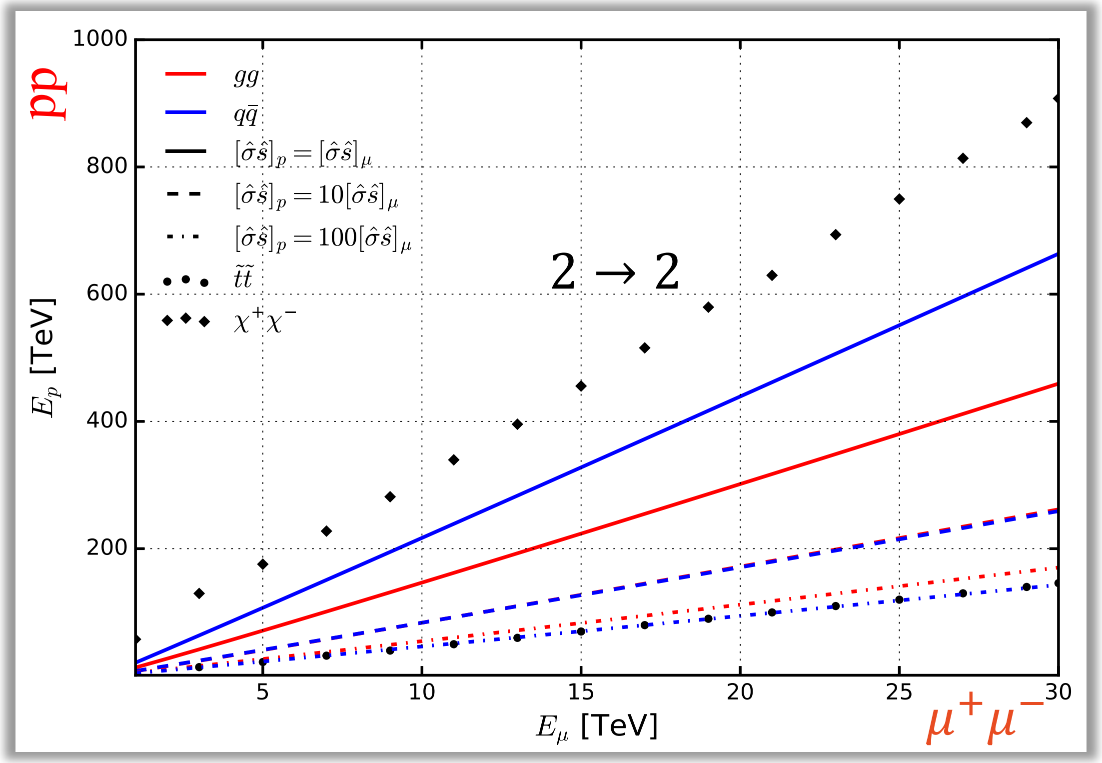
The good of Muon Collisions: New Physics

Muon, in principle, can be accelerated to very high energy without the issues of radiation losses being heavier than the electron.
The advantage in colliding muons rather than protons is that $\sqrt{s_\mu}$ is entirely available to produce short-distance reactions. At a proton collider the relevant interactions occur between the proton constituents, which carry a small fraction of $\sqrt{s_p}$

Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





Equivalent proton collider energy $\sqrt{s_p}$ required to reach the same beam-level cross section as a $\mu^+\mu^-$ collider with energy $\sqrt{s_\mu}$

The Higgs Potential: the portal to the New Physics

Higgs boson couplings to fermions and bosons reaches have to be evaluated, similar or better performance of e^+e^- are expected.
In addition, muon collider has the unique possibility to determine the Higgs potential having sensitivity also to quadrilinear coupling

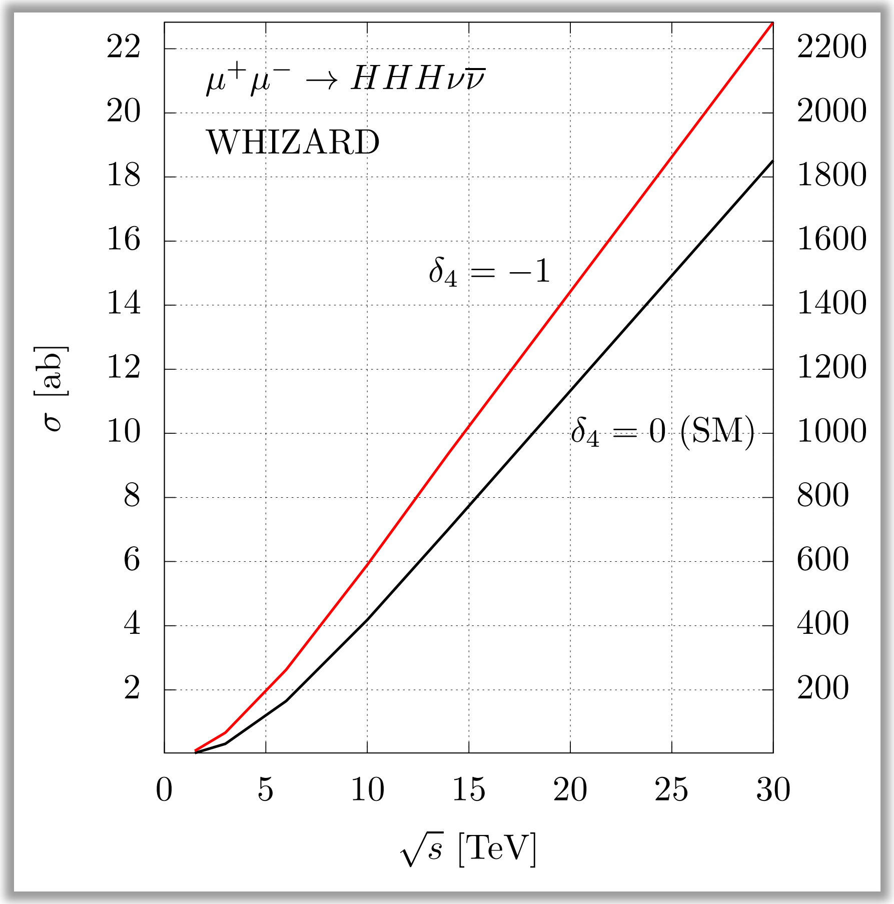
$$\lambda_3 = \lambda_{SM}(1+\delta_3) \quad \lambda_4 = \lambda_{SM}(1+\delta_4)$$

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

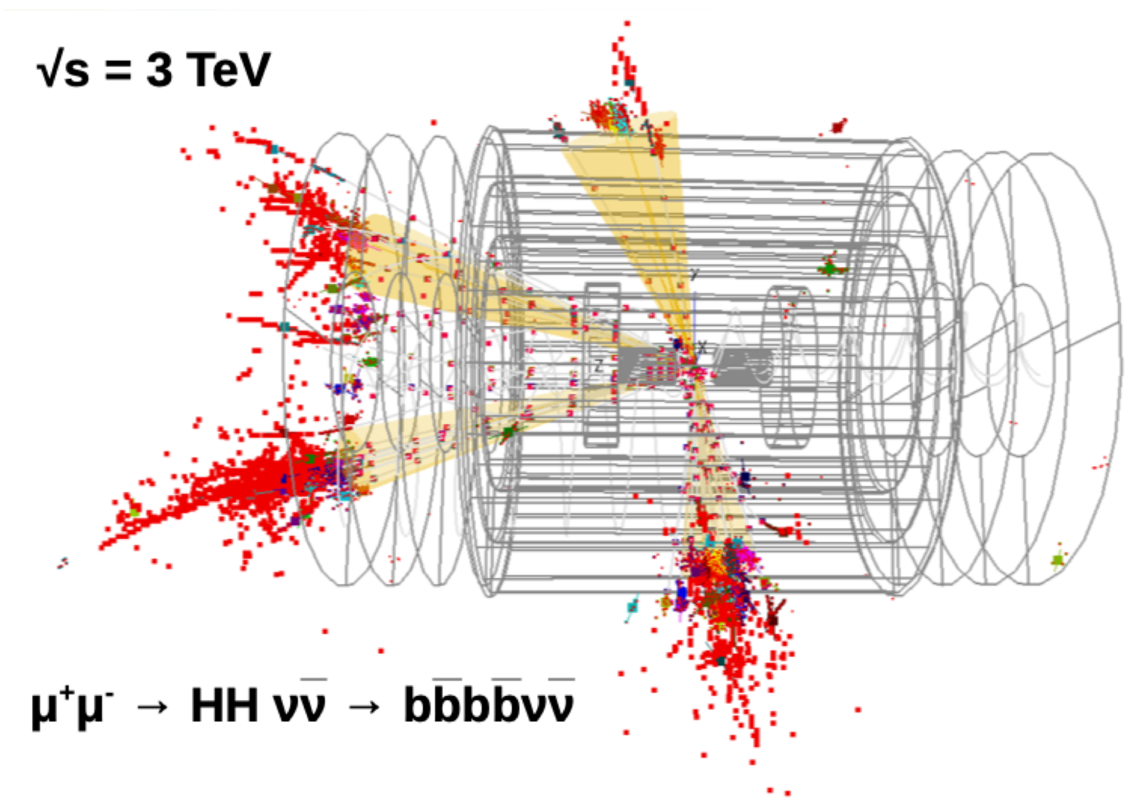
First attempt to determine the sensitivity with full simulation including the beam-induced background:

$$\frac{\Delta\sigma}{\sigma} \cong 35\%$$

By assuming:
- $\sqrt{s} = 3\ TeV$
- $\mathcal{L} = 4.4 \cdot 10^{34} cm^{-2} s^{-1}$
- T=$4.4 \cdot 10^4 s$



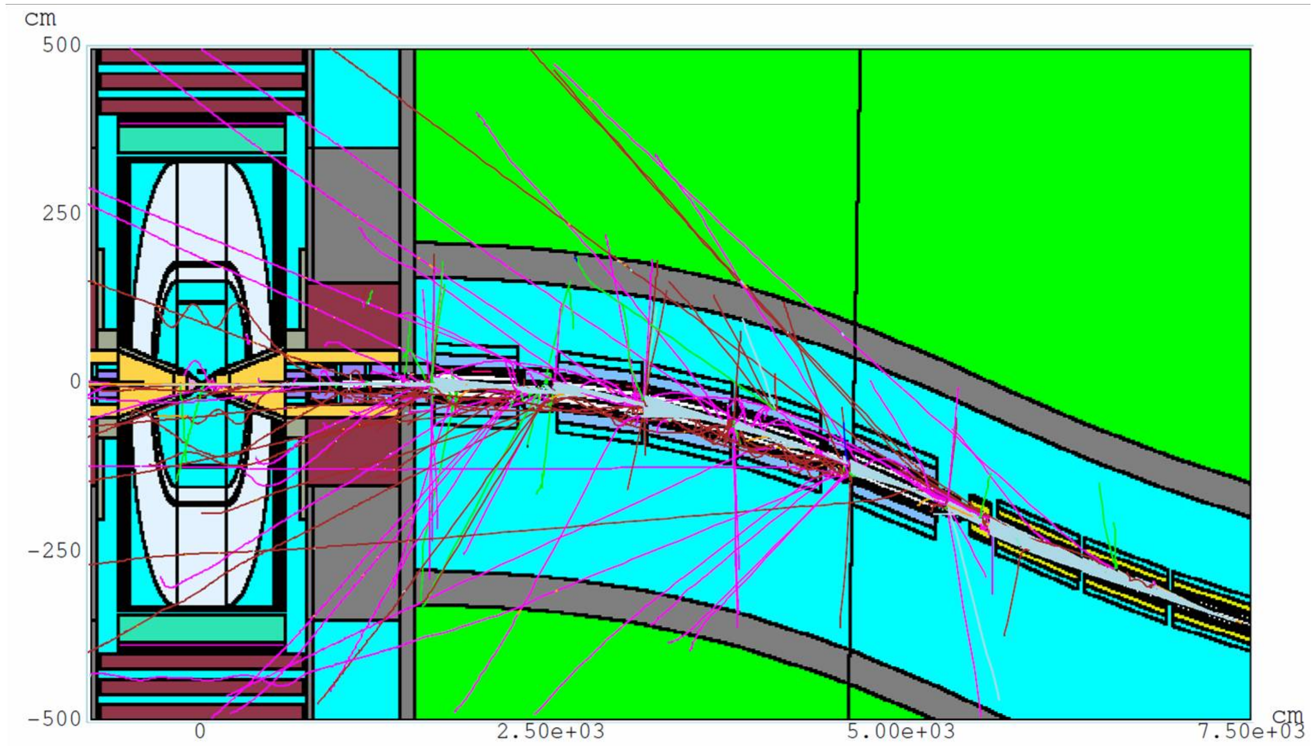
Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, M Chiesa *et al*.



The challenge: beam-induced background

- Muon decay… just a back of the envelope calculation:
  beam 0.75 TeV $\lambda = 4.8\times10^{6}$m, with $2\times10^{12}\mu$/bunch $\Rightarrow 4.1\times10^{5}$decay/meter of lattice

- Muon induced background is critical for
  - Magnets, they need to be protected
  - Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice



Electromagnetic showers induced by electrons and photons interacting with the machine components generate hadrons, secondary muons and electrons and photons.

Muon Accelerator Program, MAP, developed a realist simulation of the beam-induced backgrounds in the detector by implementing a model of the tunnel and the accelerator ±200 m from the interaction point.

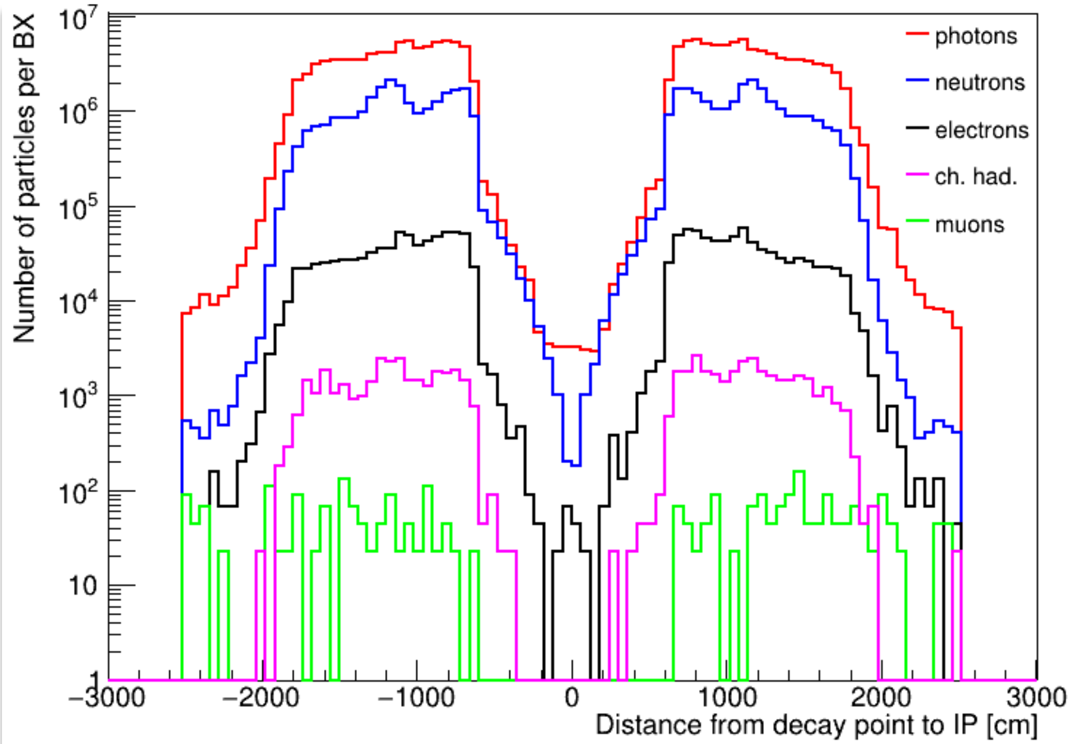
Center of mass energy of 1.5 TeV

- MARS15 has been used to generate muons and secondary and tertiary particles and transported to the detector
- Two tungsten nozzles play a crucial role in background mitigation inside the detector.

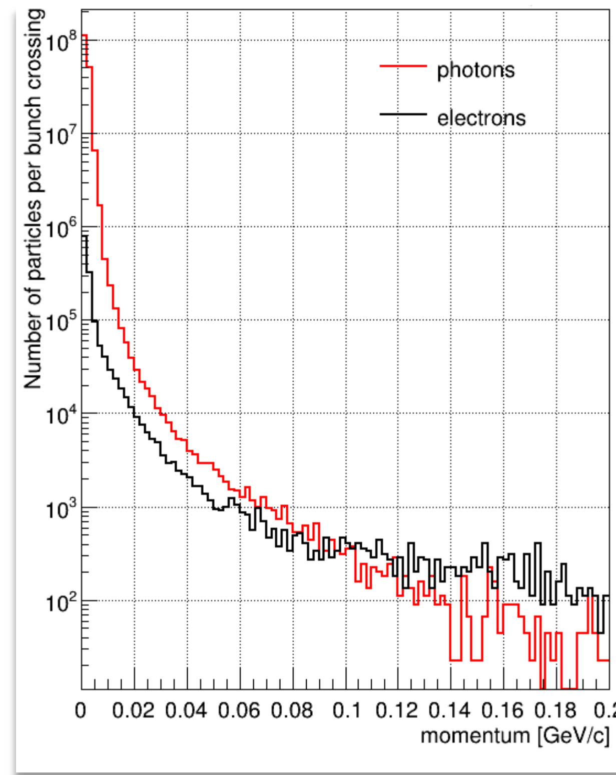
Other Center of mass energy

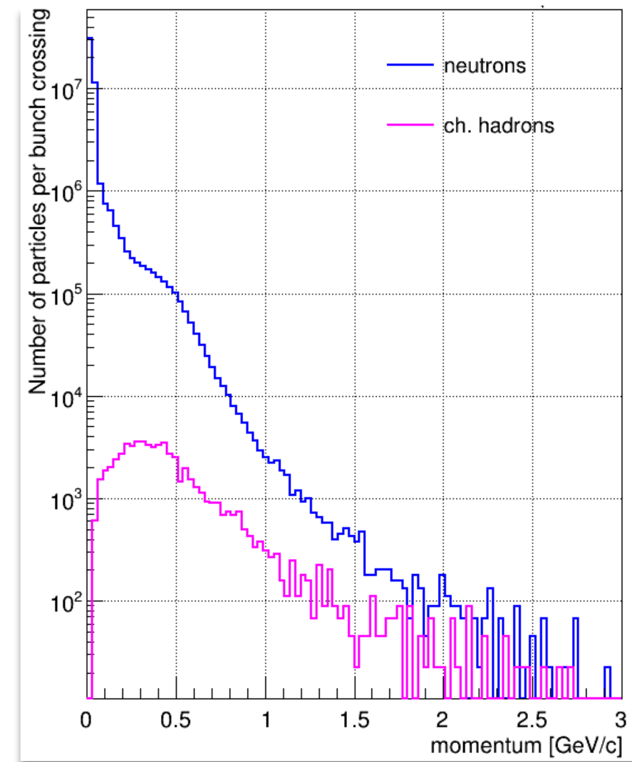
- A FLUKA-based tool is proposed to generate the beam-induced background starting from the accelerator design developed by MAP

The beam-induced background properties $\sqrt{s}=1.5$ TeV

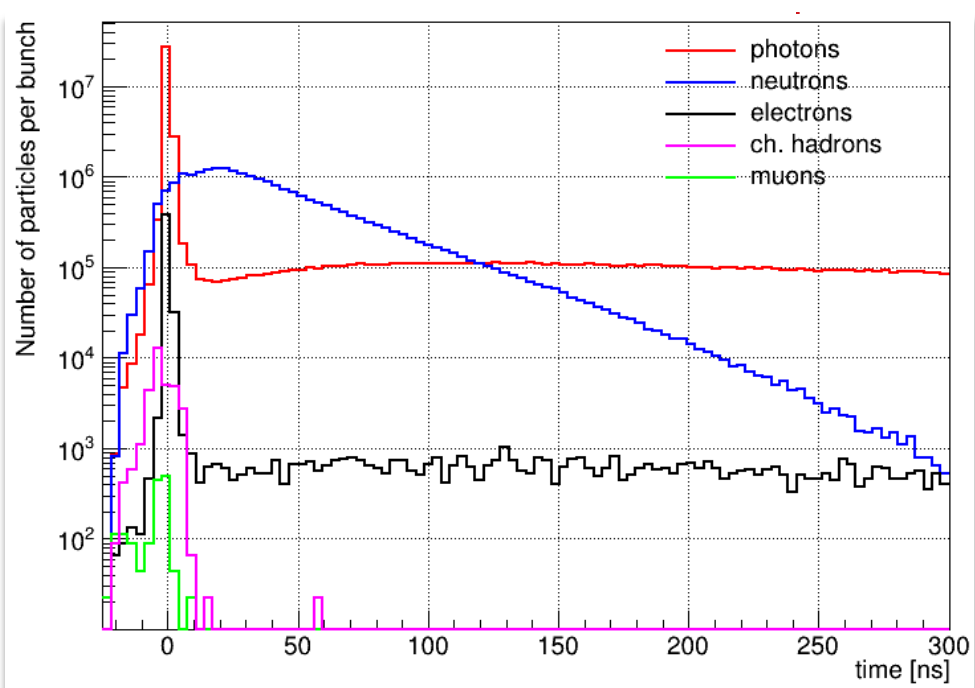


Contributions form μ decays |z| > 25 m become negligible for all background species but Bethe-Heitler muons





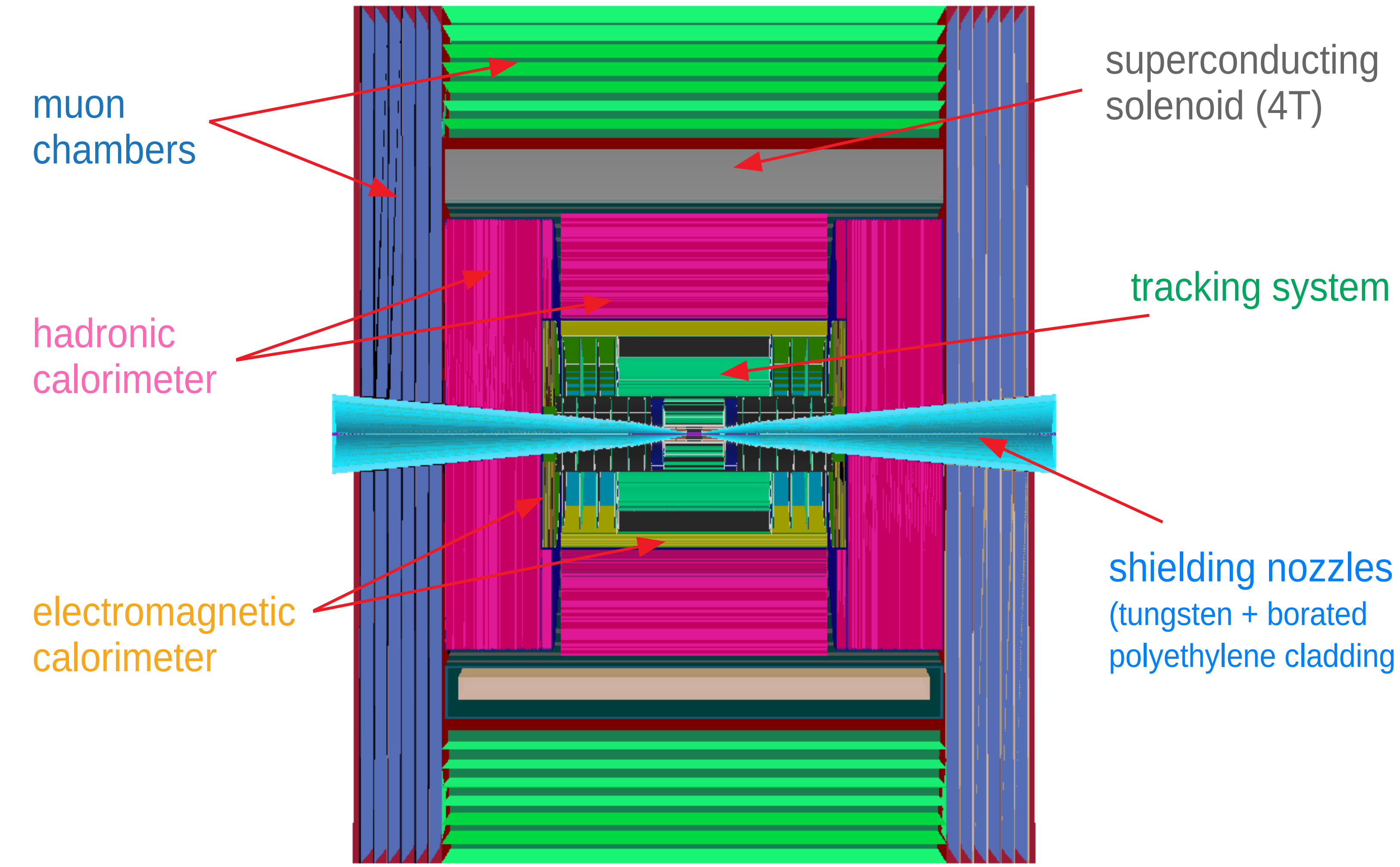
Secondary and tertiary particles have low momentum



Time information are crucial to reduce the beam-induced background

Study of Detector Response at $\sqrt{s}$ =1.5 TeV

The simulation/reconstruction tools supports signal + beam-induced background merging
CLIC Detector adopted with modifications for muon collider needs.
Detector optimization is one of the future goal.



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 ”

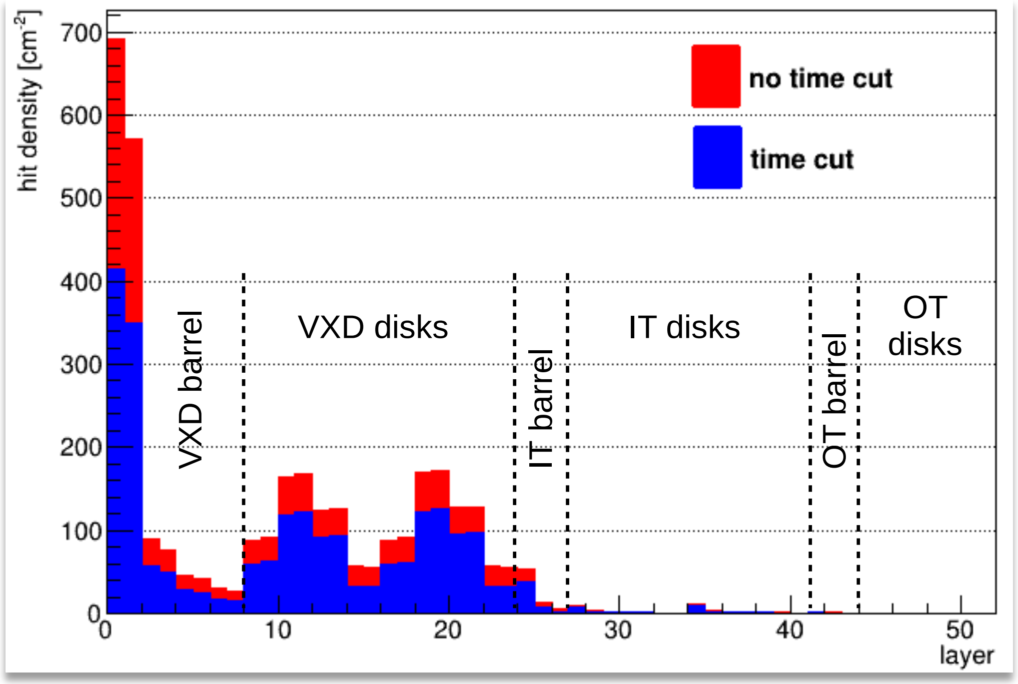
Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

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

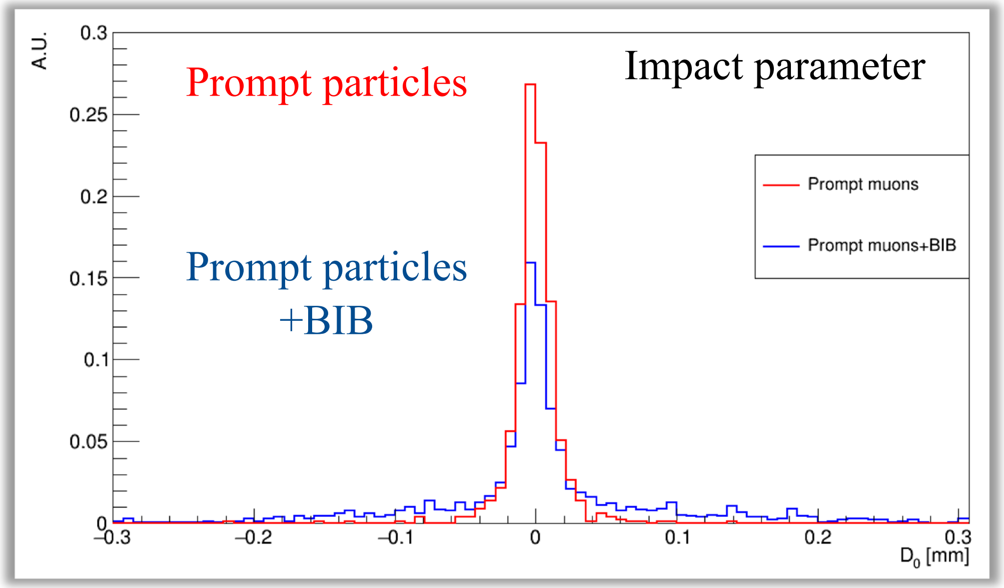
Tracking System

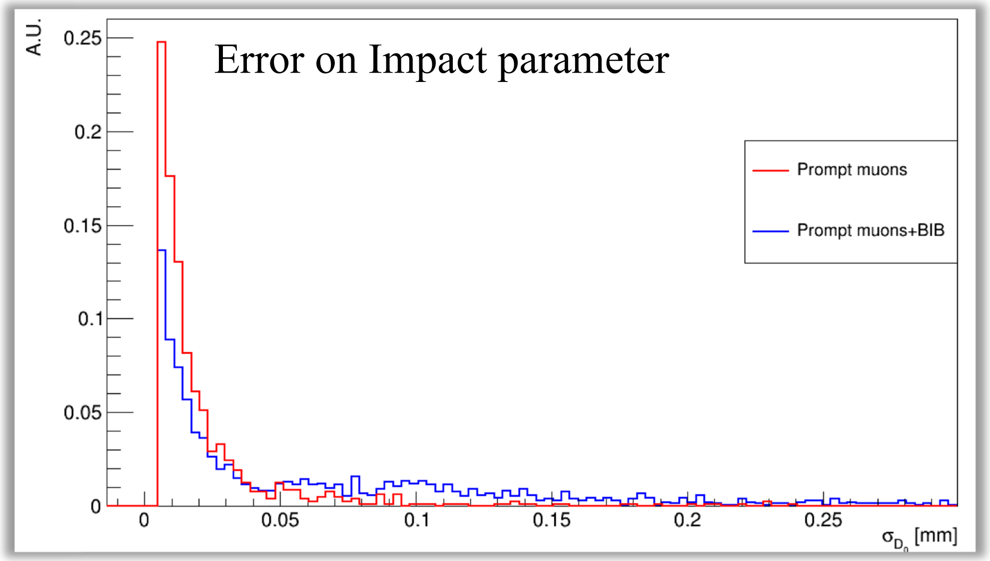
Effects of beam-induce background can be mitigated by exploiting “5D” detectors, i.e. including timing.

A ±150ps window at 50ps time resolution in the Vertex detector allows to strongly reduce the occupancy



BIB effects can be mitigated at reconstruction time:

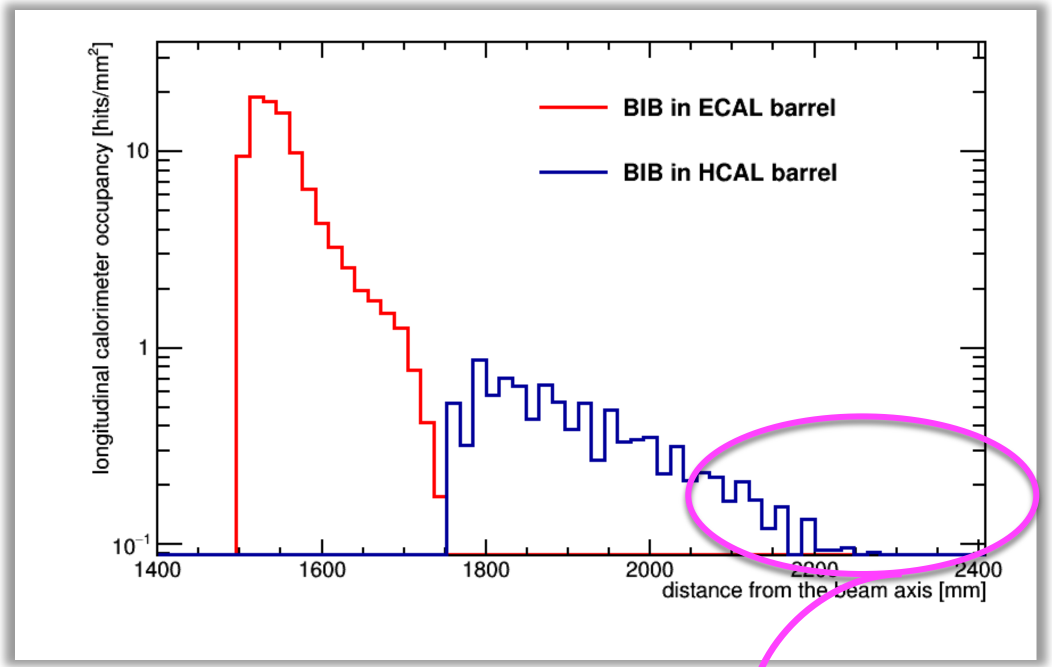




By requiring well reconstructed tracks BIB effects is minimized with almost no effect on the efficiency

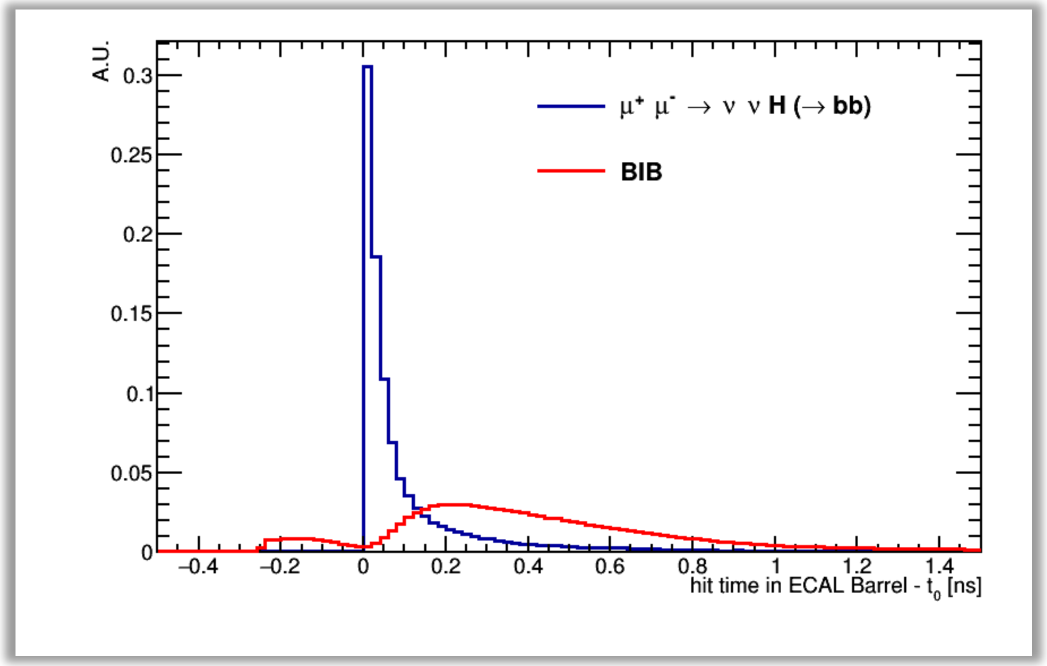
Calorimeter System

Calorimeter Occupancy

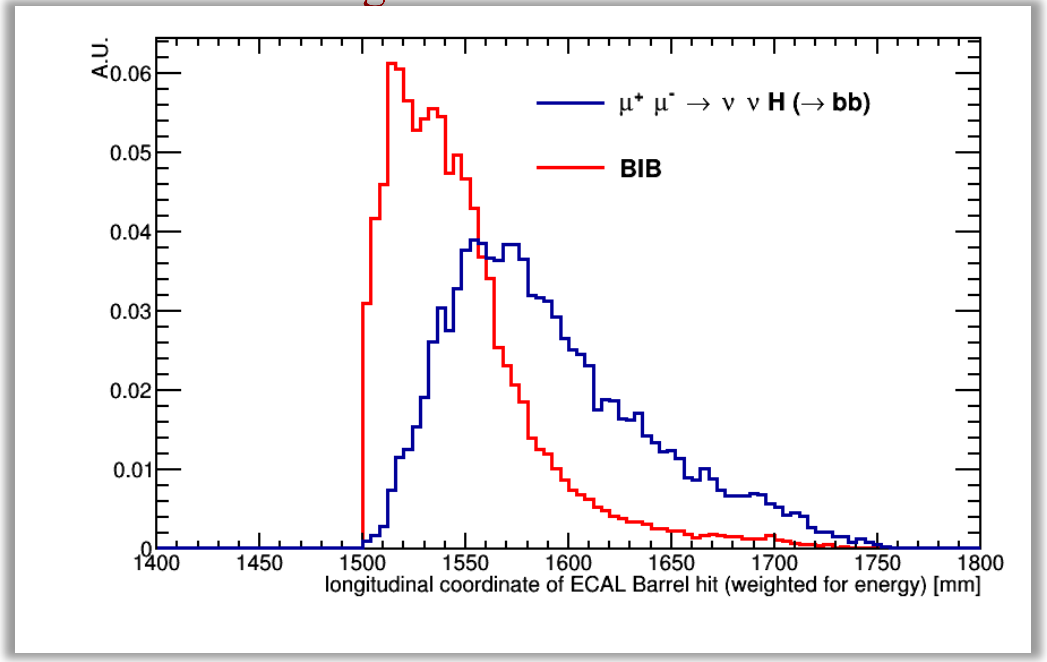


Few BIB hits arrive to the muon detectors

ECAL barrel hit arrival time – t_0



ECAL barrel longitudinal coordinate



These characteristics have to be exploited in order to:

- Optimize the jet reconstruction algorithm.
- Design the appropriate algorithm to identify b-jet.
- Propose an integrated method to efficiently reconstruct muons, in particular at very high momentum.

Data samples and Physics Generators

The studies at "low" energy ($\sqrt{s} = 1.5, 3$ TeV) can be done with the available generators: Pythia, WHIZARD, MadGraph,, tec.
The high energy signal and background generation has to be "verified" with experts to make sure all the processes are correctly evaluated

Available samples

Pythia:

- $\mu^+\mu^- \to HX, H \to fermions\ and\ bosons$
- Any physics background

$\sqrt{s} = 1.5, 3$ TeV

WHIZARD

- $\mu^+\mu^- \to HHX, H \to b\bar{b}, H \to b\bar{b}$
- $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$ inclusive
- $\mu^+\mu^- \to HHHX, H \to b\bar{b}, H \to b\bar{b}, H \to b\bar{b}$
- The physics background $\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ inclusive, needs theoretical developments, WHIZARD and MadGraph in progress

$\sqrt{s} = 1.5, 3, 10$ TeV

The path to high $\sqrt{s}$

Generate beam-induced background

Generate signal and physics background

Use the state of the art generators, collaborate with theoretical physicists

Study $\sqrt{s} = 1.5$ and 3 TeV
Infer properties at $\sqrt{s} = 10$ TeV

Combine Physics and beam-induced background

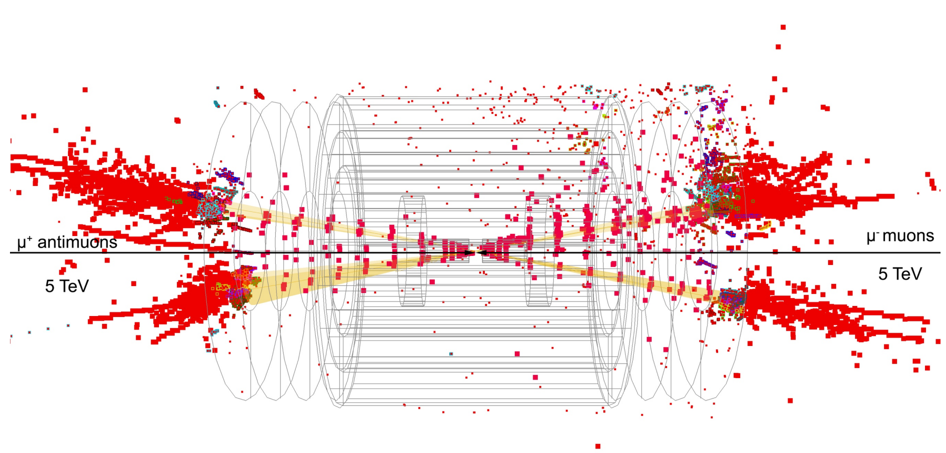
Optimize the detector design for high energy

Exploit future state of the art detectors

Design proper algorithms to reconstruct physics

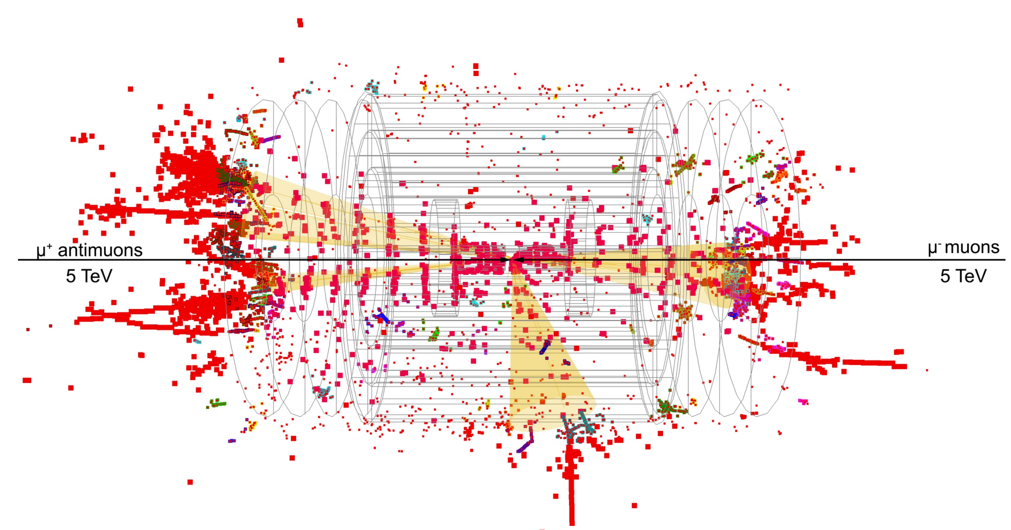
Design new reconstruction and identification algorithms: for example, multi-b-jets finale states with merged jets need fat-b-jets algorithms

√s=10 TeV



$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$

√s=10 TeV



$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$