Study of mitigation strategies of beam induced background and Higgs boson couplings measurements at a muon collider

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November 17, 2020

Higgs boson in the Standard Model

- Measurements of Higgs couplings to bosons and fermions at LHC are in agreement with SM
- Higgs potential shape is still far from being tested

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \qquad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2} \sim 0.13$$

- Direct measurement of λ_3, λ_4 are not possible at LHC (low production cross section), but are mandatory to tests the Higgs mechanism
- Precision achievable at Future Colliders is not sufficient to resolve Higgs boson potential

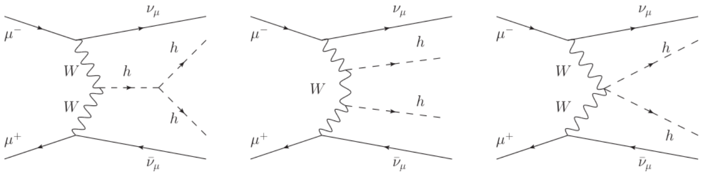
Introduction to muon collider

Advantages:

- muons are elementary particles
- synchrotron radiation and beamsstrahlung radiation are negligible

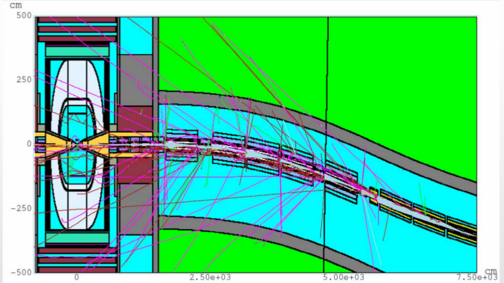
$\Rightarrow$ multi-TeV center of mass energy can be reached
$\Rightarrow$ high rates of H, HH, HHH

- In my thesis: demonstration that $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ (BR($H \to b\bar{b}$) = 58%) at $\sqrt{s}$= 3 TeV can be reconstructed.
- I evaluated the sensitivity on the HH production cross section, first step for the evaluation sensitivity on λ_3



Challenges

- Quick acceleration
- Muons decay! For a 0.75 TeV muon bunch of $2 \cdot 10^{12}$ muons, $\lambda_D = 4.7 \cdot 10^6 m \Rightarrow 4.28 \cdot 10^5$ decays/m



- $\mu^\pm \to e^\pm + \overset{(-)}{\nu}$
- Interactions with surrounding machine: photons, neutrons or hadrons
- Beam-induced background (BIB) reduction: tungsten nozzles

Detector description

Hadronic calorimeter (HCAL)
19 mm Fe absorber + scintillator (x 60)

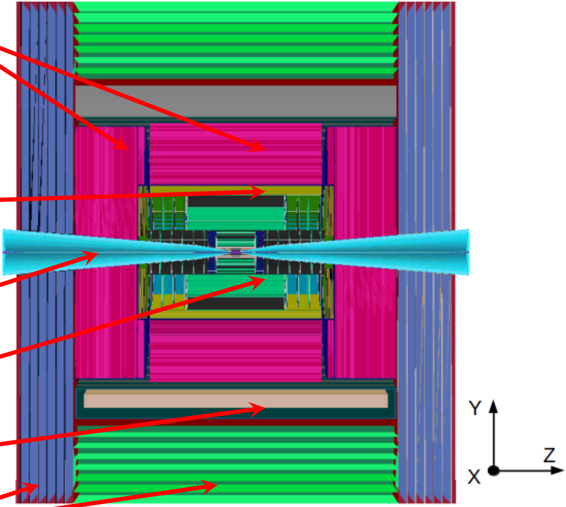
Electromagnetic calorimeter (ECAL)
1.9 mm W absorber + Si sensor (x 40)

Nozzles Optimized for $\sqrt{s}$=1.5 TeV

Tracker System

Superconducting solenoid (4T)

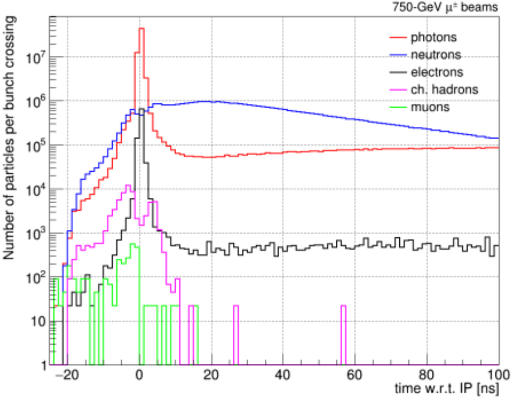
Muon Chambers



Beam-induced background characteristics

From studies of BIB at $\sqrt{s}$=1.5 TeV reaching the detector:

- Mostly photons (94%) and neutrons (4%), followed by electrons/positrons, charged hadrons and muons
- Spread in time with respect to the bunch crossing time



BIB reduction on detector components

- Large number of hits released by the beam-induced background particles in the innermost layers of the tracking system and vertex detector.
- Tuning of acquisition time window to reject hits released by BIB outside it.

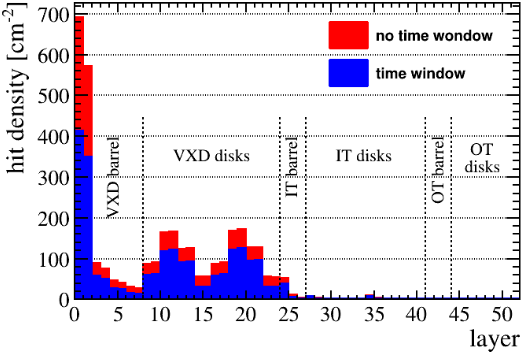
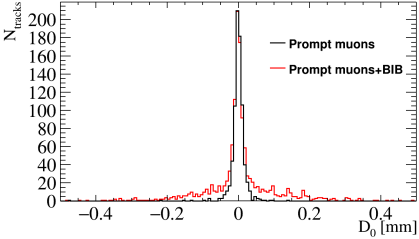
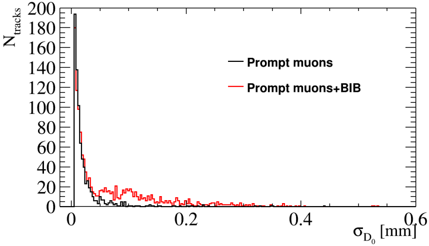


Figure: Tracker

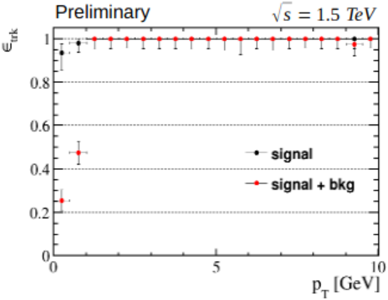
Effects of BIB on track reconstruction

Track reconstruction compared for prompt muons with and w/o BIB





- Cuts on reduced χ^2 and N_{hits} remove most BIB tracks
- Track parameters and their errors are compared
- Track efficiency: worsen for $p_T < 1$ GeV tracks



Double Higgs analysis

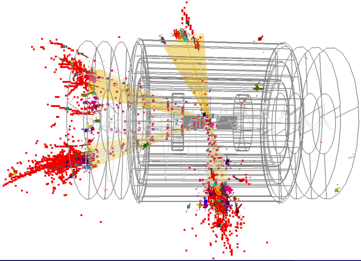
The presence of BIB worsen the b tagging efficiency:

- the b-tagging algorithm tuned to keep the BIB effects (fake secondary vertices) to negligible level
- b-tagging efficiency with BIB $\sim 60\%$ with a mis-tag $< 1\%$ at 1.5 TeV (see 2020 JINST 15 P05001)

Physics background considered: inclusive $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$:

- processes with jets in the final states different from the b quark negligible (one jet for each pair is required to be tagged)
- other physics background processes have very low cross section

Signal and background generated with WHIZARD Monte Carlo:



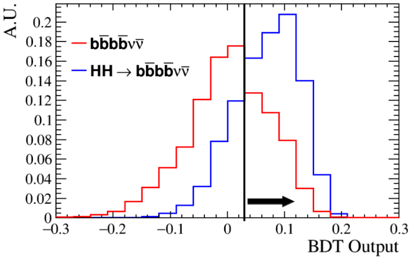
- event selection: $N_{jets}>3$, $p_T > 20$ GeV, jets paired minimizing distance from Higgs mass
- selection of the kinematic variables for classification (m_{H_1}, m_{H_2}, $\sum E_{jets}$, $\sum \vec{P}_T$, θ_{max})

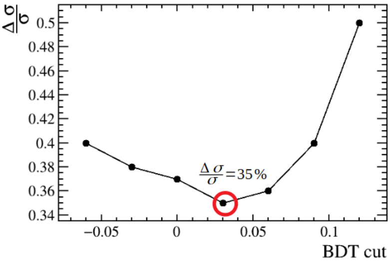
Evaluation of the cross section uncertainty

- Classification with Boosted Decision Tree (BDT)
- The sensitivity on the cross section is calculated by counting the number of signal (S) and background (B) events surviving cuts:

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \quad \Bigg| \quad \begin{array}{c} S = \sigma_{HH} \cdot BR(H \to b\bar{b})^2 \cdot L \cdot \epsilon_S \\ B = \sigma_{b\bar{b}b\bar{b}\nu\bar{\nu}} \cdot L \cdot \epsilon_B \end{array}$$

- σ_{HH} and $\sigma_{b\bar{b}b\bar{b}\nu\bar{\nu}}$ signal background cross section, ϵ_S and ϵ_B the selection efficiencies, $L = 1.3\ ab^{-1} = 4.4 \cdot 10^{34}\ cm^{-2}s^{-1} \cdot 4 \cdot 10^7$ s

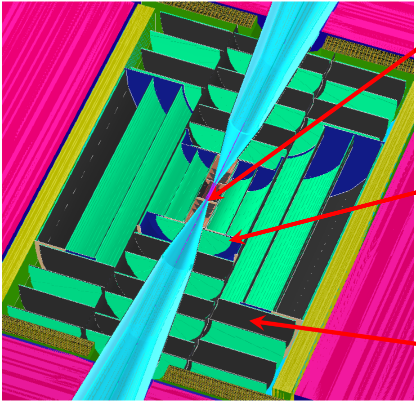




Conclusions and perspectives

- In my master's thesis I demonstrated with a full simulation that it is possible to reconstruct $\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$ process at $\sqrt{s} = 3$ TeV taking into account the effect of the beam-induced background
- My result is a sensitivity on the HH production cross section of 35%
- In these month I am working to conclude the analysis and publish the results in a paper.

Tracker Detector



Vertex detector

- 4 double-sensor barrel layers $25 \times 25 \mu m^2$
- 4+4 double-sensor disks "

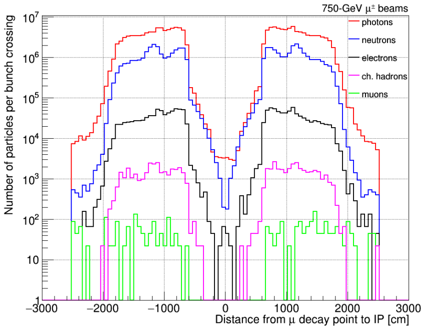
Inner tracker detector

- 3 barrel layers $50 \times 50 \mu m^2$
- 7+7 disks "

Outer tracker detector

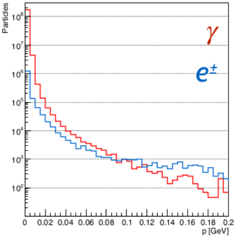
- 4 double-sensor barrel layers $25 \times 25 \mu m^2$
- 4+4 double-sensor disks "

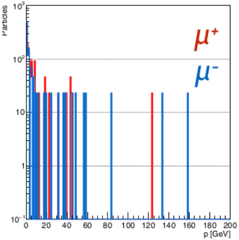
BIB characteristics

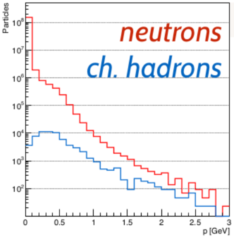


From studies of beam-induced background at $\sqrt{s}$=1.5 TeV reaching the MDI surface:

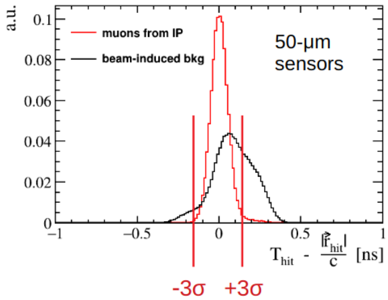
- Relatively soft momenta: $< p_{ph.} >= 1.7$ MeV, $< p_{el.} >= 6.4$ MeV, $< p_{n.} >= 477$ MeV, $< p_{ch.had.} >= 481$ MeV, higher for muons.

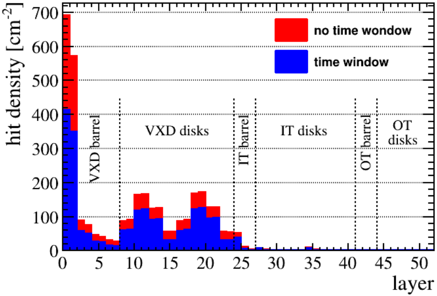




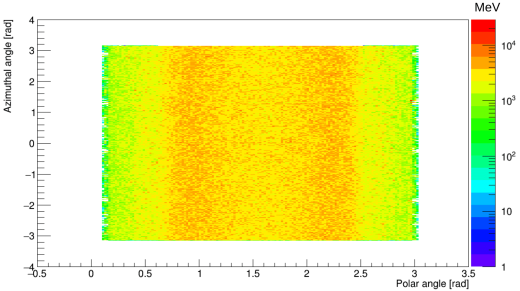


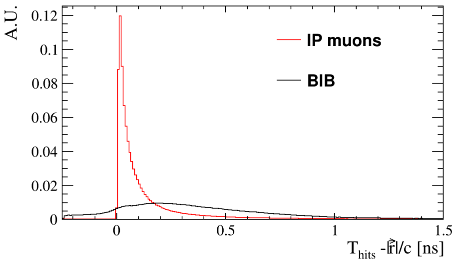
BIB reduction on tracker

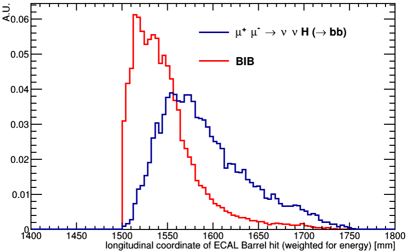




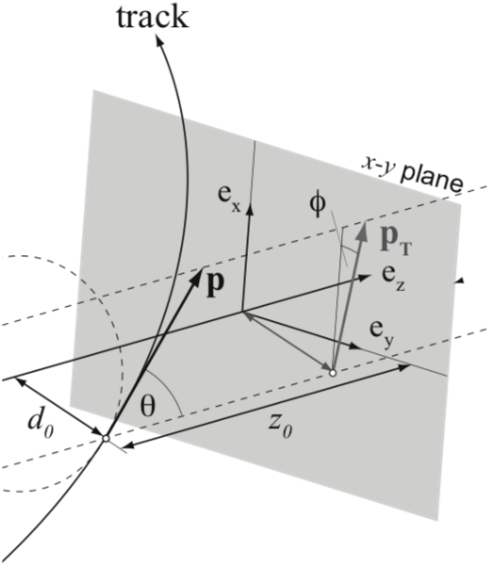
Effects of beam-induced background on calorimeter







Track parameters



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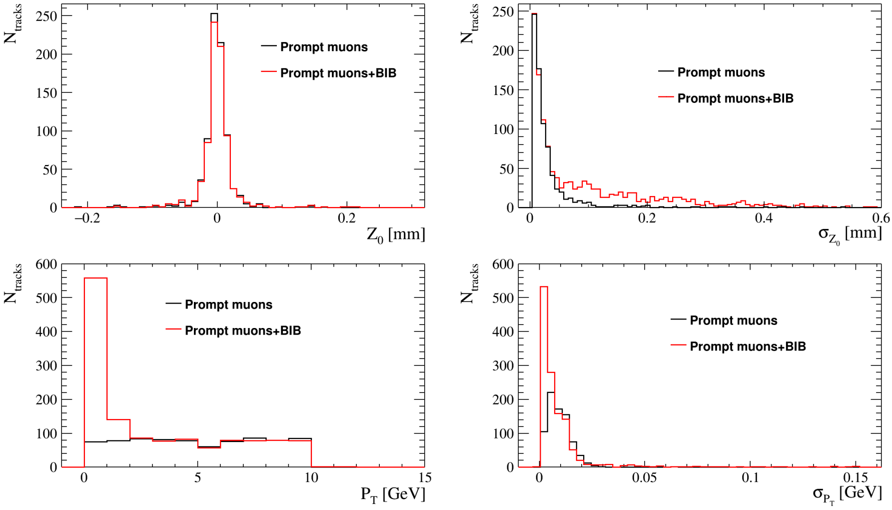

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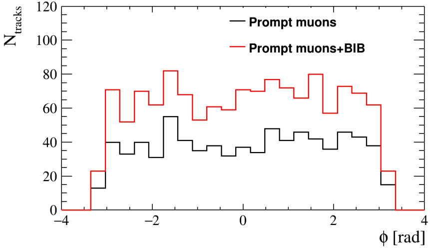
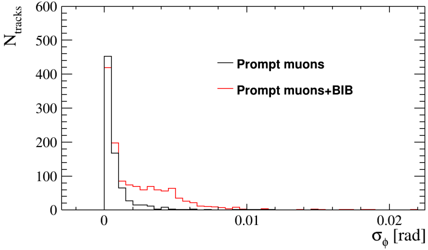
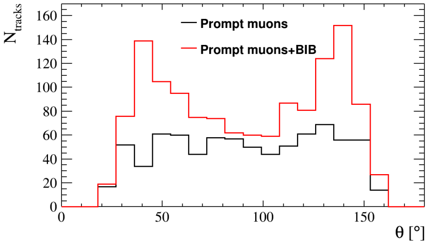
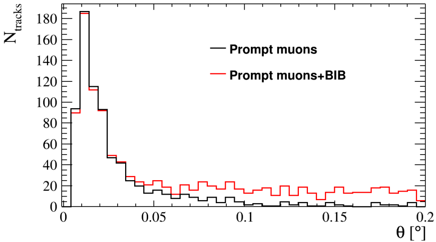








Electroweak lagrangian

With the introduction of the Higgs field, the full electroweak Standard Model lagrangian is then:

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$W^{\pm}$,Z γ kinetic energies and self-interacions

$$+\bar{L}\gamma^{\mu} \left(i\partial_{\mu} - g\frac{1}{2}\tau W_{\mu} - g' \frac{Y}{2} B_{\mu} \right) L$$
$$\bar{R} \left(i\partial_{\mu} - g' \frac{Y}{2} B_{\mu} \right) R$$

lepton and quark kinetic energies and interactions with $W^{\pm}$,Z,γ

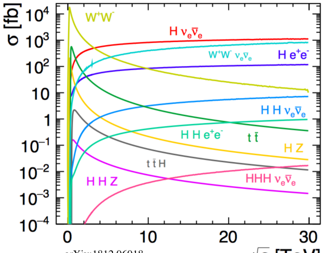
$$+ \left| \left(i\partial_{\mu} - g\frac{1}{2}\tau W_{\mu} - g' \frac{Y}{2} B_{\mu} \right) \phi \right|^2 - V(\phi)$$

$W^{\pm}$,Z and Higgs masses and couplings

$$-G_i(\bar{L}\phi R + \bar{R}\phi L)$$

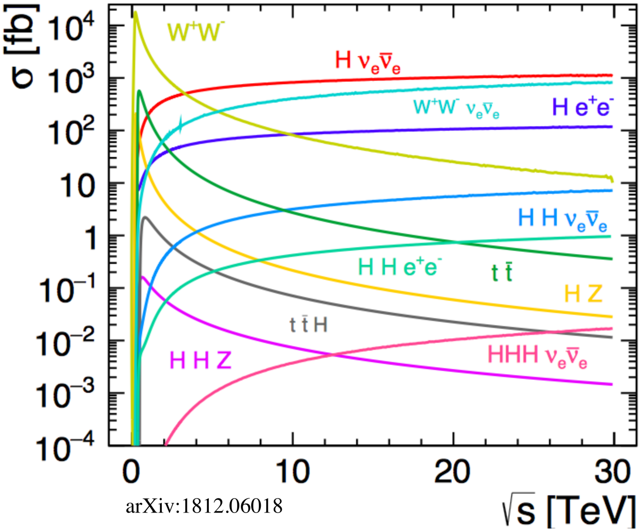
lepton and quark masses and couplings to Higgs

- CLIC with 5 ab^{-1} at $\sqrt{s} = 3$ TeV can measure λ_3 with an uncertainty of -7% and +11% using HH events (arXiv:1901.05897v2).
- Sensitivity of FCC-hh to the measurement of λ_4 using HHH events, after full operations: -2 $< \lambda_4/\lambda_4^{SM} <$ +13 at 68% CL (arXiv:1909.09166).



- At multi-TeV, a muon collider is basically a W^+W^- collider: high yields of single H, HH and HHH events.
- Sensitivity of MC at 10 ab^{-1} and $\sqrt{s}$=10 TeV to the measurement of λ_3: 5.6%.
- Sensitivity of MC at 14 TeV with 33 ab^{-1} to the measurement of λ_4: 50%.

Higgs potential



arXiv:1812.06018

Study of double Higgs events at $\sqrt{s}$= 3 TeV

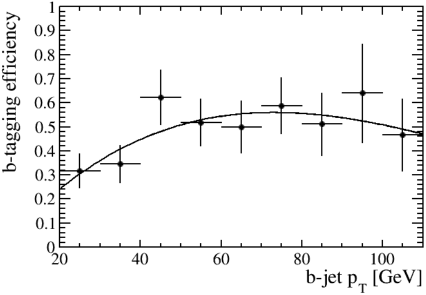
Some considerations:

- analysis performed not in the presence of BIB, as not available at $\sqrt{s}$=3 TeV;
- Previous studies at $\sqrt{s}$= 1.5 TeV are used to take into account for BIB.

Effects of beam-induced background on jet reconstruction and *b*-tagging studied at $\sqrt{s}$=1.5 TeV in 2020 JINST 15 P05001:

- jet reconstruction and *b*-tagging algorithms optimized for beam-induced background reduction;
- reconstruction of $\sim$ 25% fake jets;
- fake secondary vertices: $\sim$ 1% of mis-tag.

Study of double Higgs events at $\sqrt{s}$= 3 TeV



b-tagging efficiencies have been used for the analysis of the double Higgs at $\sqrt{s}$=3 TeV. Conservative assumptions:

- amount of beam-induced background particles decreases as the center of mass energy increases;
- nozzles angles lower at $\sqrt{s}$=3 TeV;
- negligible fake jet rate is assumed since the Particle Flow algorithm is used at $\sqrt{s}$=3 TeV.

Studies of double Higgs

- Jets paired by minimizing:

$$\sqrt{(m_{ij} - m_H)^2 + (m_{kl} - m_H)^2}$$