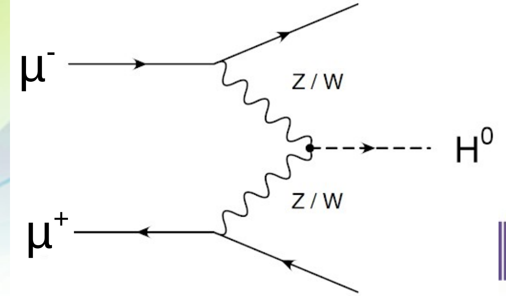
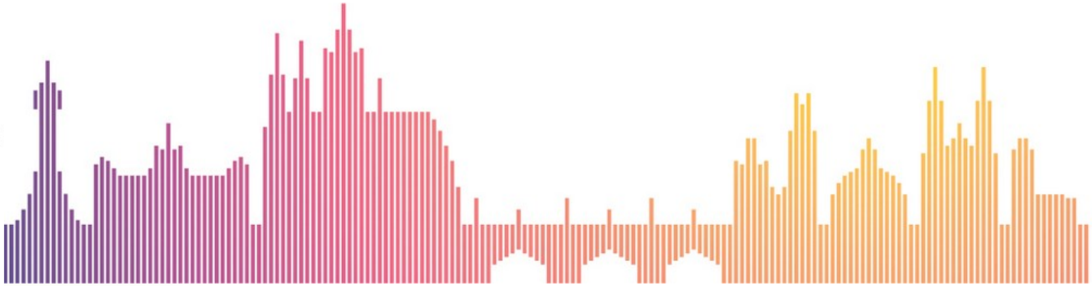
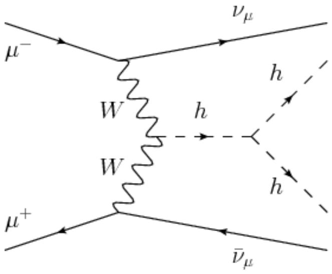
# Higgs physics possibilities at a Muon Collider







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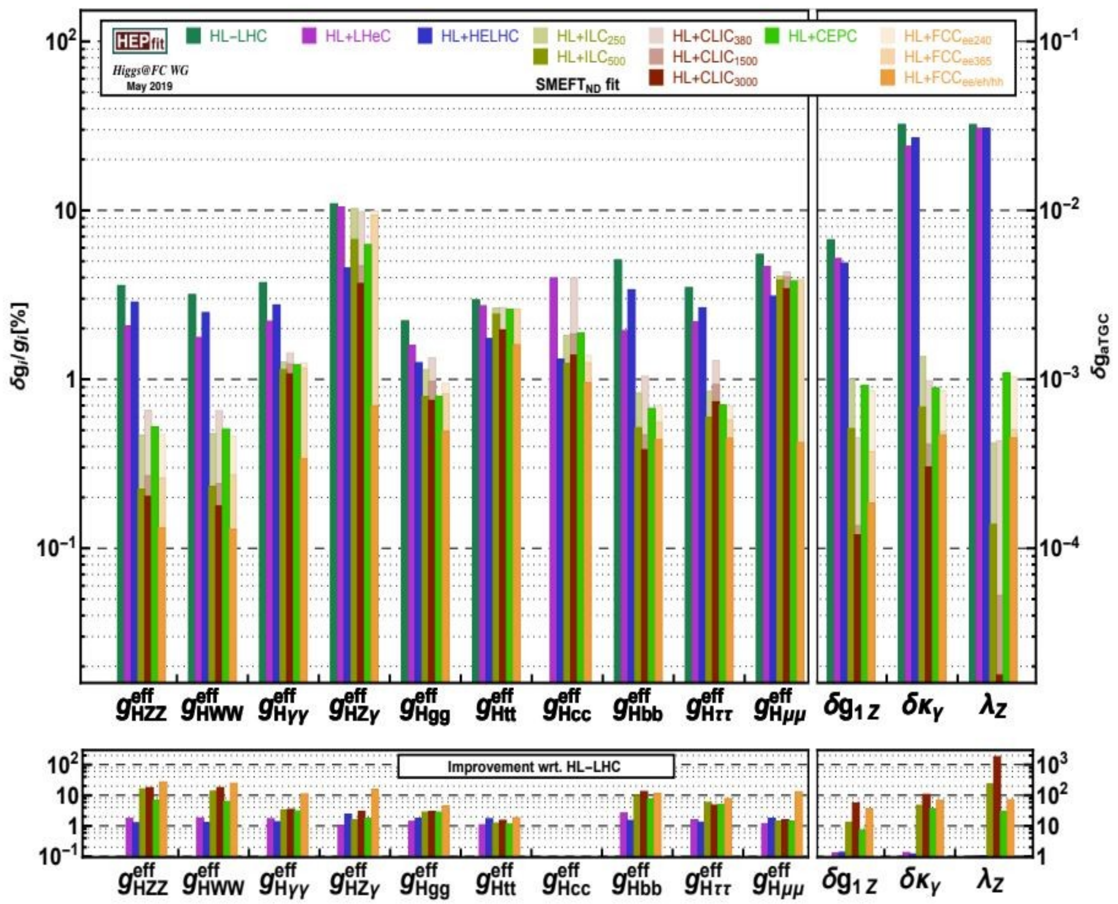
**On behalf of the International Muon Collider Collaboration**



**ICHEP2020, Prague-online, 31-07-2020**

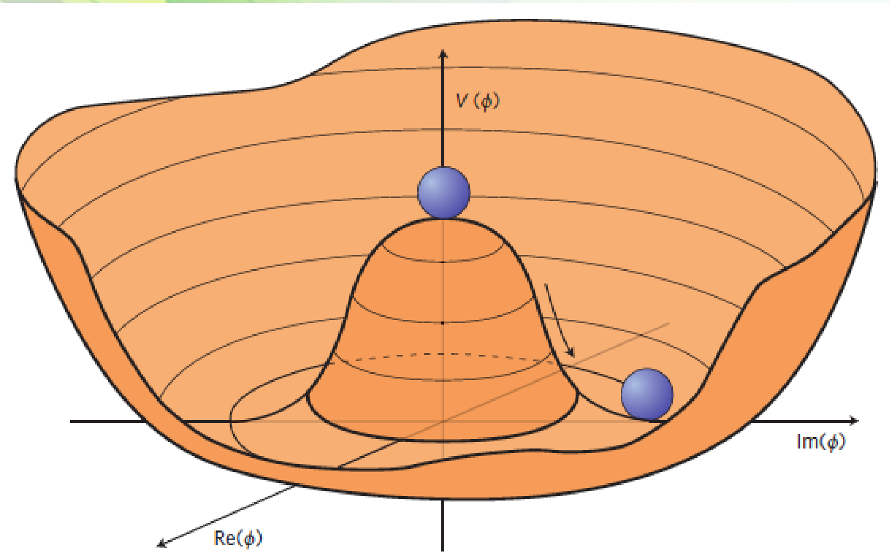
# Higgs @ Future Colliders




- One of the goal of future colliders is the precise measurement of Higgs couplings with SM particles.
- **They can push our knowledge of the couplings below the 1% precision scale**.
- As an example FCC-ee and CEPC can measure the H→ZZ coupling to the ~0.3% precision.
- This will allow to test several new physics scenarios!

# Higgs potential

- Is **our Higgs boson that Higgs boson**?
- The Electroweak Symmetry Breaking and the mass generation are ruled by the **Higgs potential**.



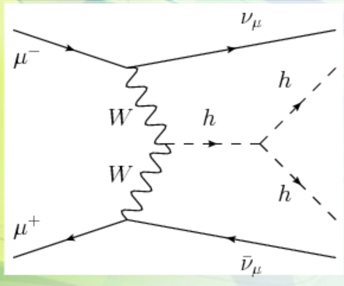

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4,$$

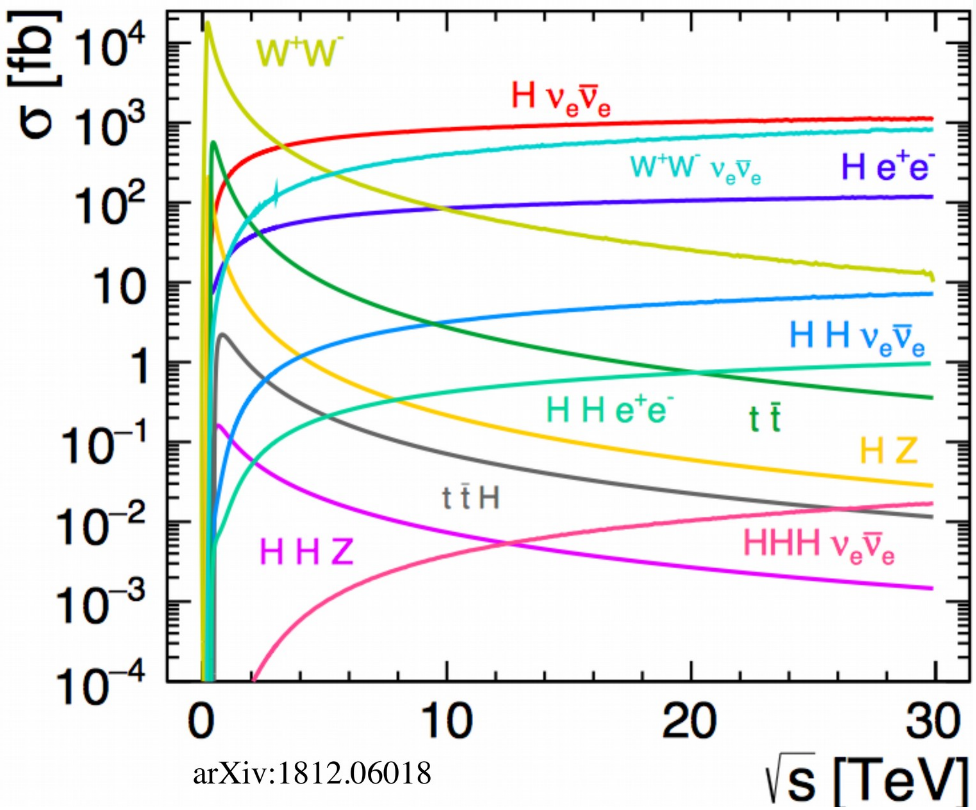
SM

$$\lambda_3 = \lambda_4 = m_H^2 / 2v^2 \equiv \lambda_{SM}$$

- Up to now there are no measurements of the Higgs potential, apart from the Higgs mass term.
- This means that **the physics of the EWSB is experimentally unexplored**.
- Remember that we still have no ideas on how the EWSB happened at cosmological level, how the neutrinos gained mass, how the mass from the General Relativity is connected to the Quantum Field Theory...
- **CLIC with 5 ab$^{-1}$ at $\sqrt{s}$ = 3 TeV can measure $\lambda_3$ with an uncertainty of -7% and +11% using HH events (**arXiv:1901.05897v2**).**
- **Sensitivity of FCC-hh to the measurement of $\lambda_4$ using HHH events, after full operations: $-2 < \lambda_4/\lambda^{SM}_4 < +13$ at 68% CL (**arXiv:1909.09166**).**

# Higgs @ Muon Collider



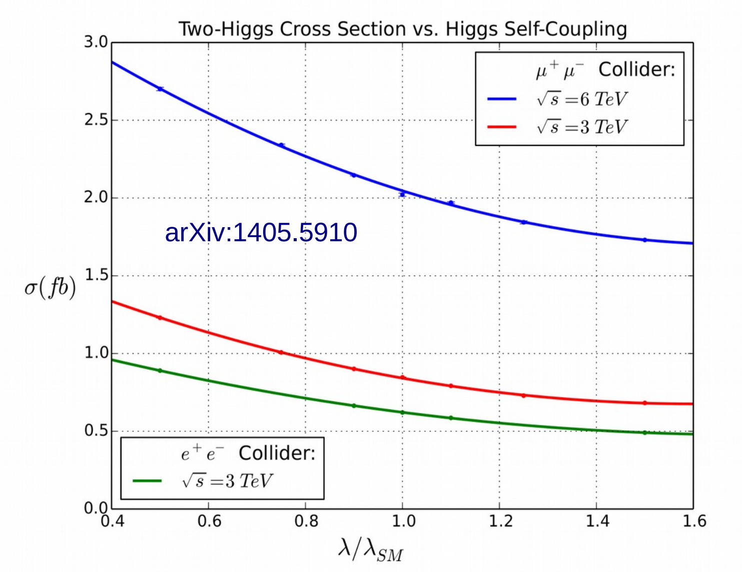

arXiv:1812.06018

- **The muon collider is the dream machine for Higgs physics measurements**:
  - Clean events as in $e^+e^-$ colliders
  - High collision energy as in hadron colliders (very low radiation losses)

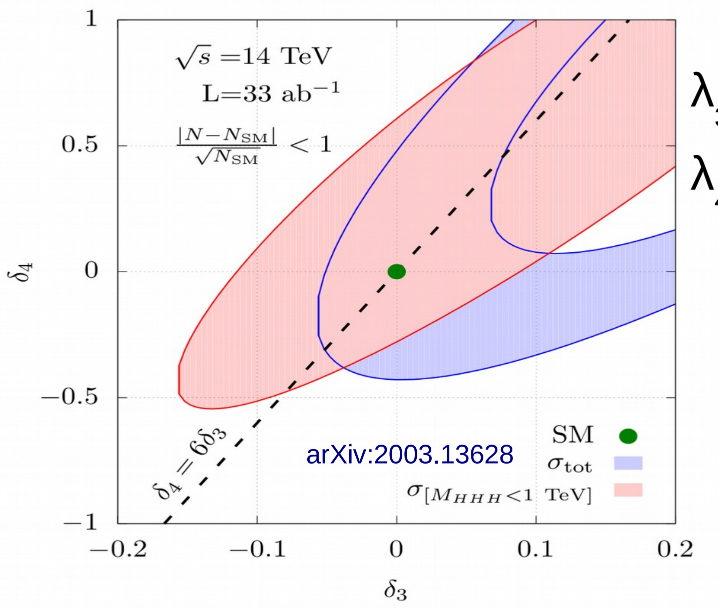
- At multi-TeV, a muon collider is basically a $W^+W^-$ collider: it will be possible to produce high yields of single H, HH and HHH events

- Technological challenges for both machine and detectors, but the project is gaining momentum:
  - Talk by Jaroslaw Pasternak on Muon Cooling → July 29 Accelerator session
  - Talk by Daniel Schulte on Accelerator Complex → July 29 Accelerator session
  - Talk by Francesco Collamati on Machine Detector Interface → July 29 Accelerator session
  - Talk by Massimo Casarsa on Detector → July 29 Future Detectors session

# Higgs @ Muon Collider




- What are the Muon Collider's advantages with respect to other Future Machines?
- The HH cross section at a Muon Collider is higher with respect to CLIC, at the same center-of-mass energy → **different initial state radiation!**




$\lambda_3=(1+\delta_3)\lambda_3^{SM}$

$\lambda_4=(1+\delta_4)\lambda_4^{SM}$

- First phenomenological studies show that at 14 TeV, with 33 ab$^{-1}$, the MC can measure the SM quadrilinear coupling with an uncertainty of 50%.
- **But what about the detector effects?**

# Detector challenges

- Detector performance at a Muon Collider is strongly limited by the **Beam-Induced Background (BIB)**:
  - Decays of muons in the circulating beams generate electrons, positrons and neutrinos
  - interactions of such particles with the machine and MDI can produce secondary particles like photons, neutrons or hadrons

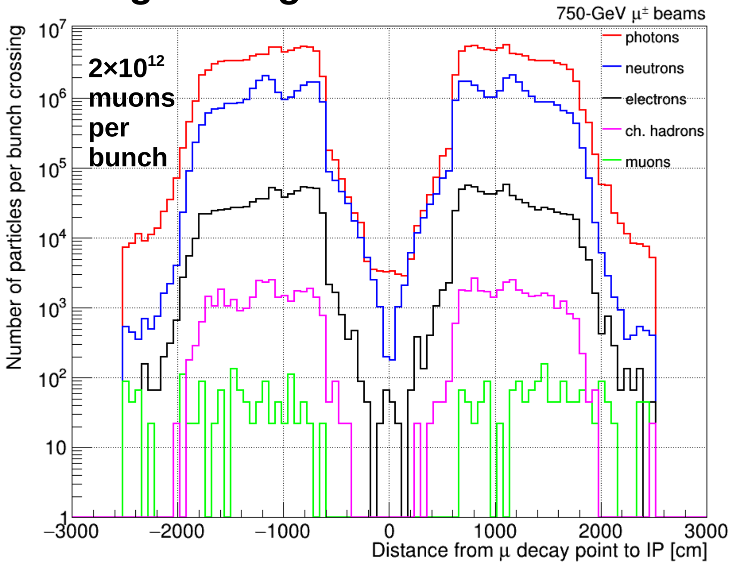
- This could pose serious limitations on the physics reach: **MDI, detectors and reconstruction algorithms should be developed in order to mitigate the BIB**.

- The Muon Accelerator Program (MAP) collaboration proposed to put **two tungsten cone-shaped nozzles** in order to reduce the BIB at the interaction point.

- **BIB is asynchronous wrt bunch crossing**: 5D sensors that can measure position, energy and time can reject part of it.

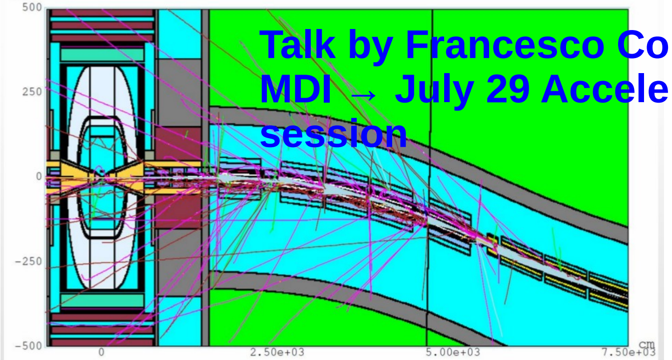
- **Full simulation studies are mandatory!**

**Background generated with MARS15**




**Available at √s=1.5 TeV. BIB at higher energies will be produced soon.**

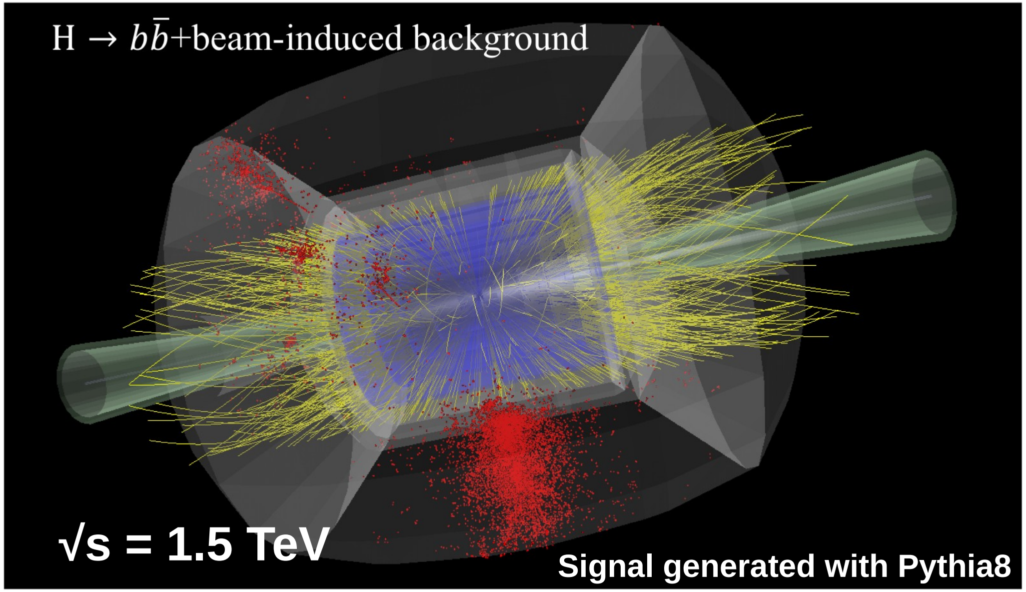
**Machine detector interface**

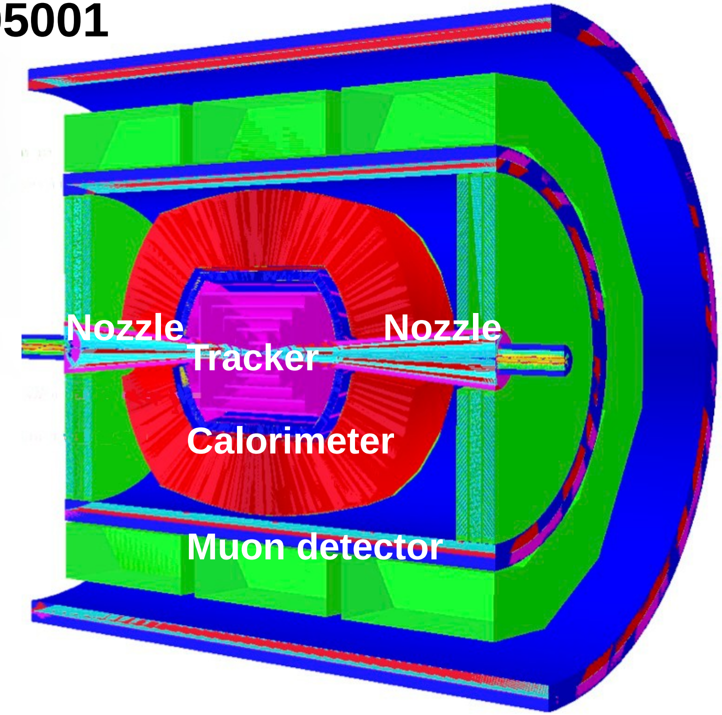


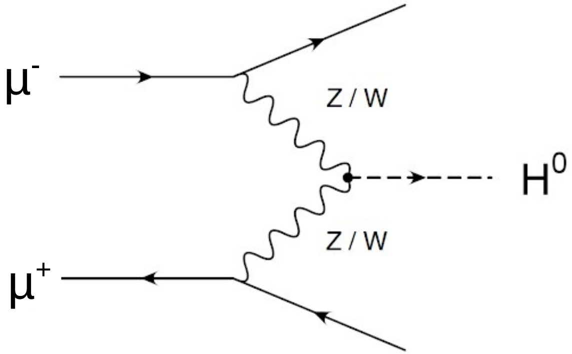
**Talk by Francesco Collamati on MDI → July 29 Accelerator session**

# $\mu^+\mu^- \rightarrow \nu\bar{\nu}\ H(\rightarrow b\bar{b})$

## 2020 JINST 15 P05001



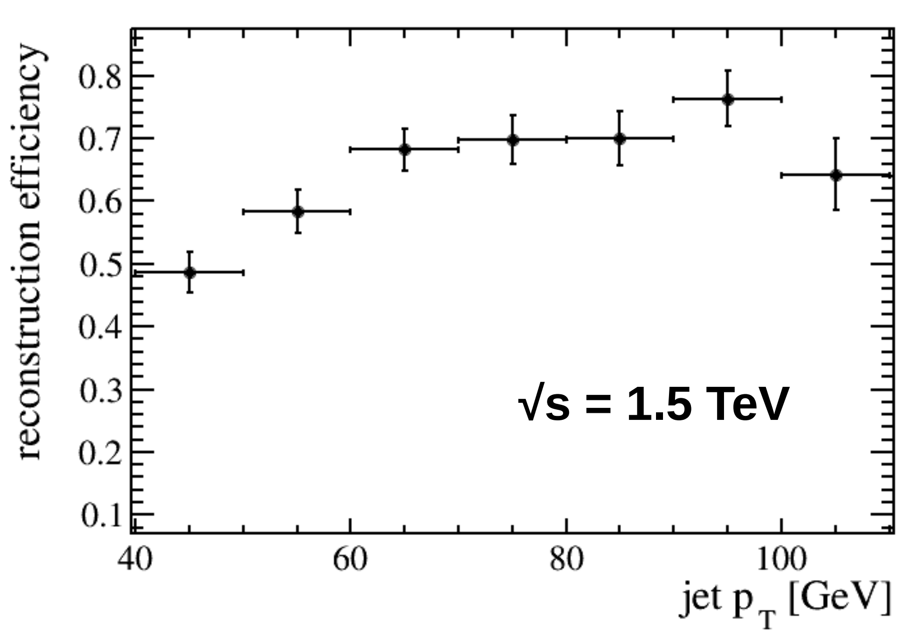



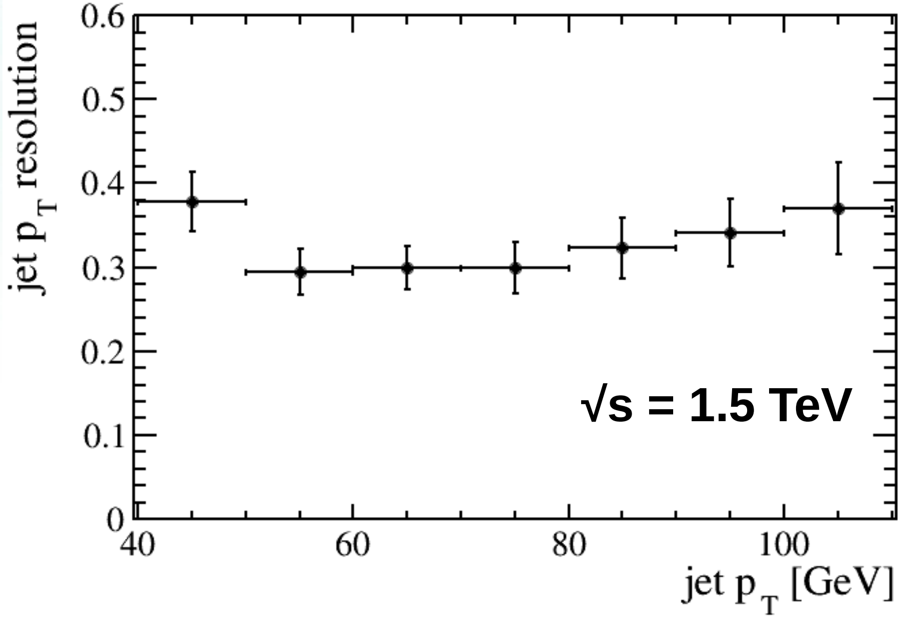




- We studied the $\mu\mu \rightarrow \nu\nu\ H(\rightarrow bb)$ production at a MC
- The goal is to determine the **sensitivity to the cross section measurement and to the Hbb couping determination**
- In the full simulation (Geant4) we used the detector developed by the MAP collaboration → not optimized for the full event reconstruction

# Jet reconstruction

**2020 JINST 15 P05001**



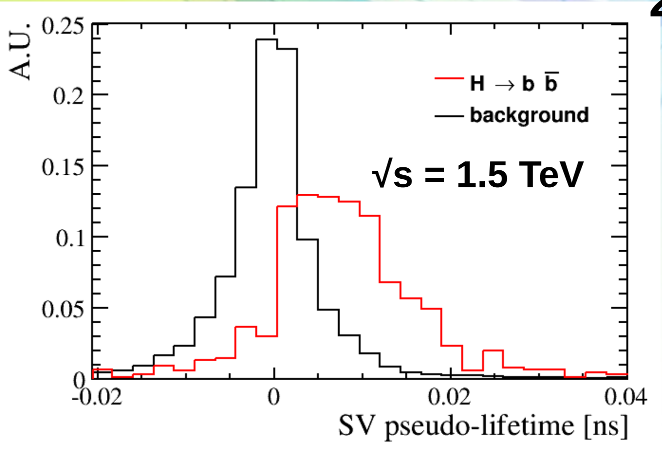

- A rough jet reconstruction algorithm is used:
  - **BIB is subtracted on a statistical basis from the calorimeter cells**
  - A cone algorithm with R=0.5 is used to cluster jets in the calorimeter
  - A jet energy correction is applied

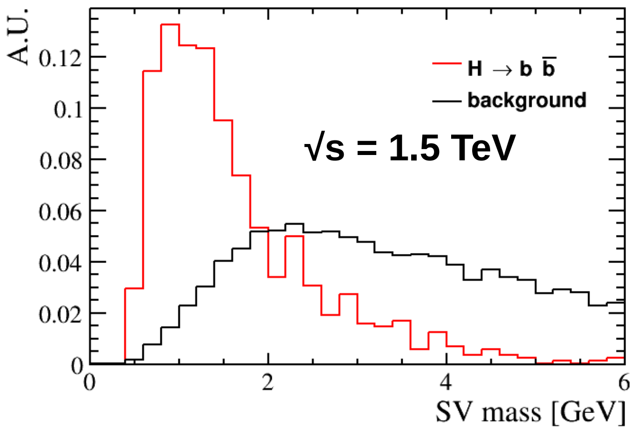
- We demonstrated that we are able to reconstruct jets with $p_T$>40 GeV, with decent performance

- Fake-jet rate ~15% → tagging is needed!

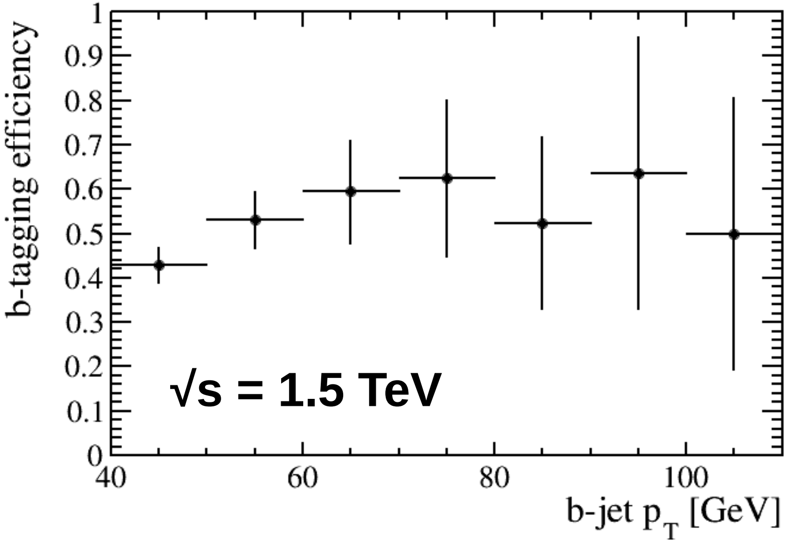
# b-jet tagging

2020 JINST 15 P05001

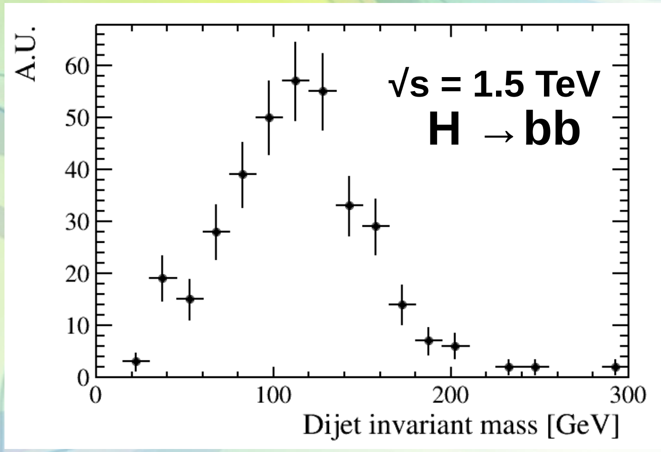



- **Secondary vertices (SV) compatible with b-hadron decays are reconstructed using tracks inside the jet cone.**
- Further cuts can be applied on SV observables to remove fake tags from the BIB combinatorial.
- We are able to tag b-jets with a ~60% efficiency and 1-3% of mis-identification.



# Cross section and Hbb coupling
**2020 JINST 15 P05001**




Two b-tagged jets with $p_T$>40 GeV, |η|<2.5 are selected

- **As a conservative approach we applied the efficiencies obtained at √s = 1.5 TeV to the 3.0 and 10 TeV case → BUT the BIB yield is expected to be lower at higher energies.**
- We assumed **4 Snowmass years of data taking**, at the luminosities expected by MAP.
- Cross section sensitivity obtained with $\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N+B}}{N}$,
- Hbb coupling sensitivity $\frac{\Delta g_{Hbb}}{g_{Hbb}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g^2_{HWW}}{\Gamma_H}}{\frac{g^2_{HWW}}{\Gamma_H}}\right)^2}$,

Taken from CLIC expectation

## Physics backgrounds

| Process |
|---|
| $\mu^+\mu^- \rightarrow \gamma^*/Z \rightarrow q\bar{q}$ |
| $\mu^+\mu^- \rightarrow \gamma^*/Z\gamma^*/Z \rightarrow q\bar{q}$ +X |
| $\mu^+\mu^- \rightarrow \gamma^*/Z\gamma \rightarrow q\bar{q}\gamma$ |

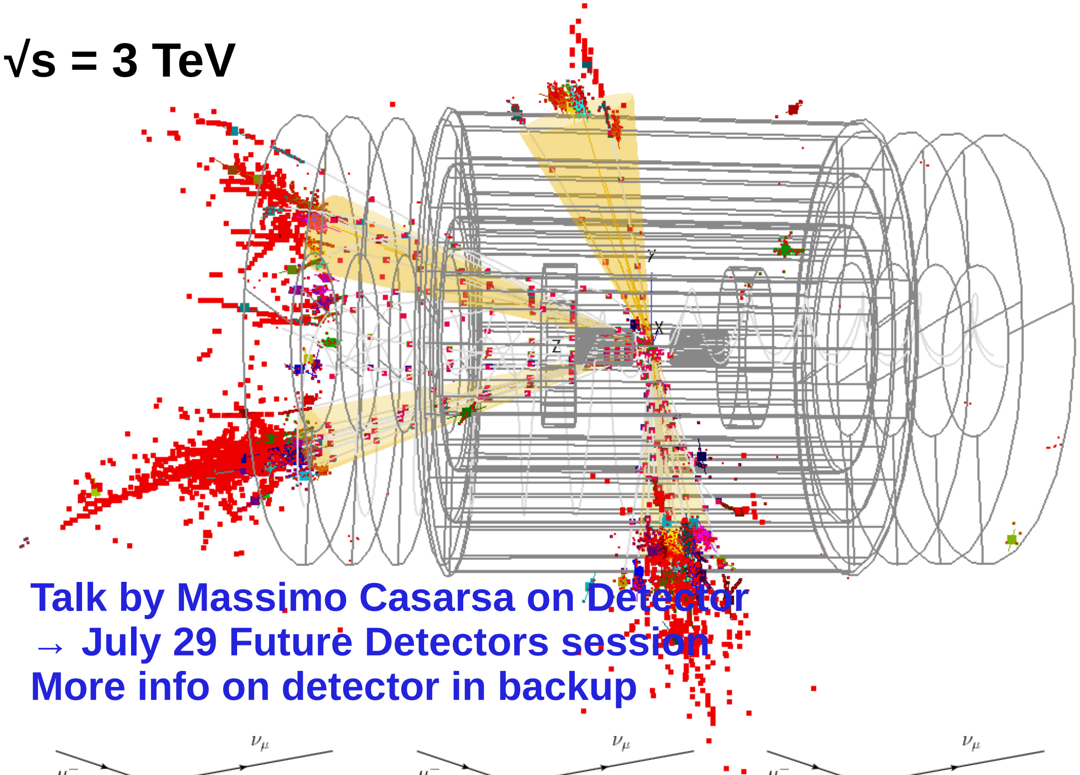
| $\sqrt{s}$ [TeV] | $A$ [%] | $\epsilon$ [%] | $\mathcal{L}$ [cm$^{-2}$s$^{-1}$] | $\mathcal{L}_{int}$ [ab$^{-1}$] | $\sigma$ [fb] | $N$ | $B$ | $\frac{\Delta\sigma}{\sigma}$ [%] | $\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%] |
|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 35 | 15 | $1.25 \cdot 10^{34}$ | 0.5 | 203 | 5500 | 6700 | 2.0 | 1.9 |
| 3.0 | 37 | 15 | $4.4 \cdot 10^{34}$ | 1.3 | 324 | 33000 | 7700 | 0.60 | 1.0 |
| 10 | 39 | 16 | $2 \cdot 10^{35}$ | 8.0 | 549 | 270000 | 4400 | 0.20 | 0.91 |

**At 3 TeV the Hbb coupling sensitivity is compatible with the one expected by CLIC, but very conservative assumptions have been done!**

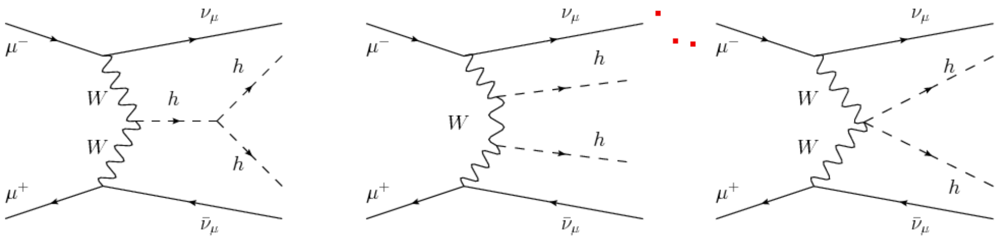
# $\mu^+\mu^- \rightarrow \nu\bar{\nu}\ H(\rightarrow b\bar{b})\ H(\rightarrow b\bar{b})$

## PRELIMINARY

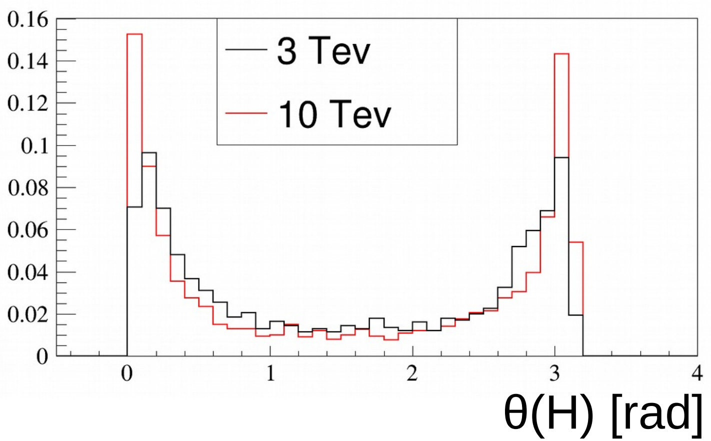
√s = 3 TeV



**Talk by Massimo Casarsa on Detector → July 29 Future Detectors session**
**More info on detector in backup**

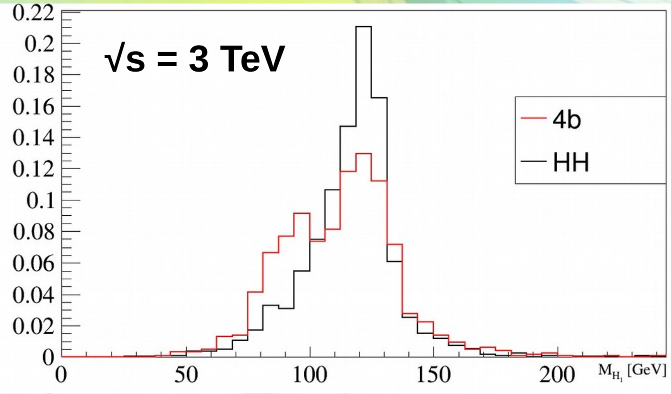



- Next step: **study of the HH production.**
- We are now using a **modified version of the CLIC detector**, with nozzles and a different vertex detector, using the ILCSoft framework for the full simulation and reconstruction.
- Signal and backgrounds are generated with WHIZARD.
- Higgs is likely to be emitted in the forward region.

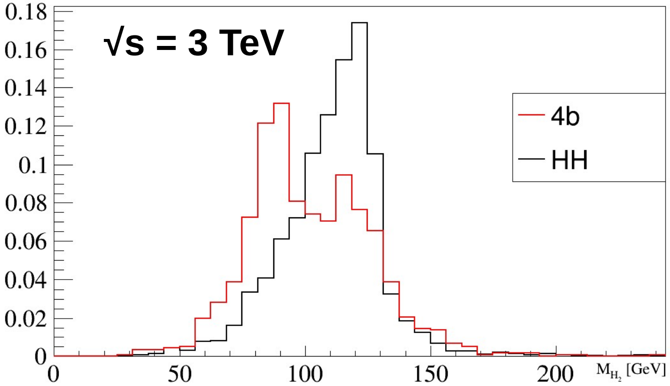


# Double Higgs kinematics

## PRELIMINARY

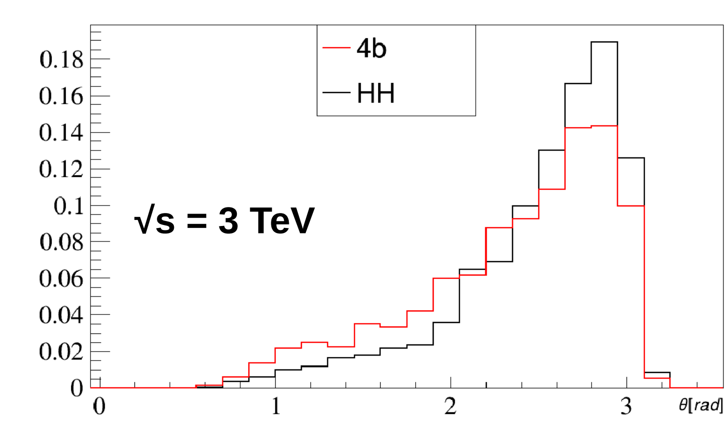



**Dijet mass of the Higgs with highest $p_T$**




**Dijet mass of the second Higgs**

**$b\bar{b}b\bar{b}$ background is mainly dominated by ZZ and H+bb events.**

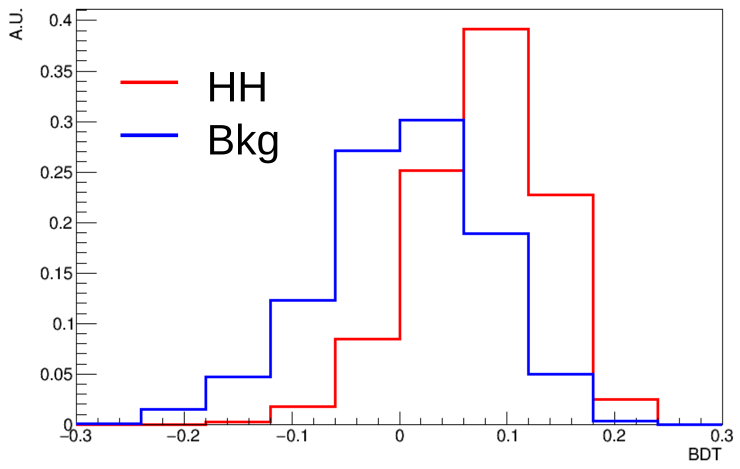


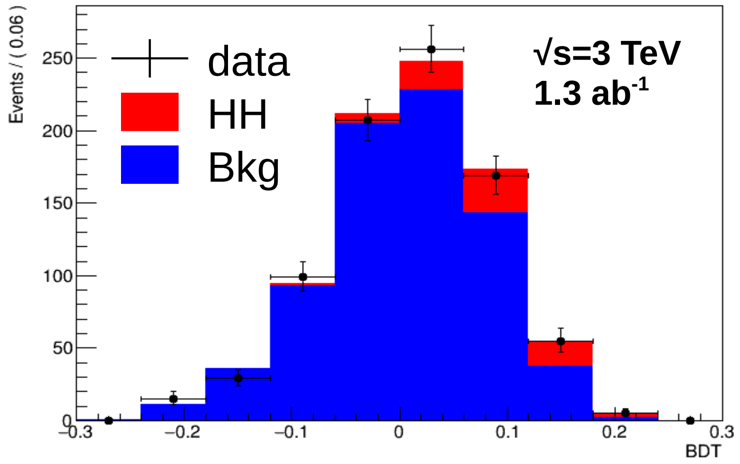

**Maximum angle between the jets**

- **Particle Flow algorithm to reconstruct jets.**
- Events with at least 4 jets with $p_T$>20 GeV are selected.
- A jet pair is assigned to a Higgs depending on the dijet invariant mass compatibility with the nominal Higgs mass.
- In addition to the H masses, **angular observables can be used to separate signal from background**.

# HH cross section measurement

**PRELIMINARY**




- As a first attempt to estimate the HH cross section uncertainty at 3 TeV, we applied the tagging efficiencies obtained in the 1.5 TeV case → **Again this is very conservative!**
- A 5-observable Boosted Decision Tree has been trained to separate signal from background.
- **With 1.3 $ab^{-1}$ (4 years of data taking) at 3 TeV we expect to select 67 HH events and 745 background events.**
- With a simple fit to the BDT → **An uncertainty of 33% on the cross section has been obtained**.

# Conclusions and Perspectives

- **The Muon Collider is the dream machine for Higgs Physics.**

- It may allow the measurement of the Higgs potential and couplings with an excellent precision.

- Full simulation studies to determine the Muon Collider Physics reach are ongoing.

- **We demonstrated that with a 3 TeV Muon Collider we can measure in 4 years the Hbb coupling with a precision comparable to CLIC.**

- **Studies on the measurement of the HH cross section are on-going:**
  - With conservative assumptions we can already obtain good results

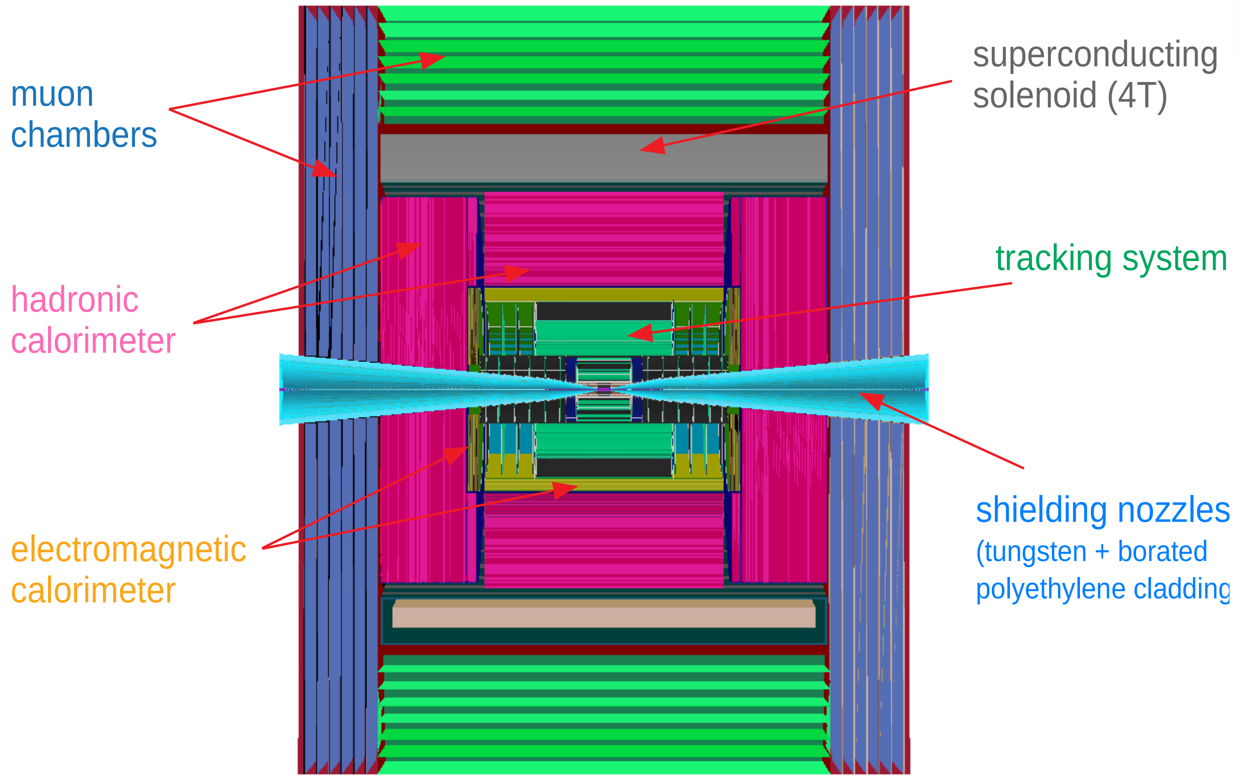
- **This is just the beginning: there are a lot of rooms for detector improvements!**

# Backup

# Design a detector at √s = 1.5 TeV

For detector studies we are currently using **ILCSoft**, which will be part of the common software for future colliders → Key4hep

Modified version of CLIC detector: we included two nozzles, we adapted the forward tracking station to them, we modified the Vertex detector geometry




Vertex Detector (VXD)
- 4 double-sensor barrel layers $25x25\mu m^2$
- 4+4 double-sensor disks ”

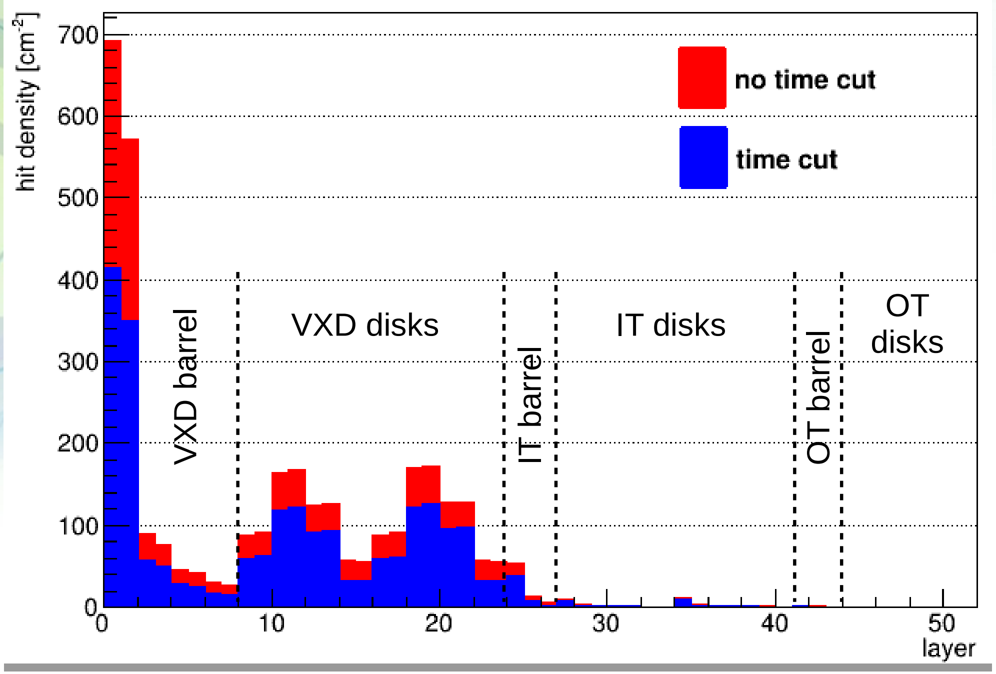
Inner Tracker (IT)
- 3 barrel layers $50x50\mu m^2$
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers $50x50\mu m^2$
- 4+4 disks ”

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

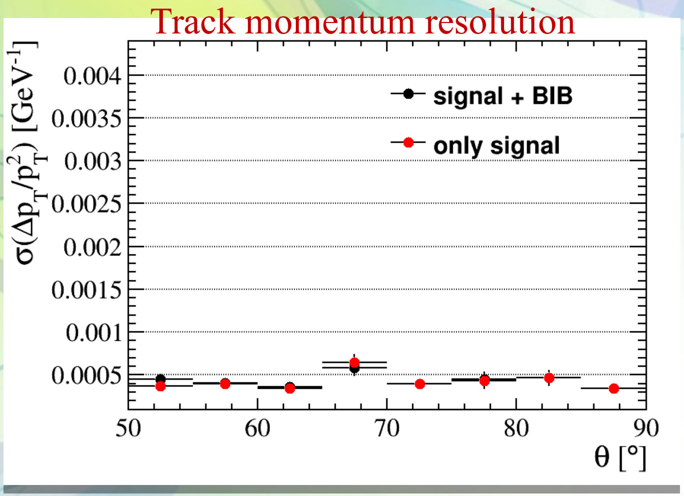
Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, $30x30\ mm^2$

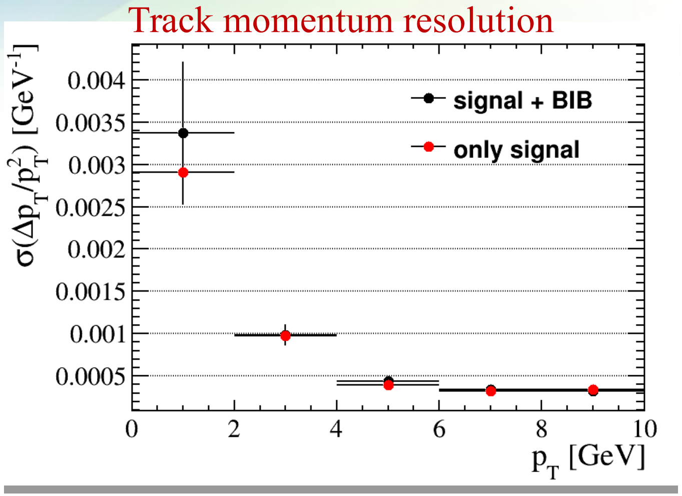
# Background in tracking system

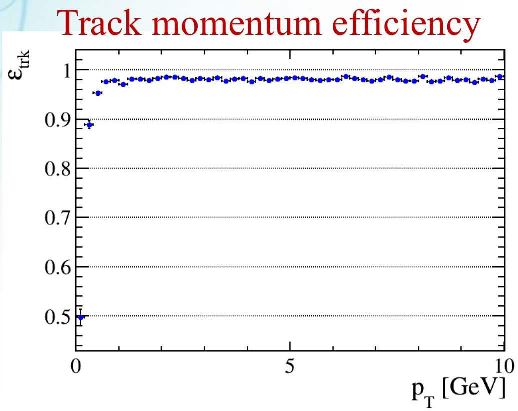



- The Beam-induced background (BIB) produces high occupancies in the Vertex Detector (VXD).
- Occupancies are almost at the same level of CLIC in the Tracker stations.
- 5D sensors that can measure position, energy and time are necessary to mitigate the BIB.
- **The tracking in the VXD region is the real challenge**.
- We are developing a combinatorial rejection strategy based on **dual layer sensors**.

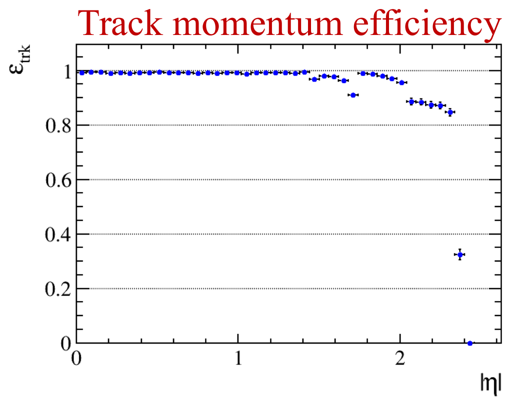
# Tracking performance



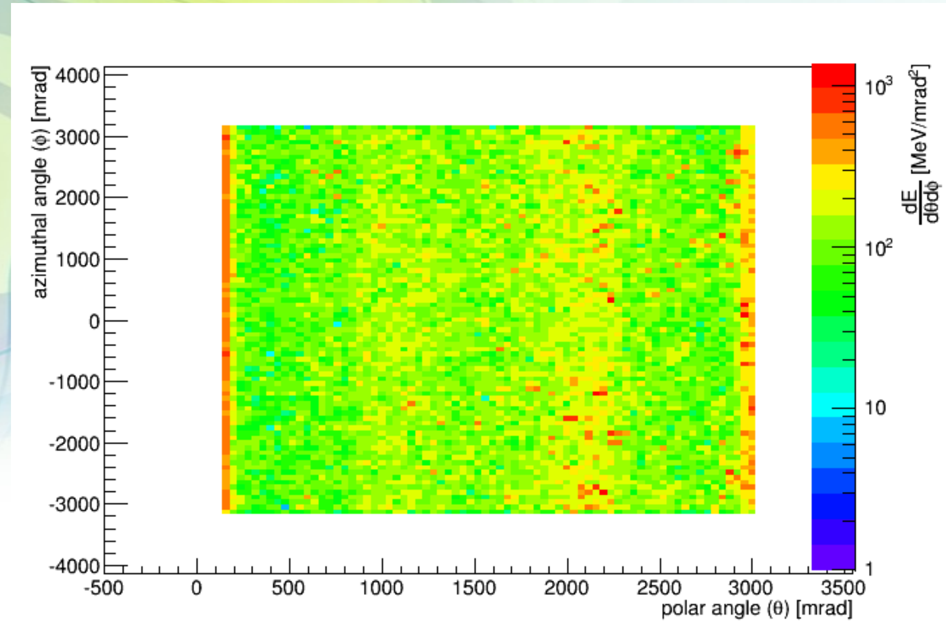




Signal=muon gun

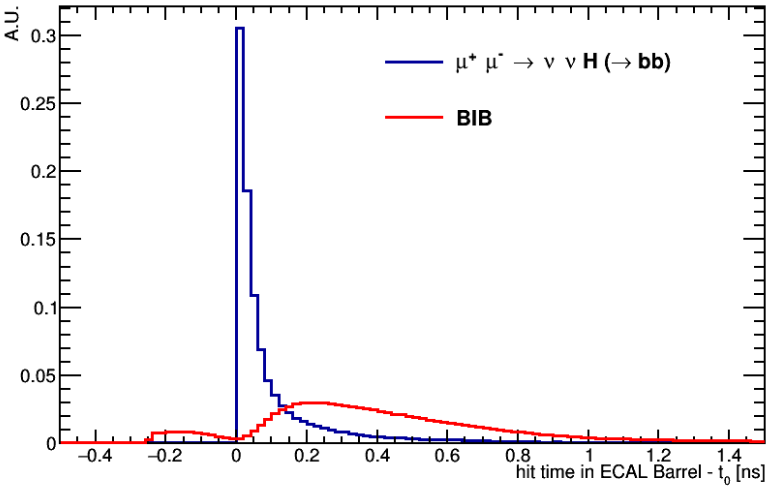



- We are now studying the properties of the **Conformal Tracking algorithm** available in ILCSoft.
- Good tracking efficiencies and resolutions.
- Efficiency loss at low transverse momentum and in the forward region (near the nozzles).

# Background in calorimeter



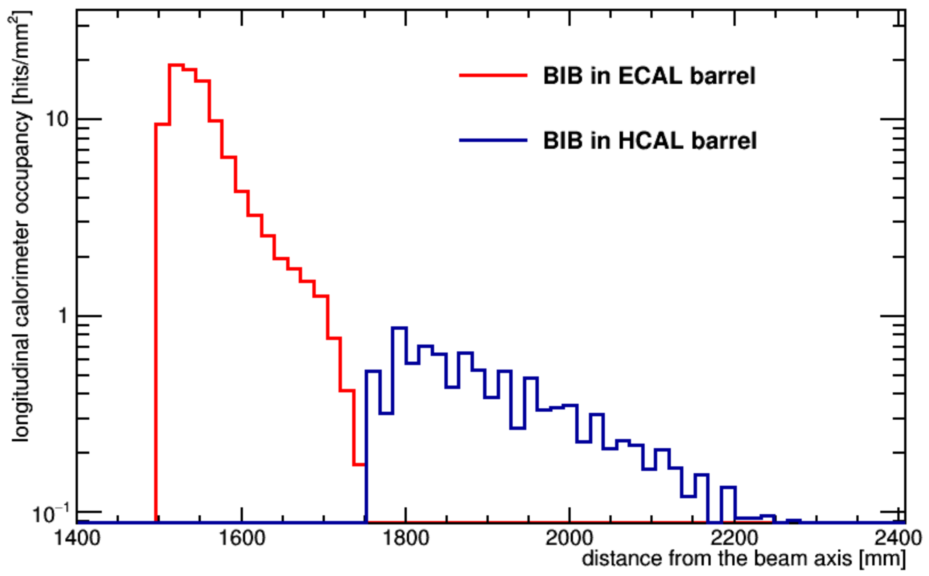

The background is **diffused**




Part of the background is **asynchronous with respect to the signal**

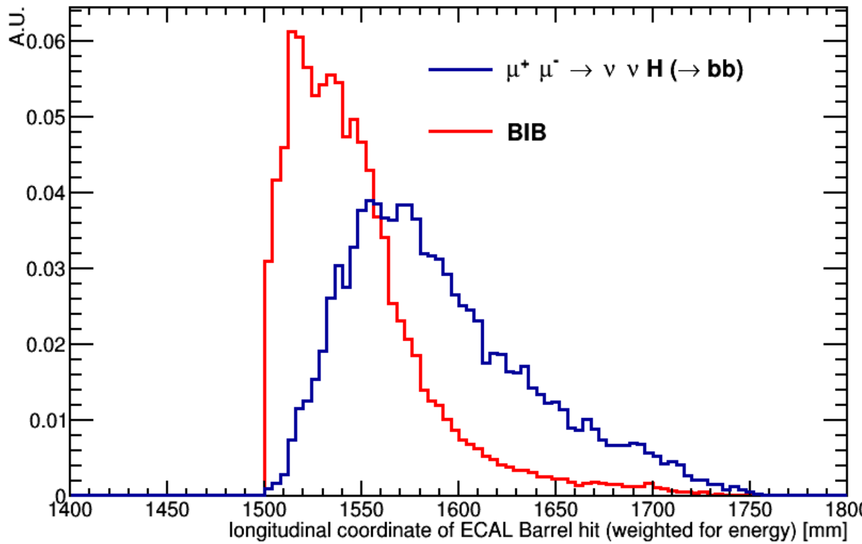
# Background in calorimeter

Calorimeter Occupancy




Low occupancy in HCAL

ECAL barrel longitudinal coordinate




Longitudinal calorimeter segmentation can be exploited to reconstruct showers and reject the BIB