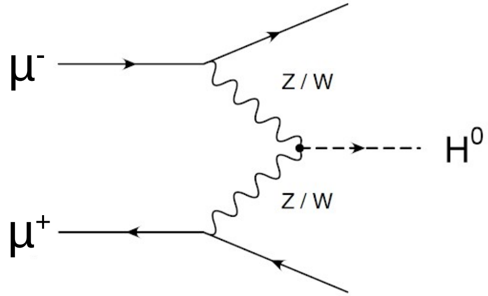
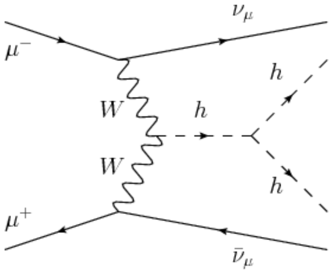
Study of Higgs couplings and self-couplings precision @Muon Collider





Lorenzo Sestini (INFN Padova)

LoI proponents:

C. Aimè, F. Balli, N. Bartosik, L. Buonincontri, M. Casarsa, M. Chiesa, F. Collamati, C. Curatolo, D.Lucchesi, B. Mele, F. Maltoni, B. Mansoulié, A. Nisati, N. Pastrone, F. Piccinini, C. Riccardi, P. Sala, P. Salvini, L. Sestini, I. Vai, D. Zuliani

EF01 Snowmass meeting, 10-12-2020

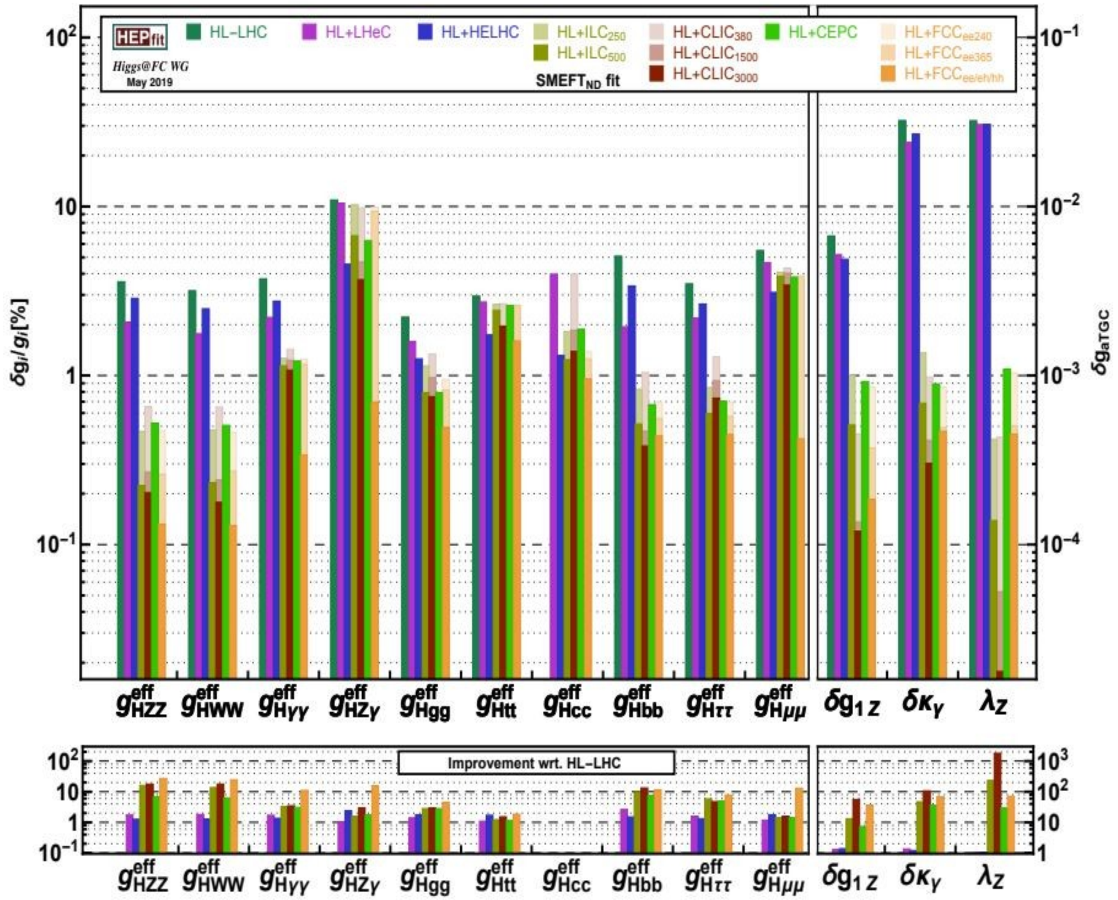
Proposed activities from LoI

- Determination of the **accuracy on the coupling of the Higgs boson to W and Z bosons, to the b-quark and to the muon** at $\sqrt{s}$ = 1.5 TeV for which we already have the beam-induced background (BIB) and then at $\sqrt{s}$ = 3.0 TeV where the BIB will be simulated as Snowmass activity (see Muon Collider: Machine Detector Interface Studies LoI) and extrapolated to $\sqrt{s}$ = 10 TeV.

- Estimation of the **accuracy of the trilinear Higgs coupling measurement** from double Higgs production:
  - Sample of **HH→bbbb** will be generated by using WHIZARD/MadGraph at the three center of mass energies together with the relevant physics background.
  - Signal and physics background events will be fully simulated and reconstructed, in particular new b-jet tagging techniques based on advanced AI method will be used.
  - The uncertainty on the trilinear coupling will be evaluated from the uncertainty on the HH production cross section, that will be determined by using advanced AI methods to separate signal from background and trilinear from no self-interaction processes.

- Determination of the **quadrilinear Higgs self-coupling accuracy**:
  - Generate a sample of **HHH →bbbbbb** at the three different center of mass energies and reconstruct them following procedure similar to what will be done for HH, with the additional requirement of separate HHH from HH.
  - Find a way to generate the physics background constituted by 6 jets + neutrinos
  - Study and identify the physics observables sensitive to trilinear and quadrilinear self-couplings and finally, fit to these quantities for the determination of the accuracy.

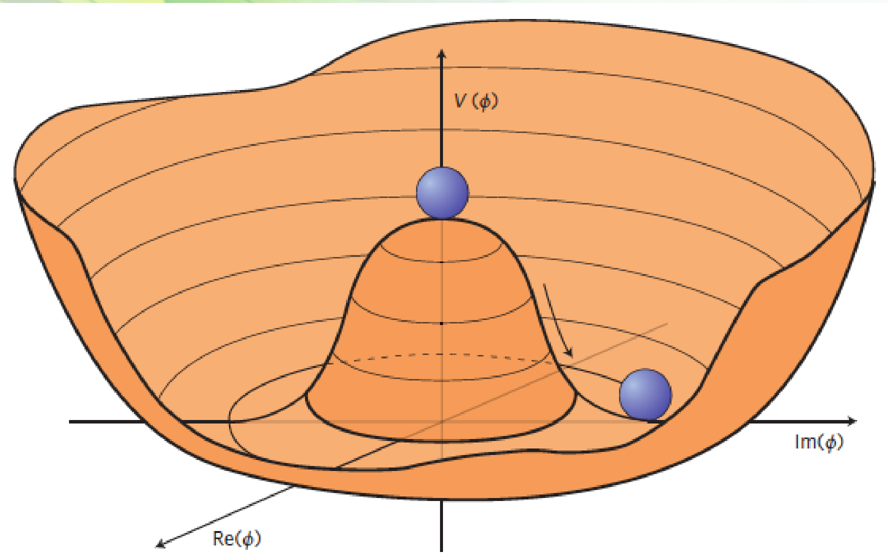
Higgs @ Future Colliders



- 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 can measure the $H \to ZZ$ 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**.



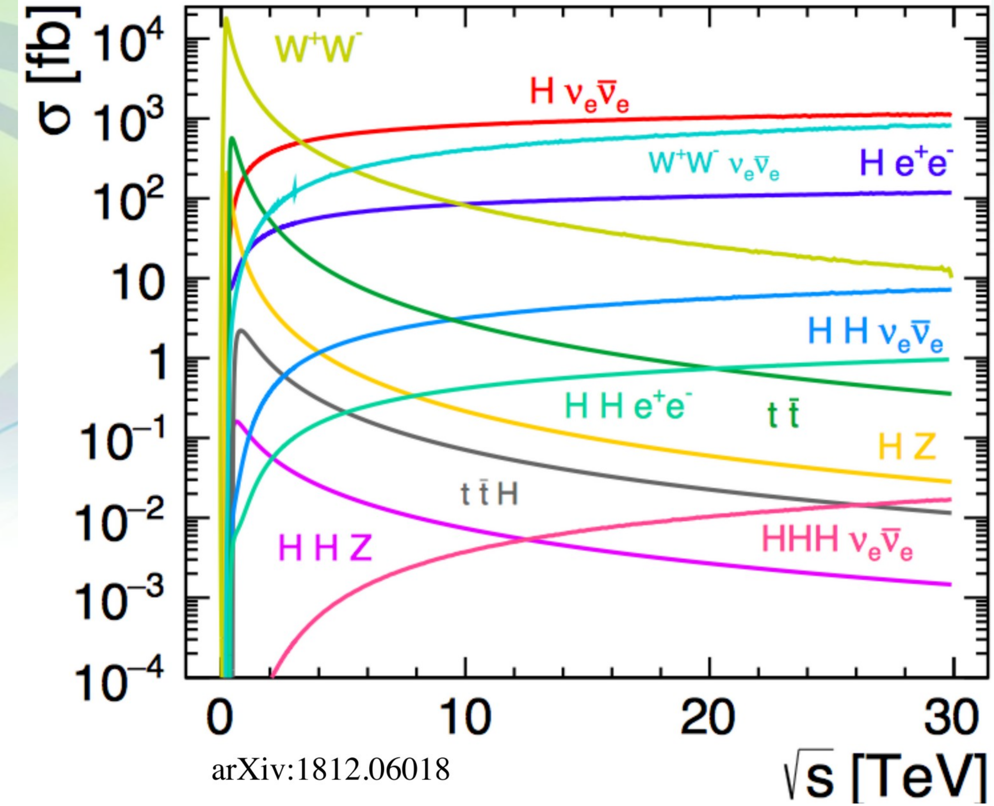
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4,$$

SM

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

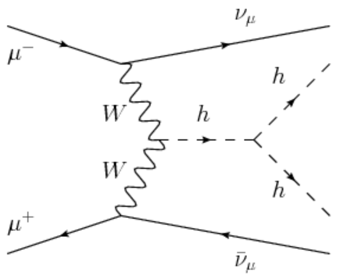
- Up to now there are no measurements of the Higgs potential, apart from the Higgs mass term.
- This means that **the physics of the EWSB is experimentally unexplored**.
- Remember that we still have no ideas on how the EWSB happened at cosmological level, how the neutrinos gained mass, how the mass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

Higgs @ Muon Collider

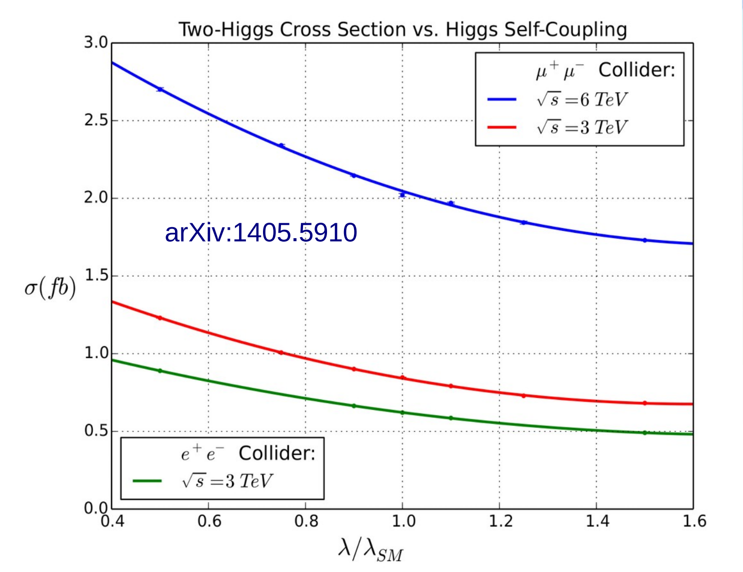


- **The muon collider is the dream machine for Higgs physics measurements**:
  - Clean events as in e^+e^- colliders
  - High collision energy as in hadron colliders (very low radiation losses)

- 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

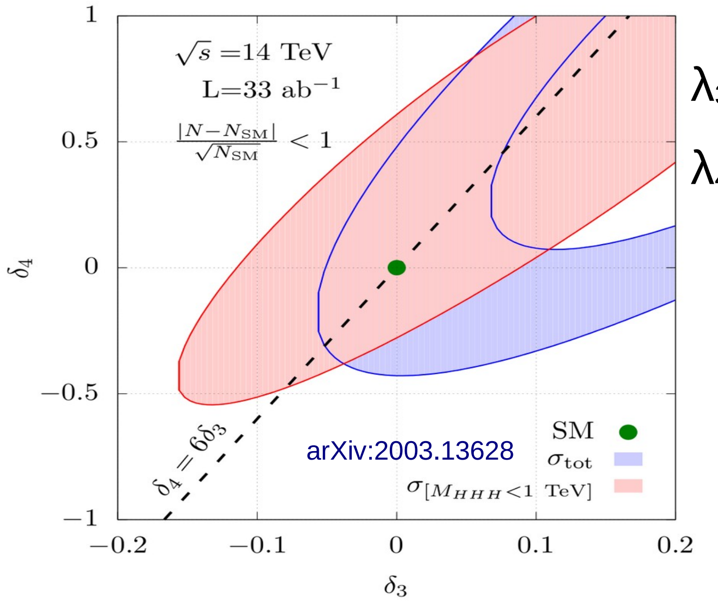


Higgs @ Muon Collider



- 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

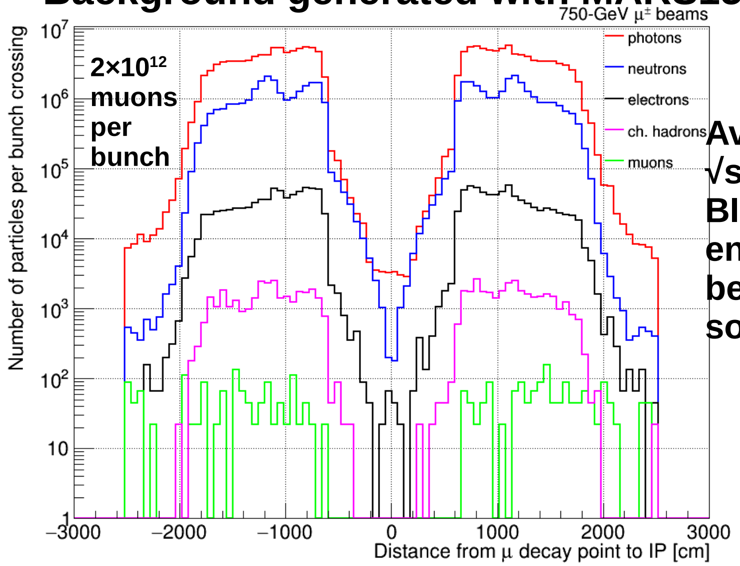
- Detector performance at a Muon Collider is strongly limited by the **Beam-Induced Background (BIB)**:
  - Decays of muons in the circulating beams generate electrons, positrons and neutrinos
  - interactions of such particles with the machine and machine detector interface (MDI) can produce secondary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

- **Full simulation studies are mandatory!**

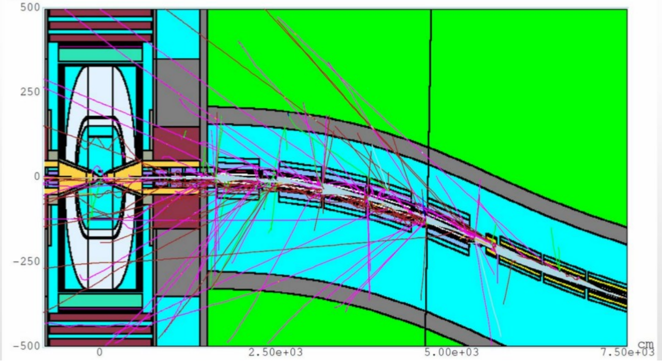
The detector and reconstruction challenges will be discussed later in Max talk

Background generated with MARS15



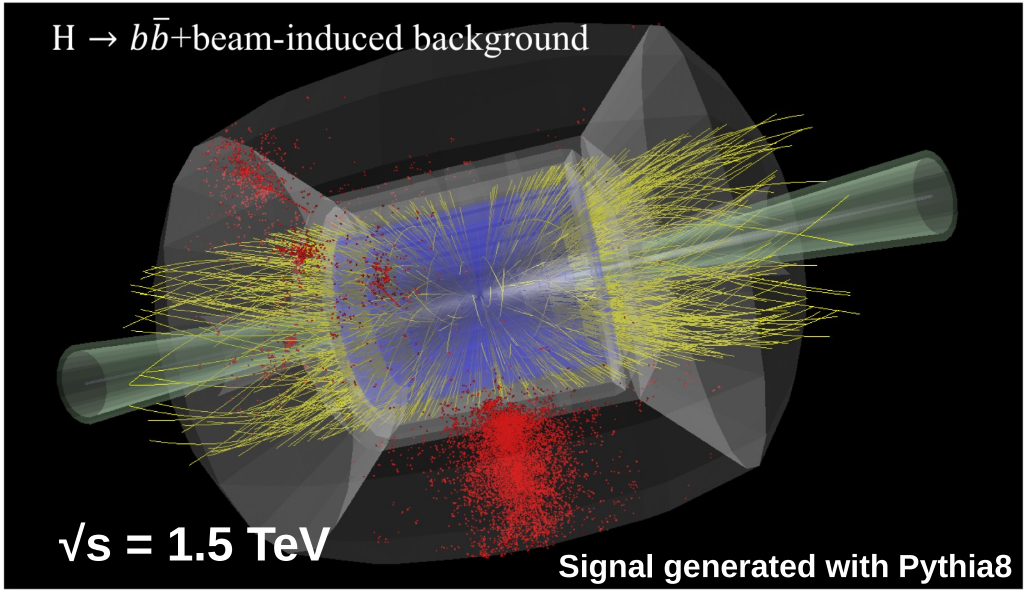
Available at √s=1.5 TeV. BIB at higher energies will be produced soon.

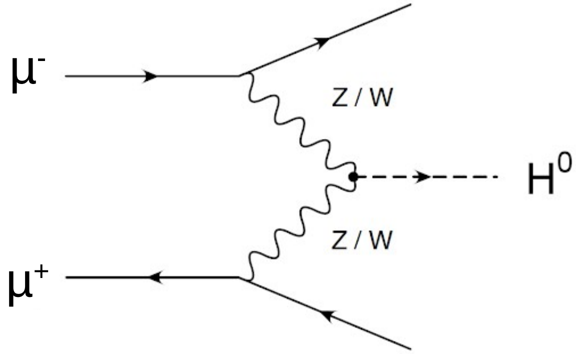
Machine detector interface



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

2020 JINST 15 P05001

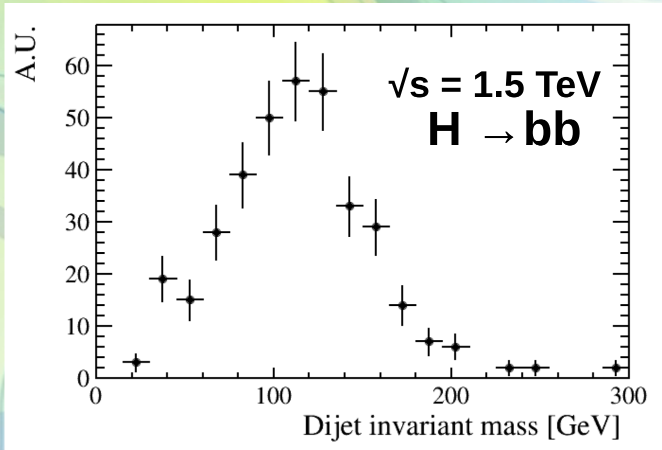




- We studied the μμ → νν H(→bb) production at a muon collider, using the old simulation framework (ILCroot)
- The goal was to determine the **sensitivity to the cross section measurement and to the Hbb coupling determination**
- In the full simulation (Geant4) we used the detector developed by the MAP collaboration, BIB available only at √s = 1.5 TeV

Cross section and Hbb coupling

2020 JINST 15 P05001



Two b-tagged jets (cone algorithm with calorimeter clusters + SV-tagging with tracking) with p_T>40 GeV, |η|<2.5 are selected

Physics backgrounds

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

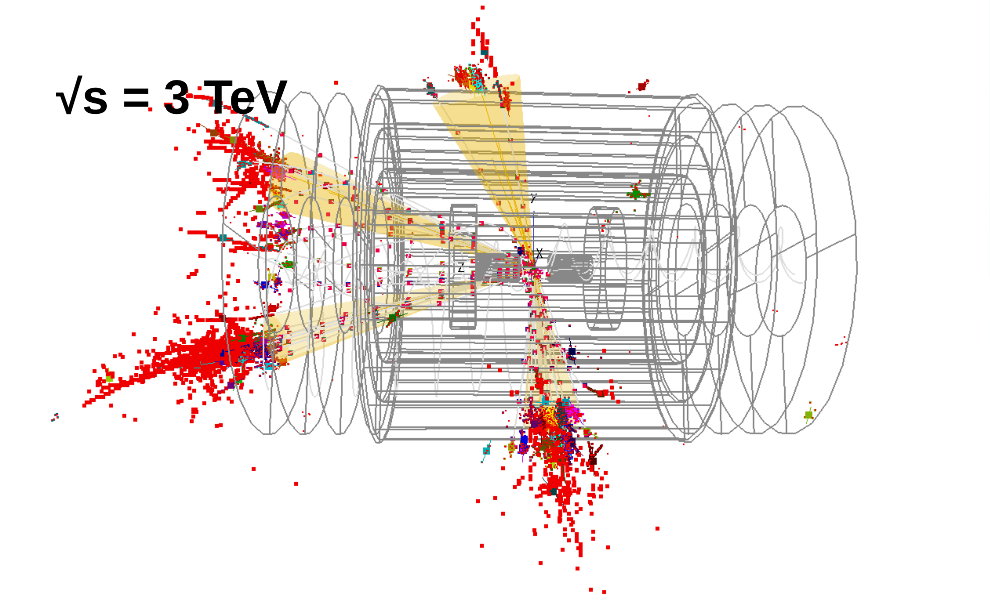
- **As a conservative approach we applied the efficiencies obtained at √s = 1.5 TeV to the 3.0 and 10 TeV case → BUT the BIB yield is expected to be lower at higher energies**
- We assumed **4 Snowmass years of data taking**, at the luminosities expected by MAP.
- Cross section sensitivity obtained with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

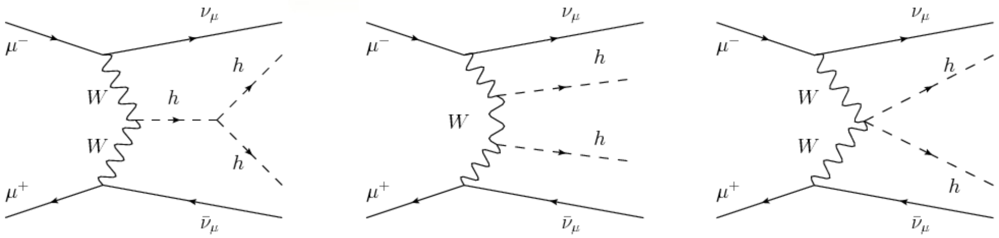
$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot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

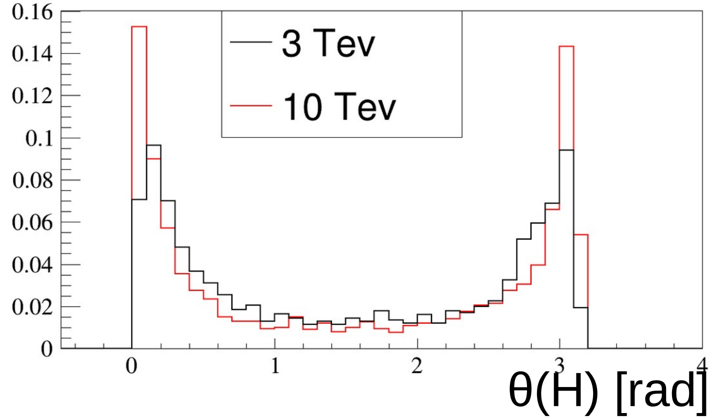
At 3 TeV the Hbb coupling sensitivity is compatible with the one expected by CLIC (1%), but very conservative assumptions have been done → further studies on 3 TeV BIB and HWW coupling determination are needed

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

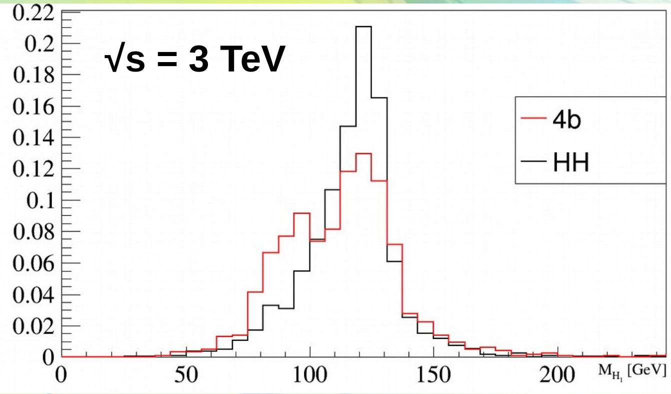


- Next step: **study of the HH production.**
- We are now using a **modified version of the CLIC detector**, with nozzles inserted and the vertex detector similar to the MAP one, using the ILCSoft framework for the full simulation and reconstruction.
- Signal and backgrounds are generated with WHIZARD.
- Full simulation is performed without the BIB, at least for now, **but b-jet identification efficiencies obtained from the previous study are applied to determine the number of expected events.**
- Higgs is likely to be emitted in the forward region.

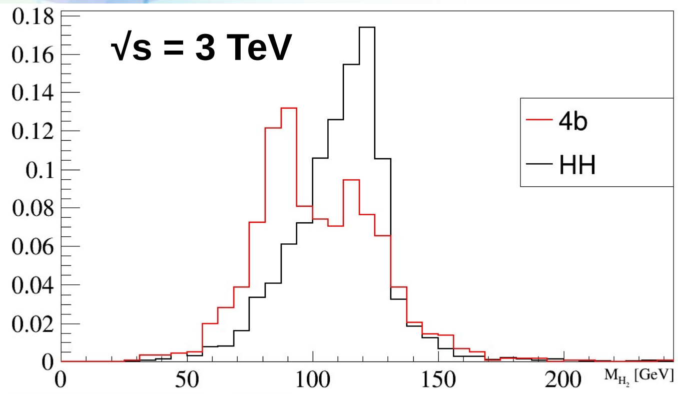




Double Higgs kinematics

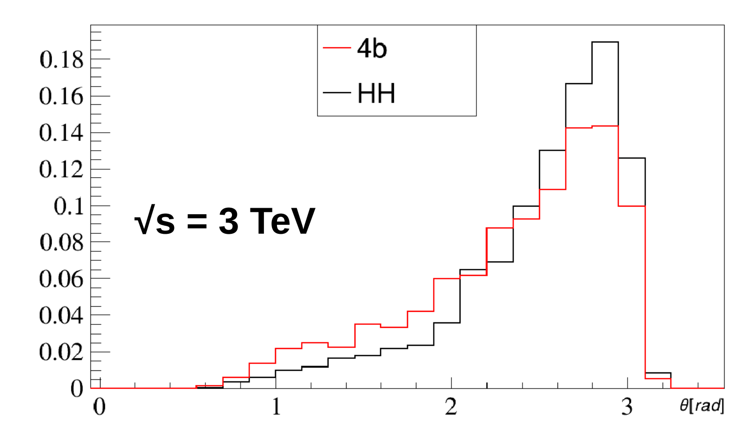


Dijet mass of the Higgs with highest p_T



Dijet mass of the second Higgs

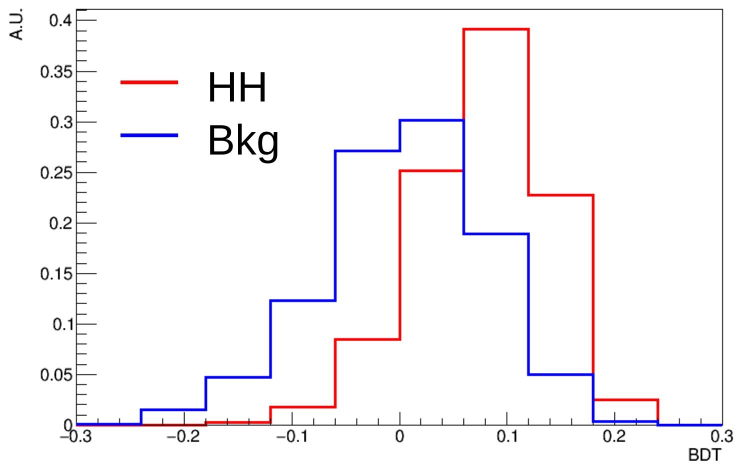
$b\bar{b}b\bar{b}$ background is mainly dominated by ZZ and H+bb events.

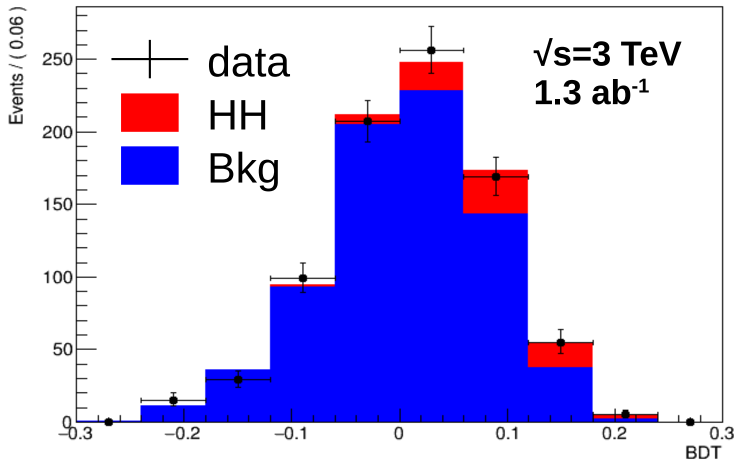


Maximum angle between the jets

- **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**.

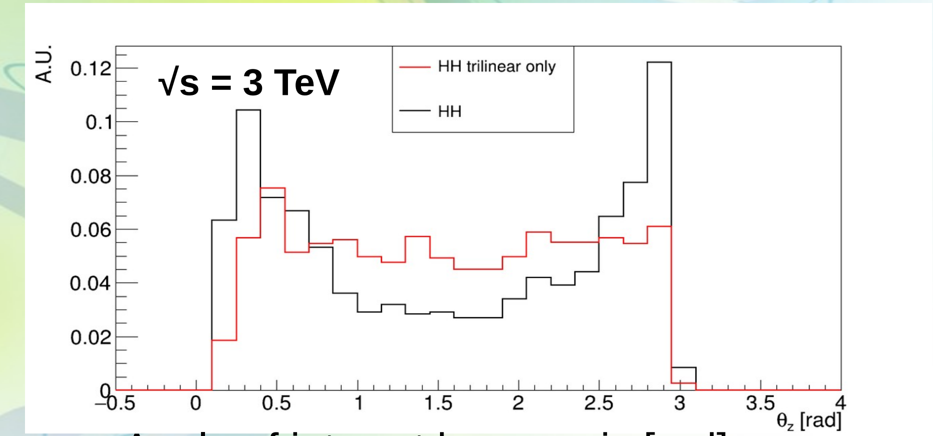
HH cross section measurement



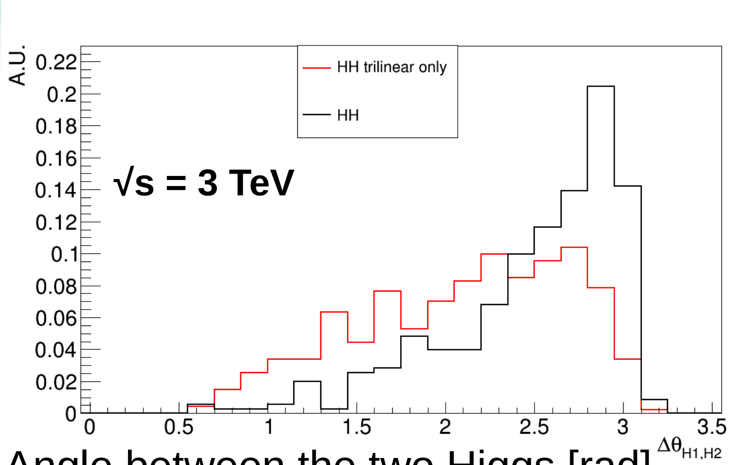


- As a first attempt to estimate the HH cross section uncertainty at 3 TeV, we applied the tagging efficiencies obtained in the 1.5 TeV case in the presence of the BIB → **Again this is very conservative!**
- **One b-tag per Higgs candidate is required.**
- **With 1.3 ab^{-1} (4 years of data taking)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

Trilinear coupling measurement

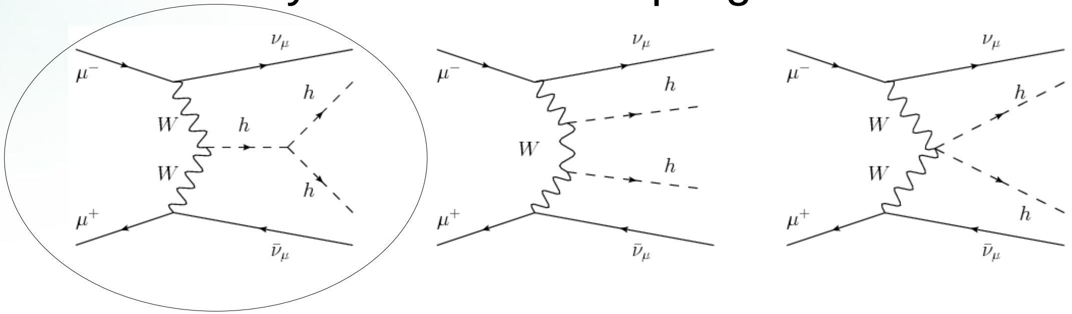


Angle of jets wrt beam axis [rad]



Angle between the two Higgs [rad]

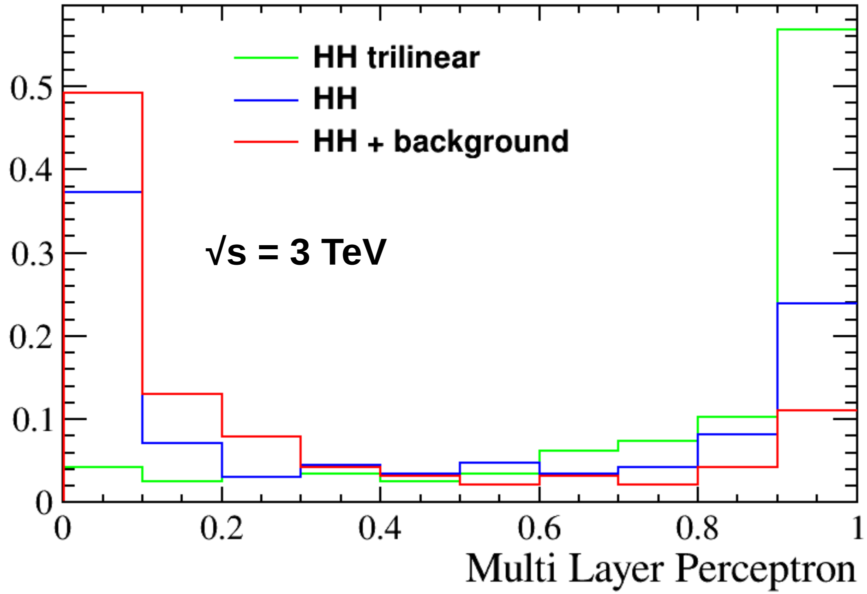
- We simulated HH events just with the process mediated by the trilinear coupling.



- **By comparing HH from trilinear vs total HH it is possible to see differences in angular observables.**

- How much these differences can be exploited in the trilinear extraction depends also on the size of the interference between the diagrams.

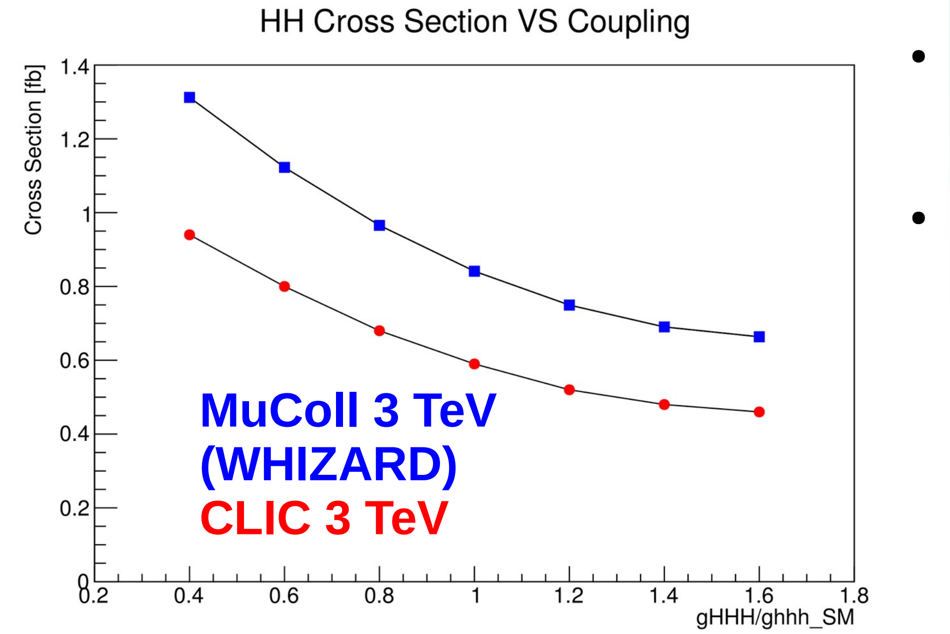
Trilinear coupling measurement

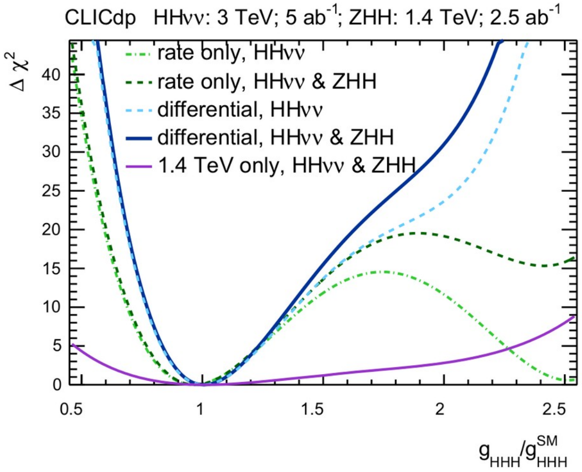


- A possible strategy is to train a MVA discriminator for the separation of HH-trilinear and background.
- Observables in input: m(H1), m(H2), angle between the two H, the angles between the jets in the pairs, p_T of leading jet in each pair.
- A good discrimination is achieved.

Trilinear coupling measurement

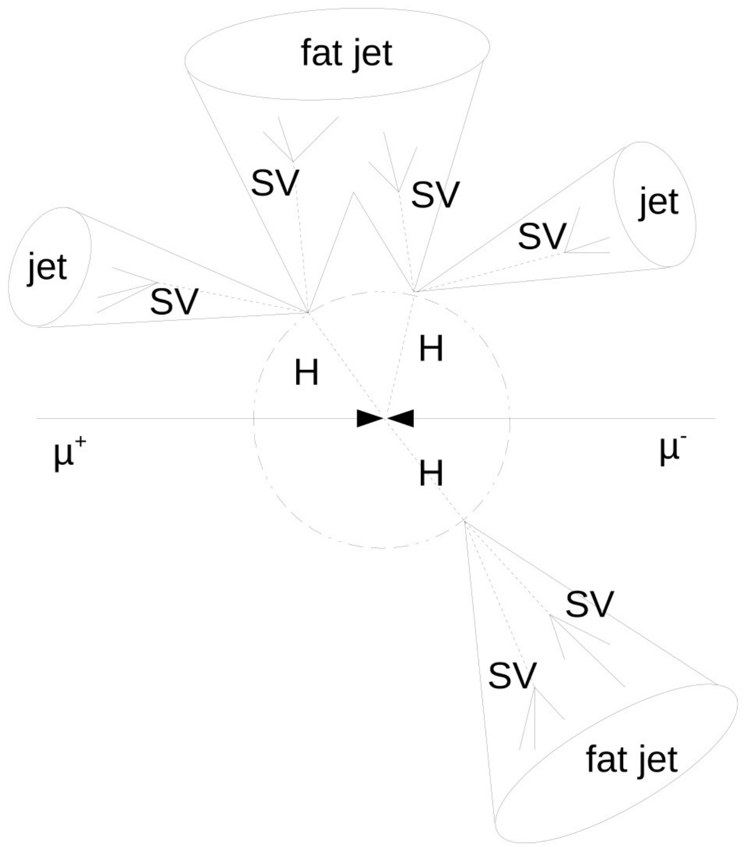
- The simulation of HH at different λ_3 is on-going
- The number of selected events with a MLP cut can be compared with the expectation at different λ_3.
- A χ^2 technique could be employed to determine the λ_3 confidence interval for the measurement.





From CLIC study

HHH and quadrilinear coupling measurement



- We have already generated the signal at 10 TeV with WHIZARD.
- The reconstruction of HHH$\rightarrow b\bar{b}b\bar{b}b\bar{b}$ events is not trivial since they can have complicated topologies.
- As an example fat jets from H decay, or jets from different H decays that accidentally merge.
- We need to develop dedicated reconstruction algorithm → identification with AI.
- The generation of the irreducible background $\mu\mu \rightarrow b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ is not an easy task (WHIZARD? ALPGEN?).
- Even in this case the distribution of relevant observables should be compared with simulation performed at different λ_3 and λ_4, to extract the self-couplings.

Conclusions and plans

- **All the studies should be updated with the detector developments → talk from Max**

- **Accuracy on the coupling of the Higgs boson to W and Z bosons, to the b-quark and to the muon:**
  - Consolidate the $H \rightarrow bb$ study at 1.5 TeV, and investigate the 3 TeV case when the corresponding BIB will be generated
  - Study the muon final states for HWW, HZZ and $H\mu\mu$ accuracy determination

- **Accuracy of the trilinear Higgs coupling measurement:**
  - Conclude the $HH \rightarrow bbbb$ study by extracting the trilinear coupling sensitivity

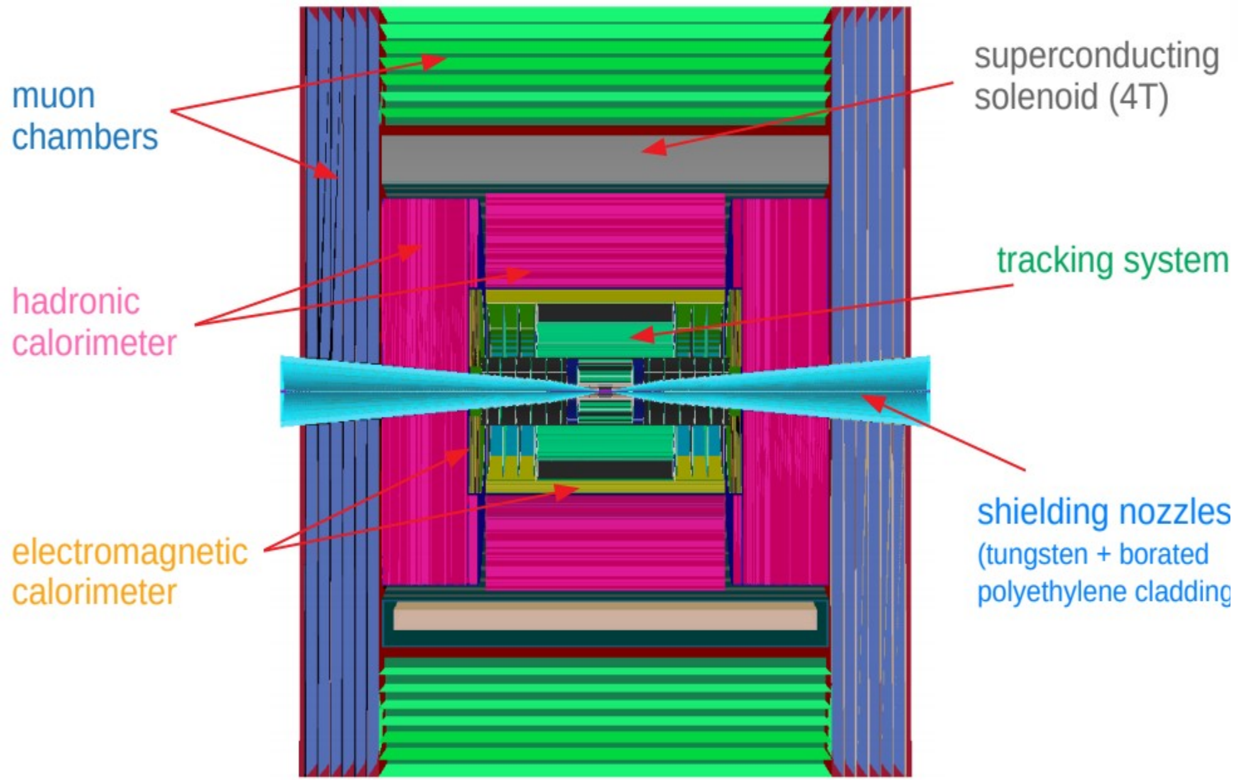
- **Quadrilinear Higgs self-coupling accuracy:**
  - Define the reconstruction strategy
  - Generate and simulate the backgrounds
  - Simultaneous trilinear and quadrilinear coupling extraction

Backup

Design a detector at $\sqrt{s}$ = 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 ”

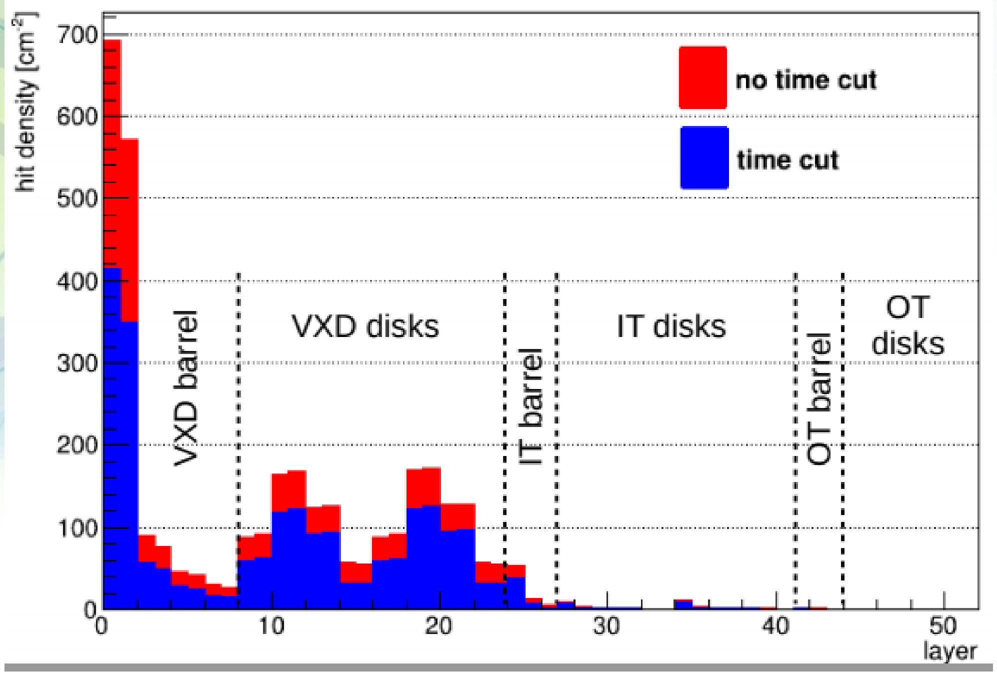
Inner Tracker (IT)
- 3 barrel layers $50x50\mu m^2$
- 7+7 disks ”

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

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

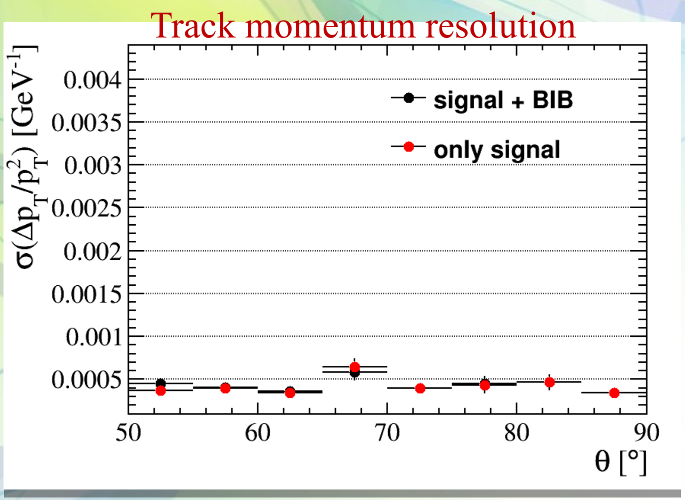
Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, $30x30\ mm^2$

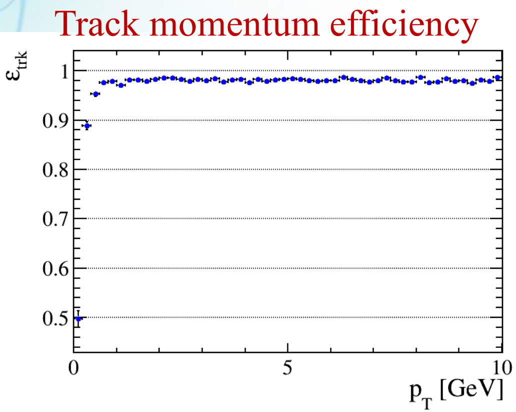
Background in tracking system



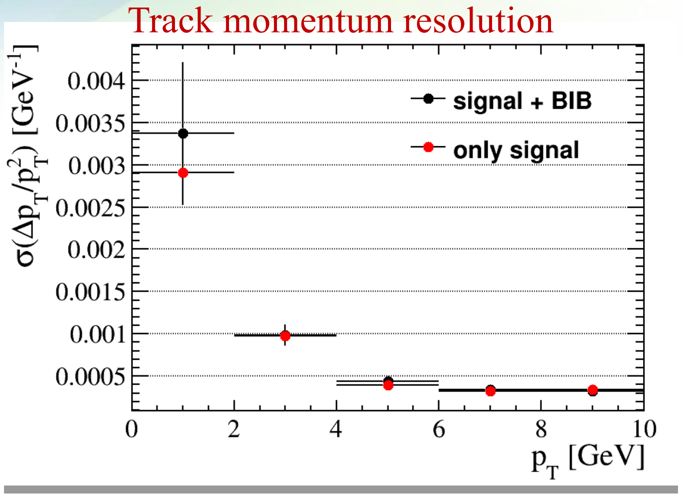
- The Beam-induced background (BIB) produces high occupancies in the Vertex Detector (VXD).
- Occupancies are almost at the same level of CLIC in the Tracker stations.
- 5D sensors that can measure position, energy and time are necessary to mitigate the BIB.
- **The tracking in the VXD region is the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

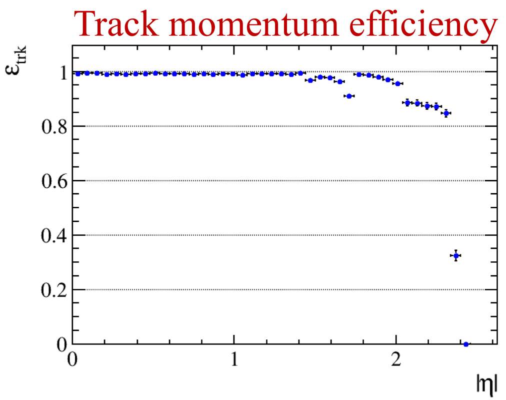
Tracking performance





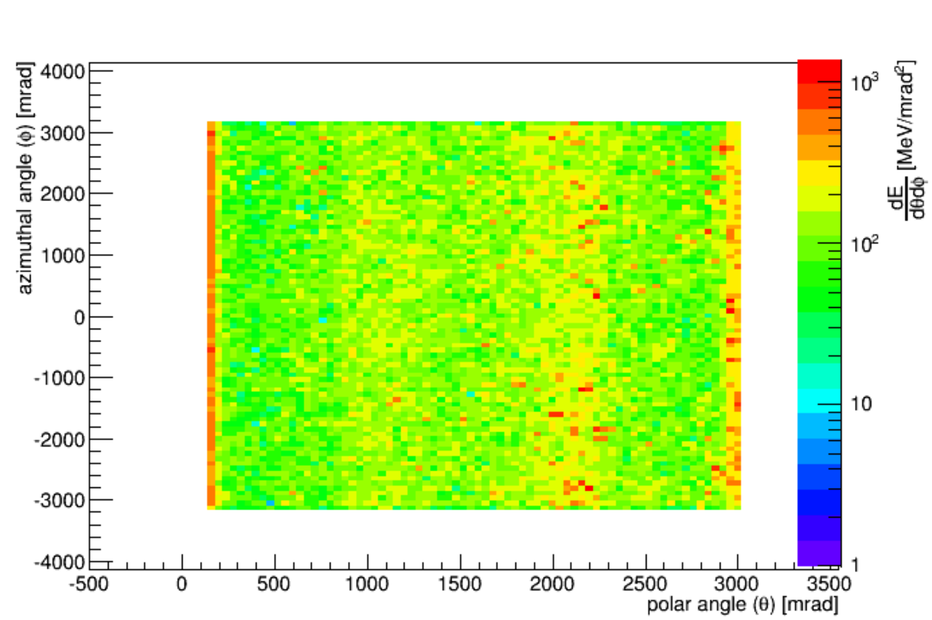
Signal=muon gun



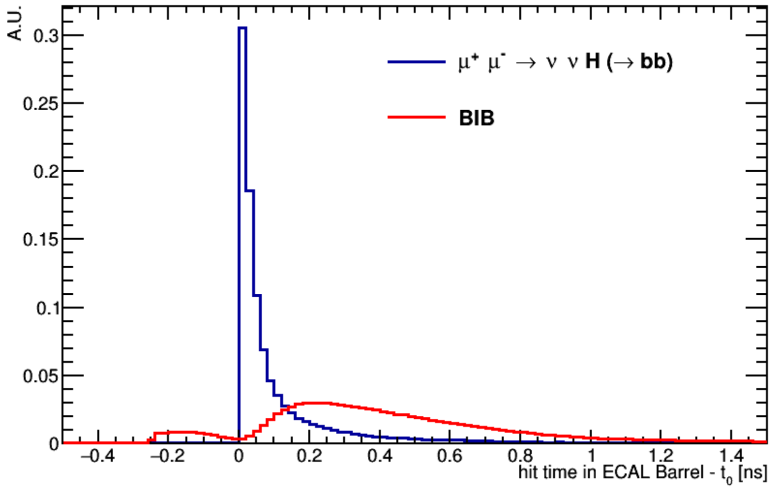


- We are now studying the properties of the **Conformal Tracking algorithm** available in ILCSoft.
- Good tracking efficiencies and resolutions.
- Efficiency loss at low transverse momentum and in the forward region (near the nozzles).

Background in calorimeter



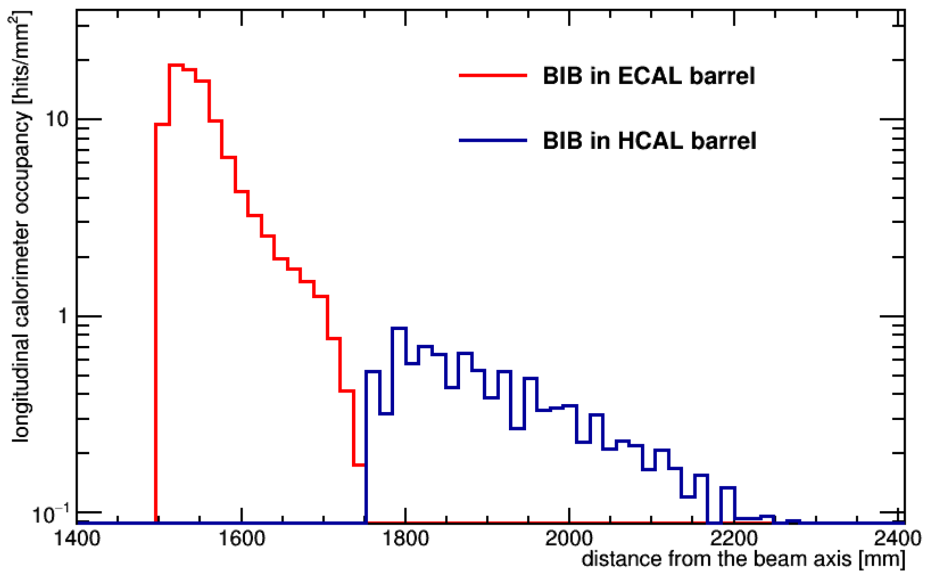
The background is **diffused**



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

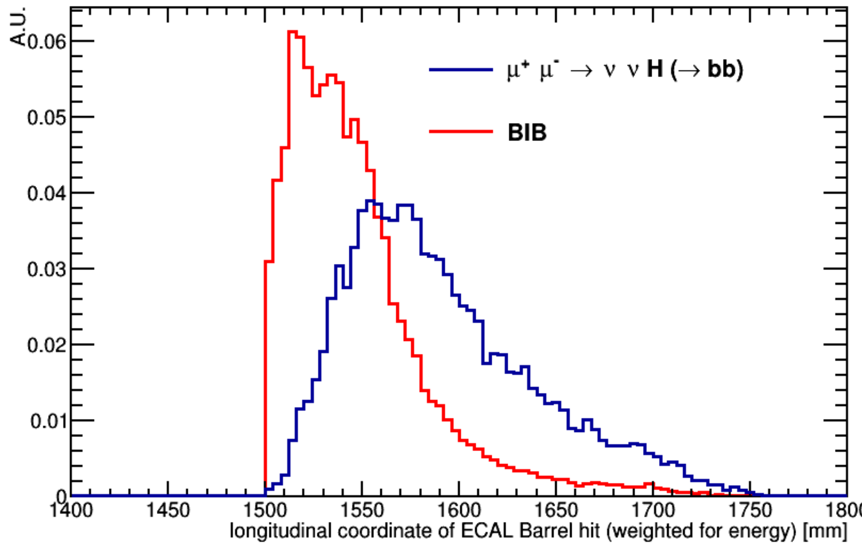
Background in calorimeter

Calorimeter Occupancy



Low occupancy in HCAL

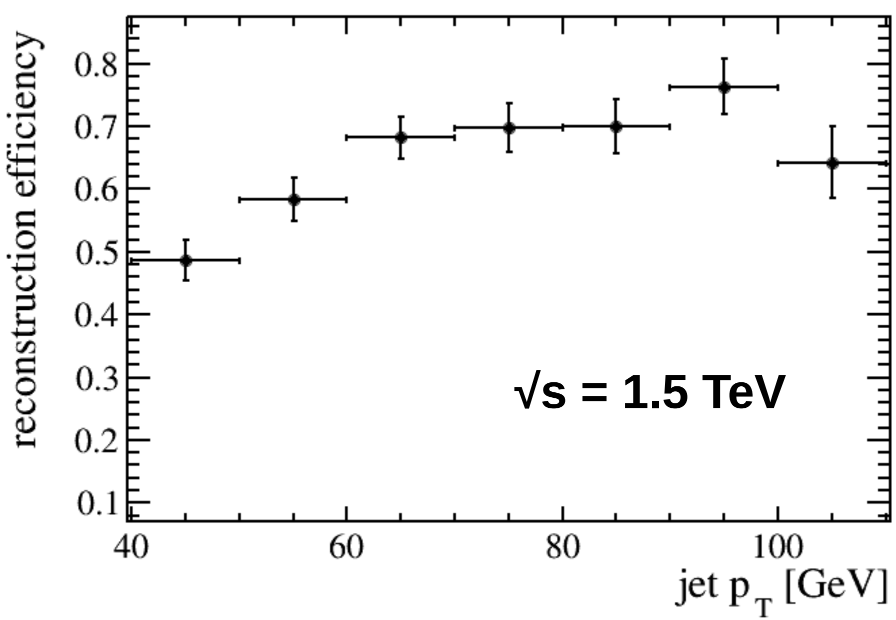
ECAL barrel longitudinal coordinate

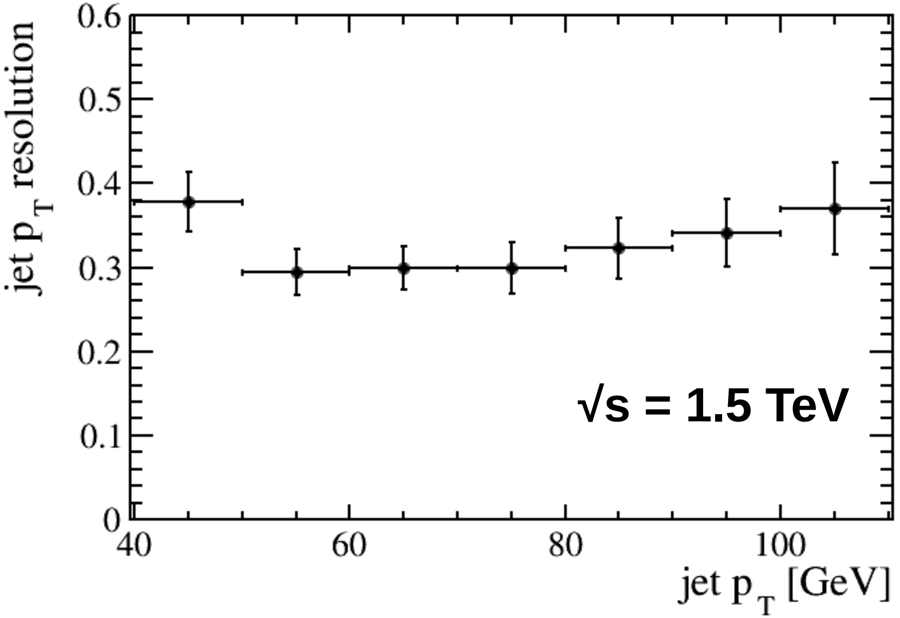


Longitudinal calorimeter segmentation can be exploited to reconstruct showers and reject the BIB

Jet reconstruction

2020 JINST 15 P05001



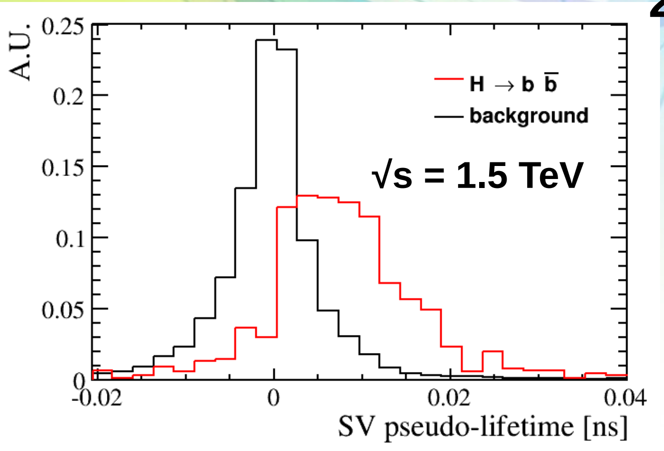


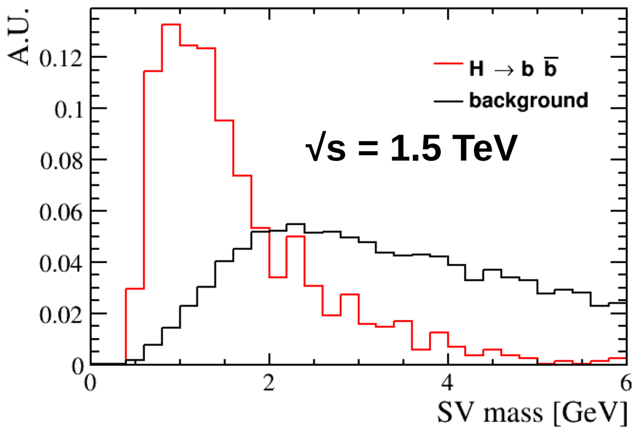
- A rough jet reconstruction algorithm is used:
  - **BIB is subtracted on a statistical basis from the calorimeter cells**
  - A cone algorithm with R=0.5 is used to cluster jets in the calorimeter
  - A jet energy correction is applied

- 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.