# Reconstruction of 4b jets event at a Muon Collider

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for
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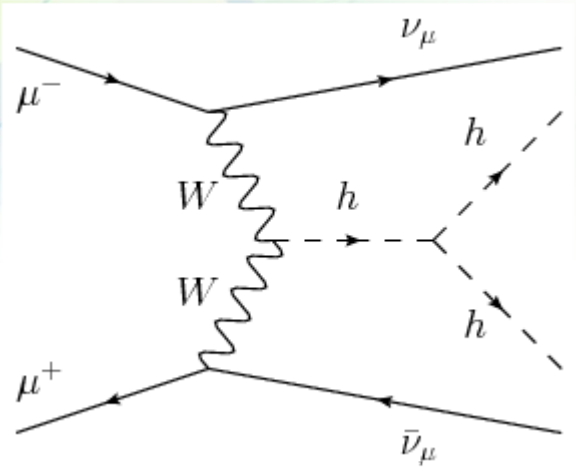
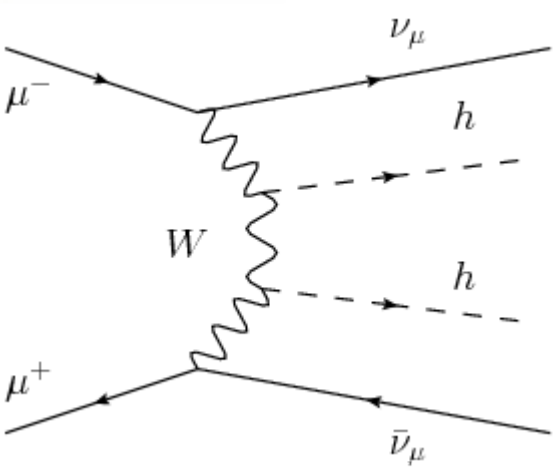
# Introduction

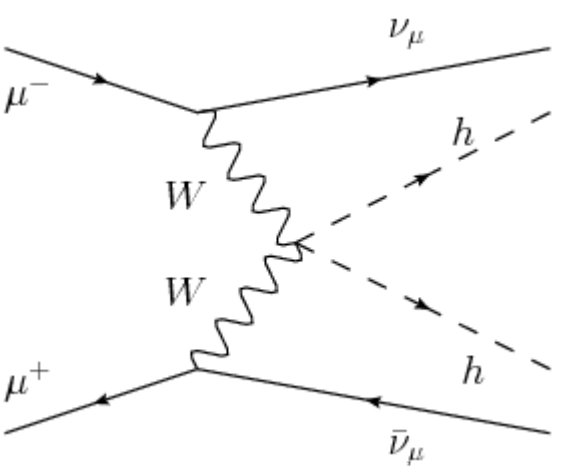
- We have already demonstrated that Higgs physics is possible at a Muon Collider https://arxiv.org/abs/2001.04431.
- We studied the measurement of the $\mu^+\mu^- \rightarrow H(\rightarrow b\bar{b})\,\nu\bar{\nu}$ cross section and the determination of the Higgs coupling with b-quarks.
- We are now moving to the study of the $\mu^+\mu^- \rightarrow HH\,\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$ process.
- **The goal is to determine the sensitivity of a Muon Collider experiment to the measurement of the Higgs self-coupling, using a full simulation.**
- In this talk we want to show the progress on the double H simulation and analysis.
- We considered the $\sqrt{s}$ = 3 TeV and $\sqrt{s}$ = 10 TeV, studies are more advanced for the 3 TeV case.

# Double Higgs events generation

- We have generated 1000 double Higgs events at **NLO with Whizard**.
- All NLO diagram contributions are considered, not only those with Higgs self-couling.
- Few examples:

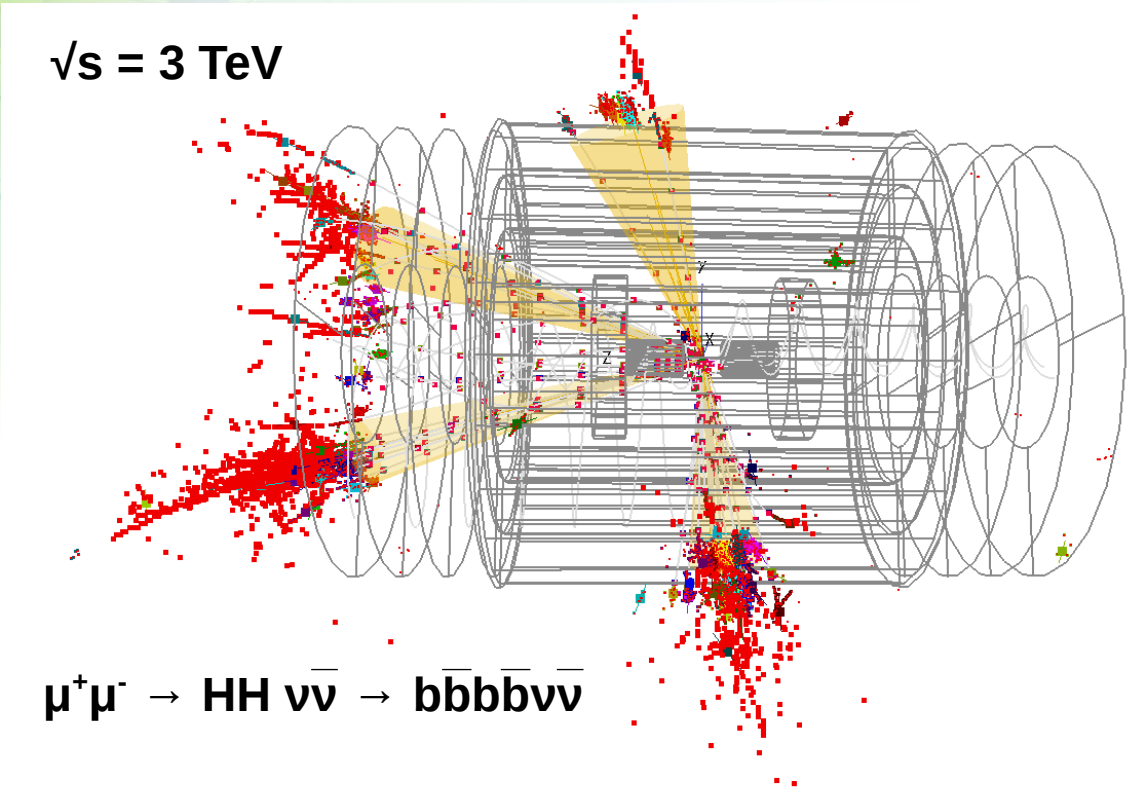


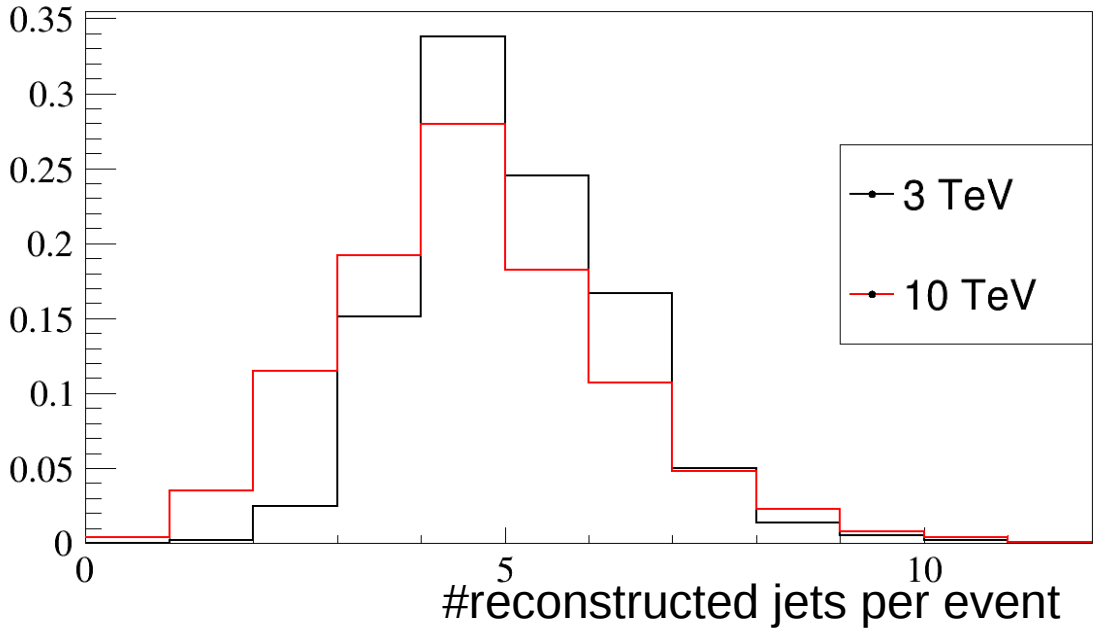
# Double Higgs events simulation and reconstruction

- Detector layout, simulation, tracks and calorimeter reconstruction described in the previous talks.
- The analysis is performed with the **ILCsoft framework**.
- **At least for now Beam Induced Background is not considered**.



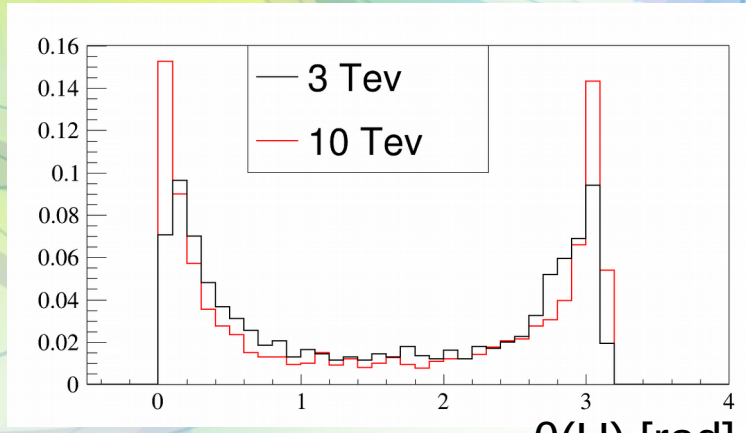
# Jets reconstruction

- We are using **FastJet** as reconstruction software.
- Particle flow algorithm for tracks and calorimeter clusters selection.
- $k_t$ with R=0.5 as jet clustering algorithm.

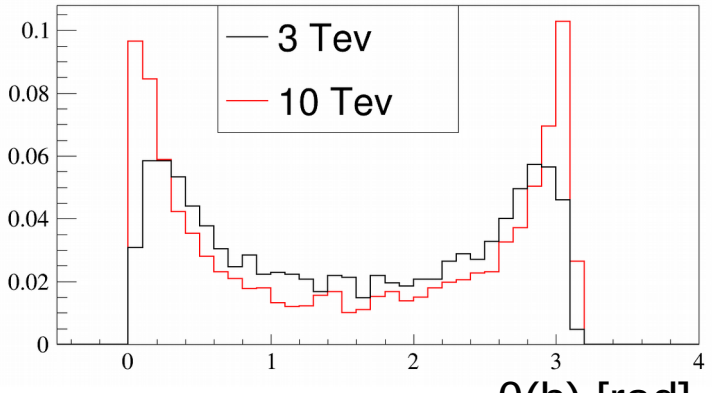



- Number of reconstructed jets per event.
- Many events with less than 4 jets, especially in the 10 TeV case.
- This is probably due to the acceptance (e.g. nozzle) and $b\bar{b}$ collimation.
- A different reconstruction strategy is probably needed at 3 and 10 TeV cases.

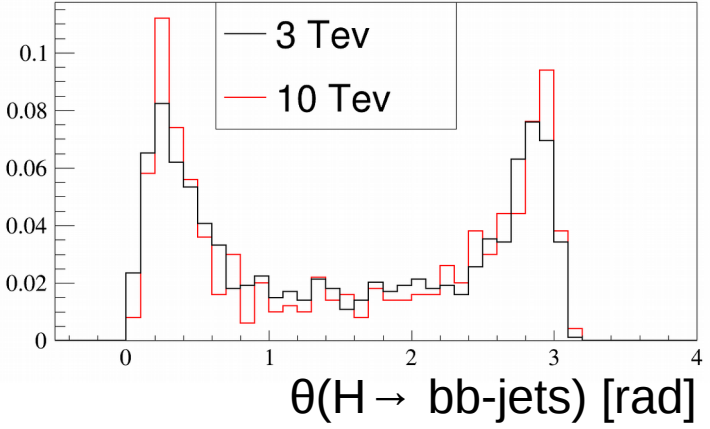
# HH → $b\bar{b}b\bar{b}$ kinematics



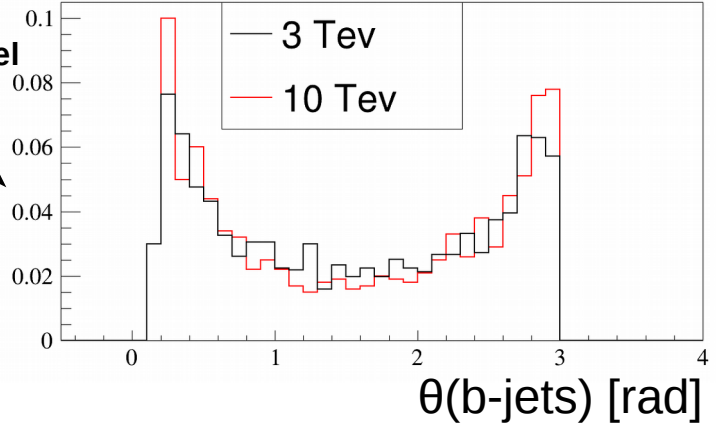

**Truth-level (no acceptance cuts are applied)**



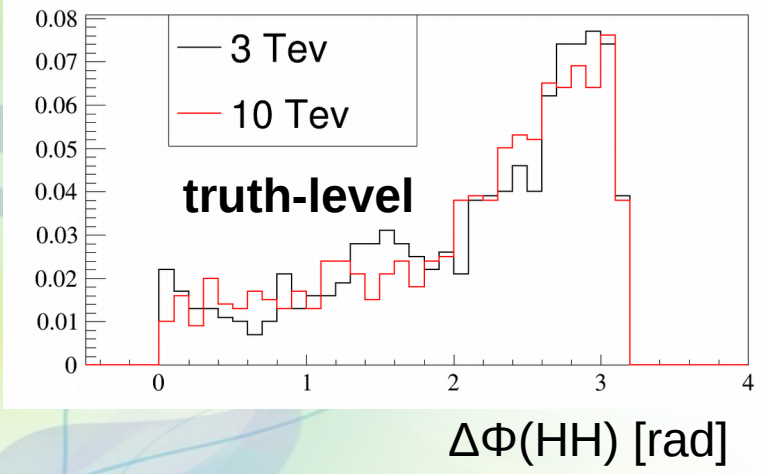

- Higgs and b quarks are emitted in the forward region, at 10 TeV they are more forward with respect to 3 TeV

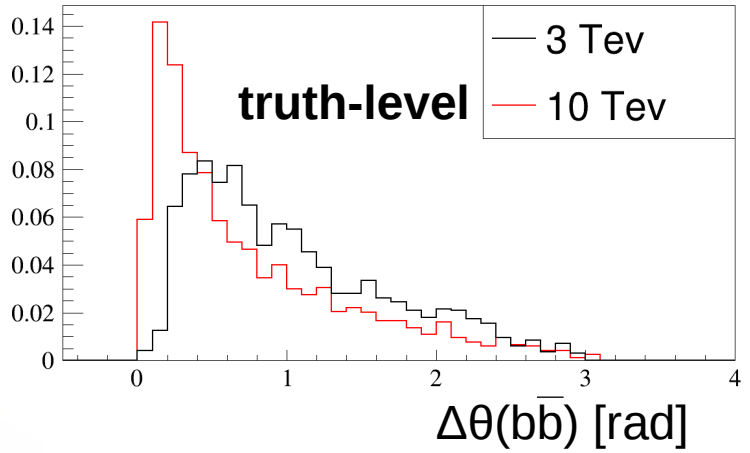



**Reconstructed-level**

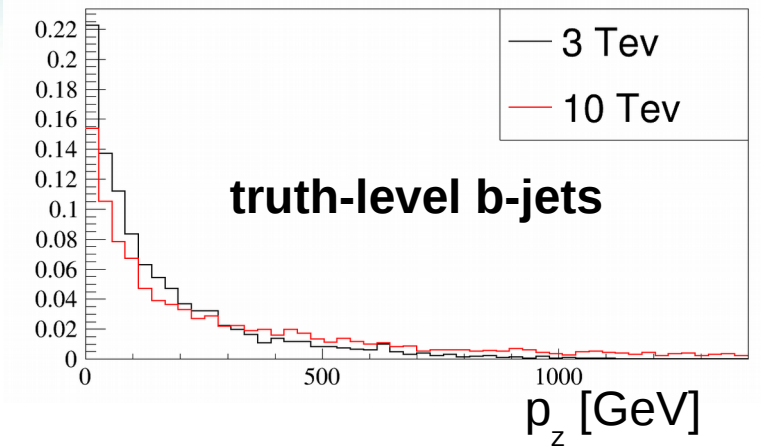


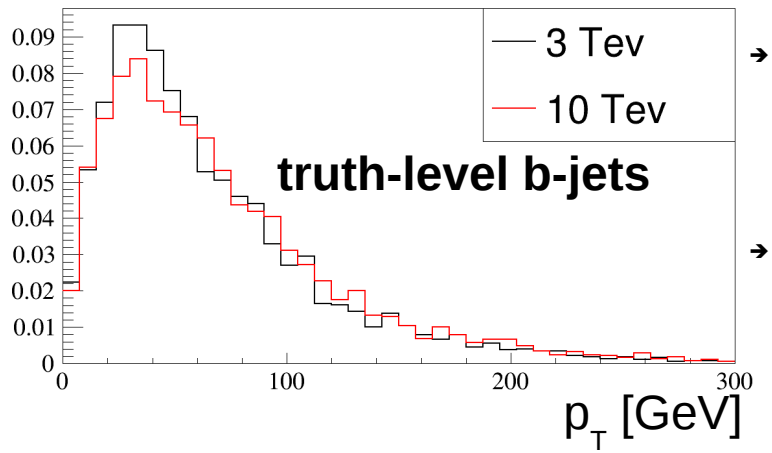
# HH → $b\bar{b}b\bar{b}$ kinematics



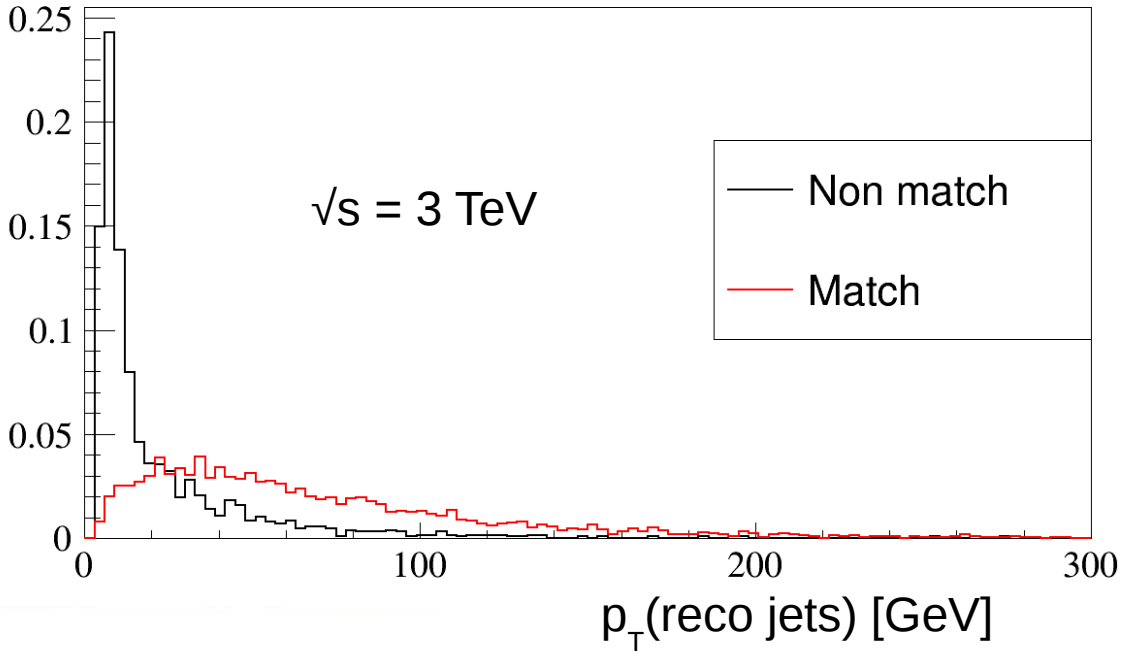

- The two Higgs are almost back-to-back.
- **The two b-quarks are collimated.**




- Jets at 10 TeV are more boosted along the z-axis with respect to 3 TeV.
- The $p_T$ distribution is compatible in the two cases.

# b-jets reconstruction at 3 TeV

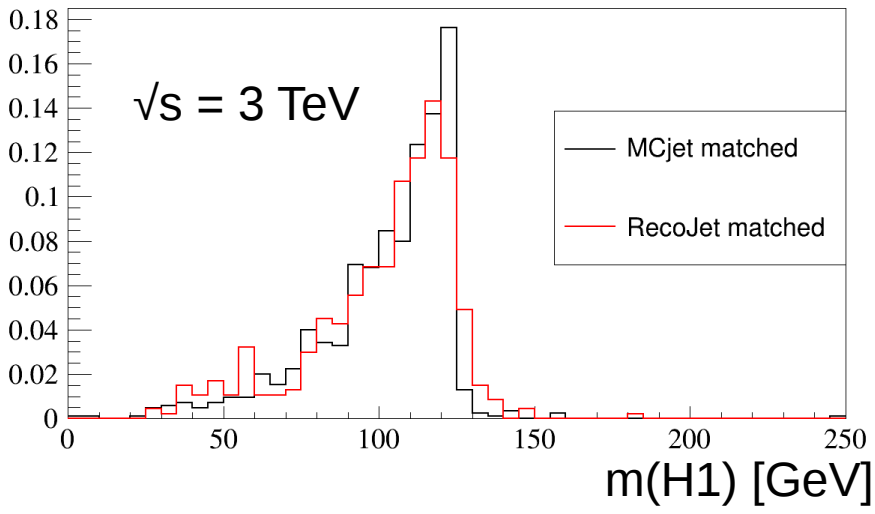


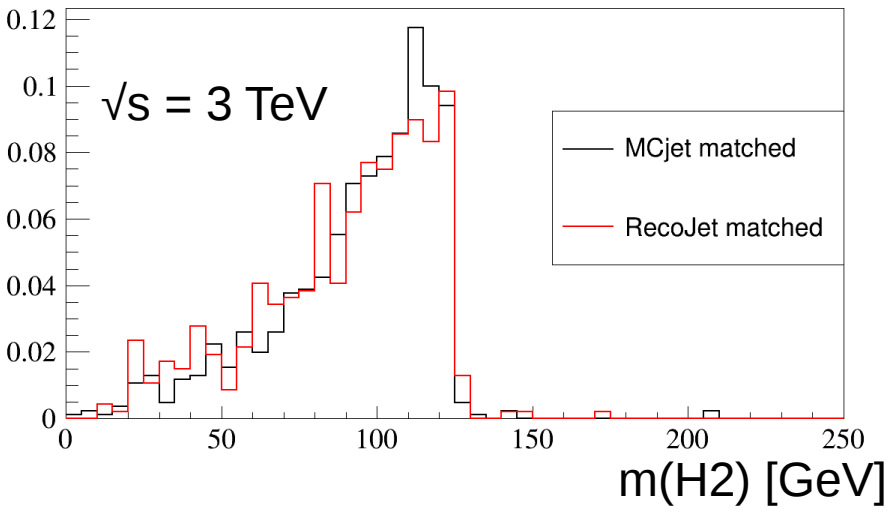

- **From now on only the 3 TeV case is considered.**
- Transverse momentum of reconstructed jets.
- Matched and not-matched with true b-jets.
- Not-matched jets are generated by Initial State Radiation and Final State Radiation, or reconstruction artifacts.

- **Efficiency of b-jets reconstruction: 87%**
- **Rate of not-matched jets: 27%**
- **b-tagging and $p_T$ cuts are necessary**

# Higgs reconstruction at 3 TeV

- Minimization of the following figure of merit: $M^2 = (m_{ij} - m_H)^2 + (m_{kl} - m_H)^2$
- $m_H$ is the nominal Higgs mass, $m_{ij}$ and $m_{kl}$ are dijet invariant masses
- Reconstructed jets matched with true b-jets are used (other jets should be removed by b-tag)
- H1 is defined as the Higgs with the highest jets $p_T$ sum in the event, H2 is the second one.



# First look at 3 TeV background

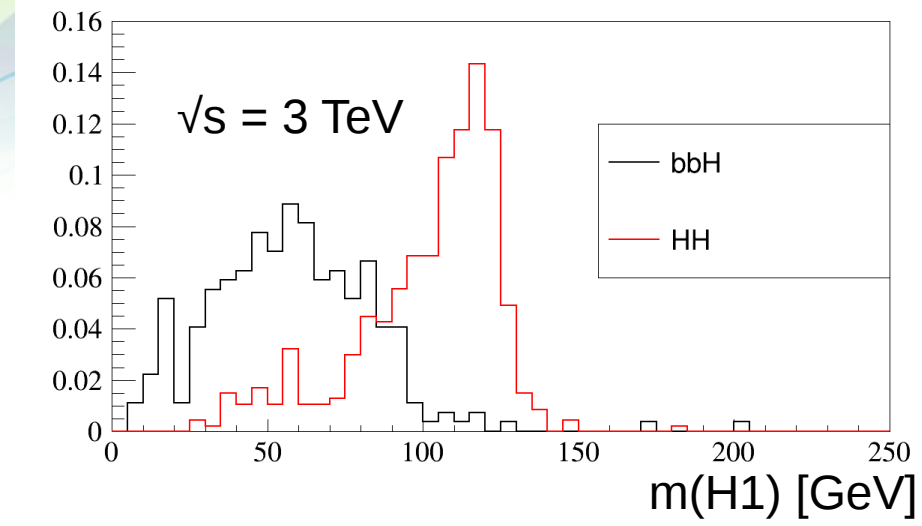
- Irreducible background: **μμ → $b\bar{b}b\bar{b}\nu\nu$ from electroweak or single Higgs processes.**
- **It is being generated with Whizard**. In this talk **μμ → $b\bar{b}H(\rightarrow b\bar{b})\nu\bar{\nu}$** at LO with Pythia 8.
- According to CLIC paper [https://arxiv.org/abs/1901.05897] after selection μμ → $b\bar{b}H(\rightarrow b\bar{b})\nu\bar{\nu}$ is the dominant background at 3 TeV.
- At a 3 TeV Muon Collider we expect (considering just reconstruction efficiencies without BIB):
  - **in the order of 500 HH events**
  - **in the order of 150 Hbb events**

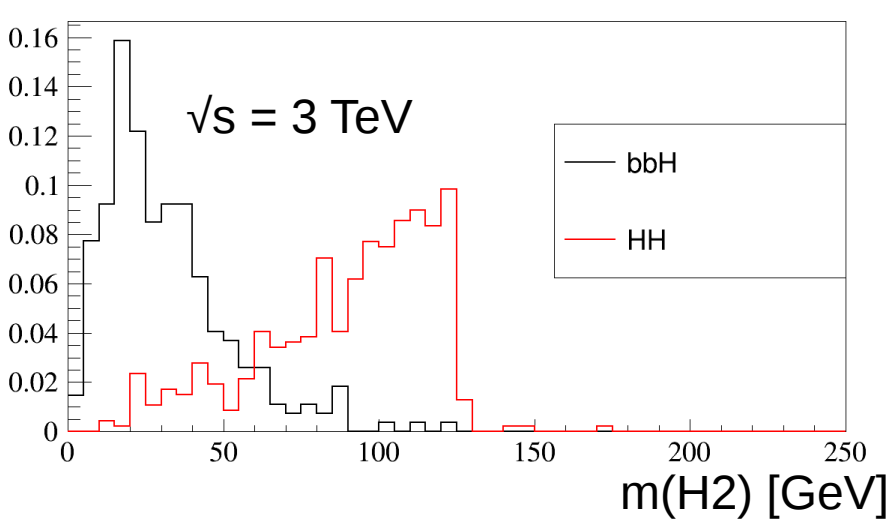
$$N = \sigma \epsilon L$$

| | |
|---|---|
| luminosity | $4.4 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| time | $4 \cdot 10^{7}$ s |
| σ(HH) | 0.84 fb |
| ε(HH) | 47% |
| σ(bbH) | 0.39 fb |
| ε(bbH) | 27% |

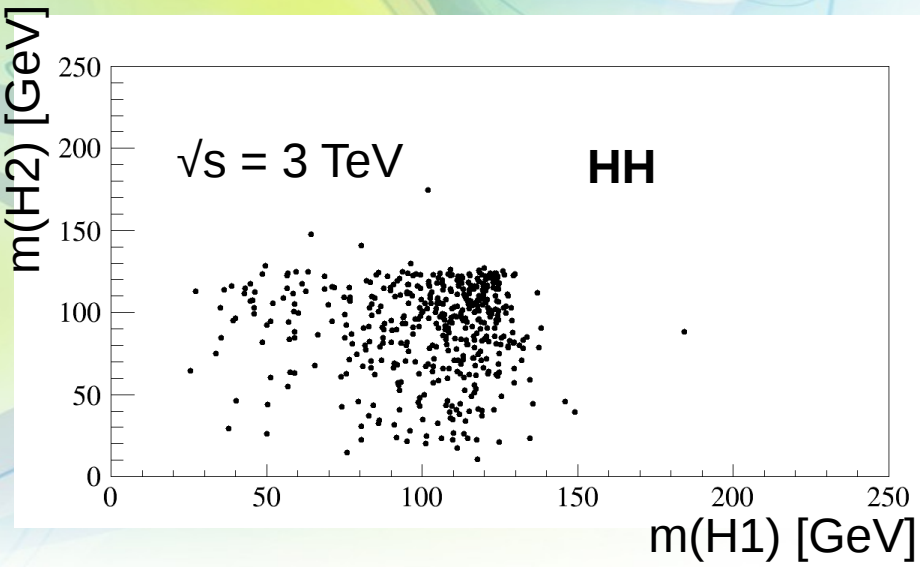
# $b\bar{b}H$ reconstruction at 3 TeV

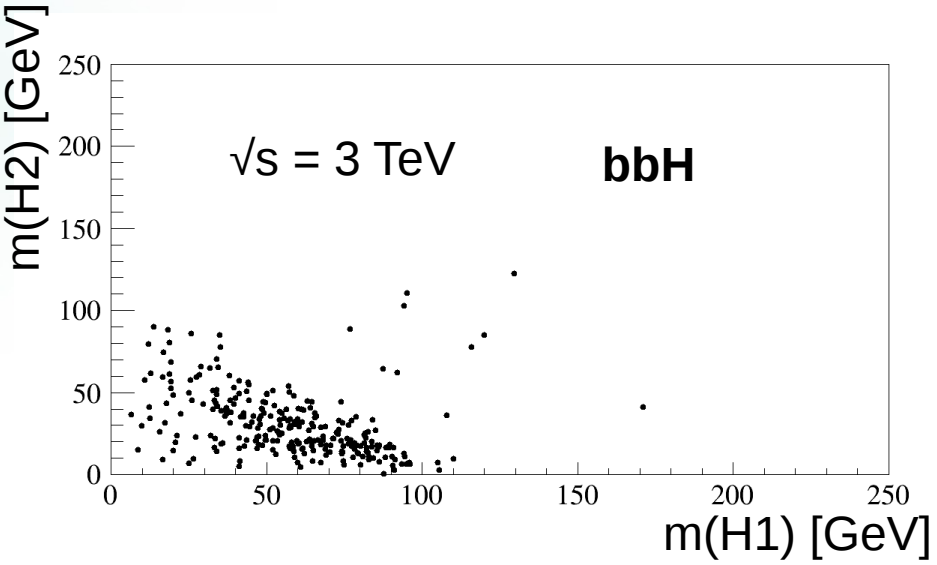
- Same selection and reconstruction strategy as for the signal
- Minimization of $M^2 = (m_{ij} - m_H)^2 + (m_{kl} - m_H)^2$
- In the comparison: reconstructed jets matched with true b-jets for HH signal, all reconstructed jets for background



# $b\bar{b}H$ reconstruction at 3 TeV




- Good signal/background separation in the mass space.
- We should be able to remove most of the bbH background with a multivariate analysis.
- These distributions may be smeared by the effect of the Beam Induced Background.

# Analysis strategy and next steps

- Need to define a **b-tagging strategy**. How many tagged jets should we require?
- Measure the reconstruction and b-tagging efficiencies, including also the **Beam-Induced Background effects**.
- Study the full background.
- Train a discriminator to separate the signal from the background.
- Define an ad-hoc strategy for the 10 TeV case. Since b-quarks from H are more collimated, should we consider **fat jets**?
- The last steps will be the HH cross section uncertainty estimation and the Higgs self-coupling sensitivity extrapolation.

# Backup slides