Determination of the double Higgs cross section and trilinear Higgs coupling sensitivities at Muon Collider

Laura Buonincontri (University of Padova and INFN)

Donatella Lucchesi, Camilla Curatolo, Lorenzo Sestini, Sergo Jindariani, Alessio Gianelle, Paolo Andreetto, Nazar Bartosik, Massimo Casarsa, Katherine Pachal, Hannsjoerg Weber, Lawrence Lee, Simone Pagan Griso, Karol Krizka, Maximilian Swiatlowski, Marco Valente

On behalf of the International Muon Collider Collaboration

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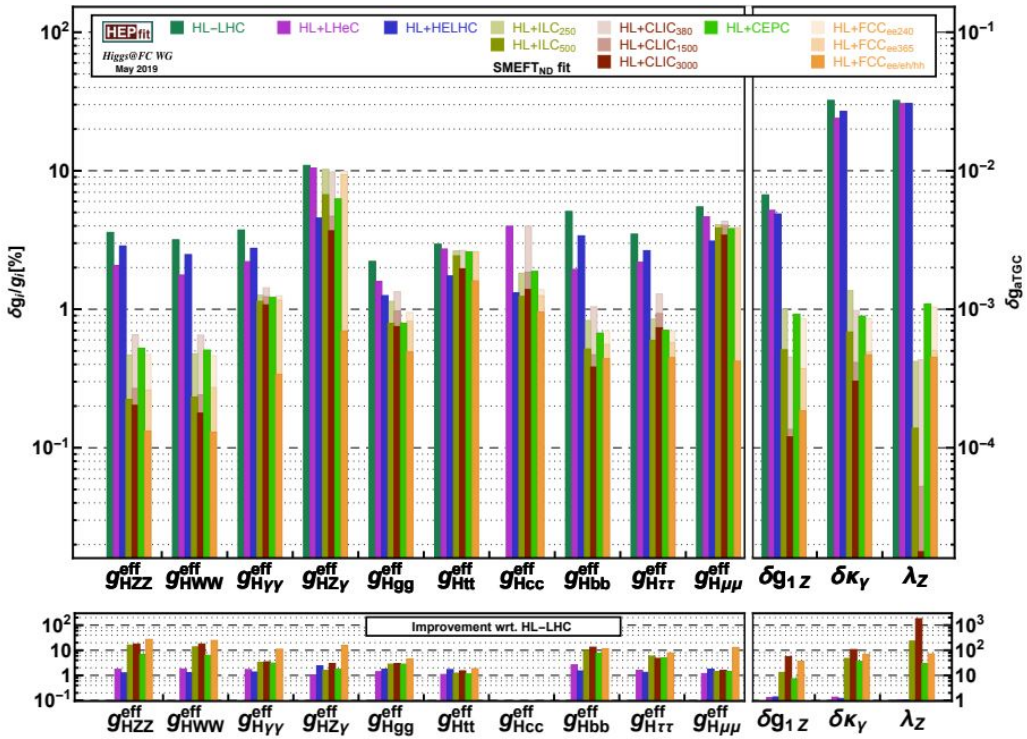
Higgs at Future Colliders

Results performed so far on Higgs couplings to SM particles are in agreement with the SM predictions.



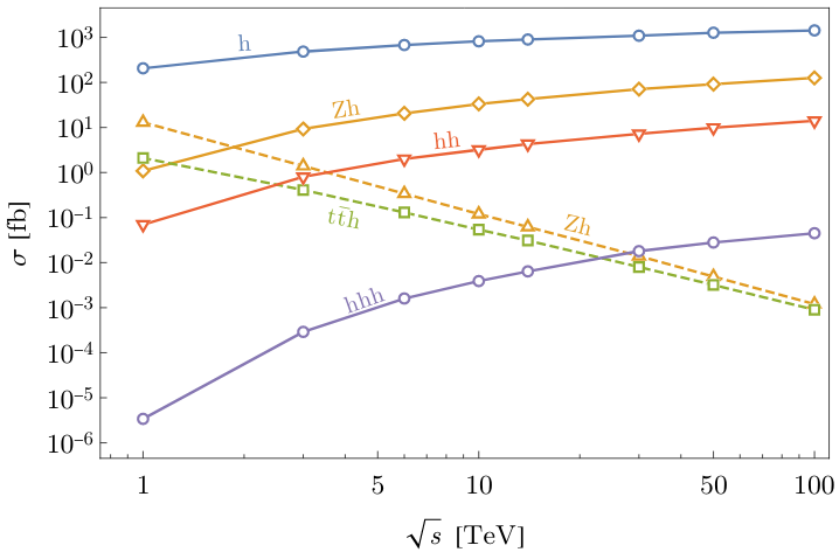
- One of the goal of future colliders is the measurement of Higgs couplings with SM particles with precision below the 1% precision scale.
- This would allow to reveal possible deviations from the SM.
- Recent theoretical studies for Muon Collider shows competitive results: X. Wang's talk later and arXiv:2103.14043.

Higgs potential

After the electroweak symmetry breaking:

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

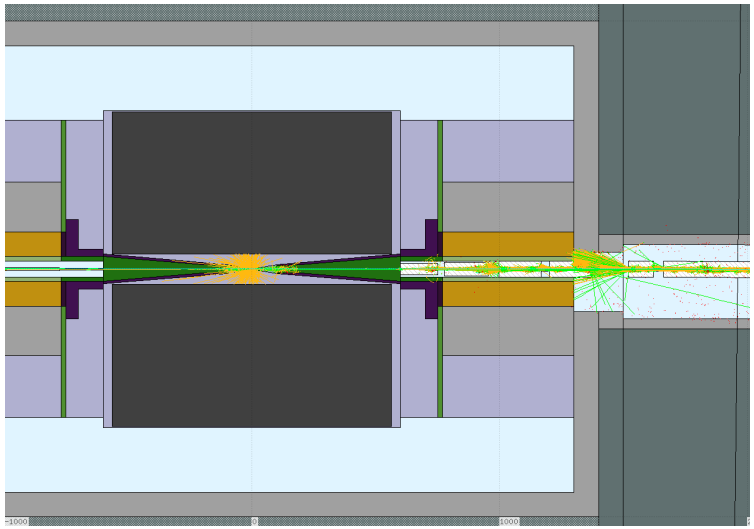
- $m_H = 125.10 \pm 0.14$ GeV; λ_3 and λ_4 never been measured so far.
- CLIC with 5 ab^{-1} at $\sqrt{s} = 3$ TeV can measure λ_3 with an uncertainty of -7% and +11% using HH events (Eur. Phys. J. C 80, 1010 (2020)).

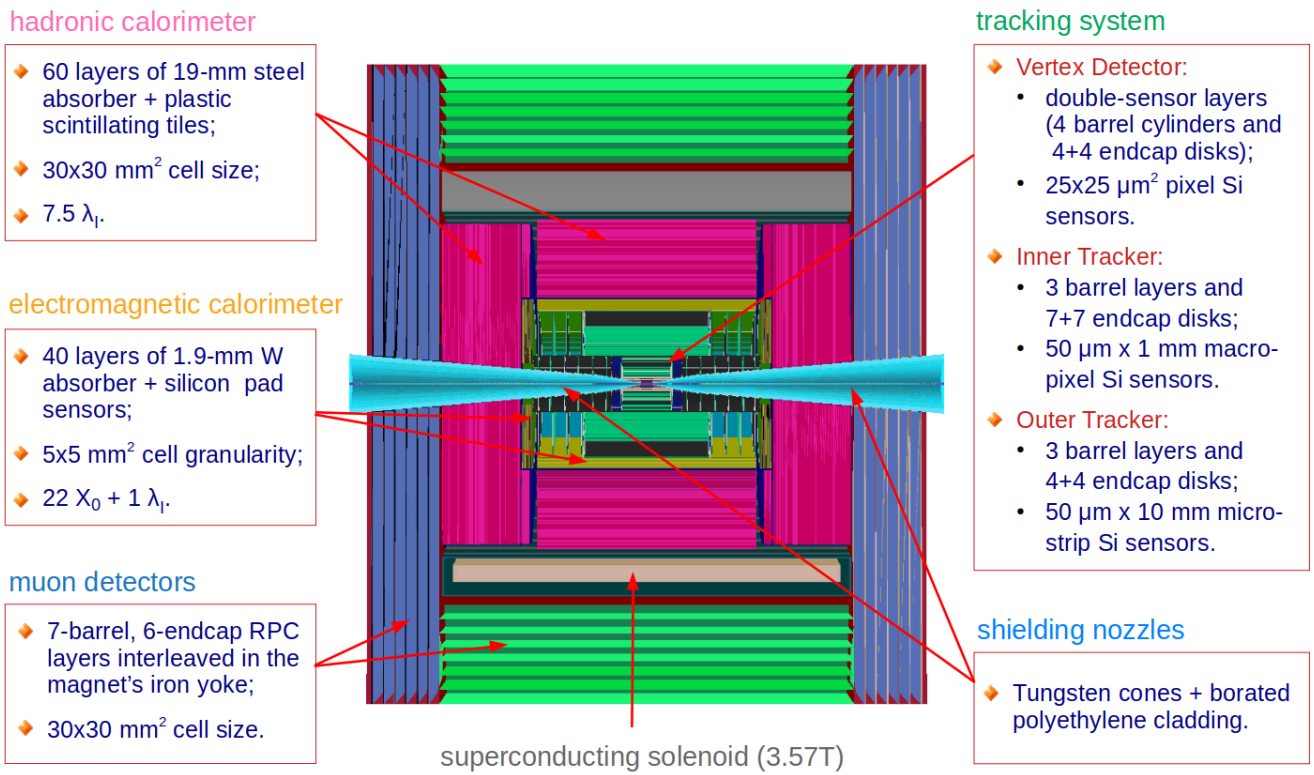


- Muon collider is the ideal machine to study Higgs physics: high yields of single H, HH and HHH events are produced.
- Theoretical studies: sensitivity of MC at 10 ab^{-1} and $\sqrt{s}$=10 TeV to the measurement of λ_3: 5.6% (see X. Wang's talk later).
- In this presentation: evaluation of the sensitivity on $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ cross section and on λ_3 including detector effects

Detector challenges

- Full simulation at 1.5 TeV to evaluate effects of the Beam-Induced Background (BIB) on the detector components and to devise strategies for BIB reduction showed: see C. Curatolo' s talk, L. Sestini' s and M. Casarsa's (later) and H. Weber's (tomorrow) talks.
- Detector used for the full simulation: see S. Pagan Griso's (tomorrow) and N. Bartosik's talks.

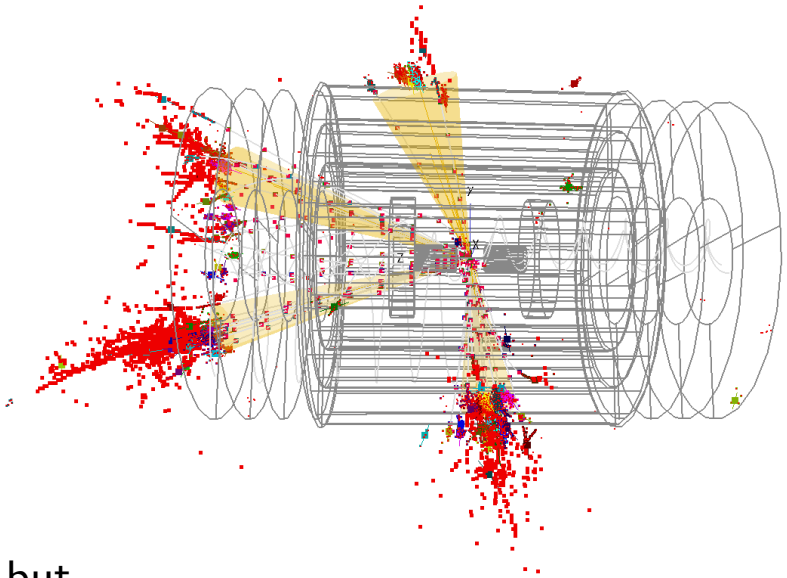




$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$: some considerations

- ILCSoftware framework is used for the full simulation and reconstruction.
- Signal and backgrounds at $\sqrt{s}$=3 TeV generated with WHIZARD

Signal	Cross section [fb]
$\mu^+\mu^- \to HH\nu\bar{\nu}$	0.8
Physics background	Cross section [fb]
$\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$	3.3
$\mu^+\mu^- \to b\bar{b}H\nu\bar{\nu}$ (signal included)	1.7

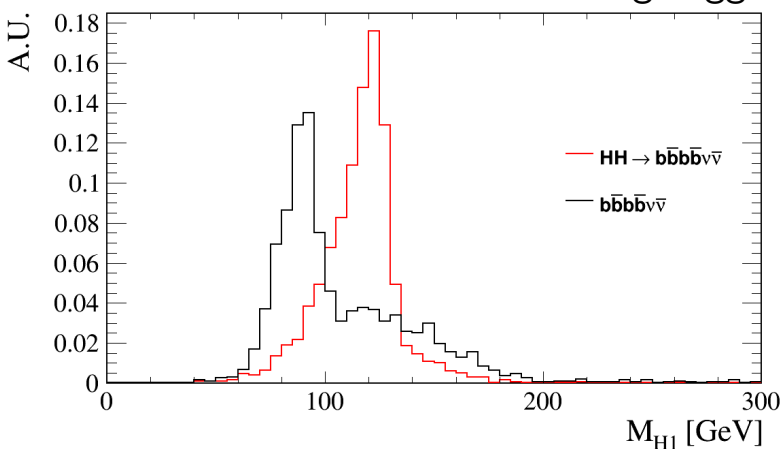


- The simulation is performed without the BIB, but
- *b*-tagging efficiency in presence of the BIB of the order of $\sim 60\%$ with a mis-tag $\sim 1\%$ at 1.5 TeV are used to weight events (see 2020 JINST 15 P05001).
- One jet for each pair is required to be tagged: processes with jets in the final states different from the *b* quark are negligible (to be verified).
- Reconstruction performed under conservative assumption (jet reconstruction with BIB still under optimization).

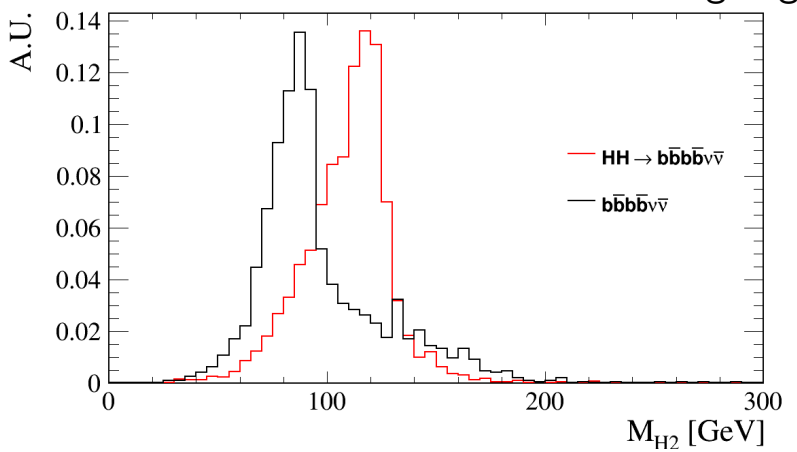
Studies of double Higgs

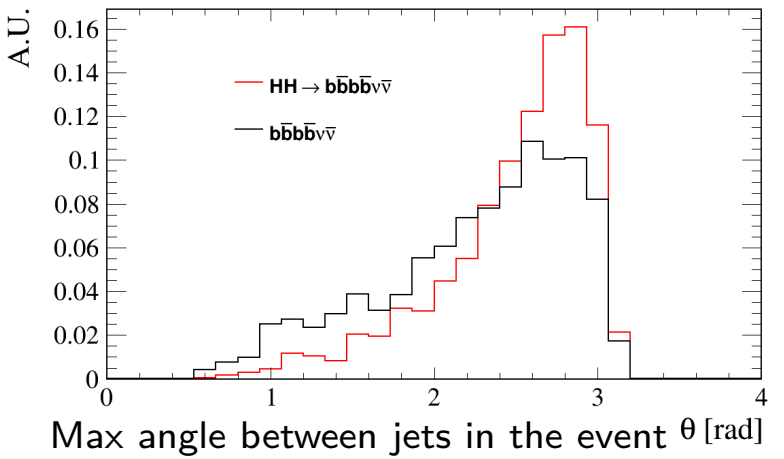
- Event selection: $N_{jets}>3$ and minimum transverse momentum $p_T > 20$ GeV
- Jets paired by minimizing the figure of merit: $M = \sqrt{(m_{ij} - m_H)^2 + (m_{kl} - m_H)^2}$
- Selection of the kinematic variables used to distinguish the signal ($\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$) and the physics background ($\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$): m_{H_1},m_{H_2}, $\sum E_{jets}$, max jet P_T for each pair, $\Delta\theta_{max}$.

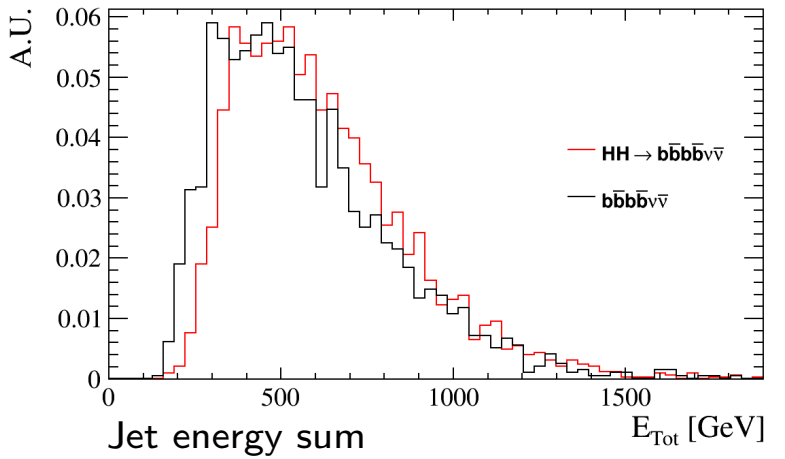
Invariant mass of the leading Higgs



Invariant mass of the sub-leading Higgs

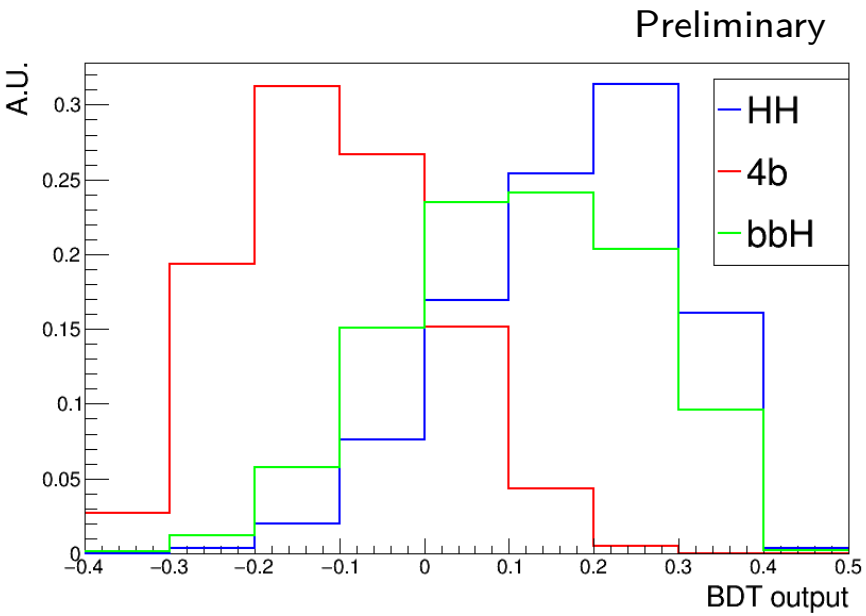


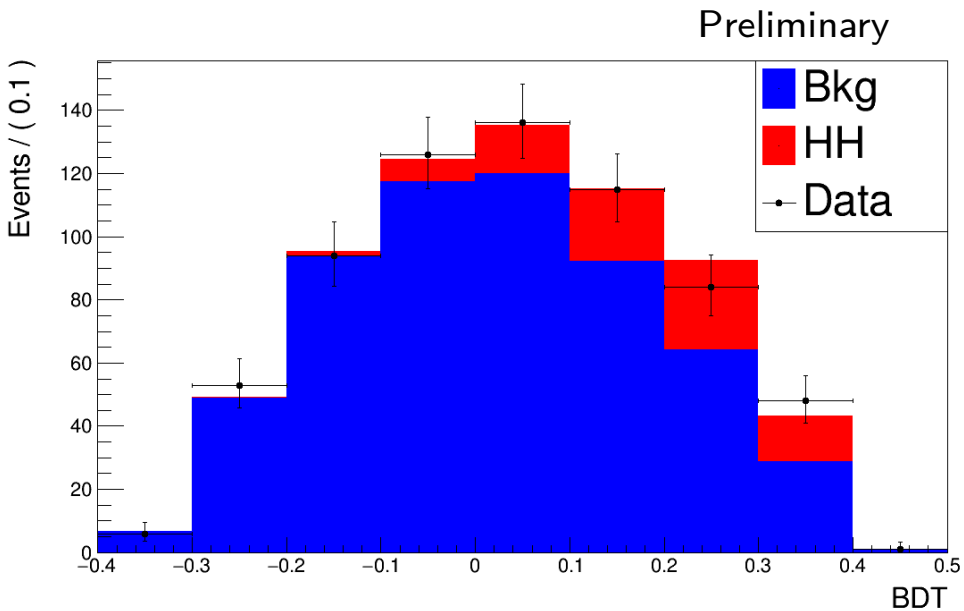




HH cross section measurement

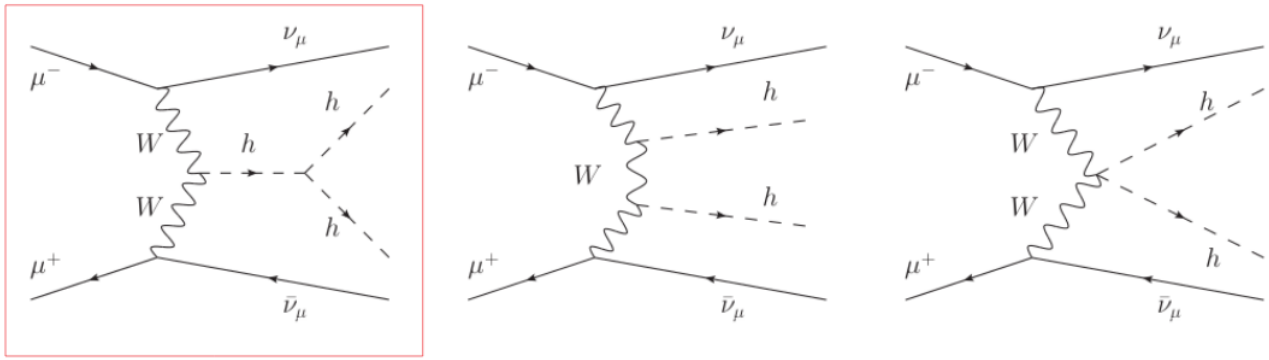
- Classification of signal and background events by using a Machine Learning technique (Boosted Decision Tree)
- With 1.3 ab^{-1} (4 years of data taking) at 3 TeV we expect to select 65 HH events and 561 background events.
- With a simple fit to the BDT an uncertainty of $\sim 30\%$ on the cross section has been obtained.



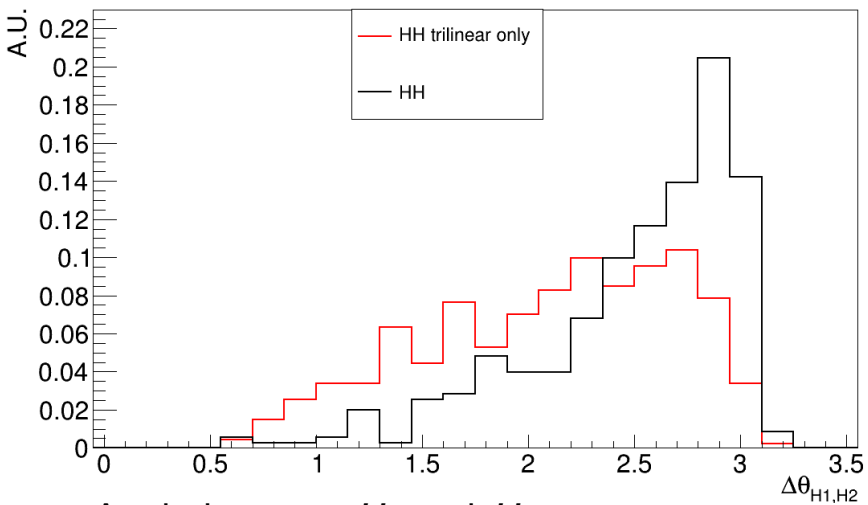


Toward trilinear coupling measurement

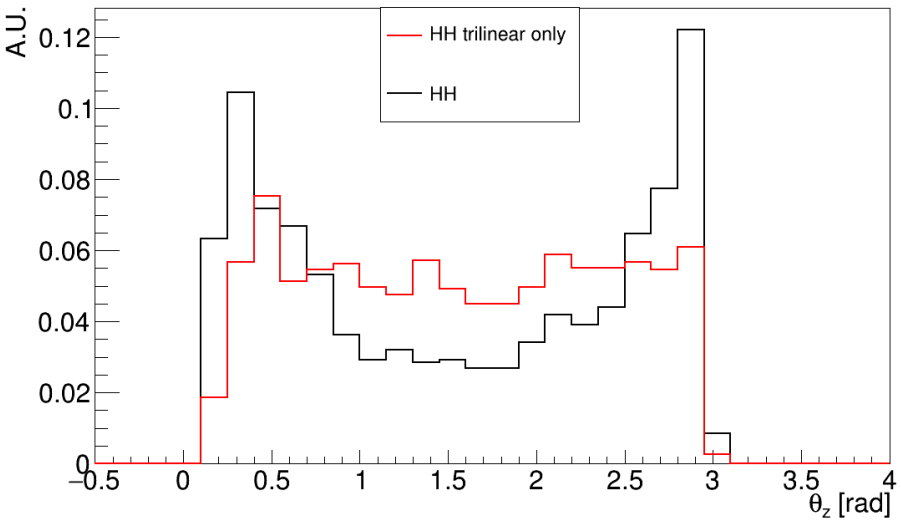
- Generation with WHIZARD and simulation of HH events just with the process mediated by the trilinear coupling



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



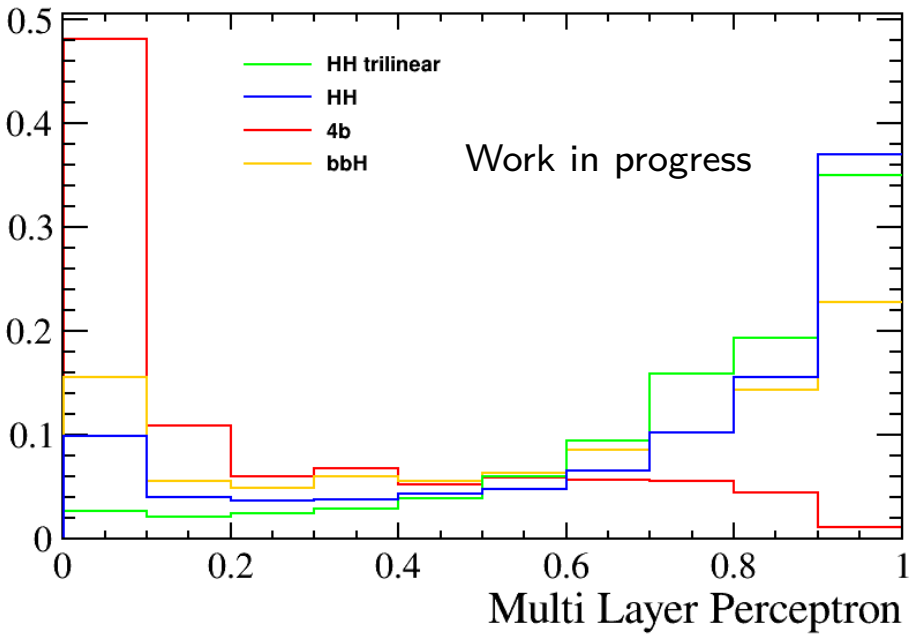
Angle between H_1 and H_2

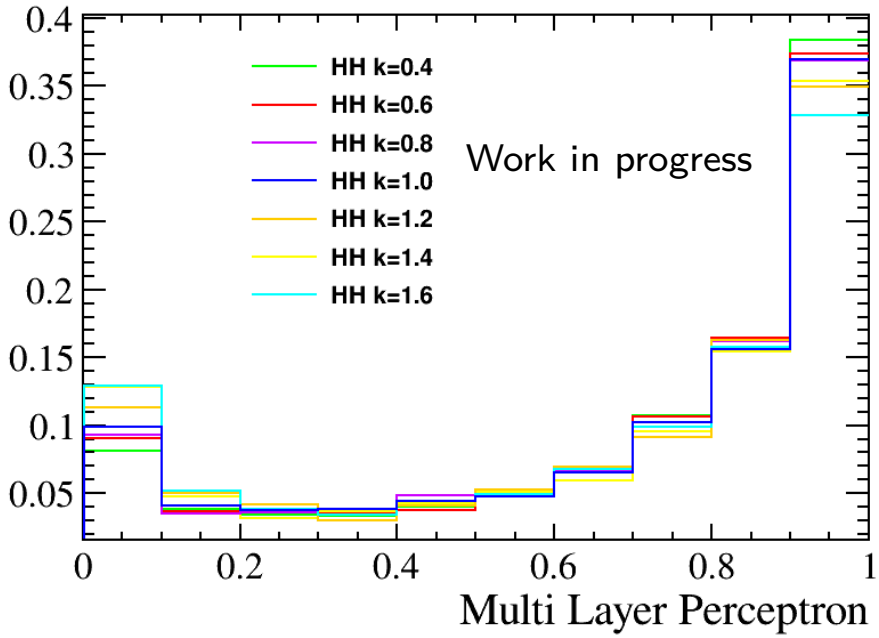


Angle between selected jets and z axis

Toward trilinear coupling measurement

- Idea: train a Multi Layer Perceptron (MLP) discriminator for the separation of HH-trilinear and background $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$.
- Preliminary results of the application of the MLP to signal and background samples (fig. left)
- Set of $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ samples generated with WHIZARD Monte Carlo for different $\kappa = \frac{\lambda}{\lambda_{SM}}$=(0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6)
- Next steps: compare the number of selected events with a MLP cut with the SM expectation at different couplings.
- A χ^2 technique could be employed to determine the λ_3 confidence interval for the measurement.

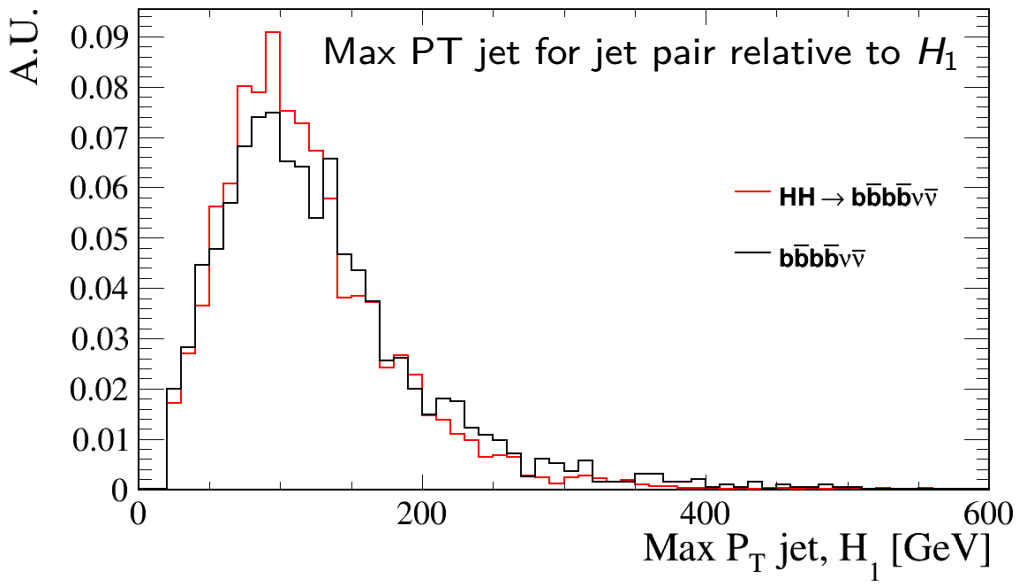


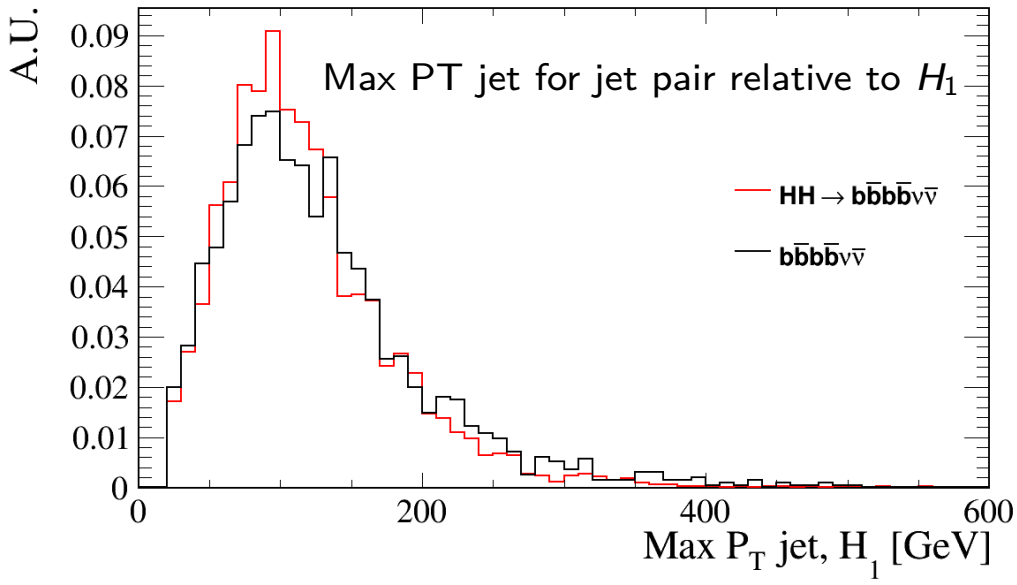


Conclusions and plans

- With conservative assumptions we can already obtain good results on the uncertainty of the double Higgs cross section ($\sim$ 30% at 1.3 ab^{-1} and $\sqrt{s} = 3$ TeV);
- but we aim at $\sqrt{s} = 10$ TeV!
- Improvement expected with the new algorithms on jet reconstruction and b jets identification;
- add other final states to improve statistics;
- first look at the trilinear coupling sensitivity seems encouraging for the determination.

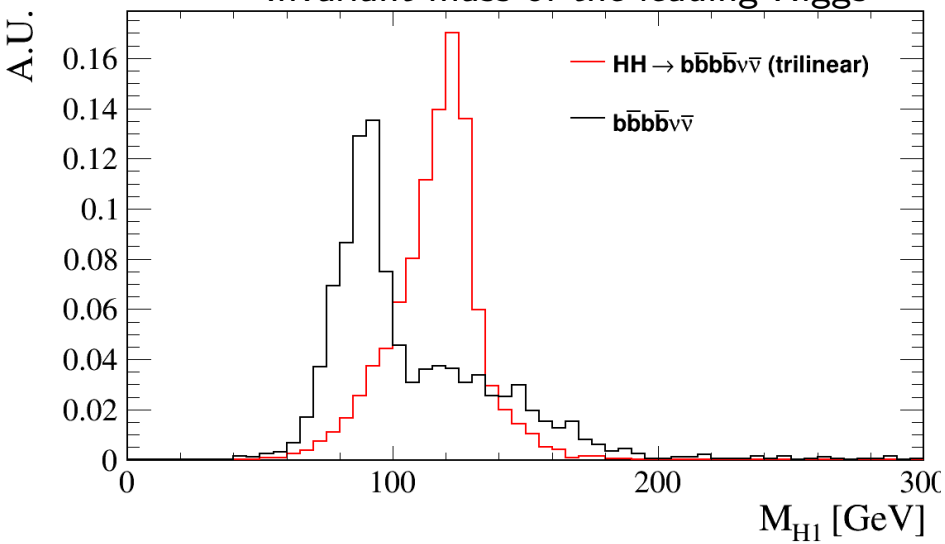
Additional variables for the uncertainty on the HH cross section analysis



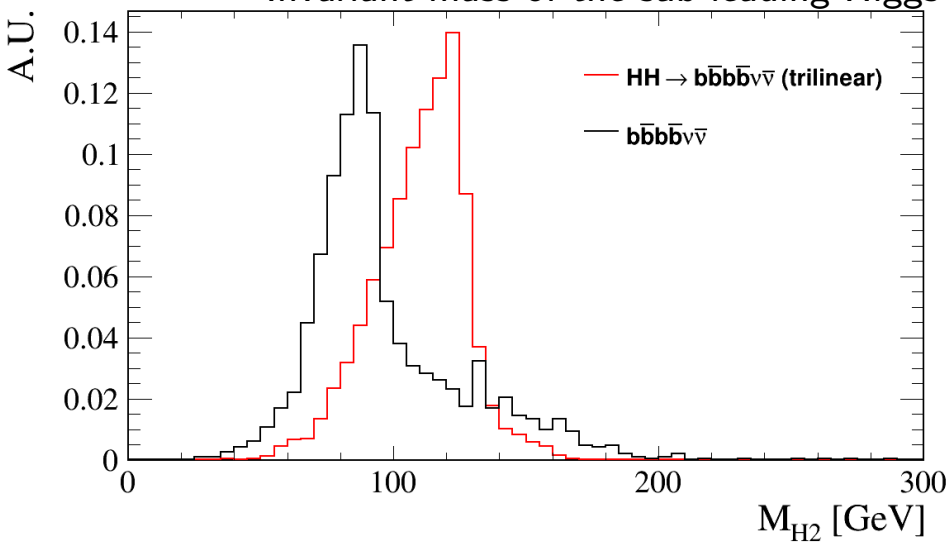


Variables for the uncertainty on the trilinear coupling analysis

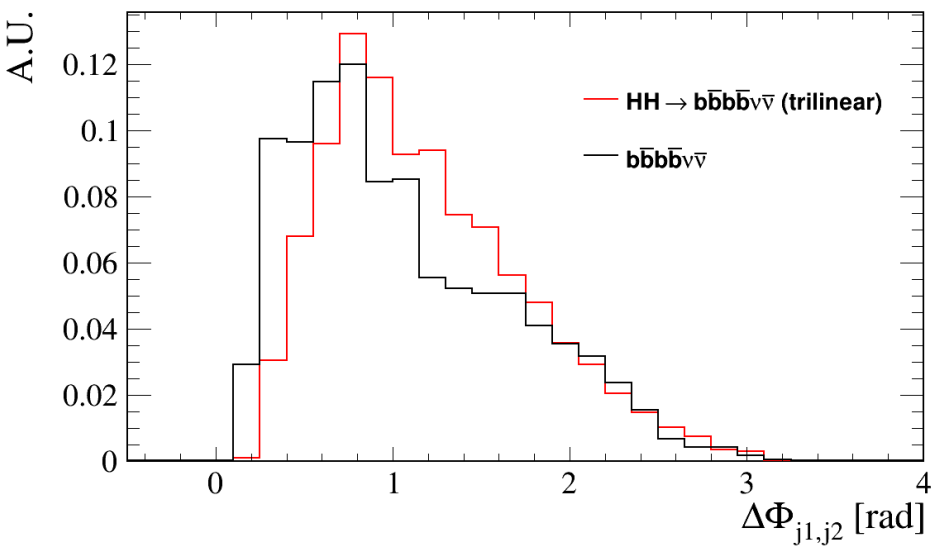
Invariant mass of the leading Higgs



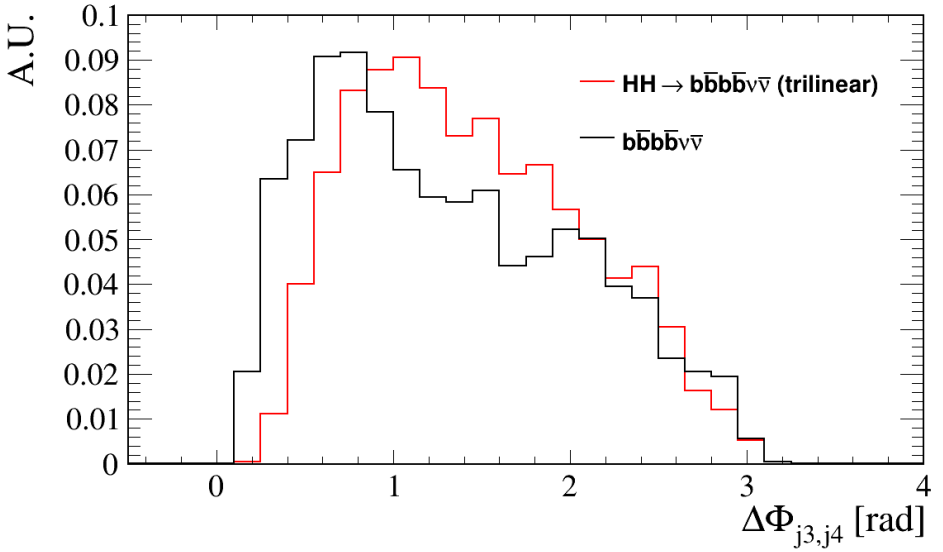
Invariant mass of the sub-leading Higgs



Angle between jets associated to the leading Higgs

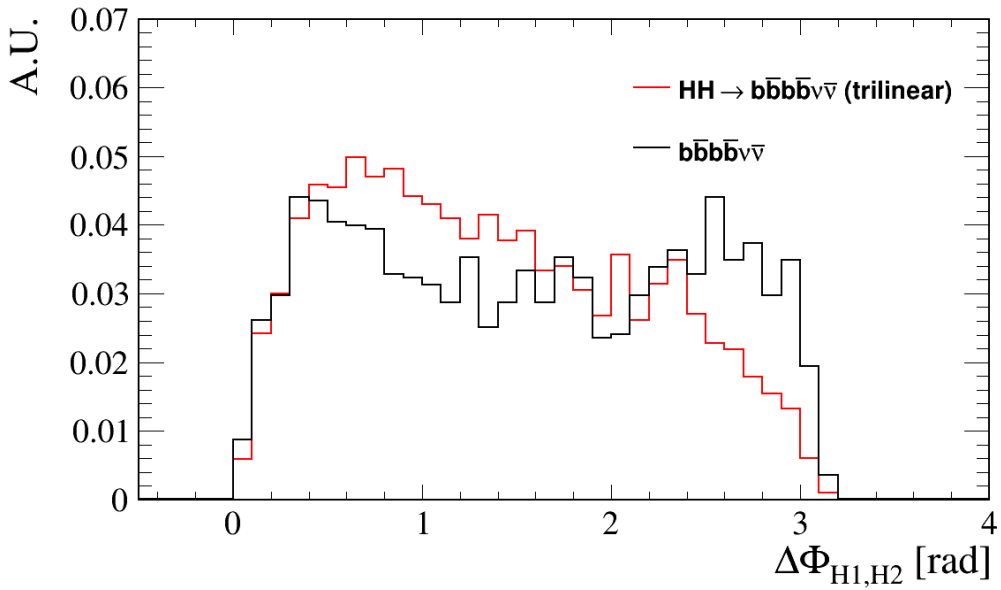


Angle between jets associated to the sub-leading Higgs

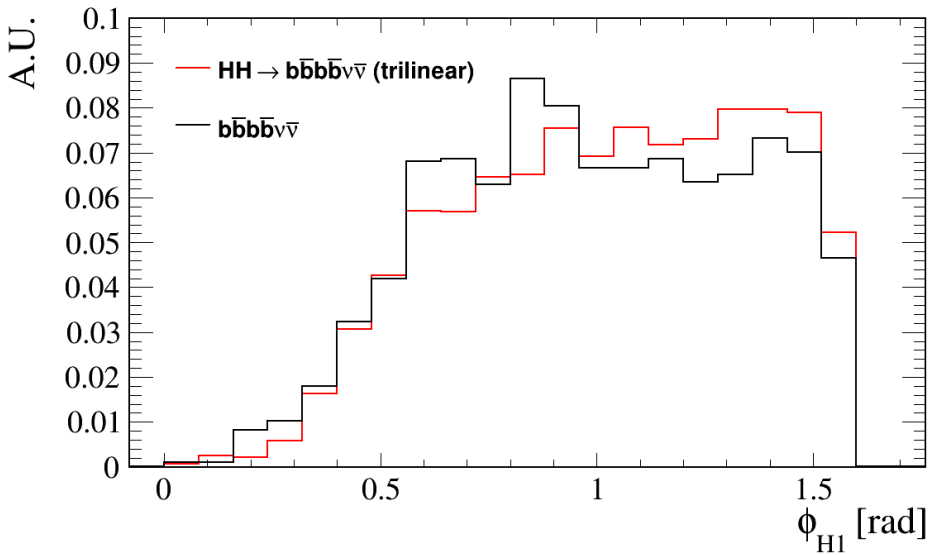


Variables for the uncertainty on the trilinear coupling analysis (II)

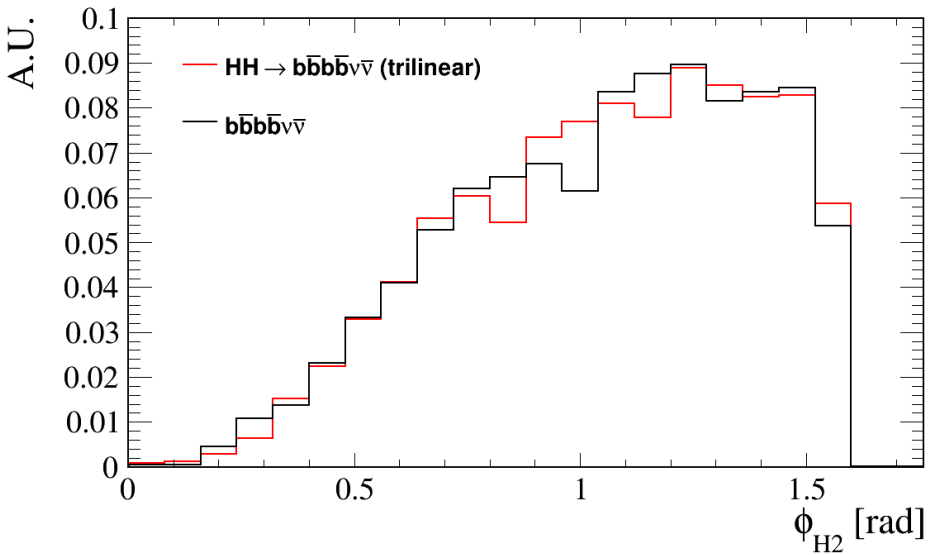
Angle between the two Higgs



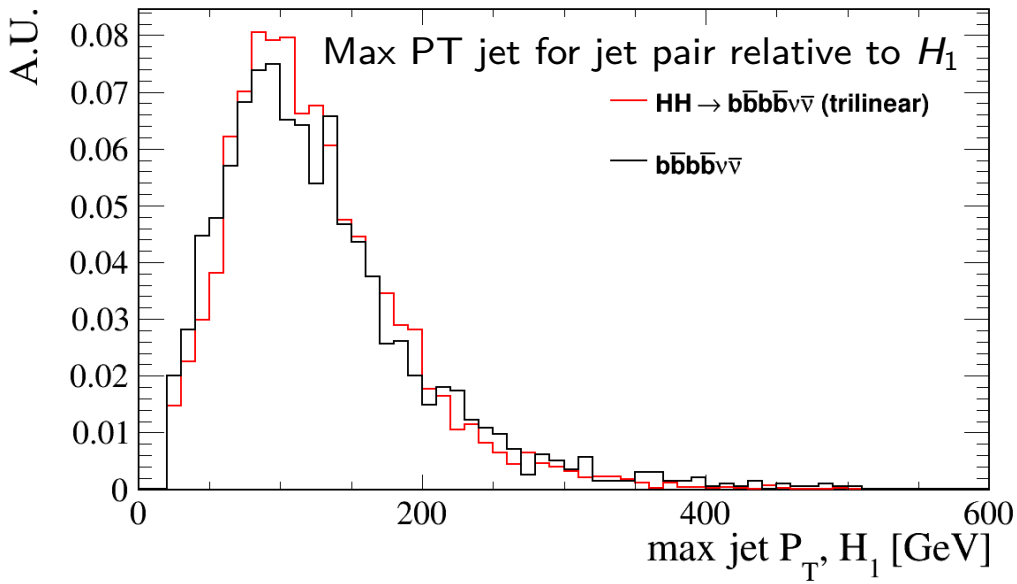
Helicity angle between the outcoming jets wrt H1

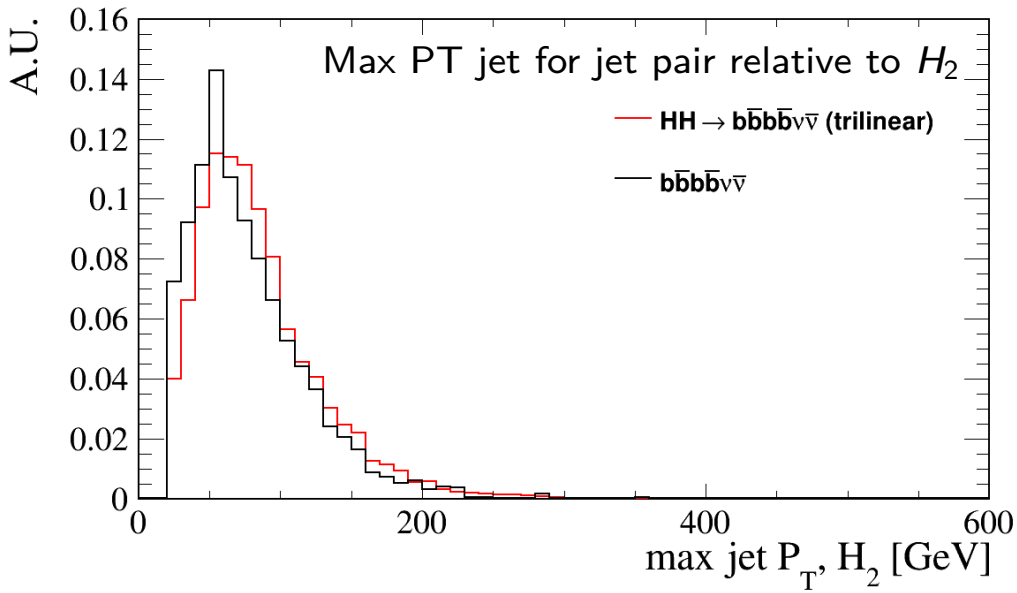


Helicity angle between the outcoming jets wrt H2



Variables for the uncertainty on the trilinear coupling analysis (III)





Cross section HH different couplings