ICHEP 2022 BOLOGNA

International MUON Collider Collaboration

INFN Istituto Nazionale di Fisica Nucleare

# Higgs Physics at Muon Collider with detailed detector simulation

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**On behalf of the Muon Collider Detector and Physics group**

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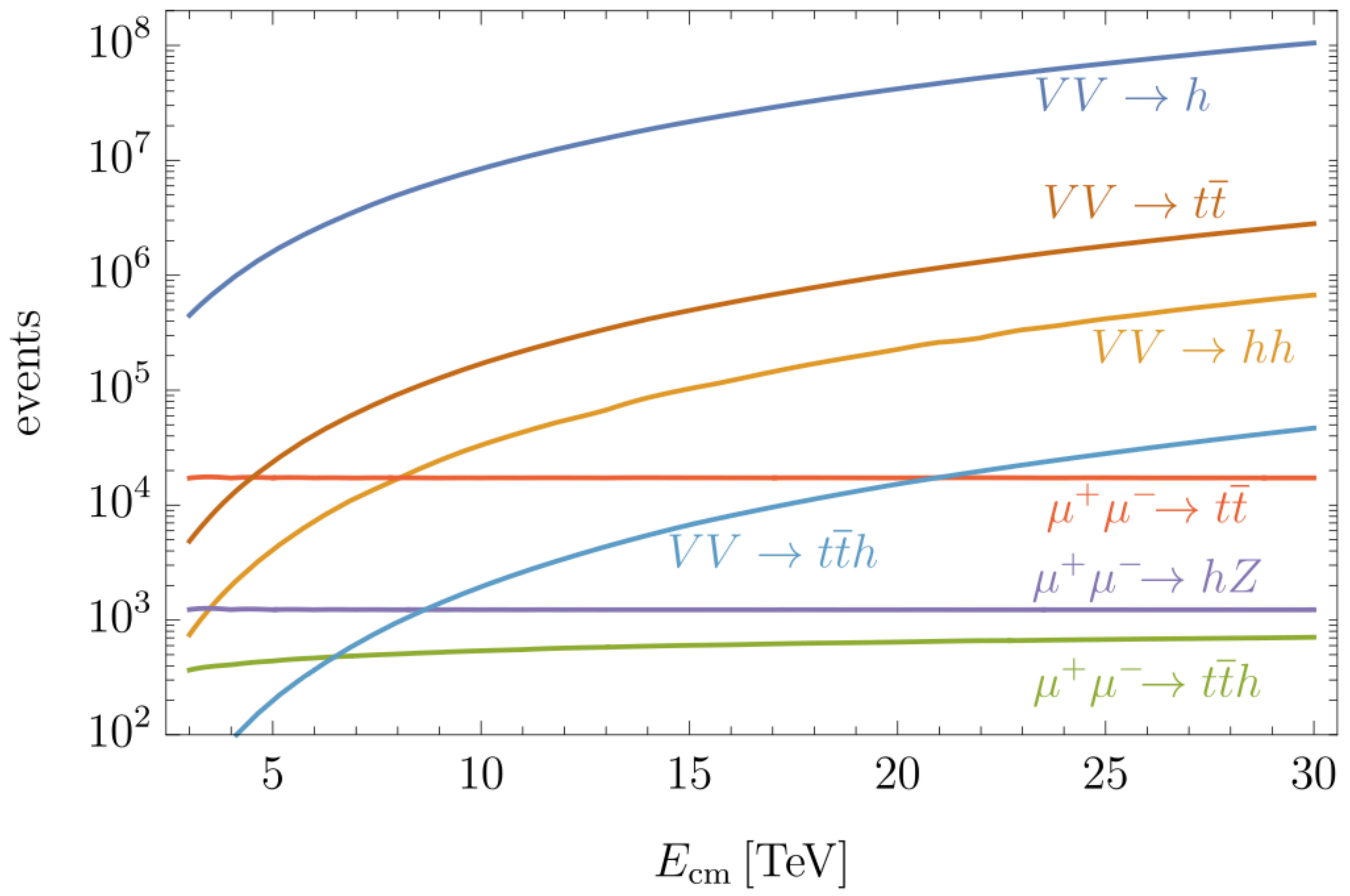
# Higgs Physics at Muon Collider

- **The Muon Collider is the ideal facility for Higgs Physics**
- Cleaner collisions as in electron-positron colliders and energy frontier as in hadron colliders
- At the first proposed stage for a Muon Collider (3 TeV) of about **500k Higgs are produced with 1 ab$^{-1}$**
- **In this talk: Higgs Physics at 3 TeV is demonstrated with detailed detector simulation**

Overview of Muon Collider project at ICHEP 2022: talk by Daniel Schulte

https://arxiv.org/abs/2203.07256



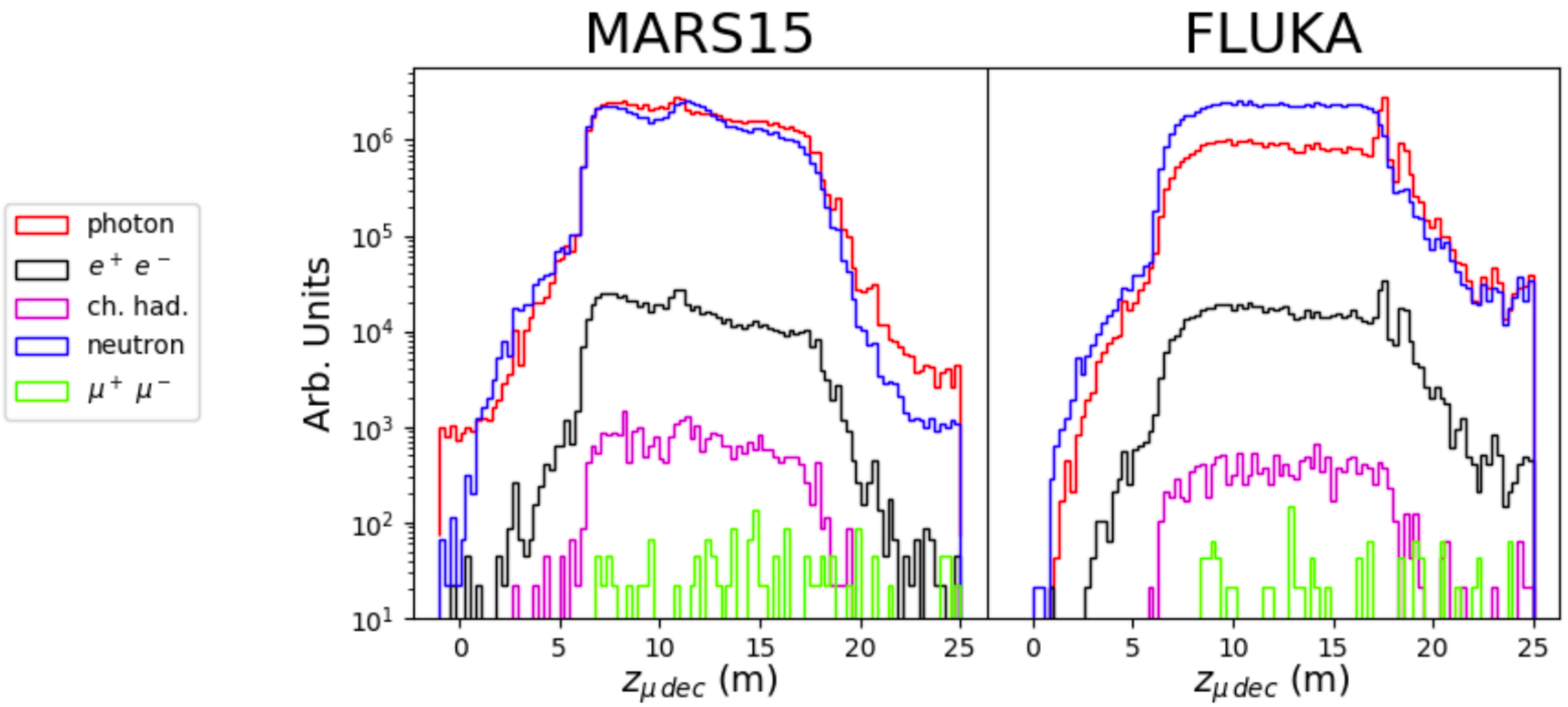

| $\sqrt{s}$ | $\int \mathcal{L}dt$ |
|---|---|
| 3 TeV | 1 ab$^{-1}$ |
| 10 TeV | 10 ab$^{-1}$ |
| 14 TeV | 20 ab$^{-1}$ |

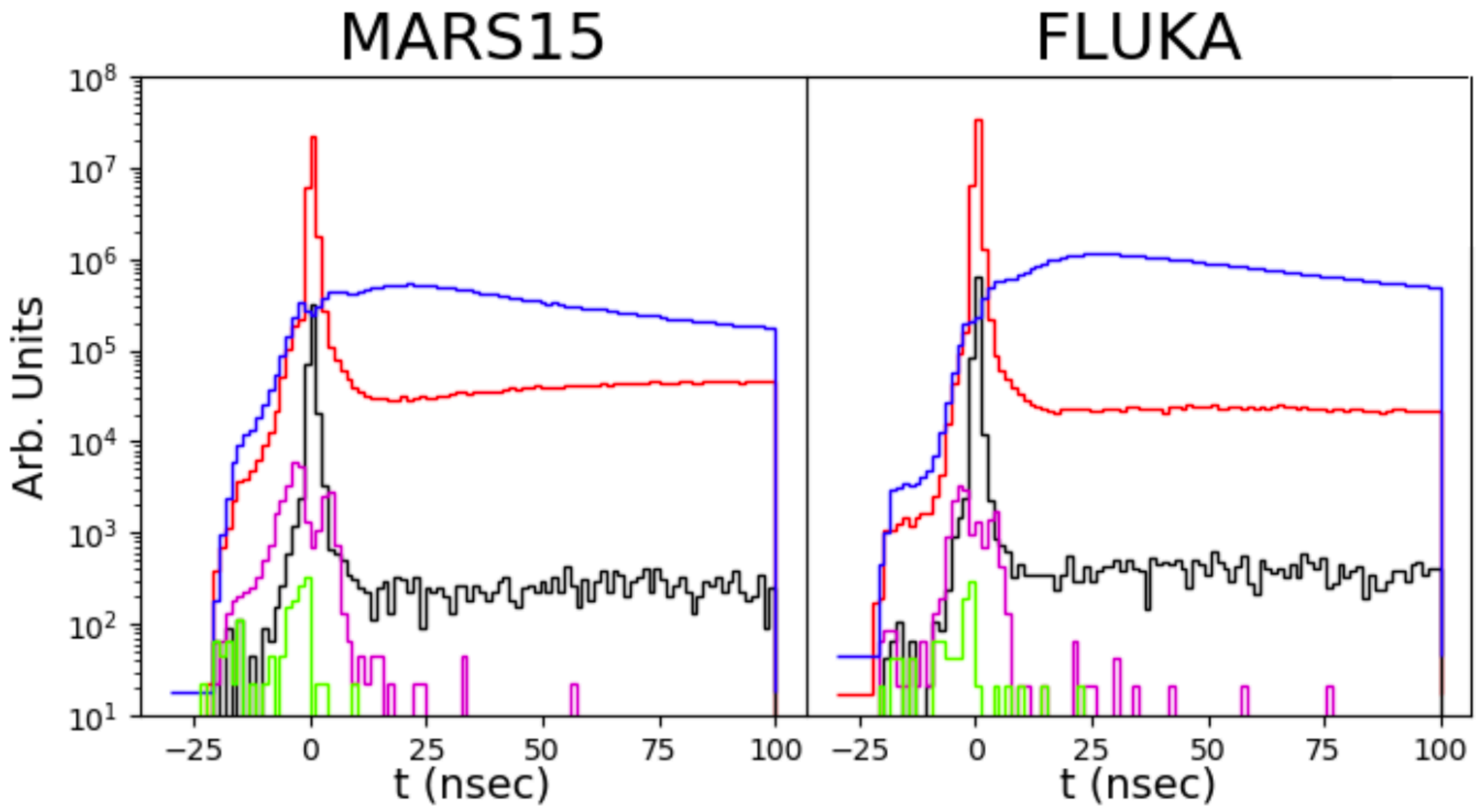
**5 years of data taking, 1 experiment**

# Beam-induced background (BIB)

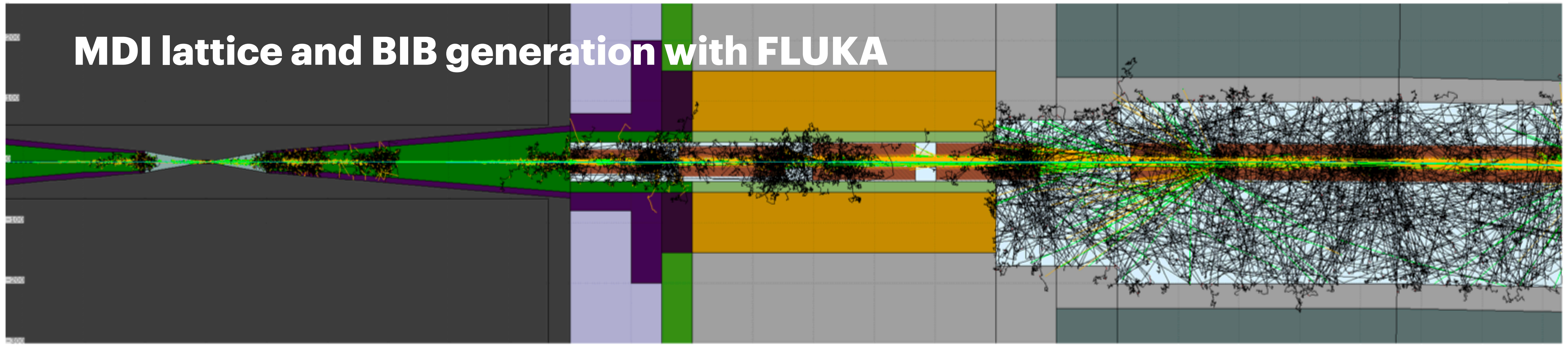
- It is produced by the decay in flight of muons, and subsequent interactions
- The BIB is mitigated by the Machine Detector Interface (*e.g.* two tungsten nozzles are inserted)
- **In order to assess the physics reach of a Muon Collider it is fundamental to study the impact of the BIB on the detector**
- The BIB is simulated with MARS15 or FLUKA, by considering the machine and the Machine Detector Interface lattice

https://arxiv.org/abs/2105.09116




**Muon Collider software framework: talk by Paolo Andreetto tomorrow**



# Detector

## hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 $mm^2$ cell size;
- 7.5 $\lambda_I$.

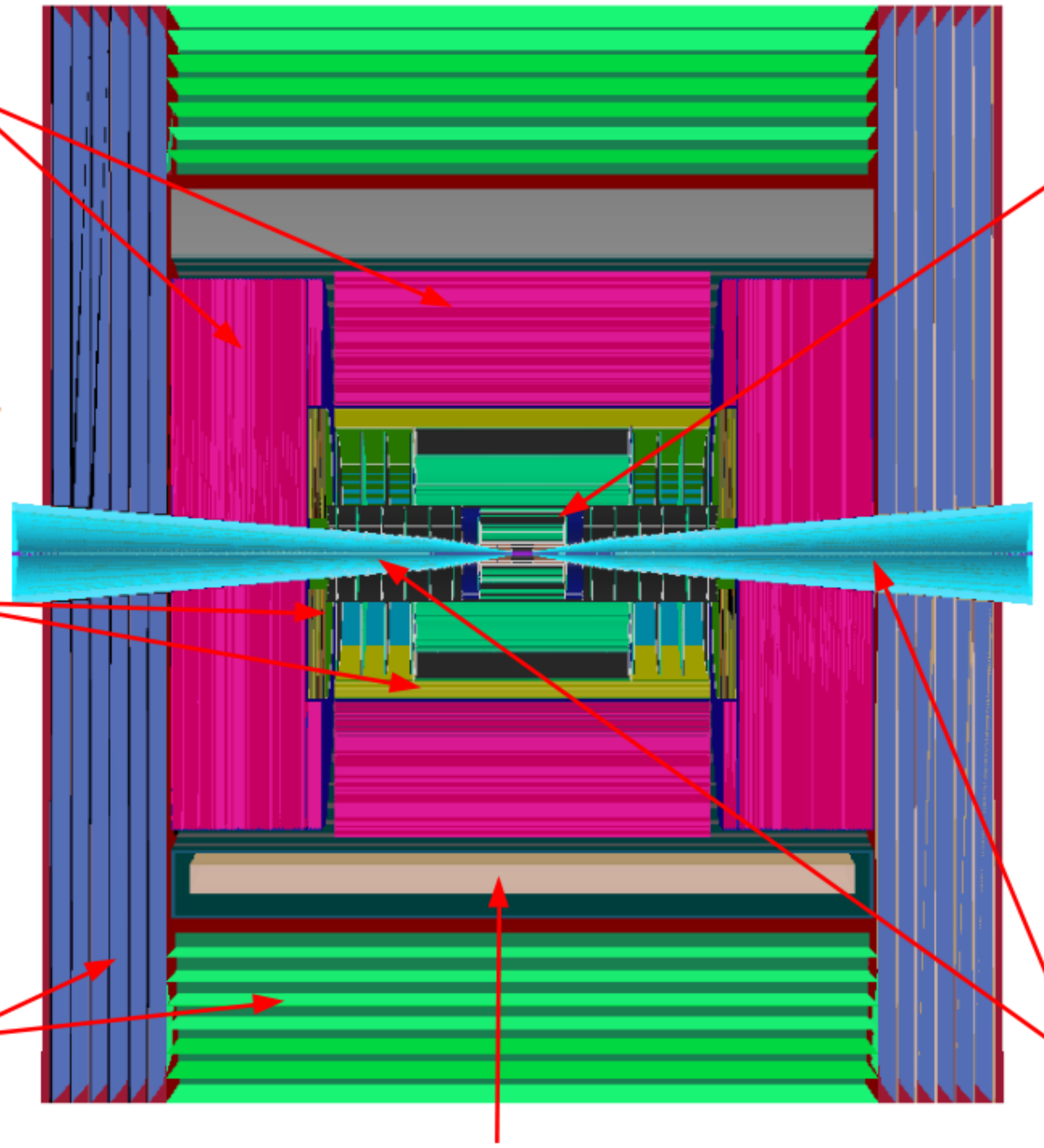
## electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 $mm^2$ cell granularity;
- 22 $X_0$ + 1 $\lambda_I$.

## muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 $mm^2$ cell size.

**<u>Talk on Muon Collider calorimeter</u> by Eleonora Diociaiuti**



superconducting solenoid (3.57T)

## tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 $\mu m^2$ pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

## shielding nozzles

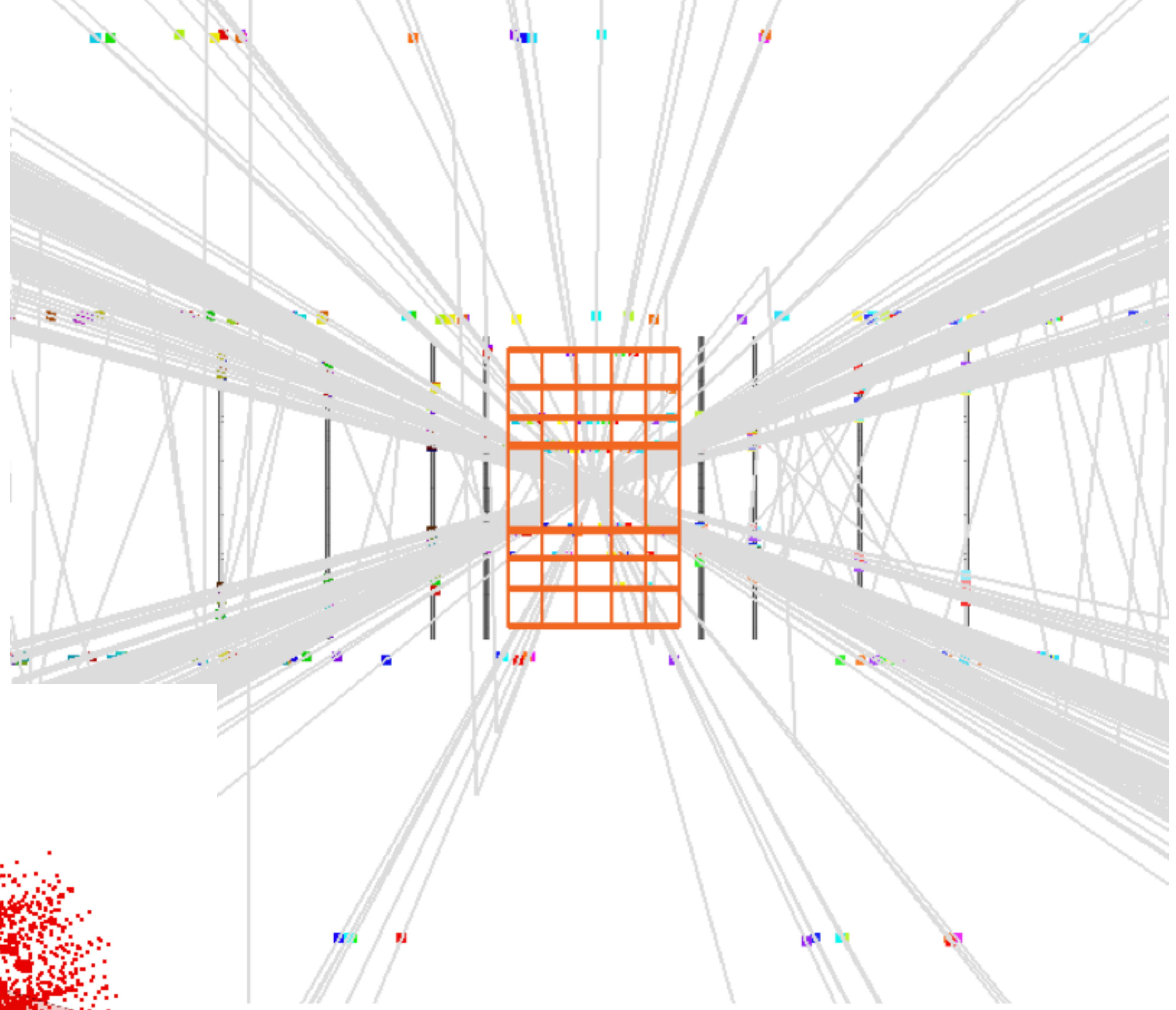
- Tungsten cones + borated polyethylene cladding.

- **The interaction of BIB/signal with the detector is simulated with Geant4**

# Physics objects reconstruction

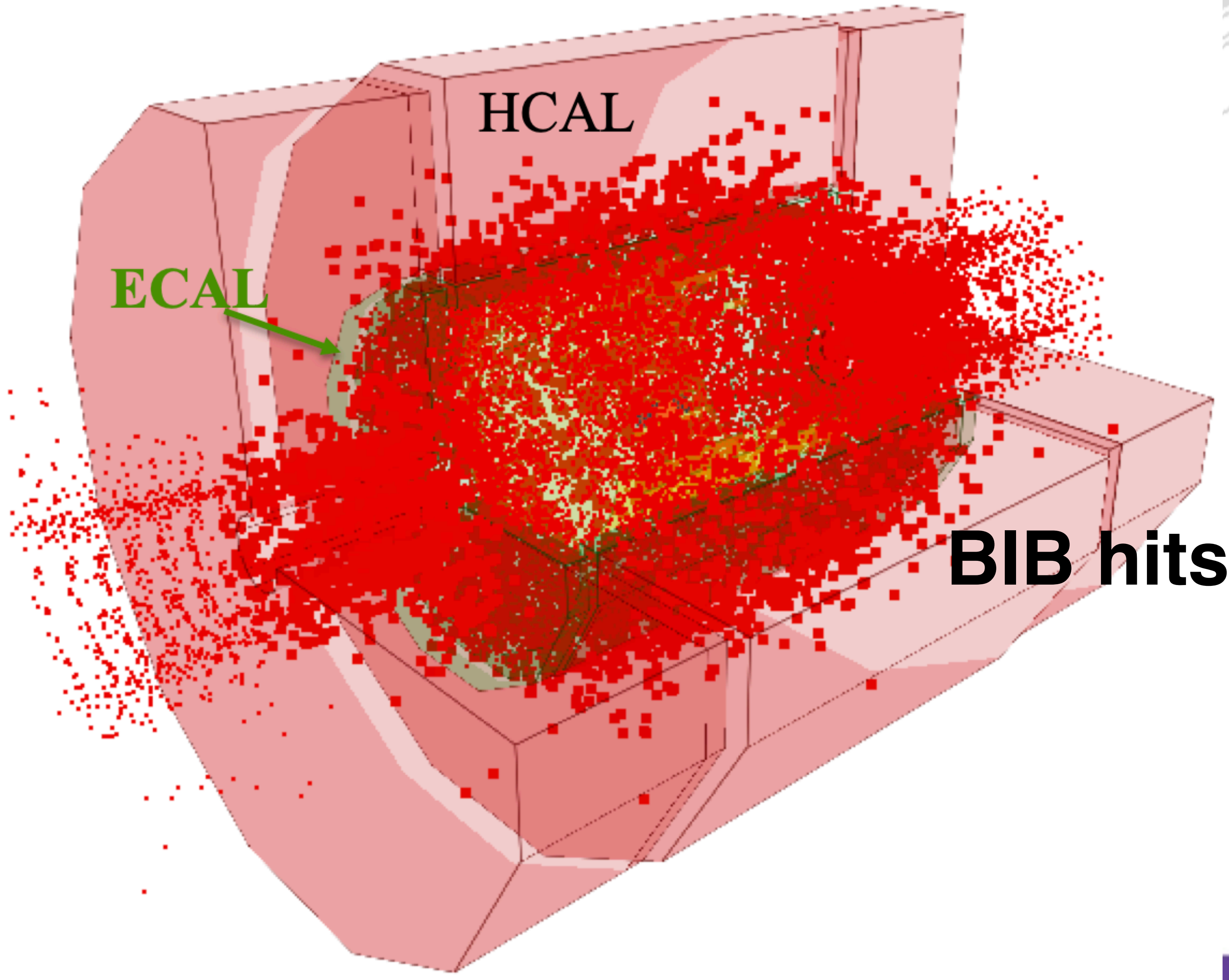
- **Reconstruction** in this environment is not trivial:
  - the **high hit multiplicity from the BIB in the vertex detector/ tracking modules** produces a significant combinatorial problem
  - A diffuse BIB background is present in the calorimeters
  - The nozzles, that are fundamental for BIB mitigation, reduce the acceptance in the forward region

**Combinatorial tracks from BIB**



**Most of the BIB particles are asynchronous with respect to the bunch crossing: timing is crucial for reconstruction**

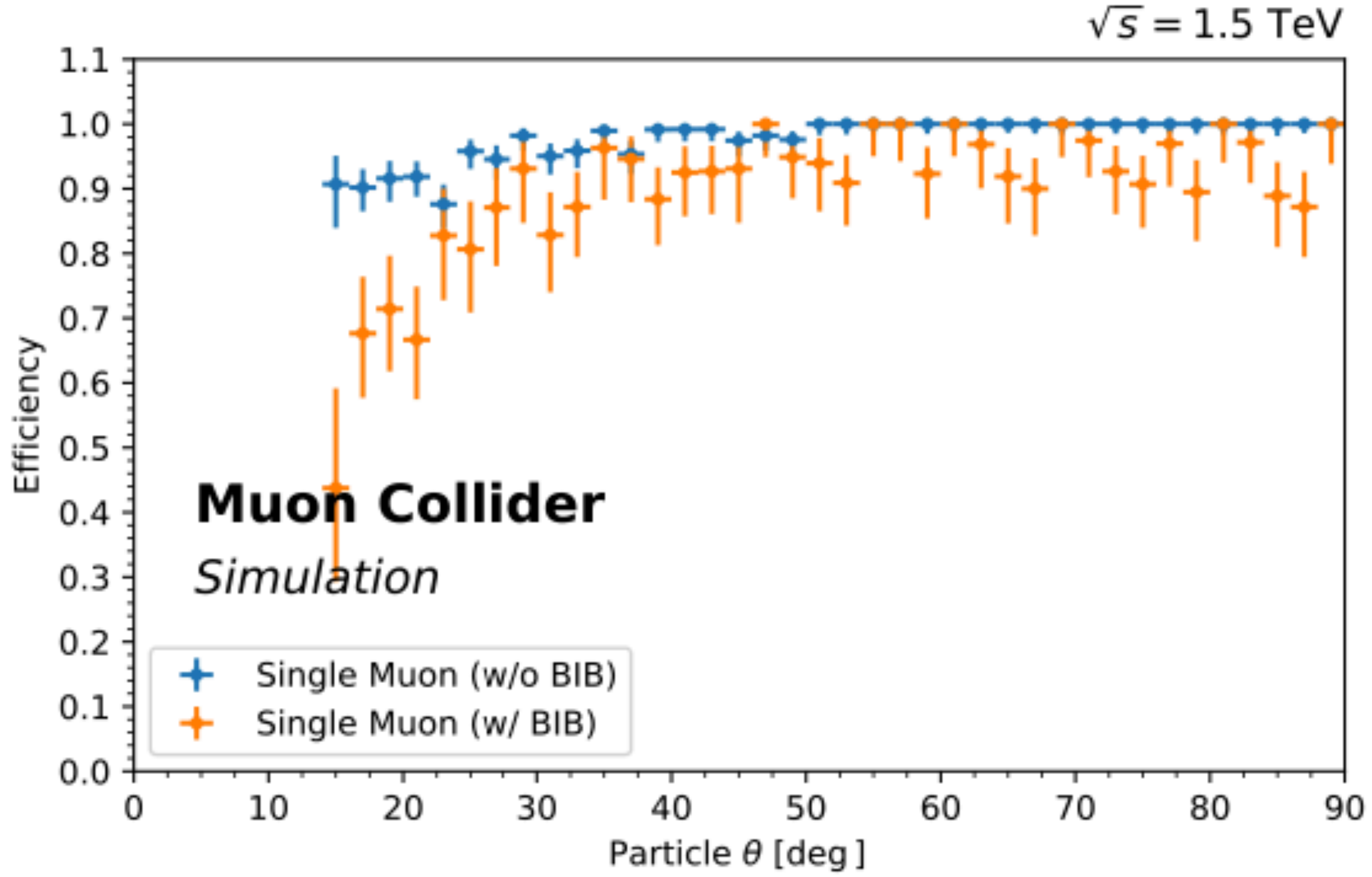
**More details on Muon Collider reconstruction in the poster by Paola Salvini**



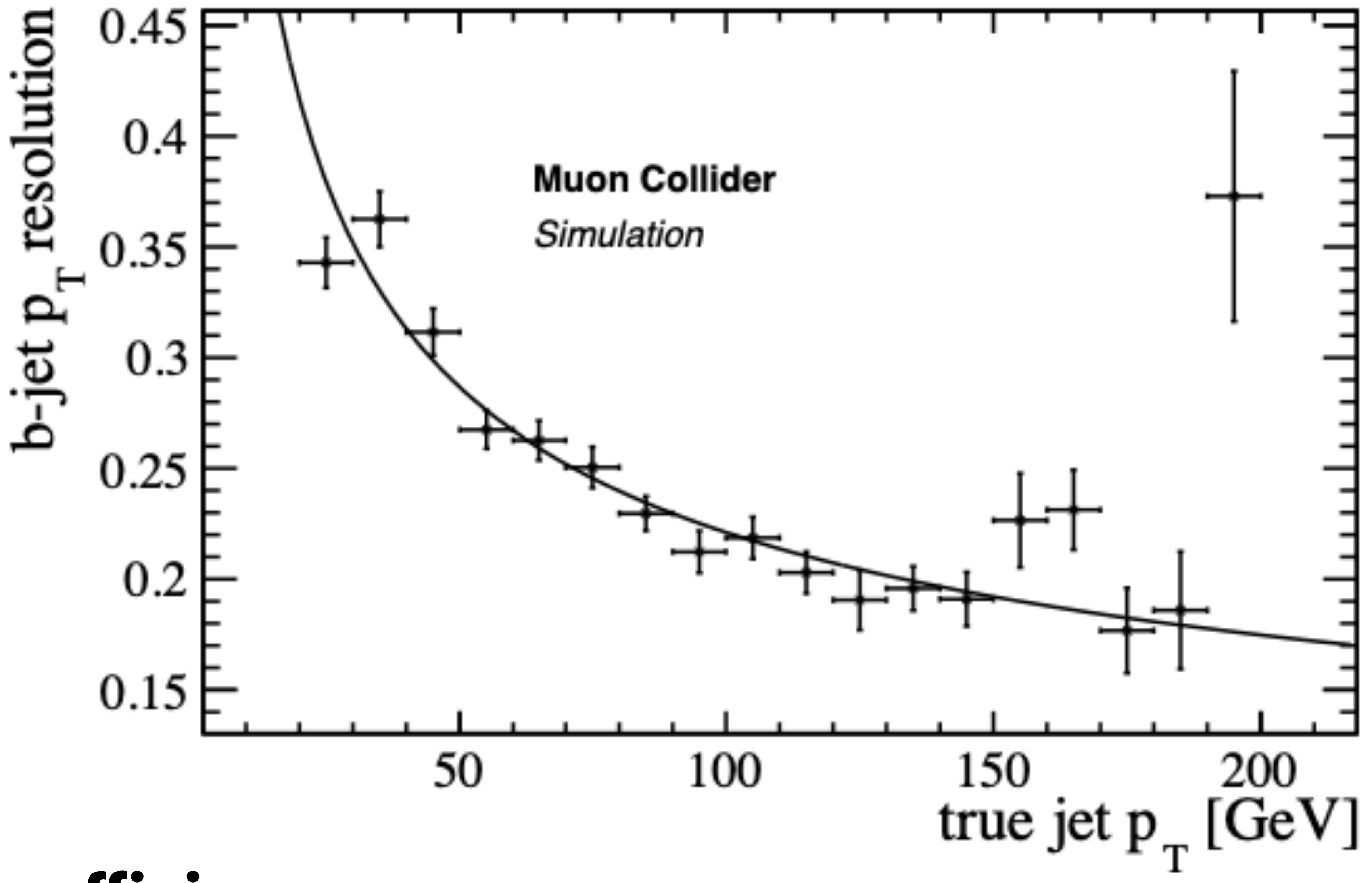

**BIB hits in calorimeters**

# Physics objects reconstruction

## Track reconstruction efficiency




## Jet momentum resolution

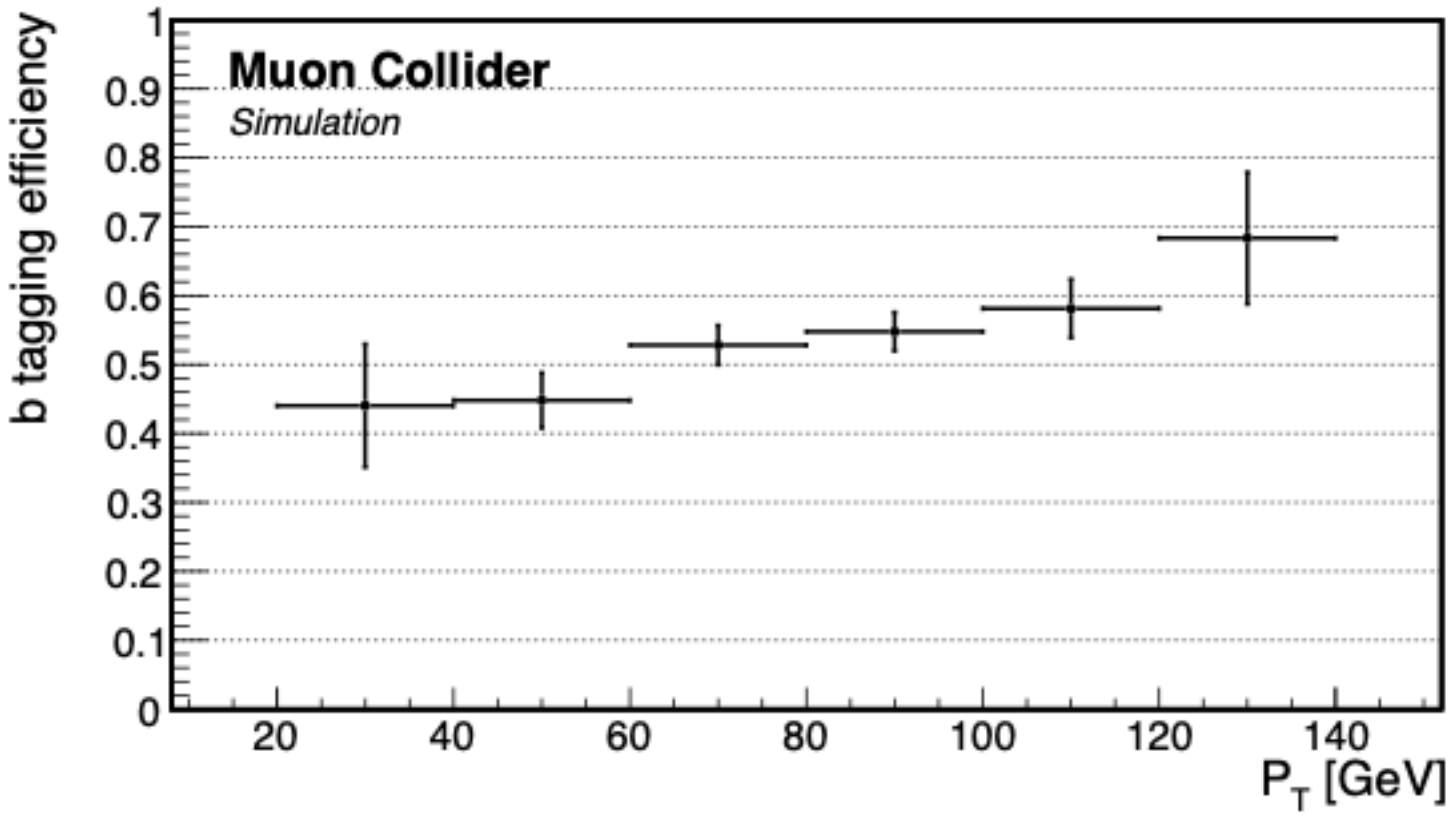



**Reconstruction algorithms are not yet fully optimized**

**Muon fiducial region**

- $10° < \theta < 170°$
- $p_T > 20$ GeV

## Secondary Vertex tagging efficiency




**Jet fiducial region**

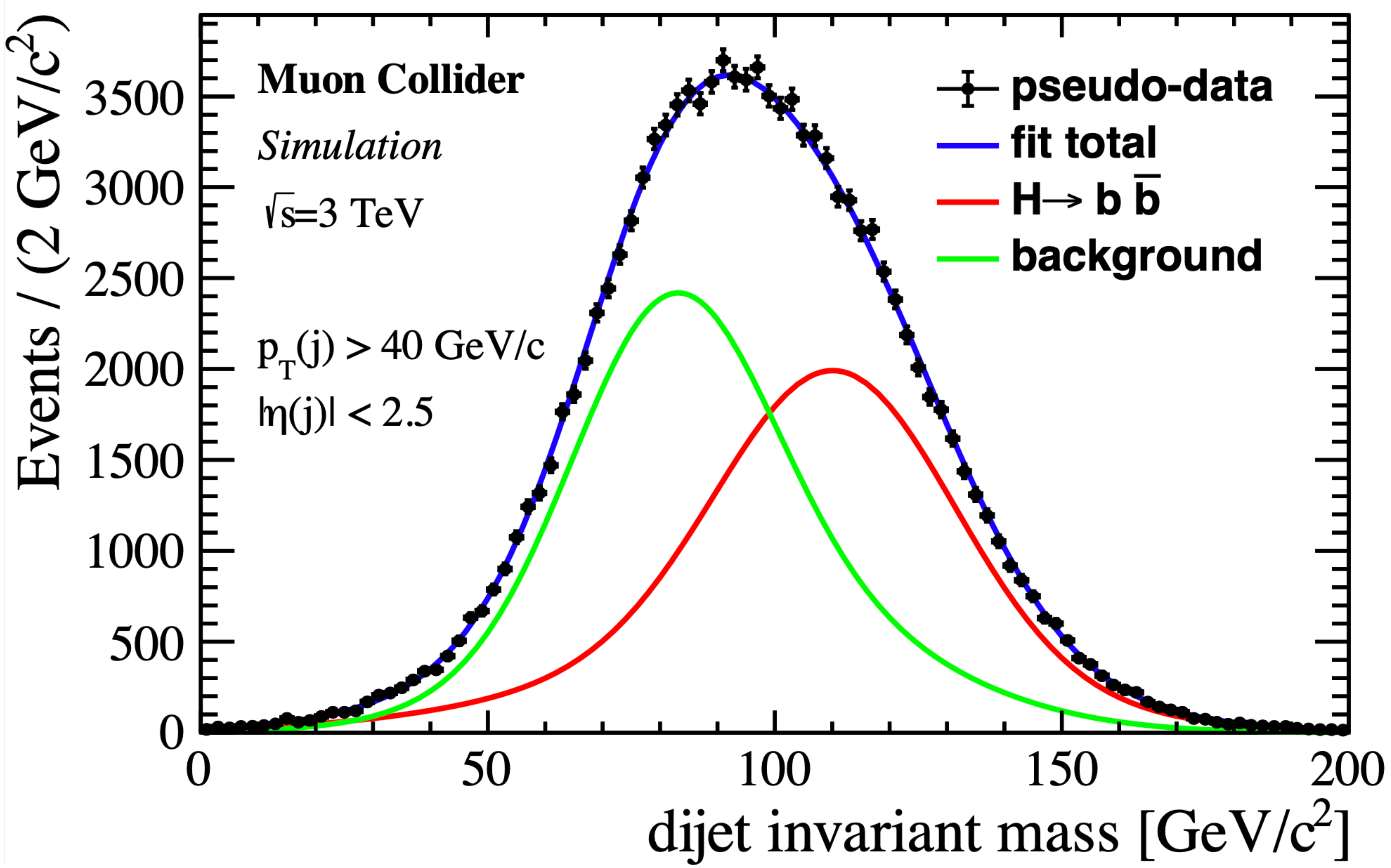
- $|\eta| < 2.5$
- $p_T > 20$ GeV

https://arxiv.org/abs/2203.07964

# $H \rightarrow b\bar{b}$

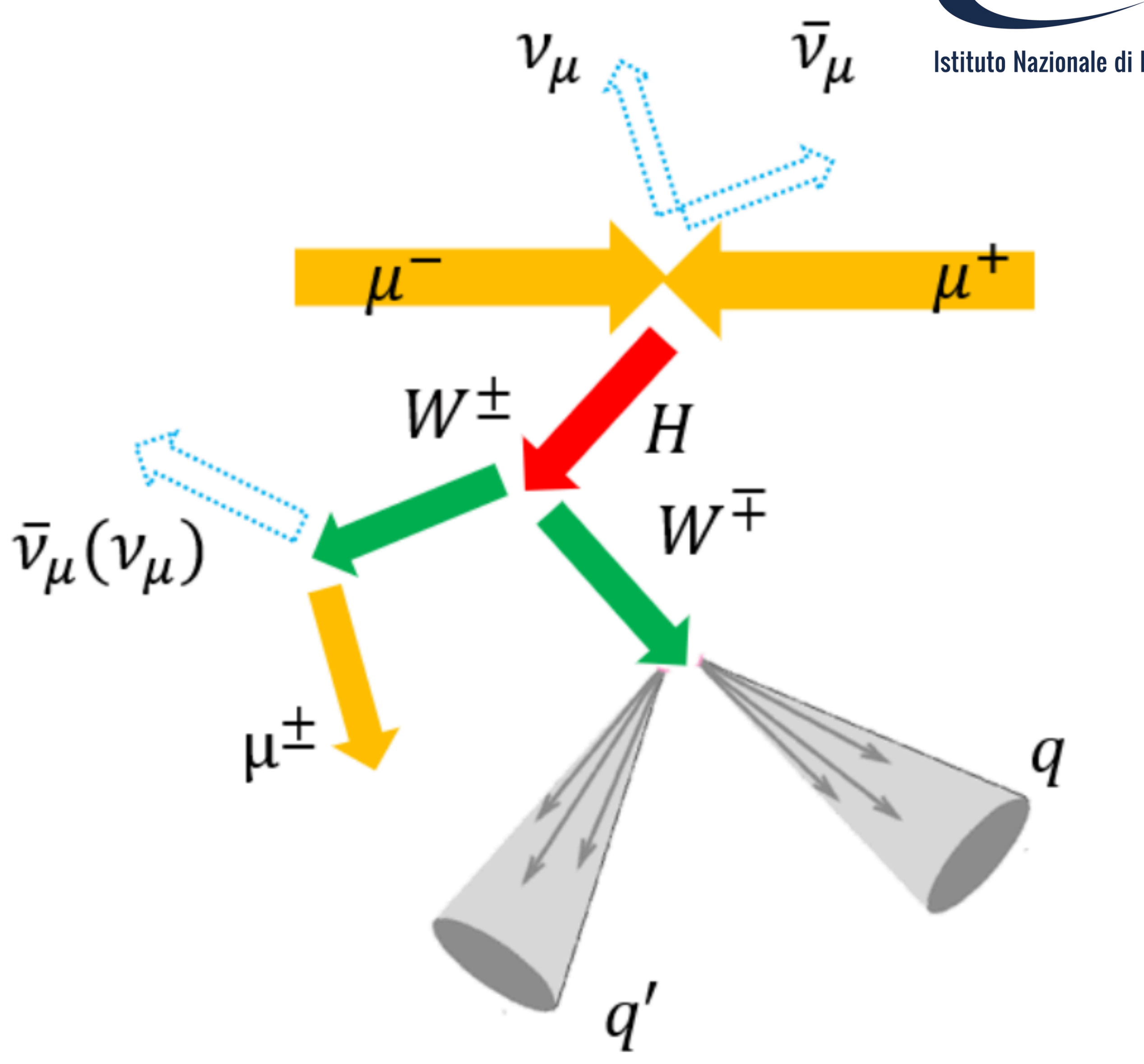
- Signal **$\mu^+\mu^- \rightarrow H(\rightarrow b\bar{b})+X$** and background $\mu^+\mu^- \rightarrow qq + X$ (with q=b or c) generated with WHIZARD+Pythia8. X is pair of neutrinos or muons
- **Two jets with a Secondary Vertex tag are required.** Background from light jets is considered negligible
- **59.5k signal events and 65.4k background events are expected with 1 ab$^{-1}$**
- Selected background is mainly coming from $Z \rightarrow b\bar{b}/c\bar{c}$ decays
- The signal yield can be extracted with a fit to the invariant mass distribution

***L*=1 ab$^{-1}$**

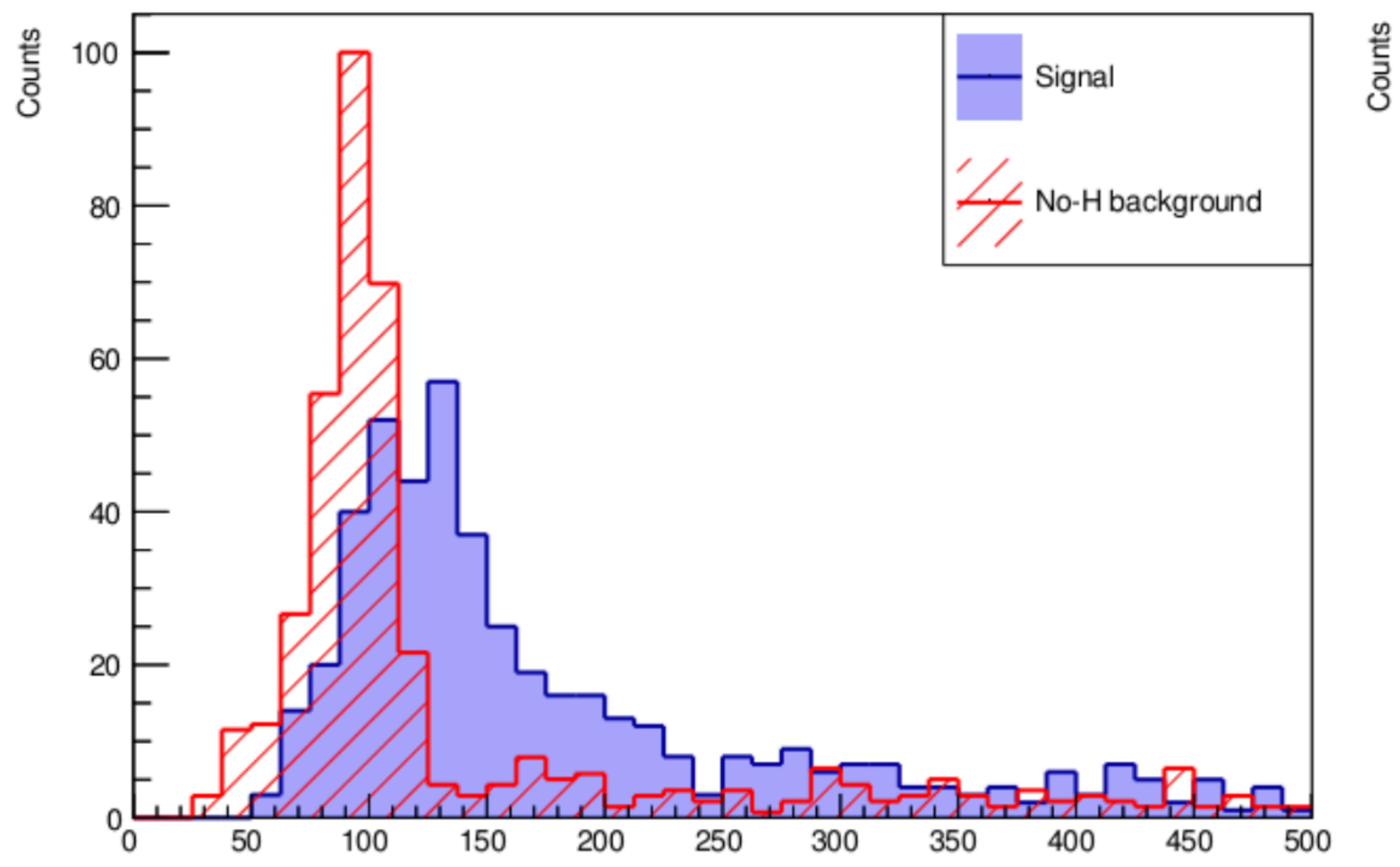



**A relative statistical uncertainty on the $H \rightarrow b\bar{b}$ cross section of 0.75% is found** → **Compatible with results obtained with parametric simulations https://arxiv.org/abs/2203.09425**

# H → WW*

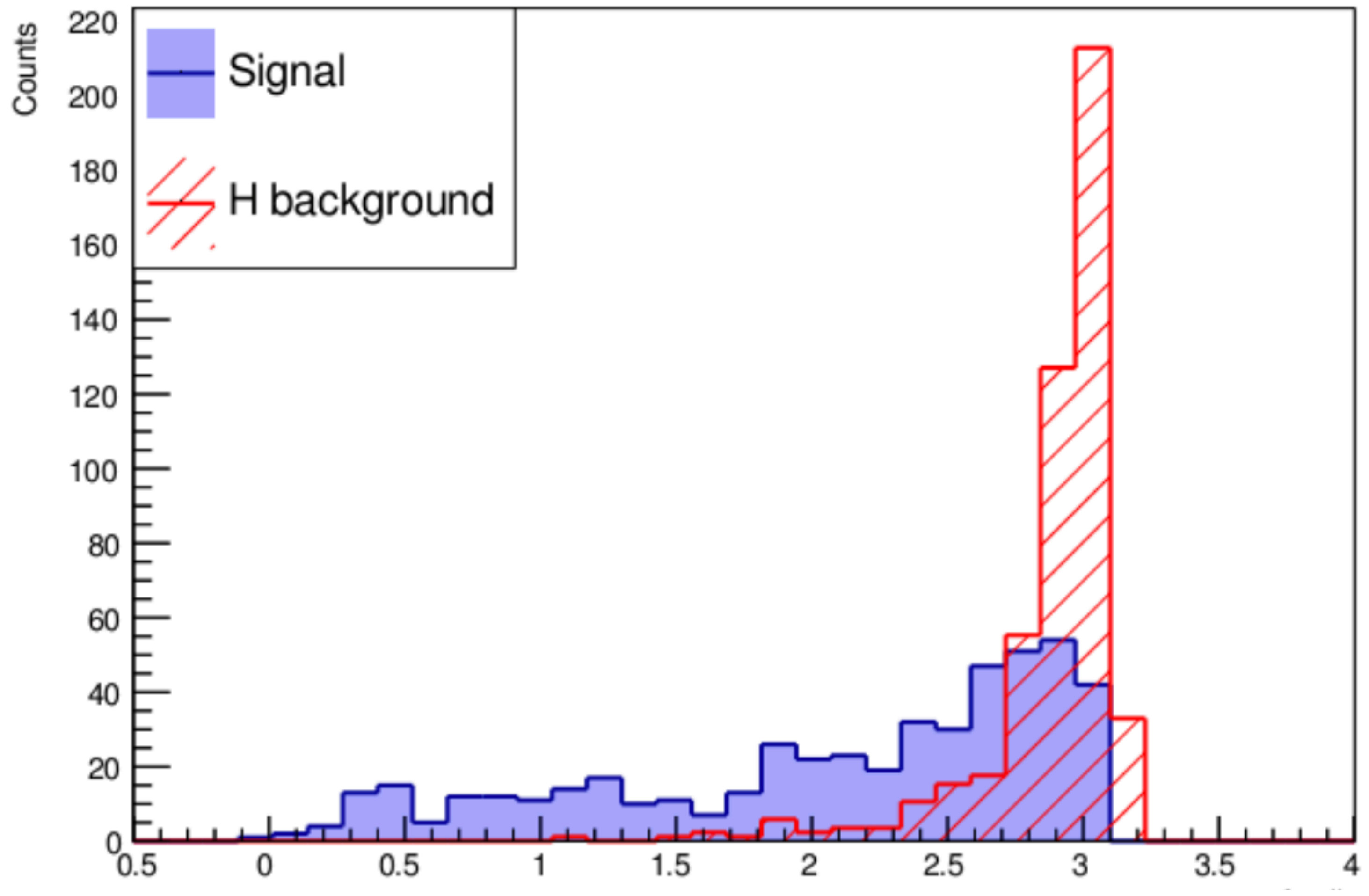



- **Muon + 2 jets final state is considered**
- Signal and backgrounds are generated with WHIZARD+Pythia8
- Two types of background: with and without Higgs decays
- Two multivariate discriminators (Boosted Decision Tree, BDT) are used to distinguish the signal from each type of background
- Of about 2.4k signal events and 2.6k background events are expected after all requirements
- **A relative uncertainty on the H→ WW* cross section of 2.9% is obtained**




[Gev]

$$m_H = \sqrt{(E_W + E_\mu)^2 - (\vec{p}_W + \vec{p}_\mu)^2}$$




$$A_{\mu,W} = \pi - cos^{-1}\left(\frac{\vec{p}_\mu \cdot \vec{p}_W}{|\vec{p}_\mu| \cdot |\vec{p}_W|}\right)$$

***L*=1 ab$^{-1}$**

| Event | Expected Events |
|---|---|
| $\mu^+\mu^- \to H\nu\bar{\nu} \to WW^*\nu\bar{\nu} \to qq\mu\nu\nu\bar{\nu}$ | $2430 \pm 150$ |
| $\mu^+\mu^- \to\to qq\mu\nu$ | $2600 \pm 1300$ |
| $\mu^+\mu^- \to\to qqll$ | $< 100$ $C.L. = 68\%$ |
| $\mu^+\mu^- \to\to qq\nu\nu$ | $< 100$ $C.L. = 68\%$ |
| $\mu^+\mu^- \to H \to WW^* \to qqqq$ | $< 10$ $C.L. = 68\%$ |
| $\mu^+\mu^- \to H \to bb$ | $< 150$ $C.L. = 68\%$ |
| $\mu^+\mu^- \to H \to \tau\tau$ | $< 4$ $C.L. = 68\%$ |

http://hdl.handle.net/20.500.12608/28559

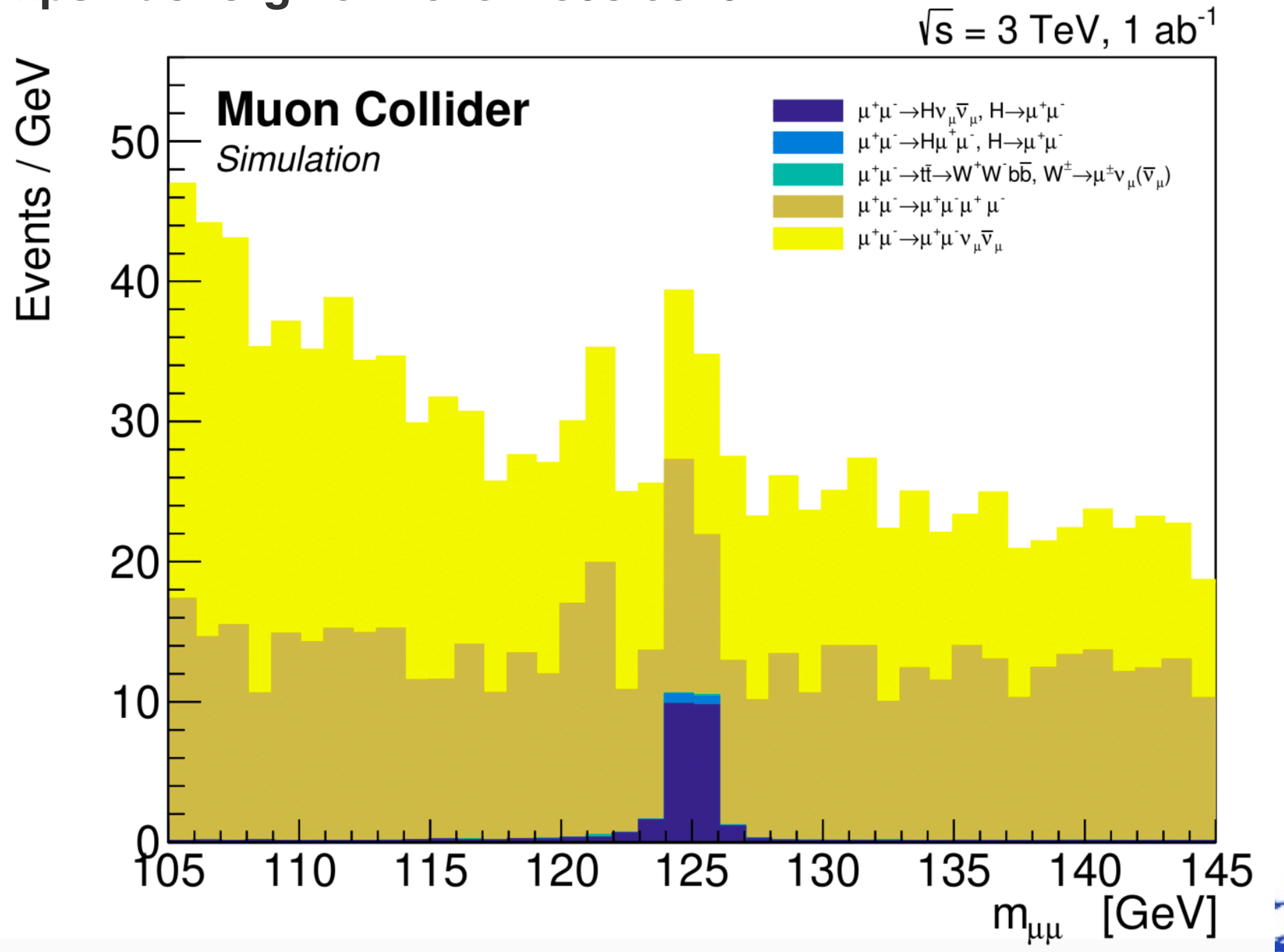
# $H \to \mu^+\mu^-$

- Signal and backgrounds generated with MadGraph5+Pythia8
- Two main backgrounds: $\mu^+\mu^- \to \mu^+\mu^- \nu\nu$ and $\mu^+\mu^- \to \mu^+\mu^- \mu^+\mu^-$
- Two multivariate discriminators (BDTs) are trained to distinguish the signal from the two main backgrounds
- Signal yield extracted with an unbinned maximum likelihood fit to the **dimuon invariant mass distribution**
- **A relative uncertainty on the $H \to \mu^+\mu^-$ cross section of 38% is found**

| Process $105 < m_{\mu\mu} < 145$ GeV | Expected events with |
|---|---|
| [l]$\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu$, $H \to \mu^+\mu^-$ | 24.2 |
| [l]$\mu^+\mu^- \to H\mu^+\mu^-$, $H \to \mu^+\mu^-$ | 1.6 |
| $\mu^+\mu^- \to \mu^+\mu^-\nu\bar{\nu}_\mu$ | 636.5 |
| $\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$ | 476.4 |
| [tl]$\mu^+\mu^- \to t\bar{t} \to W^+W^-b\bar{b}$, $W^\pm \to \mu^\pm\nu_\mu(\bar{\nu}_\mu)$ | 1.1 |

***L*=1 ab$^{-1}$**

https://doi.org/10.22323/1.398.0579

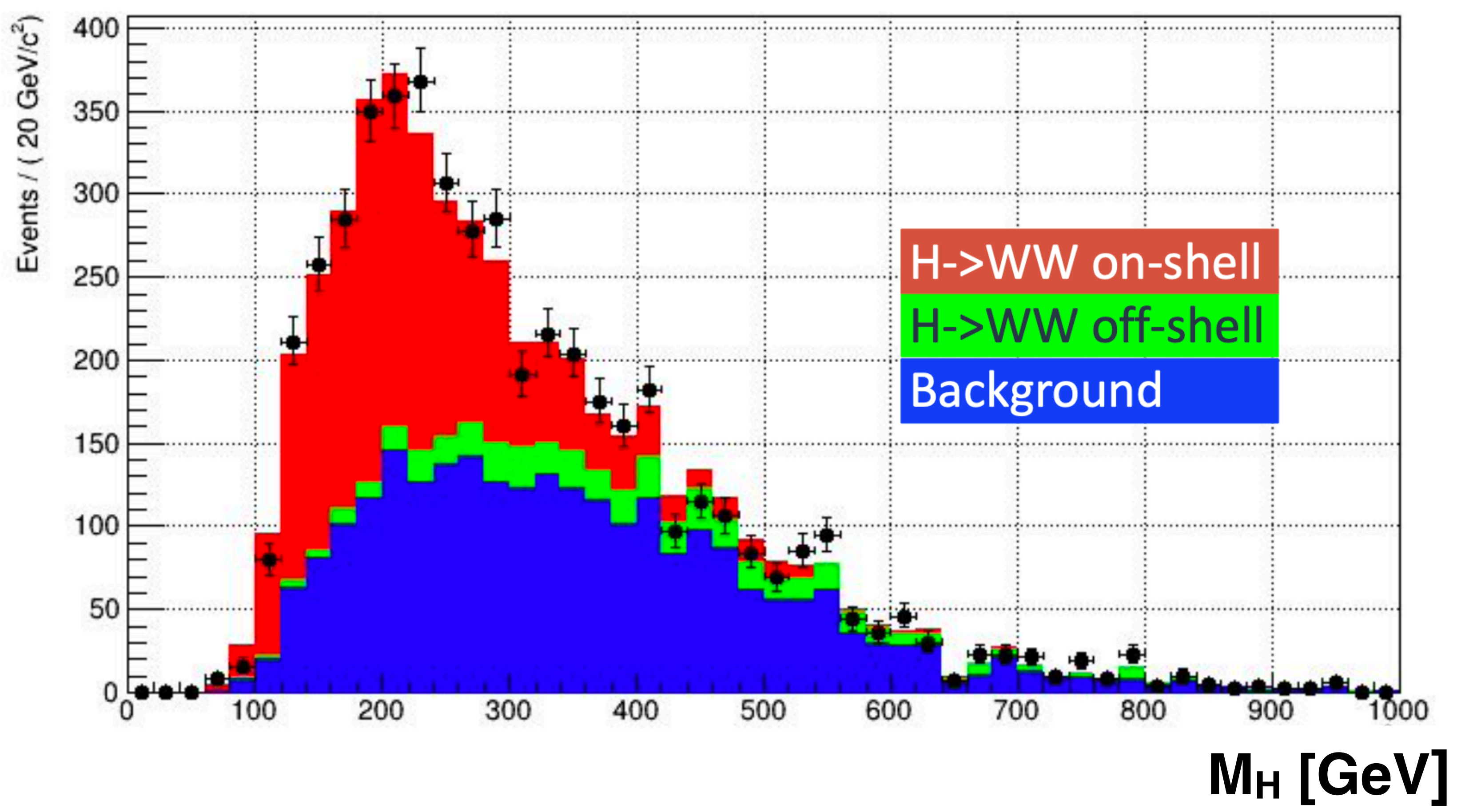


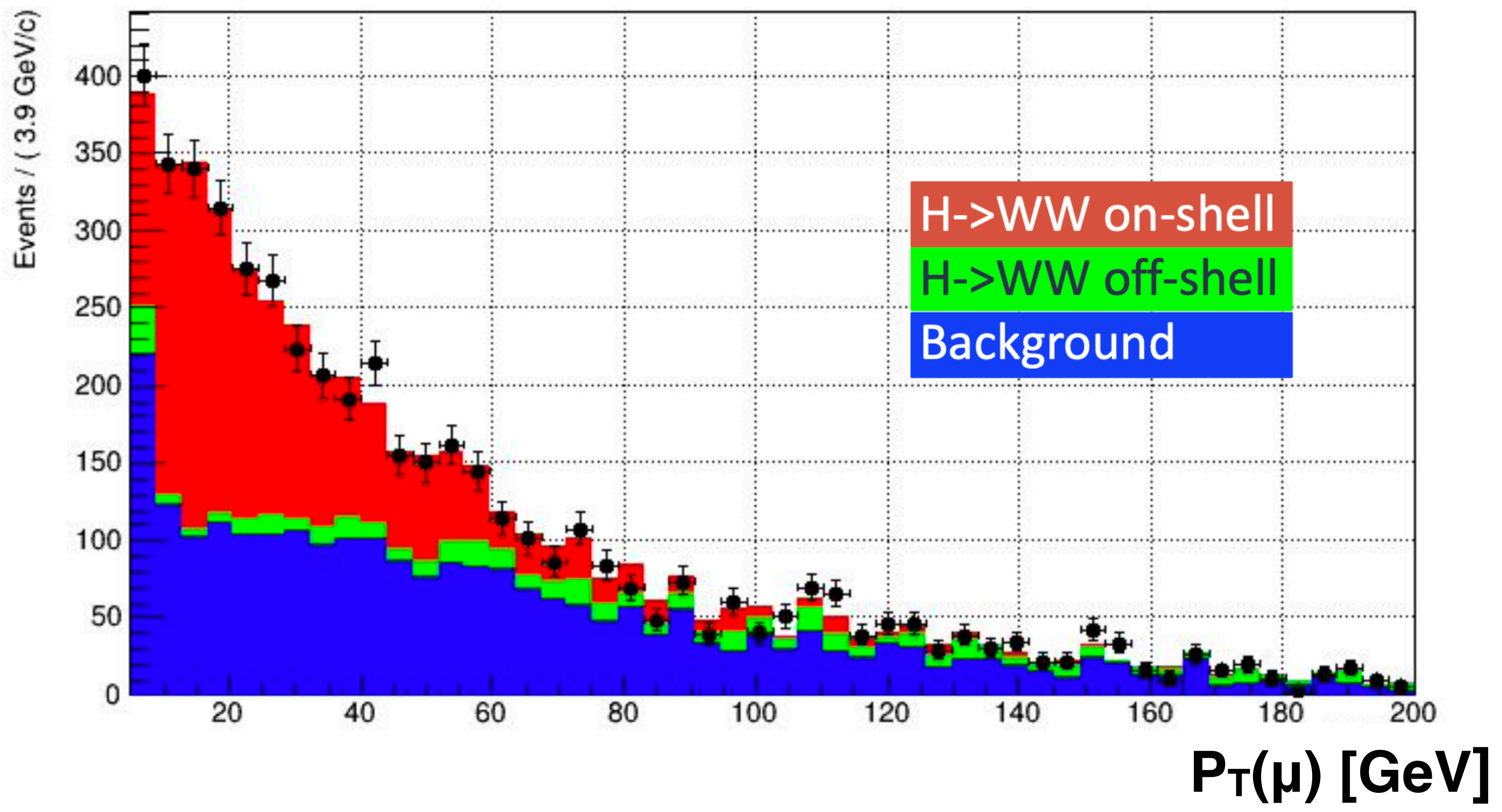
# Measurement of Higgs width

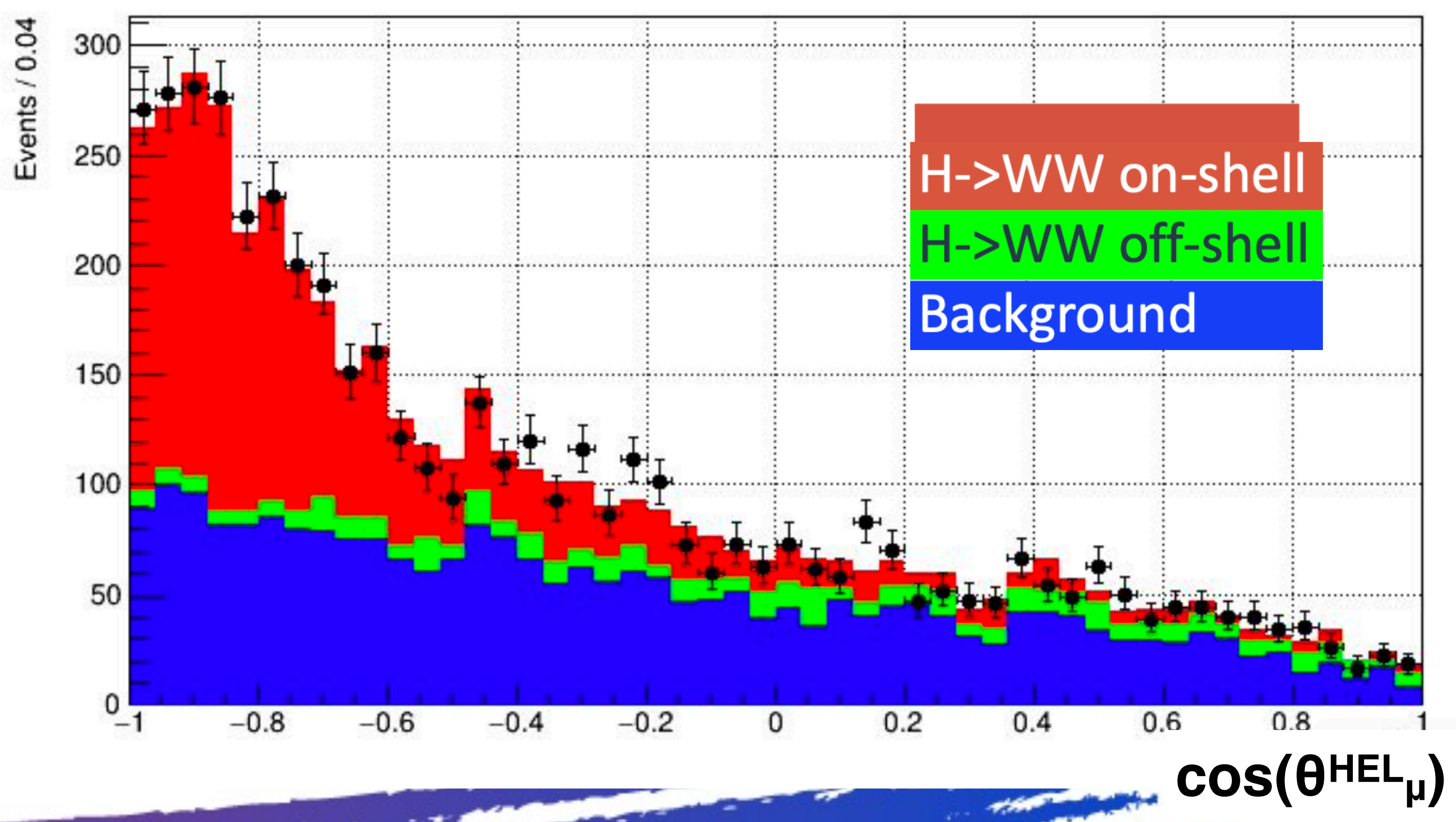
- The measurement of the Higgs width ($\Gamma_H$) can be obtained by determining the number of **on-shell and off-shell H →WW* and H →ZZ* processes**
- The ratio between the off-shell and on-shell is proportional to $\Gamma_H$
- (Di)muon + 2 jets final state is considered
- Signal samples have been generated with MadGraph5, background with WHIZARD
- **Three observables are simultaneously fitted** to extract the on-shell and off-shell signal yields: Higgs mass, muon momentum, muon helicity angle
- **A relative uncertainty on $\Gamma_H$ of 5.3% is found**

***L*=1 ab$^{-1}$**

| Process | Expected events |
|---|---|
| On-shell $H \to ZZ \to \mu^+\mu^- jj$ | 38.2 |
| Off-shell $H \to ZZ \to \mu^+\mu^- jj$ | 56.0 |
| $\nu\bar{\nu}\mu^+\mu^- jj$ background | 458.3 |
| On-shell $H \to W^+W^- \to \mu\nu_\mu jj$ | 1803.4 |
| Off-shell $H \to W^+W^- \to \mu\nu_\mu jj$ | 411.4 |
| $\nu\bar{\nu}\mu\nu_\mu jj$ background | 2520.3 |



# Couplings with fermions and bosons

- **The previous measurements are simultaneously fitted to obtain the couplings measurement**
- In this way the precision on the couplings is obtained
- The results are compared with those obtained by CLIC, that uses several datasets with different energies
- **Direct comparison is difficult** since the 3-energy-stages CLIC program (link) can be exploited in 25 years after the first beam commissioning, while the Muon Collider can collect 1 $ab^{-1}$ in 5 years

| | Full simulation $1\ \mathrm{ab}^{-1}$ @ 3 TeV | CLIC $0.5\ \mathrm{ab}^{-1}$ @ 350 GeV, $1.5\ \mathrm{ab}^{-1}$ @ 1.4 TeV, $2\ \mathrm{ab}^{-1}$ @ 3 TeV |
|---|---|---|
| $\Gamma_H$ | 5.3% | 3.5% |
| $g_{HZZ}$ | 5.6% | 0.8% |
| $g_{HWW}$ | 1.3% | 0.9% |
| $g_{Hbb}$ | 1.7% | 0.9% |
| $g_{H\mu\mu}$ | 19.1% | 7.8% |

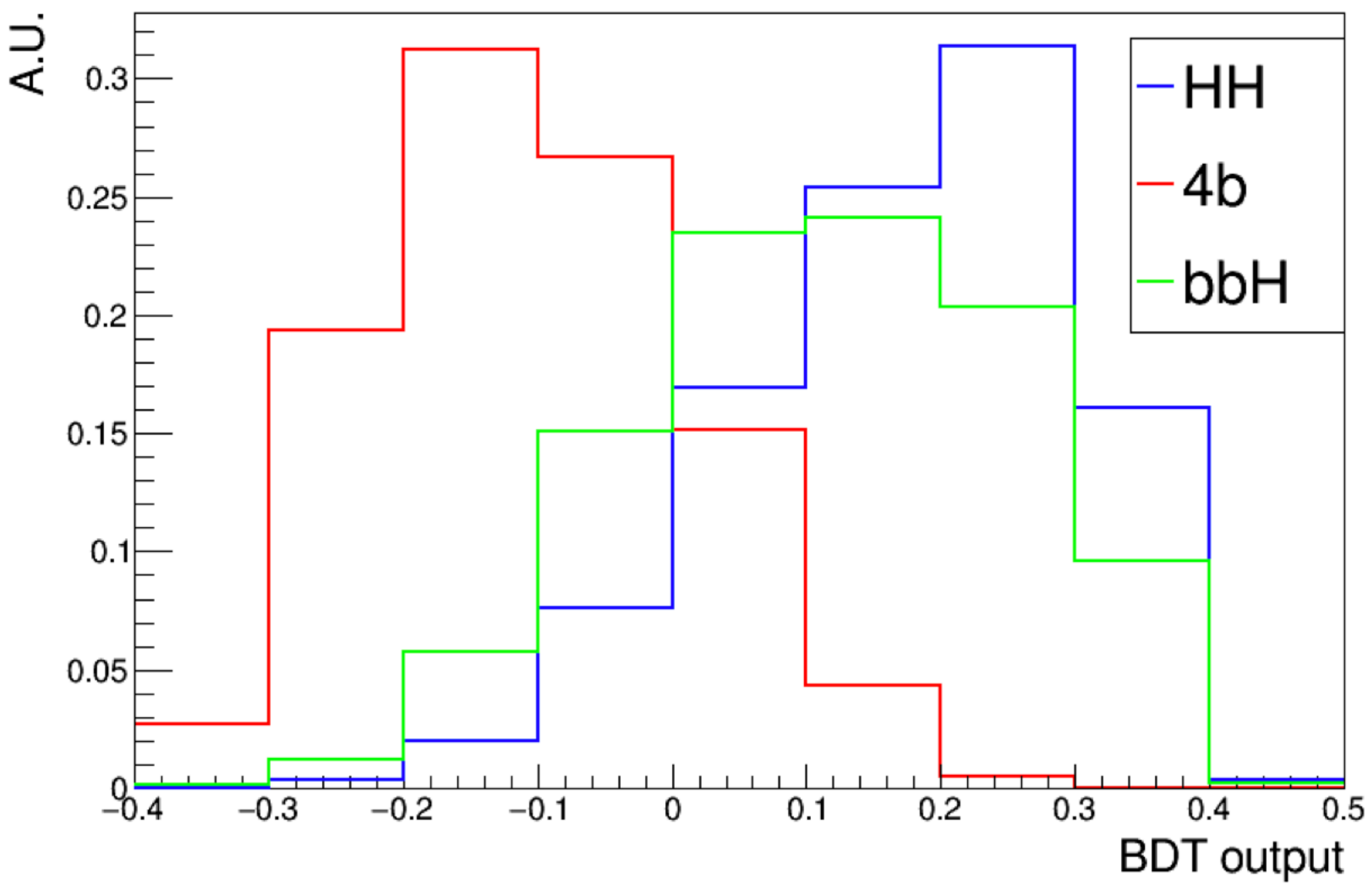
**CLIC Higgs Physics:**
**Eur. Phys. J. C 77, 475 (2017)**

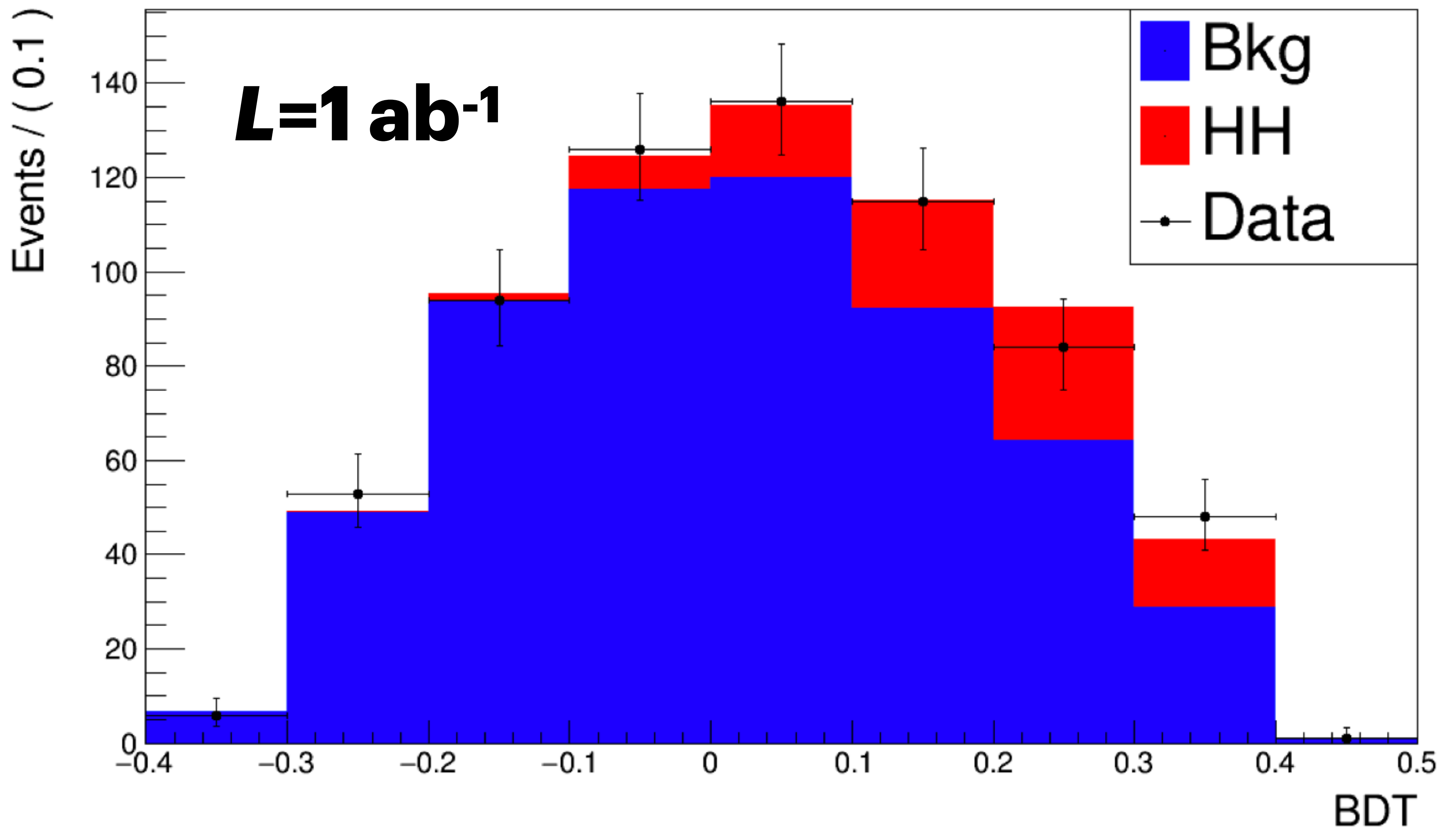
# $HH \rightarrow b\bar{b}\, b\bar{b}$ cross section

- Signal and backgrounds (bbbb and H+bb) generated with WHIZARD+Pythia8
- Four jets final state: two Secondary Vertex tag out of four jets are required
- 50 HH and 432 background events are expected with 1 $ab^{-1}$

- A boosted decision tree (BDT) is trained to separate the signal from the background, input observables from kinematic
- A fit to the BDT output is performed to determine the cross section uncertainty
- **Uncertainty on $HH \rightarrow b\bar{b}b\bar{b}$ cross section of about 30% is found**

http://hdl.handle.net/20.500.12608/22861



# Trilinear coupling

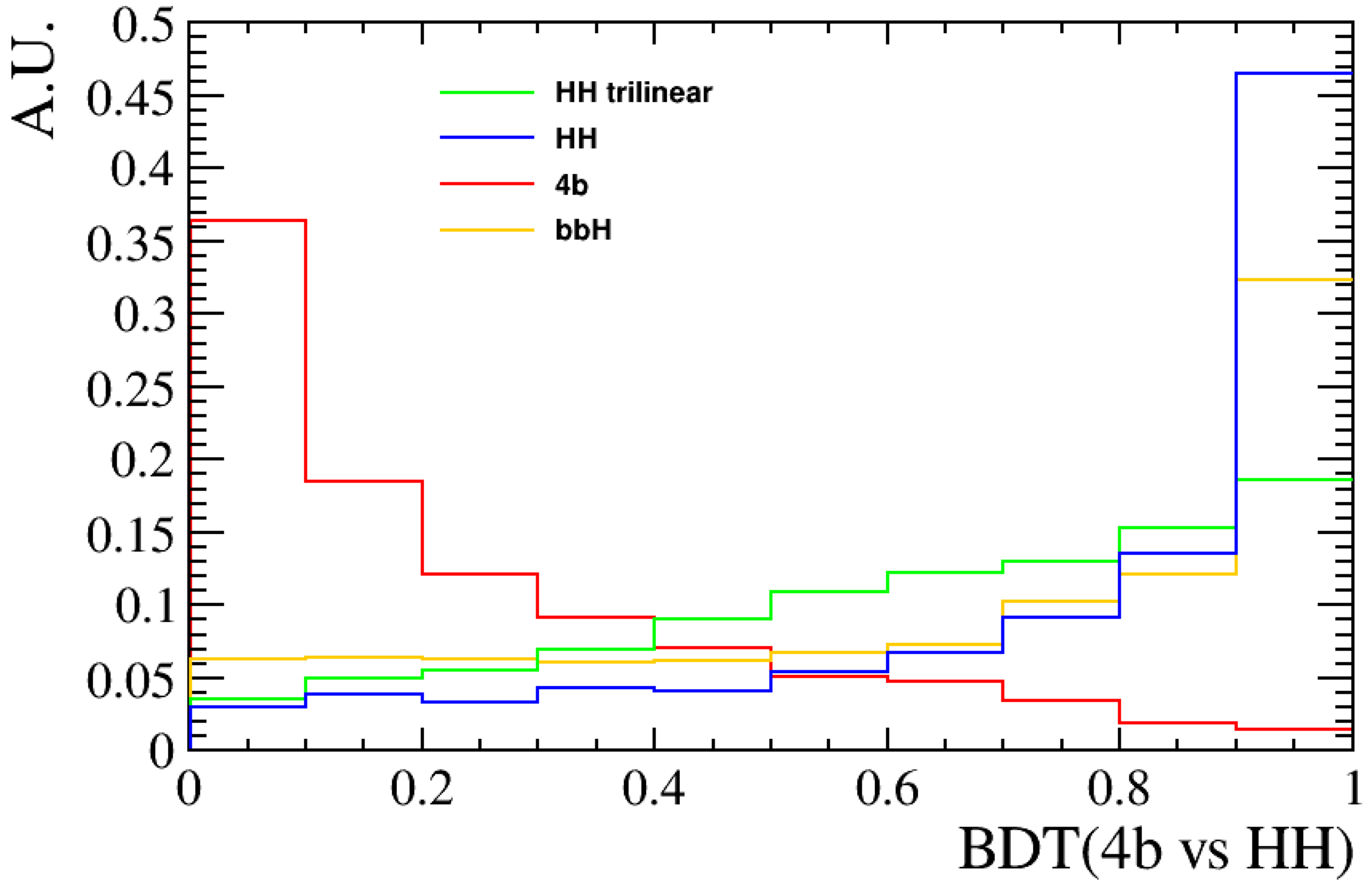
- Two BDTs are trained to separate HH→4b from 4b and HH vs HH trilinear (*e.g.* only trilinear diagrams are included)

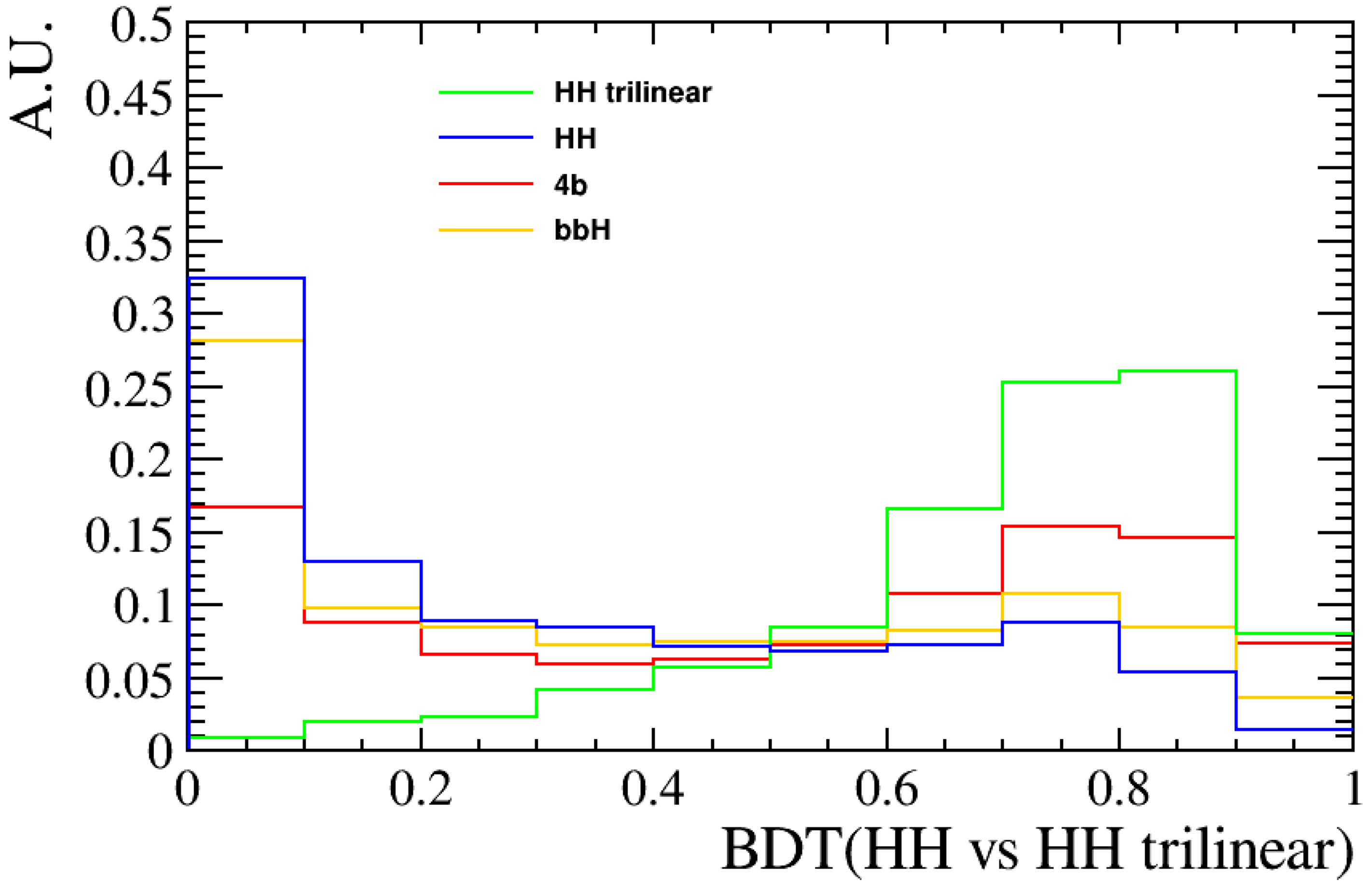
- The templates obtained with different coupling hypotheses are compared with pseudo-experiments.

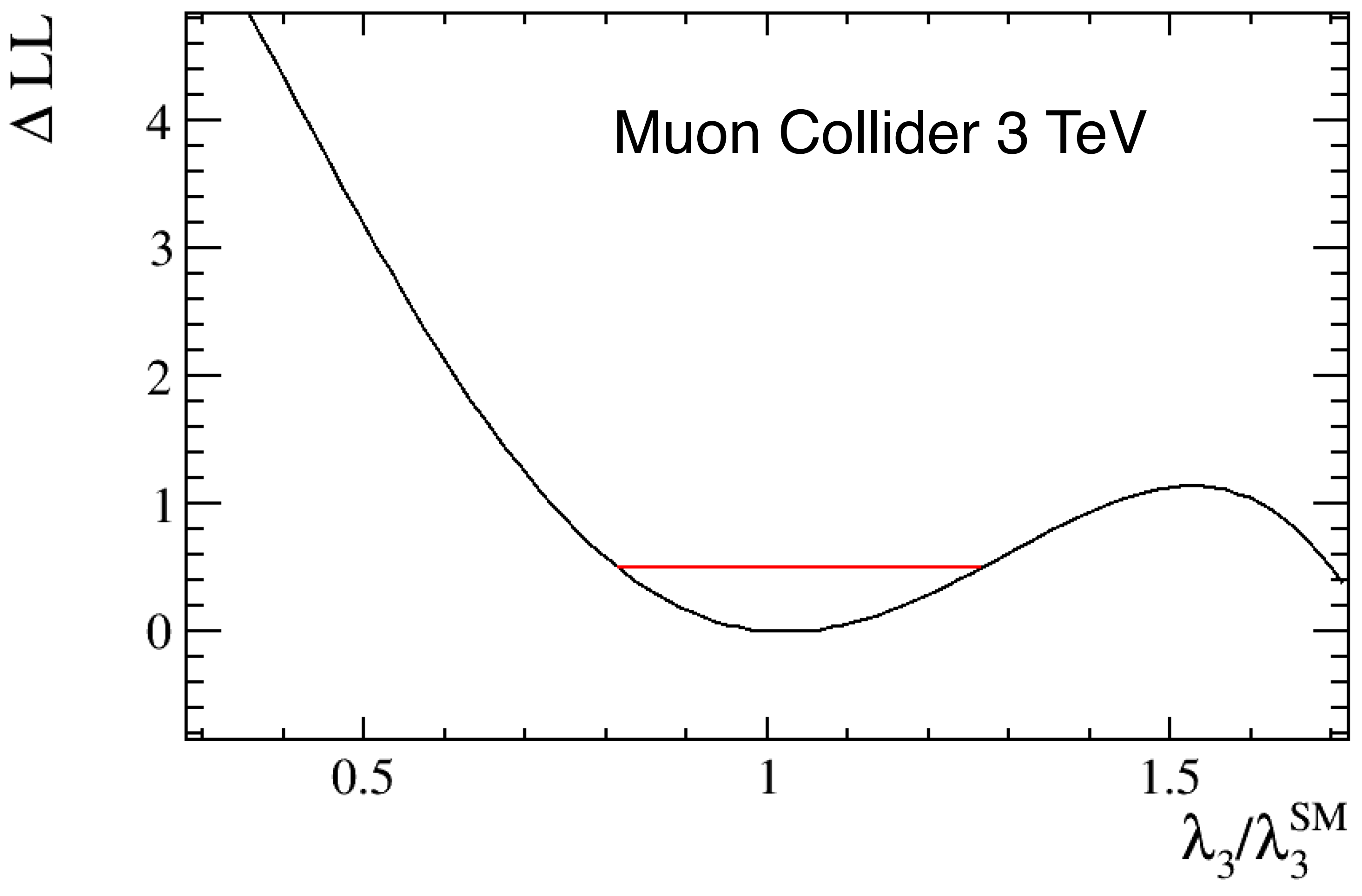
- A likelihood technique is used to determine the sensitivity on $\lambda_3$

- The preliminary result **on the $\lambda_3$ statistical uncertainty is** of about **20% with 1.0 ab$^{-1}$** (at 68% CL)

- CLIC has [-8%,+11%] at 68% CL with 2.5 ab$^{-1}$ at 1.4 TeV + 5 ab$^{-1}$ at 3 TeV [Eur. Phys. J. C 80, 1010 (2020)]



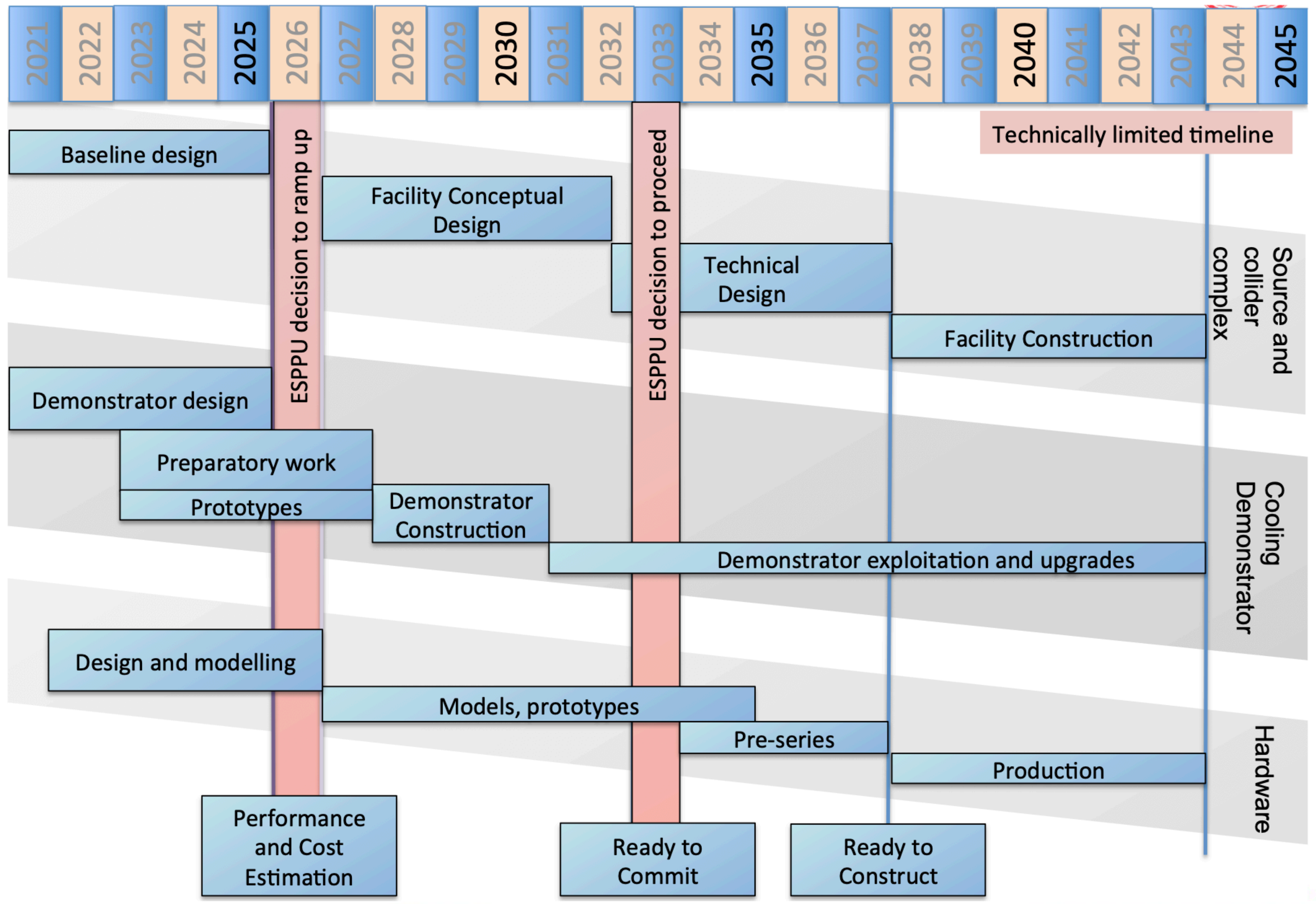




***L*=1 ab$^{-1}$**

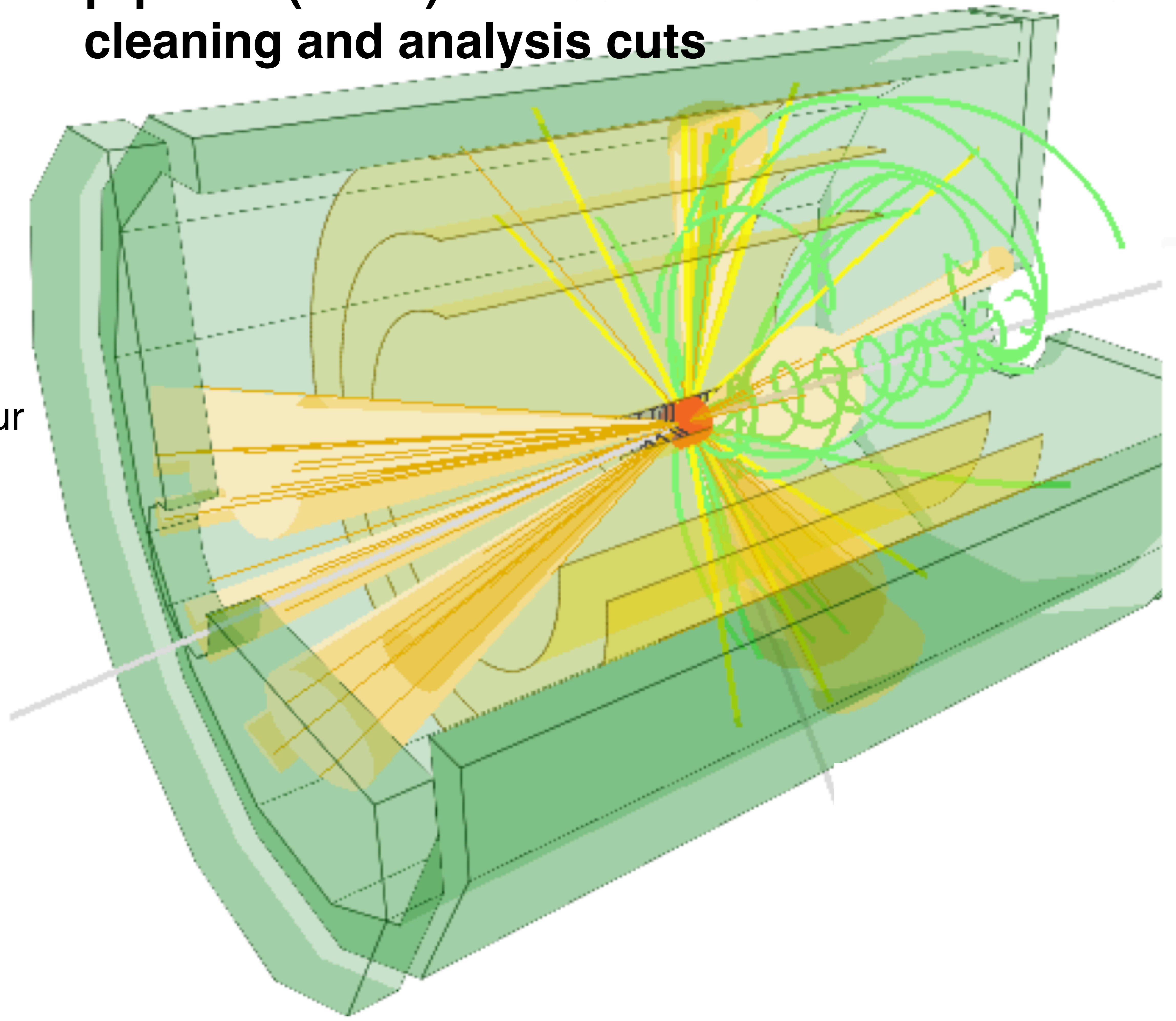
# Conclusions

- **The Muon Collider environment is very different from electron-positron and hadron colliders**
- A huge effort is on-going to design the MDI, the detector and the reconstruction algorithms
- In this talk I have demonstrated that **Higgs physics at Muon Collider is possible**, **by using a detailed simulation of the experiment**
- Just few key channels have been considered but we plan to expand our studies

**Roadmap for a 3 TeV Muon Collider**




**$\mu^+\mu^- \to H(\to b\bar{b})+X$ reconstructed event without cleaning and analysis cuts**



# Thanks for your attention!

# Backup

# Requirements for Higgs analyses

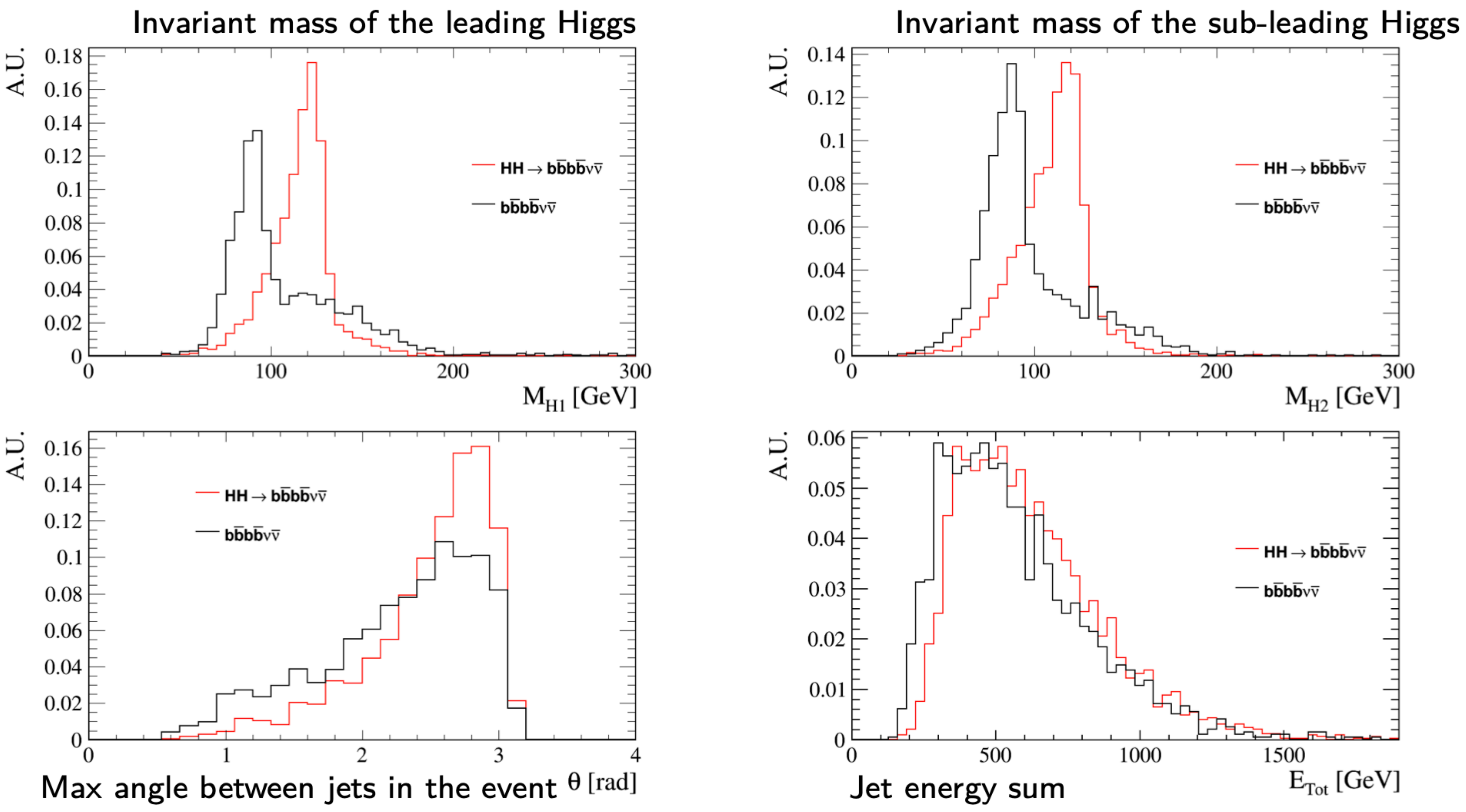
| $H \to ZZ \to \mu^+\mu^- jj$ | $H \to W^+W^- \to \mu\nu_\mu jj$ |
|---|---|
| $5$ GeV $< P_{T,\mu} < 300$ GeV | $5$ GeV $< P_{T,\mu} < 200$ GeV |
| $20$ GeV $< P_{T,j} < 300$ GeV | $20$ GeV $< P_{T,j} < 200$ GeV |
| $M_{\mu^+\mu^-} < 105$ GeV | $M_{\mu,MET} < 400$ GeV |
| $10$ GeV $< M_{jj} < 320$ GeV | $M_{jj} < 150$ GeV |
| $M_H < 1$ TeV | $M_H < 1$ TeV |

| Preselection requirements |
|---|
| Two opposite-charge muons |
| $10^\circ < \theta_\mu < 170^\circ$ |
| $105 < m_{\mu\mu} < 145$ GeV |
| $p_T(\mu^\pm) > 5$ GeV |
| $p_T(\mu^+\mu^-) > 30$ GeV |
| $p_T(\mu^+) + p_T(\mu^-) > 50$ GeV |

$H \to \mu^+\mu^-$

# HH and trilinear coupling

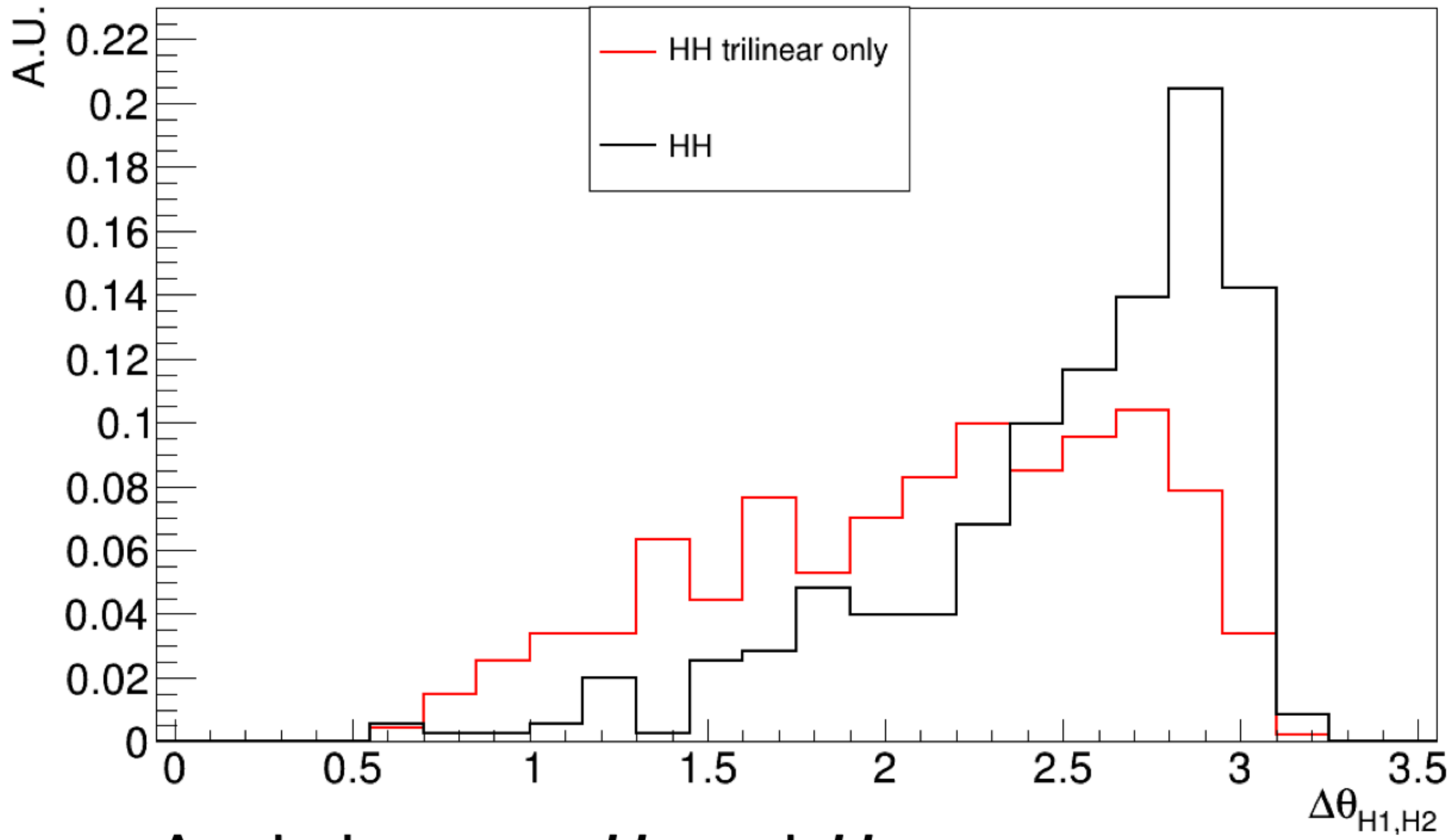
- **μμ → HHνν** is reconstructed in the four b-jets final state.
- |η(jet)|<2.5, $p_T$(jet)>20 GeV fiducial region, two SV-tag out of four jets are required.
- Signal and backgrounds are generated at NLO with WHIZARD.
- Irreducible backgrounds are $b\bar{b}b\bar{b}$ and H(→ $b\bar{b}$)$b\bar{b}$
- Kinematical variables can be used to separate the signal from the background.



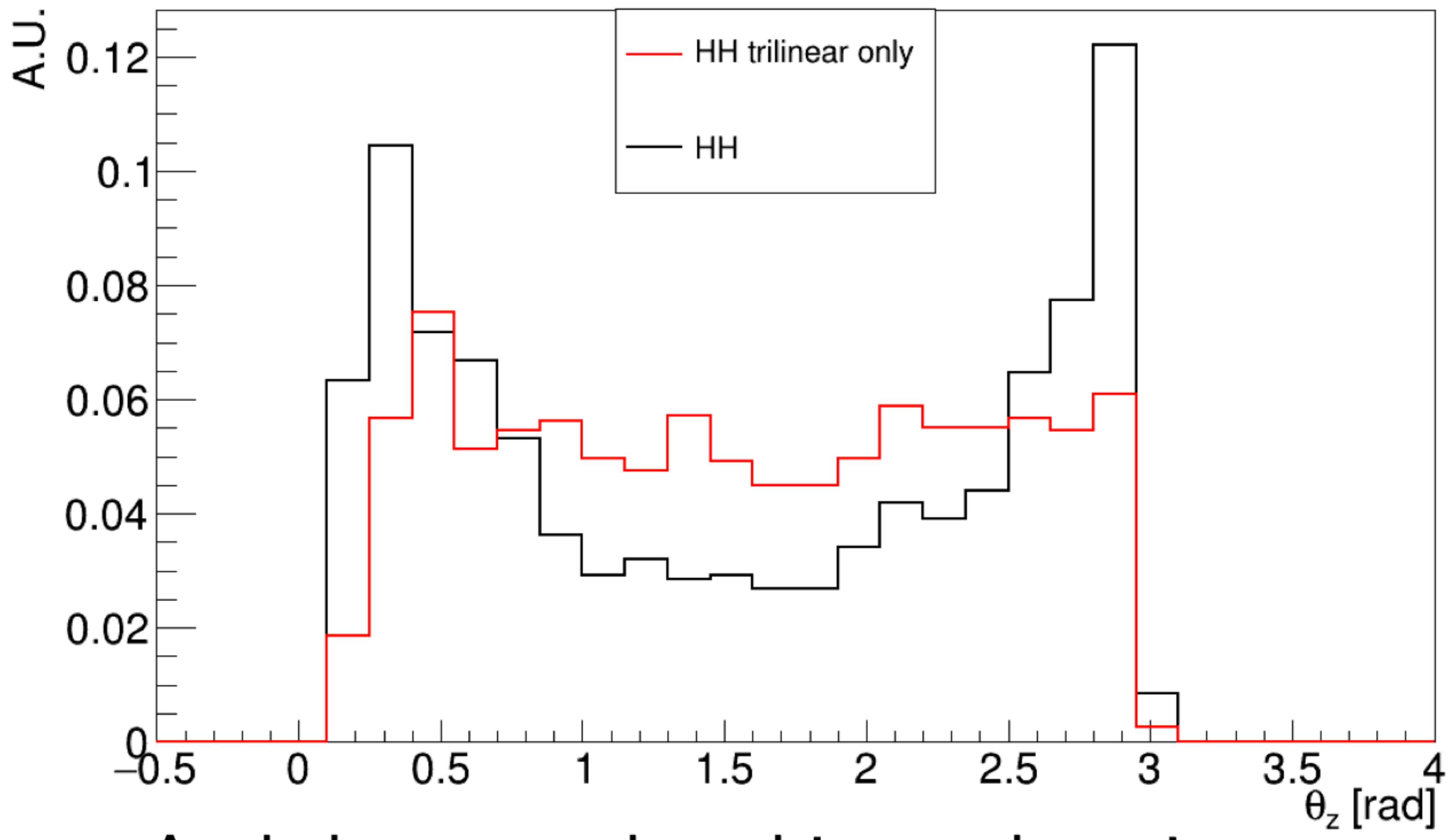
# HH and trilinear coupling

- The kinematic of the HH process is also used to **separate the HH from the HH trilinear-only contribution**.

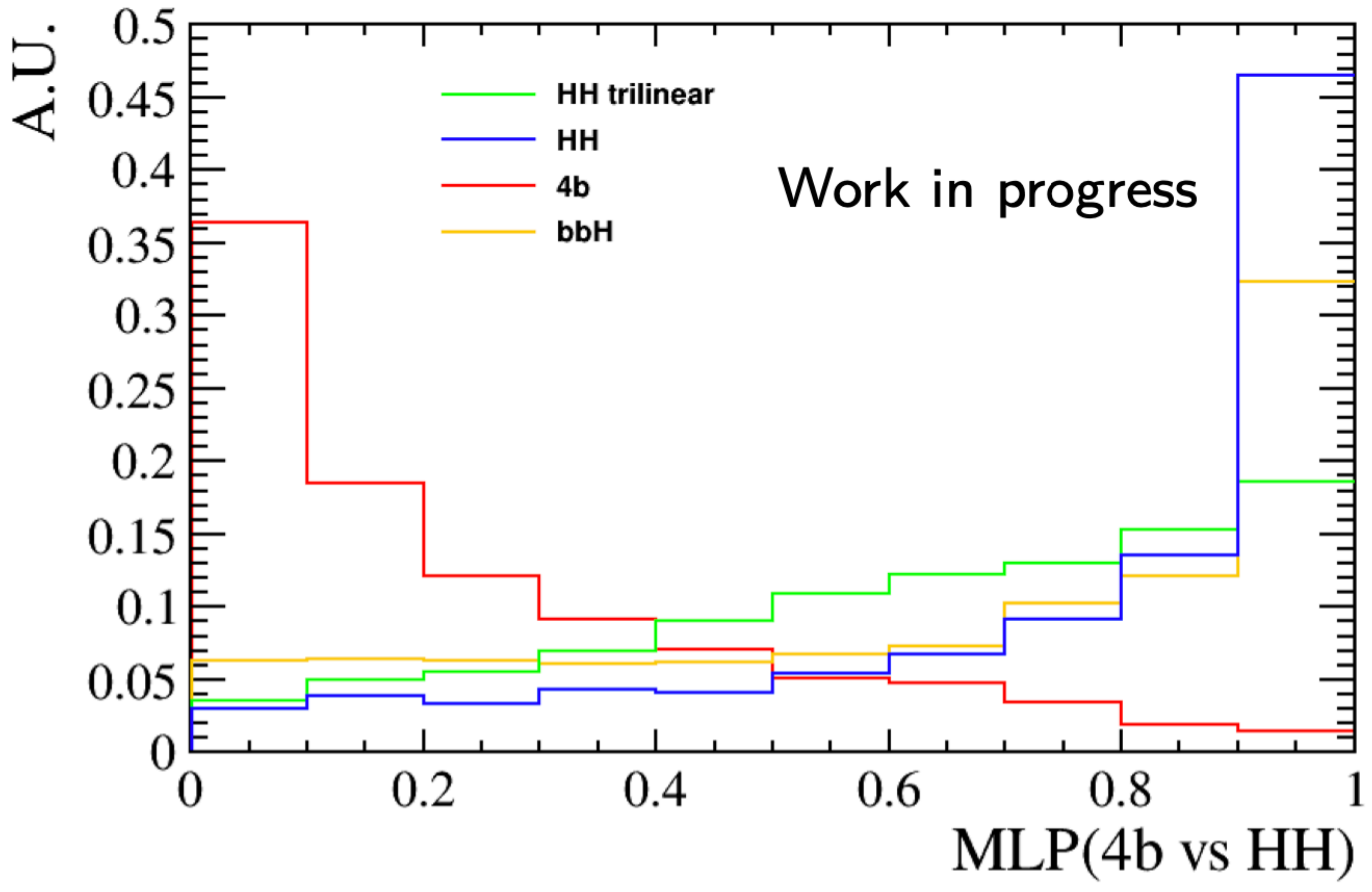
- Two multi-layer perceptrons are trained: **MLP (4b vs HH)** and **MLP(HH vs HH trilinear)**.

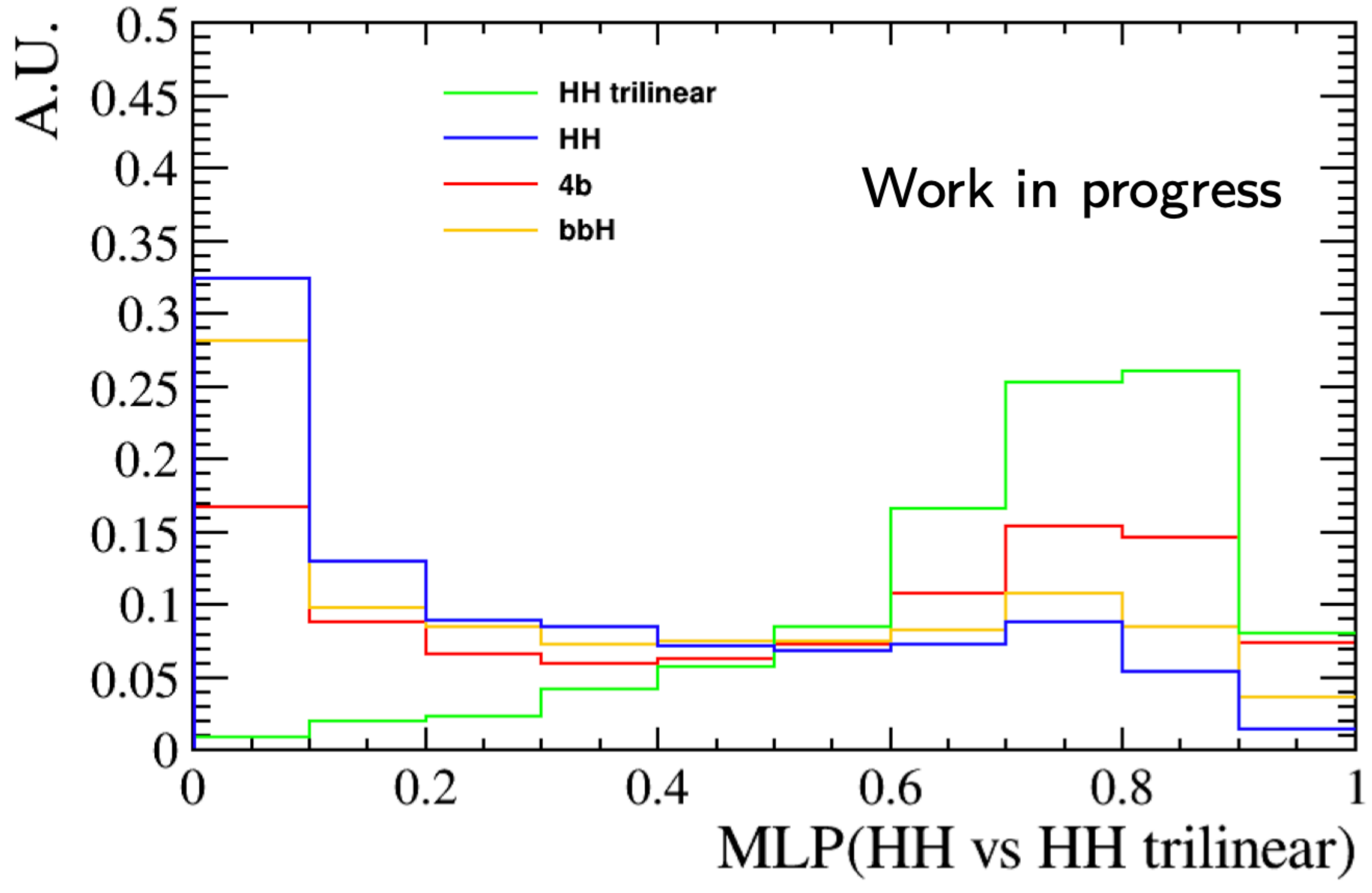



Angle between $H_1$ and $H_2$




Angle between selected jets and $z$ axis



# Luminosity measurement

**μμ → μμ Bhabha events counting**

$$\frac{\Delta L_{int}}{L_{int}} = \sqrt{\frac{\Delta N_{ev}{}^2}{N_{ev}{}^2} + \frac{\Delta \sigma_B{}^2}{\sigma_B{}^2}} = \left(\frac{\Delta N_{ev}}{N_{ev}}\right) \oplus \left(\frac{\Delta \sigma_B}{\sigma_B}\right)$$

$$\frac{\Delta N_{Bhabha}}{N_{Bhabha}} = \frac{1}{\sqrt{N_{Bhabha}}} = 0.002$$

**Study at 1.5 TeV**