Higgs reconstruction at Muon Collider

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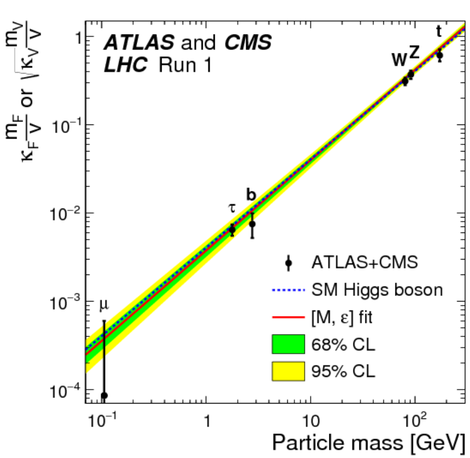
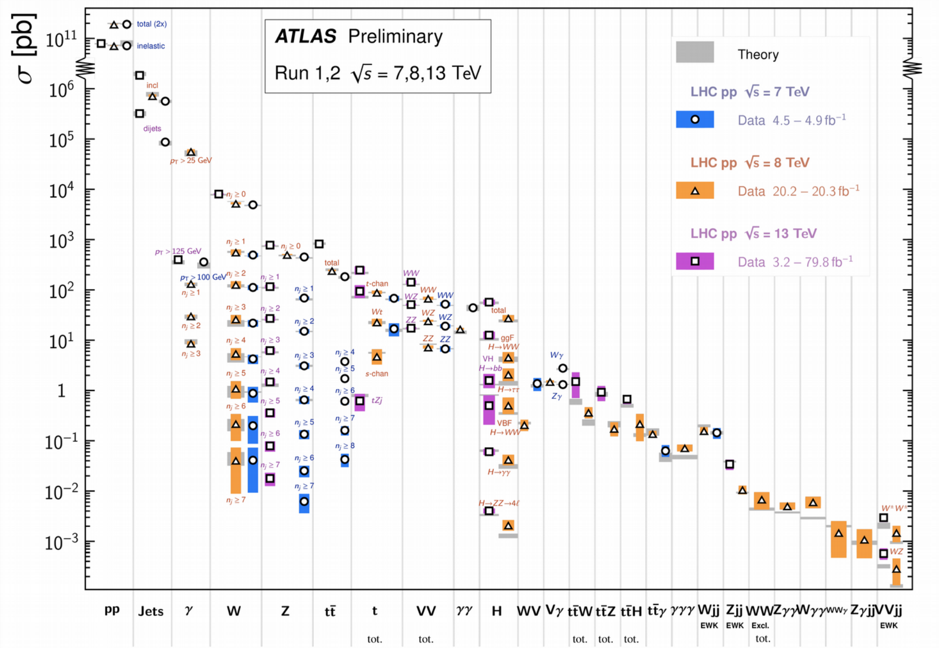
Introduction

- The Standard Model is greatly confirmed at LHC energies.

- **But many sectors of the SM are poorly known or unexplored**, as example:

  - Higgs interaction with light fermions.
  - Higgs self-interaction.
  - Top-quark interaction with gauge bosons and Higgs known at 10% level.



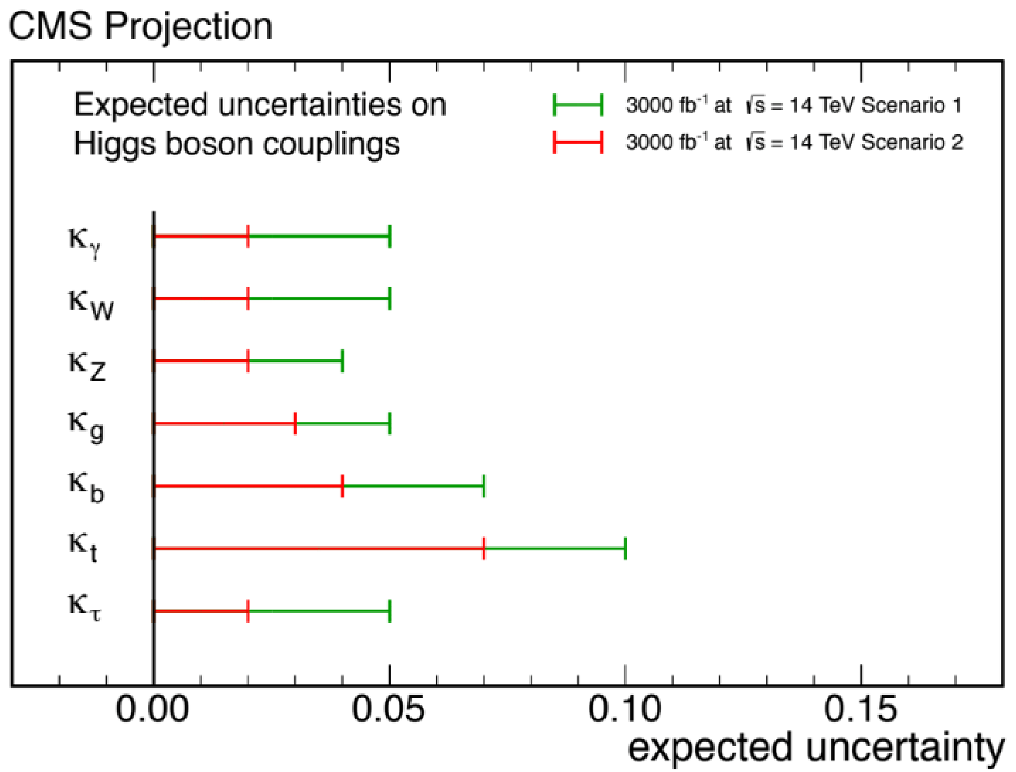


Introduction

- HL-LHC prospects on Yukawa coupling
- If Λ_{NP} is the New Physics energy scale, the precision that should be achieved to probe it is:

$$\frac{\Delta k}{k} = \frac{5\%}{\Lambda_{NP}^2}$$

- If Λ_{NP} = 10 TeV then 0.05% precision is needed.
- **The Higgs sector can be the portal for New Physics.**
- **Muon Collider is an ideal machine to study it.**



Higgs production at Muon Collider

- Main Higgs production channels at Muon Collider generated with Pythia 8.
- Comparison with CLIC results (ISR included) to cross check our Monte Carlo cross sections. https://arxiv.org/pdf/1608.07538.pdf
- Cross sections are compatible apart from small differences.
- **WW fusion dominates at multi-TeV energies.**

$\sqrt{s}$ = 350 GeV

Process	σ [fb] @ CLIC	σ [fb] @ Muon Collider
$l^+l^- \to HZ$	133	136
$l^+l^- \to l^+l^- H$ (ZZ fusion)	7	3.3
$l^+l^- \to \nu_l \nu_l H$ (WW fusion)	34	32

$\sqrt{s}$ = 1.4 TeV

Process	σ [fb] @ CLIC	σ [fb] @ Muon Collider
$l^+l^- \to HZ$	8	7.3
$l^+l^- \to l^+l^- H$ (ZZ fusion)	28	30
$l^+l^- \to \nu_l \nu_l H$ (WW fusion)	276	294

$\sqrt{s}$ = 3 TeV

Process	σ [fb] @ CLIC	σ [fb] @ Muon Collider
$l^+l^- \to HZ$	2	1.48
$l^+l^- \to l^+l^- H$ (ZZ fusion)	48	51.4
$l^+l^- \to \nu_l \nu_l H$ (WW fusion)	477	500

$H \to b\bar{b}$ at Muon Collider

- $H \to b\bar{b}$ has the highest branching ratio:
  - ➔ Coupling with b
  - ➔ Coupling with μ (Higgs Factory)
  - ➔ Coupling with W (multi-TeV)

- We chose this channel to test our **full detector simulation**.

- At multi-TeV → Physics backgrounds are orders of magnitude smaller than signal.

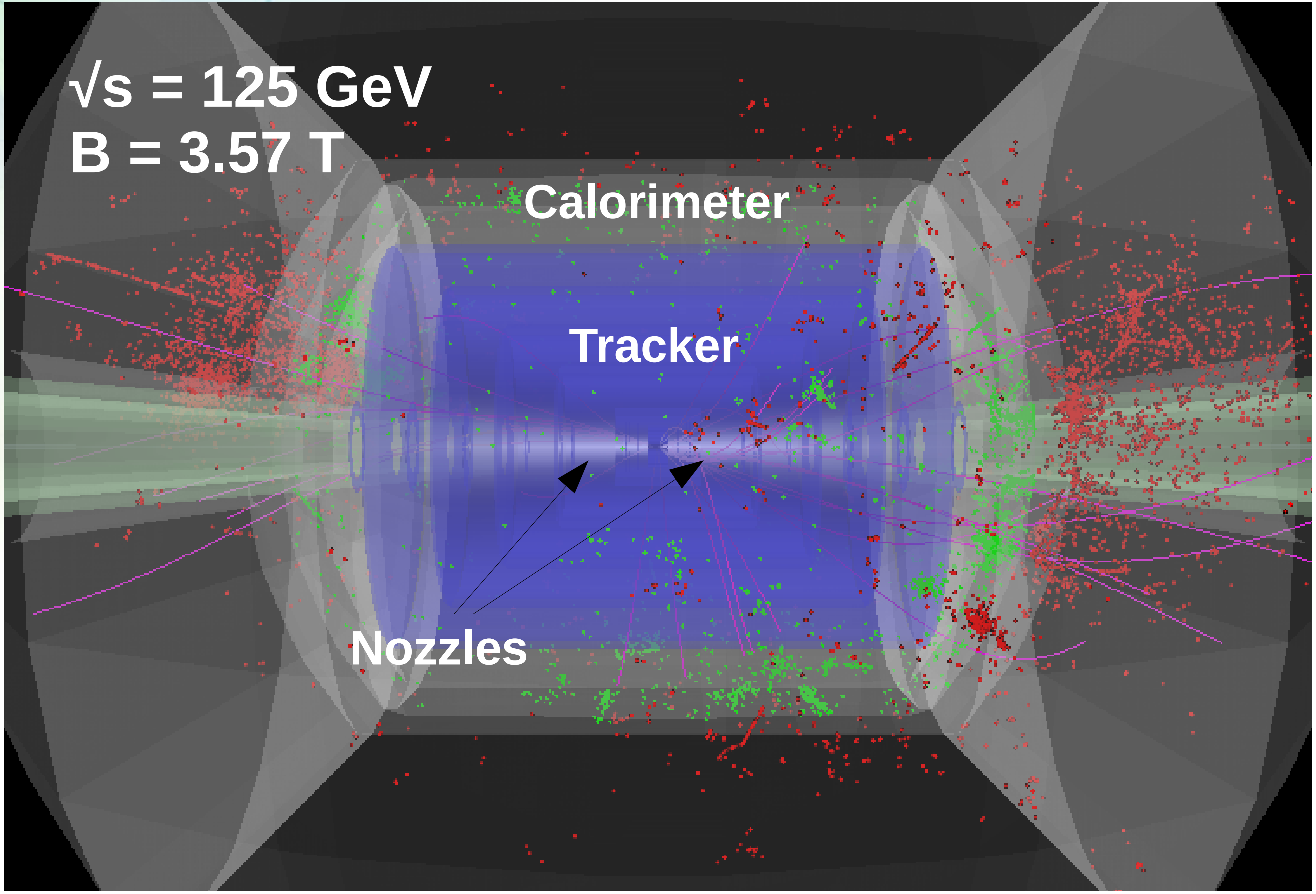
- **BUT beam-induced background is the real issue**.

Processes with 2 b-quarks in the final state

Process	σ [pb] @ 125 GeV	σ [pb] @ 1.5 TeV	σ [pb] @ 10 TeV
$\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$	19	0.046	0.0014
$\mu^+\mu^- \to \gamma^*/Z\ \gamma^*/Z \to b\bar{b} + X$	0.11	0.029	0.0013
$\mu^+\mu^- \to \gamma^*/Z\ \gamma \to b\bar{b} + \gamma$	23	0.12	0.0034
$\mu^+\mu^- \to H \to b\bar{b}$ (s-channel)	40	-	-
$\mu^+\mu^- \to HZ \to b\bar{b} + X$	-	0.004	~0.0001
$\mu^+\mu^- \to \mu^+\mu^- H(\to b\bar{b})$ (ZZ fusion)	-	0.018	0.055
$\mu^+\mu^- \to \nu_\mu \nu_\mu H(\to b\bar{b})$ (WW fusion)	-	0.18	0.54

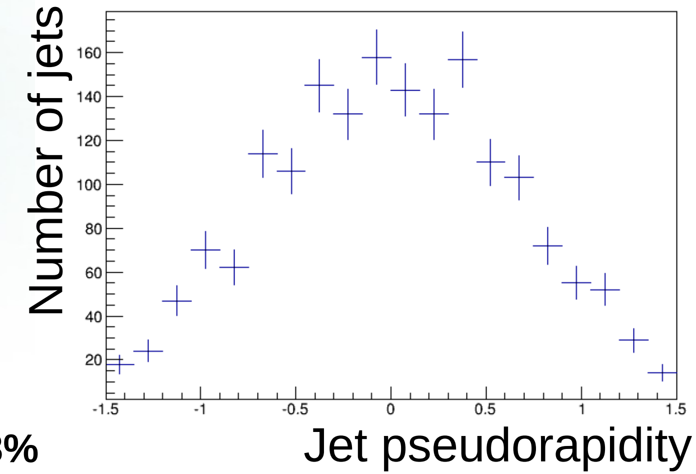
$H \to b\bar{b}$ in simulation

- This is how a signal event looks in the ILCRoot simulation.
- Tracks and calorimeter hits displayed (see Nazar's talk).
- Beam-induced background not present here.
- Center of mass energy considered for comparisons: **125 GeV and 1.5 TeV**.

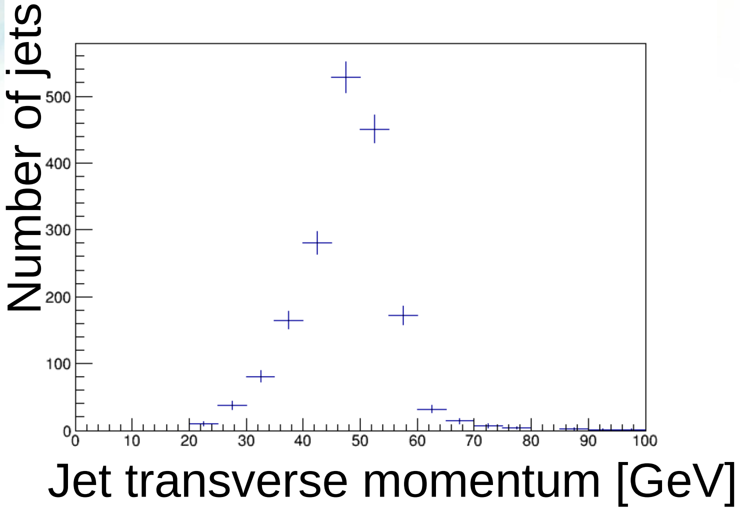


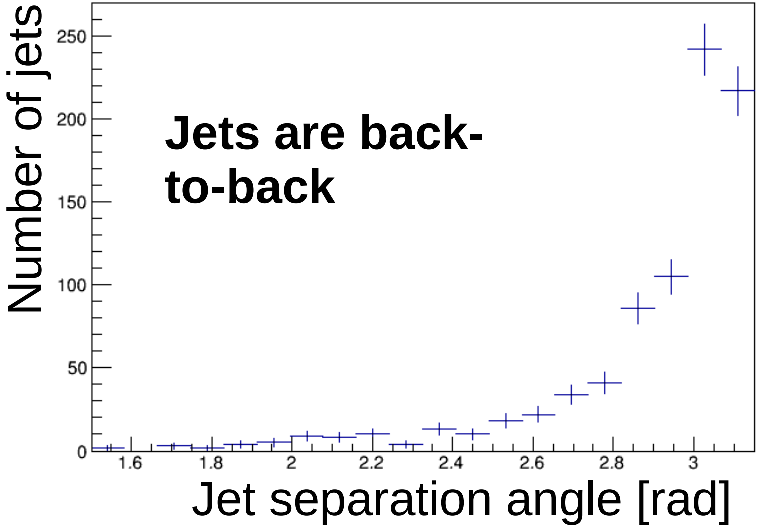
$H \rightarrow b\bar{b}$ reconstruction at $\sqrt{s}$ = 125 GeV

- Jets are reconstructed using **Particle Flow inputs (tracks and isolated clusters)** and a Cone clustering with R = 2.0
- Jet Energy corrections are applied
- 1000 events generated
- Measured distributions plotted



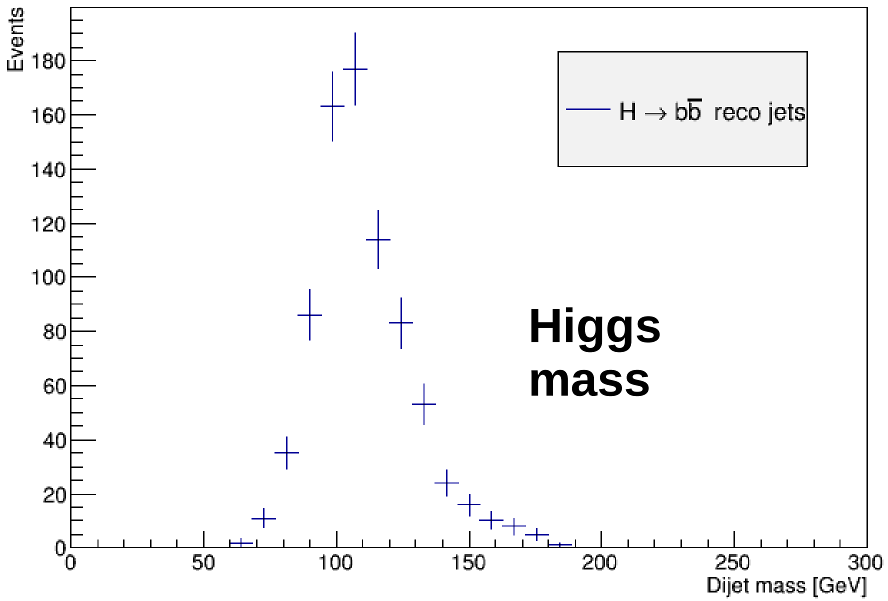
p_T > 10 GeV
|η| < 1.5 ──► **Higgs selection efficiency = 78%**

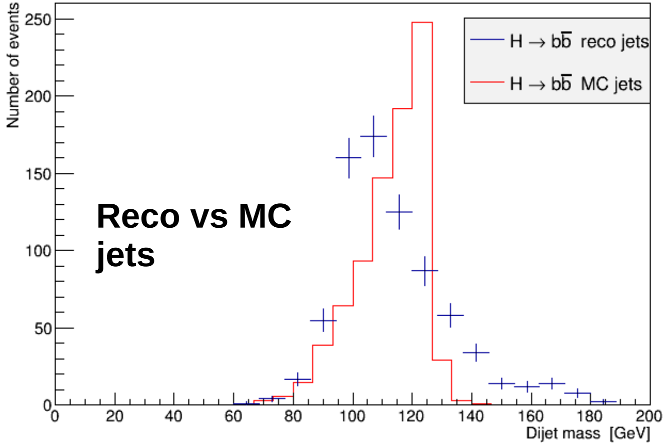


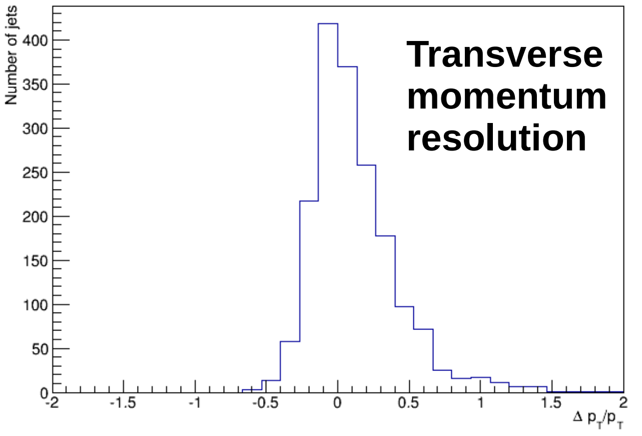


H → $b\bar{b}$ mass distribution at √s = 125 GeV

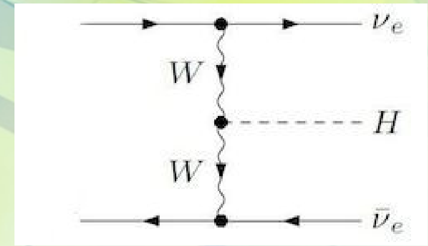
- **Higgs mass peak resolution → 15%**
- Excellent result for distinguish it from Z → bb and not-resonant backgrounds



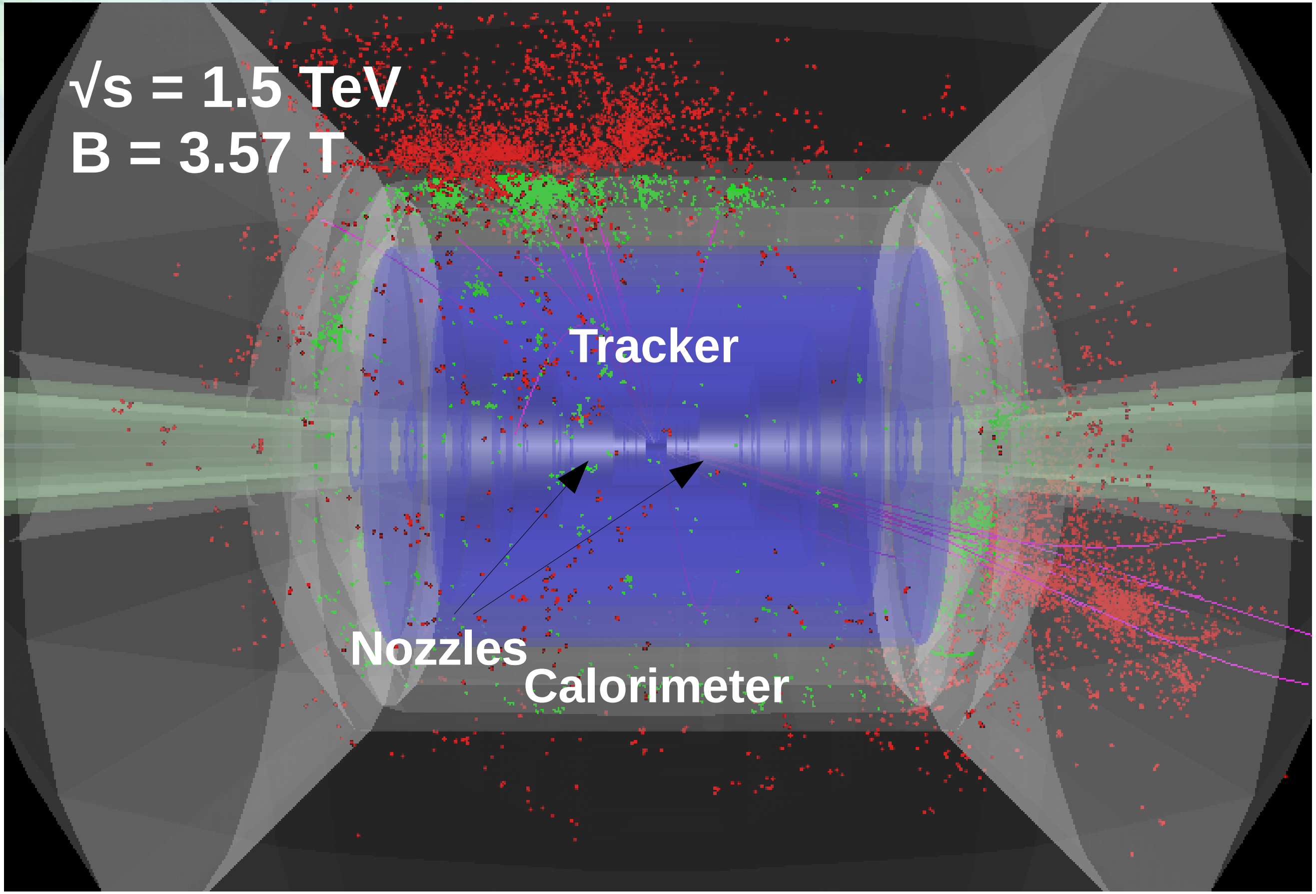




$H \to b\bar{b}$ at $\sqrt{s}$ = 1.5 TeV



WW fusion is the main production channel: 2 neutrinos in association



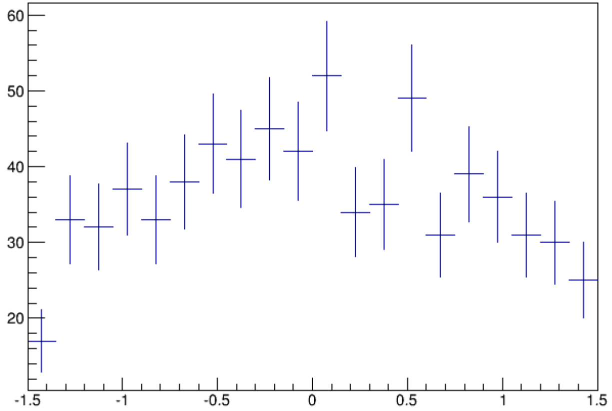
H→$b\bar{b}$ reconstruction at √s = 1.5 TeV

- Jets are reconstructed using Particle Flow inputs (tracks and isolated clusters) and a Cone clustering with **R = 1.0**
- 500 events generated

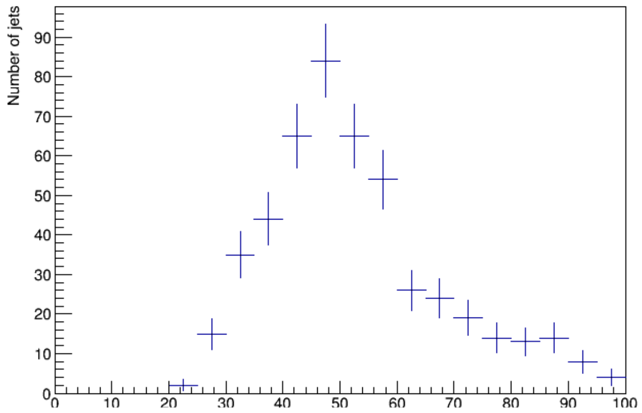
p_T> 10 GeV

|η| < 1.5

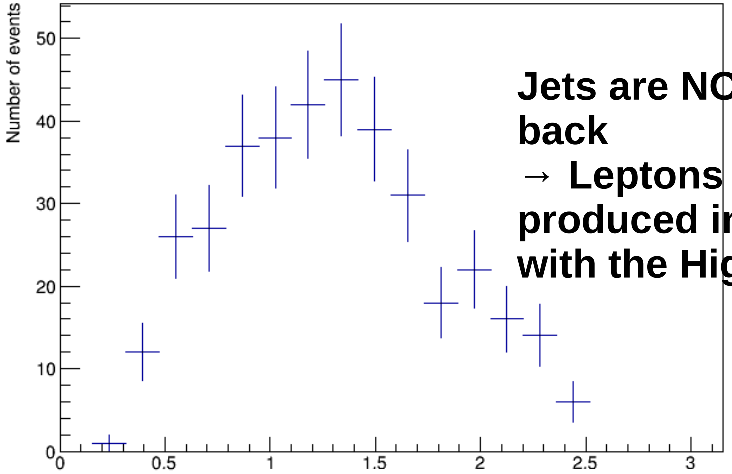
Higgs selection efficiency = 76%
Almost identical to Higgs Factory



Jet pseudorapidity



Jet transverse momentum [GeV]

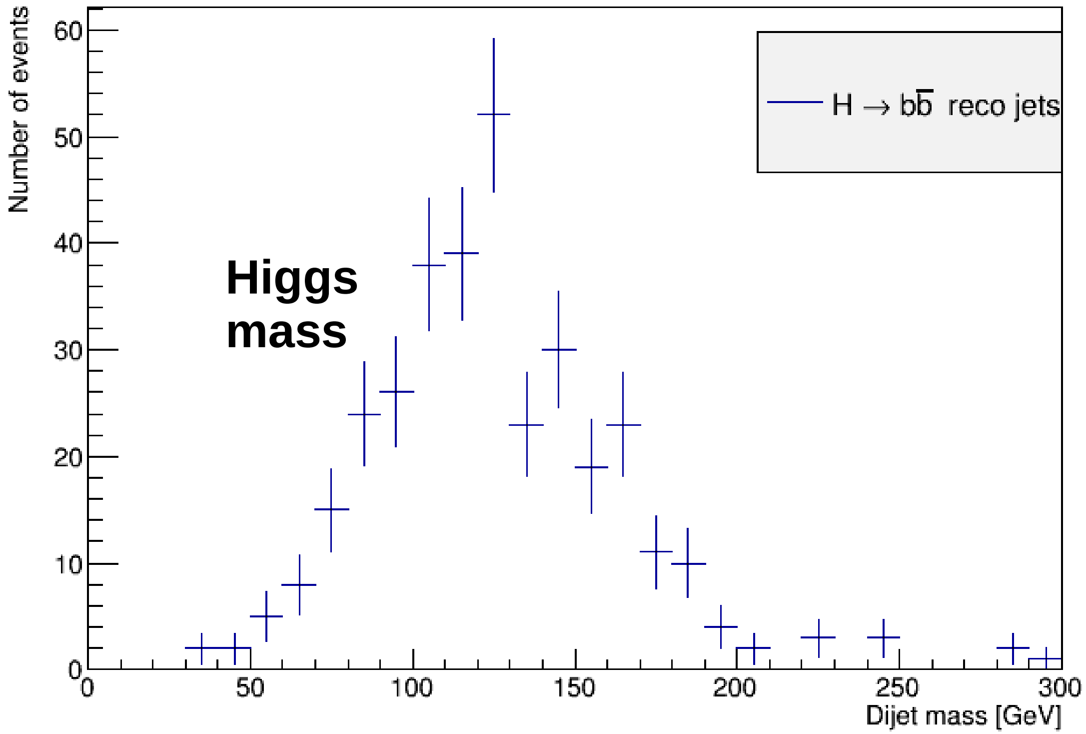


Jets are NOT back-to-back
→ Leptons are produced in association with the Higgs

Jet separation angle [rad]

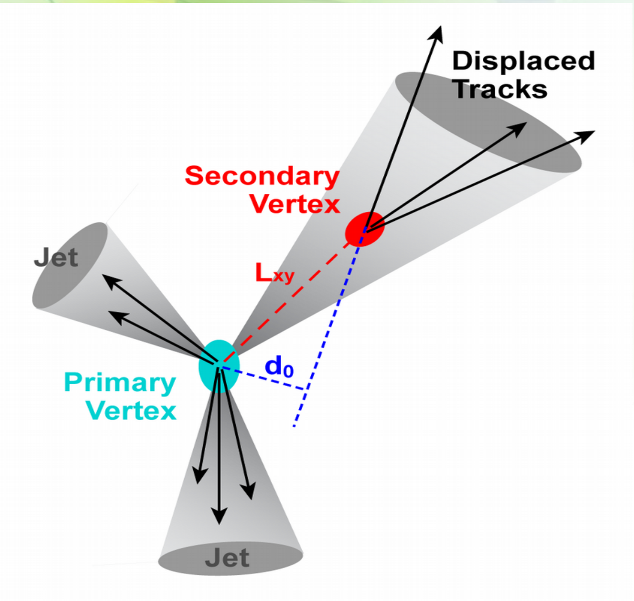
$H \rightarrow b\bar{b}$ mass distribution at $\sqrt{s}$ = 1.5 TeV

- **Higgs mass peak resolution = 30%**
- **Worst resolution with respect to Higgs Factory case (15%)**
- Improvements under study:
  - B field
  - Jet radius
  - Particle Flow inputs



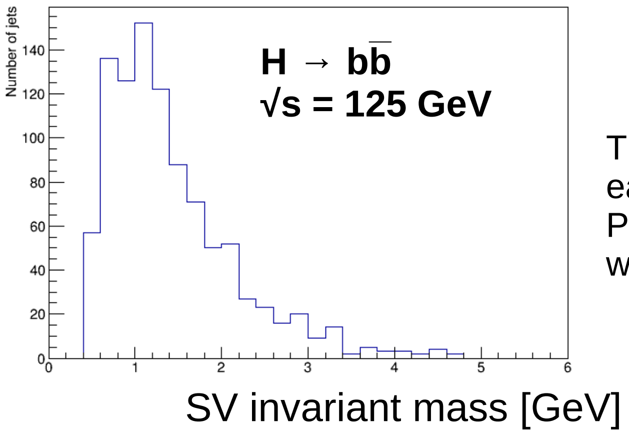
b-tagging

b-tagging algorithm:
3-tracks secondary vertex reconstruction inside the jet cone (similar to LHCb) → tracks with significant impact parameter are used

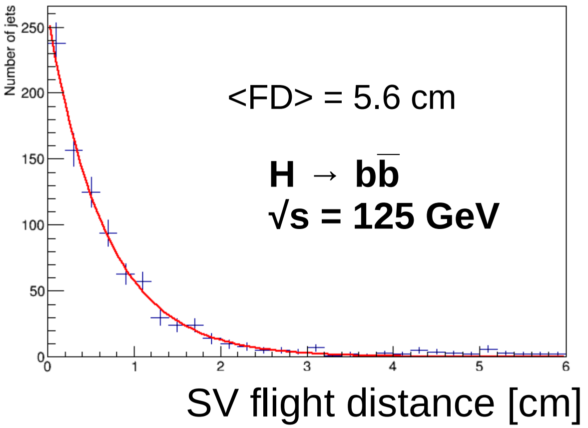


SV-tagging efficiency (N_{tag}/N_{rec})
at √s = 125 GeV →
63% similar to LHC experiments

First b-tagging study at Muon Collider

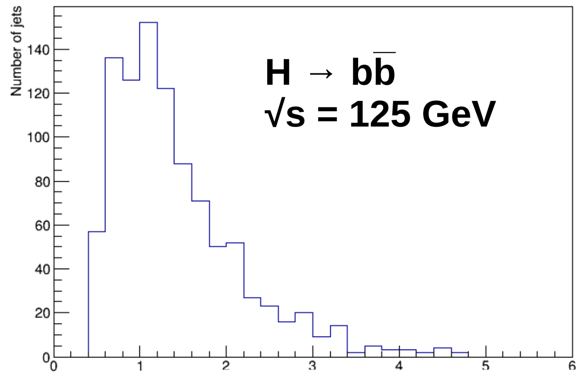


The pion mass is assigned to each track
Peak at ~1 GeV consistent with LHCb result

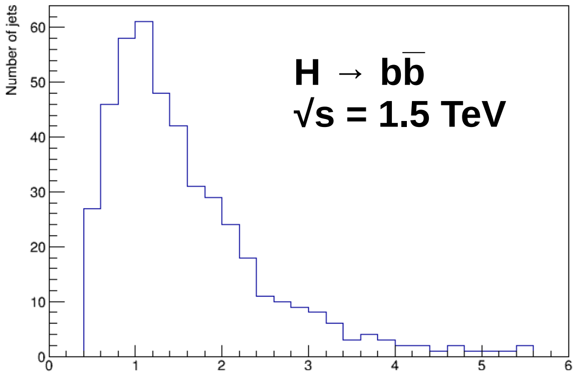


A cut on the SV mass and flight distance can help to reduce the background contamination

b-tagging $\sqrt{s}$ = 125 GeV vs $\sqrt{s}$ = 1.5 TeV



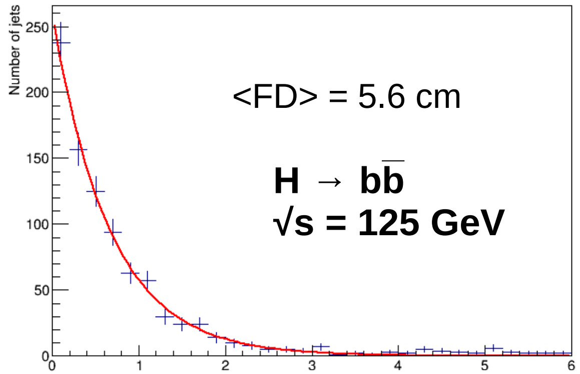
SV invariant mass [GeV]



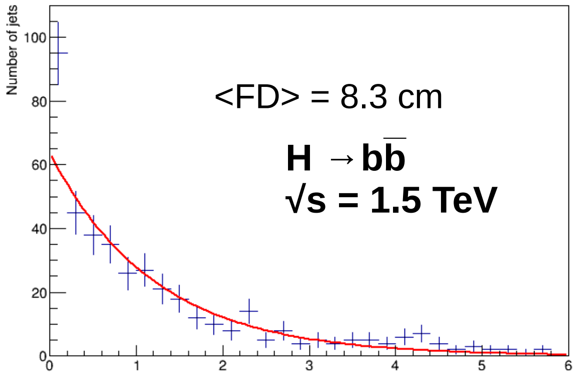
SV invariant mass [GeV]

SV-tagging efficiency (125 GeV) = 63%

SV-tagging efficiency (1.5 TeV) = 69% → Improved tagging efficiency at 1.5 TeV



SV flight distance [cm]



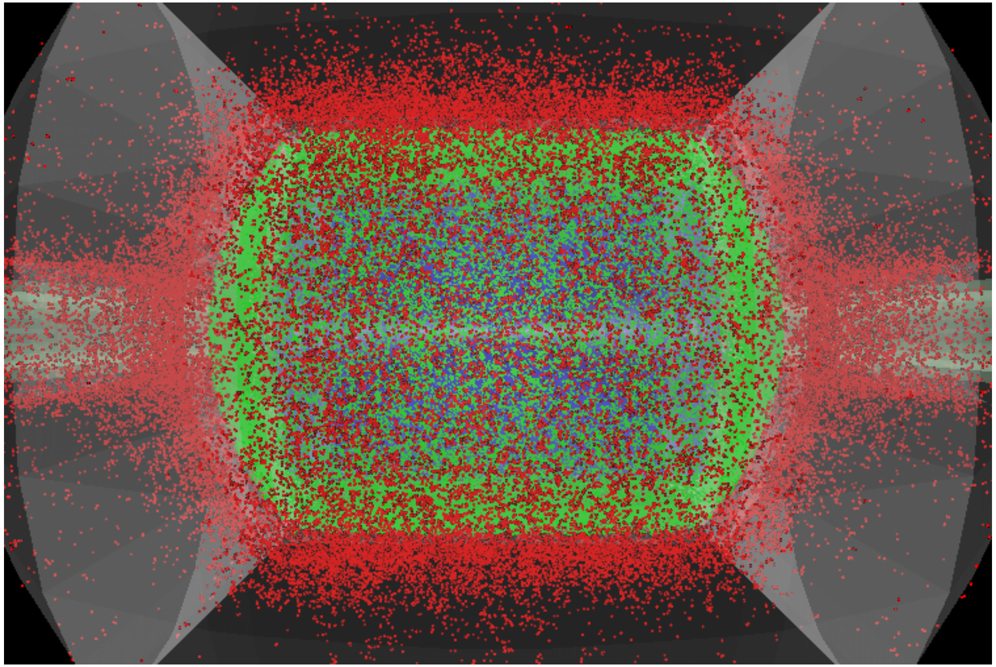
SV flight distance [cm]

→ Jets are more boosted → higher flight distance

Effects of the beam-induced background

- We understood the Higgs reconstruction @ Muon Collider in the absence of beam-induced background → Jets reconstruction, b-tagging

- **What can be the effect of the beam induced background?**
  - A significant amount can be removed with detector-level requirements (see Nazar's talk)
  - Random hits assigned to signal tracks and calorimeter clusters → momentum degradation
  - Fake tracks and calorimeter clusters → to be removed with the jet clustering (anti-kt?)
  - Use Regions of Interest algorithms for reconstruction, as proposed for HL-LHC.



Computational challenge

- The effects of the beam-induced background are impossible to predict without a full detector simulation of signal + background as it is now.

➔ Simulation of 1 background event
- **~ 1200 hours**
- ~ 20 GB RAM
- ~ 60 GB hard disk

➔ Simulation of 1000 signal events
- ~ 90 hours
- ~ 10 GB hard disk

➔ Merging of 1 signal event with 1 background event
- ~ 100 hours

Applying physical cuts before the simulation is impossible

↓

We have to face challenges

- Software debugging and optmization
- Parallelization
- Grid

Tests done on Intel(R) Xeon(R) CPU E5-2665 0 @ 2.40GHz (8x)

Goals and Conclusions

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- We demonstrated:
  - → Full detector simulation works correctly
  - → $H \to b\bar{b}$ reconstructed properly without machine background
  - → In the absence of the beam-induced background physical performance are at the LHC level (without detector optimization!)

- Goals: → Simulate a signal + background sample → Obtain efficiencies and resolutions as a function of the kinematic → Apply them to a parametric simulation (as example Delphes) → **Obtain a realistic estimation of the precision on any measurement/search @Muon Collider**

- **A big effort is needed on detector optimization design, simulation, reconstruction algorithms implementations and on the full development of a computing framework suitable for this brand new machine.**