Study of b- and c-jets identification for Higgs coupling measurements at Muon Collider

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Higgs 2021

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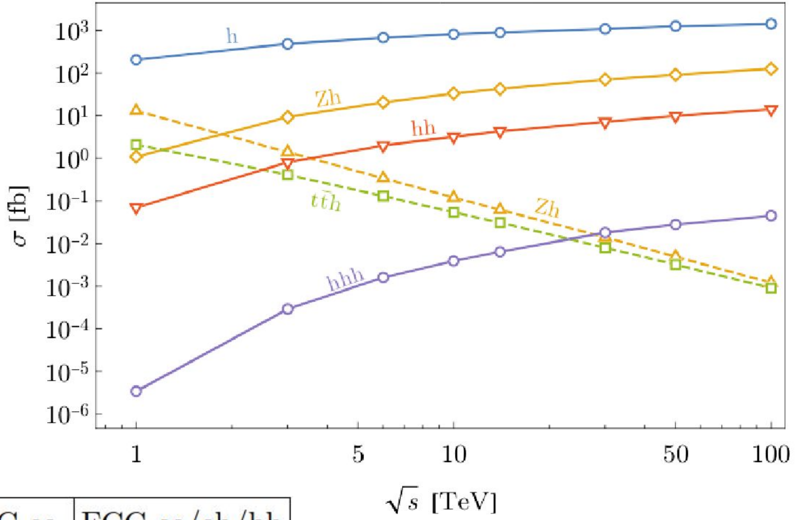
Objective

The Muon collider could provide precision typical of a lepton collider with an energy reach of an hadron collider. The 3 TeV C.M. energy machine is an Higgs factory that can provide measurements of **Yukawa couplings**.



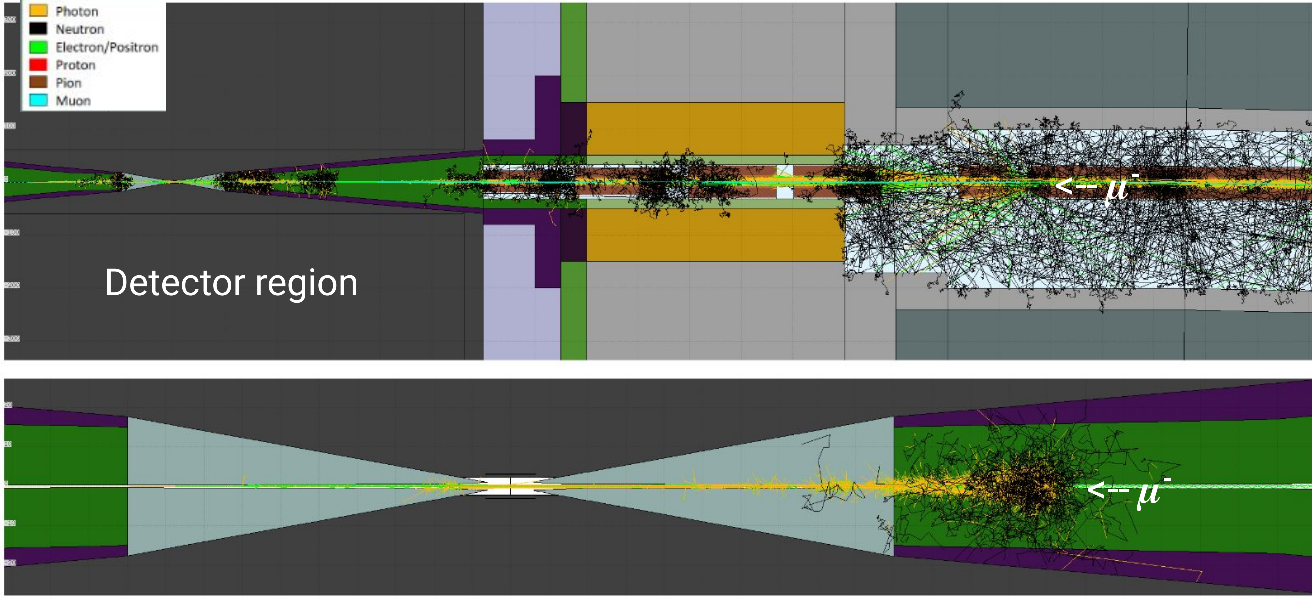
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43

"Higgs Boson studies at future particle colliders,"Journal of High Energy Physics 2020, vol. 139. https://doi.org/10.1007/JHEP01(2020)139

In this presentation results on **H->bb-bar at √s=3 TeV by using Secondary Vertex (SV)** jets identification are presented together with a preliminary investigation of a Deep Neural Network (**DNN**) in order to separate **H->cc-bar** from **H->bb-bar.**

Beam **I**nduced **B**ackground (**BIB**)

Muon beams decays along the machine interact with its elements producing showers of secondary and tertiary particles.



"Advanced assessment of Beam Induced Background at a Muon Collider," `https://arxiv.org/pdf/2105.09116v2.pdf`

Mitigation strategies:

➢ shielding on magnets
➢ **M**achine **D**etector **I**nterface (**MDI**) optimized by the MAP collaboration and introduction of detector shielding (tungsten cones **Nozzles**)
➢ Appropriate detector design

Muon collider Detector

hadronic calorimeter

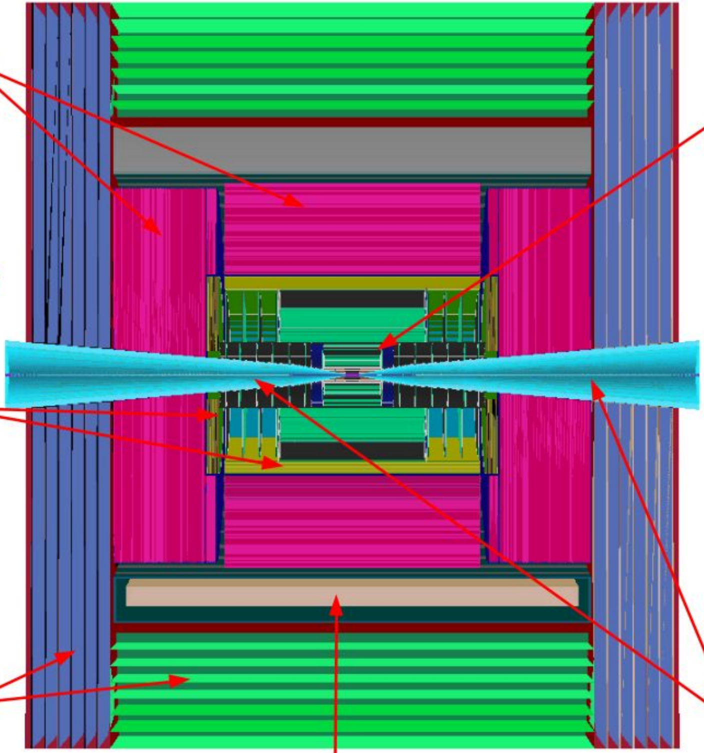
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

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

muon detectors

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



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^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.

Beam Induced Background Effects

BIB is an high source of background in the detector:

- generates high occupancy in the tracker, in particular in the layers close to the beam pipe
- behaves like an underlying event in the calorimeter ➡ need of dedicated jets, electrons and photons reconstruction algorithms
- muons are less affected

In order to take into account of the BIB effects, signal and physics background events are simulated through the detector with GEANT and the BIB events are overlaid at hit level.

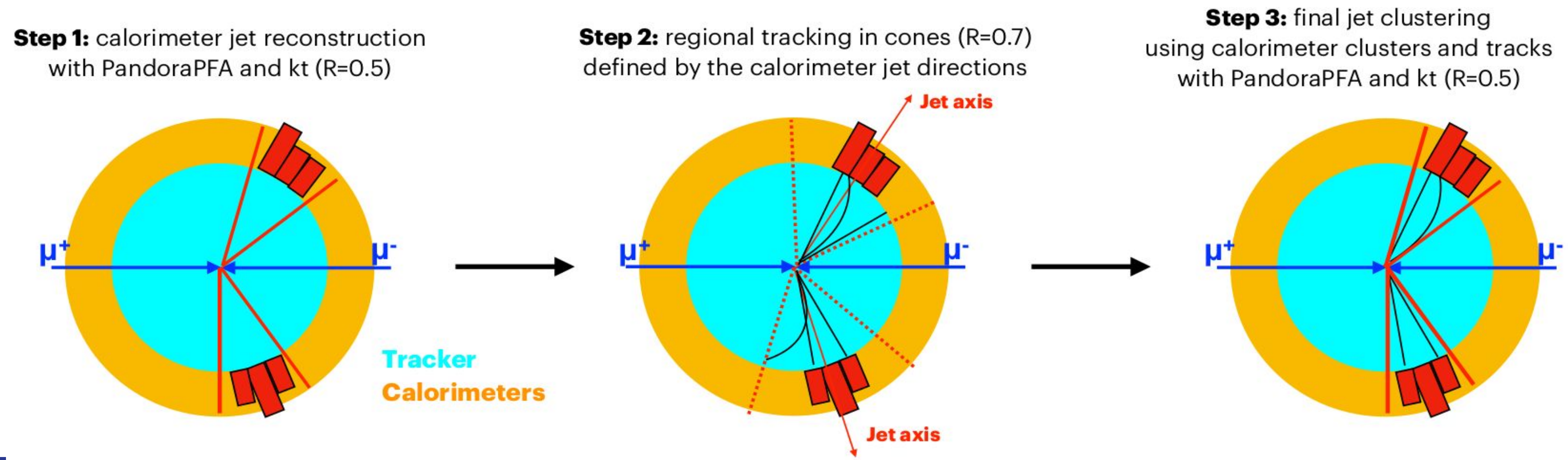
These events simulation and reconstruction is very CPU demanding, at the moment only BIB at **$\sqrt{s}$=1.5 TeV** is available

This work uses signal and physics background generated at **$\sqrt{s}$=3 TeV** and BIB at **$\sqrt{s}$=1.5 TeV** which is a conservative assumption

Jets and Tracks reconstruction

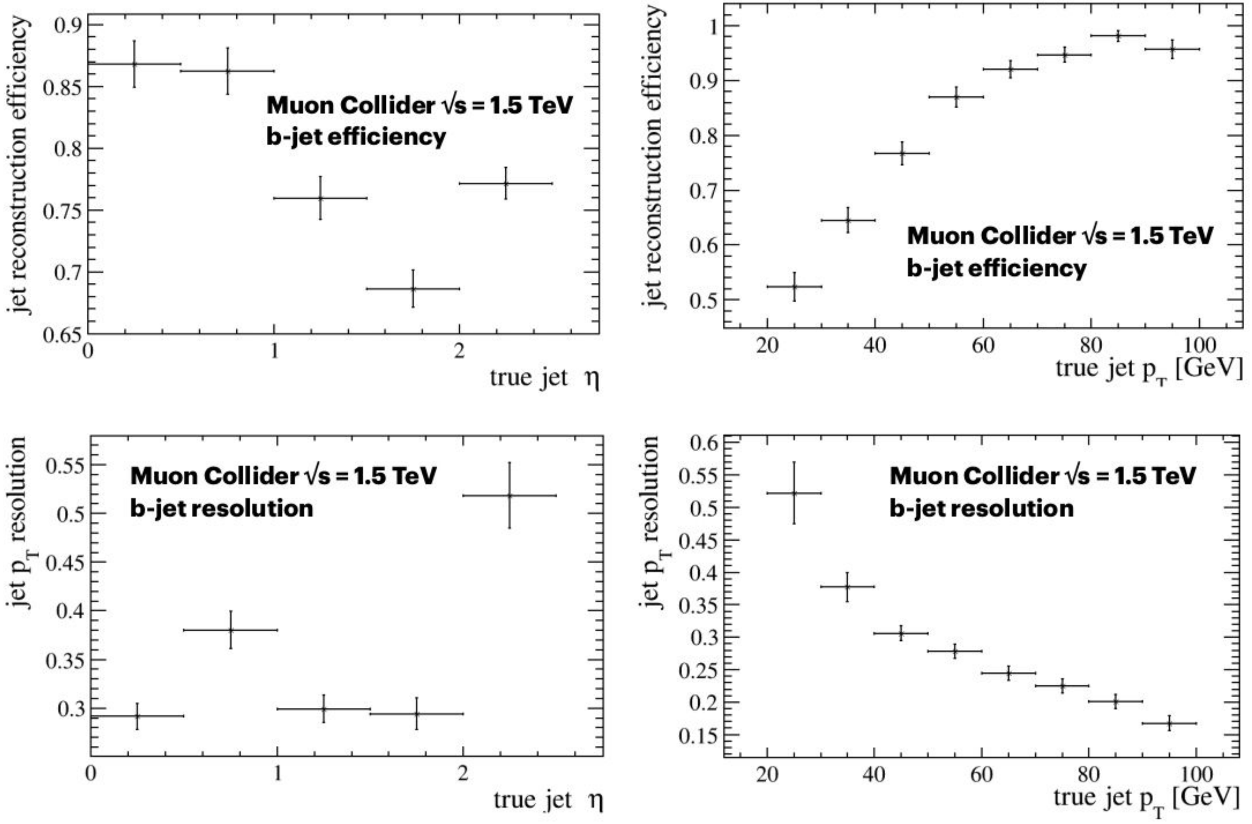
Dedicated algorithms for tracks and jets reconstruction:

- ❖ Jets reconstructed **after subtraction of "average BIB energy" loss**
- ❖ Due to high occupancy in the tracking detectors **->** **Regional tracking in a large jet cone**
- ❖ Final jets of R=0.5 reconstructed using calorimeter clusters and tracks by using particle flow algorithm



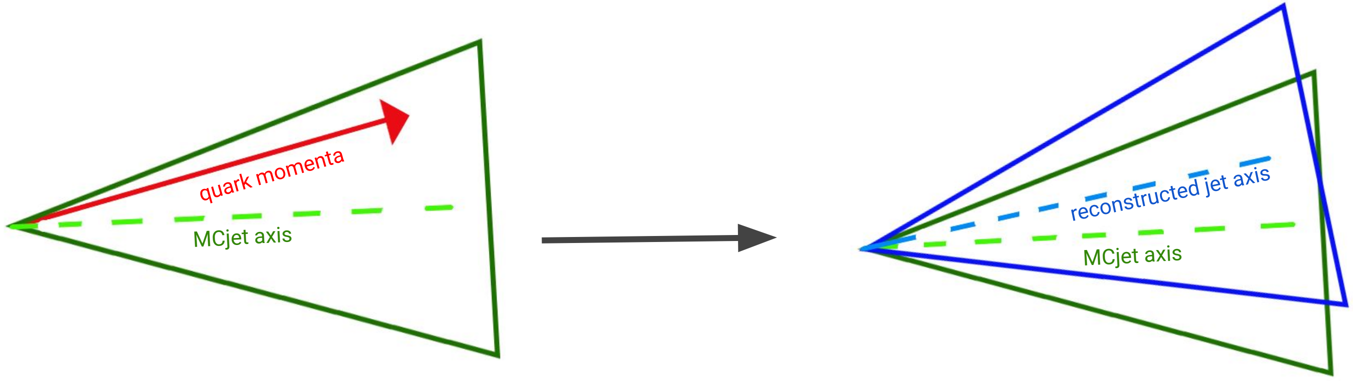
b-Jet reconstruction Performance

- b-jet of different momentum generated with Pythia
- Jet efficiency and resolution degraded at high |**η**| where the BIB effect is more pronounced
- low momentum jet reconstruction needs to be optimized, current algorithm performance affected by BIB



Secondary Vertex (SV) tagging

If a jet reconstructed using Monte Carlo truth (MCjet) contains the b quark, the reconstructed jet with the smallest ΔR (if ΔR<0.5) with that MCjet is said **matched** to a b-quark



Definition of **tagging efficiency** and **mistag**:

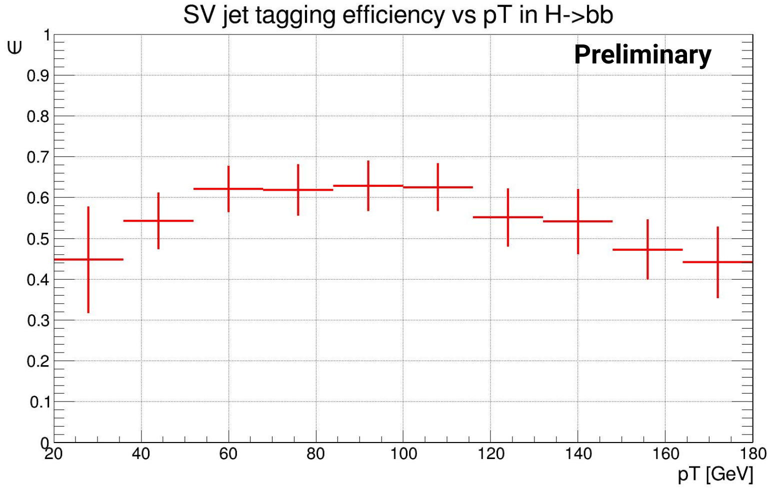
$$Eff_{SV-tag} = \frac{Number\ of\ tagged\ AND\ matched\ jets}{Number\ of\ matched\ jets}$$

$$Mistag_{SV-tag} = \frac{Number\ of\ tagged\ AND\ NOTmatched\ jets}{Number\ of\ NOTmatched\ jets}$$

H->bb-bar and bb-bar background SV-tagging

H->bb-bar events **at √s=3 TeV** generated with Pythia Monte Carlo
mu+mu→ bb-bar inclusive events generated at leading order with Pythia at **√s=3 TeV**
We require:

- two tagged jets
- $p_T^{jet} > 20$ GeV and $|\eta^{jet}| < 2.5$
- $M_{jj} < 300$ GeV



H->bb-bar: **SV**-tagging **efficiency**=**0.667±0.018**

SV-Mistag=0.0232±0.0073

H-reconstruction **efficiency=0.244±0.015**

bb-bar Background:

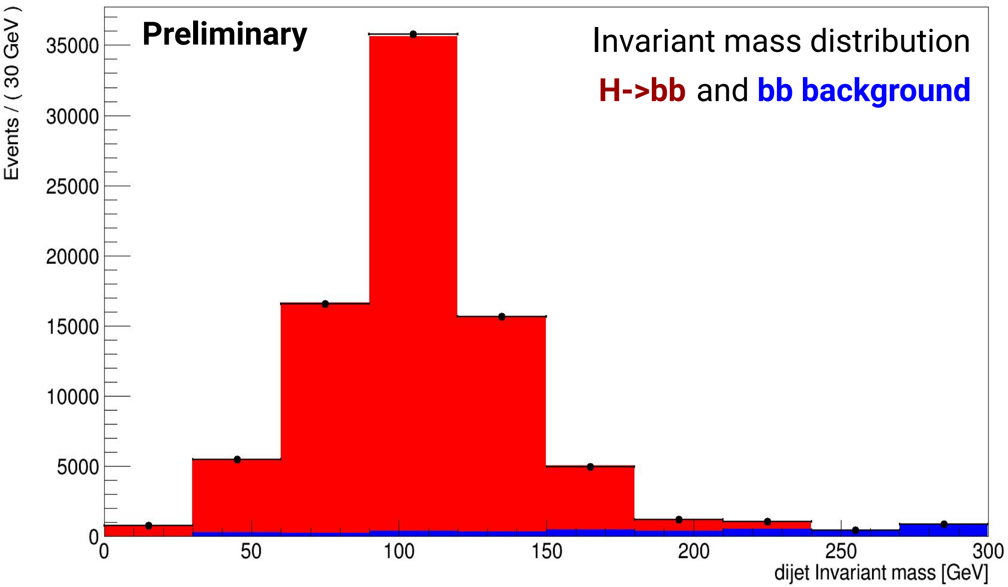
SV-tagging **efficiency**: **0.5705±0.0096**

SV-Mistag: **0.05316±0.0023**

Reconstruction efficiency: 0.121±0.017

H->bb-bar Cross Section Evaluation

The invariant mass distribution of **H + background** is given by the black dots



$$\sigma_{H\to bb} = 324 \text{ fb} \qquad \sigma_{EW\to bb} = 30.12 \text{ fb}$$

Assuming an instantaneous luminosity of $\mathcal{L}=4.4\cdot 10^{34}$ cm^{-2} s^{-1} and an integrated luminosity of $\mathcal{L}_{int}=1$ ab^{-1} :

N_H= 79 125 **N_{EW}=3636**

From a **fit** with the maximum likelihood on the dijet invariant mass distribution of **10000 pseudo-experiments**:

$$\frac{\Delta\sigma}{\sigma} = 0.36\%$$

statistical only

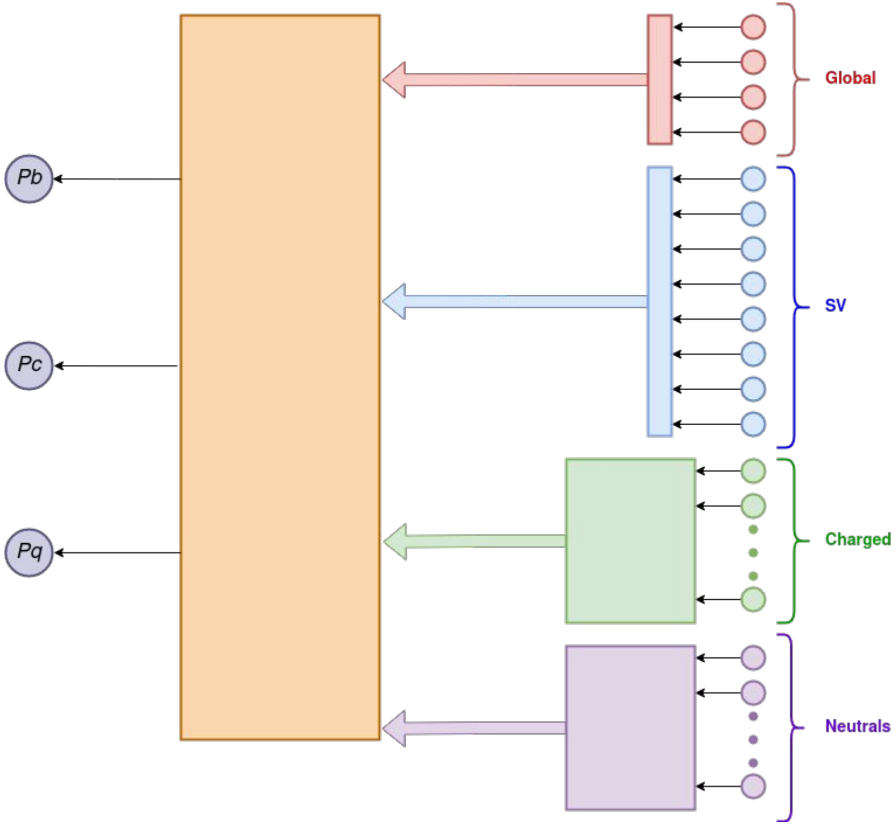
H->cc-bar vs H->bb-bar

- b- and c-jets from Higgs decay are very similar in momentum and secondary vertex properties

- very hard to separate H-> cc-bar from H->bb-bar by using kinematic variables

- b- and c-jets have a different internal structure due to the different quarks composition ➡ use of a **D**eep **N**eural **N**etwork to exploit the different flavour distributions inside the jets

DNN for jet flavour identification



Inputs observables:

Global jet variables: p_T, p_Z, E, Number of CHARGED particles, Number of NEUTRAL particles

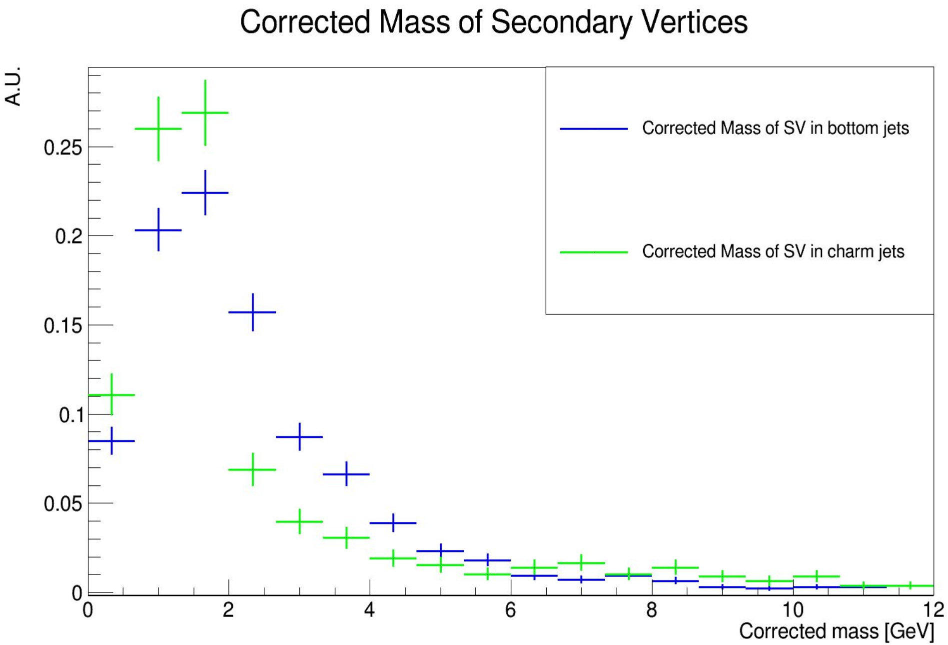
SV variables. If more than one, taken the one with highest p_T: Transv flight distance, lifetime, number of tracks, mass, corrected mass, ΔR, absolute value of the sum of charges of the tracks, ratio of p_T of SV/p_T of jet, z position

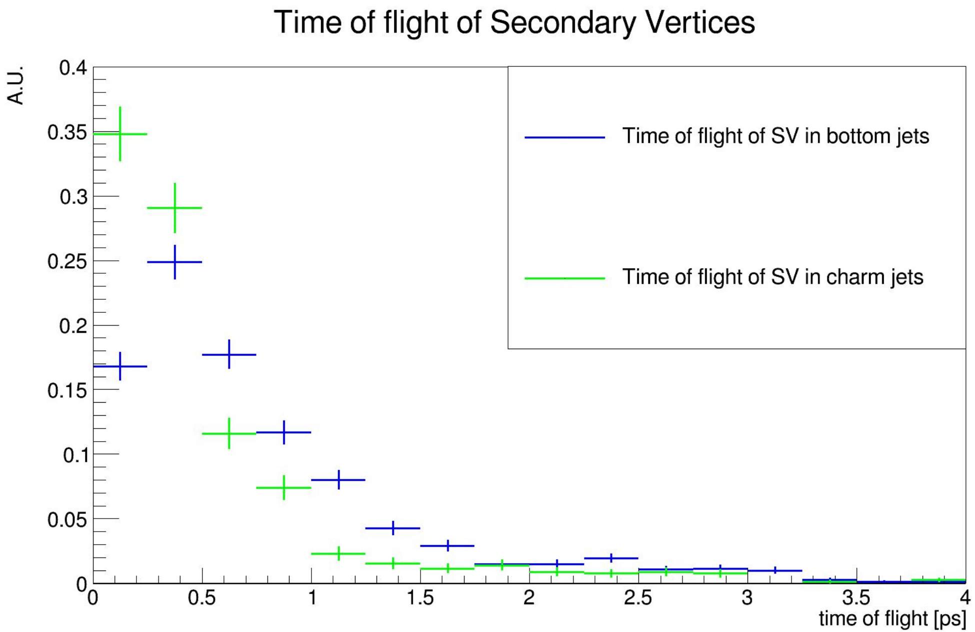
Takes up to 5 charged particles variables, choosing the ones with highest pT. For each: P_T, P_Z, Q/P; D_0, Ω, tan(λ) from the track fit

Takes up to 8 neutral particles variables, choosing the ones with highest p_T. For each: p_T, p_Z

Example of Input DNN variables distributions

Normalized distributions of some of the DNN input variables for b- and c-jets of **H->bb-bar** and **H->cc-bar**





$$M_{\text{cor}} = \sqrt{M^2 + p^2 \sin^2\theta} + p\sin\theta$$

θ = angle between p of SV and its flight direction

Conclusions

➔ The Muon collider provides a great **opportunity** to measure the **Higgs couplings** with high precision

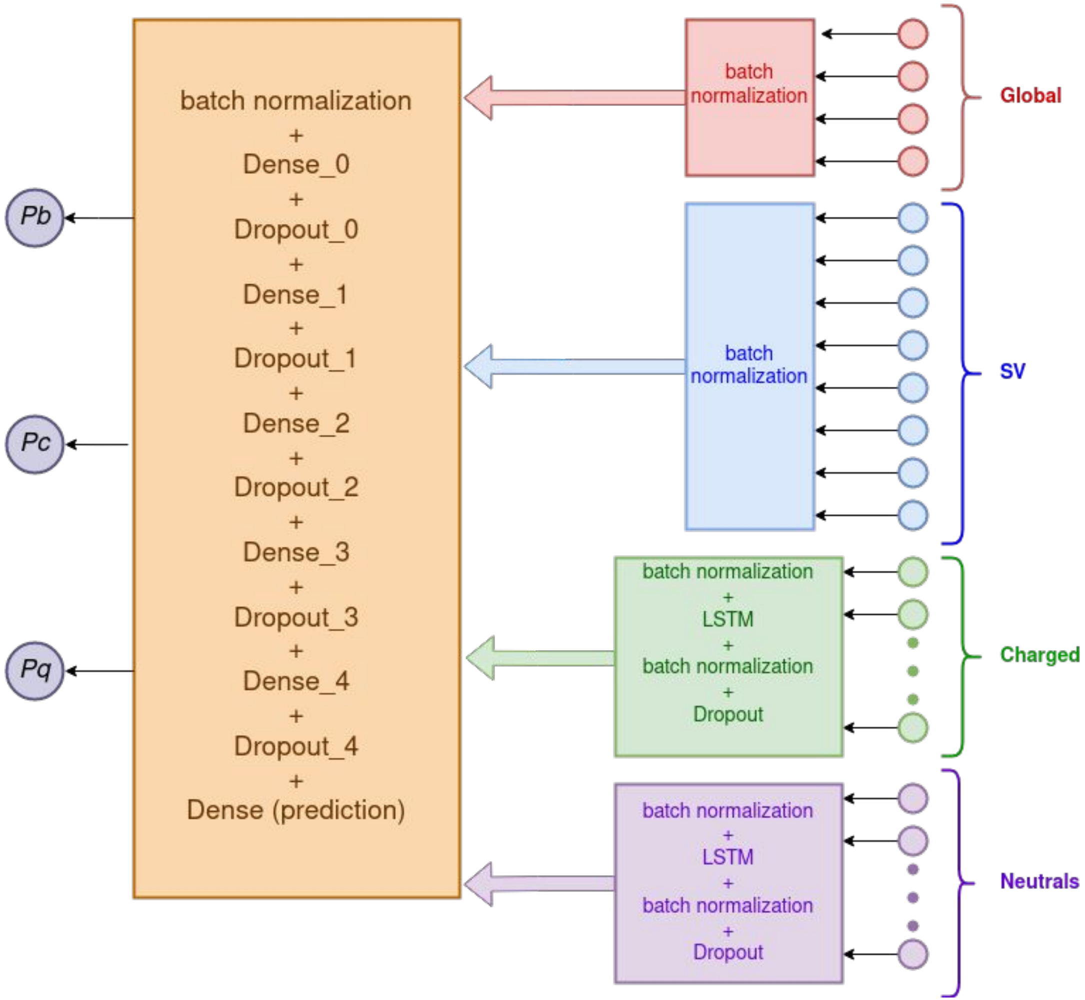
➔ Preliminary study of the **H->bb-bar** including the BIB and the physics background at **√s=3 TeV** shows that the cross section can be measured with a **statistical uncertainty** of $\frac{\Delta\sigma}{\sigma} = 0.36\%$ with 1ab^{-1} (CLIC has 0.3% with 2ab^{-1} [Eur. Phys. J. C 77, 475 (2017)])

➔ A **DNN** for jet flavour identification has been implemented to **improve** the **b-tagging** efficiency and provide a way to **tag c-jets**

Thank you for your attention!

Backup slides follow

DNN **preliminary** configuration

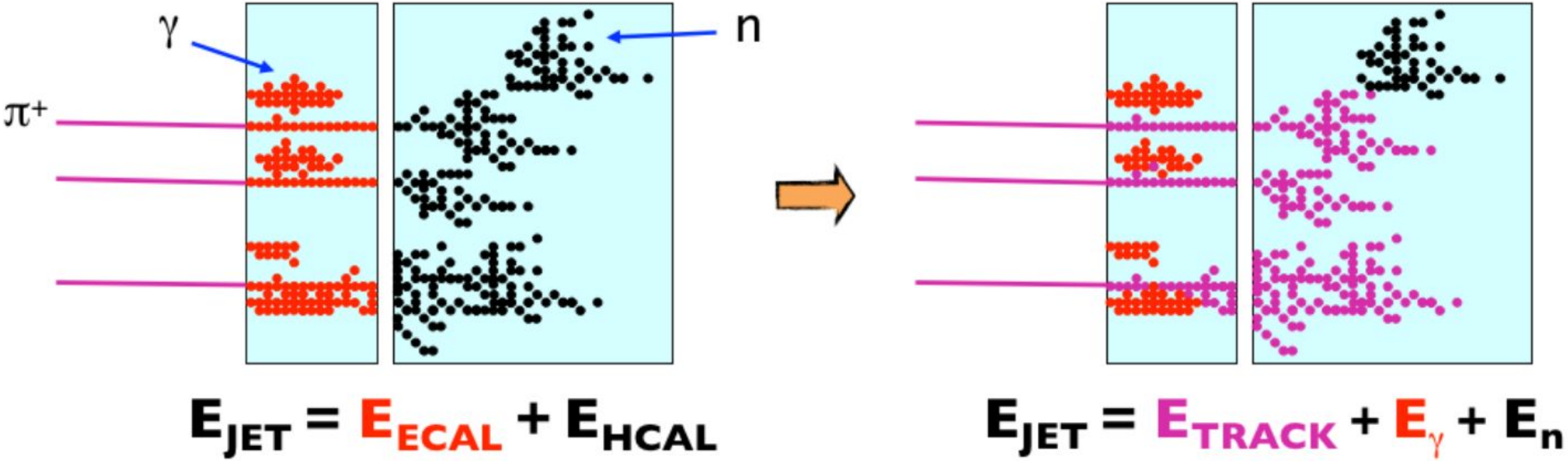


Adam optimizer with learning rate 0.0002

Categorical cross entropy loss function with softmax as activation function

Drop rate=0.1 in all dropout layer

Particle **F**low **A**lgorithm for jet energy reconstruction

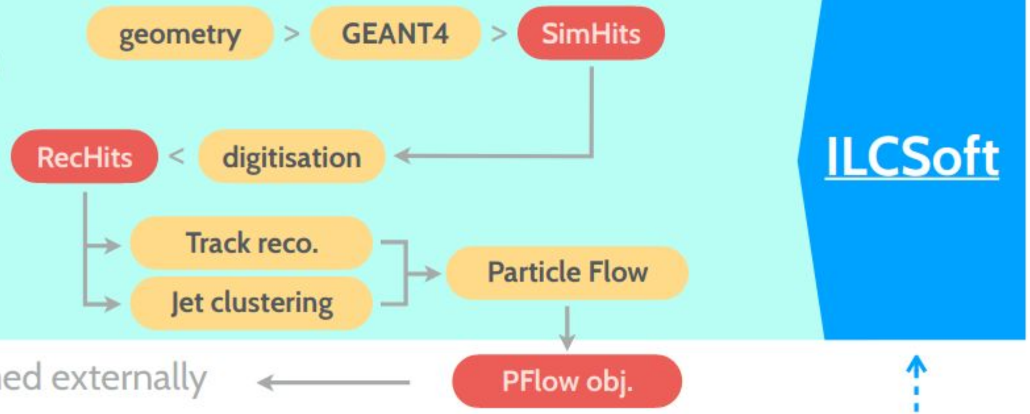


Simulation workflow

Main steps of a full-simulation study:

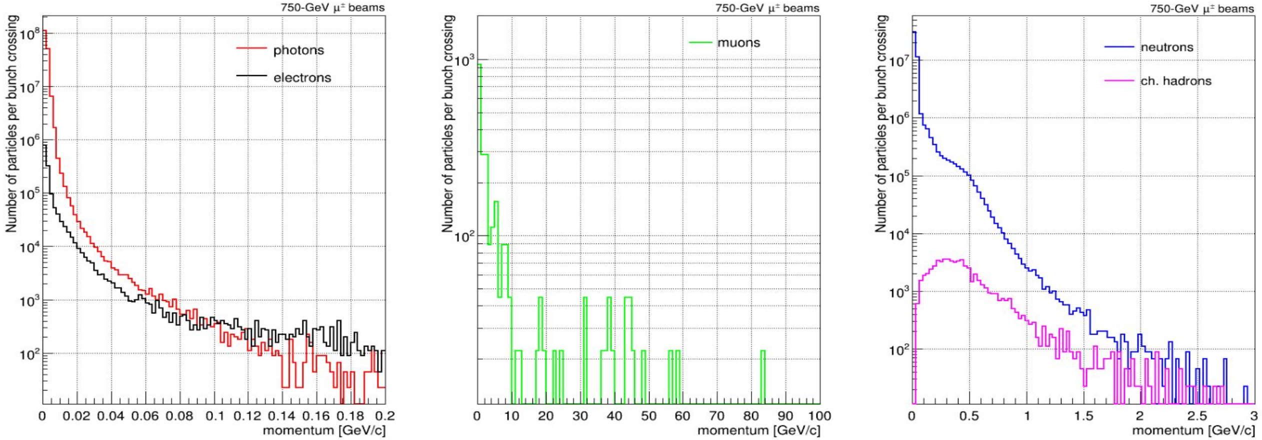
Matrix Element + Parton Shower — Beam Induced Background

1. **generation of stable input particles:** ME + PS Pythia/Madgraph/Whizard + BIB FLUKA + FlukaLineBuilder
2. **simulation of the detector response to the incoming particles** (DD4hep interface)
3. **simulation of detector effects**
   efficiency, electronics noise + thresholds, ...
4. **reconstruction of higher-level objects**
   photons, tracks, jets, particle identification
5. **higher-level analysis** ← can be performed externally ←

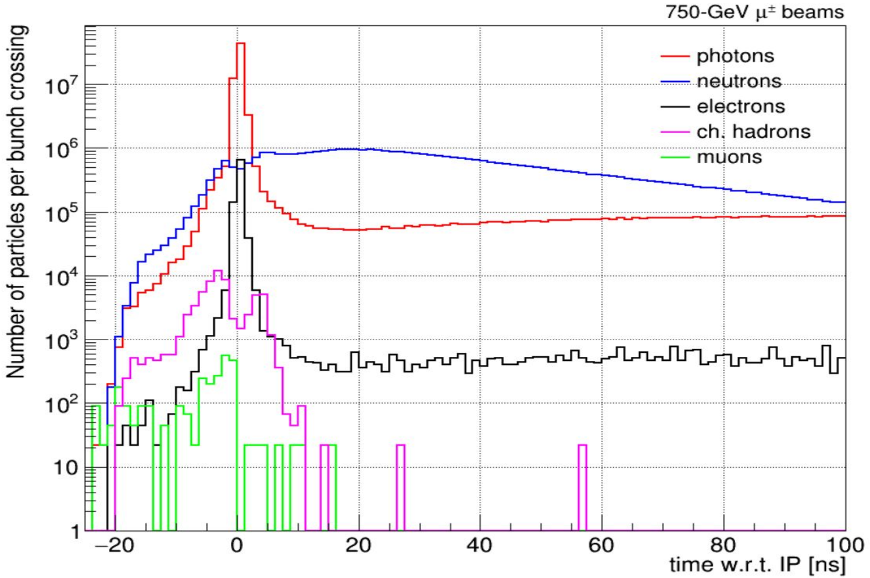


Detector simulation and event reconstruction handled within a single framework

1.5 TeV BIB characterization



Momenta spectra



Arrival time at the detector
w.r.t. bunch crossing

Summary of

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Summary

- The **Muon Collider** could provide precise determination of Higgs couplings.
- The **decays of** the beams' μ create a challenging beam induced background (**BIB**)
- A carefully designed detector and machine detector interface **can reduce it** to a manageable level

We studied the **H->bb-bar** with a **detailed simulation** at **3 TeV** in the CM, accounting for both the **inclusive->bb-bar** and the **BIB**. We identified the b-jets by looking for **Secondary Vertices** inside the jets.

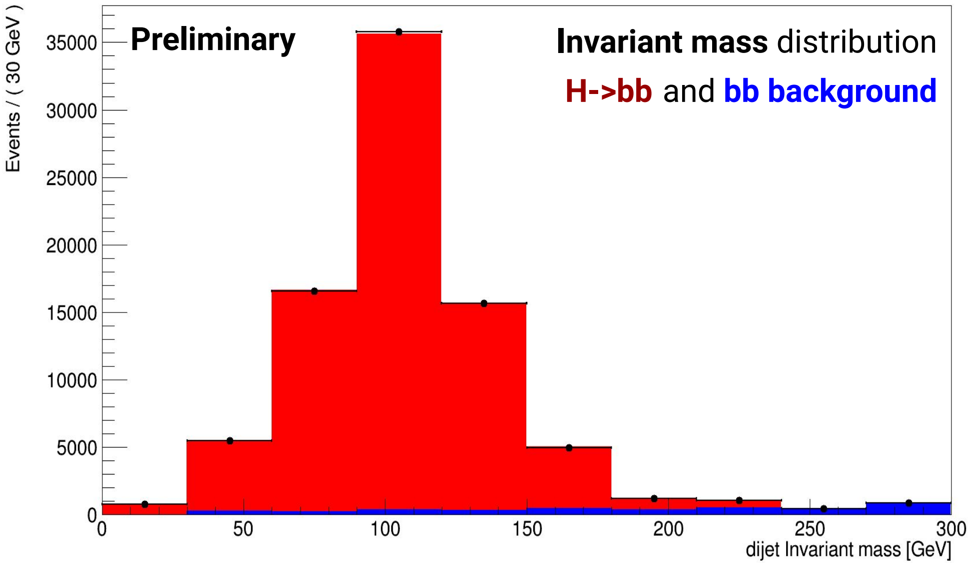
Summary continued

The Higgs was reconstructed by requiring:

- ➢ two b-tagged jets
- ➢ $p_T^{jet} > 20$ GeV and $|\eta^{jet}| < 2.5$
- ➢ $M_{jj} < 300$ GeV

From a fit on 10000 pseudo-experiments, assuming $\mathcal{L}_{int}=1\ ab^{-1}$ the **statistical uncertainty** is found to be:

$$\frac{\Delta\sigma}{\sigma} = 0.36\%$$



Deep Neural Network is under study to **improve b-jet tagging efficiency** and to **identify c-jets**, allowing us to the reconstruct **H->cc-bar**.