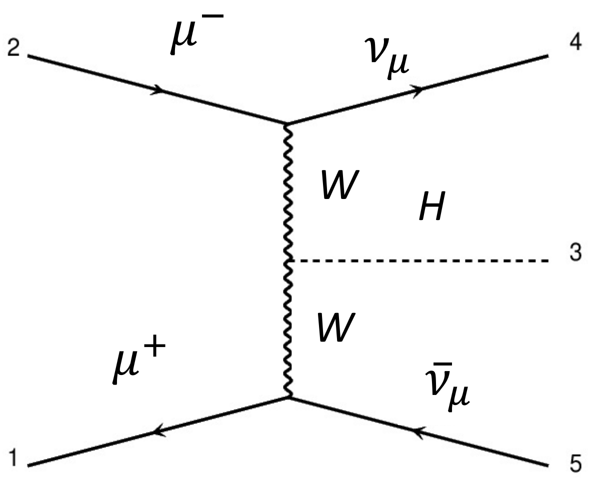
Physics at Muon Collider

Higgs Physics at a Muon Collider

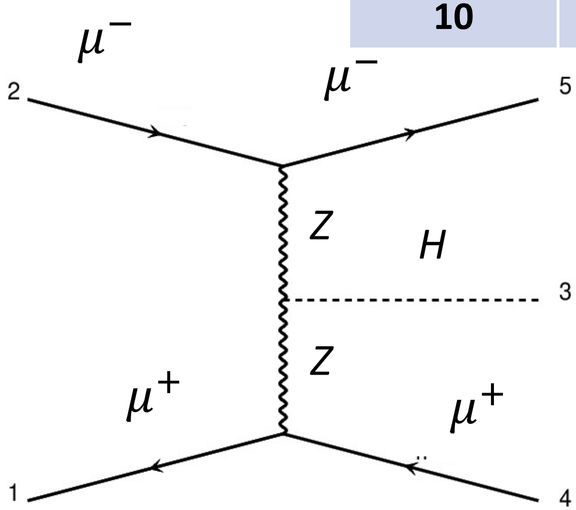
$\sqrt{s}$ $[TeV]$	$\mathcal{L}$ (4 year)$[ab^{-1}]$
1.5	0.5
3.0	1.3
10	8.0

- Dominant Higgs boson production mechanism: vector boson fusion
- Main contribution from WW fusion.



$\sigma = 2.1 \cdot 10^2\ fb\ \ (\sqrt{s}\ = 1\mathrm{TeV})$

$\sigma = 5 \cdot 10^2\ fb\ \ (\sqrt{s}\ = 3\mathrm{TeV})$



$\sigma = 1.5 \cdot 10^1\ fb\ \ (\sqrt{s}\ = 1\mathrm{TeV})$

$\sigma = 3.8 \cdot 10^1\ fb\ \ (\sqrt{s}\ = 3\mathrm{TeV})$

O(1M) Higgs produced in the low energy (<10 TeV scenario)

Clean events as in e+e- colliders with high collision energy as in hadron colliders
The muon collider is the dream machine for Higgs physics measurements

Higgs boson couplings: from present to future

- One of the goals of future colliders: precise measurement of Higgs couplings with SM particles

$$\mathcal{L} = -g_{Hf\bar{f}}\ f\bar{f}H + \frac{g_{3H}}{6}H^3 + \frac{g_{4H}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

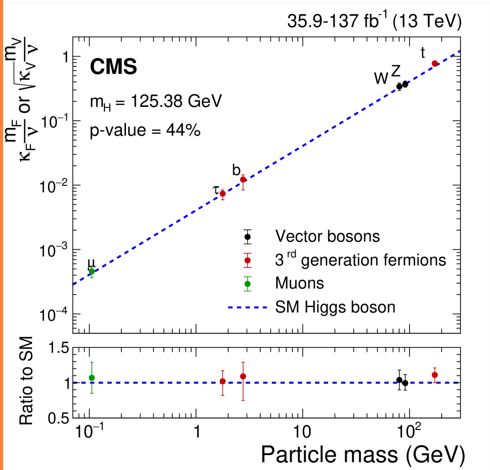
$$g_{Hf\bar{f}} = \frac{\mathrm{m_f}}{v}\ , \mathrm{g_{HVV}} = \frac{2\mathrm{m_V^2}}{v}\ , \mathrm{g_{HHVV}} = \frac{2\mathrm{m_V^2}}{v^2}\ , \mathrm{g_{3H}} = \frac{3\mathrm{m_H^2}}{v}\ , g_{4H} = \frac{3m_H^2}{v^2}$$

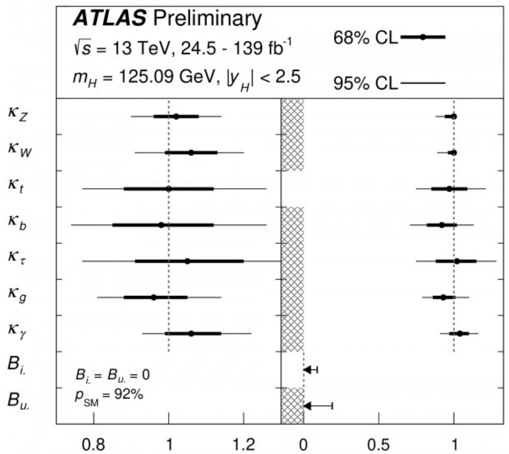
→push the knowledge of the couplings below the 1% precision

→ access un-explored couplings

→ use the Higgs boson as a tool to probe beyond standard model scenarios!

The present





The future

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_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
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_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
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
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

What has been explored this year in Bari

First estimation of Higgs couplings to Z bosons and c-quark

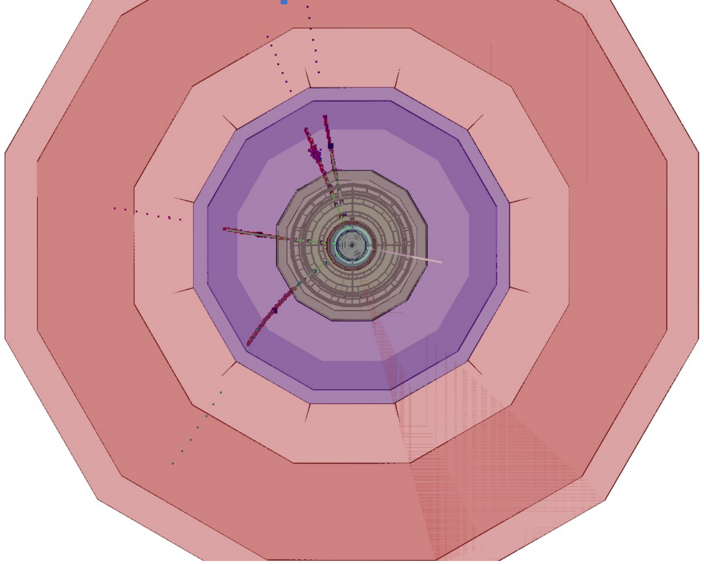
- $H \rightarrow ZZ^{*} \rightarrow 4\mu$ **(Master thesis, A. Zaza)**
- $\mathrm{H} \rightarrow c\bar{c}$**(Master thesis, P. Mastrapasqua)**

Supervisor: A. Colaleo

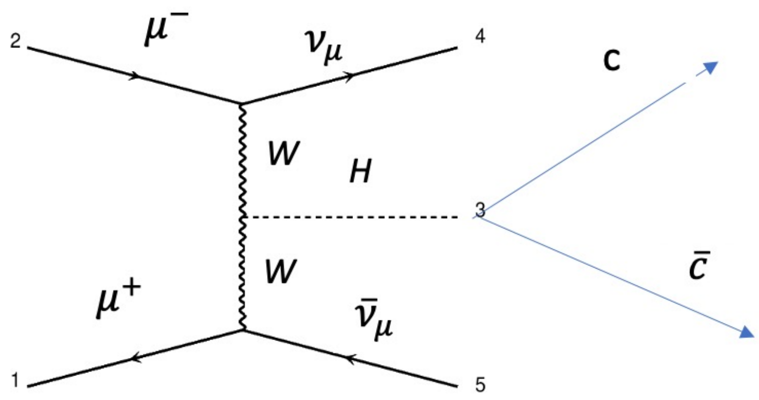
Co-supervisor: R. Venditti

Support: F. Errico

$H \rightarrow ZZ^{*} \rightarrow 4\mu$



$\mathrm{H} \rightarrow c\bar{c}$



$\mathrm{H} \to \mathrm{ZZ}^* \to 4\mu$ Signal and background

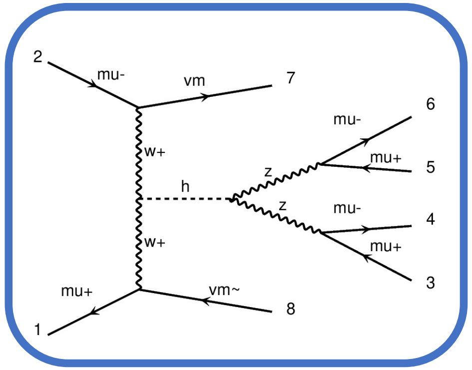
$\mathrm{H} \to \mathrm{ZZ}^* \to 4\mu$ is a standard candle in the Higgs sector:

- large signal/background ratio
- small yields $[\mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) = 2.62 \cdot 10^{-2}, \mathrm{BR}(\mathrm{Z} \to \mu^+\mu^-) = 3.37 \cdot 10^{-2}]$
- favored to measure the Higgs boson coupling to Z bosons at a muon collider.
- MC samples fully simulated with the latest geometry of the Muon Collider

➢ SIGNAL PROCESS:

$\mu^+\mu^- \to \mathrm{H}\nu_\mu\overline{\nu_\mu}$

$\hookrightarrow \mathrm{ZZ}^* \to 4\mu$



SIGNAL $H \to ZZ^* \to 4\mu$

$\sqrt{s}$ (TeV)	L (fb^{-1})	σ (fb)	Expected events
1.5	500	$9.14 \cdot 10^{-3}$	4.57
3.0	1300	$1.47 \cdot 10^{-2}$	19.16

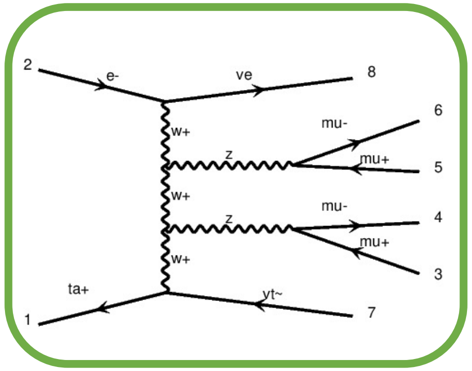
➢ SM IRREDUCIBLE BACKGROUND:

$\mu^+\mu^- \to 4\mu\ \nu_\mu\overline{\nu_\mu}$

$\sim$ 5000 Feynman diagrams

Selections applied at the generator level:

$p_T > 5\ GeV;\ \ |\eta| < 2.5;\ \ 10 < m_{\mu^+\mu^-} < 150\ GeV.$

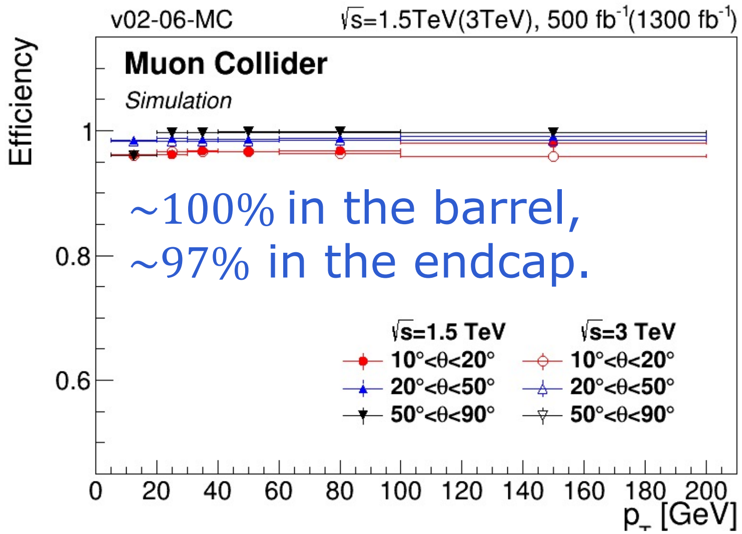


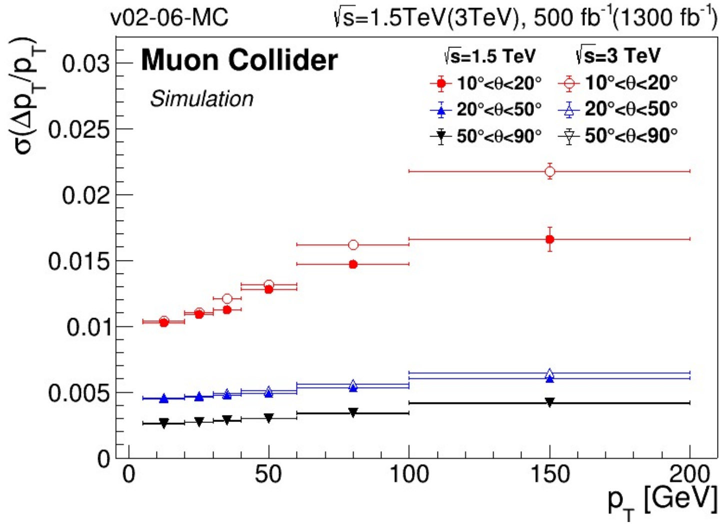
4μ-SM BACKGROUND

$\sqrt{s}$ (TeV)	L (fb^{-1})	σ (fb)	Expected events
1.5	500	$9.18 \cdot 10^{-3}$	4.59
3.0	1300	$1.79 \cdot 10^{-2}$	23.21

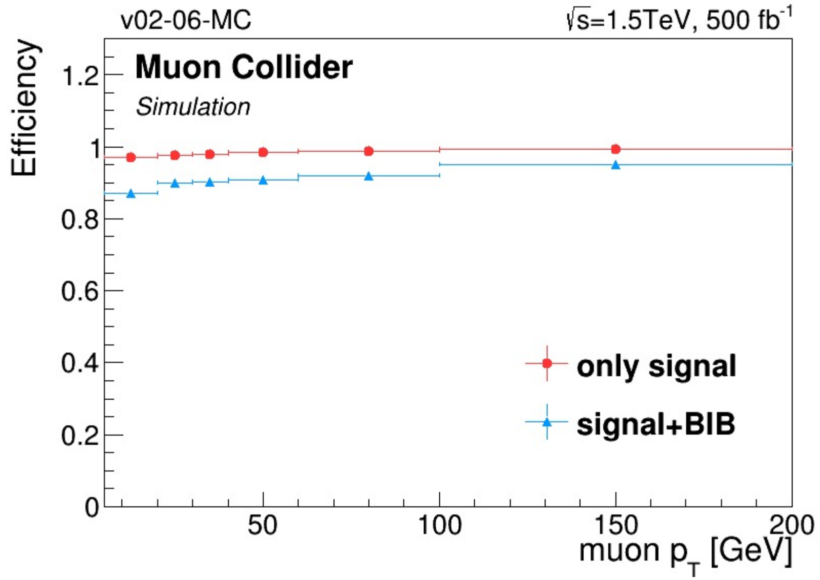
Muon reconstruction performance

- Track reconstruction based on conformal tracking
- Muons are reconstructed with a particle flow approach combining tracker tracks with hits in calorimeters and muon system





Estimation of the impact of the BIB: cone-filter for tracker hits to reduce the processing time.



- Tracking efficiency slightly reduced when including BIB **O(10%)** → mitigation strategy under development
- Results used for parametric evaluation of the BIB impact on the final results

$H \to ZZ^* \to 4\mu$ topological selection

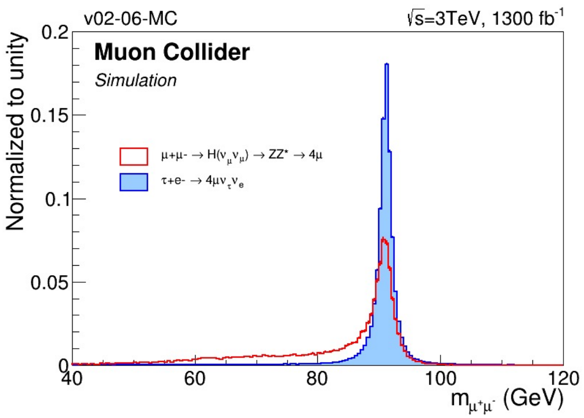
Good quality final state muons:
- $p_T > 5\ GeV$; $|\eta| < 2.5$;
- $D_0 < 2mm$; $Z_0 < 10mm$;

Z candidates:
OS muon pairs $12 < m_{\mu\mu} < 120\ GeV$.

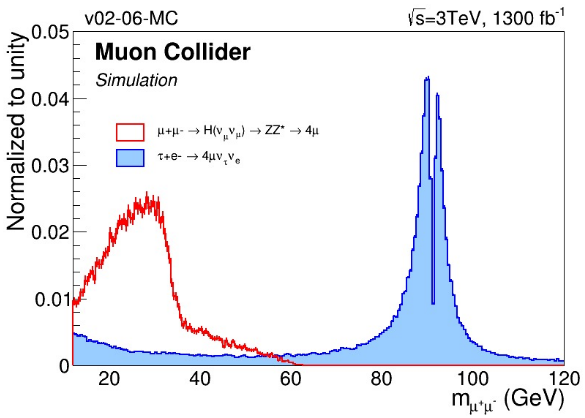
ZZ candidates: non-overlapping Zs
- Z_1: Z candidate with mass closest to the nominal value
- Z_2: other Z candidate

Selection of ZZ candidates:
- $\Delta R(\mu_i, \mu_j) > 0.02$
- $p_{T,\mu_i} > 20$ GeV
- $p_{T,\mu_j} > 10$ GeV
- Z_1 mass > 40 GeV
- $m_{4\mu} > 70$ GeV
- Arbitration based on Z1 mass

Z_1 reconstructed mass



Z_2 reconstructed mass



$\sqrt{s} = 1.5$ TeV

Signal		Background	
Events	Efficiency (%)	Events	Efficiency (%)
2.97±0.02	65.13±.21	3.93±0.01	85.77±0.01

$\sqrt{s} = 3$ TeV

Signal		Background	
Events	Efficiency (%)	Events	Efficiency (%)
10.77±0.06	56.19 ± 0.22	18.6 ±0.1	80.04 ±0.09

$H \to ZZ^* \to 4\mu$ Preliminary results

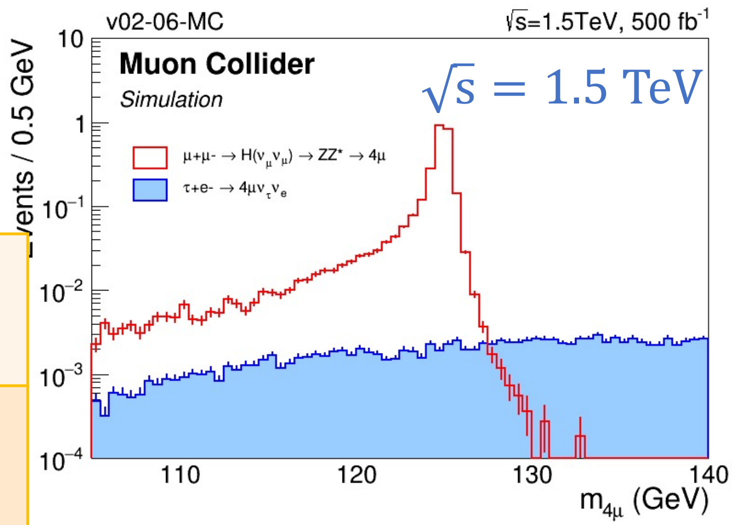
$$\sigma(\mu^+\mu^- \to H\nu\nu \to ZZ\nu\nu) = \sigma(\nu\nu H) \cdot BR(H \to XX) = \frac{g^2_{HWW}\, g^2_{HXX}}{\Gamma_H}$$

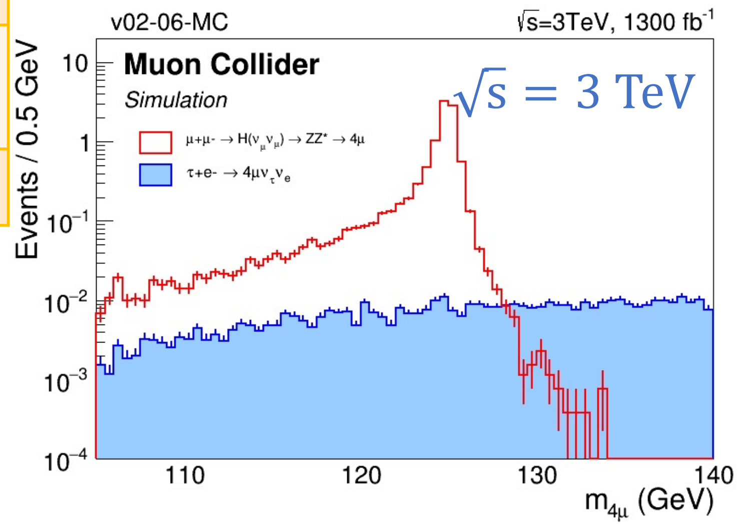
Relative uncertainty on the *HXX* coupling (X any SM particle)

$$\frac{\Delta g_{Hxx}}{g_{Hxx}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g^2_{HWW}}{\Gamma_H}}{\frac{g^2_{HWW}}{\Gamma_H}}\right)^2}$$

	$\sqrt{s} = 1.5$ TeV L=500fb^{-1}			$\sqrt{s} = 3$ TeV L=1300fb^{-1}		
Results	Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$	Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$
Without BIB	3.65	60	**30**	6.91	32	**16**
With BIB	3.08	71	**36**	5.85	37	**19**

- Results can be improved by a factor 2 including all the leptonic channels (assuming same efficiencies)
- Further improvement: inclusions of the fully hadronic final states





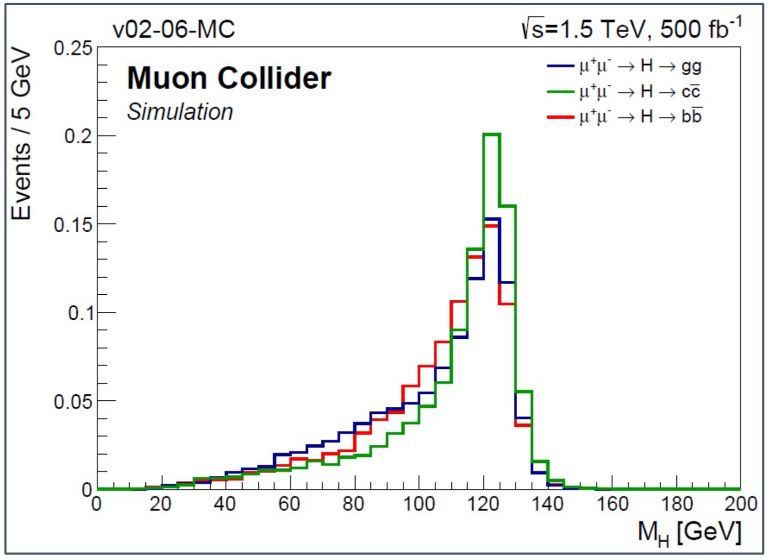
H-to-c-quark coupling at Muon Collider

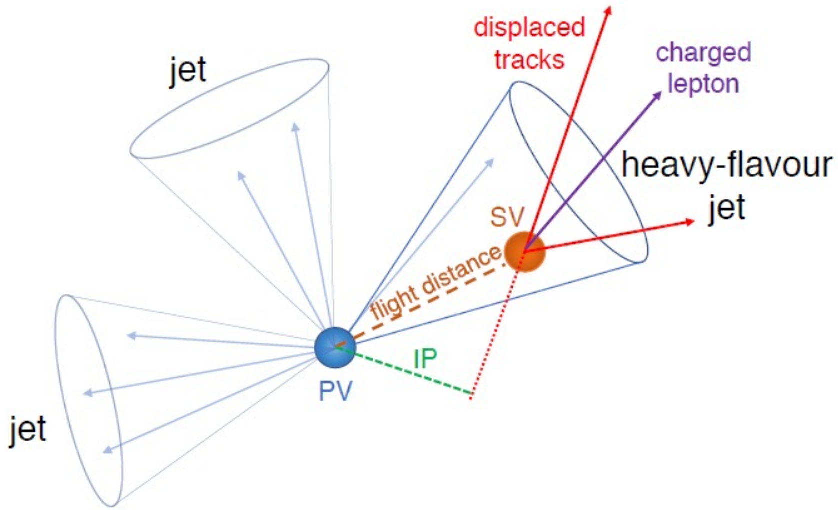
	physics process	σ (fb)	generator
c-jet samples	$\mu^+\mu^- \to H\nu\bar{\nu} \to c\bar{c}\ \nu\bar{\nu}$	8.9	pythia
	$\mu^+\mu^- \to c\bar{c}\ 2leptons$	399	madgraph
b-jet samples	$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\ \nu\bar{\nu}$	180	pythia
	$\mu^+\mu^- \to b\bar{b}\ 2leptons$	508	madgraph
light-flavour-jet samples	$\mu^+\mu^- \to H\nu\bar{\nu} \to gg\ \nu\bar{\nu}$	26.4	pythia
	$\mu^+\mu^- \to 2light\ 2leptons$	2.8 . le6	madgraph

$H \to gg$, $H \to c\bar{c}$, $H \to b\bar{b}$

are kinematically indistinguishable.

- Dedicated tagger to discriminate c jets from b and light-flavour ones.
- Heavy-flavour hadron characteristics:
  1. **Secondary vertices (SV)**
  2. **Displaced tracks**
  3. **Low-energy non isolated leptons**

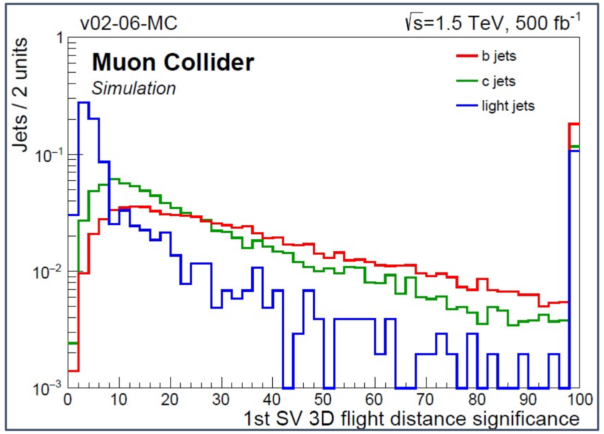




C-jet tagging algorithm: the variables

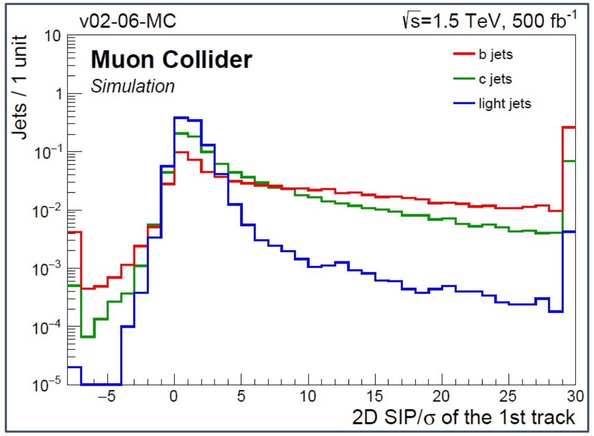
- Vertex category
- Number of SV, Number of tracks from SV
- 2D and 3D SV flight distance significance
- Corrected mass, Mass-energy fraction
- SV Boost, Energy ratio , ΔR (SV, jet-axis)

Vertex variables



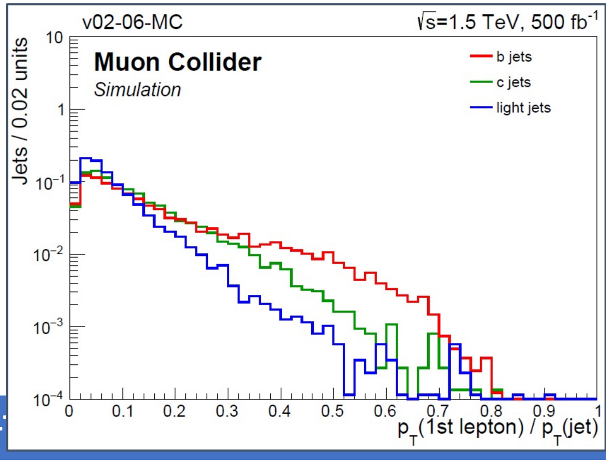
- 2D, 3D signed impact parameter (SIP) significance
- Number of tracks in jet
- ΔR (track, jet-axis) ,ΔR (Σ tracks, jet-axis)
- 2D, 3D SIP significance of the first track above invariant mass threshold
- $p_{L-jaxis}$ and $p_{L-jaxis}/p$, $p_{T-jaxis}$ and $p_{T-jaxis}/p, E_T$ (Σtracks) / E_T (jet)

Track variables

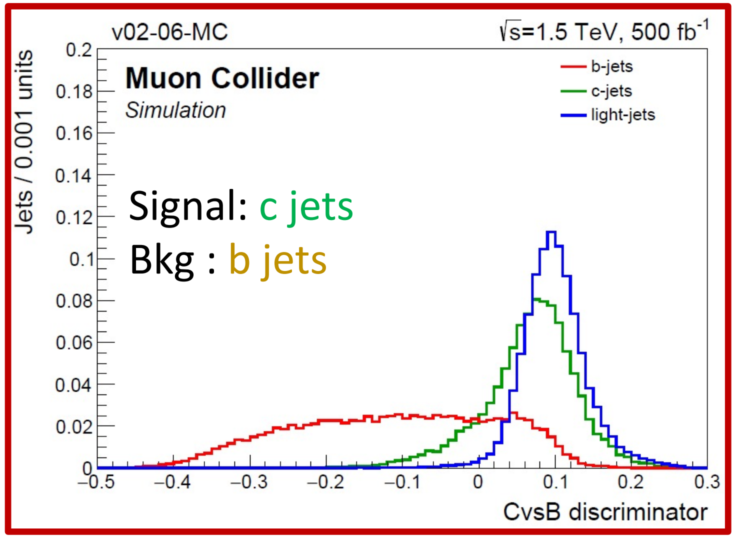


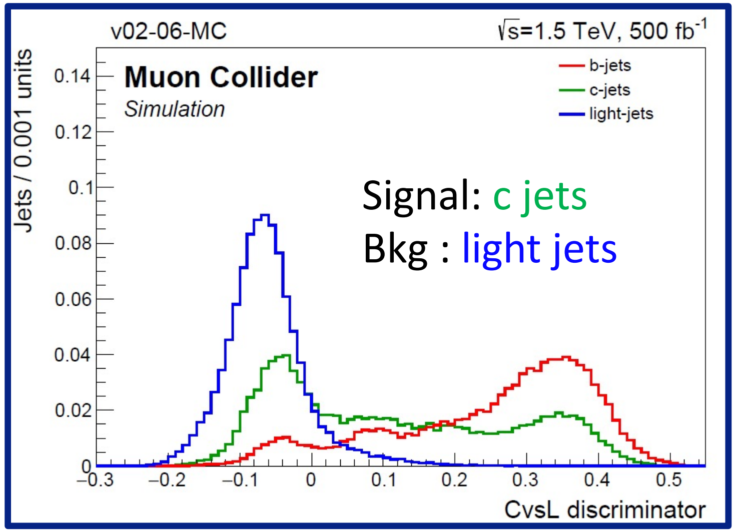
- Lepton category
- $\mathrm{p_T}/\mathrm{p_T}(\mathrm{jet})$
- $p_{T-jaxis}$, $p_{L-jaxis}/p(\mathrm{jet})$

Lepton variables



C-jet tagging algorithm



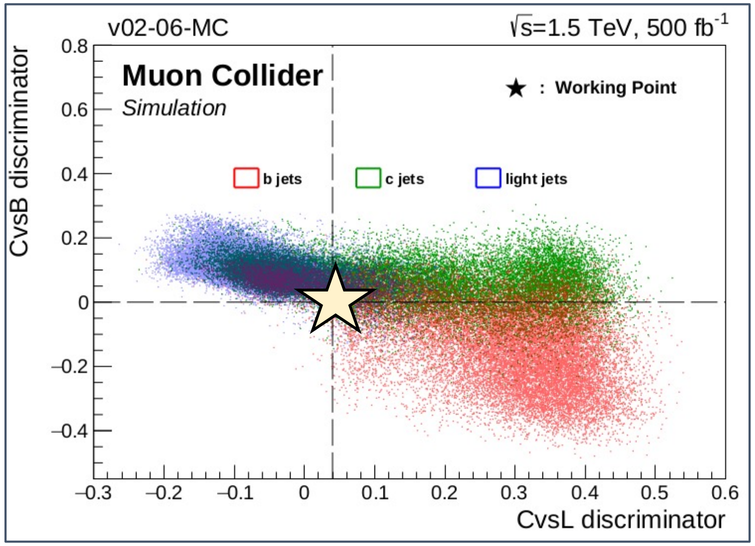


The variables are combined in a single Boosted Decision Tree.

Two independent taggers :

- CvsB : separate c-jets from b-jets
- CvsL : separate c-jets from light flavor

	b misid. probability			light misid. probability		
c-tag eff.	MuColl (w/o BIB)	CMS	CLIC (w/o overlay)	MuColl (w/o BIB)	CMS	CLIC (w/o overlay)
50%	7.5%	11%	7%	2.3%	14 %	3 %
60%	10%	14%	11%	6.3%	25 %	6 %
70%	14%	20%	15%	16%	40 %	12 %
80%	19%	26%	23%	31%	55 %	25 %
90%	28%	40%	32%	55%	75 %	52 %



$(CvsL, CvsB)$	c efficiency	b contamination	$light-flav.$ contamination
(0.04, 0.00)	**40 %**	**13 %**	**5 %**

H → $c\bar{c}$ preliminary results

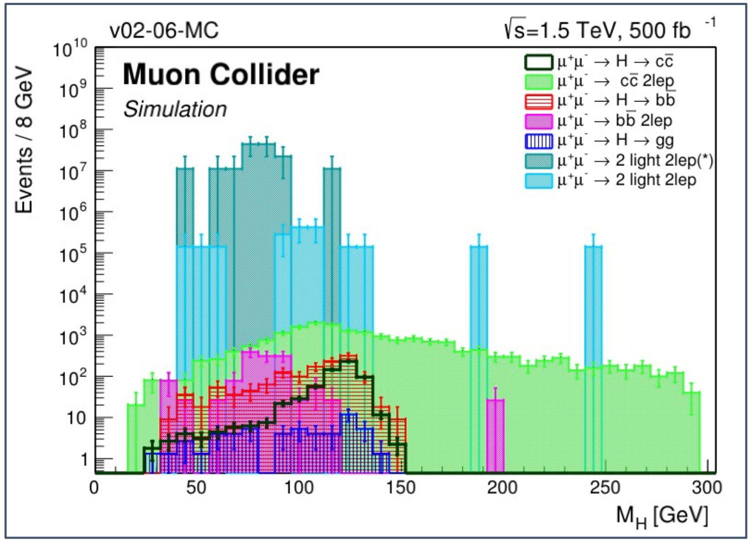
- After flavor tagging, Higgs candidates are built using the two highest pT jets and further topological selections are applied
- $E_H > 130$ GeV, $pT_H > 30$ GeV
- $\Delta R(j_1, j_2) < 3$, $m_H \in [110,130]$ GeV

$\sqrt{s}$ = 1.5 TeV, 500 fb^{-1} (no BIB overlay)		
$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
9.5	10.5 %	**5.5 %**

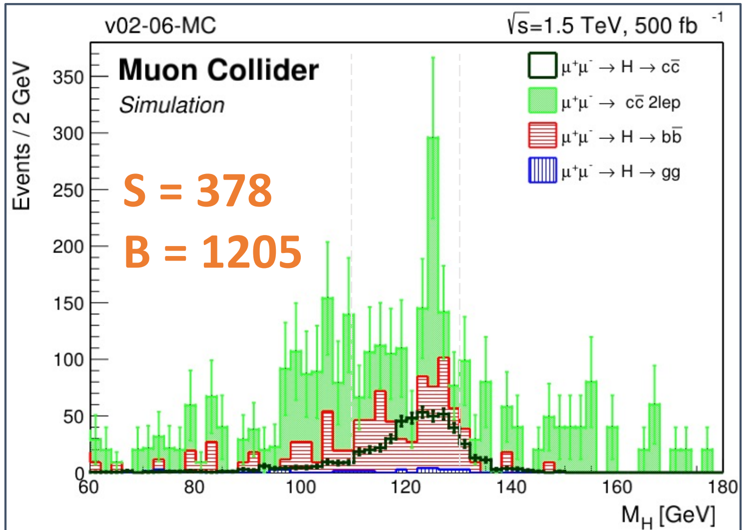
Projection at $\sqrt{s}$ = 3 TeV, 1300 fb^{-1} (assuming same selection efficiencies)		
$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
20.4	4.9 %	**2.6 %**

CLIC: 350 GeV, 500 fb^{-1}: **6.2** % precision
CLIC: 1.4 TeV, 1500 fb^{-1}: **2.3** % precision

Before topological selections



After topological selections



Summary

- **The Muon Collider is the dream machine for Higgs Physics and beyond**
- So far measured Higgs couplings with full simulation/extrapolations ($\sqrt{s}$=3 TeV):
  - **Hbb: 1% (published result)**
  - **Hcc: 2.3%**
  - **HZZ: 8%** (only electron and muon final states)

- Precision improves with increasing energy → Muon Collider has the potential to reach higher energy wrt electron-based colliders.

Goal for next year:

- Inclusion of the BIB and impact on the final results
- Re-optimize analysis strategy for both Hcc and HZZ
- Optimize muon and jet reconstruction (next slide)

Perspectives and future challenges

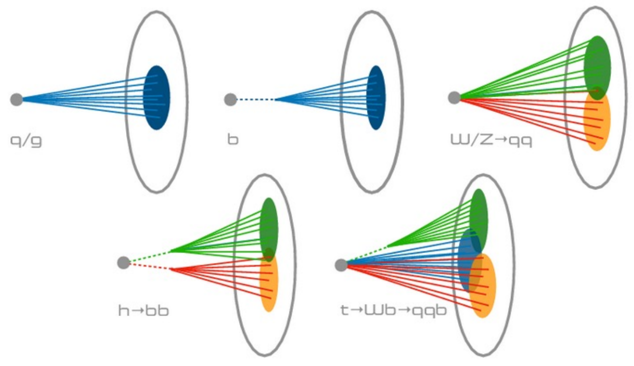
The reconstruction of final states leptons and jets play a crucial role.

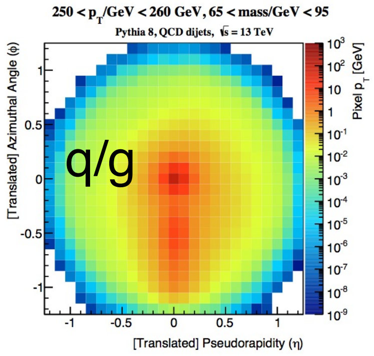
- Efficient vertexing and tracking rely on **high granular tracker**
- Reliable jet reconstruction limited by the **calorimeters**
- **Muon tagging** is crucial and muon stations are not yet fully exploited

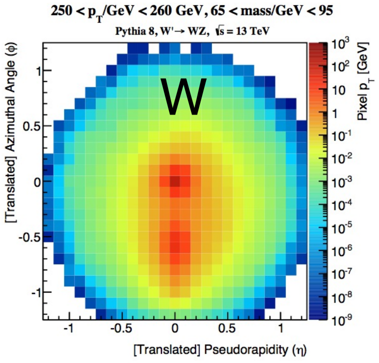
Physics channel will drive the detector design

- Presently, just the Higgs sector has been considered
- Near future: keep going in the Higgs sector and exploring BSM multi-TeV signature

- BSM signatures/Going up with COM energies poses new challenges → e.g. merging final state jet in a single fat jet
  - Jet substructure and flavor tagging relies on information created at one spatial location during the decay of the original particle.
  - Detector design should be optimized accordingly

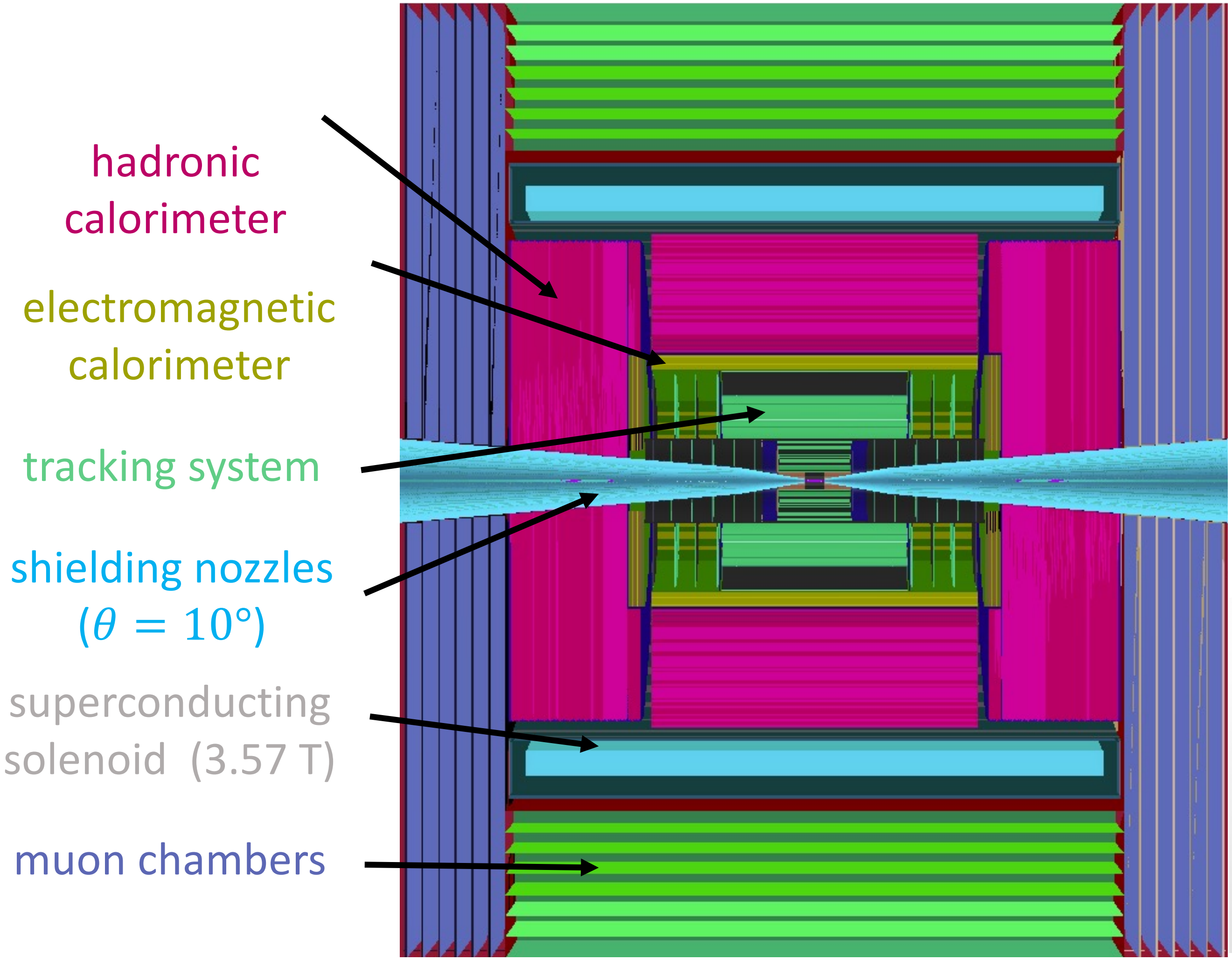






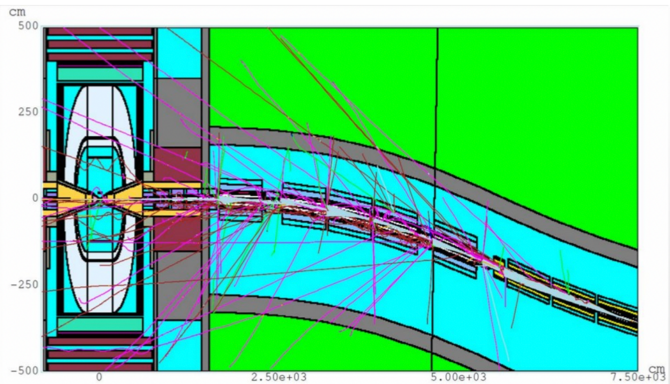
Backup

The Muon Collider experiment and challenges



Main challenges:

- **Muon production**
- **Beam-Induced Background (BIB)**: Decays of circulating beam muons into electrons, positrons and neutrinos→interactions with the machine → production of secondary particles



Jet reconstruction

- Complex task: **tracker info** + **energy deposits in calorimeters**
- Particle reconstruction is performed through Pandora Particle Flow (PF) algorithm → improve the jet energy resolution.
- Output of PF is used for jet clustering: k_T algorithm with radius parameter R = 1.0.