Higgs physics at a muon collider

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on behalf of the International Muon Collider Collaboration

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Why a muon collider

	Advantages	Disadvantages
e^+e^- colliders	All the center of mass energy available in the hard collision, no pile-up	Large synchrotron radiation losses
Hadron colliders	Low synchrotron radiation losses	Unknown fraction of E_{CM} available to colliding partons, pile-up from QCD events

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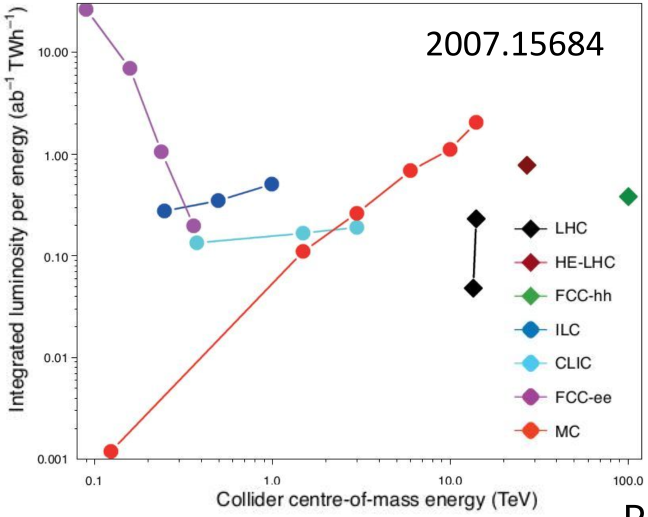
Muon collider has advantages from both e^+e^- and hadron colliders:

- Clean collisions as in e^+e^- colliders and energy frontier as in hadron colliders

Problem: Beam Induced Background (BIB)

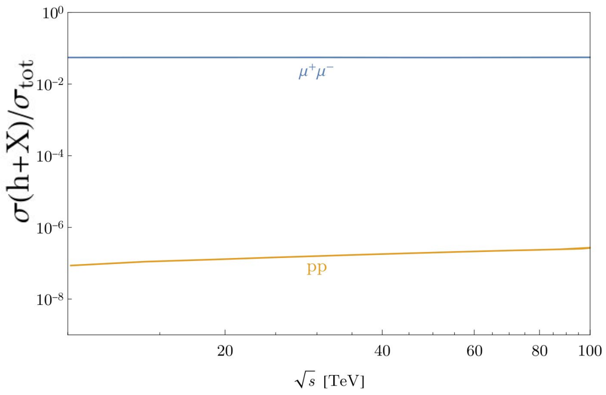
- It is produced by the decay in flight of muons in circulating beams, and subsequent interactions

Features of a muon collider

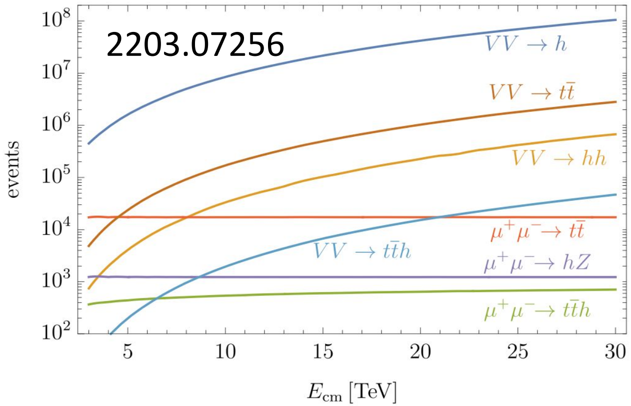


Highest energy efficiency above ~2TeV

Inclusive Higgs cross section over total cross section



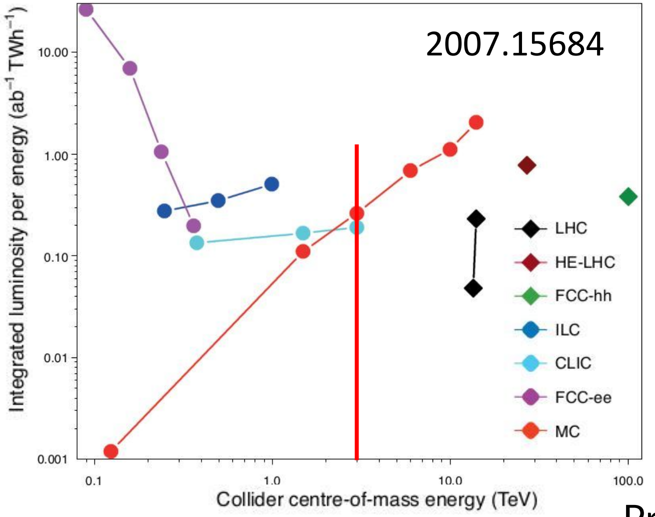
Produced events increase with E_{CM} (increase in luminosity considered)



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

Luminosity increasing as $E_{CM}{}^2$
5 years, 1 experiment

Features of a muon collider



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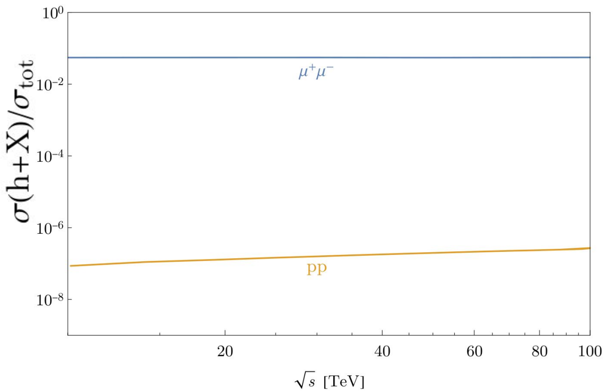
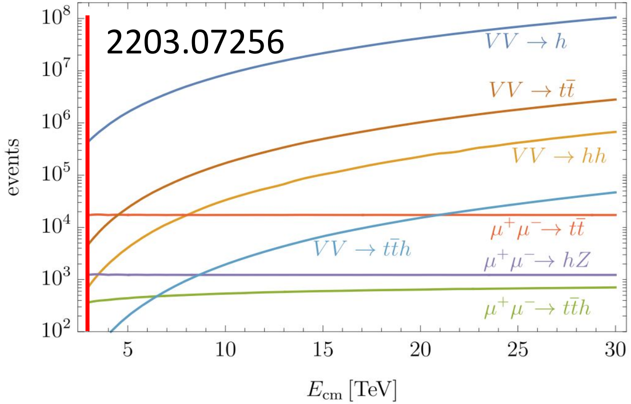


Produced events increase with E_{CM} (increase in luminosity considered)



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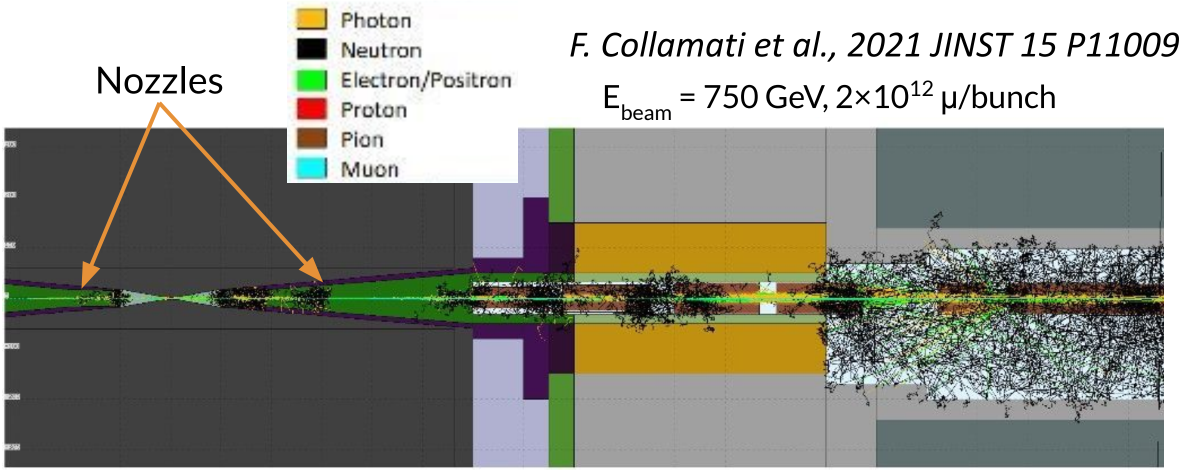
14 TeV	20 ab^{-1}

Luminosity increasing as E_{CM}^2
5 years, 1 experiment

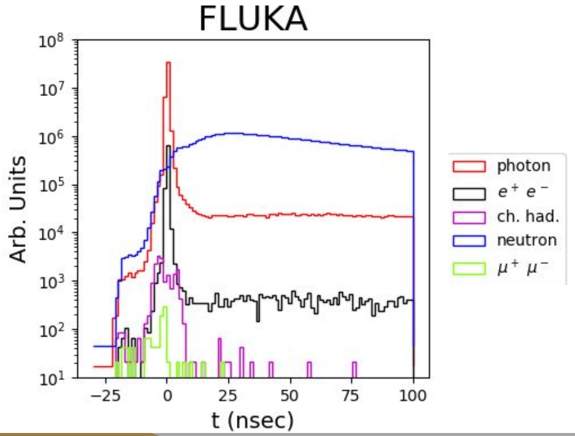
Features of a muon collider

- BIB produced mainly by decays of muons in circulating bunches, and subsequent interactions of decay products with surrounding material
  - **O(10^8)** BIB particles enter the detector at each bunch crossing
- Mitigated by the Machine Detector Interface (MDI): two nozzles made of tungsten and borated polyethylene
- Most BIB particles are out of time with respect to bunch crossing
- Current MDI optimized for 1.5 TeV muon collider
  - Preliminary studies on 3 TeV BIB shows that it's similar to the 1.5 TeV one



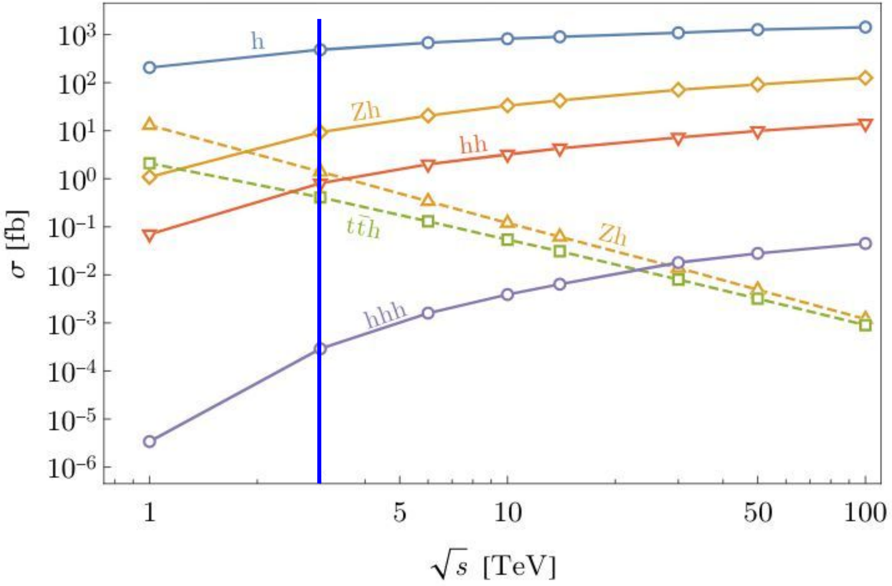
F. Collamati et al., 2021 JINST 15 P11009

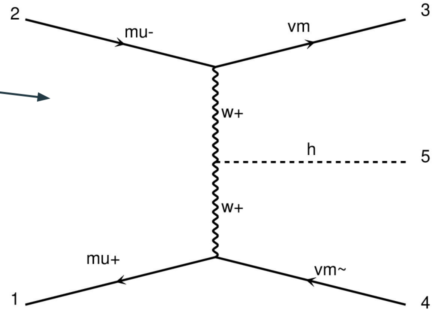
E_{beam} = 750 GeV, 2×10^{12} μ/bunch

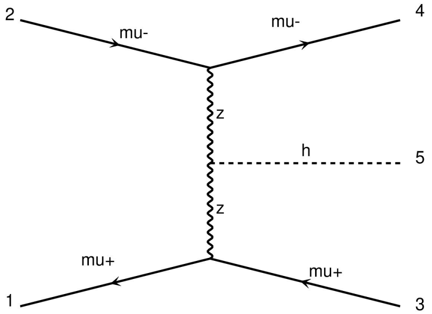


Higgs at a muon collider

- At multi-TeV energy, Higgs mainly produced by Vector Boson Fusion (VBF)
- **~500k** events expected with **1 ab^{-1} @ 3 TeV**
- **Higgs physics studies at 3 TeV** presented in this talk
  - 1.5 TeV BIB included



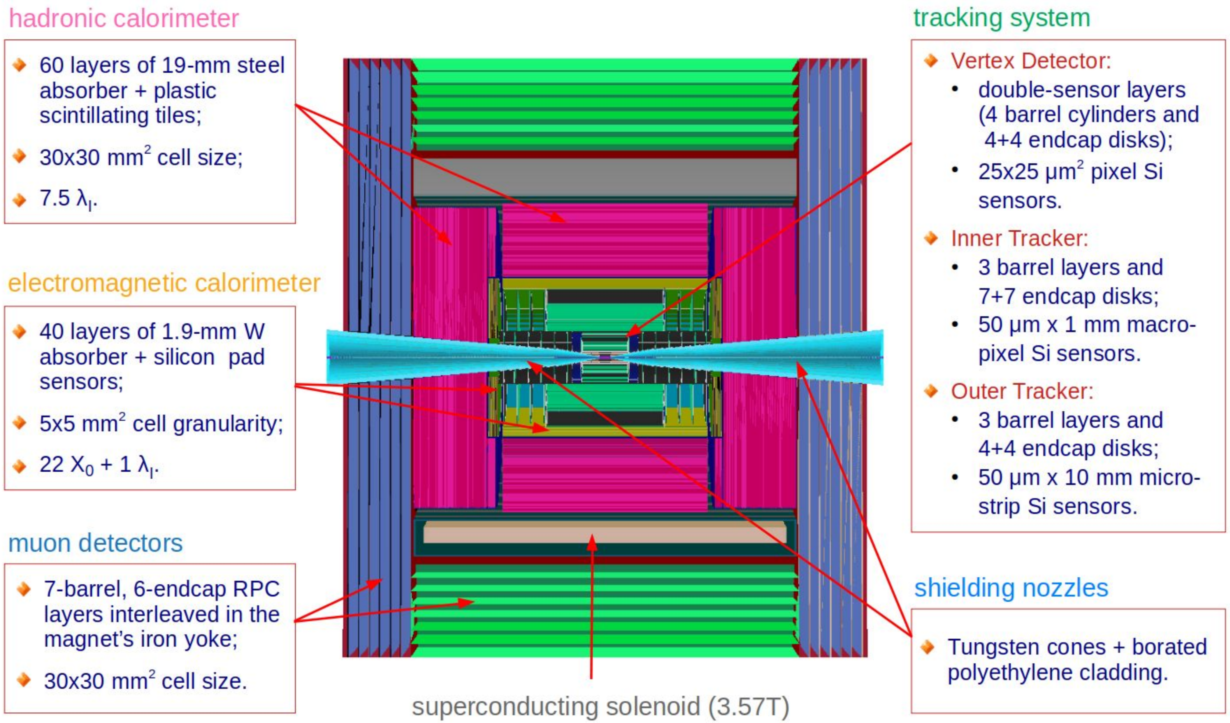




The muons Smasher's guide, Rept.Prog.Phys. 85 (2022) 8, 084201

3 TeV Muon Collider Detector

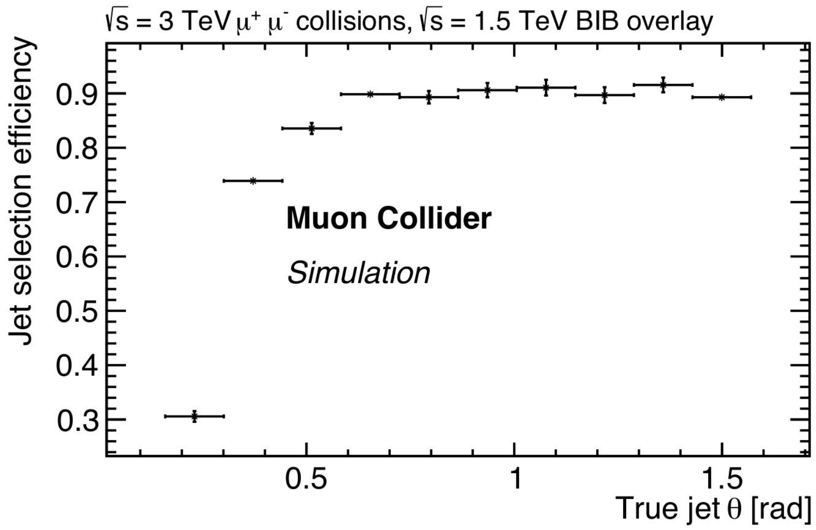
- High hit multiplicity in tracking system due to BIB particles -> combinatorial problems
- Diffuse BIB background in calorimeters
- High hit multiplicity in the forward region of muon detectors
- Nozzles are fundamental to mitigate BIB, but also reduce acceptance

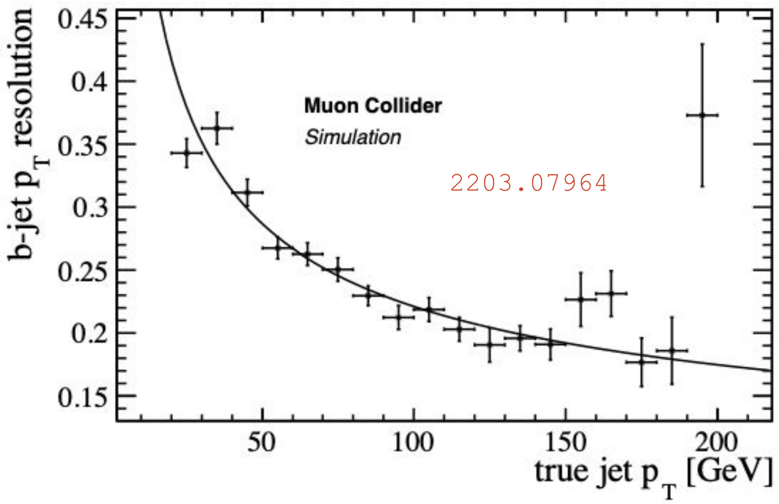


https://confluence.infn.it/display/muoncollider/Muon+Collider+Detector

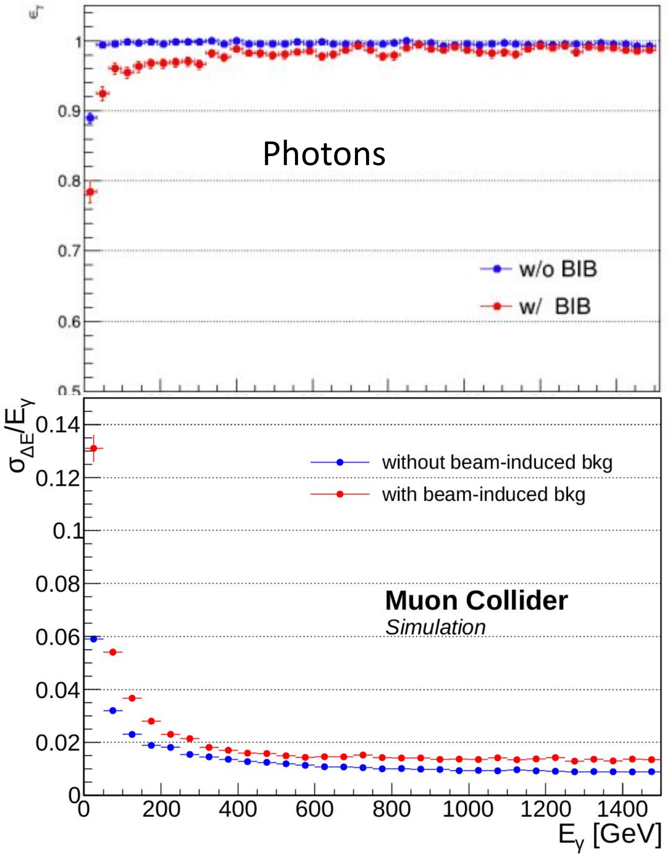
Physics object reconstruction

- Particles reconstructed from tracking and calorimeter informations, clustered with $k_T(\Delta R=0.5)$ to make jets
  - Requirement on number of hits in each track applied in track selections
  - Large threshold (2 MeV) applied to calorimeter hits
  - Timing cuts on tracking and calo hits
  - Further suppress fake jets with a requirement on the number of tracks ($N_{trk} > 0$)





Physics object reconstruction



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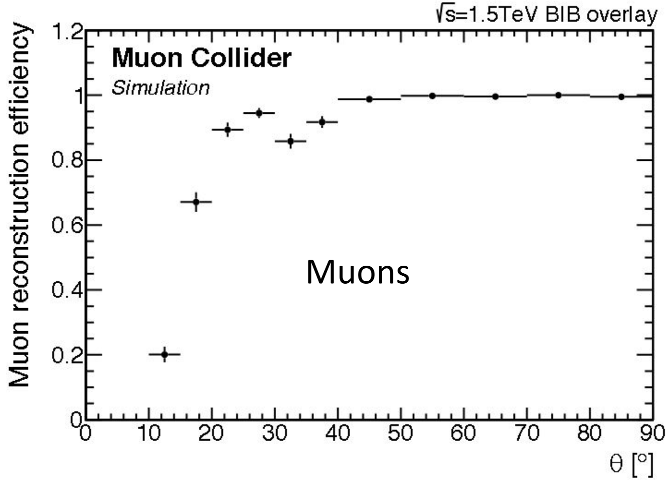
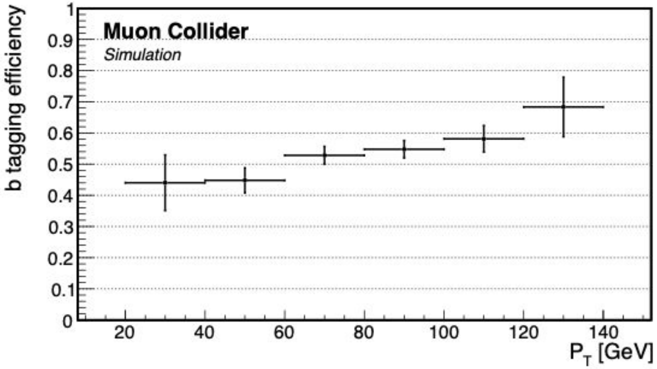
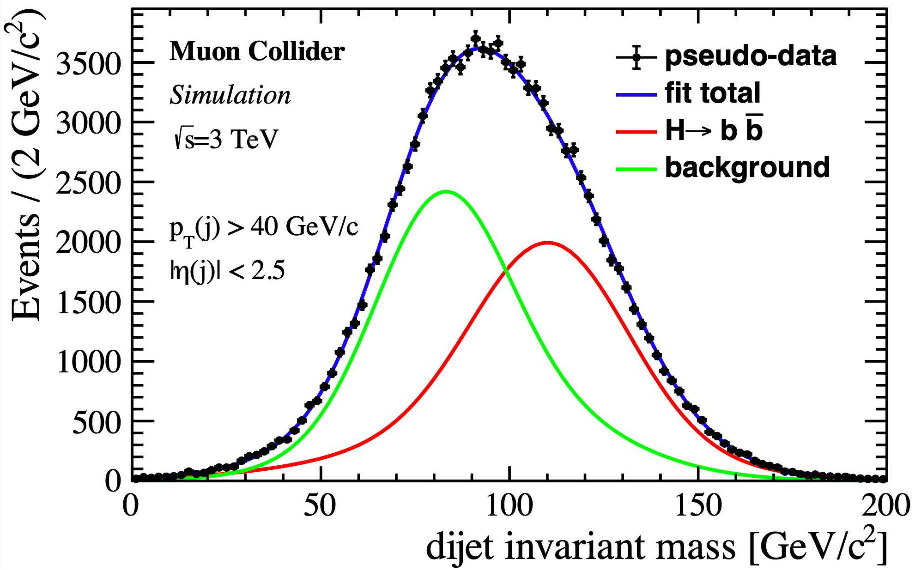




$\sigma(\mu^+\mu^- \to H\nu\nu) \times BR(H \to bb)$

- Signal μμ->(H->bb)X and background μμ->qqX (q=b,c) generated with Whizard+Pythia8
  - Background mainly from Z->bb and Z->cc
- Two jets with a Secondary Vertex tag are required. Background from light jets considered negligible
- S= 59 500, B=65 400 in 1 ab^{-1}
- Signal yield from template fit to pseudo-experiments using invariant mass
- Statistical relative uncertainty on σ x BR = 0.75%



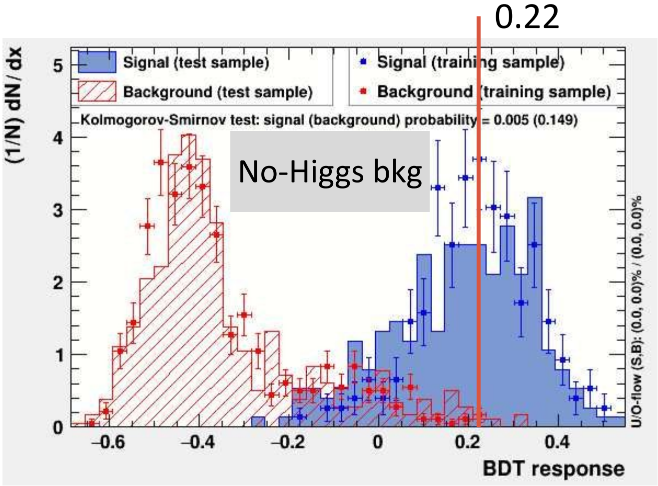
http://hdl.handle.net/20.500.12608/3238

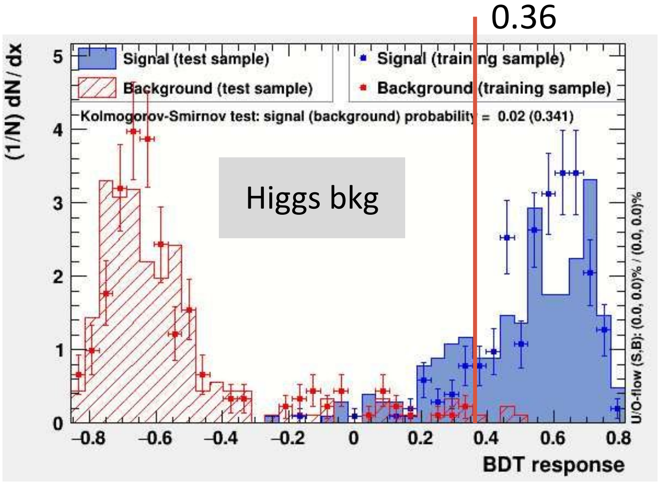
σ(μ⁺μ⁻->Hνν)×BR(H->WW*)

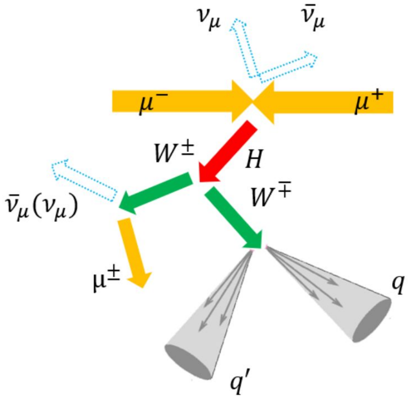
- 1 Muon + 2 jets final state
- Signal and backgrounds (with and without Higgs) simulated with Whizard+Pythia8
- Cuts on two BDTs to select signal vs backgrounds
- S=2 430, B=2 600 in 1 ab^{-1}

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

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow \mathbf{2.9\%}$$

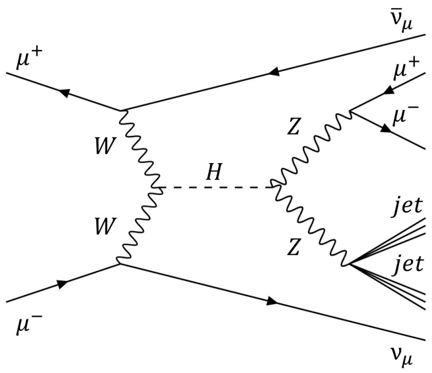




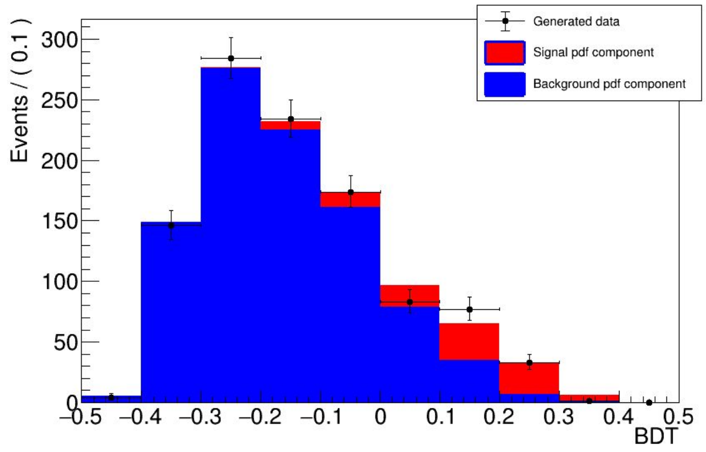


http://hdl.handle.net/20.500.12608/28559

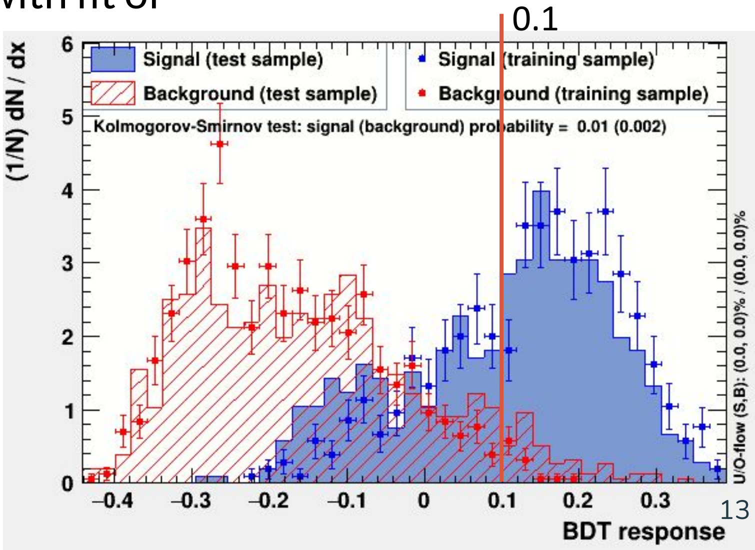
$\sigma(\mu^+\mu^- \to H\nu\nu) \times BR(H \to ZZ^*)$



- 2 muons + 2 jets final state
- Signal generated with MG5+Pythia8, while inclusive $\mu^+\mu^-$ -> νν $\mu^+\mu^-$ jj background (excluding signal) is generated with Whizard+Pythia8
- BDT used to select signal vs background
- Resolution obtained with cut-based approach and with fit of BDTs, giving the same result

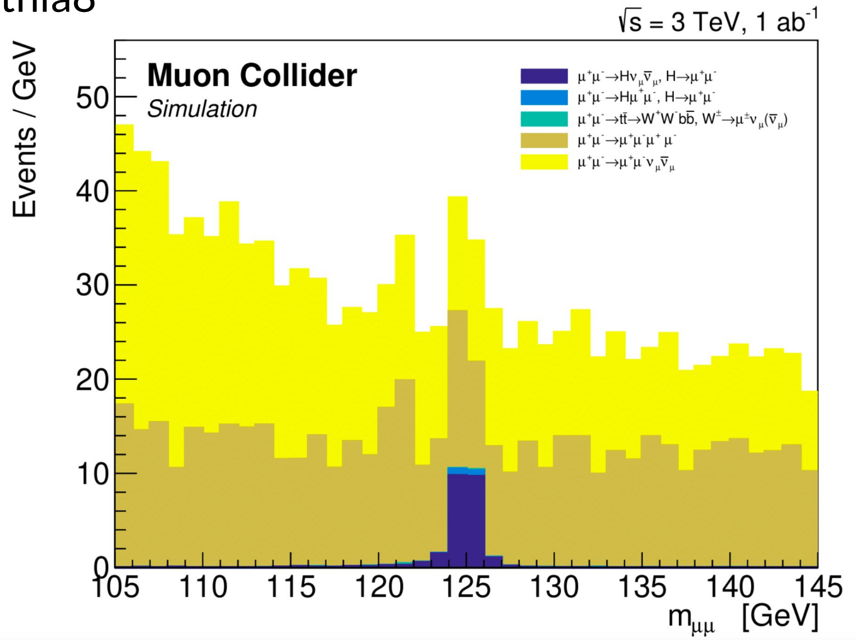


$$\frac{\Delta\sigma}{\sigma} = \mathbf{17\%}$$



$\sigma(\mu^+\mu^- \rightarrow H\nu\nu) \times BR(H \rightarrow \mu^+\mu^-)$

- Signal and backgrounds generated with MG5+Pythia8
- BIB not used (low impact in muon chambers)
- $10° < \theta_\mu < 170°$, $p_T^\mu > 5$ GeV: reject hits from BIB
- Selection cuts on two BDTs trained to discriminate signal from the backgrounds
- Uncertainty on signal yield obtained from unbinned maximum likelihood fit to dimuon invariant mass



Process $105 < m_{\mu\mu} < 145$ GeV	Expected events with 1 ab^{-1}
[l]$\mu^+\mu^- \rightarrow H\nu_\mu\bar{\nu}_\mu$, $H \rightarrow \mu^+\mu^-$	24.2
[l]$\mu^+\mu^- \rightarrow H\mu^+\mu^-$, $H \rightarrow \mu^+\mu^-$	1.6
$\mu^+\mu^- \rightarrow \mu^+\mu^-\nu\bar{\nu}_\mu$	636.5
$\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$	476.4
[tl]$\mu^+\mu^- \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}$, $W^\pm \rightarrow \mu^\pm\nu_\mu(\bar{\nu}_\mu)$	1.1

Relative uncertainty on **σ = 38%**

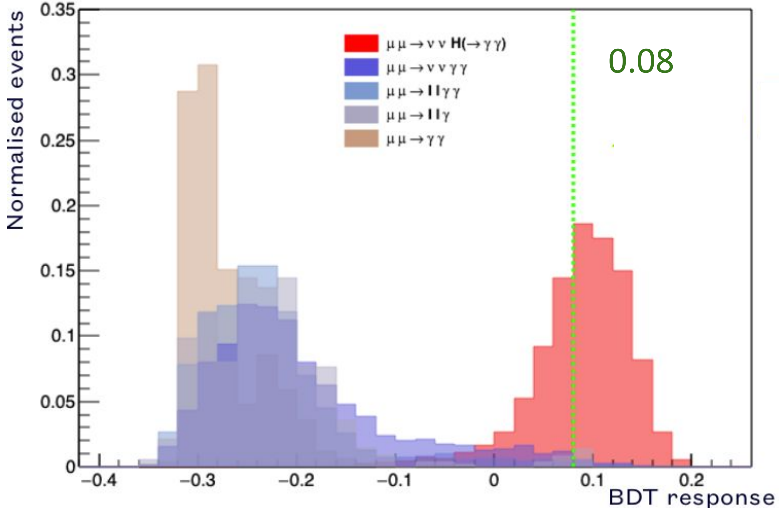
https://doi.org/10.22323/1.398.0579

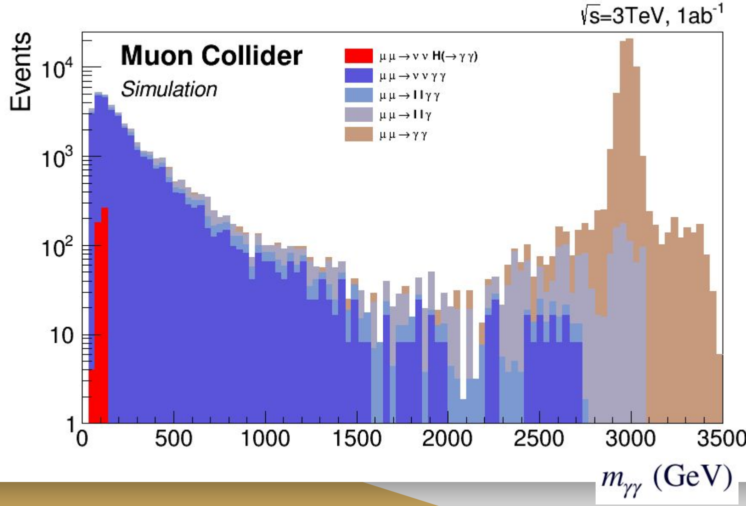
$\sigma(\mu^+\mu^- \to H\nu\nu)\times BR(H \to \gamma\gamma)$

- Signal and backgrounds generated with MG5+Pythia8
- Preliminary result: **No BIB at the moment** and some minor bkg still missing
- Used a BDT to perform signal vs. background separation
- Cut on BDT output to maximize S/√(S+B)

Process	σ (fb)	Events
$\mu\mu \to H\nu\nu, H \to \gamma\gamma$	0.9025 ± 0.0026	707
$\mu\mu \to \nu\nu\gamma\gamma$	81.98 ± 0.27	30168
$\mu\mu \to ll\gamma\gamma$	4.419 ± 0.016	2678
$\mu\mu \to ll\gamma$	159.0 ± 0.6	4738
$\mu\mu \to \gamma\gamma$	60.15 ± 0.03	59933

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow \mathbf{8.9\%}$$

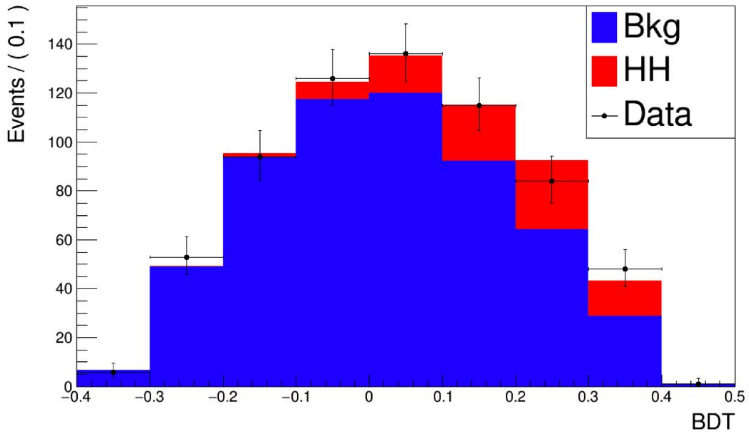




$\sigma(\mu^+\mu^- \to HH\nu\nu) \times BR(H \to bb)^2$

- Signal and backgrounds (H+bb and 4b) generated with Whizard+Pythia8
- Simulation performed without BIB but b-tagging efficiency in the presence of BIB is used to weight events
- Selection requirements:
  - 4 jets, at least 3 of them with p_T > 20 GeV, and at least 2 must contain a secondary vertex
  - Jet paired to minimize $$M = \sqrt{(m_{ij} - m_H)^2 + (m_{kl} - m_H)^2}$$
  - S = 50, B = 432 in 1 ab^{-1}
- BDT trained for sig-vs-bkg discrimination, fit on BDT output to find resolution
  - **Δσ/σ of 30%** is found

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



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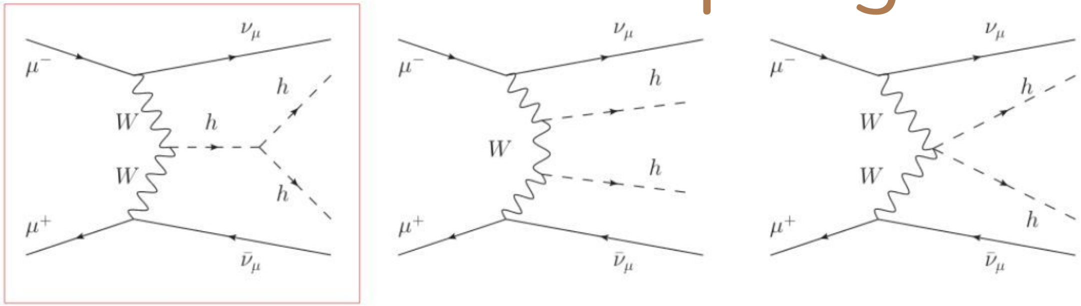
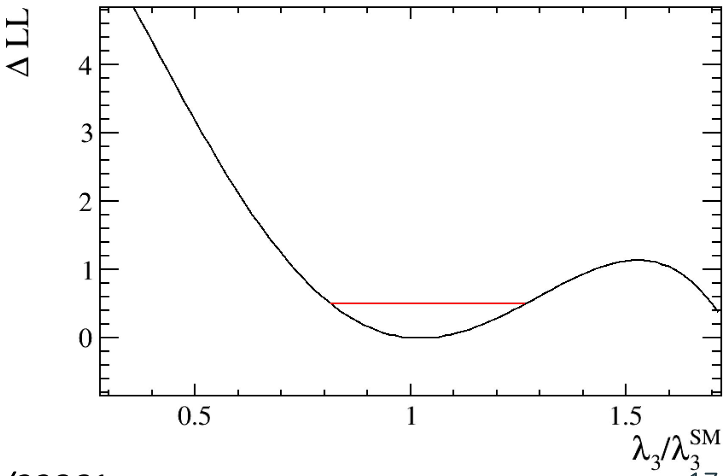
Trilinear coupling



- Generation (WHIZARD) and simulation of HH from trilinear coupling only
- Two MLPs are used: HH vs 4b and HH from trilinear only vs total HH
- Simulated HH events with different λ_3 hypothesis, resolution on λ_3 obtained from a likelihood scan
  - Stat. uncertainty of ~**20% @ 68% CL** is found



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Comparison with CLIC

Measurement	Statistical precision	
	1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	0.4%	0.3%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	38%	25%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$	15%	10%*
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	1.0%	0.7%*
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	5.6%	3.9%*

Measurement	Statistical precision 350 GeV 500 fb^{-1}
$\sigma(ZH) \times BR(H \to b\bar{b})$	0.86%
$\sigma(ZH) \times BR(H \to WW^*)$	5.1%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	1.9%

$$\frac{\Delta[\sigma(HH\nu_e\bar{\nu}_e)]}{\sigma(HH\nu_e\bar{\nu}_e)} = 44\% \text{ at } 1.4\,\text{TeV}, \; 20\% \text{ at } 3\,\text{TeV}$$

$$\Delta\lambda/\lambda = 54\% \text{ at } \sqrt{s} = 1.4\,\text{TeV}, \; 29\% \text{ at } \sqrt{s} = 3\,\text{TeV}$$

Muon Collider 1 ab^{-1} @ 3 TeV	
H->WW	2.9%
H->ZZ	17%
H->bb	0.75%
H->μμ	38%
H->γγ	8.9%
HH->4b	30%
λ_3	20%

Differences:
H->bb from combined measurement of hadronic Higgs decays
H->ZZ* with llqq final state, and l = {e, μ, τ}
H->WW* with qqqq and llqq final state, and l = {e, μ}

Higgs physics at the CLIC electron–positron linear collider, Eur. Phys. J. C (2017) 77:475

Comparison with FCC-ee

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \rightarrow b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \rightarrow W^+W^-$	±1.2		±2.6	±3.0
$H \rightarrow ZZ$	±4.4		±12	±10
$H \rightarrow \gamma\gamma$	±9.0		±18	±22
$H \rightarrow \mu^+\mu^-$	±19		±40	

Muon Collider 1 ab^{-1} @ 3 TeV	
H->WW	2.9%
H->ZZ	17%
H->bb	0.75%
H->μμ	38%
H->γγ	8.9%
HH->4b	30%
λ_3	20%

Sensitivity on trilinear coupling λ: 42% in global (Higgs+EW) fit, 12% when alone

Future Circular Collider Study, Volume 2 - The Lepton Collider (FCC-ee)

Conclusions

- The Muon Collider is very different from electron-positron and hadron colliders, with new very interesting features
- Muons in beams decay and produce BIB. Full simulation is essential to evaluate the impact of the BIB on physics measurements and understand how to deal with it
- A huge effort is on-going to design the MDI, the detector and the reconstruction algorithms
- This talk demonstrates that Higgs physics at Muon Collider is possible, by using a detailed simulation of the experiment

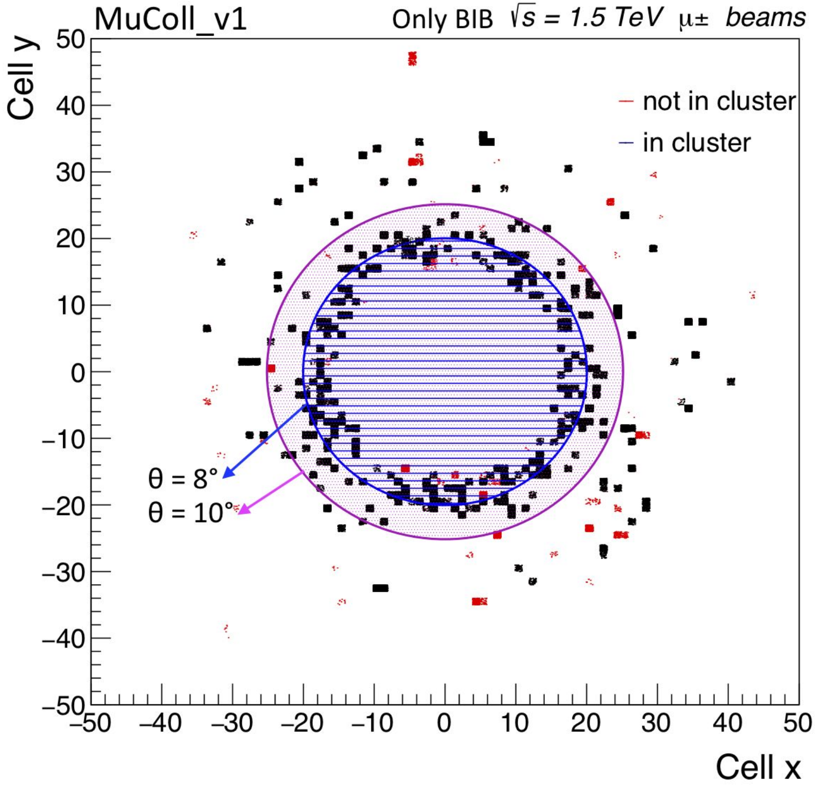
Comparison with fast sim studies

Full sim		Fast sim	
H->WW	2.9%	H->WW	1.7%
H->ZZ	17%	H->ZZ	11%
H->bb	0.75%	H->bb	0.76%
H->μμ	38%	H->μμ	40%
H->γγ	8.9%	H->γγ	6.1%
HH->4b	30%		
λ_3	20%	λ_3 (95% CL)	25%

Differences:
H->bb from combined measurement of hadronic Higgs decays
H->ZZ* with llqq final state, and l = {e, μ, τ}
H->WW* with qqqq and llqq final state, and l = {e, μ}

- *High precision Higgs from high energy muon colliders*, JHEP **08** (2022), 185
- *Electroweak couplings of the Higgs boson at a multi-TeV muon collider*, Phys.Rev.D 103 (2021) 1, 013002

BIB in muon chambers



First layer endcap

Effects of nozzles on BIB

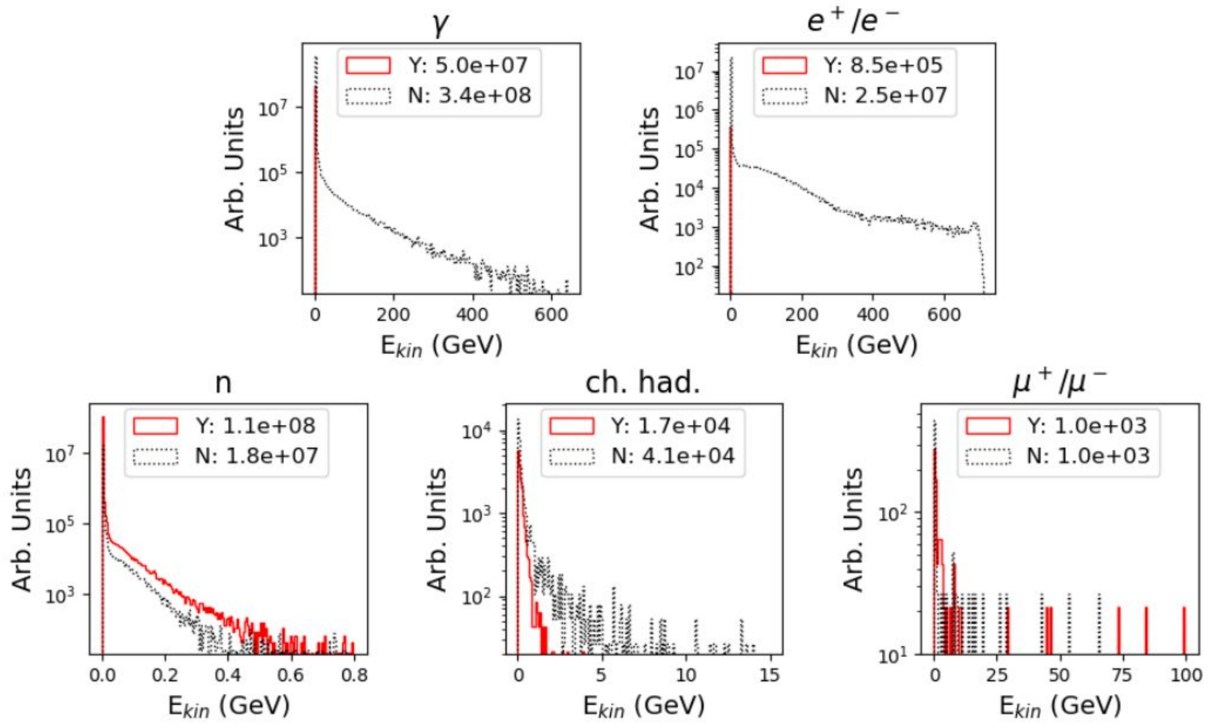


Figure 11. Comparison of number and energy spectra of the BIB: with nozzles (Y) in solid red line and without nozzles (N) in dotted black line.

Muon Collider roadmap