LeptonPhoton 2025

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Monona Terrace Community and Convention Center
Madison, Wisconsin US

International MUON Collider Collaboration

MuCol

INFN Istituto Nazionale di Fisica Nucleare

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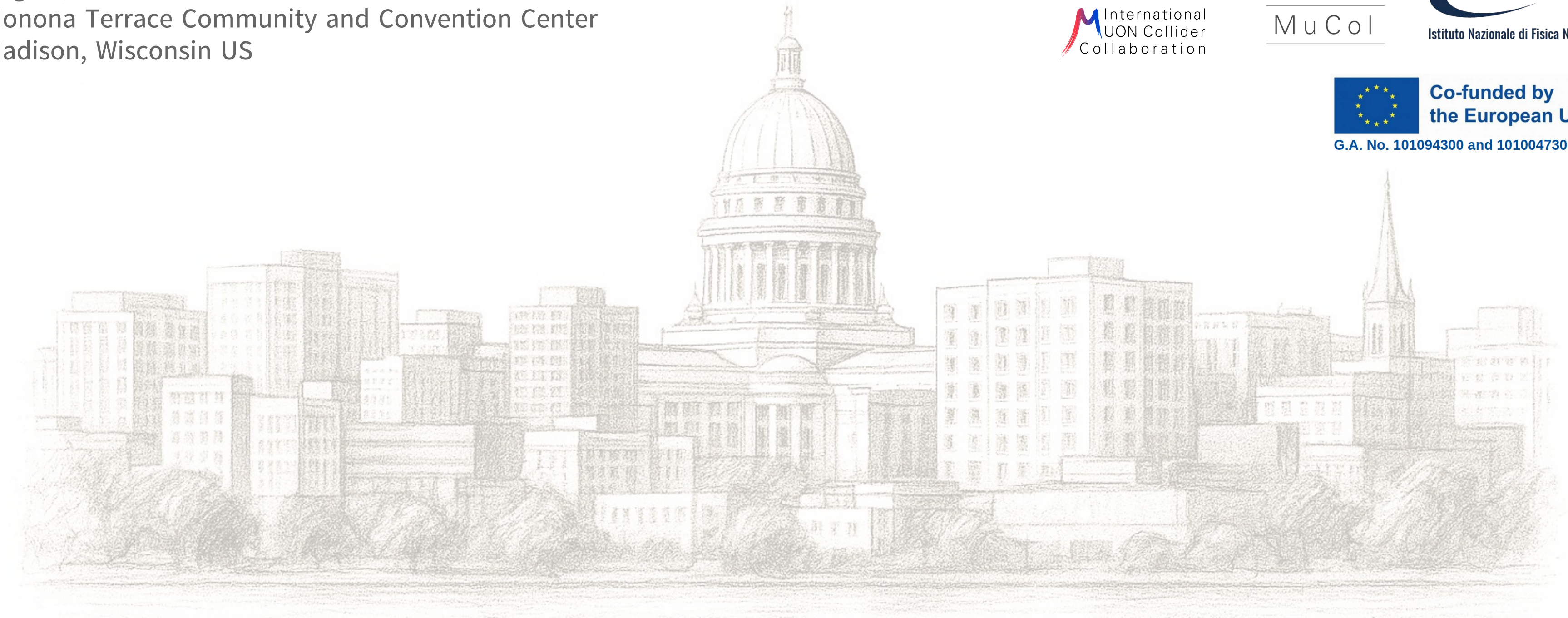
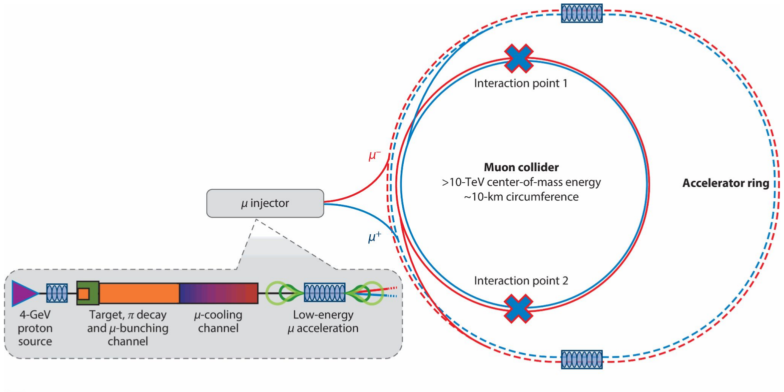


Higgs physics at a $\sqrt{s}$ = 10 TeV Muon Collider

Andreetto P., Casarsa M., Gianelle A., Lucchesi D., **Palombini L.**, Sestini L., Zuliani D.

Why a multi-TeV Muon Collider?

- In the landscape of future colliders, a multi-TeV Muon Collider could combine the precision of a lepton machine with the energy reach of a hadron collider
- A Muon Collider could also represent the most effective, space-time efficient way of achieving **~10 TeV partonic center-of-mass energy collisions**
- S. Jindariani's talk



Casarsa M, et al. 2024
Annu. Rev. Nucl. Part. Sci. 74:233–61

Energy

- Direct reach for heavy new particles
- Test of SMEFT operators at high energy
- UV behaviour of the Standard Model
- …

Precision

- Electroweak precision tests
- Characterization of the Higgs sector
- Determination of the Higgs self coupling
- …

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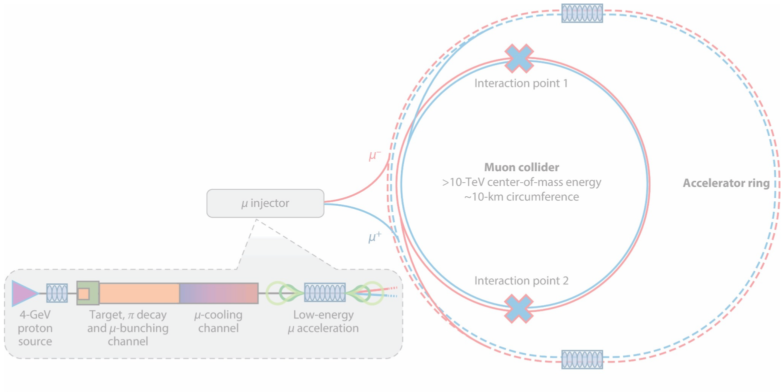

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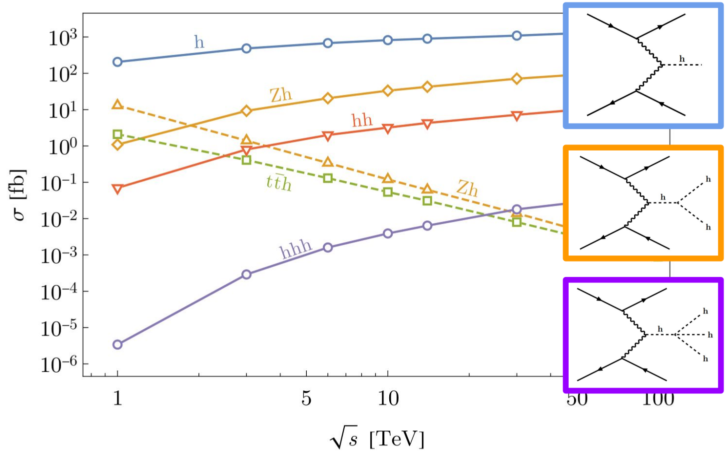
Studying the Higgs sector at a Muon Collider

A √s = 10 TeV Muon Collider would enable to deeply and extensively study the Higgs sector:

- Vector Boson Fusion is the main production mode
- predicted integrated luminosity of **10 ab^{-1} / 5 years per interaction point**
  - ↳ **~ 10^7 single-Higgs events per IP**
  - ↳ **~ $4 \cdot 10^4$ double-Higgs events per IP**
  - ↳ **two interaction points**
- unprecedented precision on the Higgs-SM couplings and determination of the Higgs trilinear self-coupling at the percent level

	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^5	9.3×10^6
ZH	11	35	1.1×10^4	3.5×10^5
$t\bar{t}H$	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

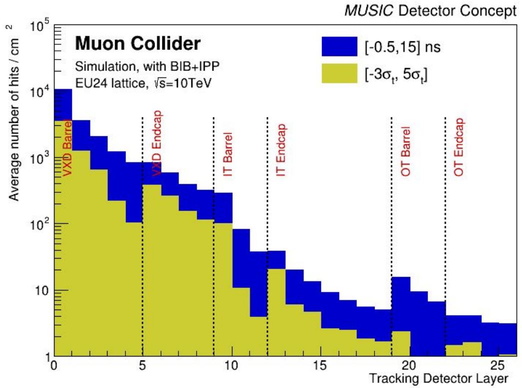
$$\mathcal{L}_H^{ug} = (\partial_\mu h\, \partial^\mu h)/2 - m_h h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

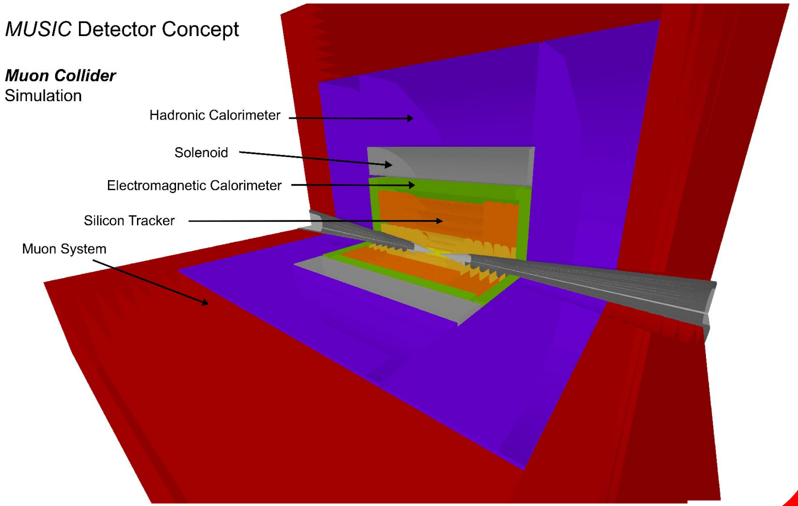


doi.org/10.1088/1361-6633/ac6678

Challenges of a Muon Collider experiment

- The main challenges for an experiment at a multi-TeV Muon Collider are the **machine-induced backgrounds**
  - ↳ mainly secondary particles from muon decays and incoherent e^+e^- pair production at bunch crossing
- A dedicated **interaction region lattice, machine-detector interface, and detector concept (MUSIC)** were developed for a $\sqrt{s}$ = 10 TeV stage of a Muon Collider
  - ↳ inputs for the 2026 ESPPU: MUSIC detector, Higgs Physics, main IMCC document
  - ↳ talks by M. Casarsa and K. F. Di Petrillo
- New physics study: assess the achievable performance on key Higgs sector observables, using detailed detector simulations



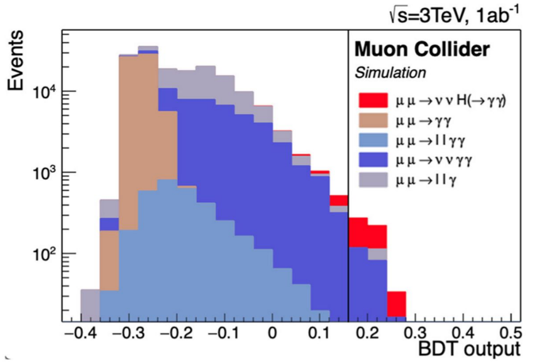


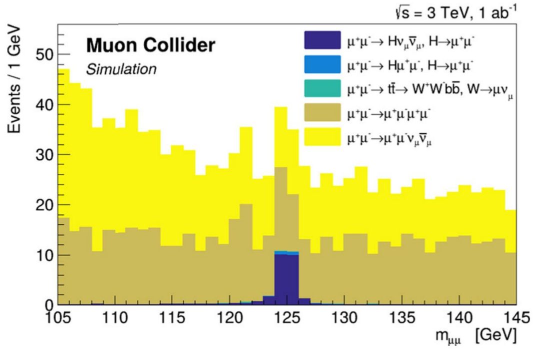
Previous studies at $\sqrt{s}$ = 3 TeV

- Detailed studies for a 3 TeV stage MuC → *Eur. Phys. J. C* **85**, 221 (2025)
- 3 TeV experimental scenario: L = 1 ab^{-1} per interaction point in 5 years, only 1 IP considered
- O(1-10)% level precision on the Higgs couplings to SM particles and ~30% uncertainty on the trilinear self coupling

$\sqrt{s}$ = 3 TeV, 1 ab^{-1}, 1 exp.	full simulation with beam-induced bkg
$\sigma(H \to b\bar{b})$	0.78%
$\sigma(H \to WW^* \to q\bar{q}'\mu\nu_\mu)$	2.9%
$\sigma(H \to ZZ^* \to q\bar{q}\mu^+\mu^-)$	17%
$\sigma(H \to \mu^+\mu^-)$	39%
$\sigma(H \to \gamma\gamma)$	7.5%
$\sigma(HH \to b\bar{b}b\bar{b})$	33%
λ_3/λ_3^{SM}	[0.81, 1.44] @ 68% C.L.**

* includes also the electron channel
** uses only the HH → $b\bar{b}b\bar{b}$ channel



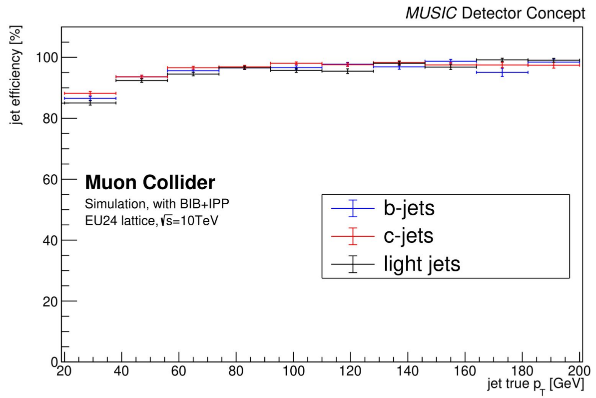


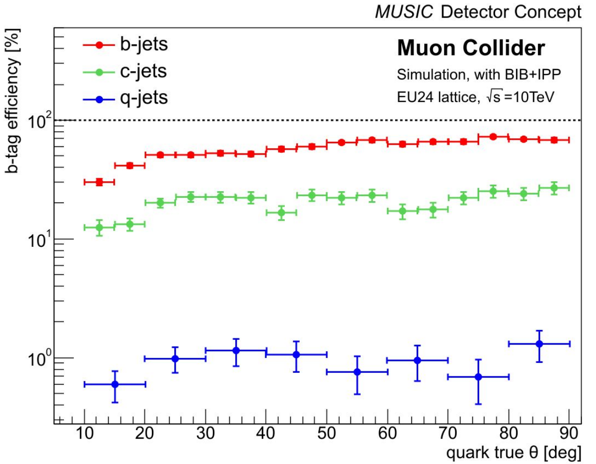
Higgs studies at $\sqrt{s}$ = 10 TeV

- 10 TeV experimental scenario: 2 interaction points, L = 10 ab^{-1} per IP in 5 years of operations
- Methodologies of the study:
  - ↳ signal and relevant physics background samples generated using WHIZARD + PYTHIA
  - ↳ machine backgrounds simulated using FLUKA (secondaries from muon decays) and GUINEA PIG (incoherent e^+e^-)
  - ↳ the detector response is simulated using GEANT4, with machine backgrounds being overlaid event by event
- The statistical sensitivity on the cross section for a representative set of Higgs decay channels is evaluated
  - ↳ $H \to bb$, $H \to WW^*$, $HH \to bbbb$
- The statistical confidence interval on the trilinear coupling modifier κ_3 is evaluated in the $HH \to bbbb$ channel

$H \to b\bar{b}$ process reconstruction with MUSIC

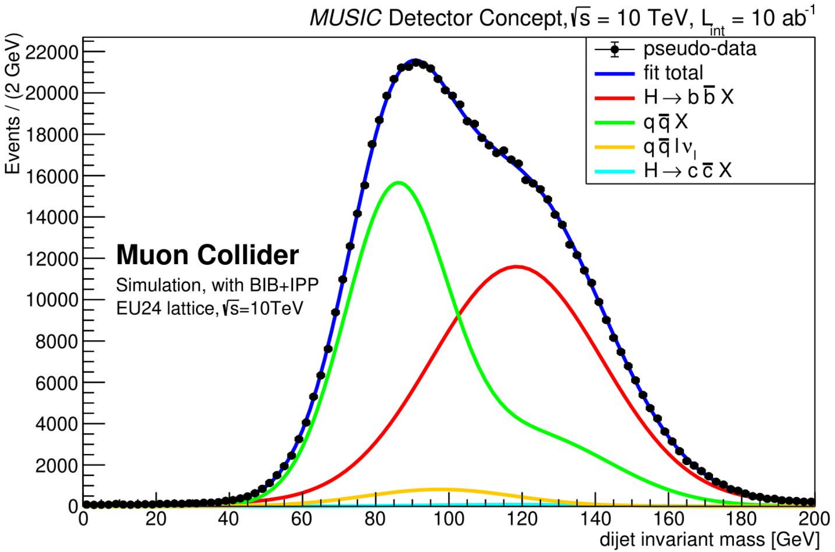
- Jet reconstruction via k_T algorithm, R = 0.5
- Machine backgrounds may generate fake jets
  - ↳ quality selections reduce fake rate to ~0.5/event
- Present jet flavor tagging procedure is based on the reconstruction of secondary vertices
  - ↳ look for displaced vertices and/or a high p_T muon in the jet
  - ↳ apply two independent Deep Neural Networks on the vertex properties: one for b vs light jets, one for b vs c jets
- Simple method that guarantees reliable but very conservative tagging performance
- Working towards an integration of the present state-of-the-art machine learning tools developed for the LHC experiments → huge improvement margin
- Details in [M. Casarsa's talk]





The $H \to b\bar{b}$ reconstruction and analysis

- Final state requirements:
  - ↳ at least two reconstructed jets, $p_T > 40$ GeV/c
  - ↳ both jets b-tagged
- Main backgrounds: $\mu\mu \to qqX$, $qql\nu$, $H \to cc$ (with X = νν, μμ as VBF dominates)
- Z and H distributions overlap, but separation is good enough to statistically extract the signal yield
- Unbinned maximum-likelihood template fit to the dijet invariant mass (m_{jj}), to extract the signal yield
- **$\Delta\sigma$(stat.)/ σ = 0.20%,** 2 IPs, 10 ab^{-1} per IP (5 years)

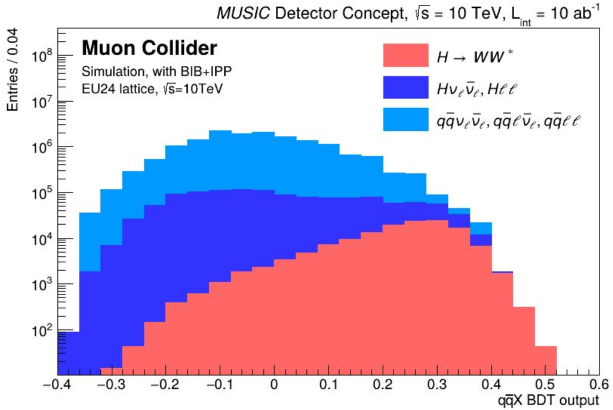


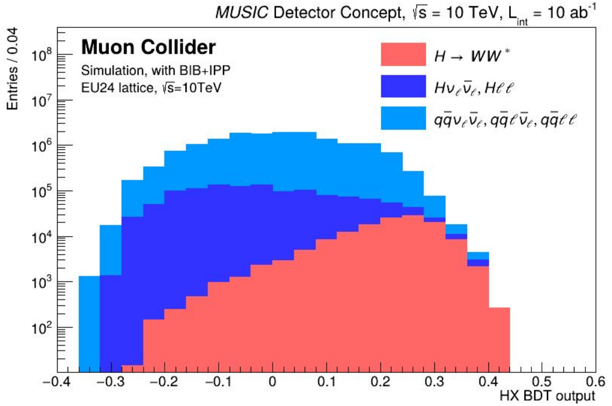
🚩 Wide margin of improvement, especially from jet reconstruction and flavor tagging

The H→WW* reconstruction and analysis

- Consider only WW*→qqμν, with requirements:
  - ↳ at least two jets, p_T > 20 GeV/c
  - ↳ at least one isolated muon, p_T > 10 GeV/c
- Main backgrounds: μμ→qqX, qqlν, HX with the Higgs not decaying to WW* (X = νν, μμ)
- Two independent Boosted Decision Trees (BDT)
  - ↳ discriminate signal from non-resonant backgrounds
  - ↳ discriminate signal from the HX background
  - ↳ use: muon and jets p_T and θ, μ isolation, jet components number, p_T θ and inv. mass of the hadronic W candidate, θ and inv. mass of the H candidate, acollinearity angles μ-W, μ-H, W-H, missing E_T, and scalar sum of jets and μ p_T
- 2D binned maximum-likelihood template fit on the two BDT outputs to extract the signal yield
- **Δσ(stat.)/ σ = 0.41%,** 2 IPs, 10 ab^{-1} per IP (5 years)

🚩 The study will be soon completed by the inclusion of WW*→qqeν

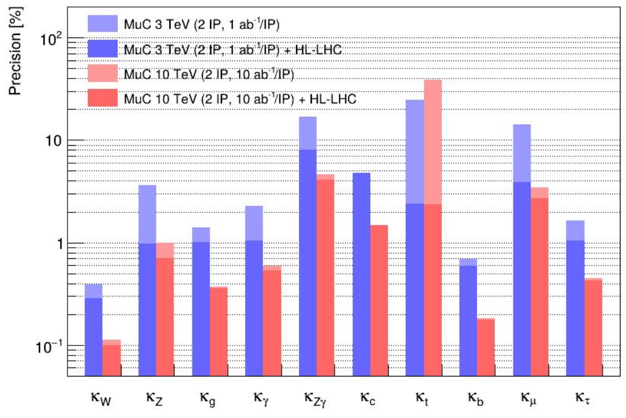


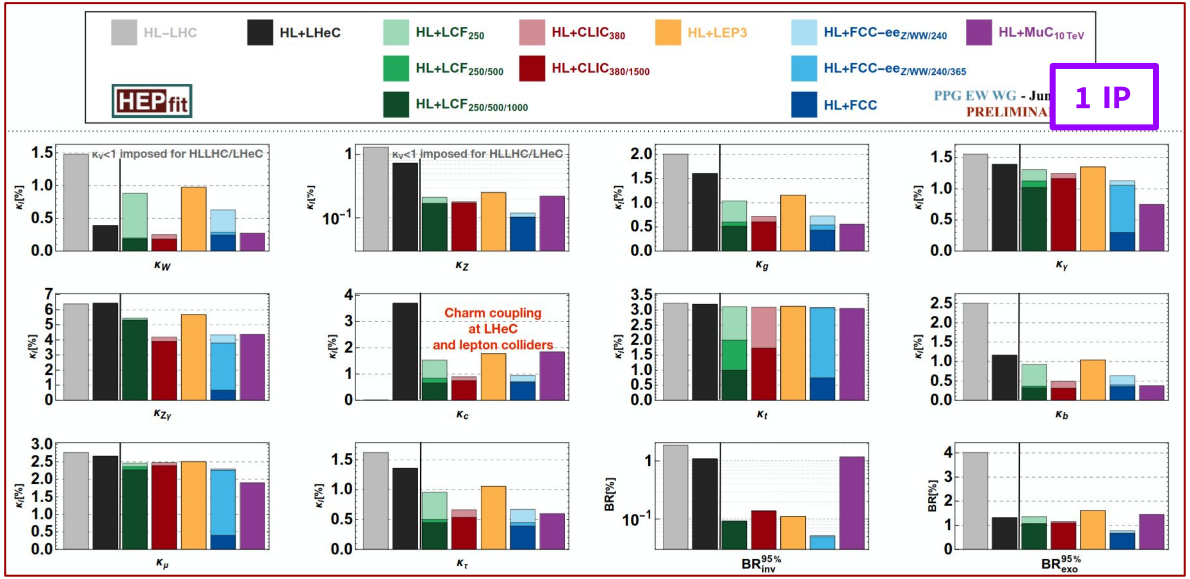


- Higgs couplings at 3 and 10 TeV are evaluated using parametric simulations, tuned on the detailed simulation results
- percent to permille precisions reached for 1 ab^{-1} at $\sqrt{s}$ = 3 TeV and 10 ab^{-1} at $\sqrt{s}$ = 10 TeV

How does it compare to other Future Colliders?

JHEP08(2022)185



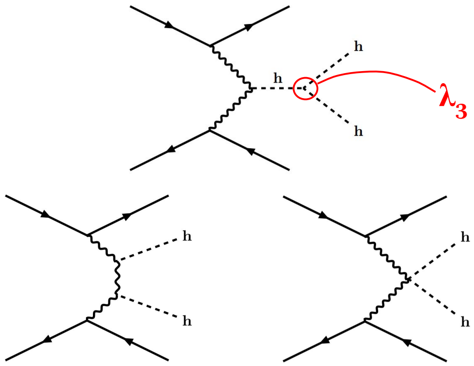


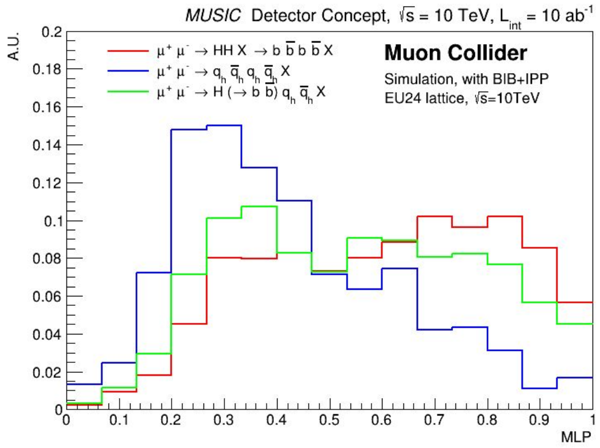
All reported MuC results are evaluated as 1 IP, while FCC-hh as 2 IPs. For an equal comparison, MuC results are to be scaled for the doubled statistics.

from J. de Blas talk at the ESPPU Open Symposium

Make it two: the HH $\rightarrow b\bar{b}b\bar{b}$ channel

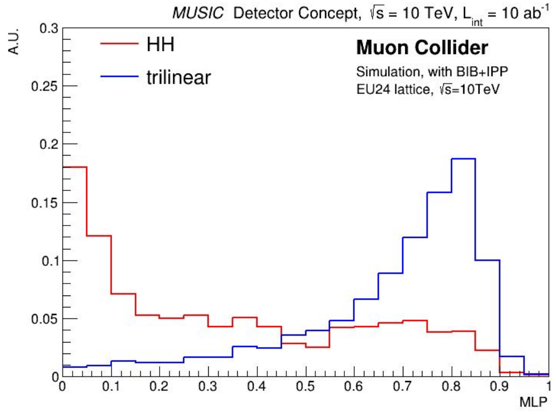
- Final state requirements:
  - ↳ at least four jets, p_T > 20 GeV/c
  - ↳ at least one jet per pair b-tagged
  - ↳ Higgs candidates by minimizing $\sqrt{[(m_{jj,1} - m_h)^2 + (m_{jj,2} - m_h)^2]}$
- Main backgrounds: $\mu\mu \rightarrow 4q_hX$, $H(\rightarrow bb)q_hq_h$ (with q_h = b,c X = νν, μμ)
- MultiLayer Perceptron (MLP) to discriminate the HH signal from the backgrounds
  - ↳ use all jets p_T, Higgs candidates separation, separation between highest p_T jets of the two pairs
- Binned maximum-likelihood template fit on the MLP output to extract the signal yield
- **$\Delta\sigma$(stat.)/ σ = 4.2%,** 2 IPs, 10 ab^{-1} per IP (5 years)

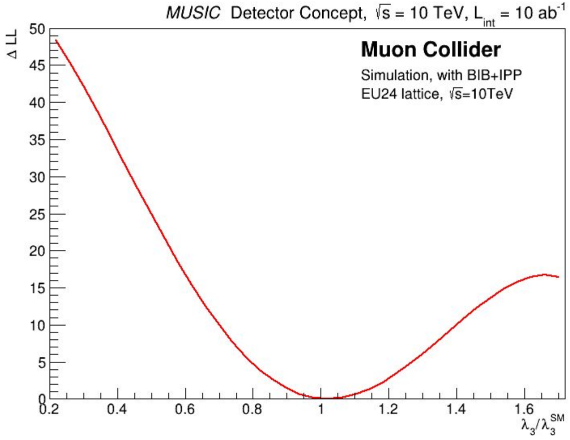




- Studied only in the HH→bbbb channel
- MLP to discriminate between the trilinear vertex contribution and the other double Higgs production modes
- 2D binned maximum-likelihood template fit on the two MLP outputs
  - ↳ discrimination between HH signal and other backgrounds
  - ↳ discrimination between trilinear vertex and other HH modes
  - ↳ for the second MLP: separation between H candidates, θ of highest pT jet of each pair, helicity angles of H candidates
- **$\delta\lambda_3$ (stat.) = [-4.2, +5.7]% ,** 2 IPs, 10 ab^{-1} per IP (5 years)

🚩 Similarly to H→bb, significant improvements are expected from the upgrade of the present jet reconstruction and tagging methods



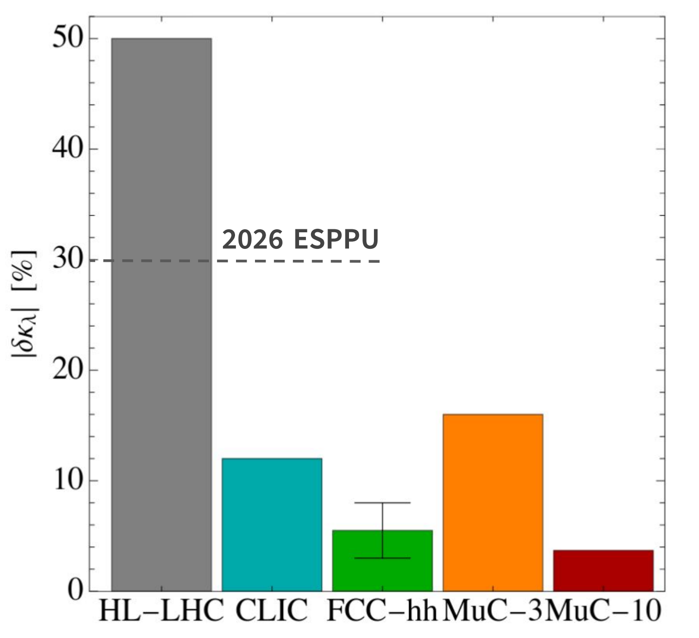


Higgs trilinear self-coupling overview

arXiv:2504.21417

- The Higgs trilinear coupling at 3 and 10 TeV was evaluated using parametric simulations
  - ↳ tuned to previous detector performance, will be updated with improved results
- percent-level precision achievable in 5 years of operation
- compares well with the detailed simulation result
  - ↳ the detailed study of HH→bbWW* will be added soon

The reported MuC results is evaluated as 1 IP, while FCC-hh as 2 IPs. For an equal comparison, MuC result is to be scaled for the doubled statistics.

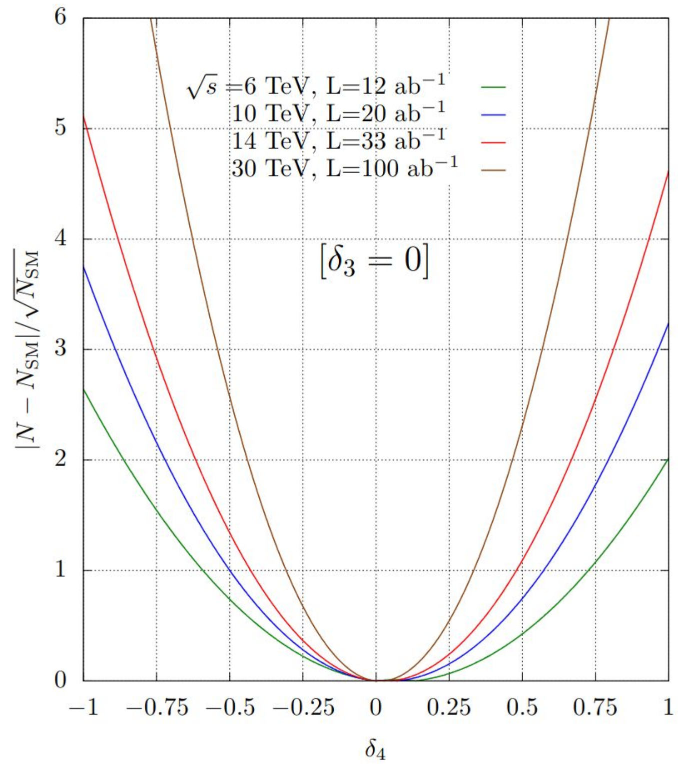


🚩 A 10 TeV Muon Collider is the only machine able to obtain a percent-level precision in the measurement of λ_3 in such a short time of operation

The Higgs quartic self coupling

JHEP **2020**, 98 (2020) has evaluated the possibility to constrain the Higgs quartic self-coupling λ_4 at a $\sqrt{s}$ = 10 TeV Muon Collider:

- phenomenology study on the process $\mu\mu \to HHHX$, $HHH \to 6b$ (with X = $\nu\nu$, $\mu\mu$)
- assumes total L = 20 ab^{-1}
  - ↳ ~ 80 events expected
- possible to obtain an O(50%) uncertainty on λ_4, assuming no deviations from the SM on λ_3



Summary

- A $\sqrt{s}$ = 10 TeV Muon Collider would open the possibility of studying the Higgs sector with unprecedented accuracy, thanks to its large sample of single and double Higgs events, achievable in just 5 years of data taking
- A detailed simulation study has been carried out, evaluating the achievable results in the presence of the main machine-induced backgrounds
  - ↳ sub-percent level precision on the Higgs couplings to SM particles
  - ↳ percent level precision on the Higgs trilinear self-coupling
  - ↳ all with the reference scenario: 2 IPs, L = 10 ab^{-1} / IP, equivalent to 5 years of operation
- Phenomenology studies show the possibility to put bounds on the Higgs quartic coupling with ~50% level uncertainty, assuming L = 20 ab^{-1}
- The studies done so far demonstrate that experiments at a 10 TeV Muon Collider allow studying the Higgs sector, including the Higgs potential, in great detail

Thank you!

Backup

Experimental challenges of a Muon Collider

The main challenges for an experiment at a multi-TeV Muon Collider are the **machine-induced backgrounds** :

Muon decay products ("BIB")

- ~TeV electrons and positrons strike the machine's and detector's material

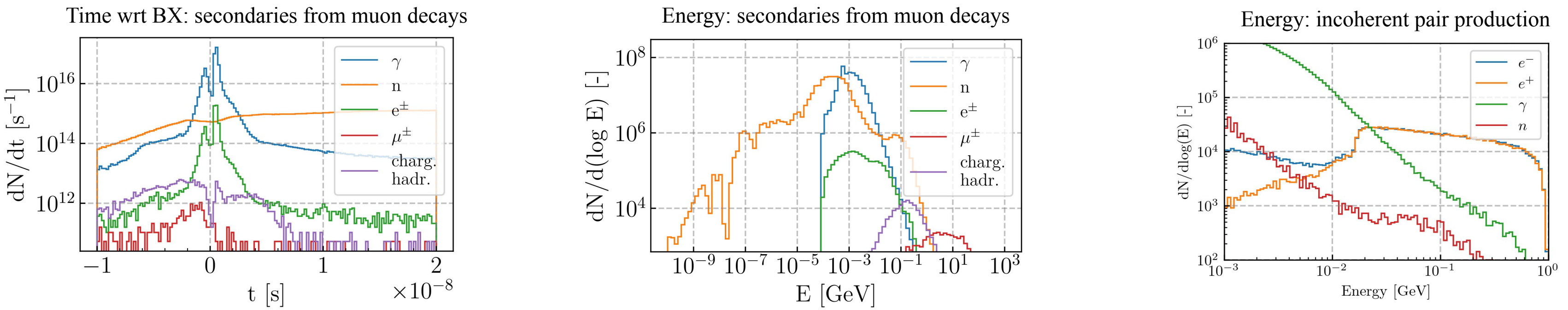
✓ specifically designed tungsten shieldings absorb most of the generated shower particles

Incoherent pair production ("IPP")

- EM interactions of colliding muons generate soft e^+e^- pairs at the IP, in time with the bunch crossing

✓ strong magnetic field confines most particles in the innermost detector region

🚩 Novel detector technologies and dedicated reconstruction algorithms to minimize the effects of both



Signal and background yields

- H→bb

Process	σ [fb]	ϵ_{presel}[%]	ϵ_{tag} [%]	N_{exp}
$\mu^+\mu^- \to H(\to b\bar{b})X$	490	22.2	32.4	351518
$\mu^+\mu^- \to H(\to c\bar{c})X$	24.3	22.2	4.49	2422
$\mu^+\mu^- \to q\bar{q}\nu_\ell\bar{\nu}_\ell$	2674	25.6	5.00	341598
$\mu^+\mu^- \to q\bar{q}\ell\ell$	4339	1.86	1.31	10533
$\mu^+\mu^- \to q\bar{q}\ell\nu_\ell$	9763	21.46	0.10	20974

- H→WW*→qqμv

Process	σ [fb]	ϵ_{presel} [%]	N_{exp}
$\mu^+\mu^- \to H(\to WW^* \to q\bar{q}\mu\nu_\mu)X$	26.3	47.3	137493
$\mu^+\mu^- \to H\nu_\ell\bar{\nu}_\ell$	820	12.2	1000906
$\mu^+\mu^- \to H\ell\ell$	84.8	12.5	106226
$\mu^+\mu^- \to q\bar{q}\ell\nu_\ell$	9763	11.4	11110294
$\mu^+\mu^- \to q\bar{q}\nu_\ell\bar{\nu}_\ell$	2674	10.2	2731663
$\mu^+\mu^- \to q\bar{q}\ell\ell$	4339	1.8	772342

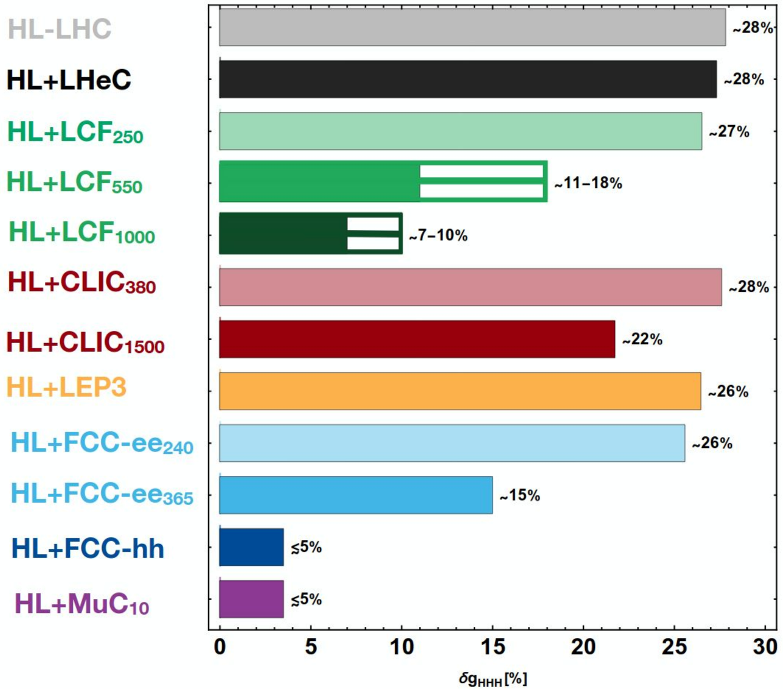
- HH→bbbb

Process	σ [fb]	ϵ[%]	N_{exp}
$\mu^+\mu^- \to HHX \to b\bar{b}b\bar{b}X$	1.14	18.47	2100
$\mu^+\mu^- \to H(\to b\bar{b})q_h\bar{q}_hX$	7.27	15.56	11307
$\mu^+\mu^- \to q_h\bar{q}_hq_h\bar{q}_hX$	10.89	8.99	9787

Higgs couplings from parametric simulation

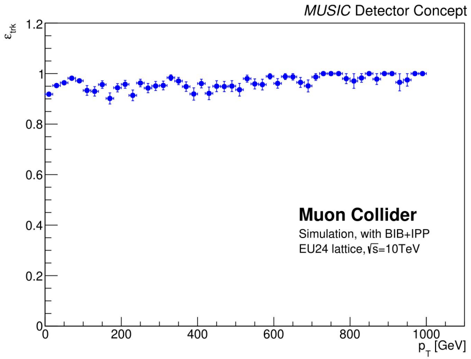
Channel	$\Delta\sigma/\sigma$ (%)	
	3 TeV	10 TeV
bb	0.76	0.21
cc	13	4.0
gg	3.3	0.89
$\tau^+\tau^-$	4.0	1.1
$WW^*(jj\ell\nu)$	1.7	0.45
$WW^*(4j)$	5.7	1.3
$ZZ^*(4\ell)$	45	12
$ZZ^*(jj\ell\ell)$	11	3.2
$ZZ^*(4j)$	65	14
$\gamma\gamma$	6.1	1.6
$Z(jj)\gamma$	47	13
$\mu^+\mu^-$	40	9.8
$ttH(bb)$	61	53

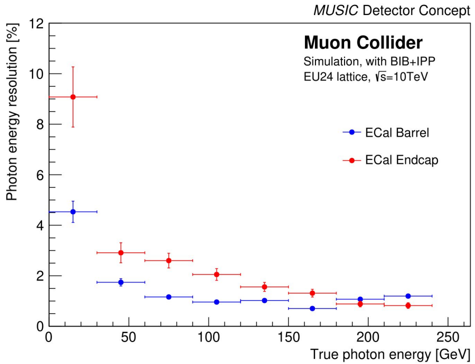
- Predictions via DELPHES simulation, JHEP08(2022)185

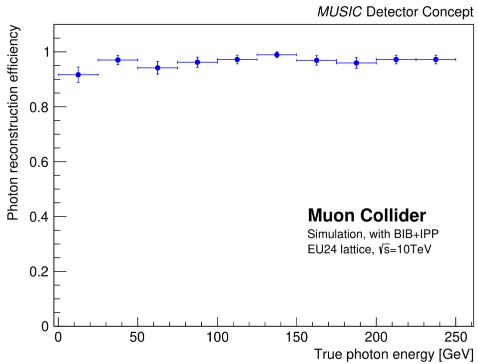


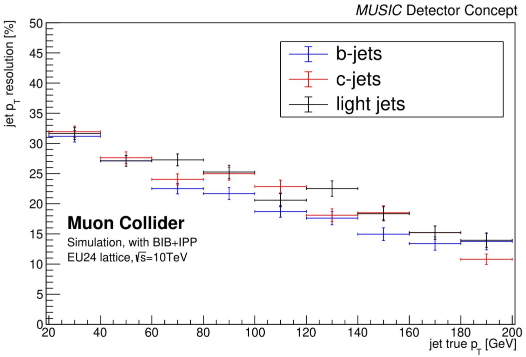
from J. de Blas talk at the ESPPU Open Symposium

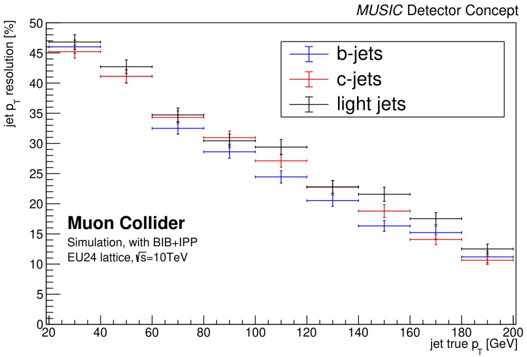
MUSIC reconstruction performance

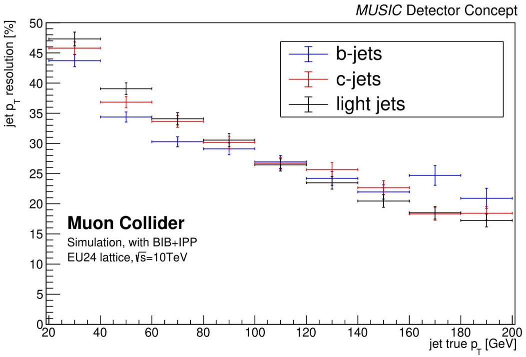




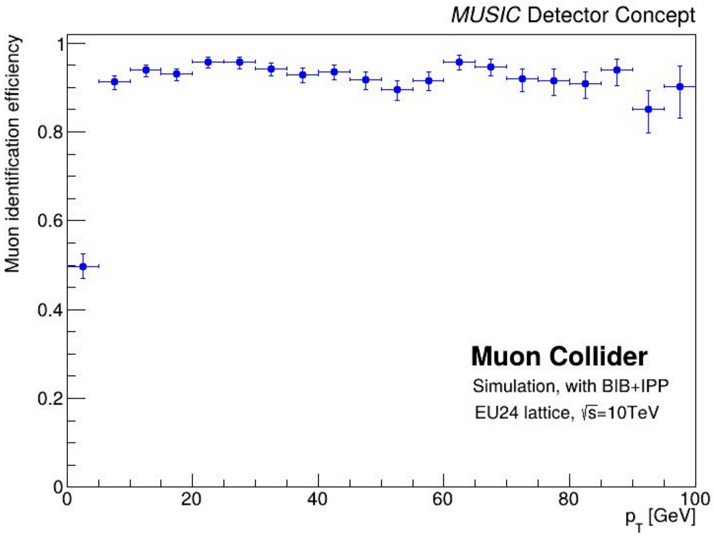


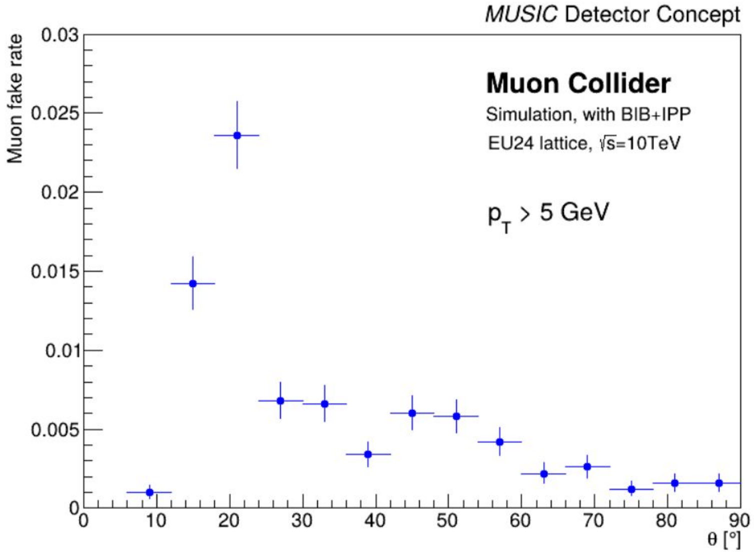






MUSIC muon reconstruction performance





MUSIC jet flavor tagging

- Search for muon in jet cone
  - p_T > 5 GeV/c, $|\eta|$ < 1.5
- Search for secondary vertex in jet cone
  - Reconstruction via LCFIplus (doi.org/10.1016/j.nima.2015.11.054)
  - L < 50mm, L/σ_L > 2 (L = 3D distance from primary vertex)
- Two independent Deep Neural Networks (DNN)
  - discrimination b/light jets
  - discrimination b/c jets
- Selection in the 2D probability space of the two DNNs