Higgs self-coupling possibilities at a multi-TeV Muon Collider

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A Muon Collider

International MUON Collider Collaboration

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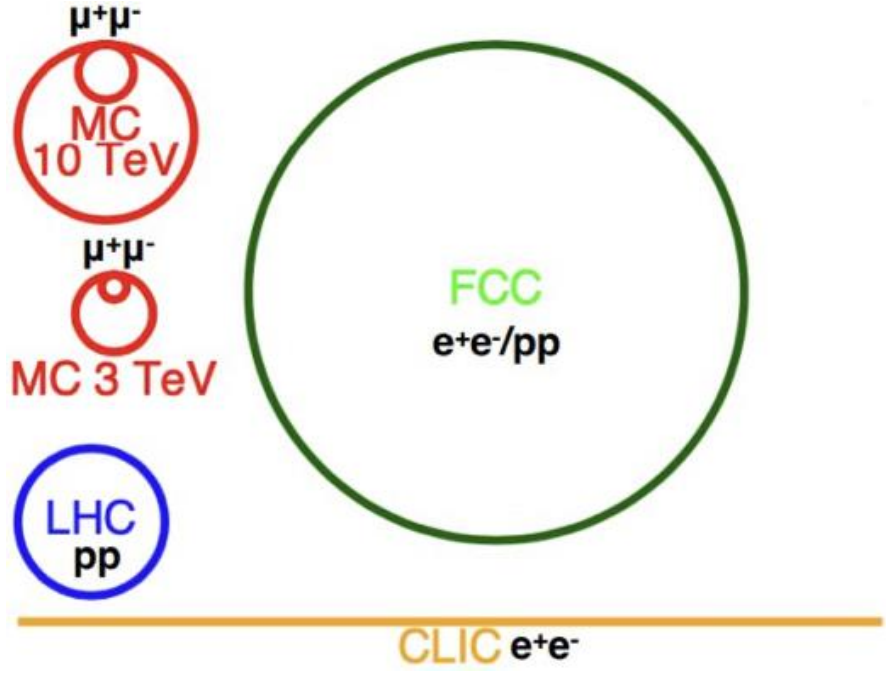
- A Muon Collider is being considered as an option for a next generation accelerator facility
- Studies at 3 and 10 TeV showed several advantages but also technological challenges

Muon Collider pros:

- **m_μ>>m_e** hence negligible synchrotron radiation
- **Point-like particle**: all energy is available for the collision
- Perfect for direct search of new heavy states
- Low QCD background wrt to hadronic machines
- **broad physics reach**: SM precision tests, BSM direct and indirect search, lepton flavour universality tests

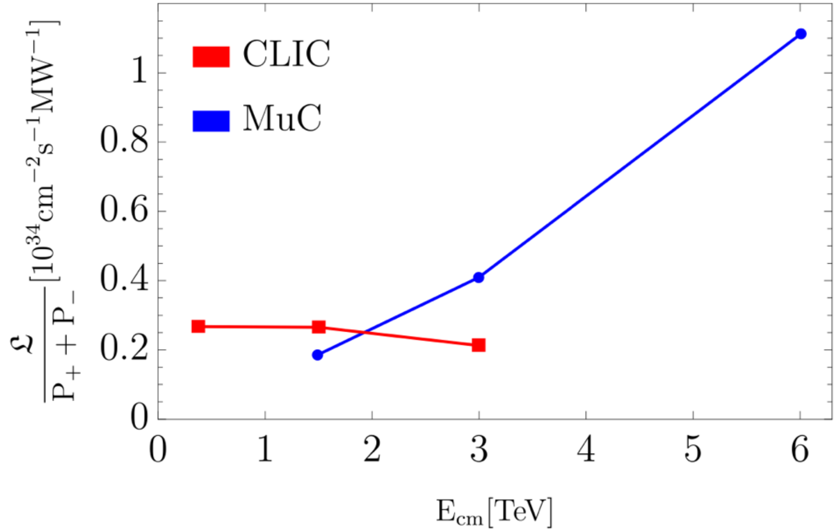
Muon Collider cons:

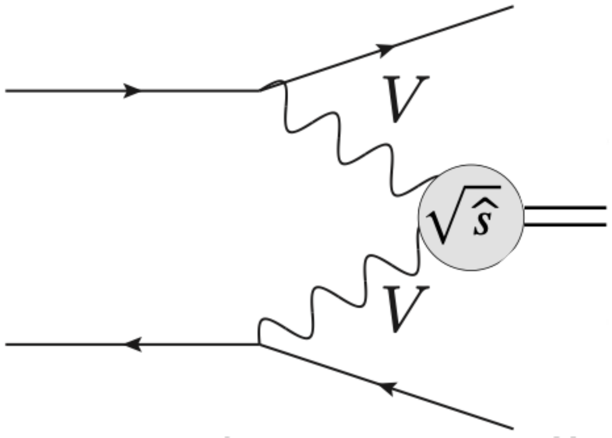
- **τ_0= 2.2µs :** very fast cooling and fast-ramping magnet system needed
- µ decay + interaction with machine: **beam-induced background (BIB)**, partially shielded by nozzles
- **Intensive neutrino flux**

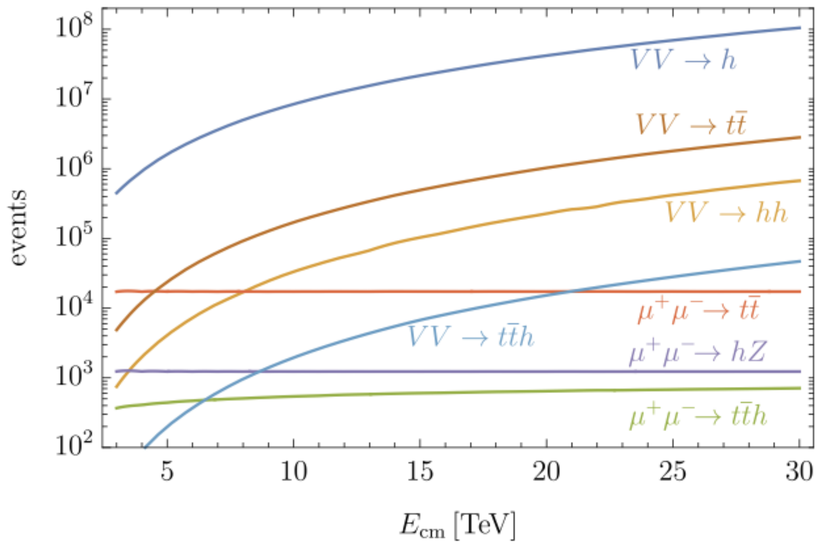


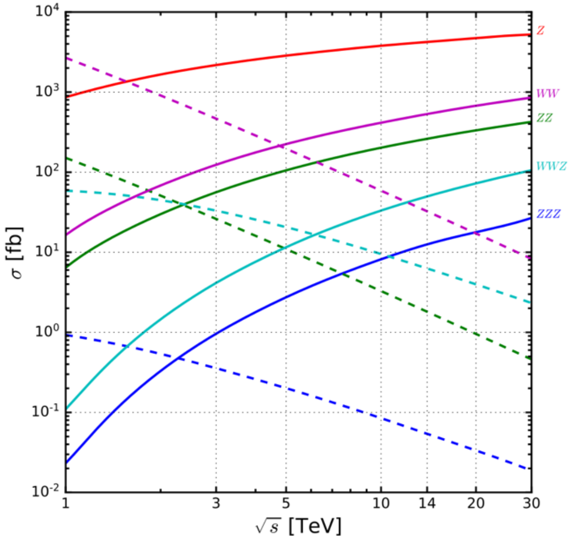
The unique high-energy path

- **Unique** combination of properties at **higher energies**
  - VBF fusion XS increases with energy
  - No QCD background and small annihilation XS -> clean physics environment
  - Possibility to do precision electroweak physics
  - Lumi/power ratio improves linearly with energy



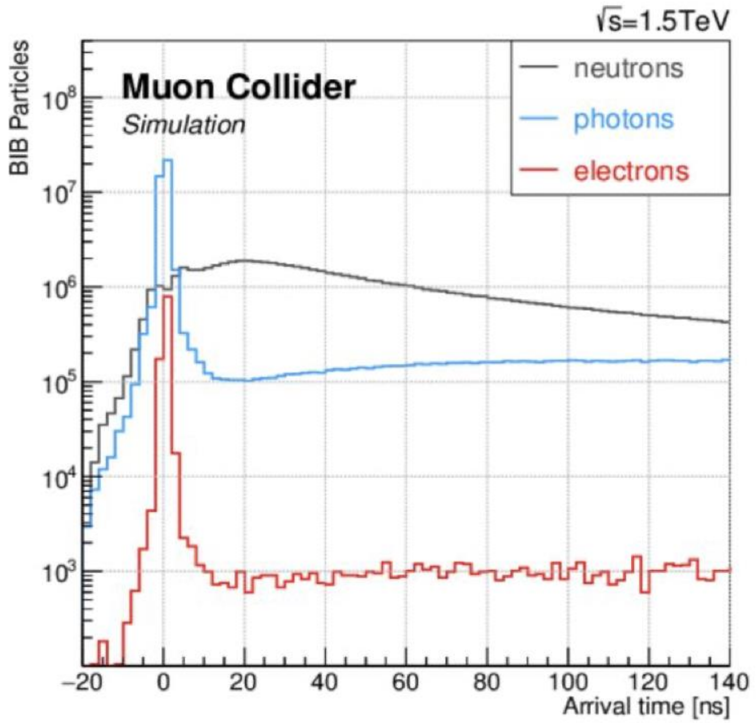


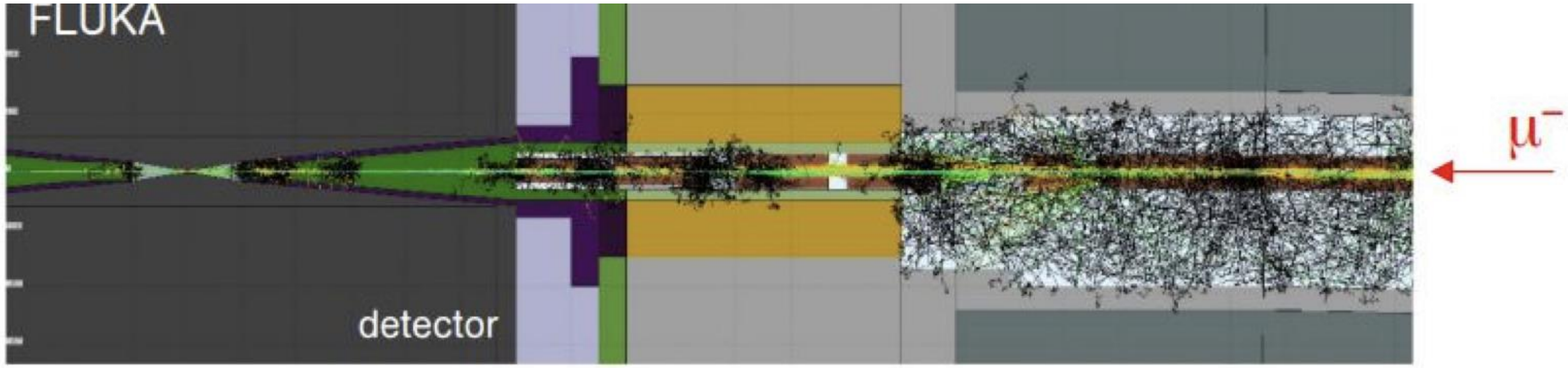




Beam Induced Background

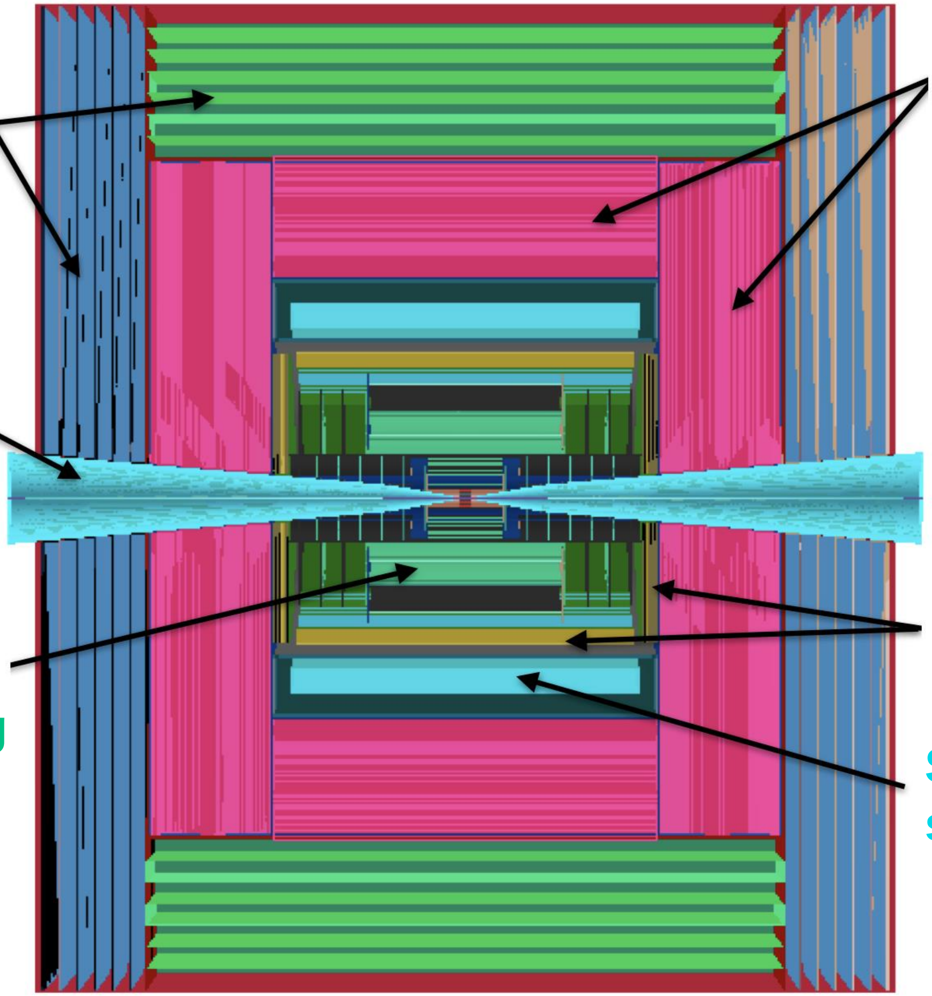
- Muons decay → decay products interact with machine elements
- → **Tungsten nozzles** mitigate radiation coming to the detector
- Still working on the MDI optimization for 10 TeV
- Despite the nozzles → **intense fluxes of particles reach the detector**:
  - high multiplicity of particles in the tracker (mainly in first layers)
  - diffuse low-energy background in calorimeters
- BIB is off-time wrt bunch crossing → algorithms and detectors tailored to exploit these features
- Innovative techniques and optimised algorithms are fundamental to mitigate the impact of BIB





10 TeV Detector concept

- **Main physics requirements**→ ability to reconstruct:
    - boosted low-pT physics objects from Standard Model processes;
    - central energetic physics objects from decays of BSM massive states;
    - exotic experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
- **Machine background conditions**: high levels of BIB dictates technological choices, reconstructed algorithms and detector design
- Studies at 3 TeV performed with a legacy detector concept from CLIC



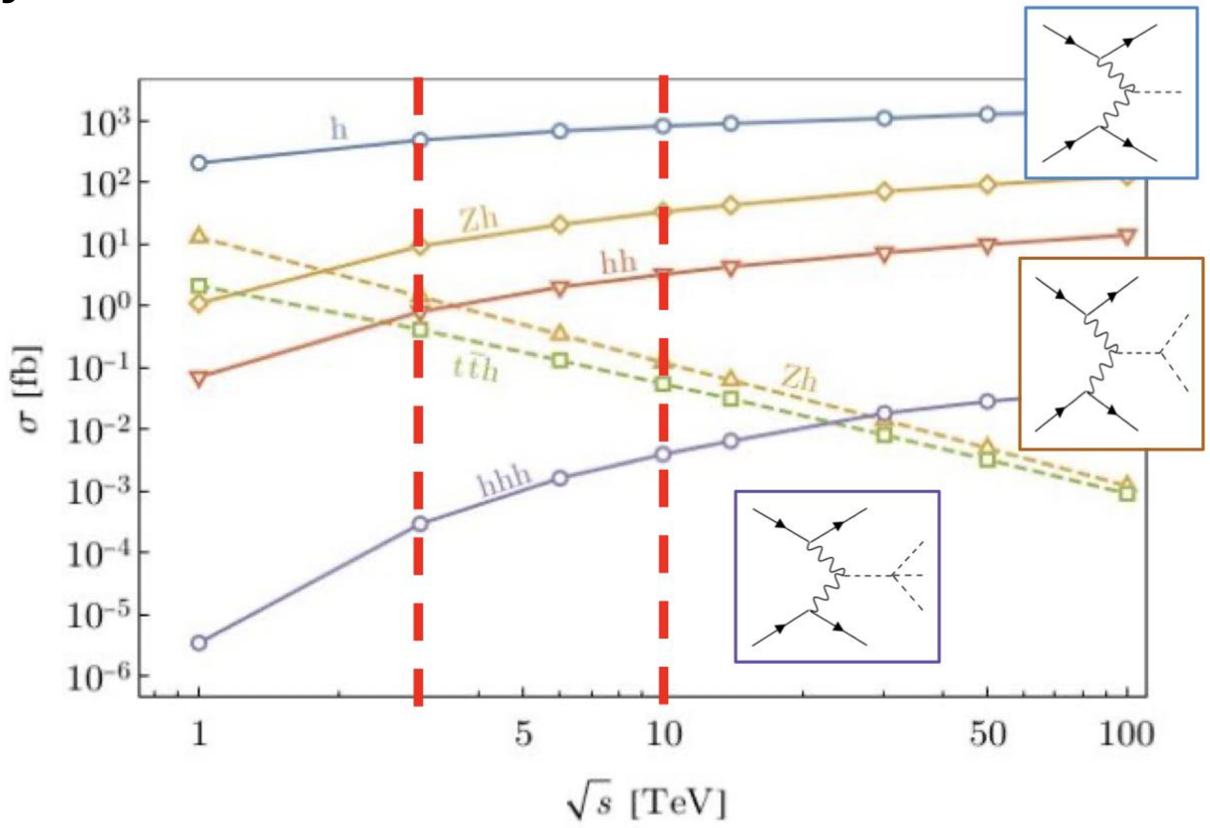
Higgs Physics @ Muon Collider

The last ESPPU identified Higgs Physics as the main physics target at future colliders:

- Measure Higgs couplings to fermions and bosons at ~O(1%) level
- Measure Higgs potential with multi-Higgs processes

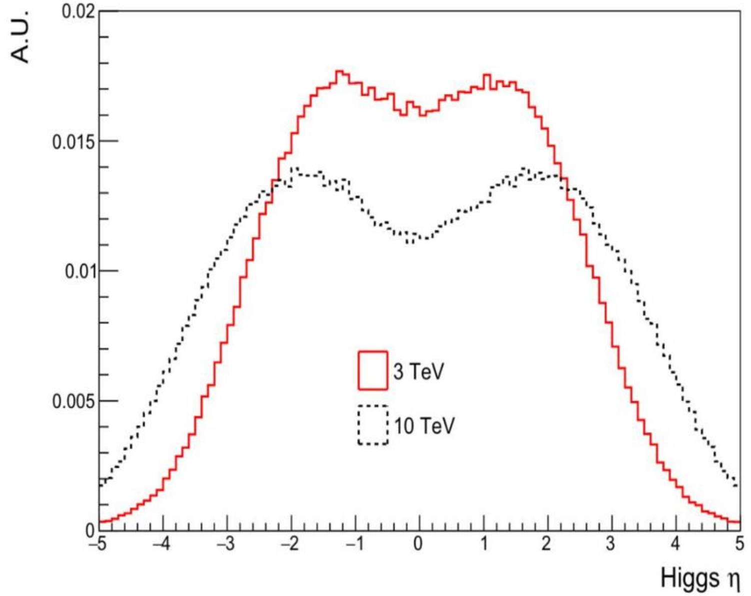
The **Muon Collider** is by all means **a Higgs factory**

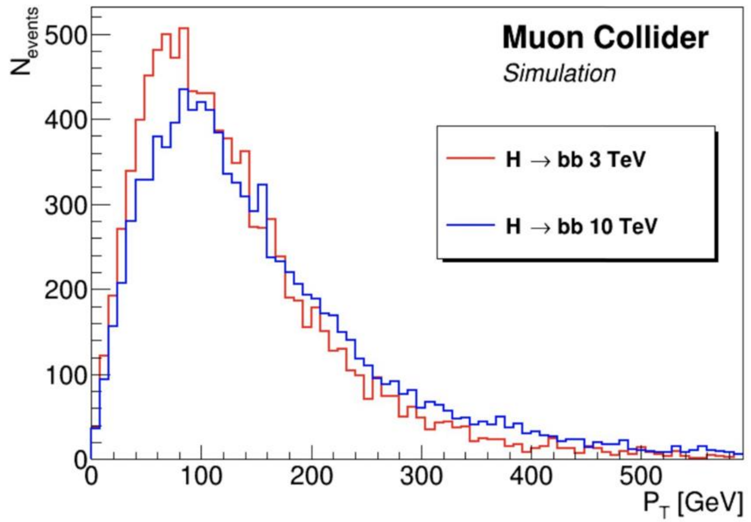
Energy	Luminosity	number of Higgs
3 TeV	1 ab^{-1}	5×10^5
10 TeV	10 ab^{-1}	9.5×10^6
14 TeV	20 ab^{-1}	2.2×10^7
30 TeV	90 ab^{-1}	1.2×10^9



Higgs physics with detailed detector simulation

- **Higgs Physics at 10 TeV is similar to 3 TeV**
  - Objects **more boosted** in the forward region
  - Transverse momentum distributions similar
- While configuring 10 TeV detector, a study has been done for Higgs Physics at 3 TeV, using **detailed detector simulation**
- Main purposes of this work:
  - Prove that **BIB is under control**
  - Compare results with the no-BIB case
- List of studies:
  - Higgs cross-sections (bb, WW*, ZZ*, μμ, γγ)
  - Higgs width Γ
  - Double Higgs cross-section ***(This talk)***
  - Trilinear self-coupling λ_3 **(This talk)**





Results at 3 TeV: realistic vs. no BIB case

- Results of full simulation compared with studies obtained without BIB

- Results are overall in **good agreement** in most channels

- → **BIB is under control**

Decay channel	With BIB	Without BIB
H→bb	**0.75%**	0.76%
H→WW	**2.9%**	1.7%
H→ZZ	**17%**	11%
H→μμ	**38%**	40%
H→γγ	**7.6%**	6.1%

- We are confident to reach the results obtained by phenomenological studies despite the BIB presence

Coupling precisions and potential

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- **Coupling measurements** simulated with full and parametric simulations → results are consistent and very close to the phenomenological studies
  - *See talk from A. Montella on single Higgs couplings*
- **Di-Higgs** production is sensitive to **trilinear Higgs self-coupling λ_3**
  - Extrapolation to higher energies and luminosities from pheno studies → **Muon Collider provides competitive results wrt other machines**
- Possibility to access **Higgs quartic self-coupling λ_4** (only pheno study for now), expectations: **$\delta\lambda_4$= 50% at E_{com}= 14 TeV with 20 ab^{-1}**

The Muon Collider is **definitely competitive** in the landscape of future colliders

- After HL-LHC a MuCol would improve more the sensitivity wrt FCC-ee, except for Z and c couplings

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC

Experiment	Luminosity	COM Energy	$\delta\lambda_3$
CLIC	5 ab^{-1}	3 TeV	-7%,+11%
ILC	8 ab^{-1}	1 TeV	10%
FCC-hh	30 ab^{-1}	100 TeV	3%
Muon Collider	**2 ab^{-1}**	**3 TeV**	**15%**
Muon Collider	**10 ab^{-1}**	**10 TeV**	**3.5%**
Muon Collider	**20 ab^{-1}**	**14 TeV**	**2.5%**
Muon Collider	**90 ab^{-1}**	**30 TeV**	**1%**

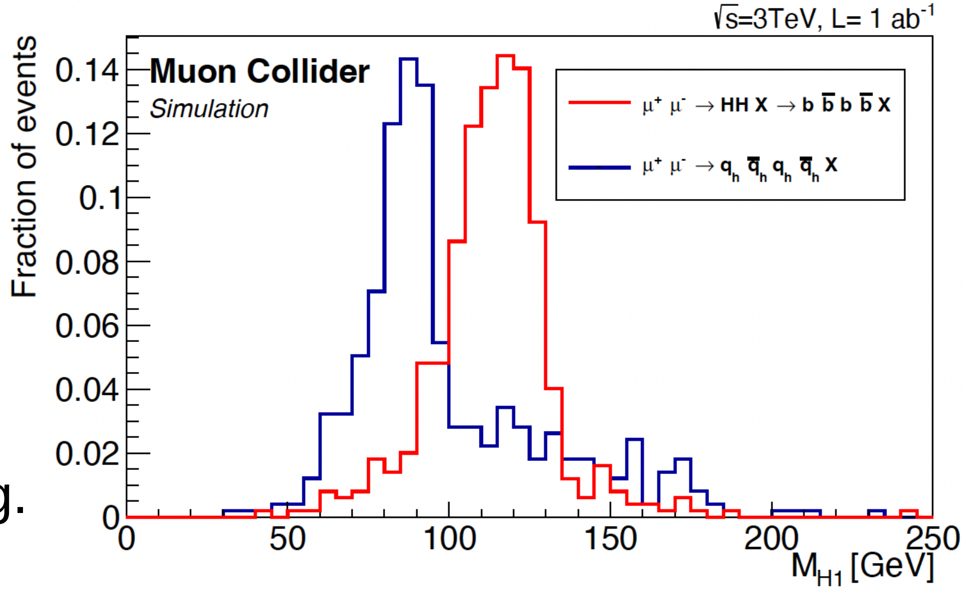
Requires more time than MuC (FCC-hh)

Di-Higgs production

- Di-Higgs production is particularly sensitive to trilinear Higgs self-coupling λ_3
- Here **only the HH→bbbb channel has been considered**
- Event selection: **4 jets with p_T > 20 GeV e $|\eta|<2.5$**
  - HH candidates are obtained by minimising $\sqrt{[(m_{12}-mH)^2 + (m_{34}-mH)^2]}$
  - B-jet tagging identification algorithms required for one jet per di-jet pair
- **Neural Network** to separate signal from background
- Result at 3 TeV with 1 ab^{-1} in 5y: **$\Delta\sigma/\sigma$ ~ 33%**

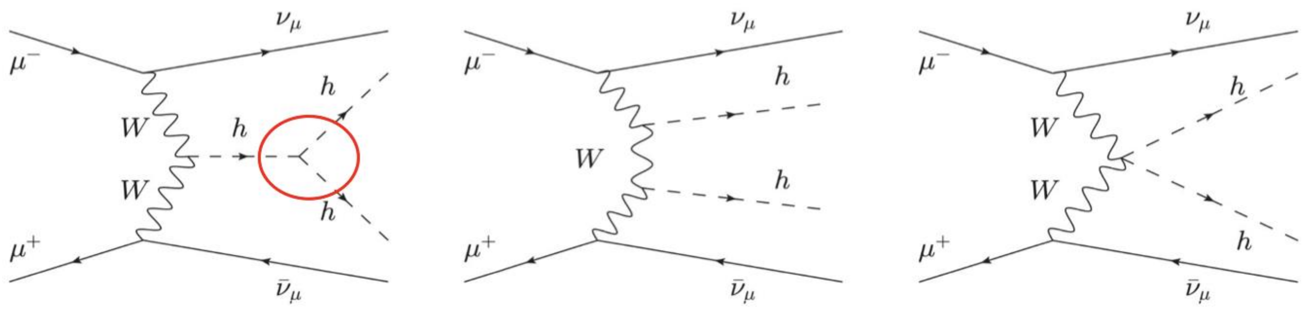
- At 10 TeV we can combine this result with other channels, e.g. **HH→bbWW**

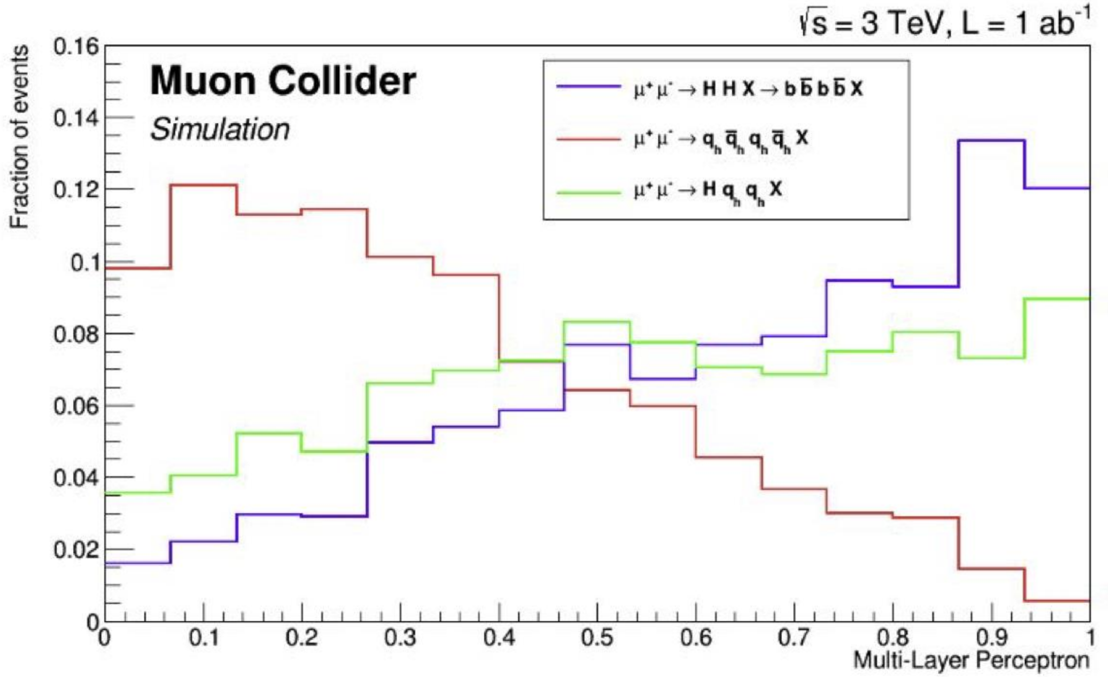
- **Background**: double quark-antiquark production (very abundant at LHC, small at muon collider)



Trilinear coupling from Di-Higgs

- HH→bbbb can be used to probe the precision on the **trilinear Higgs self-coupling λ_3**
- Samples of HH→bbbb have been simulated with WHIZARD for different values of $\kappa_\lambda=\lambda_3/\lambda_{SM}$
- Two MLPs are used to separate:
  - HH→bbbb from backgrounds
  - Trilinear contribution from other HH processes
- Pseudo-datasets are generated from 2D distributions of the two MLPs outputs
- Maximum-likelihood template fit performed for each κ_λ hypothesis

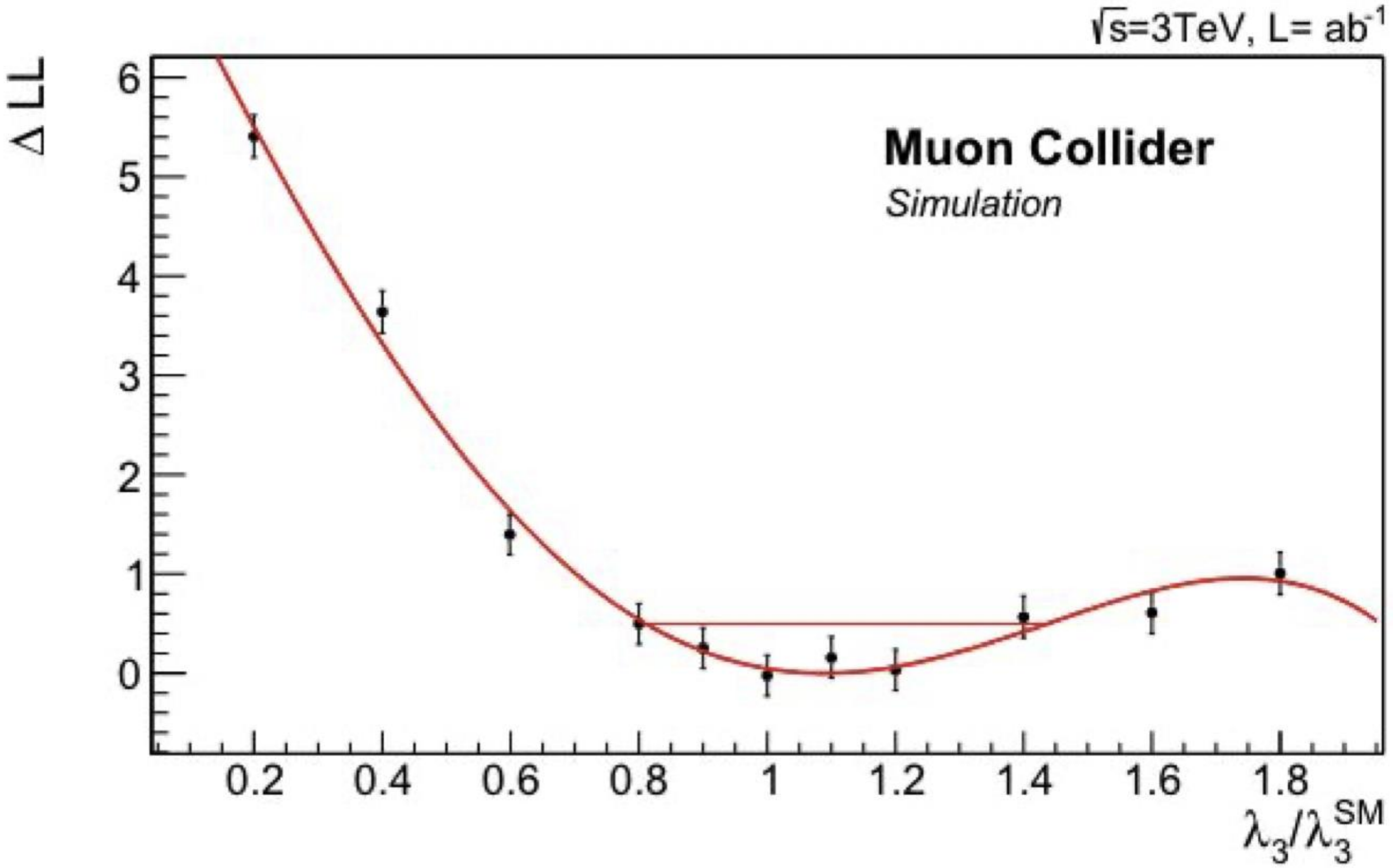




Trilinear coupling: results at 3 TeV

- Result: bound $0.81 < \kappa_\lambda < 1.44$ at 68% CL for 3 TeV, $1ab^{-1}$ in 5y
- Good precision despite 0.3 fb XS
- Full simulation study shows **comparable** results wrt expectations from pheno studies

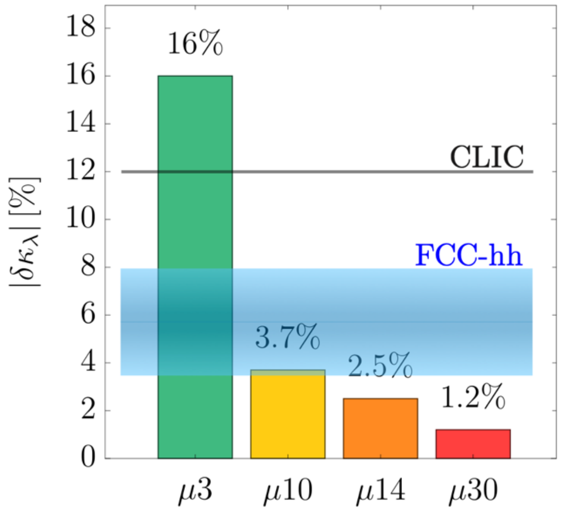
  (15% at 3 TeV with $2ab^{-1}$)
- Pheno studies extrapolation show that very high energy Muon Colliders (> 10 TeV) provide the most precise results among all future colliders



Going towards 10 TeV

- Having understood the 3 TeV case, we are studying the **10 TeV Muon Collider**
  - **Detector concept defined**
- Several considerations can be done:
  - BIB is going to impact **as 3 TeV case** (or even **less** with MDI well optimised)
  - **Reconstruction algorithm to be optimized**
  - Algorithms will be **tailored** for physics cases (e.g. ML for jets reconstruction)
- **The Muon Collider is one of the most interesting machine to study Higgs Physics**
  - Surpasses FCC-ee, except for a few decay channels and width measurements
  - Competitive with FCC-hh
    - Only parametric studies for now and requiring more time than MuC

Object	Requirements
muons	$\frac{\Delta p_T}{p_T} = 0.4\%$
photons	$\frac{\Delta E}{E} = 3\%$
jets	$\frac{\Delta p_T}{p_T} = 15\%$
b-jets	$\frac{\Delta p_T}{p_T} = 15\%$ b efficiency $= 60\ \%$ c mistag $= 20\ \%$
b-jets (for λ_3)	$\frac{\Delta p_T}{p_T} = 10\%$ b efficiency $= 76\ \%$ c mistag $= 20\%$



Summary + take home message

- Precision Higgs Physics will be the next milestone for future colliders
- The Muon Collider provides **clear advantages**:
  - Several high energy stages (at 10 TeV and beyond)
  - High statistics and access to multi-Higgs processes
  - Higgs physics reach competitive with FCC-hh, above FCC-ee (in almost all observables)
- Together with some important challenges:
  - R&D effort to satisfy machine requirements
  - Detector and algorithms optimisation to cope with **BIB presence**
- **Higgs physics at 10 TeV is similar to 3 TeV**
  - The 3 TeV Higgs physics case has been well understood
    - Study with detailed detector simulation provides **excellent agreement with pheno parametric studies**
    - This study paves the way to future studies at 10 TeV in time for the next ESPPU