Higgs Physics at Muon Collider

Luca Castelli on behalf of IMCC

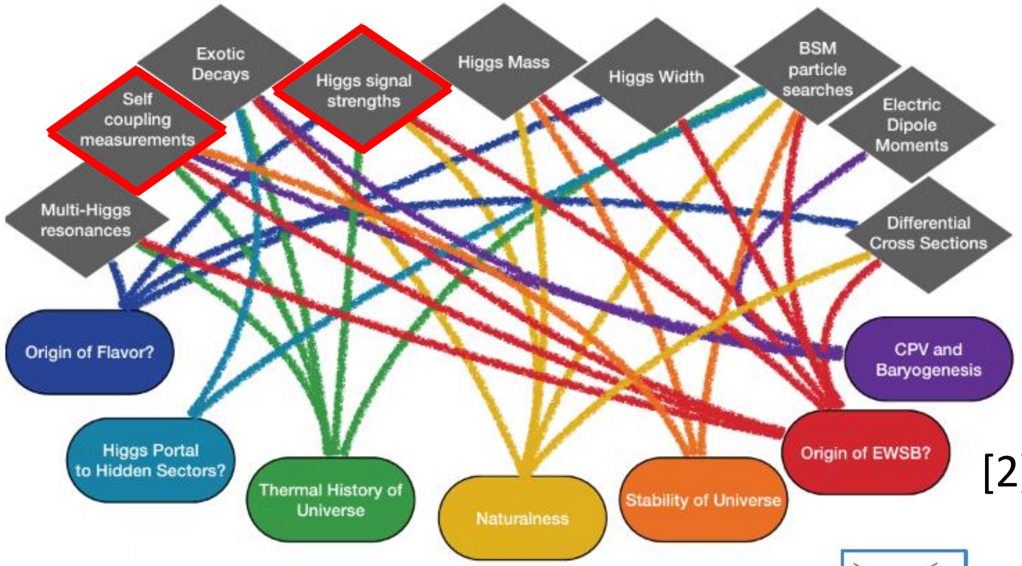
*Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

Higgs Physics at Future Colliders

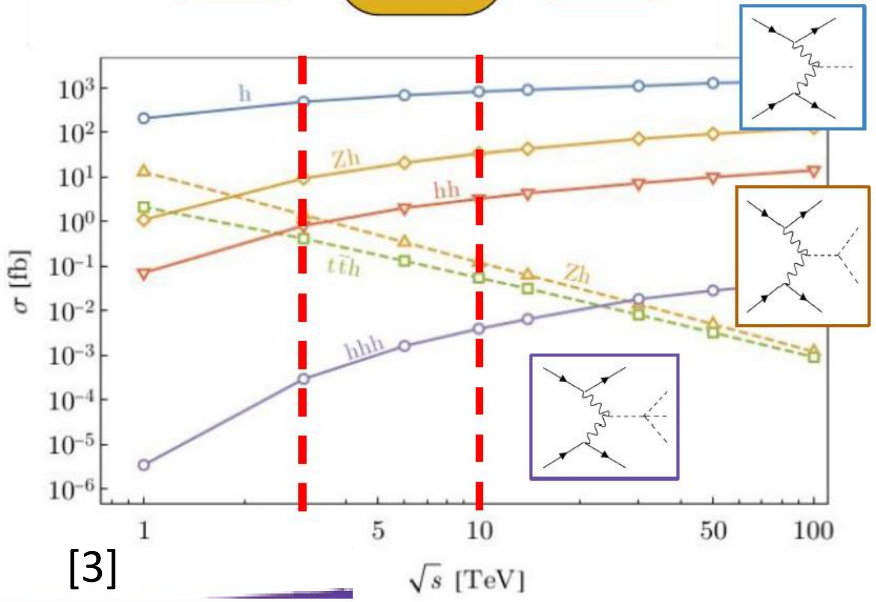
- Several open question on the Higgs Boson
- Future Collider goals:
  - Measuring Higgs coupling to fermions and boson at $\sim O(1\%)$ level
  - Measure Higgs Potential
- The Muon Collider:

Energy [TeV]	*Luminosity* $[ab^{-1}]$	*Number of Higgs*
3	*1*	$5 \cdot 10^5$
10	*10*	$9.5 \cdot 10^6$
14	*20*	$2.2 \cdot 10^7$

[1]



[2]

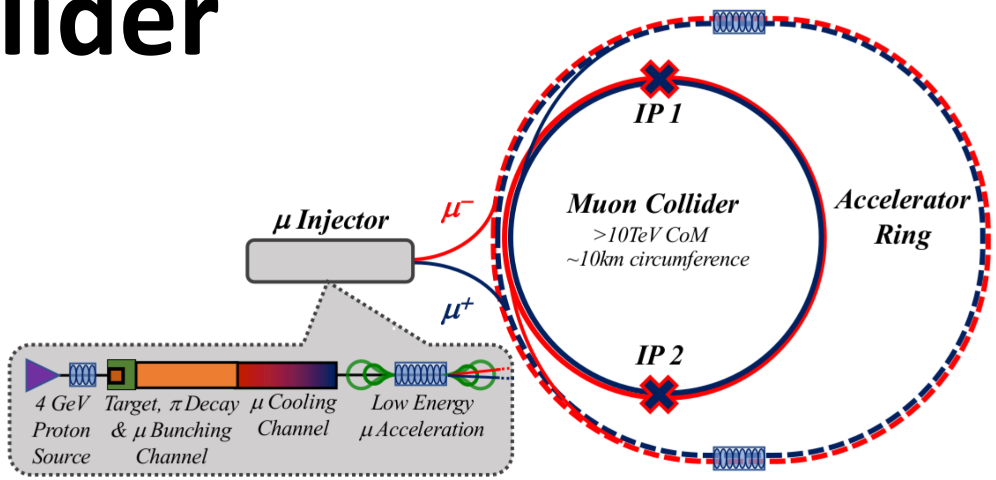


[3]

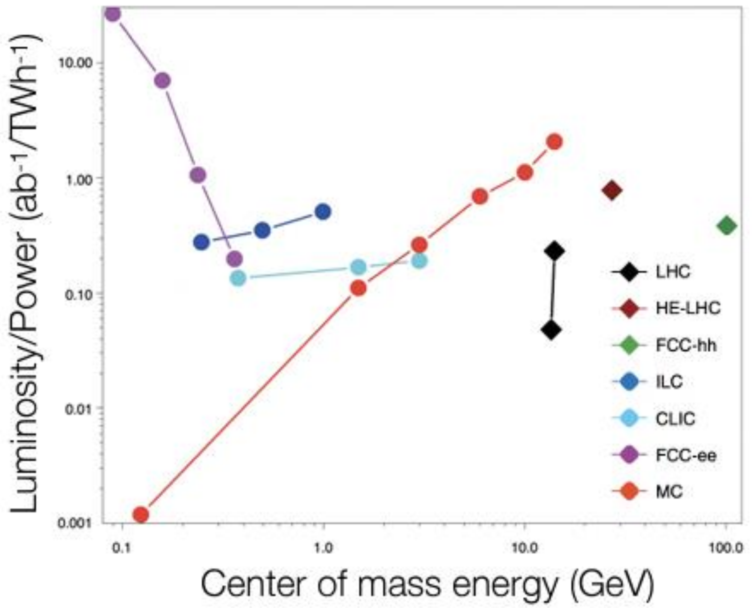
The Muon Collider

- **Motivation**
  - Both a precision and high energy collider
  - Luminosity scales with energy
  - Cost effective and sustainable machine
- **Challenges**
  - Muon beam production, cooling and acceleration
  - Beam Induced Background
  - Neutrino flux

[5]



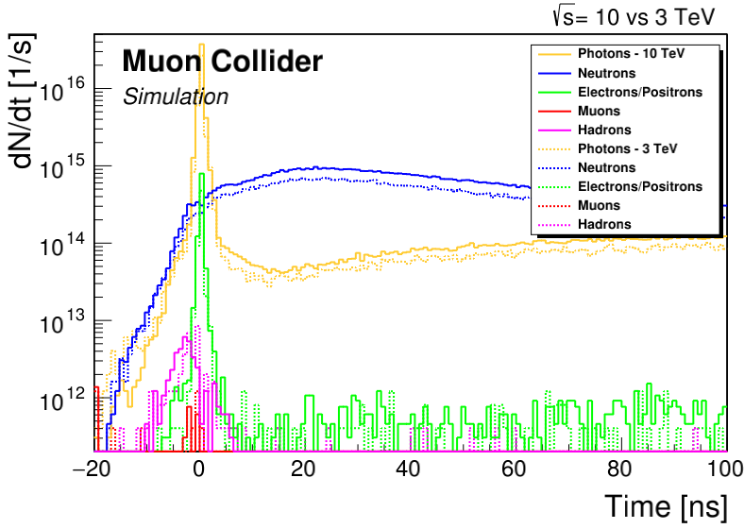
[3]

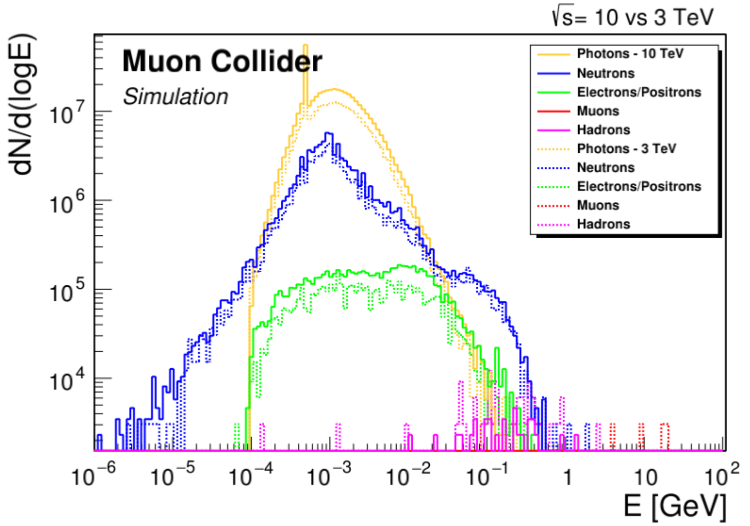


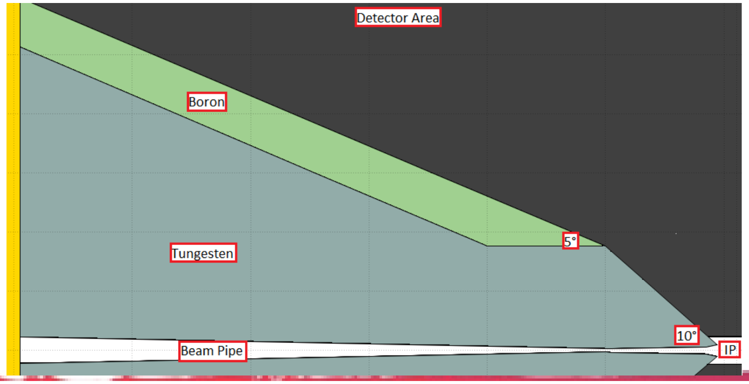
[4]

Beam Induced Background (BIB)

- Muon decay products interact with the machine
- Intense flux of particle reaches the detector
- Mitigation strategies required:
  - Tungsten nozzles mitigate the radiation coming to the detector
  - Readout window removes BIB off-time w.r.t. bunch crossing
- 10 TeV and 3 TeV BIB after mitigation strategies applied



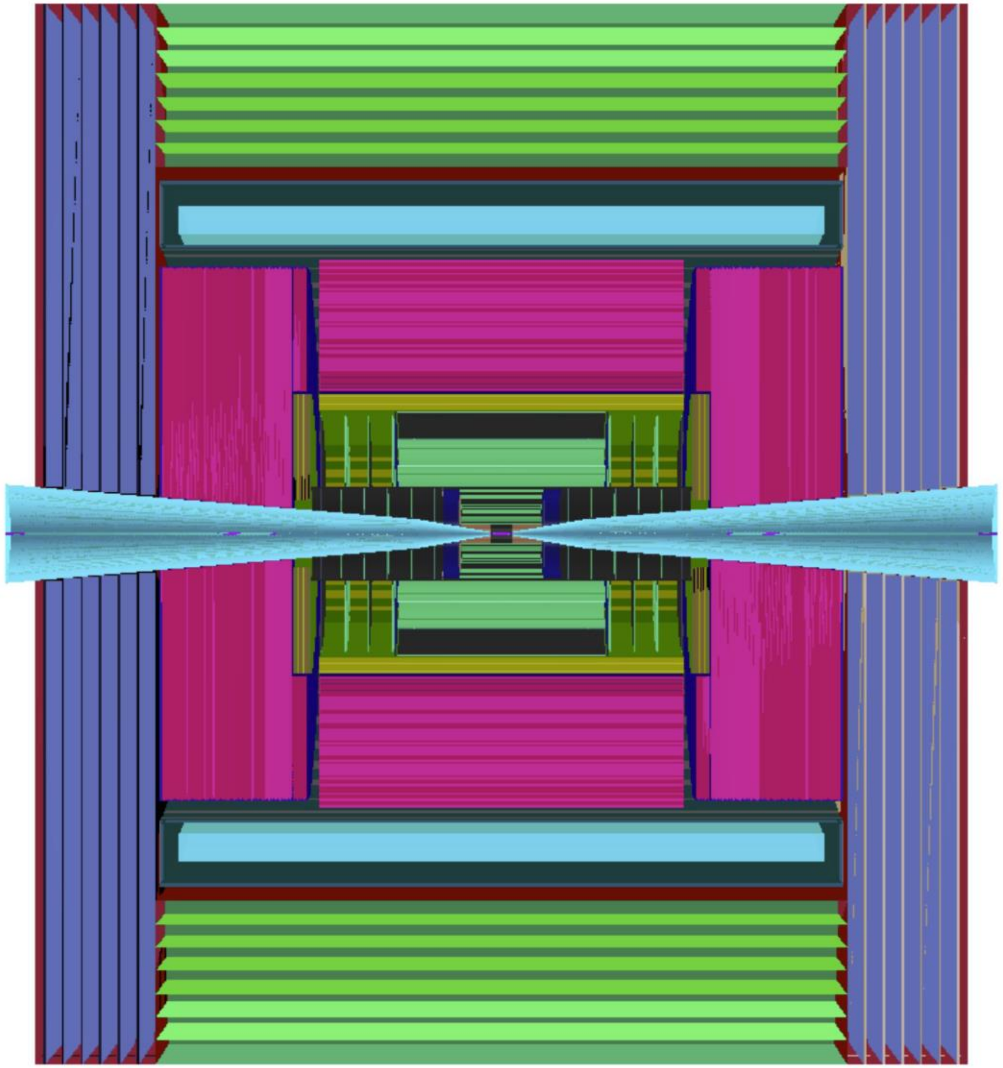




Tungsten Nozzle

Muon Collider Detector

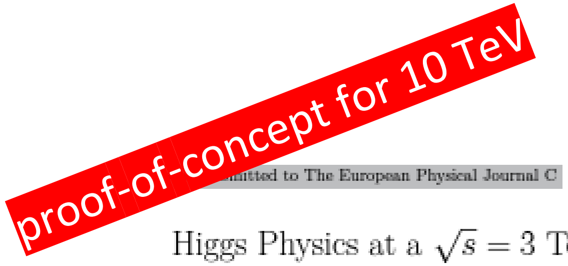
- 3 TeV detector based on CLIC studies [3]
  - Modified to accommodate the nozzles
- Two different detector configuration are under study for 10 TeV [6, 7]
- For the results in this talk:
  - Geant4-based simulation of the detector
  - 1.5 TeV BIB produced with MARS [8] (valid approximation of 3 TeV [9]) included
  - Reconstruction algorithms not optimized, i.e., performance are underestimated



Higgs studies with detailed detector simulation

- 3 TeV studies:
  - Higgs cross-section ($bb, WW^*, ZZ^*, \mu\mu, \gamma\gamma$)
  - Higgs width Γ
  - Double Higgs cross-section
  - Trilinear self- coupling λ_3
  - Comparison with parametric studies
- Comparison between 3 and 10 TeV physics
  - Objects are more boosted in the forward region
  - Transversal momentum distributions are similar
- **3 TeV studies are proof-of-concept for 10 TeV**

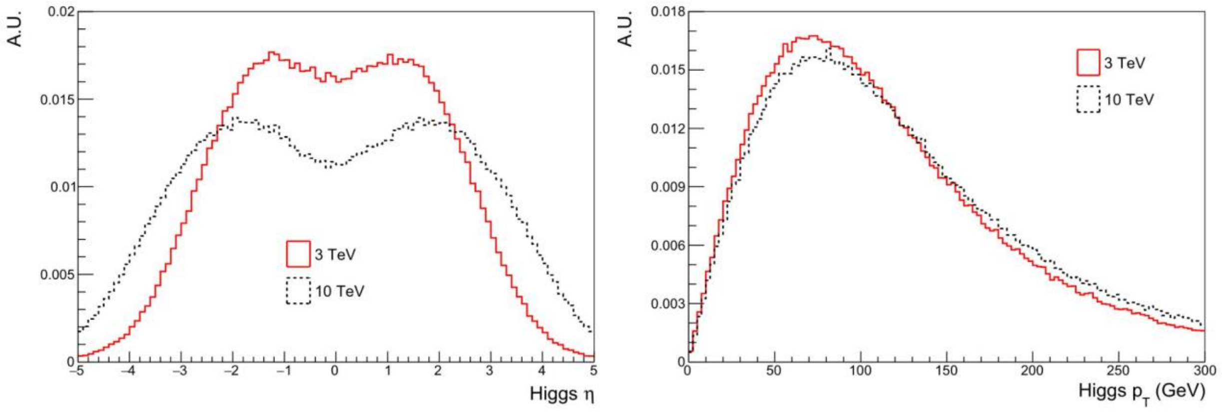
[10]



...itted to The European Physical Journal C

Higgs Physics at a $\sqrt{s} = 3$ TeV Muon Collider with detailed detector simulation

Paolo Andreetto[a], Nazar Bartosik[b], Laura Buonincontri[a,c], Daniele Calzolari[c,d], Vieri Candelise[e,f], Massimo Casarsa[e], Luca Castelli[g,h], Mauro Chiesa[i], Anna Colaleo[j,k], Giacomo Da Molin[l], Matthew Forslund[m], Luca Giambastiani[a,c], Alessio Gianelle[a], Karol Krizka[n], Sergo Jindariani[o], Anton Lechner[d], Donatella Lucchesi[a,c], Leo Mareso[c], Paola Mastrapasqua[p], Patrick Meade[m], Alessandro Montella[q], Simone Pagan Griso[r], Nadia Pastrone[b], Lorenzo Sestini[a], Rosamaria Venditti[j,k], Angela Zaza[j,k], Davide Zuliani[a,c]

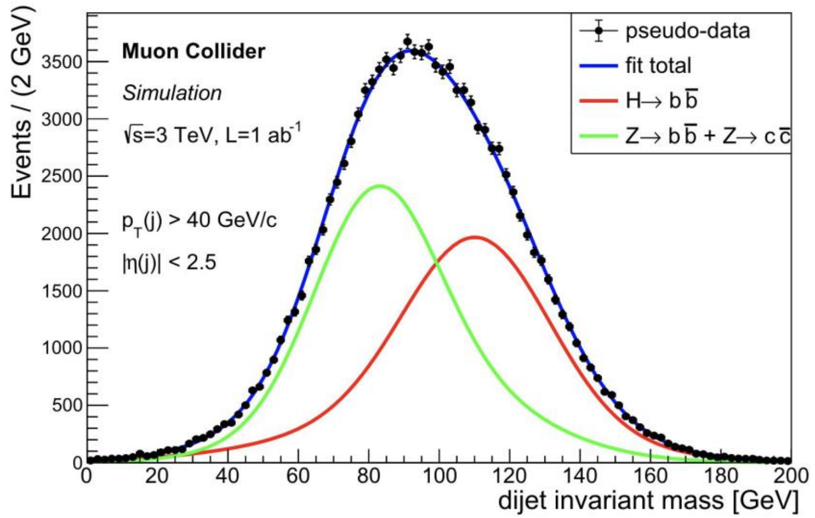


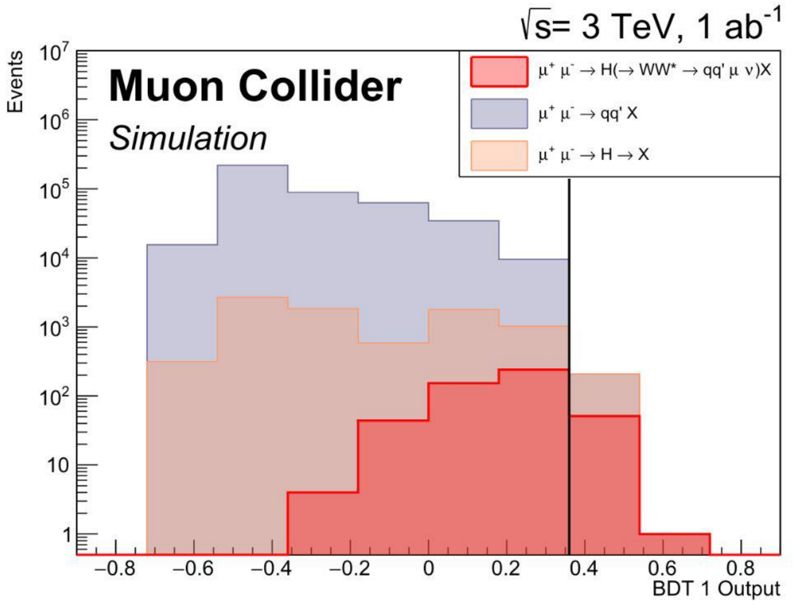
[11]

Higgs cross-section

[10]

- For each process signal and related background were simulated
- Precision on the cross-section:
  - $H \rightarrow bb$, estimated by unbinned maximum-likelihood fit on the invariant mass distribution
  - $H \rightarrow WW^*, ZZ^*, \mu\mu, \gamma\gamma$: statistical sensitivity of a counting experiment after BDT application for background rejection

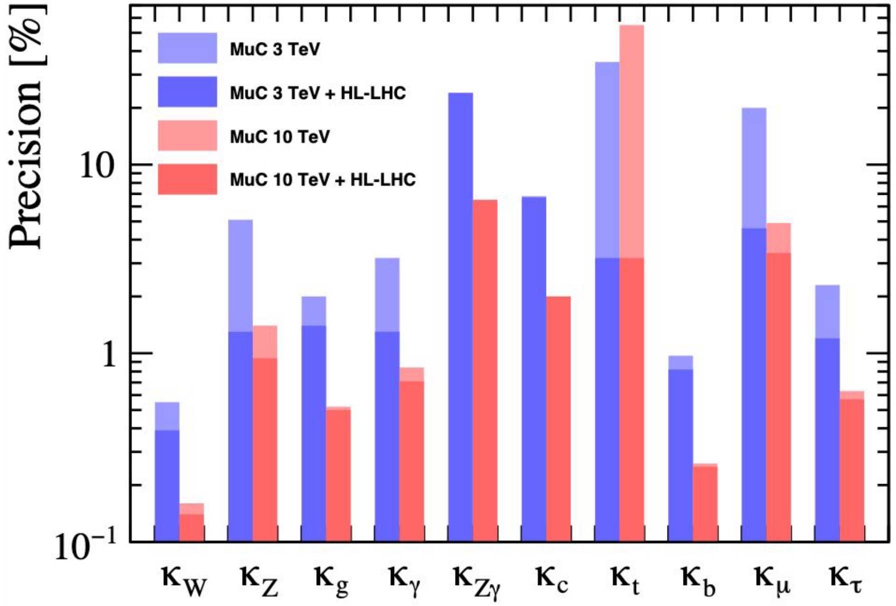




Comparison with parametric studies

- The full simulation results are compared with parametric studies (performed with Delphes card, without BIB [12])
- Results in very good agreement despite BIB being included in the full simulation
- We are confident to reach results obtained with the fast simulation at **10 TeV**

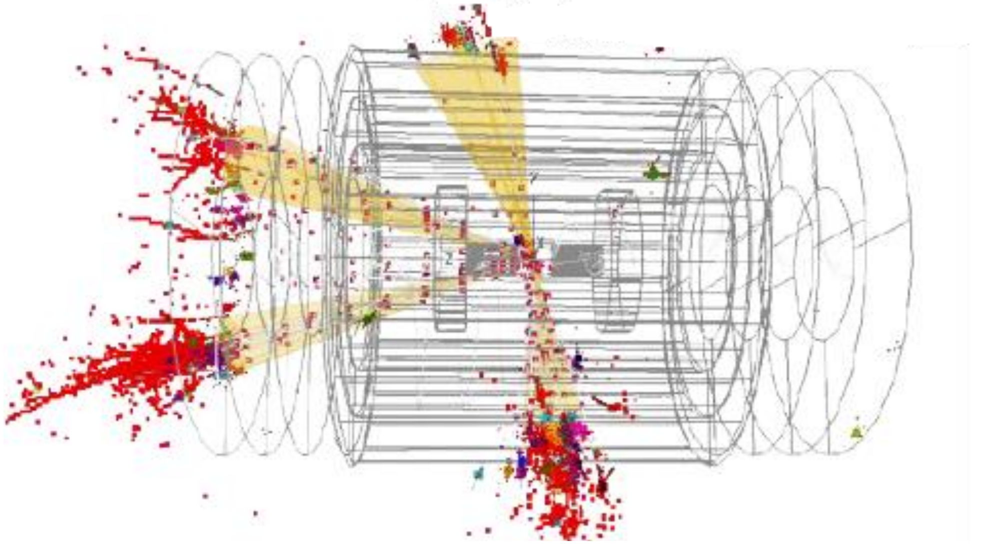
Process	Full Simulation	Parametric Simulation
$H \rightarrow bb$	*0.75%*	*0.76%*
$H \rightarrow WW^*$	*2.9%*	*1.7%*
$H \rightarrow ZZ^*$	*17%*	*11%*
$H \rightarrow \mu\mu$	*38%*	*40%*
$H \rightarrow \gamma\gamma$	*7.6%*	*6.1%*

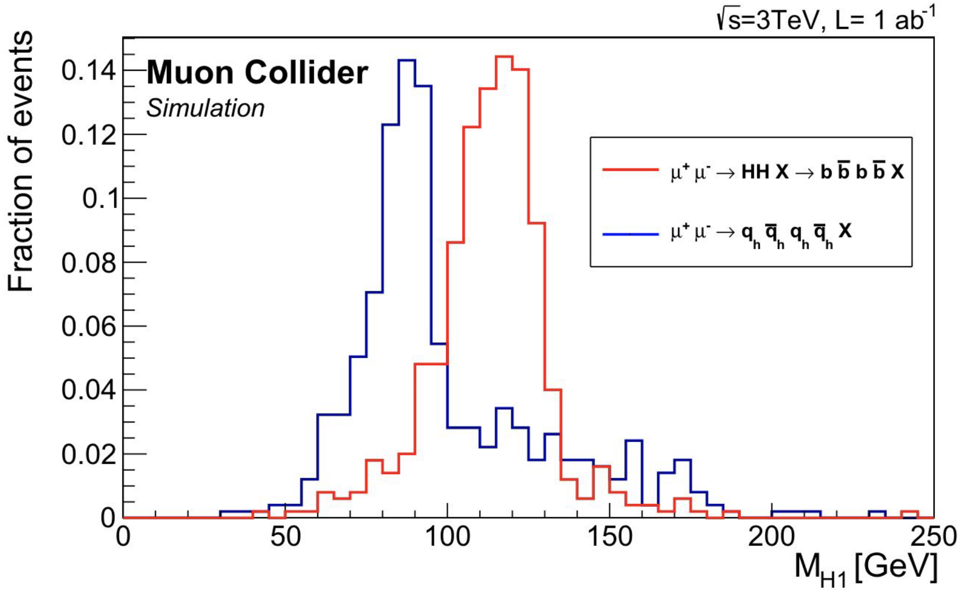


[13]

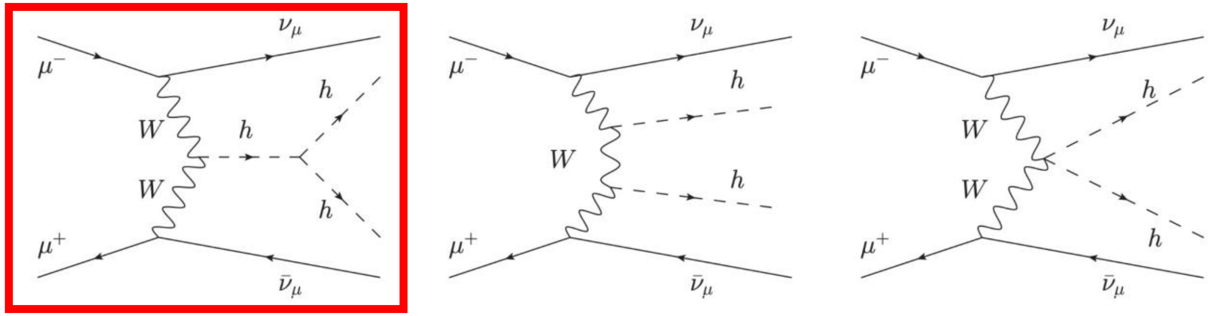
Double Higgs cross-section

- Signal: $\mu\mu \rightarrow \mathrm{HH} + \mathrm{X} \rightarrow bbbb + X$
  - More signals as $\mathrm{HH} \rightarrow bbWW$ or $\mathrm{HH} \rightarrow bb\gamma\gamma$ will be considered at 10 TeV
- Background: $\mu\mu \rightarrow \mathrm{H}(\rightarrow \mathrm{bb})\mathrm{qq} + \mathrm{X}, \mu\mu \rightarrow \mathrm{qqqq} + \mathrm{X}$
- Event selection:
  - 4 jets with $p_T > 20$ GeV, $|\eta| < 2.5$
  - At least 1 jet identified as b-jet
- Background discrimination with Neural Network
- At 3 TeV, with $L = 1\ ab^{-1}/5\ years$ $\frac{\Delta\sigma}{\sigma} = 33\%$





Precision on trilinear self-coupling λ_3

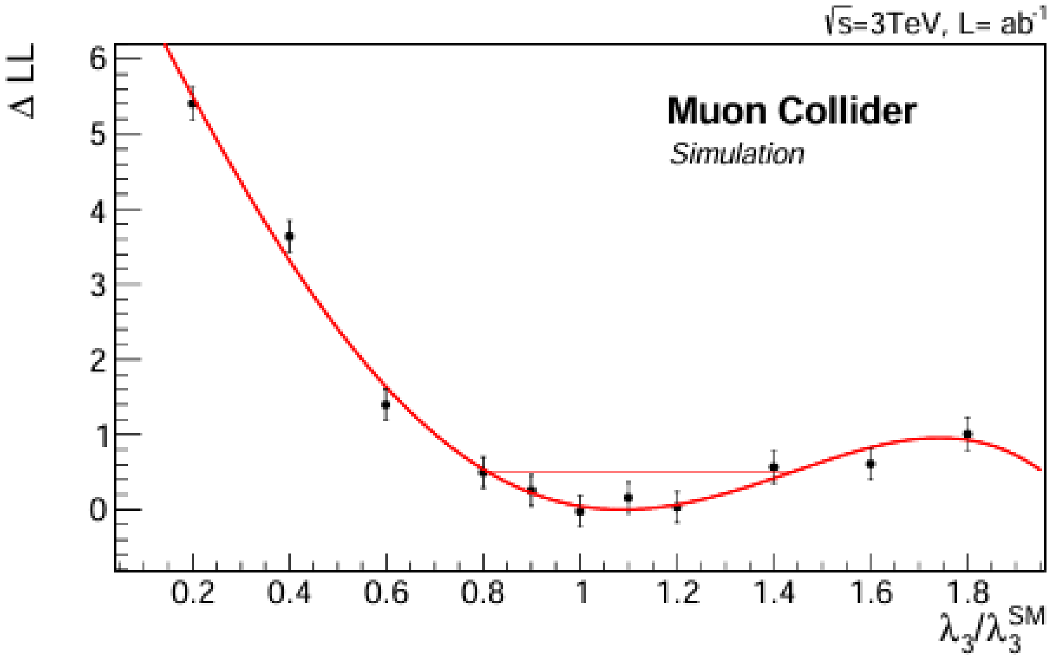


- μμ → HH production cross-section is sensitive to λ_3
- Samples of HH → $bbbb$ simulated with different values of $\kappa_\lambda = \frac{\lambda_3}{\lambda_{SM}}$
- Generated pseudo-datasets for $\kappa_\lambda = 1$ to performed a log-likelihood scan
- The 68% confidence interval is the interval around κ_λ = 1 where the fitted polynomial has a value below 0.5
- At 3 TeV, with $L = 1\ ab^{-1}/5\ years$:

$$0.81 < \kappa_\lambda < 1.44$$

- Compatible with the parametric simulation:

$$0.73 < \kappa_\lambda < 1.35$$



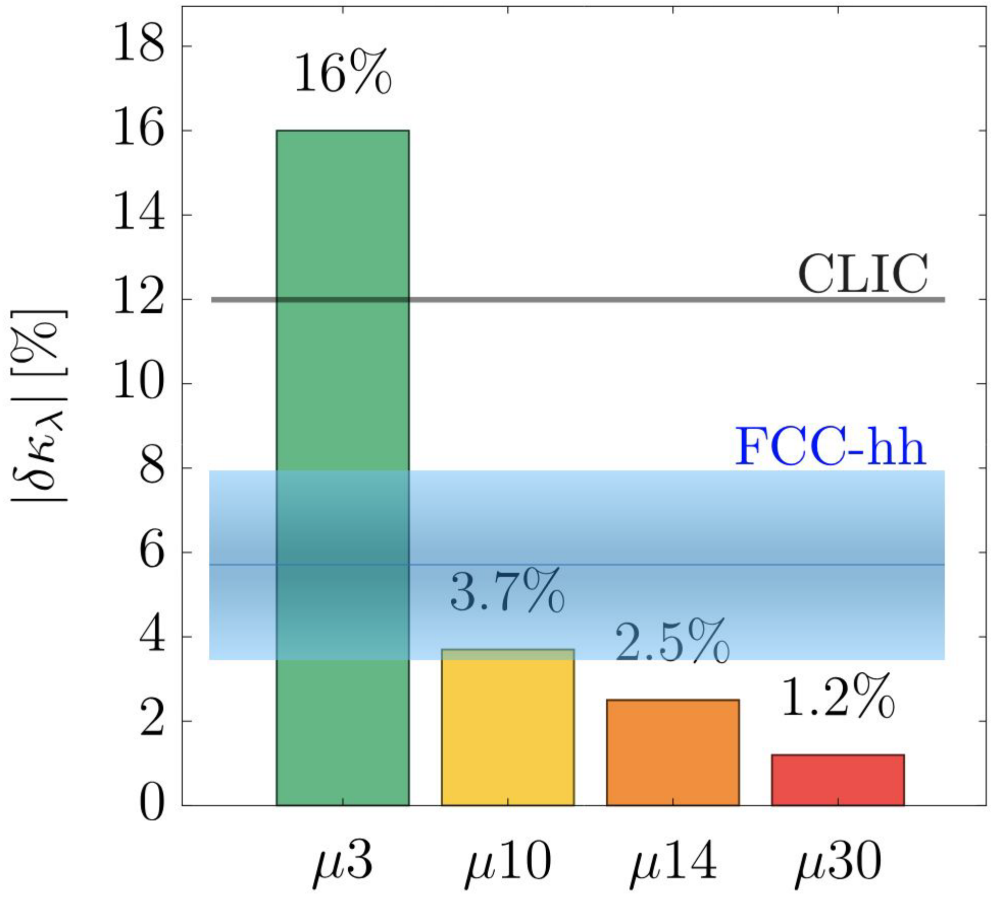
Higgs potential beyond 3 TeV

- Full simulation studies are comparable with parametric studies
- Going to higher energies and luminosities, the Muon Collider can achieve the most precise results
- Possible to measure the Higgs quartic self-coupling λ_4:
  - $\delta\lambda_4 = 50\%$, at $\sqrt{s} = 14\ TeV, L = 20\ ab^{-1}$(parametric studies only) [16]

Experiment	Luminosity	COM Energy	$\delta\lambda_3$
CLIC[14]	$5\ ab^{-1}$	*3 TeV*	*-7%, +11%*
ILC[14]	$8\ ab^{-1}$	*1 TeV*	*10%*
FCC-hh[15]	$30\ ab^{-1}$	*100 TeV*	*3.2%*
Muon Collider [3]	$2\ ab^{-1}$	*3 TeV*	*15%*
Muon Collider	$10\ ab^{-1}$	*10 TeV*	*3.5%*
Muon Collider	$20\ ab^{-1}$	*14 TeV*	*2.5%*

Going to 10 TeV

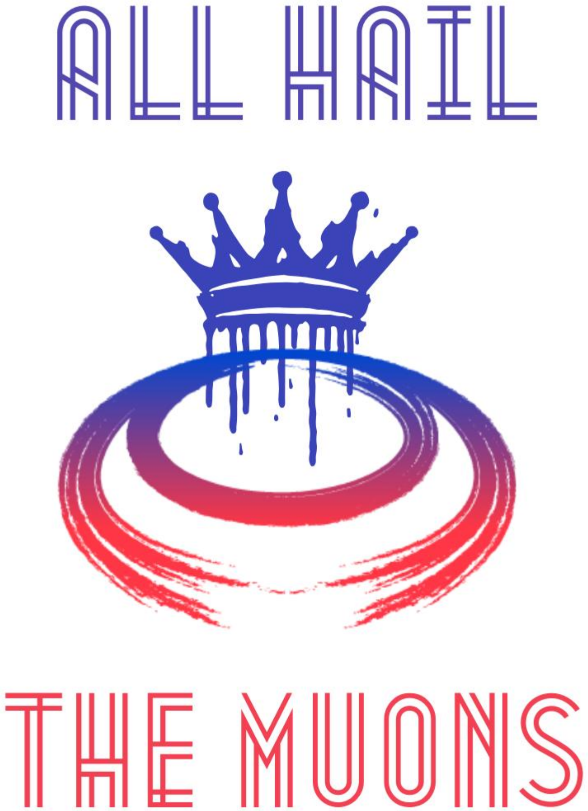
- 3 TeV full simulation results are compatible with parametric simulation despite including the Beam Induced Background. We can expect this to be the case for 10 TeV as well.
- 10 TeV optimization is ongoing considering:
  - Detector
  - Machine-Detector Interface (nozzles, BIB shielding…)
  - Reconstruction algorithm
- 10 TeV full simulation studies will be performed by the next European Strategy (March 2025)



[3]

Conclusion

- Precision Higgs Physics will be the milestone for future colliders
- The Muon Collider is a unique machine with clear advantages…
  - High energy stages ⇒ 10 TeV and beyond
  - High statistics and access to multi-Higgs processes
- … and challenges:
  - R&D necessary to satisfy machine requirements
  - Mitigation strategy of the Beam Induced Background
- The Higgs physics at 10 TeV is similar to 3 TeV
- Detail detector simulation agrees with parametric studies
- **The 10 TeV full detector simulation will be ready for the next ESPPU**



Thank you for the attention

Reference

- [1] P. Maede, Higgs coupling at Muon Collider, indico.cern
- [2] S. Dawson, P. Meade, I. Ojalvoc, C. Vernierid, Report of the Topical Group on Higgs Physics for the Energy Frontier: The Case for Precision Higgs Physics, arxiv.org
- [3] C. Accettura et al., Towards a Muon Collider, arxiv.org
- [4] K. Long, D. Lucchesi, M. Palmer, N. Pastrone, D. Schulte, V. Shiltsev, Muon Colliders: Opening New Horizons for Particle Physics, arxiv.org
- [5] C. Accettura et al., Interim report for the International Muon Collider Collaboration, arxiv.org
- [6] M. Casarsa, C. Giraldin, D. Lucchesi, L. Palombini, L. Sestini, D. Zuliani, Detector-1 configuration quick overview, MuSIC Detector
- [7] K. Kennedy, A New Detector Concept for a 10 TeV Muon Collider, Maia Detector
- [8] F. Collamati, C. Curatolo, D. Lucchesi, A. Mereghetti, N. Mokhov, M. Palmer and P. Sala, Advanced assessment of beam-induced background at a muon collider, iop.org

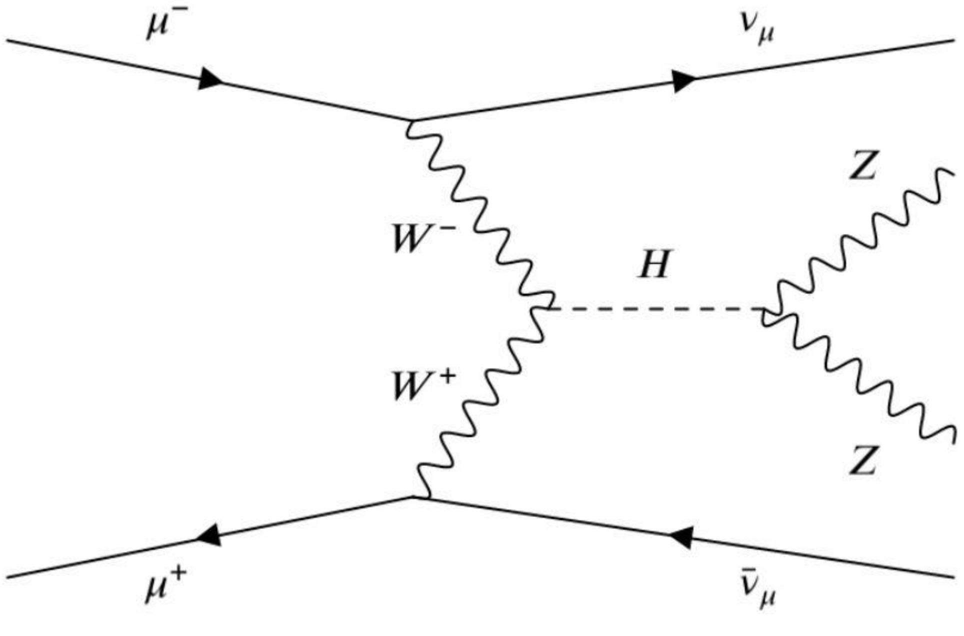
Reference

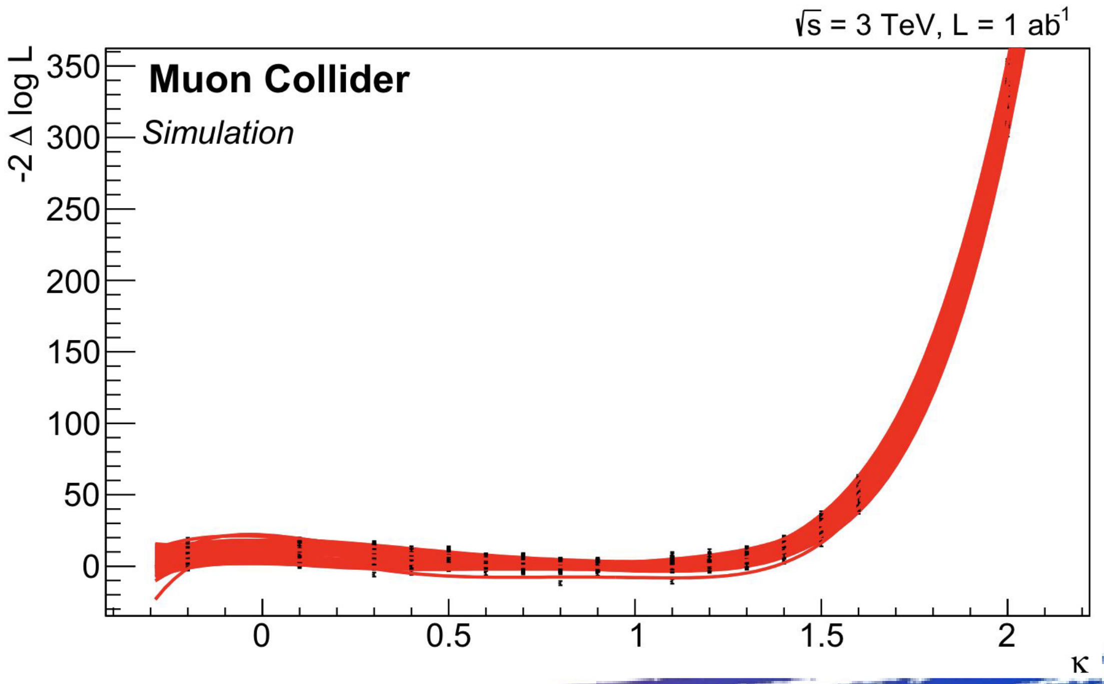
- [9] N. Bartosik, D. Calzolari, L. Castelli, A. Lechner, D Lucchesi, Machine-Detector interface for multi-TeV Muon Collider, pos.sissa.it
- [10] P. Andreetto et al., Higgs Physics at a $\sqrt{s} = 3\ TeV$ Muon Collider with detailed detector simulation, arxiv.org
- [11] M. Forslund, P. Meade, Precision Higgs Width and Couplings with a High Energy Muon Collider, arxiv.org
- [12] M. Forslund, P. Meade, High precision higgs from high energy muon colliders, springer.com
- [13] M. Casarsa, D. Lucchesi, L. Sestini, Experimentation at a muon collider, arxiv.org
- [14] J. de Blas et al., Higgs Boson studies at future particle colliders, arxiv.org
- [15] B. Stapf, A. Taliercio, E. Gallo, K. Tackmann, P. Mastrapasqua, Higgs self-coupling measurements at the FCC-hh, arxiv.org
- [16] M. Chiesa et al., Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, arxiv.org

Backup

Higgs Width Γ

- e^+e^- colliders measure the Higgs width using ZH events and measuring the recoil mass
- At >3 TeV Muon Collider, the ZH cross section is rather small, ○ therefore, the “on-shell/off-shell” analysis is employed
- $\mu^+\mu^- \rightarrow \nu\nu ZZ$ is considered as the process most sensitive to κ
- A maximum likelihood template fit to κ is done to extract precision on κ
- Combination with expected precision on $\sigma(H \rightarrow ZZ^*)$ show a precision on $\frac{\Gamma}{\Gamma_{SM}} = 1^{+71\%}_{-88\%}$
- Results are comparable with expectations from parametric studies
- For 10 TeV: $\Delta\Gamma = 3.4\%$





Muon Collider Parameters

Target integrated luminosities

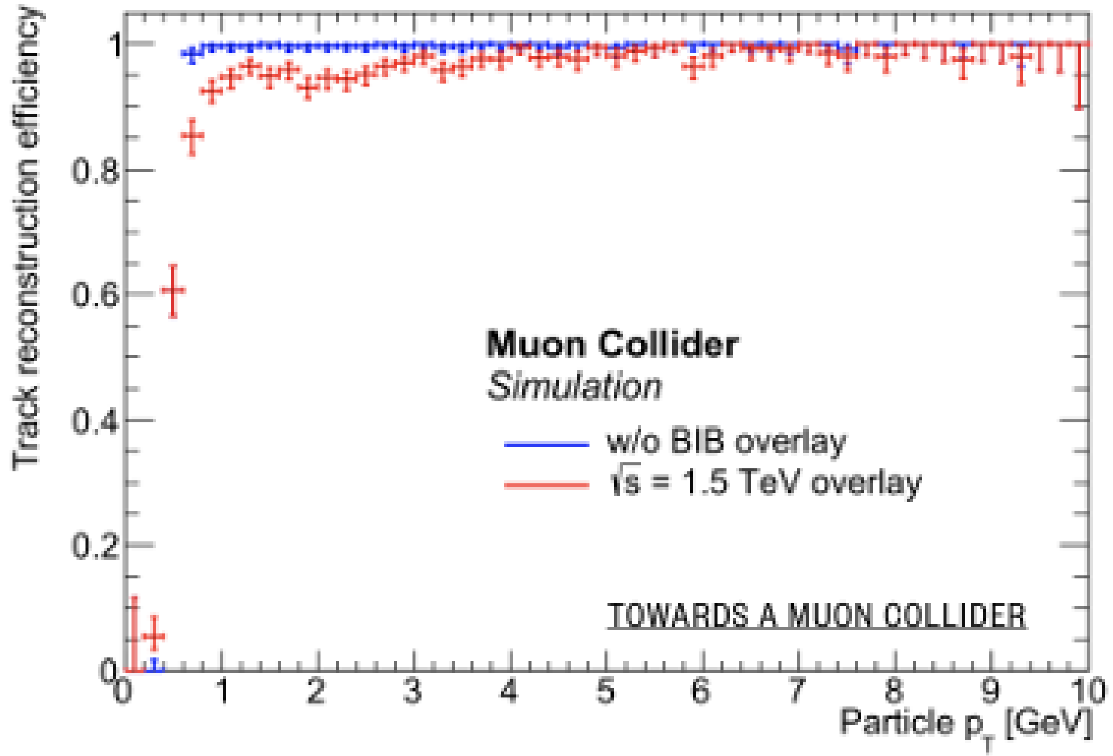
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

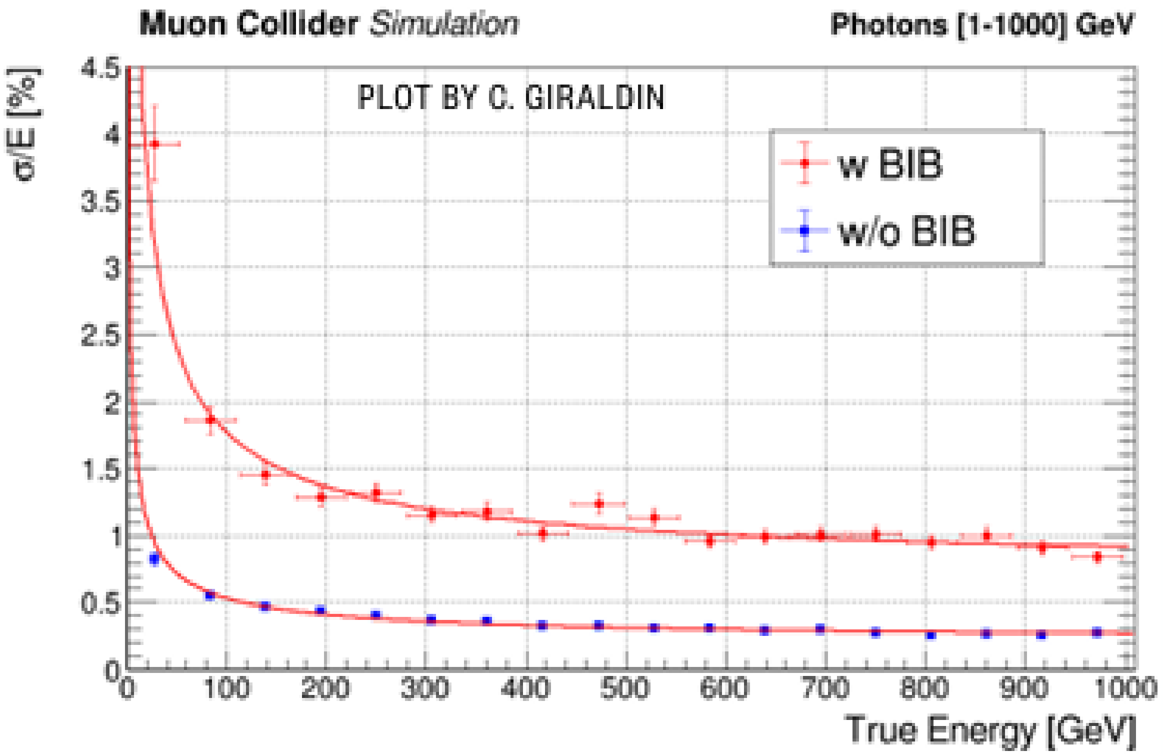
Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

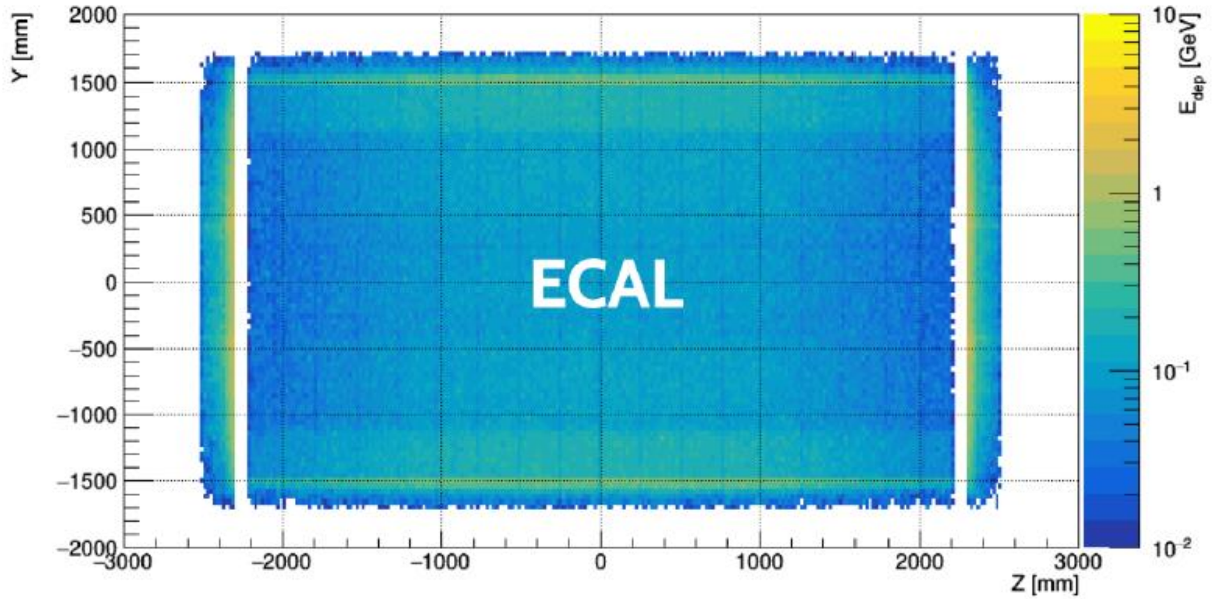
Detector performance

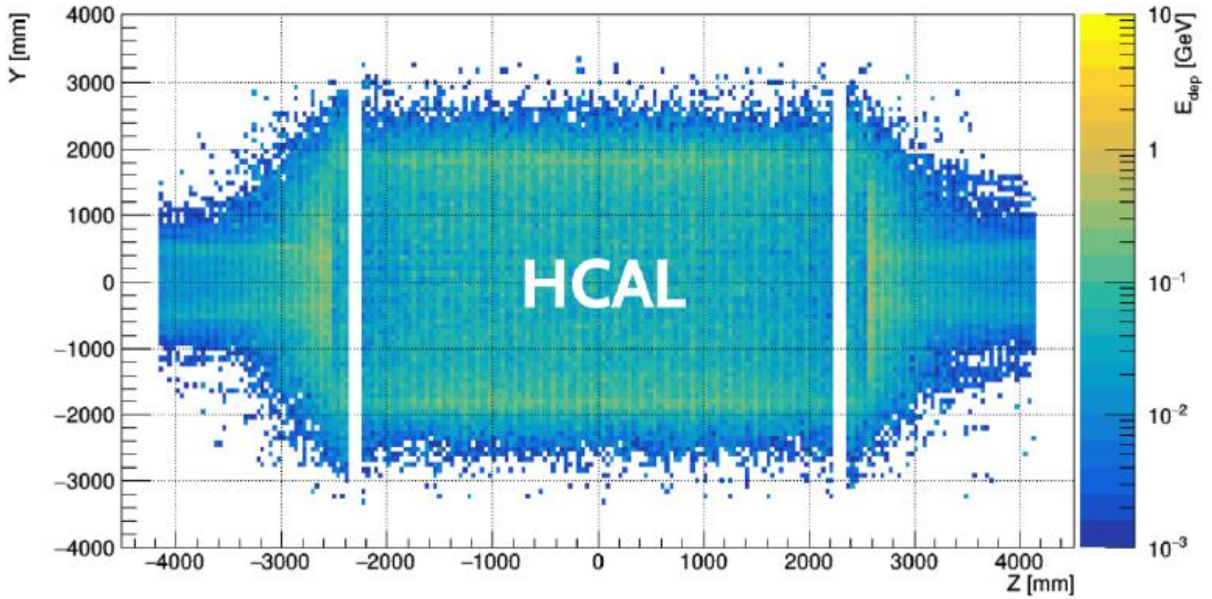




BIB discrimination

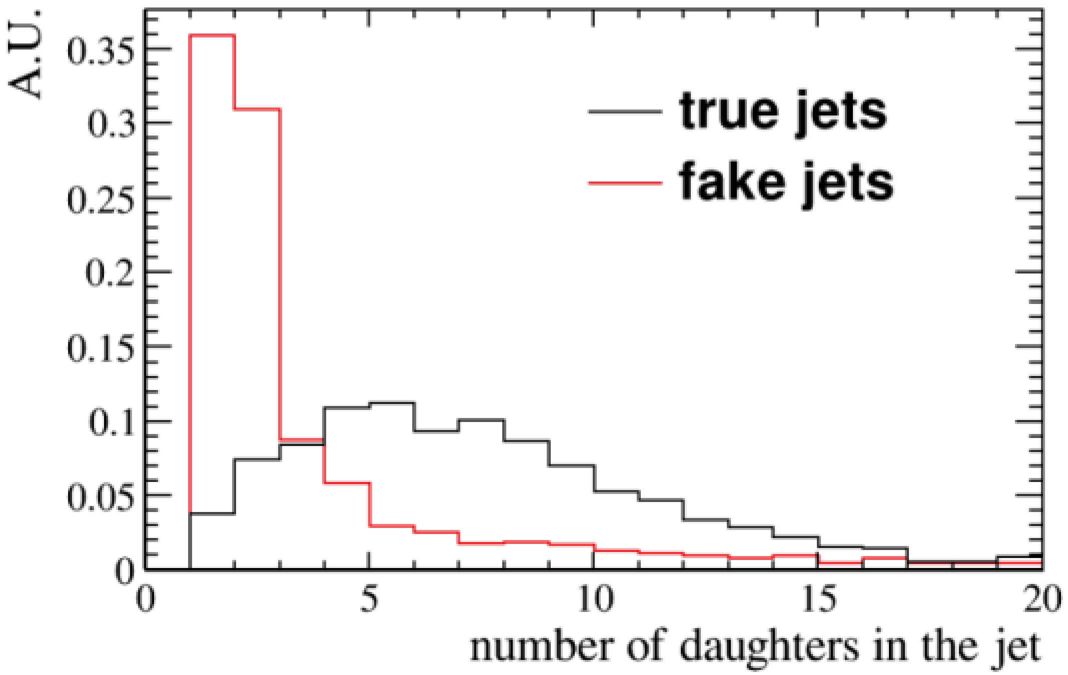
- **Energy deposit on calorimeters:**

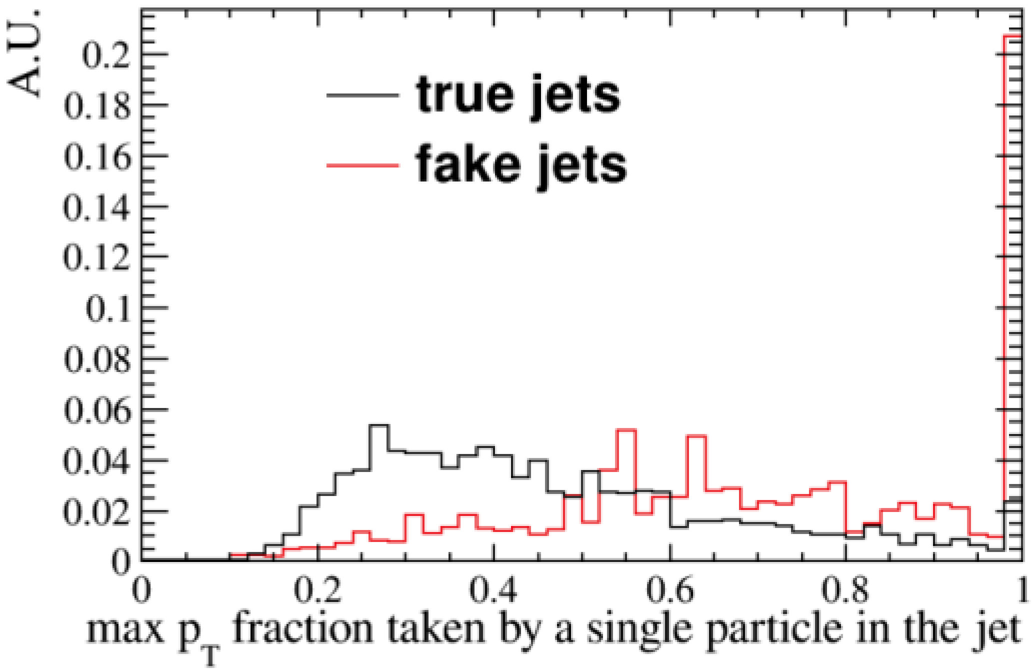




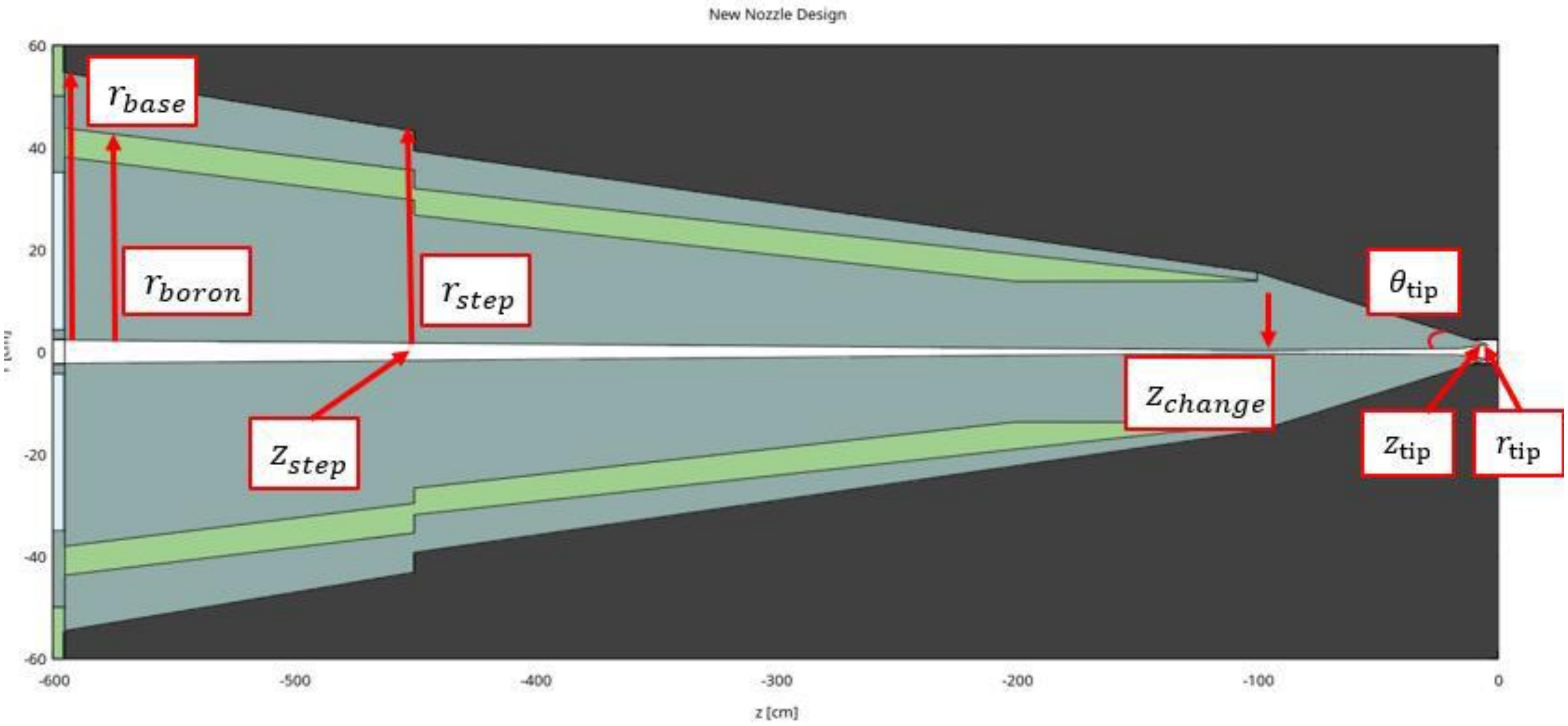
BIB discrimination

- **Jets reconstruction:**





Nozzle Optimization



Forward Muons

- Two main candidates:
  - Nozzle: Small detector, high dose for BIB
  - Cavern: Large detector, clean environment
- $\sim 50\%$ of forward muon tagging in the nozzle