Higgs Physics at Multi-TeV Muon Collider

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On behalf of IMCC

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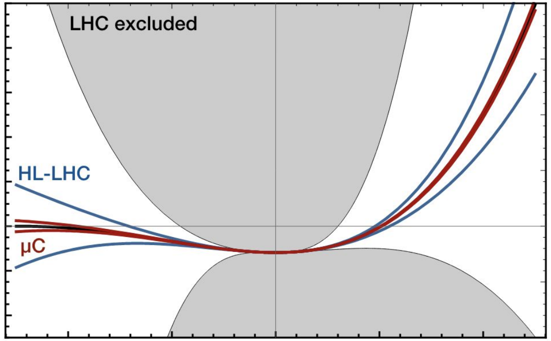
Higgs Physics at Muon Collider

- 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

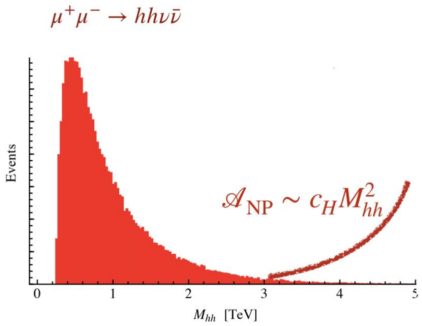


credits: Craig, Petrossian-Byrne

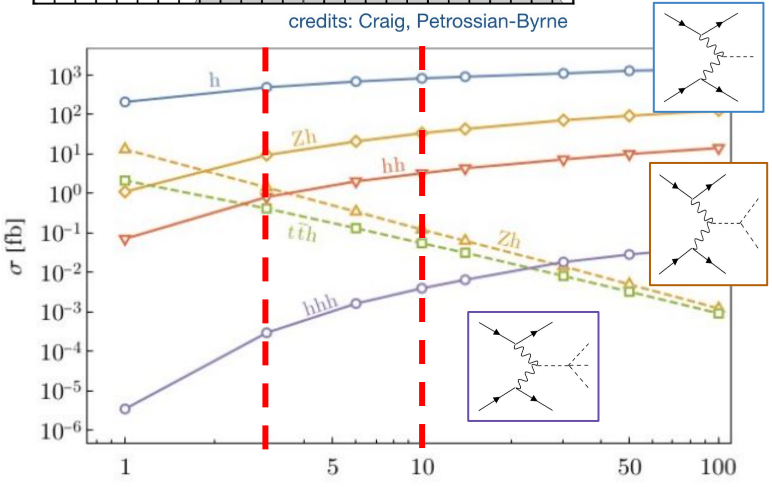
- The **Muon Collider** is by all means a **Higgs factory**

from P. Meade presentation

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



(see also Contino et al. 1309.7038)

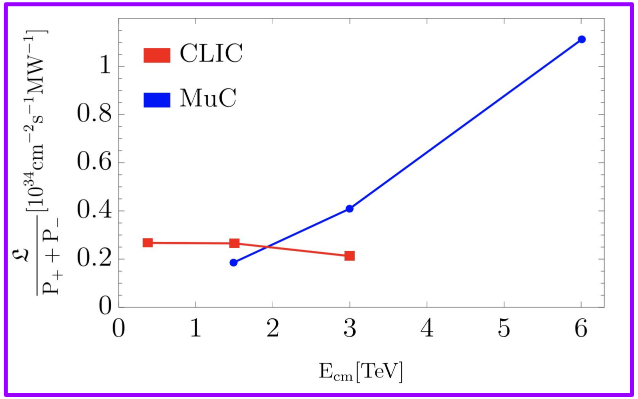


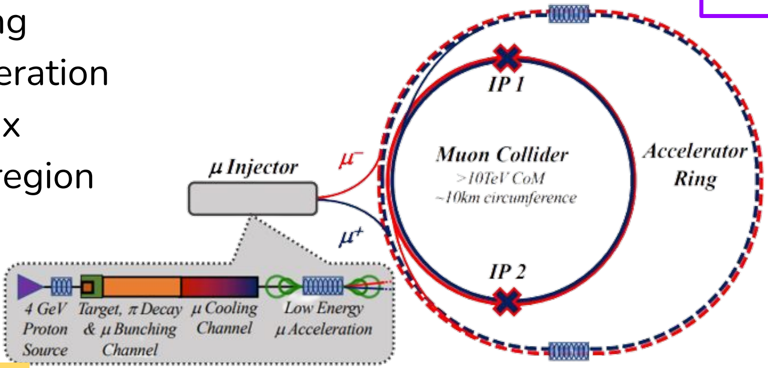
[2303.08533] Towards a Muon Collider

The Muon Collider

- A Muon Collider has several **advantages**:
  - possibility to accelerate muons to higher energies
  - **higher luminosities** with **higher energies**
  - **cost effectiveness** and **sustainability**

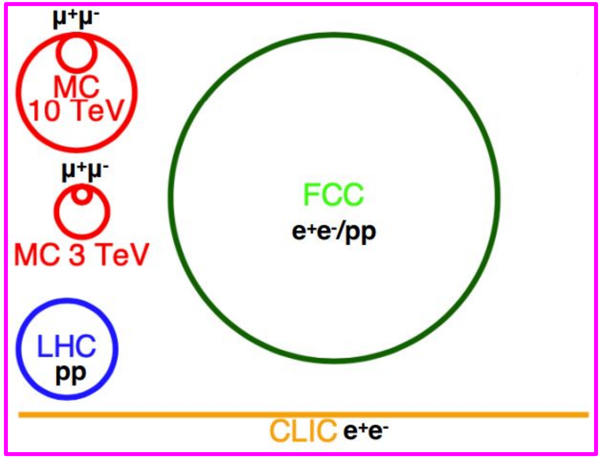
- There are also some **key challenges (R&D effort)**:
  - Proton source
  - Muon cooling
  - Beam acceleration
  - Neutrino flux
  - Interaction region





Talk by D. Lucchesi

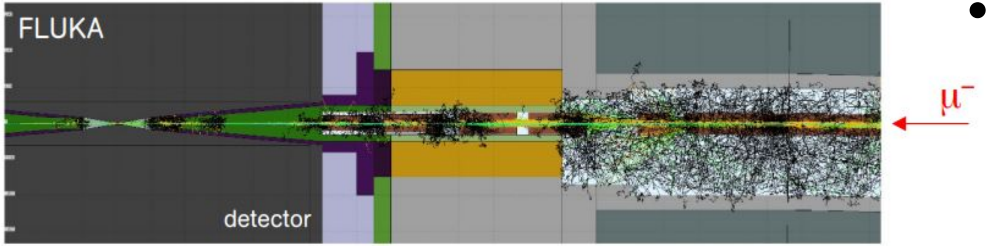
[2303.08533] Towards a Muon Collider

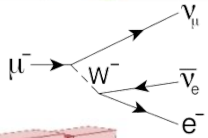


[2407.12450] Interim report for the International Muon Collider Collaboration

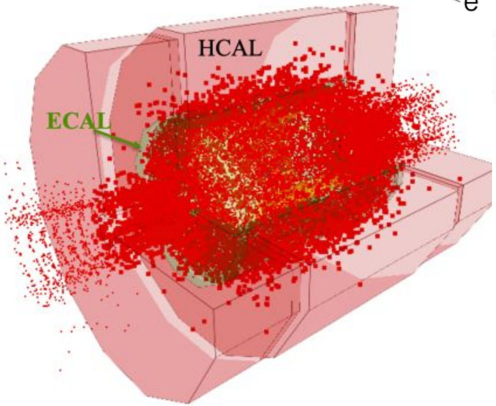
Beam-Induced Background (BIB)

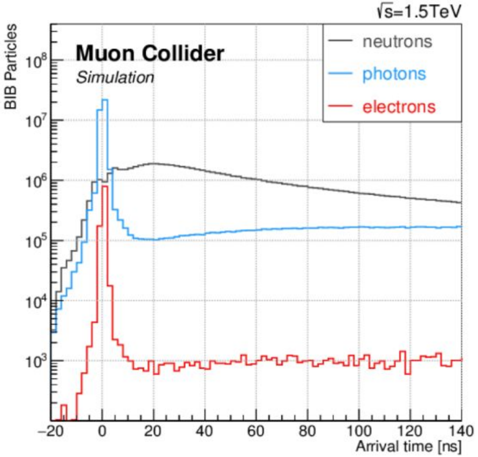
[2105.09116] Advanced assessment of Beam Induced Background at a Muon Collider





τ = 2.2 μs





[2303.08533] Towards a Muon Collider

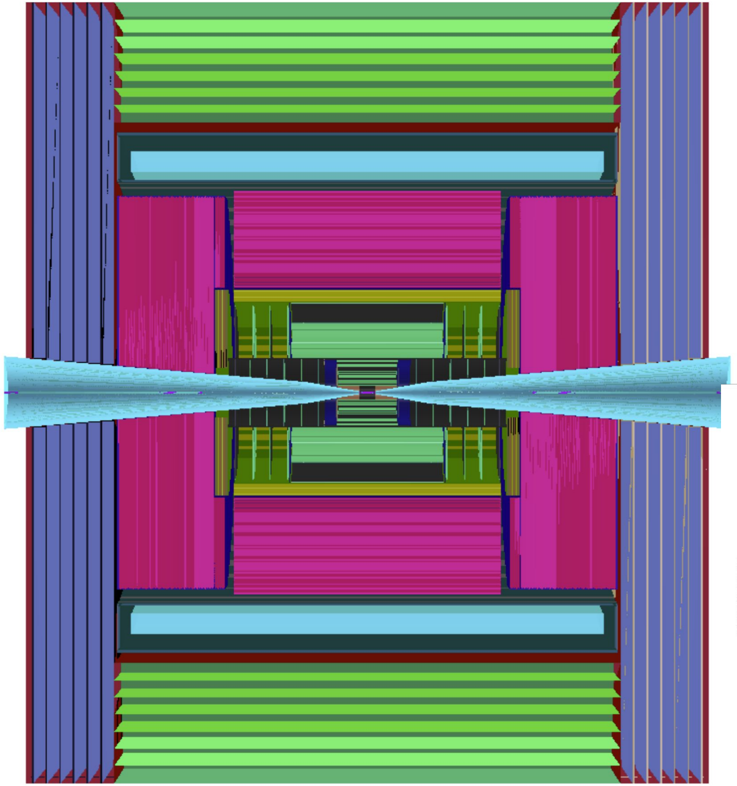
- Muons decay → decay products interact with machine:
  → **intense fluxes of particles reach the detector**:
  - high multiplicity of particles in the tracker (mainly in first layers)
  - **diffuse background in calorimeters**

- **Innovative techniques** and optimised algorithms are fundamental to mitigate the impact of BIB
  - Tungsten **nozzles** mitigate radiation coming to the detector
  - **BIB is off-time wrt bunch crossing**, algorithms tailored to exploit these features

- Fundamental to have an **optimised concept** of the detector at 10 TeV

Muon Collider detector

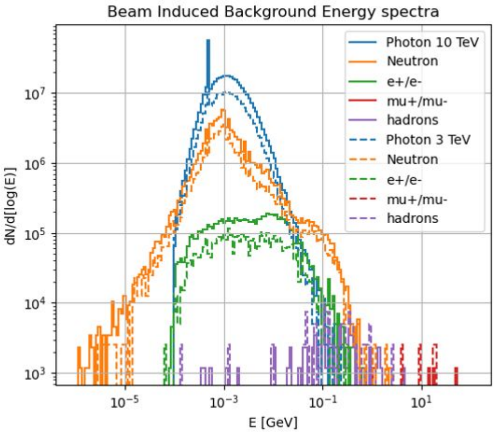
[2303.08533] Towards a Muon Collider

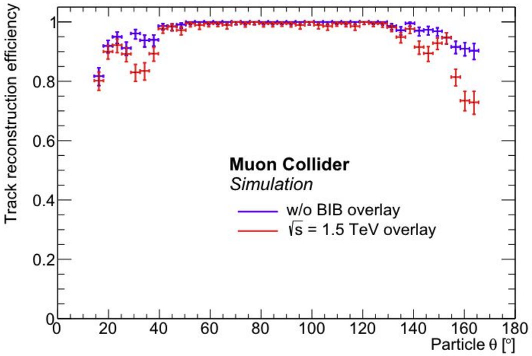


- **3 TeV configuration** from CLIC detector
  - VXD updated to accommodate IR and nozzles
- For 10 TeV configuration, **detector** and **MDI** optimisation is in progress

Talks by M. Casarsa and D. Calzolari

- BIB simulated by MARS @ 1.5 TeV → **same/less** impact from BIB @ **10 TeV**
- Algorithms not optimised → **performance underestimated**





Higgs at Muon Collider with detailed detector simulation

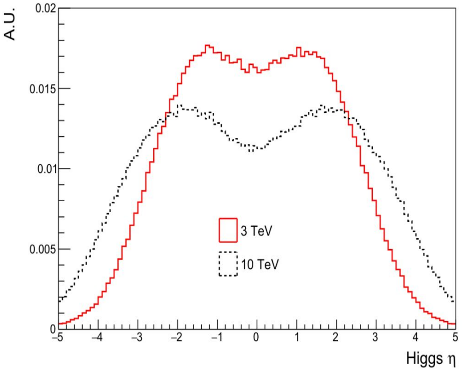
- **Higgs Physics at 10 TeV is similar to 3 TeV**
  - Objects **more boosted** in the forward region
  - Transverse momentum distributions similar

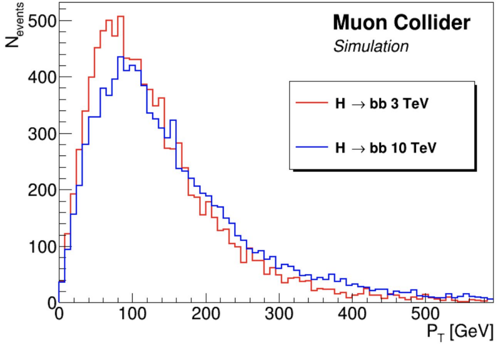
- While configuring 10 TeV detector, a study has been done for Higgs Physics at 3 TeV, using **detailed detector simulation**

- Main purposes of this work:
  - Prove that **BIB is under control**
  - Compare results with parametric studies

- List of studies:
  - Higgs cross-sections (bb, WW*, ZZ*, μμ, γγ)
  - Higgs width Γ
  - Double Higgs cross-section
  - Trilinear self-coupling λ_3

[2405.19314] Higgs Physics at a 3 TeV Muon Collider with detailed detector simulation





[2308.02633] Precision Higgs Width and Couplings with a High Energy Muon Collider

Preprint submitted to The European Physical Journal C

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

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Proof-of-concept for coming 10 TeV studies

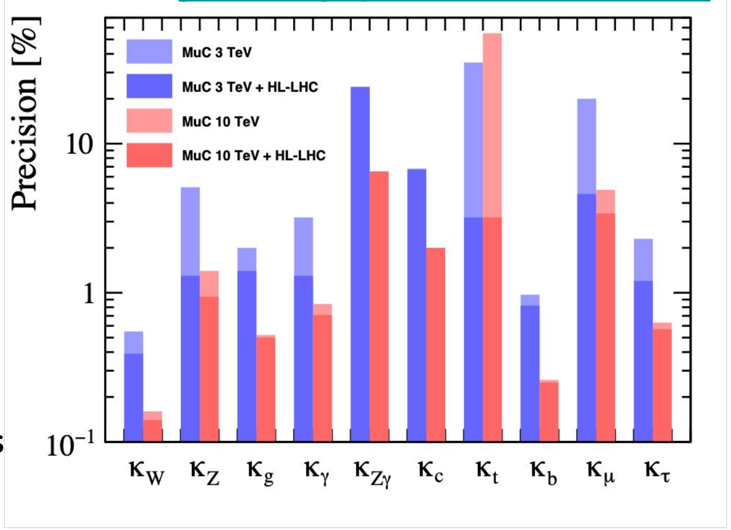
Results at 3 TeV and comparison with parametric studies

- Results obtained with full simulation are compared with parametric studies (obtained with **Delphes card**)
- Results are in **good agreement** → **BIB is perfectly under control**

Higgs decay channel	Full simulation	Parametric simulation
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%

[2308.02633] Precision Higgs Width and Couplings with a High Energy Muon Collider

[2311.03280] Experimentation at a muon collider

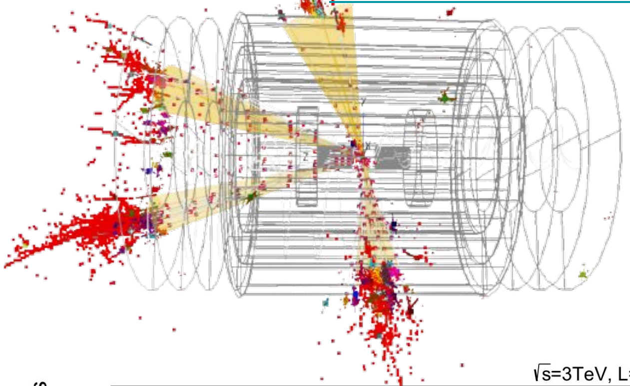


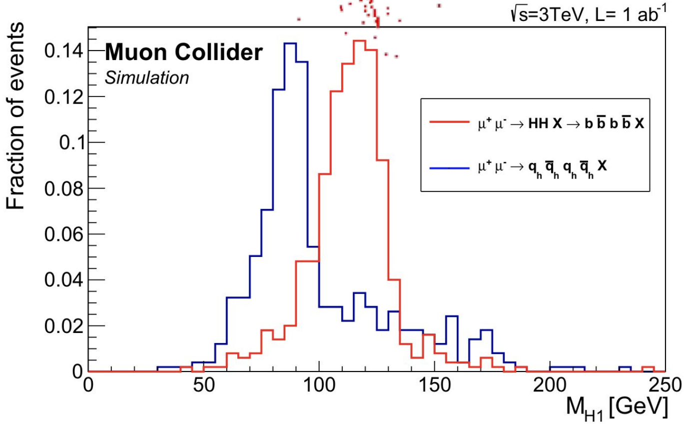
- We are confident to reach results obtained by **pheno studies**
- The Muon Collider is definitely **competitive** in the landscape of future colliders

Di-Higgs production

[2405.19314] Higgs Physics at a 3 TeV Muon Collider with detailed detector simulation

- 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 $\sqrt{[(m_{12}-m_H)^2 + (m_{34}-m_H)^2]}$
  - B-jet tagging identification algorithms required for one jet per di-jet pair





- **Neural Network** to separate signal from background

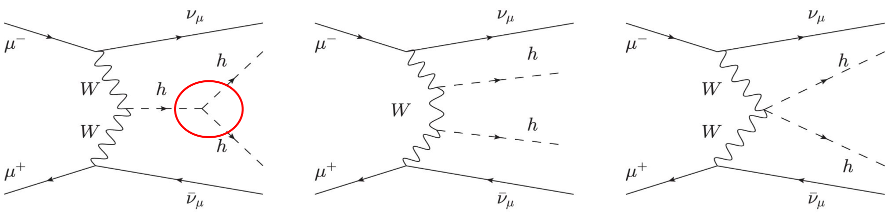
E_{com} = 3 TeV, 1 ab^{-1} / 5 years
$\Delta\sigma/\sigma$ ~ 33%

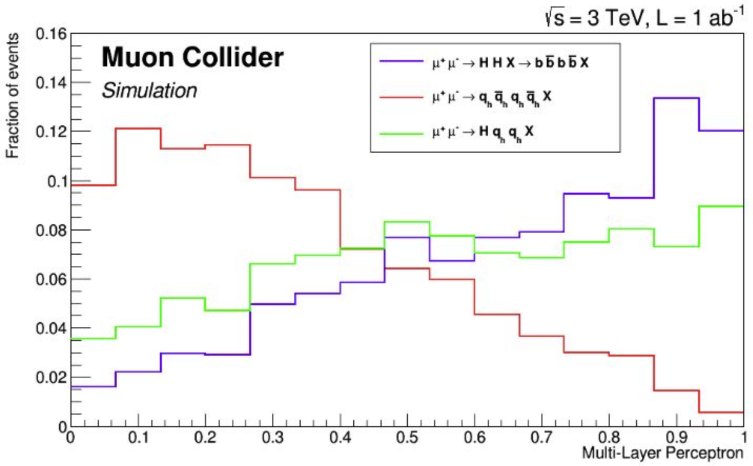
- At 10 TeV we can combine this result with other channels, e.g. **HH→bbWW**

Higgs potential at Muon Collider

- 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 MLPs outputs
- A maximum-likelihood template fit is done for each κ_λ hypothesis

[2405.19314] Higgs Physics at a 3 TeV Muon Collider with detailed detector simulation





Higgs potential at Muon Collider - beyond 3 TeV

- Full simulation study shows **comparable** results wrt expectations from pheno studies
- Extrapolation to higher energies and luminosities
  → **Muon Collider provides most precise results**

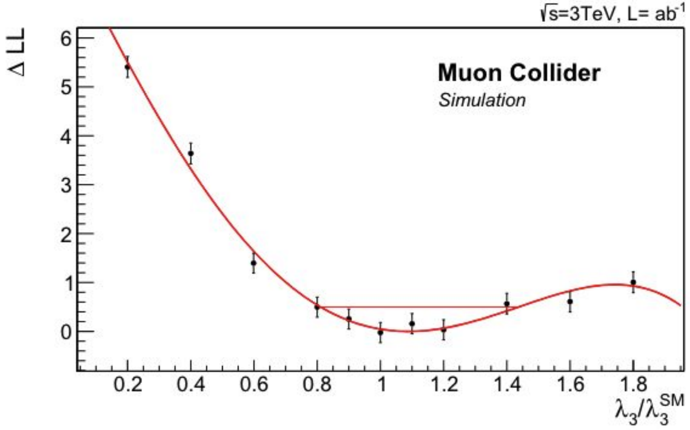
[1910.00012] Higgs boson potential at colliders: status and perspectives

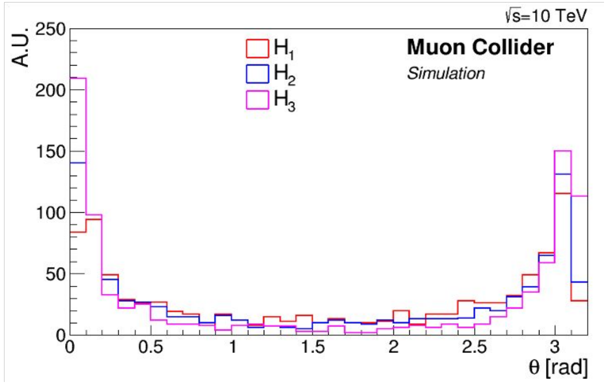
Experiment	Luminosity	COM Energy	$\delta\lambda_3$
CLIC	5 ab^{-1}	3 TeV	-7%,+11%
ILC	8 ab^{-1}	1 TeV	10%
FCC-hh	30 ab^{-1}	100 TeV	3%
Muon Collider	**2 ab^{-1}**	**3 TeV**	**15%**
Muon Collider	**10 ab^{-1}**	**10 TeV**	**3.5%**
Muon Collider	**20 ab^{-1}**	**14 TeV**	**2.5%**
Muon Collider	**90 ab^{-1}**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

- Possibility to access **Higgs quartic self-coupling λ_4**
  - As of now, only pheno study (detailed study in progress)

Expectations: $\delta\lambda_4$= 50% at E_{com}= 14 TeV with 20 ab^{-1}

[2405.19314] Higgs Physics at a 3 TeV Muon Collider with detailed detector simulation



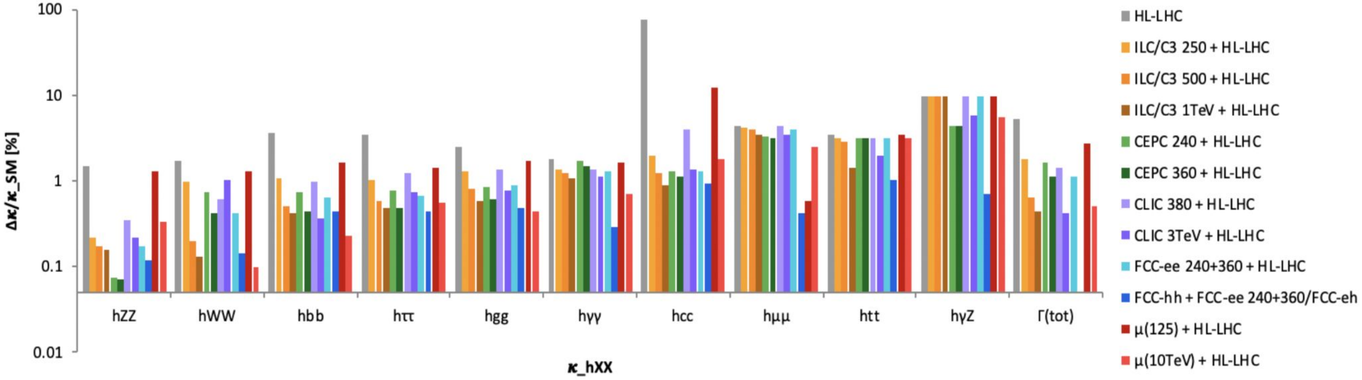


Going to 10 TeV

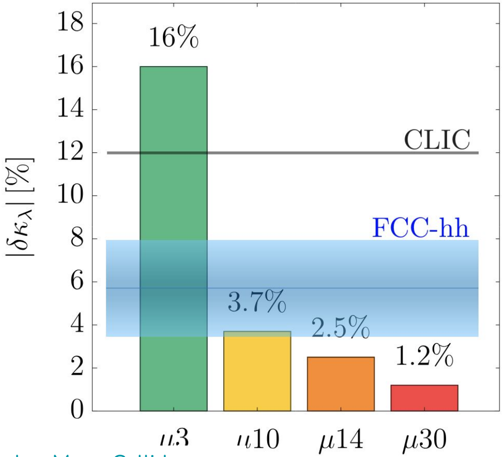
- Having understood the 3 TeV case, we are studying the **10 TeV Muon Collider**
- Several considerations can be done: Talks by M. Casarsa, D. Calzolari and R. Gargiulo
    - BIB is going to impact **as 3 TeV case** (or even **less** with MDI well optimised)
    - **Detector is going to be optimised** (to cope with BIB radiation)
    - Algorithms will be **tailored** for physics cases (e.g. ML for jets reconstruction)

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 $= 20\%$

- **The Muon Collider is one of the most interesting machine to study Higgs Physics**



[2209.07510] Report of the Topical Group on Higgs Physics for Snowmass 2021



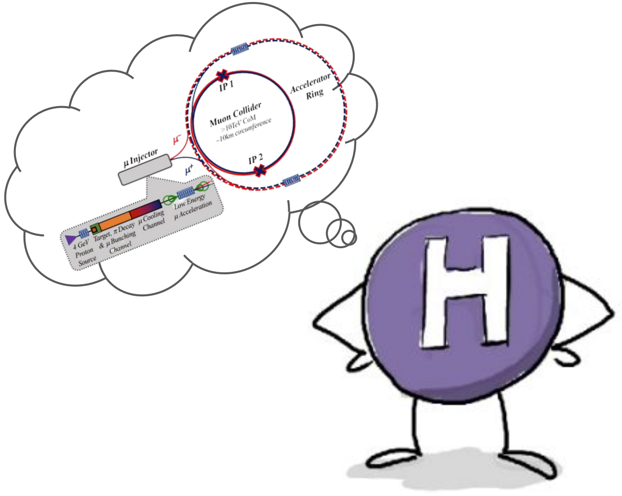
[2303.08533] Towards a Muon Collider

Conclusions

- 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
- Together with some important challenges:
  - R&D effort to satisfy machine requirements
  - Detector and algorithms optimisation to cope with **BIB presence**

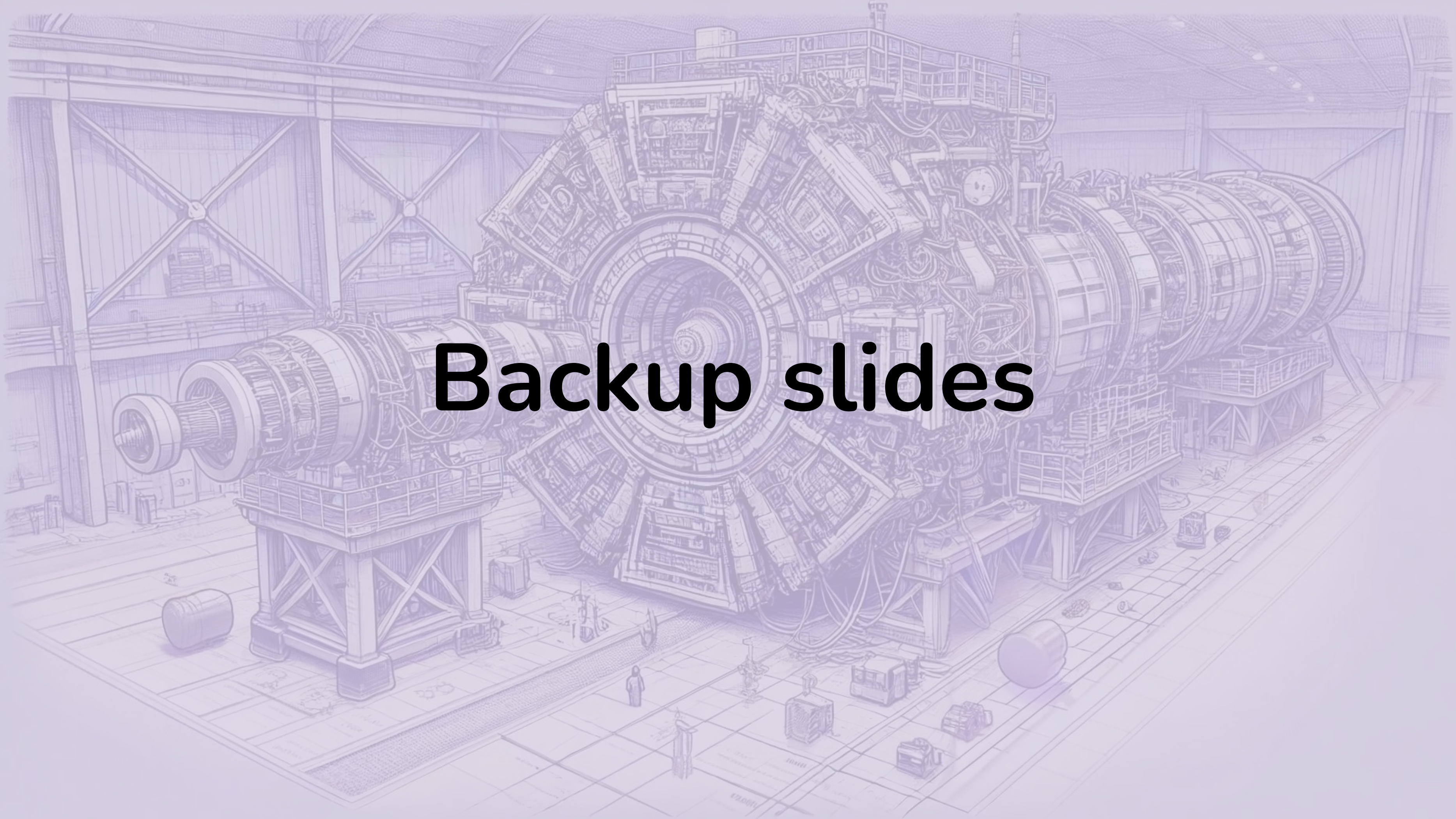
- **Higgs physics at 10 TeV is similar to 3 TeV**
- The 3 TeV Higgs physics case has been well understood
  - Study with detailed detector simulation provides **excellent agreement with pheno parametric studies**

- This study paves the way to future studies at 10 TeV in time for the next ESPPU



Thank you for your attention!

Backup slides



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}

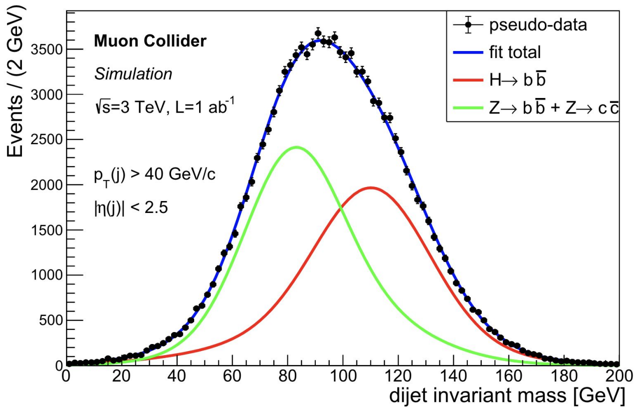
Note: currently focus on 10 TeV, also explore 3 TeV

- 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

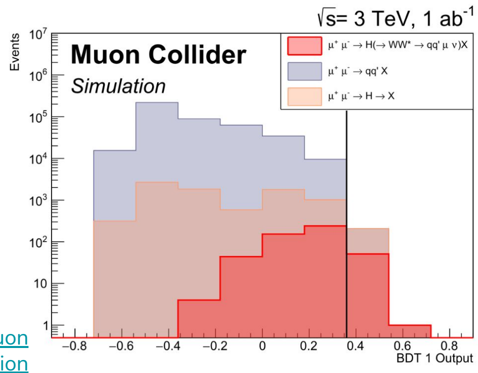
Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**	**2 (6)**
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	**MW**	**5.3**	**14.4**	**20**	**28**
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5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

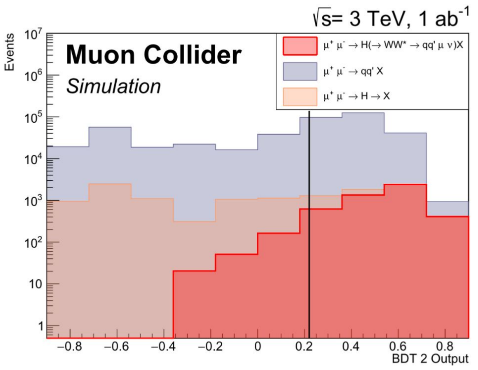
Results for H→bb and H→WW* at 3 TeV

- **H→bb**: two jets in the final state
  - k_T algorithm, p_T > 40 GeV and |η|<2.5
  - Two jets with a Secondary Vertex tag are required. Background from light jets is considered negligible
  - Background mainly coming from Z→bb/cc



- **H→WW***: muon + 2 jets is the final state
- Signal and backgrounds generated with WHIZARD + Pythia8
- Two types of backgrounds:
  - with Higgs decay
  - without Higgs decay
- Two BDTs to separate signal from each kind of background





[2405.19314] Higgs Physics at a 3 TeV Muon Collider with detailed detector simulation

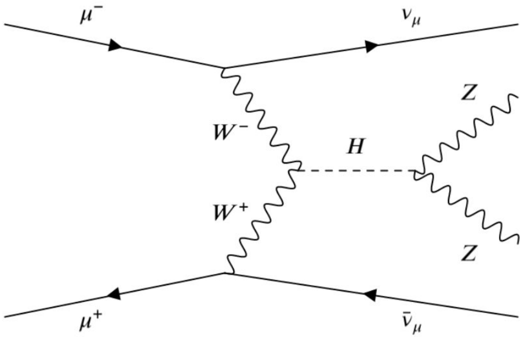
Higgs width Γ

- 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

- $\mu\mu \to \nu\nu Z(\to\mu\mu)Z(\to qq)$ 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 σ(H→ZZ*) show a precision on $\Gamma/\Gamma_{SM}=1^{+71\%}_{-88\%}$

- Results are comparable with expectations from pheno parametric studies
- **For 10 TeV: ΔΓ=3.4%**
  ($\Gamma/\Gamma_{SM}=1^{+2.1\%}_{-0.4\%}$ with forward muon tagging)

$$\frac{\sigma(H \to ZZ^*)}{\sigma^{SM}(H \to ZZ^*)} \propto \frac{\kappa^4}{\Gamma_H/\Gamma_H^{SM}}$$



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