Higgs physics at a muon collider

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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 |
Why a muon collider

|               | Advantages                                                                 | Disadvantages                                           |
|---------------|-----------------------------------------------------------------------------|----------------------------------------------------------|
| e²e⁻ 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 $E_{\text{CM}}$ available to colliding partons, pile-up from QCD events |

Muon collider has advantages from both e²e⁻ and hadron colliders:
- Clean collisions as in e²e⁻ 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 \( \sim 2\text{TeV} \)**

- **Inclusive Higgs cross section over total cross section**

- **Produced events increase with \( E_{\text{CM}} \) (increase in luminosity considered)**

- **Luminosity increasing as \( E_{\text{CM}}^2 \)**
  - 5 years, 1 experiment

### Table

| \( \sqrt{s} \) (TeV) | \( \int \mathcal{L} dt \) (ab\(^{-1}\)) |
|----------------------|---------------------------------------|
| 3                    | 1                                     |
| 10                   | 10                                    |
| 14                   | 20                                    |
Features of a muon collider

- Highest energy efficiency above ~2 TeV
- Inclusive Higgs cross section over total cross section
- Luminosity increasing as $E_{CM}^2$
- 5 years, 1 experiment

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

$E_{beam} = 750$ GeV, $2 \times 10^{12}$ $\mu$/bunch

*F. Collamati et al., 2021 JINST 15 P11009*
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

Photons

Muons

Muon Collider

Muon reconstruction efficiency

b tagging efficiency
\[ \sigma(\mu^+\mu^-\rightarrow H\nu\nu) \times BR(H\rightarrow bb) \]

- Signal \( \mu\mu\rightarrow(H\rightarrow bb)X \) and background \( \mu\mu\rightarrow qqX \) \((q=b,c)\) generated with Whizard+Pythia8
  - Background mainly from \( Z\rightarrow bb \) and \( Z\rightarrow cc \)
- 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 \( \sigma \times BR = 0.75\% \)

http://hdl.handle.net/20.500.12608/3238
$\sigma(\mu^+\mu^-\rightarrow H\nu\nu) \times \text{BR}(H\rightarrow WW^*)$

- 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 $1\,\text{ab}^{-1}$

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

| Event | Expected Events |
|-------|-----------------|
| $\mu^+\mu^- \rightarrow H\nu\nu \rightarrow WW^*\nu\nu \rightarrow q\bar{q}\mu\mu\nu\nu$ | $2430 \pm 150$ |
| $\mu^+\mu^- \rightarrow q\bar{q}\mu$ | $2600 \pm 1300$ |
| $\mu^+\mu^- \rightarrow q\bar{q}l$ | $< 100 \text{ C.L.} = 68\%$ |
| $\mu^+\mu^- \rightarrow q\bar{q}\nu\nu$ | $< 100 \text{ C.L.} = 68\%$ |
| $\mu^+\mu^- \rightarrow H \rightarrow WW^* \rightarrow qq\bar{q}$ | $< 10 \text{ C.L.} = 68\%$ |
| $\mu^+\mu^- \rightarrow H \rightarrow bb$ | $< 150 \text{ C.L.} = 68\%$ |
| $\mu^+\mu^- \rightarrow H \rightarrow \tau\tau$ | $< 4 \text{ C.L.} = 68\%$ |

http://hdl.handle.net/20.500.12608/28559
\[ \sigma(\mu^+\mu^-\rightarrow H\nu\nu) \times BR(H\rightarrow ZZ^*) \]

- 2 muons + 2 jets final state
- Signal generated with MG5+Pythia8, while inclusive \( \mu^+\mu^- \rightarrow \nu\nu \)
  \( \mu^+\mu^- jj \) 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

\[ \frac{\Delta \sigma}{\sigma} = 17\% \]
\( \sigma(\mu^+\mu^-\rightarrow H\nu\nu)\times BR(H\rightarrow\mu^+\mu^-) \)

- Signal and backgrounds generated with MG5+Pythia8
- BIB not used (low impact in muon chambers)
- \(10^\circ < \theta_\mu < 170^\circ, p_T^{\mu} > 5\) 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                                      | Expected events with 1 ab\(^{-1}\) |
|----------------------------------------------|-----------------------------------|
| \([4l]\mu^+\mu^- \rightarrow H\nu\nu\bar{\nu}_\mu, H \rightarrow \mu^+\mu^-\)  | 24.2                              |
| \([4l]\mu^+\mu^- \rightarrow H\mu^+\mu^-\), H \rightarrow \mu^+\mu^-\)   | 1.6                               |
| \(\mu^+\mu^- \rightarrow \mu^+\mu^-\nu\nu_\mu\)                        | 636.5                             |
| \(\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-\)                        | 476.4                             |
| \([4l]t\bar{t}\mu^+\mu^- \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}, W^{\pm} \rightarrow \mu^\pm\nu_\mu(\bar{\nu}_\mu)\) | 1.1                               |

\(\sigma = 38\%\)

https://doi.org/10.22323/1.398.0579
\[ \sigma(\mu^+\mu^- \rightarrow H\nu\nu) \times \text{BR}(H \rightarrow \gamma\gamma) \]

- 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 \( S/\sqrt{S+B} \)

\[ \frac{\Delta \sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \rightarrow 8.9\% \]

| Process         | \( \sigma \) (fb) | Events |
|------------------|-------------------|--------|
| \( \mu\mu \rightarrow H\nu\nu, H \rightarrow \gamma\gamma \) | 0.9025 ± 0.0026 | 707    |
| \( \mu\mu \rightarrow \nu\nu\gamma \) | 81.98 ± 0.27     | 30168  |
| \( \mu\mu \rightarrow l\gamma\gamma \) | 4.419 ± 0.016    | 2678   |
| \( \mu\mu \rightarrow l\gamma \) | 159.0 ± 0.6      | 4738   |
| \( \mu\mu \rightarrow \gamma\gamma \) | 60.15 ± 0.03     | 59933  |

\( \bar{\nu}_S = 3\text{TeV}, 1\text{ab}^{-1} \)

\( m_{\tau\tau} \) (GeV)
\[ \sigma(\mu^+\mu^- \rightarrow HH\nu\bar{\nu}) \times \text{BR}(H\rightarrow bb)^2 \]

- 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 \( p_T > 20 \text{ GeV} \), 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
  - \( \Delta\sigma/\sigma \) of 30% is found

| Signal                            | Cross section [fb] |
|----------------------------------|--------------------|
| \( \mu^+\mu^- \rightarrow HH\nu\bar{\nu} \) | 0.8                |
| Physics background               |                    |
| \( \mu^+\mu^- \rightarrow bbb\bar{b}\nu\bar{\nu} \) | 3.3                |
| \( \mu^+\mu^- \rightarrow bbH\nu\bar{\nu} \) (signal included) | 1.7                |

http://hdl.handle.net/20.500.12608/22861
● 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 $\lambda_3$ hypothesis, resolution on $\lambda_3$ obtained from a likelihood scan
  ○ Stat. uncertainty of $\sim20\%$ @ 68% CL is found

http://hdl.handle.net/20.500.12608/22861
Comparison with CLIC

| Measurement                  | Statistical precision |
|------------------------------|-----------------------|
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow b\bar{b})\) | 0.4% 0.3% |
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow \mu^+\mu^-)\) | 38% 25% |
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow \gamma\gamma)\) | 15% 10%* |
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow WW^*)\) | 1.0% 0.7%* |
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow ZZ^*)\) | 5.6% 3.9%* |

| Measurement                  | Statistical precision |
|------------------------------|-----------------------|
| \(\sigma(ZH) \times BR(H \rightarrow b\bar{b})\) | 0.86% |
| \(\sigma(ZH) \times BR(H \rightarrow WW^*)\) | 5.1% |
| \(\sigma(Hu\bar{u}) \times BR(H \rightarrow b\bar{b})\) | 1.9% |
| \(\Delta[\sigma(HHu\bar{u}\bar{u})] / \sigma(HHu\bar{u}\bar{u})\) | 44% at 1.4 TeV, 20% at 3 TeV |

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

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

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%
\(\lambda_3\) 20%

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

| √s (GeV) | 240 | 365 |
|----------|-----|-----|
| Luminosity (ab⁻¹) | 5   | 1.5 |
| \(\delta(\sigma \text{BR})/\sigma \text{BR} (%)\) | HZ  | \(\nu\bar{\nu}\) H | HZ  | \(\nu\bar{\nu}\) H |
| H → b\bar{b} | ±0.3 | ±3.1 | ±0.5 | ±0.9 |
| H → W⁺W⁻ | ±1.2 | ±2.6 | ±3.0 |
| H → ZZ | ±4.4 | ±12  | ±10  |
| H → γγ | ±9.0 | ±18  | ±22  |
| H → μ⁺μ⁻ | ±19  | ±40  |

Sensitivity on trilinear coupling \(\lambda\): 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%     | 1.7%     |
| H->ZZ          | 17%      | 11%      |
| H->bb          | 0.75%    | 0.76%    |
| H->μμ          | 38%      | 40%      |
| H->γγ          | 8.9%     | 6.1%     |
| HH->4b         | 30%      |          |
| $\lambda_3$   | 20%      | $\lambda_3$ (95% CL) 25% |

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

- *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

MuColl_v1

Only BIB $\sqrt{s} = 1.5$ TeV $\mu^\pm$ beams

- not in cluster
- in cluster

$\theta = 8^\circ$
$\theta = 10^\circ$
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.
