# Higgs physics at a future Muon Collider

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on behalf of the **International Muon Collider Collaboration**

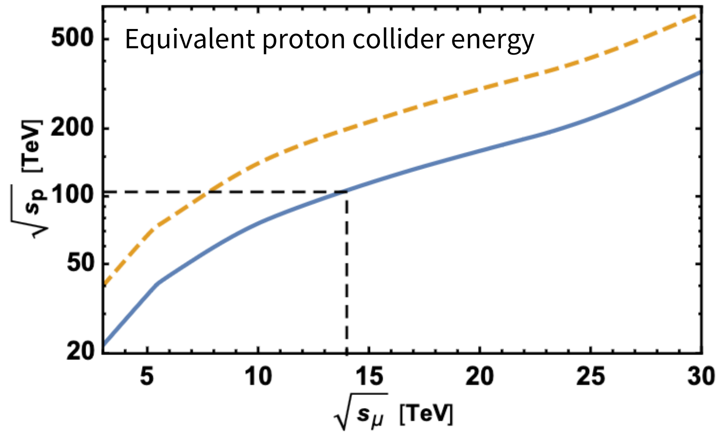
Obergurgl, 29/03/2023

# OUTLINE

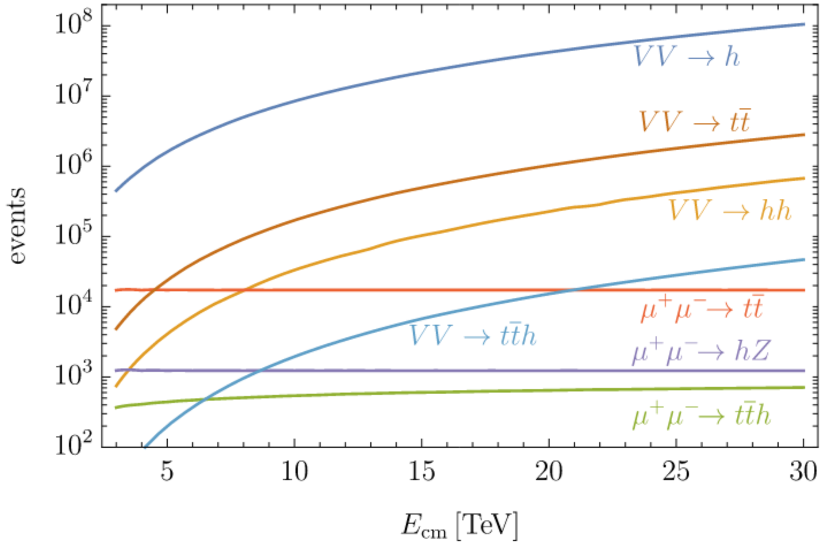
- Muon Collider project
- Object reconstruction
- Higgs physics
- Higgs coupling precision

# Multi-TeV Muon Collider

https://arxiv.org/pdf/2203.07256.pdf




- Ideal machine to reach high center-of-mass energy and luminosity
- Negligible synchrotron radiation losses




- Ideal facility for **Higgs Physics**

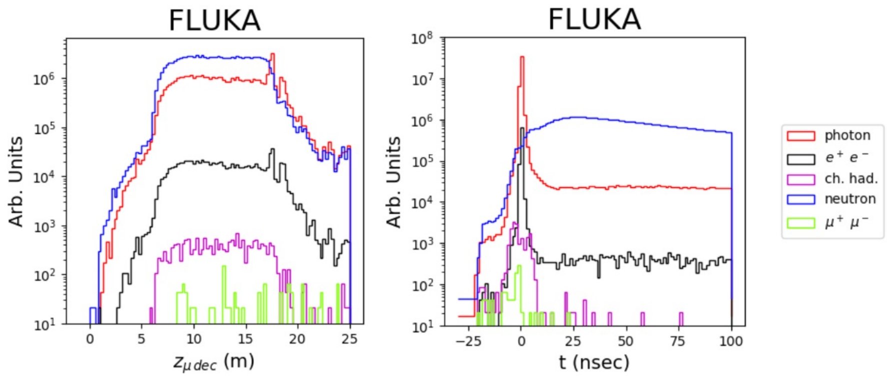
~500k Higgs produced with 1 $ab^{-1}$ (3 TeV)

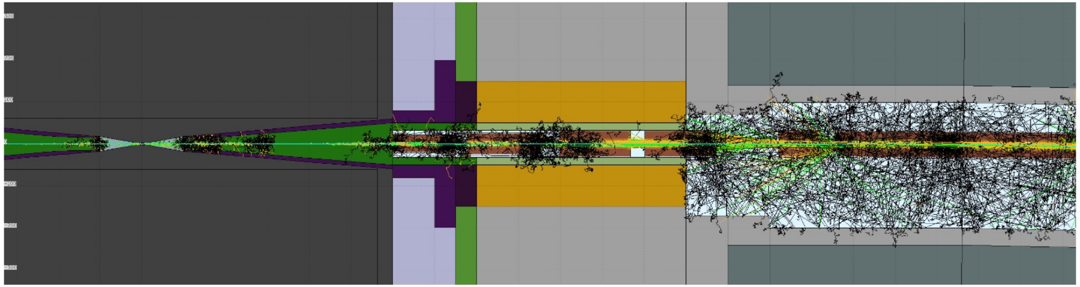
Proposed scenarios (5 years data taking)

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

# Beam Induced Background (BIB)

- Intense flux of particles originated by the deacy of beam muons and secondary interaction with the detector
- BIB simulated with MARS15 or FLUKA
- Machine Detector Interface and Detector carefully designed in order to mitigate BIB



Fundamental to determine and reduce the BIB impact on object reconstruction

https://arxiv.org/pdf/2105.09116.pdf

# Detector structure

### hadronic calorimeter

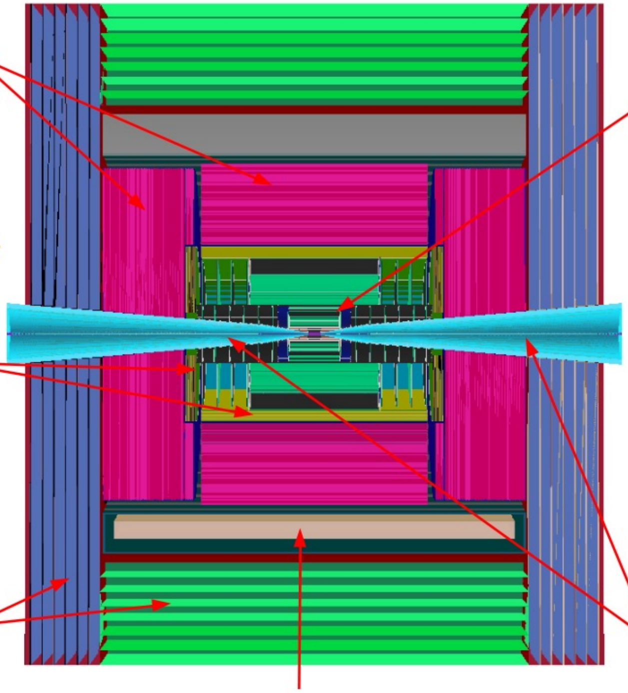
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 $mm^2$ cell size;
- 7.5 $\lambda_I$.

### electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 $mm^2$ cell granularity;
- 22 $X_0$ + 1 $\lambda_I$.

### muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 $mm^2$ cell size.



superconducting solenoid (3.57T)

### tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 $\mu m^2$ pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

### shielding nozzles

- Tungsten cones + borated polyethylene cladding.

Geometrical acceptance $10° < \theta < 170°$

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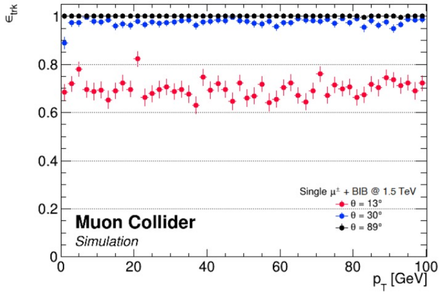
https://confluence.infn.it/display/muoncollider/Muon+Collider+Detector

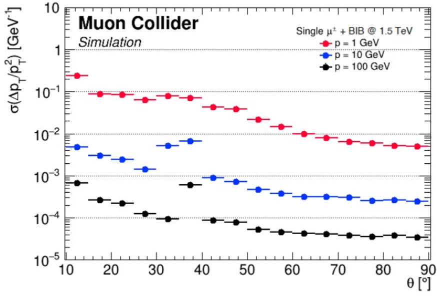
Reconstruction algorithms
https://github.com/MuonColliderSoft

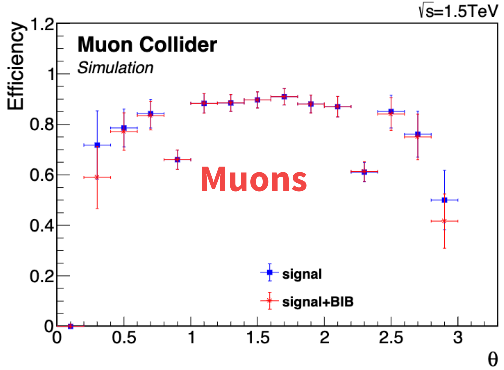
# Object reconstruction

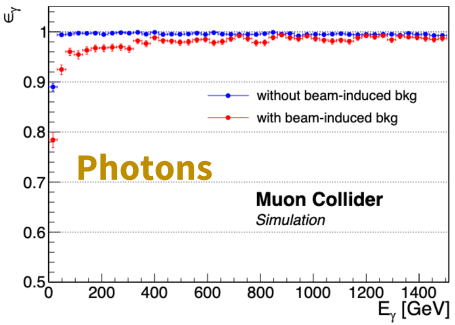
Reconstruction with BIB is not trivial (still under optimization)

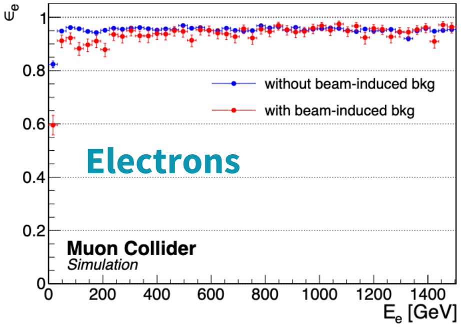
## Tracks

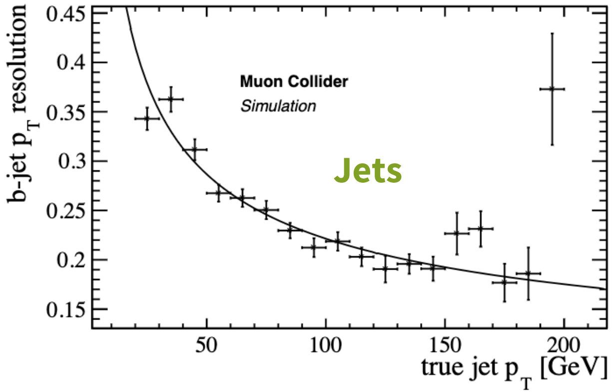



https://arxiv.org/abs/2203.07964

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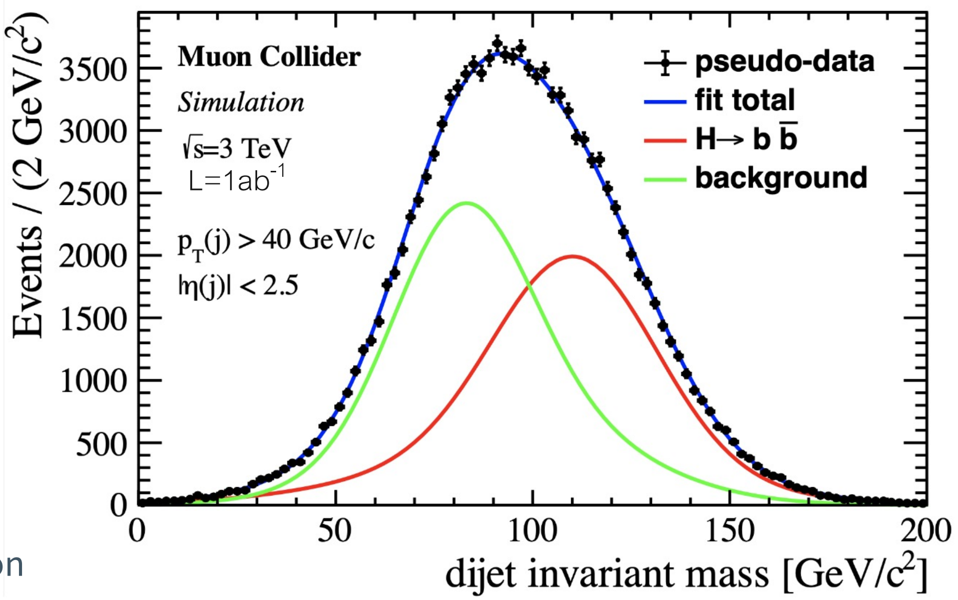
# Higgs Physics
## $H \rightarrow b\bar{b}$

- MC samples generated with WHIZARD + Pythia8
- Two b tagged jets are required (secondary vertex tag). Very small light mistag probability.
- Background in the signal region consists mainly of Z → $b\bar{b}/c\bar{c}$
- Signal yield extracted with a fit to the invariant mass distribution

$$\frac{\Delta\sigma_{Hbb}}{\sigma_{Hbb}} = \frac{\sqrt{S+B}}{S} \sim 0.75\%$$

| | Signal | SM background |
|---|---|---|
| Sim. process | $\mu^+\mu^- \rightarrow H(\rightarrow b\bar{b}) + X$ | $\mu^+\mu^- \rightarrow qq + X$ |
| Exp. events | 59.5K | 65.4K |




Compatible with results from parametric simulation https://arxiv.org/abs/2203.09425

# Higgs Physics
## $H \to WW^*$

- Muon + 2 jets final state considered
- MC samples generated with WHIZARD + Pythia8
- Two types of backgrounds (with and without Higgs decays) reduced with two different BDT discriminators

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

$$\frac{\Delta\sigma_{HWW^*}}{\sigma_{HWW^*}} \sim 2.9\%$$

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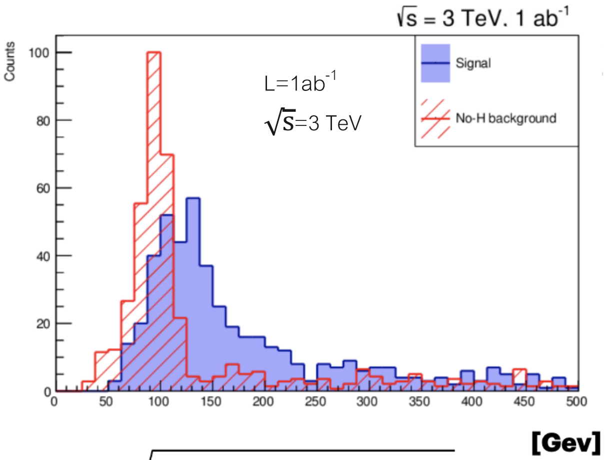
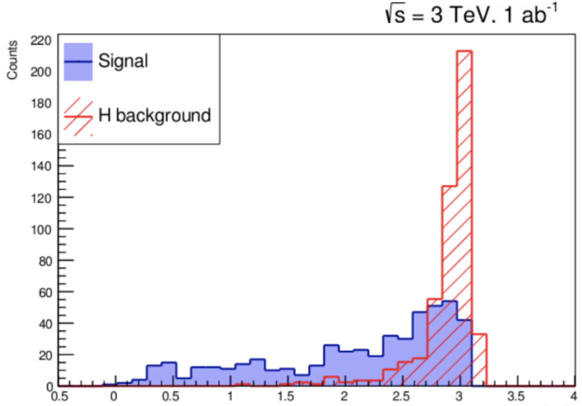



$$m_H = \sqrt{(E_W + E_\mu)^2 - (\vec{p}_W + \vec{p}_\mu)^2}$$




$$A_{\mu,W} = \pi - cos^{-1}\left(\frac{\vec{p}_\mu \cdot \vec{p}_W}{|\vec{p}_\mu| \cdot |\vec{p}_W|}\right)$$

https://thesis.unipd.it/handle/20.500.12608/28559

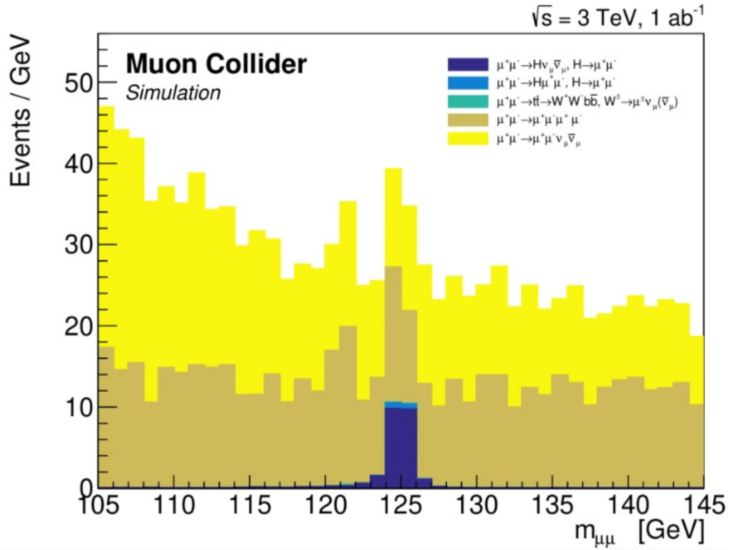
# Higgs Physics

## $\mathrm{H} \rightarrow \mu^+\mu^-$

https://doi.org/10.22323/1.398.0579

- MC samples generated with WHIZARD + Pythia8
- Two main backgrounds reduced with two different BDT discriminators
- Signal yield extracted with an unbinned maximum likelihood fit to the dimuon invariant mass distribution

| Category | Simulated process | Expected events ($105 < m_{\mu\mu} < 145$ GeV) |
|---|---|---|
| Signal | $\mu^+\mu^- \rightarrow H(\rightarrow \mu^+\mu^-)\nu\bar{\nu}$ | 24.2 |
| | $\mu^+\mu^- \rightarrow H(\rightarrow \mu^+\mu^-)\mu^+\mu^-$ | 1.6 |
| SM background | $\mu^+\mu^- \rightarrow \mu^+\mu^-\nu\bar{\nu}$ | 636.5 |
| | $\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ | 476.4 |
| | $\mu^+\mu^- \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}$, $W^\pm \rightarrow \mu^\pm\nu(\bar{\nu})$ | 1.1 |




$$\frac{\Delta\sigma_{H\mu^+\mu^-}}{\sigma_{H\mu^+\mu^-}} \sim 38\%$$

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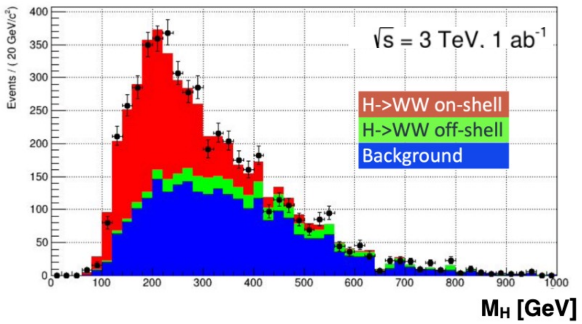
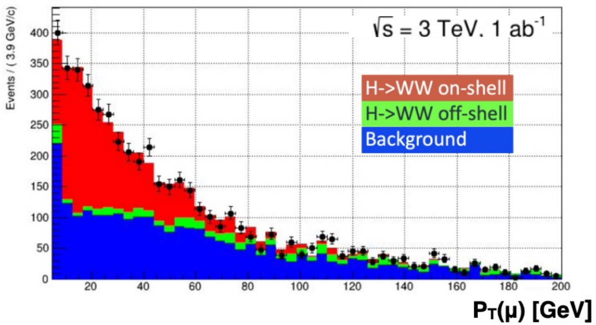
# Higgs Physics
# Higgs width measurement

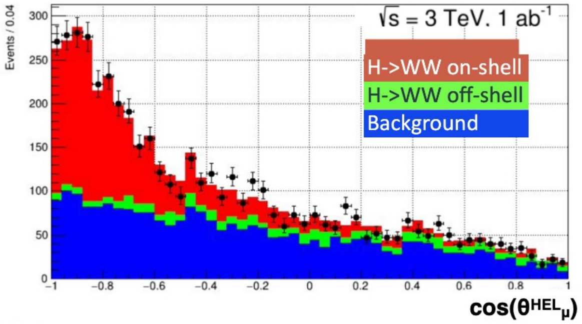
- The Higgs width ($\Gamma_H$) can be measured by determining the number of on-shell and off-shell $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ processes
  - The ratio between off-shell and on-shell events is proportional to $\Gamma_H$
- Final state considered: **(Di)muon+2 jets**
- MC signal samples generated with MadGraph5, background with WHIZARD
- On-shell and off-shell signal yields obtained from **Higgs mass, muon momentum** and **muon helicity angle** simultaneously fitted

| Process | Expected events |
|---|---|
| On-shell $H \rightarrow ZZ \rightarrow \mu^+\mu^- jj$ | 38.2 |
| Off-shell $H \rightarrow ZZ \rightarrow \mu^+\mu^- jj$ | 56.0 |
| $\nu\bar{\nu}\mu^+\mu^- jj$ background | 458.3 |
| On-shell $H \rightarrow W^+W^- \rightarrow \mu\nu_\mu jj$ | 1803.4 |
| Off-shell $H \rightarrow W^+W^- \rightarrow \mu\nu_\mu jj$ | 411.4 |
| $\nu\bar{\nu}\mu\nu_\mu jj$ background | 2520.3 |

$$\frac{\Delta\Gamma_H}{\Gamma_H} \sim 5.3\%$$



# Higgs couplings with fermions and bosons

- Previous measurements are simultaneously fitted to obtain the **expected relative precision on Higgs couplings**
- Results are compared with those quoted by the CLIC collaboration, computed by using several datasets with different energies
- **Direct comparison is difficult**, since the 3-energy-stages CLIC program (link) can be exploited in 25 years, while the Muon Collider can collect 1 $ab^{-1}$ in 5 years

*CLIC Higgs Physics:*
*Eur. Phys. J. C 77, 475 (2017)*

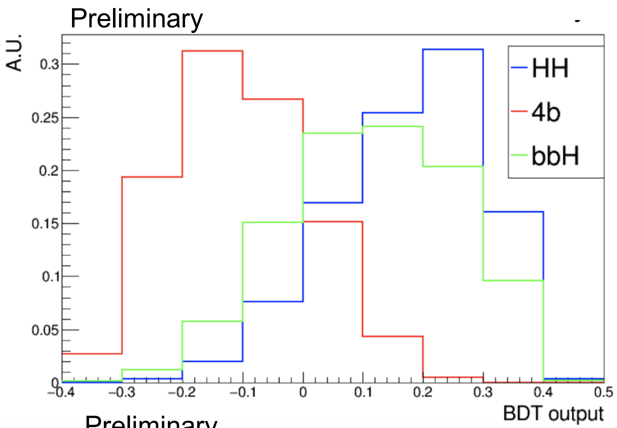
| | Full simulation<br>1 $ab^{-1}$ @ 3 TeV | CLIC<br>0.5 $ab^{-1}$ @ 350 GeV<br>1.5 $ab^{-1}$ @ 1.4 TeV<br>2 $ab^{-1}$ @ 3 TeV |
|---|---|---|
| $\Gamma_H$ | 5.3% | 3.5% |
| $g_{HZZ}$ | 5.6% | 0.8% |
| $g_{HWW}$ | 1.3% | 0.9% |
| $g_{Hbb}$ | 1.7% | 0.9% |
| $g_{H\mu\mu}$ | 19.1% | 7.8% |

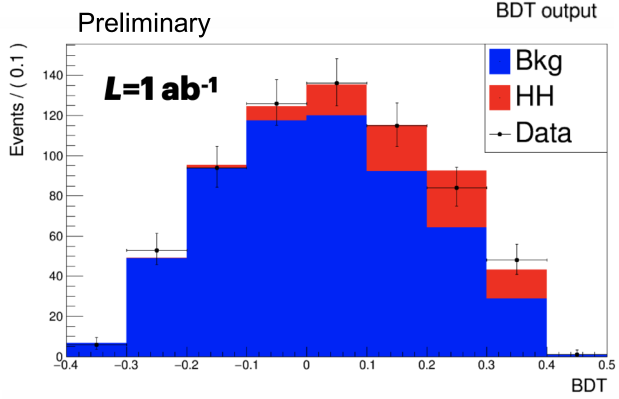
# Higgs Physics
## $HH \rightarrow b\bar{b}b\bar{b}$

| | Signal | SM background |
|---|---|---|
| Sim. process | $\mu^+\mu^- \rightarrow HH(\rightarrow b\bar{b}b\bar{b}) + X$ | $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b} + X$<br>$\mu^+\mu^- \rightarrow Hb\bar{b} + X$ |
| Exp. events | 50 | 432 |

- MC samples generated with WHIZARD + Pythia8
- Two b tagged jets (secondary vertex tag) out of four jets are required
- A boosted decision tree (BDT) is trained to separate the signal from the background
  - Kinematic input variables
- Cross section uncertainty extracted from a fit to the BDT output

$$\frac{\Delta\sigma_{HHbbbb}}{\sigma_{HHbbbb}} \sim 30\%$$



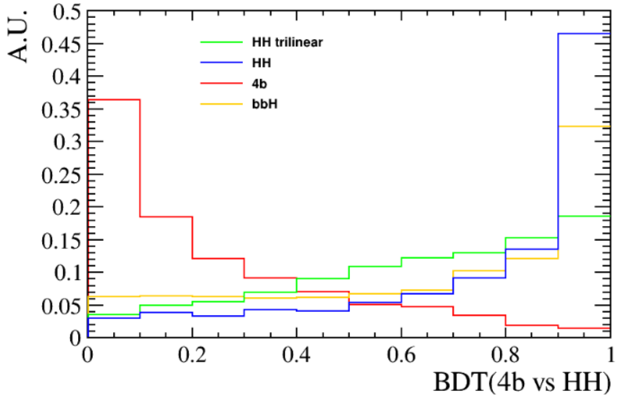

http://hdl.handle.net/20.500.12608/22861

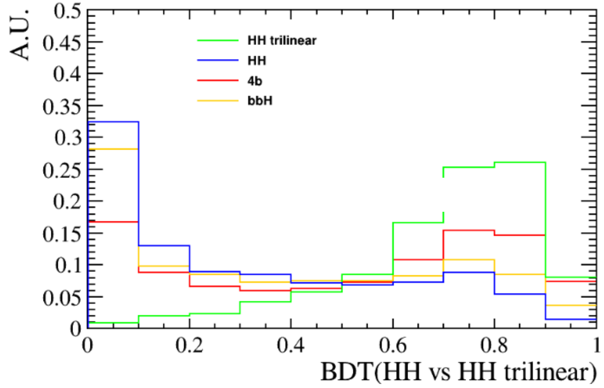
# Higgs trilinear coupling

- Two BDTs trained to separate signal from **4b** and **HH trilinear** (only trilinear diagrams considered)
- The templates obtained with different coupling hypotheses are compared with pseudoexperiments
- Sensitivity on $\lambda_3$ determined with a likelihood technique (preliminary result)

$$\frac{\Delta\lambda_3}{\lambda_3} \sim 20\% \quad @68\%\ \text{C.L.}$$

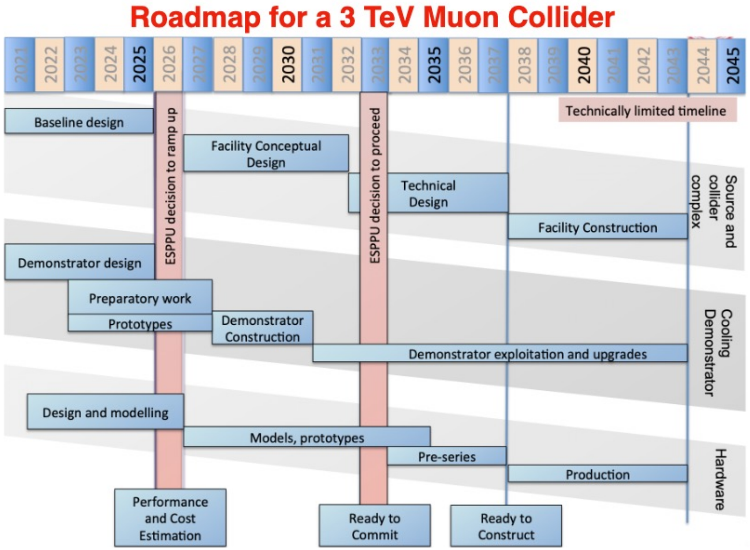
- CLIC: [-8%,+11%] at 68% CL with 2.5 $ab^{-1}$ at 1.4 TeV + 5 $ab^{-1}$ at 3 TeV [Eur. Phys. J. C 80, 1010 (2020)]



# Conclusions

- On-going huge effort for MDI design and reconstruction algorithms development
- Simulation studies with detector reconstruction demonstrate that **Higgs physics** is possible at the Muon Collider
- More processes will be studied in future



# Thank you for your attention!

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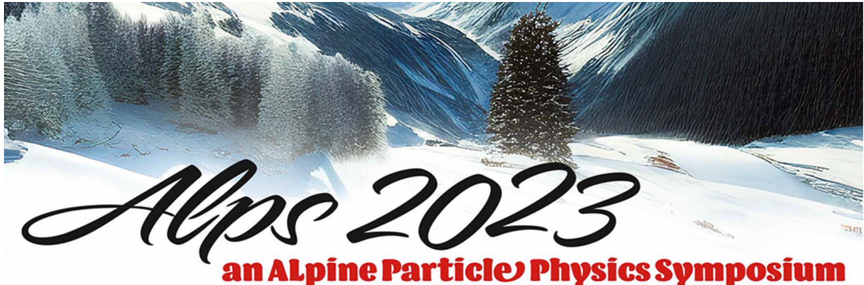
Collaboration



# Backup

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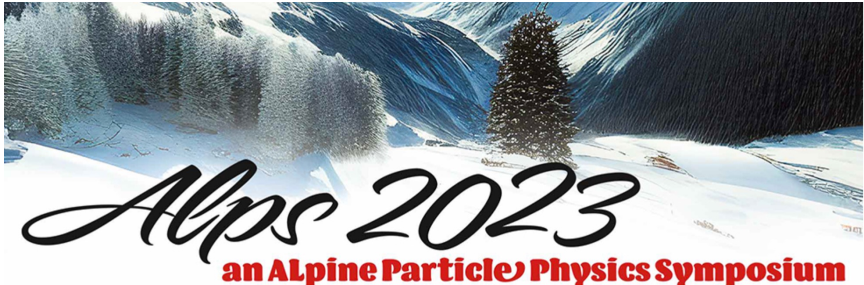
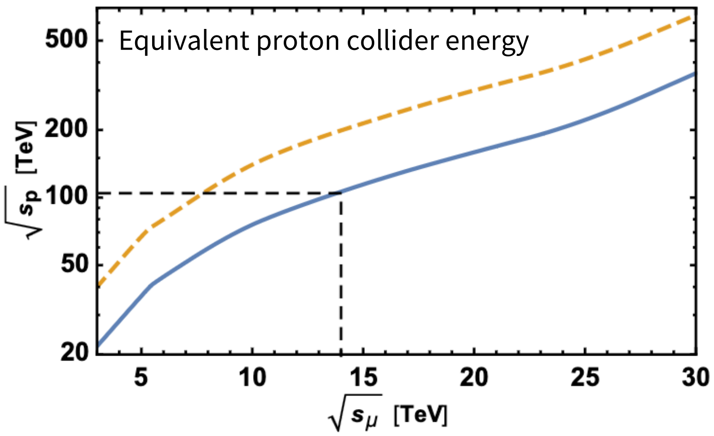


# Muon Collider

https://arxiv.org/pdf/2203.07256.pdf




Equivalence is defined in terms of the pair production cross-section for heavy particles, with mass close to the muon collider kinematical threshold of √sμ/2 . The equivalent √sp is the proton collider center of mass energy for which the cross-sections at the two colliders are equal.

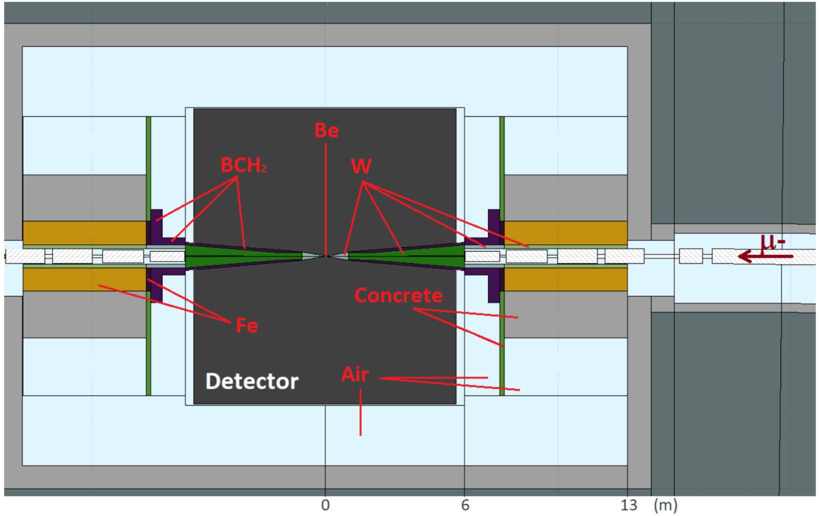



**Figure 2.** Interaction region. The passive elements, the nozzles and the pipe around the interaction point are constituted by iron (Fe), borated polyethylene ($BCH_2$), berillium (Be), tungsten (W) and concrete. The detector outer shape is a 11.28 m long cylinder of 6.3 m radius. The space between the outer shape and the nozzles is considered as a perfect particle absorber (“blackhole”). The bunker is a 26 m-long cylinder with a radius of 9 m.

https://arxiv.org/pdf/2105.09116.pdf

# Higgs Physics at future colliders

| kappa-0 | HL-LHC | LHeC | HE-LHC | | ILC | | | CLIC | | | CEPC | FCC-ee | | FCC-ee/eh/hh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | S2 | S2′ | 250 | 500 | 1000 | 380 | 15000 | 3000 | | 240 | 365 | |
| $\kappa_W$ [%] | 1.7 | 0.75 | 1.4 | 0.98 | 1.8 | 0.29 | 0.24 | 0.86 | 0.16 | 0.11 | 1.3 | 1.3 | 0.43 | 0.14 |
| $\kappa_Z$ [%] | 1.5 | 1.2 | 1.3 | 0.9 | 0.29 | 0.23 | 0.22 | 0.5 | 0.26 | 0.23 | 0.14 | 0.20 | 0.17 | 0.12 |
| $\kappa_g$ [%] | 2.3 | 3.6 | 1.9 | 1.2 | 2.3 | 0.97 | 0.66 | 2.5 | 1.3 | 0.9 | 1.5 | 1.7 | 1.0 | 0.49 |
| $\kappa_\gamma$ [%] | 1.9 | 7.6 | 1.6 | 1.2 | 6.7 | 3.4 | 1.9 | 98⋆ | 5.0 | 2.2 | 3.7 | 4.7 | 3.9 | 0.29 |
| $\kappa_{Z\gamma}$ [%] | 10. | – | 5.7 | 3.8 | 99⋆ | 86⋆ | 85⋆ | 120⋆ | 15 | 6.9 | 8.2 | 81⋆ | 75⋆ | 0.69 |
| $\kappa_c$ [%] | – | 4.1 | – | – | 2.5 | 1.3 | 0.9 | 4.3 | 1.8 | 1.4 | 2.2 | 1.8 | 1.3 | 0.95 |
| $\kappa_t$ [%] | 3.3 | – | 2.8 | 1.7 | – | 6.9 | 1.6 | – | – | 2.7 | – | – | – | 1.0 |
| $\kappa_b$ [%] | 3.6 | 2.1 | 3.2 | 2.3 | 1.8 | 0.58 | 0.48 | 1.9 | 0.46 | 0.37 | 1.2 | 1.3 | 0.67 | 0.43 |
| $\kappa_\mu$ [%] | 4.6 | – | 2.5 | 1.7 | 15 | 9.4 | 6.2 | 320⋆ | 13 | 5.8 | 8.9 | 10 | 8.9 | 0.41 |
| $\kappa_\tau$ [%] | 1.9 | 3.3 | 1.5 | 1.1 | 1.9 | 0.70 | 0.57 | 3.0 | 1.3 | 0.88 | 1.3 | 1.4 | 0.73 | 0.44 |

arXiv:1905.03764v2

# Higgs Physics at future colliders

| collider | (1) di-H excl. | (2.a) di-H glob. | (3) single-H excl. with HL-LHC | (3) single-H excl. w/o HL-LHC | (4) single-H glob. |
|---|---|---|---|---|---|
| HL-LHC | $^{+60}_{-50}$% (50%) | 52% | 47% | 125% | 50% |
| HE-LHC | 10-20% (n.a.) | n.a. | 40% | 90% | 50% |
| $ILC_{250}$ | – | – | 29% | 126% | 49% |
| $ILC_{350}$ | – | – | 28% | 37% | 46% |
| $ILC_{500}$ | 27% (27%) | 27% | 27% | 32% | 38% |
| $ILC_{1000}$ | 10% (n.a.) | 10% | 25% | n.a. | 36% |
| $CLIC_{380}$ | – | – | 46% | 120% | 50% |
| $CLIC_{1500}$ | 36% (36%) | 36% | 41% | 80% | 49% |
| $CLIC_{3000}$ | $^{+11}_{-7}$% (n.a.) | n.a. | 35% | 65% | 49% |
| FCC-$ee_{240}$ | – | – | 19% | 21% | 49% |
| FCC-$ee_{365}$ | – | – | 19% | 21% | 33% |
| FCC-$ee^{4IP}_{365}$ | – | – | 14% | n.a. | 24% |
| FCC-eh | 17-24% (n.a.) | n.a. | n.a. | n.a. | n.a. |
| FCC-ee/eh/hh | 5% (5%) | 6% | 18% | 19% | 25% |
| LE-FCC | 15% (n.a) | n.a | n.a. | n.a. | n.a. |
| CEPC | – | – | 17% | n.a. | 49% |

arXiv:1905.03764v2

# Higgs Physics at the Muon Collider parametric studies

Table 2: 68% probability sensitivity to modifications on the Higgs coupling from the $\kappa$ fit, assuming no BSM contributions to the Higgs width.

| Coupling | HL-LHC | HL-LHC + 125 GeV $\mu$-coll. 5 / 20 $fb^{-1}$ | HL-LHC + 3 TeV $\mu$-coll. 1 $ab^{-1}$ | HL-LHC + 10 TeV $\mu$-coll. 10 $ab^{-1}$ | HL-LHC + 10 TeV $\mu$-coll. + $e^+e^-$ $H$ fact (240/365 GeV) |
|---|---|---|---|---|---|
| $\kappa_W$ [%] | 1.7 | 1.3 / 0.9 | 0.4 | 0.1 | 0.1 |
| $\kappa_Z$ [%] | 1.5 | 1.3 / 1.0 | 0.9 | 0.4 | 0.1 |
| $\kappa_g$ [%] | 2.3 | 1.7 / 1.4 | 1.4 | 0.7 | 0.6 |
| $\kappa_\gamma$ [%] | 1.9 | 1.6 / 1.5 | 1.3 | 0.8 | 0.8 |
| $\kappa_c$ [%] | - | 12 / 5.9 | 7.4 | 2.3 | 1.1 |
| $\kappa_b$ [%] | 3.6 | 1.6 / 1.0 | 0.9 | 0.4 | 0.4 |
| $\kappa_\mu$ [%] | 4.6 | 0.6 / 0.3 | 4.3 | 3.4 | 3.2 |
| $\kappa_\tau$ [%] | 1.9 | 1.4 / 1.1 | 1.2 | 0.6 | 0.4 |

arXiv:2203.07261v1

International MUON Collider Collaboration

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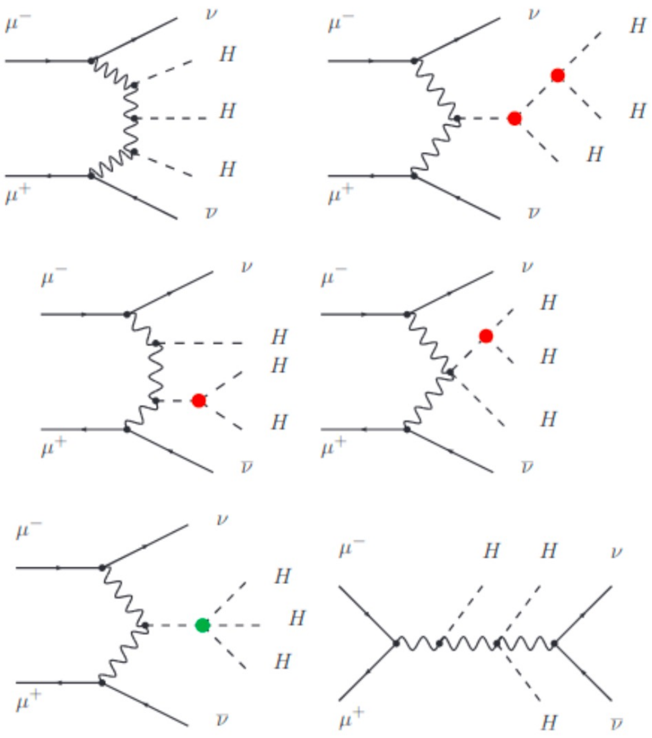
# Double Higgs production at the Muon Collider




http://hdl.handle.net/20.500.12608/22861

# Higgs Physics

# Higgs width measurement

| Process | Expected events |
|---|---|
| On-shell $H \to ZZ \to \mu^+\mu^- jj$ | 38.2 |
| Off-shell $H \to ZZ \to \mu^+\mu^- jj$ | 56.0 |
| $\nu\bar{\nu}\mu^+\mu^- jj$ background | 458.3 |
| On-shell $H \to W^+W^- \to \mu\nu_\mu jj$ | 1803.4 |
| Off-shell $H \to W^+W^- \to \mu\nu_\mu jj$ | 411.4 |
| $\nu\bar{\nu}\mu\nu_\mu jj$ background | 2520.3 |

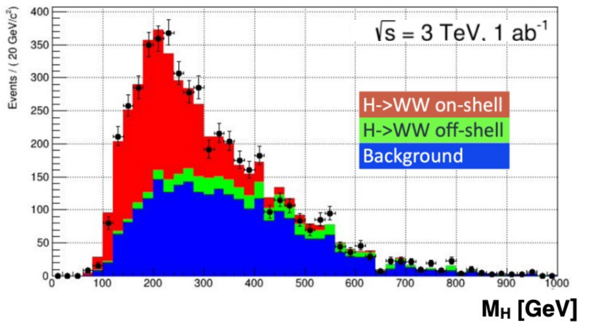
| | H→ $WW$ | H→ $ZZ$ |
|---|---|---|
| BR | 2.137E-01 | 2.619E-02 |

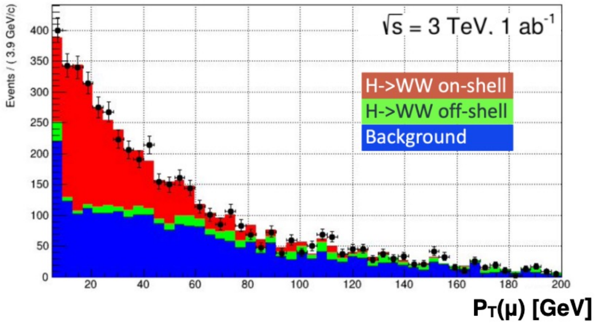
| | $Z \to \mu\mu$ | $W \to \mu\nu$ |
|---|---|---|
| BR | ~3% | ~10% |

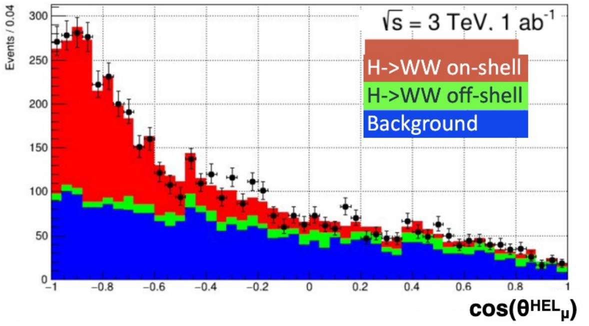
$$\frac{\Delta\sigma_{\Gamma_H}}{\sigma_{\Gamma_H}} \sim 5.3\%$$

$$\sigma^{\text{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p \Rightarrow \sigma^{\text{off-shell}} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_H,$$

$\mu_p$ is the on-shell H boson signal strength in the production mode being considered

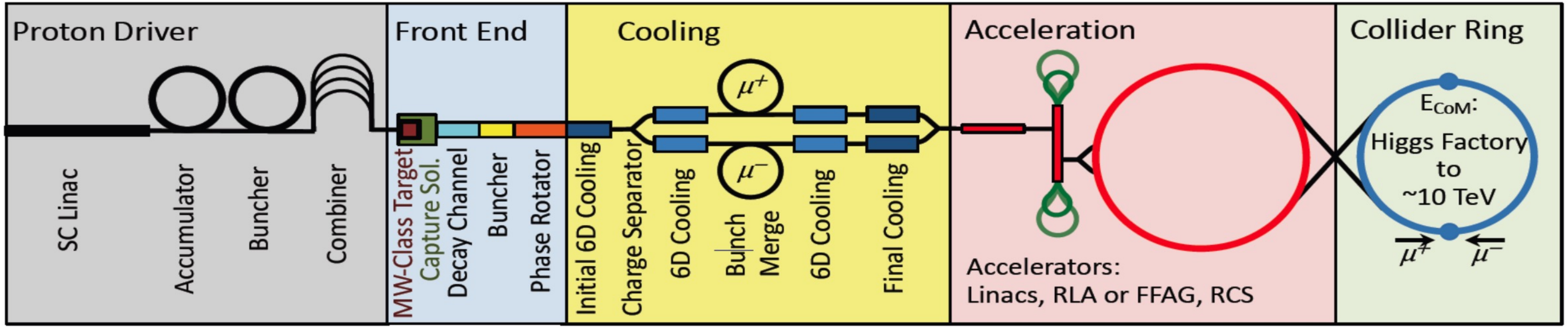



A. Zaza

# Accelerator
# Proton Driver scheme




Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

https://agenda.infn.it/event/28874/contributions/169177/attachments/94436/129235/ICHEP_2022.pdf