Muon Collider Facility

Presentazione Nuovi Esperimenti 2021
Sezione di Padova
June 16, 2020

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Brief history

- The MAP , Muon Accelerator Program studied in details muon collider start to end having as muon source pion decays. The main difficulty was the muon cooling: conventional beam cooling methods can not works for μ beams.

- In 2014 the Particle Physics Project Prioritization Panel (P5) decided *Realign activities in accelerator R&D with the P5 strategic plan. Redirect muon collider R&D and consult with international partners on the early termination of the MICE muon cooling R&D facility.*

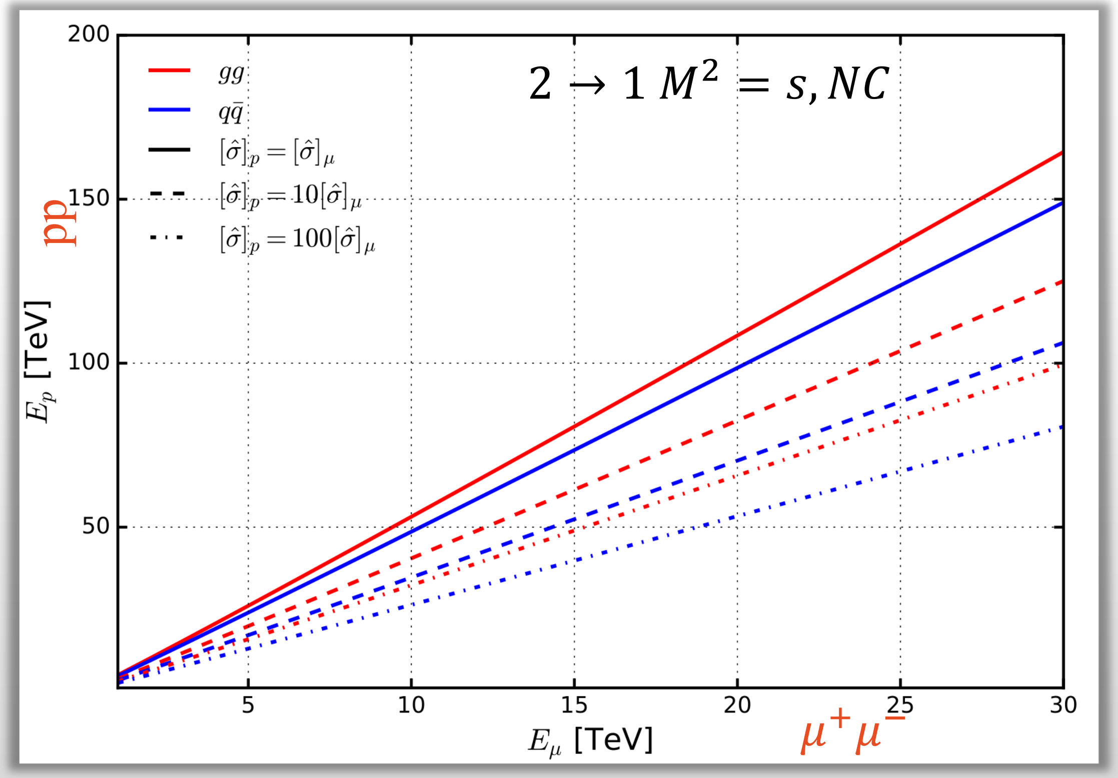
- An Italian effort, LEMMA, revives the idea of muon collider proposing a new source of muons, e^+ annihilation on target, $e^+e^- \rightarrow \mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold, $\sqrt{s} \sim 0.212$ GeV

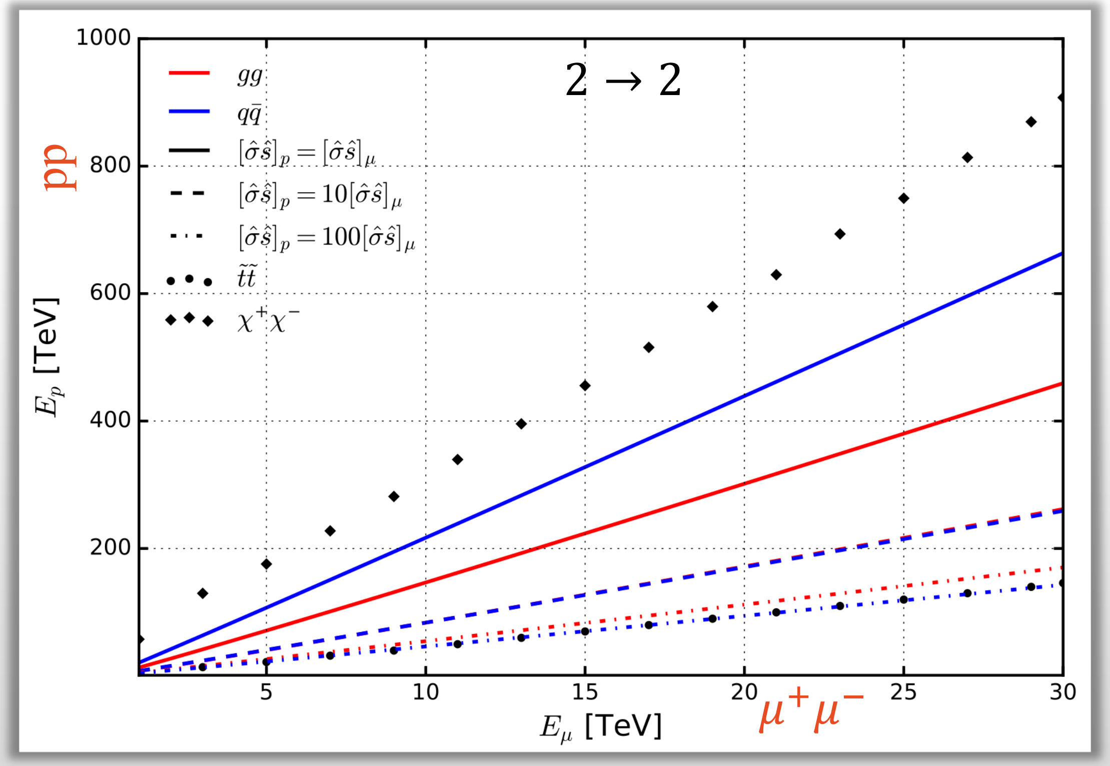
- CERN forms a working group on muon collider in 2017 in order to revise the project in view of the 2019 European Particle Physics Strategy. The group submits an Input Document to EU Strategy Update - Dec 2018: "Muon Colliders" (arXiv:1901.06150), *FINDINGS and RECCOMENDATIONS:*
  - **Set-up an international collaboration to promote muon colliders**
  - and **organize the effort on the development of both accelerators and detectors** and to define the road-map towards a CDR by the next Strategy update

Physics Motivations: Discovery Potential

The advantage in colliding muons rather than protons is that $\sqrt{s_\mu}$ is entirely available to produce short-distance reactions. At a proton collider the relevant interactions occur between the proton constituents, which carry a small fraction of $\sqrt{s_p}$

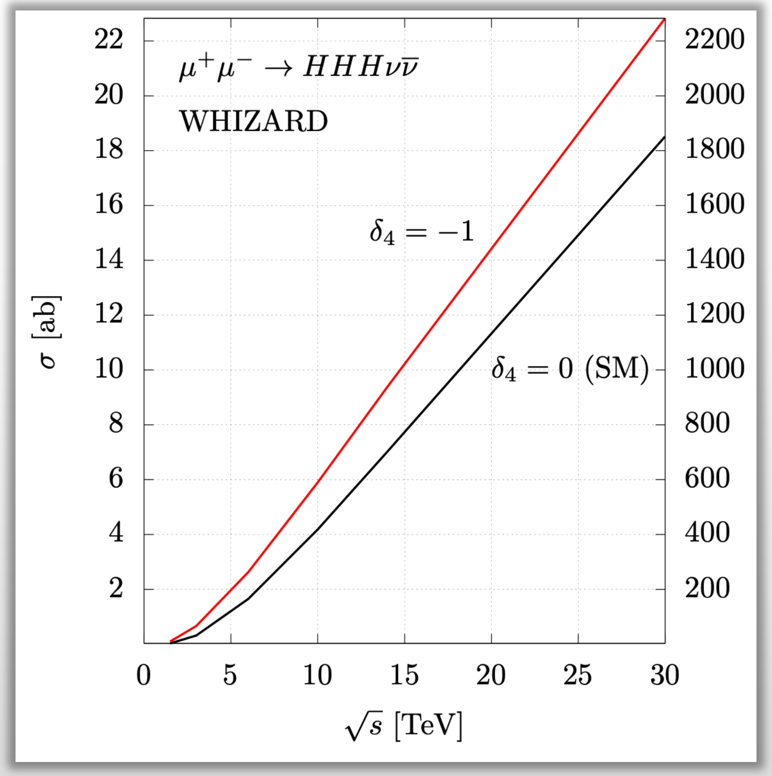
Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





Physics Motivations: Discovery Potential through the Higgs Boson

Higgs boson couplings to fermions and bosons reaches have to be evaluated, similar or better performance of e^+e^- are expected. In addition, muon collider has the unique possibility to determine the Higgs potential having sensitivity also to quadrilinear coupling



$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

$$\lambda_3 = \lambda_{SM}(1 + \delta_3)$$
$$\lambda_4 = \lambda_{SM}(1 + \delta_4)$$

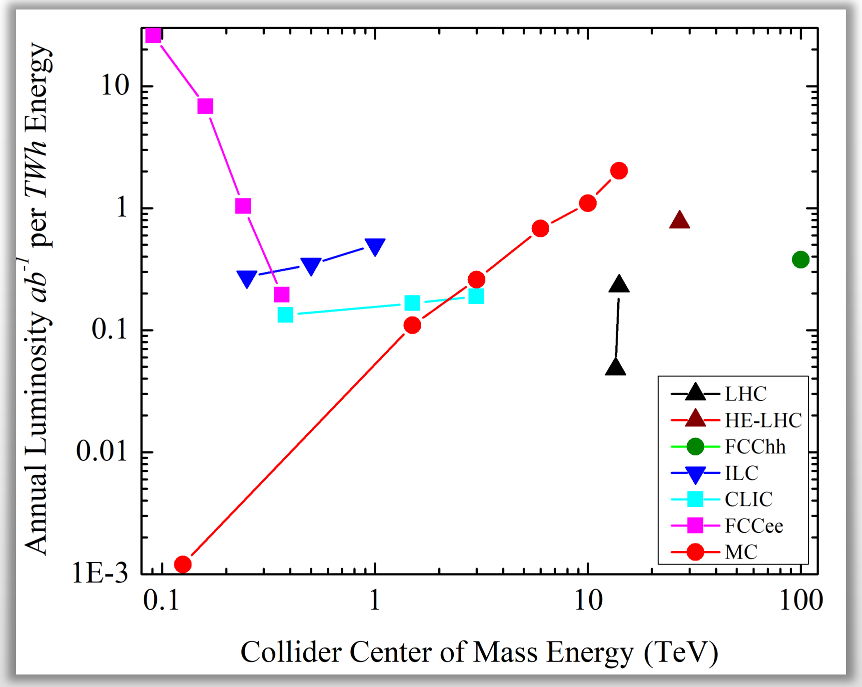
Muon Collider with several TeV CM energy and with integrated luminosities of the order of several tens of attobarns, could provide enough events to allow a determination (a SM) quartic Higgs self-coupling with an accuracy in the tens of percent.

Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, M Chiesa *et al*.

Economic Motivations

The luminosity per beam power is independent of collision energy in linear lepton colliders, but increases linearly for muon colliders

Cost accounting is not uniform across the projects, estimates for LHeC and muon collider are prorated from the costs of other projects



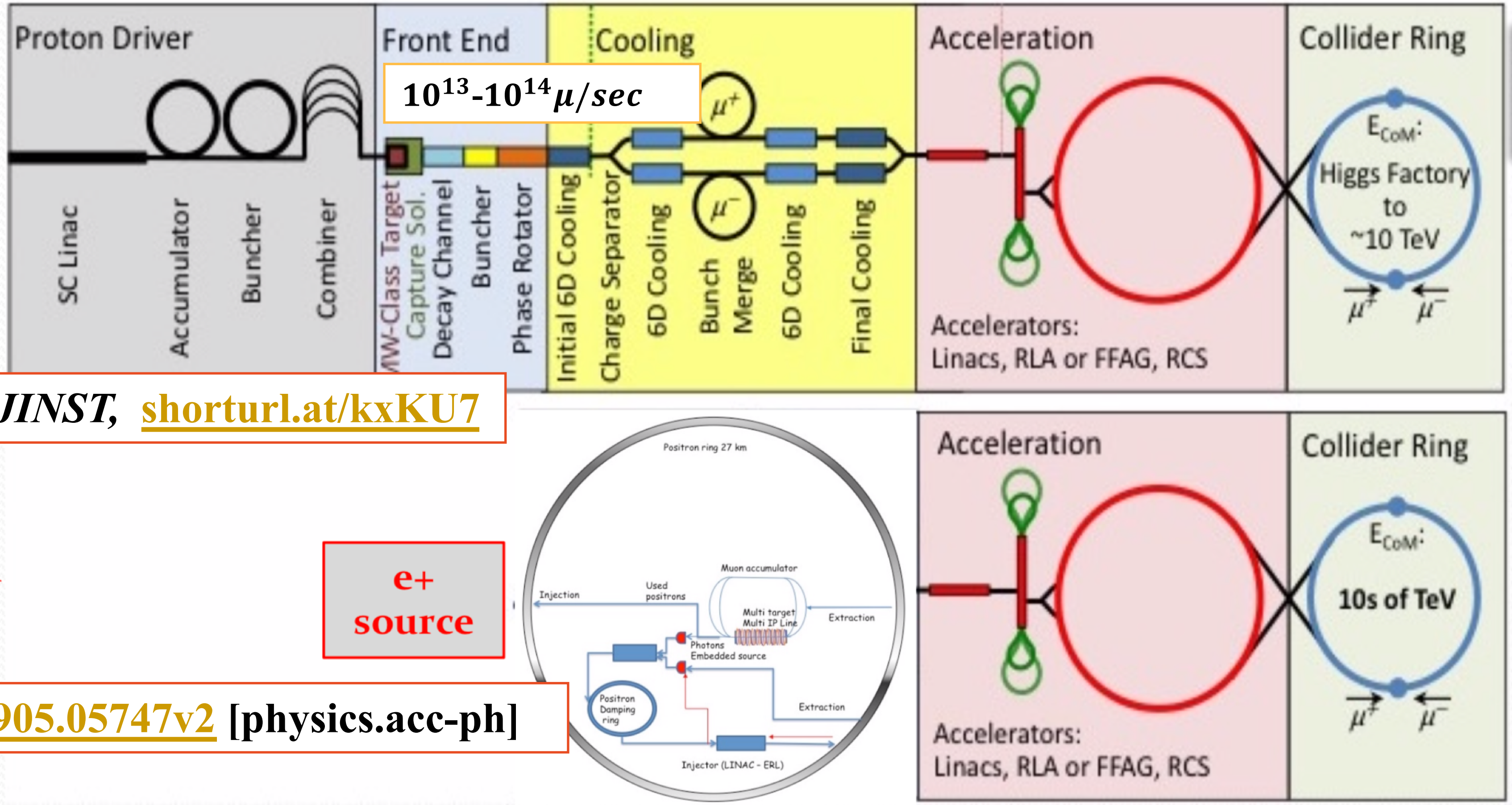
Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{int}$ (ab^{-1})	Time (years)	Power (MW)	Cost
ILC	e^+e^-	0.25	1	2	11	129	4.8-5.3BILCU
		0.5	1	4	10	163(204)	8.0 BILCU
		1	1			300	+(n/a)
CLIC	e^+e^-	0.38	1	1	8	168	5.9 BCHF
		1.5	1	2.5	7	370	+ 5.1 BCHF
		3	1	5	8	590	+7.3 BCHF
CEPC	e^+e^-	0.091&0.16	2	16+2.6	2+1	149	5 B USD
		0.24	2	5.6	7	266	+(n/a)
FCC-ee	e^+e^-	0.091&0.16	2	150+10	4+1	259	10.5 BCHF
		0.24	2	5	3	282	
		0.365 & 0.35	2	1.5+0.2	4+1	340	+1.1 BCHF
LHeC	ep	1.3	1	1	12	(+100)	1.75* BCHF
HE-LHC	pp	27	2	20	20	220	7.2 BCHF
FCC-hh	pp	100	2	30	25	580	17(+7) BCHF
FCC-eh	ep	3.5	1	2	25	(+100)	1.75 BCHF
Muon Collider	$\mu\mu$	14	2	50	15	290	10.7* BCHF

arXiv:2003.09084

Muon Collider Schema

MICE muon cooling   First Results in 2018

MAP



10^{13}-10^{14} μ/sec

Almost ready to go for a CDR

MUON JINST, shorturl.at/kxKU7

LEMMA

e+ source

arXiv:1905.05747v2 [physics.acc-ph]

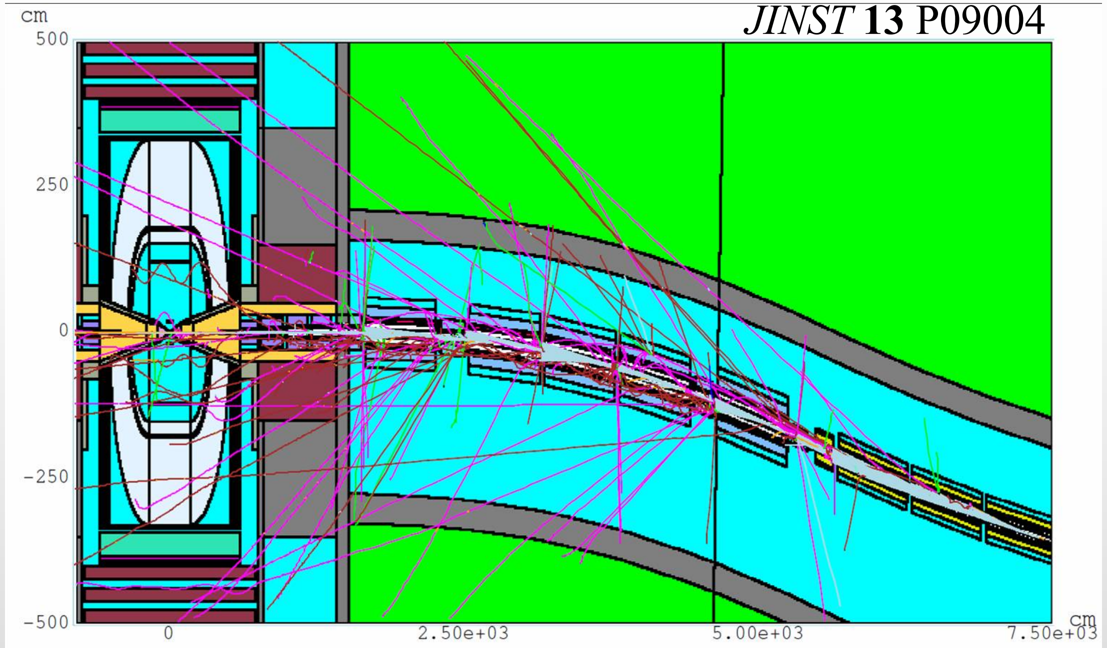
Need consolidation to overcome technical limitation but it can reach very high CM Energies

The Challenge: beam-induced background

Muon induced background is critical for:

- Magnets, they need to be protected
- Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice

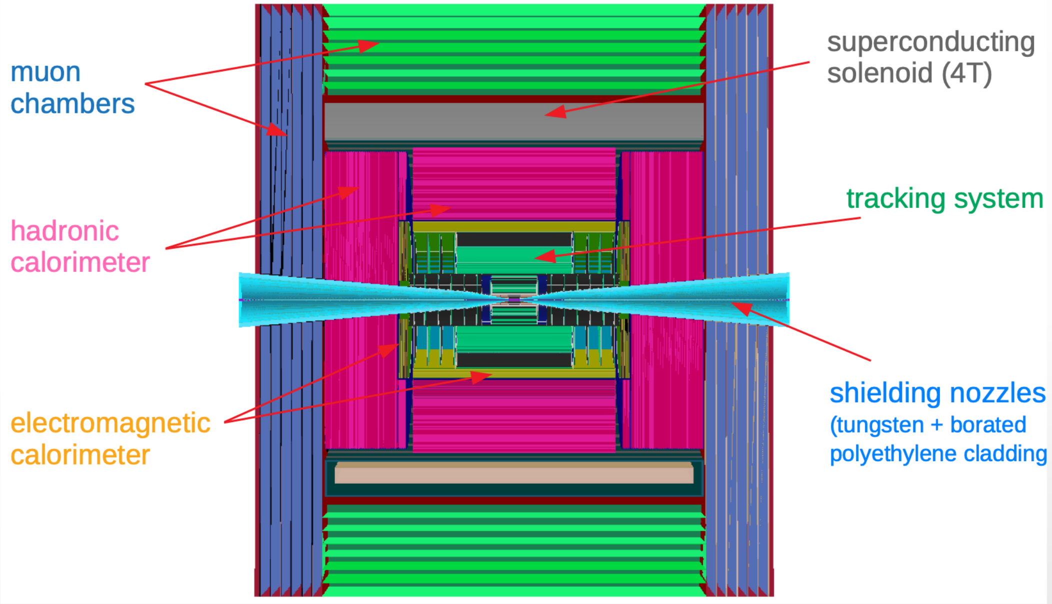
JINST **13** P09004



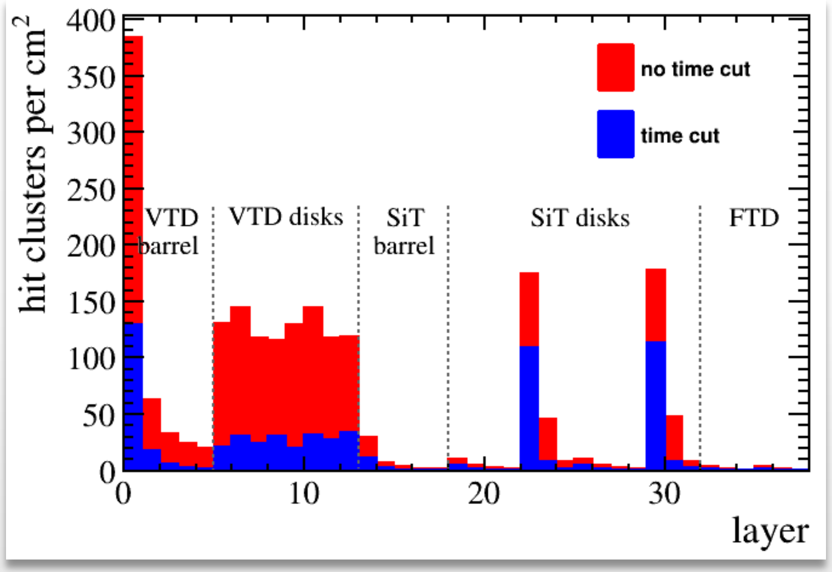
- MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel ±200 m from the interaction point.
- Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.
- Two tungsten nozzles play a crucial role in background mitigation inside the detector.

Detector Response Simulation at $\sqrt{s}$ =1.5 TeV

The simulation/reconstruction tools supports signal + beam-induced background merging



Effects of beam-induce background can be mitigated by exploiting “5D” detectors, i.e. including timing



Results on $\mu^+\mu^- \rightarrow HX, H \rightarrow b\bar{b}$ published on JINTST as Detector and Physics Performance at a Muon Collider

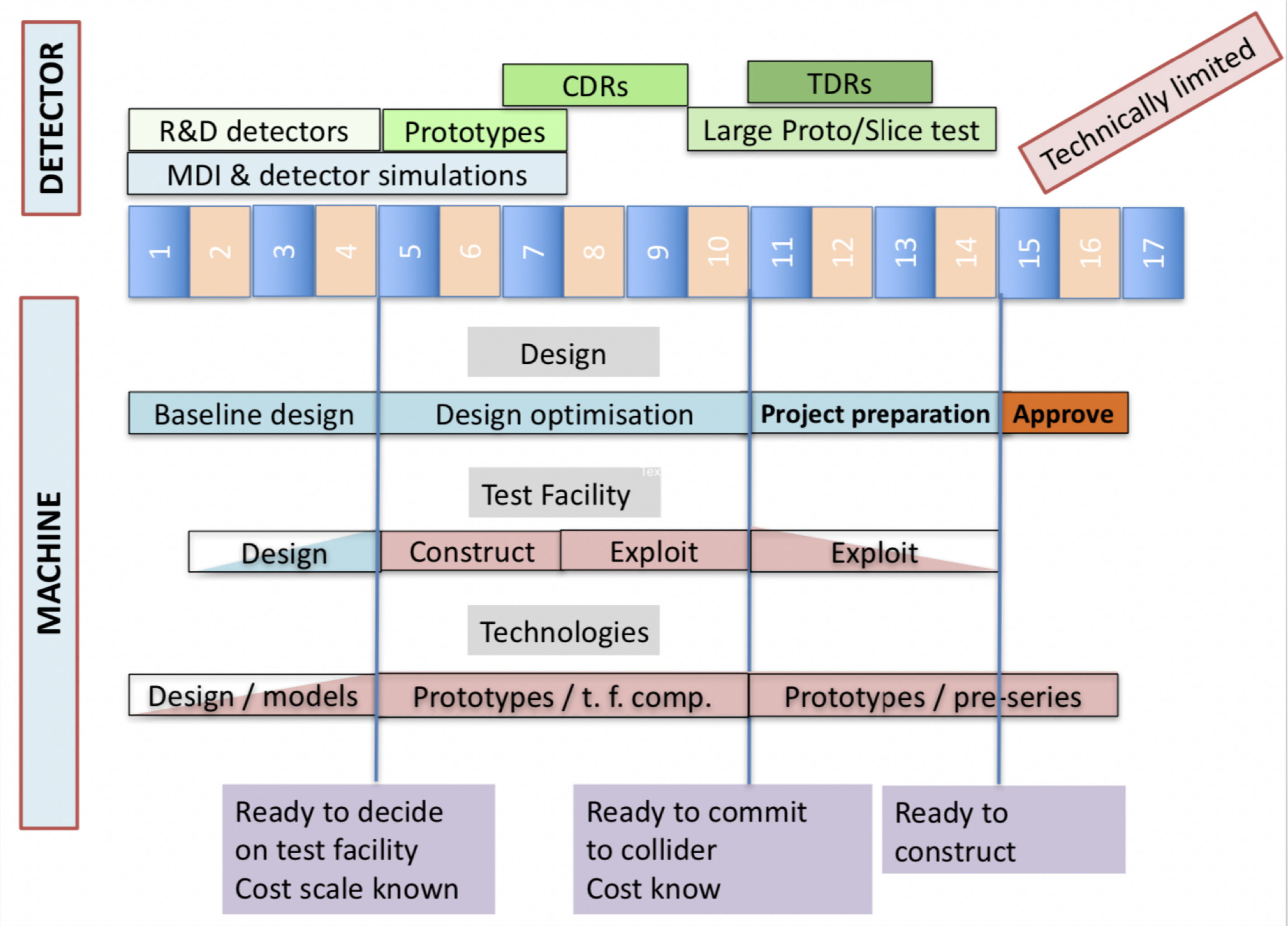
Starting of an International Collaboration

- The aim is to to develop an integrated muon collider design concept that encompasses the physics, the detectors, and accelerator.

- Start-to-end facility design:
  - Collider from source to final acceleration
  - Machine detector interface to protect detector and magnet from beam-induced background
  - Neutrino, for bad and good!
  - Physics reaches at several CM energies
  - Demonstrators and R&D facilities

- The Snowmass Process for the next Particle Physics Project Prioritization in US just started and the muon collider facility and its physics reach is very popular.

Possible Schedule



Physics Briefing Book
arXiv:1910.11775v2

Activities in Padova and Interested People

1) Study and optimization of Machine Detector Interface
2) Development and maintenance of the code for simulation and reconstruction.
3) Study of the performance of the detector, in particular calorimeter and jets, possible synergies with LHCb upgrade phase 2. Do we have other synergies with LHC upgrades?
4) Study of Higgs boson physic reaches (L. Buonincontri Tesi magistrale)
5) Test beam for $e^+e^- \to \mu^+\mu^- \Rightarrow$ Marco Zanetti

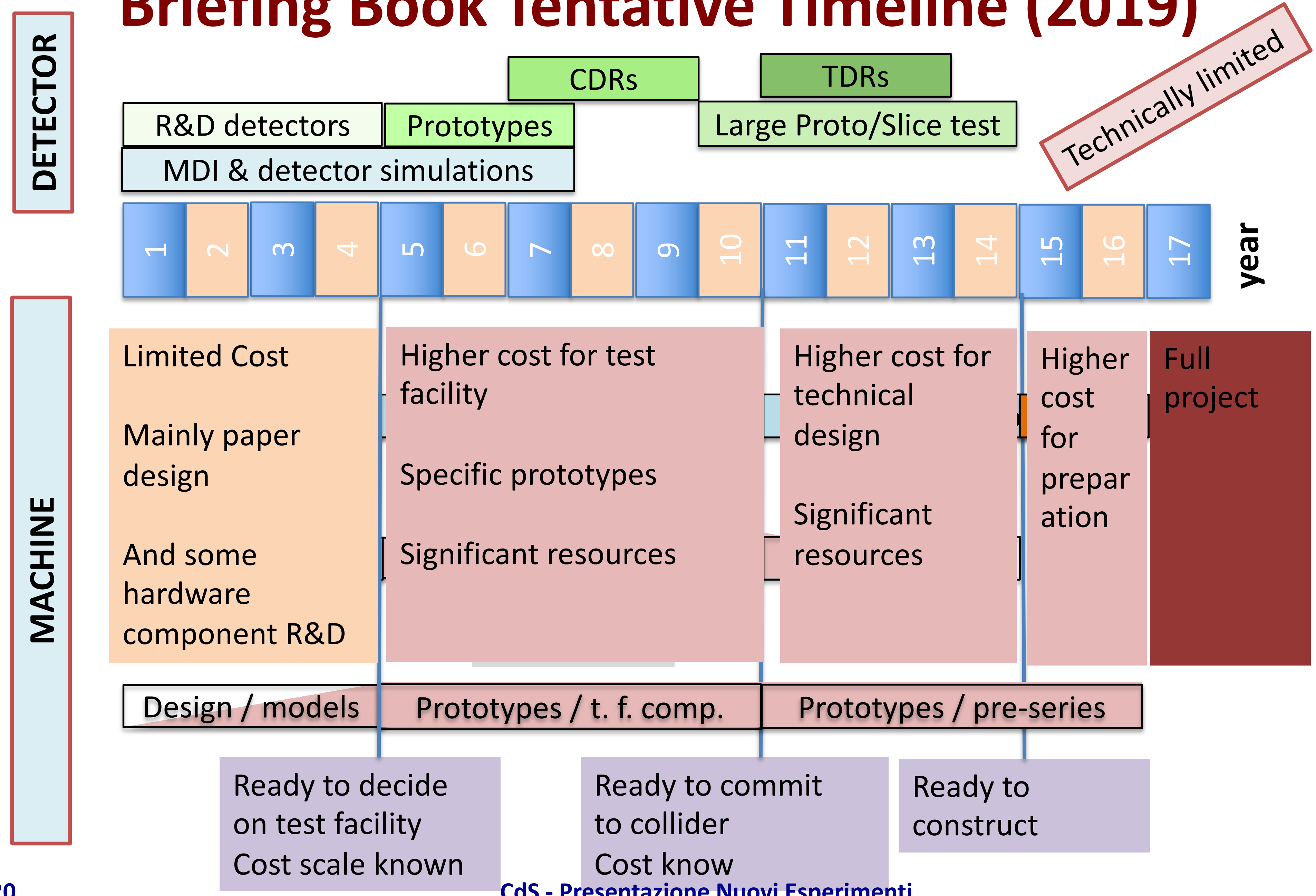
Richieste

- Risorse calcolo, servizi calcolo
- Consumi per test beam sul R&D rivelatori
- Missioni
- Test beam ”Lemma” ⇒ Marco Zanetti

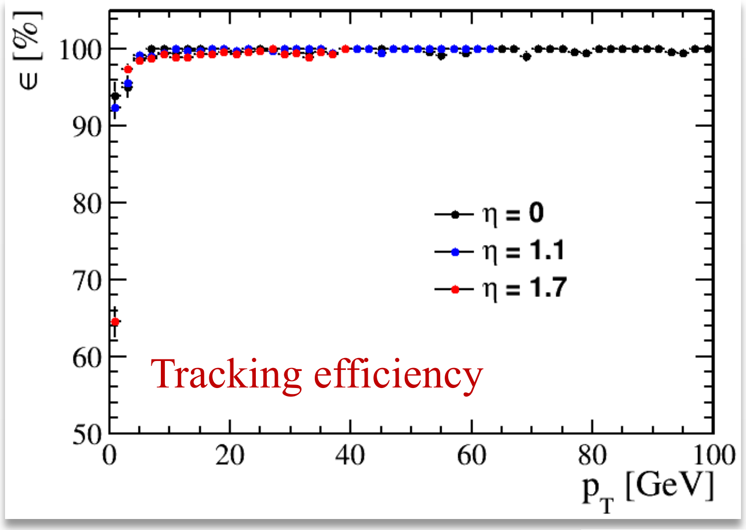
Nome Cogome	Posizione
Paolo Andreetto	Permanente
Alessandro Bertolin	Permanente
Camilla Curatolo	AR
Tommaso Dorigo	Permanente
Umberto Dosselli	Permanente
Alessio Gianelle	Permanente
Donatella Lucchesi	Permanente
Mauro Morandin	Permanente
Lorenzo Sestini	Permanente
Marco Zanetti	Permanente
Davide Zuliani	Dottorando

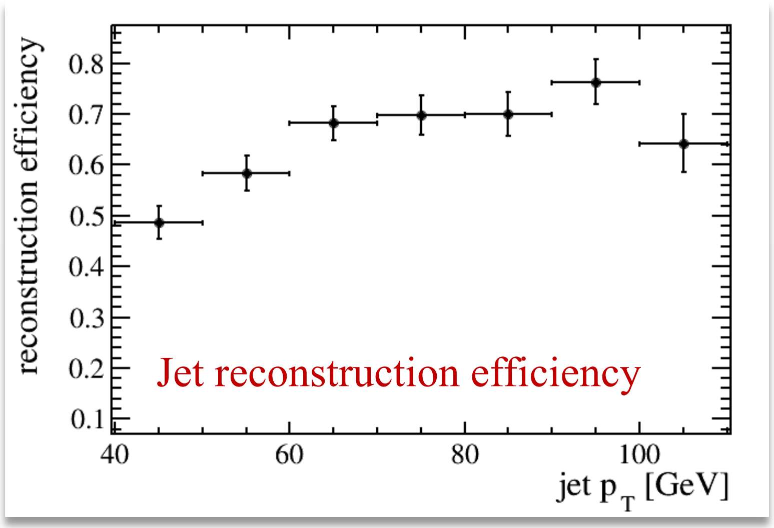
BACKUP

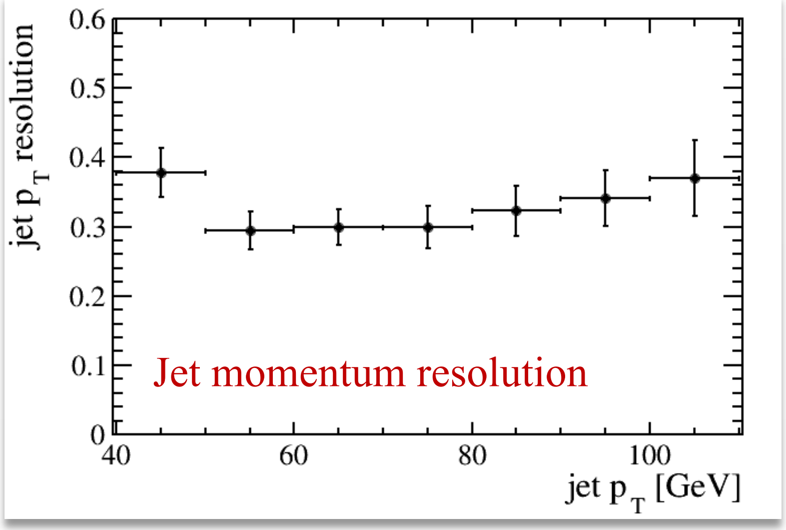
Briefing Book Tentative Timeline (2019)

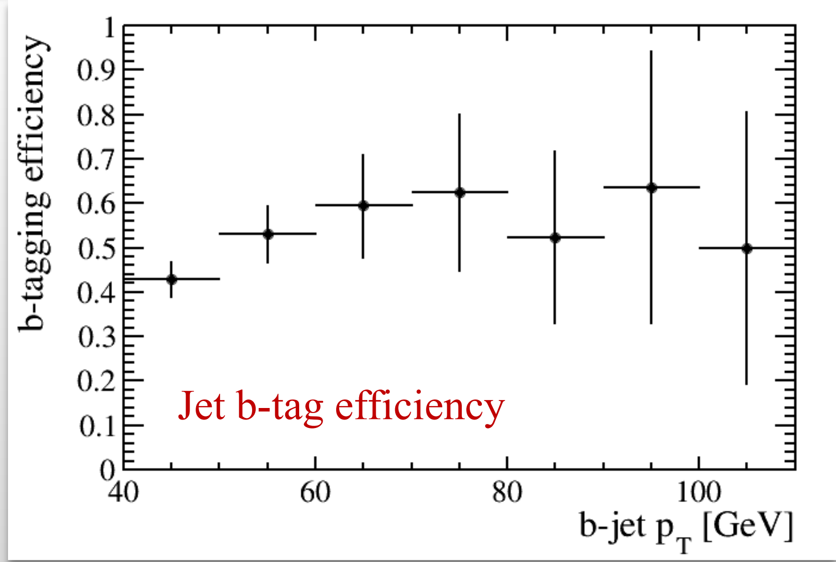


Detector Performance at $\sqrt{s}$ =1.5 TeV









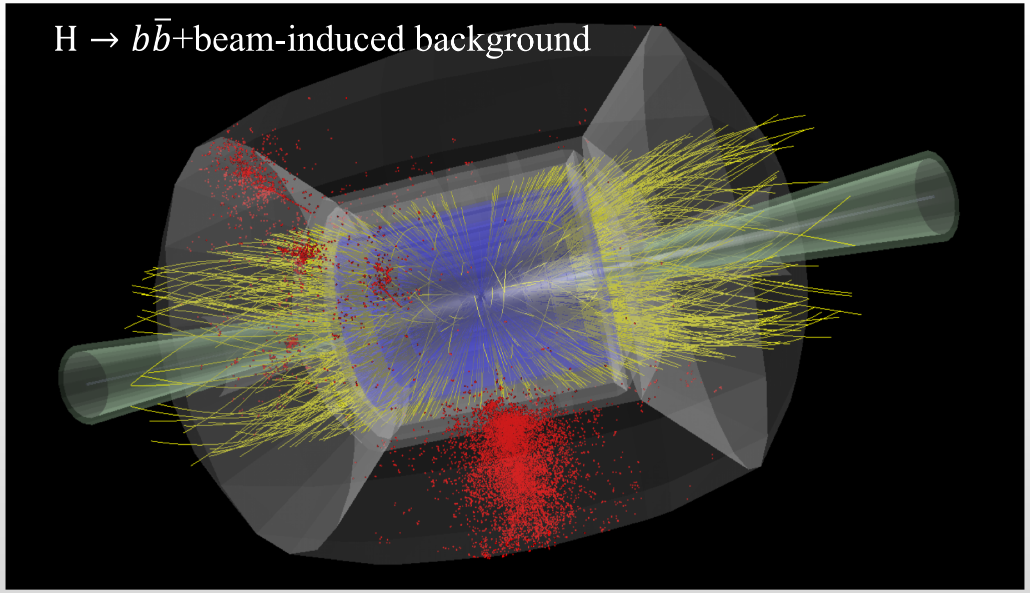
Background tagging:

- fake rate: 1 ÷ 3 %
- Tests done so far show fake rate is manageable.

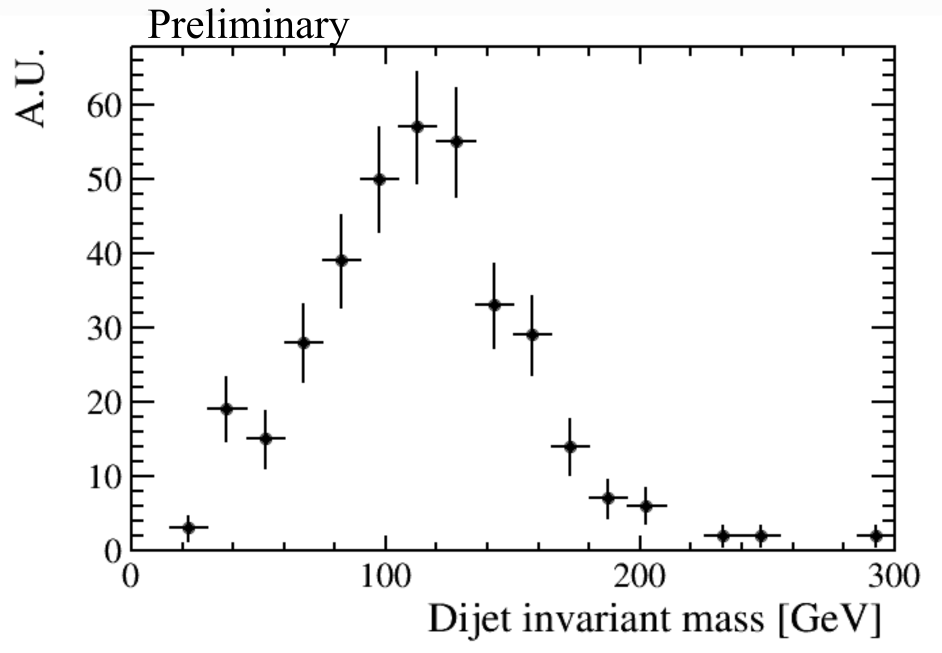
$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

$\mu^+\mu^- \rightarrow HX, H \rightarrow b\bar{b}$ and $\mu^+\mu^- \rightarrow b\bar{b}X$ generated @$\sqrt{s} = 1.5\ TeV$ with PYTHIA 8

Process	cross section [pb]
$\mu^+\mu^- \rightarrow \gamma^*/Z \rightarrow b\bar{b}$	0.046
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma^*/Z \rightarrow b\bar{b}$ +X	0.029
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma \rightarrow b\bar{b}\gamma$	0.12
$\mu^+\mu^- \rightarrow HZ \rightarrow b\bar{b}$ +X	0.004
$\mu^+\mu^- \rightarrow \mu^+\mu^- H\ H \rightarrow b\bar{b}$ (ZZ fusion)	0.018
$\mu^+\mu^- \rightarrow \nu_\mu\nu_\mu H\ H \rightarrow b\bar{b}$ (WW fusion)	0.18 Signal



$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



Higgs $b\bar{b}$ Couplings: Assumptions

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR\left(H \to b\bar{b}\right) = \frac{N_s}{A\varepsilon\mathcal{L}T}$$

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N_s + B}}{N_s}$$

$$4\left(\frac{\Delta g_{Hbb}}{g_{Hbb}}\right)^2 = \left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta(g^2{}_{HWW}/\Gamma_H)}{g^2{}_{HWW}/\Gamma_H}\right)^2$$

Obtained, with several approximations, from e^+e^-: 2% @1.4TeV and 1.8% @ 3TeV arXiv:1608.07538v2

N_s : number of signal events.
B: number of background events, $\mu^+\mu^- \to q\bar{q}$ from Pythia + beam-induced background
σ: cross section times BR
A: acceptance; removed nozzle region for $\sqrt{s}$ =1.5 TeV, 2 jets $|\eta| < 2.5$, and $p_T > 40$ GeV
ε: measured with the full simulation at $\sqrt{s}$ =1.5 TeV

$t = 4 \cdot 10^7$ s
One detector

Assumptions for Higgs $b\bar{b}$ Couplings at $\sqrt{s} = 3, 10$ TeV

- Nozzles and interaction region are not optimized for these energies, nor is the detector.
- Efficiencies obtained with the full simulation at $\sqrt{s}$ = 1.5 TeV used for the higher center-of-mass energy cases, with the proper scaling to take into account the different kinematic region.
- At higher $\sqrt{s}$ the tracking and the calorimeter detectors are expected to perform significantly better since the yield of the beam-induced background decreases with $\sqrt{s}$
- The uncertainty on $\frac{\Delta(g^2_{HWW}/\Gamma_H)}{(g^2_{HWW}/\Gamma_H)}$ is taken from the CLIC at $\sqrt{s}$ = 3 TeV and used also at $\sqrt{s}$ = 10 TeV

Conservative Assumptions

Higgs $b\bar{b}$ Couplings Results

- The instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP
- The acceptance, A, the number of signal events, N, and background, B, are determined with simulation

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [$cm^{-2}s^{-1}$]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies