Muon Collider Initiative

Sezione di Padova
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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, revived 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 formed 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 submitted 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

Brief history and starting point for the future

- Several workshops have been organized by the CERN working group where the project acquired momentum

- June 19, 2020 the Eu Strategy was published, where at page 14en, we read:
  […] In addition to the high field magnets the accelerator R&D roadmap could contain:
  an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e^+e^- colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;
  […]

- CSN1 opened a new research line, RD_MuCol

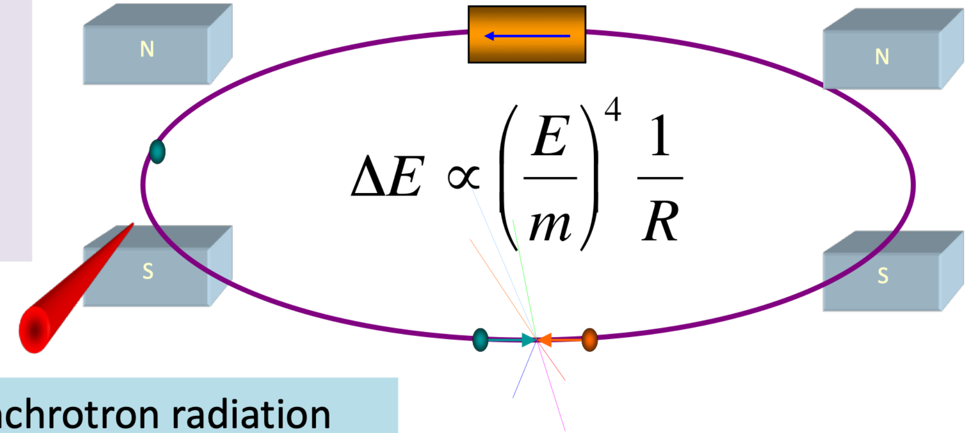
- Great interest in US at the ongoing U.S. Snowmass process

- First meeting to prepare the international collaboration hosted by CERN on July 3, 2020 Agenda

Lepton Collider Energy Limit

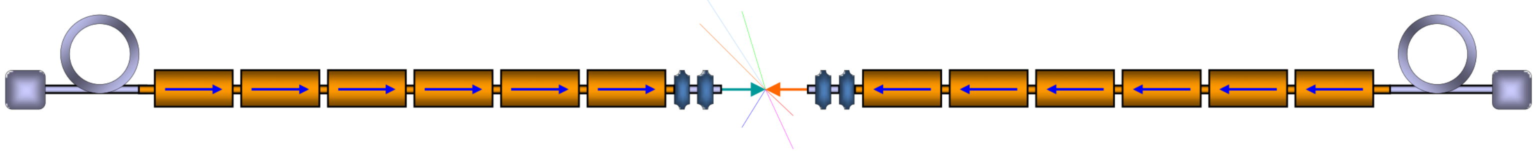
Electron-positron rings are **multi-pass** but limited by synchrotron radiation

That is why **proton rings** are energy frontier (otherwise would use e^+e^- in LHC)



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron linear colliders avoid synchrotron radiation
But are **single pass** is acceleration and collision
This limits energy and luminosity (CLIC cost extrapolated to 14 TeV: O(60 GCHF), power O(1.7-2.8 GW)

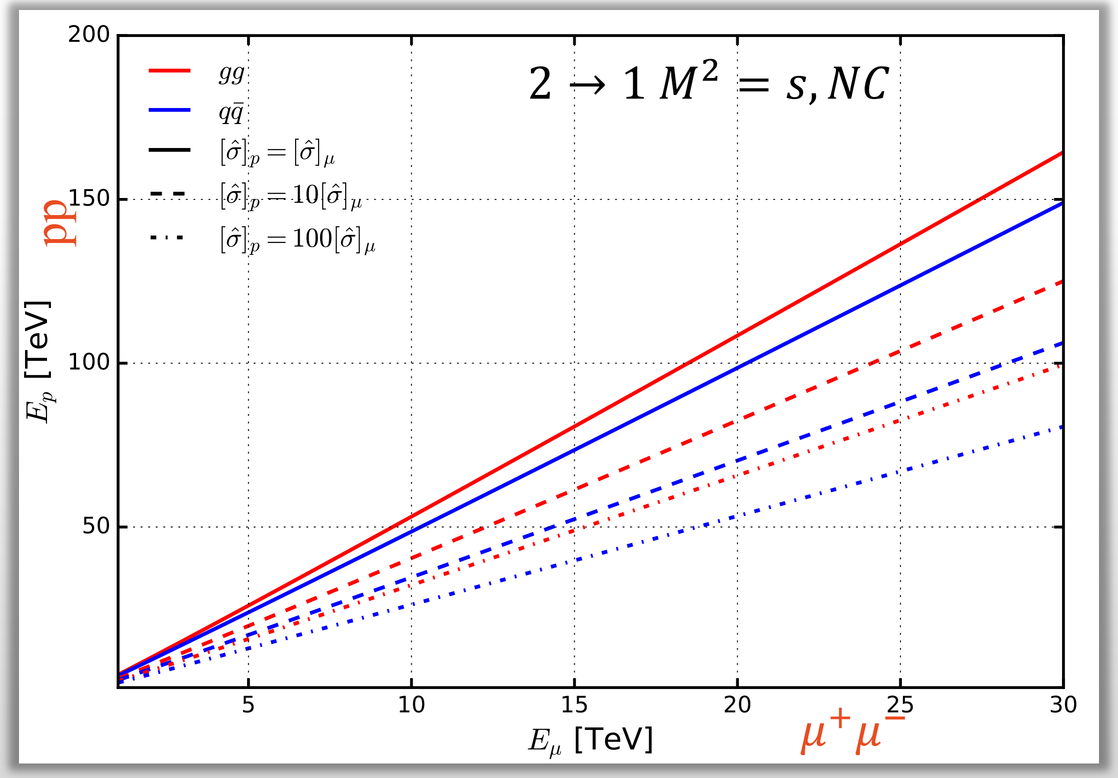


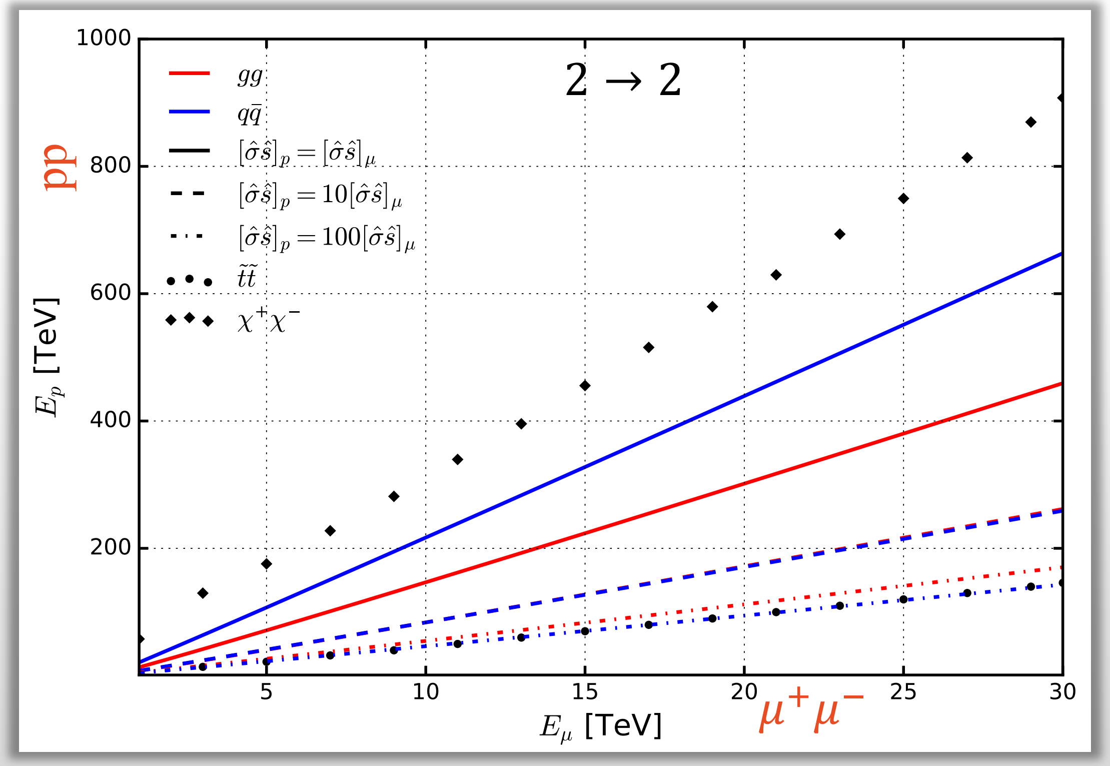
Novel approach: **muon collider**
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs

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 $\sqrt{s_p}$

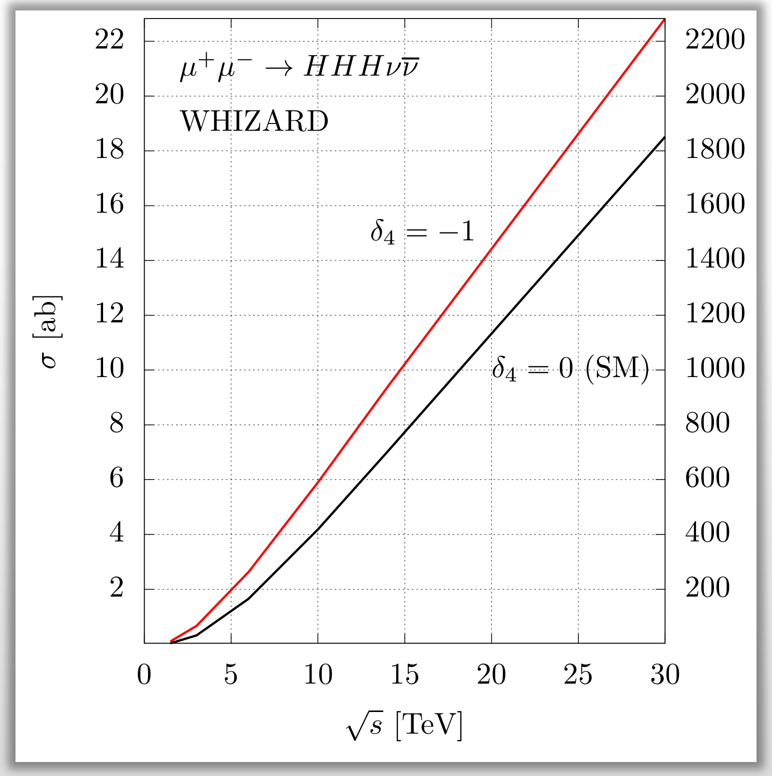
Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





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



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

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

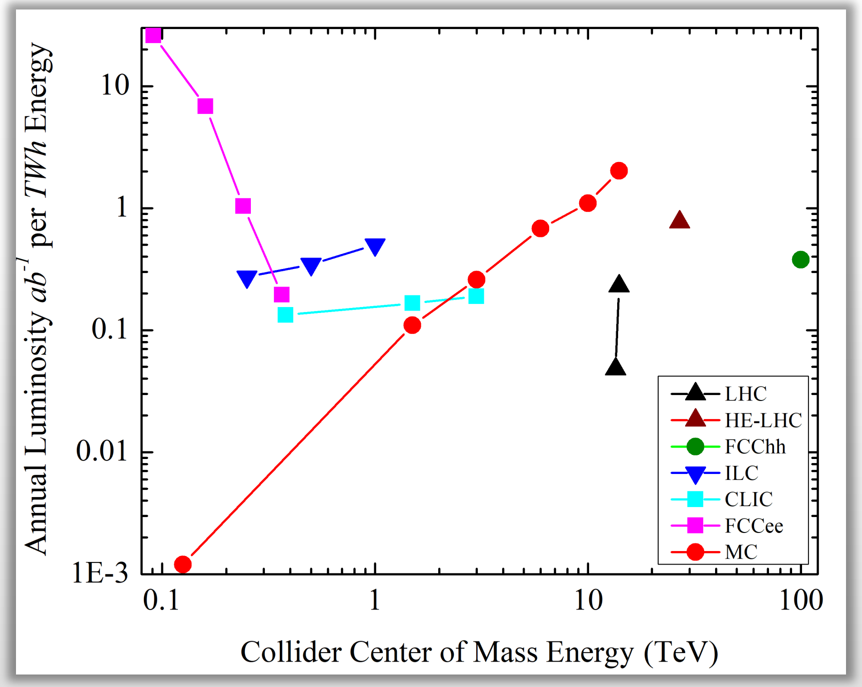
Muon Collider with several TeV CM energy and with integrated luminosities of the order of several tens of attobarns, could provide enough events to allow a determination (a SM) quartic Higgs self-coupling with an accuracy in the tens of percent.

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

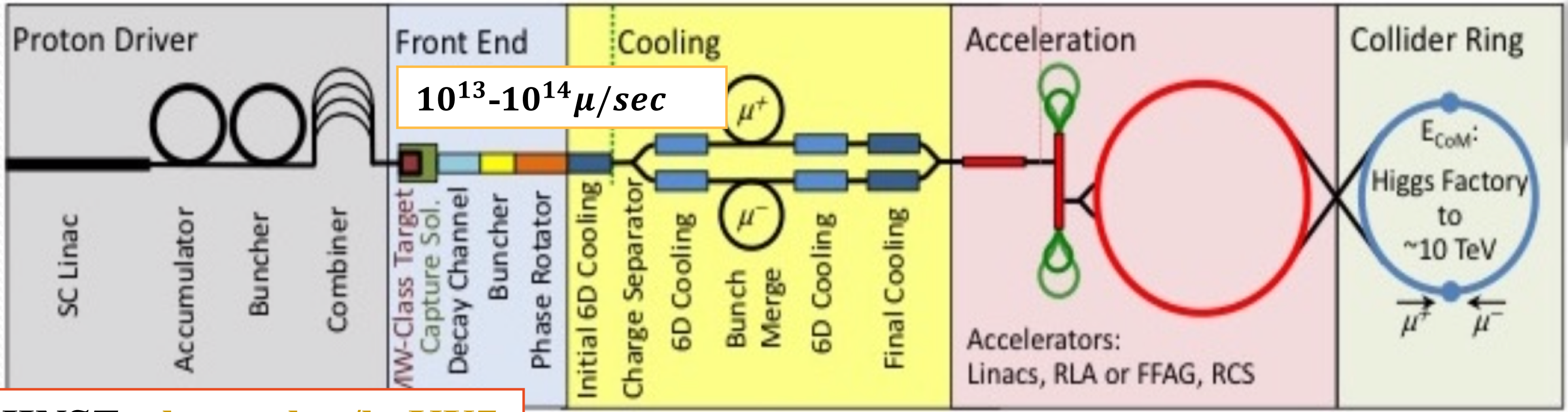
arXiv:2003.09084

Muon Collider Schema

MICE muon cooling First Results in 2018

Muon Accelerator Program

MAP



10^{13}-10^{14} μ/sec

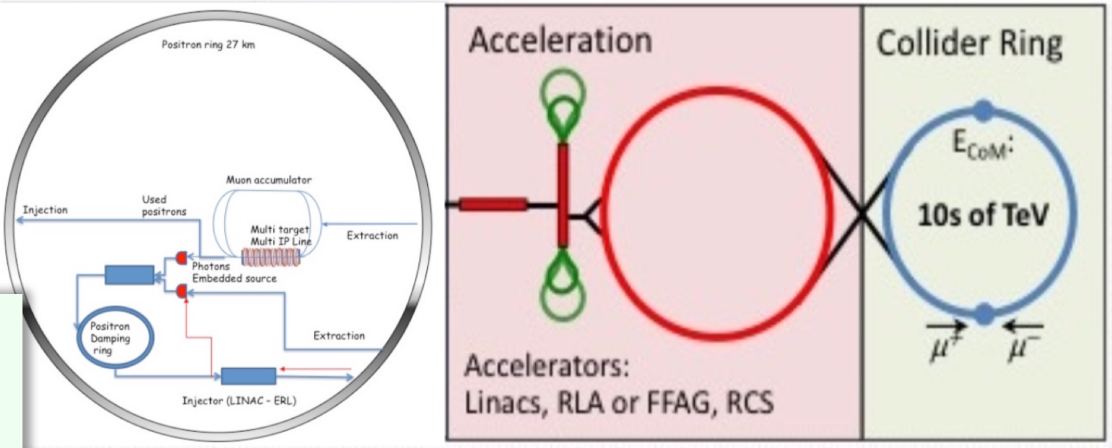
Almost ready to go for a CDR

MUON JINST, shorturl.at/kxKU7

LEMMA

arXiv:1905.05747v2

e+ source



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

Contribution of test beam @CERN, next test funded by INFN, to be confirmed due to covid-19 probably in 2022.

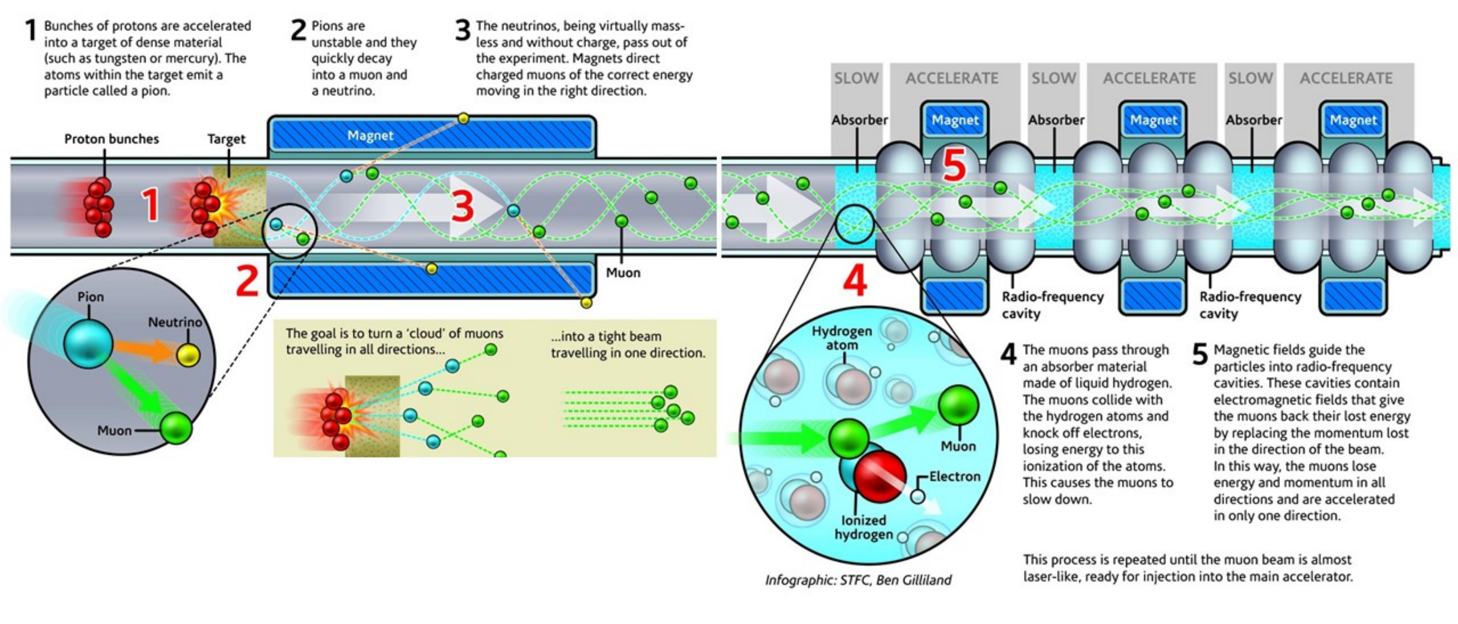
Muons can be cooled!

MICE muon cooling

First Results in 2018


MENU
nature
We'd like to understand how you use our websites in order to
Article | Open Access | Published: 05 February 2020
Demonstration of cooling by the Muon Ionization Cooling Experiment
MICE collaboration

An effective O(10%) reduction of transverse emittance of initially dispersed 140 MeV/c muons passing through a prototype ionization cooling channel cell.

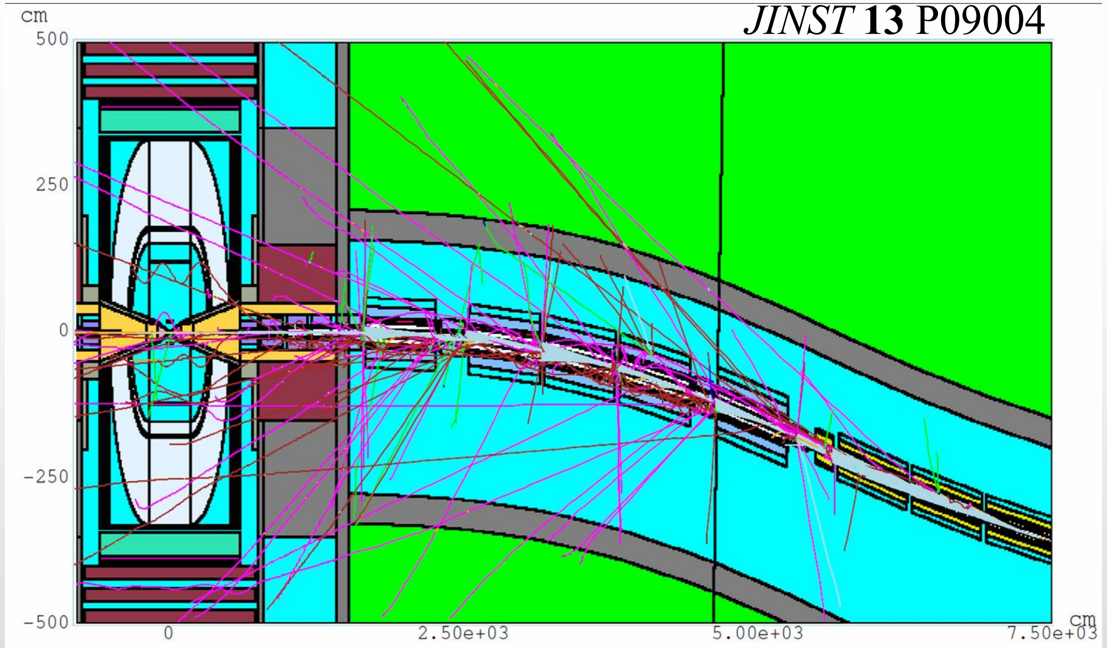


A cooling cell consists of a sequence of LiH or liquid hydrogen absorbers within a lattice of up to 3.5 T solenoids that provide the required particle focusing

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.

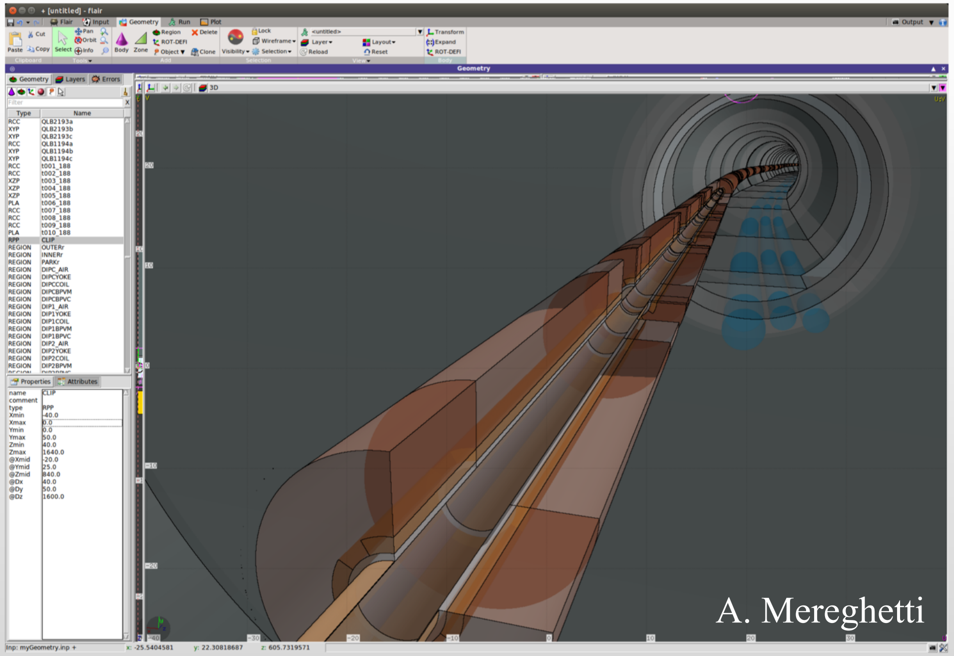
The beam-induced background simulation

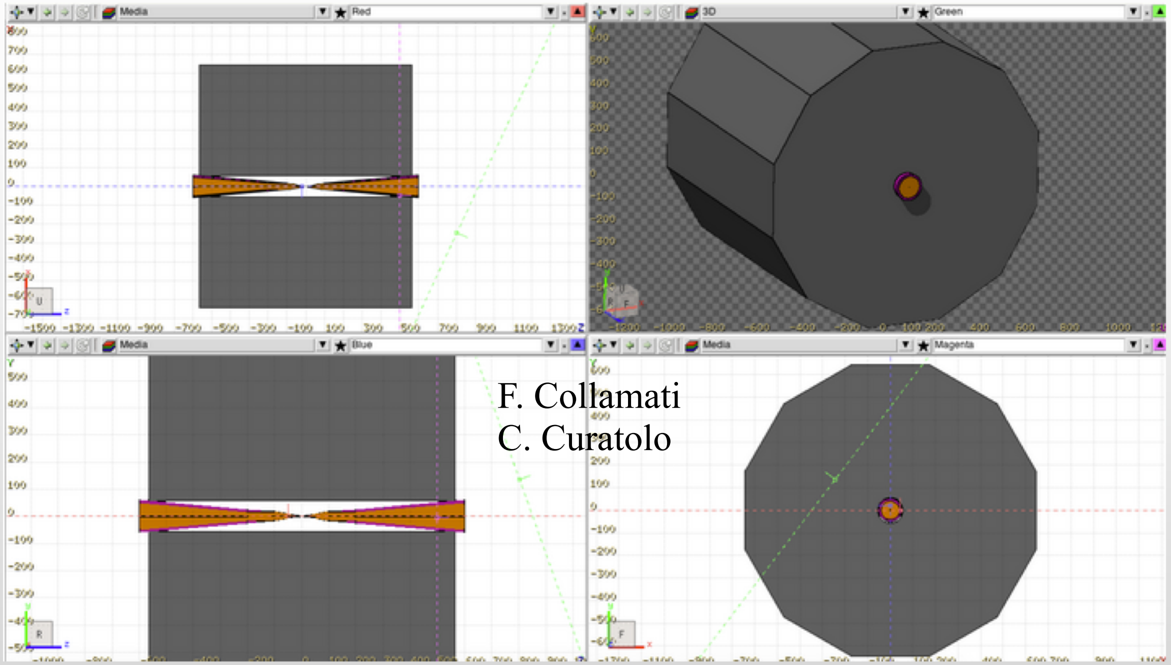
Input data
Output data
Software program

IR detailed description → LineBuilder → FLUKA DB

Detector nozzle description → Flare + new code → Detector Nozzle position

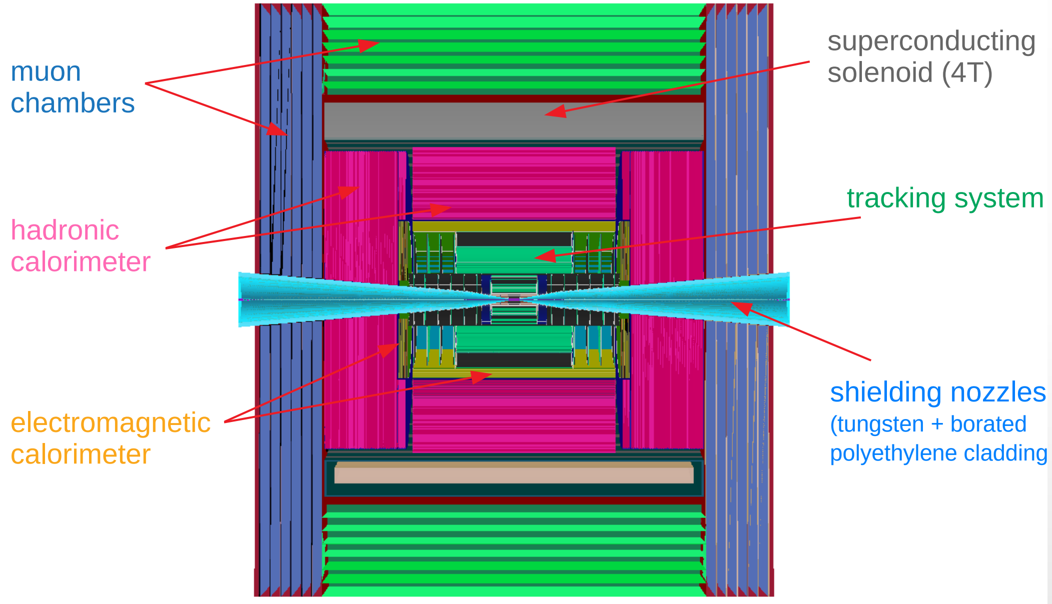
FLUKA DB, Detector Nozzle position → FLUKA simulation
Muon decay and interaction
With material → Background on the detector envelope



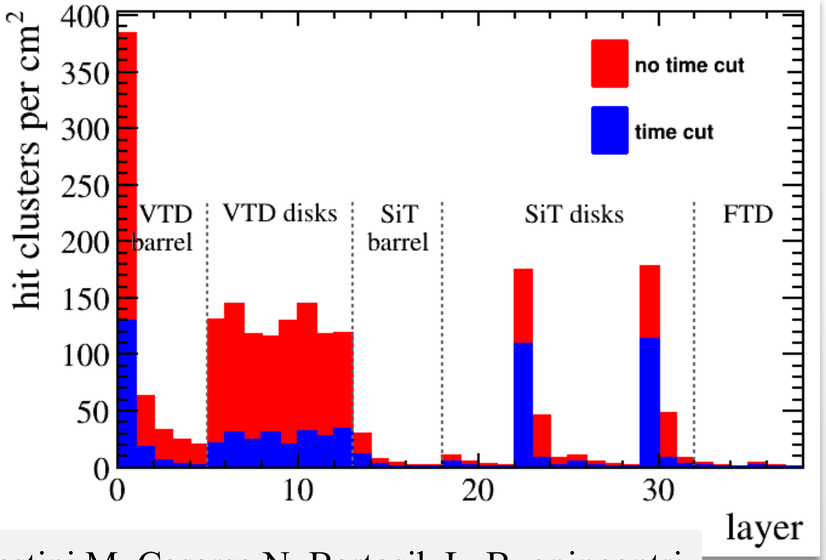


Detector Response Simulation at $\sqrt{s}$ =1.5 TeV

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

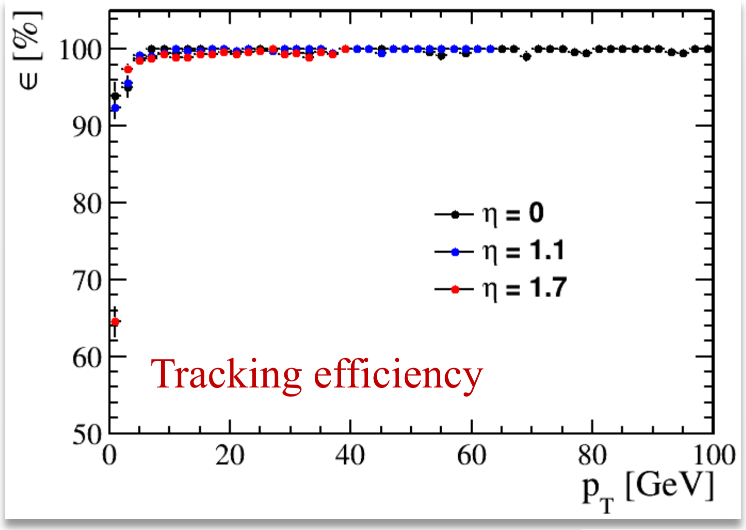


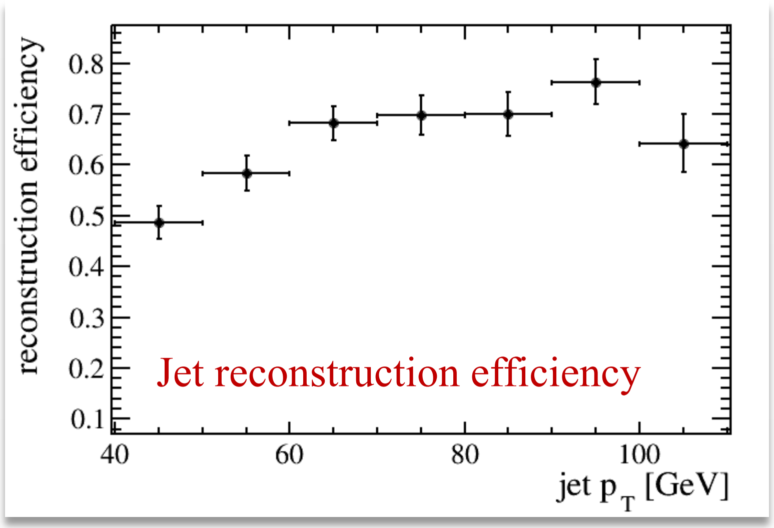
L.Sestini M. Casarsa N. Bartosik L. Buonincontri

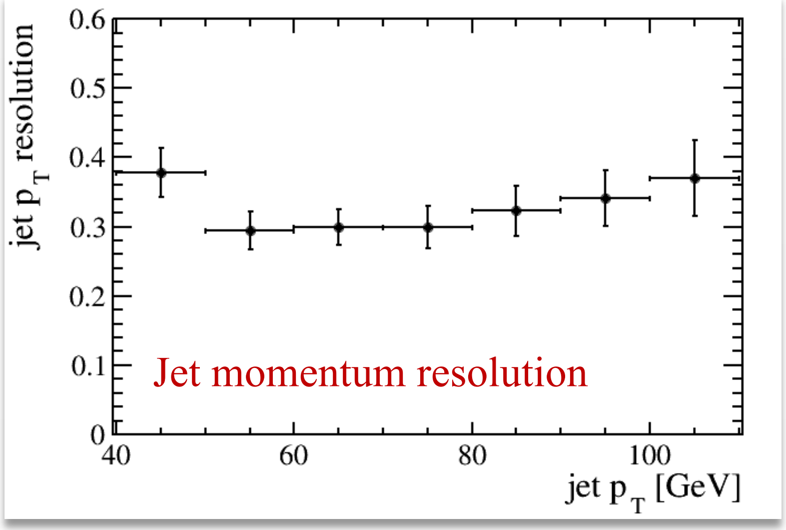
Code developed and maintained by:
P. Andreetto
A. Gianelle

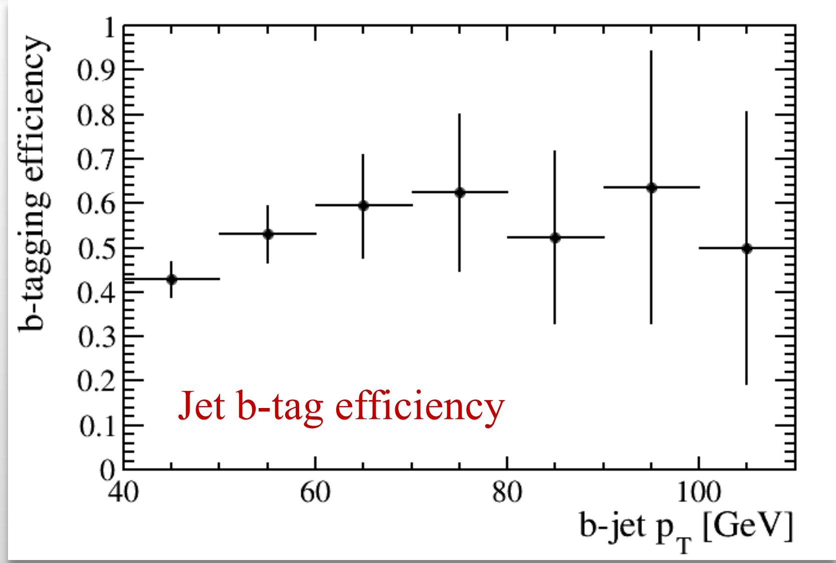
Results on $\mu^+\mu^- \to HX, H \to b\bar{b}$ published on JINTST as Detector and Physics Performance at a Muon Collider

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









L.Sestini M. Casarsa N. Bartosik L. Buonincontri

Background tagging:

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

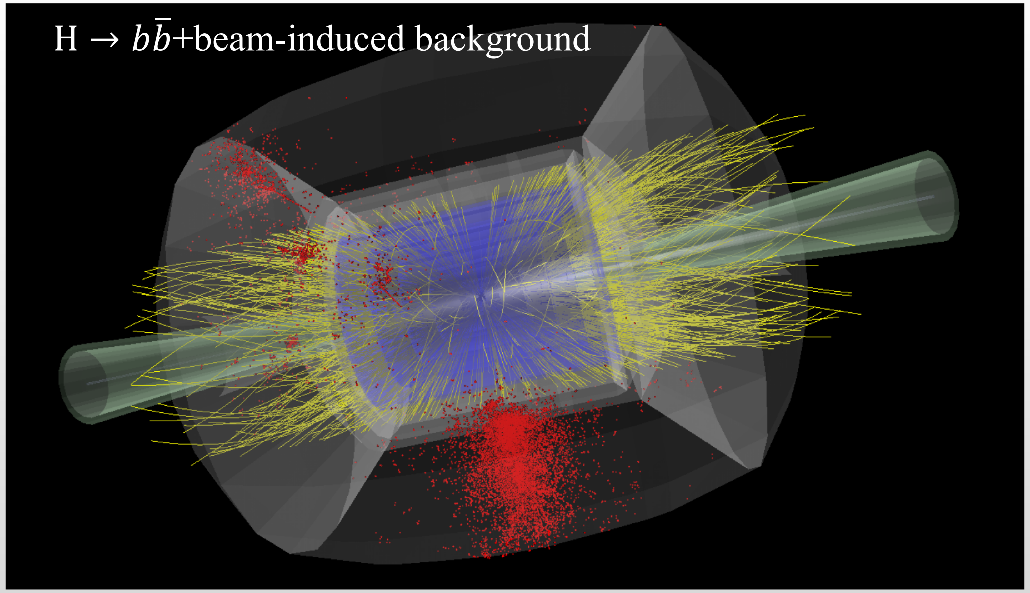
$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

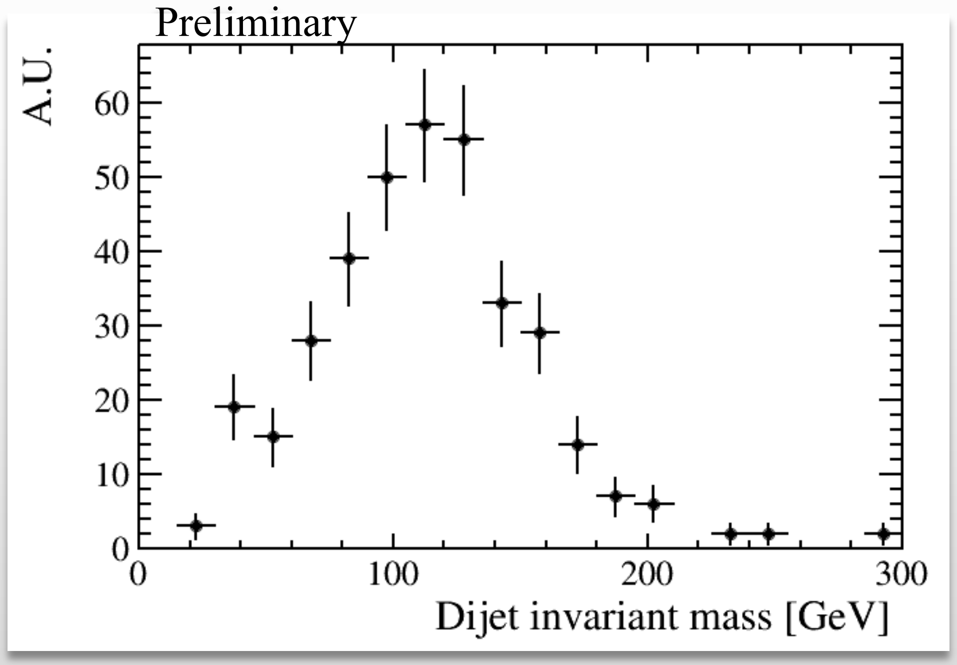
$\mu^+\mu^- \rightarrow HX, H \rightarrow b\bar{b}$ and $\mu^+\mu^- \rightarrow b\bar{b}X$ generated @$\sqrt{s}$ = 1.5 TeV with PYTHIA 8

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
$\mu^+\mu^- \rightarrow \nu_\mu\nu_\mu H\ H \rightarrow bb$ (WW fusion)	0.18 Signal

L.Sestini M. Casarsa N. Bartosik L. Buonincontri

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





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

At this point we have the proof of concept on machine and detector

Time to move forward to demonstrate that machine and detector can be built

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.

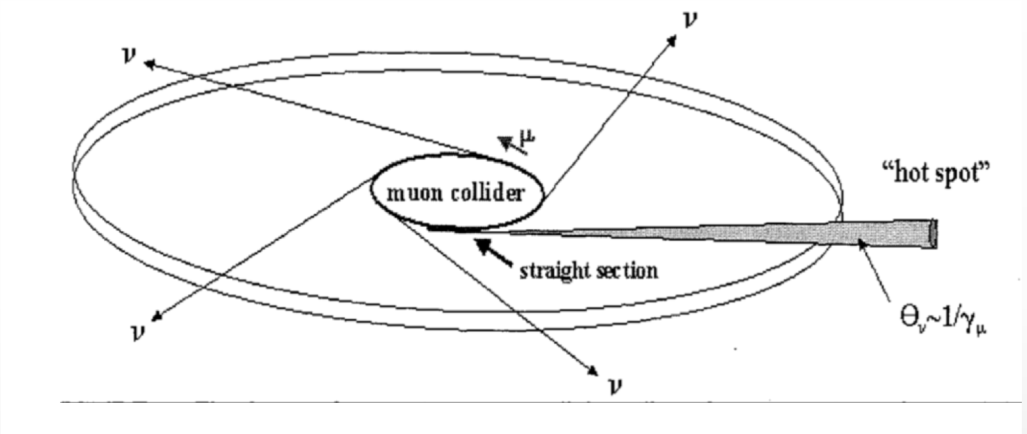
- Start-to-end facility design:
  - Collider from source to final acceleration
  - Machine detector interface to protect detector and magnet from beam-induced background
  - Neutrino, for bad and good!
  - Physics reaches at several CM energies
  - Demonstrators and R&D facilities

Fields of Expertise for the Muon Collider Study

- **Physics Motivation** Study the physics potential of the collider, establish physics benchmark points, refine requirements for energy and luminosity.
- **Experiment and Physics Simulation** Performance of collider and detector, event reconstruction, simulation tools, performance benchmark points, detector performance goals.
- **Detector Design and R&D** Detector development, prototypes, detector performance goals, . . .
- **Machine Detector Interface** Background and its mitigation, detector and machine interplay, simulation tools.
- **High-energy Collider Design** This mainly includes the lattice design, beam dynamics and accelerator physics of initial acceleration of the muons, the high-energy accelerator and the collider ring or potentially a combined accelerator and collider ring. This has a strong list with the neutrino radiation, for which mitigation techniques need to be found, the cost and power consumption of the collider. New simulation tools might be required.
- **Proton-based Muon Source** The design of the proton, the muon production and the cooling complexes. Includes improvement of the performance to reach design goal, identification of risks. New simulation tools might be required.
- **Positron-based Muon Source** The design of the positron production, muon production and target, muon accumulation complexes. New simulation tools might be required.
- **Magnets** Includes high-field superconducting focusing magnets for the collision point, high-field dipoles and combined function magnets for the collider and highest-field solenoids for the muon production and cooling. Also includes fast ramping, normal or superconducting magnets with power converters and energy recovery.
- **Radio Frequency Technology** Including superconducting RF for high energy acceleration and and normal-conducting high-gradient RF for the cooling. Also the proton complex needs RF.
- **Radiation, Shielding, Losses, Targets, Collimation, Materials** Protection of the detector and the collider magnets from muon decay products. High power target for the muon production using protons or positrons. Protection of machine from target debris. Protection of accelerator complex.
- **Other Technologies** This includes efficient cooling of the significant losses from muon decays. Also vacuum, instrumentation, machine protection and more need to be explored.

Other Synergies

So far we never discuss the neutrino, for the bad and the good.
At the IP and in any straight section we produce intense beams of high energy neutrino and anti-neutrino



The radiation hazard due to neutrino induced radiation has to be studied in details to mitigate it
Neutrino beams can be use for physics measurements ⟶ need to be investigated

Activities in Padova and Interested People so far

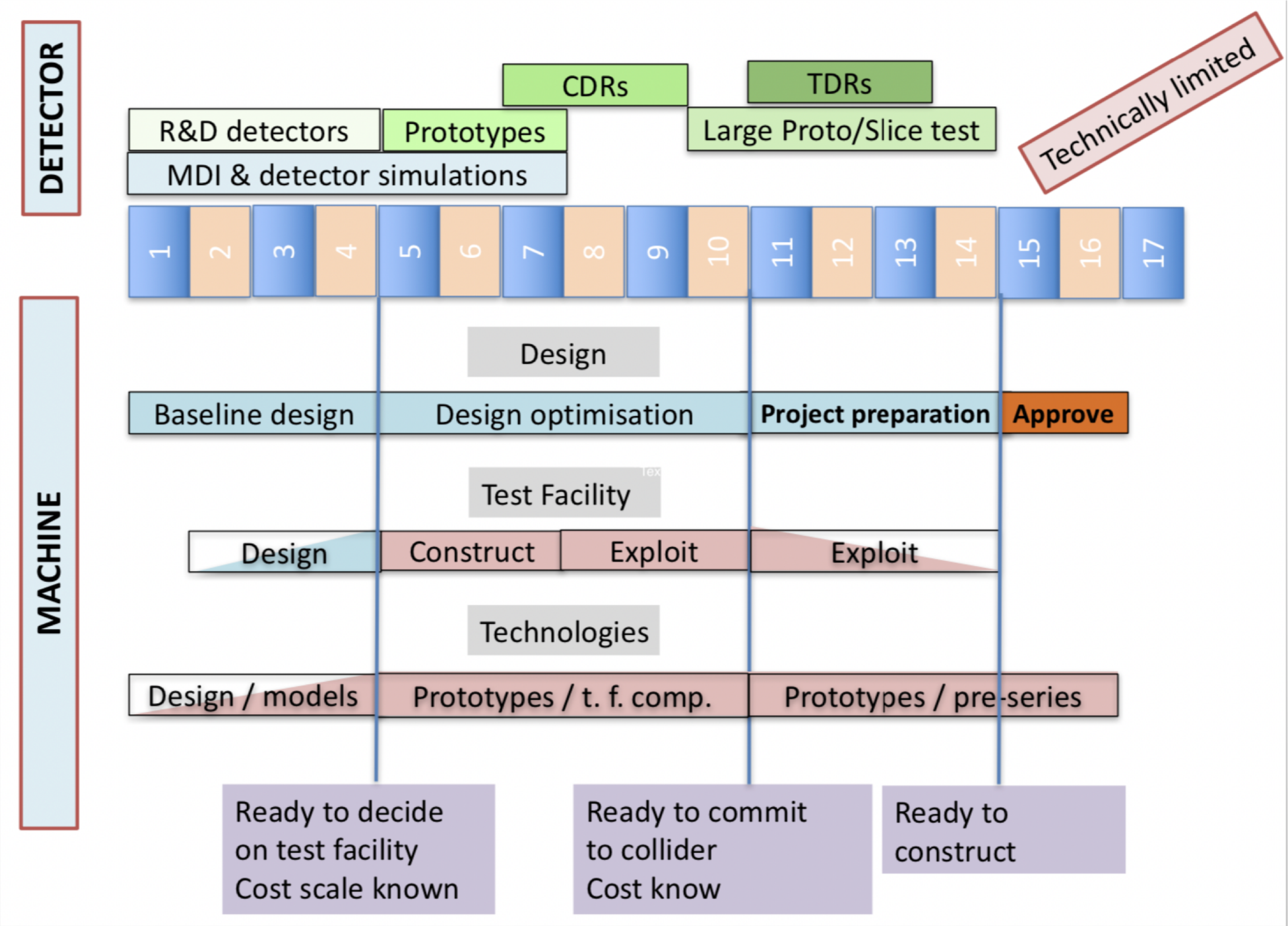
1) Study and optimization of Machine Detector Interface
2) Development and maintenance of the code for simulation and reconstruction.
3) Study of the performance of the detector, in particular calorimeter and jets, possible synergies with LHCb upgrade phase 2. Do we have other synergies with LHC upgrades?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

There are a lot of synergies:

- New detectors developments and R&D
- New advanced algorithms for simulation, reconstruction and analysis development

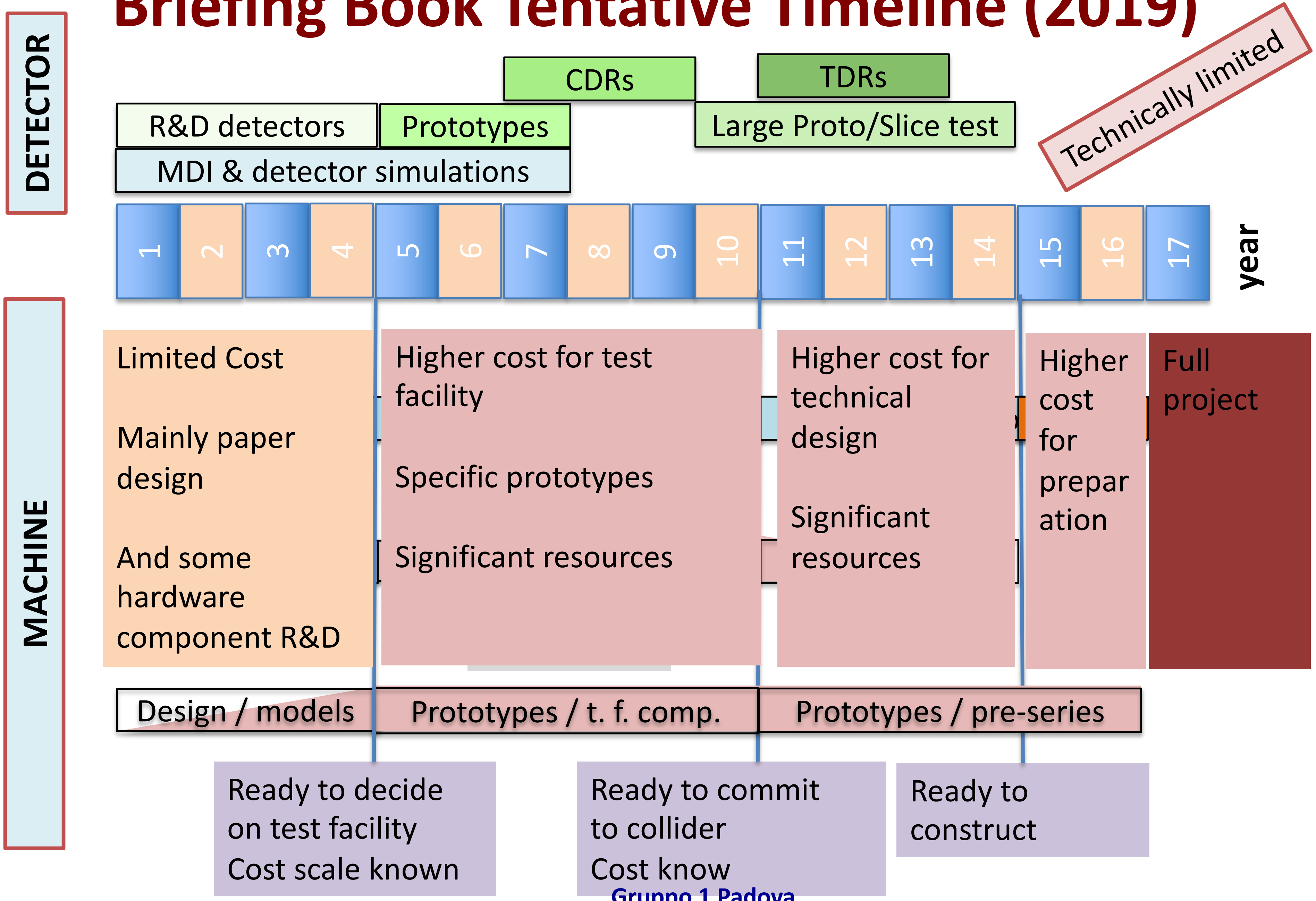
Nome Cogome	Posizione
Paolo Andreetto	Permanente
Alessandro Bertolin	Permanente
Camilla Curatolo	AR
Tommaso Dorigo	Permanente
Umberto Dosselli	Permanente
Alessio Gianelle	Permanente
Donatella Lucchesi	Permanente
Mauro Morandin	Permanente
Lorenzo Sestini	Permanente
Marco Zanetti	Permanente
Davide Zuliani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

Possible Schedule



Physics Briefing Book
arXiv:1910.11775v2

Briefing Book Tentative Timeline (2019)



BACKUP

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