Topic of the Week

Tuesday 14 Jul 2020, 14:00 → 15:00 US/Central

Sunrise - WH11NE (Fermilab)

Yuri Gershtein (Rutgers State Univ. of New Jersey (US)), Zoltan Gecse (Fermi National Accelerator Lab. (US))

Status of Muon Collider Studies

July 14, 2020

Donatella Lucchesi

University of Padova And INFN

P. Andreetto, N. Bartosik, A. Bertolin, L. Buonincontri, M. Casarsa, F. Collamati, C. Curatolo, A. Ferrari, A. Ferrari, A. Gianelle, A. Mereghetti, N. Mokhov, M.Palmer, N. Pastrone, C. Riccardi, P. Sala, L. Sestini, I. Vai

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare

Muon Collider Collaboration

- June 19, 2020 the Eu Strategy updated 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;*
  […]

- To facilitate the implementation of the EU Strategy the CERN Laboratory Directors Group (LDG) on July 2nd :
  - Agree to start building the collaboration for international muon collider design study
  - Accept the proposal of the organization
  - Accept the goals of the first phase

International Muon Collider Collaboration kick-off virtual meeting on July 3rd

(>260 participants) https://indico.cern.ch/event/930508/

Muon Collider Collaboration

LDG Decisions:

Daniel Schulte appointed ad interim project leader

Nadia Pastrone, Lenny Rivkin and Daniel Schulte will start collecting MoUs

Proposed Plan:

- A start-to-end collider design in particular in the view that this would be the first facility of its kind.
- A machine detector interface that protects the detector from collider background while allowing good machine performance.
- A physics and detector study to assess the physics reach of the collider.
- The design of a demonstrator to be built in the second half of the decade.

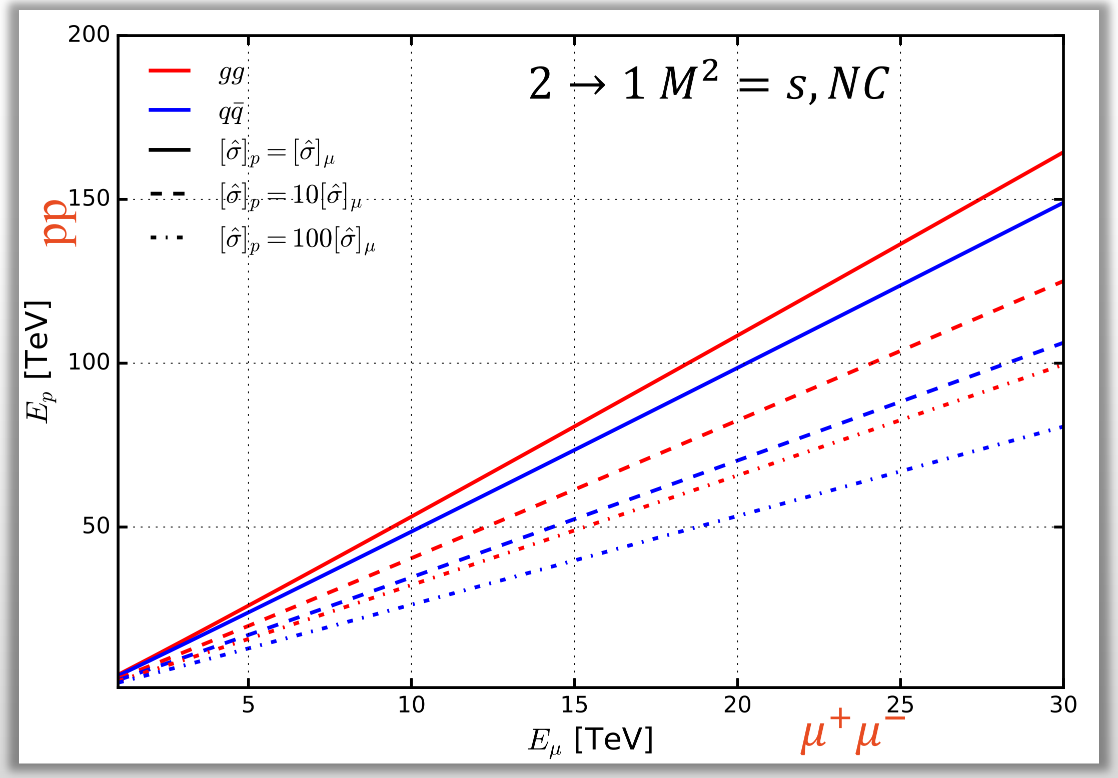
Scope

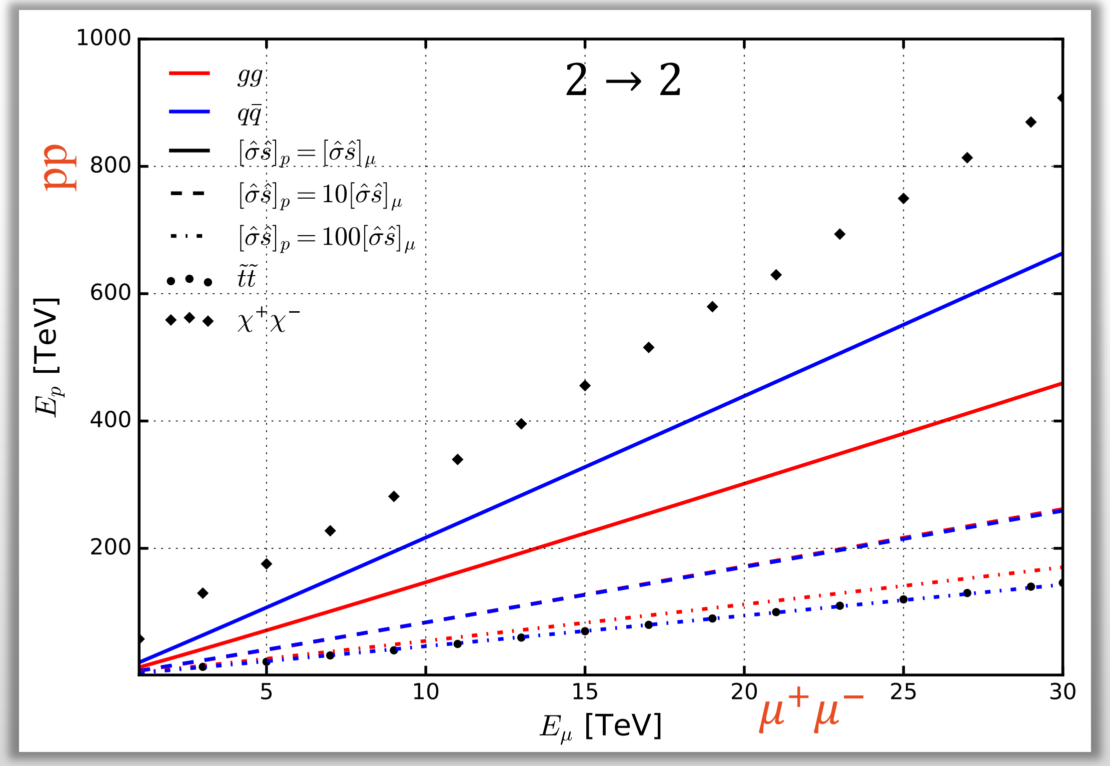
- develop a baseline concept for a muon collider at two centre-of-mass energy ranges: 3 TeV , 10 TeV or above
- explore the potential to use the technology for other purposes such as a Higgs or neutrino factory, provided this is found synergetic with the high-energy collider study
- identify an **R&D path** toward a conceptual design
- design a **demonstrator**

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 $\sqrt{s_p}$

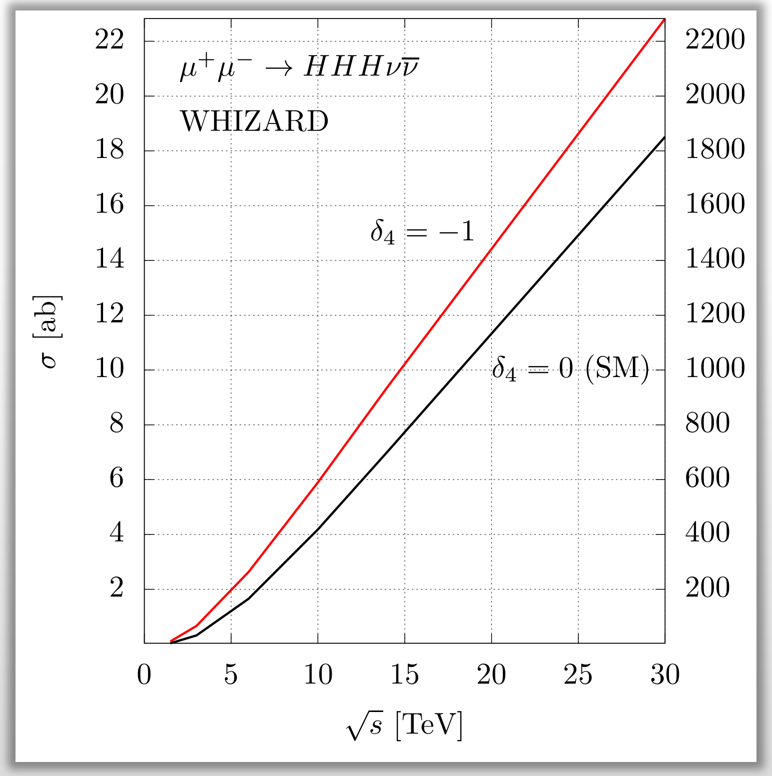
Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





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



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

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

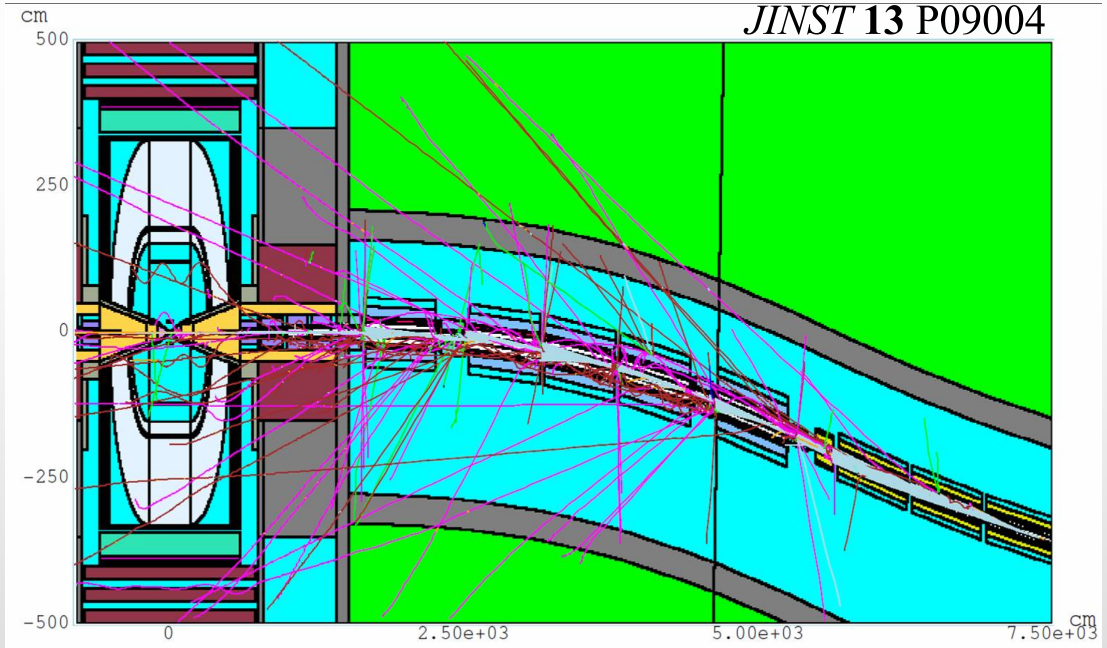
Muon Collider with several TeV CM energy and with integrated luminosities of the order of several tens of attobarns, could provide enough events to allow a determination (a SM) quartic Higgs self-coupling with an accuracy in the tens of percent.

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

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



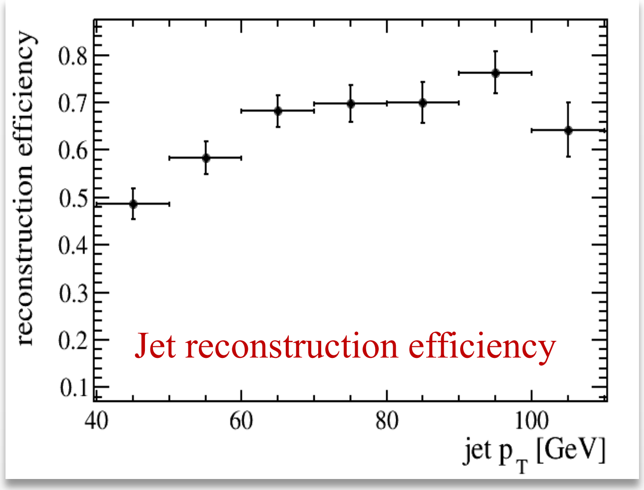
JINST **13** P09004

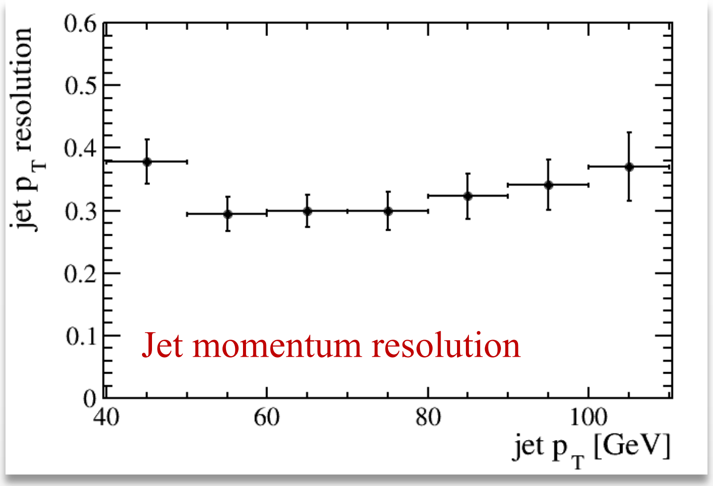
- MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel and the accelerator ±200 m from the interaction point.
- Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.
- Two tungsten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

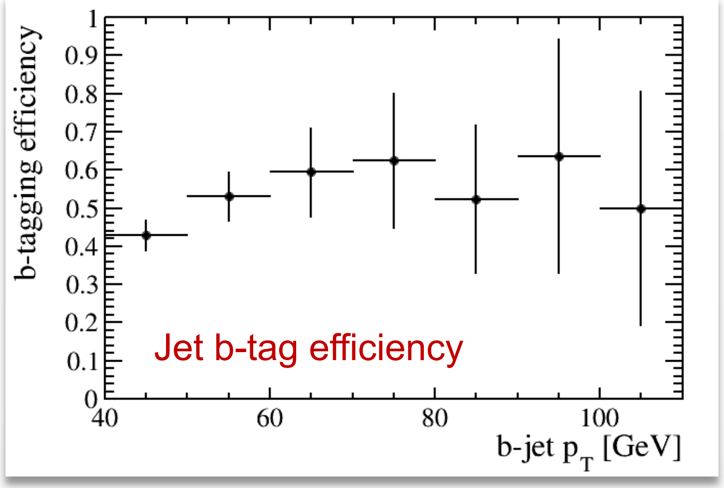
Detector Performance at $\sqrt{s}$ =1.5 TeV

Using the MAP detector and framework, performance have been determined using **simple and rough methods** for the reconstruction

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







Background tagging:

- fake rate: 1 ÷ 3 %
- Tests show fake rate is manageable

CLIC with Machine Learning method is factor 2 better at 1.4 TeV

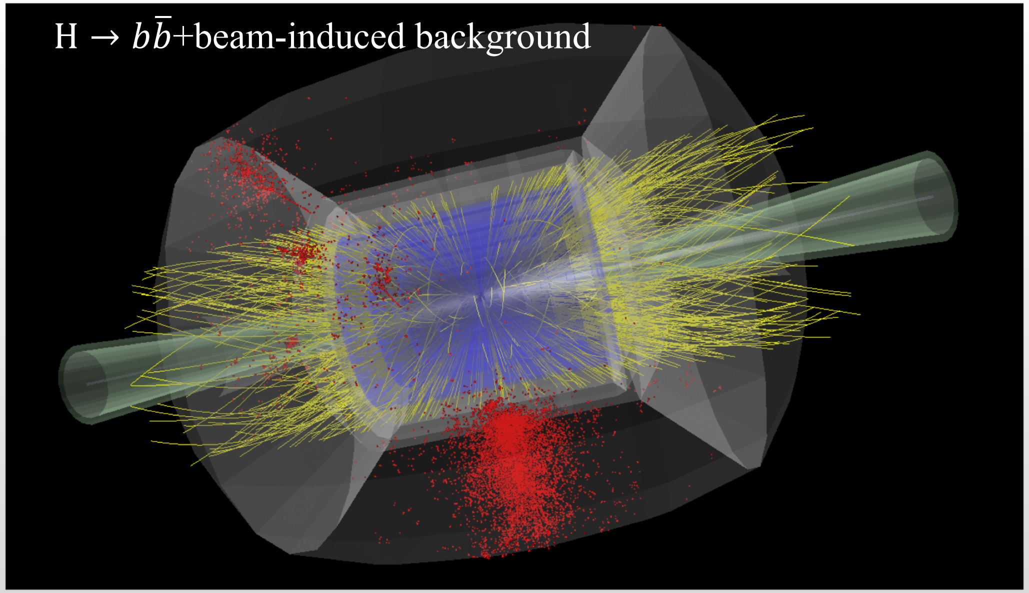
$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

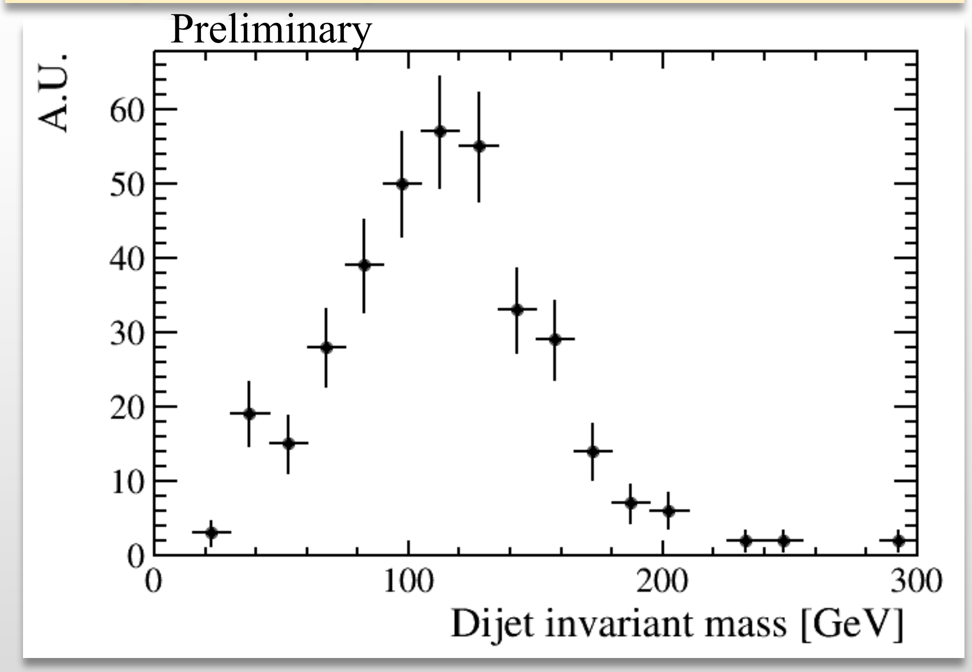
$\mu^+\mu^- \to HX, H \to b\bar{b}$ and $\mu^+\mu^- \to b\bar{b}X$ generated @$\sqrt{s}$ = 1.5 TeV with PYTHIA 8

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

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

$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + 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
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.

Results published on JINTST as Detector and Physics Performance at a Muon Collider

New Developments

Goal: Flexible framework to study physics performance taking into account machine induced background

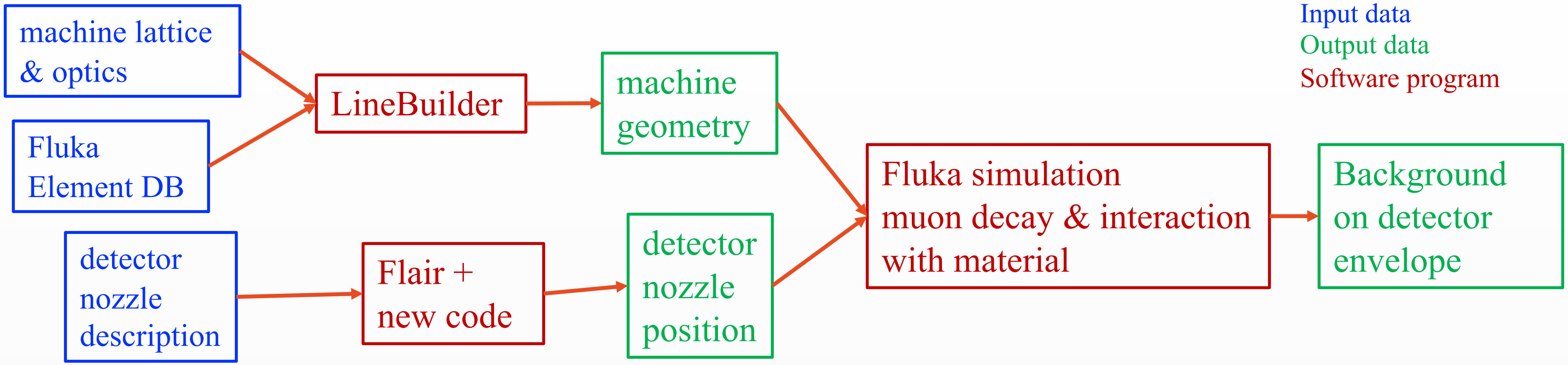
- Set up a framework to produce the beam-induced background:
  - Reproducing the $\sqrt{s}$=1.5 TeV to compare with MAP results.
  - Ready to study new center of mass energies, Interaction Region design is needed.

- ILCSoft, which will be part of the Future Collider Framework, Key4hep, is used.

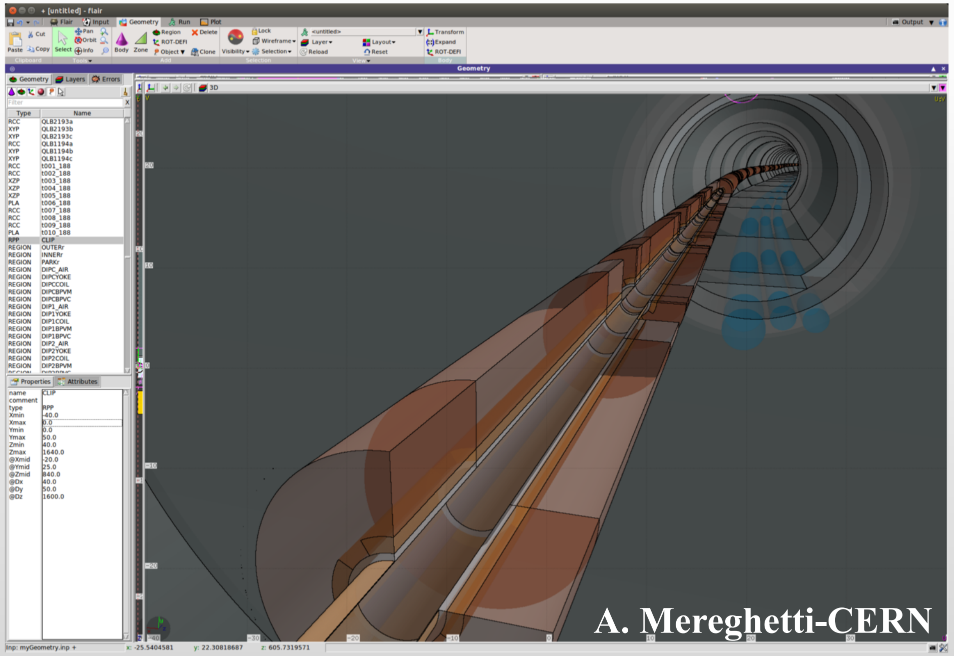
  Thanks to CLIC group: A. Sailer, M. Petric, E. Brondolin. Code maintained by P. Andreetto A. Gianelle.
  - Virtual Organization "muoncoll.infn.it" available, code distributed via CVMFS and singularity container
  - Data workflow need to be optimized to meet muon collider requirements.
  - Mandatory to have the possibility to overlay physics events with beam-induced background: Physics performance strongly affected by it.

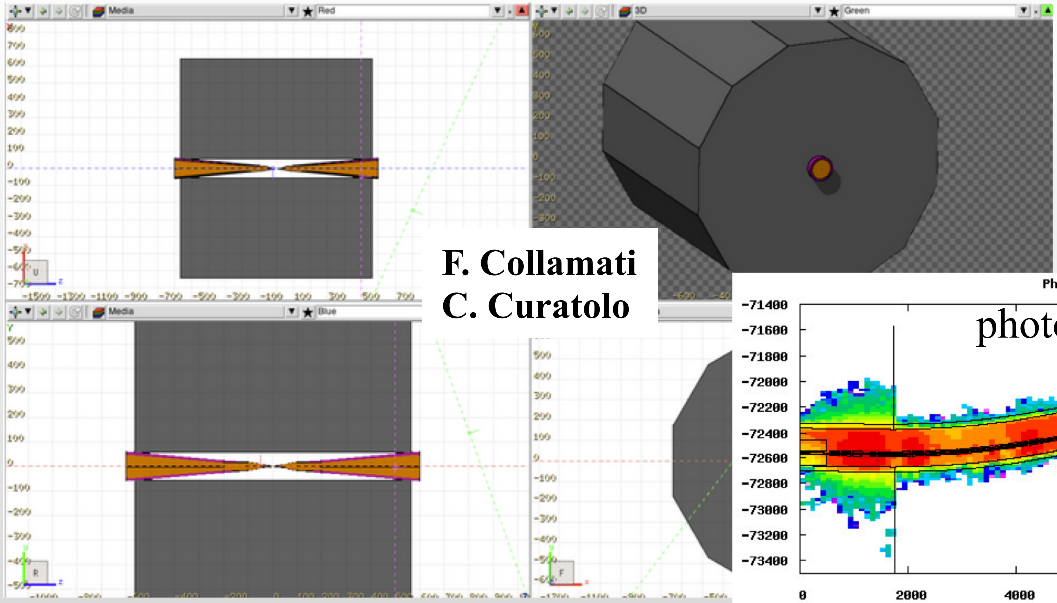
- CLIC detector modified:
  - include nozzles.
  - Adjust tracker to the muon collider conditions.

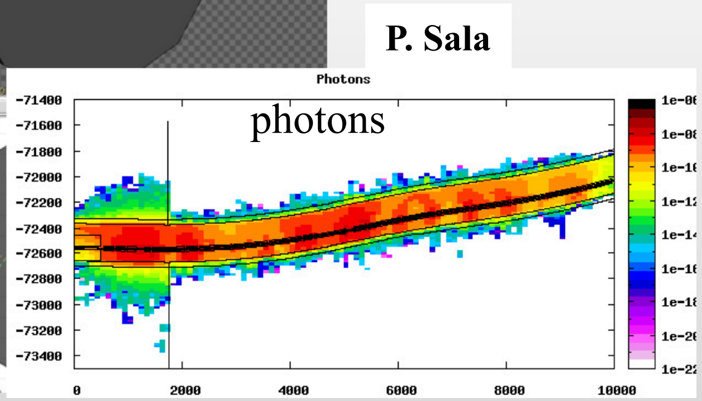
The beam-induced background simulation



Input data
Output data
Software program

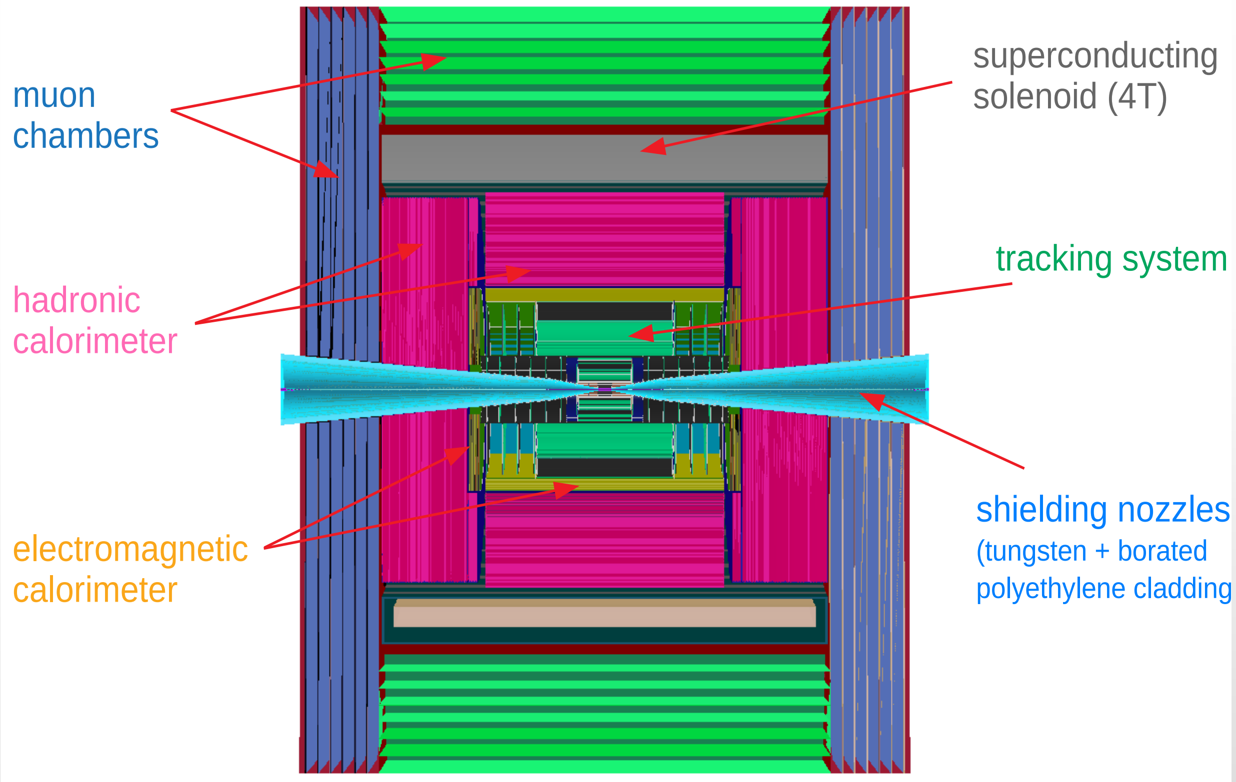






Study of Detector Response at $\sqrt{s}$ =1.5 TeV

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



CLIC Detector adopted with modifications for muon collider needs.
Detector optimization is one of the future goal.

Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks ”

Inner Tracker (IT)
- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers 50x50μm^2
- 4+4 disks ”

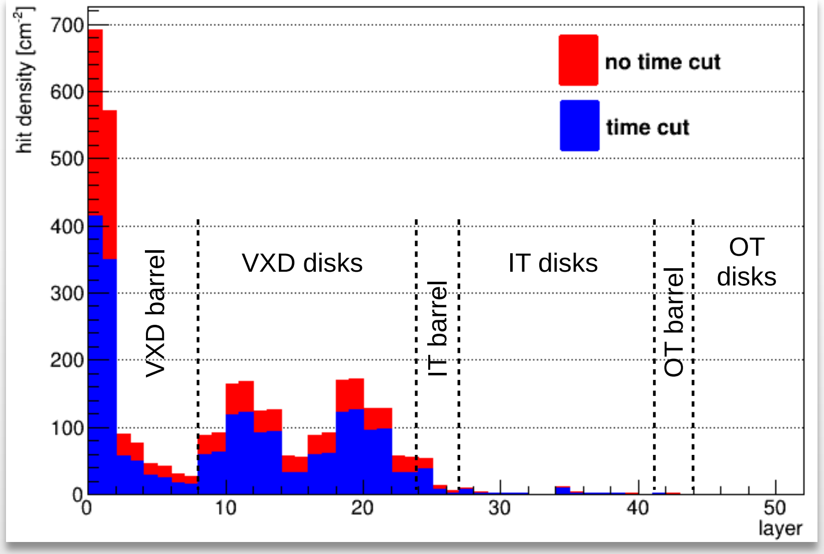
Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

Tracking performance

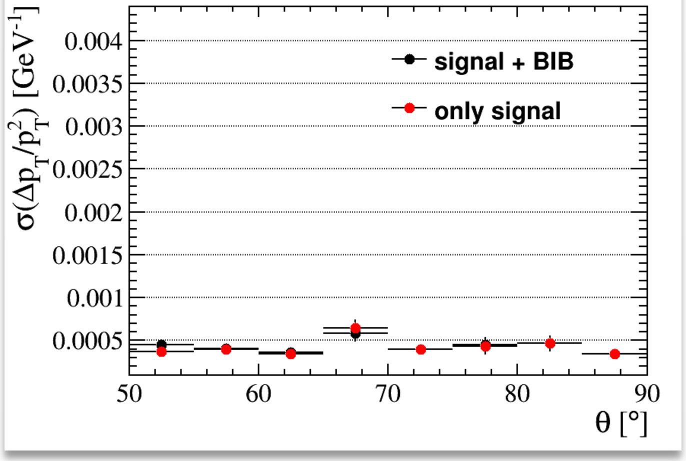
L.Sestini M. Casarsa N. Bartosik L. Buonincontri

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

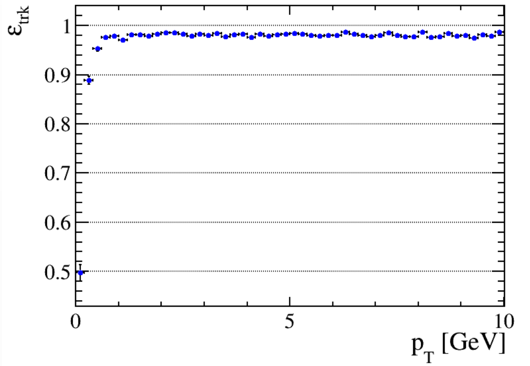


- Simplified digitization: position + time smearing. Realistic digitization in progress.
- Double-layer based BIB rejection in progress.

Track momentum resolution

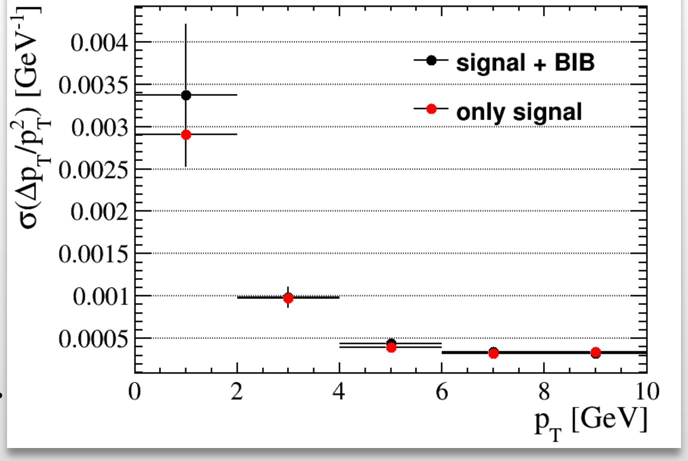


Track momentum efficiency

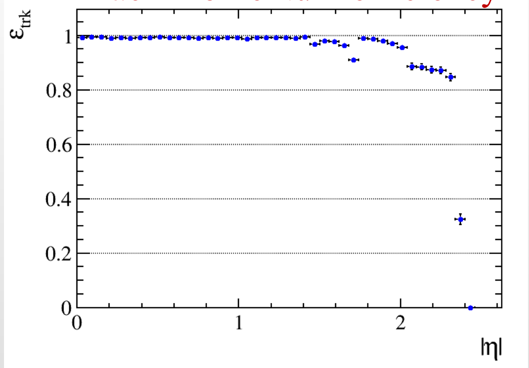


Signal=muon gun

Track momentum resolution



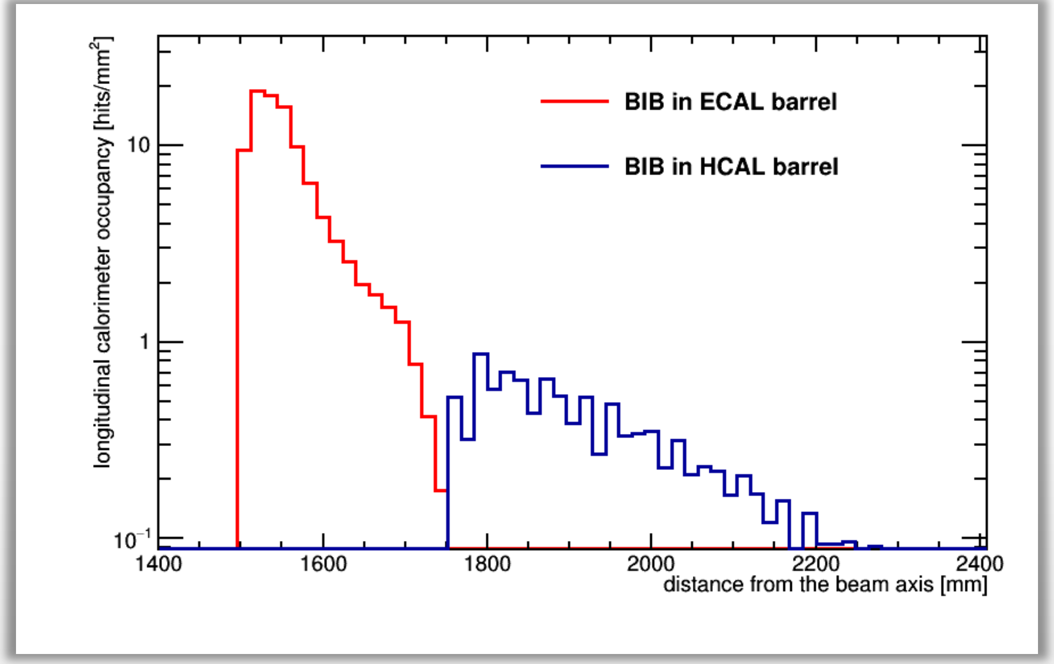
Track momentum efficiency



Calorimeter performance

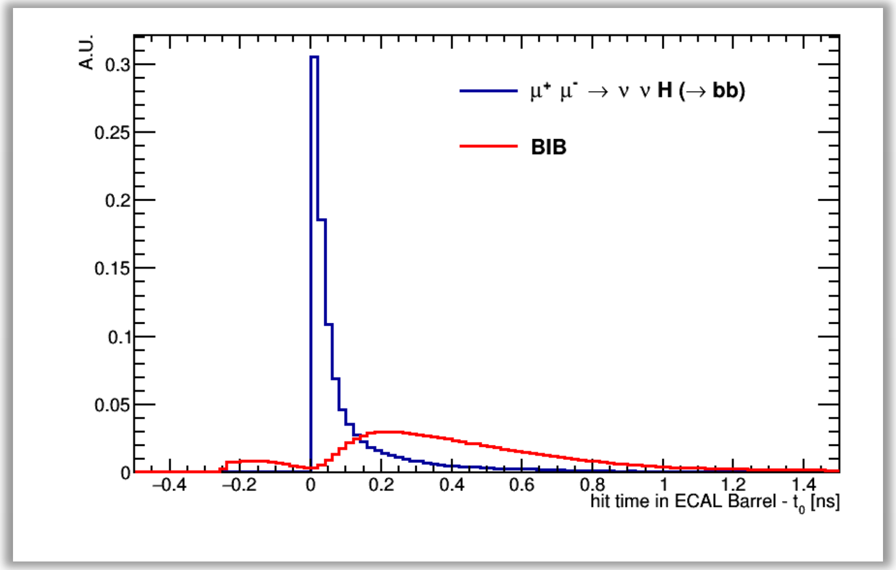
L.Sestini M. Casarsa N. Bartosik L. Buonincontri

Calorimeter Occupancy

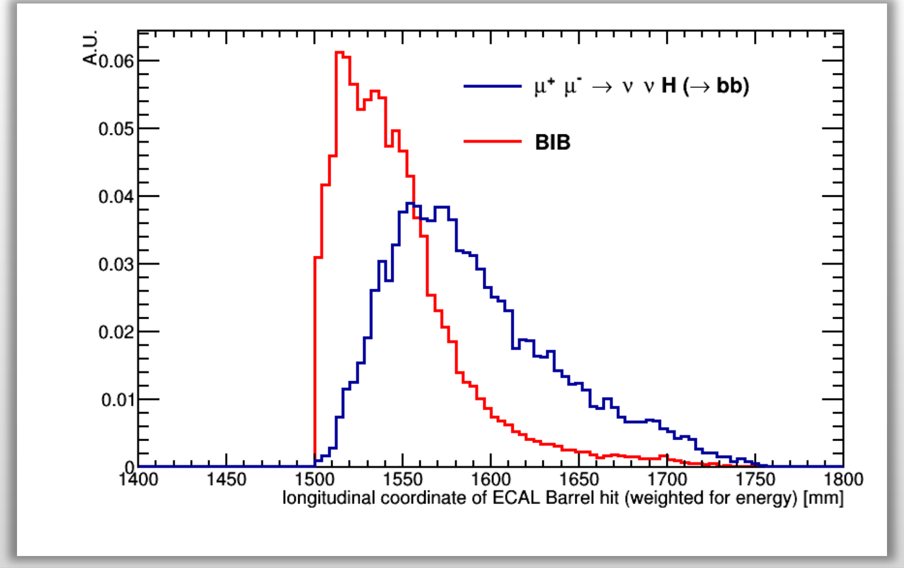


- New jet reconstruction algorithm based on particle flow is in progress.
- New jet b-tag algorithm based on machine learning methods under development.

ECAL barrel hit arrival time – t_0



ECAL barrel longitudinal coordinate

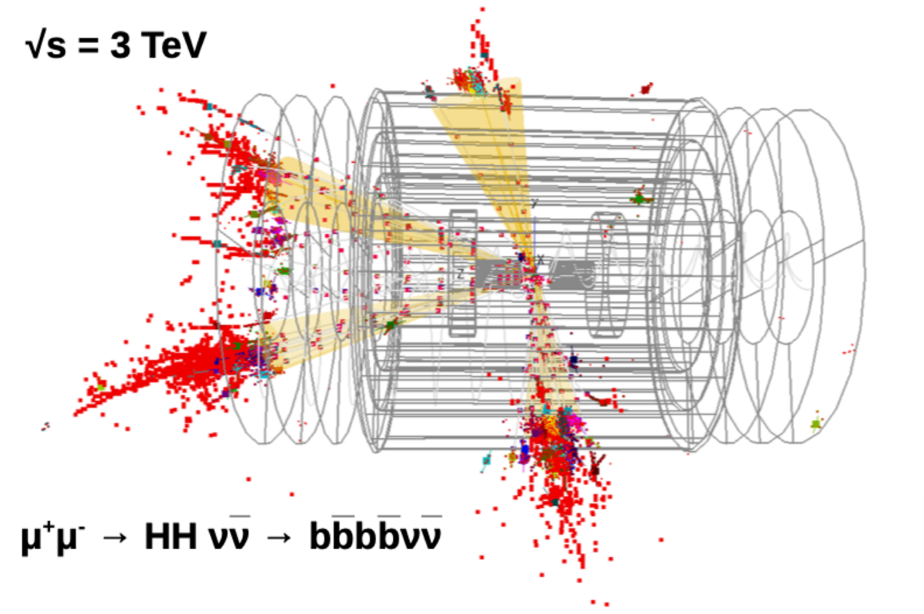


Study of double Higgs production

Muon Collider is the best place to measure Higgs self-couplings

$\mu^+\mu^- \rightarrow HHX, H \rightarrow b\bar{b}, H \rightarrow b\bar{b}$

$\mu^+\mu^- \rightarrow HHHX, H \rightarrow b\bar{b}, H \rightarrow b\bar{b}, H \rightarrow b\bar{b}$



We started the study by producing:

- $\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$
- $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$ inclusive

with WHIZARD 2.8.2 at $\sqrt{s} = 3$ TeV

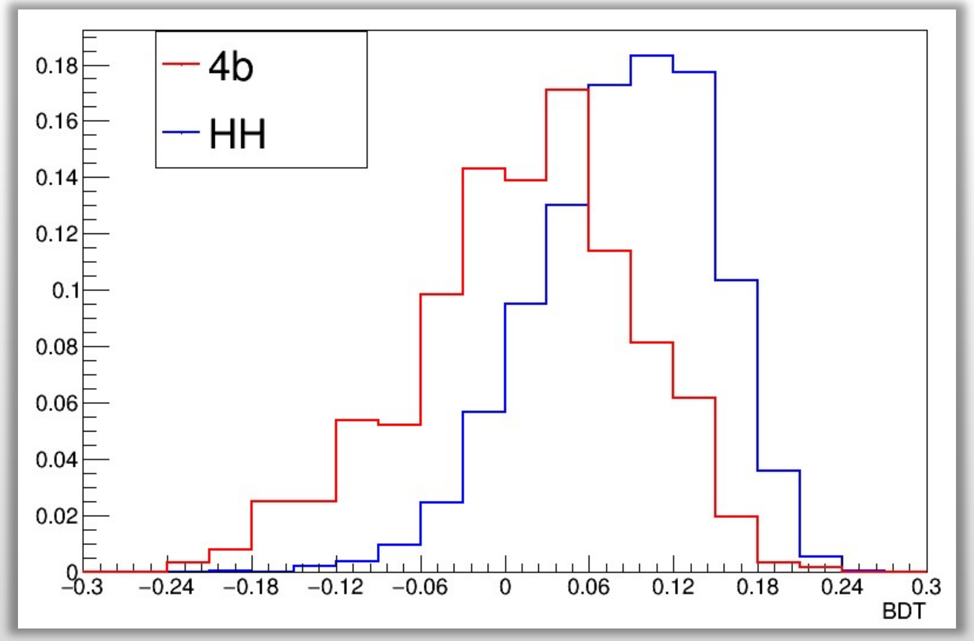
- Detector acceptance and MDI of $\sqrt{s} = 1.5$ TeV
- Detector performance determined at $\sqrt{s} = 1.5$ TeV events weighted to take into account for the different energy

Conservative assumptions

Study of double Higgs production: preliminary results

Very preliminary event selection and reconstruction:

- N_{jets}>3 with P_T>20 GeV, b-tag jets P_T>40 GeV
- Jets combined in pairs, with invariant masses (m_{ij},m_{kl}), one jet per pair is required to be b-tagged
- For each pair $(m_H-m_{ij})^2+(m_H-m_{kl})^2$ is minimize to determine the candidate
- Separate signal from background using a BDT with few input variable: $m_{H1,2}$, $\sum E_{jets}$, $\sum \vec{P}_{jets}$, max angle between jets



$$S = \sigma_{HH} Br(H \rightarrow b\bar{b}) \mathcal{L}_{int} \frac{N_{sig}^{cuts}}{N_{sig}^{tot}} \qquad B = \sigma_{4b} \mathcal{L}_{int} \frac{N_{bck}^{cuts}}{N_{bck}^{tot}}$$

Assumptions

$\mathcal{L}_{int} = 1.3\ ab^{-1}$

$t = 4 \cdot 10^7$ s and one detector

Cut between 0.6 and 0.9 on BDT output to maximize

$$Significance = \frac{S}{\sqrt{S+B}}$$

$$\frac{\Delta\sigma}{\sigma} = 0.40$$

Summary

- A flexible framework which include background simulation, detector simulation and event reconstruction is in use to study the detector requirements at different center of mass energies.

- Further software developments are needed, we are contributing to the effort of the common software for future colliders in the Turnkey Software, any help is welcome!

- We have just an hypothesis of the detector, tracker system, calorimeter detector and muon system need to be designed to meet the requirements.

- We are investigating all the possible R&D necessary to exploit the state of the art "5D" detectors and beyond to determine the synergies with the upgrade of existing experiments and new projects.

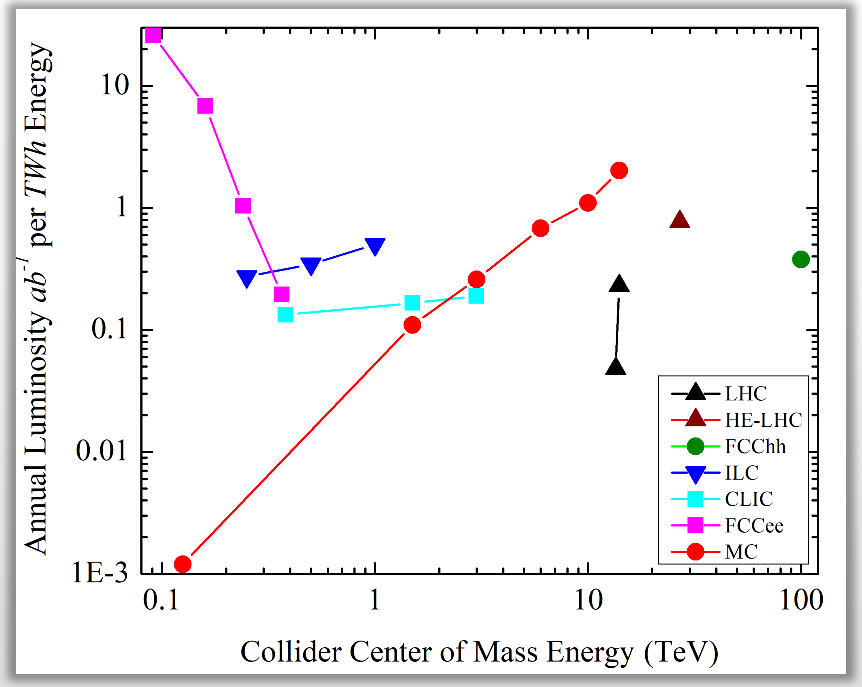
- A general dedicated meeting to discuss all these above items will be scheduled on July 27th

BACKUP

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



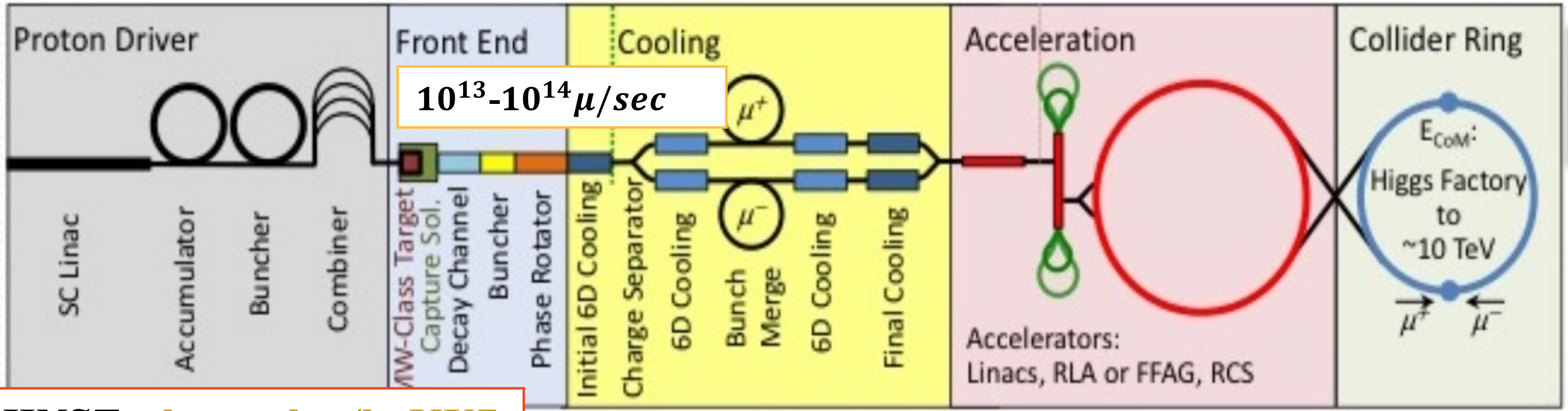
Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{\mathrm{int}}$ (ab^{-1})	Time (years)	Power (MW)	Cost
ILC	e^+e^-	0.25	1	2	11	129	4.8-5.3BILCU
		0.5	1	4	10	163(204)	8.0 BILCU
		1	1			300	+(n/a)
CLIC	e^+e^-	0.38	1	1	8	168	5.9 BCHF
		1.5	1	2.5	7	370	+ 5.1 BCHF
		3	1	5	8	590	+7.3 BCHF
CEPC	e^+e^-	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

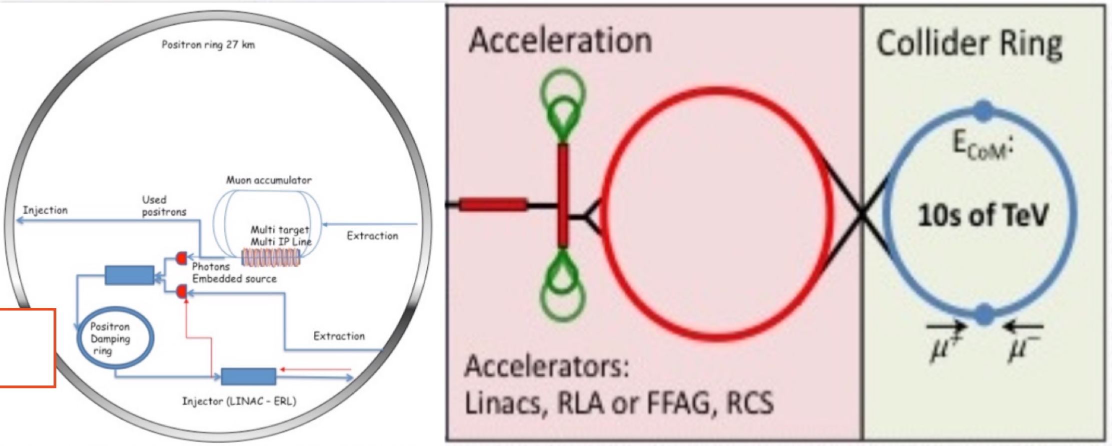


Almost ready to go for a CDR

MUON JINST, shorturl.at/kxKU7

LEMMA

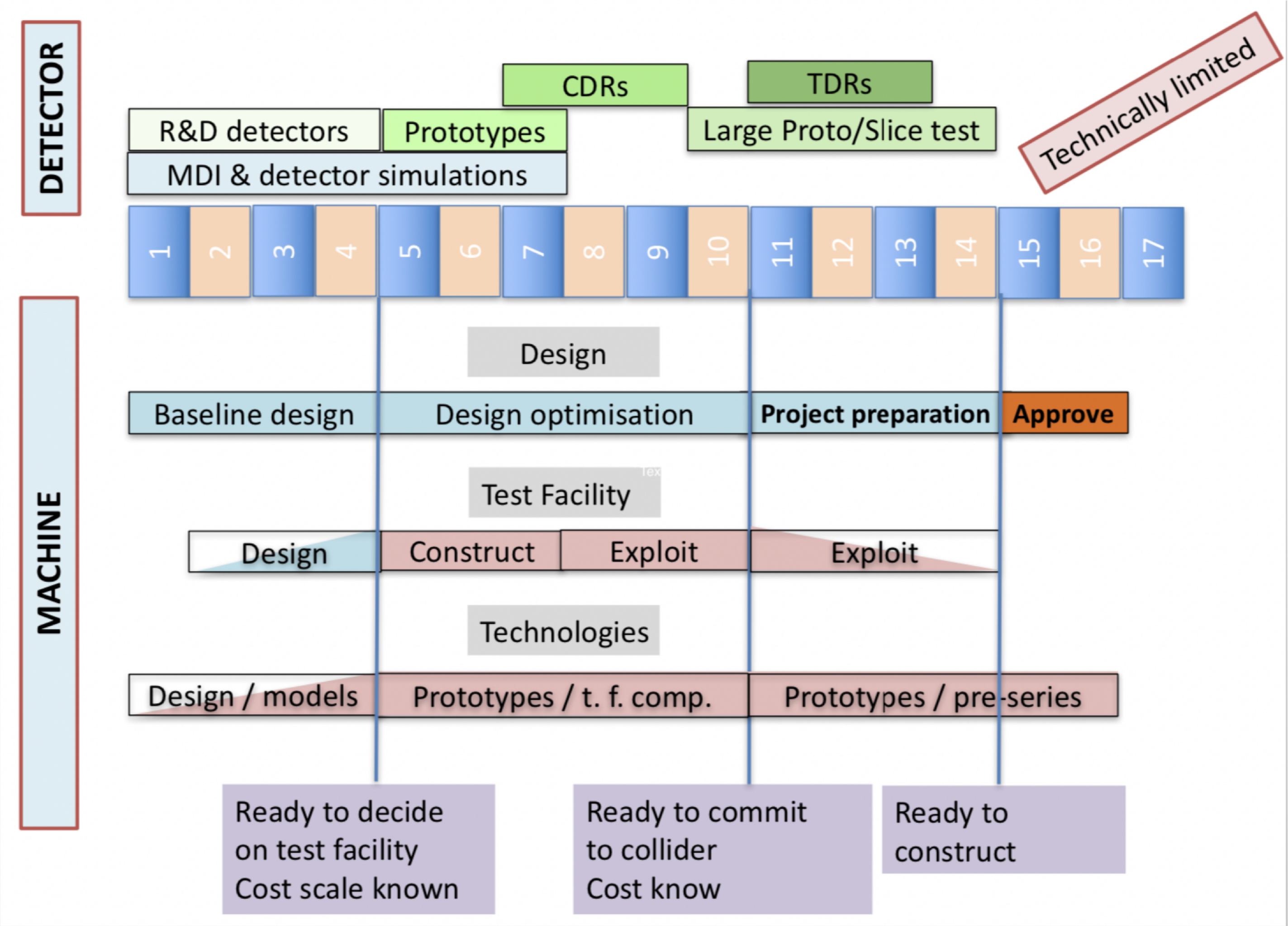
e+ source



arXiv:1905.05747v2 [physics.acc-ph]

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

Possible Schedule



Physics Briefing Book
arXiv:1910.11775v2

Briefing Book Tentative Timeline (2019)