UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare

La Thuile 2021 - Les Rencontres de Physique de la Vallée d'Aoste

Towards the Muon Collider

Donatella Lucchesi

University of Padova and INFN,

for

MuonCollider-Detector-Physics Group

Motivations

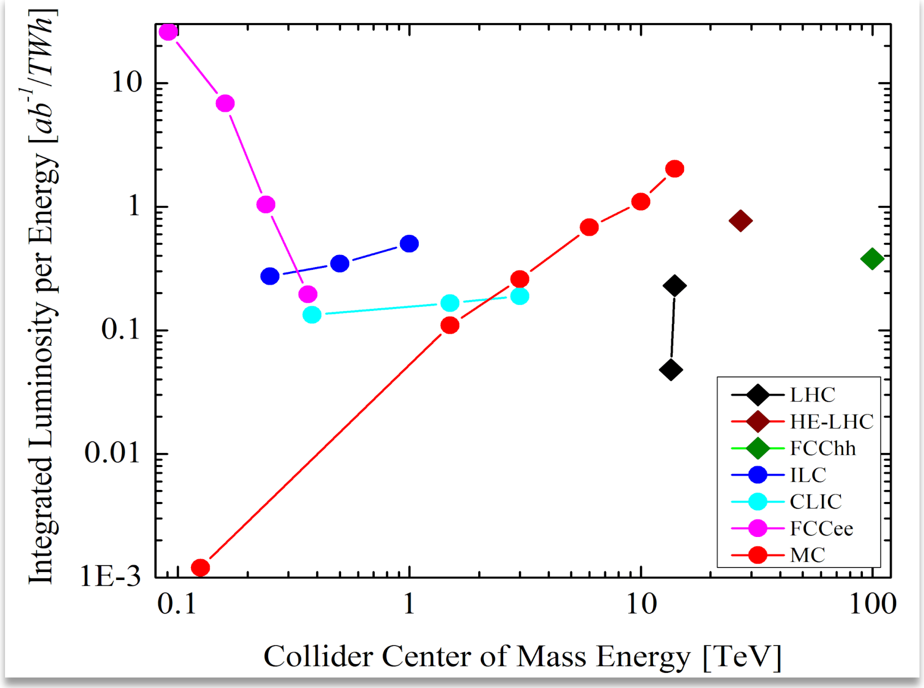
The 2020 Update of the European Strategy for Particle Physics recommended to "investigate the possibility to have bright muon beams".

SnowMass 2021 process sees a renovate interest in the Muon Collider following the large experience of MAP (Muon Accelerator Program).

Why muons?

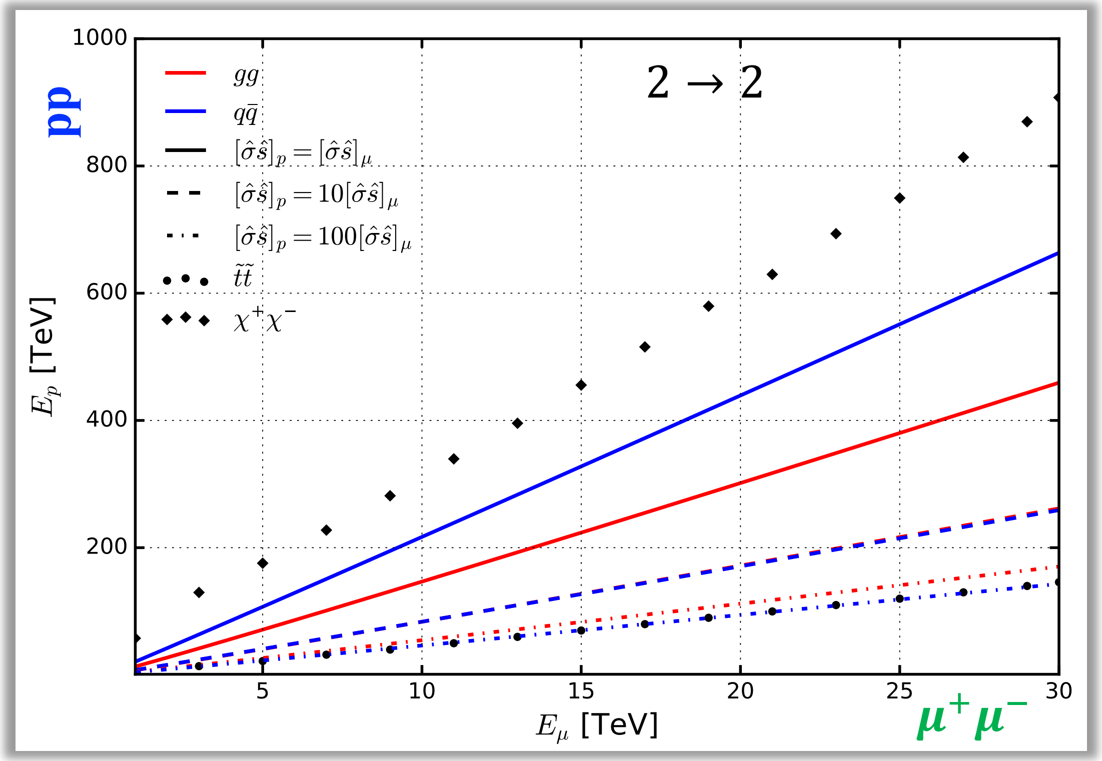
Muons do not suffer of synchrotron radiation up to very high energy $\Longrightarrow$ can be used in circular accelerators.

Full cost to operate a muon collider facility not evaluated in detail yet but going to high energy it is "convenient" respect to e^+e^-. Energy consumption similar to FCC-hh.



Physics Discovery Potential

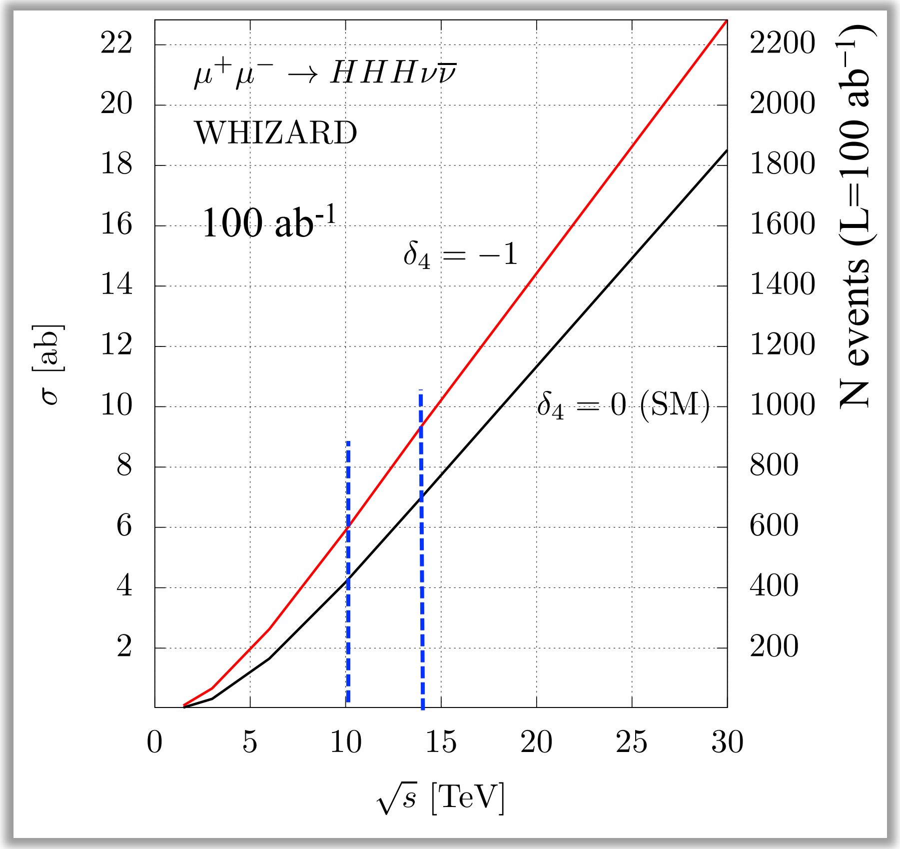
- Muons: elementary particles ⇒ $\sqrt{s_\mu}$ entirely available to produce short-distance reactions.
- Protons: formed by partons ⇒ interactions occur between the proton constituents ⇒ fraction of $\sqrt{s_p}$ enter in the short-distance reactions.



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

Physics Discovery through the Higgs Boson

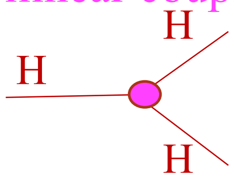
- Higgs boson couplings to fermions and bosons are expected to be measured with a precision similar or better than e^+e^- .
- Muon collider has the unique possibility to allow the determination of the Higgs potential:



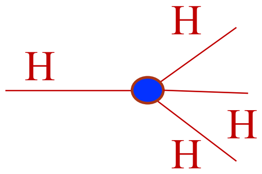
$$V(h) = \frac{1}{2}m_H^2h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

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

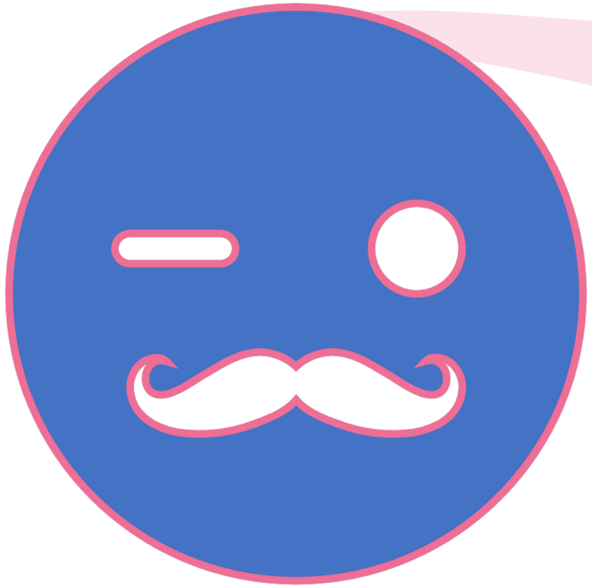
Trilinear coupling



Quadrilinear coupling



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



If the Muon Collider is such a "dream machine" why we do not have it yet?

Muons Decay!

Muons decay with an average lifetime of $2.2 \cdot 10^{-6}$ seconds at rest, at $\sqrt{s} = 3$ TeV they live for about $3.1 \cdot 10^{-2}$ seconds. In this very short time, produced muons have to: be accelerated, transferred in the collider and make them interact, possibly several times.

Design the facility

Number of muons decay particles…back of the envelope evaluation:

beam 1.5 TeV $\lambda = 9.3 \times 10^6$m, with $2 \times 10^{12} \mu$/bunch $\Rightarrow 2 \times 10^5$decay per meter of lattice.

Beam induced background, if not properly treated, could be critical for:

- Magnets, they need to be protected.
- People, due to neutrino induced radiation.
- Detector, the performance depends on the rate of background particles arriving to each subdetector.

Study all of them

The Facility

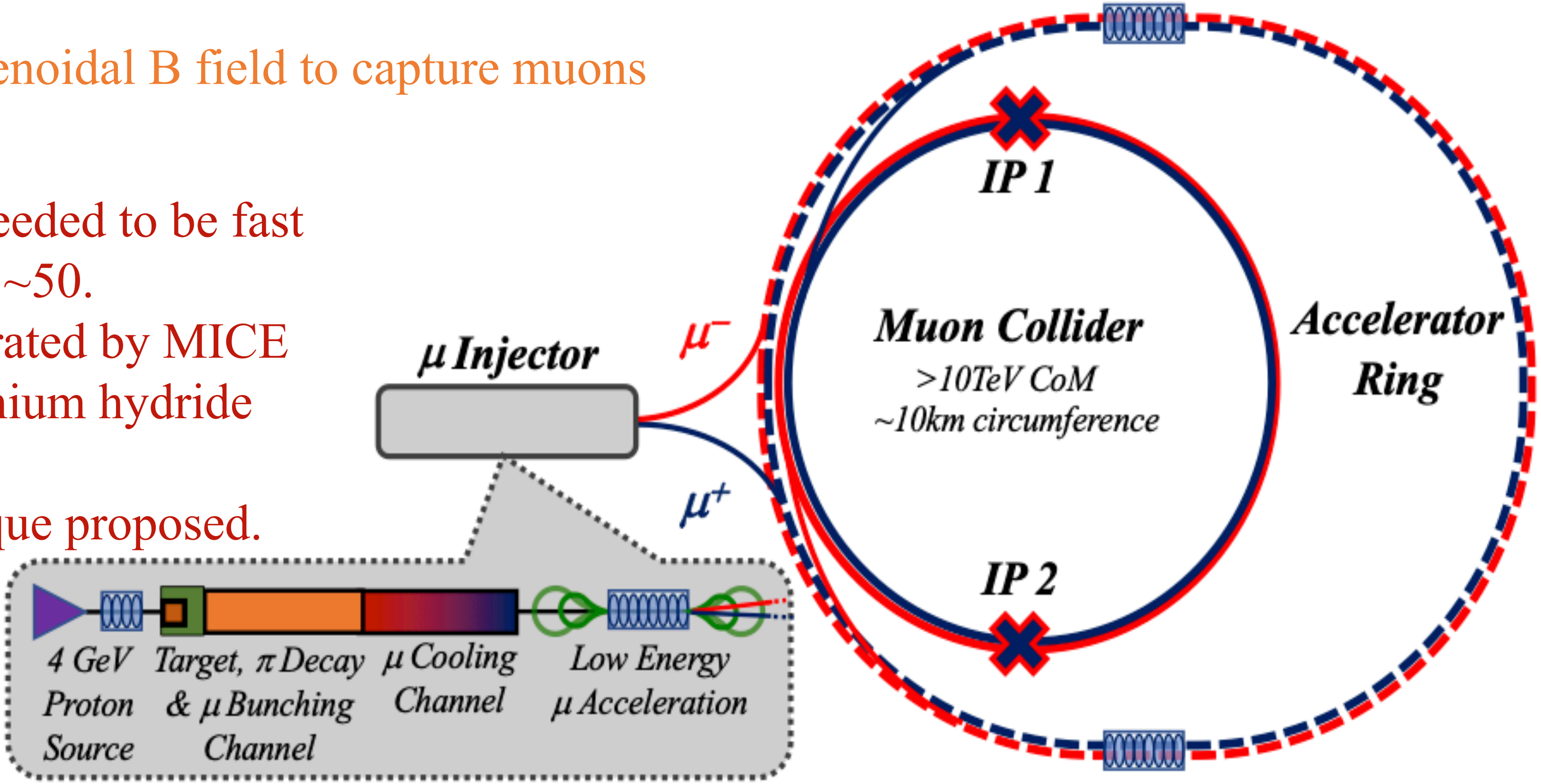
MAP facility design is considered as the baseline

Proton Driver: intense proton source on a MW class target produces bunched pions.

Front-end: $\pi \rightarrow \mu\nu$ decay in solenoidal B field to capture muons
RF cavities to bunch muons

Cooling: "ionization cooling" needed to be fast

- 6D phase space reduction of ~50.
- Transverse cooling demonstrated by MICE with liquid hydrogen and lithium hydride absorbers.
- Longitudinal cooling technique proposed.



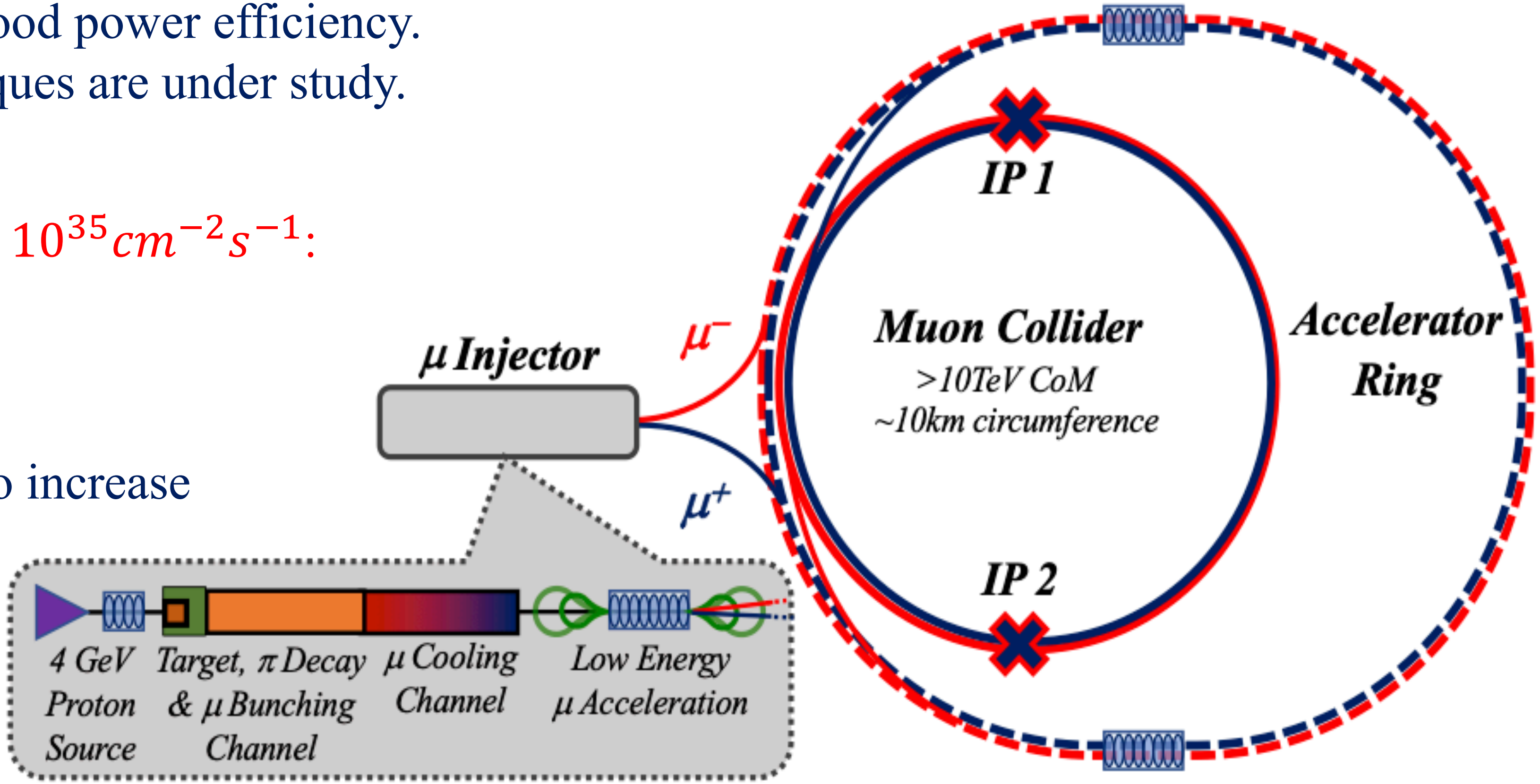
The Facility: Rings

Acceleration Stage:

- Fast to limit the number of muon decay.
- Keep low emittance.
- Limit the cost and have good power efficiency.
- Several accelerator techniques are under study.

Collider Ring, luminosity goal $10^{35} cm^{-2} s^{-1}$:

- Low beta function at IP.
- Small emittance.
- Short bunch length.
- Small ring circumference to increase collision rate.



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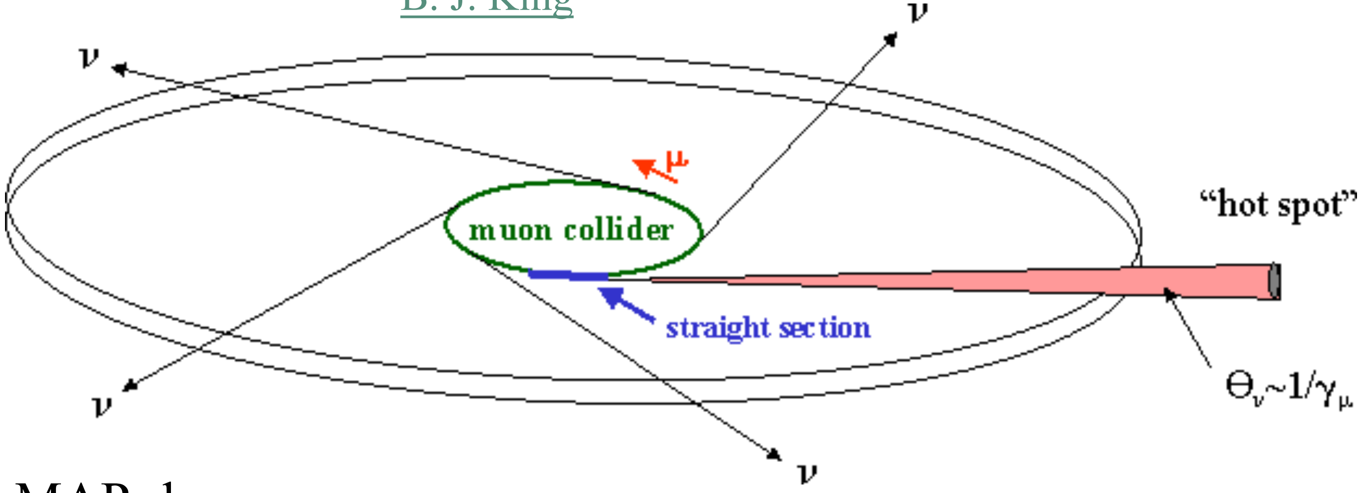
Neutrino Induced Radiation Hazard

- Neutrinos from intense muon beams are very well collimated, $\theta \approx 1/\gamma$. At 1TeV $\theta \approx 10^{-4}$.
- Neutrinos beams interact with matter, interaction products could originate radiological hazard when reach the earth surface.

B. J. King



Radiation hazard studied since the beginning MAP shows:

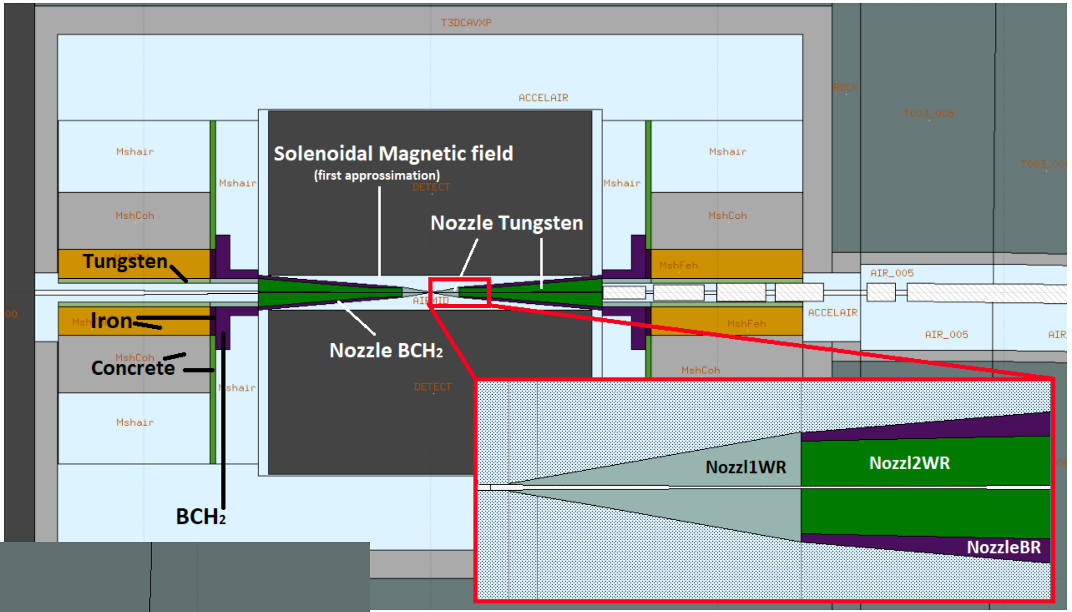
- Along the collider arcs no issues for E_{beams}~1.5TeV.
- Solutions for the straight sessions already proposed Mokhov-Ginneken .

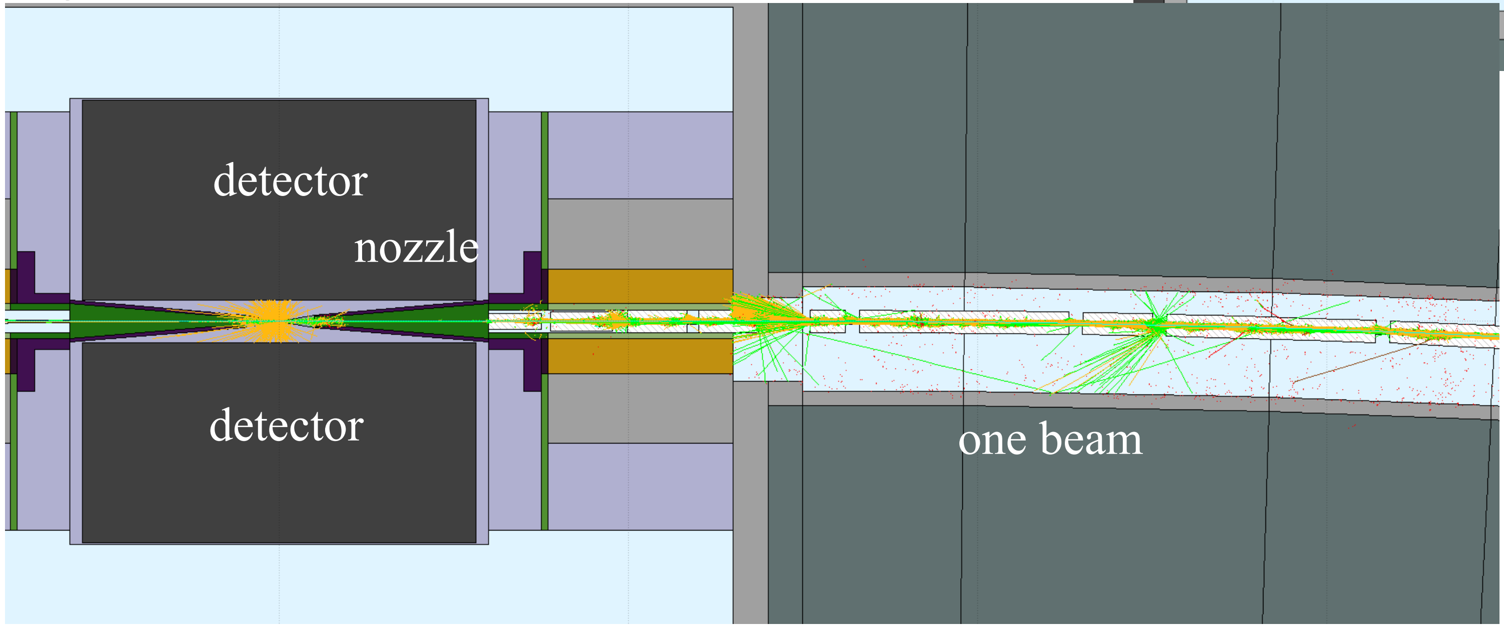
New studies are in progress to reach high energies (10 TeV):

- Careful design of the collider in particular the straight sections to mitigate the effects.
- Evaluation of the accelerator site characteristics.

The Beam-Induced Background - BIB

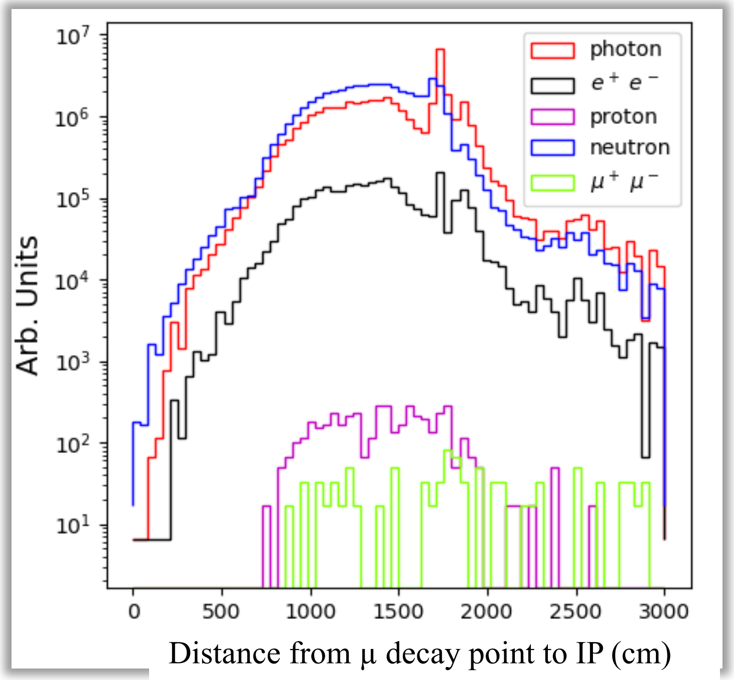
- MAP developed a realistic simulation of beam-induced backgrounds by implementing a model of the tunnel and the accelerator.
- Secondary and tertiary particles simulated with MARS15 and now with FLUKA transported to the detector.
- Two tungsten nozzles are crucial in background mitigation inside the detector.

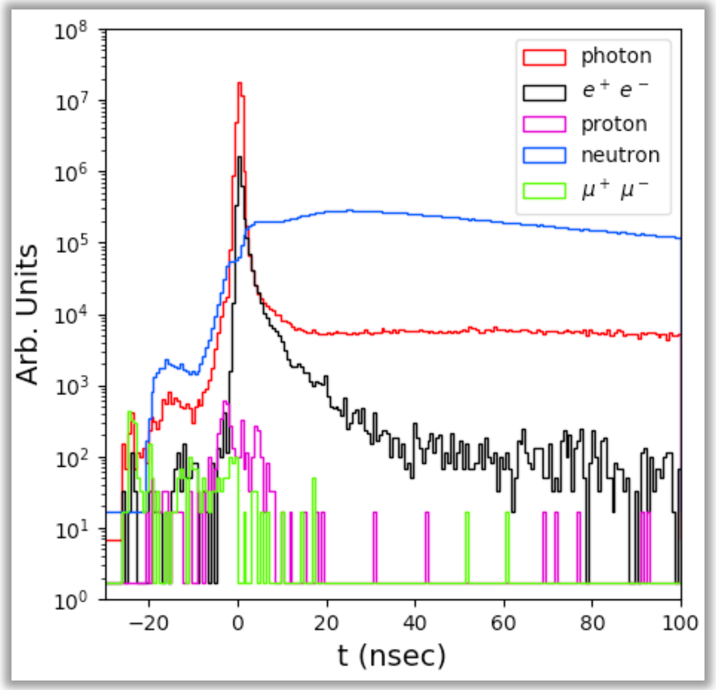


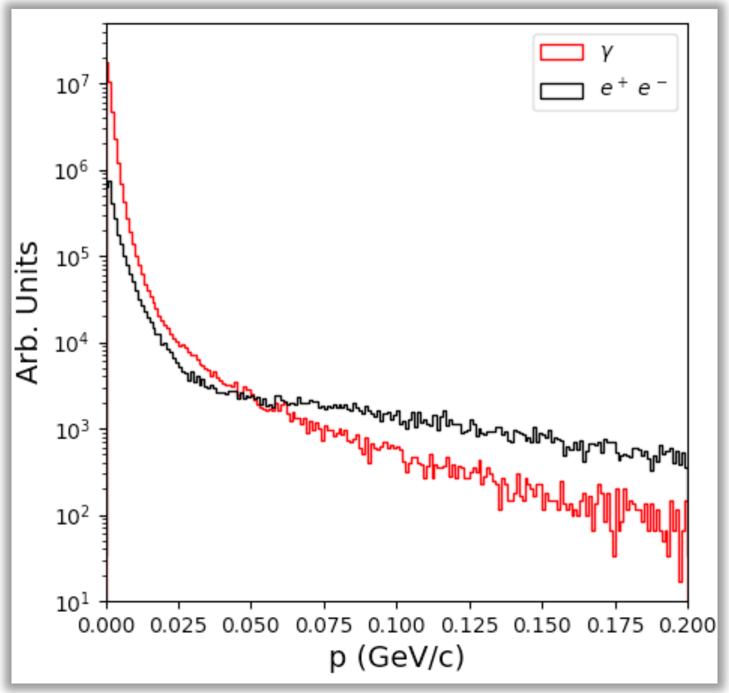


Yellow: photons
Green: e^+e^-
Red: Hadrons

The Beam-Induced Background properties $\sqrt{s}$ =1.5 TeV







Integration path for BIB contribution to the interaction region depends on $\sqrt{s}$ and accelerator lattice

Timing distribution determined by $\sqrt{s}$ and accelerator lattice

Secondary and tertiary particles have low momentum

BIB characteristics strongly affect detectors design ➞ detailed evaluation is needed. Full simulation available for $\sqrt{s}$=1.5 TeV, 3 TeV in progress. Higher $\sqrt{s}$, new strategy to be defined.

Full Simulation of the Detector at $\sqrt{s}$ =1.5 TeV

hadronic calorimeter

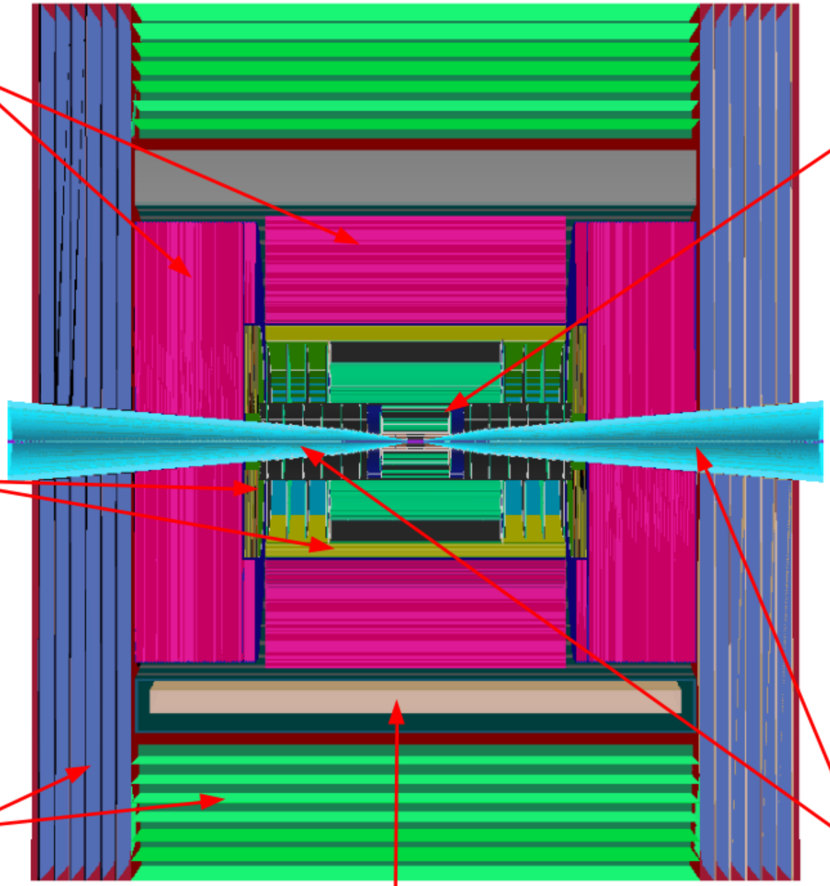
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_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 μm^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

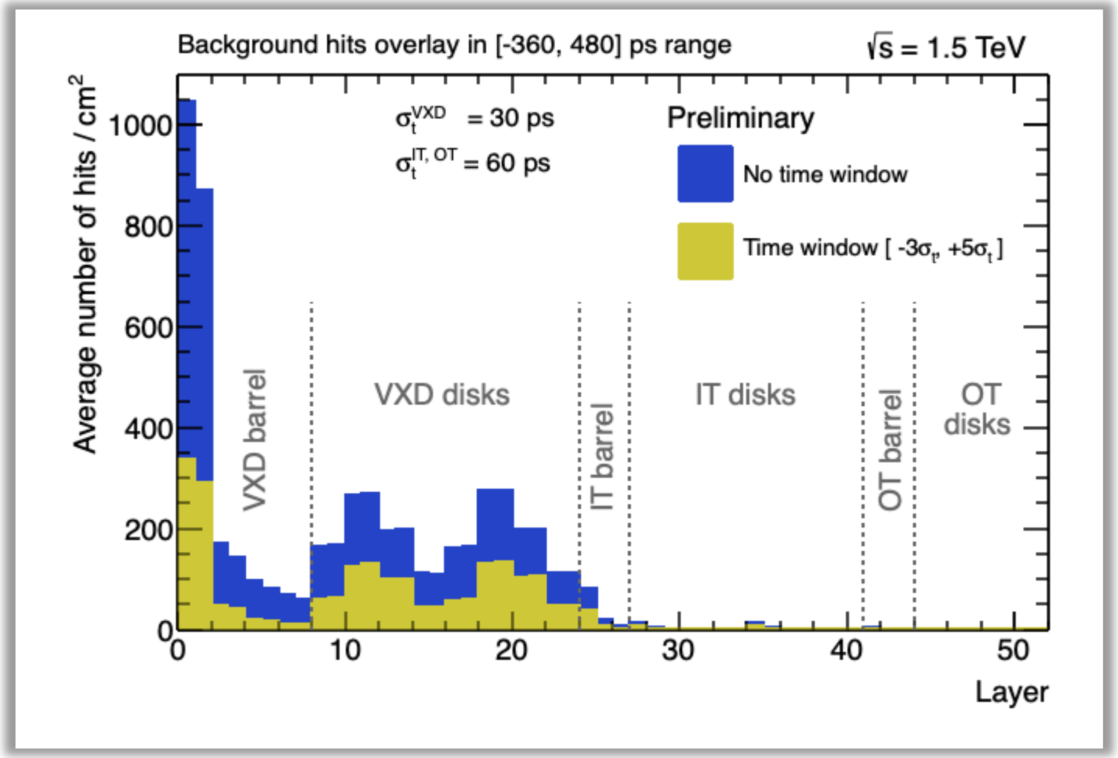
- Tungsten cones + borated polyethylene cladding.

CLIC Detector technologies adopted with important modifications to cope with BIB.

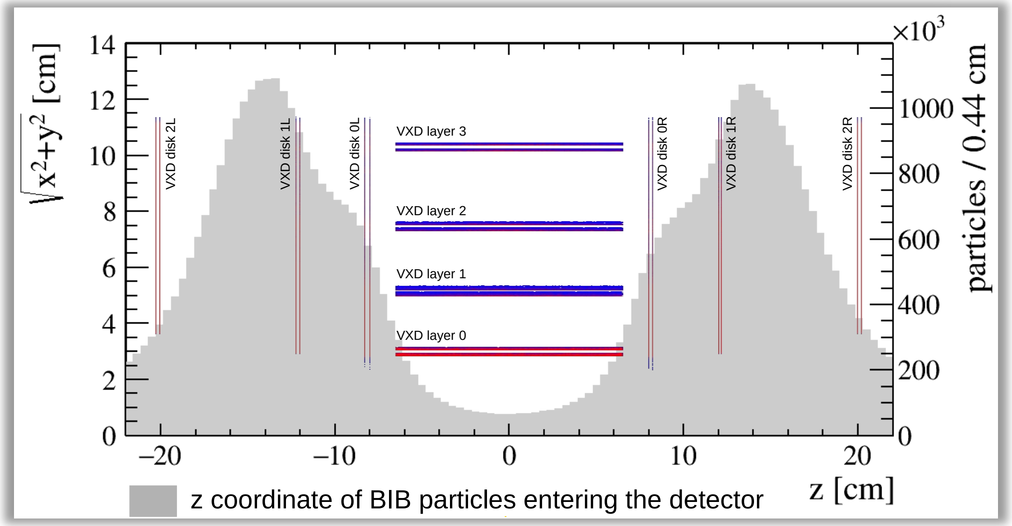
Detector design optimization at $\sqrt{s}$=1.5 (3) TeV is in progress.
Room for collaboration!

Tracker Characteristics $\sqrt{s}$ =1.5 TeV

The impact of BIB on tracking system could be severe if not mitigated



Vertex detector barrel properly designed to not overlap with the BIB hottest spots

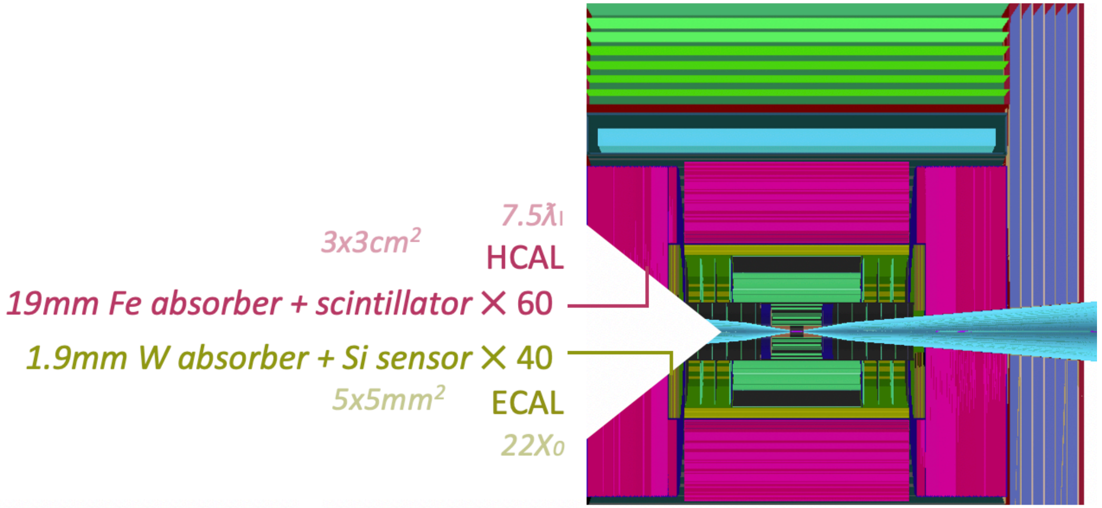


Tracking performance have been studied applying timing and energy cuts on clusters reconstruction compatible with IP time spread.

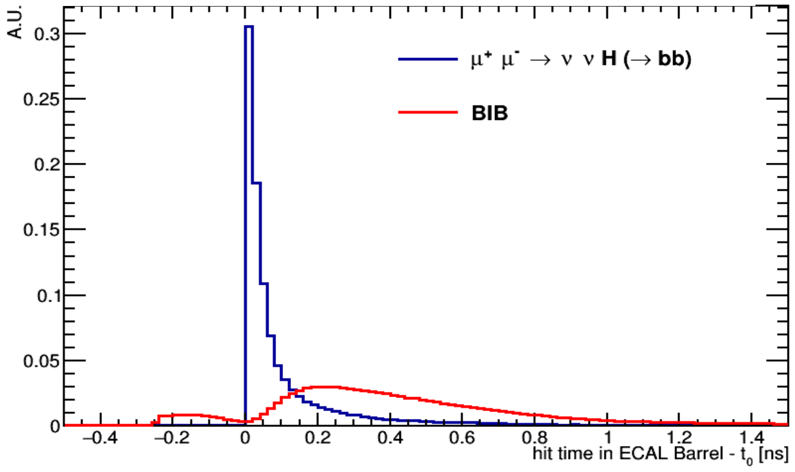
Calorimeter Characteristics at $\sqrt{s}$ =1.5 TeV

Current simulation is based on CLIC configuration:

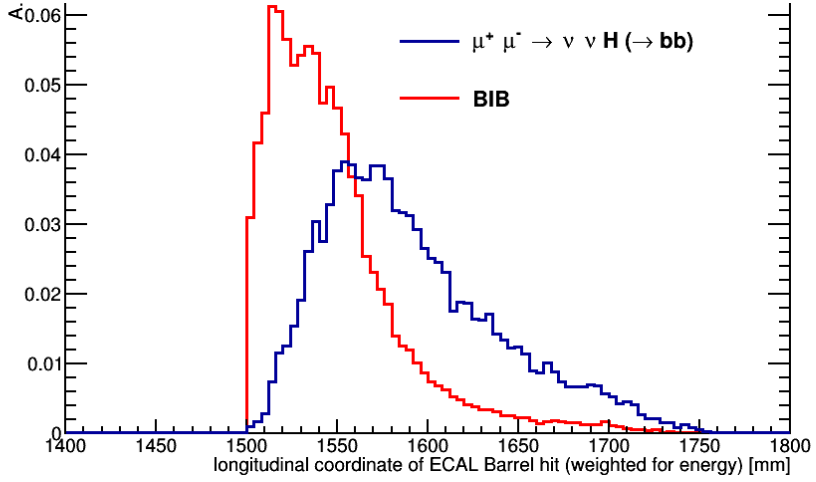
Silicon + tungsten for ECAL, Iron + Scintillator for HCAL.



ECAL barrel hit arrival time – t_0



ECAL barrel longitudinal coordinate

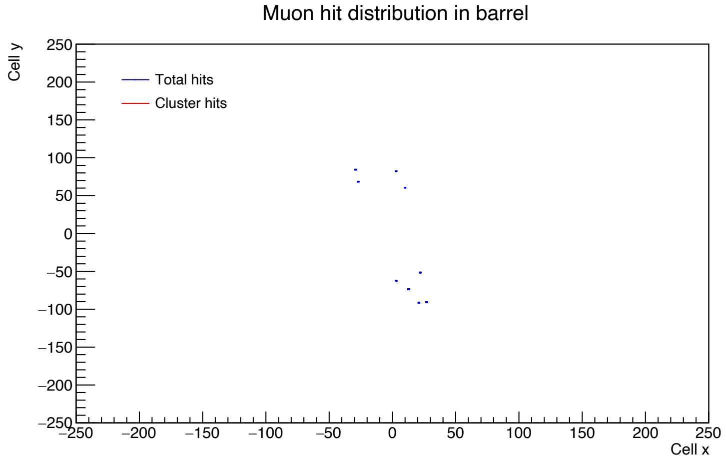


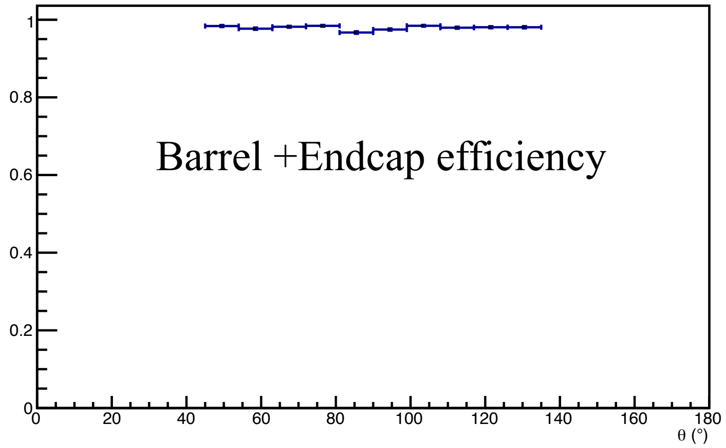
In progress:

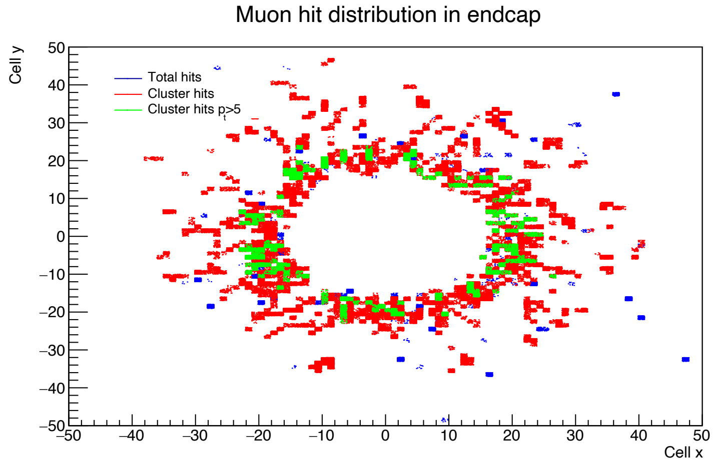
- Design appropriated and cheaper calorimeter system
- Optimization of jet reconstruction algorithm and design appropriate algorithm to identify b-jets.

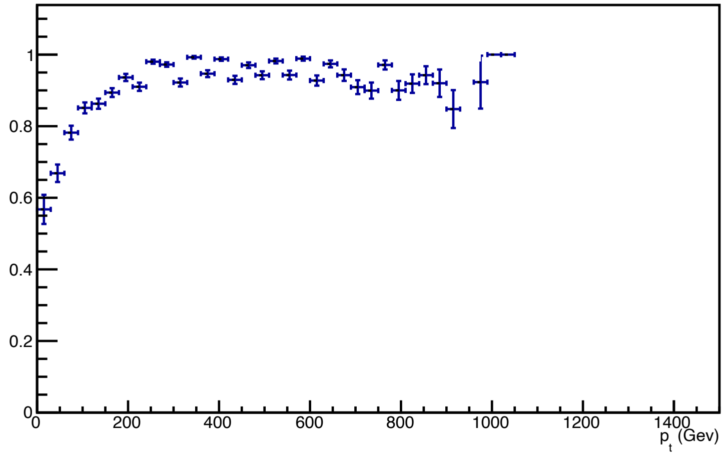
Muon Reconstruction

Muon Reconstruction with BIB at $\sqrt{s} = 1.5$ TeV

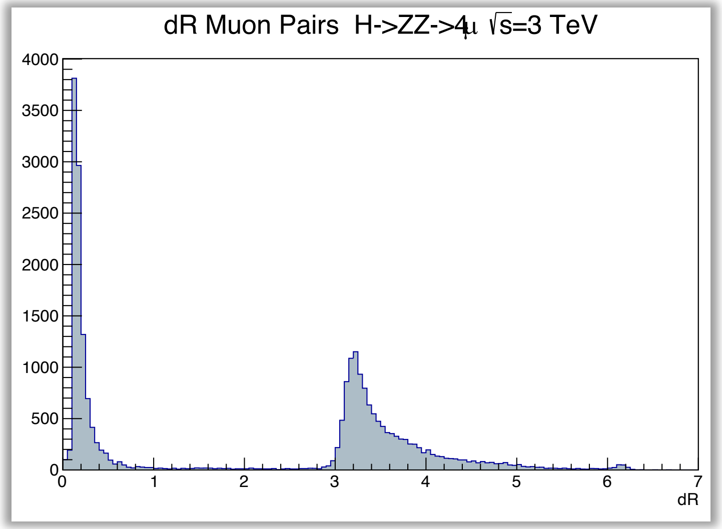


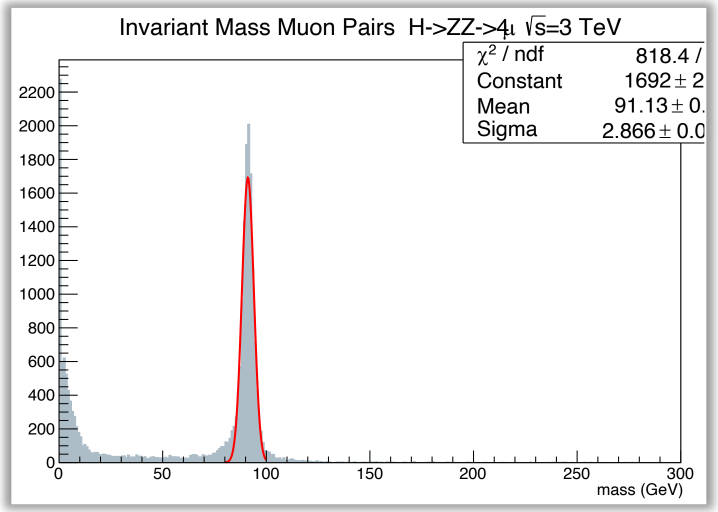






$\mu^+\mu^- \rightarrow H \rightarrow ZZ \rightarrow 4\mu$ at $\sqrt{s} = 3$ TeV





With this detector and the performance obtained so far on objects reconstruction, which accuracy do we get on Higgs physics?

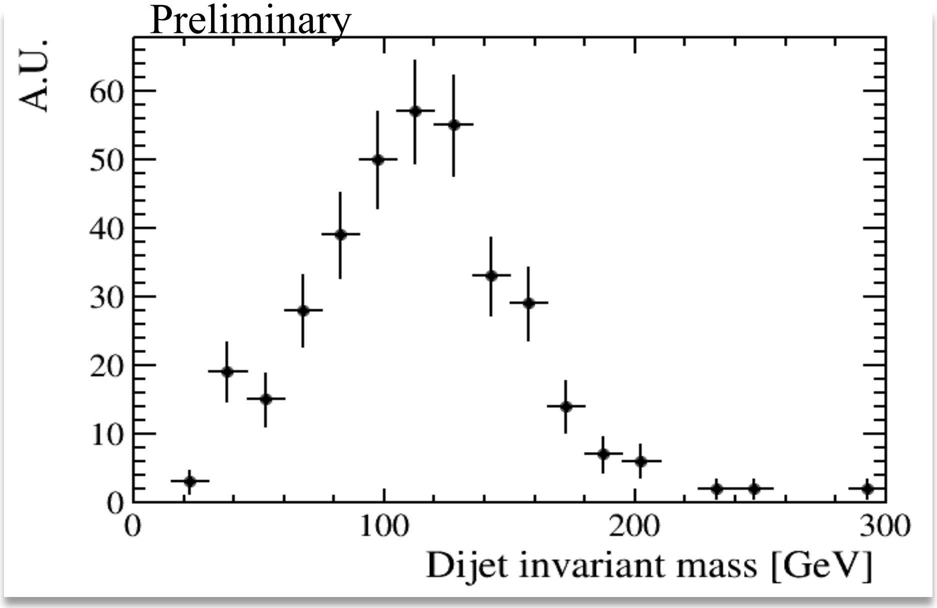
$\mu^+\mu^- \rightarrow b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

$\mu^+\mu^- \rightarrow HX, H \rightarrow b\bar{b}$ and $\mu^+\mu^- \rightarrow b\bar{b}X$ generated at $\sqrt{s} = 1.5\ TeV$ + BIB fully simulated

- Instantaneous luminosity, $\mathcal{L}$, at different √s, from MAP.
- Running time $t = 4 \cdot 10^7$ s ⇒ **4 Snowmass years**
- **Only one detector**

	$\sqrt{s}$ [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

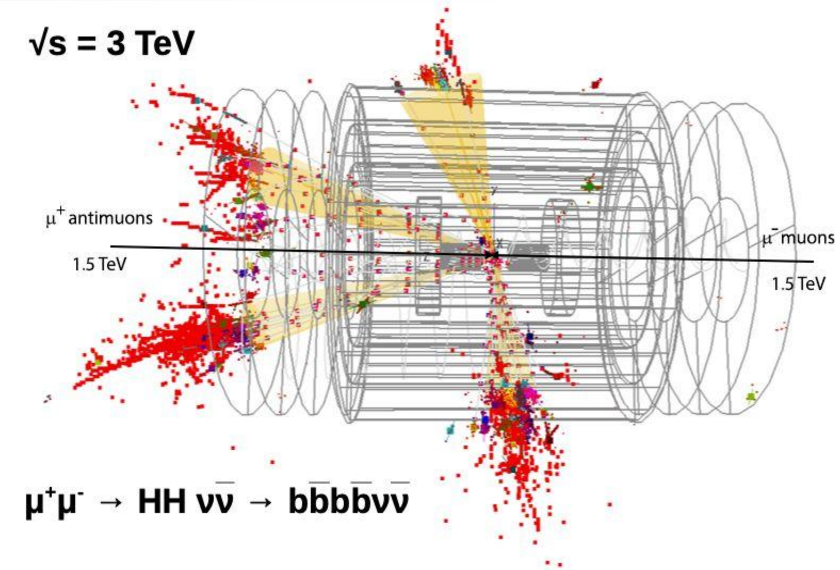
Results published on JINST



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

Update available soon.

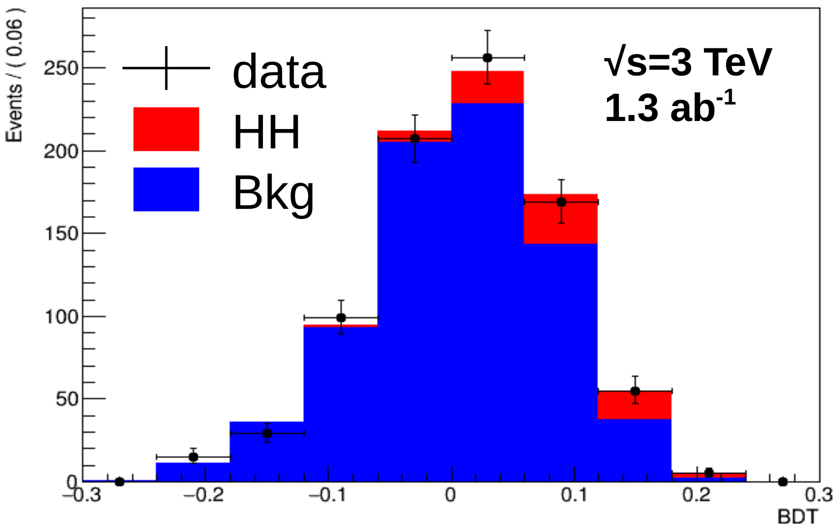
Double Higgs Production Study at $\sqrt{s} = 3$ TeV



Assumptions
- $\mathcal{L}_{int} = 1.3\ ab^{-1}$
- Running time $t = 4 \cdot 10^7$ s ⇒ **4 Snowmass years**
- One detector

Very preliminary event selection and reconstruction.

- Detector and physics objects performance determined at $\sqrt{s} = 1.5$ TeV.
- Events weighted to take into account for the different energy.



With a simple fit to the BDT output

$$\frac{\Delta\sigma}{\sigma} = 0.33$$

Update available soon.

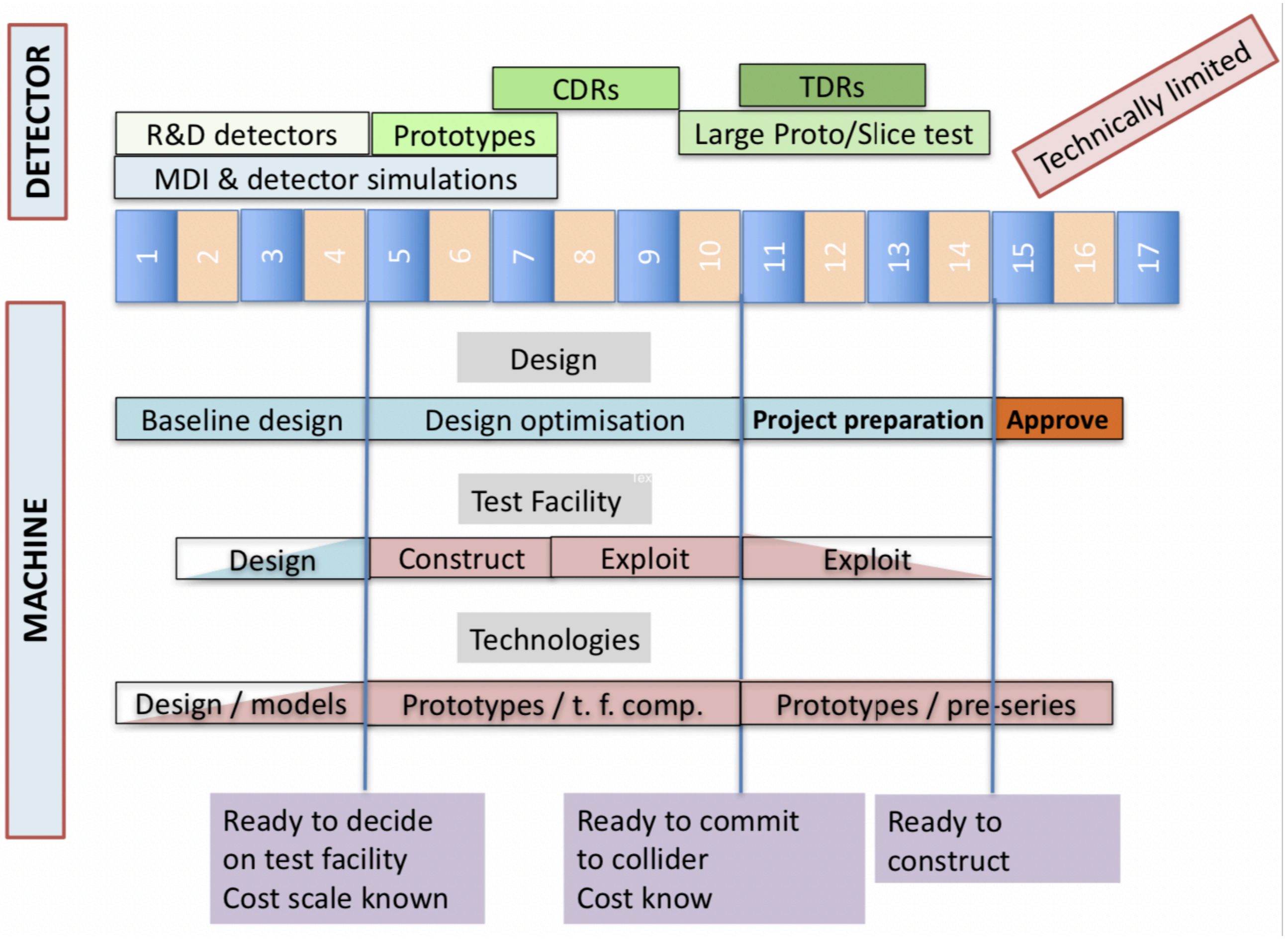
To Conclude

The simulation of the machine and the detector is demonstrating that a Muon Collider could be a serious future accelerator machine. We need to work together to demonstrate that it is feasible.

An International Collaboration is being formed, hosted by CERN to:

- Provide a baseline concept with expected performance, cost and risks.
- Identify an R&D path to the demonstrator.

Contacts:
[MuonCollider-Facilty]
[MuonCollider-Detector-Physics Group]



SnowMass2021 started a muon-collider-forum: slack channel [muon-collider-forum]

Muon Collider is a chance not to be missed!