IPPP topical meeting on physics with high-brightness stored muon beams

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Europe/Rome timezone

Experimental Aspects of Muon Colliders

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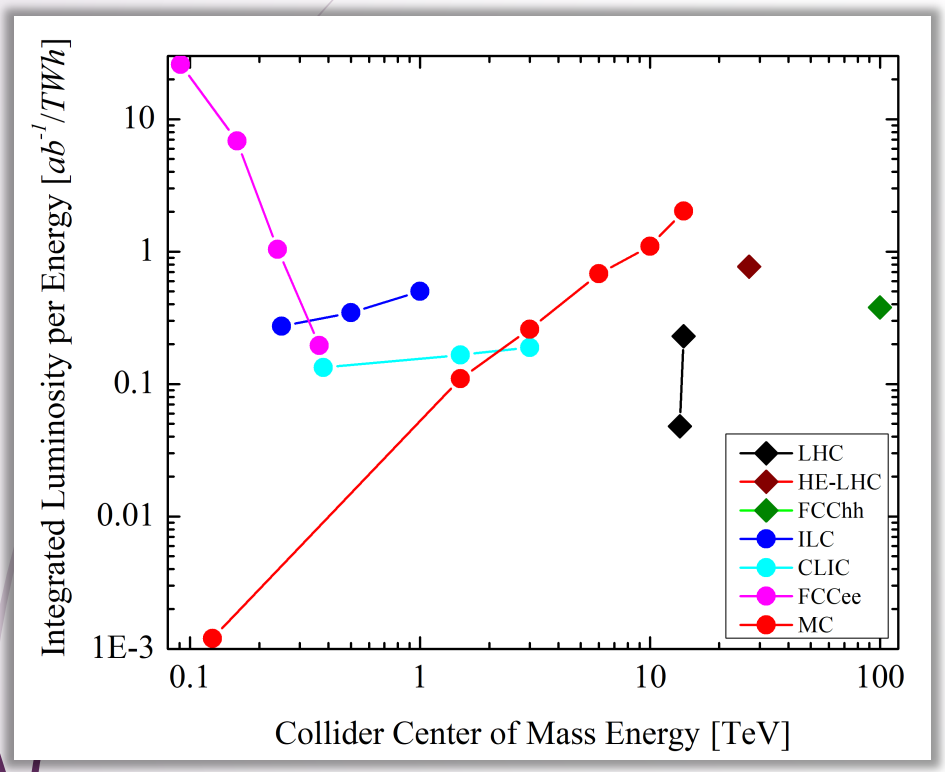
for

MuonCollider-Detector-Physics Group

Muon Collider Parameters in numbers

[Muon colliders to expand frontiers of particle physics]



Parameter	Unit	1.5 TeV	3 TeV
Luminosity	$10^{34}cm^{-2}s^{-1}$	1.25	4.4
N μ/bunch	10^{12}	2	2
Bunches/beam		1	1
σ_E/E	%	0.1	0.1
σ_z	mm	10	5
$\sigma_{x,y}$	μm	6	3

Set the Scene for Detector Requirements

a) **Beam Induced Background (BIB)**: Muons per bunch: $2 \cdot 10^{12}$ ➡ many muon decay products, back of the envelope calculation: beam 0.75 TeV $\lambda = 4.8\times10^{6}$m, with $2\times10^{12}\mu$/bunch ⇒ 4.1×10^{5}decay per meter of lattice

b) **Beam characteristics**:

- One bunch per beam
- Collision time: 10 μs at $\sqrt{s} = 1.5$ TeV and 15 μs at $\sqrt{s} = 3$ TeV

⬇

Long enough to assume not to have online selections: triggerless à la LHCb, strategies for possible online event selections are starting to be thought.

- Bunch length, $\boldsymbol{\sigma}_z$=10 mm at $\sqrt{s} = 1.5$ TeV and $\boldsymbol{\sigma}_z$=5 mm at $\sqrt{s} = 3$ TeV

Collision time resolution

⬇ $\boldsymbol{\sigma}_t \simeq 30$ ps

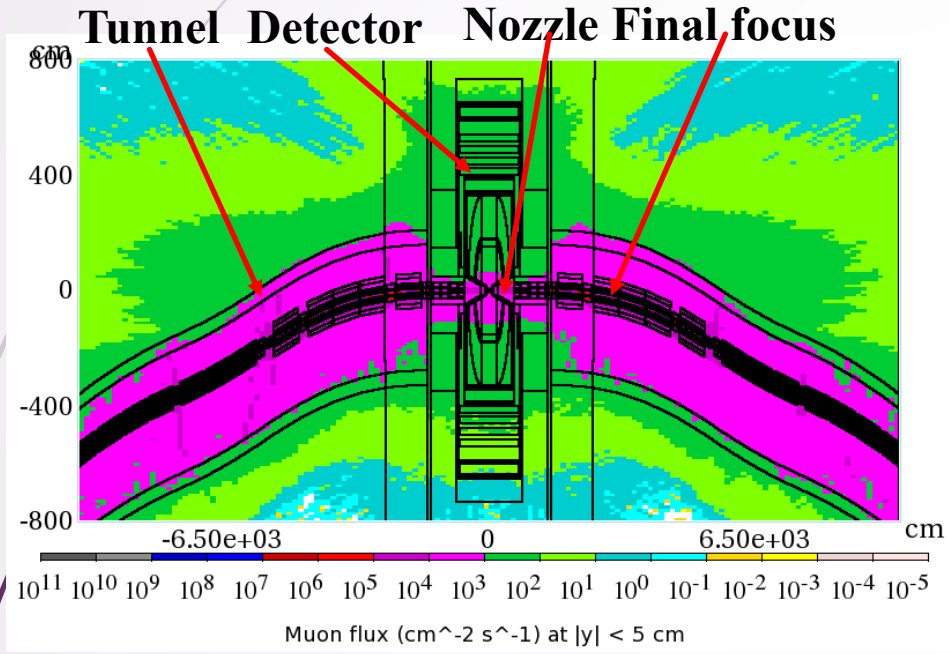
⬇ $\boldsymbol{\sigma}_t \lesssim 20$ ps

Important for tracker design

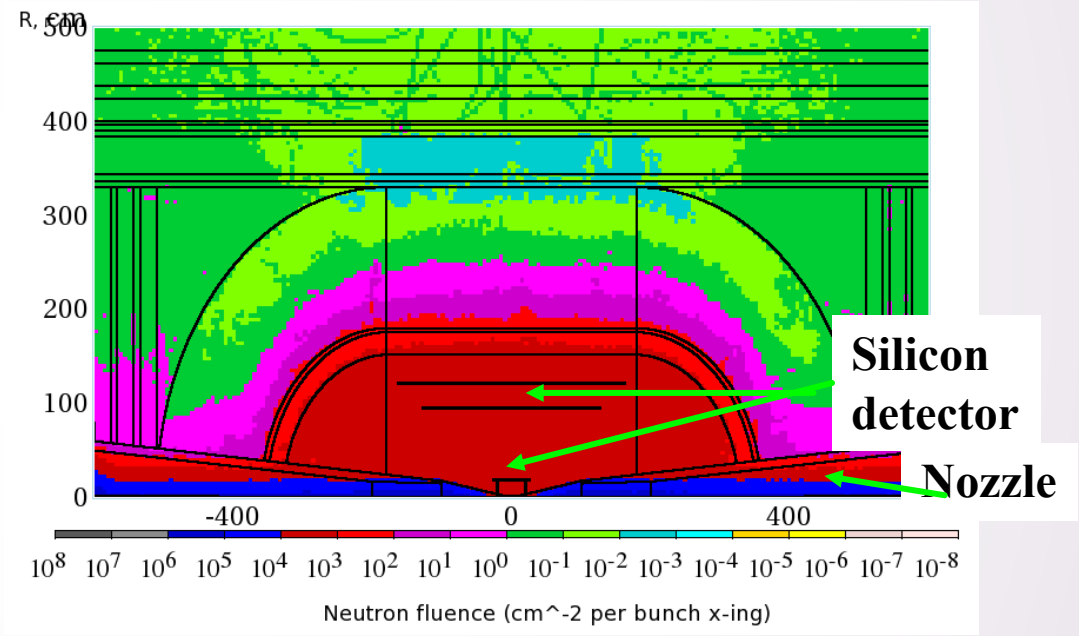
Set the Scene for Detector Requirements cont'd

c) Radiation Levels

N. Mokhov et al. Fermilab-Conf-11-094-APC-TD

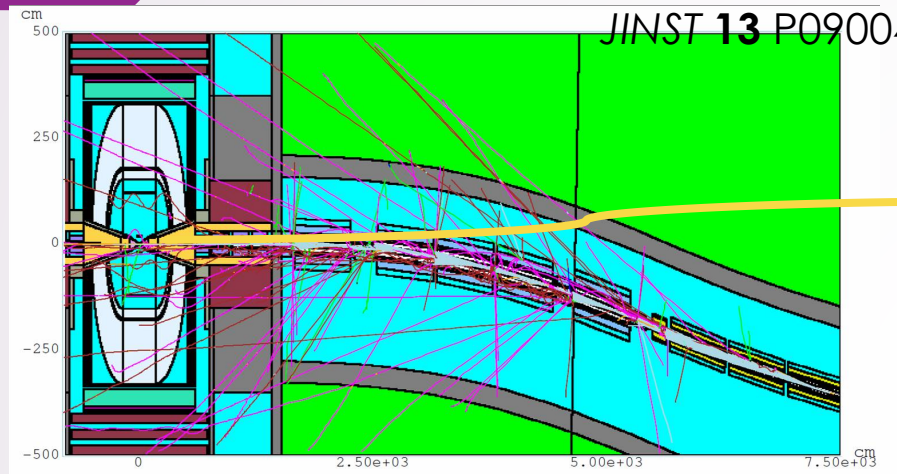


Muon flux: E~ 10-100 GeV in the detector. Produced as Bethe-Heitler pairs.



Neutron maximum fluence and absorbed dose in the innermost layer of the Si tracker for a one-year operation are at a 10% level of that in the LHC detectors at the nominal luminosity.

Beam Induced Background Generation



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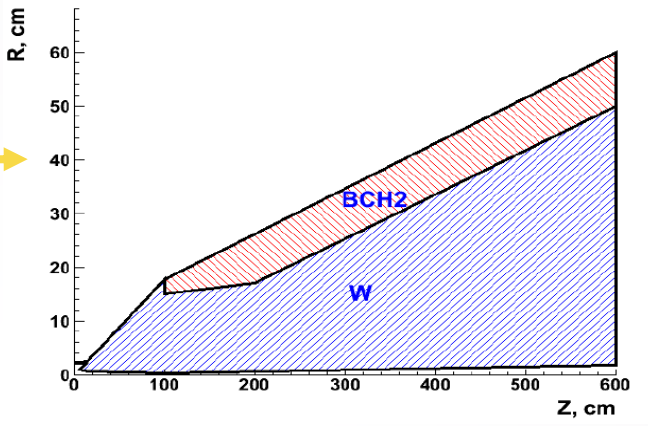
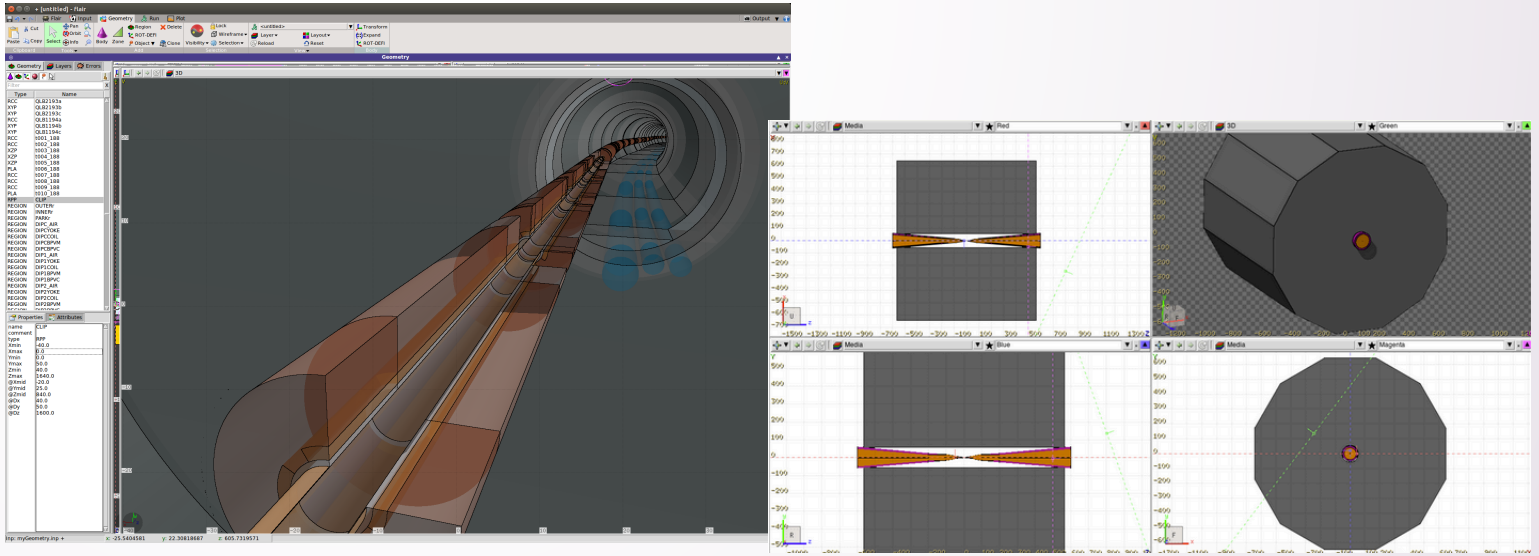


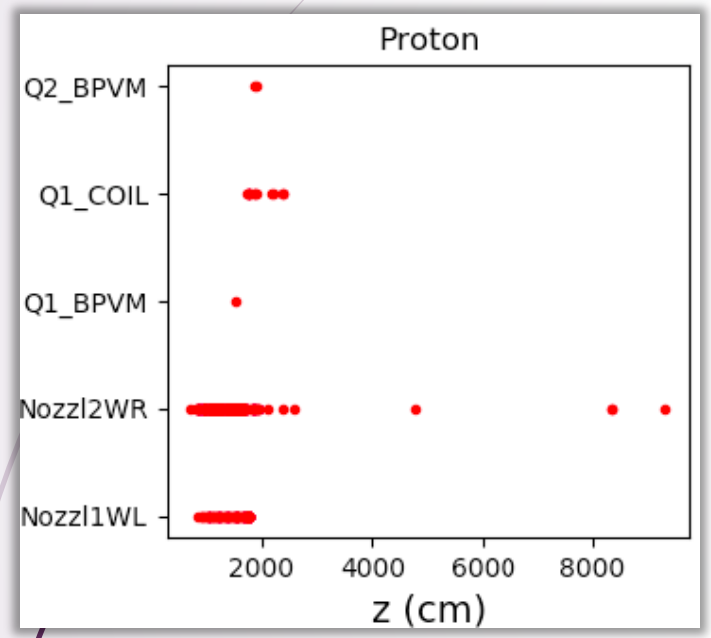
Nozzle to be optimized as function of $\sqrt{s}$ and machine lattice

New tool:
LineBuilder: read machine lattice and produce Fluka elements
Fluka: generate new BIB considering all passive elements

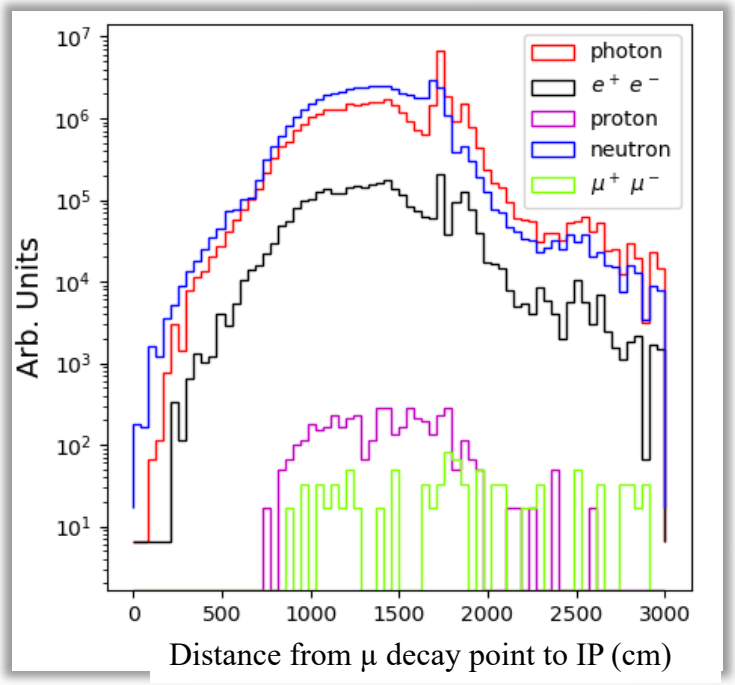


Beam-Induced Background properties $\sqrt{s}$ =1.5 TeV

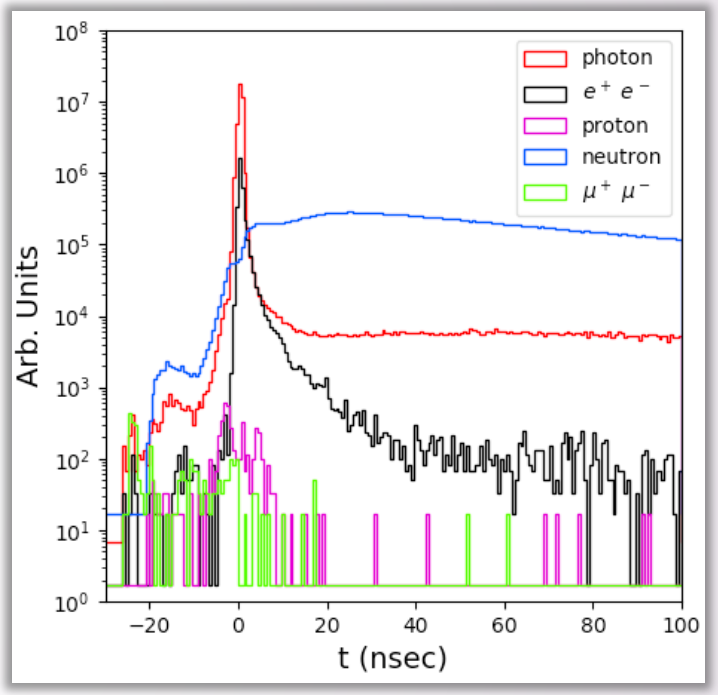
One muon beam of 750 GeV with $2 \cdot 10^{12}$ particles/bunch



Possible to study the BIB origin to mitigate it with dedicated machine-detector-interface

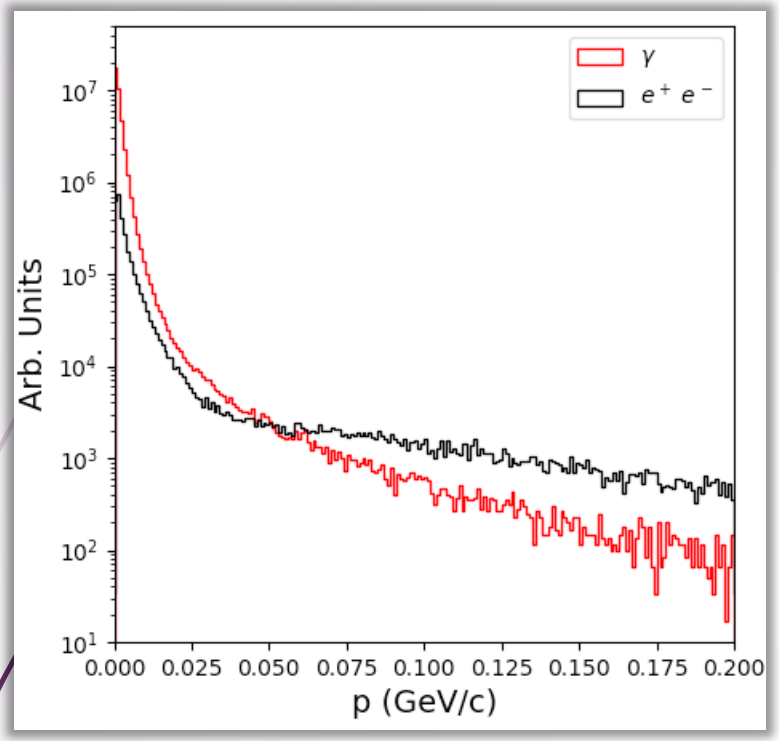


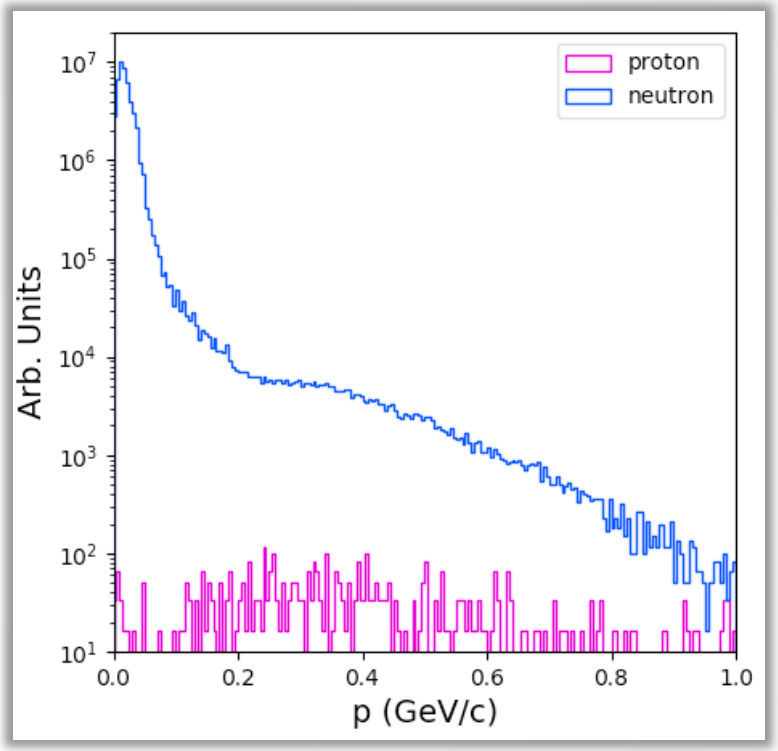
Integration path for BIB contribution to the interaction region depends on $\sqrt{s}$ and accelerator lattice



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

Beam-Induced Background properties $\sqrt{s}$ =1.5 TeV cont'd





Secondary and tertiary particles have low momentum

BIB characteristics strongly effect detectors design ➞ detailed evaluation is needed.
Study of BIB behavior at 3 TeV center of mass energies is in progress, for higher energies a new strategy has to be defined.

Detector for $\sqrt{s}$ =1.5 TeV Collisions

hadronic calorimeter

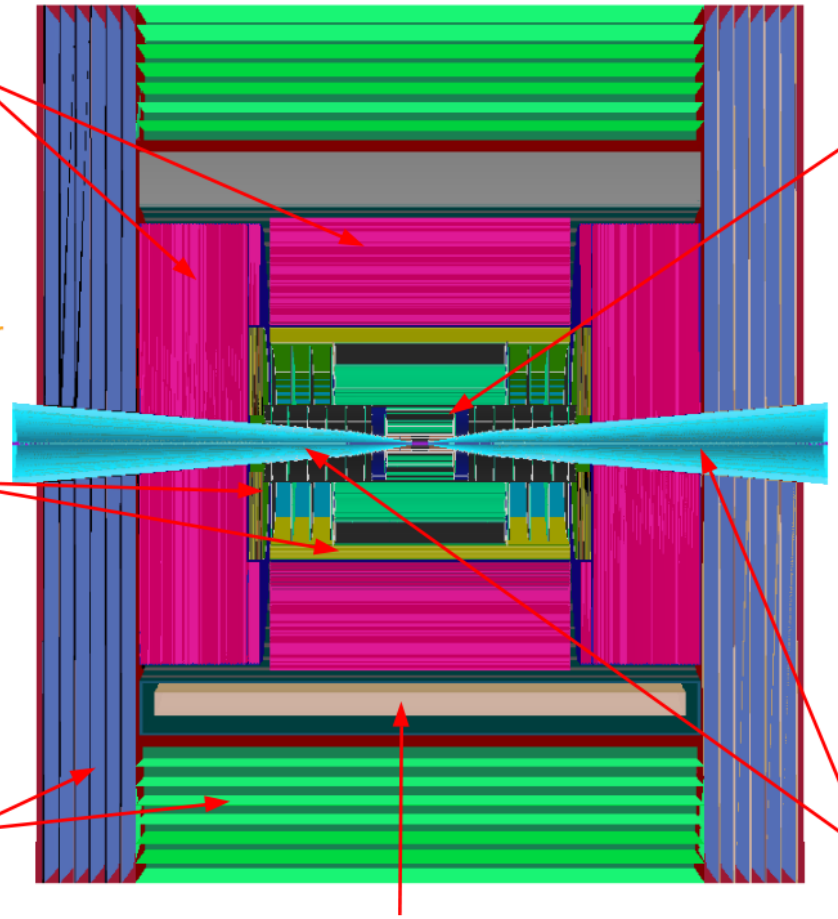
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.



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!

Full Detector Simulation and Physics Object Reconstruction

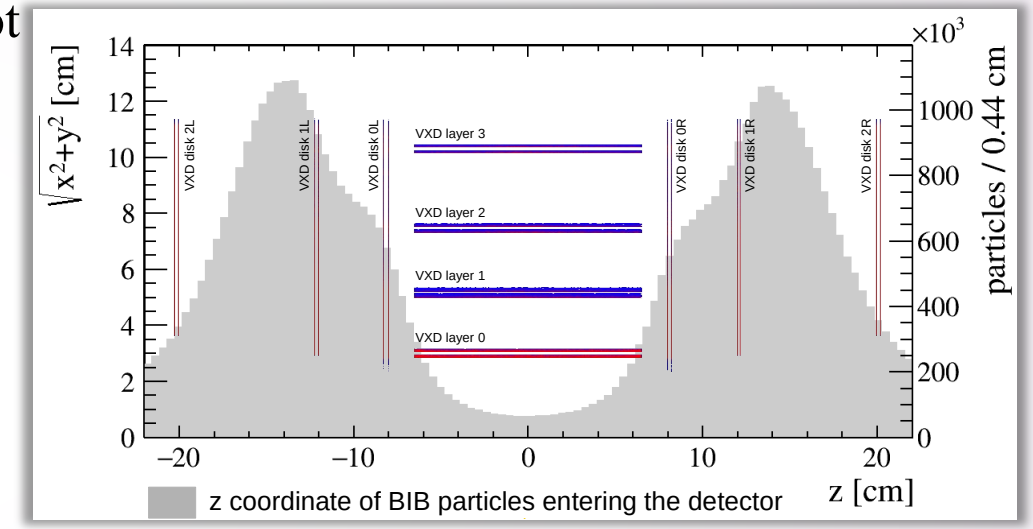
- **ILCSoft** which will be part of the Future Collider Framework, Key4hep, is used.
  The simulation/reconstruction tools support signal + beam-induced background merging.
  Presentation at Snowmass with a tutorial, and Software information on confluence Site.
- Detector geometry frozen for $\sqrt{s}$ **=1.5 TeV** studies.
- Event Full Simulation ➞ no issues.
- Track reconstruction:
  - It takes some time to do it with full BIB.
  - Several strategies almost in place (optimization needed) to reduce the combinatorics.
- Jet Reconstruction:
  - BIB effect reduction strategy ready.
  - Optimization of ParticleFlow algorithm optimization in progress.
- Jet b-tag:
  - In progress algorithm definition and optimization.
- Available simulated sample on the INFN-Tier-1 Storage Element:
  - Several BIB bunch crossings and signal+physics background samples.

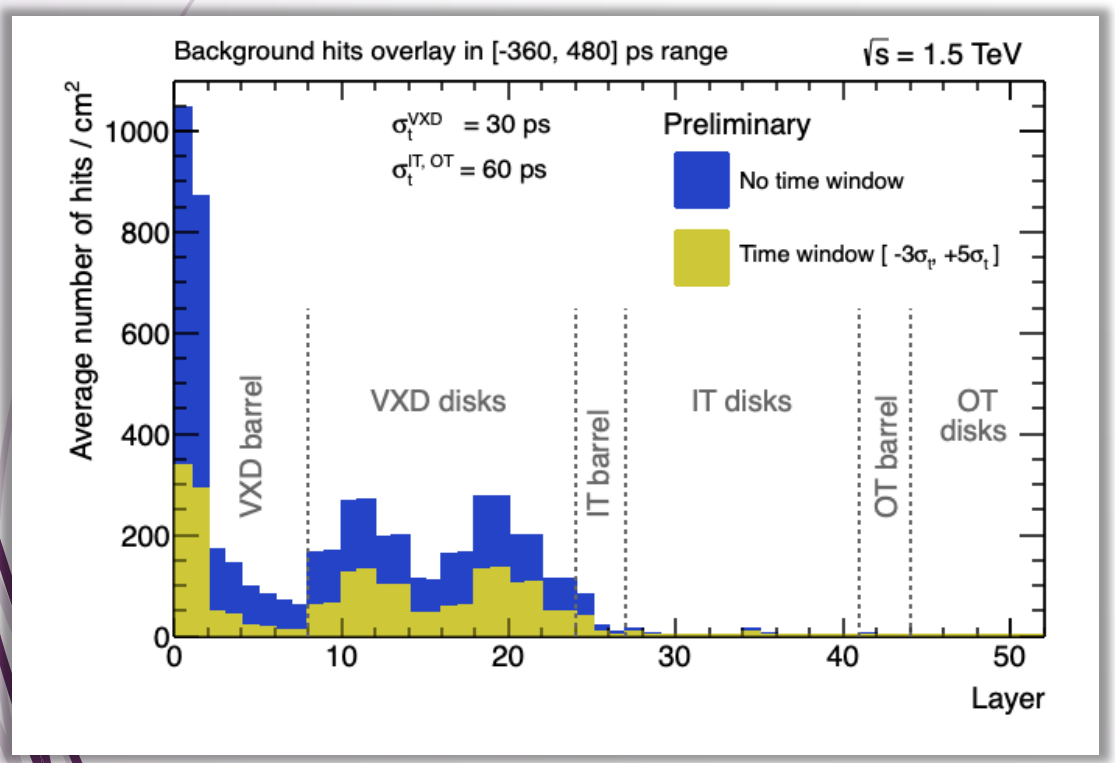
Ready to perform physics study with full simulation

Tracker Characteristics at $\sqrt{s}$ =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 around the interaction region





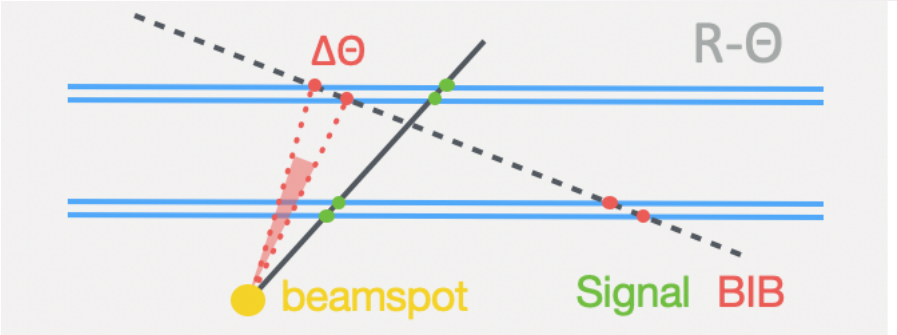
Tracking performance have been studied applying timing and energy cuts on clusters reconstruction compatible with IP time spread

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

BIB particles arrive on silicon sensors with a different angle respect to primary interaction particles:

- Cluster shape in each sensor can be exploited to reduce BIB contribution;
- Angles can be measured by correlating hits between adjacent sensors. This is the approach used for the CMS track trigger.

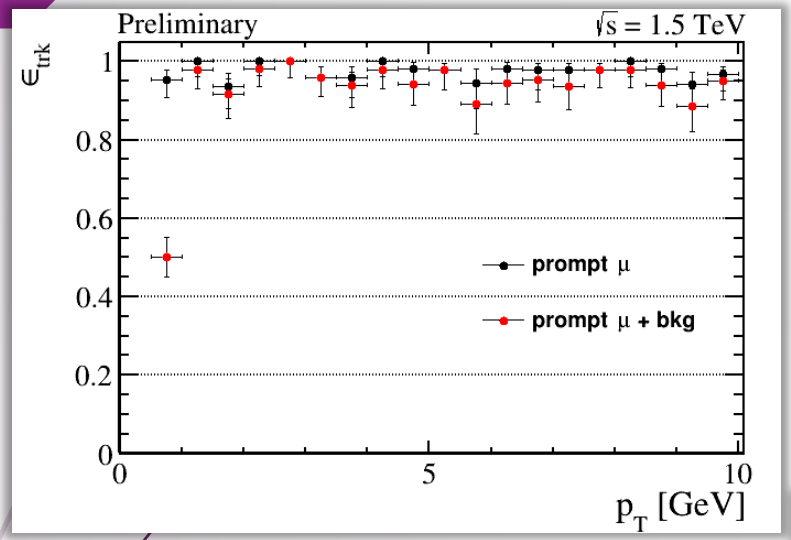
Need to be studied and tuned taking into account primary vertex smearing.

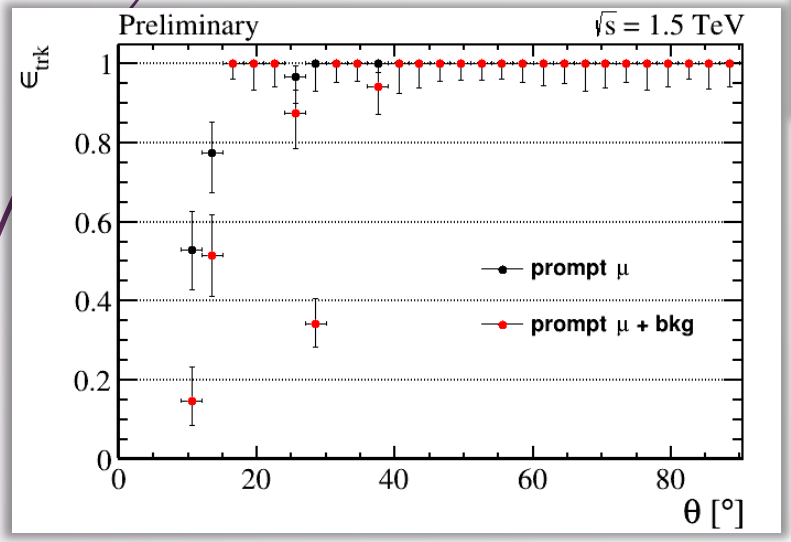


Appropriated tracker will be designed in future study

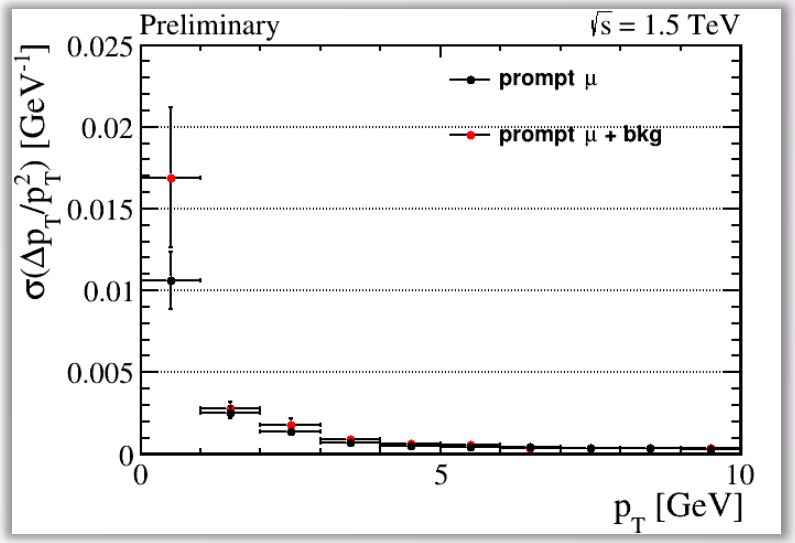
Tracking performance are studied with the current detector configuration with no tracking algorithm optimization with samples of prompt muons with BIB overlayed

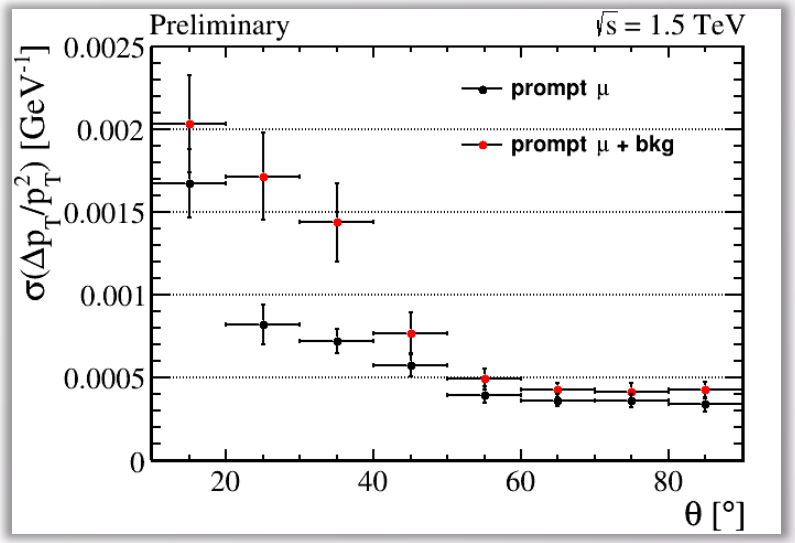
Tracking performance at $\sqrt{s}$ =1.5 TeV





Sample of prompt muons
$0 < P_T \leq 10\ GeV$
Prompt muons with BIB

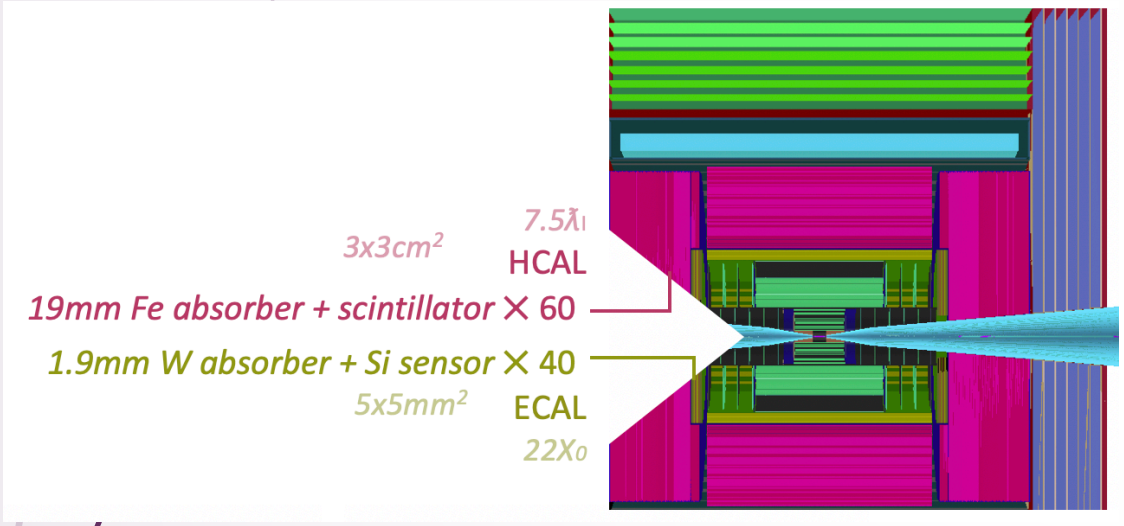


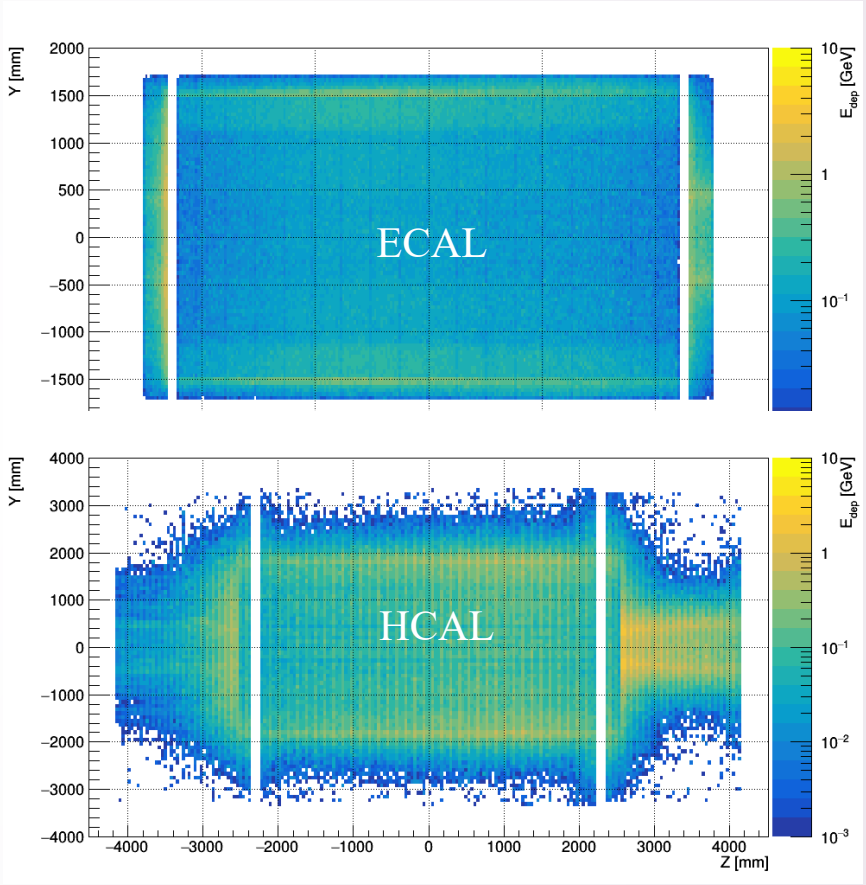


Calorimetry Study

Current simulation is based on CLIC configuration:

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

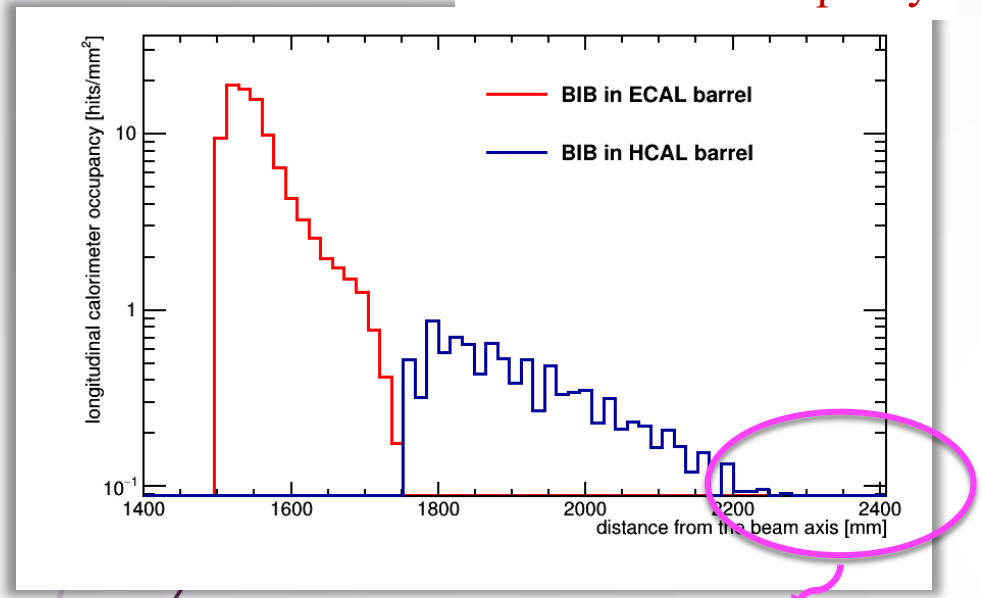




BIB deposits large amount of energy in both ECAL and HCAL

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

Calorimeter Occupancy

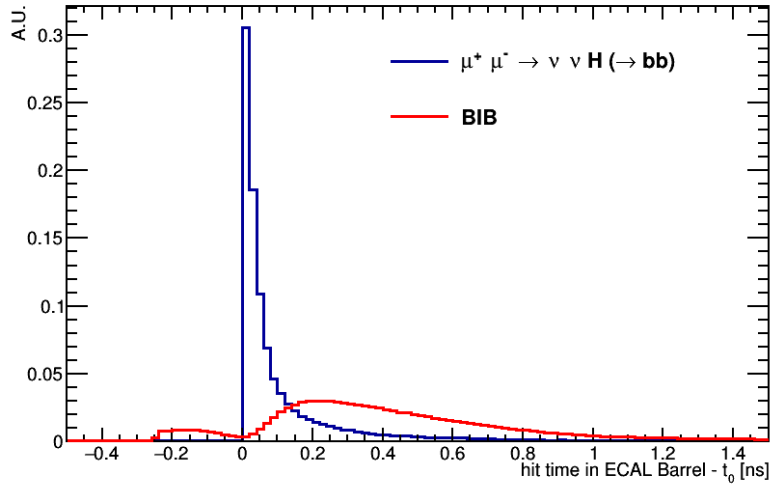


Few BIB hits arrive to the muon detectors

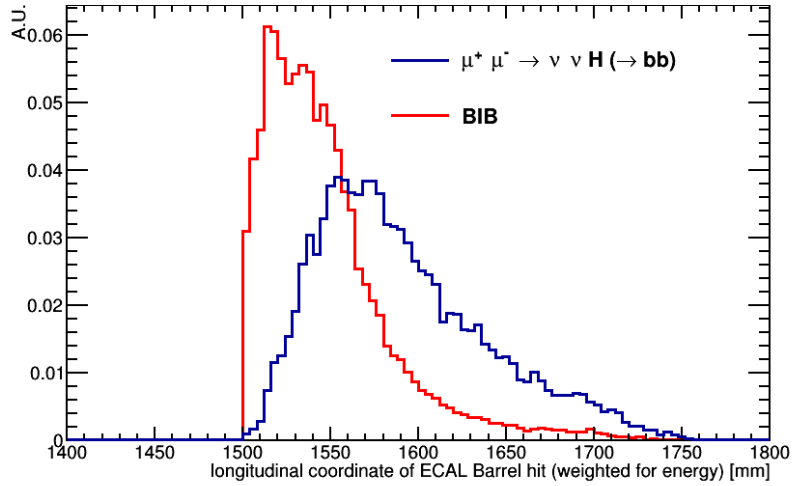
BIB characteristics to be exploited to:

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

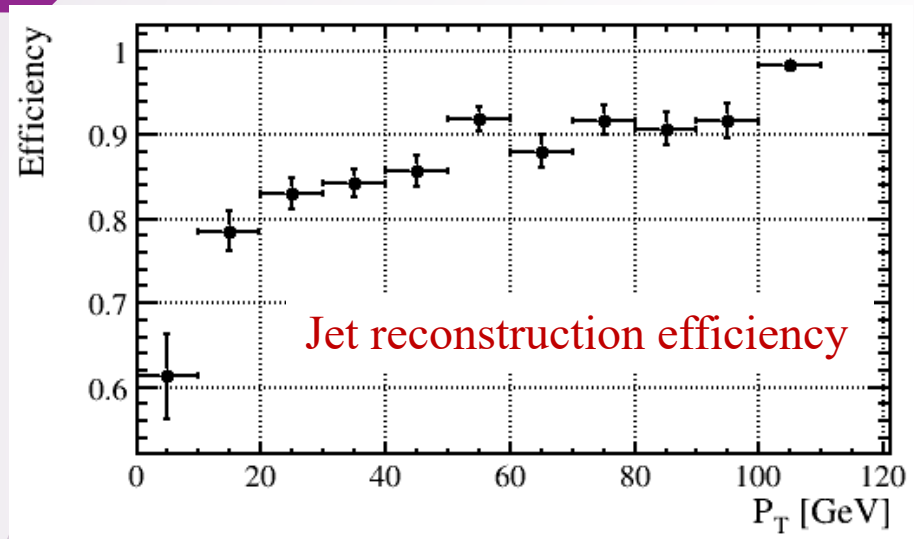
ECAL barrel hit arrival time – t_0

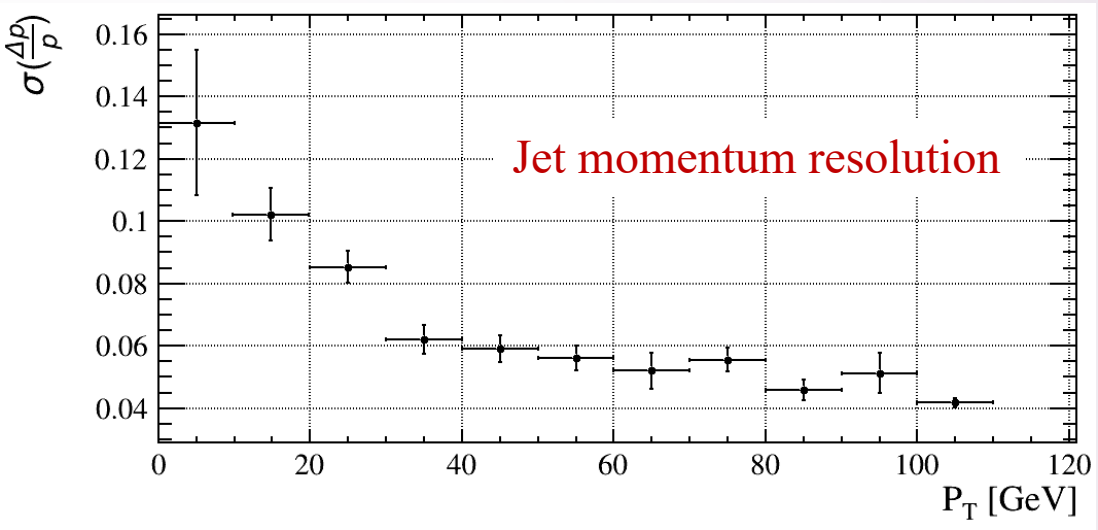


ECAL barrel longitudinal coordinate



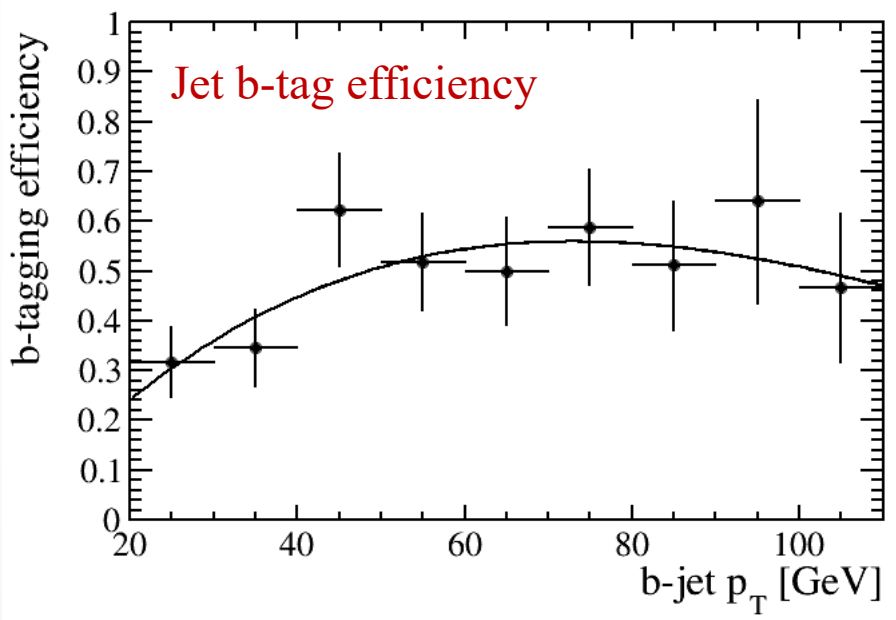
Calorimeter Reconstruction Performance $\sqrt{s}$ =1.5 TeV





Jet ParticleFlow reconstruction algorithm under optimization.

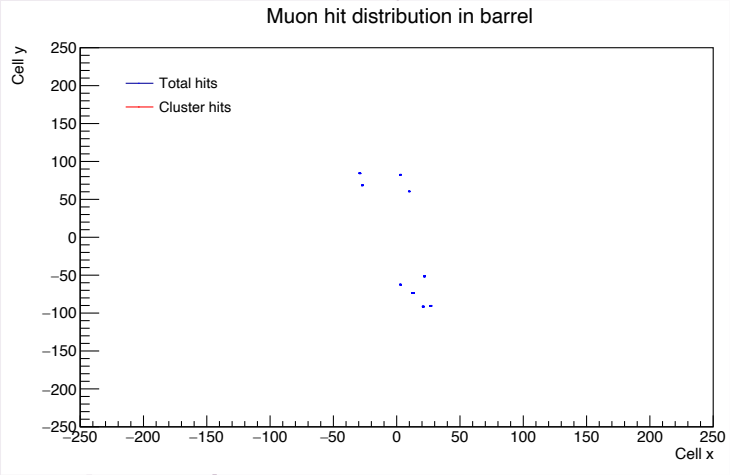
Determined with the "MAP" detector with dual-readout calorimeter and very "rough" jet reconstruction and b-tag algorithms.

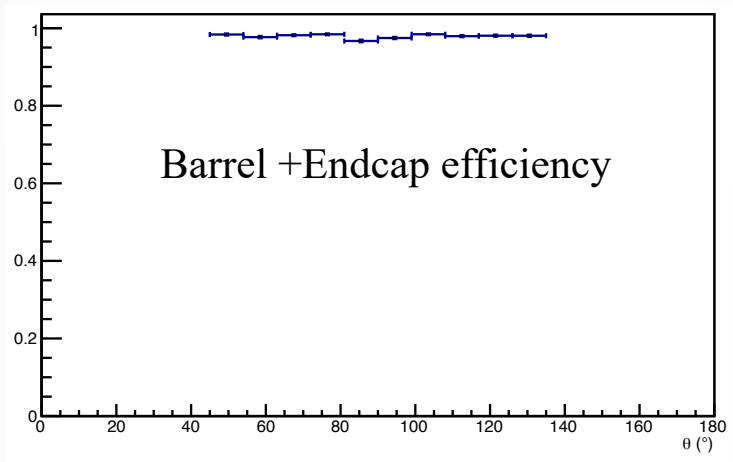


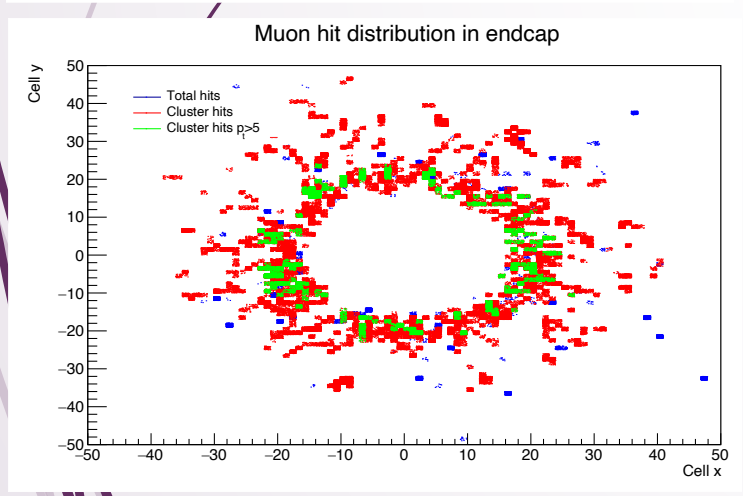
b-jet identification very simple, based on secondary vertices

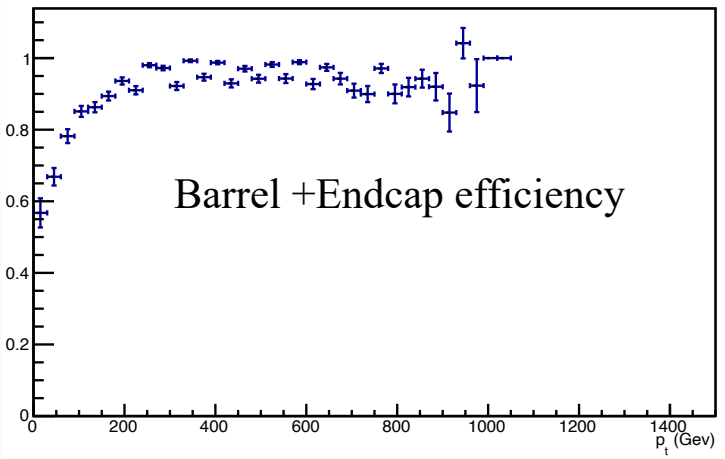
Muon Reconstruction

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

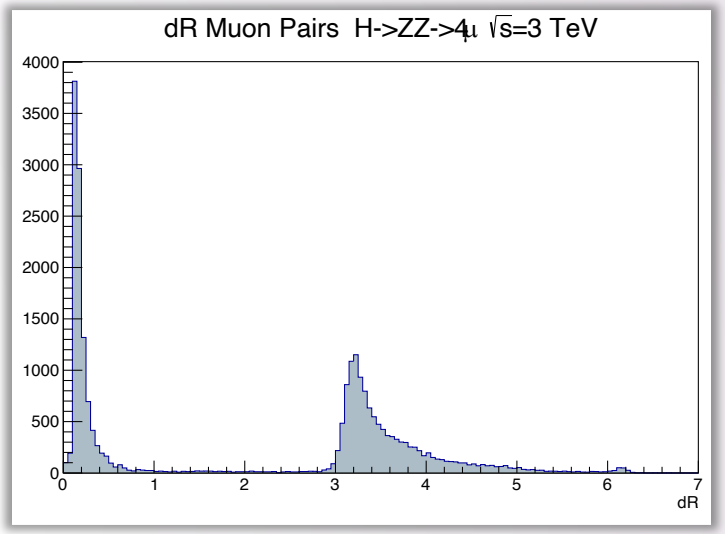


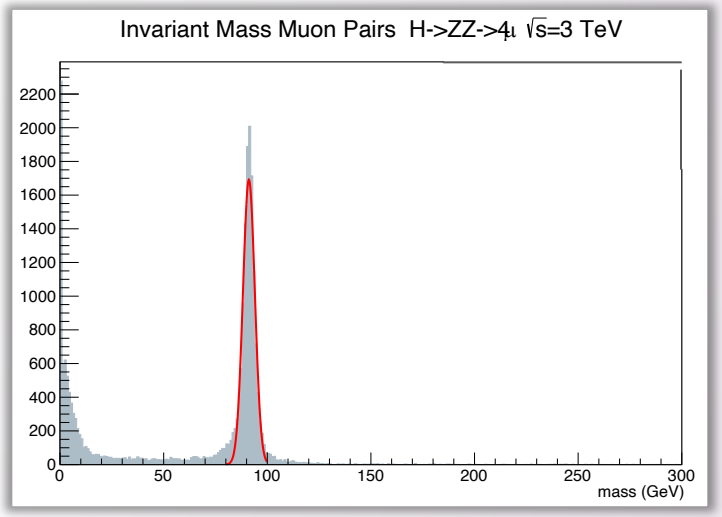






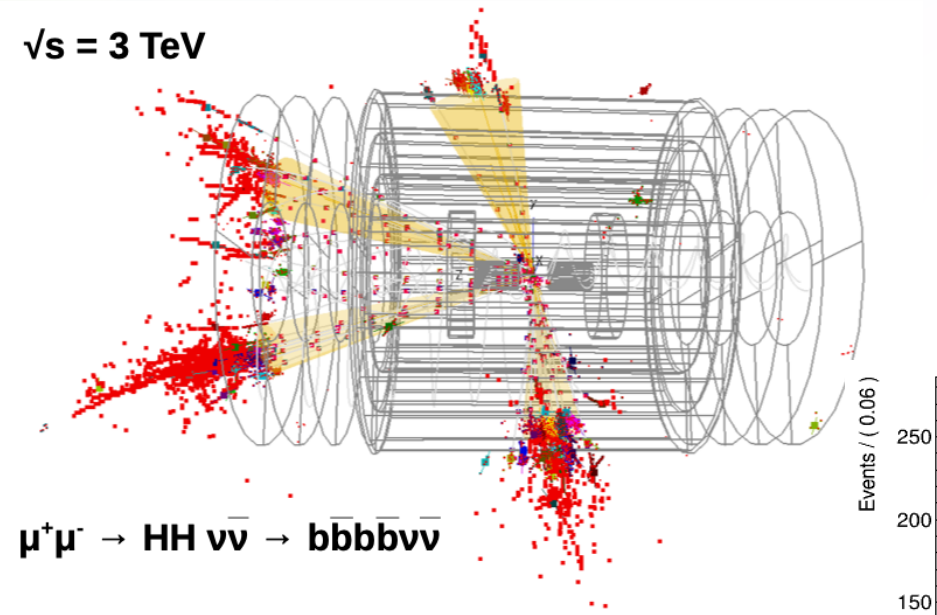
$\mu^+\mu^- \rightarrow H \rightarrow ZZ \rightarrow 4\mu$ at $\sqrt{s} = 3$ TeV





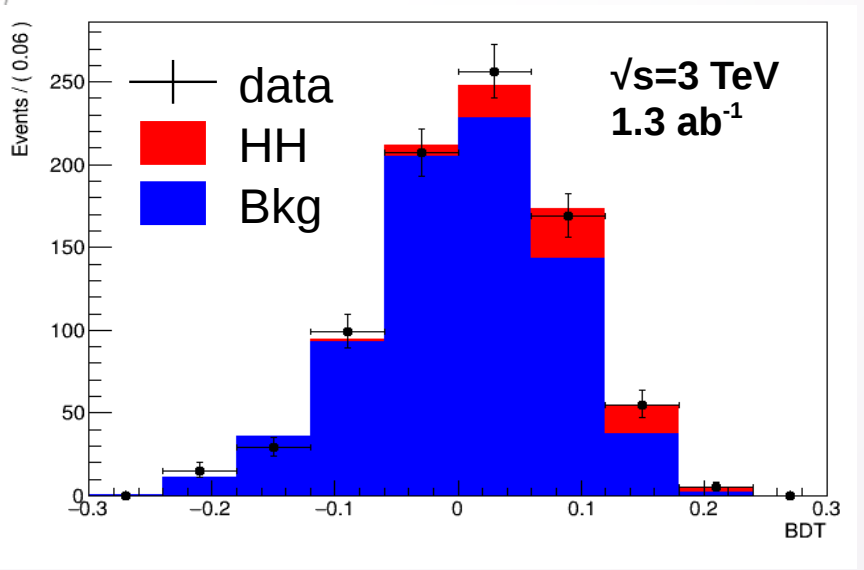
Exciting Physics measurements with the full simulated detector

The process $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ at $\sqrt{s} = 3\text{TeV}$ is under study by using the full detector simulation



Assumptions

- $\mathcal{L}_{int} = 1.3\ ab^{-1}$
- Running time $= 4 \cdot 10^7$ s
- one detector



With a simple fit to the BDT output

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

CLIC has 10% with 5 ab^{-1} and very refined analysis

Summary

- Full simulation of the detector and event reconstruction including beam-induced background available on github.
- Object reconstruction performance *almost* determined including beam-induced-background at $\sqrt{s} = 1.5$ TeV:
  - Muon reconstruction well performing, Tracking and jets well advanced but need to be optimized, b-jet tagging under development.
  - Electrons and photons in progress.
- Beam-induced-background fully studied at $\sqrt{s} = 1.5$ TeV, in progress the production of data at $\sqrt{s} = 3$ TeV with the following study with a new tool by using the machine lattice of MAP.
- Physics benchmarks under study with full simulation demonstrating the great potential of the muon collider already at low, i.e. $\sqrt{s} = 3$ TeV energies.

➢ Need an intensive study and R&D on detector technologies for $\sqrt{s} = 10$ TeV and high luminosity ➞ collaboration and support ECFA.