Detector R&D requirements for Muon Colliders

Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of 10^{35} cm^{-2} s^{-1}

- *Status of existing and on-going studies at 1.5 and 3 TeV center-of-mass energy*
- *Future steps towards 10 TeV and higher center-of-mass energy to exploit physics reach*

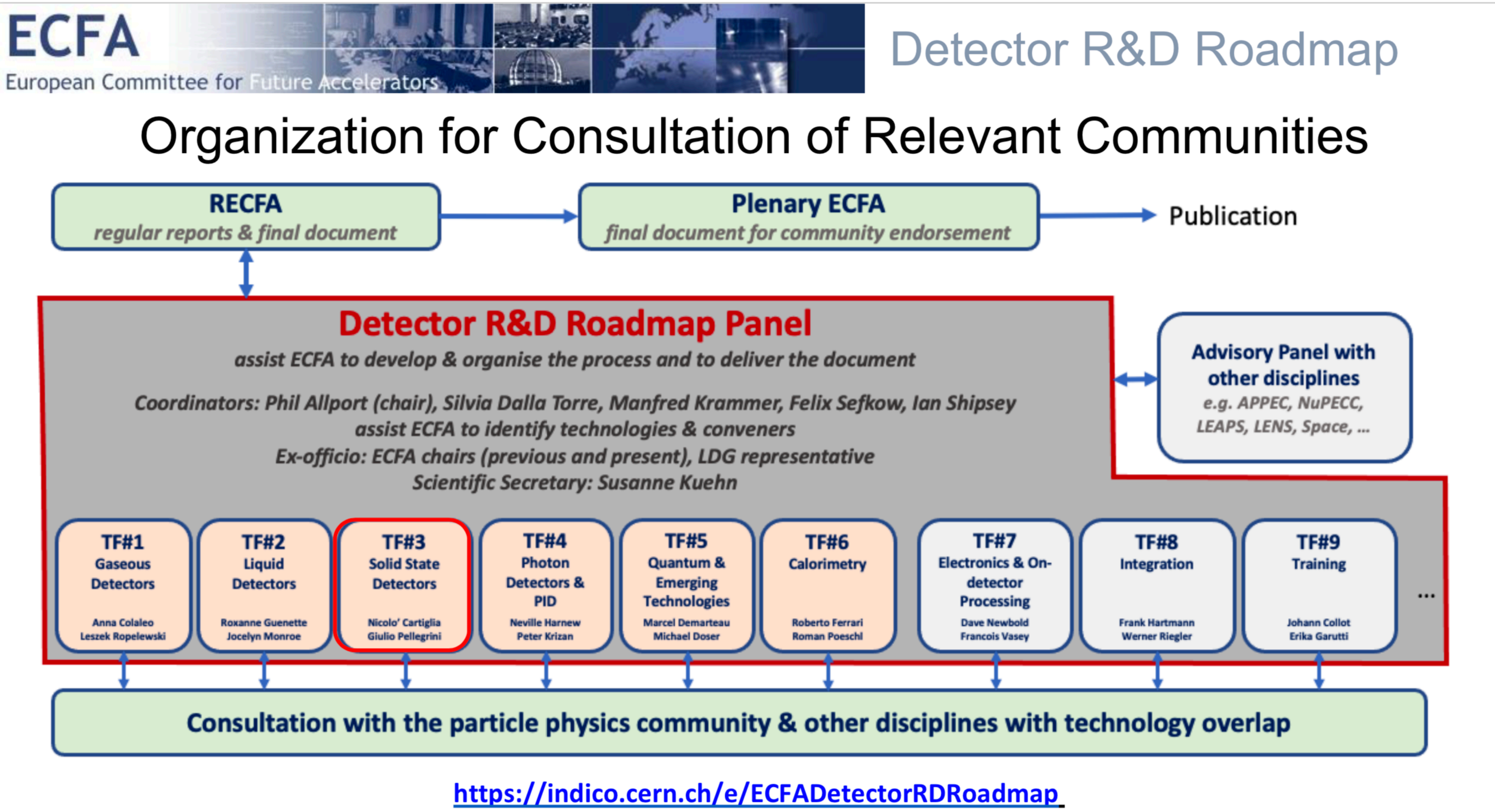
Hp: $\mathcal{L} = 2{\times}10^{35} cm^{-2} s^{-1}$ @ 10 TeV

$\int \mathcal{L} dt$ = $(E_{CM}/10\text{TeV})^2 \times 10\ ab^{-1}$

@ 3 TeV	~	1 ab^{-1}	5 years
@ 10 TeV	~	10 ab^{-1}	5 years
@ 14 TeV	~	20 ab^{-1}	5 years

~ $2{\times}10^{12} \mu/bunch$
1 bunch/beam colliding each 20-30 μs
➔ max 2 Interaction Points - IP
ONLY 1 EXPERIMENT CONSIDERED at present

ECFA Detector R&D Roadmap



Considered future facilities

Broad Topic Areas

Organization for Consultation of Relevant Communities

- Focus on the technical aspects of detector R&D requirements given the EPPSU deliberation document listed "*High-priority future initiatives*" and "*Other essential scientific activities for particle physics*" as input and organise material by Task Force.
- Task Forces start from the future science programmes to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) to estimate the period over which the required detector R&D programmes may be expected to extend.
- Within each Task Force create a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable.

Grouped targeted facilities/areas emerging from the EPPSU

1. **Detector requirements for full exploitation of the HL-LHC (R&D still needed for LS3 upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics).**
2. **R&D for long baseline neutrino physics detectors (including aspects targeting astro-particle physics measurements) and supporting experiments such as those at the CERN Neutrino Platform.**
3. **Technology developments needed for detectors at e^+e^- EW-Higgs-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2GeV of up to $5\times10^{36}cm^{-2}s^{-1}$.**
4. **The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to $30ab^{-1}$ and 1000 pile-up for 25ns BCO.**
5. **Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of 10^{35} cm^{-2} s^{-1}.**

Detector R&D Roadmap timeline

ECFA
European Committee for Future Accelerators

Process and Timeline

Organisation

May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe

Sep 2020
Structure in place with **Detector R&D Roadmap Panel**

Dec 2020
Task Forces active

Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Expert & Community Consultation

Feb 2021
Collection of requirements of future facilities & projects

Feb/March 2021
Questionnaires of Task Forces to national contacts

Task Forces liaise with experts in
- ECFA countries
- adjacent disciplines
- industry

March-May 2021
Open Symposia

Drafting Roadmap & Feedback

May 2021
Task Forces collate input from symposia

25-28 May 2021 **Drafting sessions**
- opening session with all experts involved
- plenary & parallel sessions with Task Force members
- final session of Roadmap Panel

July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

Until Sep 2021
Collect final community feedback*

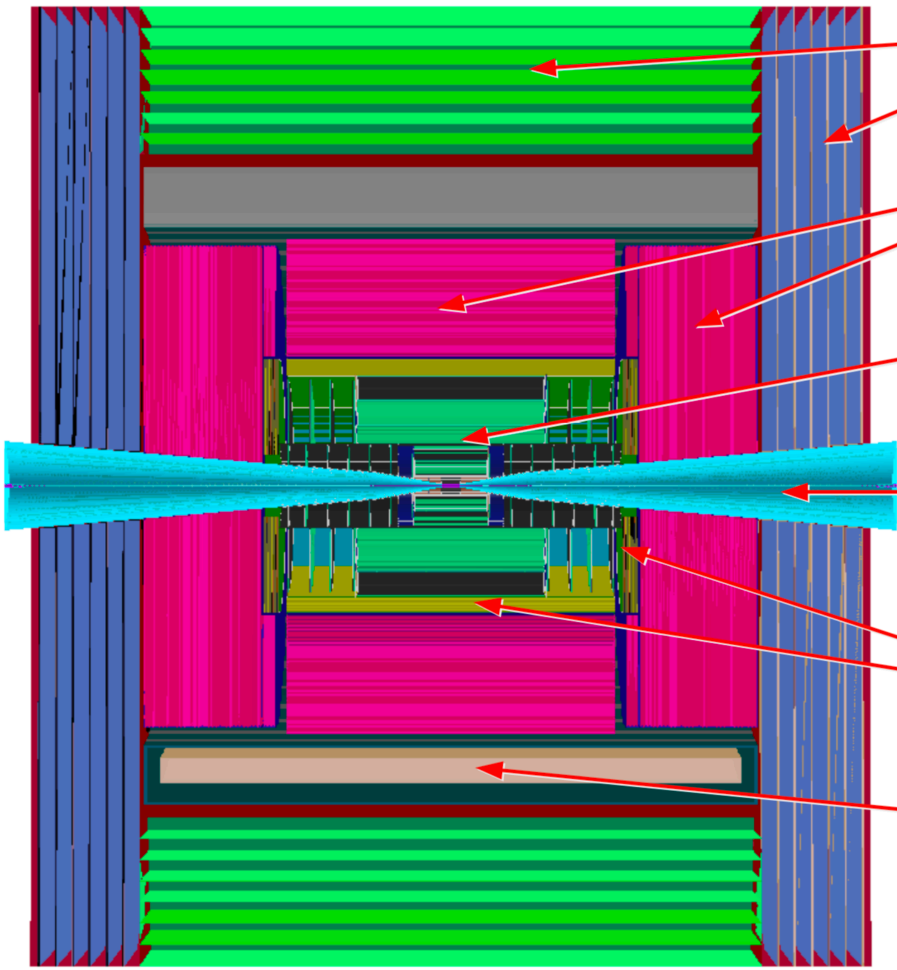
Oct 2021
Detector R&D Roadmap Document submission to RECFA and afterwards to PECFA and Council

*community feedback via RECFA delegates and National Contacts

March to May 2021 ECFA Detector R&D Roadmap 6

Detector

- Based on CLIC's detector model + the MDI and vertex detector designed by MAP.



muon detectors

hadronic calorimeters

tracking system

shielding nozzles

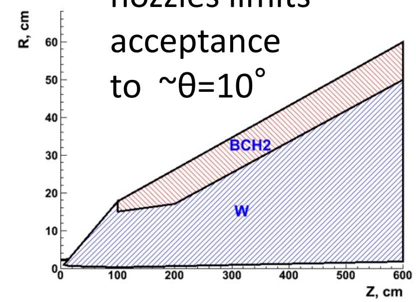
(tungsten cones + BCH_2 cladding)

reduce the BIB rate by a factor ~500

electromagnetic calorimeters

superconducting solenoid (3.57T)

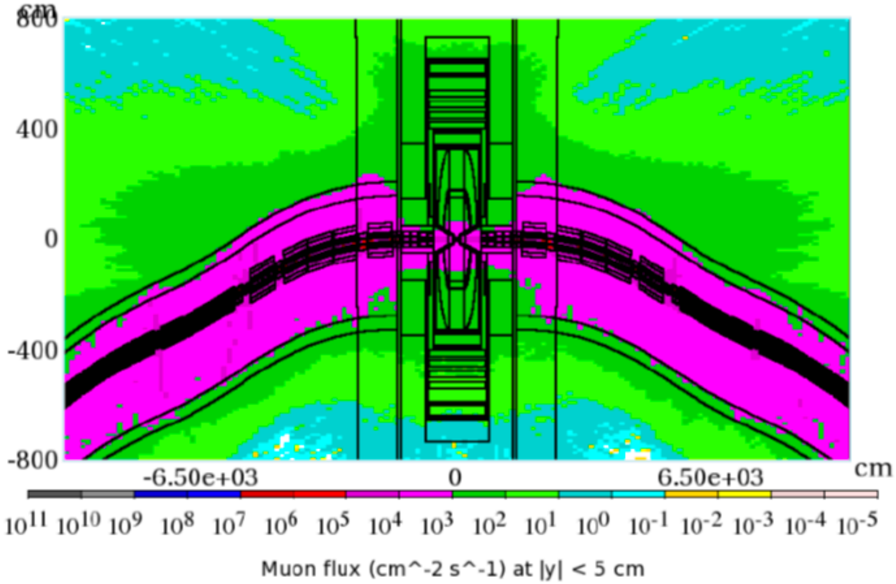
nozzles limits acceptance to ~θ=10°

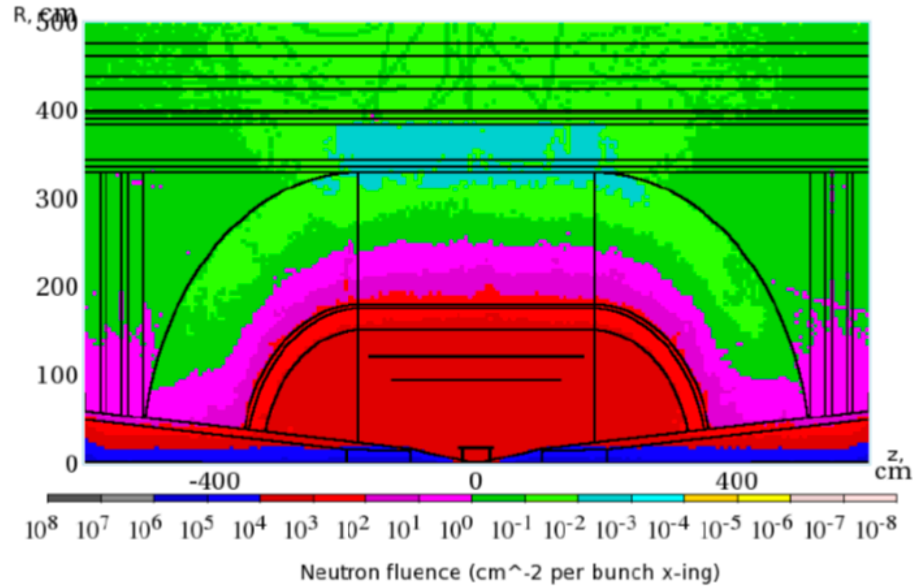


Full simulation available on github

B = 3.57 T to be studied and tuned

Muon and neutron fluences @ 1.5 TeV





Muon flux map in IR.
Muons – with energy of tens and hundreds GeV – illuminate the whole detector. They are produced as Bethe-Heitler pairs by energetic photons in EMS originated by decay electrons in lattice components.

Neutron fluence map inside the detector.
Maximum neutron 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. High fluences of photons and electrons in the tracker and calorimeter exceed those at LHC, and need more work to suppress them.

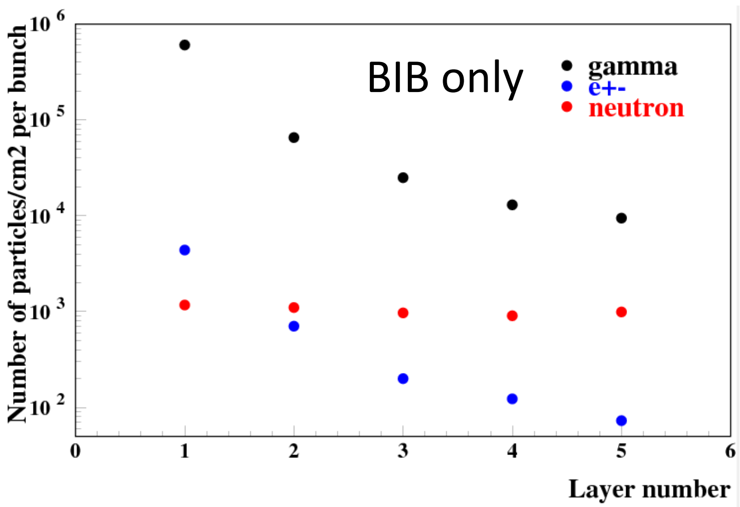
Expected fluence < HL-LHC HL-LHC < Expected dose < FCC-hh
Still expecting radiation hardness
to play a significant role, but unlikely to be a major problem
Leaves more flexibility in adapting detector design to such requirements

Fluences and dose requests to be able to compare mainly tracker constraints

JINST 13 (2018), P09004
***JINST* 15 (2020) 05, P05001**

muon beams
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔
4×10^{5} muon decays/m single bx

arXiv:1808.02154
10.18429/JACoW-IPAC2014-TUPRO029



The simulation of MDI and BIB was done with MARS15 by the MAP collaboration and later a FLUKA tool was developed to reproduce results @ 1.5 TeV center of mass with MAP lattice with optimised IR.
Data refer to this energy.

Now studies are on-going at the 3 TeV and soon planning to extrapolate to 10 TeV.

A tentative answer to be fully addressed

- The neutron fluence around 10% of HL-LHC would lead to about 2 x 10^15 neq/cm2 of the order of current HV-CMOS maps radiation tolerance. assuming only a rleatively low 10 year operation time. On the other hand you mention higher e/g fluxes and I am wondering what it would mean in Total Ionizing Dose. Do you have an idea?
  These factors together with the high timing precision requirement could be a substantial difference with sensors for an e-e collider
- Could you also give some rough numbers in terms of n_eq fluence per year and total ionising dose per year? I realise this may be derivable from the figures you include but probably best to avoid misunderstandings if you could provide these. I know you say >HL-LHC and <FCC-hh but that does cover a very wide range in terms of expected annual dose and I expect the ratio of ionising dose to 1MeV neutron equivalent fluence will not be the same as at a hadron machine.

Nazar Bartosik - Paola Sala

Assuming:
muon bunch intensity 2E12 muon/bunch 1 bunch/charge and 100 kHz data taking rate
200 days/year running time   ==> 1.7E7 seconds
Approx total 1MeV-neutron equiv fluence, relevant for the Displacement Damage in Silicon
The first estimations are:
Total Ionizing Dose on the most critical first tracking layer from FLUKA BIB simulation
1.4 Gy/year
1 MeV n-eq fluence **< 1E15 cm^-2 / year**
(So the latter one is almost the same as the HL-LHC requirements.)
We are planning to prepare more detailed fluence and TID plots
for the most critical tracker region, assuming you will need them for your report.

Muon system @ Muon Collider

Chiara Aimè, Ilaria Vai, Cristina Riccardi

The muon system, based on CLIC, instruments the iron yoke plates with:

- 7 layers of detectors in the barrel
- 6 layers in the endcap

Glass Resistive Plate Chambers (RPC) cells of 30x30 mm^2 are the technology proposed for the detectors to cover an area of 1942 m^2 in the barrel and 1547 m^2 in the endcaps.

Simulation for the Muon Collider is based on CLIC's ILCSoft software. The muon reconstruction is performed within the PANDORA PFA framework that allows to investigate cluster topologies. A cluster is defined as a combination of hits (one hit per layer) inside a cone and on neighbouring layers.

For a sample of single muons generated with transverse momentum (pT) uniformly distributed between 0.1-180 GeV.

- The cluster reconstruction efficiency is:

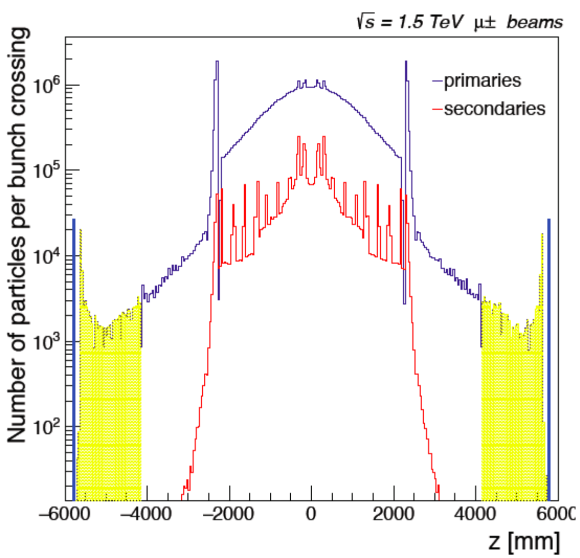
– higher than 99% for pT > 10 GeV

– higher than 98% for 8 < theta < 172.

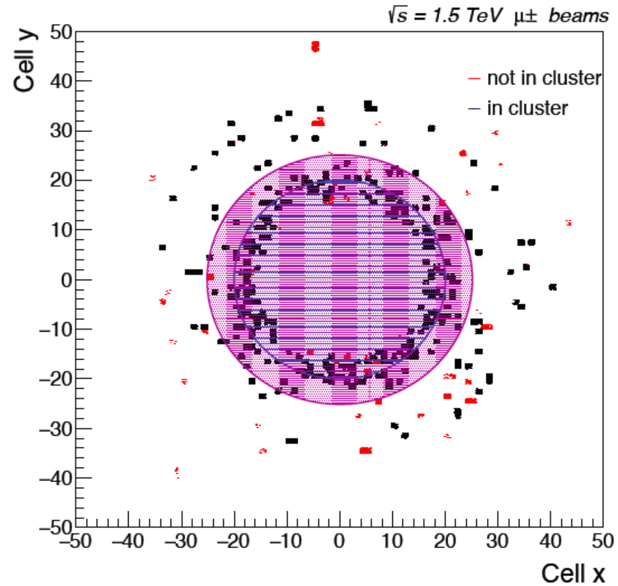
- The resolution is:

– less than 10^{-4} if pT > 30 GeV

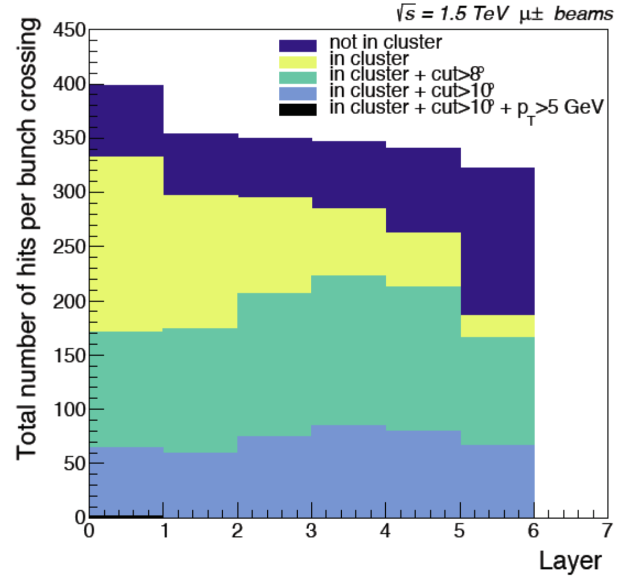
– better for the barrel region (45 < theta < 135) compared to the endcap.



Z coordinate final position for BIB particles. The first and the last bin in solid blue are the integral of all particles escaping the detector. In yellow the position of the muon system endcaps.



BIB muon hit spatial distribution in the first layer of the muon system endcap. In red the hits not associated to a cluster. The blue circle corresponds to region $\theta < 8°$, while the purple to $\theta < 10°$.



Number of hits per bunch crossing in each layer of the muon system. Different cuts are applied.

Beam Induced Background (BIB) due to the single bunch (2x$10^{12}\mu/bunch$) muon beams is dominating the particle rate at Muon Collider experiment
– affecting mostly the endcap region of the Muon detector -

Some thoughts on technologies

Glass RPC:

- $\boldsymbol{\sigma}_t$ < 100 ps
- Rate capability ~ 100-200 kHz/cm^2 , but up to now only in small prototypes
- ISSUE: gas mixture GWP

Alternatives:

HPL-RPC:

- $\boldsymbol{\sigma}_t$ < 100 ps
    - also 50 ps in MRPC configuration
- $\boldsymbol{\sigma}_x$ ~ 1 x 1 cm^2
- Rate capability ~ 1-2 kHz/cm^2
- Large size

MPGD-based:

- $\boldsymbol{\sigma}_t$ > 10 ns
- $\boldsymbol{\sigma}_x$ ~ 100 um
- Rate capability ~ 100 kHz/cm^2
- Large size

→ starting from MPDG technologies (ex. Triple-GEM) improve time resolution with alternative solution like PicoSec

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
LHCb MUON DETECTOR > 2010	Hadron Collider / B-physics (triggering)	3-GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	**Max.rate**:500 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ C/cm^2	Redundant triggering
ATLAS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	Resistive Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:15 kHz/cm^2 **Spatial res.:** <100μm **Time res.:** ~ 10 ns **Rad. Hard.:** ~ 0.5C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
CMS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~100μm **Time res.:** ~ 5-7 ns **Rad. Hard.:** ~ 0.5 C/cm^2	Redundant tracking and triggering
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300μm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
MUON COLLIDER MUON DETECTOR DESIGN	Muon Collider Physics	New generation MPGD	Total area: ~ 3500 m^2 Single unit detect: 0.3-0.4m^2	**Max.rate**: <100 kHz/cm^2 **Spatial res.:** ~100μm **Time res.:** <10 ns **Rad. Hard.:** < C/cm^2	Redundant tracking and triggering

Comments and proposal

- 1 MeV n_{eq} fluences and Total Ionizing Dose FLUKA simulation with present tracker design to be completed asap
- Tracker/vertex – Calorimeters – Muon detectors design couldd be improved but may profit by future R&Ds ➔ also on-detector electronics and reconstruction tools
- ECFA Detector R&D Roadmap will complete Symposia May 7 and will prepare drafting the report
- As an example see what we came up with a short muon detectors brainstorming to answer requests by TF1 (see Apr 29 symposium)
- Finalize inputs to the Roadmap report by mid-May also preparation to the discussion at the June workshop

extras

Other in the roadmap

Broad Topic Areas

Grouped targeted facilities/areas emerging from the EPPSU

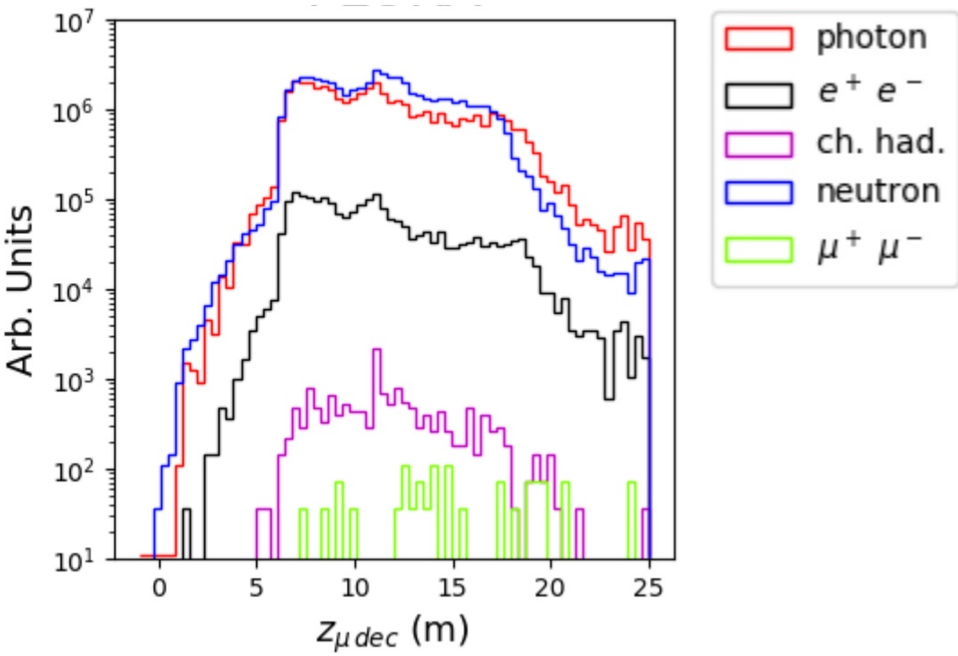
6. **Detector developments for accelerator-based studies of rare processes, DM candidates and high precision measurements (including strong interaction physics) at both storage rings and fixed target facilities, interfacing also with atomic and nuclear physics.**
7. **R&D for optimal exploitation of dedicated collider experiments studying the partonic structure of the proton and nuclei as well as interface areas with nuclear physics.**
8. **The very broad detector R&D areas for non-accelerator-based experiments, including dark matter searches (including axion searches), reactor neutrino experiments, rare decay processes, neutrino observatories and other interface areas with astro-particle physics.**

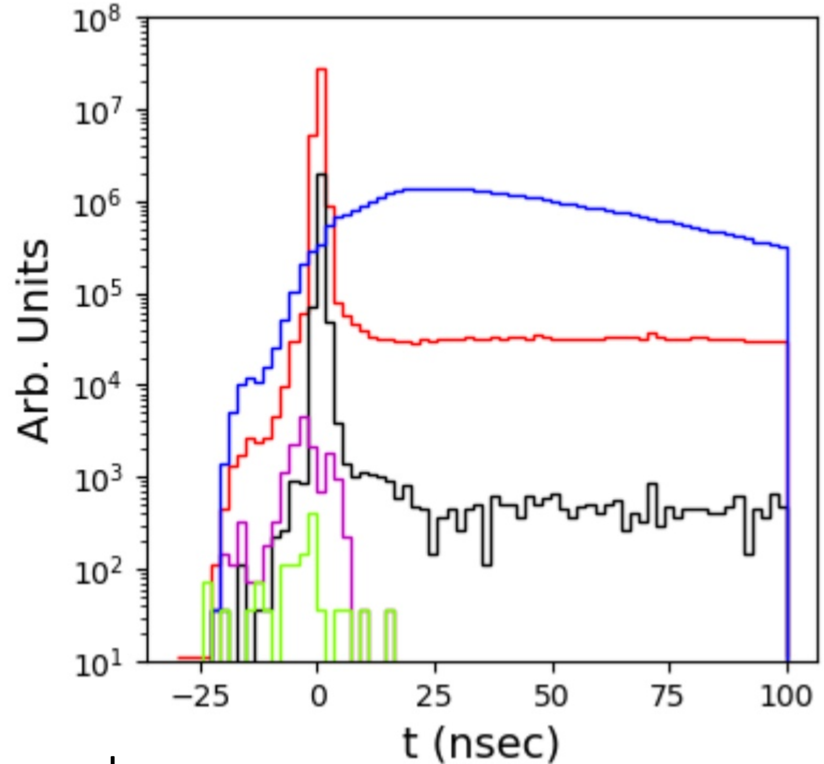
9. **Facilities needed for detector evaluation, including test-beams and different types of irradiation sources, along with the advanced instrumentation required for these.**
10. **Infrastructures facilitating detector developments, including technological workshops and laboratories, as well as tools for the development of software and electronics.**
11. **Networking structures in order to ensure collaborative environments, to help in the education and training, for cross-fertilization between different technological communities, and in view of relations with industry.**

12. **Overlaps with neighbouring fields and key specifications required for exploitation in other application areas**
13. **Opportunities for industrial partnership and technical developments needed for potential commercialisation**

Beam Induced background @ 1.5 TeV

Donatella Lucchesi et al.





Particle (E_{th}, MeV)	MARS15	FLUKA
Photon (0.2)	8.3 10^7	4.29 10^7
Neutron (0.1)	2.44 10^7	5.37 10^7
Electron/positron (0.2)	7.23 10^5	2.2 10^6
Ch. Hadron (1)	3.07 10^4	1.52 10^4
Muon (1)	1.47 10^3	1.22 10^3

muon beams
@ **0.75 TeV** with **2×10^{12}muons/bunch** ➔
4×10^5 muon decays/m single bx

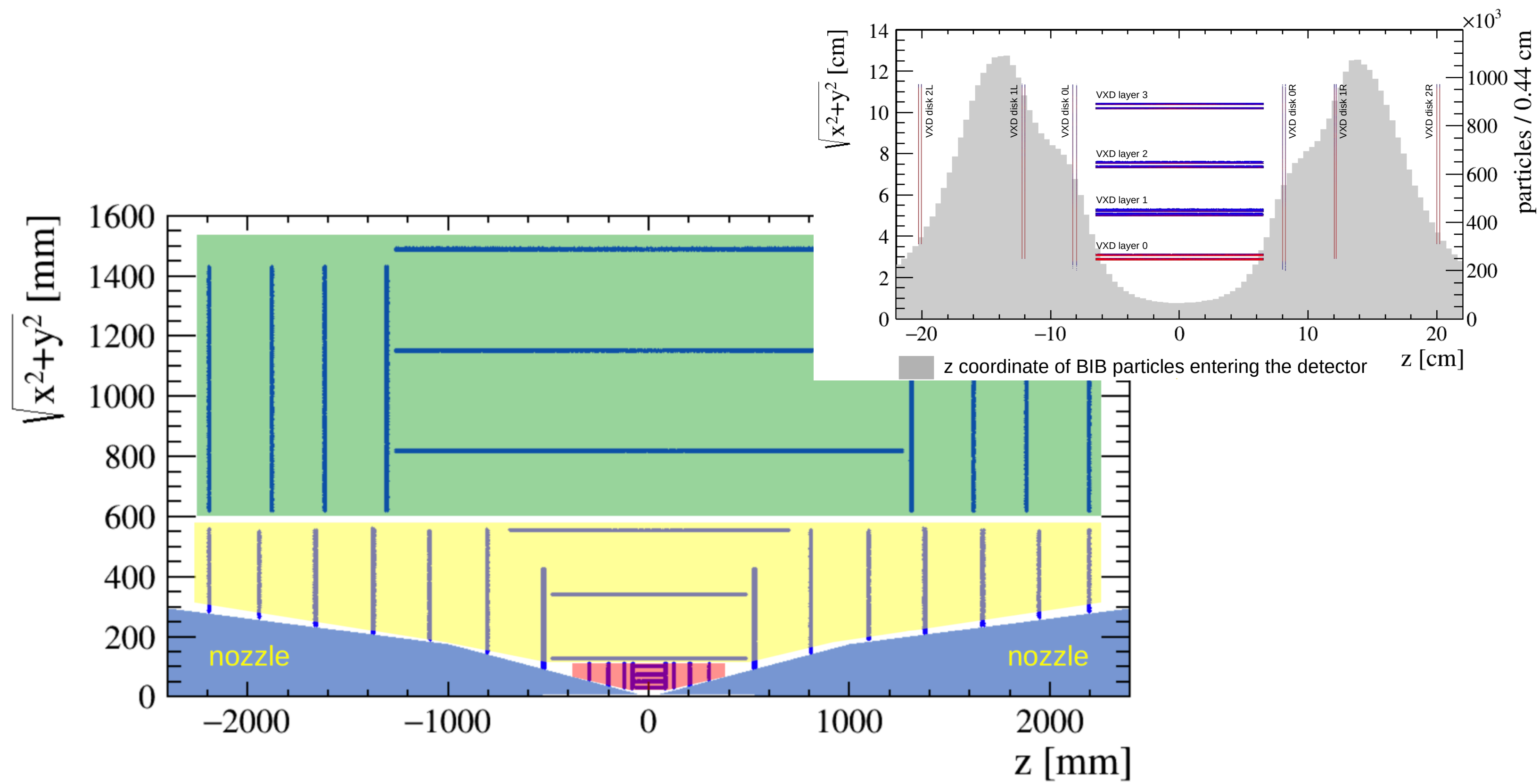
JINST 13 (2018), P09004
***JINST* 15 (2020) 05, P05001**

BIB @ 10 TeV only general consideration

- Not expected to dramatically change compared to lower energies
- BIB timing distributions to be verified

Present Tracker design

Massimo Casarsa et al.



Vertex detector (VXD)

- barrel: 4 cylindrical layers
  endcaps: 4 + 4 disks
- double-layer Si sensors:
  25x25 μm² pixels
  50 μm thick
  σ_T = 30 ps

Inner Tracker (IT)

- barrel: 3 cylindrical layers
  endcaps: 7 + 7 disks
- Si sensors:
  50 μm x 1 mm macro-pixels
  100 μm thick
  σ_T = 60 ps

Outer Tracker (OT)

- barrel: 3 cylindrical layers
  endcaps: 4 + 4 disks
- Si sensors:
  50 μm x 10 mm micro-strips
  100 μm thick
  σ_T = 60 ps

BIB properties: single beam crossing

BIB has several characteristic features → crucial for its effective suppression

1. Predominantly very soft particles (p << 250 MeV) except for neutrons

fairly uniform distribution in the detector → no isolated signal-like deposits
↳ conceptually different from pile-up contributions at the LHC

2. Significant spread in time (few ns + long tails up to a few μs)

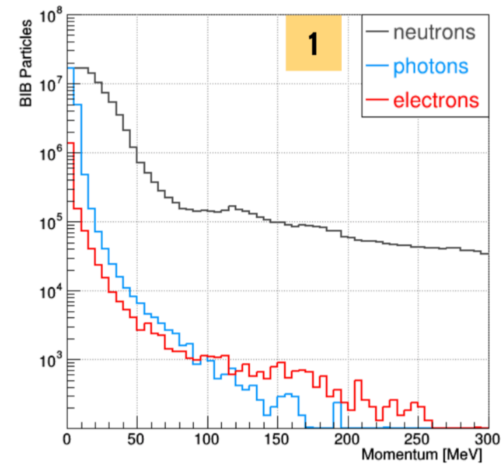
$\mu^+\mu^-$ collision time spread: ~30ps (defined by the muon-beam properties)
↳ strong handle on the BIB → requires state-of-the-art timing capabilities

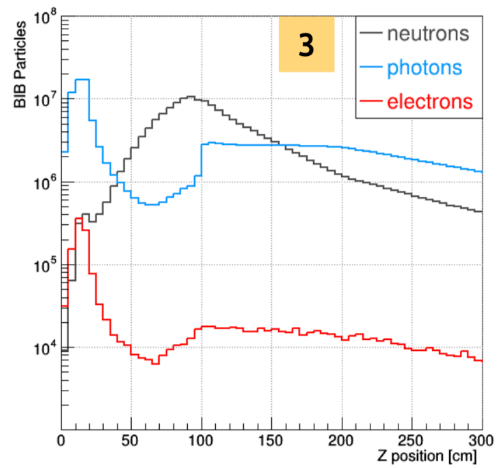
3. Large spread of the origin along the beam

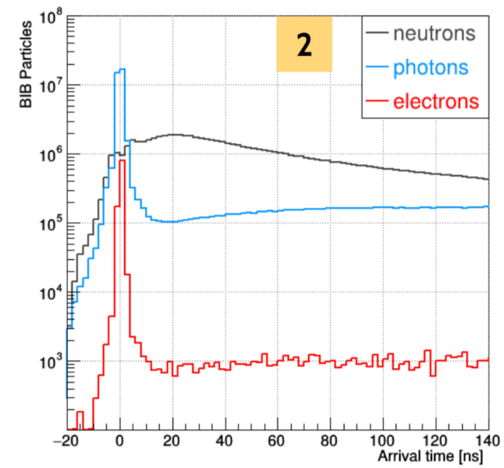
different azimuthal angle wrt the detector surface
+ affecting the time of flight to the detector

Sophisticated detector technologies and event-reconstruction strategies required to exploit these features

4D coordinates of the Interaction Point (IP) define the reference to 2 and 3

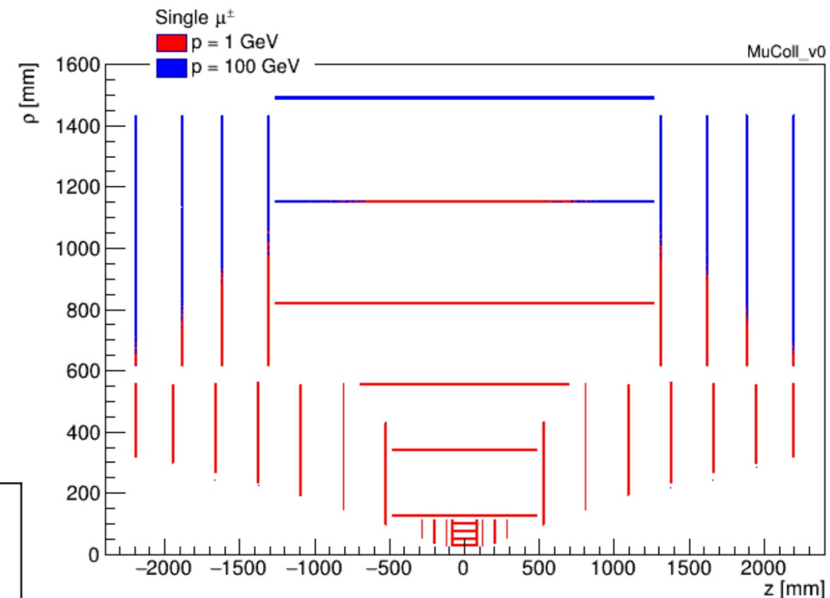




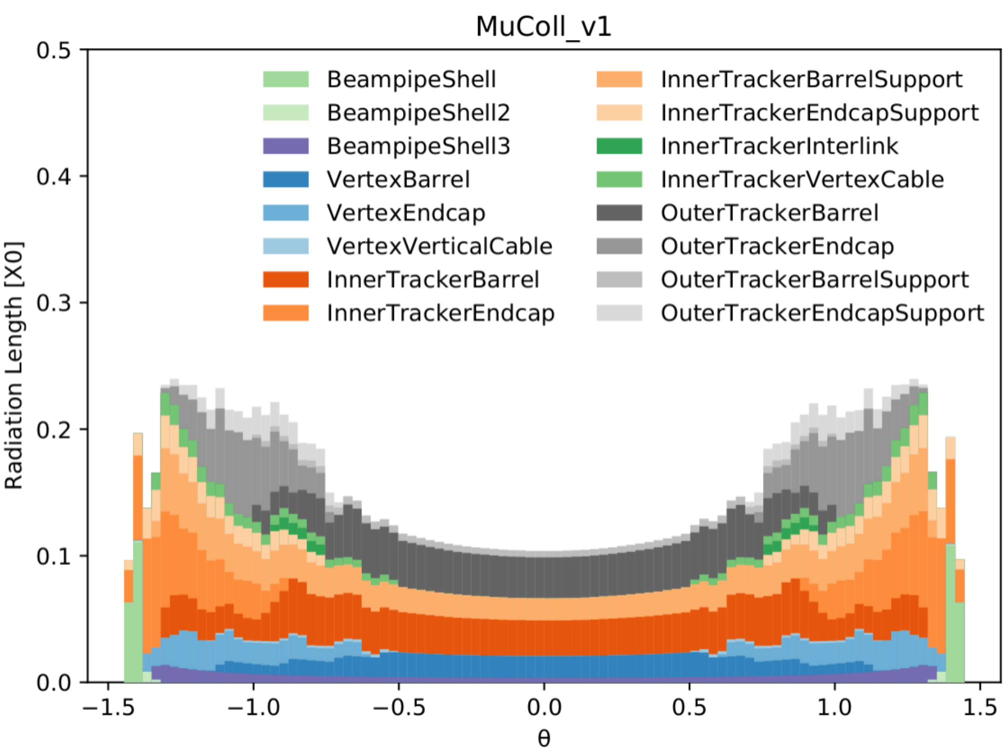


Tracker simulation

entirely silicon-based detector:
Vertex detector: 4 barrels + 4 endcaps / side
Inner Tracker: 3 barrels + 7 endcaps / side
Outer Tracker: 3 barrels + 4 endcaps / side



Material budget



Simulation including estimate of support structures and services

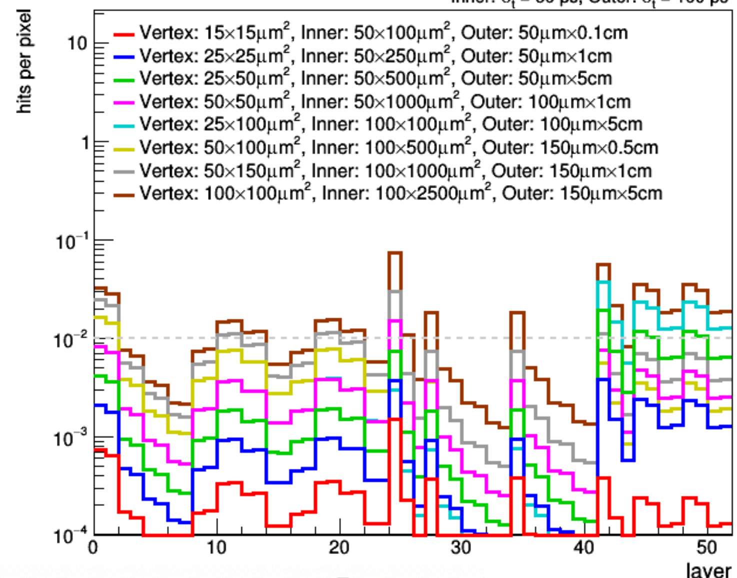
Tracker with timing considerations

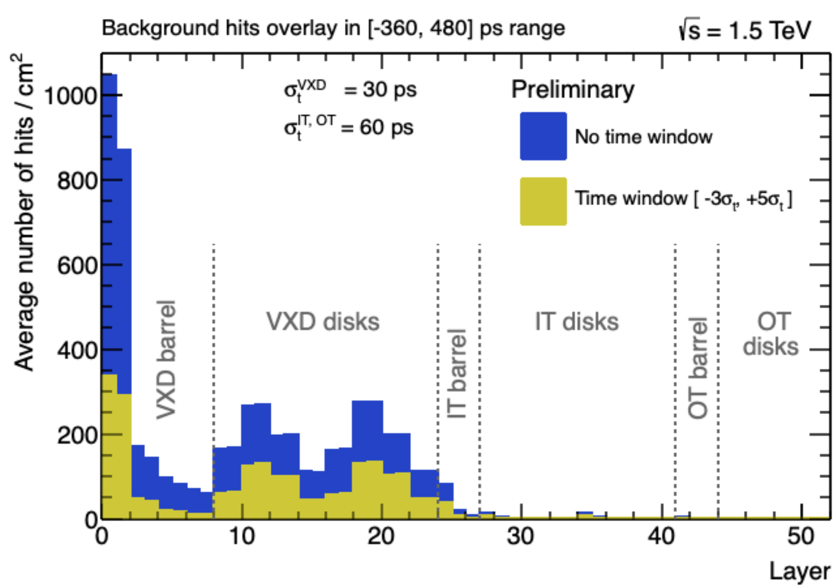
		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	729M
	E	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	462M
IT	B	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	164M
	E	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	127M
OT	B	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	117M
	E	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	56M

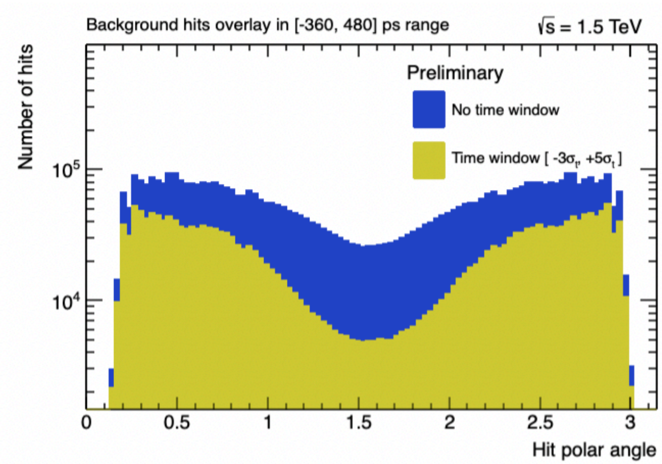
Parametric digitization, realistic digitization developed for the critical innermost layers

Timing window to reduce hits from out-of-time BIB

Granularity optimized to ensure <= 1% occupancy in each layer



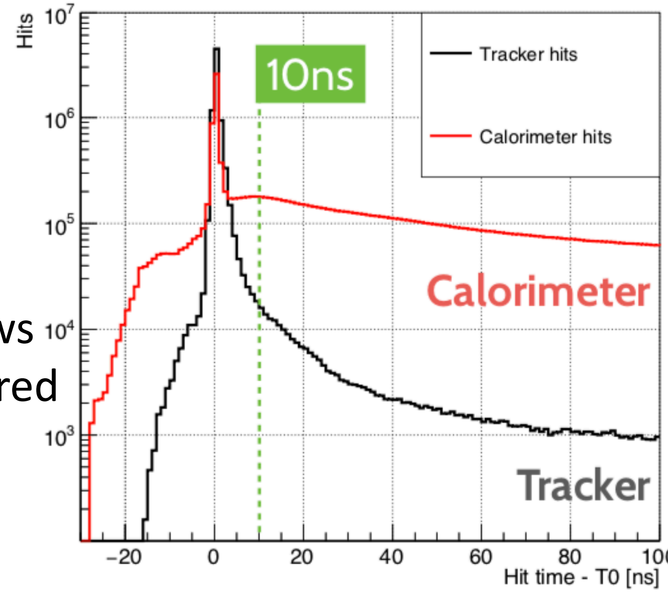




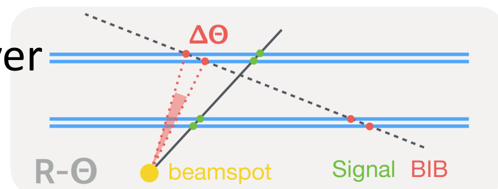
Detector simulation

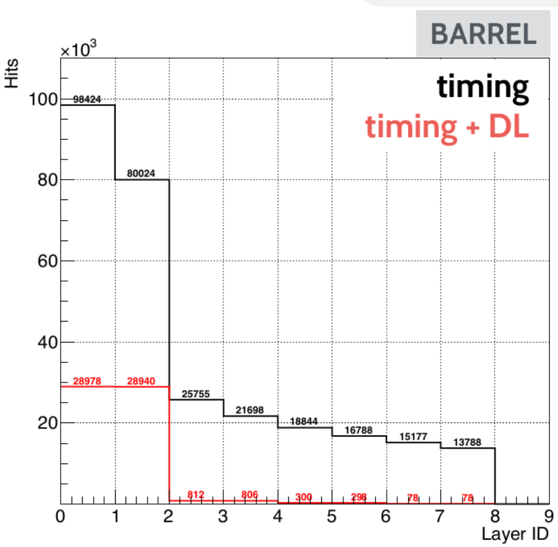
BIB introduces ~10^8 particles in a single event
→ a tremendous computation load

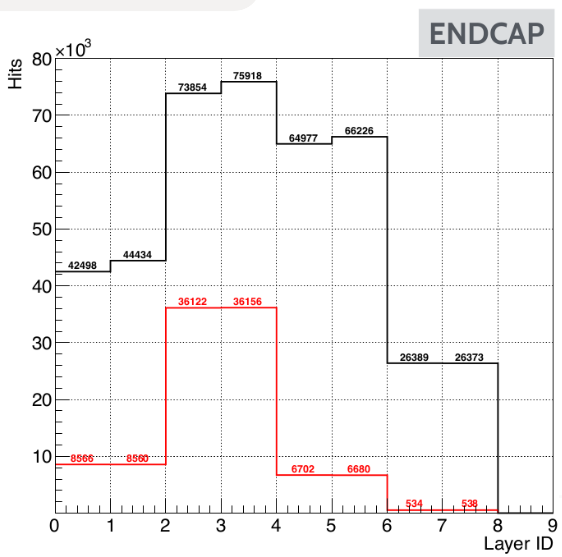
- hits at t > 10ns are outside realistic readout time windows
  ↳ accounting for TOF: particles with t > 25ns at MDI ignored
- low-energy neutrons reach the calorimeter too late
  ↳ neutrons with E*kin* < 150 MeV can be safely excluded

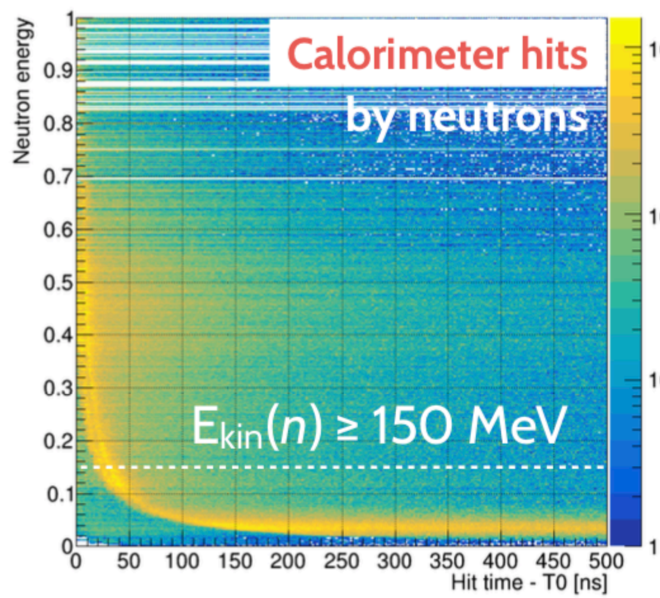


DL: double layer



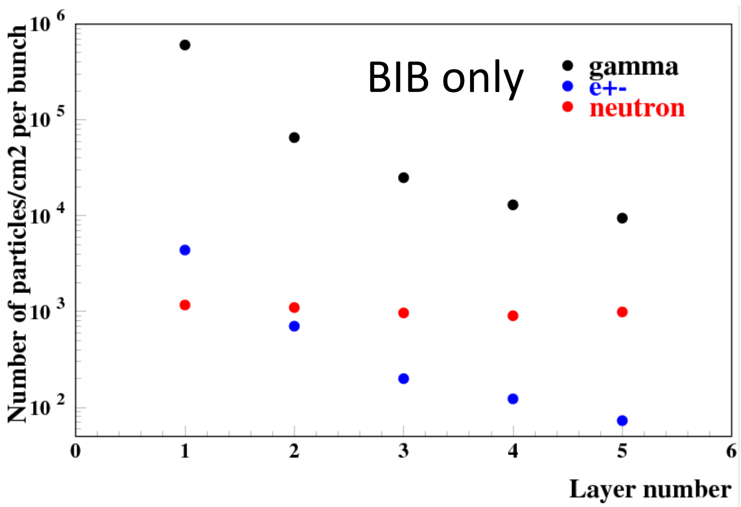




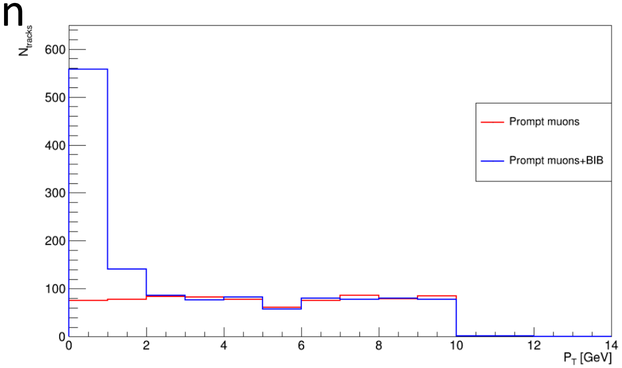


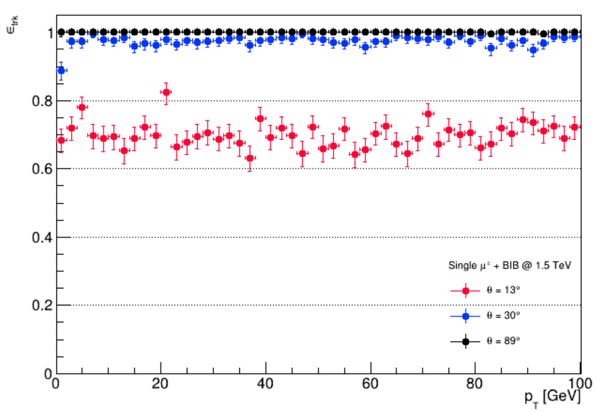
Tracking performances

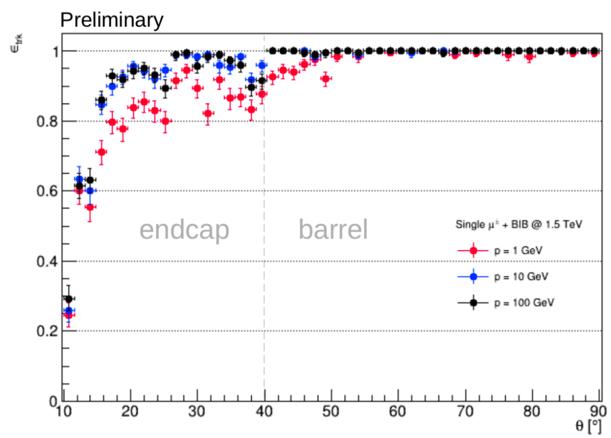
arXiv:1808.02154
10.18429/JACoW-IPAC2014-TUPRO029

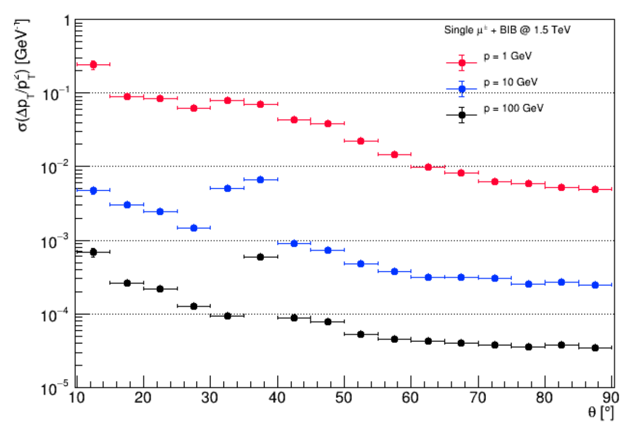


- Can successfully reconstruct muons with high purity of measurements associated to the track
- Further algorithm and geometry tuning needed to ensure high efficiency at all θ and smooth detector resolution





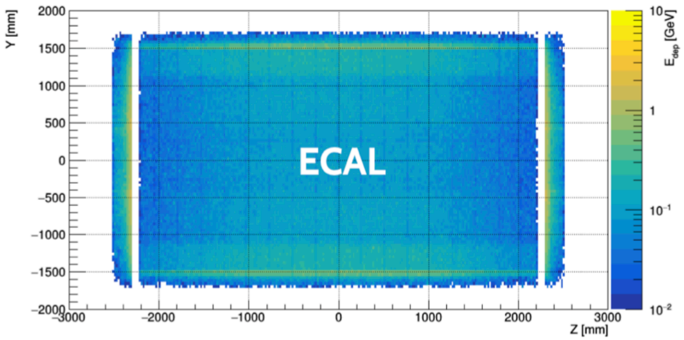


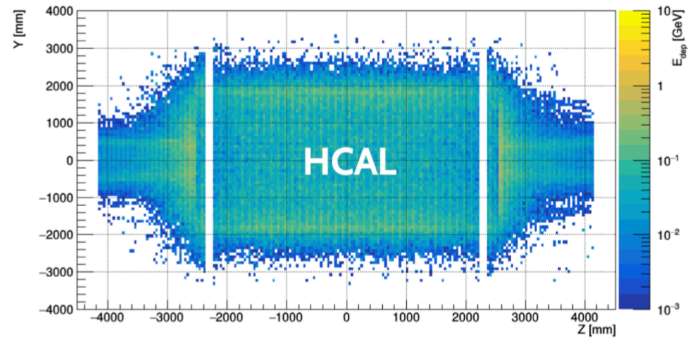


Calorimeters

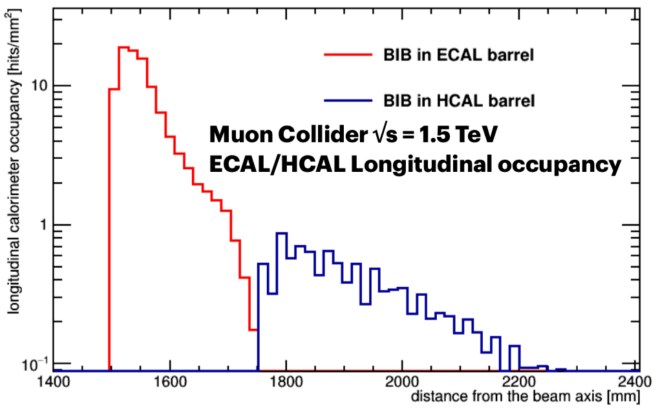
Lorenzo Sestini et al.

About 6 TeV (2.5 TeV) of energy deposited in ECAL (HCAL) by BIB



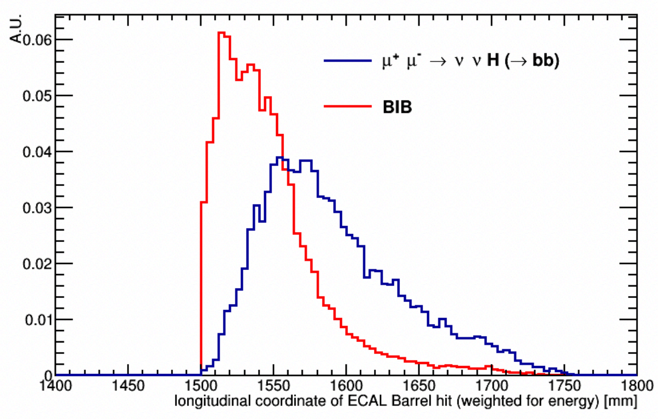


Energy deposition in calorimeters per bunch crossing

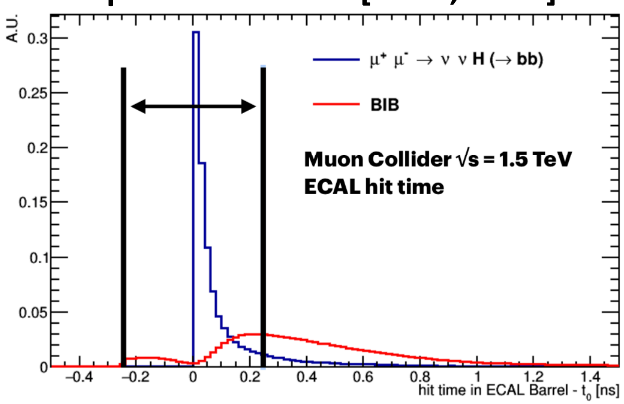


- **BIB is diffused in the calorimeters**: at the ECAL barrel surface the flux is 300 particles/cm², most of them are photons with <E>=1.7 MeV.
- BIB occupancy is lower in HCAL with respect to ECAL.

timing and longitudinal measurements play a key role in the BIB suppression



acquisition time of [-0.25,+0.25]

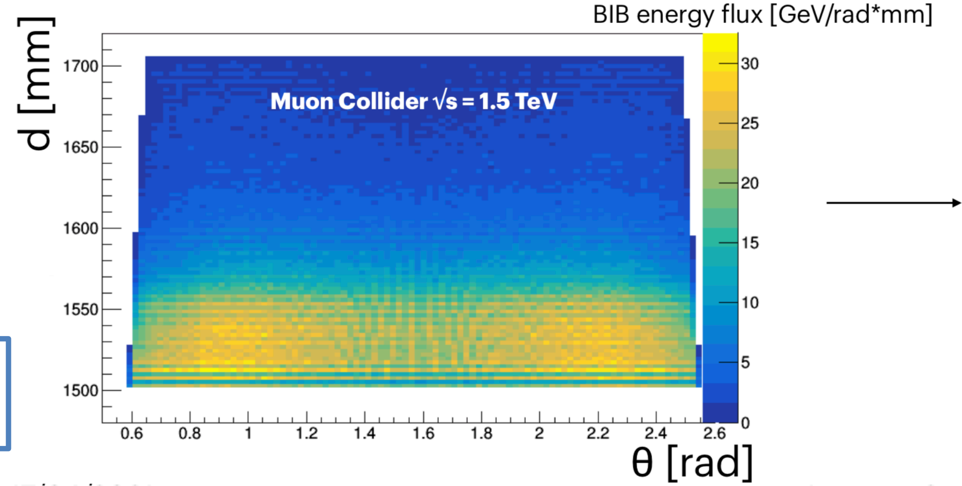


Jet reconstruction

effective BIB subtraction necessary for jet reconstruction

In each region the average BIB hit energy E_{BIB} and standard deviation σ_{BIB} is determined

➔ the energy of the accepted hit ($E_{HIT} > E_{BIB} + 2\sigma_{BIB}$) is corrected: $E_{HIT} \rightarrow E_{HIT} - E_{BIB}$



ECAL and HCAL clusters
are reconstructed with **PandoraPFA**
Calorimeters jets are clustered
with the kt algorithm, radius R=0.5

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Nucl.Instrum.Meth.A611:25-40,2009

- **To recover the jet energy ➔ full reconstruction with tracking+calorimeters**
- To reduce the tracking combinatorial problem ➔ **regional tracking strategy**