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: $\mathcal{L} = 2\times10^{35} cm^{-2} s^{-1}$ *@ 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

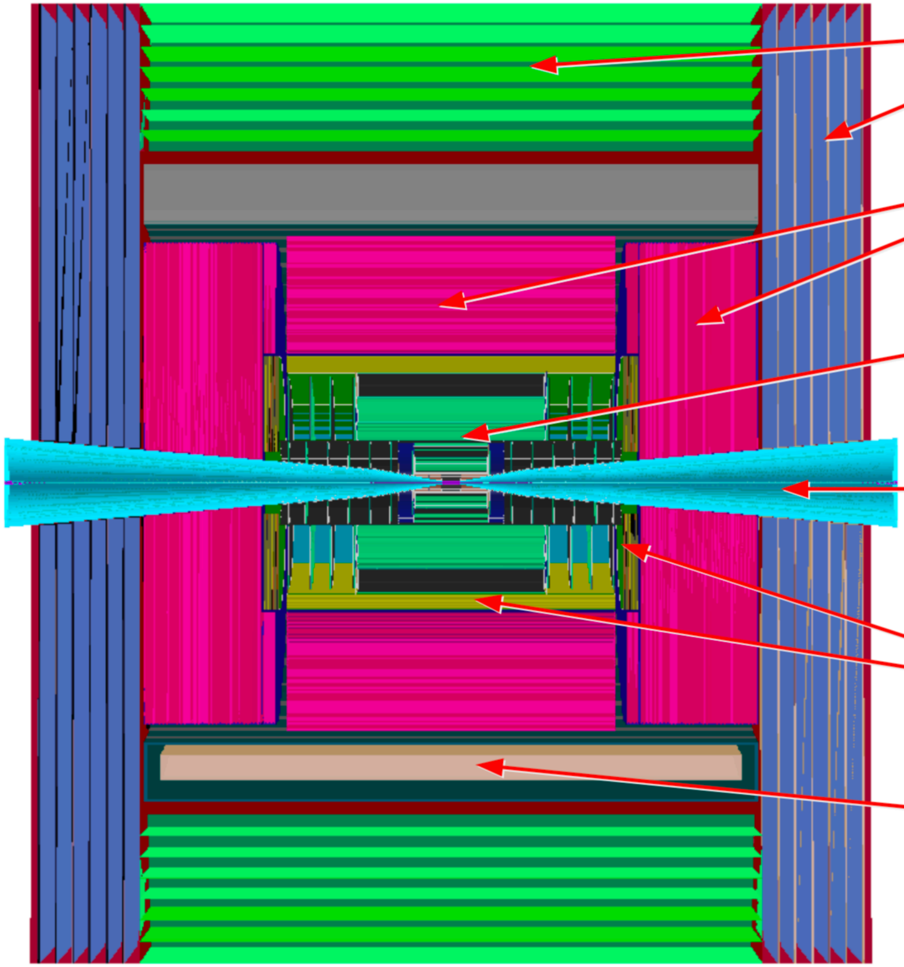
@ 14 TeV ~ 20 ab^{-1} 5 years

~ $2\times10^{12} \mu/bunch$
1 bunch/beam colliding each 20-30 μs
➔ max 2 Interaction Points - IP
ONLY 1 EXPERIMENT CONSIDERED at present

MATERIAL PRESENTED at the on-going APS-APR21 Muon Collider Symposium

Detector

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



muon detectors

hadronic calorimeters

tracking system

shielding nozzles

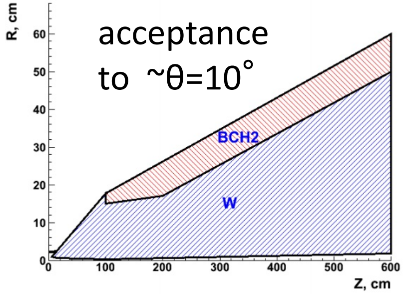
(tungsten cones + BCH_2 cladding)

reduce the BIB rate by a factor ~500

electromagnetic calorimeters

superconducting solenoid (3.57T)

nozzles limits acceptance to ~θ=10°

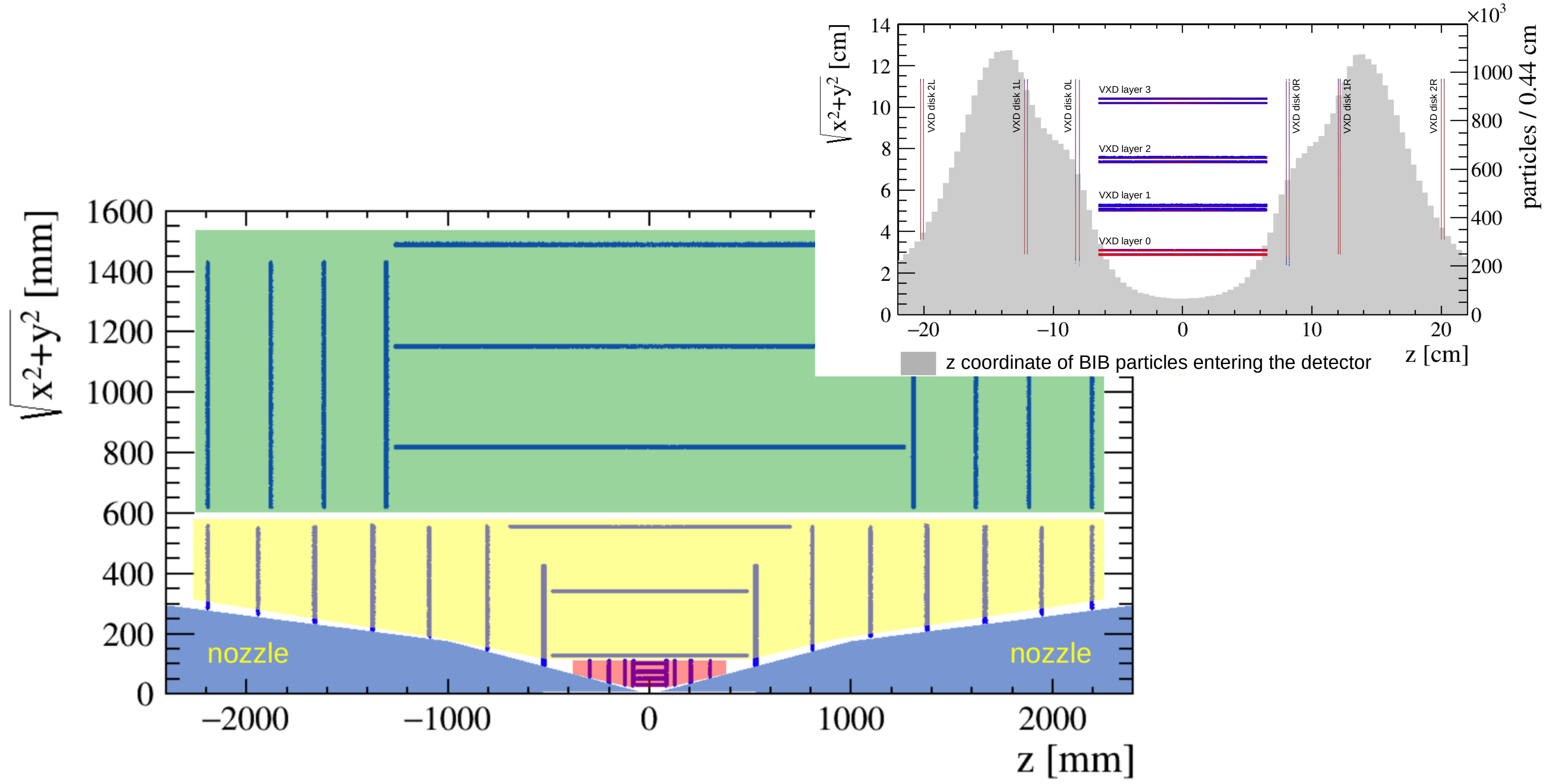


Full simulation available on github

B = 3.57 T to be studied and tuned

Present Tracker design

Massimo Casarsa et al.



Vertex detector (VXD)

- barrel: 4 cylindrical layers
  endcaps: 4 + 4 disks
- double-layer Si sensors:
  25x25 μm^2 pixels
  50 μm thick
  σ_T = 30 ps

Inner Tracker (IT)

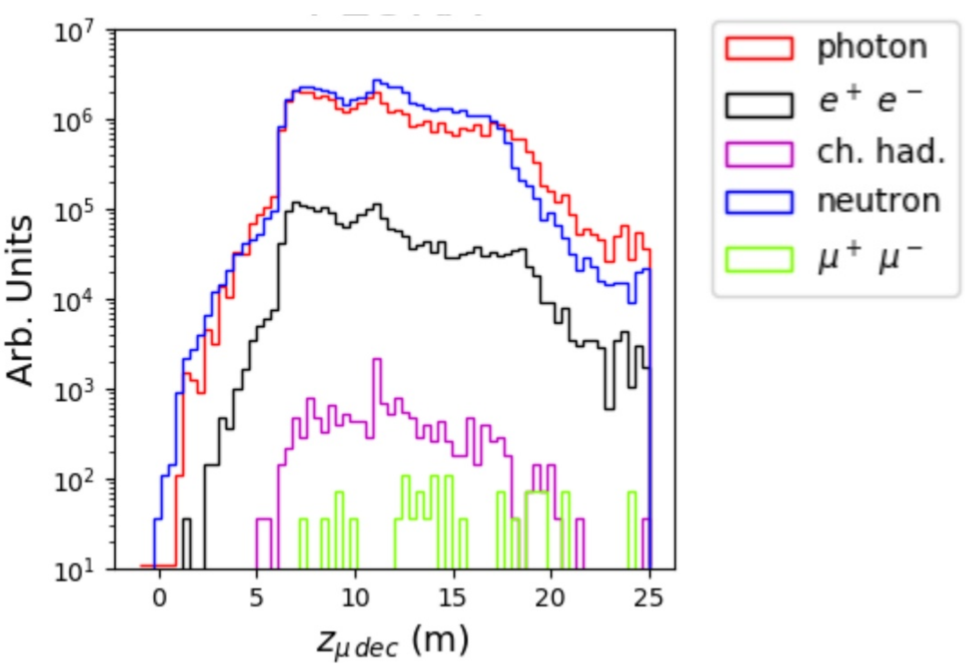
- barrel: 3 cylindrical layers
  endcaps: 7 + 7 disks
- Si sensors:
  50 μm x 1 mm macro-pixels
  100 μm thick
  σ_T = 60 ps

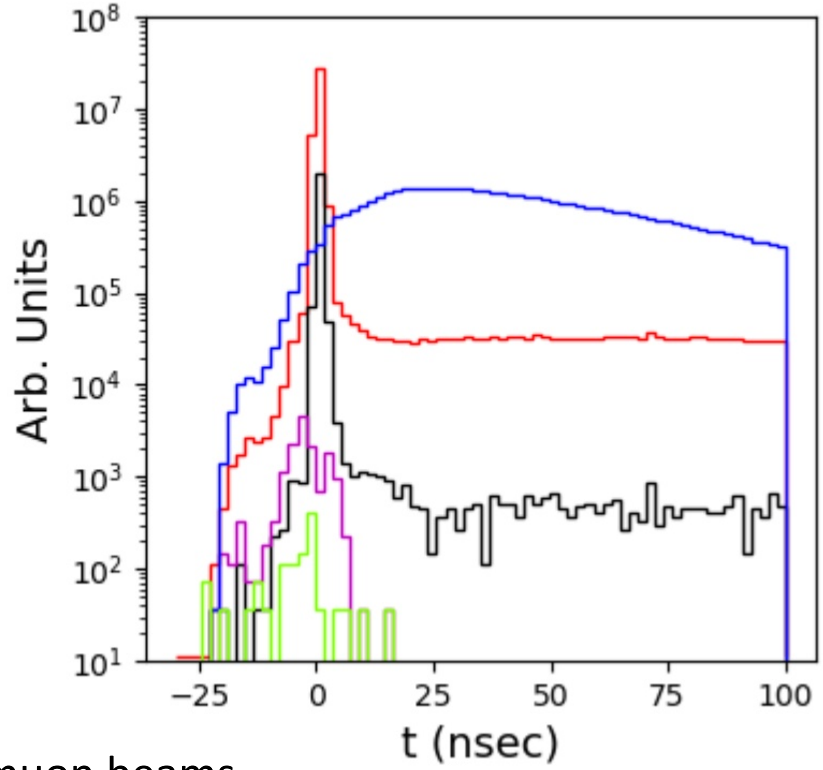
Outer Tracker (OT)

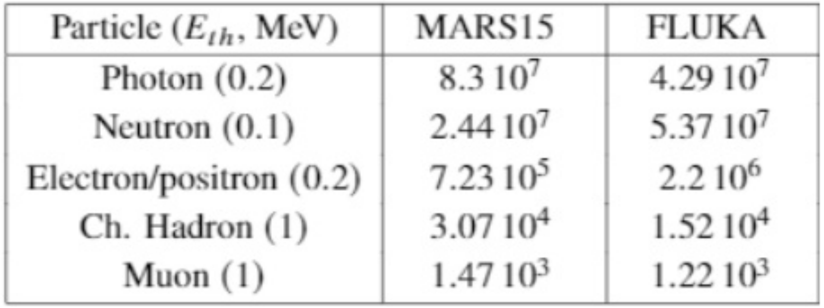
- barrel: 3 cylindrical layers
  endcaps: 4 + 4 disks
- Si sensors:
  50 μm x 10 mm micro-strips
  100 μm thick
  σ_T = 60 ps

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

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)

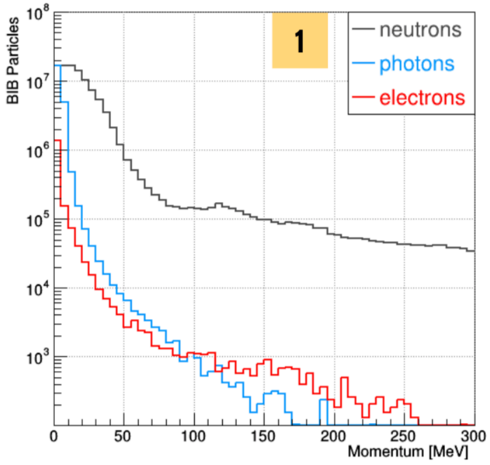
$\mu^+\mu^-$ collision time spread: ~30ps (defined by the muon-beam properties)
↳ strong handle on the BIB → requires state-of-the-art timing capabilities

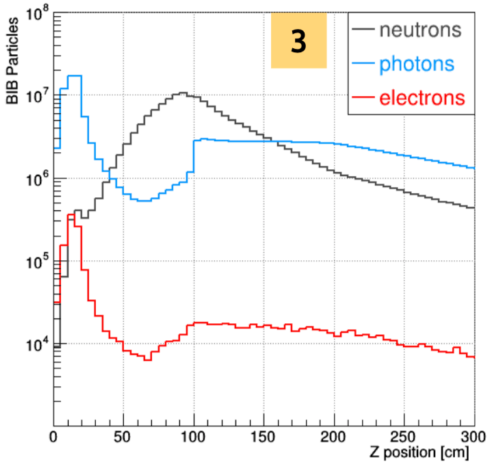
3. Large spread of the origin along the beam

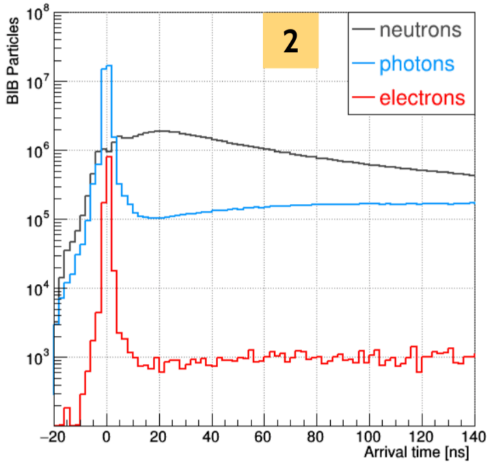
different azimuthal angle wrt the detector surface
+ affecting the time of flight to the detector

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

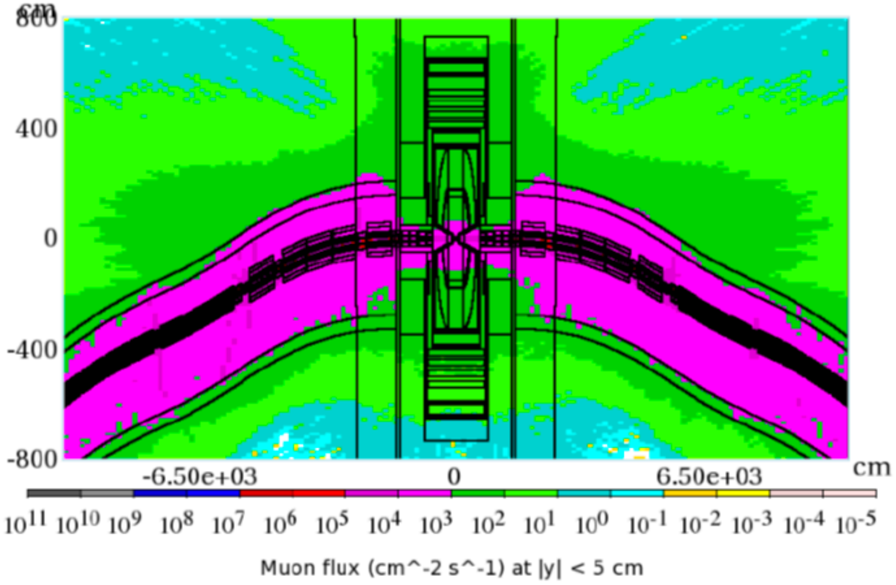
4D coordinates of the Interaction Point (IP) define the reference to 2 and 3

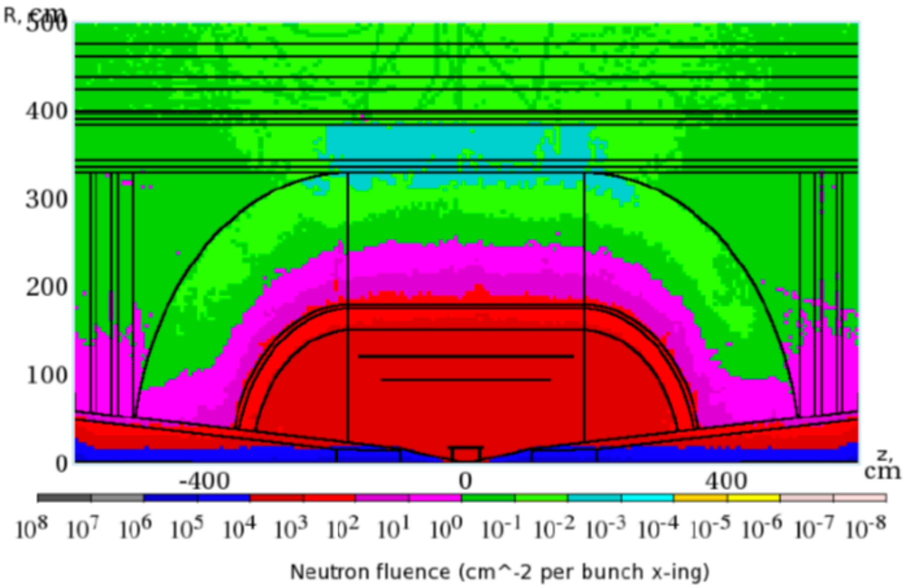






Muon and neutron fluences @ 1.5 TeV





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

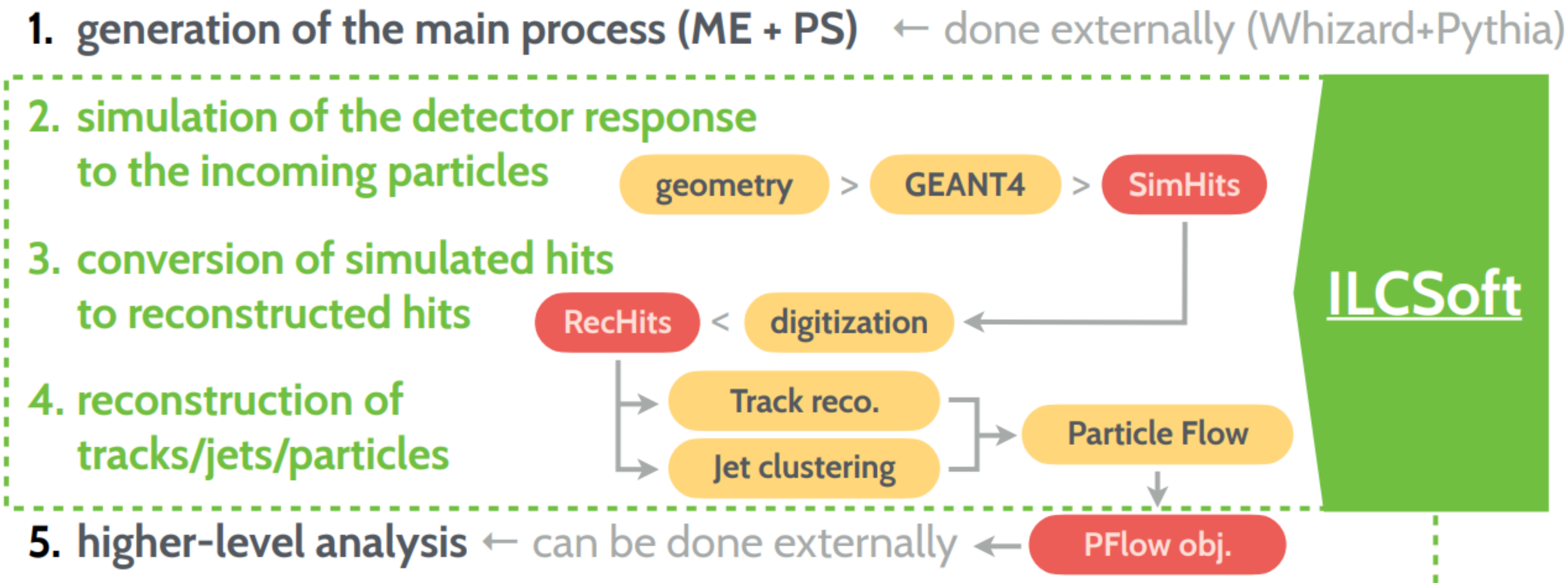
Full simulation + BIB

Nazar Bartosik et al.

Result of a simulation → list of stable particles reaching the detector region in a single bunch crossing (BX) *(mostly soft photons, neutrons, electrons)*

- collected at the outer surface of the detector and the MDI
- **2 × 180M particles** → full simulation needed for a realistic detector-performance estimation

All results shown use full simulation with BIB



1. **generation of the main process (ME + PS)** ← done externally (Whizard+Pythia)
2. **simulation of the detector response to the incoming particles**
3. **conversion of simulated hits to reconstructed hits**
4. **reconstruction of tracks/jets/particles**
5. **higher-level analysis** ← can be done externally

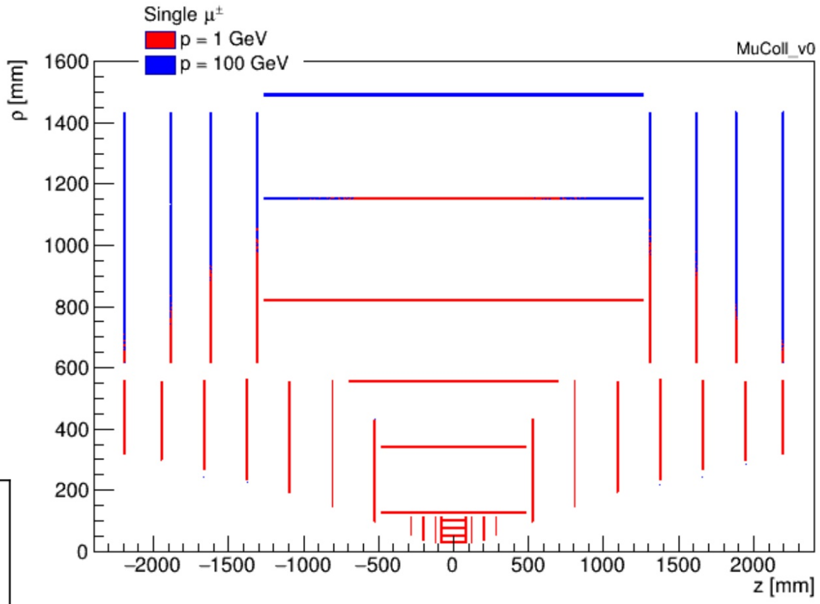
Tracker simulation

entirely silicon-based detector:

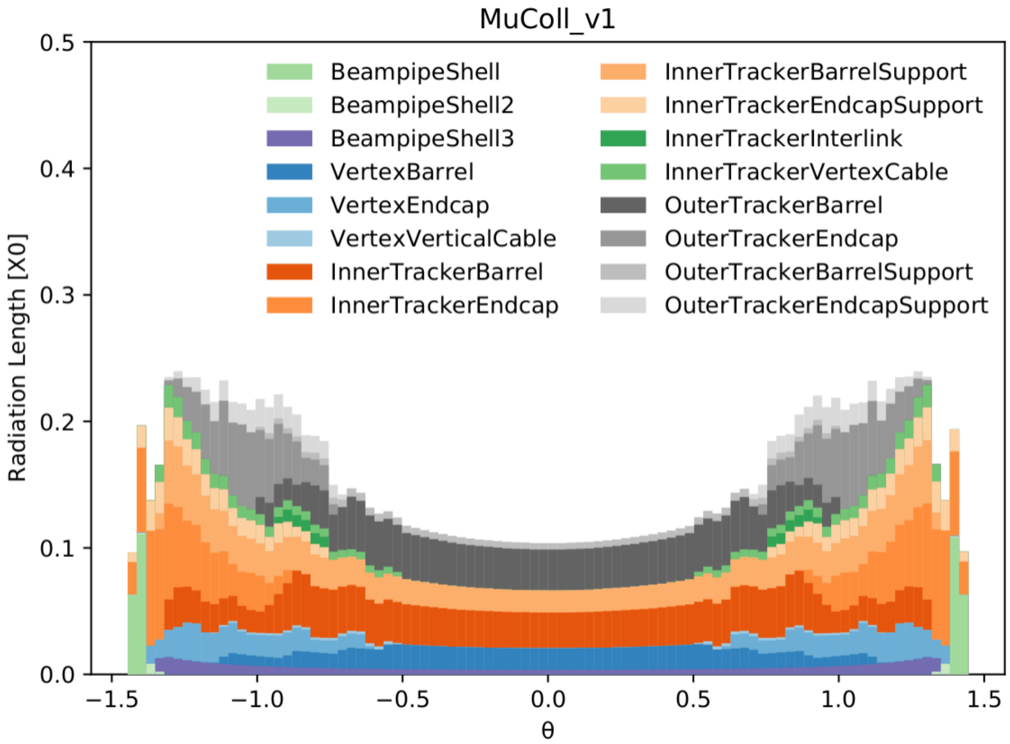
Vertex detector: 4 barrels + 4 endcaps / side

Inner Tracker: 3 barrels + 7 endcaps / side

Outer Tracker: 3 barrels + 4 endcaps / side



Material budget



Simulation including estimate of support structures and services

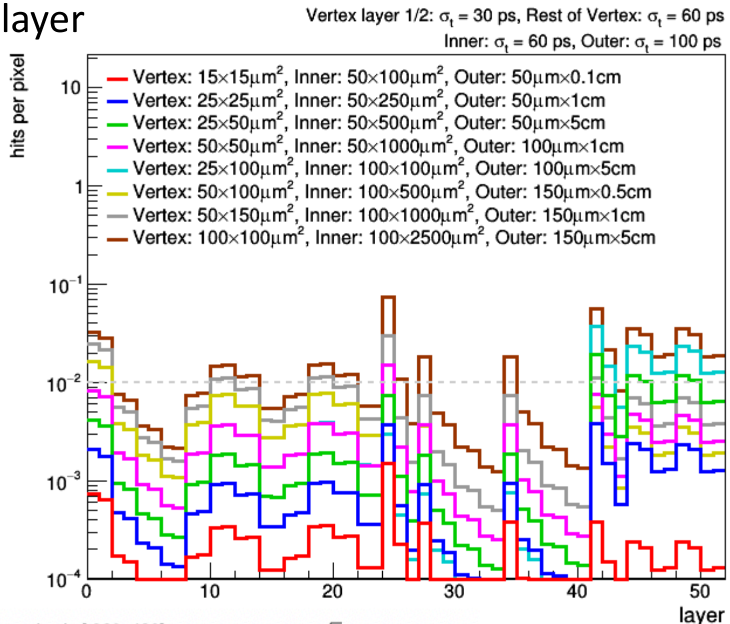
Tracker with timing considerations

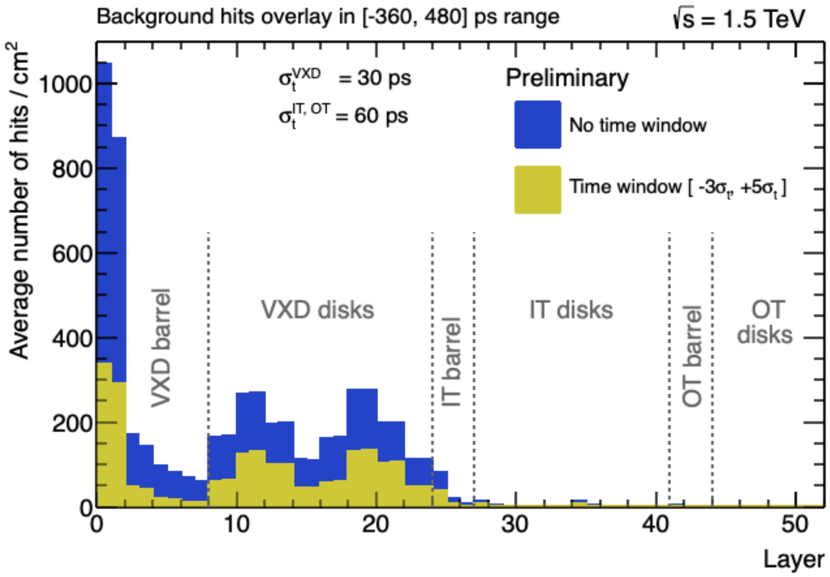
		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	729M
	E	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	462M
IT	B	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	164M
	E	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm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

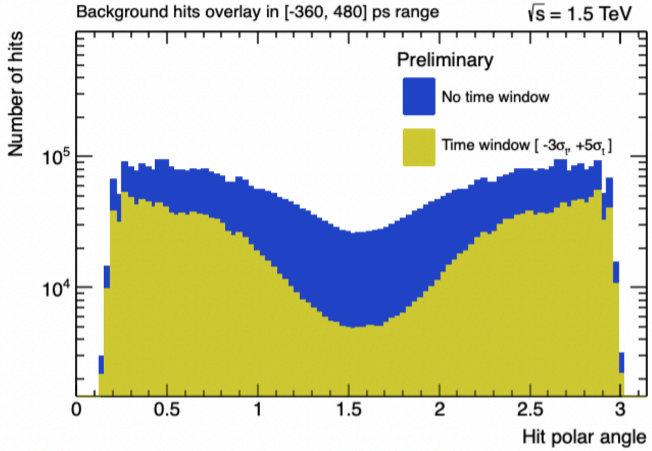
Parametric digitization, realistic digitization developed for the critical innermost layers

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

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



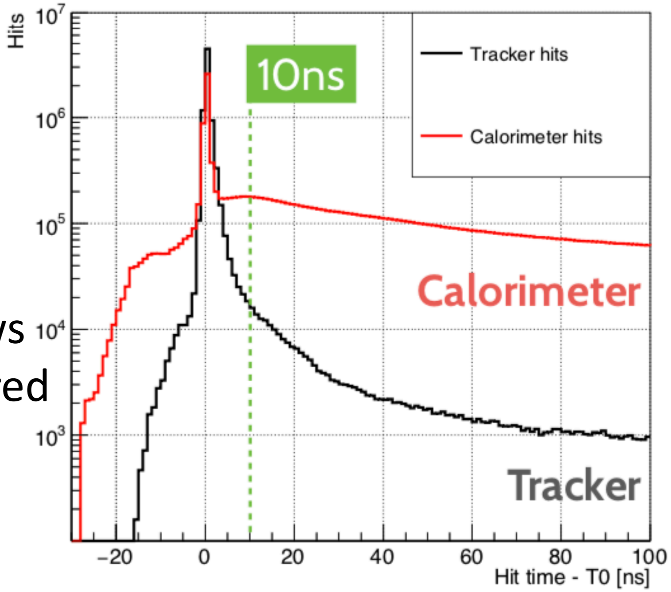




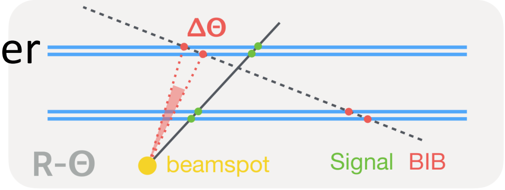
Detector simulation

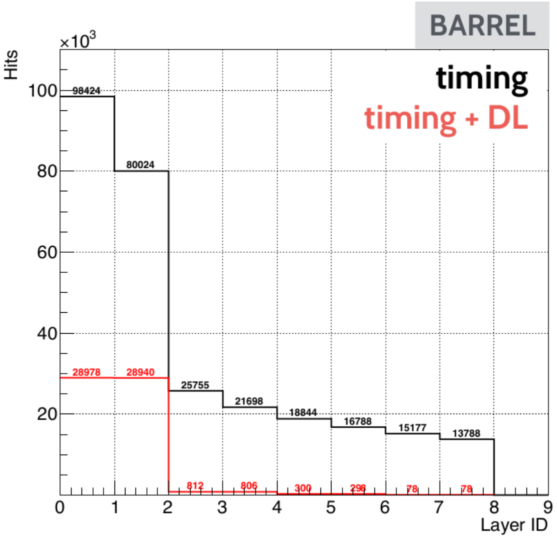
BIB introduces ~10^8 particles in a single event
→ a tremendous computation load

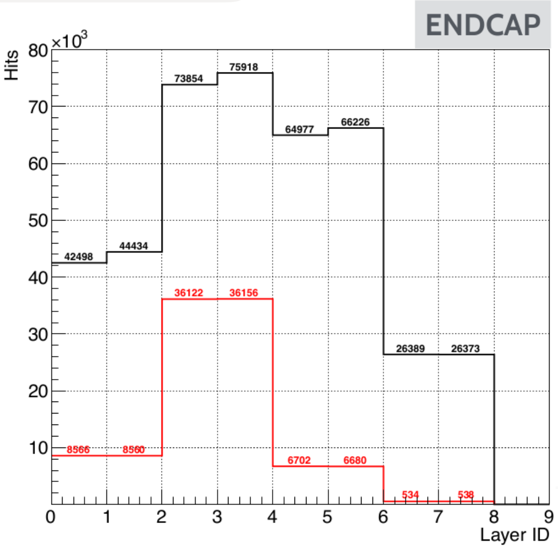
- hits at t > 10ns are outside realistic readout time windows
  ↳ accounting for TOF: particles with t > 25ns at MDI ignored
- low-energy neutrons reach the calorimeter too late
  ↳ neutrons with E*kin* < 150 MeV can be safely excluded

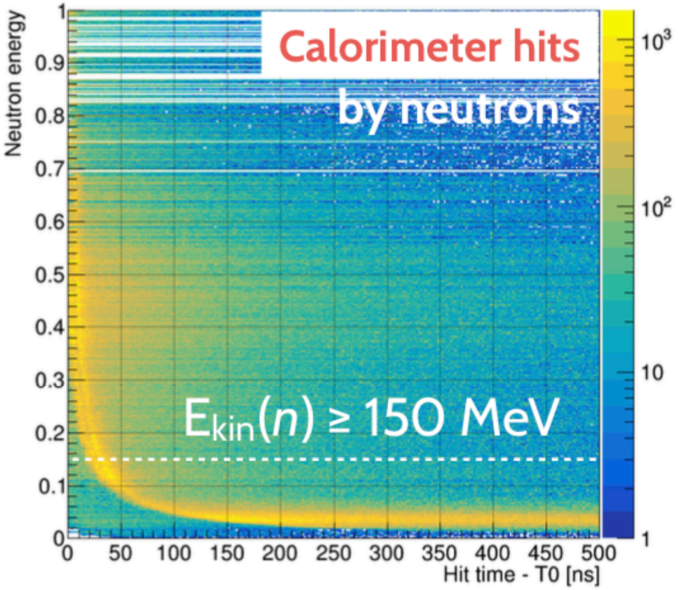


DL: double layer









Track reconstruction strategy

N.Bartosik, M. Casarsa

Reconstruction of tracks suffers from large combinatorial background

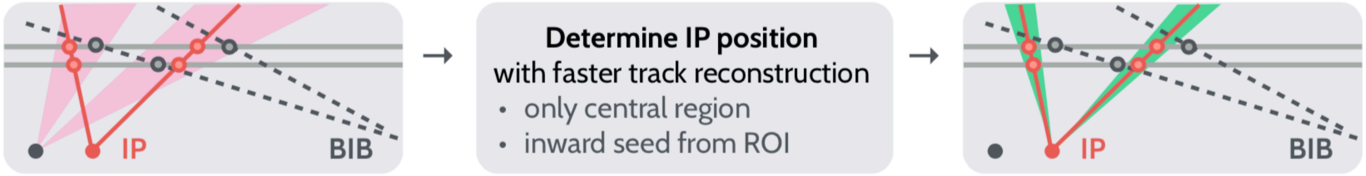
↳ *suppression of BIB hits is crucial to reconstruct events in reasonable time*

- **Selection of hits in the narrow time window tailored to the sensor position**

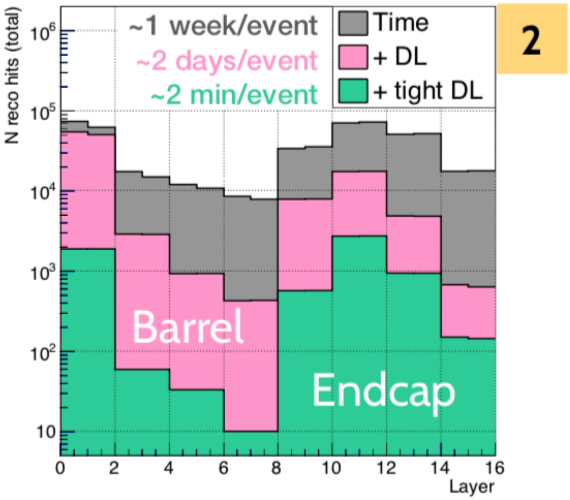
  ↳ *limited by the tracker time resolution + acceptance for slow particles*
- **Selection of hit doublets aligned with the IP (double layers in the Vertex Detector)**

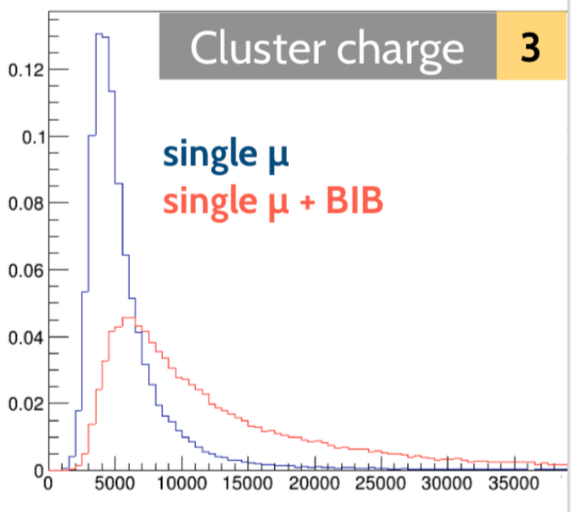
  ↳ *limited by the IP position resolution → requires multi-stage tracking strategy*
- **Cluster-based BIB suppression** (shape and charge of hit clusters)

  ↳ *sensitivity to the particle direction in a single layer → requires realistic Tracker digitisation*



Determine IP position
with faster track reconstruction
- only central region
- inward seed from ROI



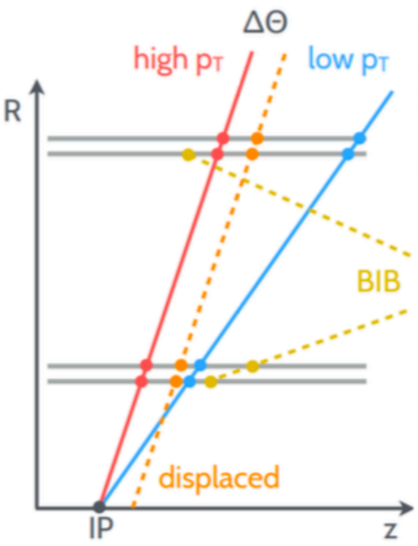


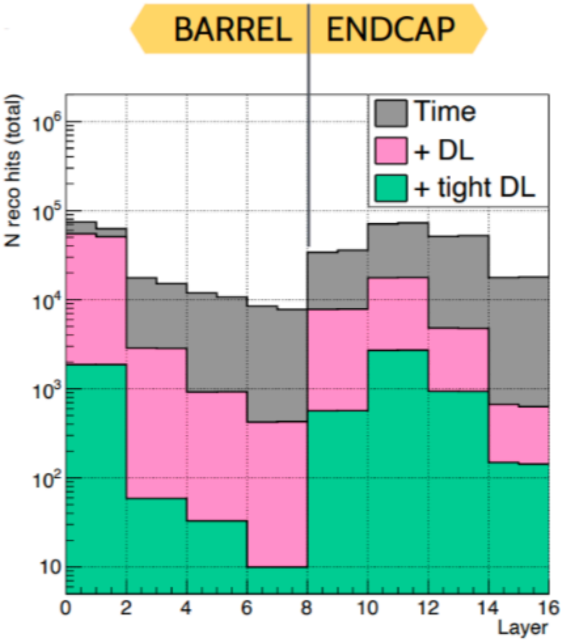
- **All these strategies require a challenging detector design**

  ↳ *high spatial and time resolution + low occupancy*
- **Currently using Conformal Tracking with state-of-the-art timing detectors**
- **Potential performance boost with ACTS tracking software**

Realistic digitization

- Double-sensor layers

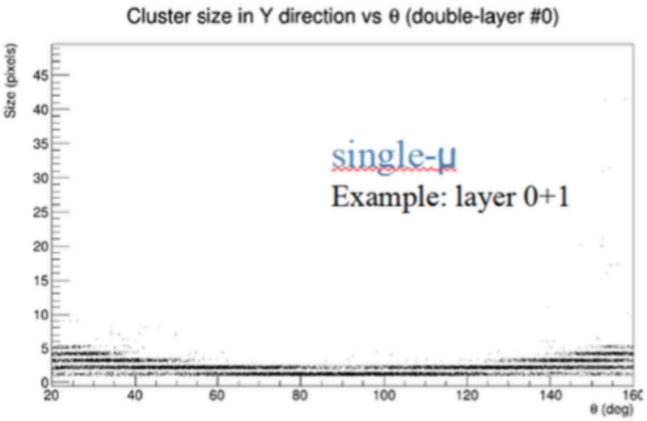


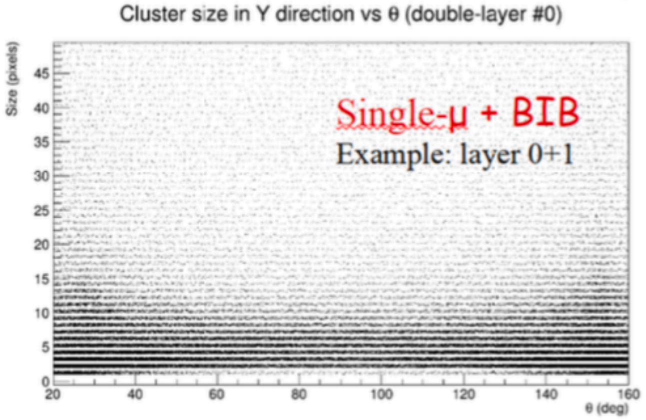


Loose: requires compatiblity with beamspot region within ~10mm
Tight: assumes knowledge of primary vertex position (or secondary-vertex)

Track reconstruction time decreases to hours or ~ 3 minutes per event

- Cluster shape analysis using realistic pixel detector digitization

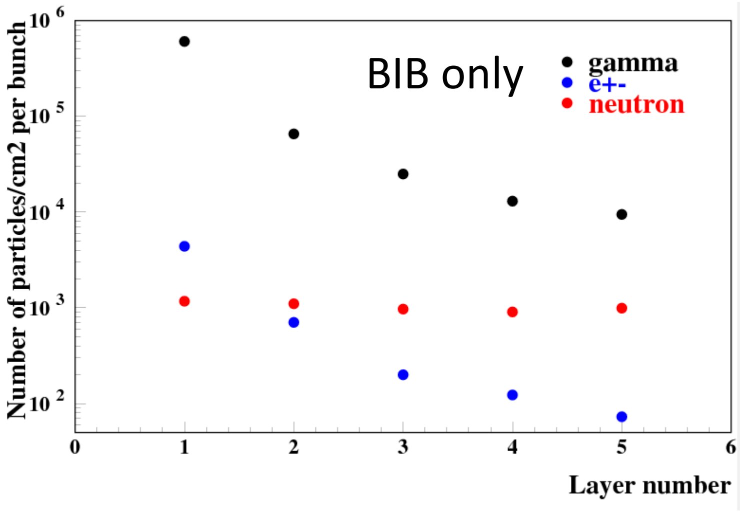




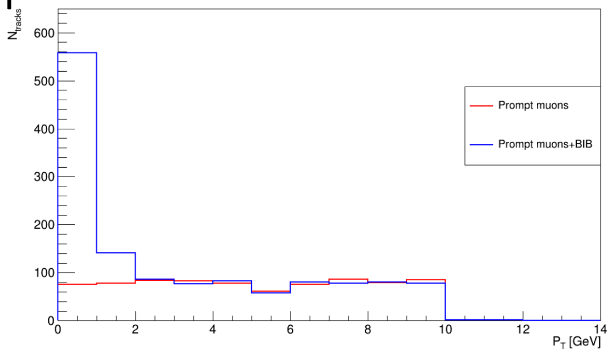
Cut Efficiency	Loose	Tight
Single muon	99.7%	99.6%
Single muon + BIB	55.2%	43.7%

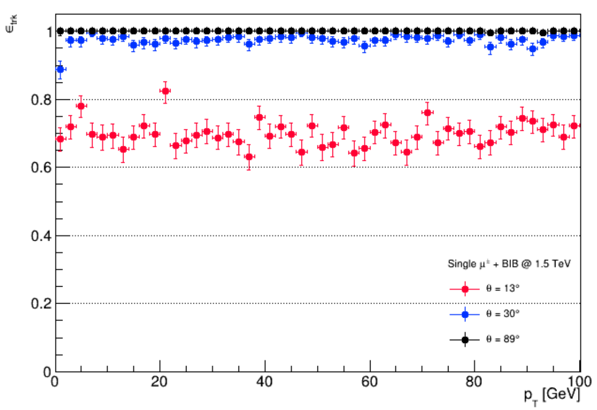
Tracking performances

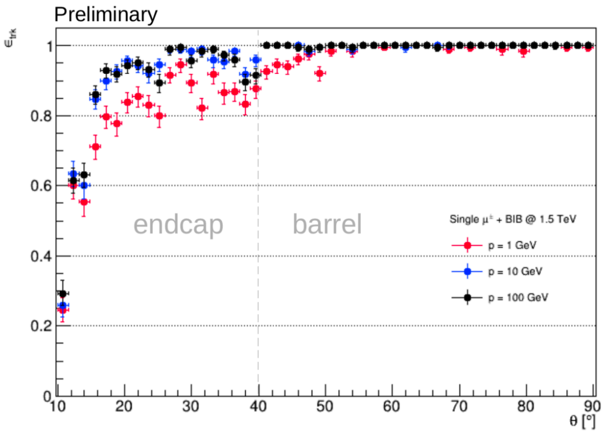
arXiv:1808.02154
10.18429/JACoW-IPAC2014-TUPRO029

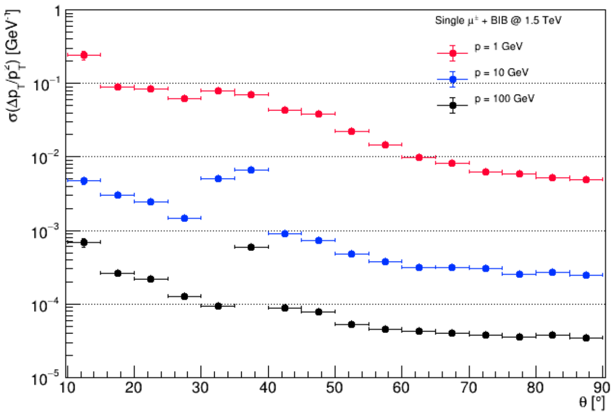


- Can successfully reconstruct muons with high purity of measurements associated to the track
- Further algorithm and geometry tuning needed to ensure high efficiency at all θ and smooth detector resolution





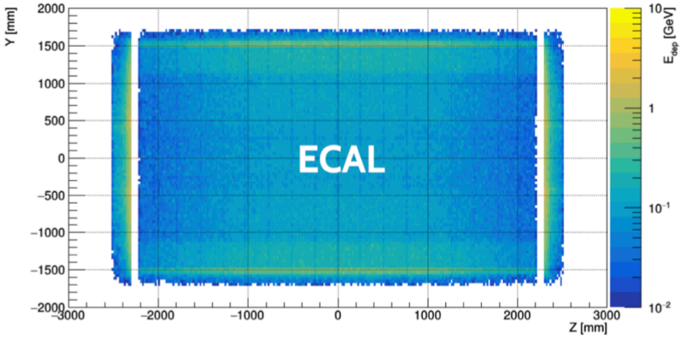


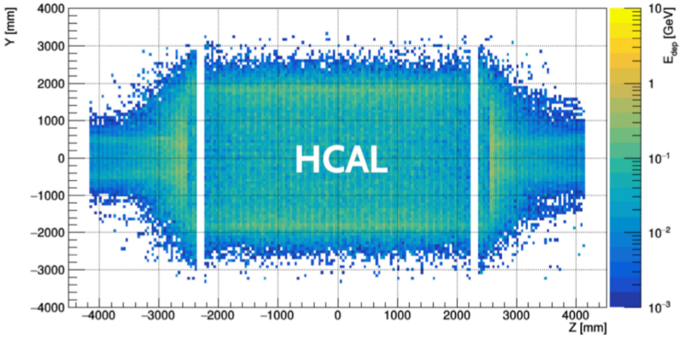


Calorimeters

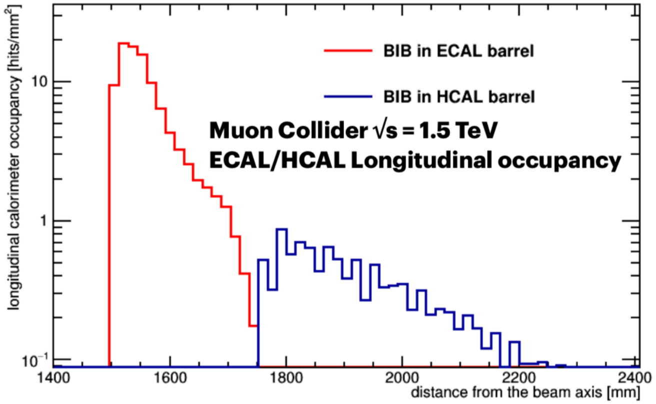
About 6 TeV (2.5 TeV) of energy deposited in ECAL (HCAL) by BIB

Lorenzo Sestini et al.



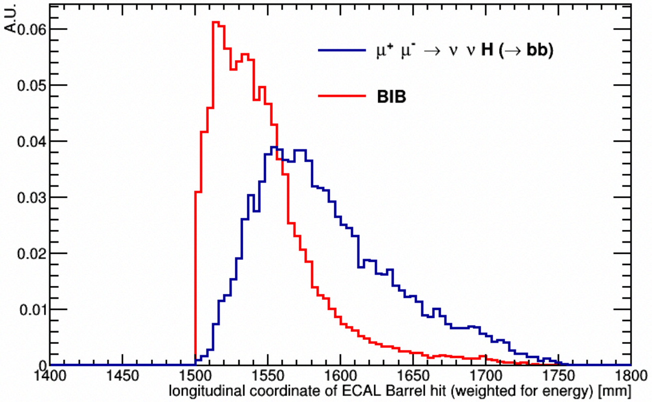


Energy deposition in calorimeters per bunch crossing

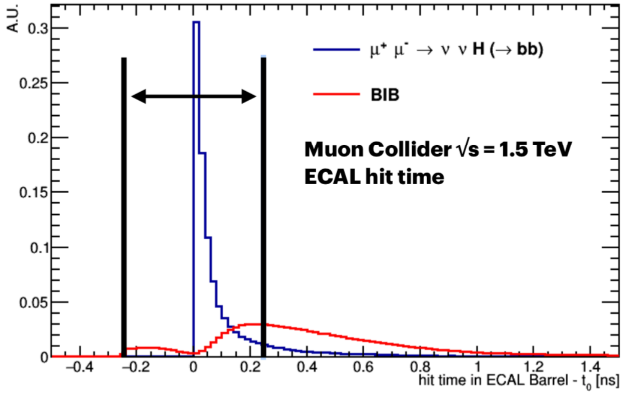


- **BIB is diffused in the calorimeters**: at the ECAL barrel surface the flux is 300 particles/cm², most of them are photons with <E>=1.7 MeV.
- BIB occupancy is lower in HCAL with respect to ECAL.

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



acquisition time of [-0.25,+0.25]

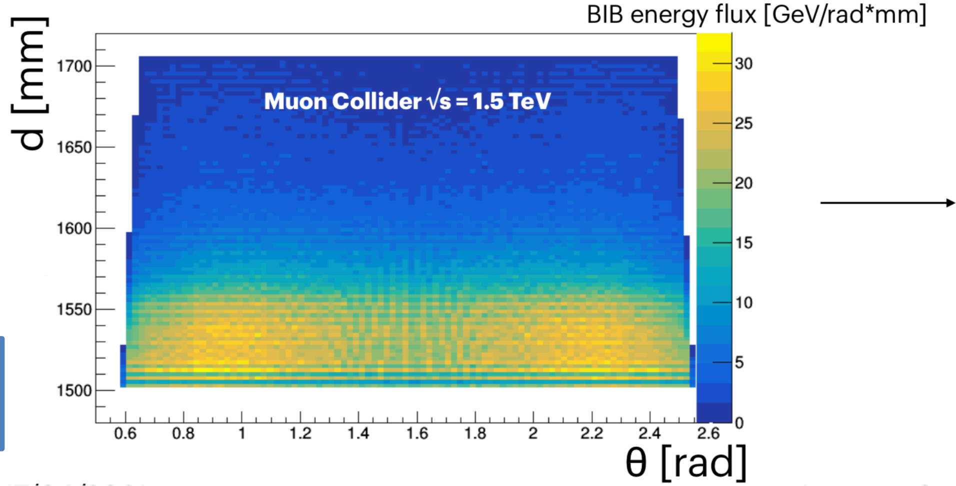


Jet reconstruction

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: $E_{HIT} \rightarrow E_{HIT} - E_{BIB}$

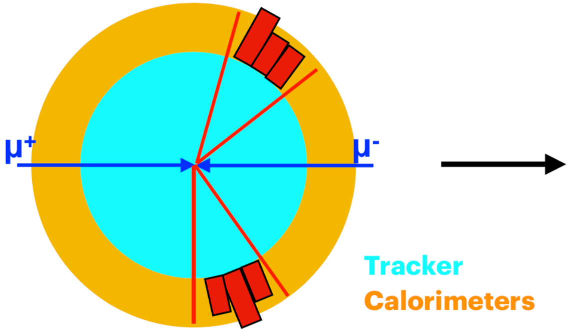


ECAL and HCAL clusters
are reconstructed with **PandoraPFA**
Calorimeters jets are clustered
with the kt algorithm, radius R=0.5

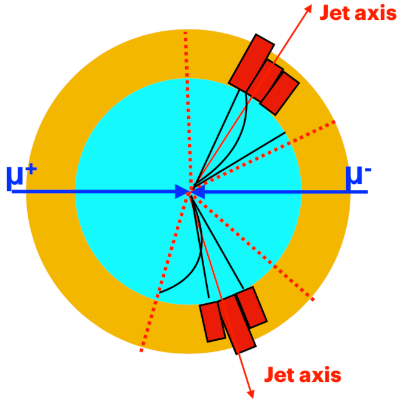
M.A. Thomson
Nucl.Instrum.Meth.A611:25-40,2009

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

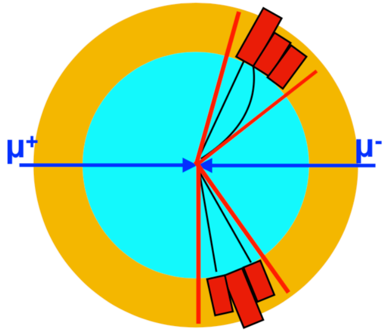
Step 1: calorimeter jet reconstruction with PandoraPFA and kt (R=0.5)



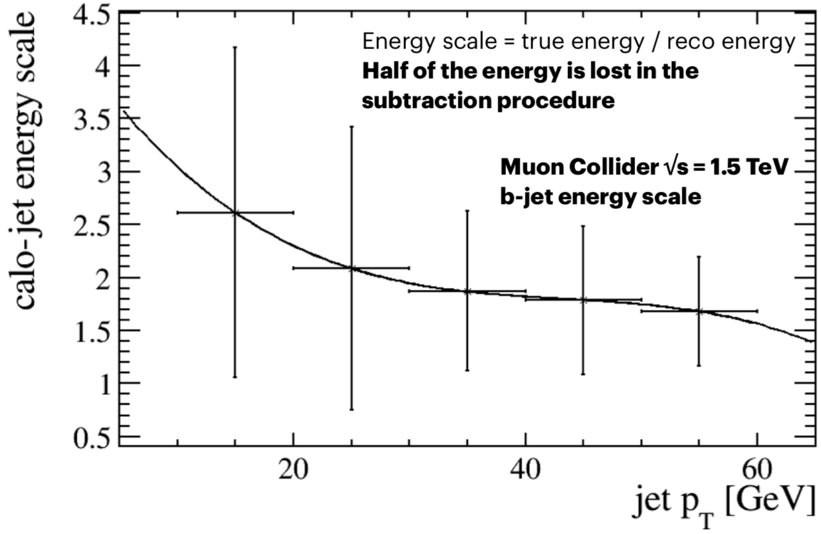
Step 2: regional tracking in cones (R=0.7) defined by the calorimeter jet directions



Step 3: final jet clustering using calorimeter clusters and tracks with PandoraPFA and kt (R=0.5)

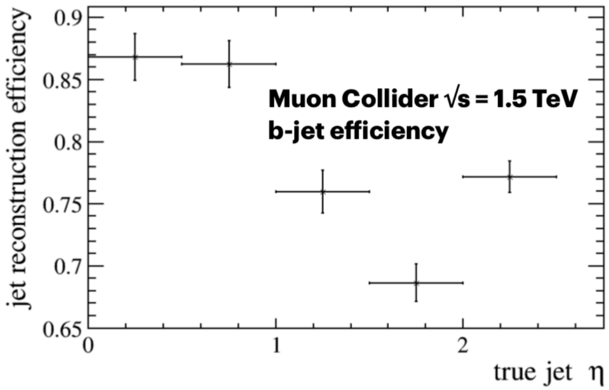


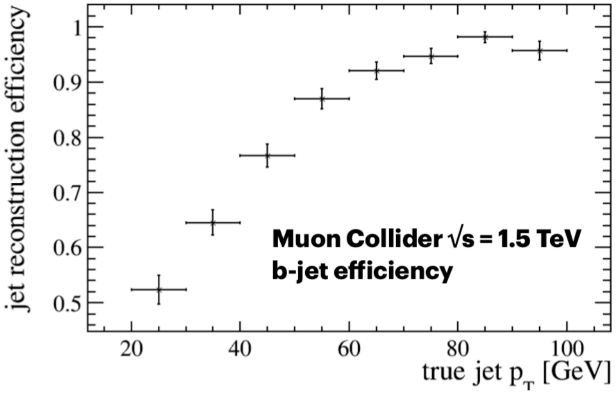
Jet reconstruction

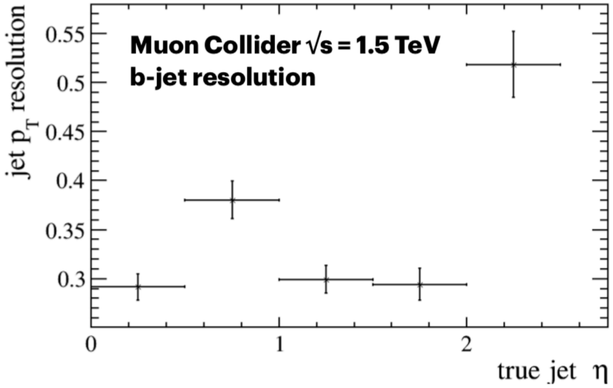

Energy scale = true energy / reco energy

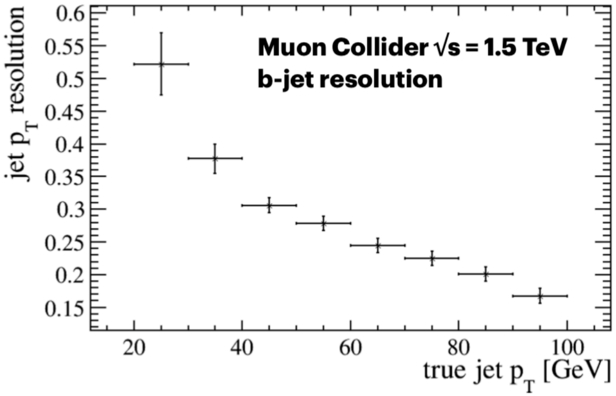
Half of the energy is lost in the subtraction procedure

Muon Collider $\sqrt{s}$ = 1.5 TeV
b-jet energy scale


Muon Collider $\sqrt{s}$ = 1.5 TeV
b-jet efficiency

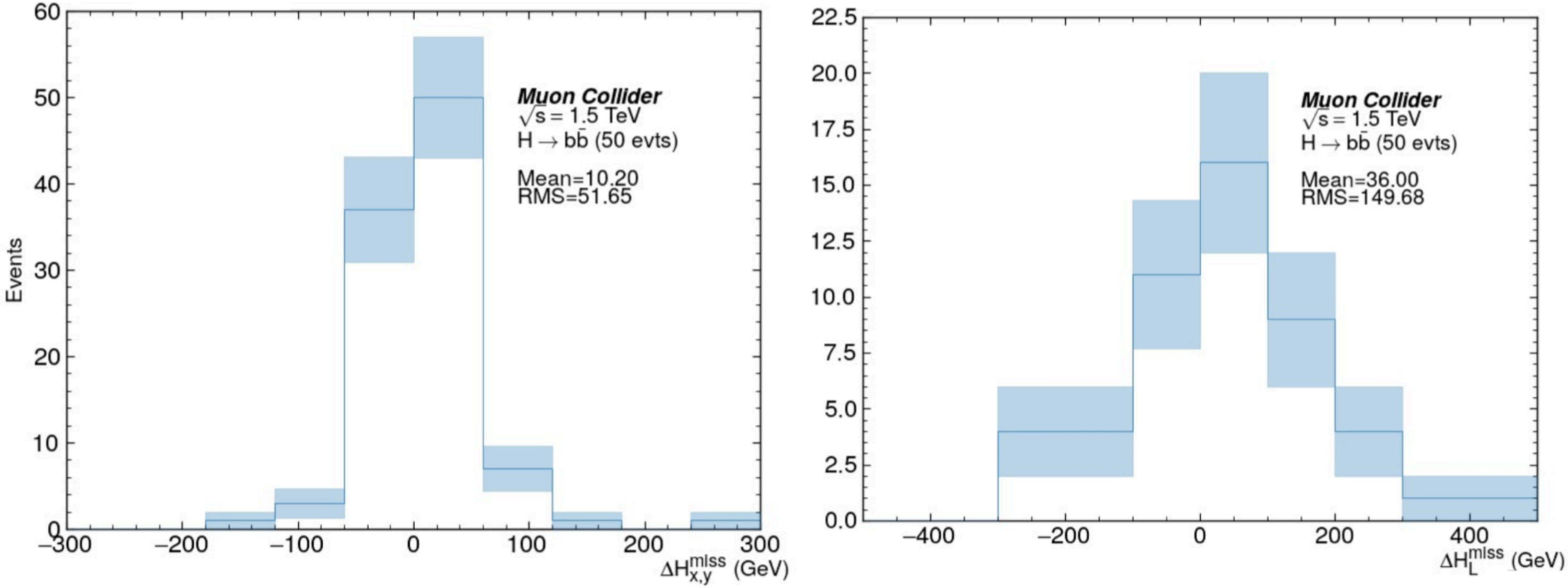

Muon Collider $\sqrt{s}$ = 1.5 TeV
b-jet efficiency


Muon Collider $\sqrt{s}$ = 1.5 TeV
b-jet resolution


Muon Collider $\sqrt{s}$ = 1.5 TeV
b-jet resolution

- **Good reconstruction efficiency at high transverse momentum (p_T) and low rapidities (η).**
- A jet energy correction dependent from η and p_T is applied.
- **15% p_T resolution at high p_T. The p_T resolution worsen in the region near the nozzles.**
- **There are many rooms for optimization at all the stages of the reconstruction algorithm.**
- On-going studies on jet identification and fake jet removal.

Preliminary Missing Energy



$\Delta H_{miss} = H_{missBIB} – H_{missnoBIB}$ → calculated in the transverse and longitudinal plane

Preliminary studies show that **the measurement in the transverse plane is more precise**

Muon reconstruction

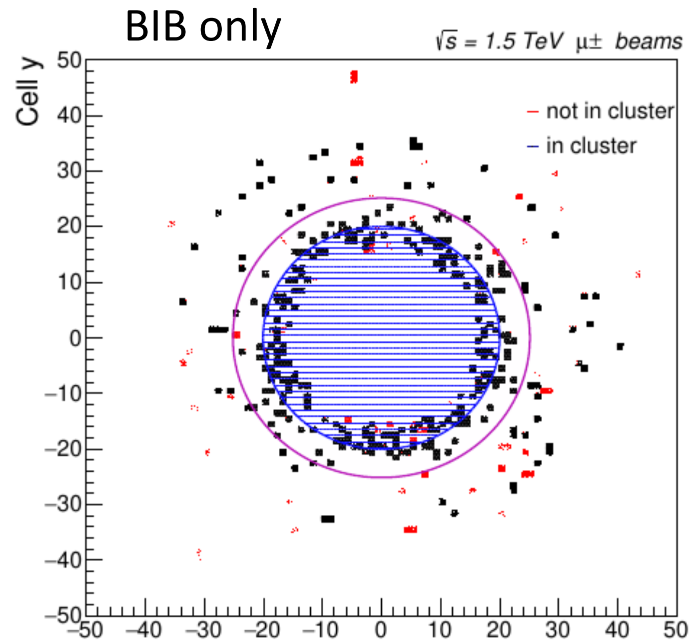
Cristina Riccardi et al.

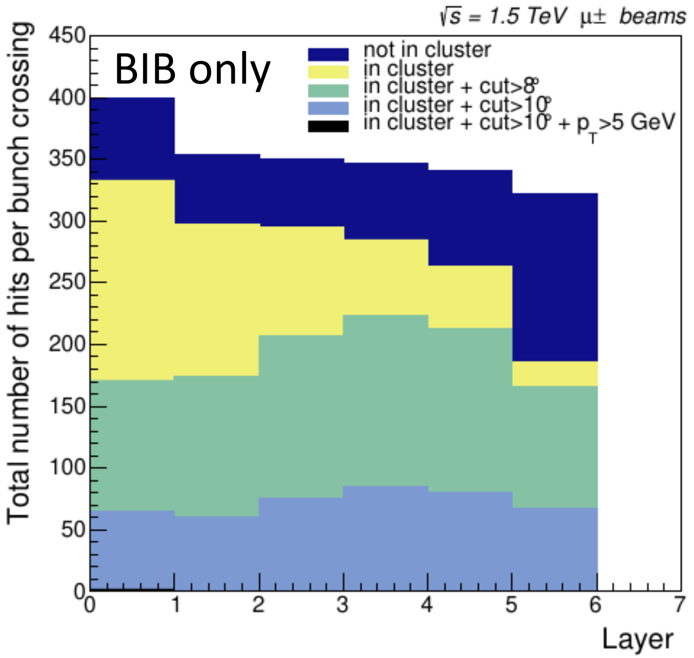
RPC cells of 30x30mm^2

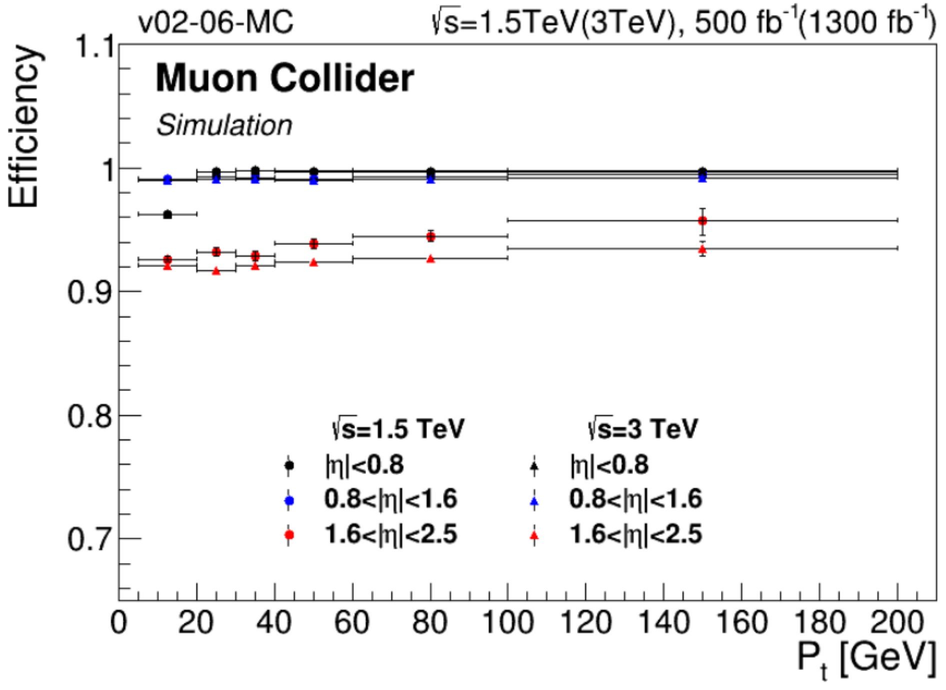
7 barrel layers, 6 endcap layers

Much reduced BIB contribution compared to tracker and calorimeter (~8% of BIB) concentrated in the low-radius endcap region

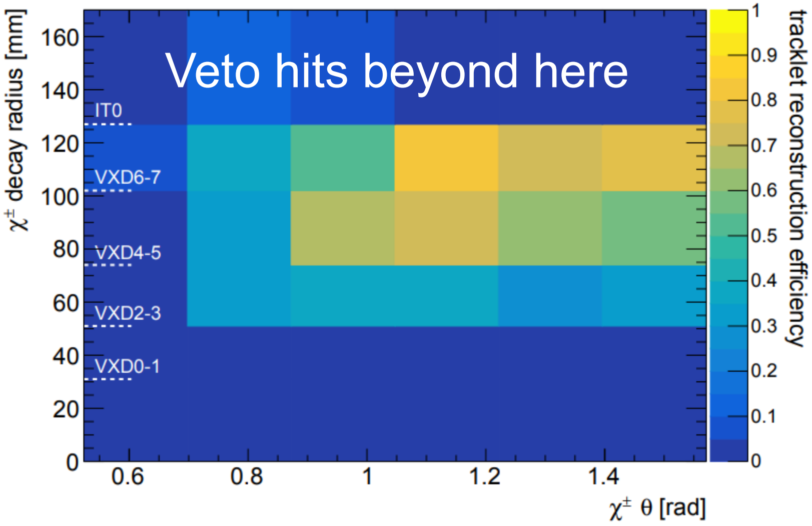
Can be effectively removed with geometrical cut to a level that does not contaminate reconstructed muons





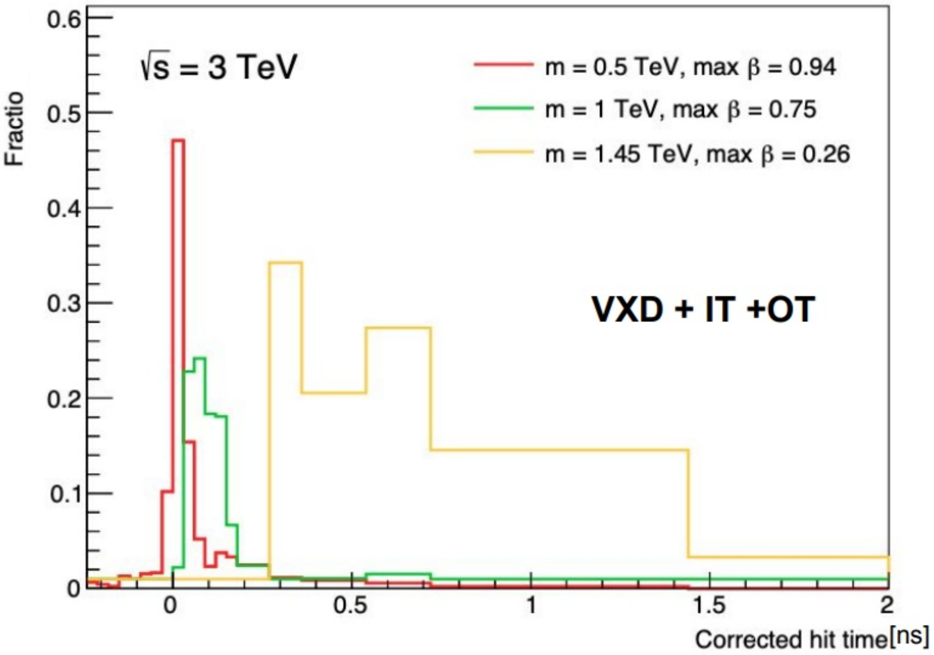


Comment on LLP detection strategy



Long-lived particles, boosted objects, ..
Attention to detector design choices, e.g.
Granularity
Acceptance for slow particles
e.g. dedicated reconstruction for short-lived "disappearing" tracks

Readout window/timing selections



Special Thanks and Contacts

Donatella Lucchesi
Nazar Bartosik
Massimo Casarsa
Sergo Jindariani
Simone Pagan Griso
Ivano Sarra
Lorenzo Sestini
Chiara Aimè
Cristina Riccardi

Francesco Collamati
Camilla Curatolo
Paola Sala

MDI

+ many others

extras

General requirements for the detector

- ✓ Track efficiency and momentum resolution – for feasibility and precision of many physics studies e.g. final states with leptons
- ✓ Good ECAL energy and position resolution for e/gamma reconstruction
- ✓ Good jet energy resolution
- ✓ Efficient identification of a secondary vertex for heavy quark tagging
- ✓ Other considerations (Missing Energy/MET, taus, substructure)

- ✓ Many ILC or CLIC considerations apply to Muon Collider detectors, although beam background conditions are different and much more challenging requiring a dedicated design for Muon Collider experiment: vertex/tracking – calorimetry – triggerless DAQ
- ✓ Detector design considerations should be driven by physics requirements and BIB considerations
- ✓ **Optimal design will very likely be different for different collision energies**

Key considerations

- ✓ **Most tracker hits and calorimeter clusters produced in the detector originate from BIB**
- ✓ Example: inner layers of the vertex tracker detector have occupancy ~x10 larger than CMS pixels in HL-LHC
  - Requires **large bandwidth for sending data off the detector**
  - High complexity of data reconstruction
- ✓ Applying filtering at various stages of data processing (both on and off the detector) is important
- ✓ Explore characteristics of the BIB that are different from the hard scatter:
  - Position, Time, Energy, Particle ID, Correlations of the above
- ✓ Higher bandwidth requires power, filtering on detector requires power

- ✓ Considering large bunch crossing intervals at the muon collider (~10-20 us), it is probably best to consider a triggerless DAQ system
- ✓ **Bunch crossing time is ~20-30 ps, defines natural time resolution**

Read-out considerations

- Per module, occupancy is significantly higher in the inner tracker layers than at the HL-LHC

➔ Requires on-detector logic (timing, double-layers) or higher bandwidth (more material, power)

- Total data rates at 1.5 TeV assumed to be tracker dominated and are ~30 Tb with **1 ns readout window (conservative)**
- Similar to total bandwidth of the LHCb triggerless DAQ. LHCb has smaller per event data volumes (~8800 5Gbps links) but operates at 40MHz (vs **100kHz for the Muon Collider**)
- Triggerless readout could probably work for this configuration. Total data rates do not look crazy even with today's commercial technology
- Studies are needed to understand system requirements at higher collider energies (different BIB) and larger readout windows (if needed for slow, heavy particles)

➔ Feasibility of triggerless readout for such scenarios need to be investigated.

Note, time between bunch crossings is very important

- Data => bandwidth => power

Read-out considerations

- Assuming module size of 20 cm^2
- With 50x50 microns pixel size, get ~800k pixels per module
- With 1% occupancy, this is 8k hits per module
- 32 bits to encode x/y/amp/time
- Data rates: 8000 * 32 bit * 100 kHz * 2(safety factor) ~ 50 Gbps
- This number is factor of ~5-10 higher than HL-LHC
- Not obvious that the technology will get us there in ~10-20 years
- More handles should be explored:

Data compression, some front-end clustering, pT-module based suppression (preliminary estimates indicate more than x5)