Muon Collider Detector: General Considerations

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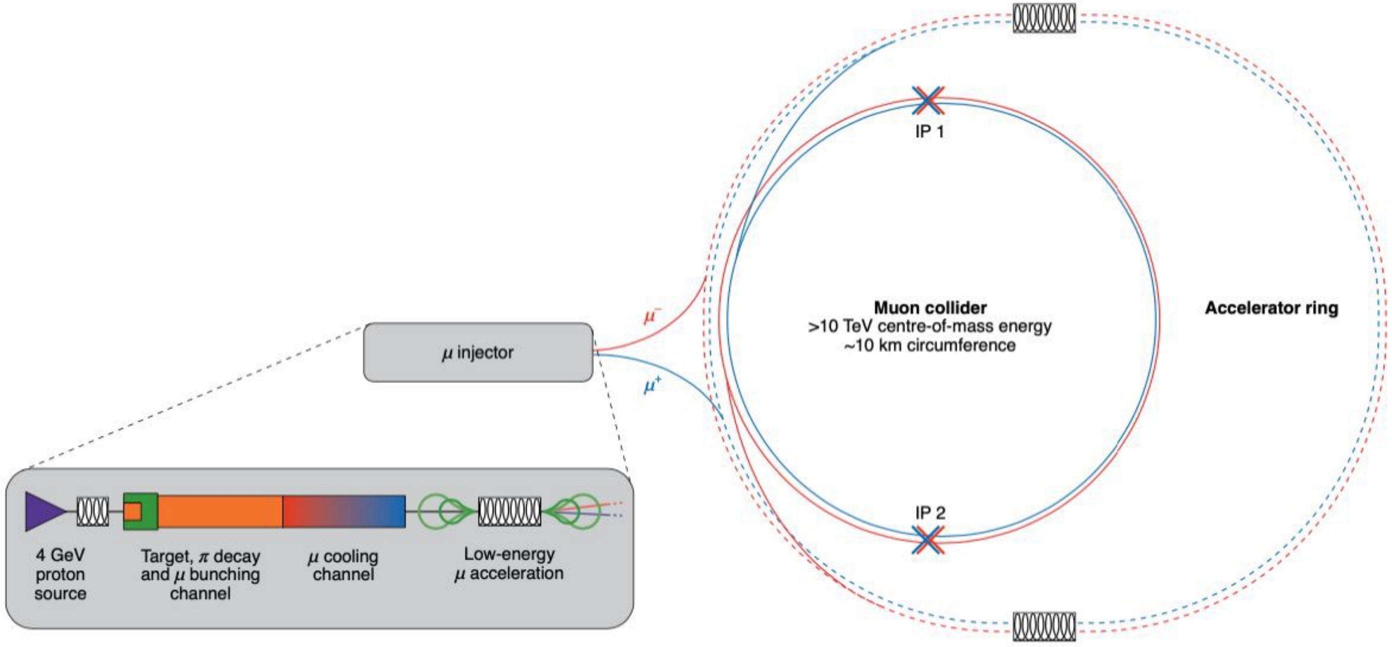
General Disclaimer

- Asked to give a review/introduction of general detector considerations for a muon collider detector
- None of this is new material and very little of it was done by me!
- Taken from IMCC, Muon Collider Forum report, and other work of others. (https://arxiv.org/abs/2303.08533, https://arxiv.org/abs/2203.07964, https://arxiv.org/abs/2209.01318)

Muon Collider: Target Parameters

Parameter	Symbol	unit	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10
Target luminosity (5 years)	$\mathcal{L}_{target,5}$	$10^{34}cm^{-2}s^{-1}$	1.8	20
Target Luminosity (10 years)	$\mathcal{L}_{target,10}$	$10^{34}cm^{-2}s^{-1}$	1	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34}cm^{-2}s^{-1}$	2.1	21
Collider circumference	C_{coll}	km	4.5	10
Collider arc peak field	B_{arc}	T	11	16
Luminosity lifetime	N_{turn}	turns	1039	1558
Muons/bunch	N	10^{12}	2.2	1.8
Repetition rate	f_r	Hz	5	5
Beam power	P_{coll}	MW	5.3	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	μm	25	25
IP bunch length	σ_z	mm	5	1.5
IP betafunction	β	mm	5	1.5
IP beam size	σ	μm	3	0.9
Protons on target/bunch	N_p	10^{14}	5	5
Protons energy on target	E_p	GeV	5	5
BS photons	$N_{BS,0}$	per muon	0.075	0.2
BS photon energy	$E_{BS,0}$	MeV	0.016	1.6
BS loss/lifetime (2 IP)	$E_{BS,tot}$	GeV	0.002	1.0



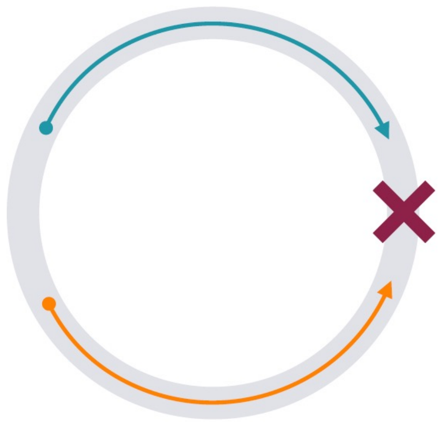
Note: repetition rate is 5 Hz
LHC repetition rate is 40 MHz

Some basics (stollen without permission from Tova Holmes)

Starting simple

- What's going on inside the collider ring:
  - Circulate two bunches and re-fill when they're depleted
  - time between collisions $t = 33\ \mu s \times \left(\frac{L}{10\ \text{km}}\right)$

Large spacing between collisions, ~1000x lower rate than LHC



$L = \text{circumference}$

Some basics (stollen without permission from Tova Holmes)

Starting simple

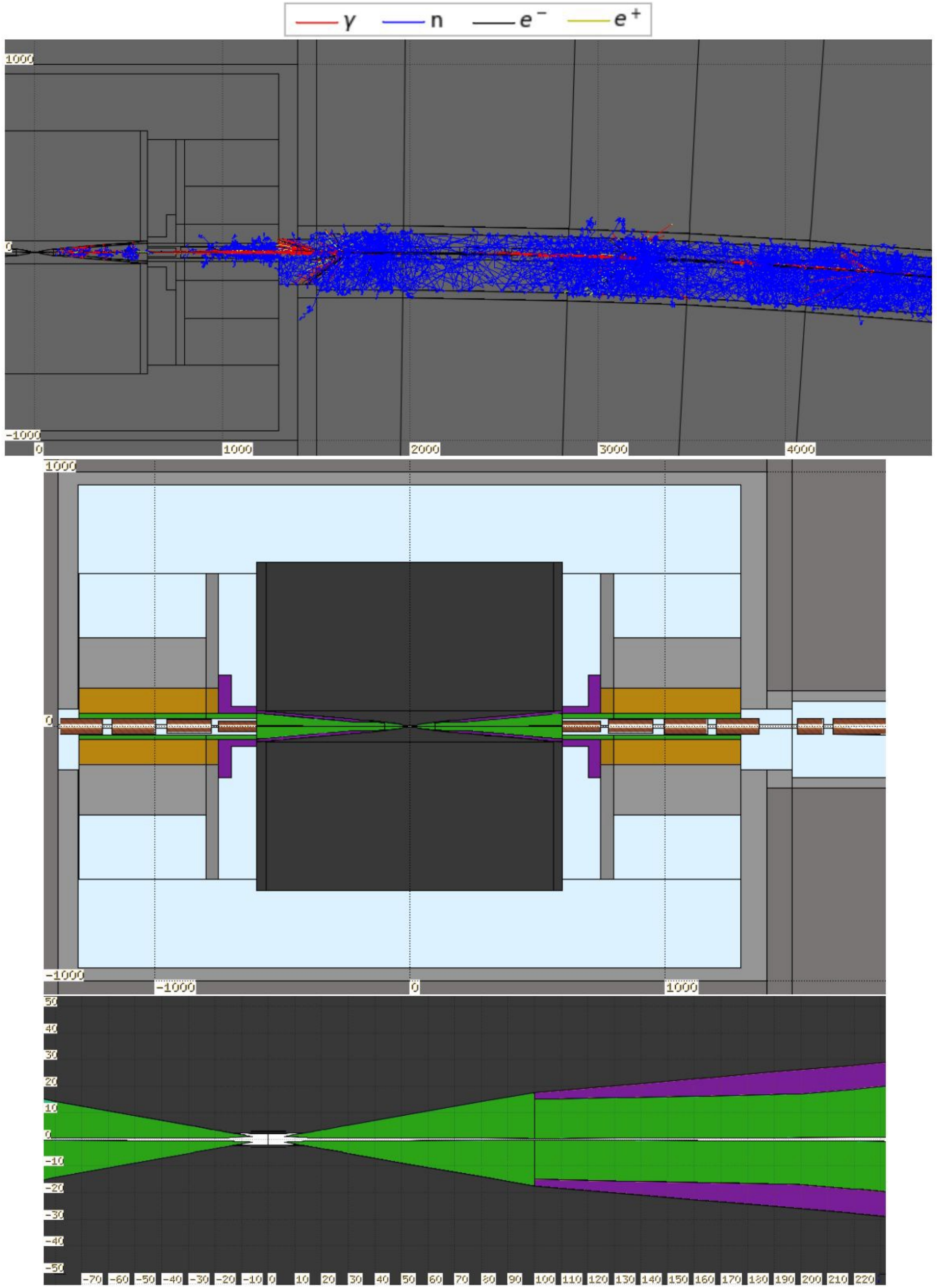
- average decay time in lab frame $\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$
- average beam crossings for each injected muon:
  $\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1\ \text{TeV}}\right) \times \left(\frac{10\ \text{km}}{L}\right)$
- fraction of muons decaying within 20m of the interaction point:
  $f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$
- total energy of decay products within 20m of the interaction point
  $E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$

L = circumference
E = beam energy

does not depend on E!

Beam Induced Background

- Beam Induced Background (BIB) from primary muon decay products, secondary and tertiary particles from showers
- Produces (mostly from decays in the few 10s of meters from the IP)
  - Electrons/positrons
  - Photons
  - Neutrons
  - Charged Hadrons
  - Muons (secondary muons can reach the detector from hundreds of meters from the IP)
- ~10^5 particles per meter of lattice

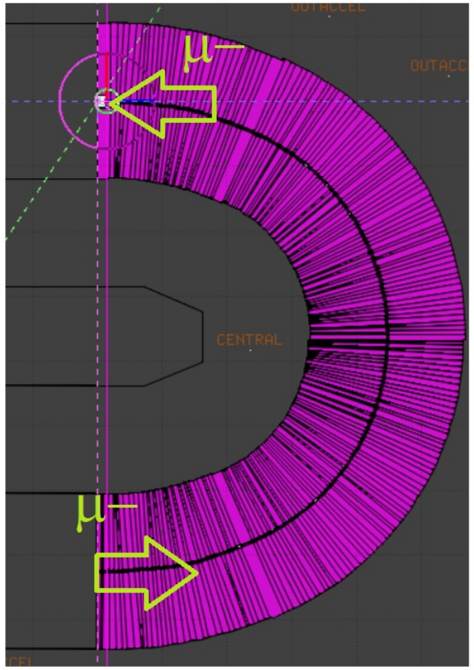


Key Feature: Machine Detector Interface and Nozzle shielding

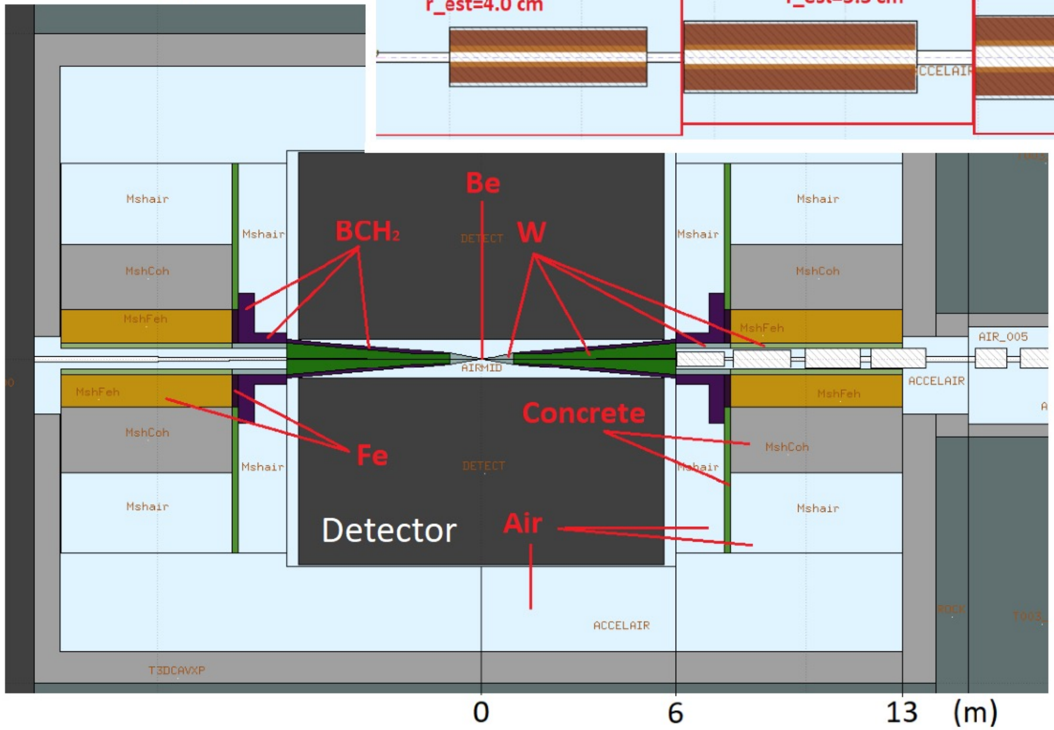
Suppresses background by a factor of ~500

Simulation tool: **LineBuilder + FLUKA**
Data analysis: **Python**

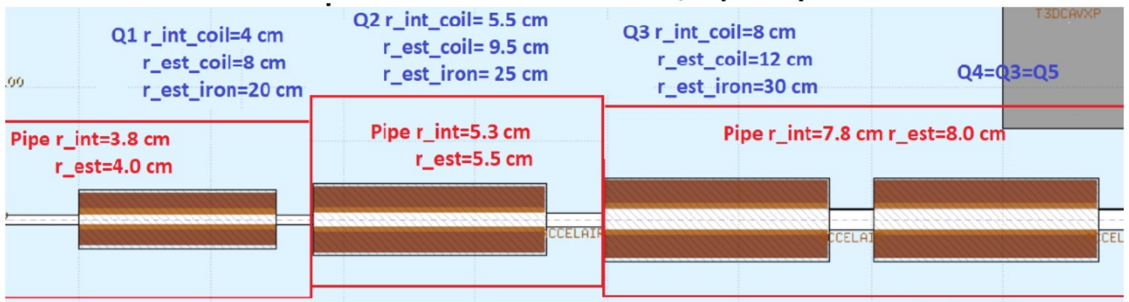
750 GeV muon beam travels half ring to IP



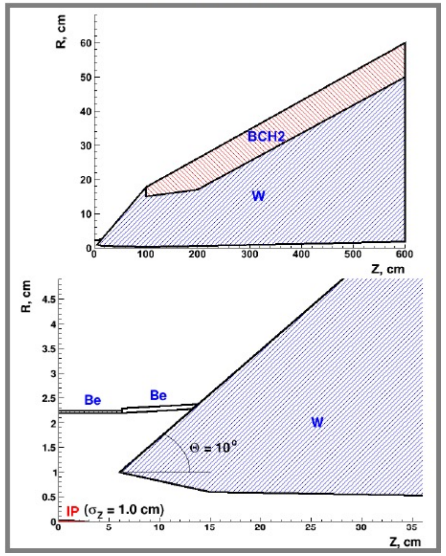
IR



IR Quadrupoles



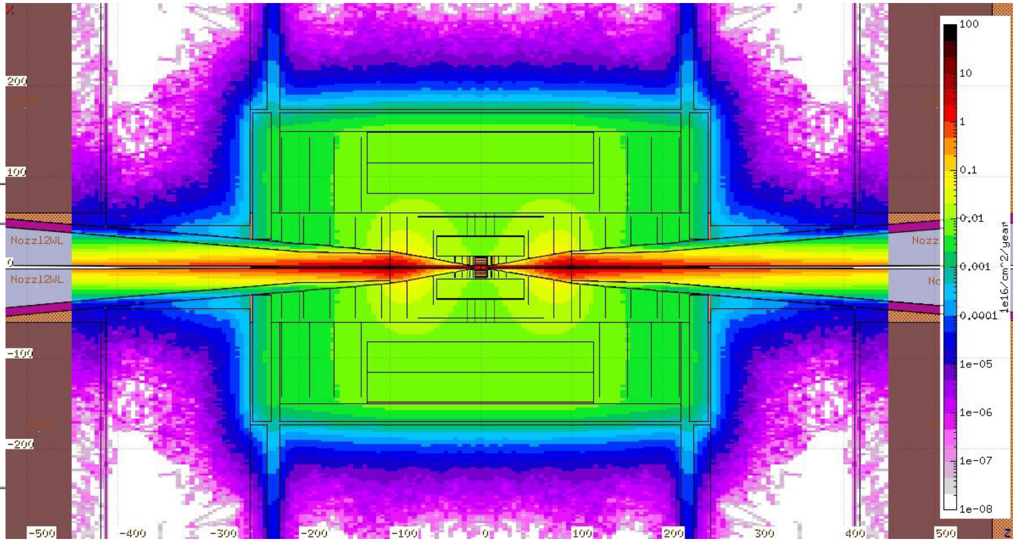
Nozzle



Some numbers

To first order no dependence on energy

Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadroms ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

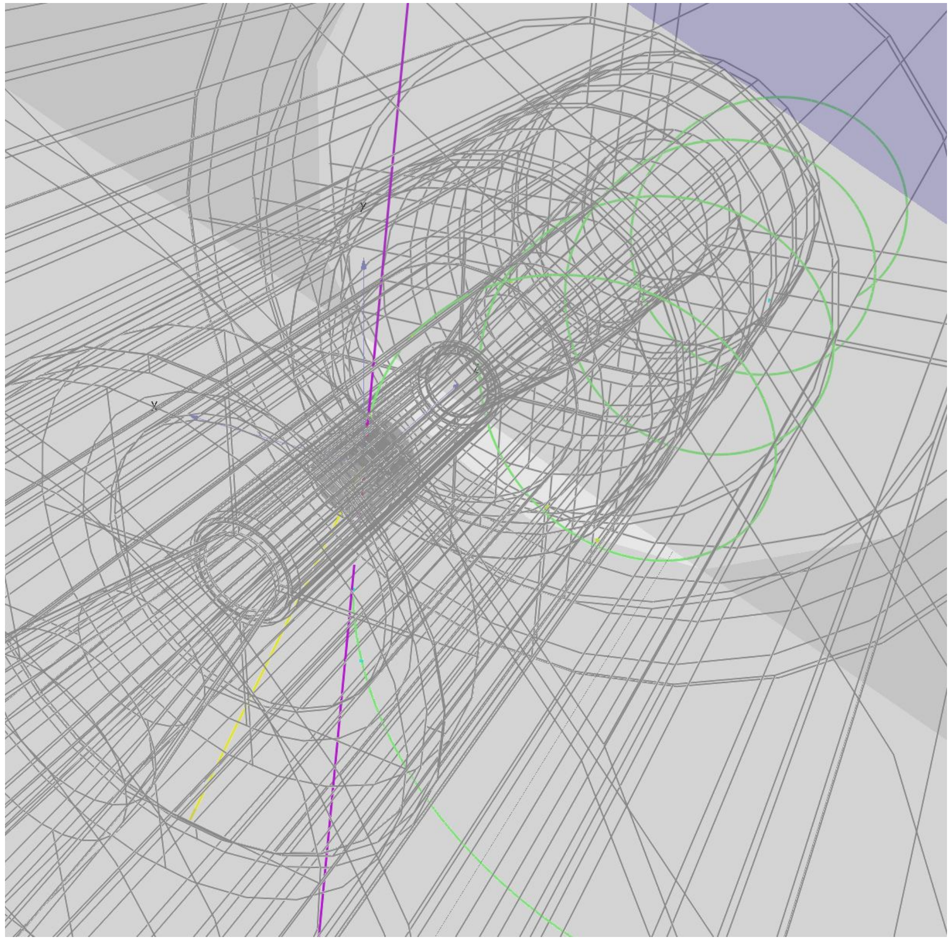


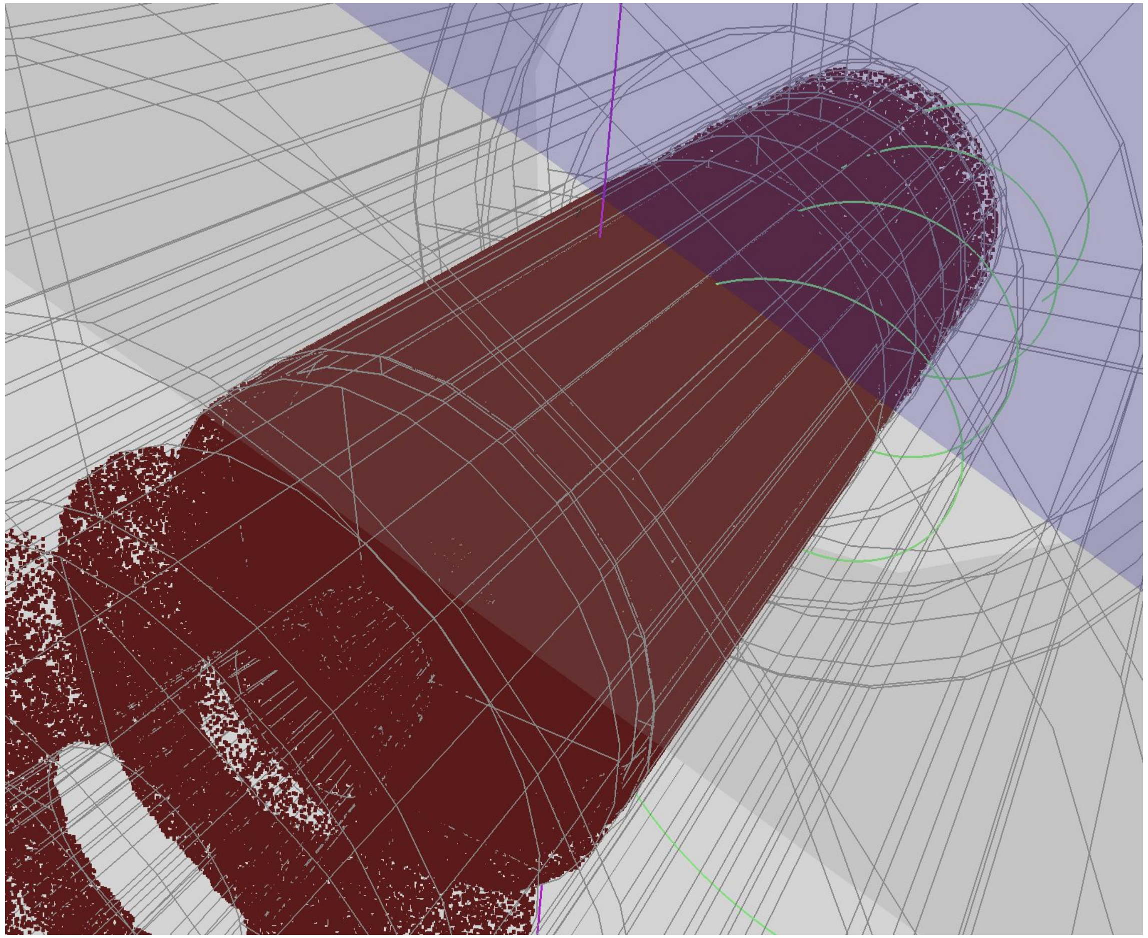
$$1MeV \frac{n_{eq}}{cm^2}$$

For 200 days of operation

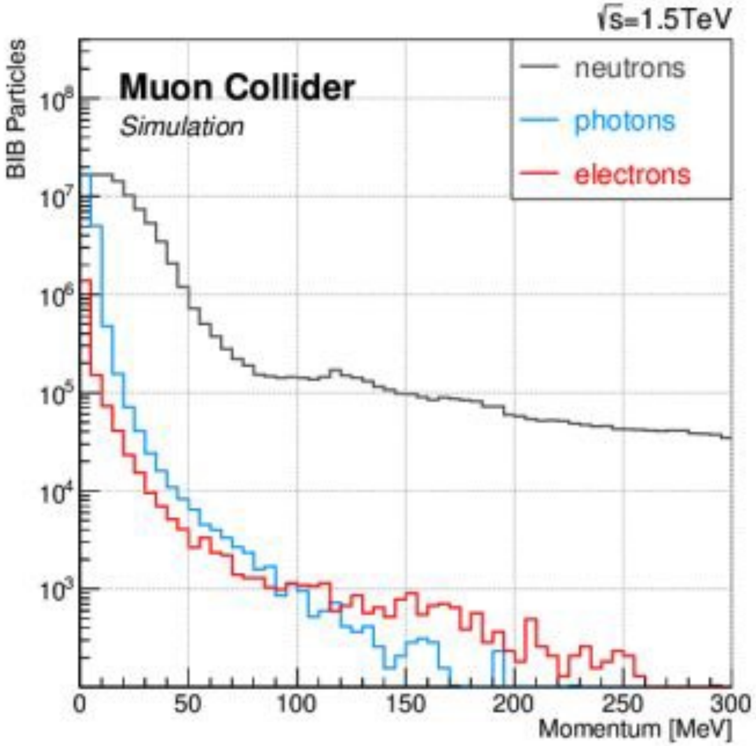
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

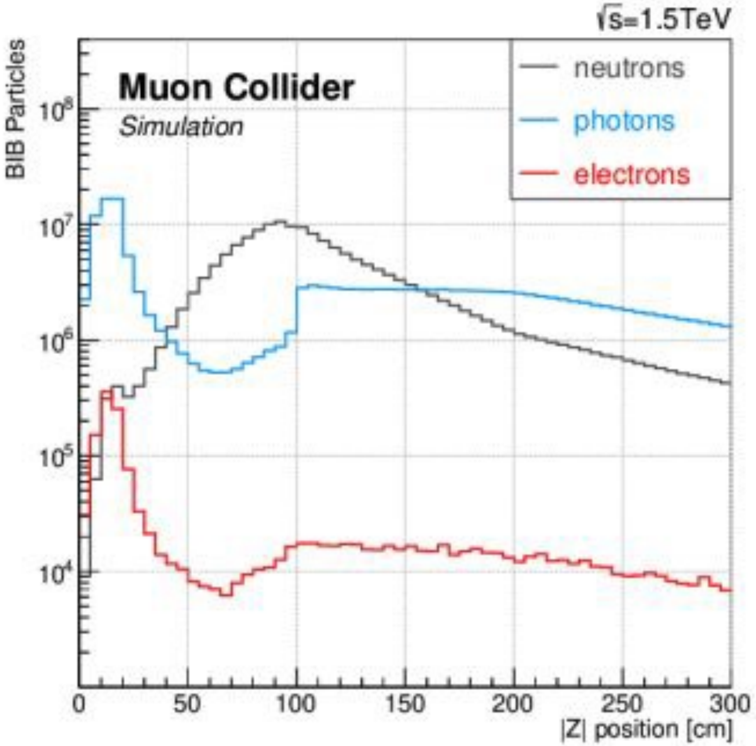
Z decay with/out beam induced background

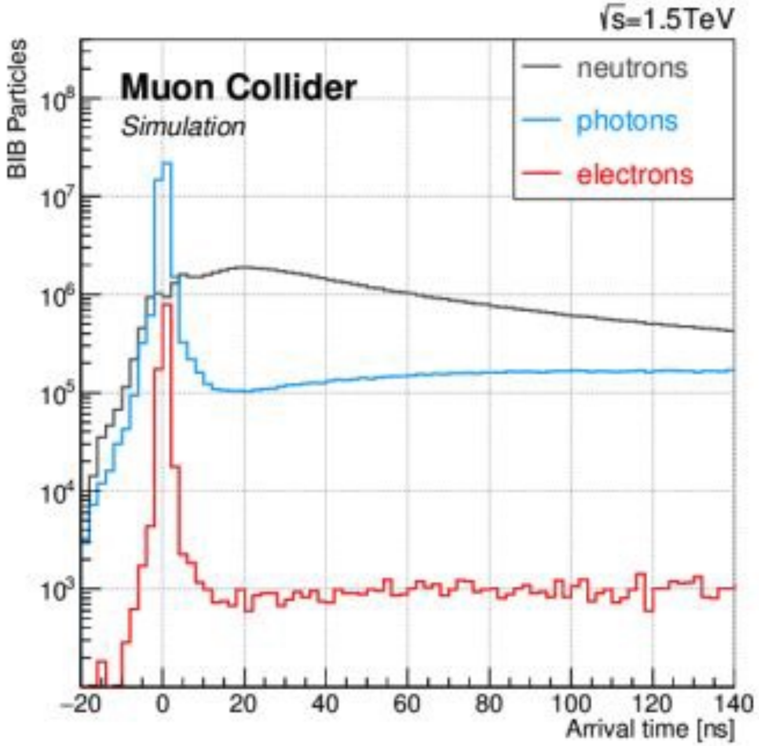




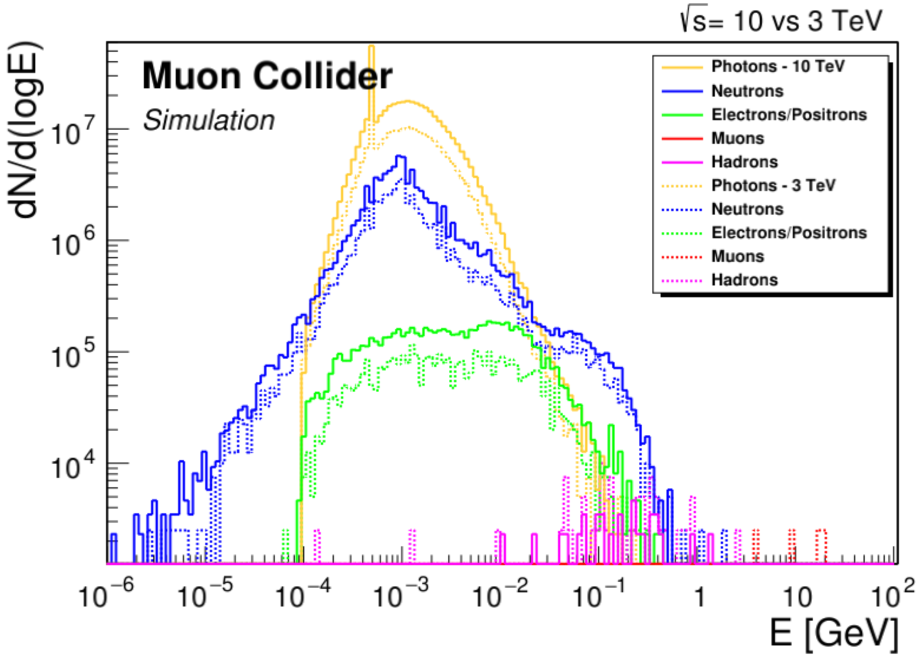
Properties of the BIB

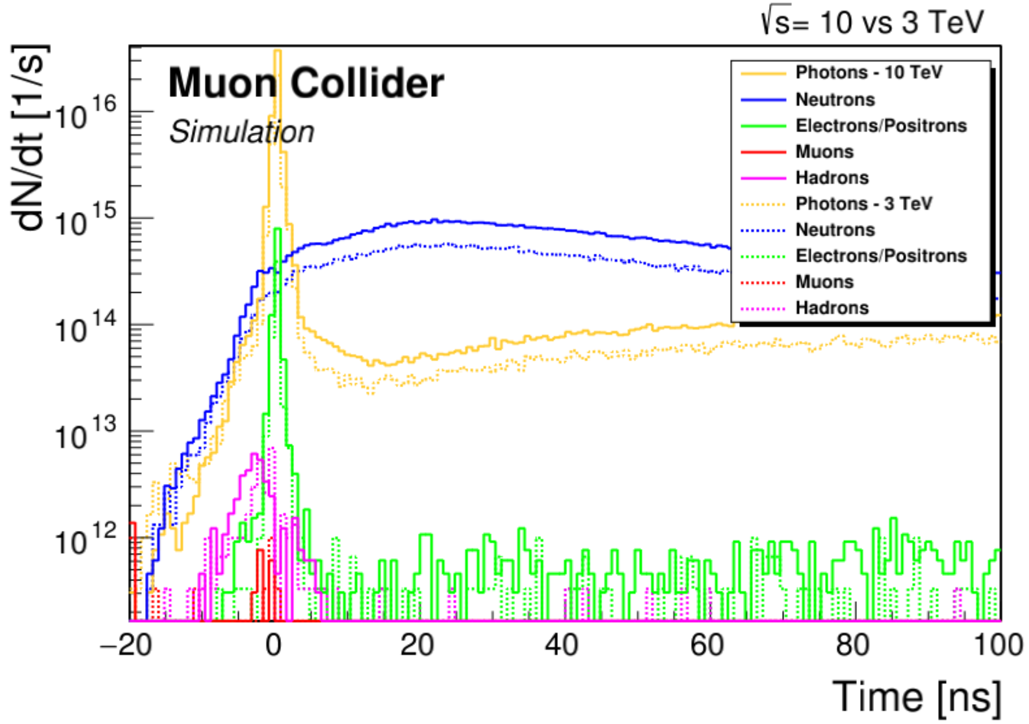






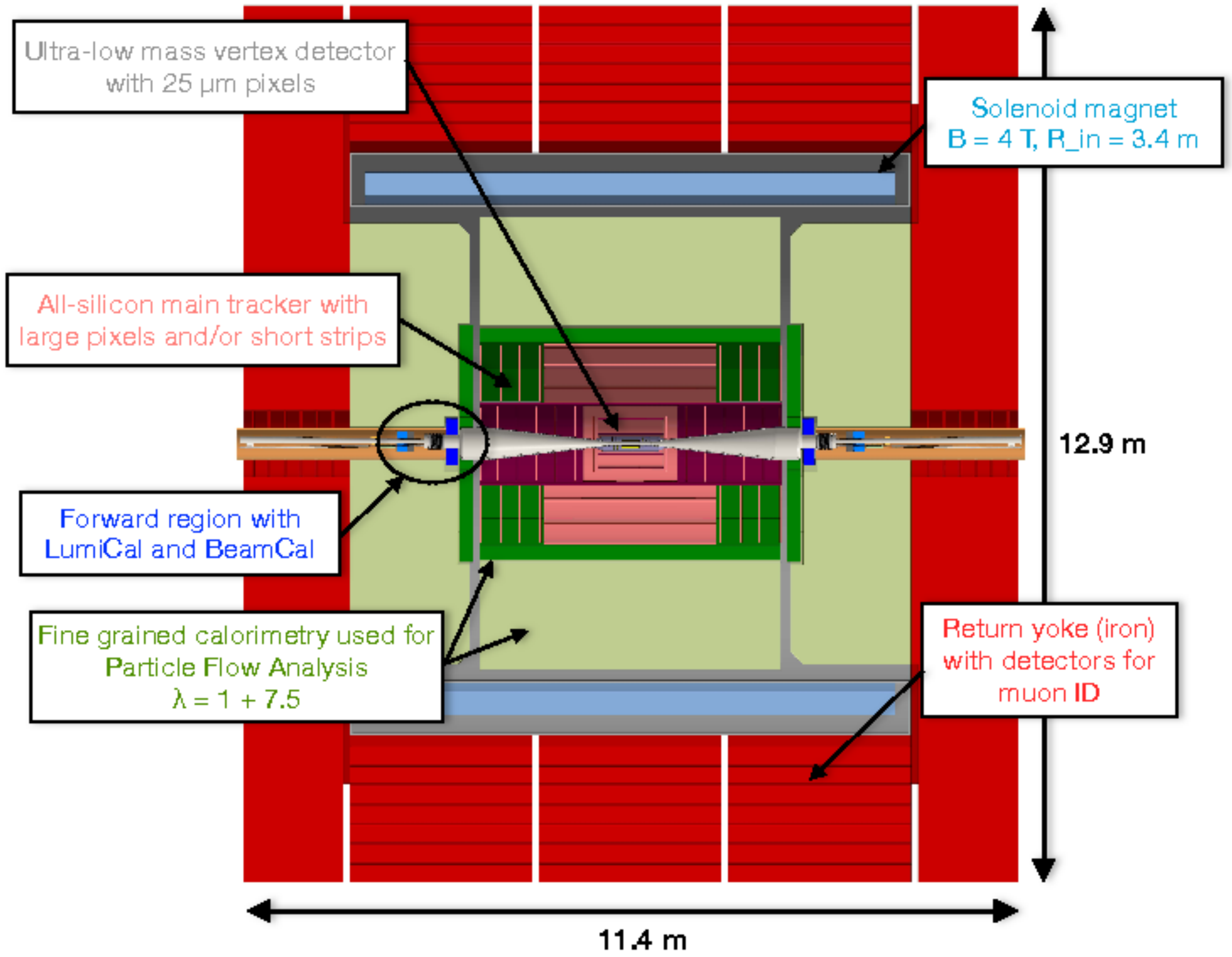
Properties of the BIB





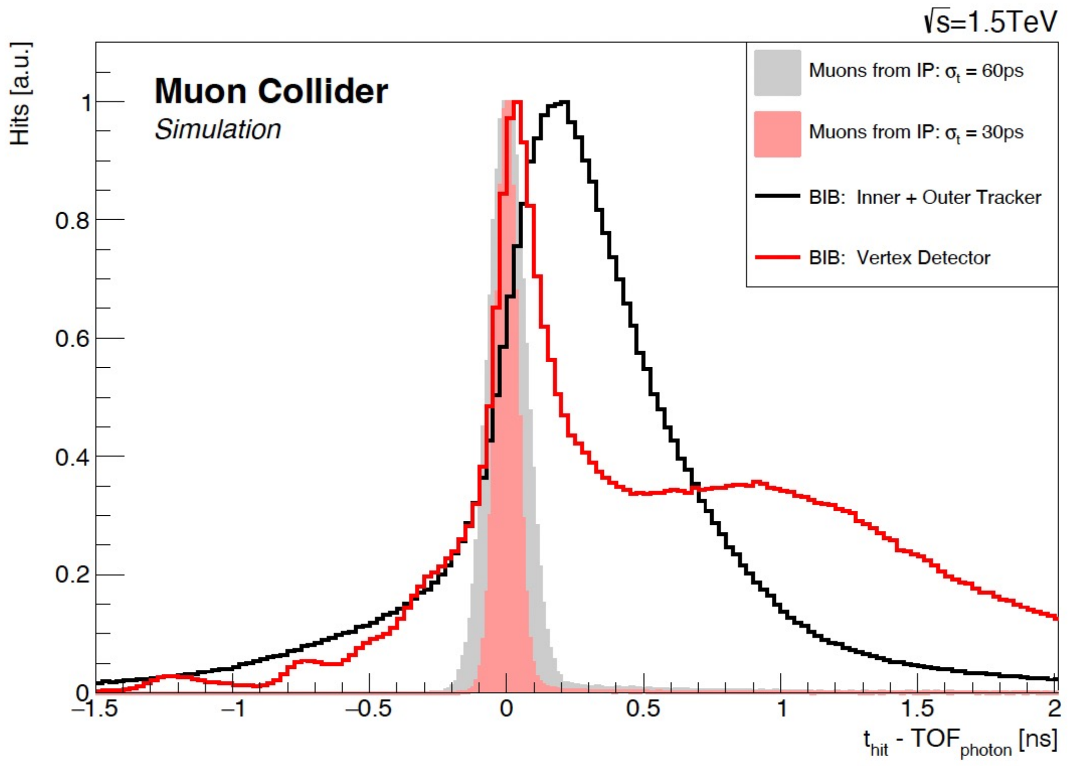
General Detector Designs

- Most detector studies have been done with a modified version of the CLIC detector which has :
  - Silicon Tracker
  - Fine grained calorimeter
  - Large volume high field solenoid
  - Muon Detectors
  - Luminosity monitors



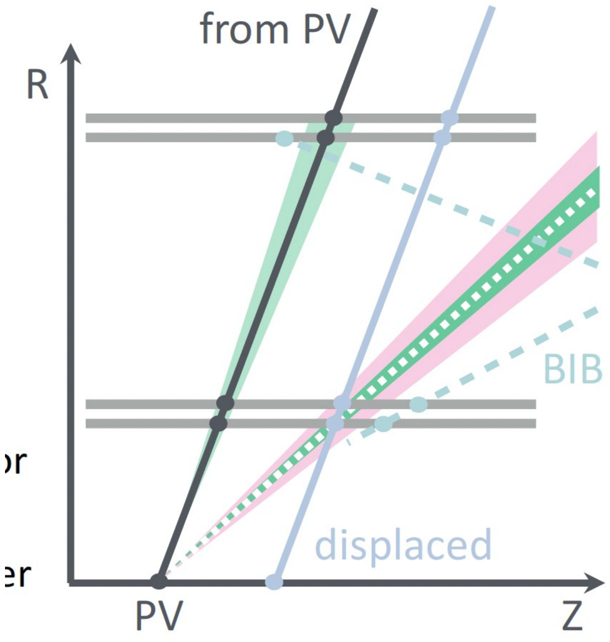
General Features of BIB compared to particles from IP

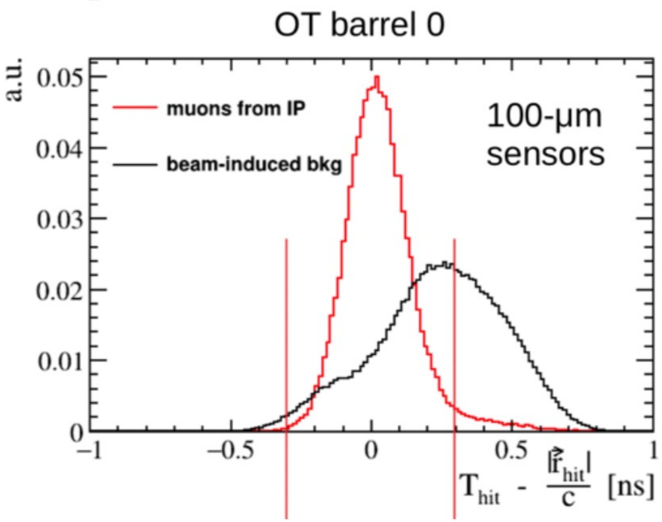
- BIB particles are generally
  - Low energy
  - Mostly arrive at the detector at times inconsistent with coming from the IP
  - Do not point towards the IP

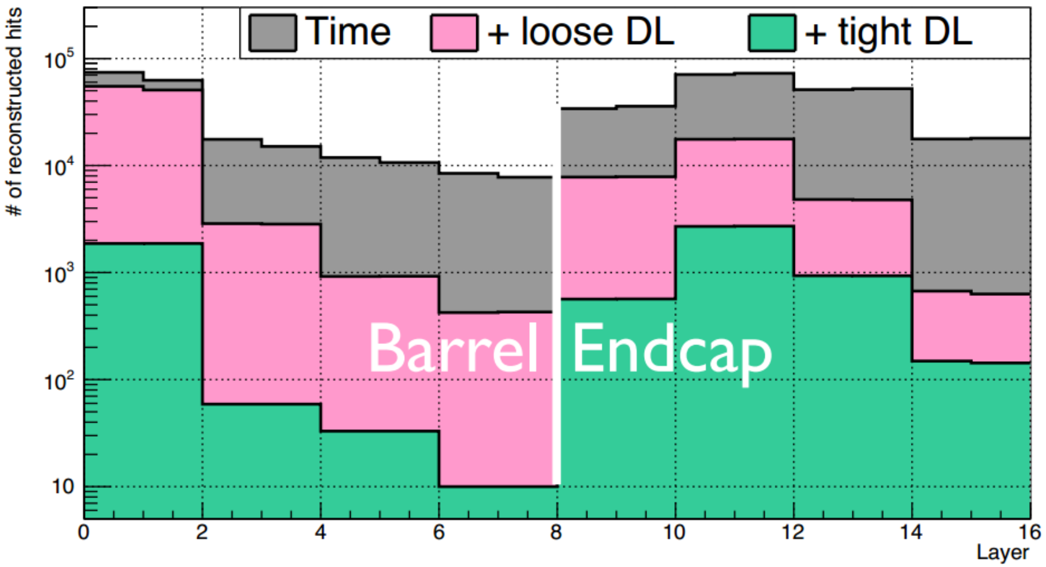


Inner Tracker

- Goal of ~1% occupancy
- Inner layer: hit density from BIB is ~3.5 /mm^2 and ~0.5 /mm^2 in first and second layer
  - Exploit hit timing of silicon sensor Utilize directional information to reject BIB hits (double layer hits only reconstructed)
  - Pulse shape information
  - Shape of hit clusters
- Assumed in these studies 30 ps resolution in inner layer, 60 in outer layers (maybe ultimately < 10 ps?)

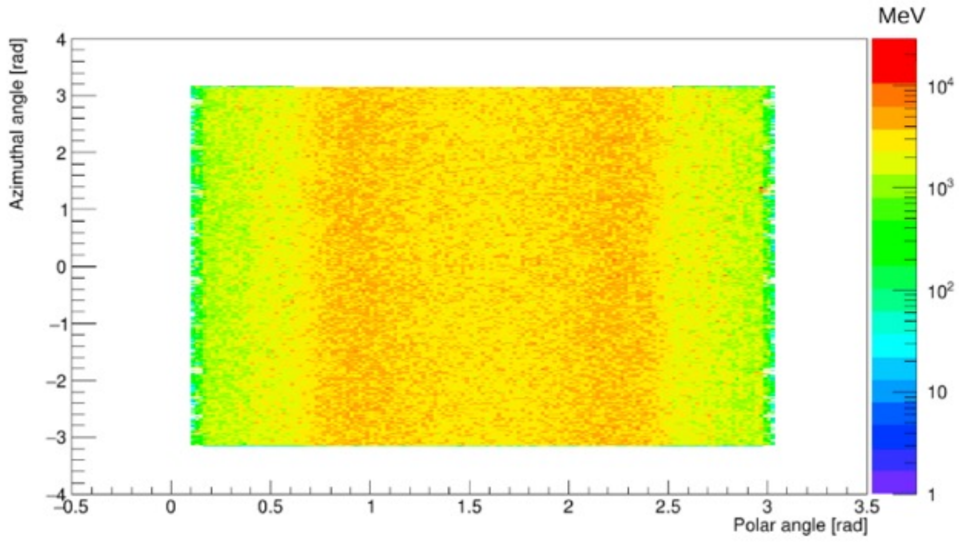


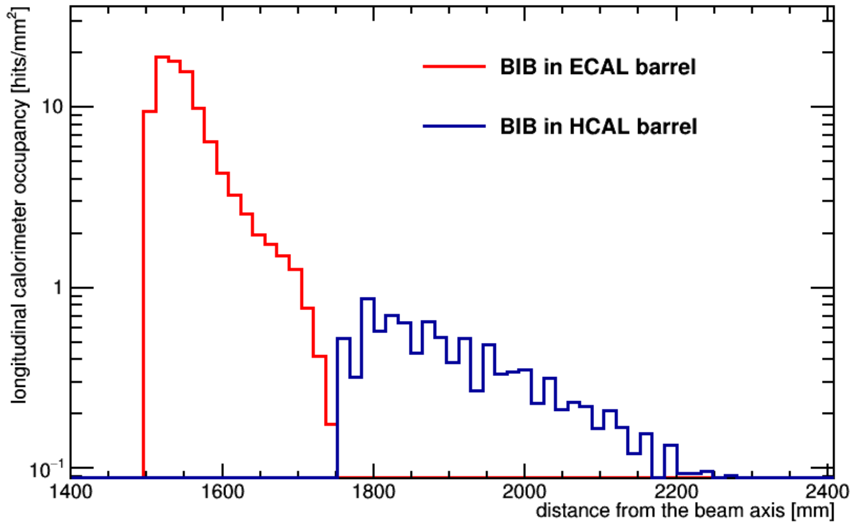




Calorimeters

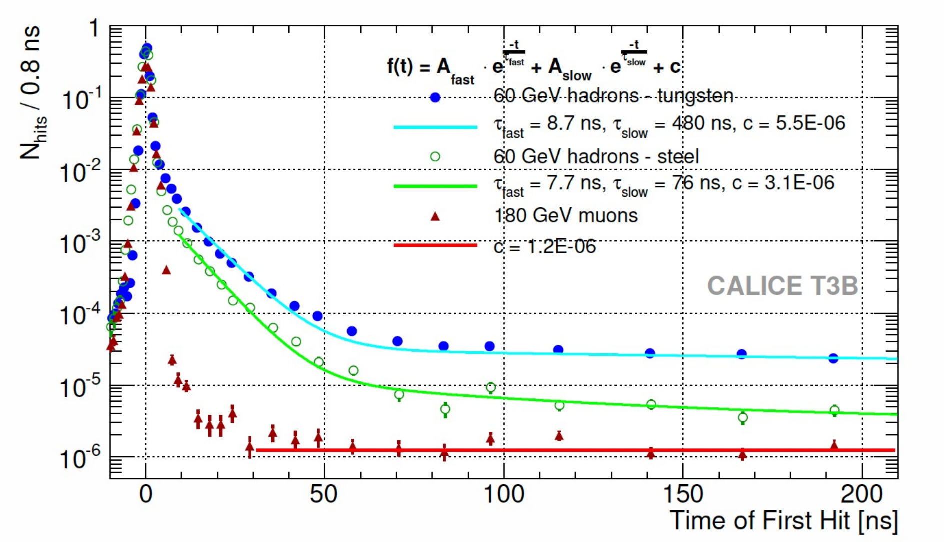
- Utilize Arrival time information to filter hits
- Have a fine enough granularity to see shower shape and directionality
- Energy thresholds to repress soft component
- BIB particles flat in phi, and reasonably flat in theta

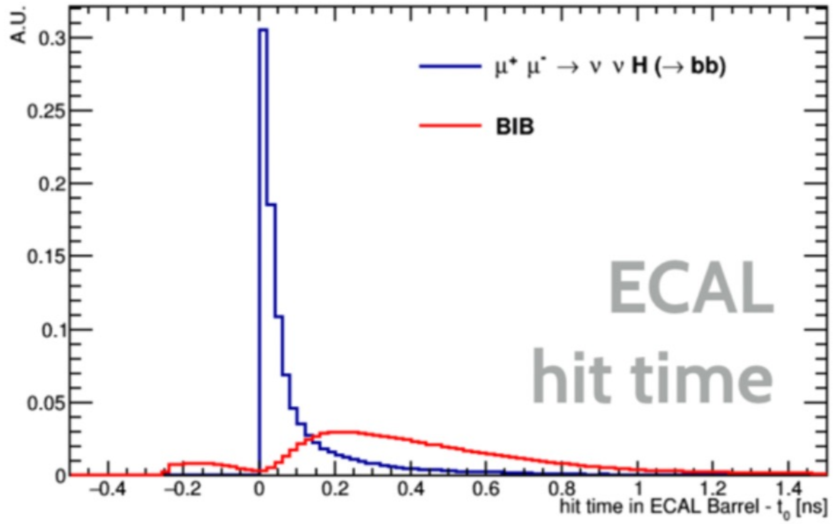


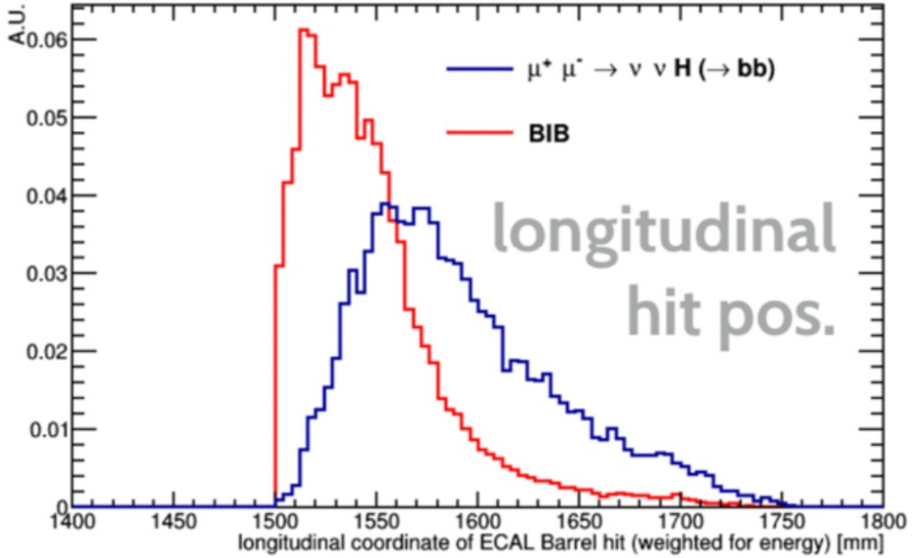


Calorimeters

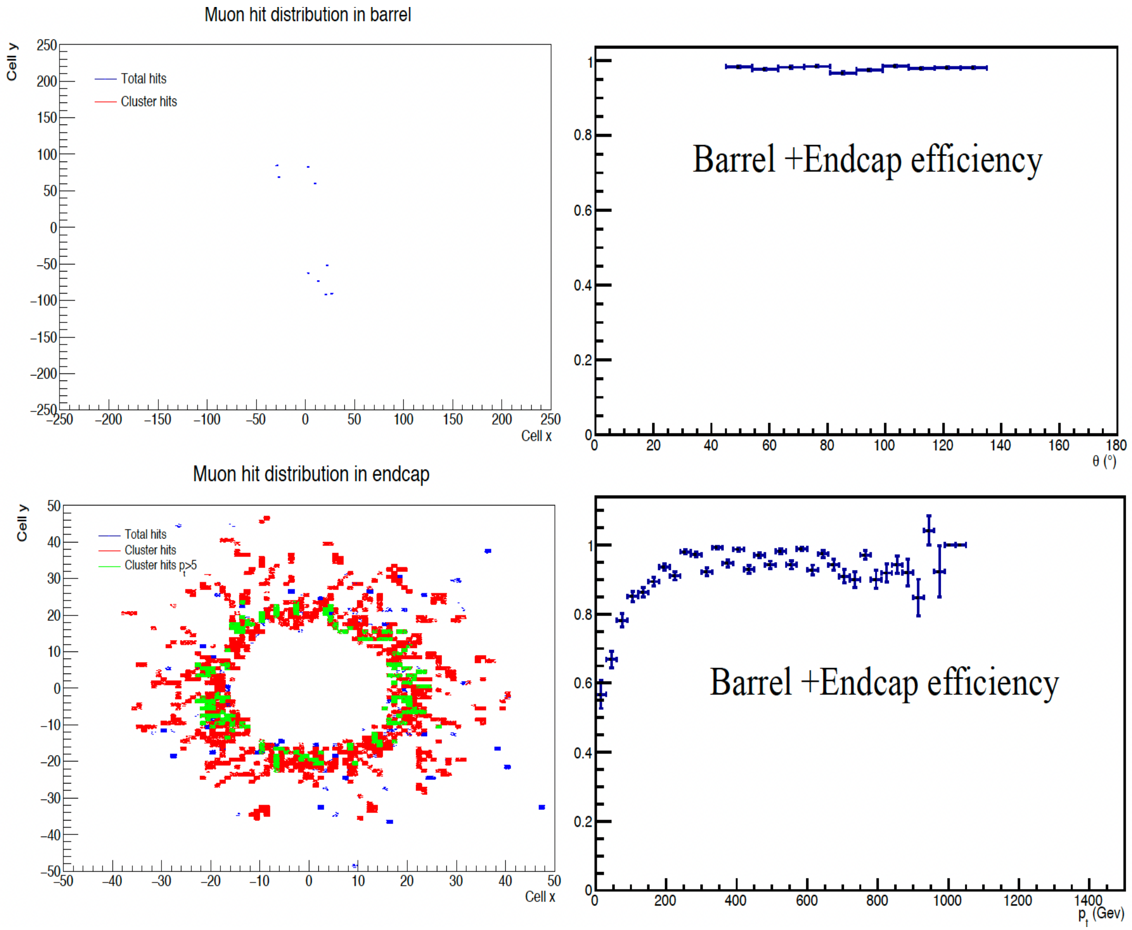
-Possibility to add preshower to absorb
 First part of BIB
-Timing of ecal looks promising
-Hadronic shower development is on a longer scale
(prompt component from ionization on ns time
Scale and much longer tail from particles produced in
Absorbing part of calorimeter)







Muon Systems



- Barrel detector has low occupancy
- Forward muon system close to the shielding cone expected to have higher occupancy from BIB
- Expectation is that "standard" muon detector system in barrel
- Forward muon system may be more challenging

Data Acquisition and Trigger

- Occupancy per module higher (factor of 5-10) than HL-LHC inner detector
  - On detector logic (timing, double layers) and or higher bandwidth
- Total data rates ~30 Tb (dominated by inner tracker)
- Note only 1 bunch per beam! Means 10-20 micro seconds between crossing rather than 25 ns at LHC! (time of beam crossing ~20 ps)
- Preliminary expectation is that a triggerless DAQ could work , perhaps with even today's technology
- However
  - Power and material requirements of higher bandwidth need to be investigated
  - Compression, front end clustering, pt module based selection need to be investigated as well

Conclusions

- Timing Structure and BIB are novel features of a muon collider that present similar but not identical challenges to pile-up with pp but have key differences that drive the overall optimization of a detector
- Generically :
  - High granularity, radiation hard, fast timing (10s of ps) , improved spatial resolution (< 10 micron) , detectors will need to be developed
  - High bandwidth smart front end readout
- Specifically for muon collider detectors:
  - Current designs are based on modified CLIC detector, continued optimization should continue
  - Recall CLIC detector designed with technology expected in next 10 years, should also study how substantial improvements over next few decades could improve performance (what will timing and spatial resolution of detectors look like 20+ years from now?)