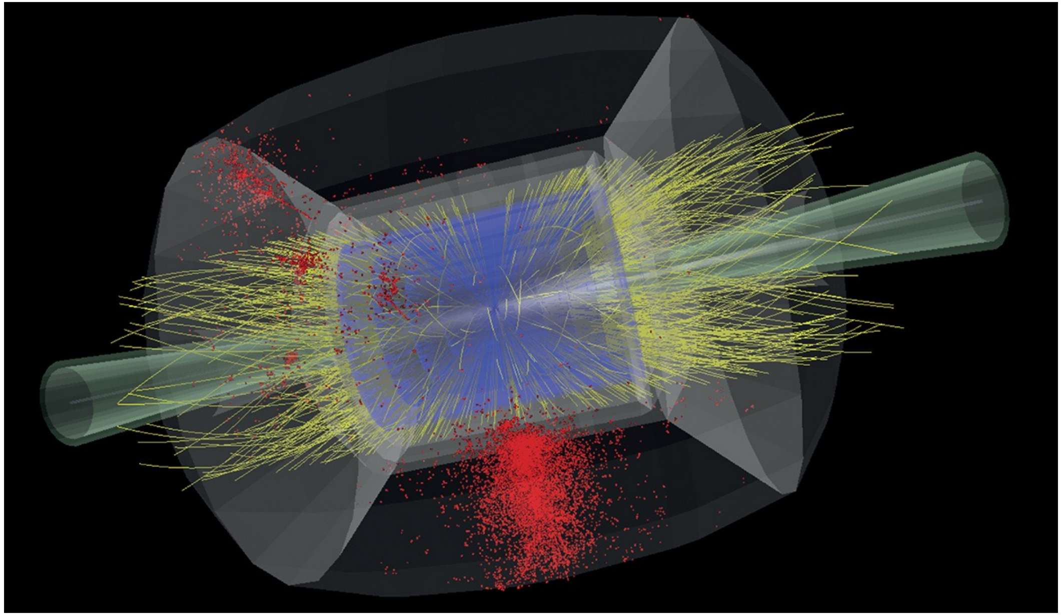


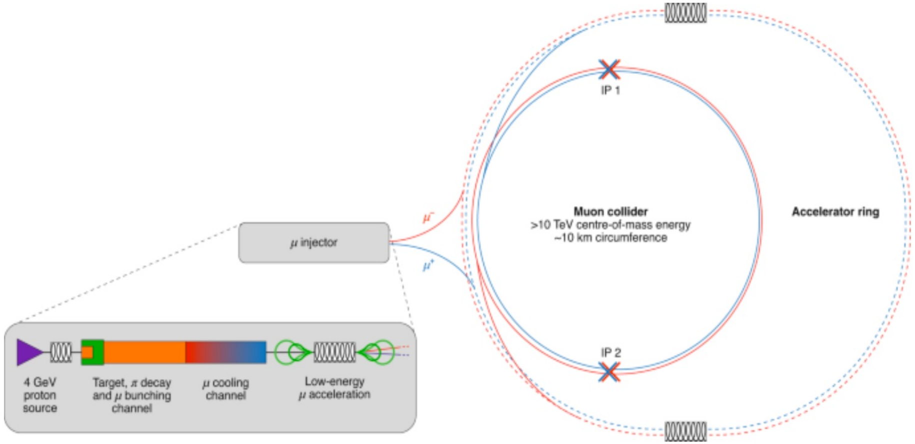
Detector needs at Muon Colliders

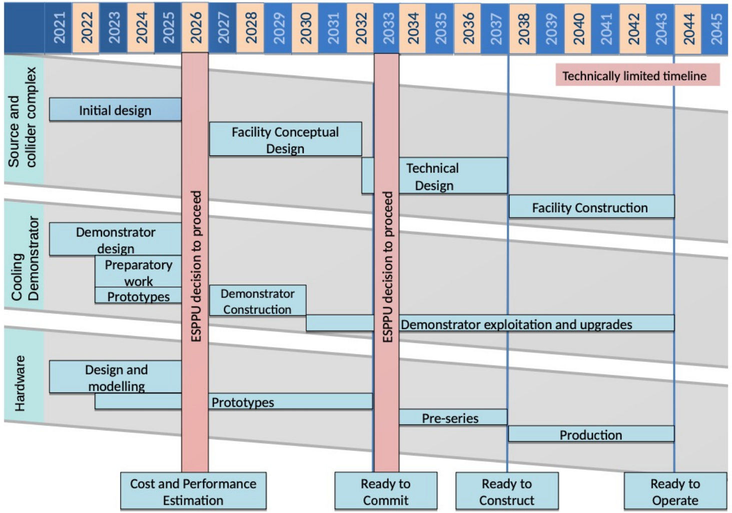
Sergo Jindariani (Fermilab)
Snowmass'2022
July 23, 2022

With huge thanks to contributors of the MC Forum, IMCC, MAP,
Muon Collider Physics and Detector Group

Muon Collider Timeline

Goal to reach 10+ TeV. Staging at 125 GeV, ~ 1TeV and 3 TeV being studied. The focus here is on a ~3 TeV detector





Technically limited schedule

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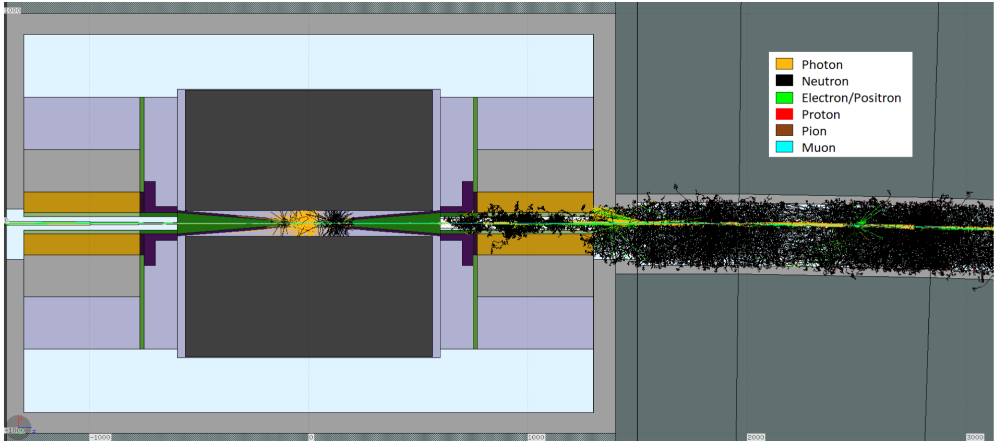
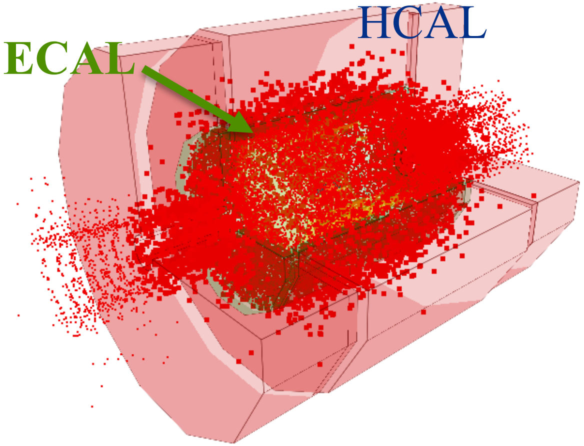
Beam Induced Background

- Beam background is one of the unique features/challenges of Muon Colliders
- Main Source of Beam Induced Background (BIB) are showers produced by electrons originating in beam muon decays
- The challenge is to separate collision particles from the BIB





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Detector

hadronic calorimeter

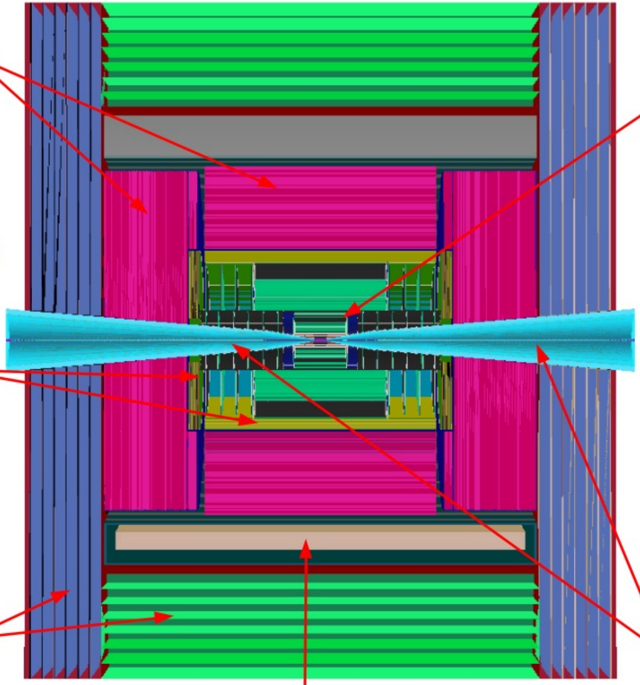
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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

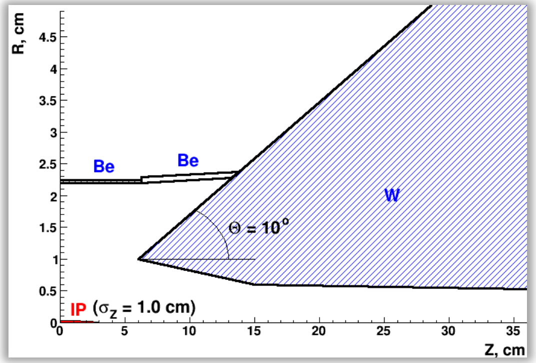
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

~10 degree acceptance limitation due to the nozzles

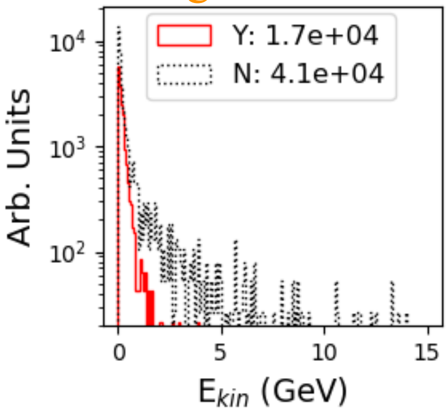
BIB properties



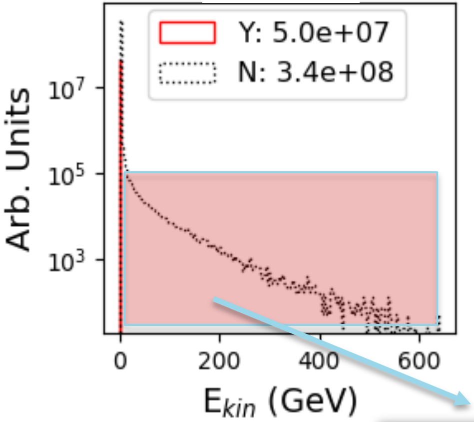
Di Benedetto et al., Journal of Instrumentation13(2018)

F. Collamati et al. 2021 JINST 16 P11009

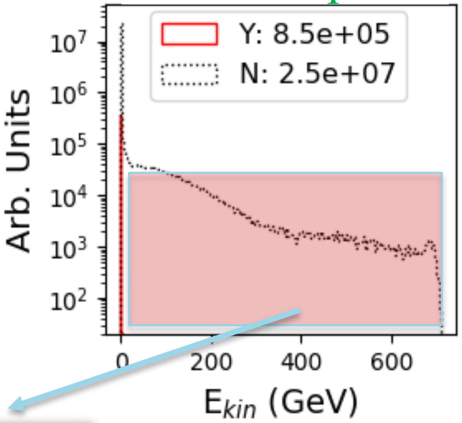
charged hadrons



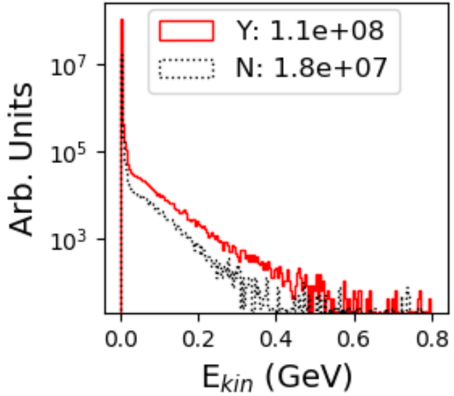
Photons



electrons/positrons



neutrons

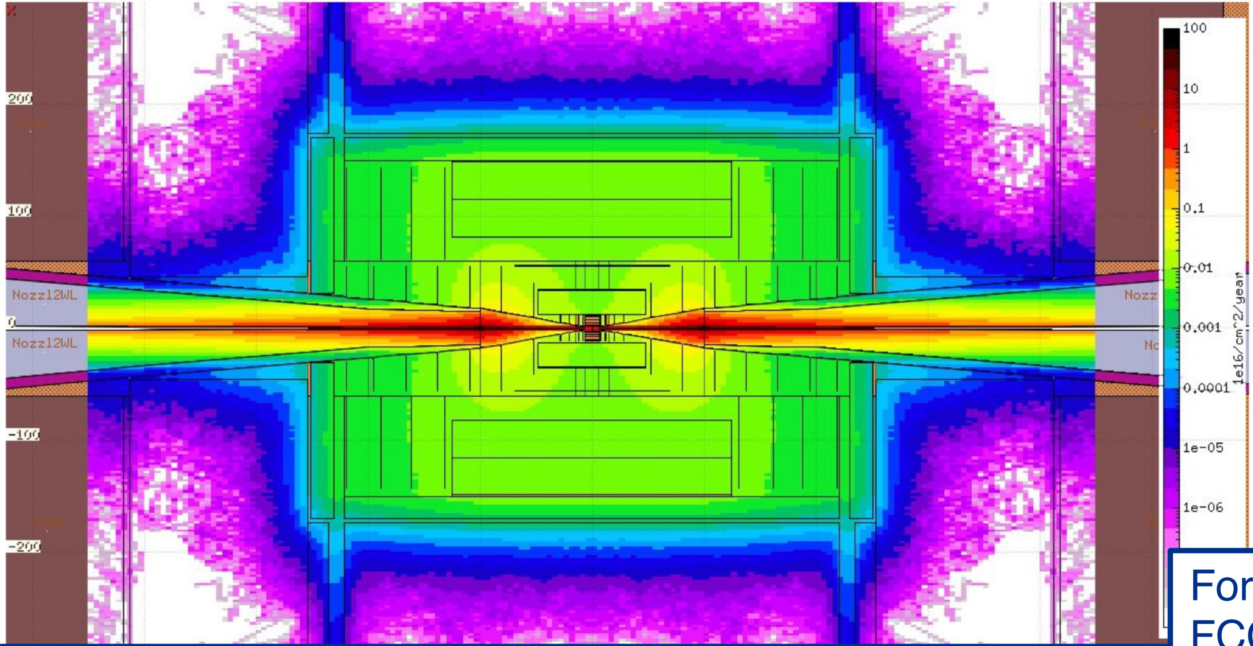


absorbed

lab

Radiation Levels

1-MeV-neq fluence for one year of operation (200 days)

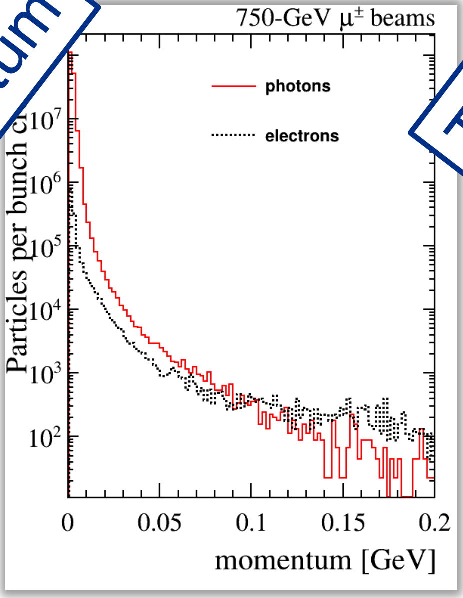


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

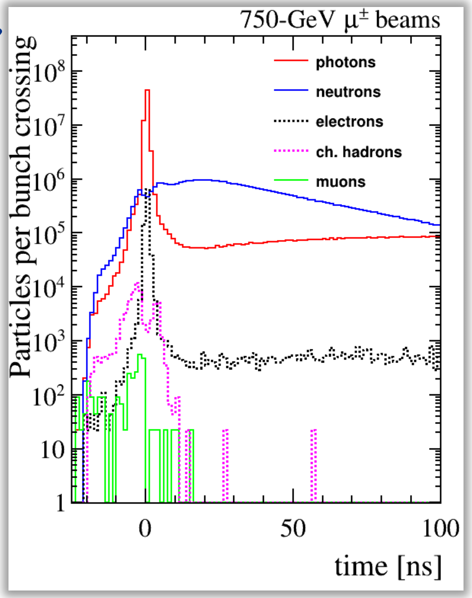
For comparison, FCC-hh requirements are ~10^{18}/cm^2/year

Remaining BIB properties

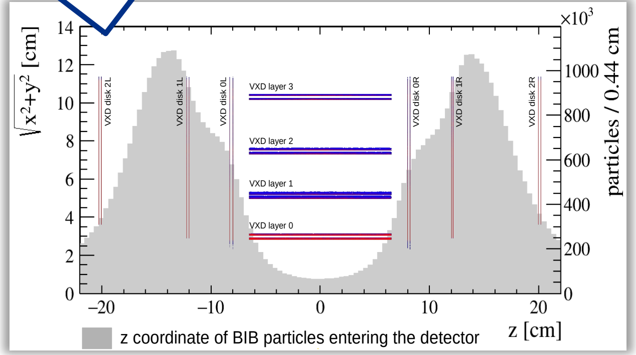
Momentum



Timing



Direction

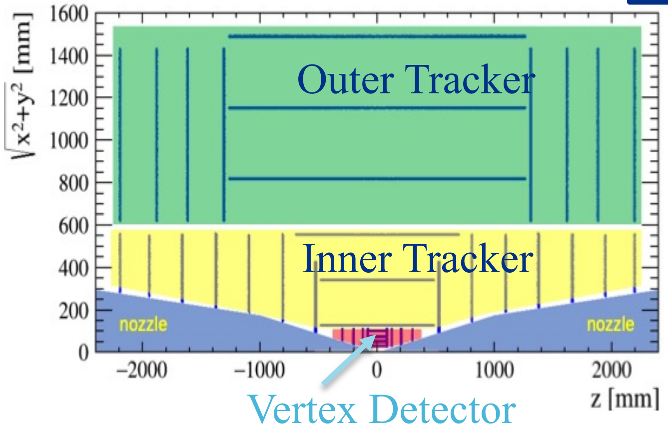


- Low momentum particles
- Partially out-of-time with respect to the bunch crossing
- Often, not pointing to the interaction region

Tracker

- Occupancy in inner layers approximately five times higher than at the LHC
- Goal: bring occupancy to <1% level. Pixel size and timing requirements optimized to achieve this goal
- Other requirements are not unique: low mass/power, radiation tolerance, low noise
- Correlation between layers
- Cluster shape

Detector Layer	ITk Hit Density [mm^{-2}]	Muon Col. Hit Density [mm^{-2}]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.22	0.51
Strip Layer 1	0.003	0.03



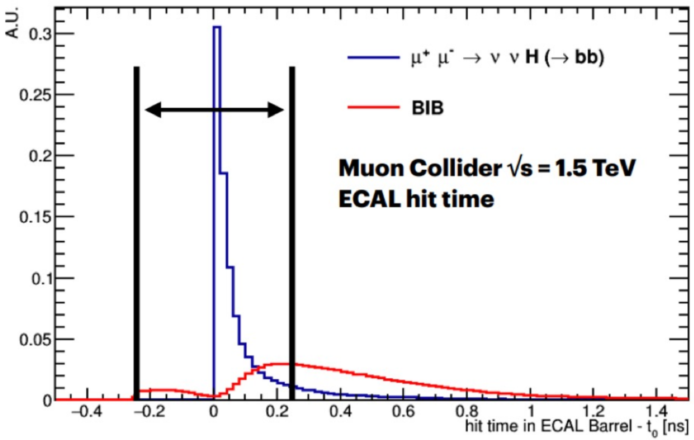
		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	729M
	E	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	462M
IT	B	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	164M
	E	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm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

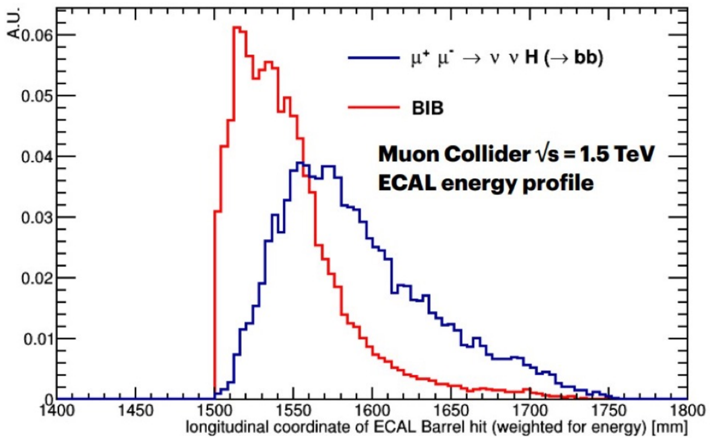
Calorimeters

- BIB dominated by neutrals: photons (96%) and neutrons (4%).
- Ambient energy about 50 GeV per unit area (~40 GeV in HL-LHC)

- high granularity
- precise hit time measurement O(100ps)
- longitudinal segmentation
- *good* energy resolution 10%/√E for photons and 35%/√E for jets or better

- Current Design:
  - ECAL: SiW with 22 X_0, 5x5 mm^2 pads
  - HCAL: Iron+Scintillator with 7.5λ
  - Study hybrid DRO options





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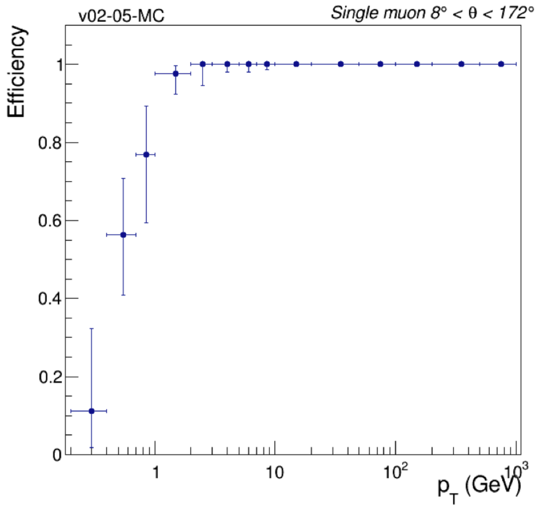
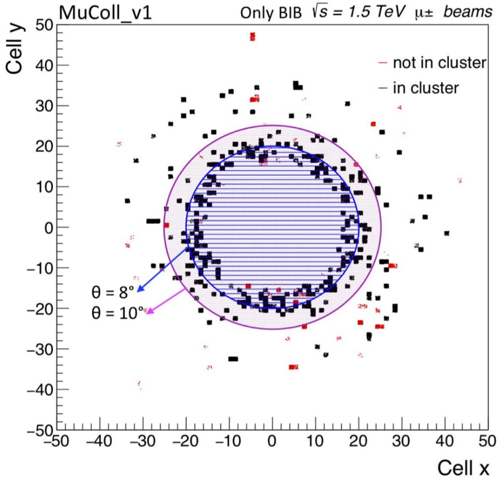
Muons

- Muon system is the lest affected by the BIB
- Current design: gaseous detectors interleaved in an iron yoke
- Targets: 100 micron resolution and 1 ns timing
- High number of hits in the forward disks due to the BIB
    - Some technologies reaching rate limits
    - Some contain gas mixture which has a high Global Warming Potential

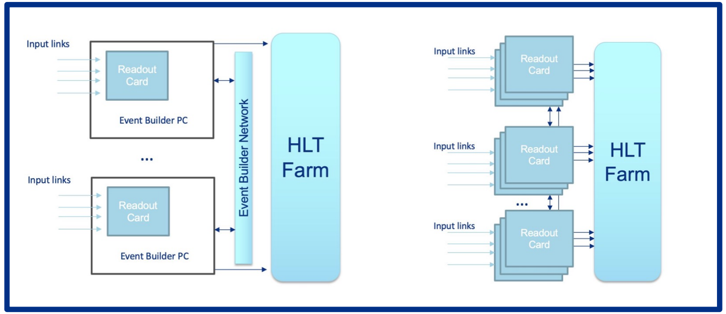




Readout/DAQ Considerations

- Key parameter - beam crossings every 10 µs.
- Streaming approach: availability of the full event data → better trigger decision, easier maintenance, simplified design of the detector front-end...

	Hit	On-detector filtering	Number of Links (20 Gbps)	Data Rates
Tracker	32-bit	$t-t_0 < 1$ ns	~3,000	30 Tb/s
Calorimeter	20-bit	$t-t_0 < 0.3$ ns E>200 KeV	~3,000	30 Tb/s



- Total data rate similar to HLT at HL-LHC ~ **streaming operation likely feasible**.
- Filtering based on event properties or event content
- Bandwidth to disk < 100 Gb/s (plenty for EWK physics)

- High bandwidth and power efficient links, FPGA/GPU acceleration, advanced algorithms

Outlook

- Baseline 3 TeV design established. Many avenues for improvements
- Synergistic with other future collider detector R&D needs
- For 10 TeV the design has to be modified, work is in progress

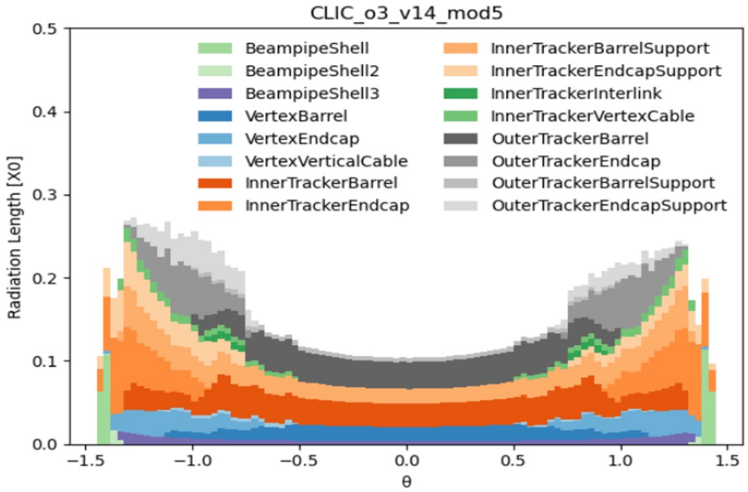
- Snowmass overview papers:
  - https://snowmass21.org/energy/muon_forum (MuC Forum Report)
  - https://arxiv.org/abs/2203.08033 (accelerator)
  - https://arxiv.org/abs/2203.07224 (detector)
  - https://arxiv.org/abs/2203.07964 (performance)

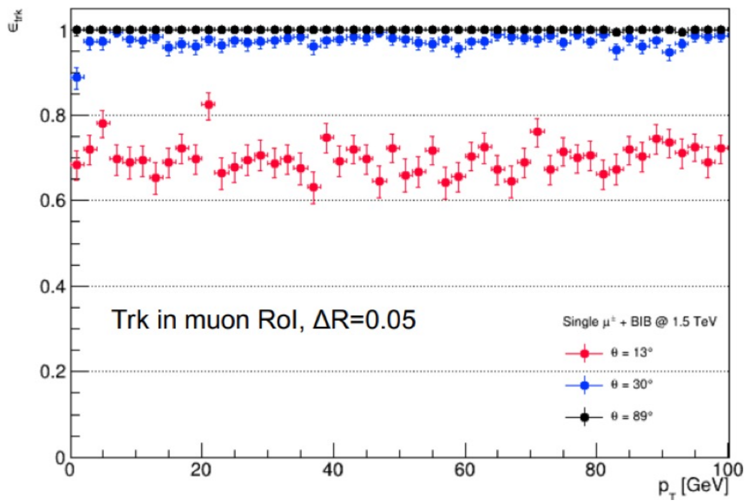
Backup

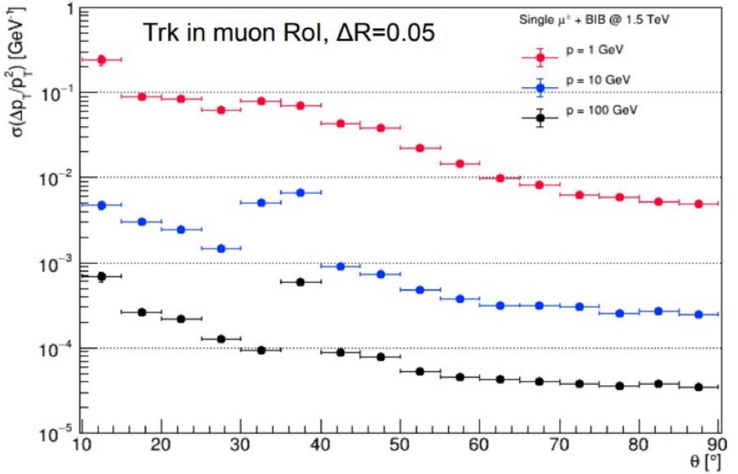
Tracking Performance

Preliminary

- With some basic hit suppression and track level cuts, get good offline track efficiency and resolutions
- Active work on tracking improvements, including Kalman based algorithm

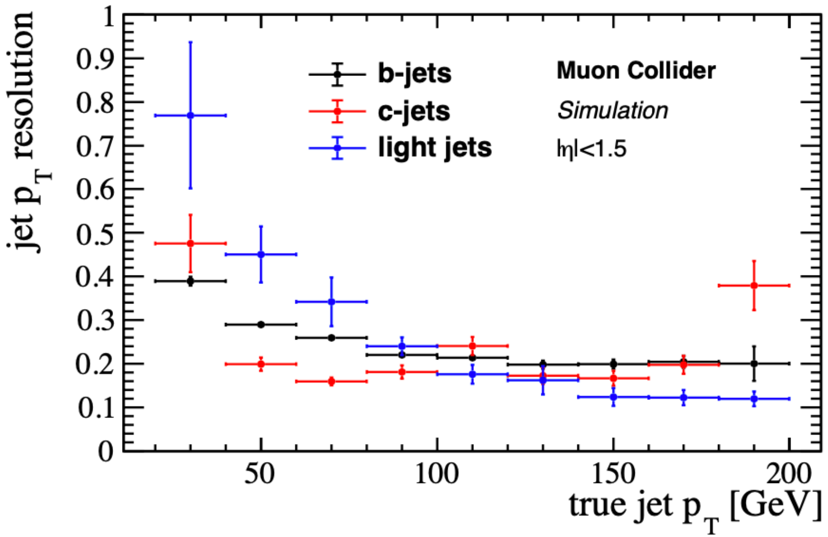


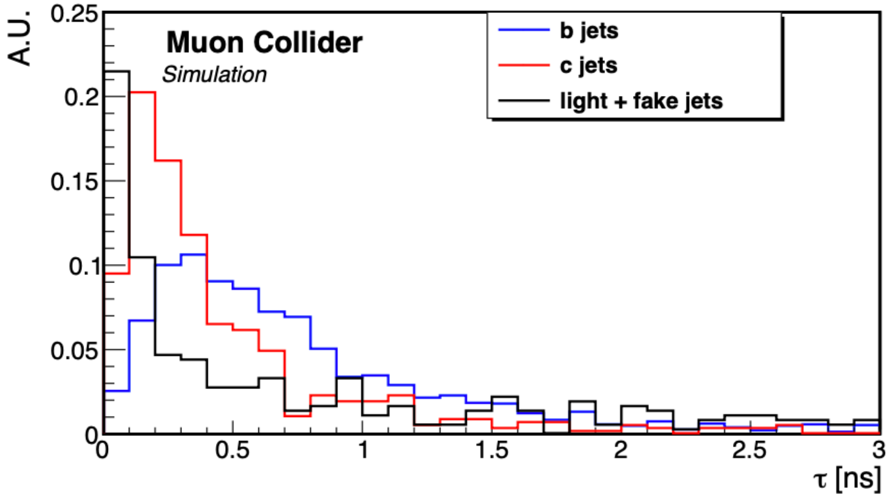




Performance

Preliminary



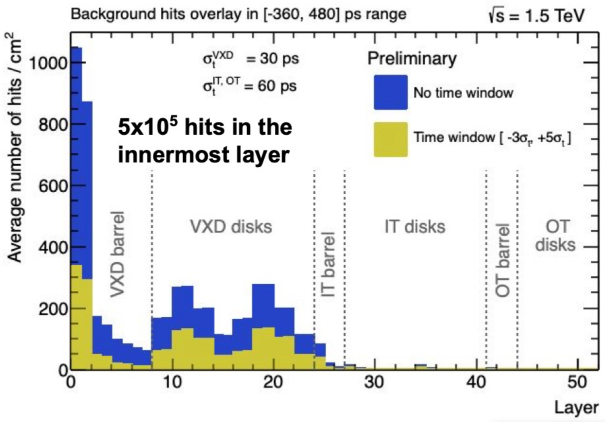


Take advantage of LHC experience with pile-up suppression techniques

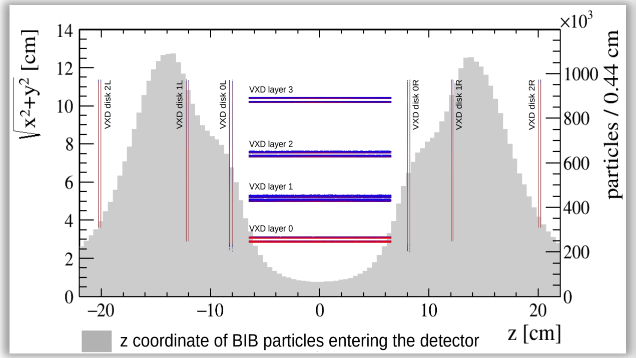
- In progress:
    - Particle-flow reconstruction and particle level pileup removal methods (e.g. Softkiller)

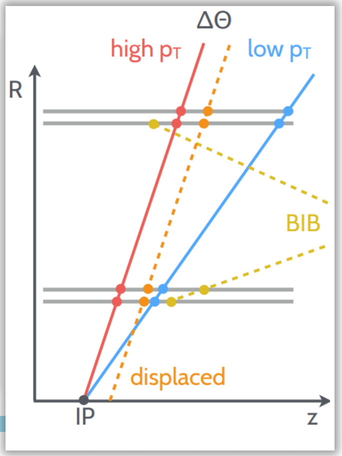
Tracker (2)

- Precision timing is critical for reducing the number of BIB hits. Up to a factor of x3 reduction in the inner layers
- Correlation between layers (a la CMS pT module) provides additional large reduction
- Other handles exist
- Some on-detector filtering may be needed



Example R&D:
- Monolithic devices
- AC-LGADs
- 3D hybrid pixels
- Intelligent sensors
- Common challenges: services, cooling, low-power ASICS





BIB as function of Energy

	MARS15	MARS15	FLUKA	FLUKA	FLUKA
beam energy [GeV]	62.5	750	750	1500 MDI Not Optimized	5000 MDI Not` Optimized
μ decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
μ decays/m per beam (for 2×10^{12} μ/bunch)	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
photons/BX (E_γ > 0.1 MeV)	170×10^6	86×10^6	51×10^6	70×10^6	116×10^6
neutrons/BX (E_n > 1 meV)	65×10^6	76×10^6	110×10^6	91×10^6	89×10^6
$e^\pm$/BX (E_e > 0.1 MeV)	1.3×10^6	0.75×10^6	0.86×10^6	1.1×10^6	0.95×10^6
charged hadrons/BX (E_h > 0.1 MeV)	0.011×10^6	0.032×10^6	0.017×10^6	0.020×10^6	0.034×10^6
muons/BX (E_h > 0.1 MeV)	0.0012×10^6	0.0015×10^6	0.0031×10^6	0.0033×10^6	0.0030×10^6

Approximately flat