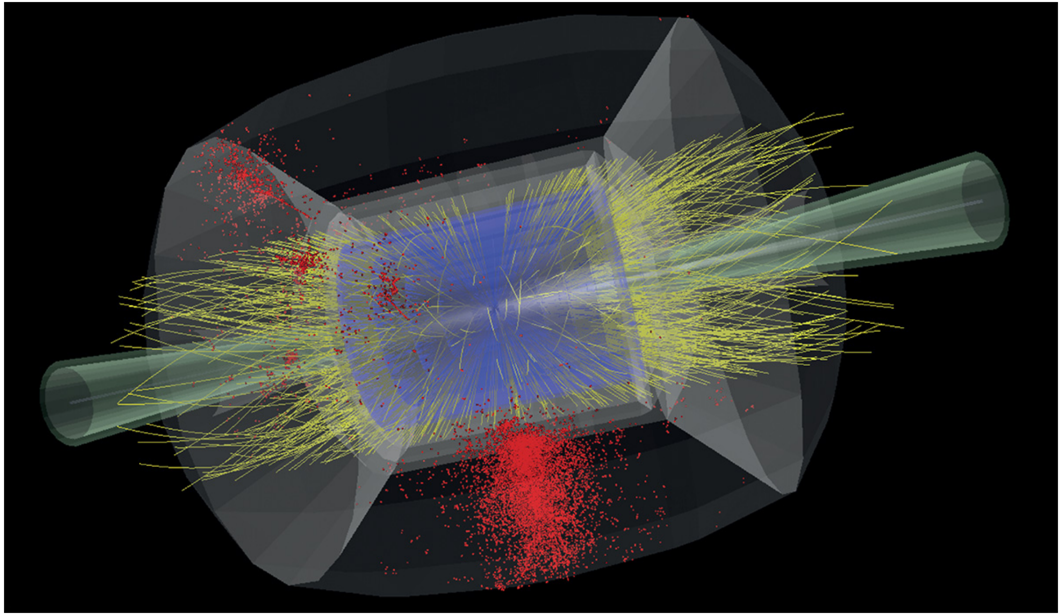

Detectors for a Muon Collider

Sergo Jindariani (Fermilab)

CPAD'2021

March 18th, 2021

On behalf of:

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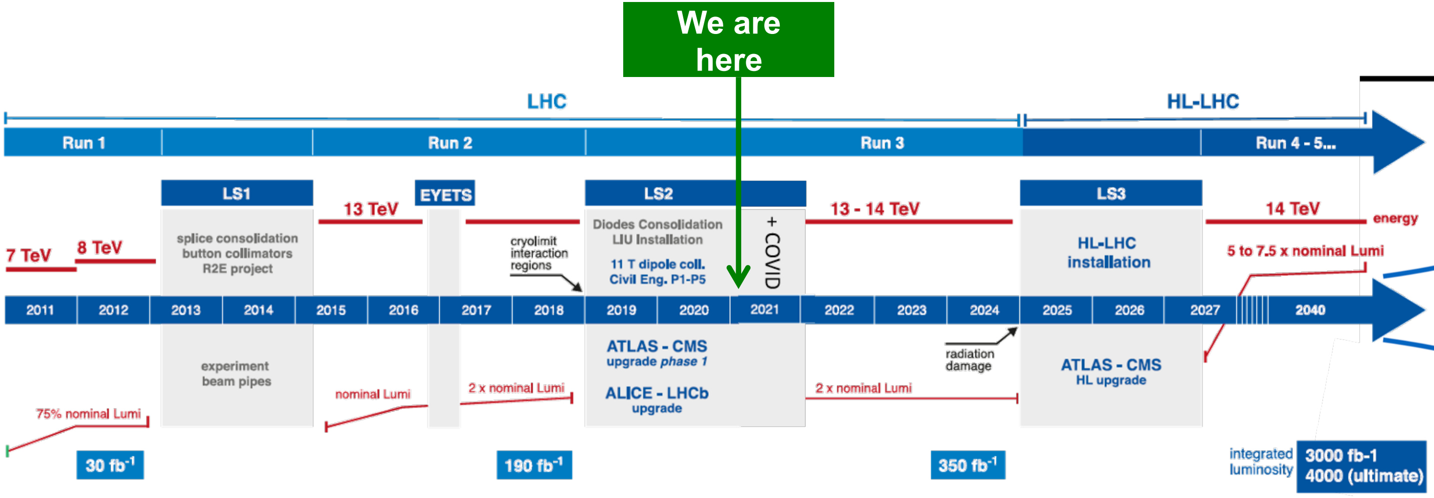
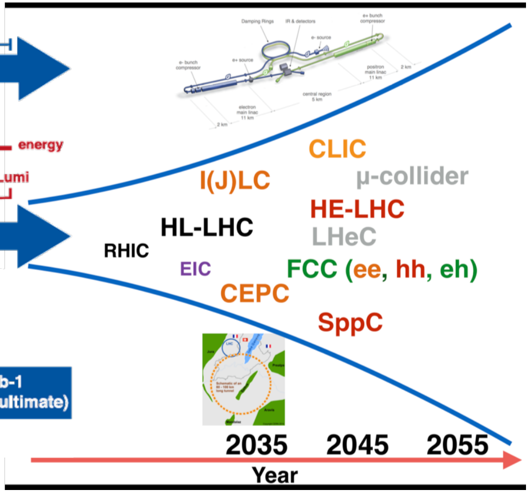
Collider Landscape





LHC + HL-LHC is the largest pp dataset for the next few decades

Variety of post-LHC colliders proposed globally

Muon Colliders

- Provides a powerful and versatile tool for HEP explorations
  - Colliding elementary particles
  - Less synchrotron radiation – can use circular accelerators
  - Luminosity per energy consumed
  - path to very high energy collisions (with plasma?)

- The 2020 Update of the European Strategy for Particle Physics recommended to "investigate the possibility to have bright muon beams"

- Resurgence of interest in Muon Colliders within Snowmass
  - Expertise in the US following the Muon Accelerator Program (MAP)

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

VBA

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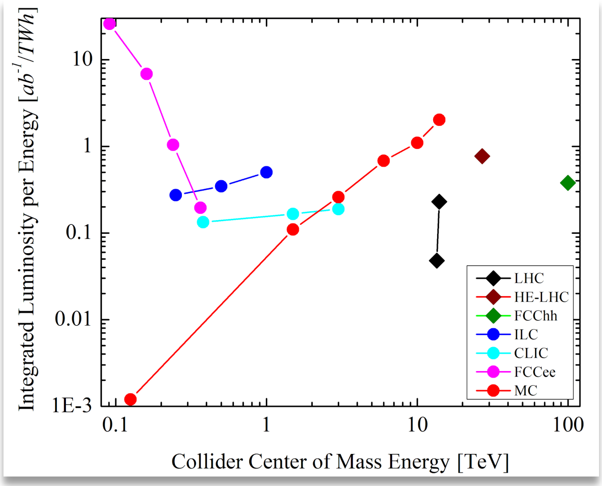
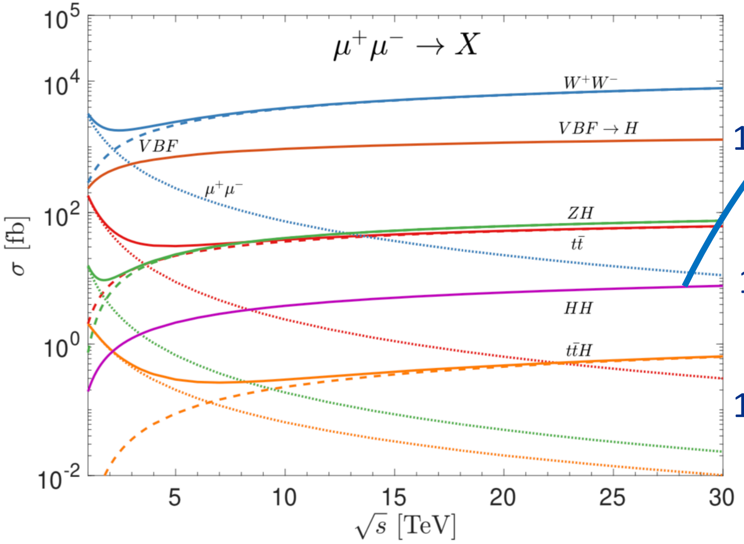
Collisions of electrons and protons in storage rings and competing high intensity muon beams can be used to study quark dynamics. It is easy to see that 10 TeV muon beams of very high luminosity (~ $10^{36} cm^{-2} sec^{-1}$) can be achieved.



Physics at Muon Colliders

[10 ab^{-1}]

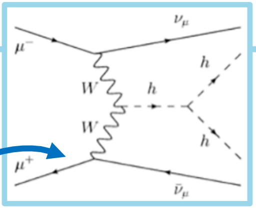


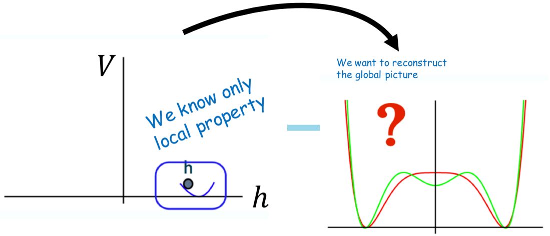
10^7 ev

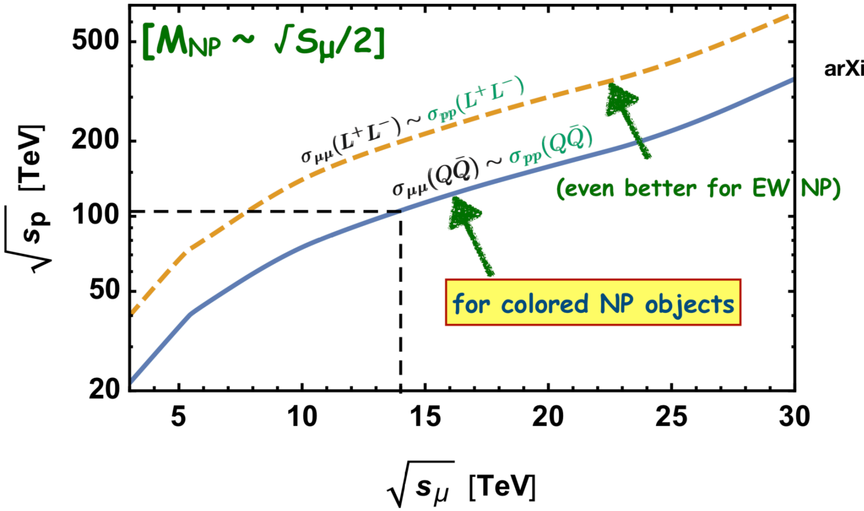
10^5 ev

10^3 ev

[T. Han, Y. Ma, K.Xie 2007.14300]







arXiv:1901.06150

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Object Requirements

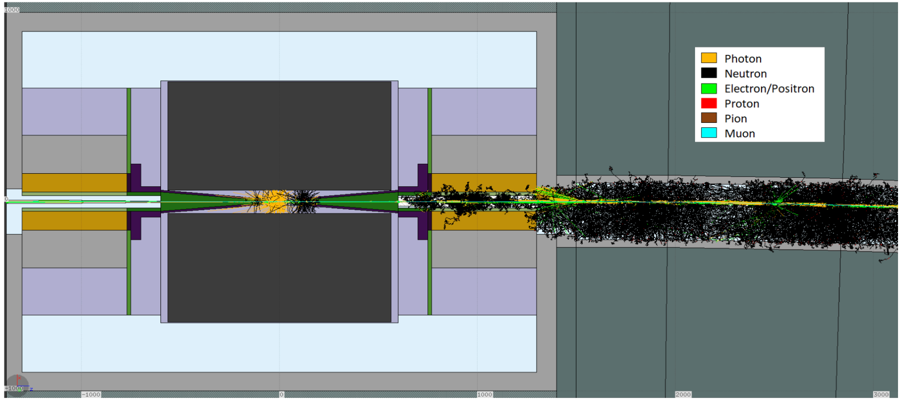
- Excellent track efficiency and momentum resolution – e.g. for Higgs final states with leptons.
- Good ECAL energy and position resolution for e/gamma reconstruction.
- Good jet energy resolution (e.g. separate hadronic Higgs/V decays, W vs Z?)
- Efficient identification of a secondary vertex for heavy quark tagging (both bottom and charm)
- Other considerations (Missing Energy/MET, taus, substructure)

- Some ILC or CLIC considerations apply to Muon Collider detectors, although it is important to remember that beam background conditions are different and much more challenging in the case of the Muon Collider.
- Optimal design will very likely be different for different collision energies

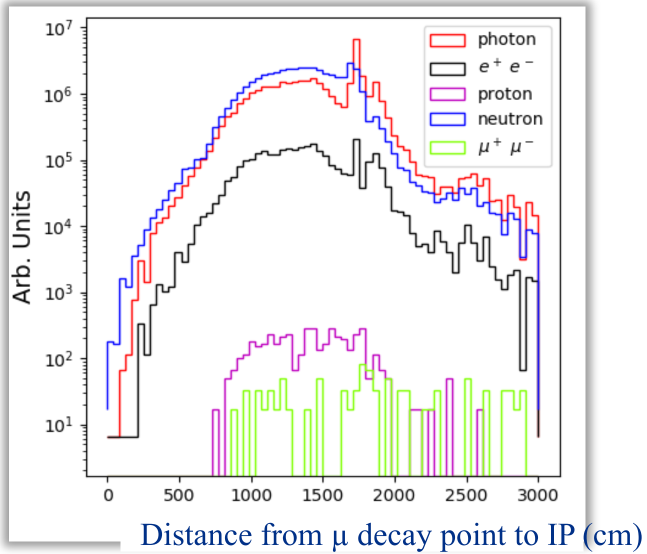
Beam Induced Background

- Three main challenges identified in the past: beam background, high power targets and neutrino radiation
- Muons decay with an average lifetime of $2.2 \cdot 10^{-6}$ seconds at rest, at $\sqrt{S} = 3$ TeV they live for about $3.1 \cdot 10^{-2}$ seconds
  - beam 1.5 TeV $\lambda = 9.3{\times}10^{6}$m, with $2{\times}10^{12}\mu$/bunch $\Rightarrow 2{\times}10^{5}$decay per meter of lattice.
- Main Source of Beam Induced Background (BIB) are beam muon decays
- Physics performance depends on the multiplicity and energy of BIB particles entering various subdetector components

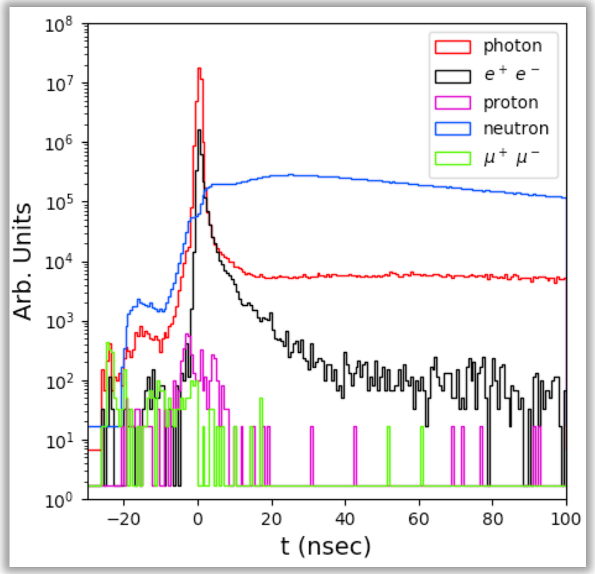
beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E^{kin}_{\text{ph.}} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E^{kin}_{\text{n}} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E^{kin}_{\text{el.}} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E^{kin}_{\text{ch.had.}} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E^{kin}_{\text{mu.}} > 1$ MeV)	2.5×10^3	2.7×10^3



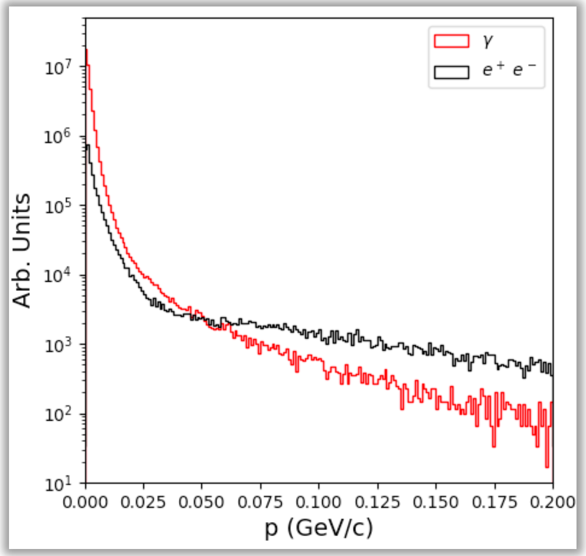
BIB properties



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



Secondary and tertiary particles have low momentum

Detector

hadronic calorimeter

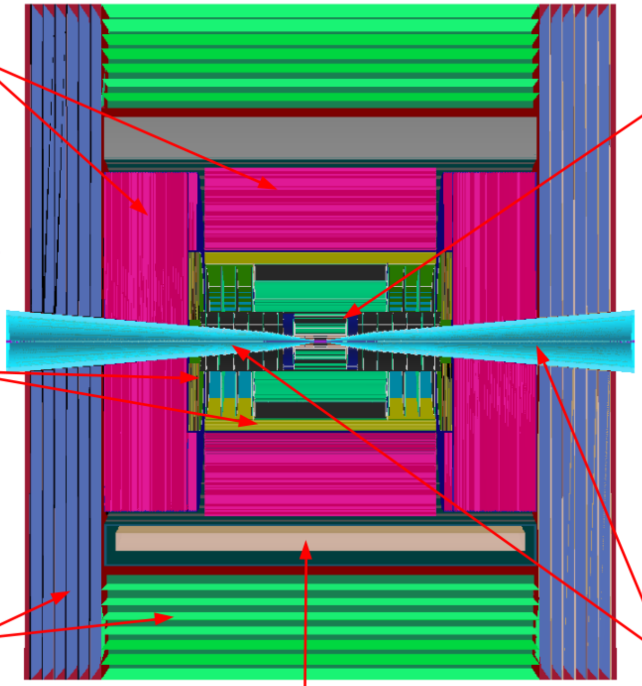
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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

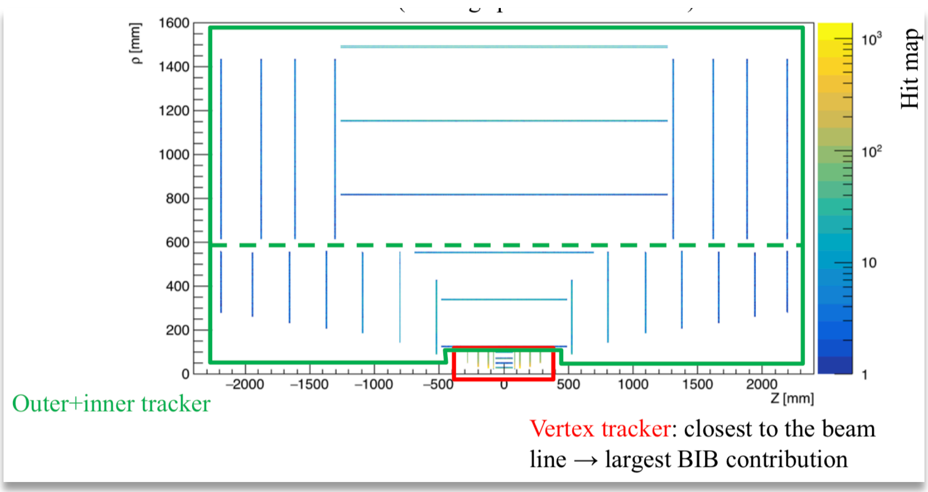
- Tungsten cones + borated polyethylene cladding.

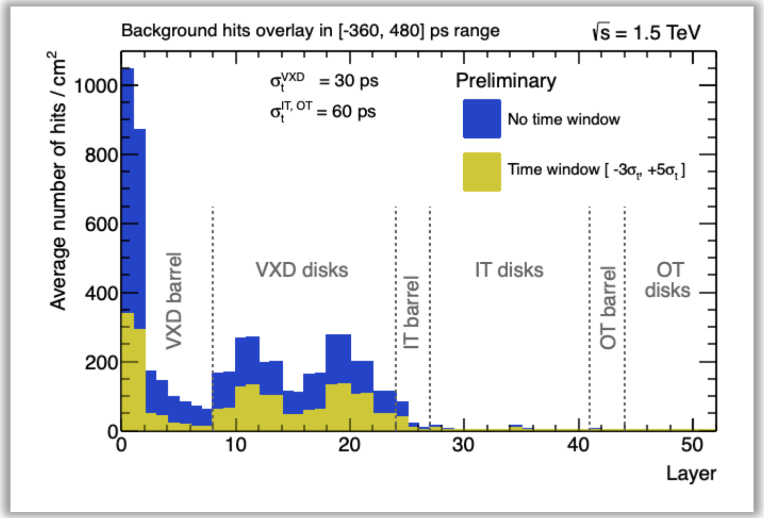
10° acceptance limitation due to the nozzles

+ few degrees of extreme occupancy in the vertex detector

Tracker

- The goal was to bring tracker occupancy to under 1% level
- With smaller pixel/strip size most of the detector can use modest timing resolution of ~60 ps.
- For innermost vertex/inner barrel layer, will benefit for better timing of 20-30 ps.
- Leads to tracker with total number of channels ~ 2B (similar to Phase-2 ATLAS/CMS).





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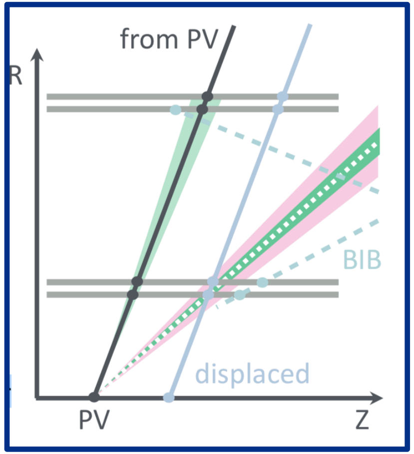
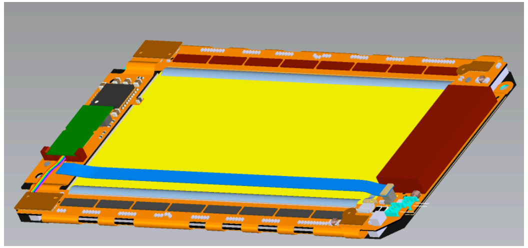
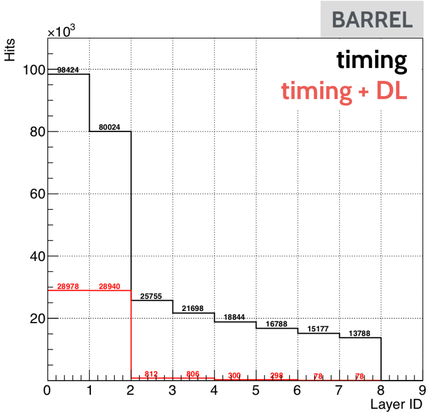
Tracker (2)

- Angles can be measured by correlating hits between adjacent sensors. This is the approach used for the CMS track trigger.
- The PS module uses short and long strips and is essentially a 1D problem.
- Pixels are 2D and there is the additional complexity of encoding and decoding of hit positions to the target IC for position correlation. This will add power and complexity.
- Studies of single sensor track angle filter (based on cluster shapes) are ongoing.





CMS pT-module



Dramatic improvement (x1000) in tracking speed with timing +DL

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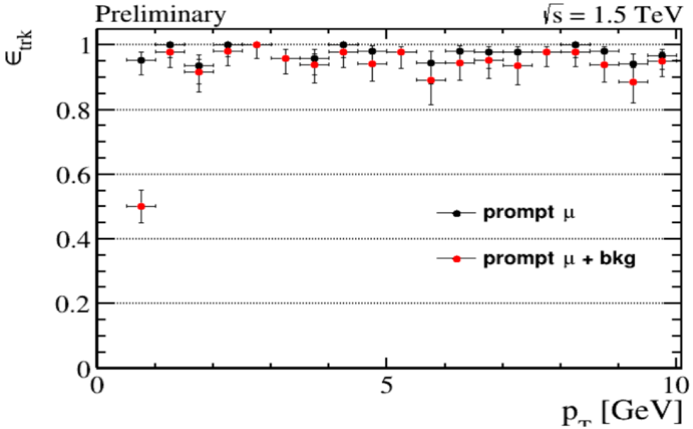
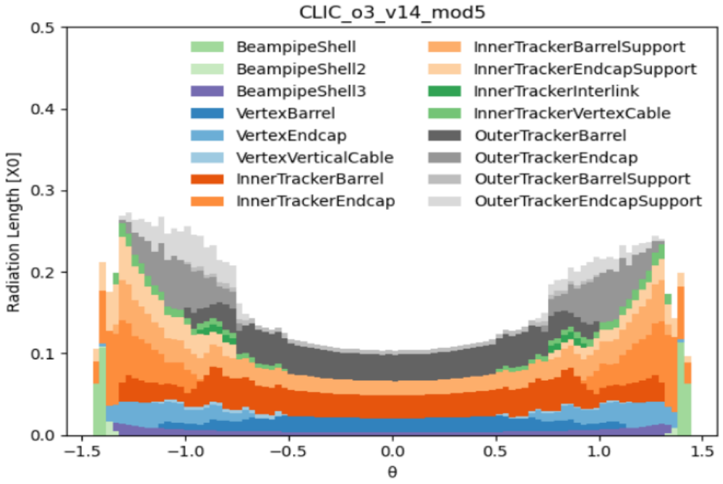
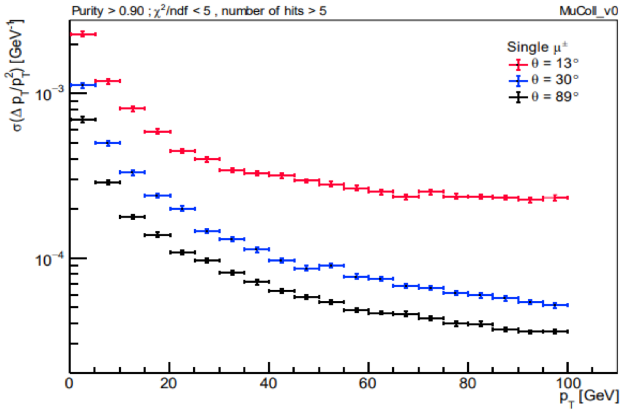
Tracking Performance

- With some basic hit suppression and track level cuts, get good offline track efficiency and resolutions
- What about online filtering to reduce readout burden? (later in the talk)

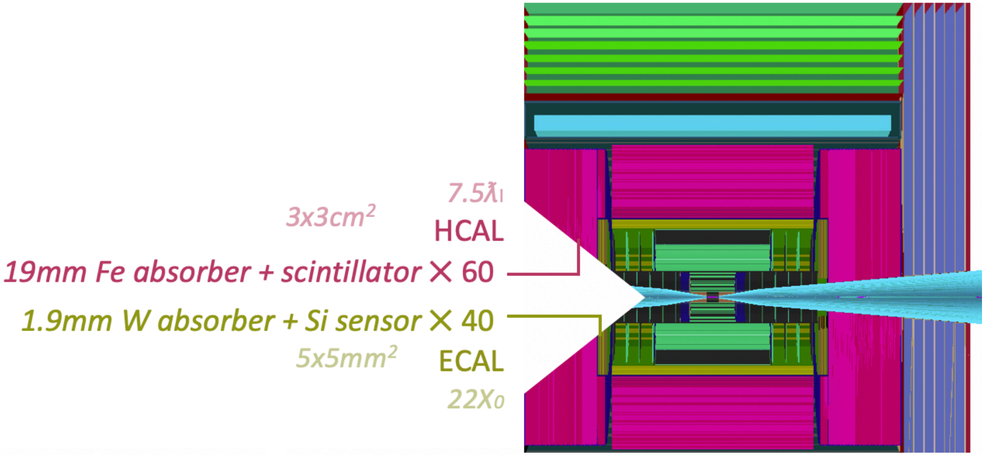




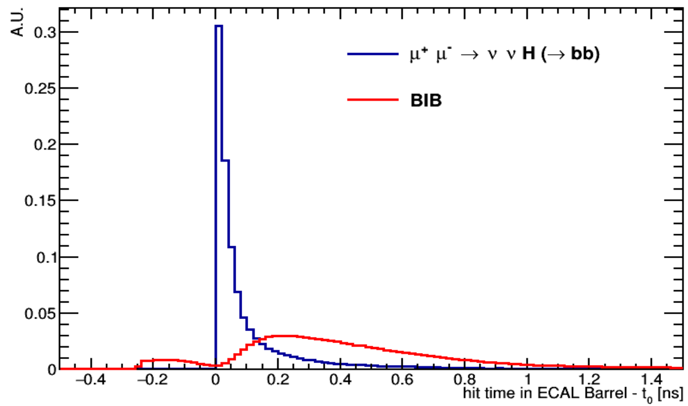


Calorimeters

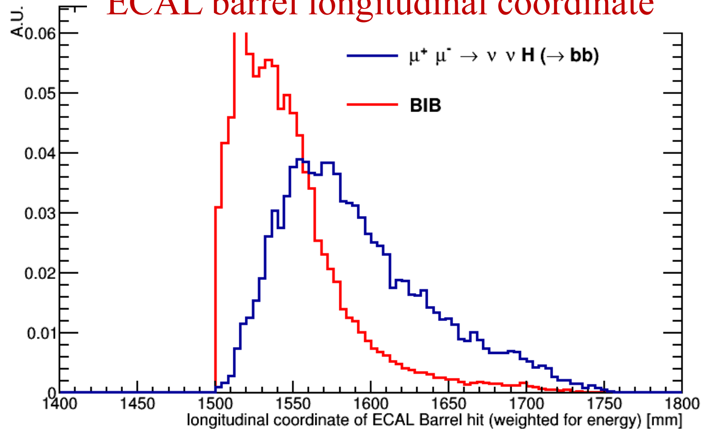
- Current simulation is based on Silicon + tungsten for ECAL and Iron+Scintillator for HCAL.
- BIB deposits large amount of energy in both ECAL and HCAL.
- Timing and longitudinal shower distribution as key discriminant



ECAL barrel hit arrival time – t_0

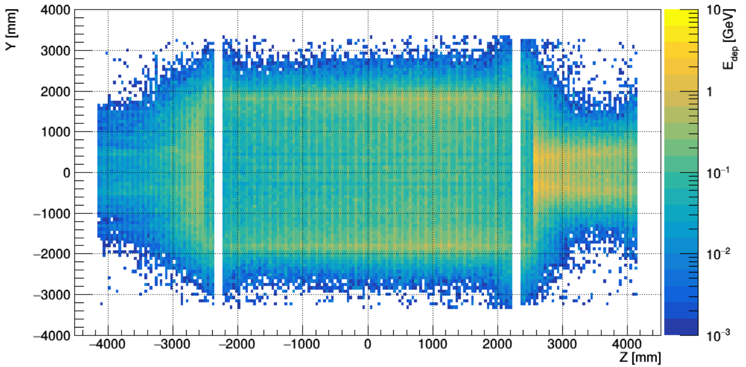


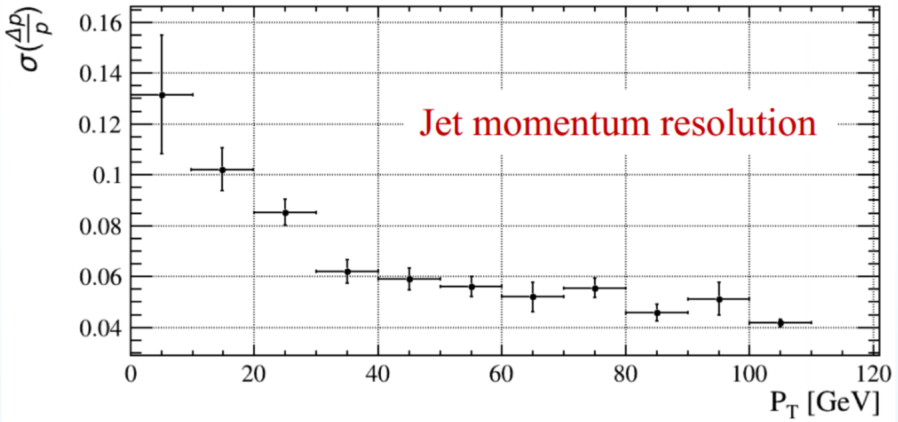
ECAL barrel longitudinal coordinate

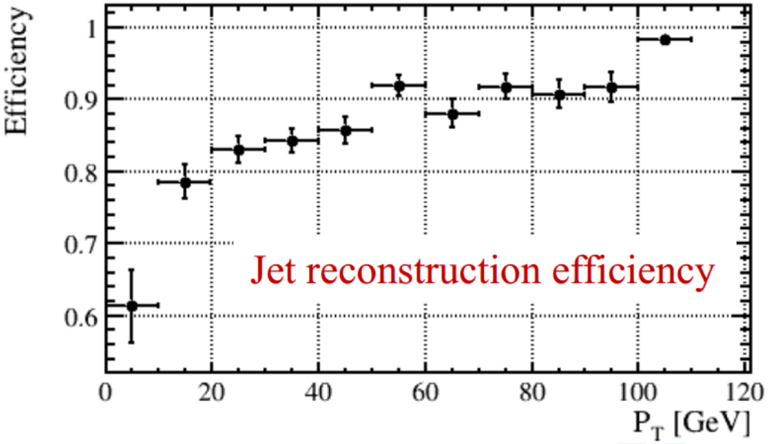


Calorimetry Performance

- Take advantage of LHC experience with pile-up suppression techniques
- In progress:
  - Particle flow algorithm
  - Particle level pileup removal methods (e.g. Softkiller)

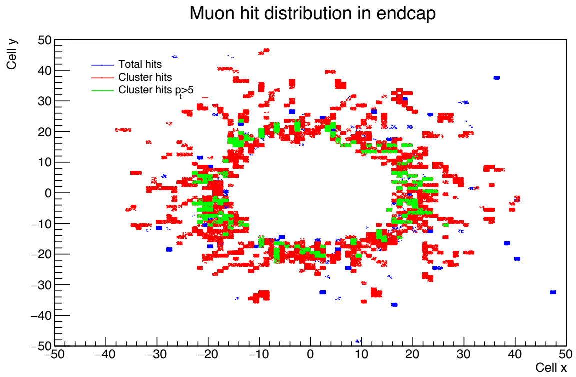


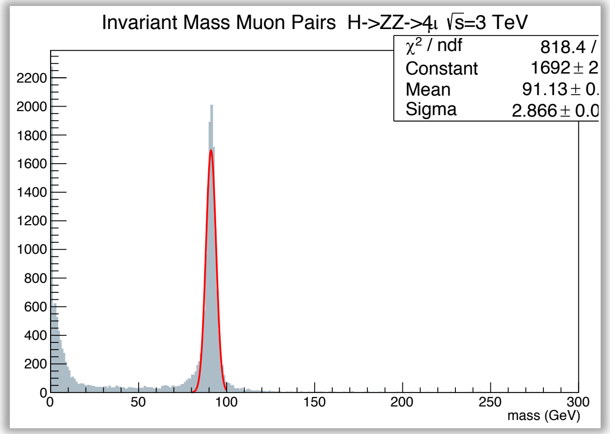


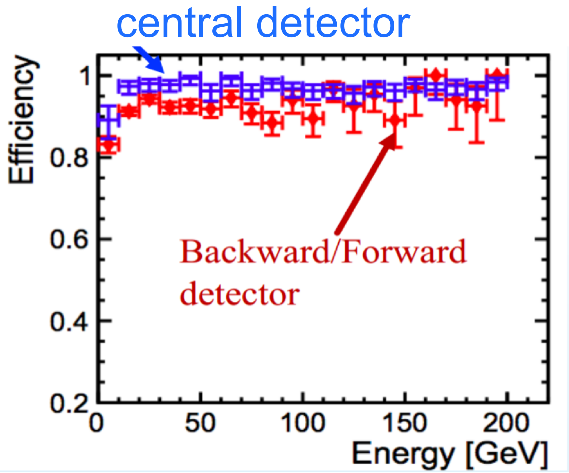


Muon Reconstruction

- Combined tracker + muon reconstruction
- High number of hits in the forward disks due to the BIB
- Good efficiency observed throughout the momentum and rapidity range, further improvements in progress







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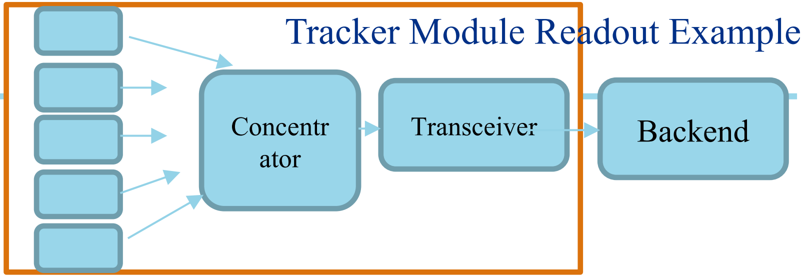
Readout/DAQ Considerations



- Data => bandwidth => power
  - Note time between collisions is 10 us= 100 kHz
- Assuming module size of 20 cm^2
  - With 50x50 microns pixel size, get ~800k pixels per module with 1ns window
  - With 1% occupancy, this is up to 8k hits per module in the inner vertex tracker
  - 32 bits to encode x/y/amp/time
- Data rates: 8k hits * 32 bit * 100 kHz * 2(safety factor) ~ 50 Gbps per module (20 cm^2) ~10 Gbps per FE Chip (4 cm^2)
  - Double compared to HL-LHC FE chip. Requires R&D.
  - More online handles should be explored: Data compression, some front-end clustering, pT-module based suppression (preliminary estimates indicate x5 rate reduction)
  - Downstream electronics needs to be able to accommodate this bandwidth

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Trigger/DAQ Considerations

- Occupancy in the inner layers is significantly higher in the inner vertex detector layers than at the HL-LHC. Quickly falls outside of the first 2 layers.
- Total data rates at 1.5 TeV for the tracker alone are ~30 Tbps with **1 ns readout window.**
    - Calorimeters will contribute at ~ same level.
    - ~100-200 readout boards running 10-20 Gbps upstream links

- Similar to upgraded LHCb readout network (40 Tbps). LHCb has smaller per event data volumes (~8800 5Gbps links) but operates at 40MHz (vs 100kHz for the Muon Collider)
- Triggerless readout could work for this configuration. Total data rates do not look crazy even with today's commercial technology. Accelerators (GPU, FPGA) will be important. A lot to learn from LHCb experience.

- Studies are needed to understand system requirements at higher collider energies (different BIB) and larger readout windows (for non-pointing, slow, heavy particles)
- Feasibility of triggerless readout for such scenarios need to be investigated. Note, time between bunch crossings is very important

Summary and Outlook

- A high energy Muon Collider is a very appealing future collider option
  - Potentially can serve as a Higgs factory while providing direct reach for New Physics

- Beam Induced Background is a major challenge for Muon Colliders
  - Detectors have to be designed with BIB in mind
  - Smart trackers with high granularity and timing capabilities
  - PF Calorimetry with good timing capabilities
  - Innovative event reconstruction strategies exploiting time correlations between different subdetectors

- Online tracker hit and calorimeter cluster filtering is very important for keeping the readout size at the manageable level. Once a conservative online filtering applied, a trigger-less readout appears to be an appealing option (at least for lower energy machines)

- Further studies and detector R&D in the areas above are necessary to solidify the case for a Muon Collider