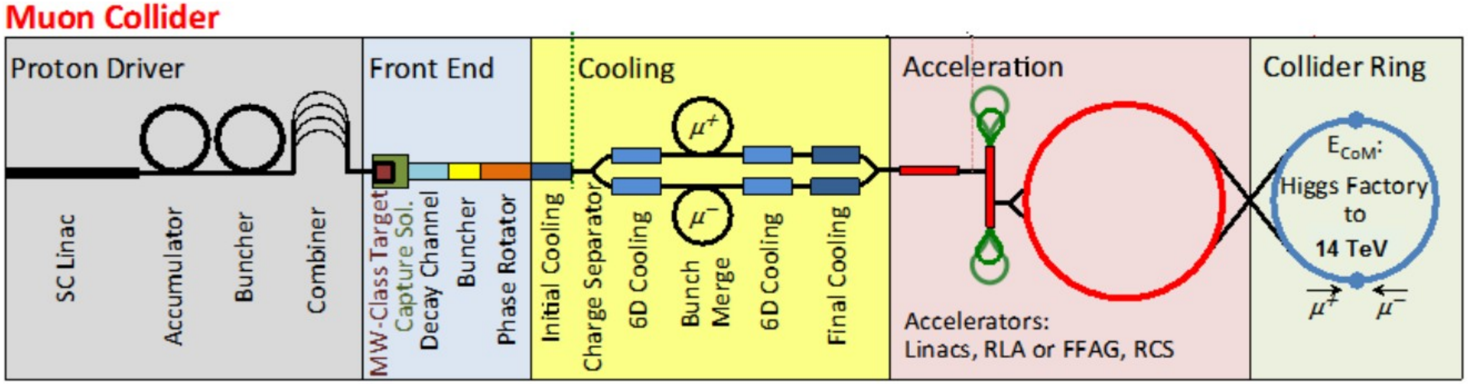
Muon Collider Detector Studies

S. Pagan Griso (LBNL)
Reporting the work of many people

Muon Collider Explorations

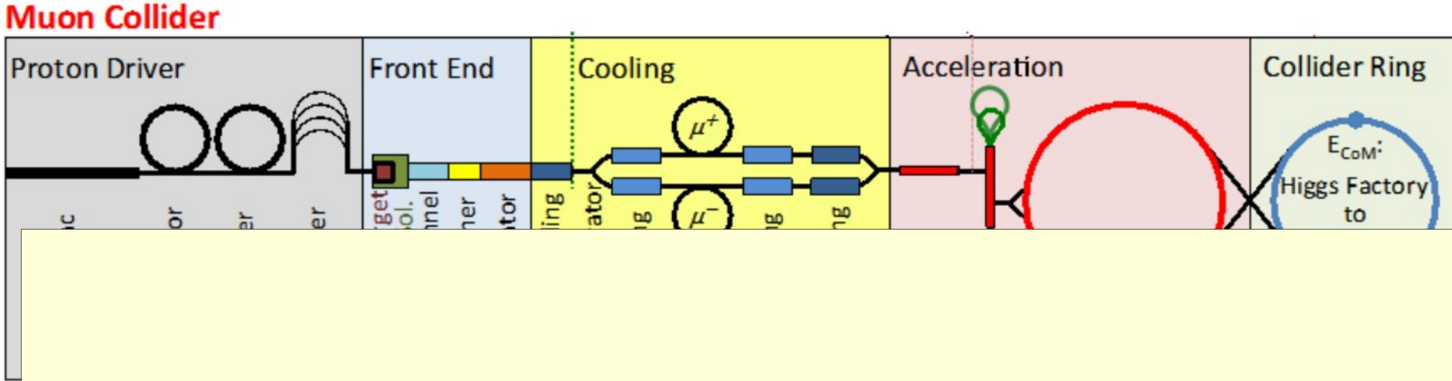
Dec 10th, 2020



Alternative acceleration concept (positron-based) being also explored

- Opportunity: provides a versatile and powerful tool for HEP exploration
- Challenges: design a system (accelerator+detector) the meets physics requirements
- Different stages of design depending on CoM energy
  - Quite advanced conceptual design for Higgs factory, 1.5 TeV
  - Good ideas of roadmap to scale up to ~ 6 TeV (and maybe to ~10 TeV)
  - In the context of Snowmass, being investigated up to 14 TeV
  - Beyond that, significant new challenges require fresh R&D

oversimplified picture



- Today I'll focus on the status and challenges of **detector design**:
  - Muon collider environment
  - Detector design and software
  - Performance
    - Inner Tracker, Calorimeters, Muon Spectrometer
  - Trigger and DAQ
  - Non-conventional detector requirements

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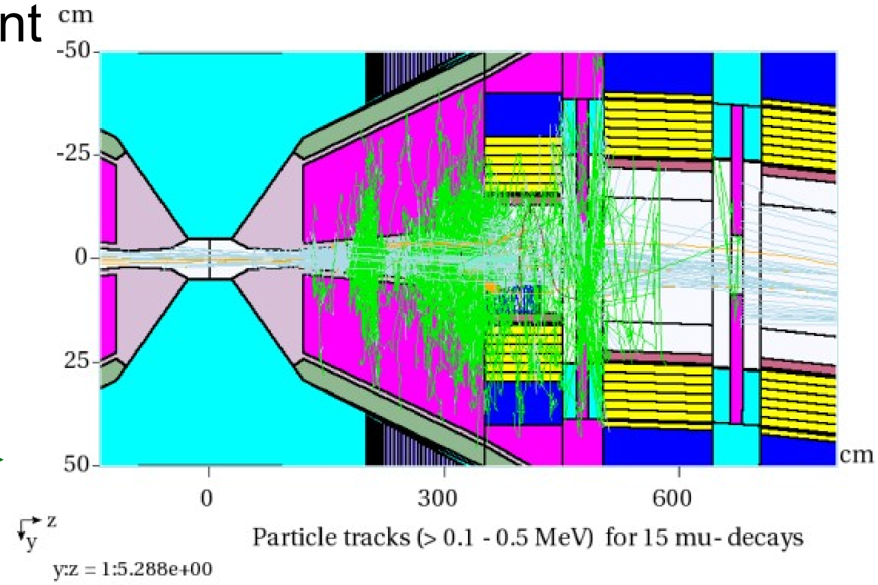
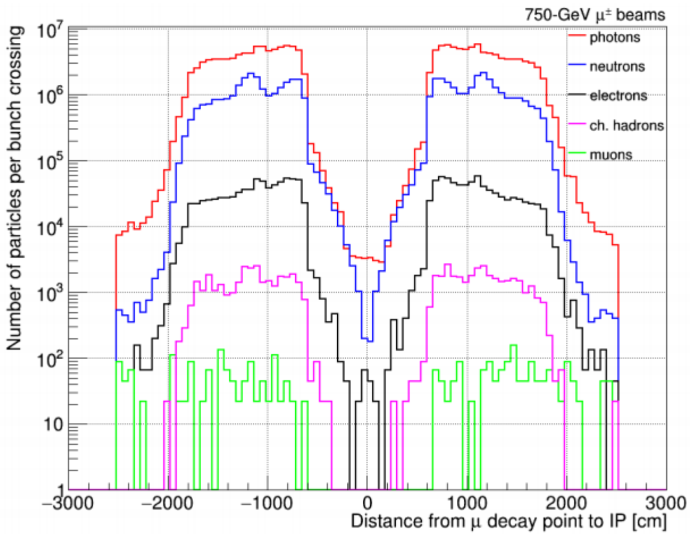
  - Beyond that, significant new challenges require fresh R&D

Beam-Induced Background (BIB)

- Detailed accelerator design studies are needed to understand the environment around the interaction point
  - Most studies presented focus on 1.5 TeV
- Main sources of BIB:
  - Incoherent e+e- pair production
  - Beam halo loss on collimators
  - Muon beam decays → **dominant**

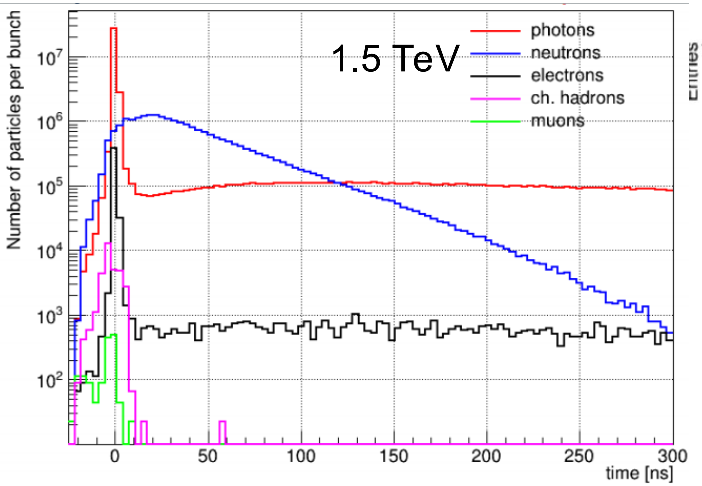


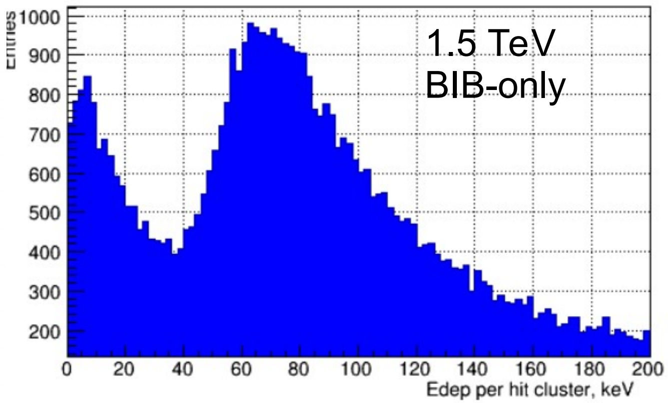


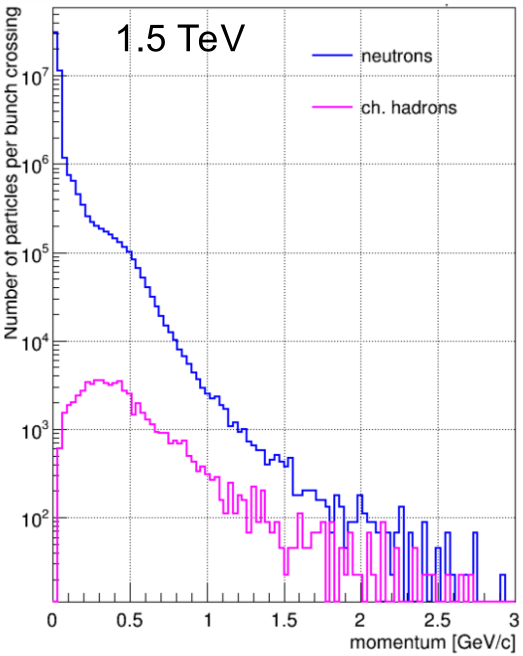
- Large flux of particles entering the detector

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 ($E^{kin}_{ph.} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E^{kin}_{n} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E^{kin}_{el.} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E^{kin}_{ch.had.} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E^{kin}_{mu.} > 1$ MeV)	2.5×10^3	2.7×10^3

BIB characterization



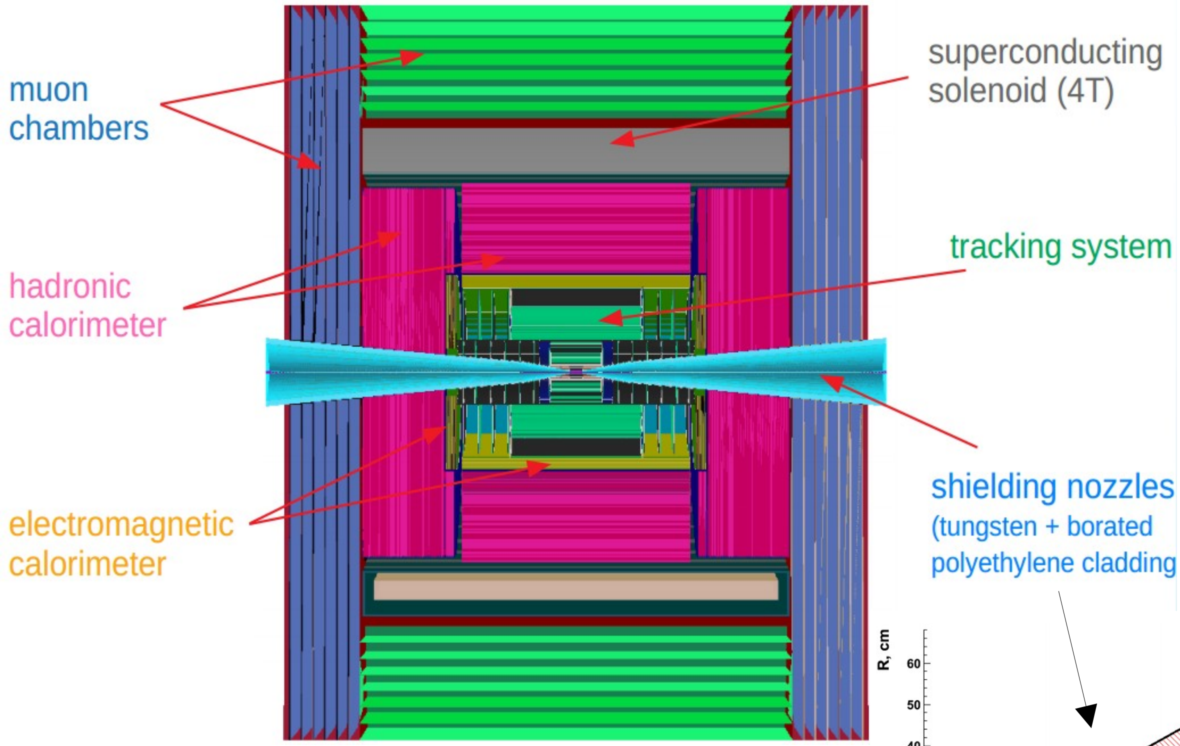




- Key findings for discrimination:
  - Precise timing and Directional information (not from IP)
  - Energy deposit (especially for low-energy γ/n interaction in Si)
  - Majority of particles with low transverse momentum
- Ongoing studies to reproduce these results and study different $\sqrt{s}$
  - Competing effects increasing $\sqrt{s}$: larger energy but longer μ lifetime in lab frame
  - Need accelerator designs for different energies to study how BIB evolves
- Re-optimization and new handles being explored now!

Detector design, √s=1.5 TeV

- Heavily based on CLIC detector, with modification for BIB suppression
- Detector optimization is one of the goals within the Snowmass timescale



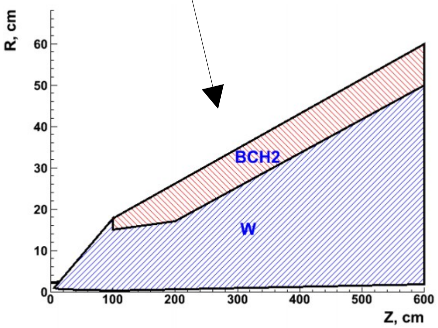
Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)
- 3 barrel layers 50x50μm^2
- 7+7 disks "

Outer Tracker(OT)
- 3 barrel layers 50x50μm^2
- 4+4 disks "

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

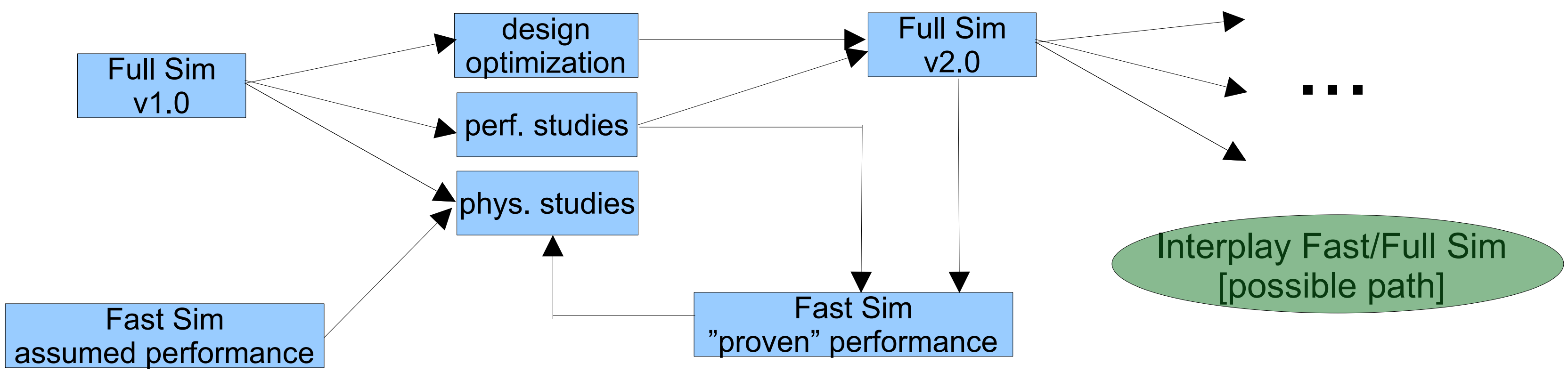
Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2



Nozzle design limits acceptance to θ=10°
- different √s might allow different designs

Software

- Need both fast and full simulation to simultaneously meet challenges of a vast physics program exploration and detailed performance assessment
- **Fast simulation**: based on Delphes (card)
  - Currently based on mix of studies so far and assumptions
  - Goal to progressively validate those assumptions with full simulation
- **Full Simulation/Reconstruction** based on ILCSoft (MuColl github)
  - Includes beam-induced background effects
  - Snowmass tutorial and twiki page
  - Available also through containers on cvmfs for easy setup

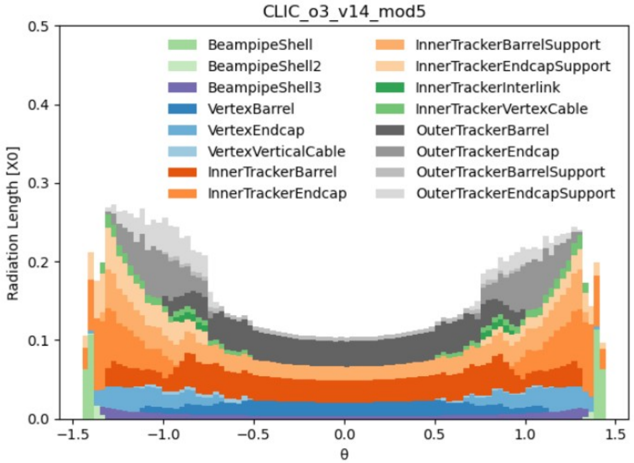


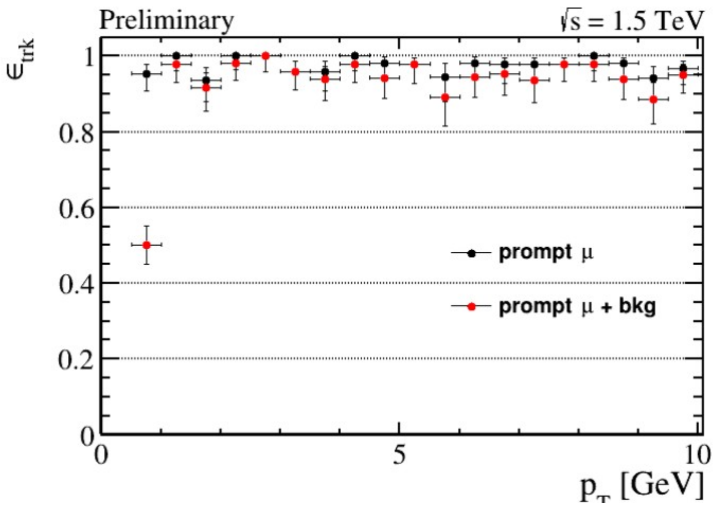
Software status

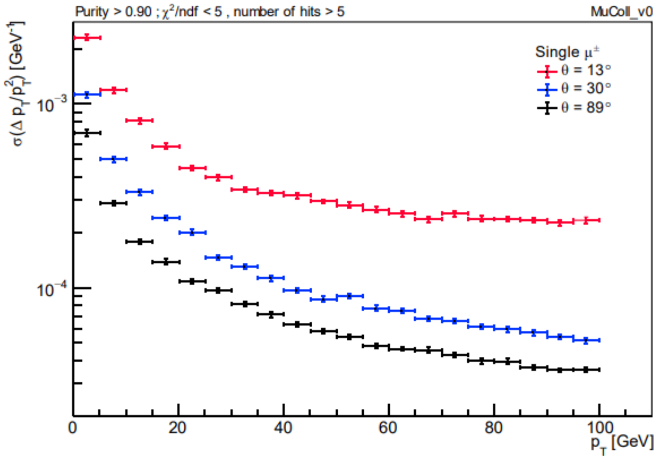
- Tagged a v1.0 version of the detector (twiki)
  - Ready to be used to perform realistic physics studies
- Simulation quite well established and easy to tweak
  - Some work on more realistic digitization in progress
- Current reconstruction software for basic performance in place
  - Tracks, jets, b-tagging, muon combined reconstruction (more work in progress)
  - Electrons, tau dedicated reconstruction need work
- Reconstruction takes a long time to run with realistic BIB
  - Dominated by track reconstruction, only partial optimization done so far

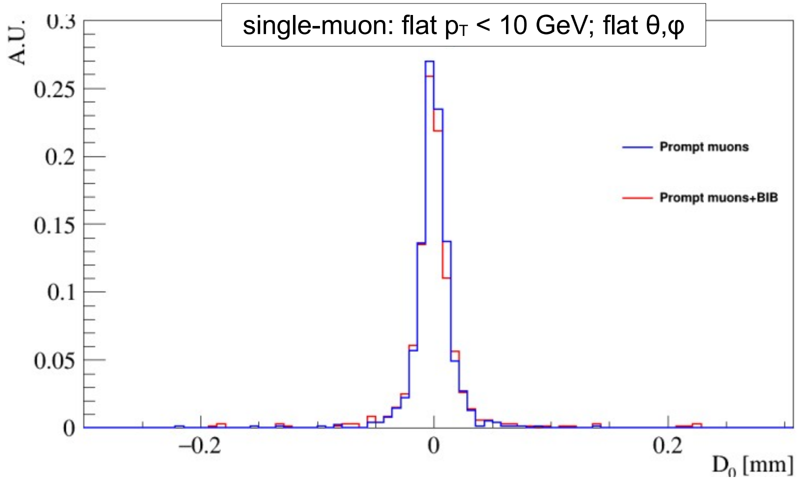
Inner Tracker performance

- Establishing basic performance and ability to reconstruct physics objects in presence of beam-induced background





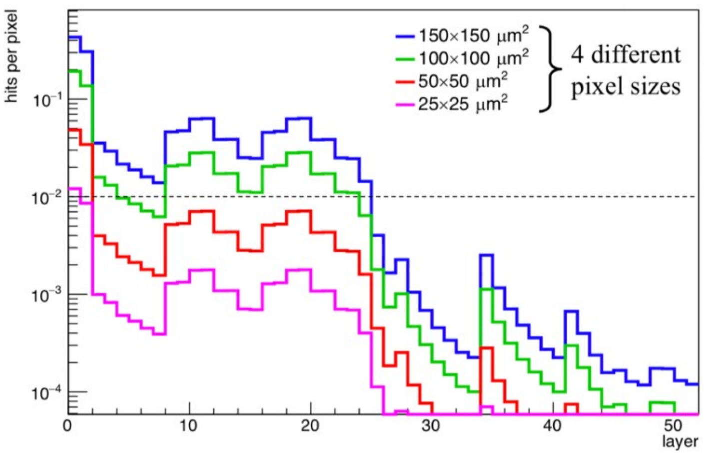




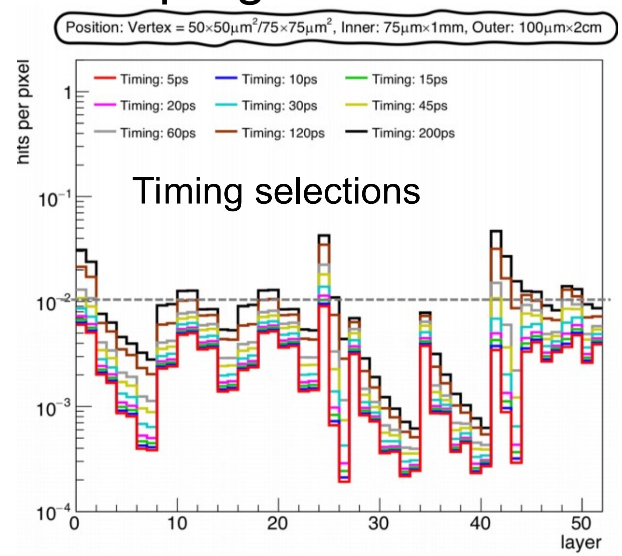
Tracker design and optimization

- Several optimization studies performed and in progress

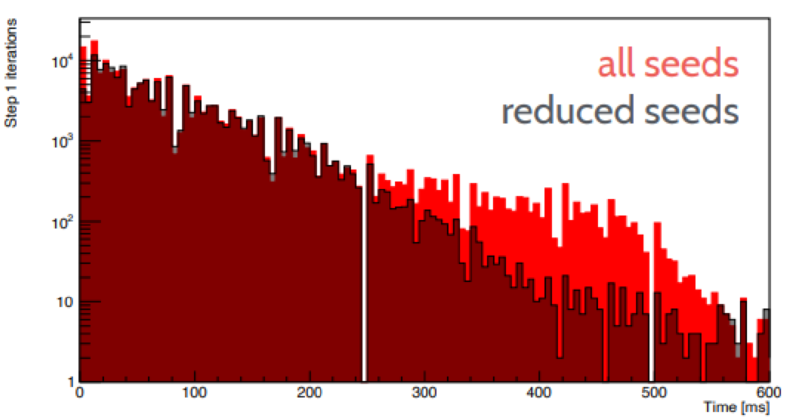
Occupancy studies → pixel pitch

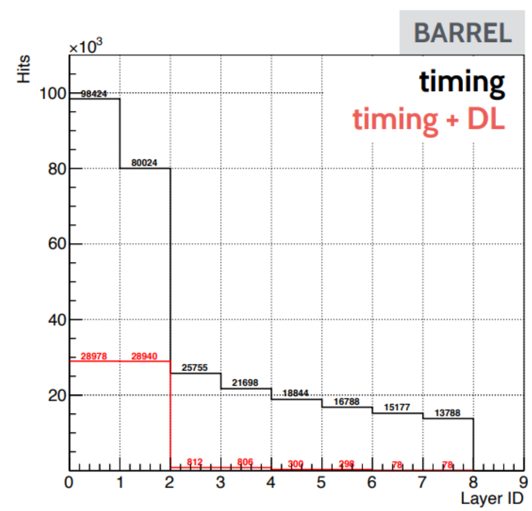


Vertex (25×25 μm²): 4.6 billion pixels
Inner (150×150 μm²): 0.9 billion pixels
Outer (150×150 μm²): 5.1 billion pixels

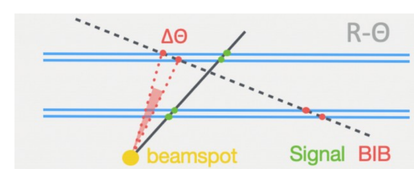


Tracking optimizations



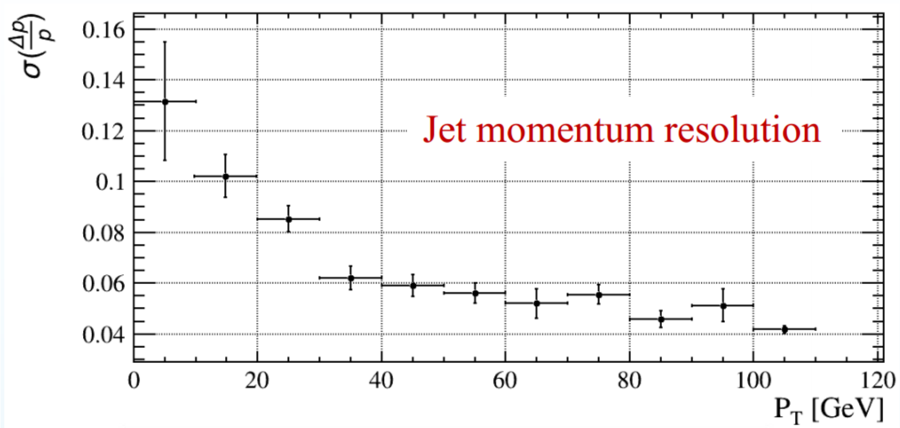


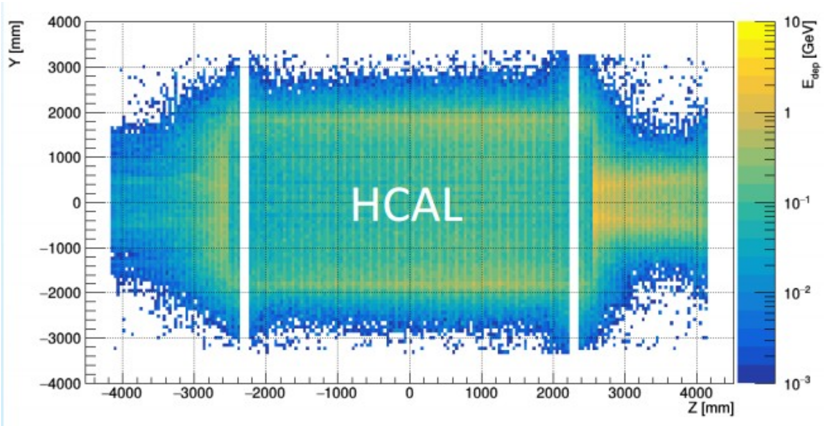
Double-Layer for directional discrimination

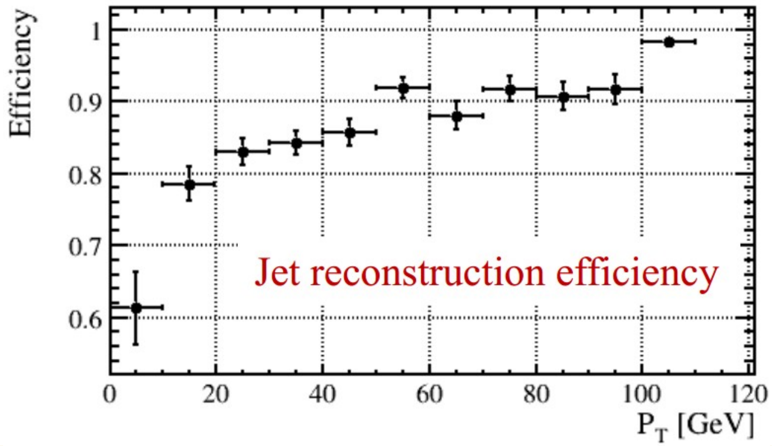


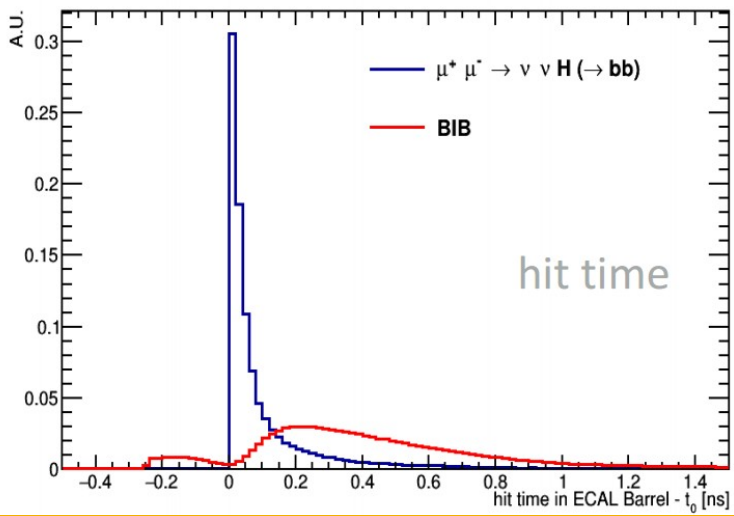
Calorimeter (Jets) performance

- BIB deposits a large amount of energy in the calorimeter
  - Take advantage of LHC experience with pile-up suppression techniques
  - Timing and longitudinal shower distribution as key discriminant
- Jet Particle flow algorithm



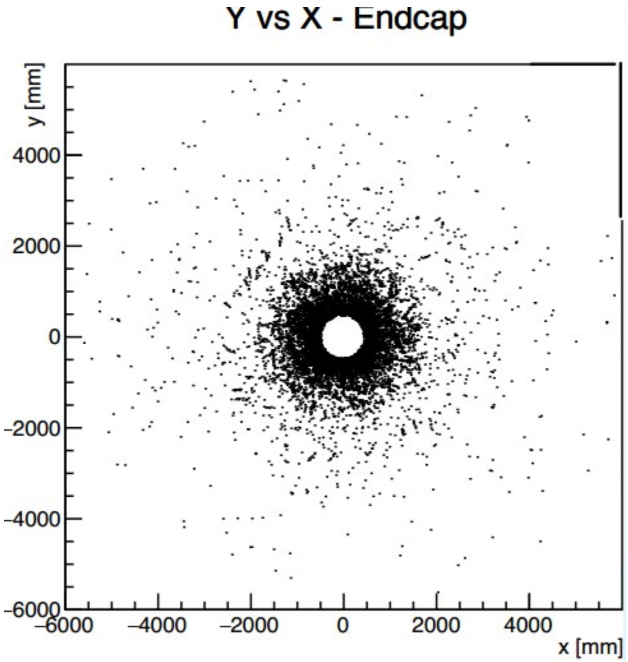


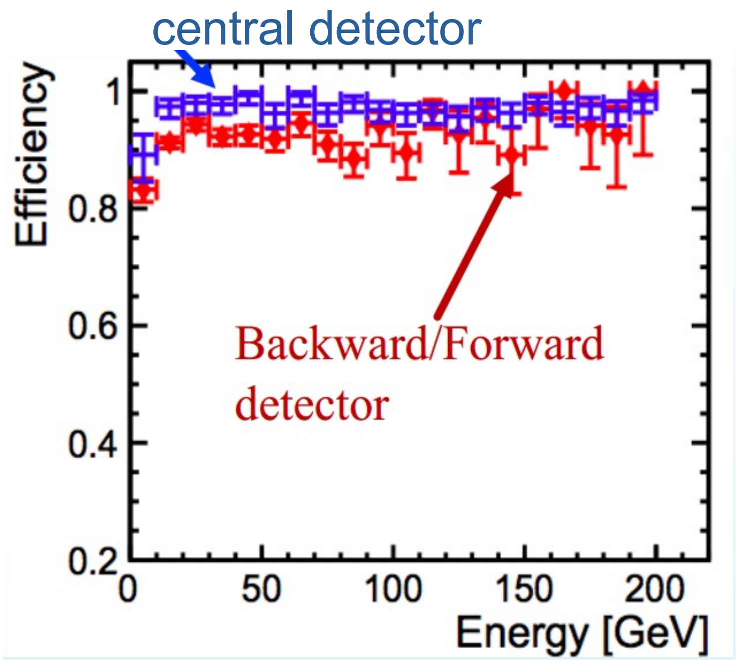




Muon reconstruction

- Combined tracker + muon reconstruction
- Large occupancy due to BIBs in the forward (endcap) detector
- Further studies in progress





More info (link)
S. Jindarai, D. Lucchesi

Trigger and DAQ considerations

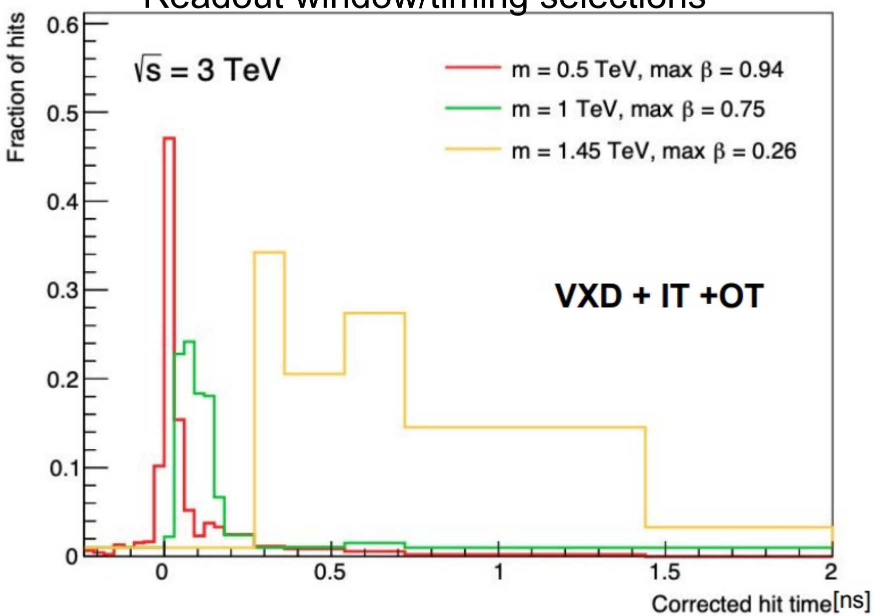
- Bunched beam with O(10 μs) bunch spacing → 100 kHz
- A critical item for transferring data is the tracker
  - For the given tracker occupancy → up to O(50Gbps) of data per module
  - About a factor 10 of HL-LHC designs
  - In-chip data reduction through logic might allow to lower this requirement
    - e.g. cluster timing, shape, double-layers logic, energy threshold, etc..
- Total data flux approx (tracker-only, assumed dominant) ~ 30Tbps
- Trigger-less readout is likely a considerable option!

More info:
CPM #131

~~Non~~-conventional detector requirements

- Awareness for requirements that have been less prominent historically
  - e.g. Long-lived particles, boosted object reconstruction
- Significant work needed to adapt detector and test designs with realistic reconstruction algorithms in full simulation
  - Several interested people have started, but landscape is huge!

Readout window/timing selections



Example slide from CPM#131

General Requirements

- Hermiticity
  - Different geometry choices that provide similar hermeticity for prompt particles can differ drastically in their coverage of particles not originating at the interaction point
- Geometry
  - Interplay of geometry choice with hermeticity, trigger-capabilities, and even data-rate reduction need to keep in mind LLP needs
- High granularity at large radius
  - Identifying decays of LLP in various sub-systems away from the interaction point and distinguish them from detector-specific backgrounds (including beam-induced backgrounds)
- Particle ID
  - Measurement of ionization energy loss and timing can boost particle ID capabilities and offer unique handles for LLP direct identification
- Timing (more later)
- Dataflow/software must be defined to not prevent LLP searches
  - Inclusive initial reconstruction and/or nimble re-reconstruction

Organization

- Building on top of what was studied long ago (e.g. MAP)
- Several European institutes involved
  - Most of the recent results shown today come from their work
  - Several Italian institutions (Padova, Torino, Trieste, …), CERN, DESY, etc..
- Large interest in the US ramping up thanks to the Snowmass process
  - Both from labs as well as universities
  - Results presented in both Energy and Instrumentation frontiers,as appropriate
  - Starting to assemble MC needs for larger sample productions
  - Mattermost channel and informal bi-weekly chats
  - New Snowmass AF-EF-TF "Muon Collider Forum"
    - Join #muon-collider-forum snowmass slack channel (link)
- Critical to maintain direct coordination of activities across US and with European Collaborators

Conclusions

- The Muon Collider environment exposes unique challenges for detectors
- Revived effort in producing a realistic detector design, simulation and reconstruction software
  - Basic setup available, together with tutorial and configurations to easily setup new studies
- Basic performance are being established, but significant work is needed to bring it to a level comparable to more mature designs for other colliders
  - A lot of freedom in experimenting and for creative solution in such a unique environment
- Plenty of topics awaiting for new people to inject their expertise and ideas
- Do not hesitate to get in contact if you'd like contribute or learn more!

BACKUP

Radiation environment

- 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