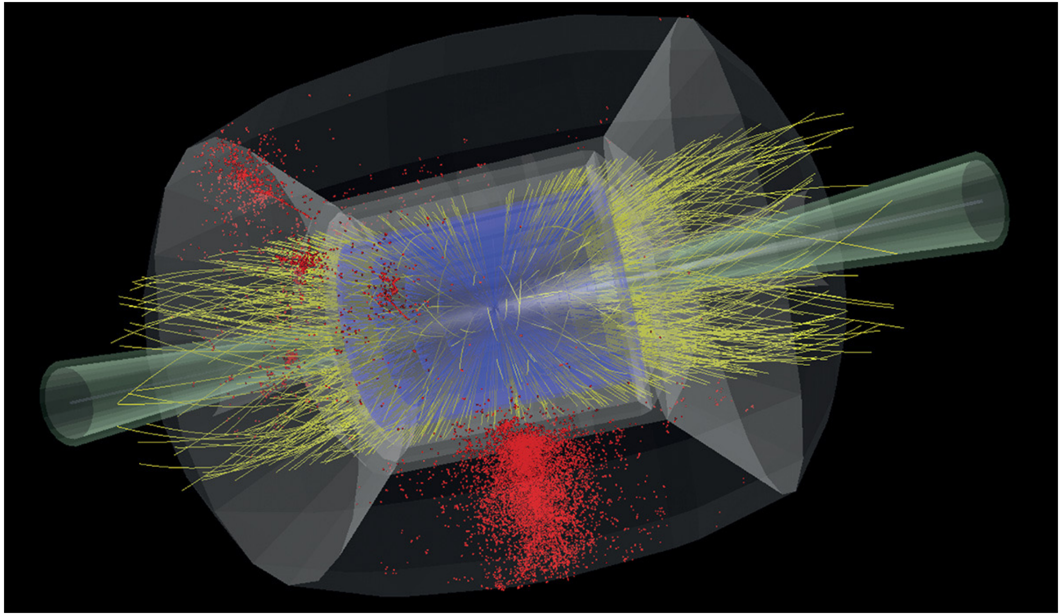


Designing a Muon Collider Detector

Sergo Jindariani (Fermilab)
VCI'2022
February 22th, 2022

On behalf of the Muon Collider Physics and Detector Group

Muon Colliders

- Provides a powerful and versatile tool for HEP explorations
  - Colliding elementary particles
  - Less synchrotron radiation than e+e- – can use circular accelerators
  - Luminosity per energy consumed
  - Path to very high energy collisions
- The 2020 Update of the European Strategy for Particle Physics recommended to "investigate the possibility to have bright muon beams"
- International Muon Collider Collaboration (IMCC) established, hosted by CERN
- Resurgence of interest in Muon Colliders within Snowmass
  - Expertise in the US from the Muon Accelerator Program (MAP)

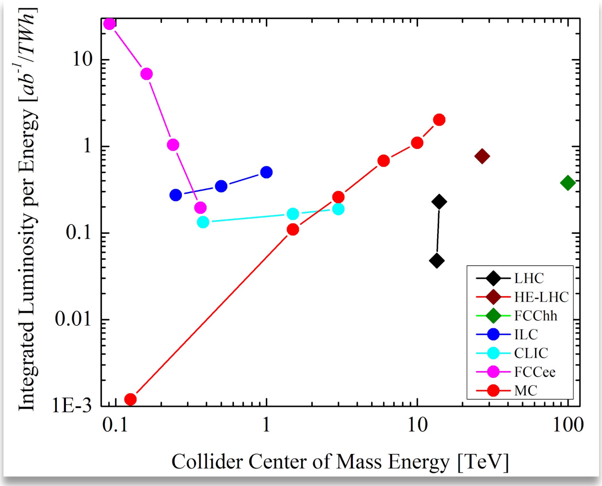
IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

VBA

L. M. Lederman

Columbia University, New York, N.Y. 10027

> 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.



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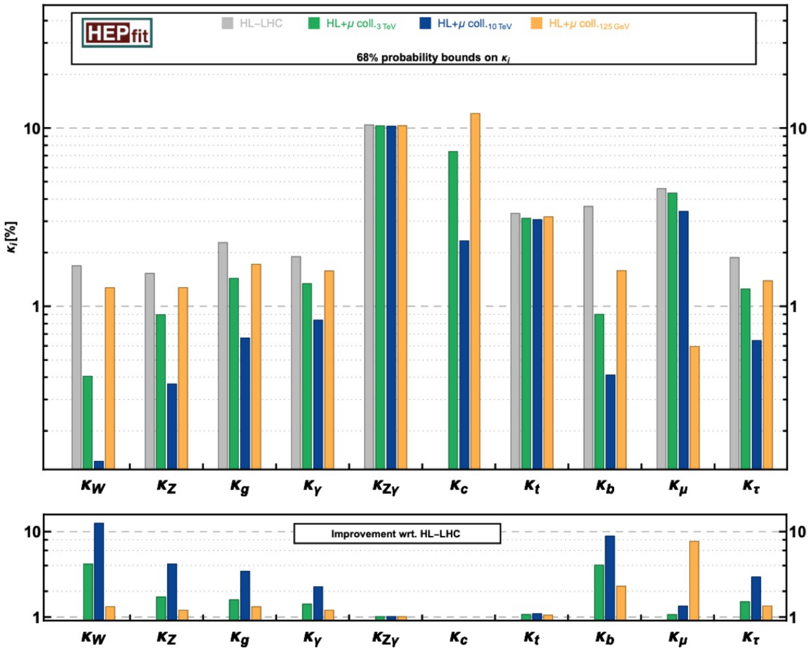
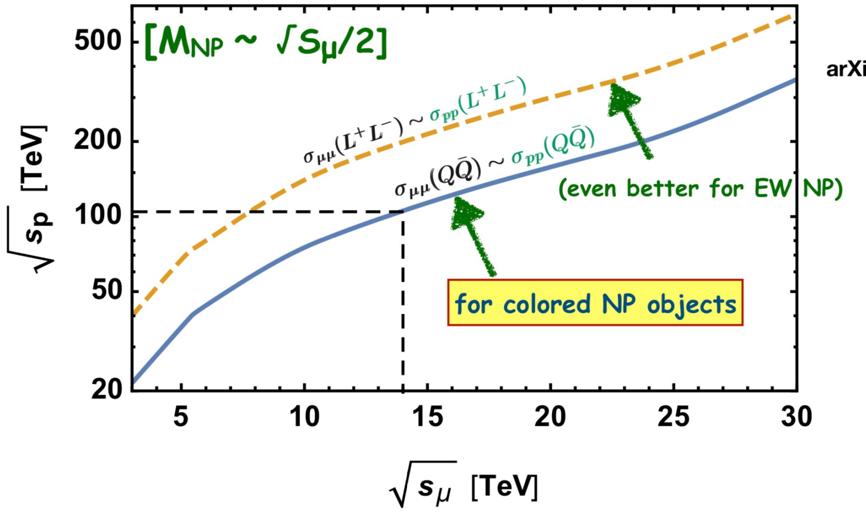
Physics at Muon Colliders



arXiv:2103.14043



arXiv:1901.06150

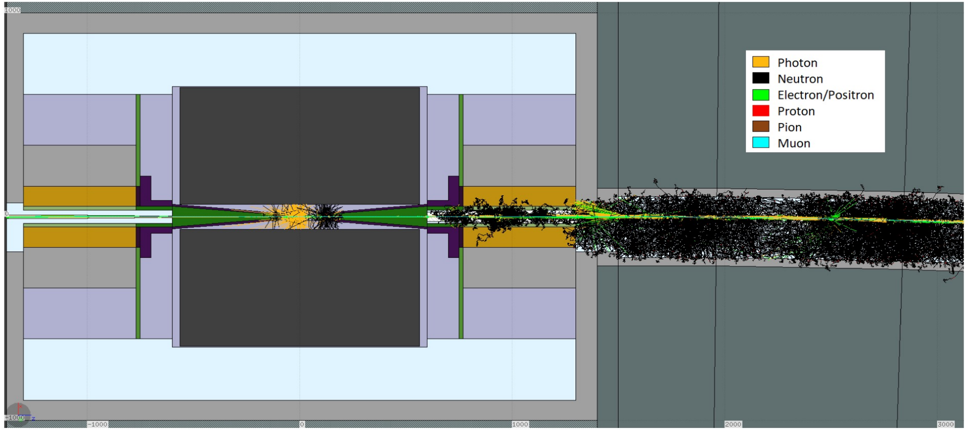
Dramatic improvement in Higgs coupling precision with respect to HL-LHC

New physics reach similar or better than 100 TeV proton-proton machine

Beam Induced Background

- Beam background identified as one of the main challenges
- Main Source of Beam Induced Background (BIB) are beam muon decays
- 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 ⇒ $2{\times}10^{5}$decay per meter of lattice.

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



Detector

hadronic calorimeter

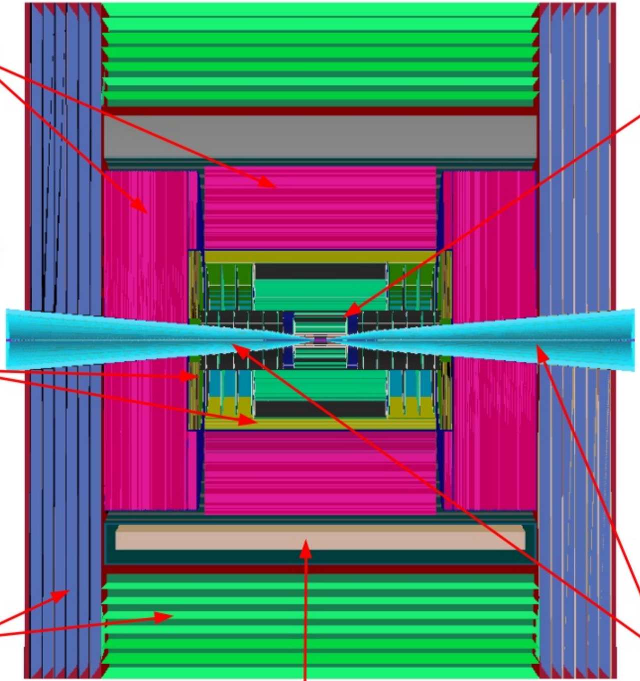
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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

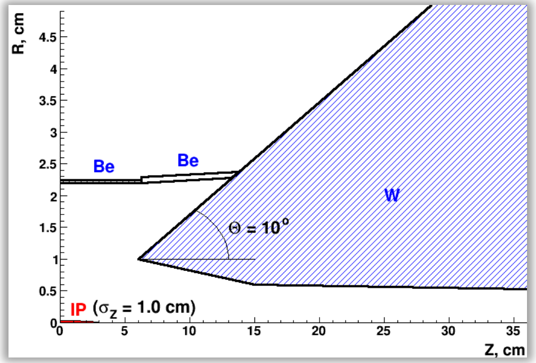
- Tungsten cones + borated polyethylene cladding.

10° acceptance limitation due to the nozzles

+ few degrees of extreme occupancy in the vertex detector

BIB properties

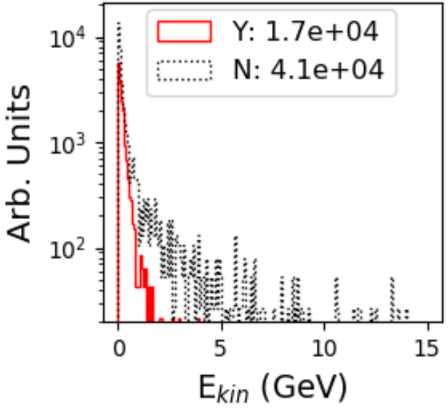
Muon beam 0.75 TeV



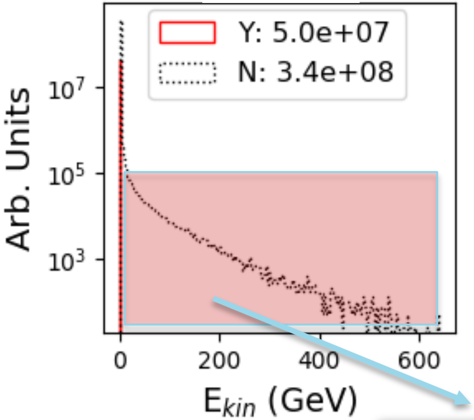
Di Benedetto et al., Journal of Instrumentation13(2018)

F. Collamati et al. 2021 JINST 16 P11009

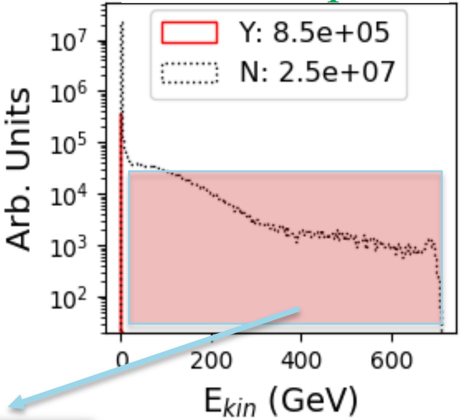
charged hadrons



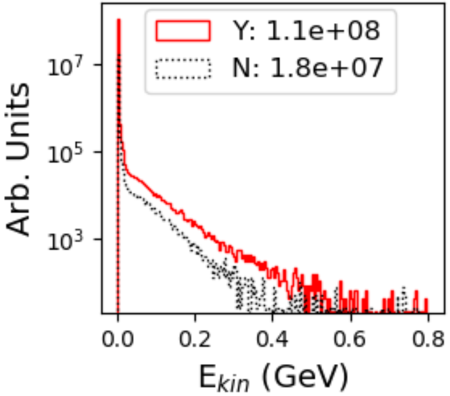
Photons



electrons/positrons



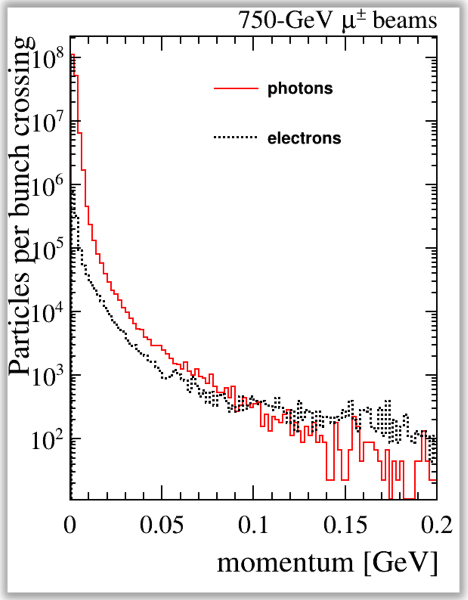
neutrons

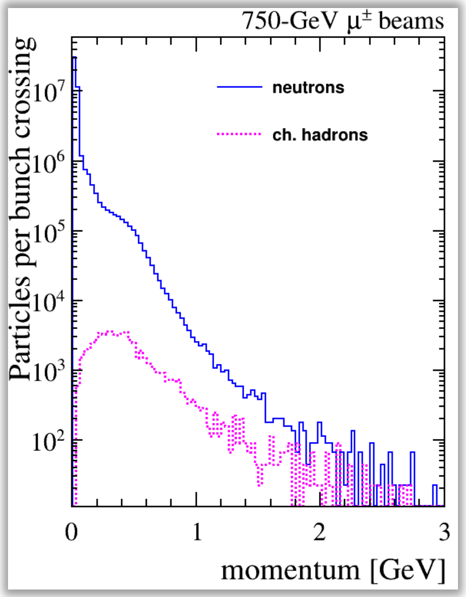


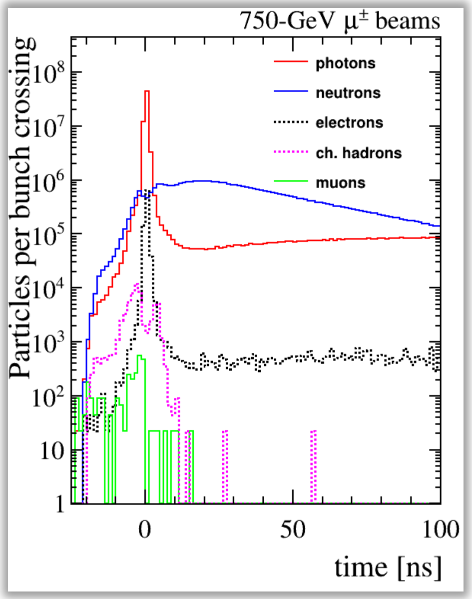
absorbed

Remaining BIB properties

Muon beam 0.75 TeV



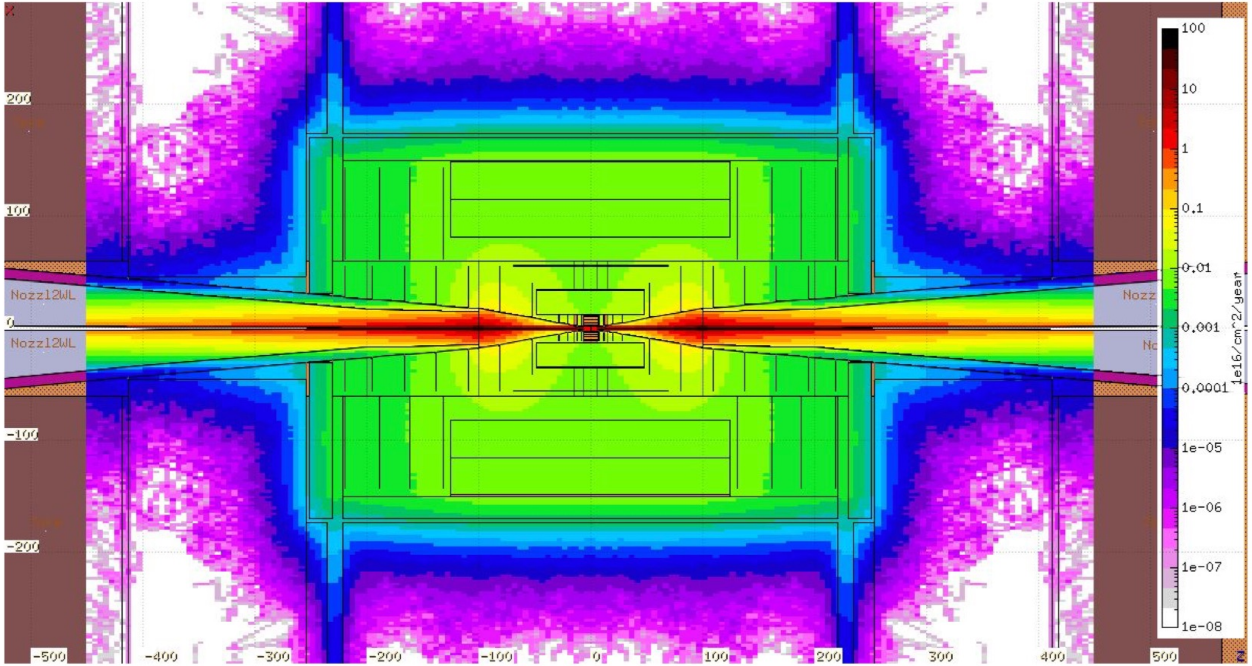




- Low momentum particles
- Partially out-of-time with respect to the bunch crossing
- Often, not pointing to the interaction region

Radiation

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



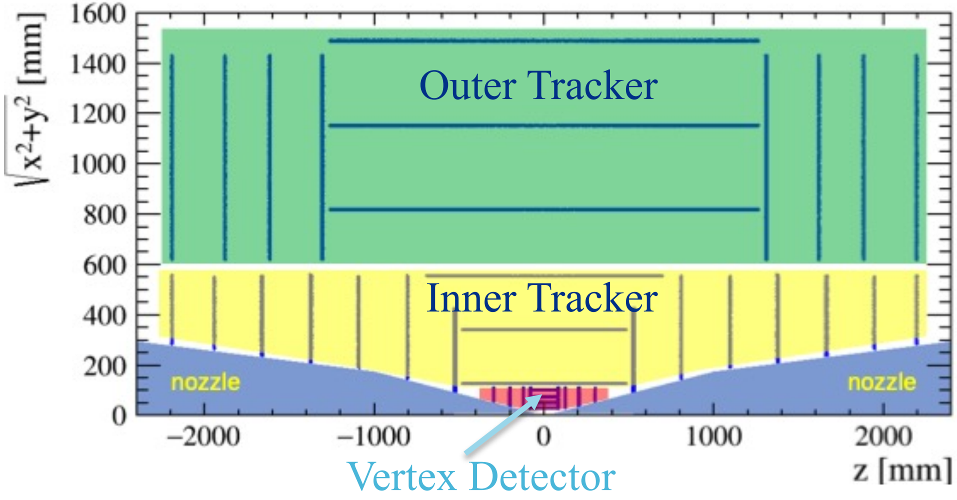
Expected (FLUKA simulation) to be approximately: ~$10^{14\text{-}15}$/cm^2/y in the tracker
~10^{14}/cm^2/y in the ECAL

Radiation levels at 3 TeV comparable to HL-LHC

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

Tracker

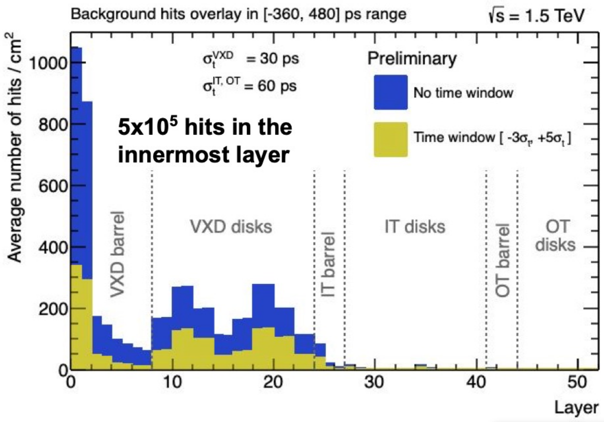
- Goal: bring occupancy to <1% level. Pixel size optimized to achieve this goal
- Timing is also important, but need to be careful to not impact efficiency for slow particles
- Other requirements are not unique: low mass/power, radiation tolerance, low noise
- Total number of channels ~ 2B (similar in size to Phase-2 ATLAS/CMS).



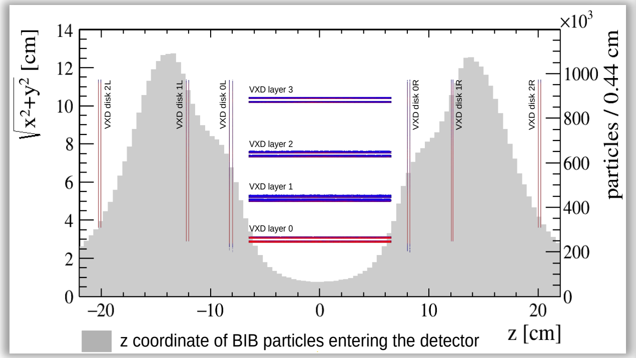
		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	729M
	E	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	462M
IT	B	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	164M
	E	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm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

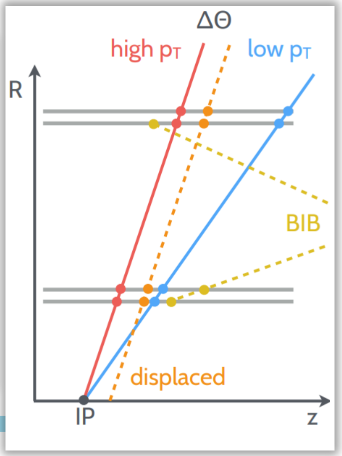
Tracker (2)

- 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
- Some on-detector filtering may be needed



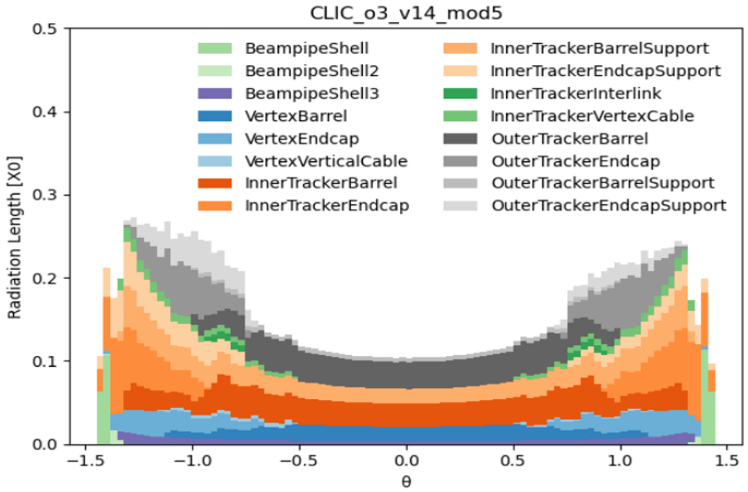
Example R&D:
- Monolithic devices
- AC-LGADs
- 3D hybrid pixels
- Intelligent sensors
- Common challenges: services, cooling, low-power ASICS

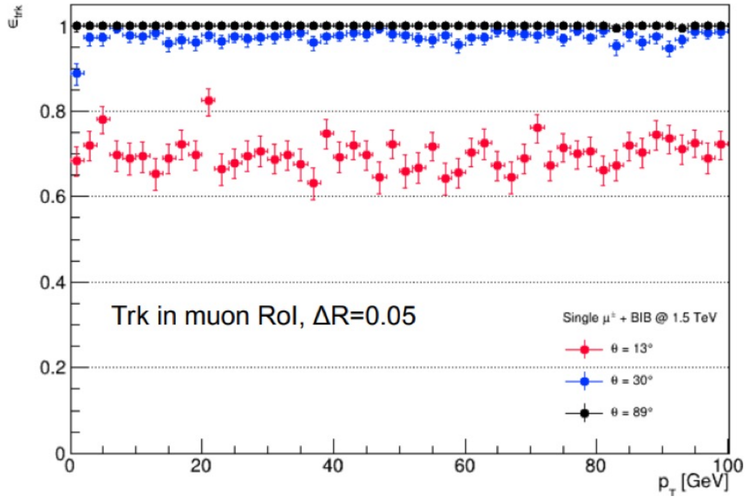


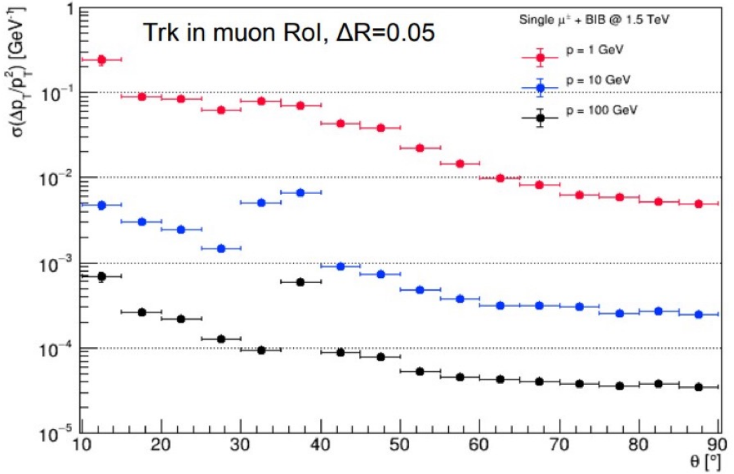


Tracking Performance

- 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

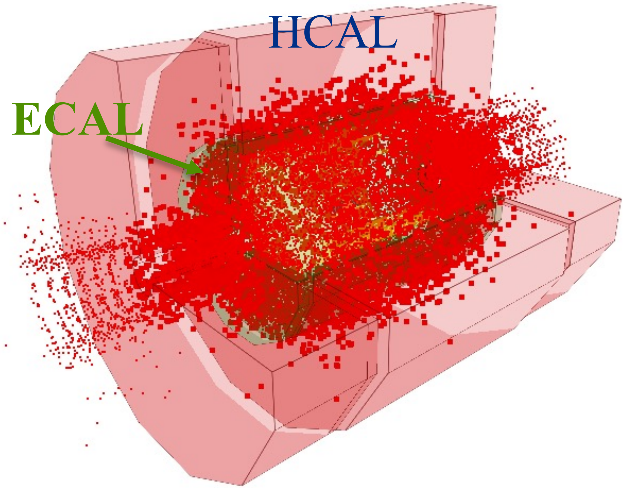


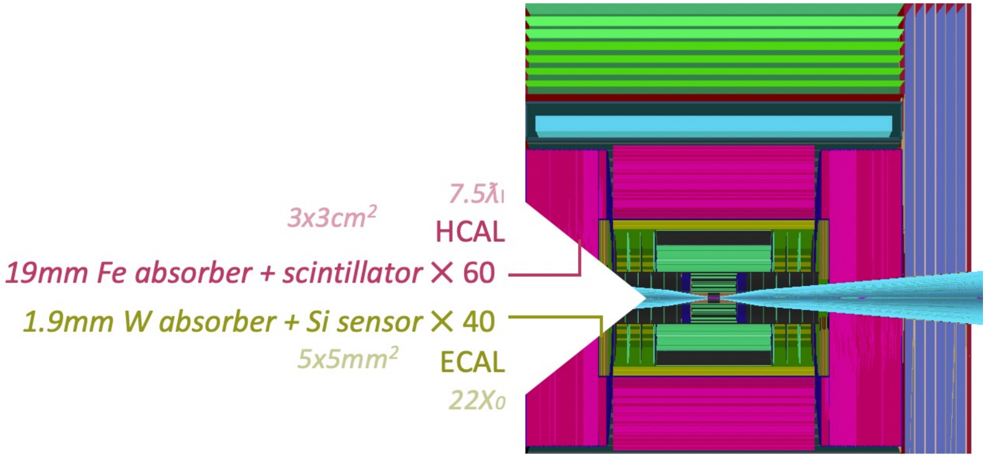


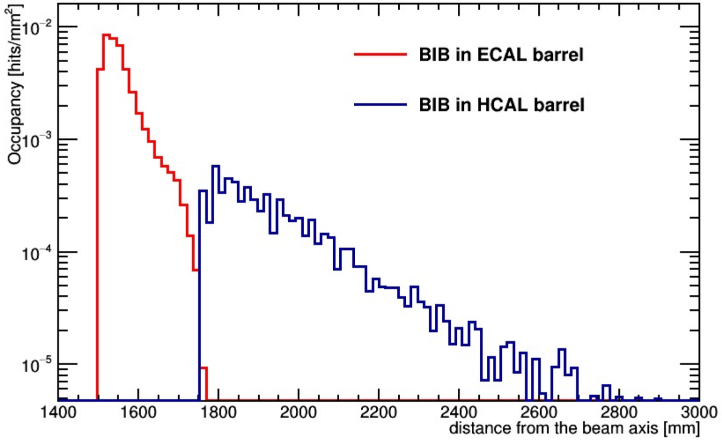


Calorimeters

- ECAL: SiW with 22 X_0, 5x5 mm^2 pads
- HCAL: Iron+Scintillator with 7.5λ
- High occupancy in the ECAL







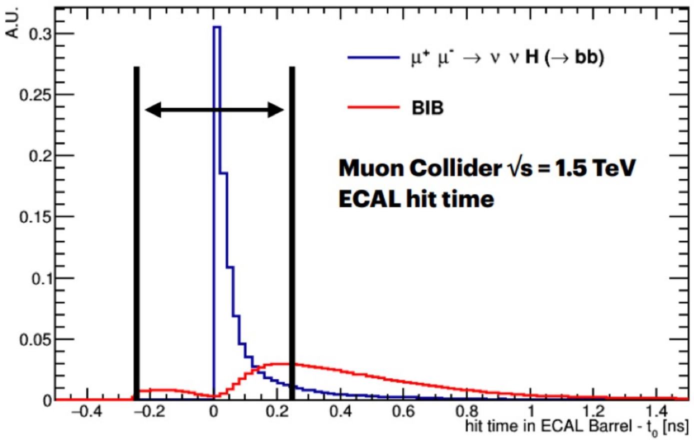
Calorimeters (2)

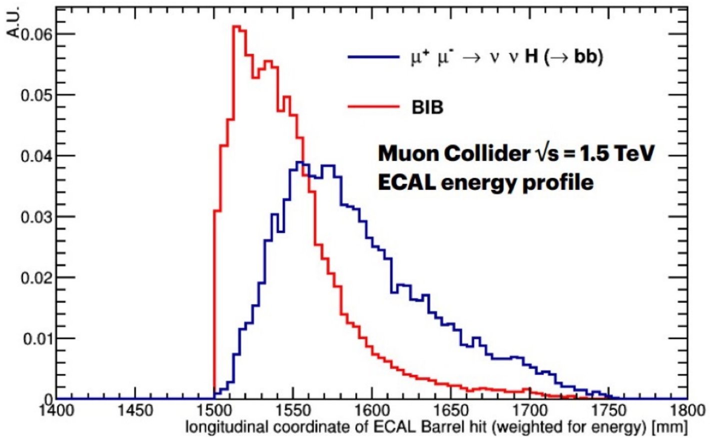
- Timing and shower profile are the key
- SiW calorimeter provides excellent granularity, good resolution, high density

- Alternatives:
  - Crystals
  - Gas detectors

Example R&D:

- Better granularity
- Better timing
- Particle tracking
- dual-readout (DR) compensation
- develop fast, rad hard materials/solutions





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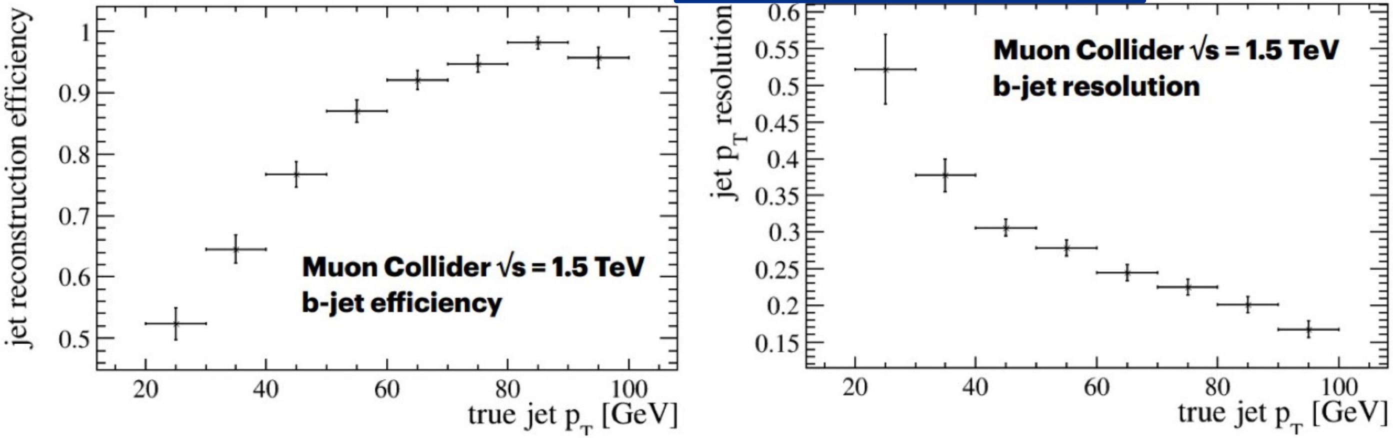
Calorimeter Performance

Preliminary
Non-PF reconstruction

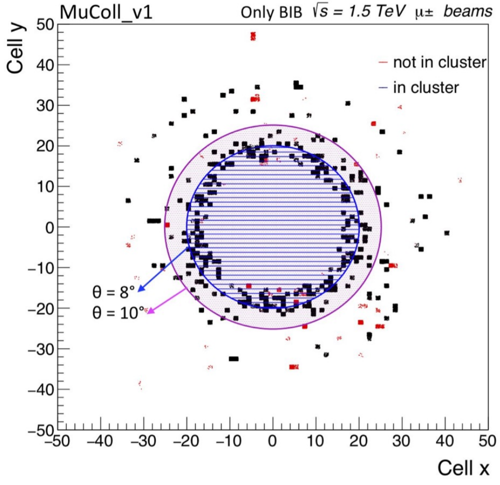


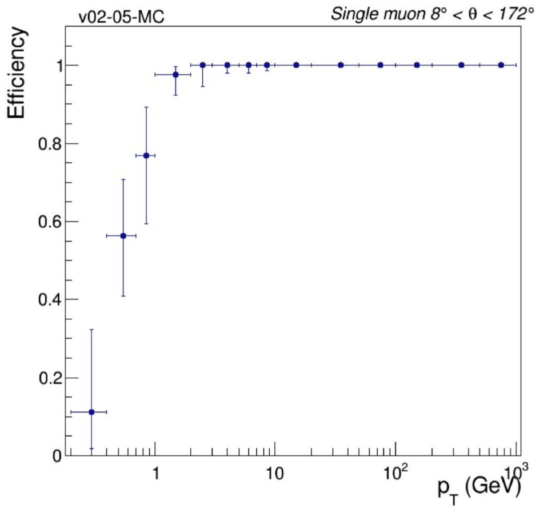
Take advantage of LHC experience with pile-up suppression techniques

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

Muon Reconstruction

- Targets 100um spacial and 1ns timing resolutions
- Current design: gaseous detectors interleaved in an iron yoke
- 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



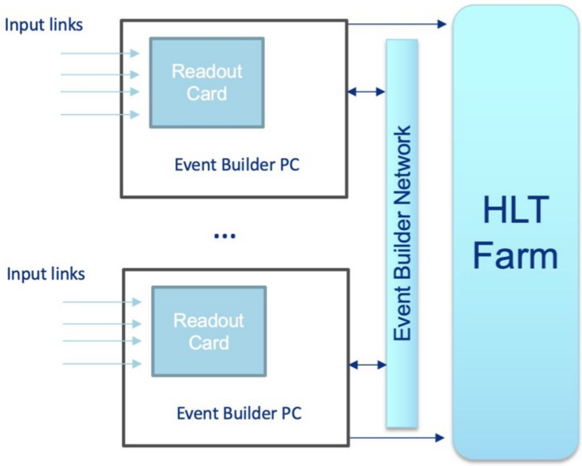


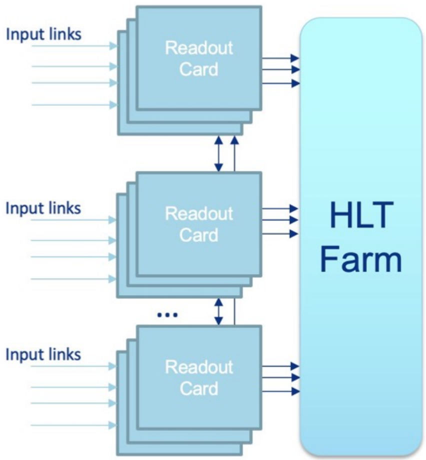
Future R&D directions: better timing and resolution (GEM, Micromegas, MRPC (gas issues), PicoSec…)

Very high energy muon momentum reconstruction in 10 TeV collisions remain challenging

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...
- However, the BIB might be prohibitive for a full triggerless TDAQ scheme





Trigger/DAQ Considerations

- Data dominated by the Tracker and the ECAL

- Input data rates at 1.5 TeV (with x2 safety factor):

	Hit	On-detector filtering	Number of Links (20 Gbps)	Event Size
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**.

- Bandwidth to disk < 100 Gb/s
  - 1.5 kHz if assuming full event size
  - For comparison, rate at 10 TeV and $L=10^{35}$ cm^{-2} s^{-1} for Higgs = 0.1Hz, VBF WW=1Hz
  - Some filtering makes sense to reduce event content

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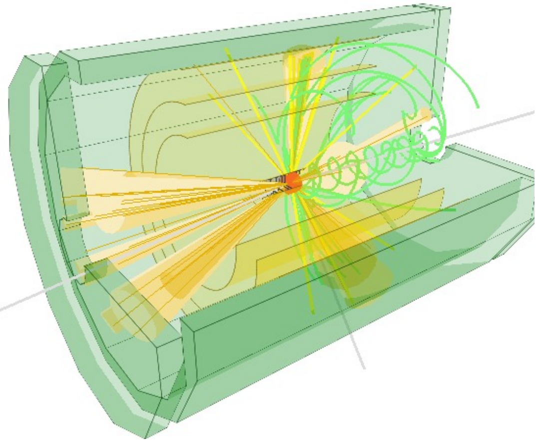
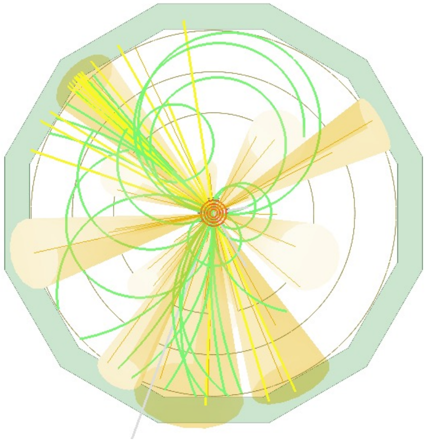
Summary and Outlook

- Presented an initial Muon Collider detector concept and the corresponding preliminary performance
- General theme – highly granular detectors with high timing resolution
- Snowmass papers in preparation (physics performance and technology R&D)



- Baseline established. Many avenues for improvements and optimization
- Committing today to a particular technology is probably premature
    - Develop further R&D efforts
    - Maintain synergies with other collider proposals



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