Challenges and synergies of a detector at high energy muon collider

Simone Pagan Griso

– presenting studies done within IMCC and beyond –

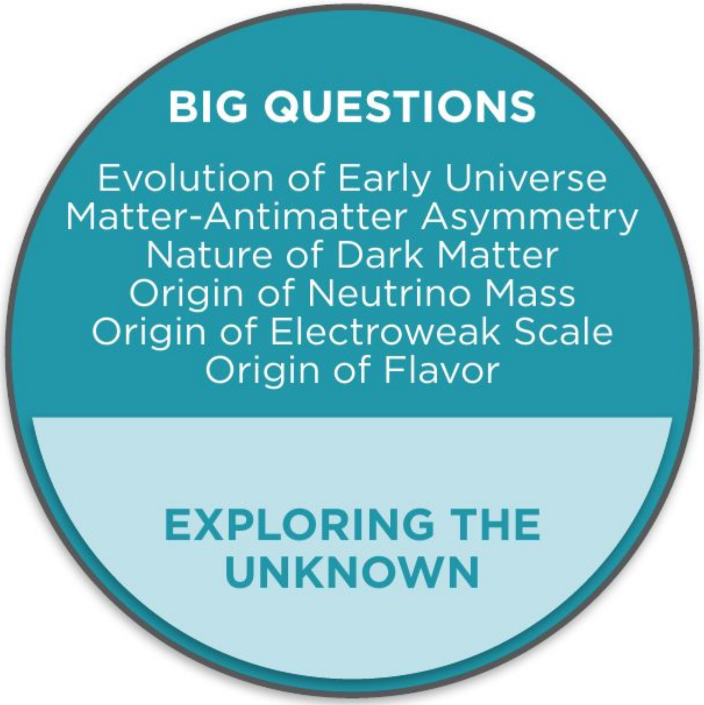
Muon4Future

Venice, May 30th 2023

BERKELEY LAB
Lawrence Berkeley National Laboratory

The physics we dream of discovering

A multi-TeV muon collider is a **powerful**, **scalable** and **flexible** experimental setup to unlock answers to very profound questions.

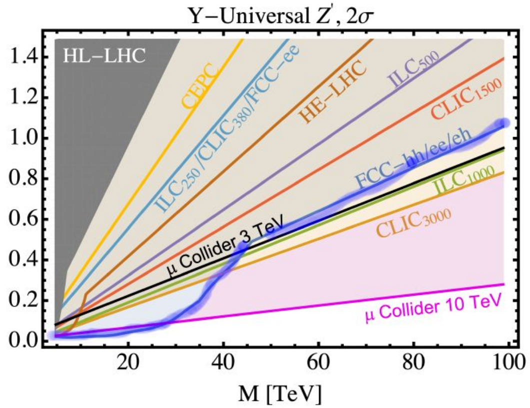


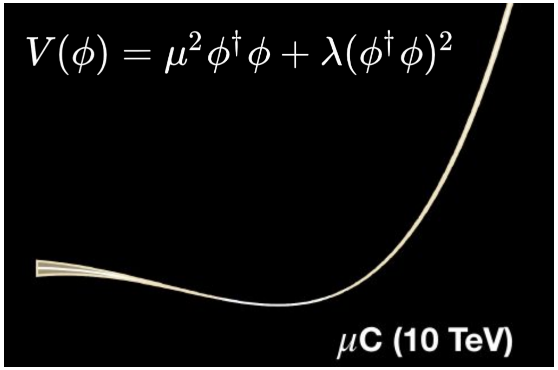
BIG QUESTIONS

Evolution of Early Universe
Matter-Antimatter Asymmetry
Nature of Dark Matter
Origin of Neutrino Mass
Origin of Electroweak Scale
Origin of Flavor

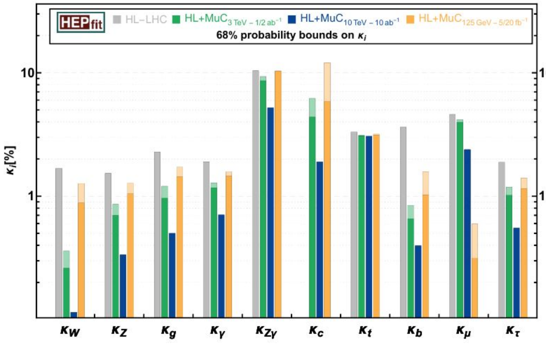
EXPLORING THE UNKNOWN

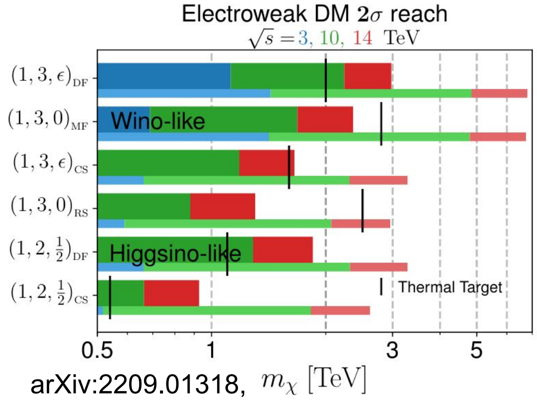
Content: Snowmass EF Report
Alternative design by T. Holmes





Credit: R. Petrossian-Byrne, N. Craig





arXiv:2209.01318,
arXiv: 2203.07351

It will be, at the same time, a **discovery** and **precision**-measurements machine.

The Muon Collider Community

The Muon Collider concept has been studied for decades

- From initial proposals back in the early ’90s
- To more recent Muon Accelerator Program (MAP) initiated at Fermilab [2011-2014]. Lots of progress still very relevant.

Nowadays… interest in Europe, US and beyond (as we’ve seen at this workshop)

Following the most recent European Strategy Report

International
MUON Collider
Collaboration

making great progress in all areas.

“Towards a Muon Collider”, arXiv:2303.08533

US Snowmass process

- ~40 contributed papers on muon colliders out of ~150 in Energy Frontier

Great interplay with IMCC, including

- Five comprehensive snowmass whitepaper, on accelerator, detectors, physics reach

arXiv: 2203.07224, 2203.07964, 2203.07256, 2203.08033, 2203.07261;
arXiv: 2209.01318 (MuC forum report)

Focus shifted from a low-energy Higgs factory towards multi-TeV muon collider.

- $\sqrt{s}$ = **1.5**, **3.0**, 6.0, **10**, 14, … TeV considered (so far)

Muon Collider Detector Design

The detector is our interface between collisions and the physics we are after.

- Is it possible to design a detector capable to unlock the promising physics behind multi-TeV muon-muon collisions?
- What technology needs to be developed and what challenges overcome?

physics/9901022
(**1999**)

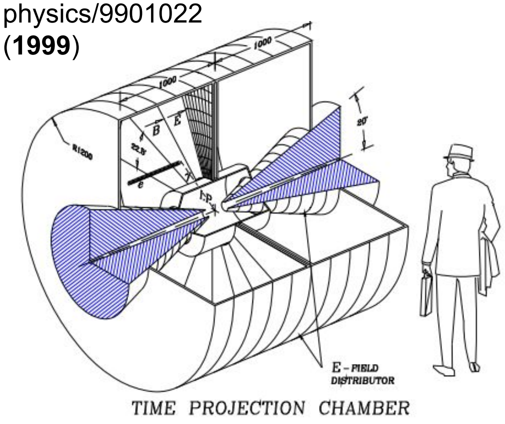


FIG. 73. Outer tracker TPC.

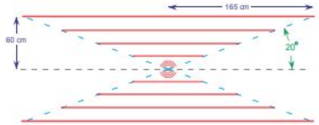


FIG. 74. Compact tracker geometry in a 4 T field.

arXiv:1308.2143
(**2013**)

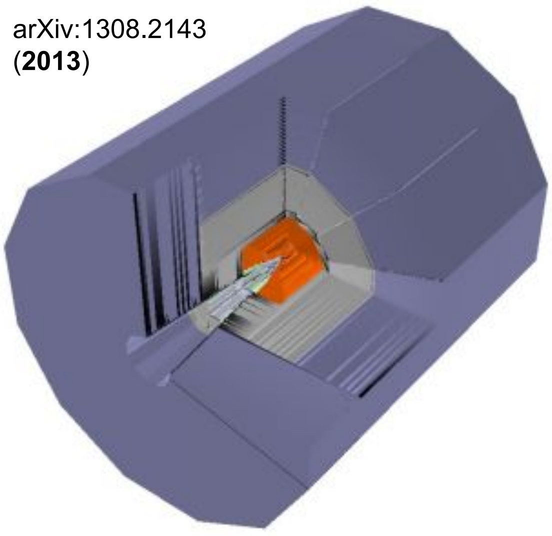
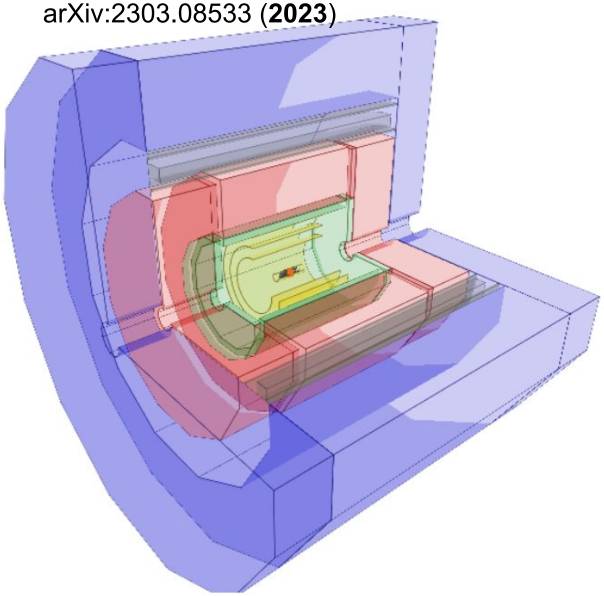


Figure 6: Illustration of the mcdrcal01 detector.

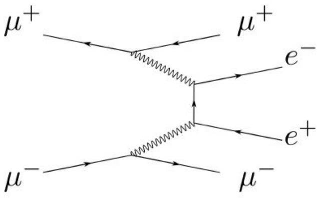
arXiv:2303.08533 (**2023**)



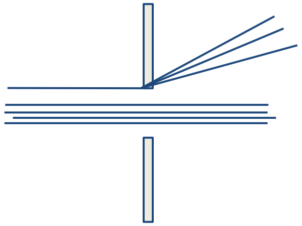
Requirements evolve and detector technology keeps innovating in ways that were not obviously predictable. The answer might simply not be as apparent at some point in time.

Beam-Induced Background (BIB)

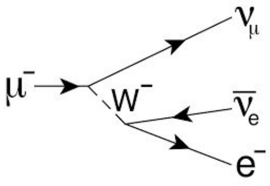
- e^+e^- pair production



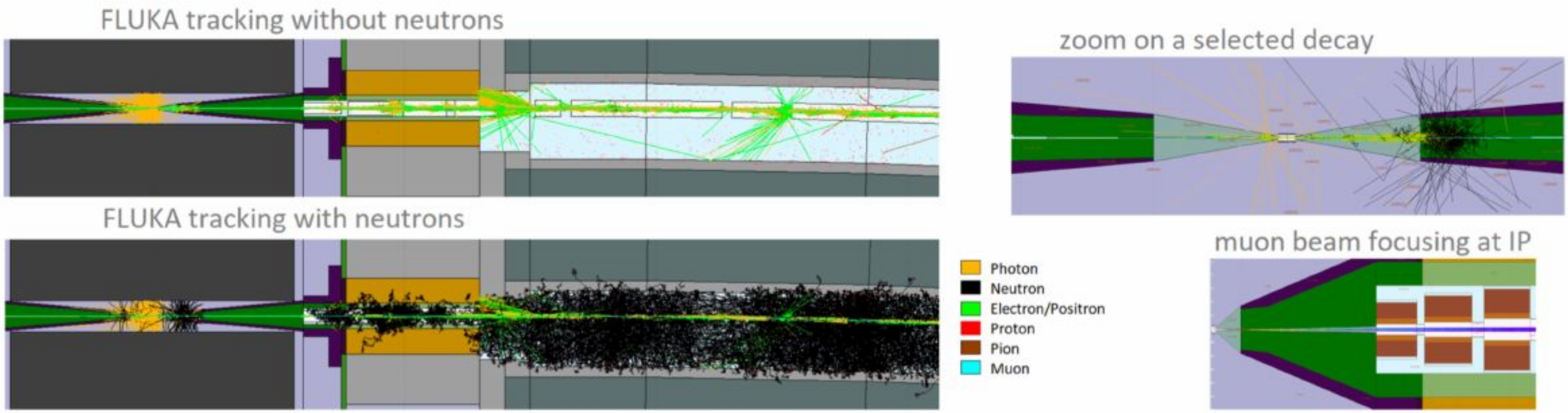
- Beam halo loss on collimators



- **Muon beam decays**



Very high-energy electrons then interact with surrounding material.


FLUKA tracking without neutrons

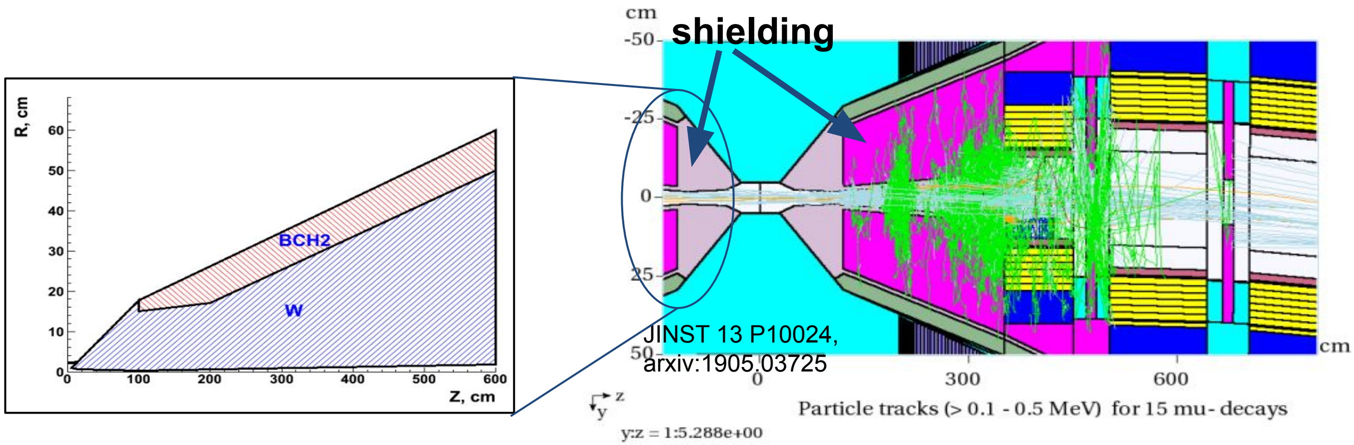
FLUKA tracking with neutrons

zoom on a selected decay

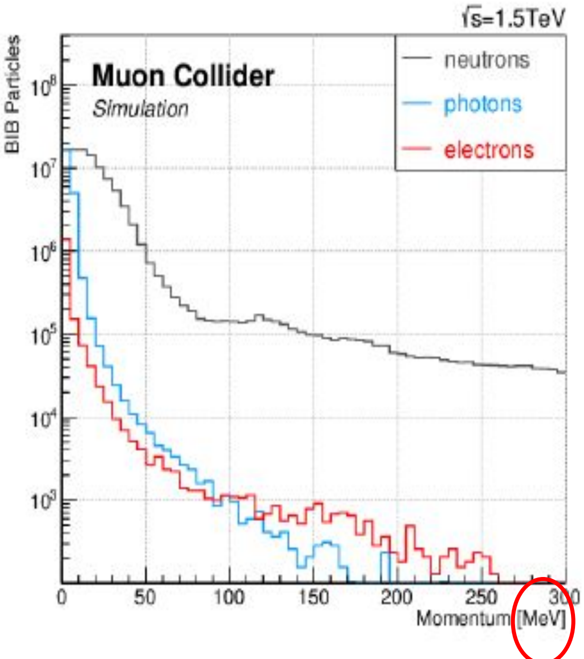
muon beam focusing at IP

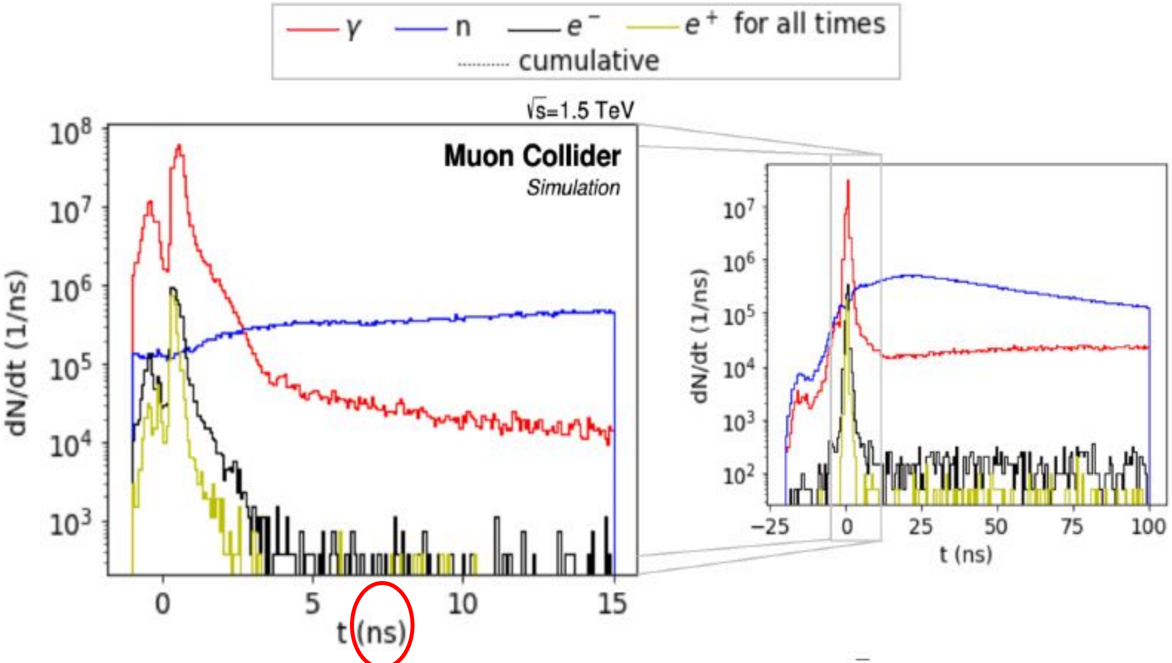
BIB characterization

Large particle multiplicity entering the detector after showering on **dedicated shielding**



JINST 13 P10024, arxiv:1905.03725

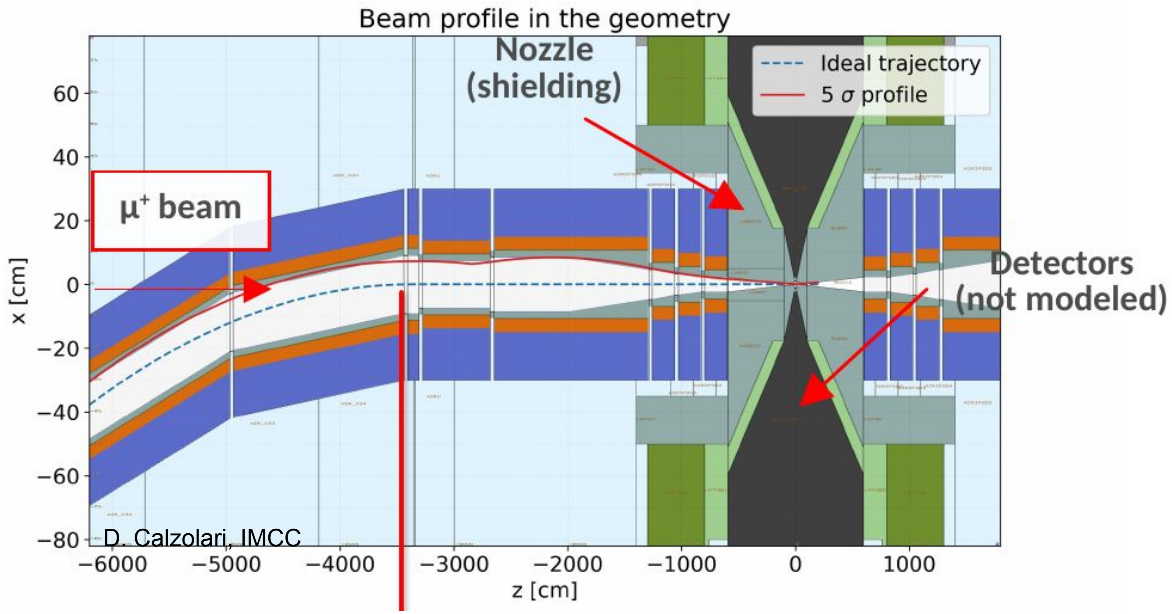




BIB simulation

Detailed simulations are needed to assess the environment around the interaction point:

- Knowledge of accelerator lattice and propagation through magnet systems
- Showering in shielding structures
- Collective beam effects
- … and much more

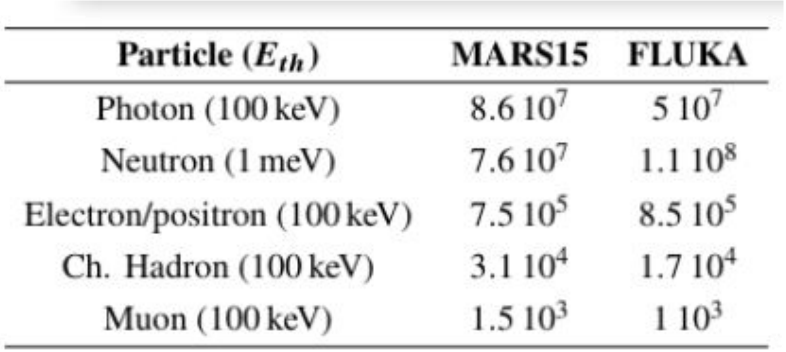


Building upon the work of the MAP Collaboration using MARS simulation.

Now using LineBuilder+FLUKA:

- reproduced older results at √s=1.5 TeV
- new results at higher √s (3, 10 TeV)
- flexible setup

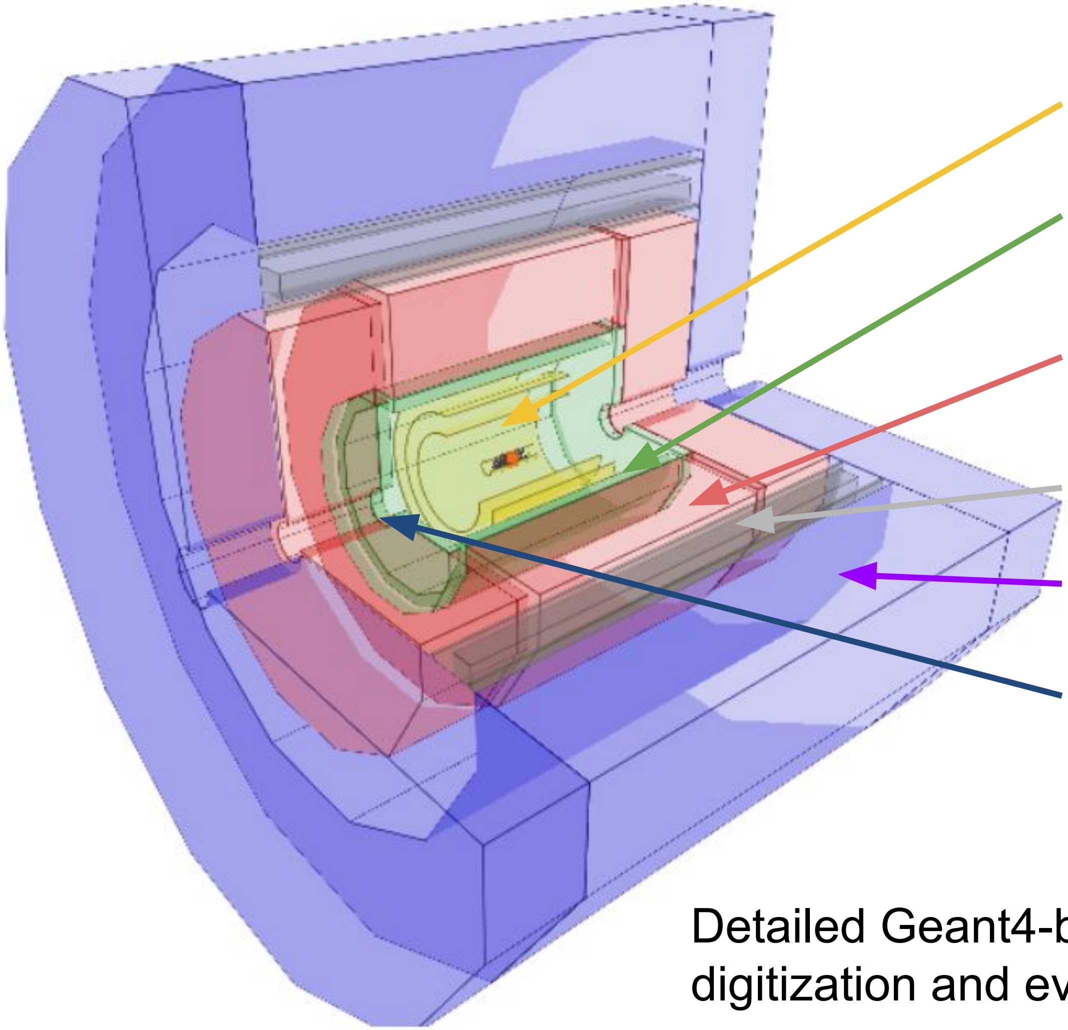
Still, very resource-intensive simulations!



Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	$8.6\ 10^7$	$5\ 10^7$
Neutron (1 meV)	$7.6\ 10^7$	$1.1\ 10^8$
Electron/positron (100 keV)	$7.5\ 10^5$	$8.5\ 10^5$
Ch. Hadron (100 keV)	$3.1\ 10^4$	$1.7\ 10^4$
Muon (100 keV)	$1.5\ 10^3$	$1\ 10^3$

A First Muon Collider Detector Design

Initially based on CLIC detector, with modification for BIB suppression
So far targeted a “low”-energy option: √s = 1.5 TeV



Silicon Tracker

EM Calorimeter (Tungsten+Si)

Hadronic Calorimeter
(Steel+Scintillators)

3.75 T Solenoid

Muon Chambers (RPC)

Nozzle (~Tungsten)

Current design limits acceptance
to θ = 10°

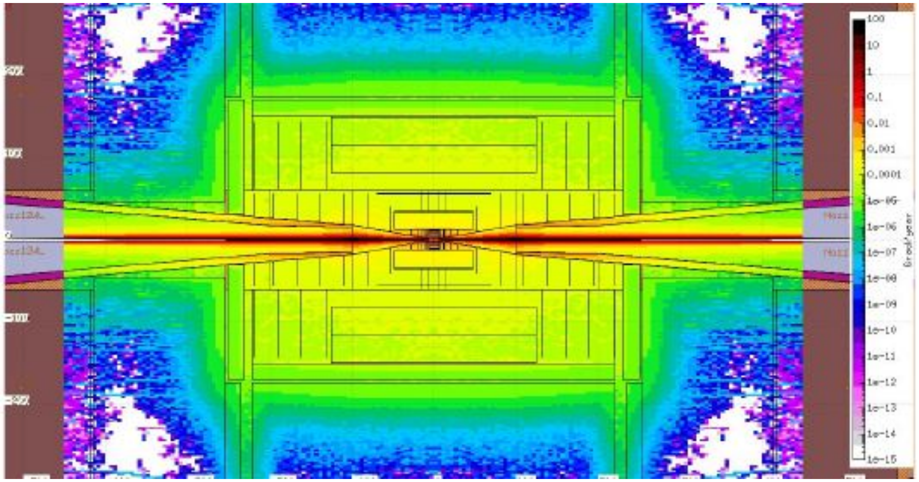
Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

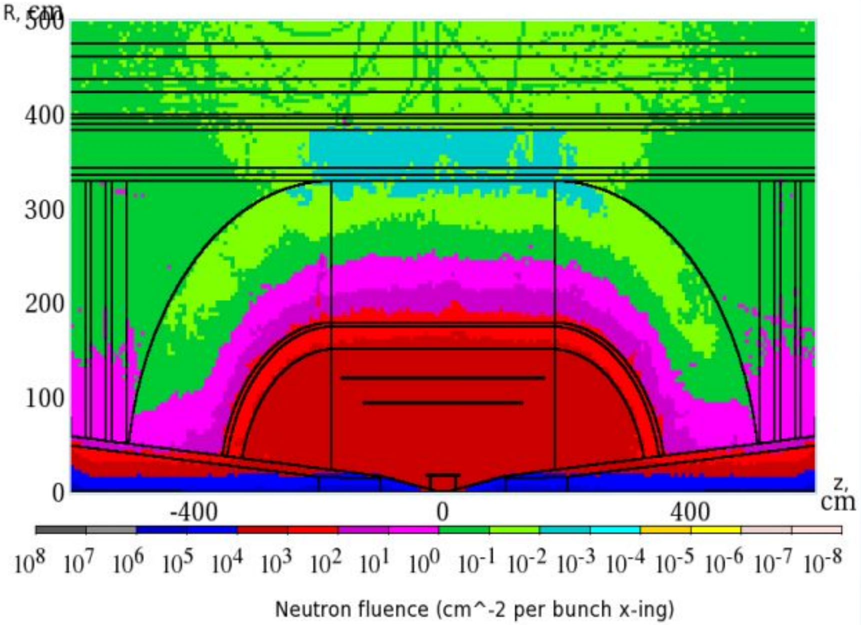
Radiation environment

Radiation hardness requirements of detectors not that different from HL-LHC.

	Maximum Dose (Mrad)	
	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1
HL-LHC	100	0.1

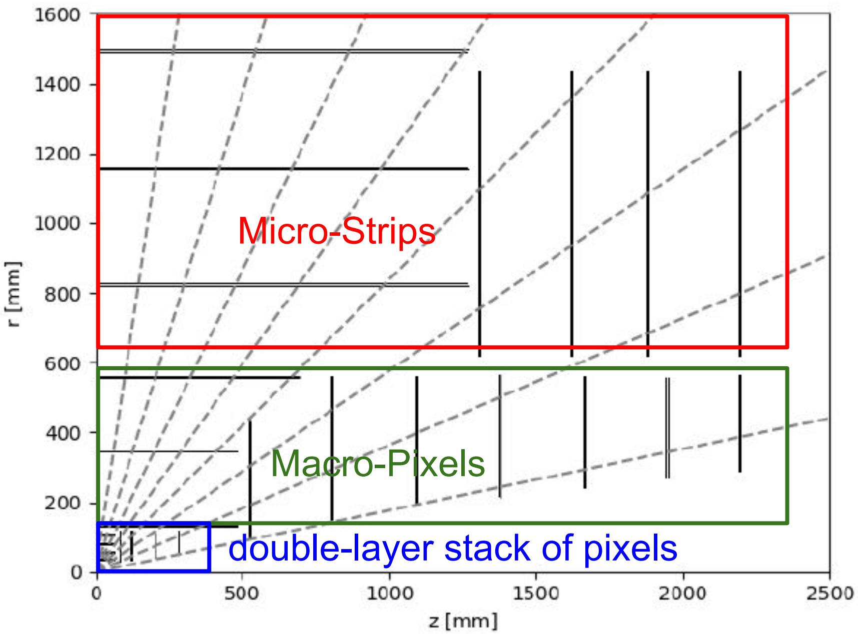
	Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm
Muon Collider	10^{15}	10^{14}
HL-LHC	10^{15}	10^{13}

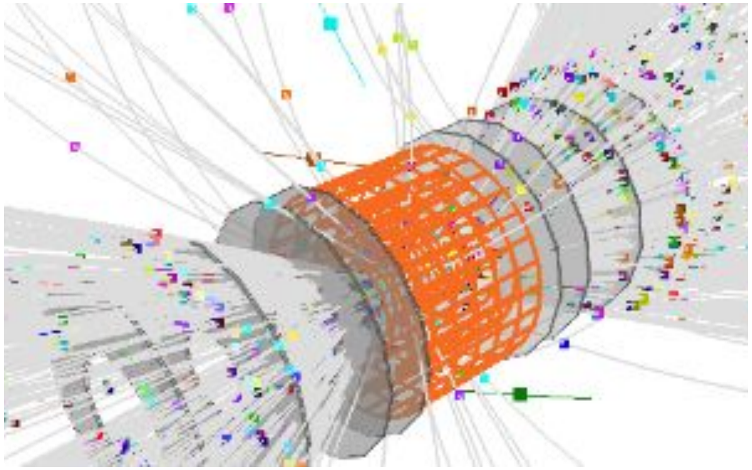


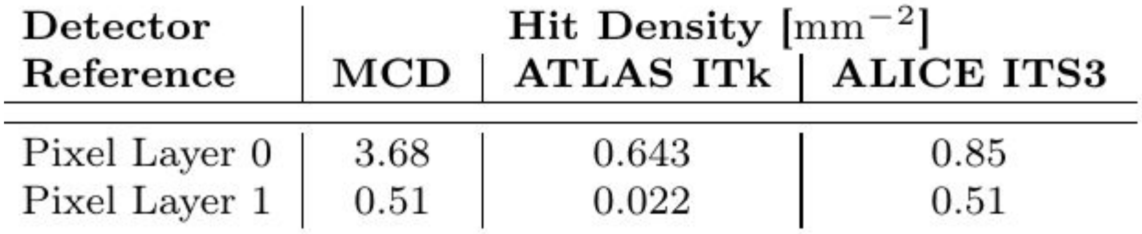


BIB in the Tracking system

Adds complexity in the event readout and reconstruction, e.g. in the inner tracker:







Detector Reference	Hit Density $[\mathrm{mm}^{-2}]$ MCD	ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

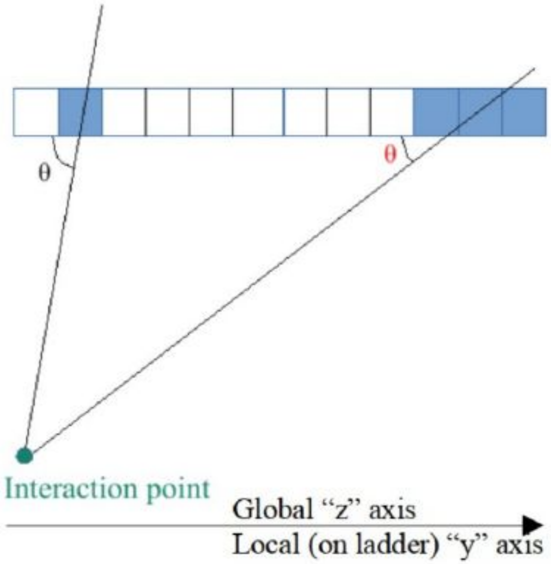
Using as ref. the ATLAS Inner Tracker for HL-LHC (ref, ref)

Hit density after timing selections, compared to expectations at HL-LHC.
Bunch crossing rate 100kHz (Muon collider) vs ~40MHz (LHC)

Reducing the impact of BIB in the Tracker

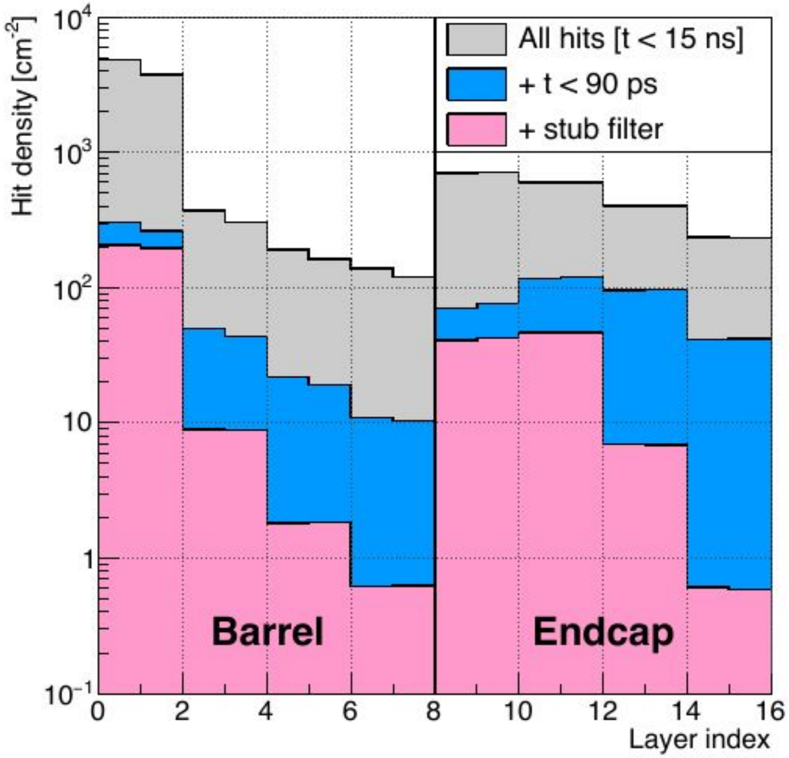
Key handles for discrimination:

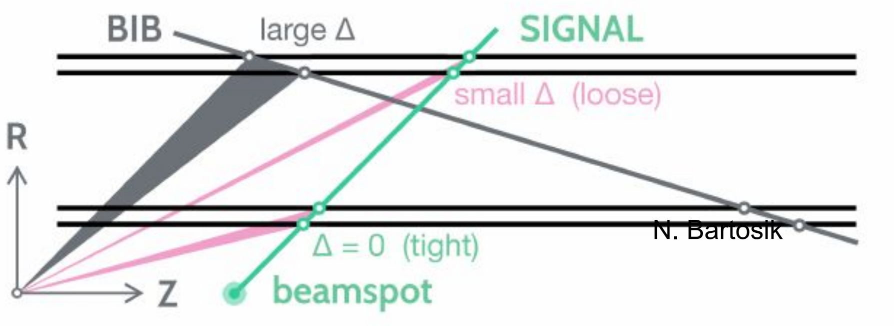
- Timing
- Directional information
  (not from interaction point)
- Energy deposition / pulse-shape analysis
  (esp. against soft photons)



Cut efficiency	Loose	Tight
Single-μ	99.3 %	99.1 %
Single-μ and BIB	37.4 %	30.7 %

arXiv:2203.07964 (updated)





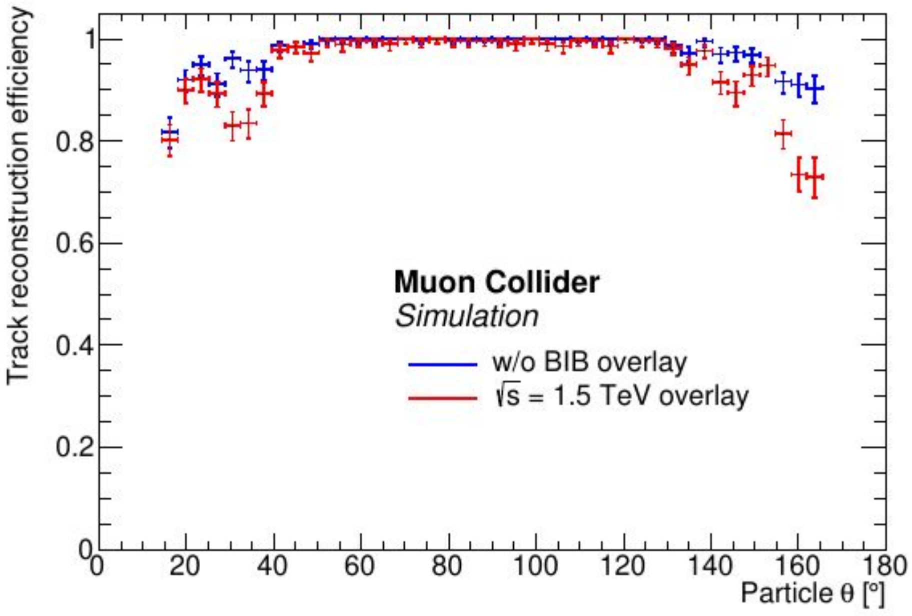
N. Bartosik

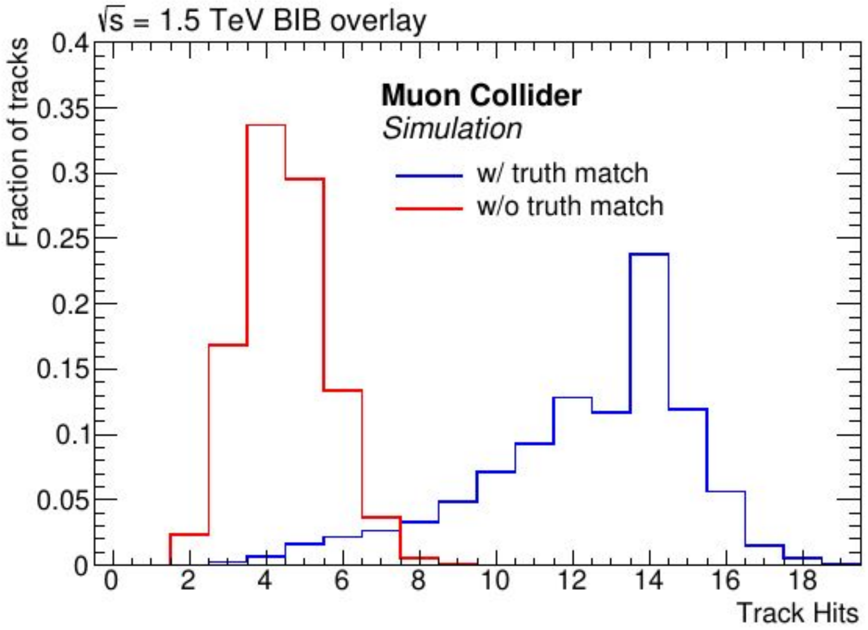
Tracking Algorithms

Smarter algorithms for event reconstruction

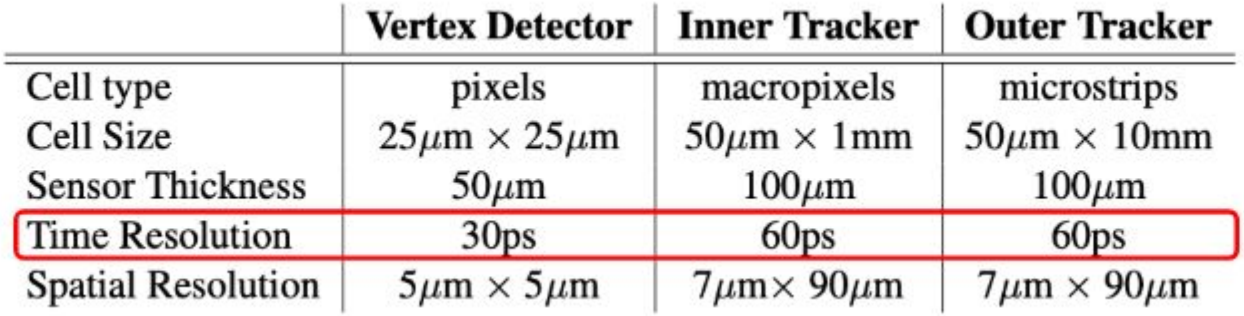
- Moved from ILC-style to LHC-style algorithms
- Modern and well-maintained code libraries (ACTS)
- Still computational challenging: O(min)/event (was: days/∞)
- BIB/fake tracks from 100k / event to O(1) / event after quality selections

Demonstrated the ability to reconstruct charged particles (p_T > 1 GeV) in this environment





Tracking detectors: technology

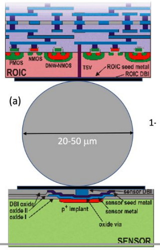


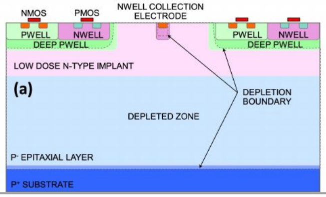
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

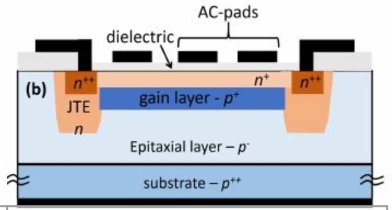
Multiple technological choices being investigated for accurate timing-aware tracking

- Hybrid pixels, CMOS-based, LGAD-based, …
- Thin sensor (layer)
- Need for powerful yet power-efficient ASICs (smaller feature size)

Synergy with HL-LHC and other projects





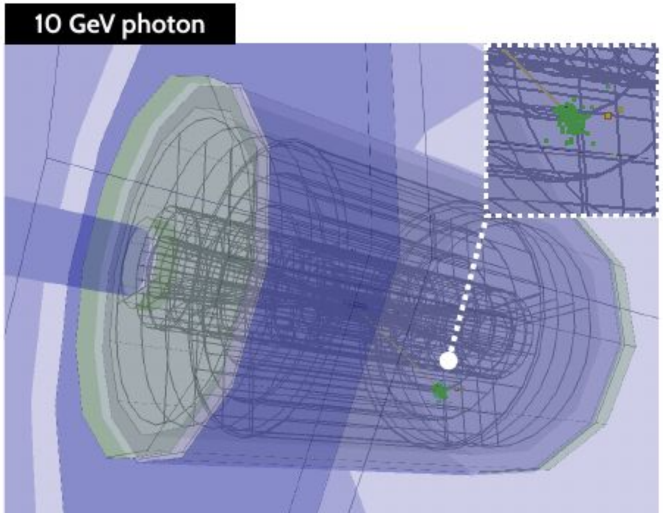


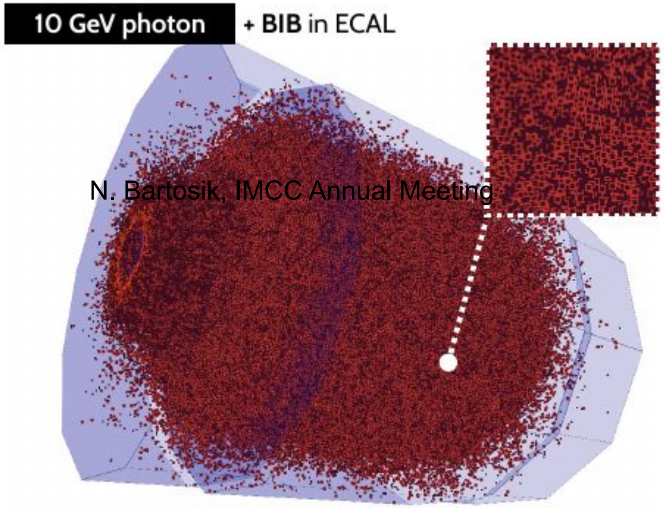
	Hybrid	CMOS-like	LGAD-like
Timing	–	+	+
Spatial Resolution	+	+	–/+
Radiation Hardness	+	–	–

BIB in the calorimeters

Diffuse Beam-Induced Background energy deposits in calorimeters.

- Somewhat similar in nature to what we're learning to deal with for HL-LHC; similar techniques effective but some key differences

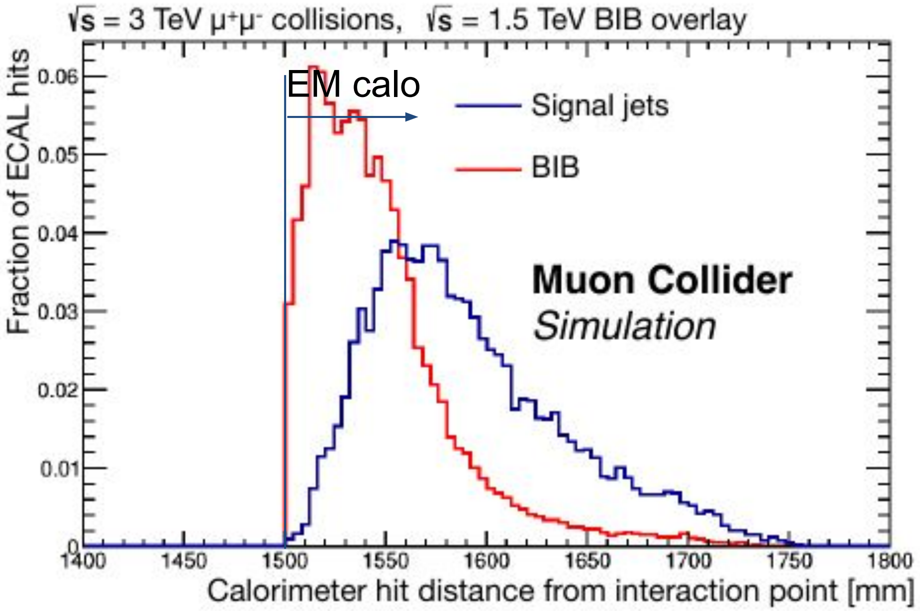




N. Bartosik, IMCC Annual Meeting

Mostly low-E photons and neutrons.

- 300 particles/cm^2 and <E> ~ 1.7 MeV/photon
- particularly severe for the EM calorimeter but steeply falling going deeper in the calorimeter and into the Hadronic Calorimeters



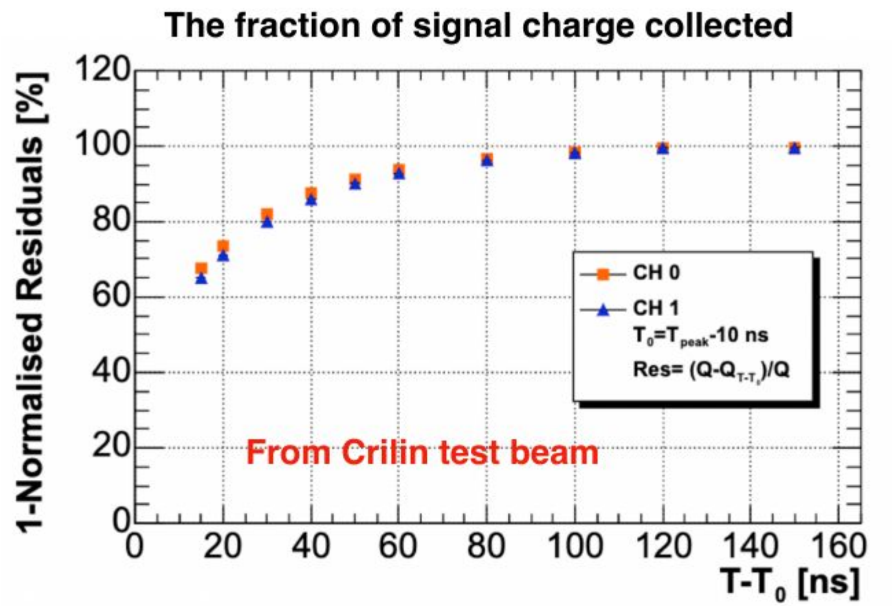
Calorimeters: performance and technology

Key detector characteristics:

- short integration time
- good time-of-arrival resolution
- longitudinal segmentation
- good radiation hardness
- good energy resolution for physics.

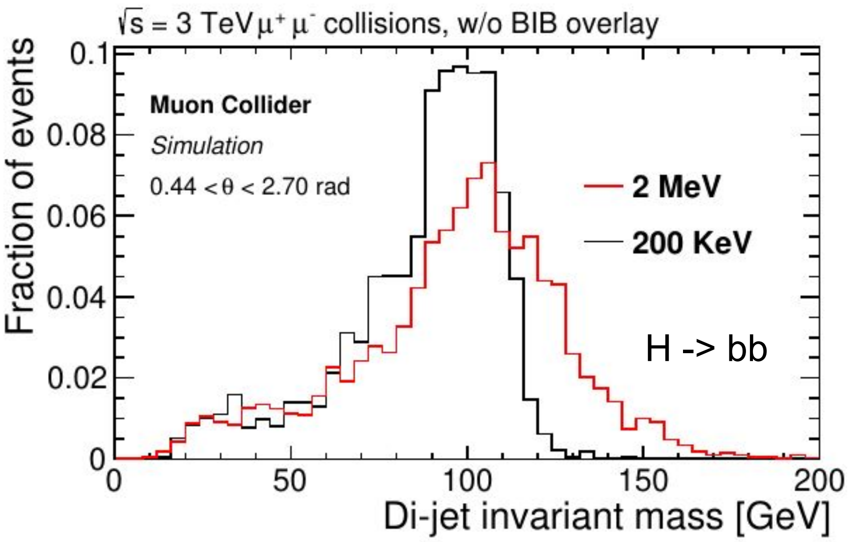
Exploring new technology

- e.g. semi-homogeneous Crilin calorimeter R&D already ongoing



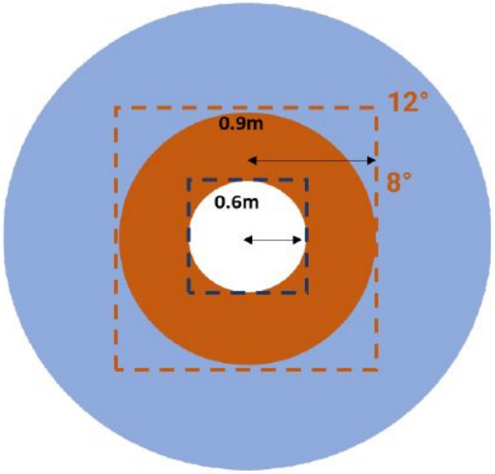
Event reconstruction, key points:

- calorimeter cell energy selection
- particle-flow approach, integrating charged particle information with appropriate selections
- energy calibration
- residual “fake” energy clusters (jets) removal



Muon System

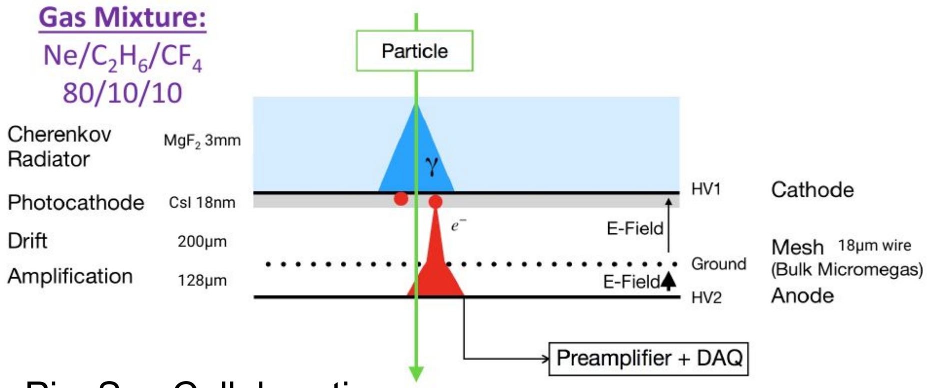
Central barrel system:
Greatly reduced BIB flux if readout window reasonably small.
Endcap layers:
Face high rates: 60kHz/cm^2 8° < θ < 12°, 2kHz/cm^2 elsewhere



Endcap – not in scale

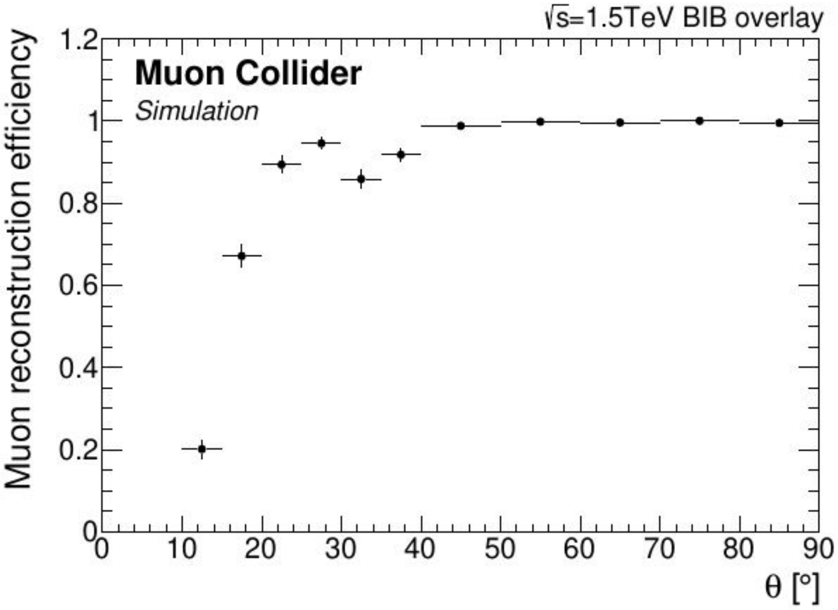
Requirements on spatial (~100μm) and time (<1ns) resolution call for gaseous detector R&D. Example of ongoing R&D:

- sub-ns timing with MicroMegas
- eco-friendly gas mixtures that maintain high detection effici



PicoSec Collaboration

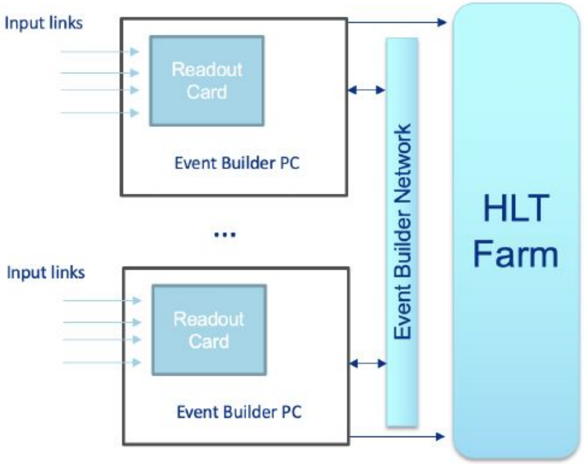
- reduced drift gap (~200μm)
- cherenkov radiator instead of trying to detect primary ionization

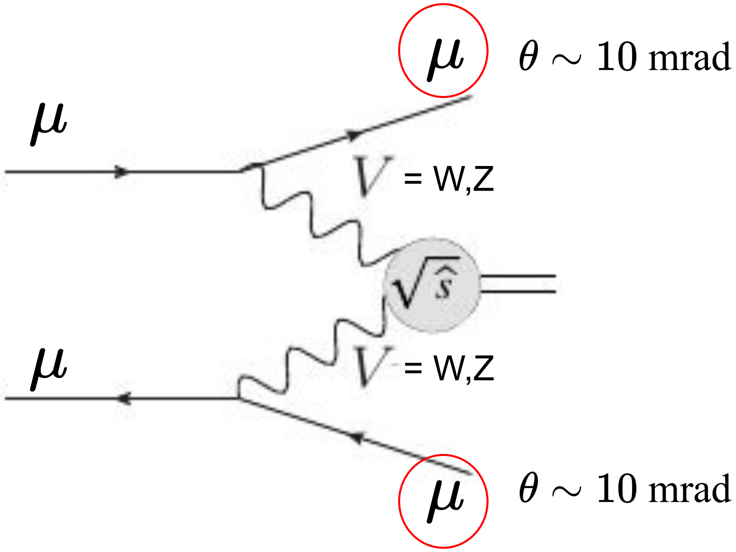


DAQ and Other Detectors

Online software processing seems reachable with the expected ~100kHz event rate, despite large data volume

- rough estimation: 60Tb/s; not that far from high-level triggers input bandwidth of HL-LHC experiments
- reduction of required data bandwidth with on-detector processing can be a game-changer.





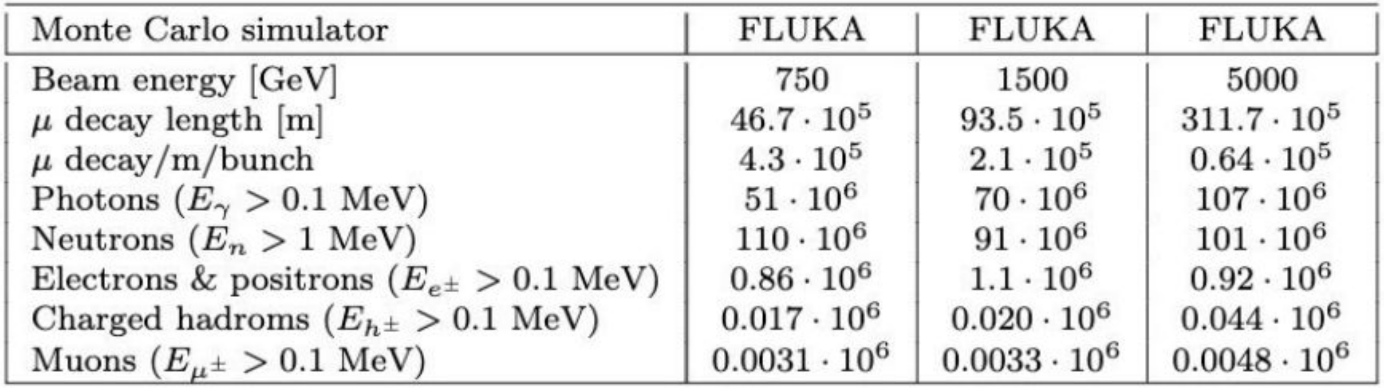
And many more detector components being investigated:

- Large physics interest in detecting very forward muons, possible synergies with very forward HL-LHC detectors? (e.g. FASER2)
- Dedicated luminosity measurement with high accuracy
- …

Towards a 10-TeV muon collider detector

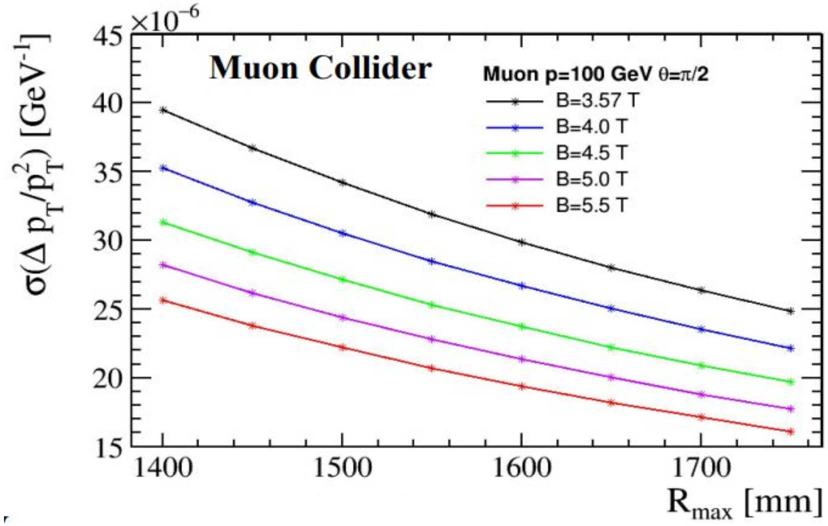
Studied BIB behavior at different c.o.m. energies, two effects roughly balance

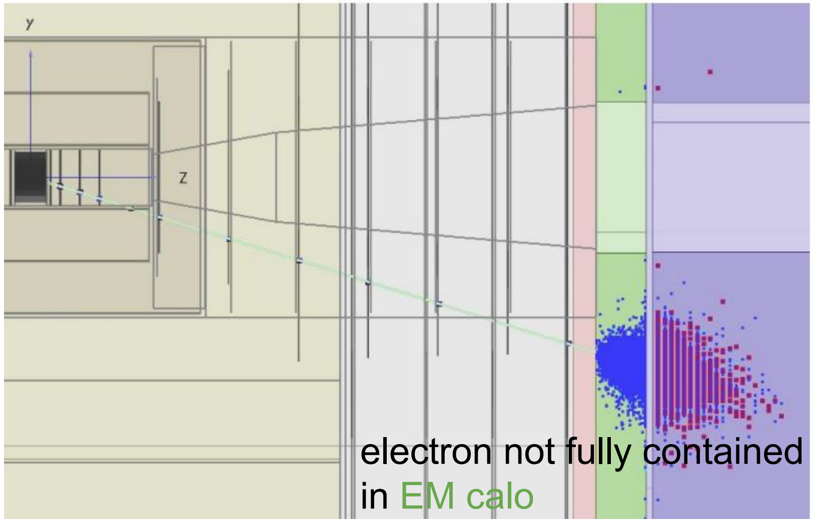
- longer lab-frame muon lifetime
- more energetic decay products



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

Detector design needs to evolve to accommodate higher p_T particles

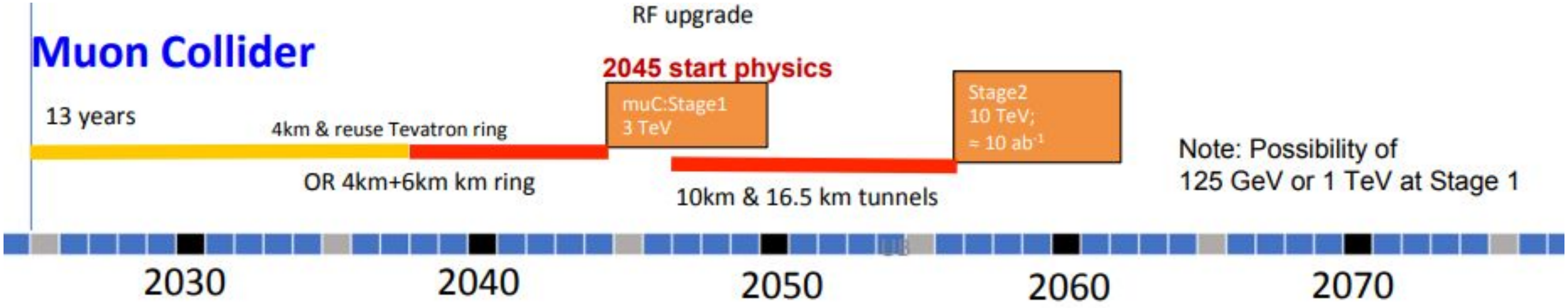




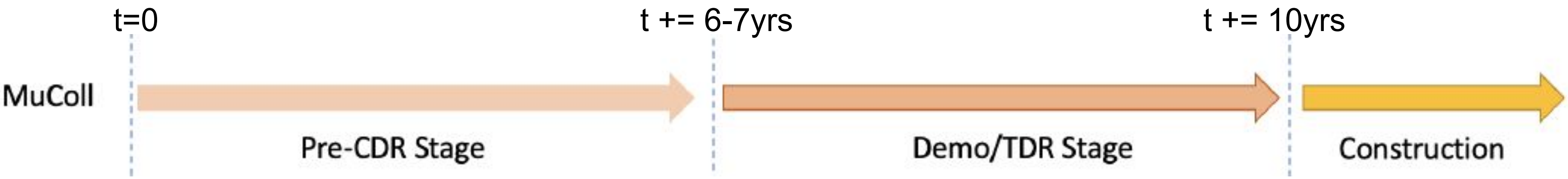
electron not fully contained in EM calo

Timelines

A technically-limited timeline would see a high-energy muon collider in 2040s
A full TDR needs to be produced by end of the 2030s.



R&D program and an accelerator-demonstration facility in the shorter term



Approximate (with input from the timelines presented by IMCC and US-Snowmass). arXiv:2209.01318.
See D. Schulte's presentation for more details.

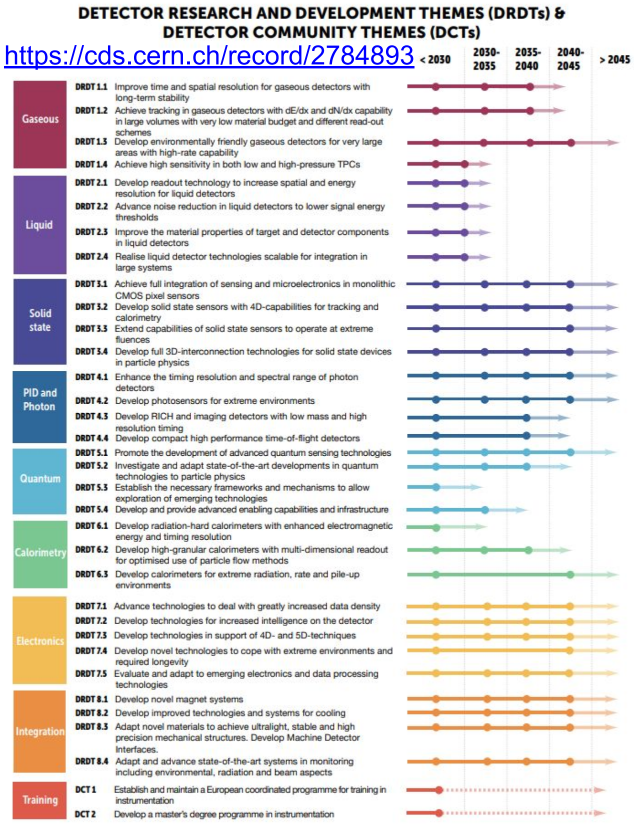
Need to take advantage of synergies among these programs and other areas of HEP and beyond for detector R&D.

Instrumentation R&D

- DOE Detector R&D BRN Report, Snowmass Instrumentation Report – US;
- 2021 ECFA Detector R&D Roadmap – Europe.

ECFA initiative to establish new detector R&D “groups” (DRD”X”).
CPAD initiative planning new detector research consortia (RDC”X”).
The two initiatives closely connect in structure and objectives.

RD	Topic
RDC1	Noble elements Detectors
RDC2	Photodetectors
RDC3	Solid State Tracking
RDC4	Readout and ASICs
RDC5	Trigger and DAQ
RDC6	Gaseous Detectors
RDC7	Low-background detectors
RDC8	Quantum and Superconducting Sensors
RDC9	Calorimetry
RDC10	Detector Mechanics



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) &
DETECTOR COMMUNITY THEMES (DCTs)

https://cds.cern.ch/record/2784893

Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
Training	DCT 1	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

Muon Collider Detector R&D

Solid-State Detectors (TF3/DRD3, RDC3)
- Radiation-hard silicon detectors with O(10ps) timing resolution
- Integrated or hybrid design

Calorimetry (TF6/DRD6, RDC9)
- High-granularity (transverse and longitudinal); good radiation hardness
- good timing resolution and low integration time (esp. ECAL)
- Scintillator or Silicon-based sampling; Crilin: semi-homogenous w/ SiPMs readout

Gaseous Detectors (TF1/DRD1, RDC6)
- Mostly Muon spectrometer: micromegas, GEM, etc.. focus on good timing resolution, sustainable gas mixtures

Photon-Detectors and PID (TF4/DRD4, RDC2)
- Less explored so far, but PID can offer additional physics oportunities

Electronics (TF7/DRD7, RDC4)
- Radiation-hard ASIC design (HL-LHC levels)
- Small feature size for more complex on-chip processing (tracker, calo?)

Trigger and DAQ (RDC5)
- Triggerless readout requires large real-time data handling

Detector Mechanics (RDC10)
- Lightweight structures, nozzle support design,

Conclusions

To extract the exciting physics behind multi-TeV muon-muon collisions, an outstanding detector is needed to disentangle beam-induced backgrounds.

An initial detector design has been simulated in detail

- proving that such a task can be accomplished
- identifying key technological developments that are needed

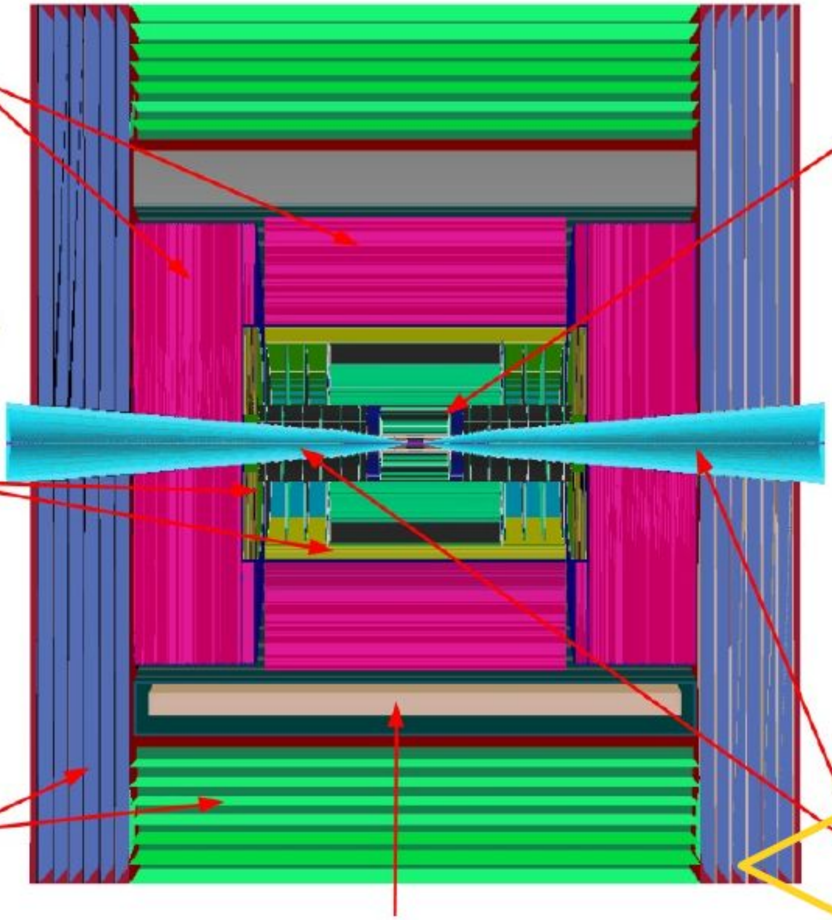
Given the long timescale involved, it is extremely beneficial to identify synergies that connect generic detector R&D and project-specific developments

Synergies with HL-LHC and other future high-energy colliders are more apparent, but identifying connections with other experiments might provide a huge boost to such developments.

I look forward to explore more these connections during the workshop!

Backup

Detector Overview



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.

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.

superconducting solenoid (3.57T)

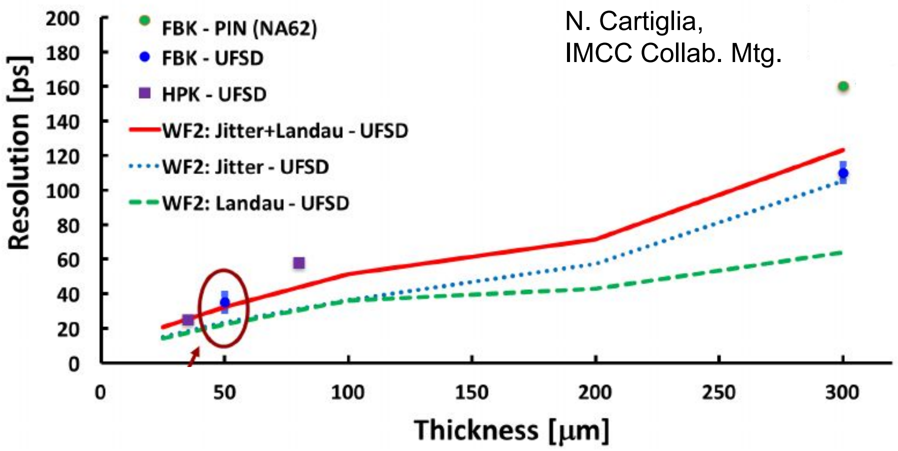
Outline

- Introduction (physics already presented by Nathaniel)
  - IMCC, european strategy and Snowmass studies
  - Future prospects - aspirations and expectations
- Beam Induced Background
  - how it is generated, how it propagates into the detector
  - nozzle and its optimization
  - simulation tools and status
  - energy dependence: naive vs detailed simulation
- Muon Collider Detector overview
- Radiation levels
- tracking system
  - BIB in numbers
  - Timing information
  - Challenges and results for track reconstruction
  - Technology
- Calorimetry system
  - BIB in numbers
  - impact of granularity and timing (integration vs arrival)
  - reco algorithms and performance
  - Technology
- Muon system: BIB in numbers and solutions
- Forward muons: challenges, detectors
- … and more: PID, luminosity measurement, …
- Summing it up

Tracking detectors: hardware & software

Need for precise 4D tracking

- Hybrid pixels, CMOS-based, LGAD-based, …
- synergy with HL-LHC and other projects
- Unlock more on-chip logic with smaller feature size

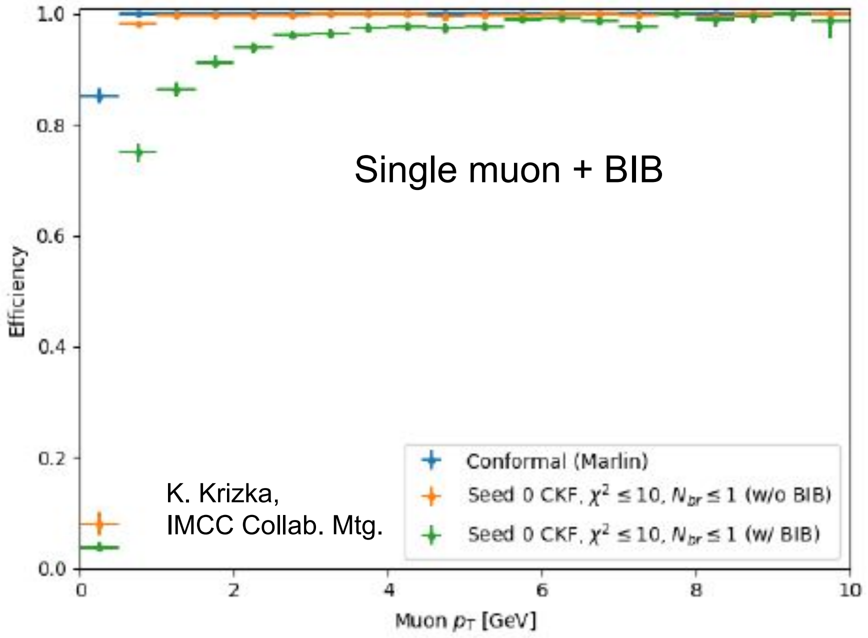


N. Cartiglia,
IMCC Collab. Mtg.

Particle identification detectors also merit more attention

Smart algorithms for event reconstruction

- Moved from ILC-style to LHC-style algorithms
- Modern and well-maintained code libraries (ACTS)
- Allowed full event reconstruction in ~4 min/event (was: days/∞)
- BIB/fake tracks from 100k / event to < 1 / event



Single muon + BIB

K. Krizka,
IMCC Collab. Mtg.