Detector design for $\sqrt{s}$ = 1.5 / 3.0 TeV and path towards 10 TeV

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on behalf of the Detector Study Group

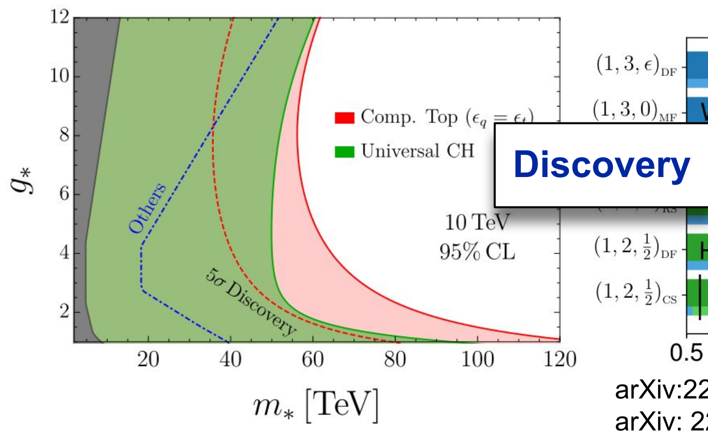
IMCC Collaboration Meeting
Orsay, June 22nd 2023

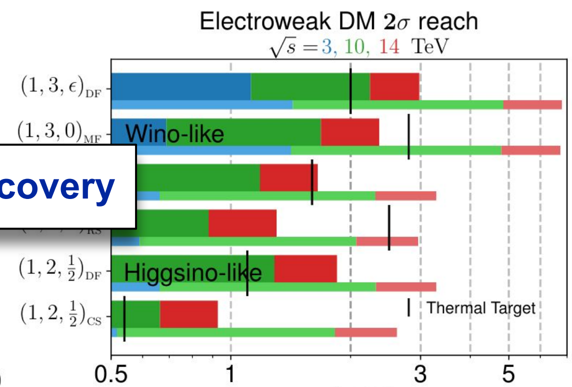
BERKELEY LAB
Lawrence Berkeley National Laboratory

The physics we dream of discovering

see Ian Low's [talk on Mon]

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

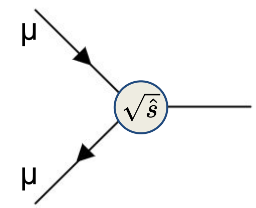




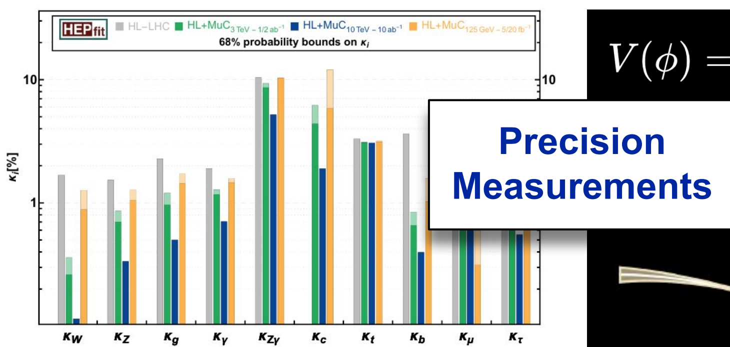
arXiv:2209.01318,
arXiv: 2203.07351

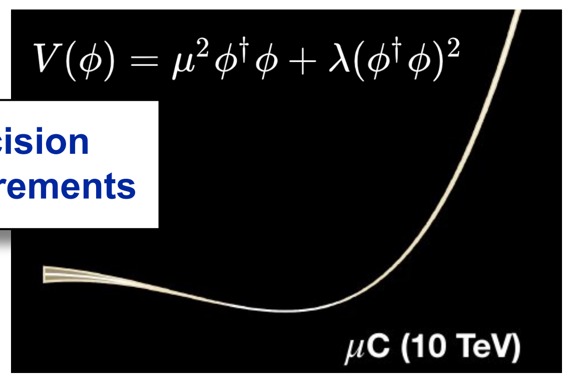
The EWK Interactions Era

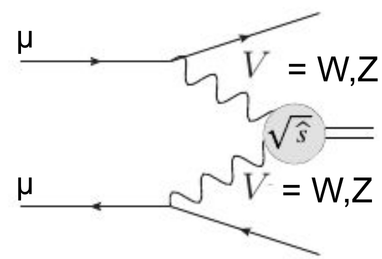
see also Muon4Future N. Craig's [talk], et al.



$\sigma \sim 1/\hat{s}$







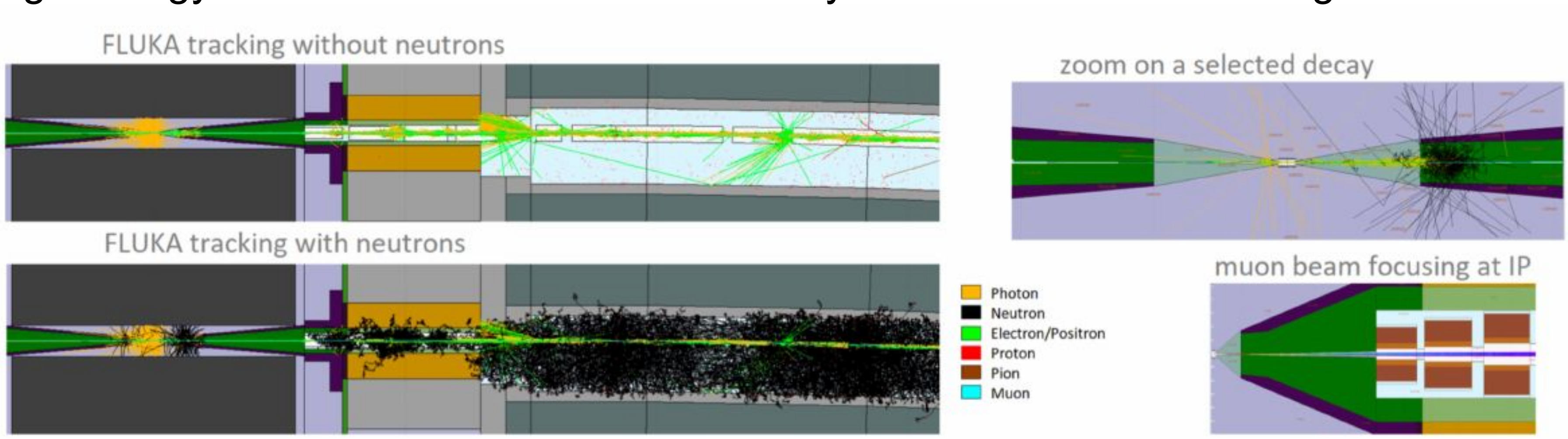
$\sigma \sim \log \hat{s}$

Credit: R. Petrossian-Byrne, N. Craig

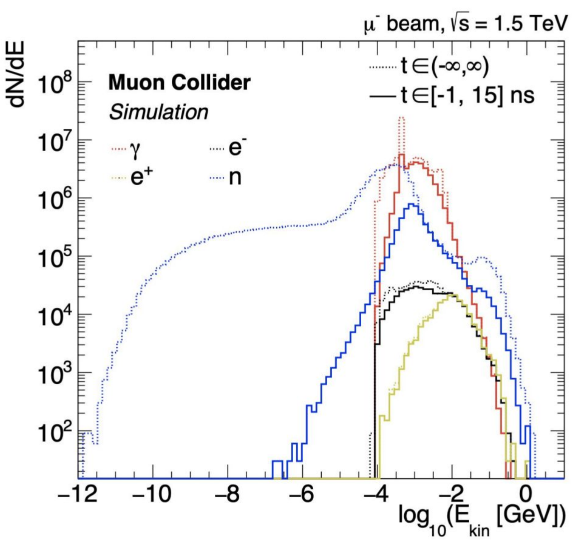
√s = 1-3 TeV ➡ beyond LHC on "light" EWK particles and precision measurements
√s = 10(+) TeV ➡ ultimate goal to reach full potential on key questions

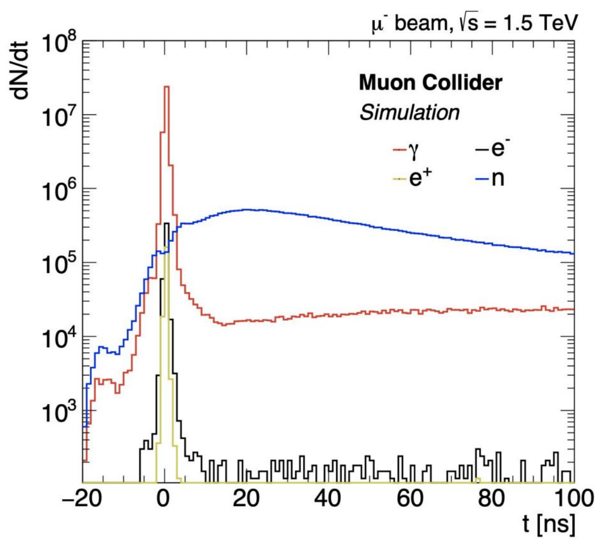
Detector Environment: Beam-Induced Background

High-energy electrons from muon beam decays interact with surrounding material.



Dedicated shielding yields a *cloud* of mostly low-energy and diffuse γ/e±/n





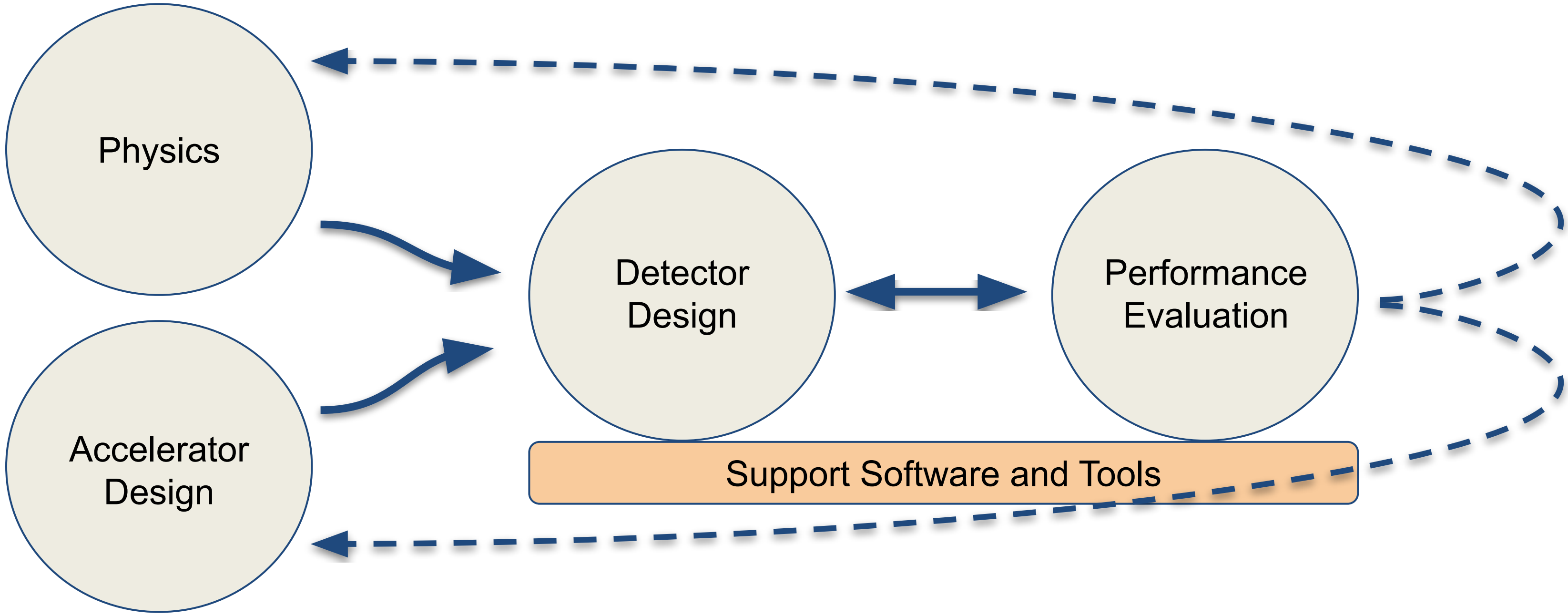
Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	$8.6\ 10^7$	$5\ 10^7$
Neutron (1 meV)	$7.6\ 10^7$	$1.1\ 10^8$
Electron/positron (100 keV)	$7.5\ 10^5$	$8.5\ 10^5$
Ch. Hadron (100 keV)	$3.1\ 10^4$	$1.7\ 10^4$
Muon (100 keV)	$1.5\ 10^3$	$1\ 10^3$

Numbers above for √s=1.5 TeV.
First simulations at √s=10 TeV now available as well.

Muon Collider Detector Design

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

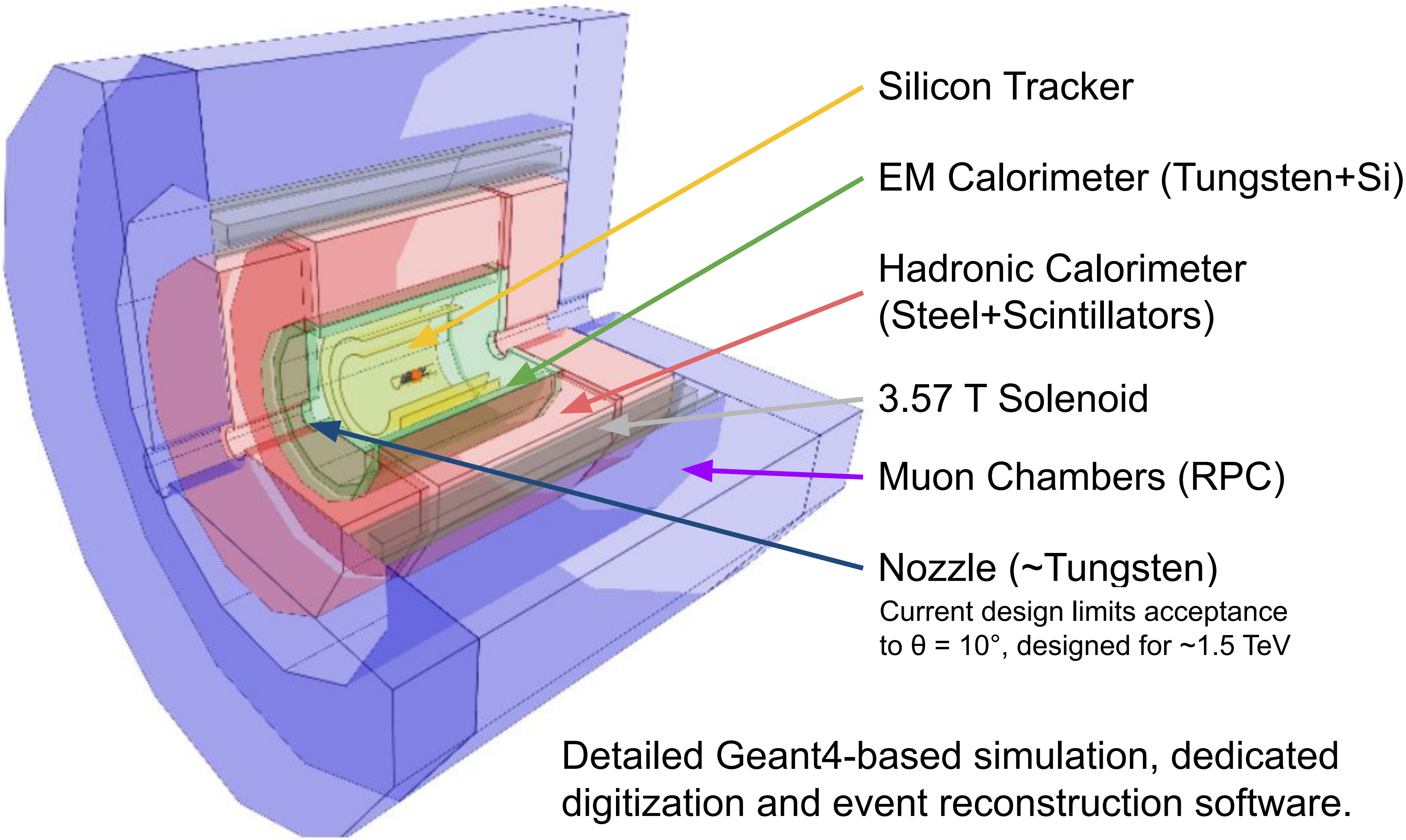
- Is it possible to design a detector capable to unlock the promising physics behind multi-TeV muon-muon collisions?
- What technology needs to be developed and what challenges overcome?
- What's optimal? What opportunities can be unlocked with new ideas?



The best answers might simply change over time.
Requirements evolve, detector technology keeps innovating.

A First Muon Collider Detector Design

Multi-purpose detector that targets very broad physics goals.



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

Radiation environment

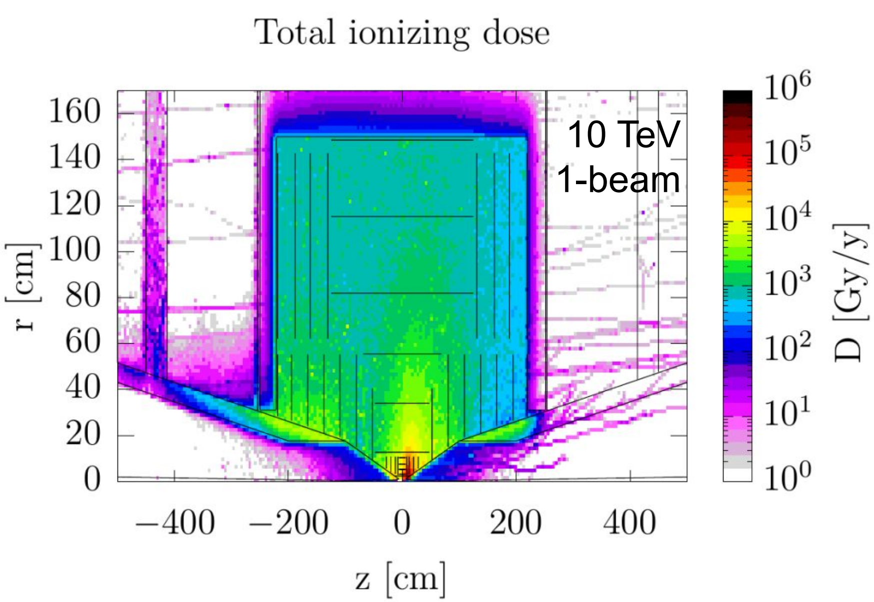
Radiation hardness requirements of detectors not that different from HL-LHC.

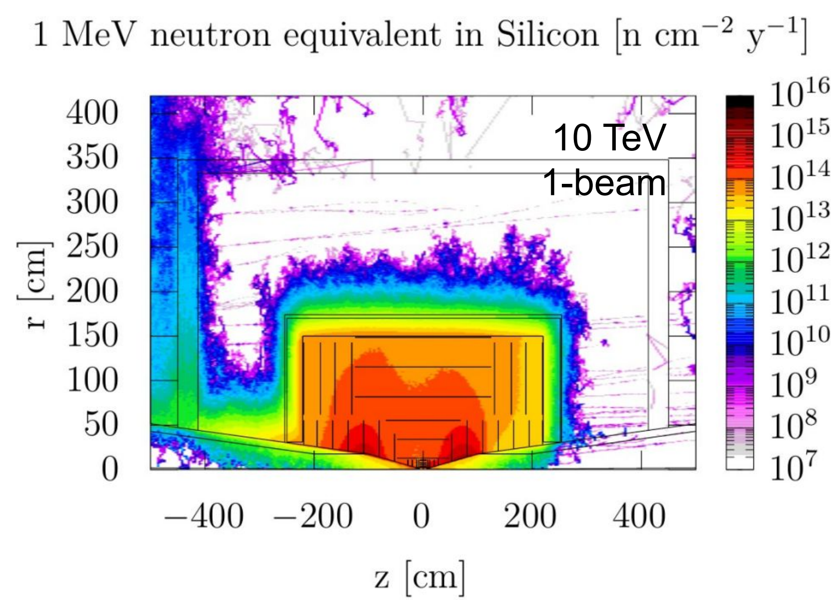
- points of attention: innermost tracker endcap disks, forward calo/muon systems

Expected dose/fluence per year of operation

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

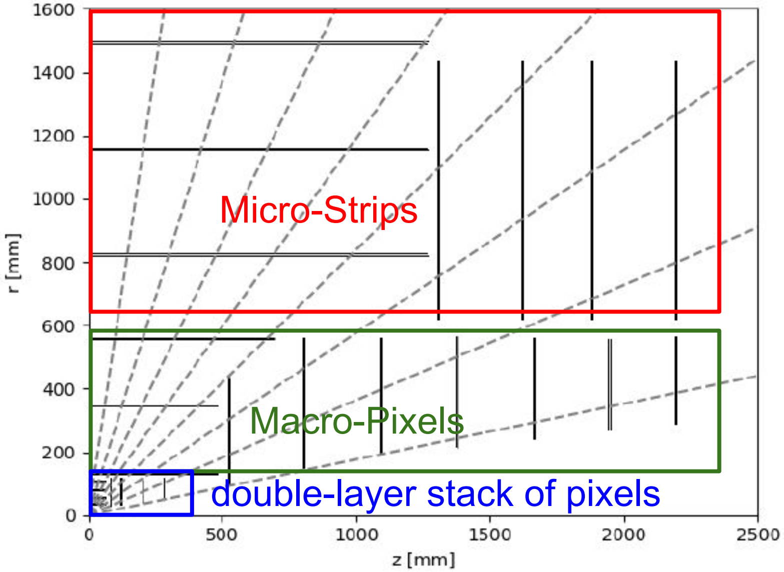
	Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm
Muon Collider	10^{15}	10^{14}
HL-LHC	10^{15}	10^{13}
Muon Collider 10 TeV	tbc	O(10^{14})

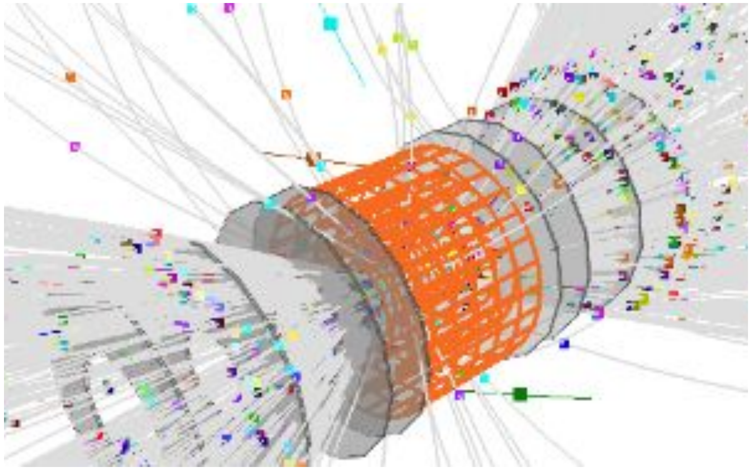


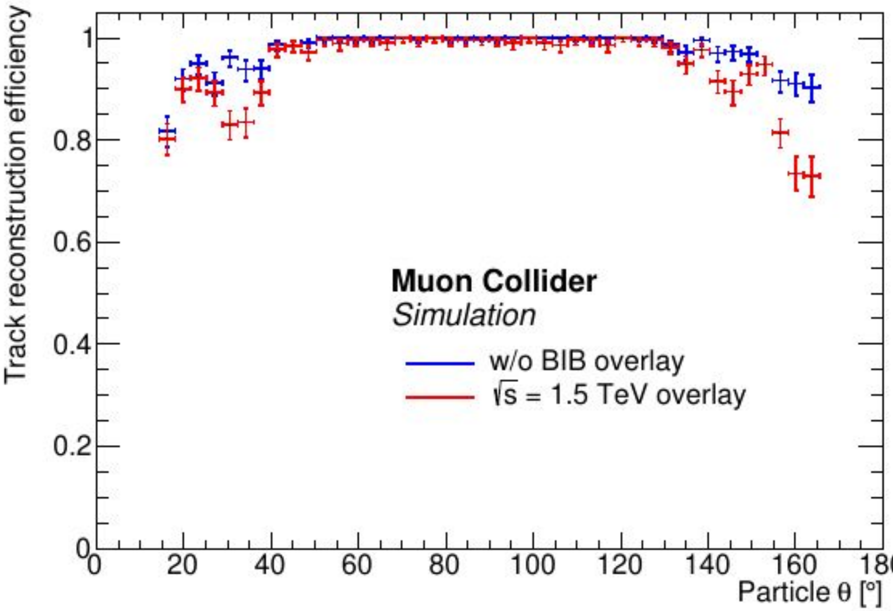


Tracking system

more info on performance:
C. Aime` talk







Smarter algorithms for event reconstruction

- Computational challenging
- BIB/fake tracks from 100k / event to O(1) / event after quality selections

Key handles for discrimination:

- Timing, Directional information, Energy deposition

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

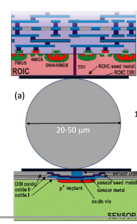
Tracking detectors: technology

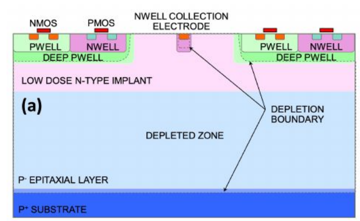
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu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

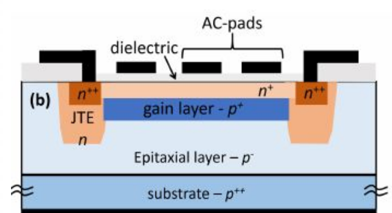
Multiple technological choices being investigated for accurate timing-aware tracking

- Hybrid pixels, CMOS-based, LGAD-based, … ⬅️ *pursue multiple options*
- Thin sensor (layer) ⬅️ *how thin do we really need it?*
- Need for powerful yet power-efficient ASICs (smaller feature size) ⬅️ *early R&D*

Synergy with HL-LHC and other projects





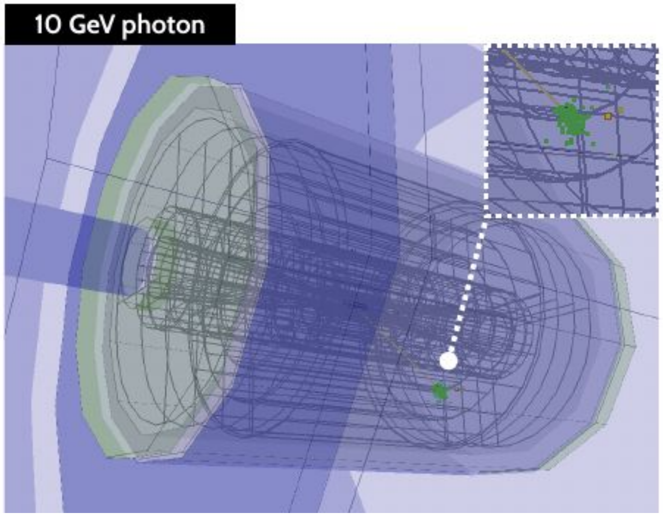


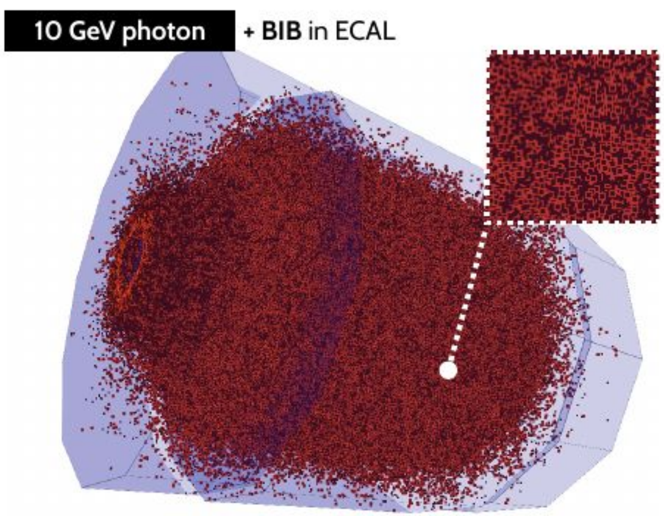
	Hybrid	CMOS-like	LGAD-like
Timing	–	+	+
Spatial Resolution	+	+	–/+
Radiation Hardness	+	–	–

BIB in the calorimeters

Diffuse Beam-Induced Background energy deposits in calorimeters.

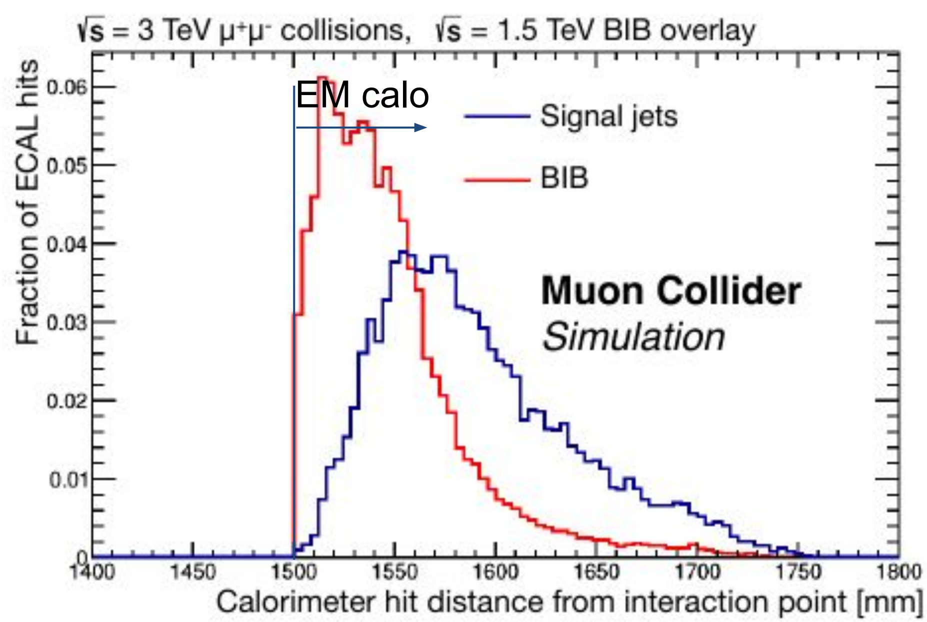
- Somewhat similar in nature to what we're learning to deal with for HL-LHC; similar techniques effective but some key differences





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



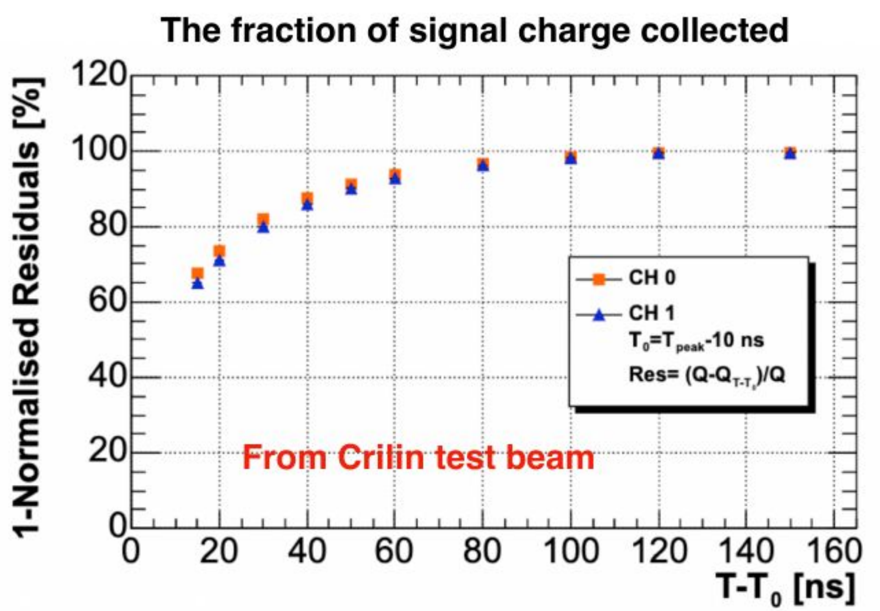
Calorimeters: performance and technology

Key detector characteristics:

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

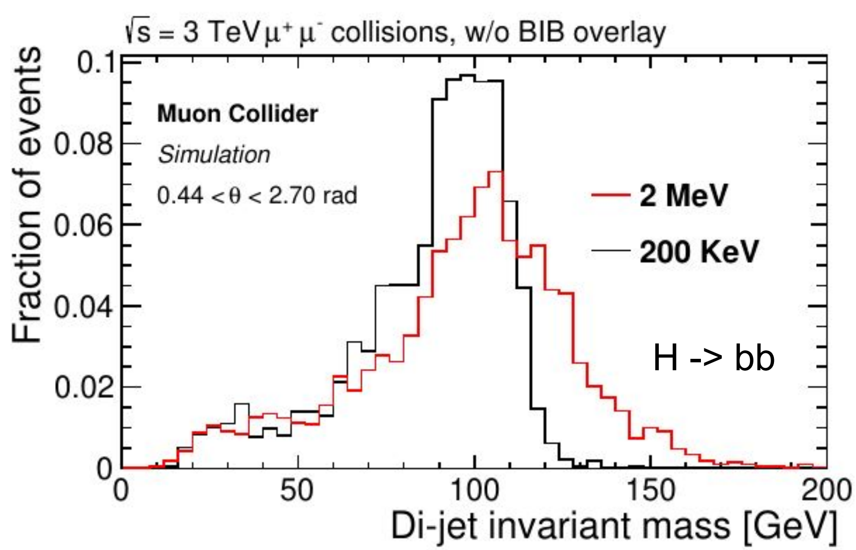
Exploring new technology

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



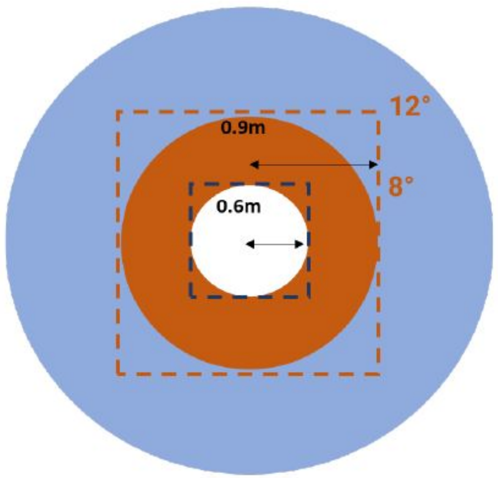
Event reconstruction, key points:

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



Muon System

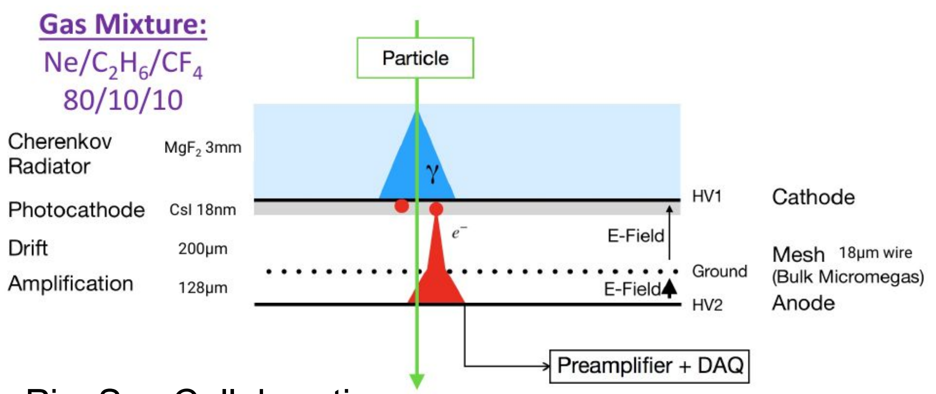
<u>Central barrel system</u>:
Greatly reduced BIB flux if readout window reasonably small.
<u>Endcap layers</u>:
Face high rates: 60kHz/cm^2 8° < θ < 12°, 2kHz/cm^2 elsewhere



Endcap – not in scale

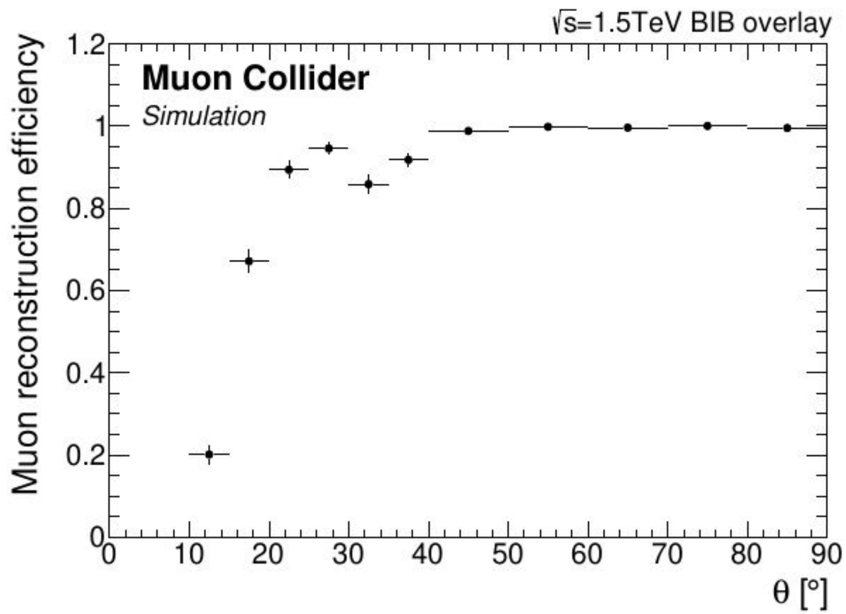
Requirements on spatial (~100μm) and time (<1ns) resolution call for gaseous detector R&D. Example of ongoing R&D:

- 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

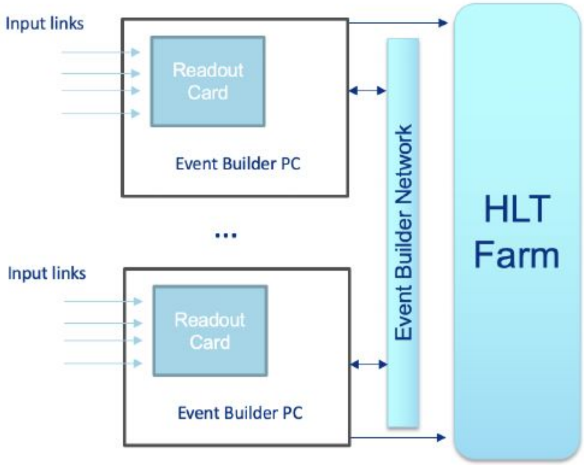


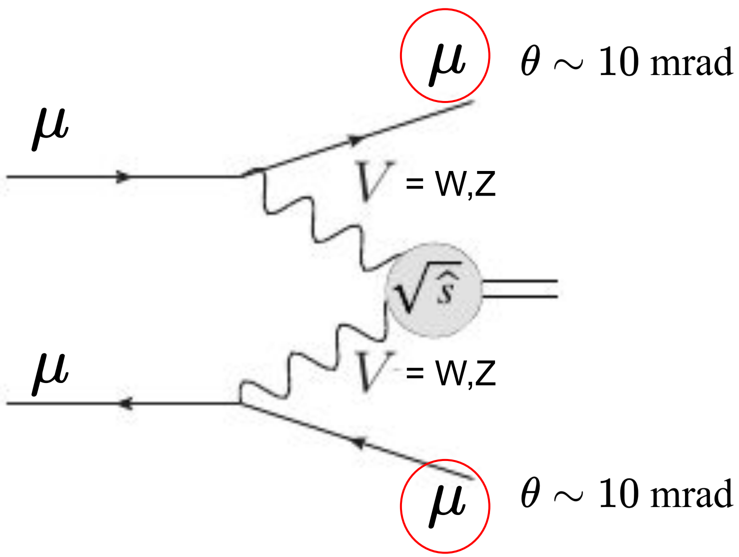
DAQ and Other Detectors

more info:
I. Ojavo talk

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.





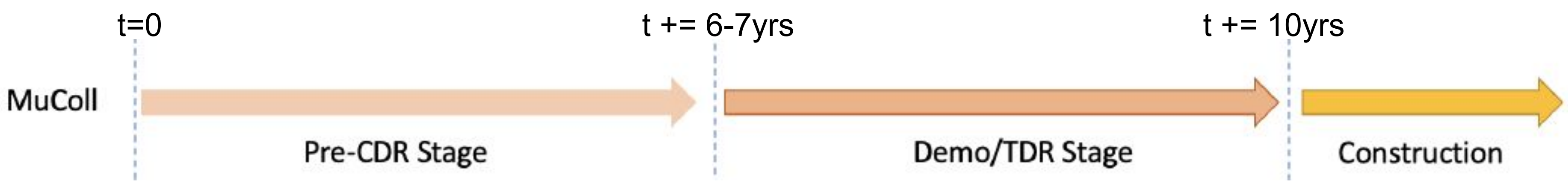
And many more detector components being investigated:

- 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
- …

Timelines and R&D

more info:
S. Jindariani and
N. Pastrone talks

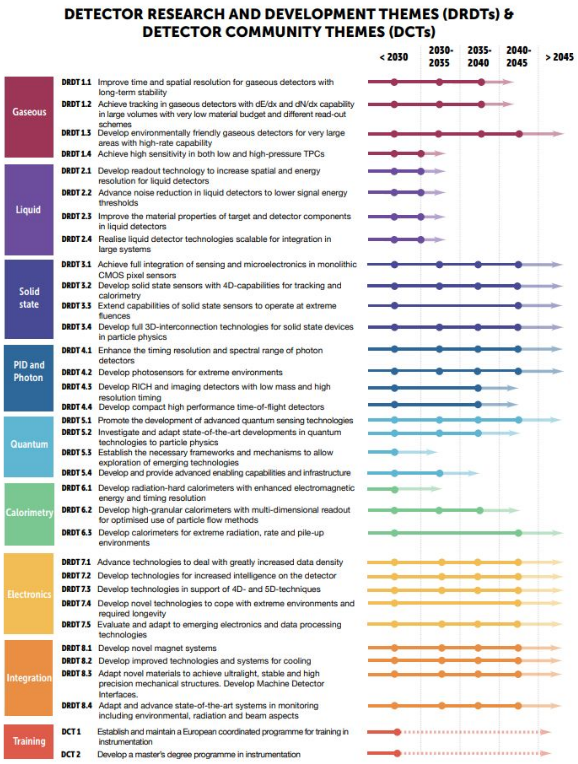
Despite a muon collider is likely ~20-30 years from operation, detector R&D is needed now to develop and prove technologies, some with historically long cycles



Note: approximate

ECFA: new detector R&D "groups" (DRD"X").
CPAD: new detector research consortia (RDC"X").
The two initiatives closely connect in structure and objectives.

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



Full-Simulation Physics Studies

more info:
L. Buonincontri talk

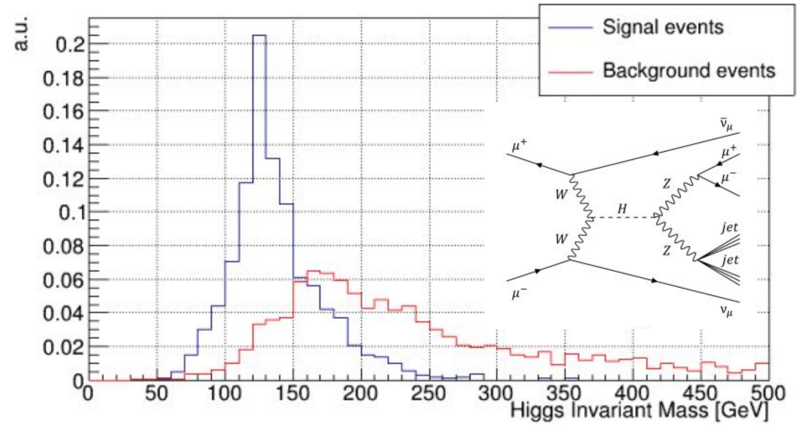
Selected benchmark physics studies using detailed simulations

- important benchmarks, difficult signatures
- validate our understanding of the detector and its requirements

Large set of (mostly Higgs-related) precision measurements:

- Higgs couplings (bb, WW, ZZ, ɣɣ, …)
- Higgs width
- Di-Higgs processes

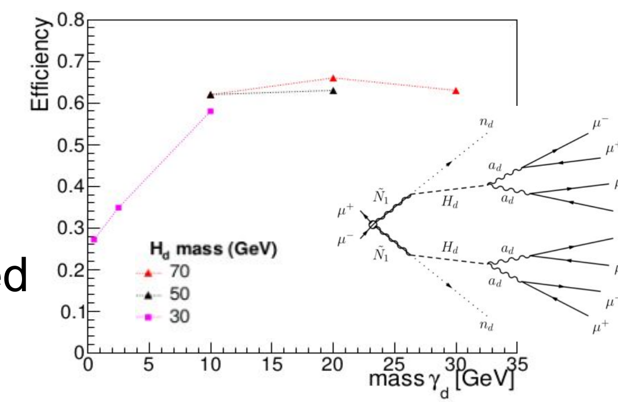
Span several final states.
Aim to expand to other key SM measurements.



Beyond-SM searches:

- Disappearing track (tracker)
- Dark photons (muon system)
- Axion-Like Particles (calorimeter)

Important for difficult backgrounds and when detailed detector/reconstruction capabilities are needed.



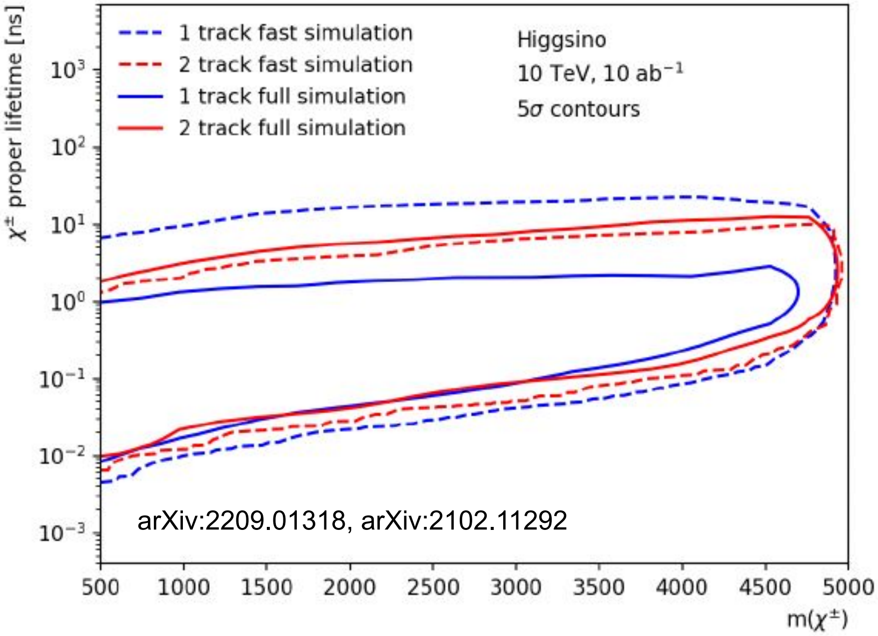
Important work to coordinate most important benchmarks scenarios with theory community (see e.g. R. Capdevilla's talks)

Fast Simulation

A fast parametric simulation allows a much larger set of physics objectives to be explored

- DELPHES implementation available
- Work to provide new cards to "bracket" performance

Important to validate results using detailed simulations!



Cross-section measurement uncertainty

Full sim		Fast sim	
H->WW	2.9%	H->WW	1.7%
H->ZZ	17%	H->ZZ	11%
H->bb	0.75%	H->bb	0.76%
H->μμ	38%	H->μμ	40%
H->γγ	8.9%	H->γγ	6.1%

See also arXiv:2203.09425

[Very preliminary. Lots of work in progress]

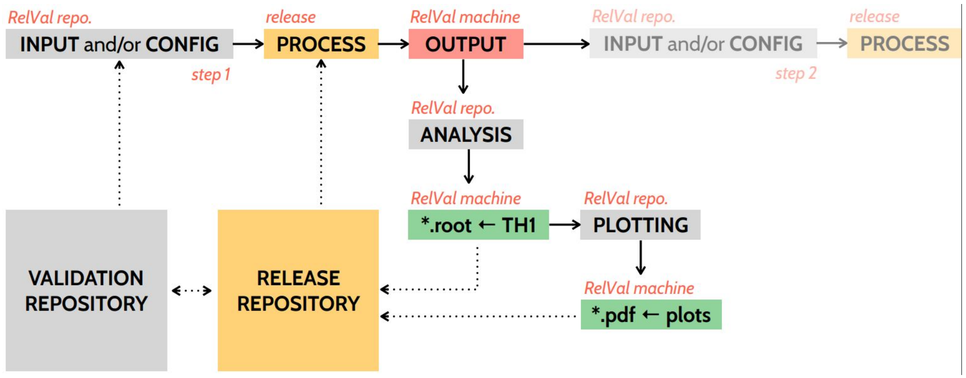
Software Development and Infrastructure

more info:
A. Gianelle and
N. Bartosik talks

Software rapidly evolving from initial ILCSoft-based solution

- lots of customization, github group being restructured
- distributed via container as well (cvmfs, dockerhub)
- tutorials to get newcomers started! (next: July 5-6)
- automation via continuous-integration (automatic checks run on github, building of container, …)
- more advanced release validation workflow being setup

Release validation workflow



Dedicated computing resources

- CERN: EOS space, computing nodes, gitlab, and more
- other resources from INFN, DESY, US (snowmass), …

Large migration project to key4hep underway

- common with other future collider projects
- modern package manager, algorithms steering (MT), …

Muon Collider Software Tutorial

- Computing Setup
- Event Generation
- Simulation
- Digitization and Reconstruction
  - Basics
  - Closer look into the configuration
  - Useful tools
  - Realistic Beam-Induced-Background (BIB)
- Study of Object Performance
  - Histogramming in Marlin (LCIO input files)
  - LCTuple (plain ROOT ntuples)
  - Python Analysis of SLCIO Files
- Algorithm Development
  - Adding a Marlin Processor
  - Tracking Custom Packages
- Advanced Topics
  - Modifying the Detector Geometry
  - Event Displays
  - BIB overlay optimisation
  - Running on batch systems
  - Tweaking particle lifetimes
  - Developing with VSCode
  - Jet reconstruction

Tutorial events

- Fermilab Workshop, Dec 16th 2022
- Snowmass '21, Sep 30th 2020

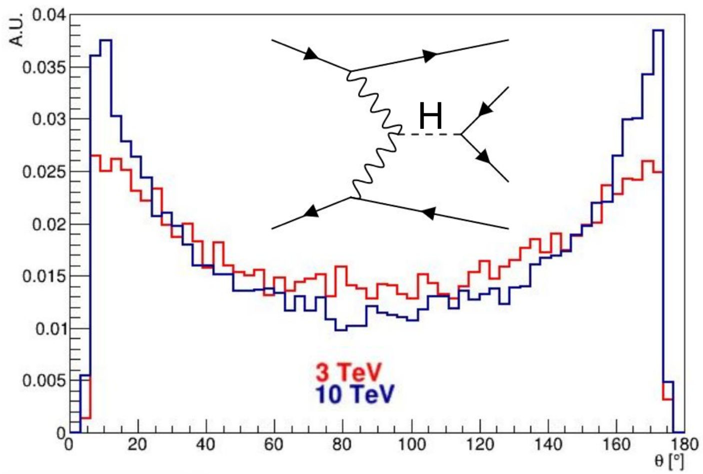
Towards a 10-TeV muon collider detector

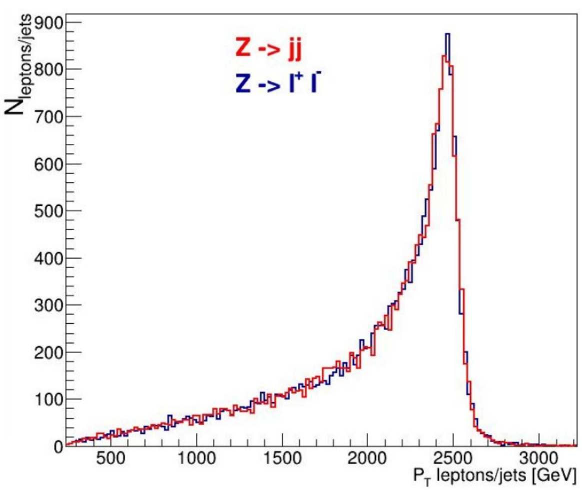
more info:
M. Casarsa and
F. Meloni talks

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)	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

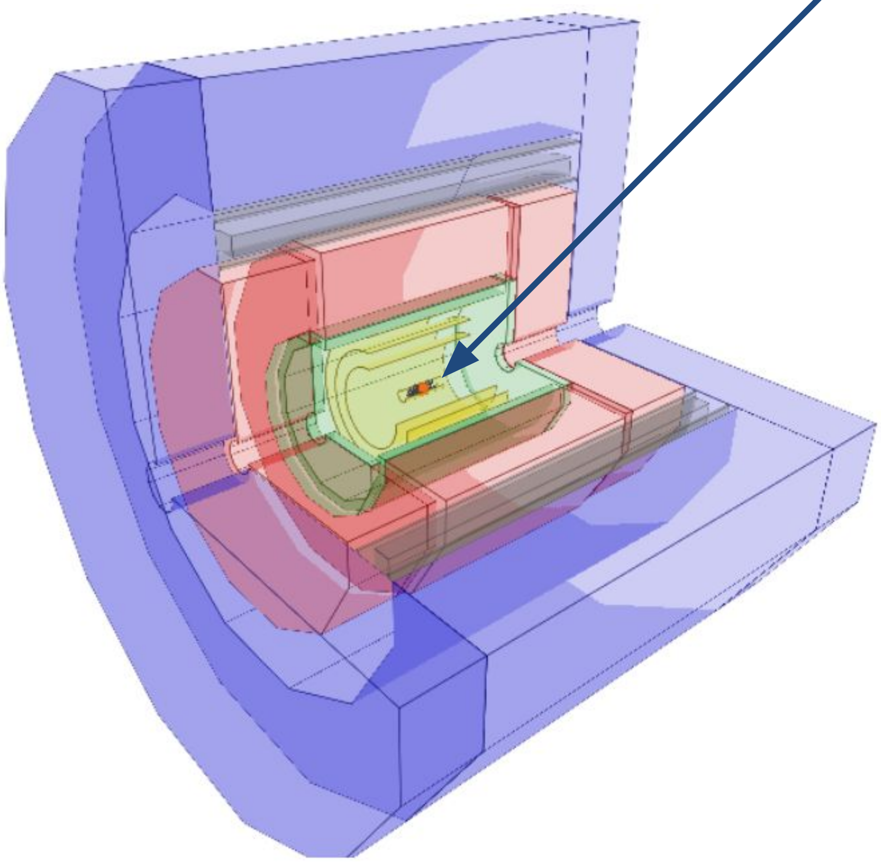
Detector design needs to evolve to accommodate a wider p_T–range of particles





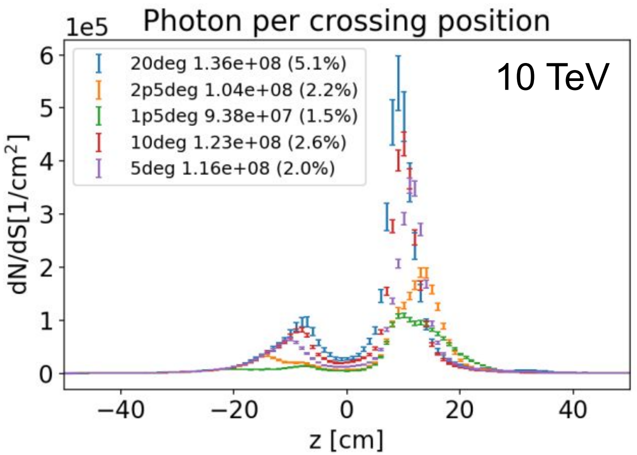
Detector design: points of attention

more info:
[D. Calzolari talk]



Nozzle

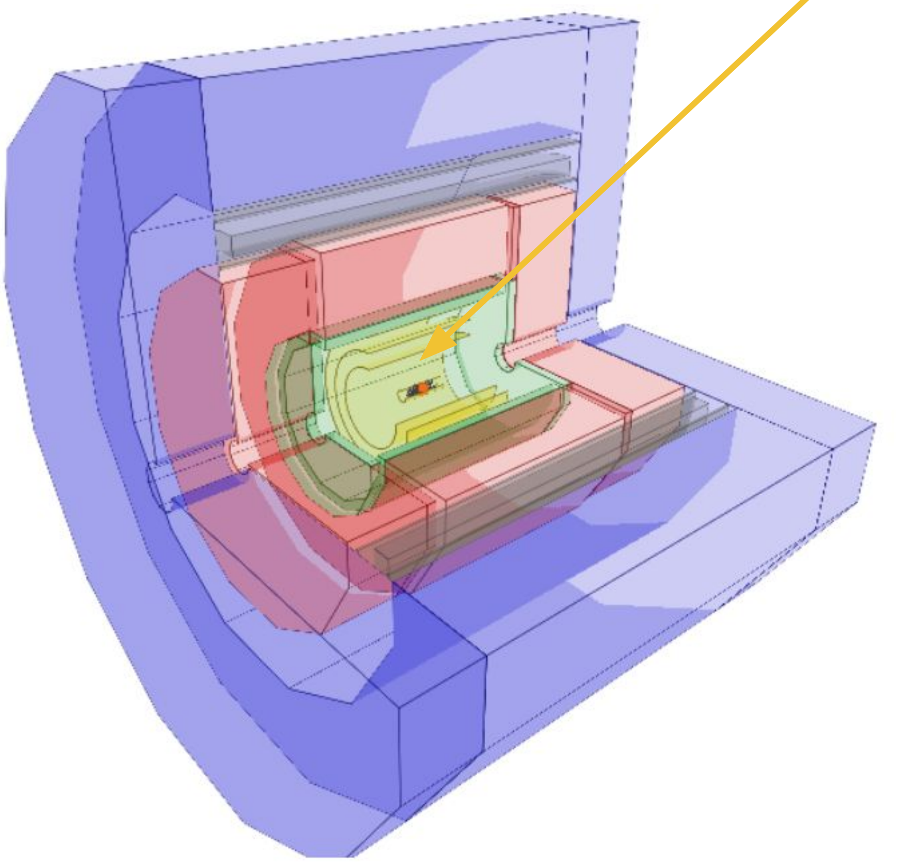
- Largely determines BIB composition seen by the detector
- Current design limits acceptance to θ = 10°, designed for ~1.5 TeV



Forward Detectors

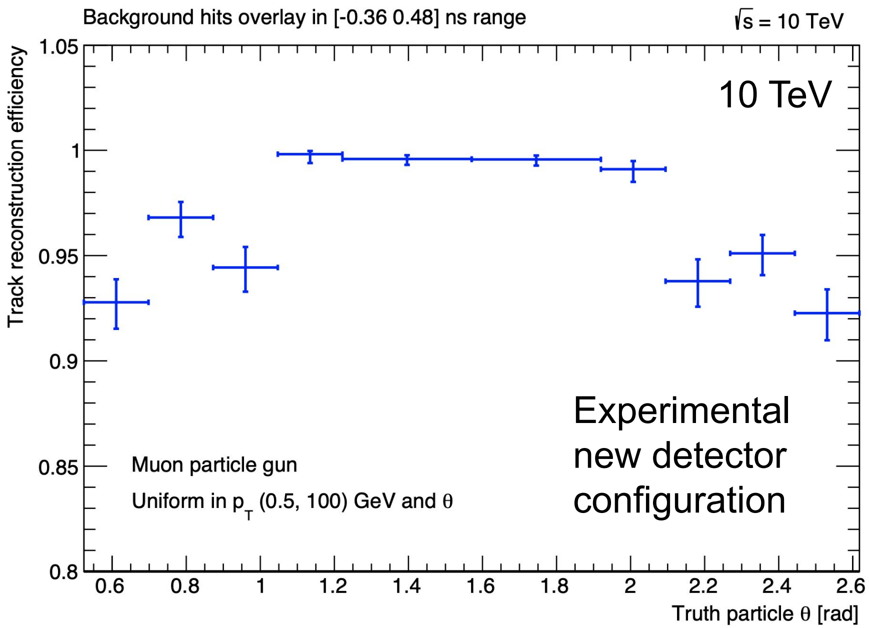
- Test concrete design ideas implementing them in the geometry
- Propagation of forward muons in accelerator lattice
- Test different momentum measurement techniques

Detector design: points of attention

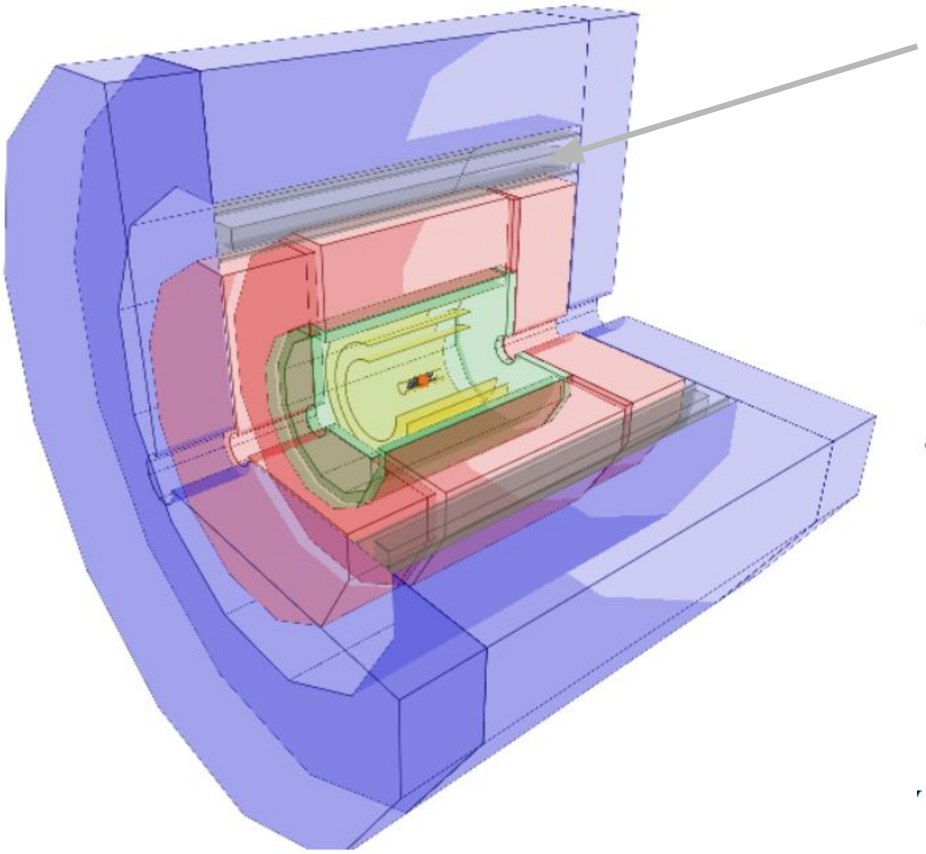


Silicon Tracker

- Geometry, layers structure
  - forward endcap, double-layers
- Granularity, timing requirements and connection with technology R&D
- Maintain sensitivity to GeV-momentum particles, and boosted objects with close-by charged particles

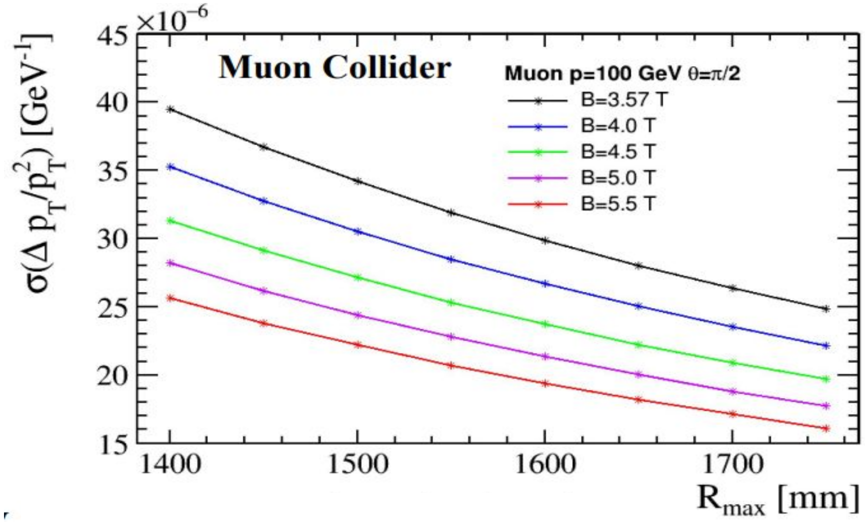


Detector design: points of attention

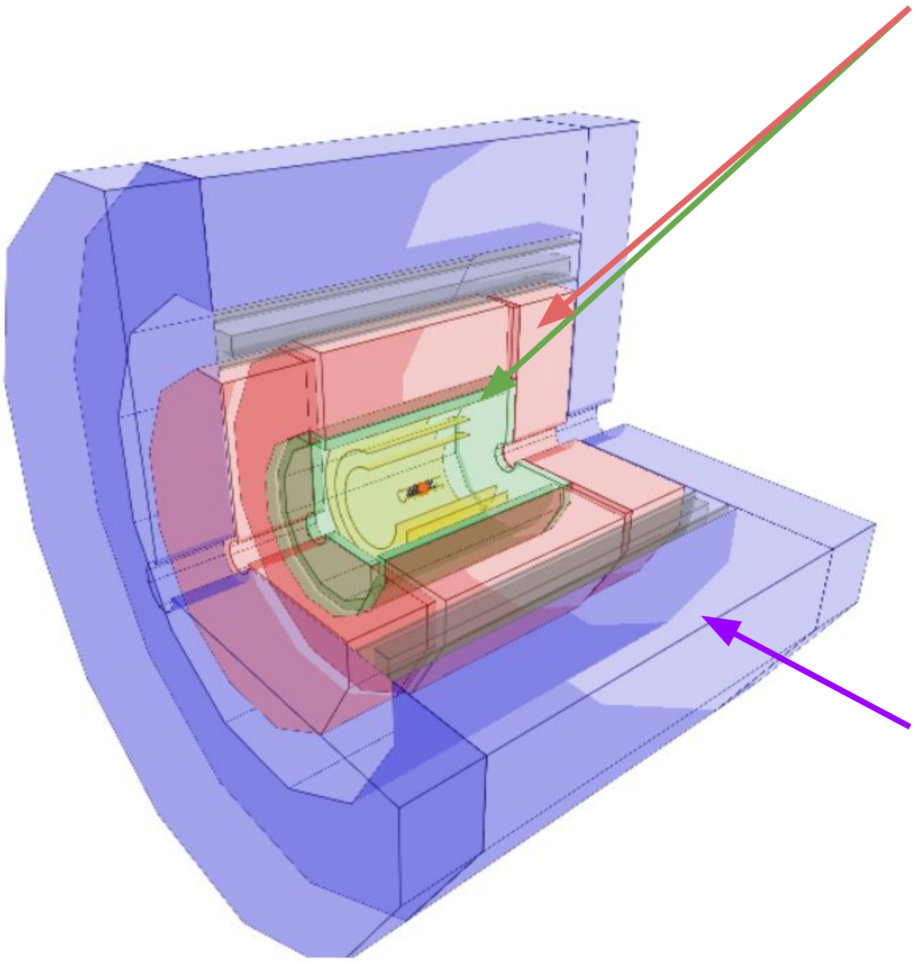


Solenoid

- Momentum resolution
- Position: inside/Outside EM calorimeter
- Impacts BIB in the detector

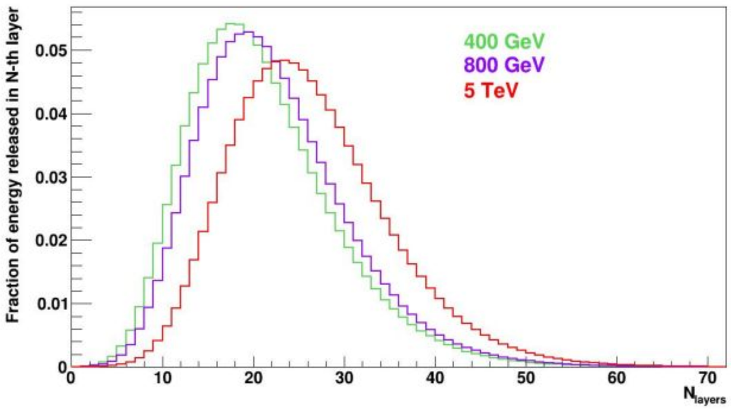


Detector design: points of attention



<u>EM/Hadronic Calorimeters</u>

- Contain showers of large-E objects
- Longitudinal segmentation and absorption structure of EM calorimeter
- Implementation of new technologies



<u>Muon System</u>

- Ensure good momentum measurement of very large p_T muons
- How to optimally maintain capability to reconstruct lower momentum muons
- Implementing newer technology ideas, mostly critical for endcap design (higher rate of BIB particles)

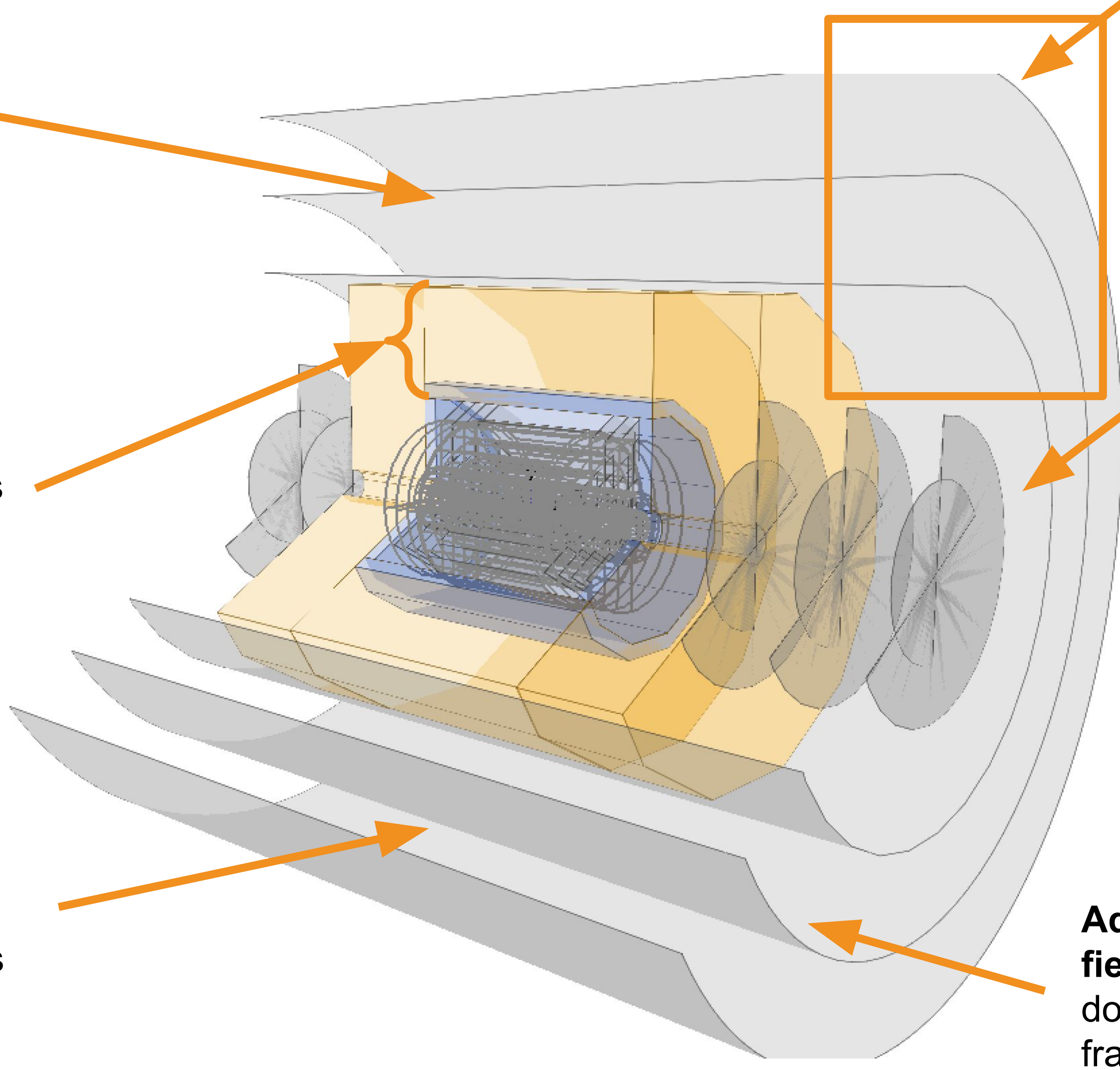
Example: early look at new detector designs

more info:
[F. Meloni talk]

No need for a Yoke: B field returned by iron in HCAL

Calorimeter depth optimised with photon and pion gun samples (changed both sampling fraction and N_{layers})

Simplified muon detector (implemented as a tracker)



Extension of barrel vs endcap will be optimised to **minimise detector surface**

Radius buggy: **meant to extend up to the barrel**

Adding toroidal field never really done in sw framework before

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

New exciting work has started towards:

- optimizing the detector and discovering new opportunities
- identifying key requirements and their interplay with dedicated detector R&D
- redesign the detector for a 10 TeV collider

This has been only possible thanks to the work of an amazingly talented and dedicated team. It requires tasks ranging from core software development, simulation tuning, performance evaluation, physics studies and more.

Lots of challenging and fun projects for newcomers!

Backup

Outline

for discussion only
(slide will be removed)

Scope. During last year's collaboration meeting focused on learning if we can have a detector that can extract physics. We can. This year we are starting to explore and optimize.

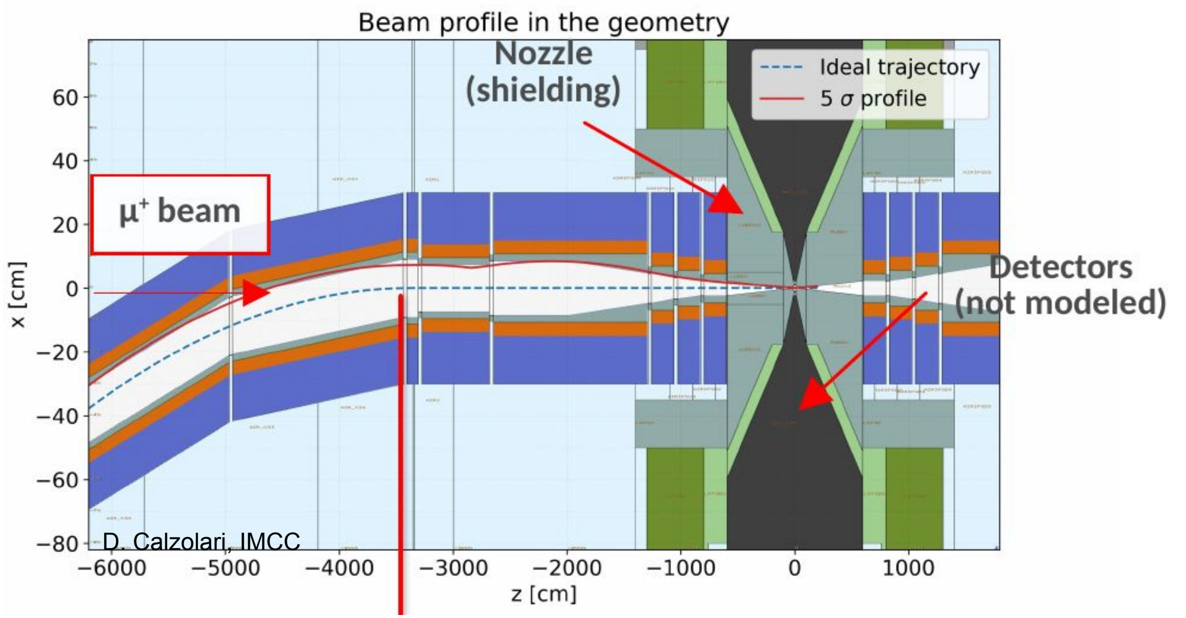
- What physics demands; center-of-mass energy
- BIB composition studies
- Detector overview (focus on 1.5-3.0 TeV)
- Tracking: perf and technology
- Calo: perf and technology
- Muon system: perf and technology
- DAQ, Fwd muons, Lumi
- Full Simulation physics studies and fast-sim (delphes card) plans
- Towards a 10 TeV design
  - nozzle optimization, radiation/BIB fluxes
  - dimension, points of interest, a few results
- Software infrastructure and migration to key4hep

Concluding remarks. What we achieved; outlook towards next year: a new design for 10 TeV, exploration and incorporation of new technologies, modern software infrastructure and detector R&D projects (see Nadia's talk).

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)	$1.5\ 10^3$	$1\ 10^3$

Detector Overview

hadronic calorimeter

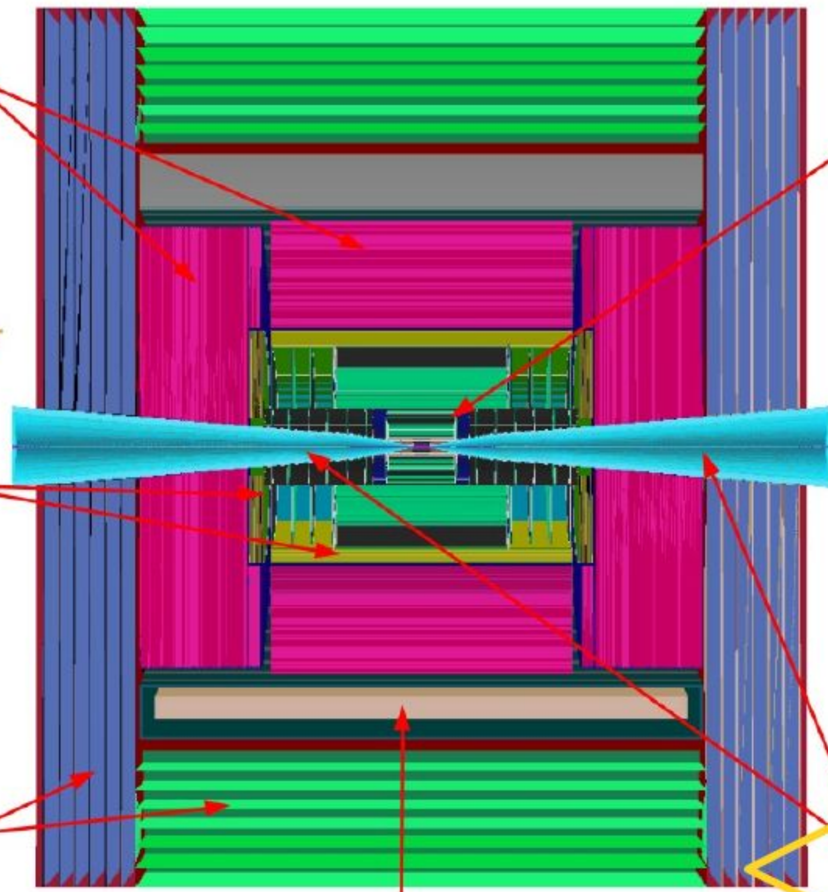
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.



superconducting solenoid (3.57T)

tracking system

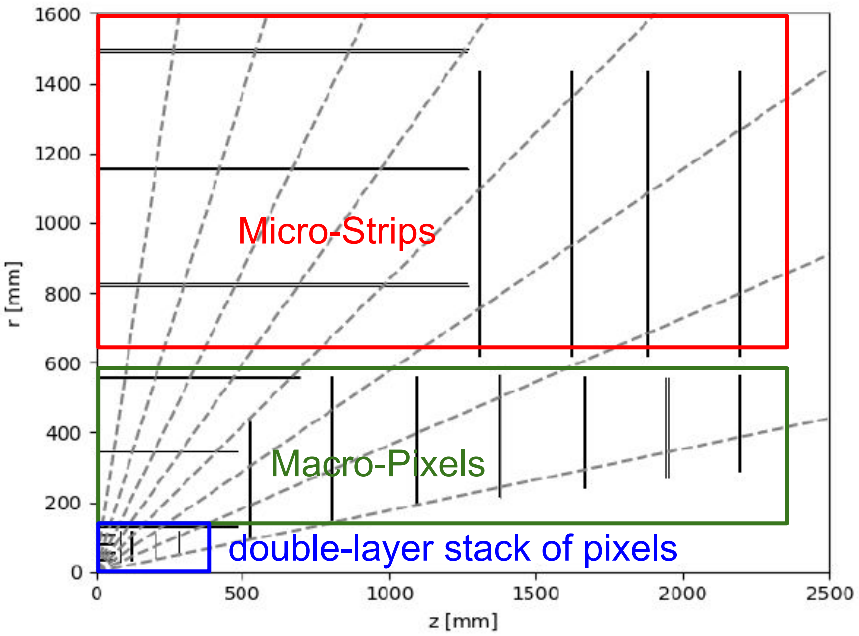
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip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

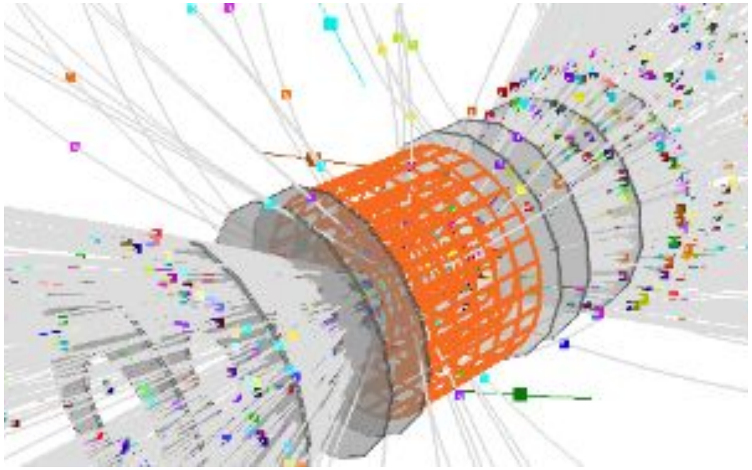
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

BIB in the Tracking system

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





Detector Reference	Hit Density [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)

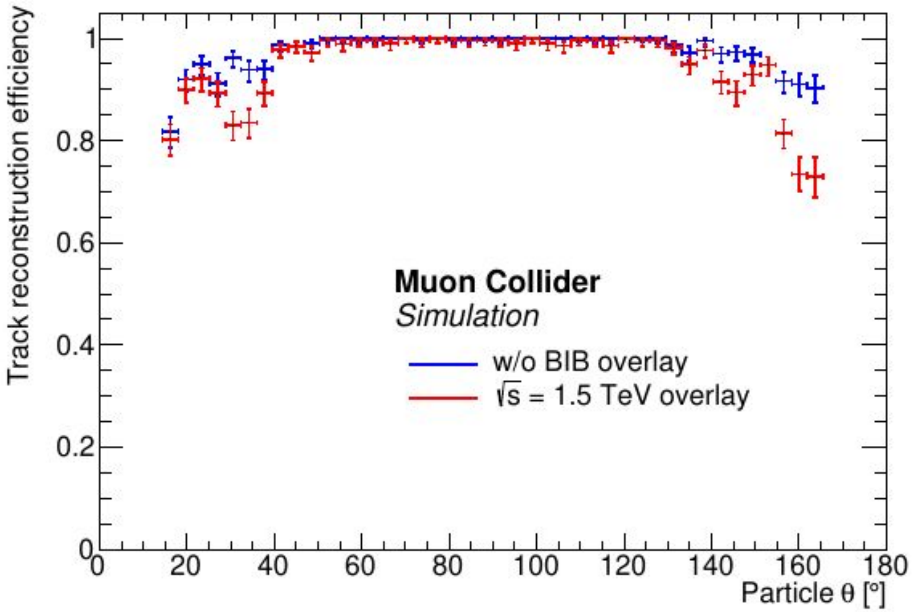
Hit density after timing selections, compared to expectations at HL-LHC.
Bunch crossing rate 100kHz (Muon collider) vs ~40MHz (LHC)

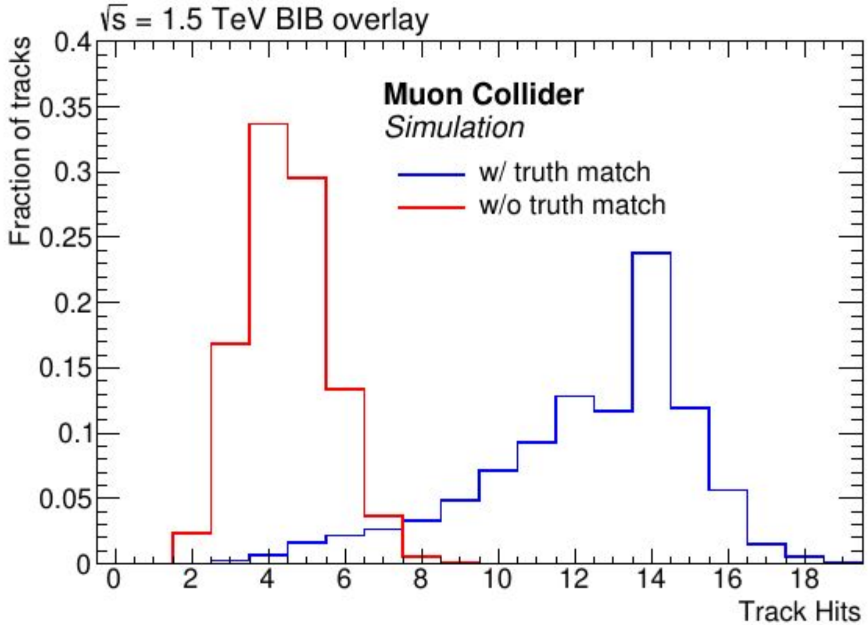
Tracking Algorithms

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

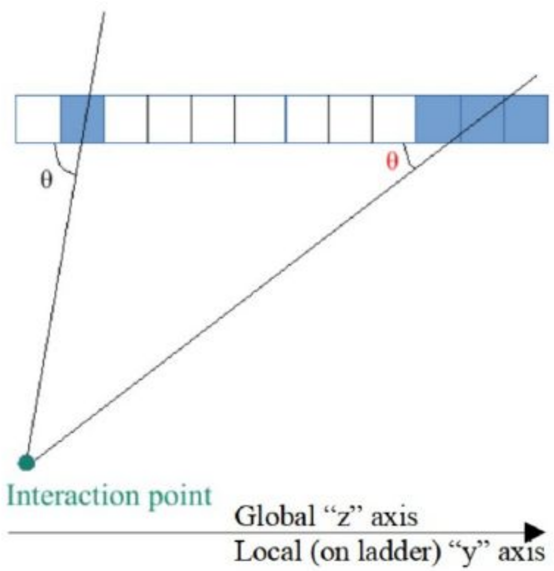




Reducing the impact of BIB in the Tracker

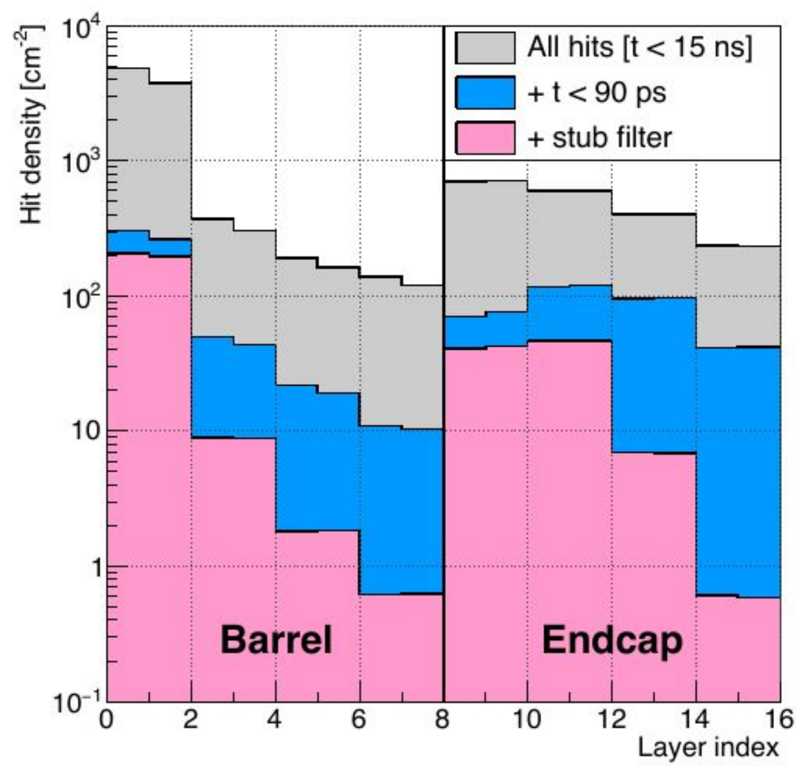
Key handles for discrimination:

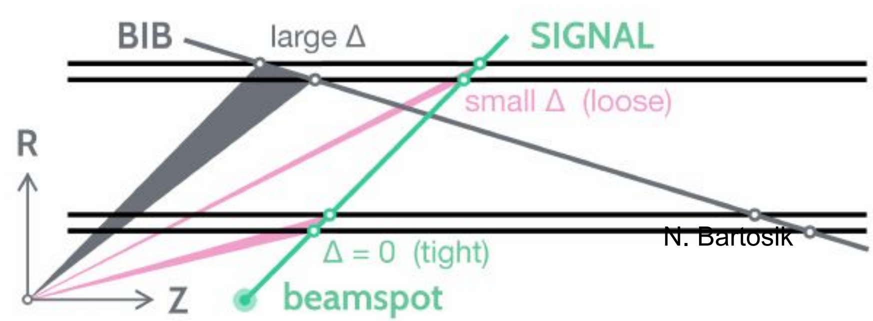
- Timing
- Directional information
  (not from interaction point)
- Energy deposition / pulse-shape analysis
  (esp. against soft photons)



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

arXiv:2203.07964 (updated)



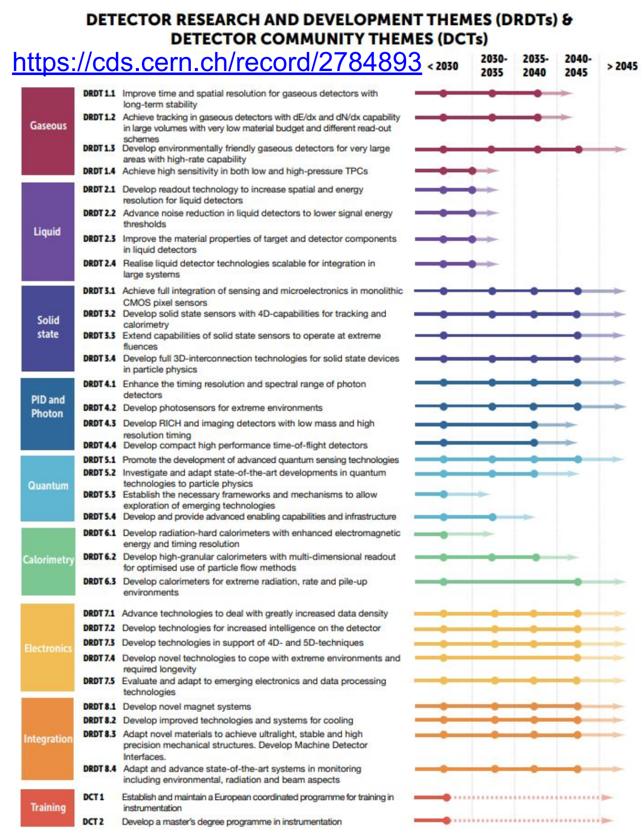


Instrumentation R&D

- 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



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,

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