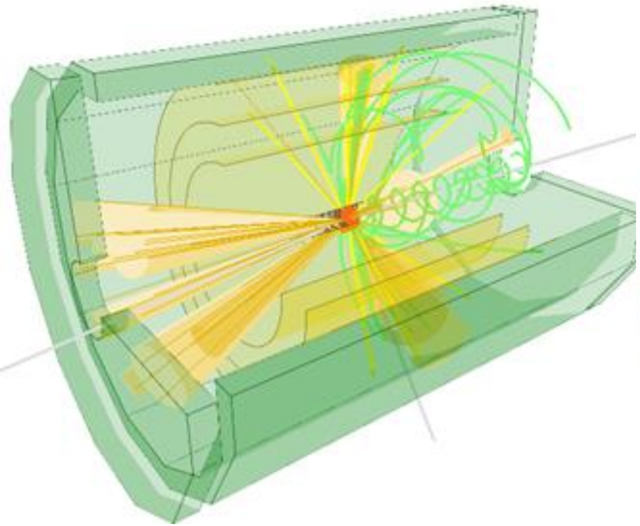
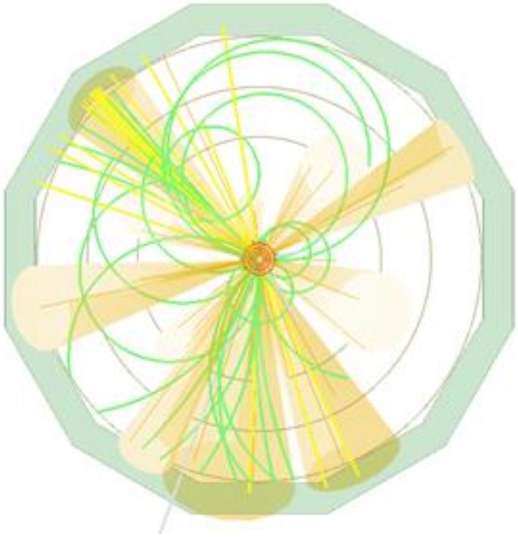




Accelerator
↓
- [x] Detector Design
↓
- [x] Detector Technology
↓
- [x] Readout & Electronics
↓
- [ ] Software & Reconstruction
↓
- [ ] Physics Analysis

Muon Collider Detector R&D and AI/ML

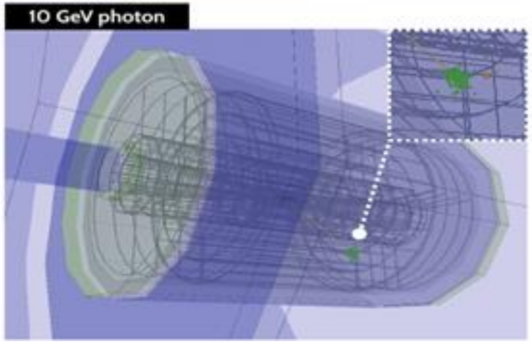
Sergo Jindariani (Fermilab)

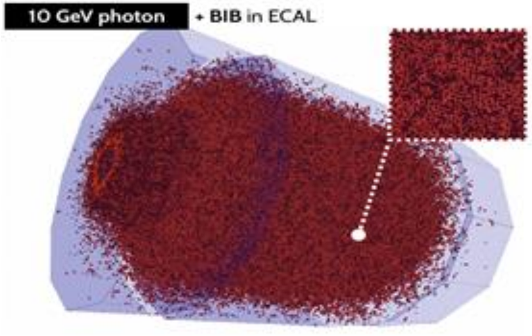
AI4MuC virtual workshop

With input and inspiration from https://arxiv.org/abs/2504.21417 and other recent publications/talks

Detector Challenges

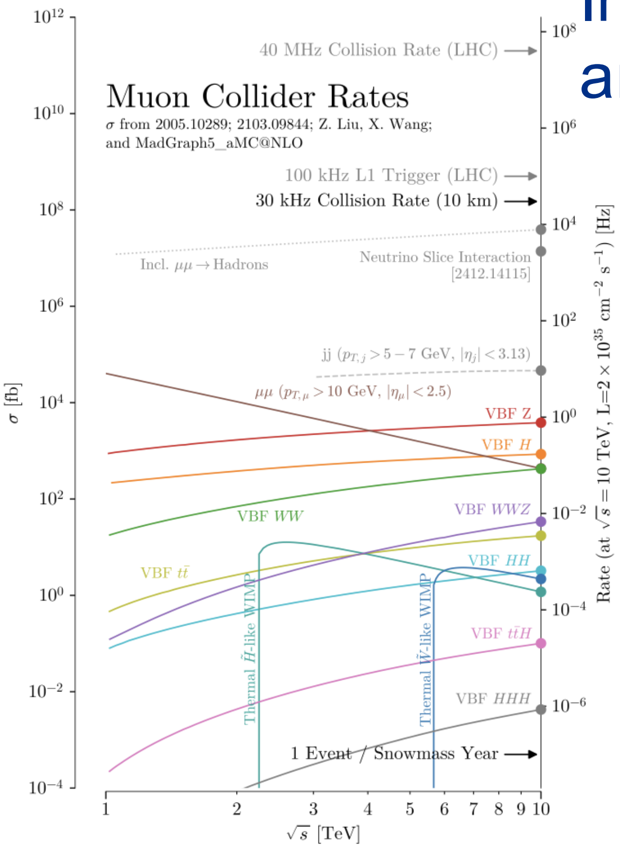
- The curse of muons – they decay and they do it quickly
- Beam-Induced Background (+ incoherent e+e- pair production)





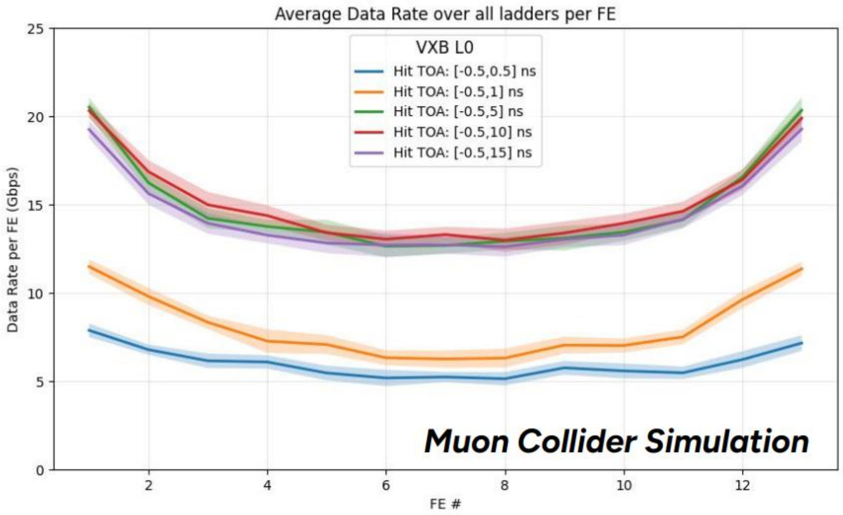
- Very challenging detector requirements
- Unprecedented detector occupancies and ***data volumes***

Detector Challenges



Interesting collisions are clean and have a rate of only few Hz

But the BIB produces a lot of data per event * 100kHz



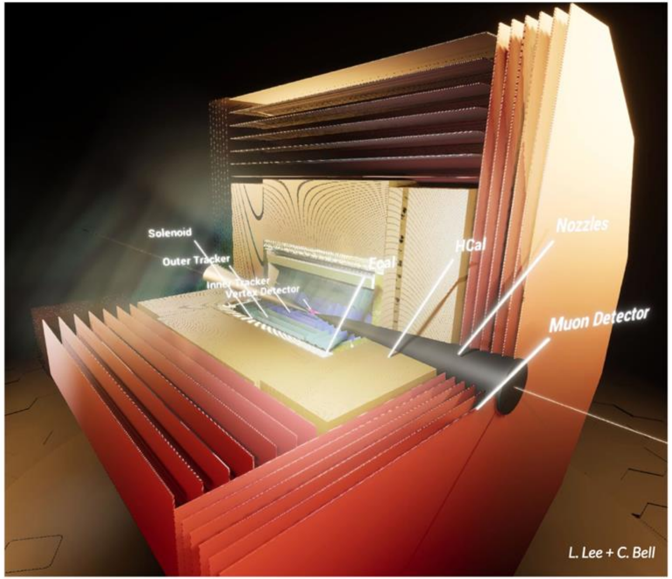
T.Holmes, L.Lee

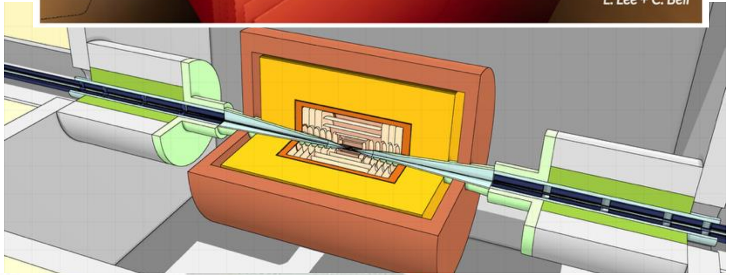
A. Rastogi et al

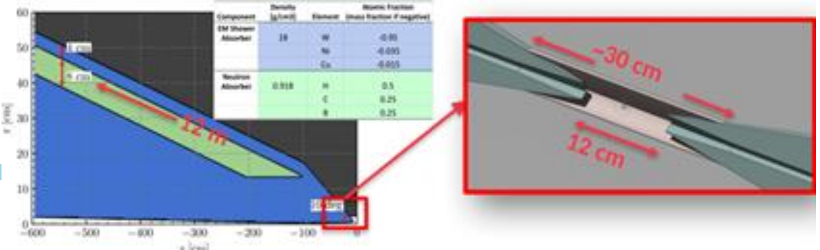
Fermilab

Overall Detector Design

- Is the geometry best suited for the physics we are pursuing?
- Interaction Region design ←→ Machine-Detector Interface ←→ the Detector
- Is the forward shielding buildable?
- Is the detector magnet buildable?
- Missing pieces – forward muon tagger, luminosity detector, PID

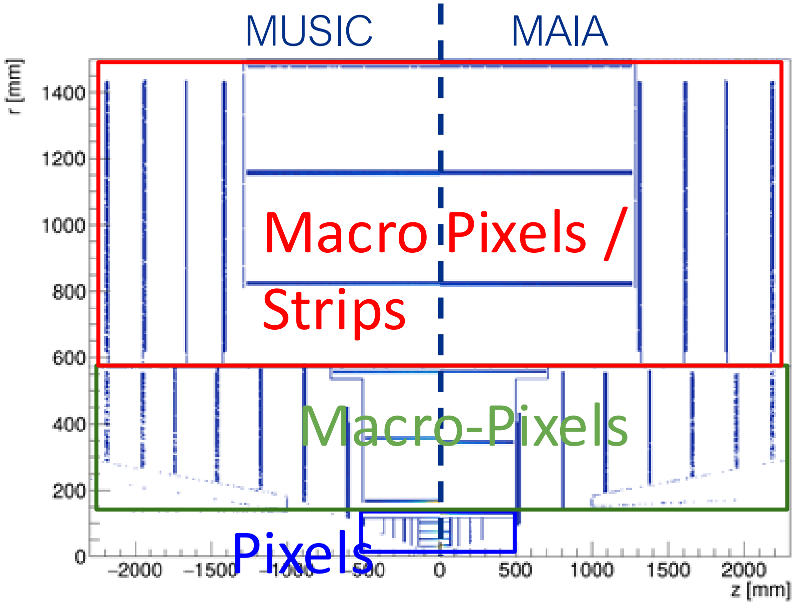






Sub-Detector Requirements

- **Requirements drive technology choices (hybrid, LGADs, MAPs, etc?)**
- **Tracker Example**
  - Precision timing (10s of ps)
  - High Granularity (as high as 25x25 microns)
  - On-detector intelligence (cluster shapes etc..)
  - Rad-hard (up to ~HL-LHC levels)
  - Light (how light?)
- All of these in a single device? Emphasis may shift depending on the location?
- What is the best practical configuration?



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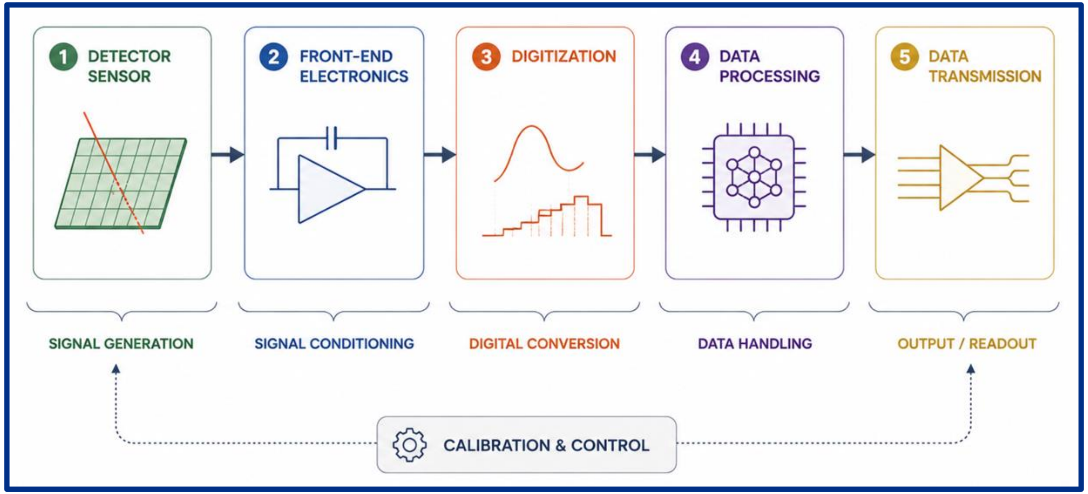
Design at the Module Level



- Sensor design (geometry, thickness, S/N, aging)

- Signal extraction and processing
- Data reduction
- Readout architecture

ASIC/FPGA

hls4ml, CGRA4ML, …

End-to-end optimization of the complete detector module

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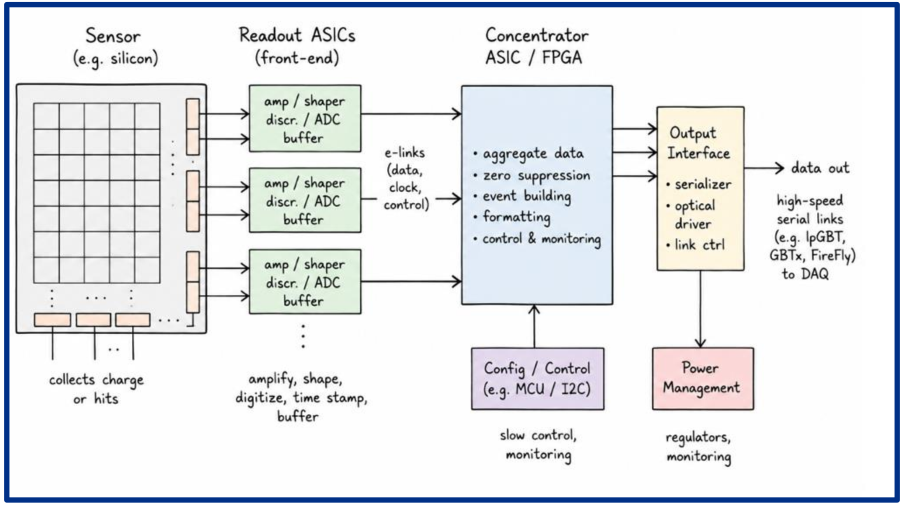
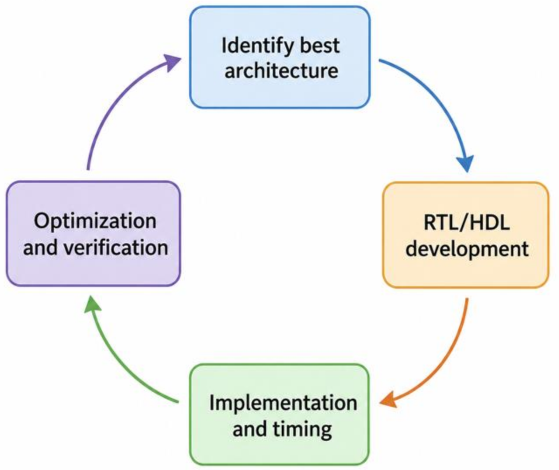
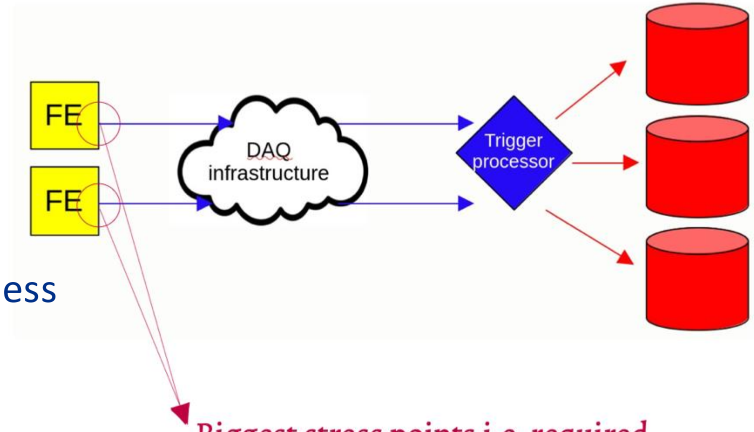
AI assisted Electronics Development





- Data processing relies heavily on ASICs/FPGAs. Long development and verification cycles, especially for ASICs.
- LHC lessons – 20+ years of development
- AI can streamline many stages of this development

Readout and DAQ



Send more or process more?

Biggest stress points i.e. required readout bandwidth.

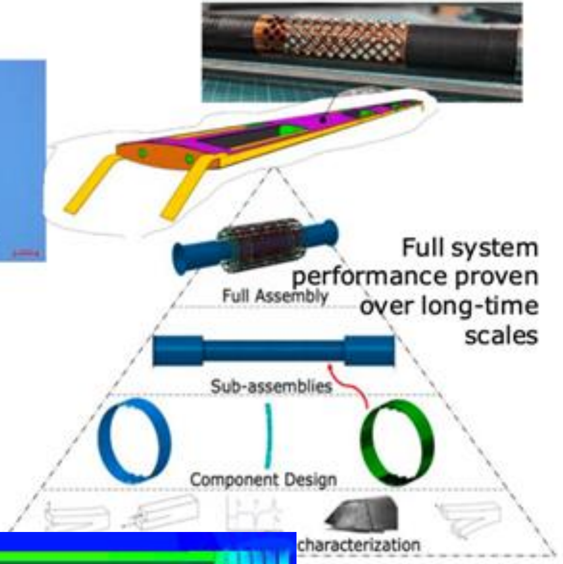
- Some front-end intelligence is necessary to make data readout manageable:
  - Some online timing cuts, but at this scale is highly non-trivial
  - Local reconstruction (e.g. cluster shape/angle, SmartPixel)
- Off-detector reconstruction is a ***farm of "self driving" AI engines*** ?

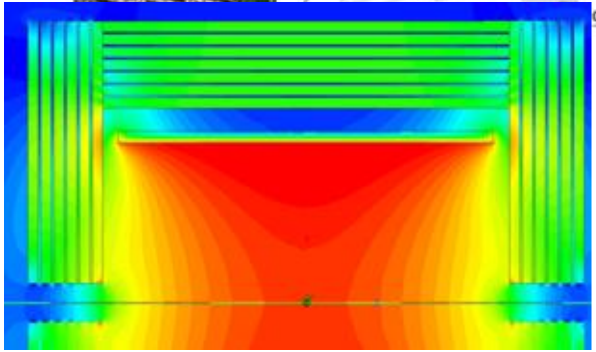
Mechanics and more

- Critical expertise developed throughout the years

- Intrinsically a complex problem
  - Multi-objective mechanical optimization
  - Generative mechanical design
  - FEA acceleration
  - Assembly planning
  - Cabling etc

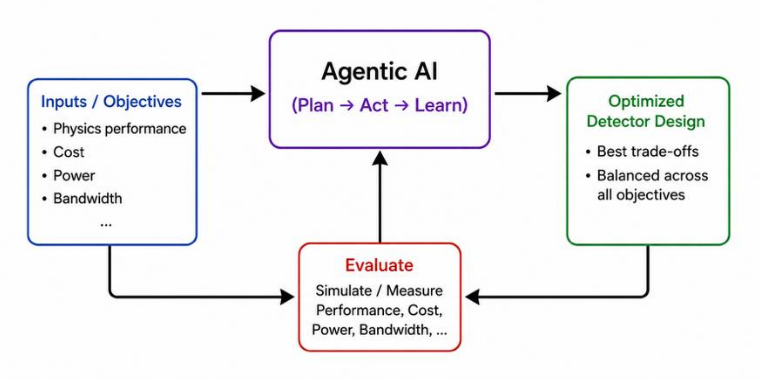
- Magnet design
  - baselined 10 TeV detector with 5 T solenoid





Towards an End-to-end optimization

- ***Agentic AI Frameworks*** for optimization workflows



- Development of ***Surrogate Models*** will greatly streamline studies and tradeoffs between things like:
  - Physics performance
  - Technical complexity
  - ***Cost***
  - ***Power***

Outlook: the first AI native HEP detector?

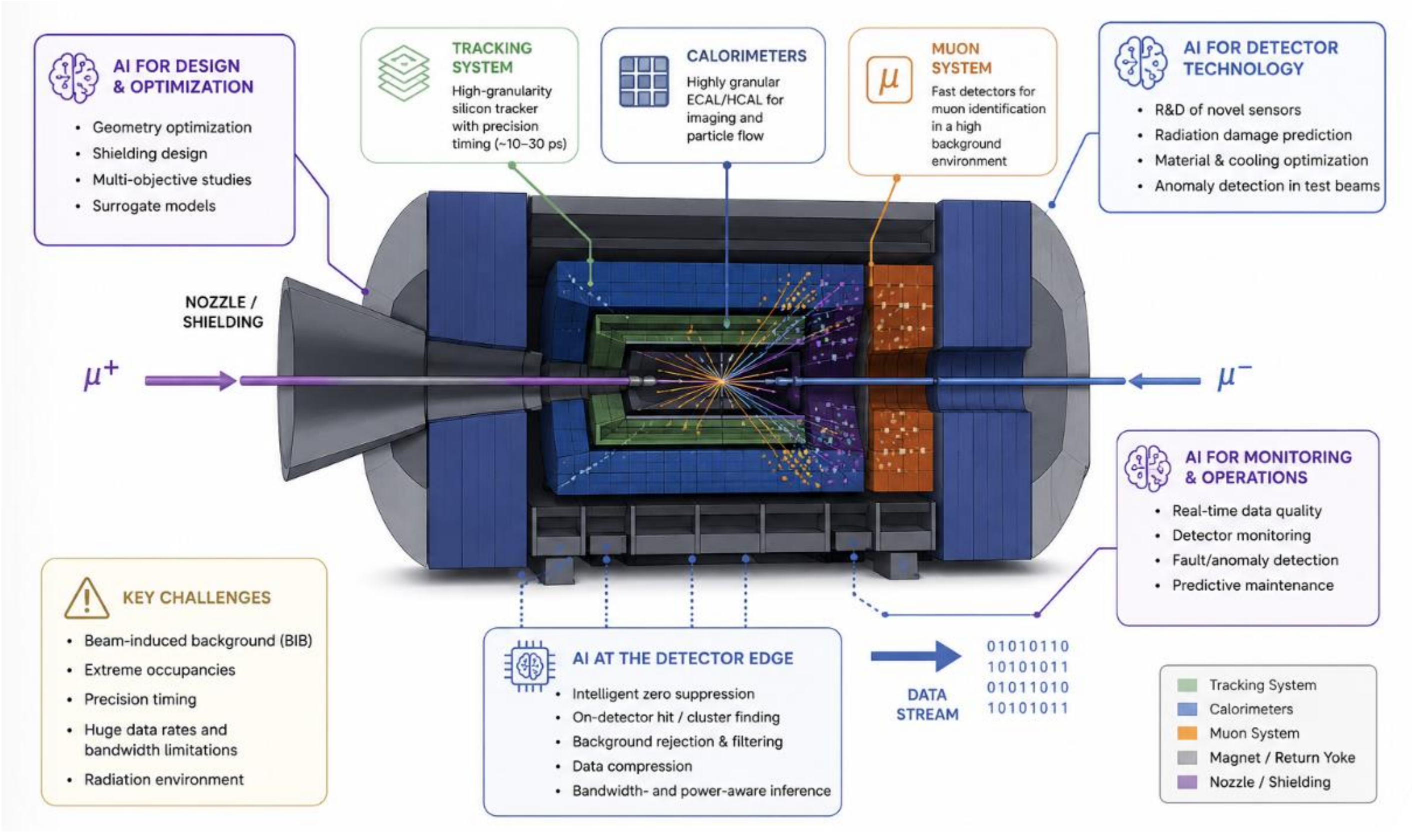


Image generated by ChatGPT

Backup

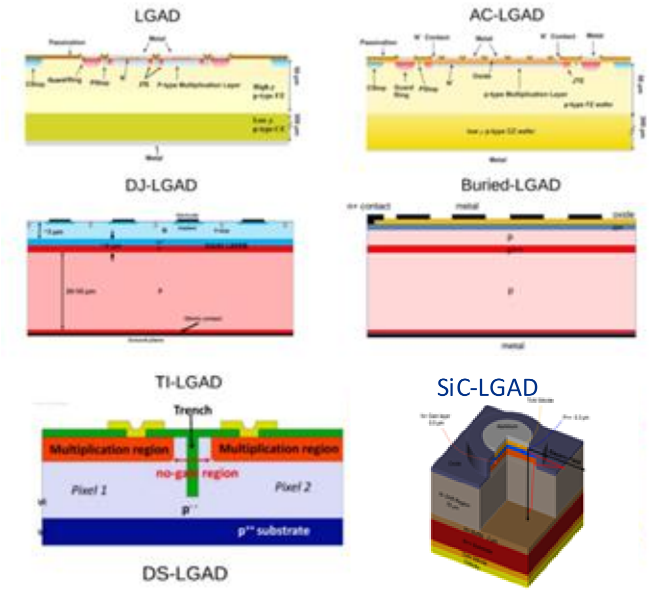
Image generated by ChatGPT

Tracking Detectors R&D

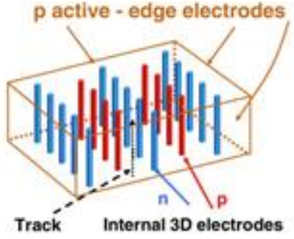
MuC detector well aligns with existing R&D interests

- Sustain large occupancy, 4D measurement (space, time), large output bandwidth
- Radiation hard, Lightweight

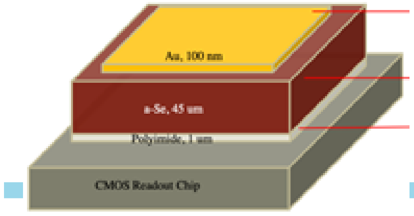
FE ASIC development identified as critical item that needs long development cycles.

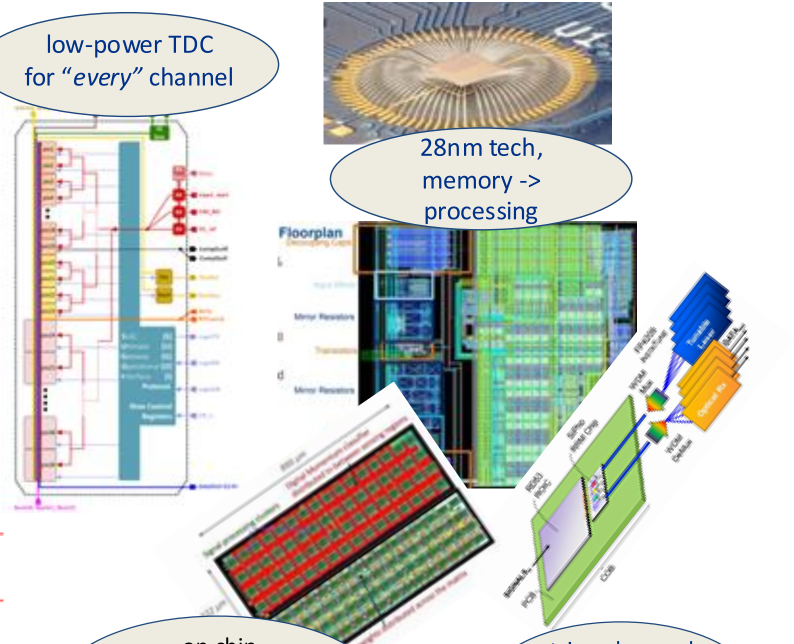


3D Sensors



Thin Film Sensors





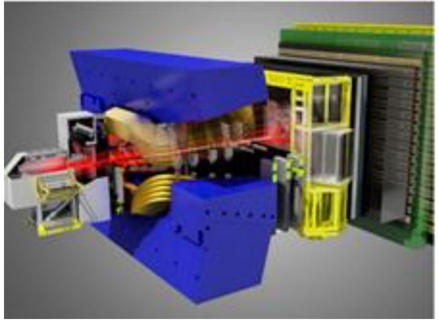
low-power TDC for "*every*" channel

28nm tech, memory -> processing

on-chip filtering / sampling / selective powering / (AI/ML?)

triggerless and high-bandwidth data transmission

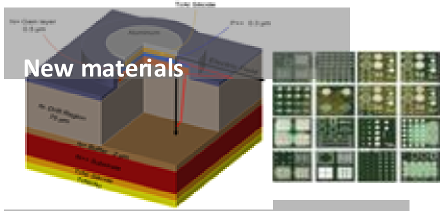
Tracking Detectors R&D



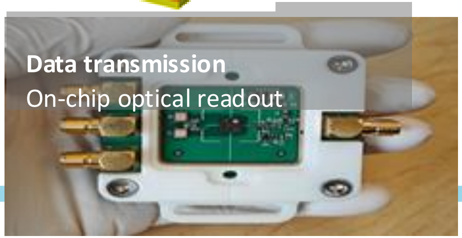
Existing projects (e.g. LHCb VELO Phase-II upgrade) already aim for a high-granularity, high-precision timing silicon detector (using 3D sensors).

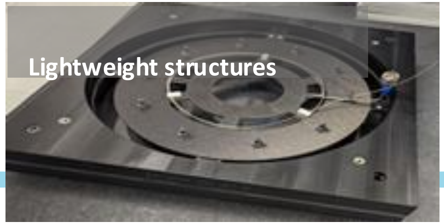
Long-standing expertise in <u>most major national labs</u> on developing current (LHC and HL-LHC) and next generation (blue-sky R&D) tracking detectors in colliders

- coupled with strong university involvement throughout the R&D chain
- requirements are more challenging that state-of-art, but achievable!

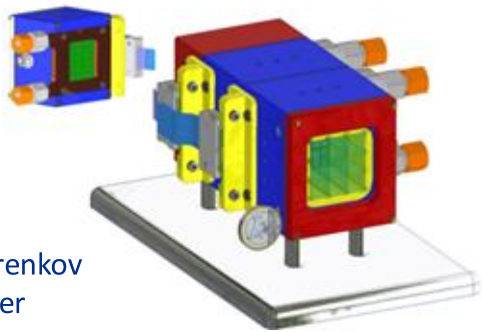


Reconstruction algorithms





EM calorimeters Highlight



Crilin
PbF2 Cherenkov Calorimeter

Highly-segmented semi-homogeneous electromagnetic calorimeter based on Lead Fluoride Crystals (PbF_2)

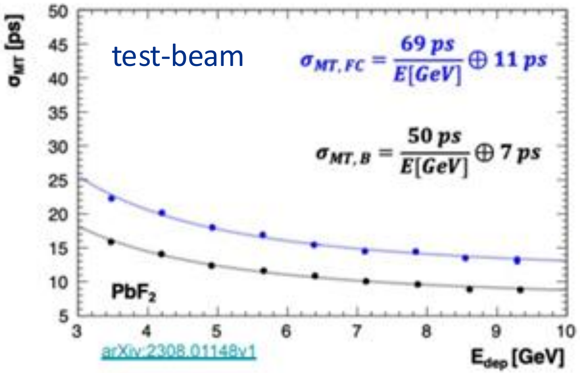
- Fast response (via chenekov radiation)
- Semi-homogeneous optimization

Prototyping and testbeam campaign to prove concept.

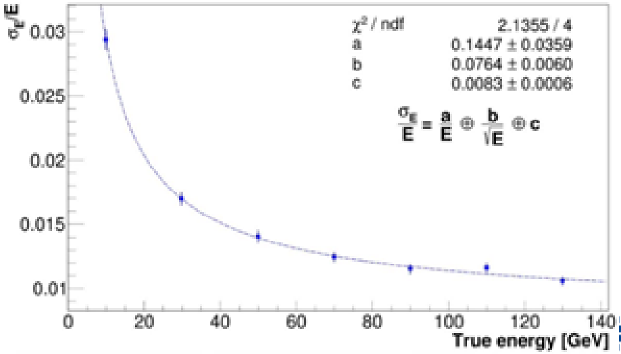
- time and energy resolution
- radiation hardness

2-layer 3x3-crystal Crilin prototype

5 layers, 7x7 crystals,
~ 250 channels now produced



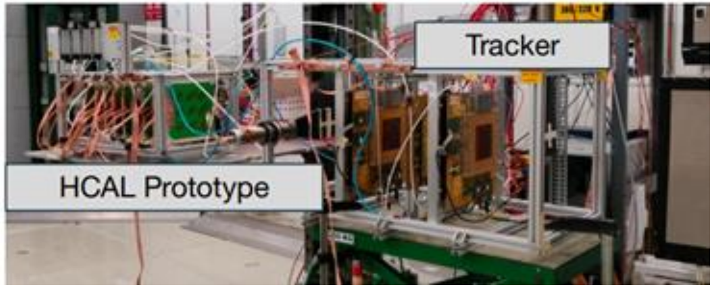
arXiv:2308.01148v1

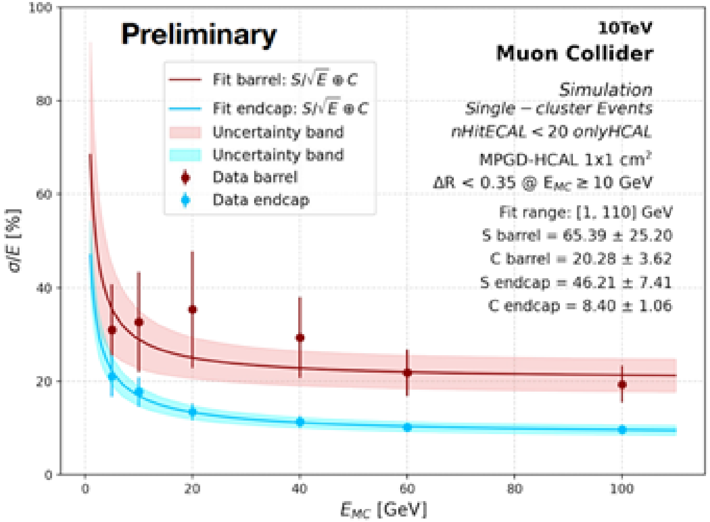


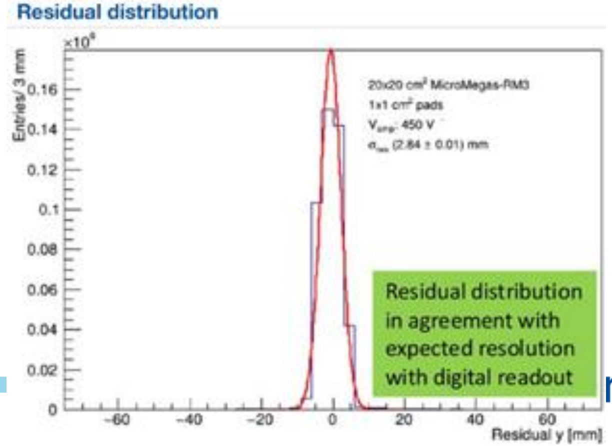
Hadronic Calorimeter Highlight

MPGD-HCAL: based on resistive Micro-Pattern Gaseous Detectors as readout layers for a sampling hadronic calorimeter

- MicroMegas, μRWELL and RPWELL
- Timing capabilities
- Requirements on front-end electronics
- Prototyping and testbeam campaigns





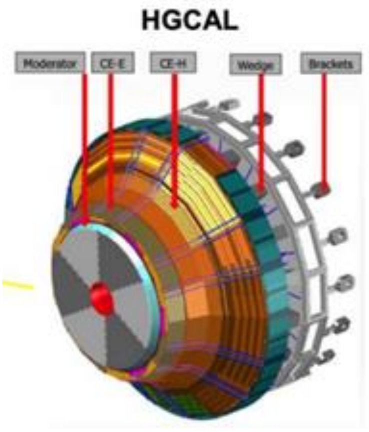


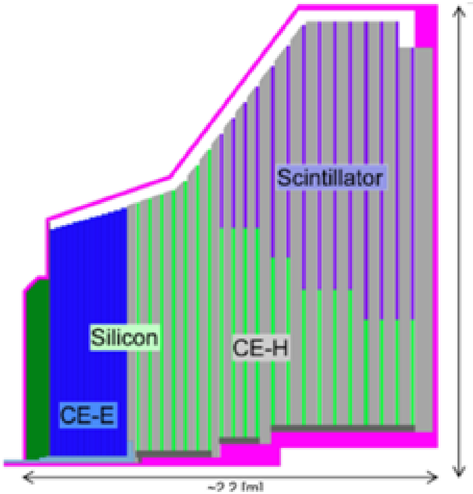
milab

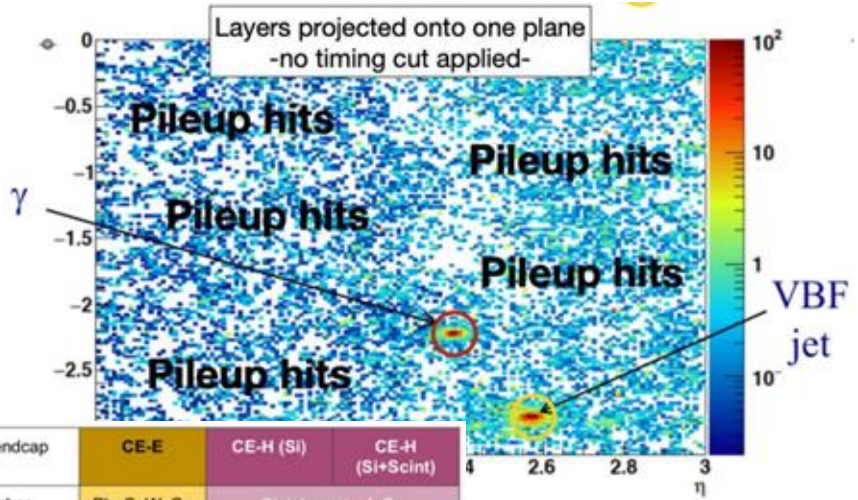
Evolution from current projects

Many more other options being developed that could and should be considered!
E.g. CMS High-Granularity (forward) calorimeter

- radiation hardness, high granularity, excellent timing
- reconstruction of shower
- US expertise (Fermilab)







Per endcap	CE-E	CE-H (Si)	CE-H (Si+Scint)
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth size	25.5 X_0, 1.7 λ	9.5 λ	
Layers	28	8	14
Weight	23 t	205 t	

Fermilab

Solenoid

Large aperture and high field solenoids are complex objects

- baselined 10 TeV detector with 5 T solenoid
- momentum resolution to high-pT particles, reduction of incoherent e^+e^- pairs

Initial studies on realistic field maps and geometry implementation

Critical item that takes many years to design and manufacture!