Detectors for a Muon Collider

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(summarizing the work of many people in US-MCC and IMCC)

Open Meeting for the National Lab Accelerator Study Group for a Muon Collider

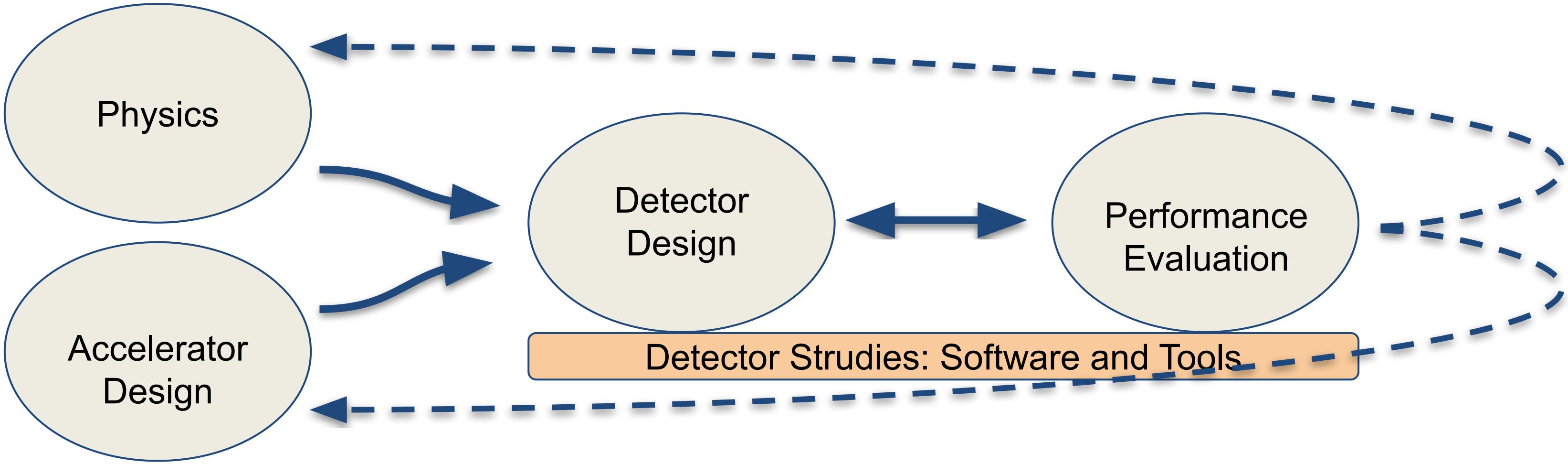
Apr 6th 2026

International MUON Collider Collaboration

BERKELEY LAB
Lawrence Berkeley National Laboratory

Introduction

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

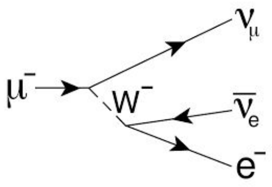


Today, I'll show an overview of detectors design

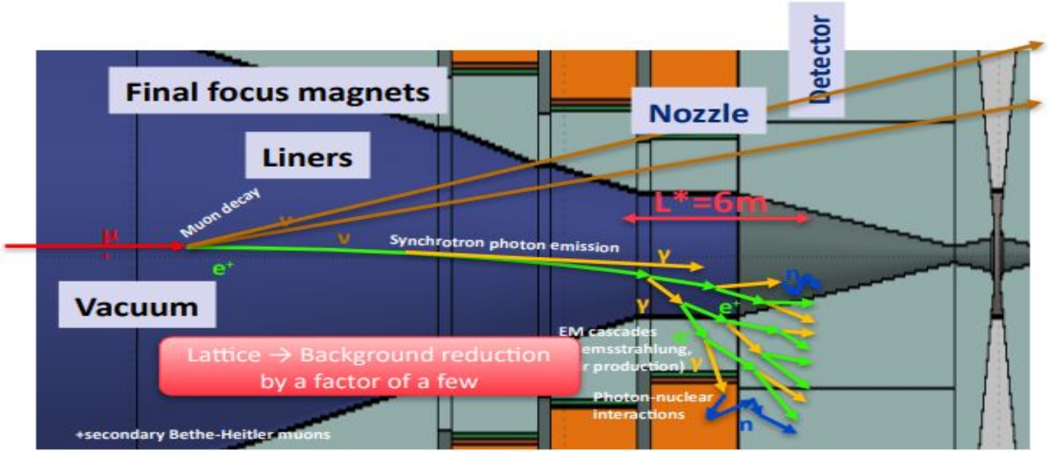
- requirements, challenges
- technological choices, R&D path
- current efforts and needs

Beam-Induced Backgrounds (BIB)

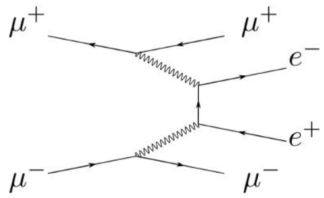
Muon beam decays



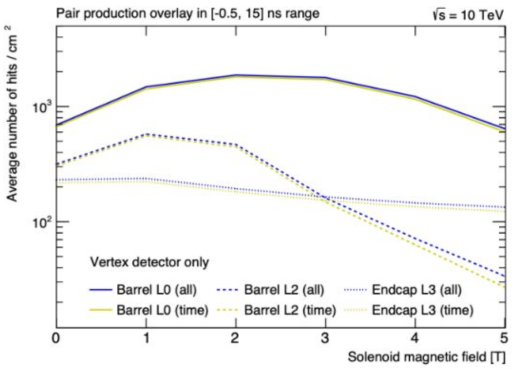
Very <u>high-energy electrons</u> then interact with surrounding material; relevant decays for the detector can be produced 10s of meters away.



e+e- pair production

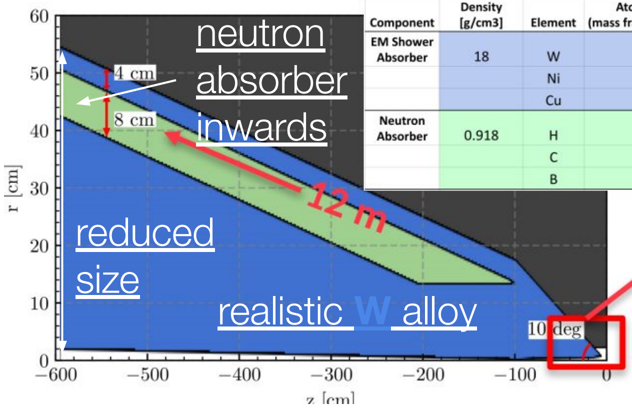


<u>Low-energy</u> e^+e^- pair production from beam-beam interactions; produced at the interaction point.

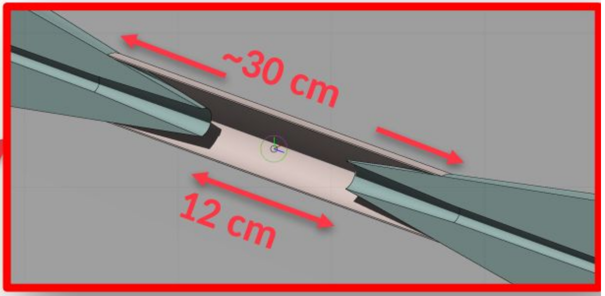


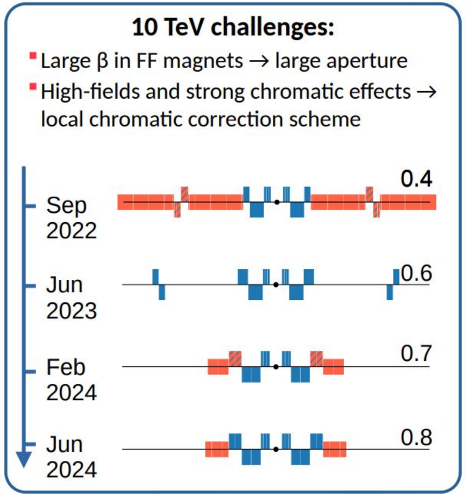
Detector shielding (nozzle)

- Dedicated shielding to suppress an otherwise too-large flux of high-energy $e^{+/-}$
- Detailed simulations to study the interplay between accelerator design and shielding
  - sim ~1 month / 0.1 bunch-crossing on a cluster (G4Beamline + FLUKA-based)
  - optimization “loop” still very “manual”
  - fast AI-assisted simulation / optimization desirable
- Most studies ran by EU colleagues
  - some efforts to ramp up in US, where expertise also exists



Component	Density [g/cm3]	Element	Atomic Fraction (mass fraction if negative)
EM Shower Absorber	18	W	-0.95
		Ni	-0.035
		Cu	-0.015
Neutron Absorber	0.918	H	0.5
		C	0.25
		B	0.25



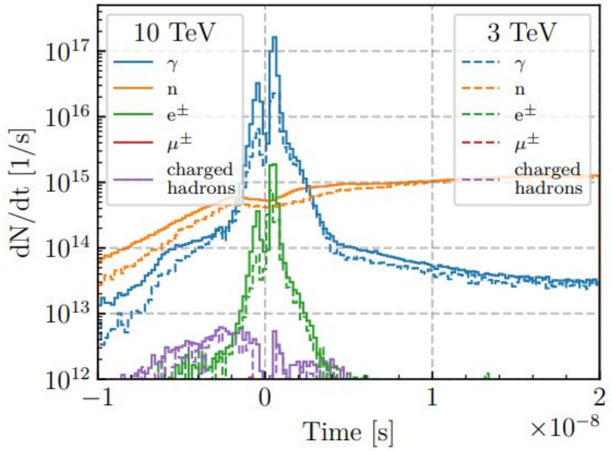


BIB characterization

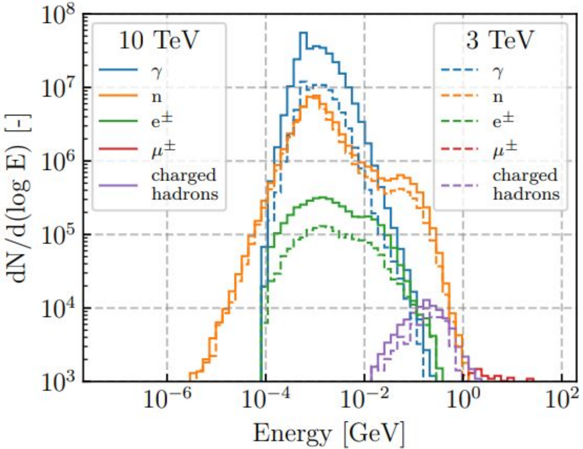
<u>Key takeaways</u> at detector volume *entrance*:

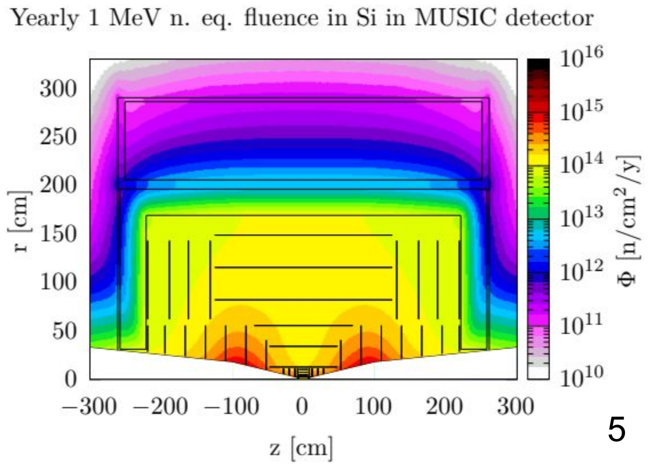
- soft photons/neutrons
- long out-of-time tail
- originate far from interaction point
- not dramatic collider energy dependence
- radiation environment < HL-LHC

<table>
<tr><th rowspan="2">Component</th><th colspan="2">Dose [kGy]</th><th colspan="2">1 MeV neutron-equivalent fluence (Si) [10^{14} n/cm^2]</th></tr>
<tr><th>MAIA</th><th>MUSIC</th><th>MAIA</th><th>MUSIC</th></tr>
<tr><td>Vertex (barrel)</td><td colspan="2">1000</td><td colspan="2">2.3</td></tr>
<tr><td>Vertex (endcaps)</td><td colspan="2">2000</td><td colspan="2">8</td></tr>
<tr><td>Inner trackers (barrel)</td><td colspan="2">70</td><td>4.5</td><td>4</td></tr>
<tr><td>Inner trackers (endcaps)</td><td colspan="2">30</td><td>11.5</td><td>10</td></tr>
<tr><td>ECAL</td><td>0.58</td><td>1.4</td><td>0.15</td><td>1</td></tr>
</table>



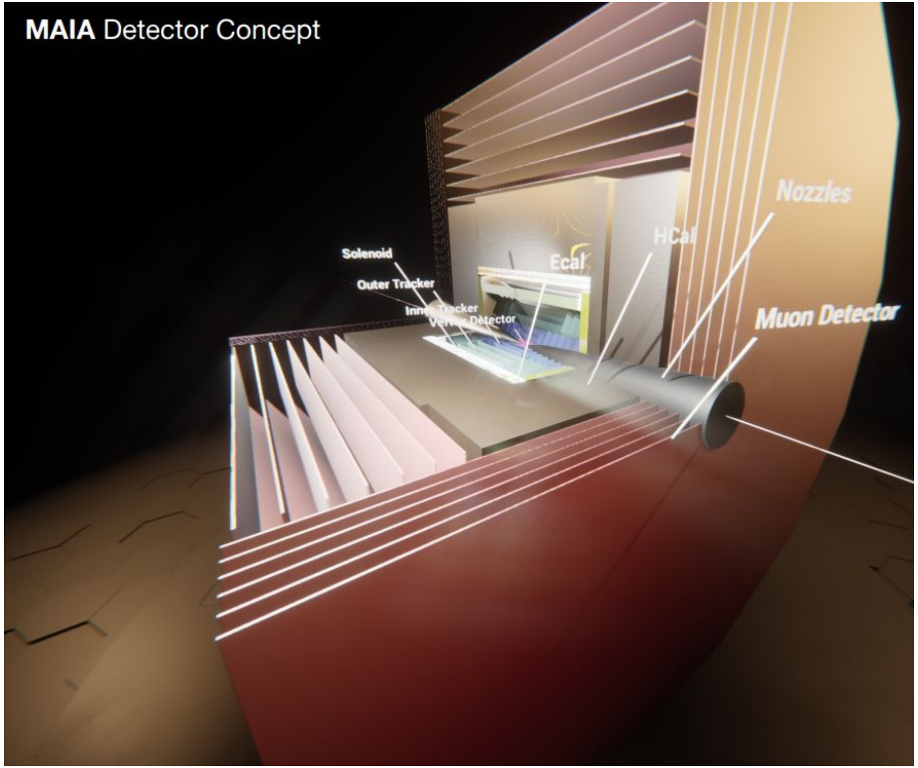
[-1, 15] ns time window





10 TeV detector concepts

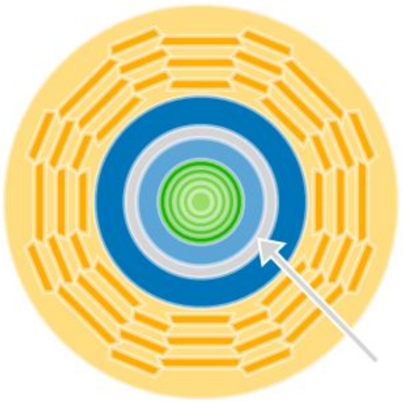
Test several detector concepts in a *realistic* 10 TeV environment



(major US involvement)

10 TeV MUSIC Detector

Solenoid between ECAL and HCAL



arXiv:2601.13189

10 TeV MAIA Detector

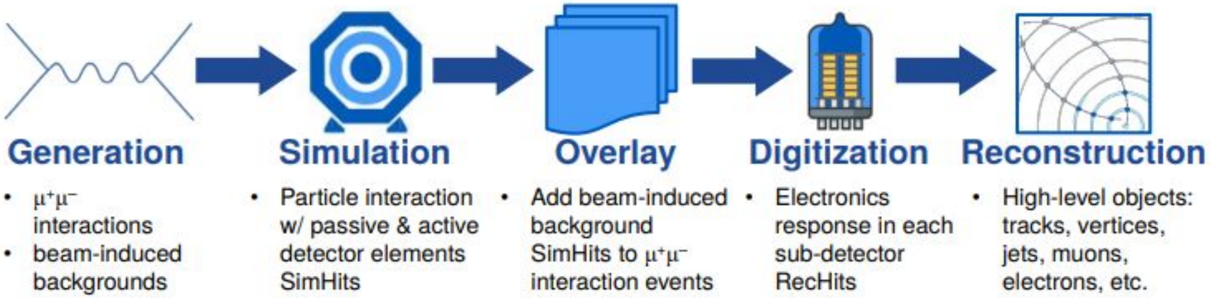
Solenoid inside Calorimeters

arXiv:2502.00181

- Solenoid strength / position / description
- Tracker layout
- EM Calorimeter technology

Software tools for detector simulation

Dedicate repository, infrastructure developed and maintained by a few key people



Muon Collider
github
doc

- Integration with key4hep software stack – common with other future colliders
  - Automatic release building from github CI
- Production of fast-simulation (Delphes) cards.
- Common resources at CERN and in US
  - OSG resources – from snowmass
  - NERSC allocation (NEW!)
    - CPU, GPU, 100 TB disk

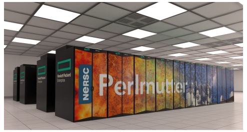
key4hep/EDM4hep

Generic event data model for HEP collider experiments

GitHub
CI/Actions

DELPHES
fast simulation

Open Science Grid



Detector Requirements

Initial assessment of main requirements for a detector to measure well high-level objects

Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	W vs Z

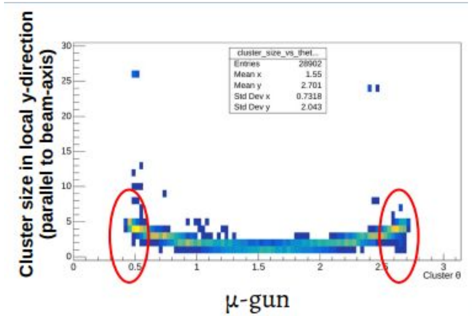
<u>Baseline</u>: mostly based on current design/ideas and physics benchmark studies
<u>Aspirational</u>: motivated by significantly better physics results achievable

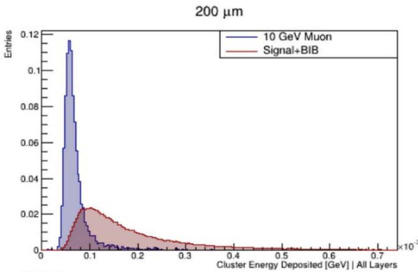
Low-level performance

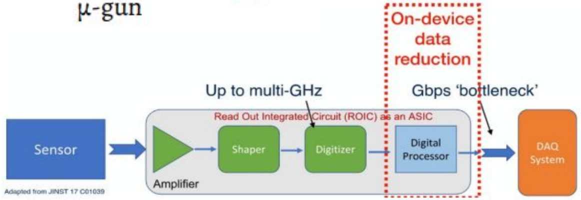
- Realistic digitization algorithms are critical to assess requirements and evaluates different detector technologies in detail
- In combination with hardware prototyping, ensures a robust design

Trackers

- sensor-specific digitization, bottom-up
- FE electronic requirements, data filtering

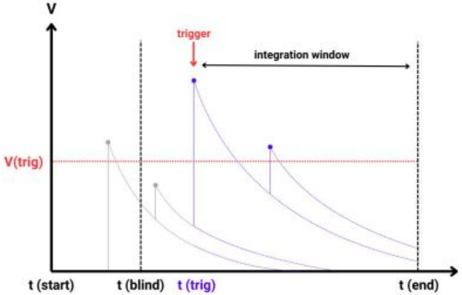


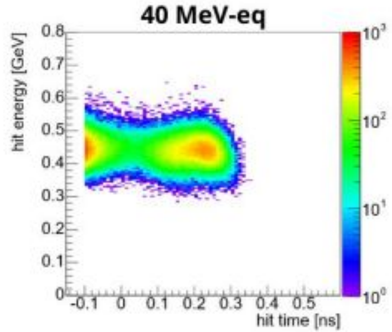




EM Calorimeters

- dedicated digitization to correctly emulate integration time and BIB pile-up signals



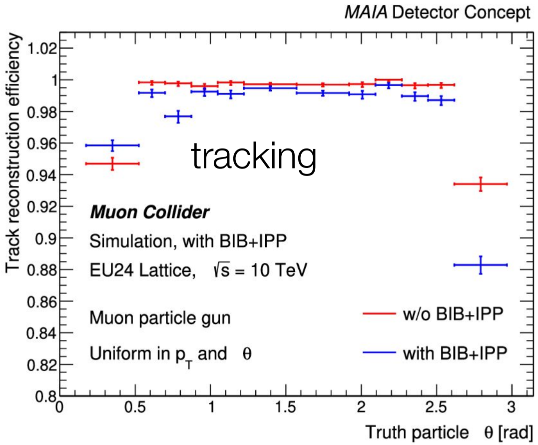


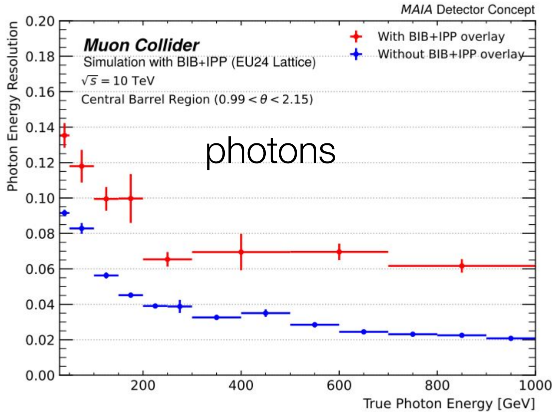
Full-Simulation detector performance

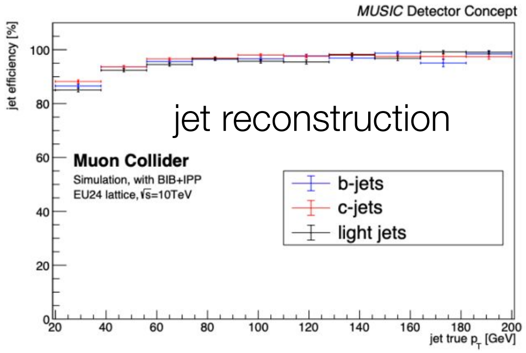
well covered
some coverage
needs more interest

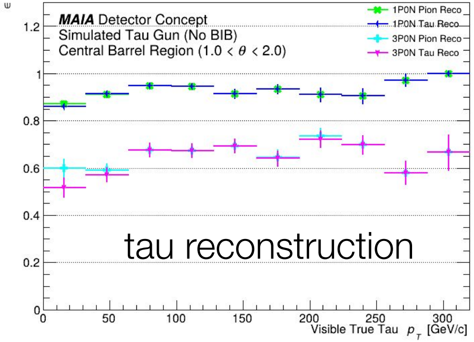
Developed a robust understanding of expected physics object performance

- Basics
  - charged-particles
  - calorimeter jets
  - particle ID
  - luminosity
  - forward muon taggers
- High-level objects
  - muons
  - electrons
  - taus
  - flavor-tagging
- High-level algorithms
  - particle flow









Tracking Detectors

Exploring all-silicon tracker layouts.

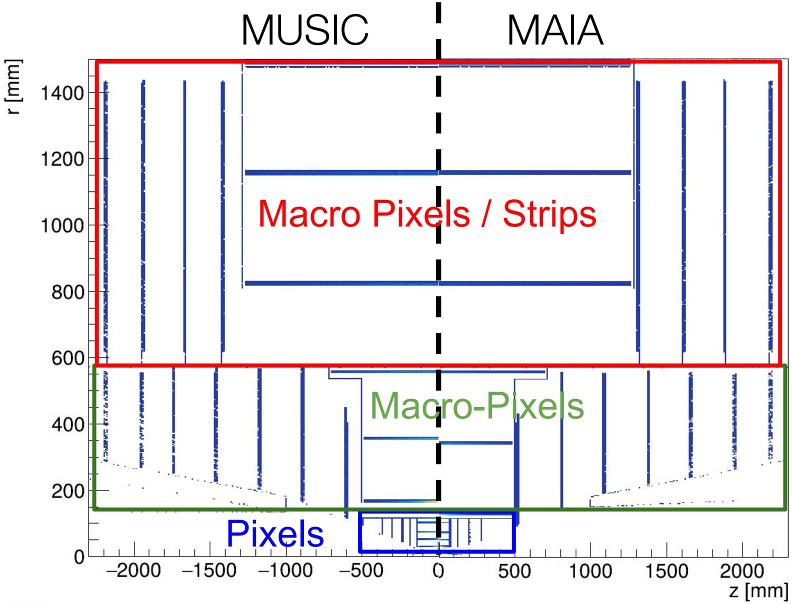
One of the most sensitive detectors to BIB

- BIB manifests as cloud of hits from many low-energy particles.

Layout optimization: slight differences

- inner detectors barrel length / position
- endcap positions optimization

<u>4(/5)D Tracking is a requirement!</u>



Sub-Detector MAIA/MUSIC	Technology	# Layers /Rings	"Cell" Size	Sensor Thickness	Hit Time Resolution	Signal Time Window
Units			μm^2	μm	ps	ns
Vertex Barrel	Pixels	4*/5	25 x 25	50	30	[-0.18, 15.0]
Vertex Endcap	Pixels	4	25 x 25	50	30	[-0.18, 15.0]
Inner Barrel	Macro-Pixels	3	50 x 1000	100	60	[-0.36, 15.0]
Inner Endcap	Macro-Pixels	7	50 x 1000	100	60	[-0.36, 15.0]
Outer Barrel	Macro-Pixels	3	50 x 10000	100	60	[-0.36, 15.0]
Outer Endcap	Macro-Pixels	4	50 x 10000	100	60	[-0.36, 15.0]

<u>Key handles for BIB discrimination:</u>

- Precision timing
- Directional information
  - cluster shape, close-by layers
- Energy deposition

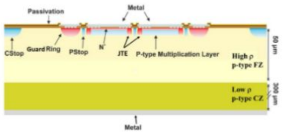
Tracking Detectors R&D

MuC detector well aligns with existing R&D interests

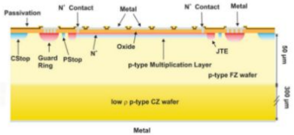
- Sustain large occupancy, 4D measurement (space, time), large output bandwidth
- Radiation hard, Lightweight

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

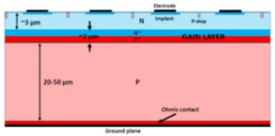
LGAD



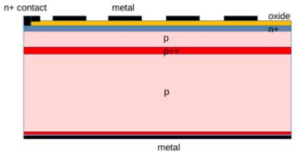
AC-LGAD



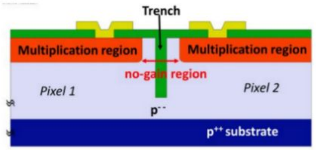
DJ-LGAD



Buried-LGAD

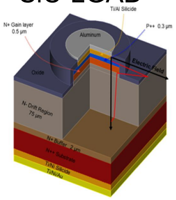


TI-LGAD



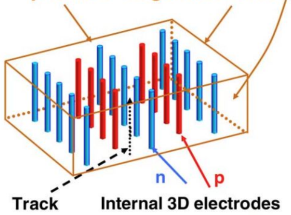
DS-LGAD

SiC-LGAD

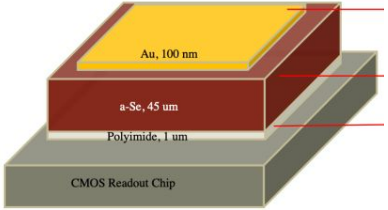


3D Sensors

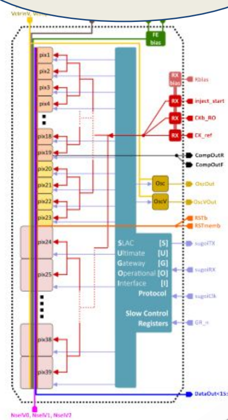
p active - edge electrodes

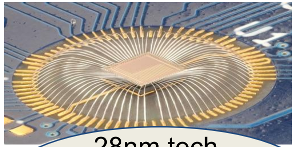


Thin Film Sensors

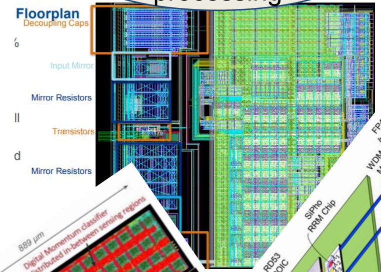


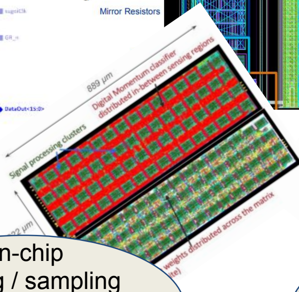
low-power TDC for “*every*” channel

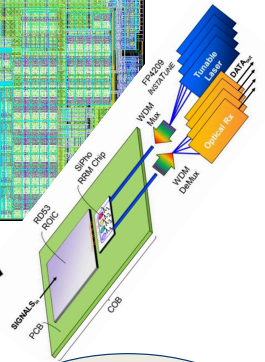




28nm tech, memory -> processing



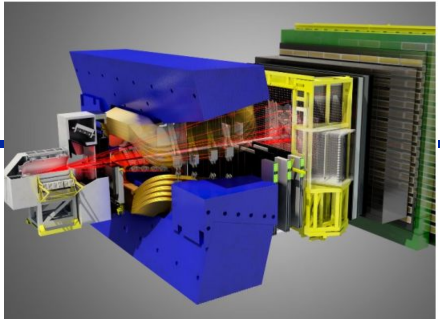




on-chip filtering / sampling / selective powering / (AI/ML?)

triggerless and high-bandwidth data transmission

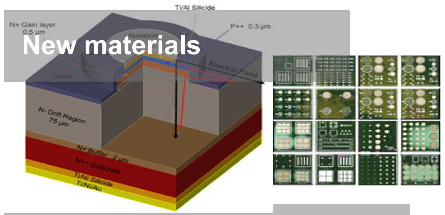
Tracking Detectors R&D

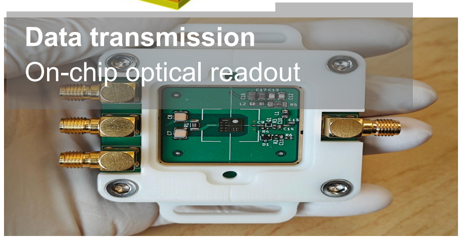


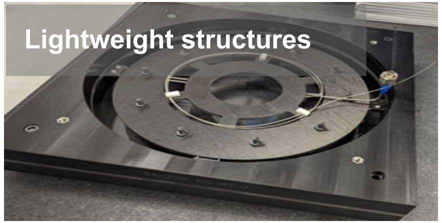
Existing projects (e.g. LHCb VELO Phase-II upgrade) already aim for a high-granularity, high-precision timing silicon detector (using 3D sensors).

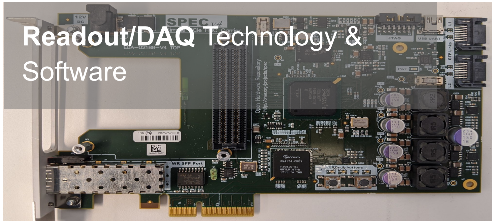
Long-standing expertise in most major national labs on developing current (LHC and HL-LHC) and next generation (blue-sky R&D) tracking detectors in colliders

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



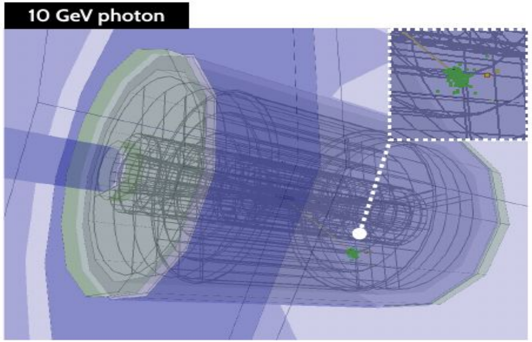


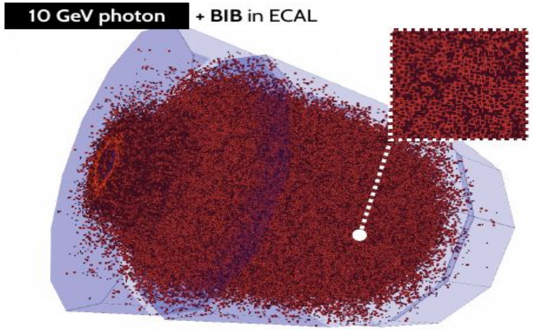




Calorimeters

Diffuse Beam-Induced Background energy deposits in both electromagnetic and hadronic calorimeters.





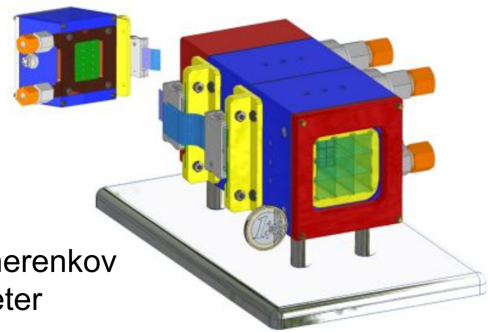
Key detector characteristics:

- large dynamic range – physics needs
- short integration time
- good time-of-arrival resolution
- longitudinal segmentation
- good radiation hardness
- good energy resolution for physics.

Both homogeneous (EM) and sampling (EM, HAD) calorimeters being considered

Sub-Detector **MAIA / MUSIC** Units	**Technology**	**Cell Size** mm^2	**# Longitudinal Slices**	**Time Resolution** ps	**Integration Time** ns	**Signal Time Window** ns
EM Cal - Barrel	W+Si / Crystal	5 x 5	50 / 6	/50	/25	[-0.25, 10]
EM Cal - Endcap	W+Si / Crystal	5 x 5	50 / 6	/50	/25	[-0.25, 10]
HAD Cal - Barrel	Iron + Scint.	30 x 30	75 / 70	–	–	[-0.25, 10]
HAD Cal - Endcap	Iron + Scint.	30 x 30	75 / 70	–	–	[-0.25, 10]

EM calorimeters Highlight



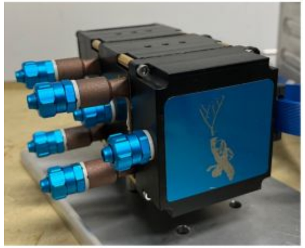
Crilin
PbF2 Cherenkov Calorimeter

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

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

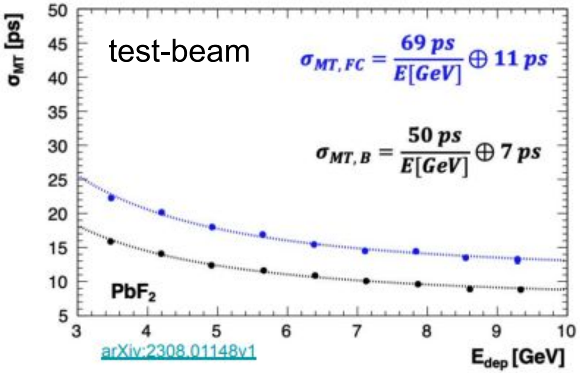
Prototyping and testbeam campaign to prove concept.

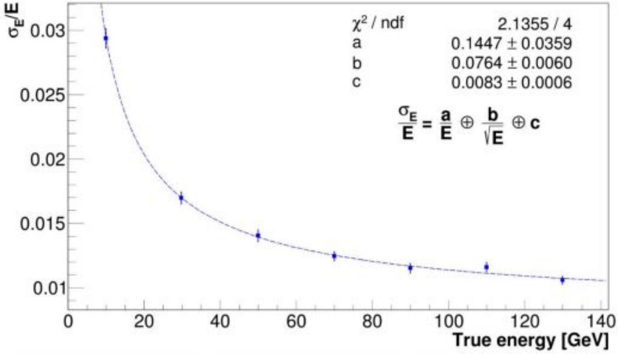
- time and energy resolution
- radiation hardness



2-layer 3x3-crystal Crilin prototype

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

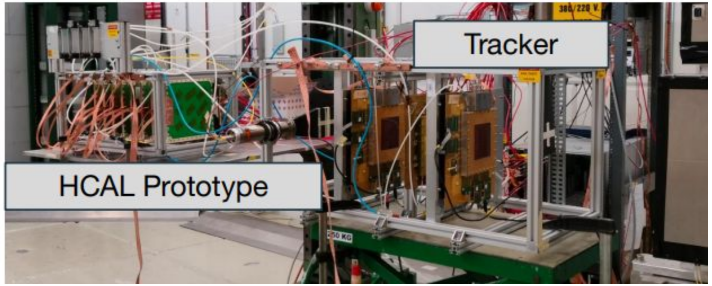


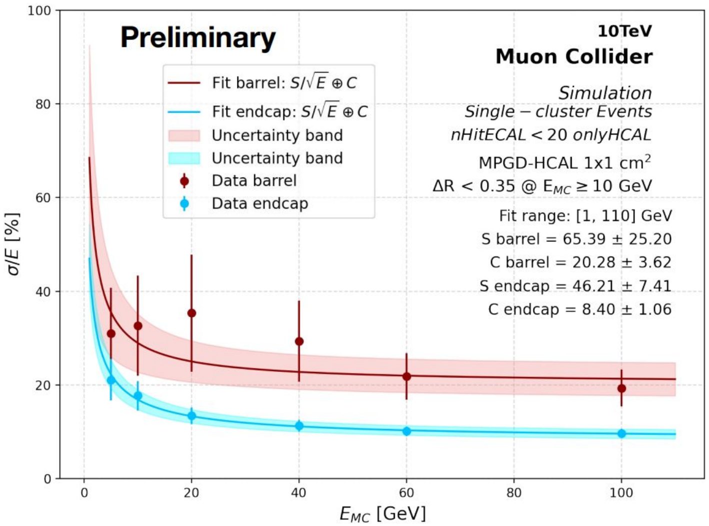


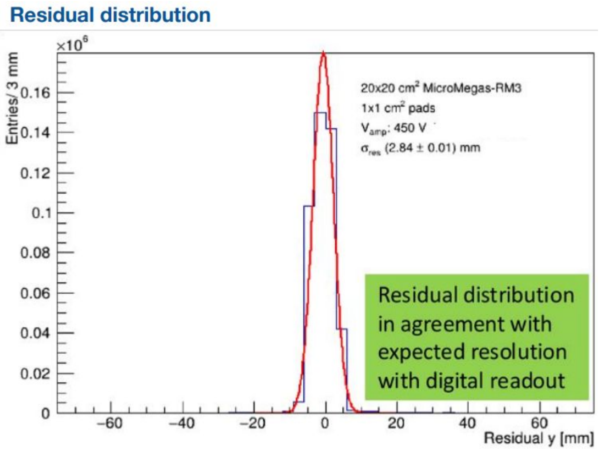
Hadronic Calorimeter Highlight

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



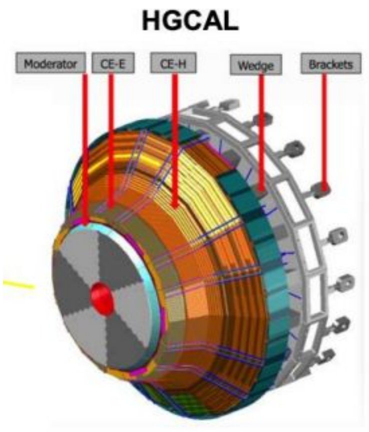


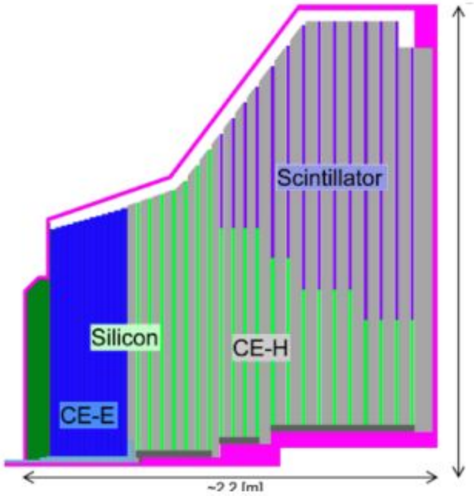


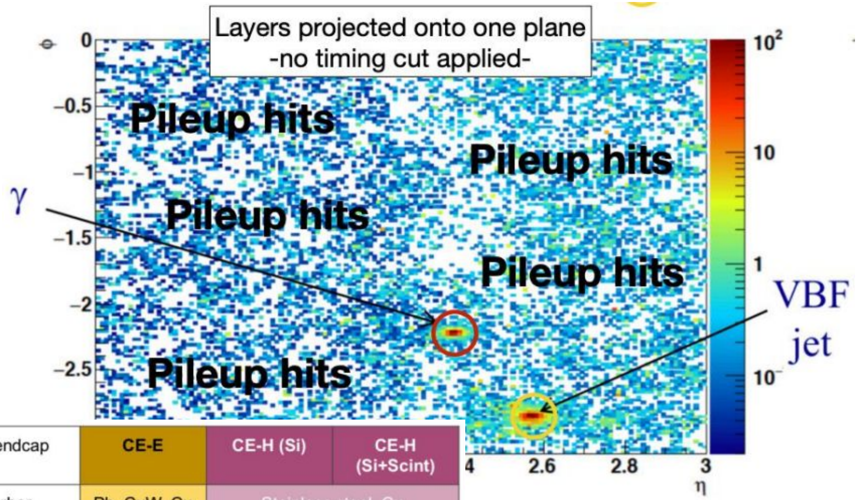
Evolution from current projects

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	

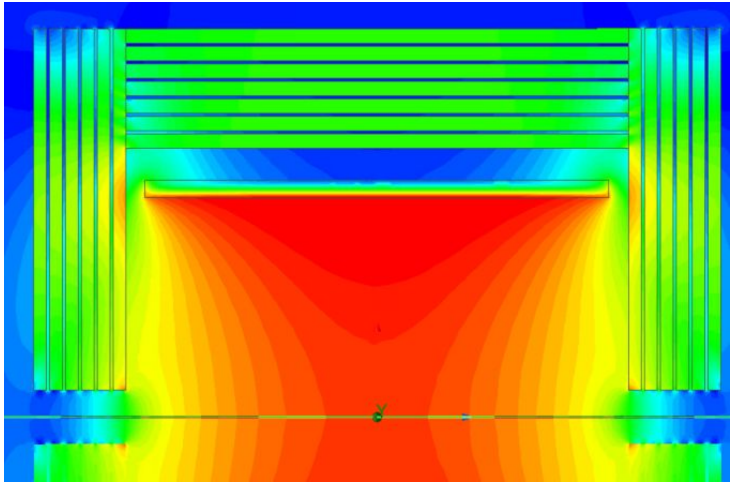
Solenoid

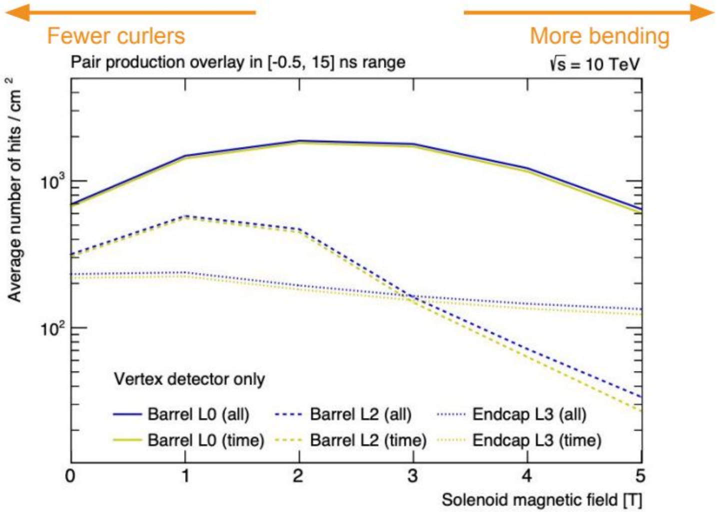
Large aperture and high field solenoids are complex objects

- 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!



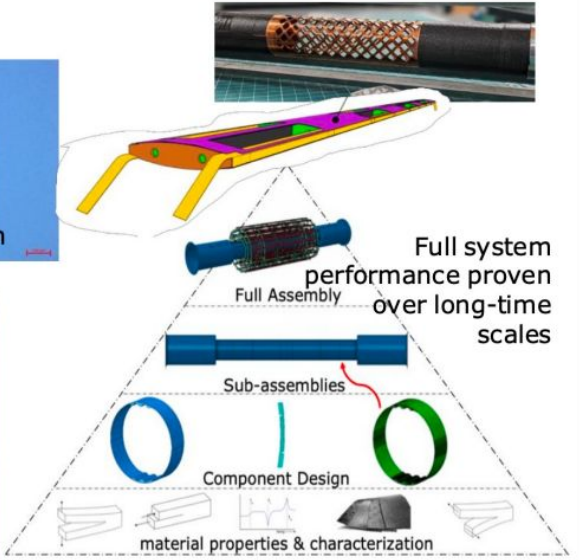


Mechanics / Integration

- Critical expertise developed throughout the years (strong national lab component)

- Common R&D items with other future colliders
  - lightweight structures
  - integrated cooling (if needed)
  - software tools to best connect design / simulation

- Specific items for a MuC detector, e.g.
  - nozzle support structures
  - tight clearance for detector integration

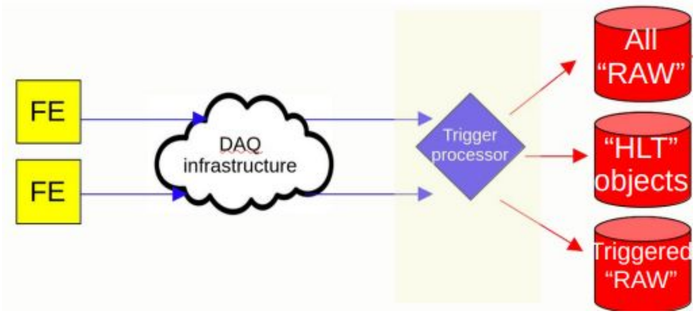


DAQ and Offline processing

A huge rate of data produced due to BIB

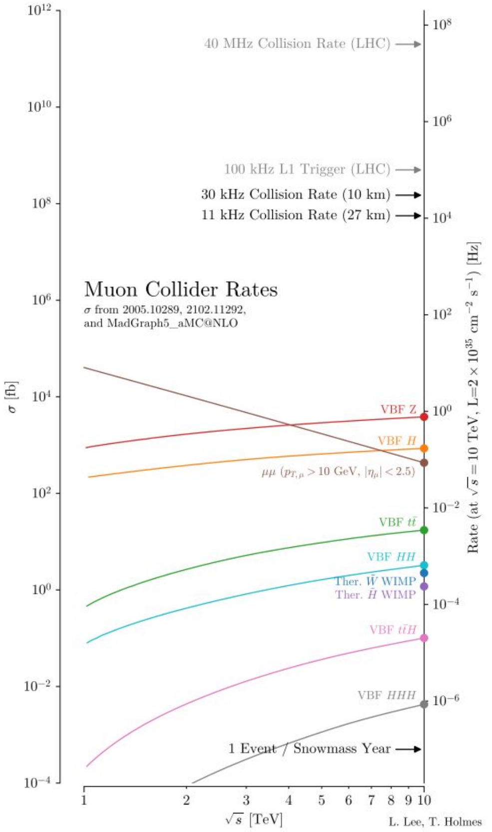
- where should data be reduced?
- what requirements on front-end electronics, DAQ and offline processing and storage?

First quantitative estimates; large interest and expertise on DAQ systems in US (national labs).



	size [MB] / event	events	total size [PB]
RAW[6]	80		400
RECO / AOD[7 8]	20	$5 \cdot 10^9$	100
analysis[9]	0.005		0.03
SIM[10]	250		25000
SIM RECO[11]	40	10^{11}	4000
SIM analysis[11]	0.01		1.0
Total			**29501**

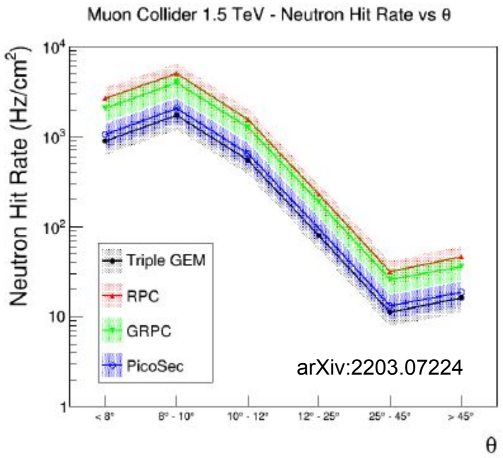
	HEPscore[1] s / event	events
Generation[2]	640	
Simulation[3]	550	10^{11}
Reconstruction (sim)[4]	1130	
Reconstruction (data)[4 5]		$5 \cdot 10^{12}$
Re-processing (sim)	1680	$2 \cdot 10^{11}$
Re-processing (data)	1130	$2 \cdot 5 \cdot 10^9$
Total		



… and much more!

Muon detectors

- central: endcap timing, reconstruction algorithms
- forward (within nozzle!): very complex!



PID detectors presently uncovered

- what technology can work within BIB?
- some LHC-experience from LHCb, ALICE

Luminosity monitoring

- online and offline measurements

Quantum detectors?! Neutrinos “detector”?

…

Organization and Engagement

Detector R&D coordinated in EU and US through the DRD / CDR groups.

- grouped by technology
- we aim to provide “vertical” coordination on muC detector needs

Critical to make it easy for the community to study what’s necessary:

- Detector-oriented wiki with practical information: https://mcd-wiki.web.cern.ch/
- Annual tutorial to help newcomers getting started since 2022.

Detector-oriented meetings within IMCC

- weekly meeting, although past EU strategy submissions have been less regular
- small-group meetings within dedicated efforts
- Slack and Mattermost communication channels.

Main issues:

- very few “technical experts” that usually try to help many new people
- very few resources in the US to combined low-level simulations and hardware R&D for at least key elements

Resources

Exercise to evaluate resources required as input for the EU strategy

- focusing on resources to be allocated for a targeted R&D
- assumes a ~equal amount from *generic* R&D projects

Area	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Simulation & Performance										
Staff	1.8	3.5	5.3	7	7	7	7	8.8	10.5	10.5
Post doc	1.8	3.5	5.3	7	7	7	7	8.8	10.5	10.5
Student	3.5	7	10.5	14	14	14	14	17.5	21	21
Material (kCHF)	0	0	0	0	0	0	0	0	0	0
Detector Technology										
Staff	4.9	9.8	14.8	19.7	19.7	19.7	19.7	24.6	29.5	29.5
Post doc	4.9	9.8	14.8	19.7	19.7	19.7	19.7	24.6	29.5	29.5
Student	9.8	19.7	29.5	39.3	39.3	39.3	39.3	49.2	59	59
Material (kCHF)	425	850	1275	1700	1700	1700	1700	2125	2550	2550
Software & Computing										
Staff	1.1	2.2	3.3	4.3	4.3	4.3	4.3	5.4	6.5	6.5
Post doc	1.1	2.2	3.3	4.3	4.3	4.3	4.3	5.4	6.5	6.5
Student	2.2	4.3	6.5	8.7	8.7	8.7	8.7	10.8	13	13
Material (kCHF)	100	200	300	400	400	400	400	500	600	600
TOTALS										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5

A few key messages

- identified items that need long development cycles
- small collaborations to tackles problems
- horizontal coordination across R&D groups and performance
- a small contribution can go a long way!

Conclusions

Tremendous progress continues in better understanding how a muon collider detector could look like.

- It’s exciting to see many new people bringing new ideas at all career stages!

To design a detector that excels in this unique environment:

- Prove a minimal design that can extract the needed physics
- Identify possible technologies that can evolve to those needs
- Explore different ideas, prove / learn from prototyping needed technologies
- Couple detailed simulations and targeted detector R&D and prototyping

Aim for a fast-loop between simulation, especially low-level, and hardware R&D

Continous support and engagement in critical areas is essential to ensure readiness

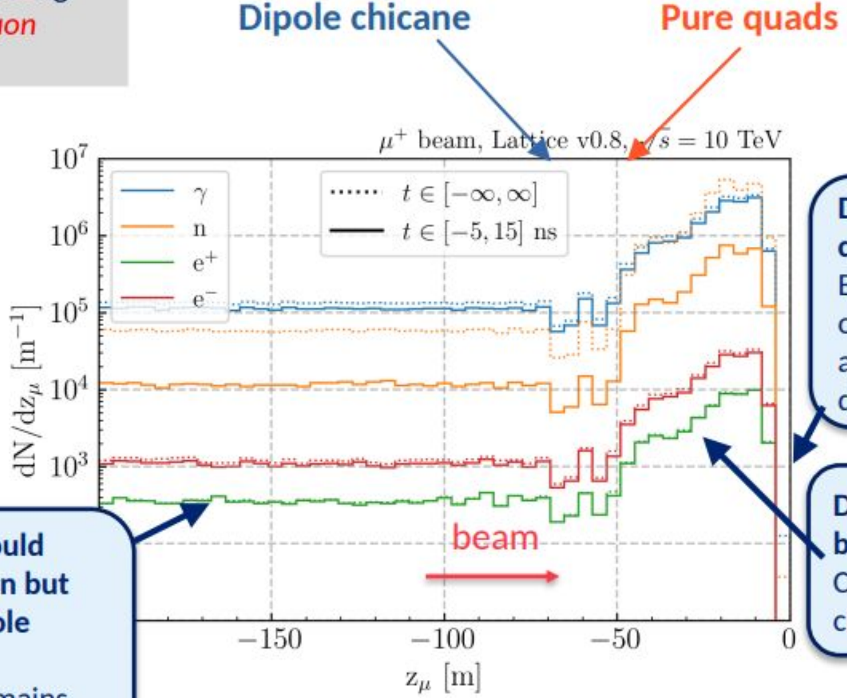
- well aligned with existing interests and expertise
- ensure critical items well fit within any accelerator-driven timeline

BACKUP

BIB and Lattice design

Number of background particles entering the detector as a function of the muon decay position:

Latest 10 TeV lattice version (v0.8)

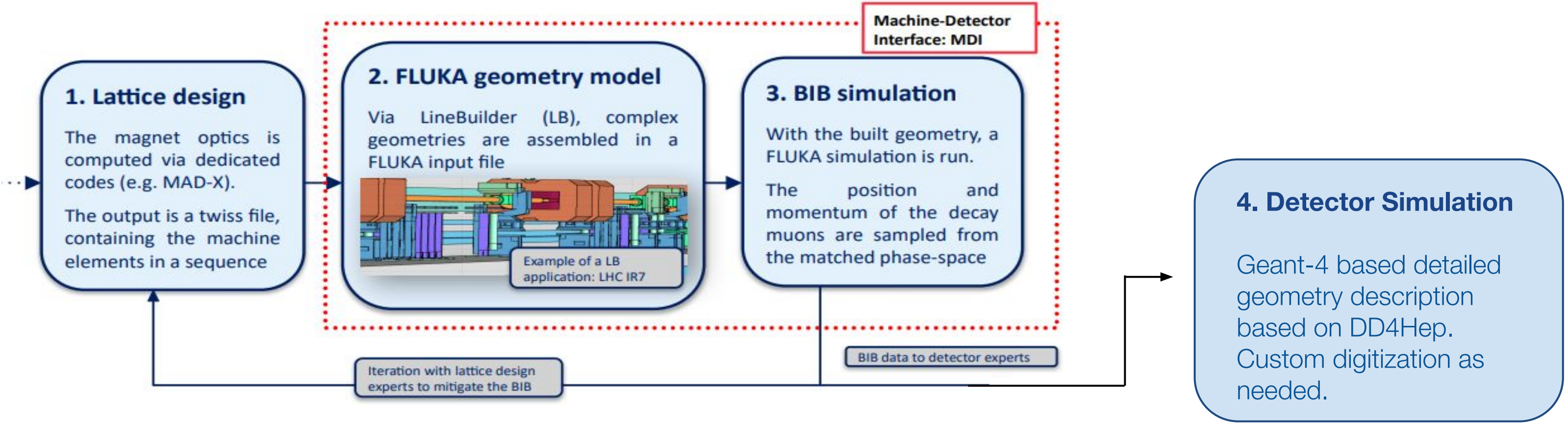


Decays inside nozzle (between IP and L*) contribute very little to the background
But: increasing L* from 6 m to 10 m yields only small improvement – O(few 10%) – at the expense of a more complex lattice design

Decays inside triplet dominate background
Can only be partially mitigate by lattice choice (e.g. dipolar component)

Decays in drift upstream of FF would yield a non-negligible contribution but can be strongly reduced by a dipole chicane
Nevertheless, the contribution remains non-zero

BIB Simulation



Software updates: highlights

Moving from ilc-soft to key4hep

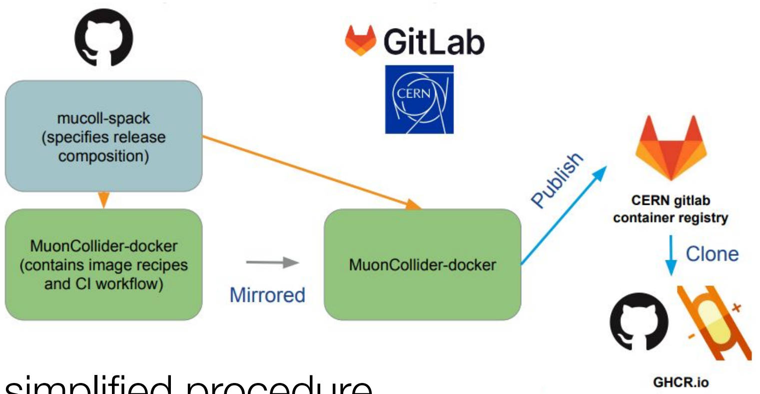
- first step done and in tutorial
- now moving towards full migration

1.	LCIO →	EDM4Hep →	EDM4Hep
2.	DD4hep →	DD4Hep →	DD4Hep
3.	Marlin →	Gaudi →	Gaudi
4.	ILCSoft →	Spack →	Spack

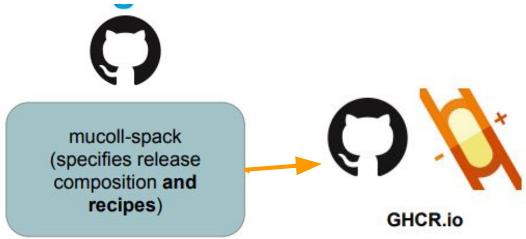
Needs:

- migration of remaining algorithms
- validation (and its automation)
- update tutorial
- new experts

Automatic release building from github CI



New simplified procedure



3 workflows

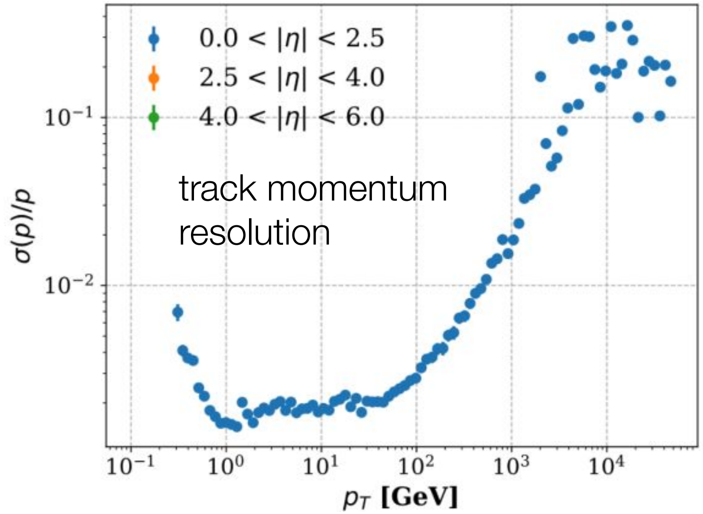
- Build-spack
- Build-minimal
- Build-sim

Automatic build of release and containers

Full vs Fast simulation

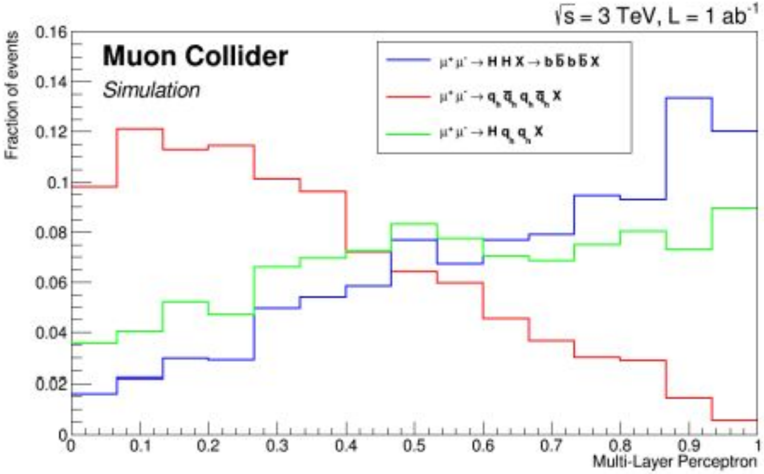
1. Maintain and improve a DELPHES card for the detector(s)
   - very short on person-power!
2. Perform key physics studies using full simulation to validate and assess cases where a simplified simulation might not be possible/easy

DELPHES card



Higgs self-coupling

arXiv:2405.19314



Tracking Detector: reconstruction algorithms

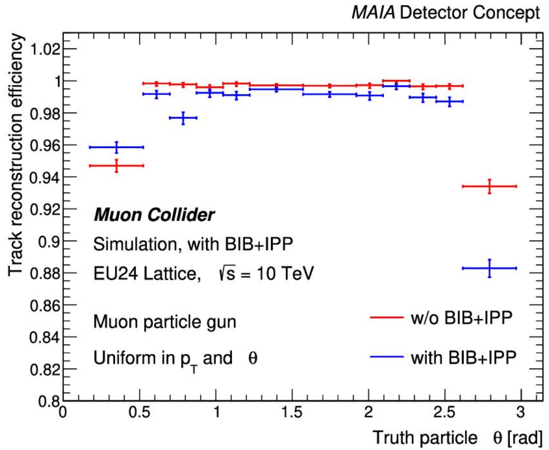
Tracking performance under control,

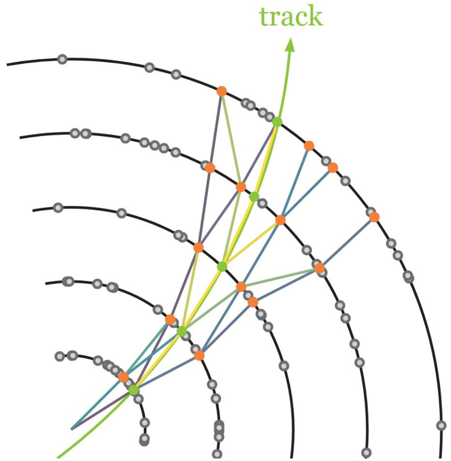
- balance between CPU time and performance
- focused on ~prompt particles and rough selections to remove hit combinatorics

Explored/-ing

- Track seeding optimization (~manual)
- Parallel tracking
- Dedicated track reconstruction
- Automated optimization
- Alternative reconstruction algorithms

Plenty of opportunities for small or big projects



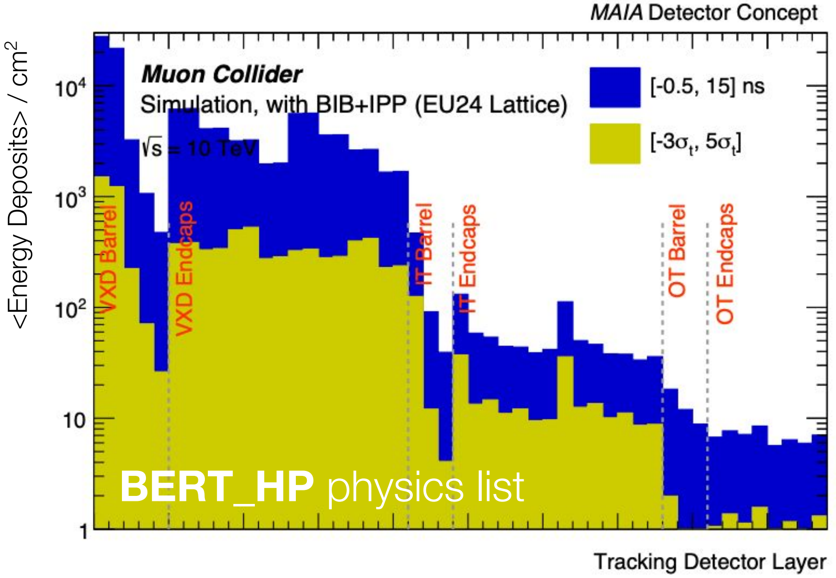


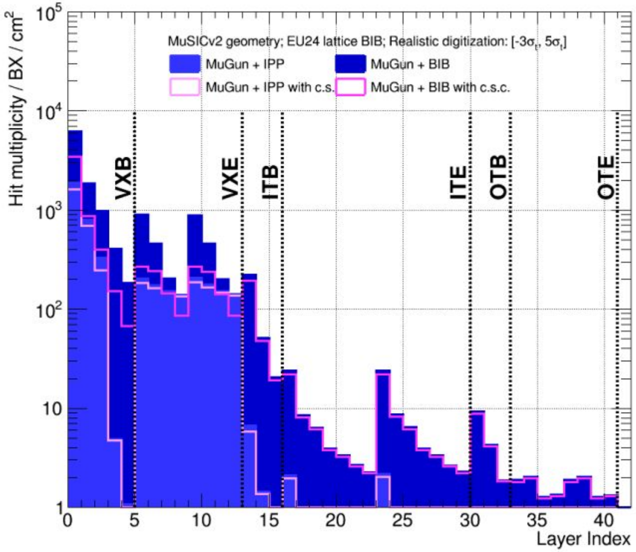
Tracking Detector: low-level performance

Improving our understanding of BIB interaction with tracker

- more realistic digitization: sensor and front-end electronics evaluation
- physics list (e.g. low-energy neutron interactions)

Critical ingredients for a sound program of technology R&D and choice!





EM Calorimeter

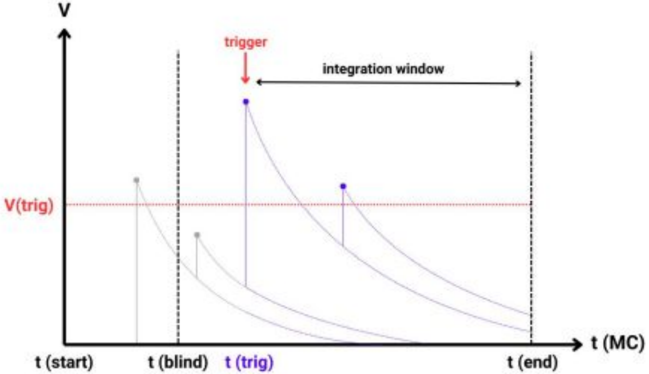
Placement of solenoid creates differences in MAIA vs MUSIC energy deposits.

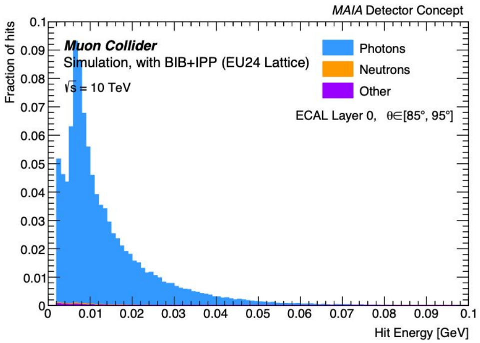
- shielding for soft BIB particles vs energy loss of object of interest

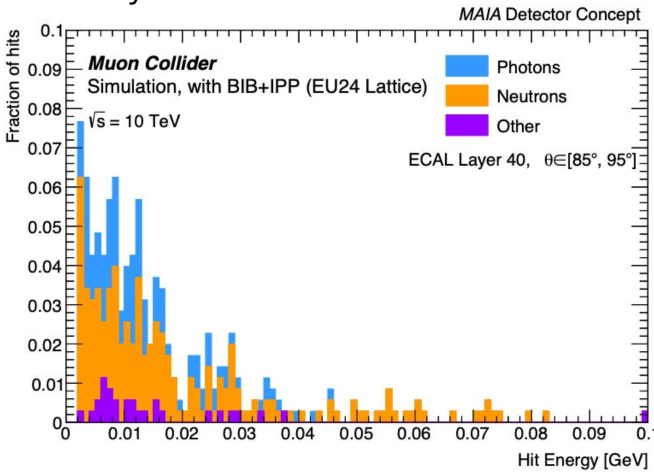
A few highlights

- interplay of testbeam and realistic digitization model for MUSIC
- high-precision G4 physics list (BERT_HP), neutrons have less penetration power (deposit most of their energy in the first layers)

inner to outer layers





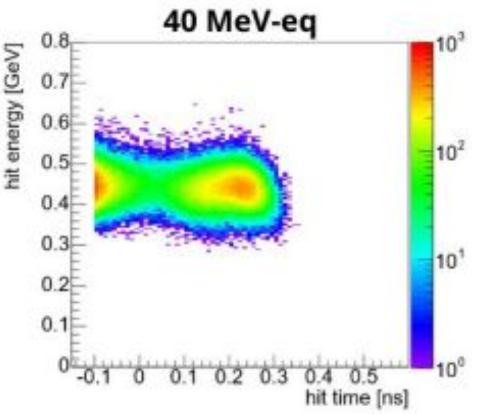


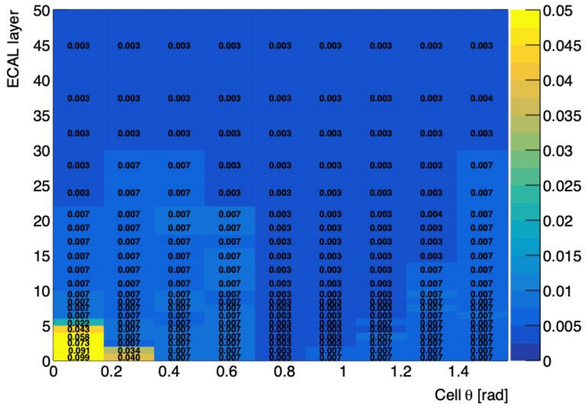
EM Calorimeter Performance

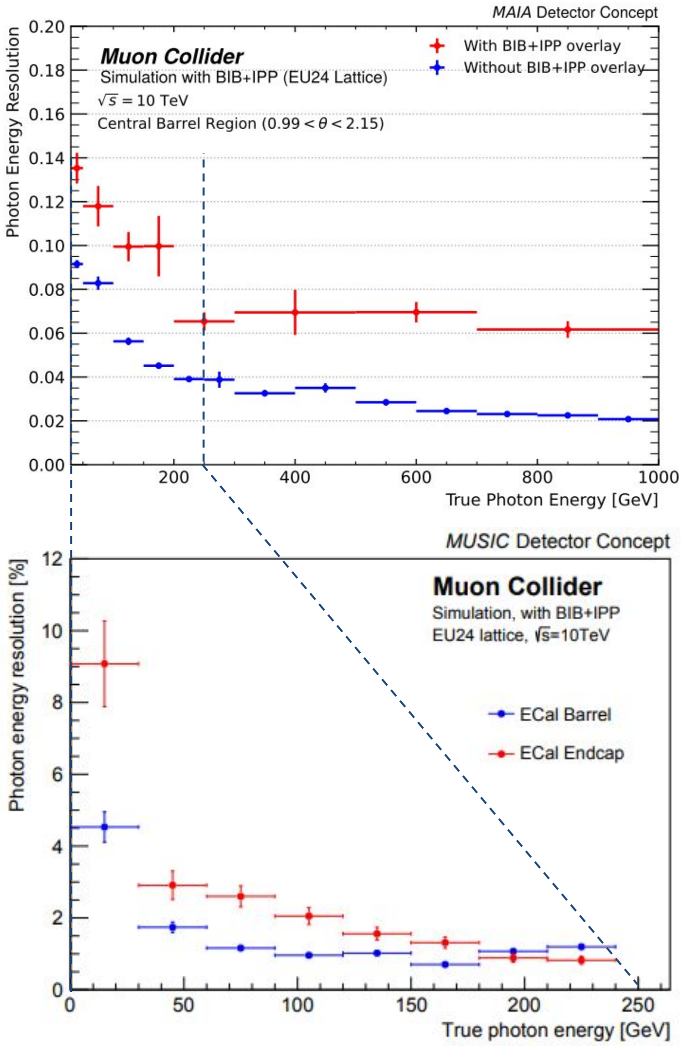
Performance evaluated with single photons and realistic backgrounds

- re-optimization of cell timing / energy selections

Lots of active work to understand achievable resolution and pro/cons of each design / choice.







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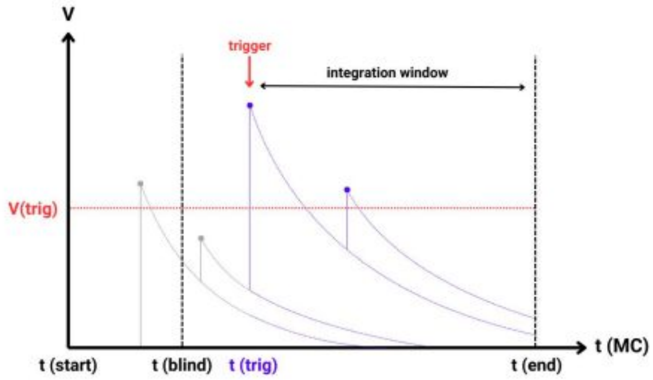
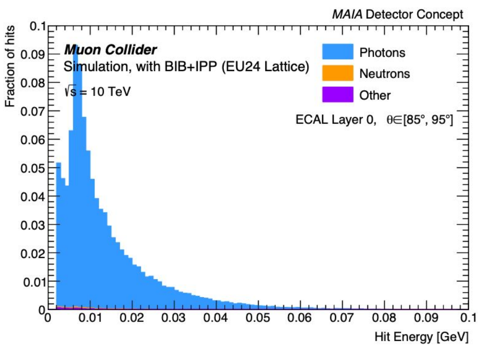
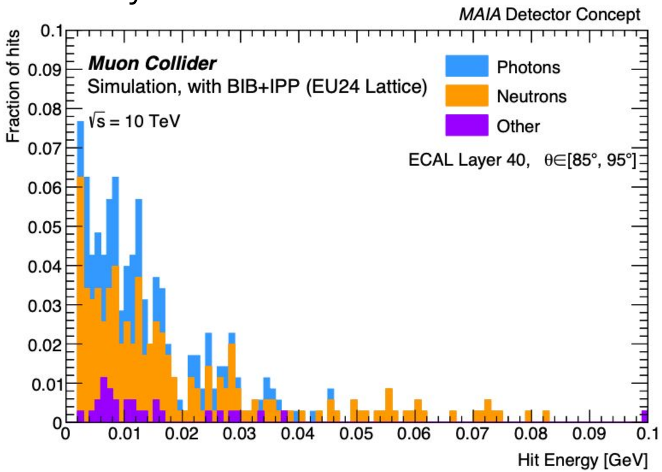






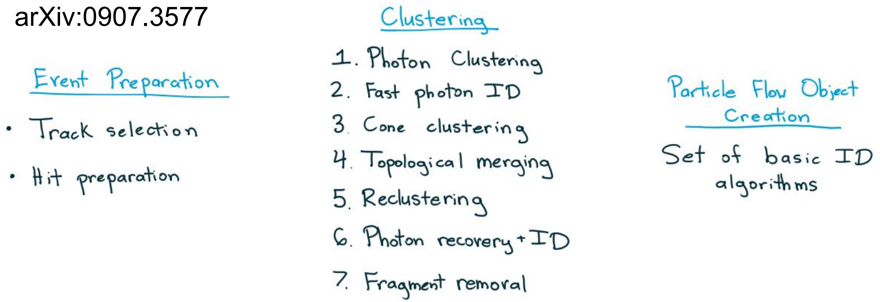
Particle Flow Reconstruction

Greg's talk

Aim to use at best information from all sub-detectors

- Pandora: designed for ILC

arXiv:0907.3577



Pursuing two main approaches

MUSIC

Piece-by-piece optimization

- jet clustering
- fake-jet removal
- jet direction correction
- jet p_T correction

MAIA

Construct a Particle Flow algorithm by stacking sub-algorithms

- easier to debug
- re-optimize for speed in this environment

Particle Flow Reconstruction

Aim to use at best information from all sub-detectors

- Pandora: designed for ILC

arXiv:0907.3577

Event Preparation

- Track selection
- Hit preparation

Clustering

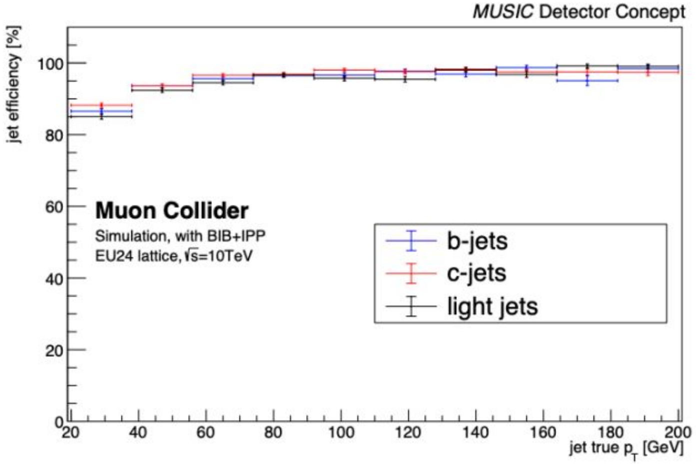
1. Photon Clustering
2. Fast photon ID
3. Cone clustering
4. Topological merging
5. Reclustering
6. Photon recovery + ID
7. Fragment removal

Particle Flow Object Creation

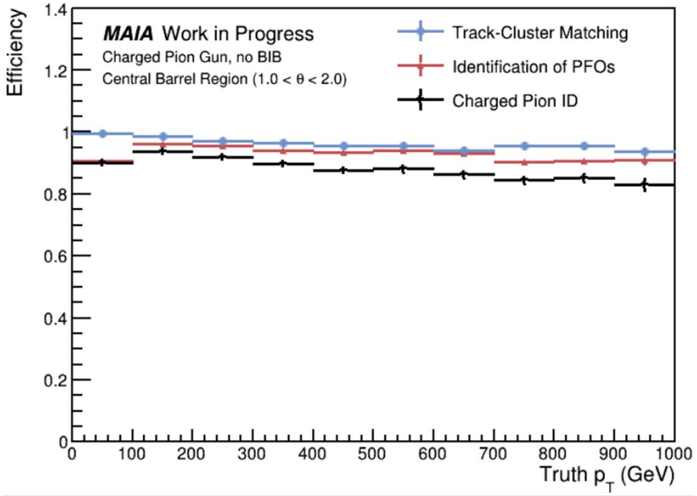
Set of basic ID algorithms

Pursuing two main approaches

MUSIC



MAIA



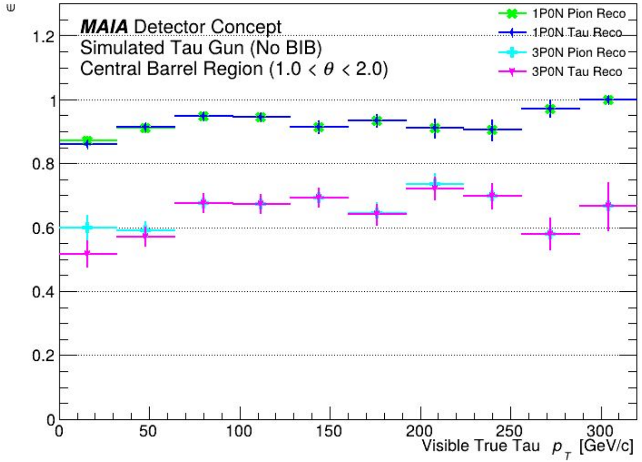
High-energy jets and flavor tagging

Rapid progress in starting to investigate more complex objects

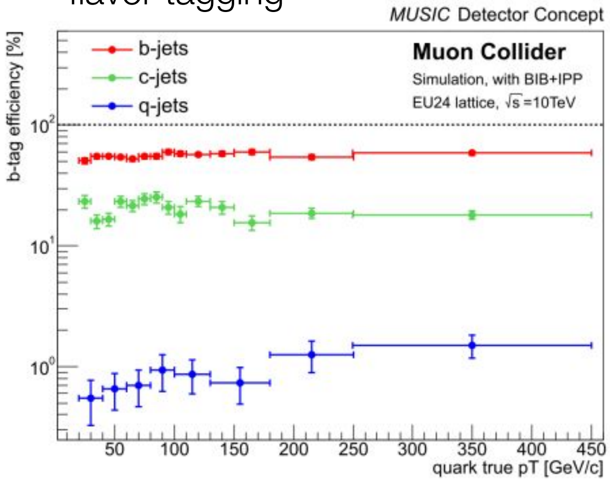
- light, b/c-jets tagging, towards more advanced taggers
- tau reconstruction and ID
- jet substructure

Great area for more people to be involved!

tau reconstruction



flavor tagging



very collimated jets