# Overview of Detector Performance Studies: MAIA and MUSIC

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(with huge thanks to many people for their inputs!)

**US Muon Collider Meeting**

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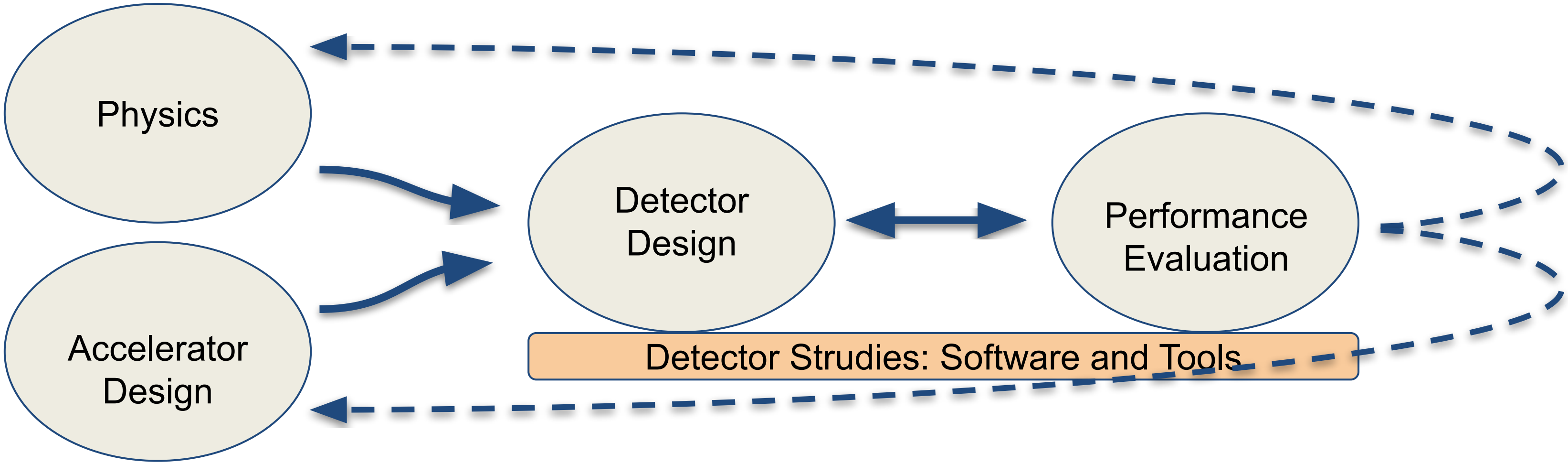
International MUON Collider Collaboration

BERKELEY LAB
Lawrence Berkeley National Laboratory

# Introduction

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

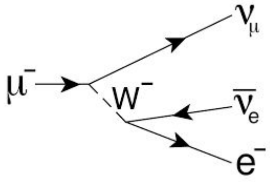



Outline:

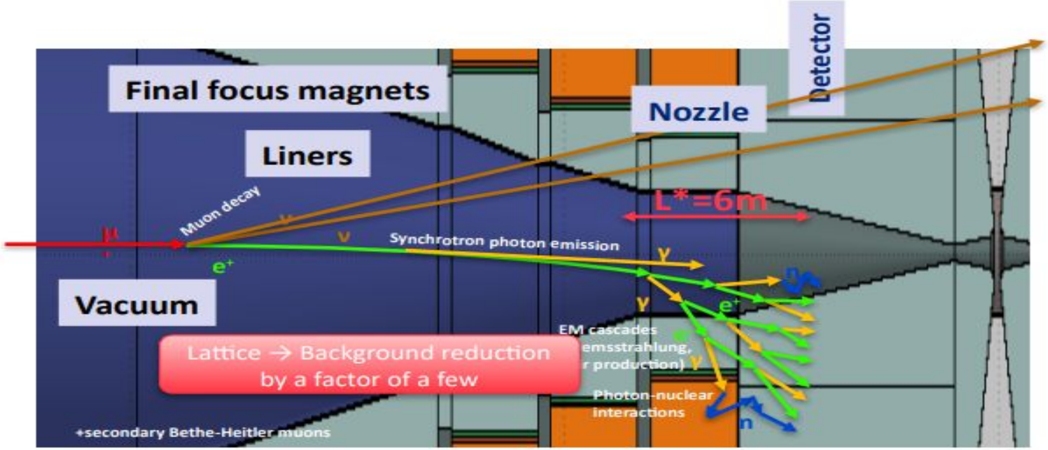
- Brief recap of Beam-Induced Backgrounds and Detector layout(s)
- Recent highlights: EU strategy input and beyond
  - looking ahead: technology choices, new ideas
  - ~~towards refined requirements and specifications~~

# Beam-Induced Backgrounds (BIB)

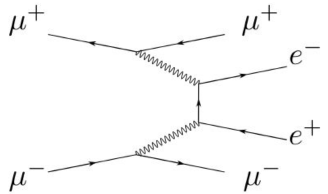
## Muon beam decays



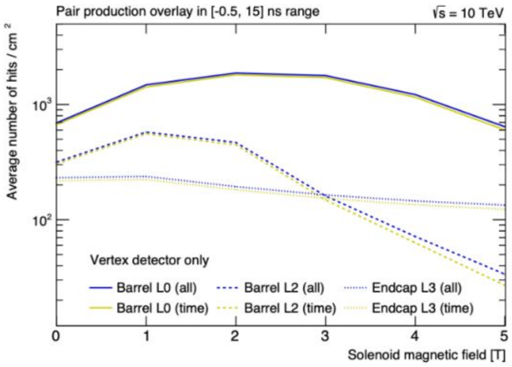

Very <u>high-energy electrons</u> then interact with surrounding material; relevant decays for the detector can be produced 10s of meters away.




## e+e- pair production




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



# Detector shielding (nozzle)

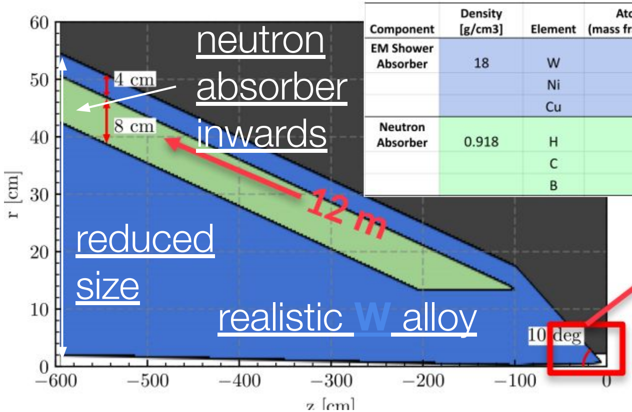
Dedicated shielding to suppress an otherwise too-large flux of high-energy $e^{+/-}$

Detailed simulations to study the interplay between:

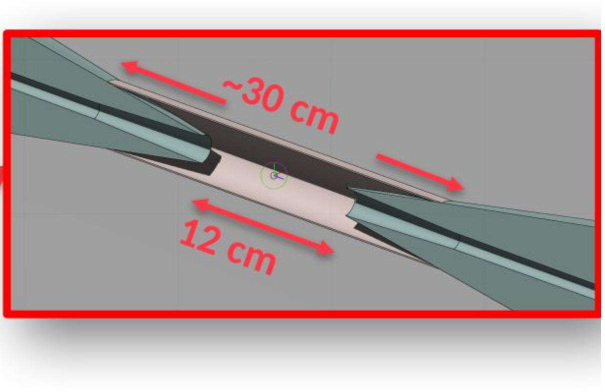
- accelerator design around interaction region
- shape of shielding

Both updated for latest design

- sim ~1 month / 0.1 bunch-crossing on a cluster

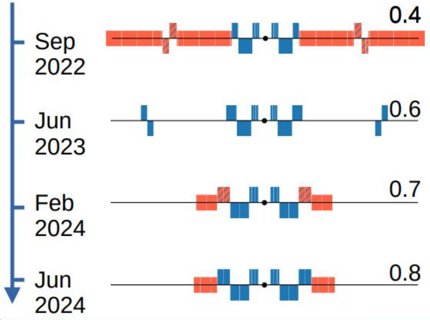



| Component | Density [g/cm3] | Element | Atomic Fraction (mass fraction if negative) |
|---|---|---|---|
| EM Shower Absorber | 18 | W | -0.95 |
| | | Ni | -0.035 |
| | | Cu | -0.015 |
| Neutron Absorber | 0.918 | H | 0.5 |
| | | C | 0.25 |
| | | B | 0.25 |




**10 TeV challenges:**

- Large β in FF magnets → large aperture
- High-fields and strong chromatic effects → local chromatic correction scheme

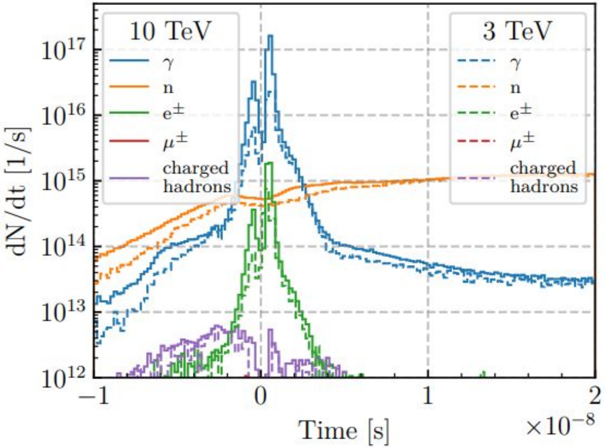


# BIB characterization

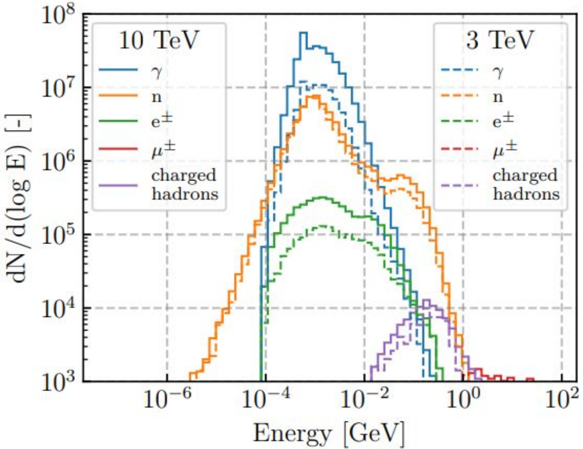
Key takeaways at detector volume *entrance*:

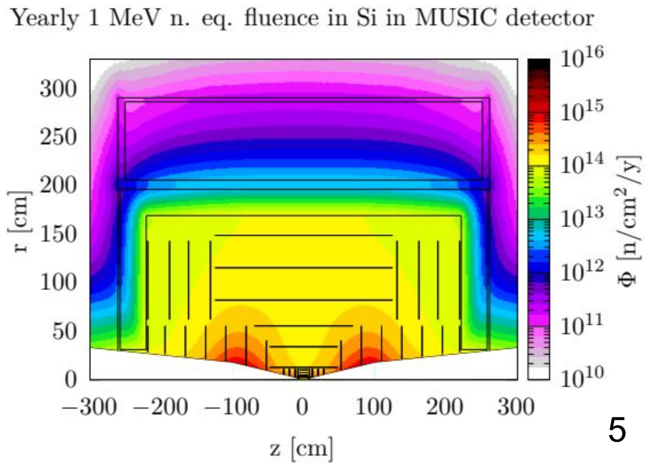
- soft photons/neutrons
- long out-of-time tail
- originate far from interaction point
- not dramatic collider energy dependence
- radiation environment < HL-LHC

| Component | Dose [kGy] | | 1 MeV neutron-equivalent fluence (Si) [$10^{14}$ n/cm$^2$] | |
|---|---|---|---|---|
| | MAIA | MUSIC | MAIA | MUSIC |
| Vertex (barrel) | 1000 | | 2.3 | |
| Vertex (endcaps) | 2000 | | 8 | |
| Inner trackers (barrel) | 70 | | 4.5 | 4 |
| Inner trackers (endcaps) | 30 | | 11.5 | 10 |
| ECAL | 0.58 | 1.4 | 0.15 | 1 |



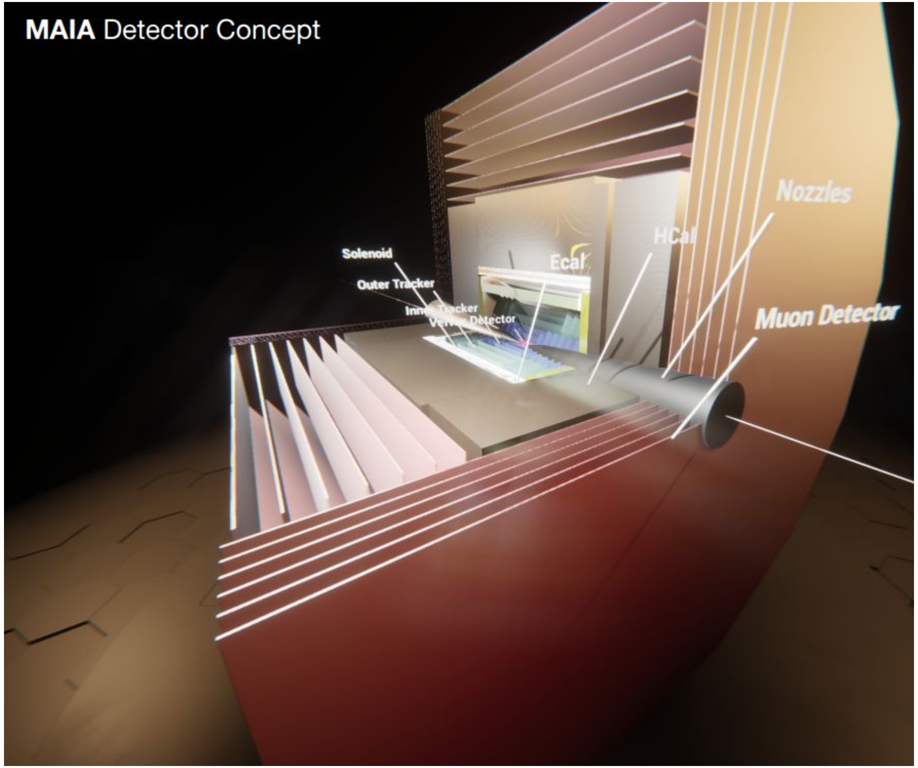

[-1, 15] ns time window

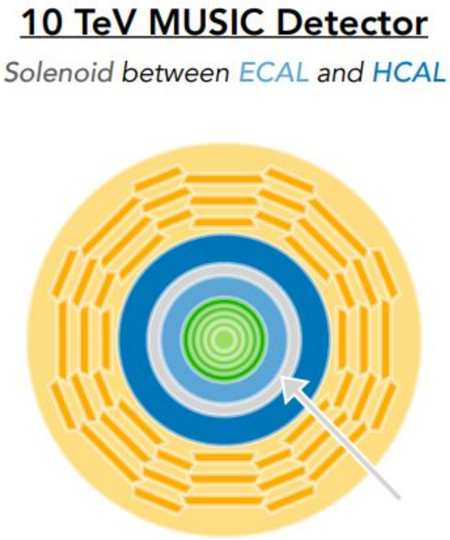


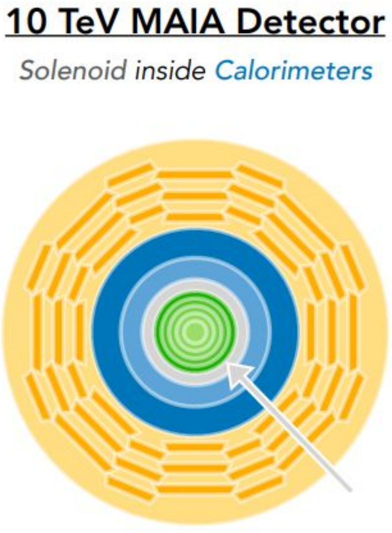



# 10 TeV detector concepts

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



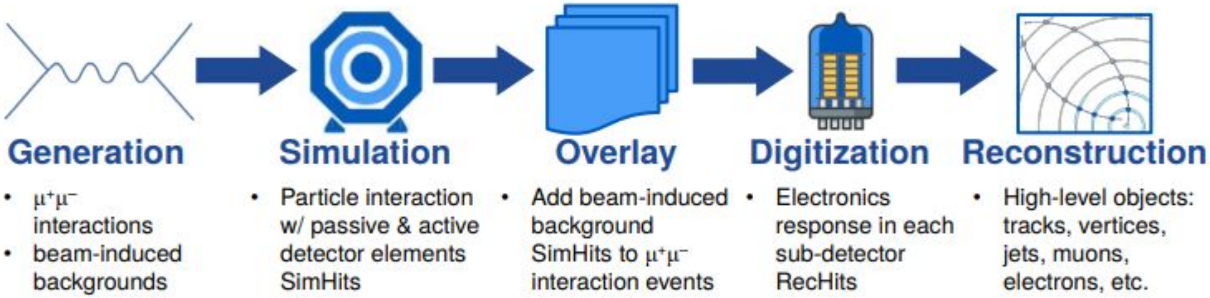

EU Strategy Input

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

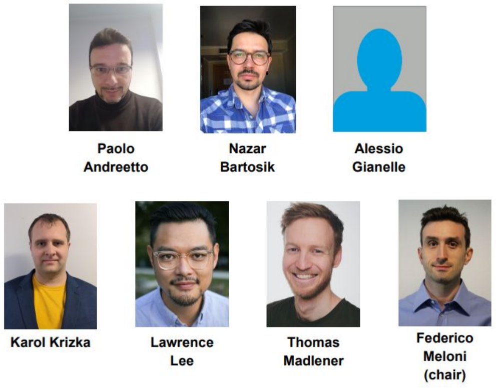



**Muon Collider**
github
doc

Taskforce to assess short, medium and long-term evolution and priorities (report)

- Integration with the key4hep framework
  - used by many future collider projects)
- Software development best practices and organization
- Software distribution
- Fast simulation development
- Documentation and Tutorials

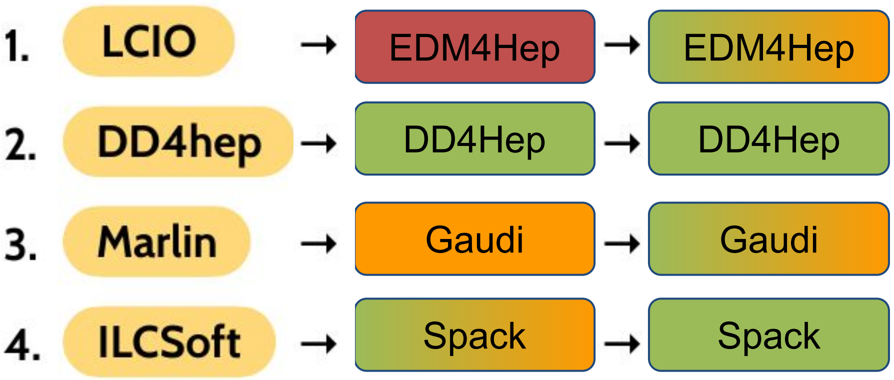
Taskforce members



# Software updates: highlights

## Moving from ilc-soft to key4hep

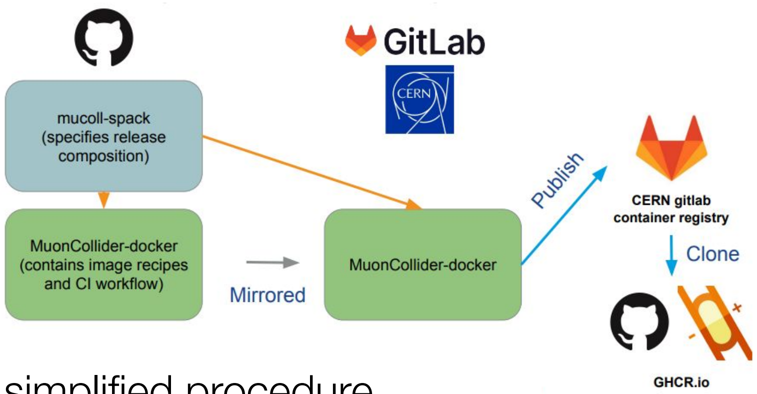
- first step done and in tutorial
- now moving towards full migration



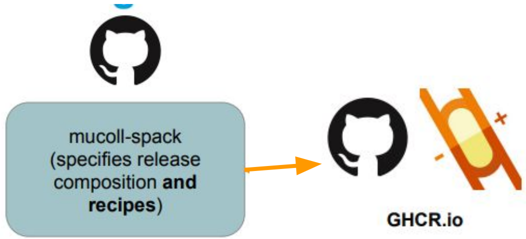

## Needs:

- 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

# Tracking Detectors

Exploring all-silicon tracker layouts.

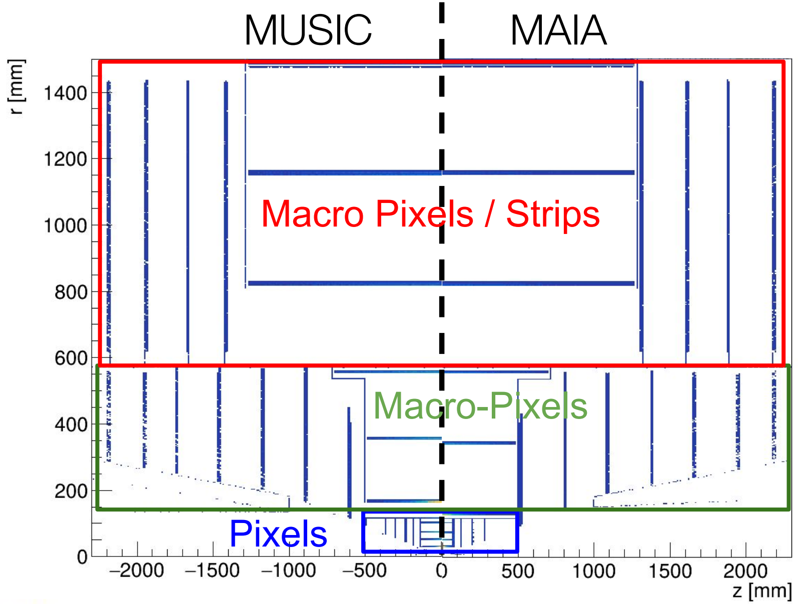
One of the most sensitive detectors to BIB

- 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 | | | $\mu m^2$ | $\mu m$ | 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>

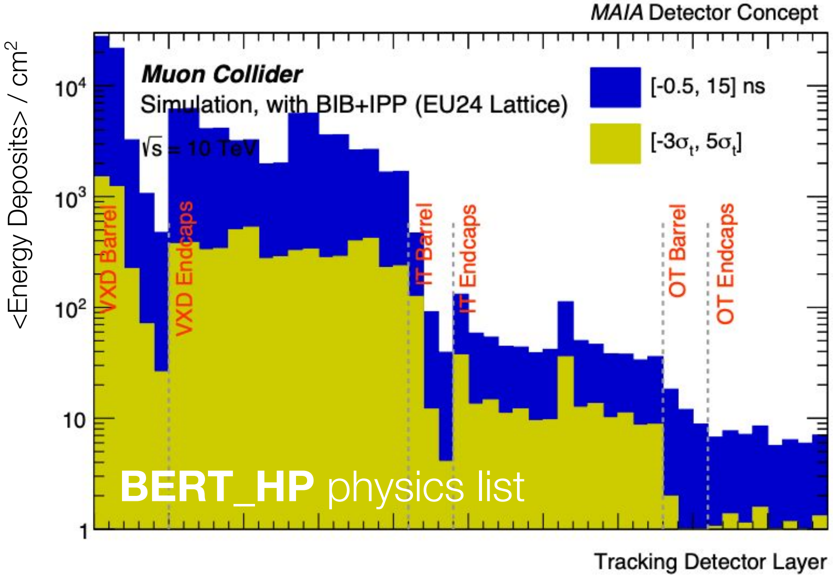
- Precision timing
- Directional information
  - cluster shape, close-by layers
- Energy deposition

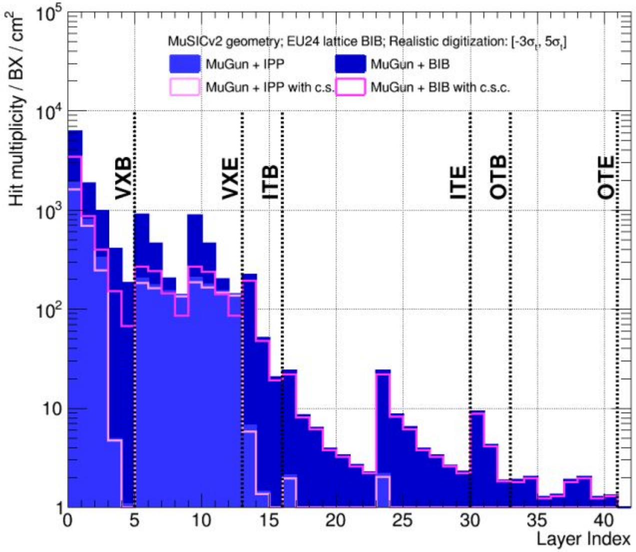
# Tracking Detector: low-level performance

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!



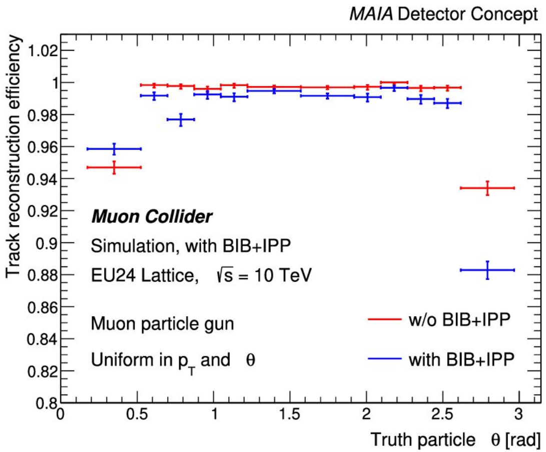



# Tracking Detector: reconstruction algorithms

Rocky's talk

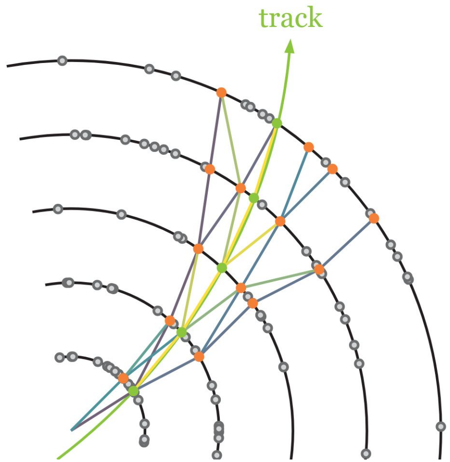
Tracking performance under control,

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




Explored/-ing

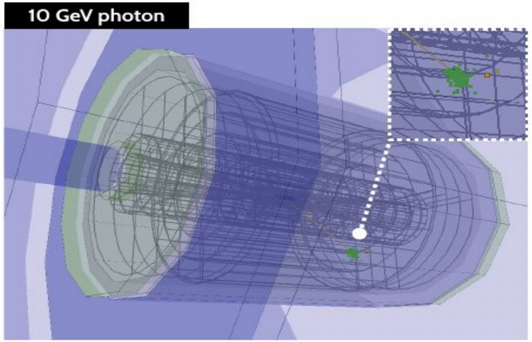
- Track seeding optimization (~manual)
- Parallel tracking
- Dedicated track reconstruction
- Automated optimization
- Alternative reconstruction algorithms

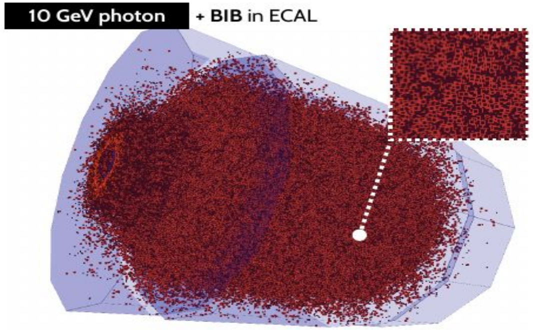



Plenty of opportunities for small or big projects

# Calorimeters

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




<u>Key detector characteristics:</u>

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

Homogeneous and sampling 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 Calorimeter

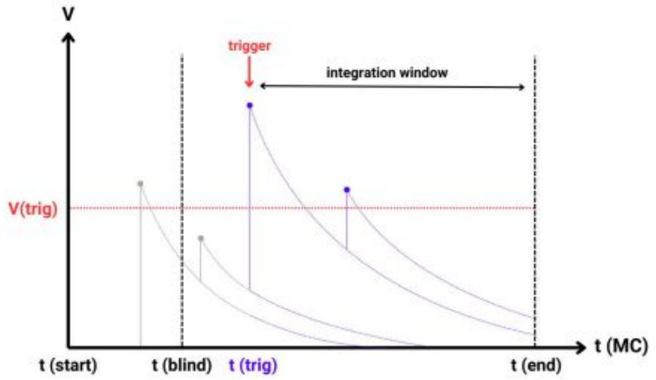
Placement of solenoid creates differences in MAIA vs MUSIC energy deposits.

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

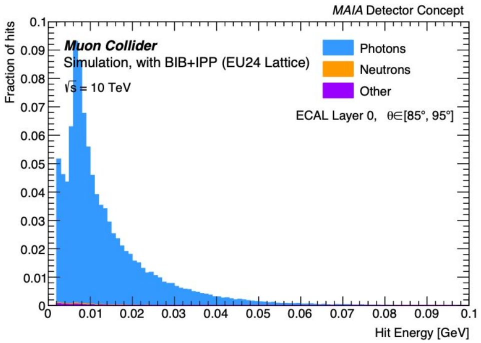
Rose's talk

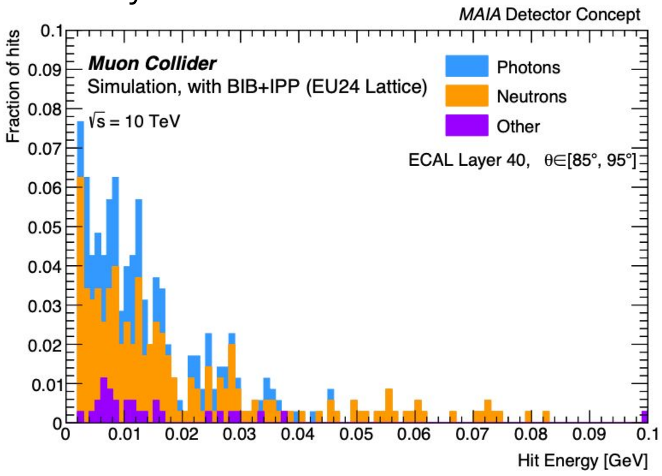
A few recent highlights

- new digitization model for MUSIC, interplay with test-beam results
- 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



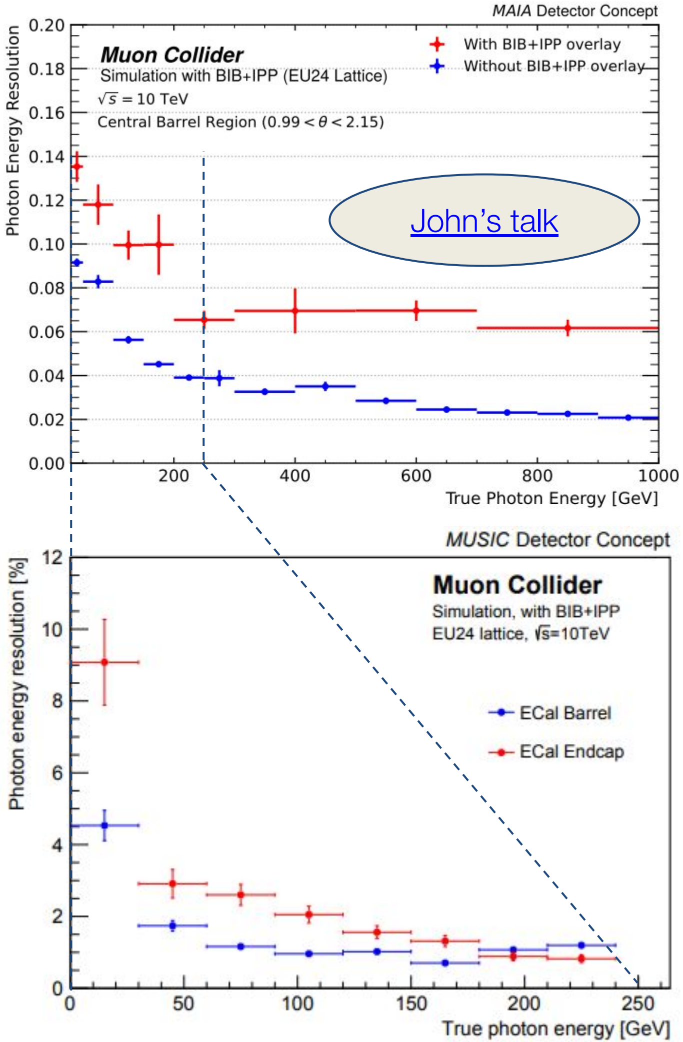



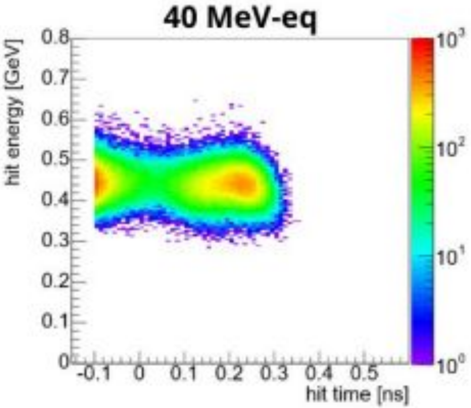
# EM Calorimeter Performance

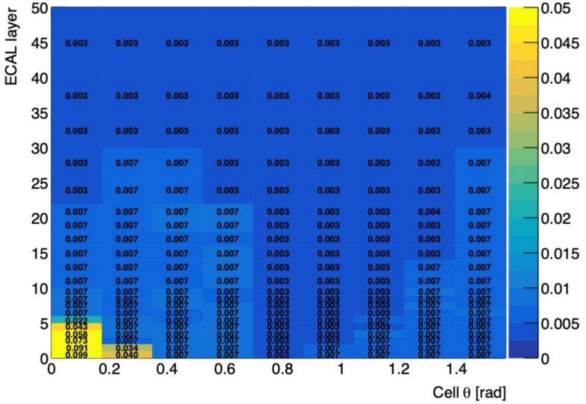
Performance evaluated with single photons and realistic backgrounds

- re-optimization of cell timing / energy selections

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



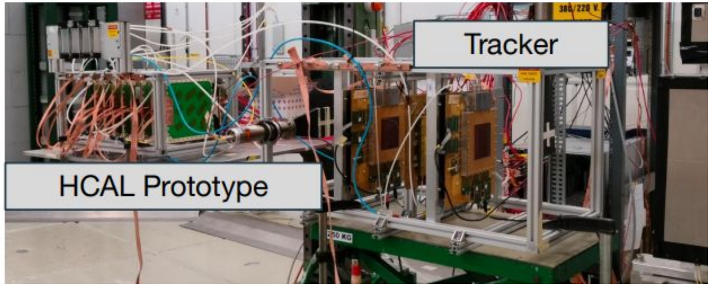



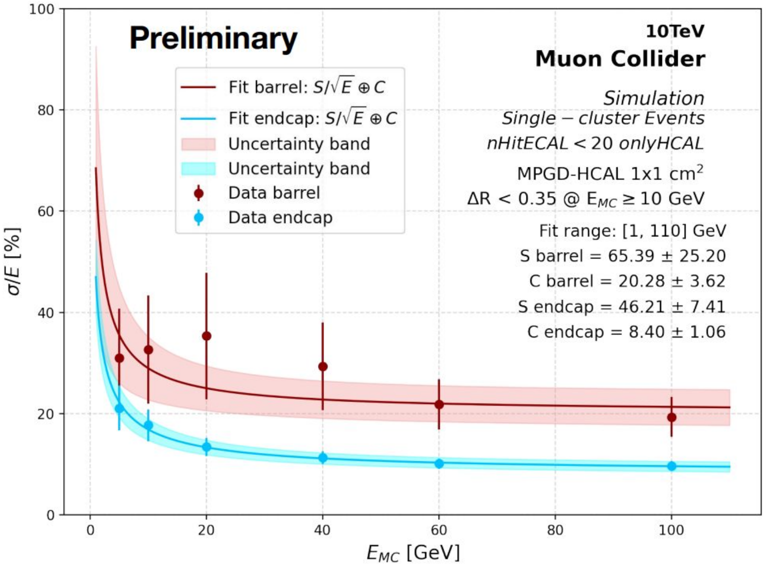



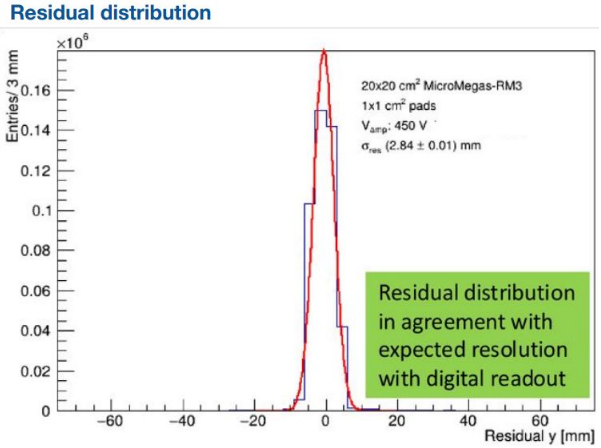
# Hadronic Calorimeter

Plan to systematically compare three MPGD technologies for hadronic calorimetry

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



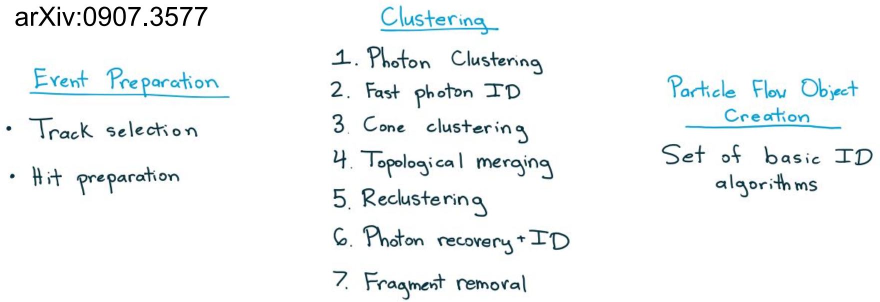
# Particle Flow Reconstruction

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**

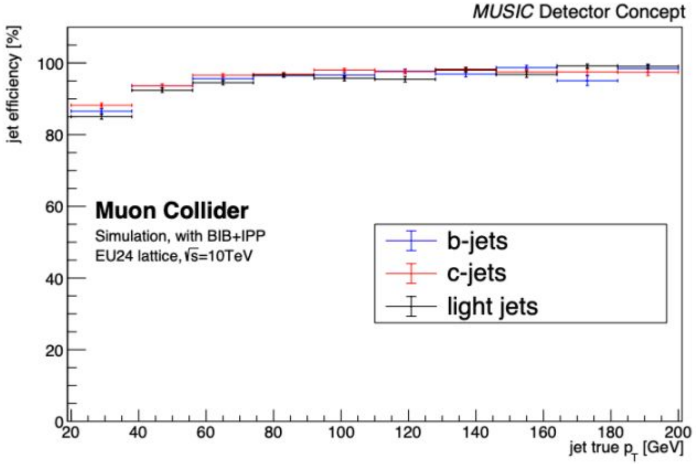
1. Photon Clustering
2. Fast photon ID
3. Cone clustering
4. Topological merging
5. Reclustering
6. Photon recovery + ID
7. Fragment removal

**Particle Flow Object Creation**

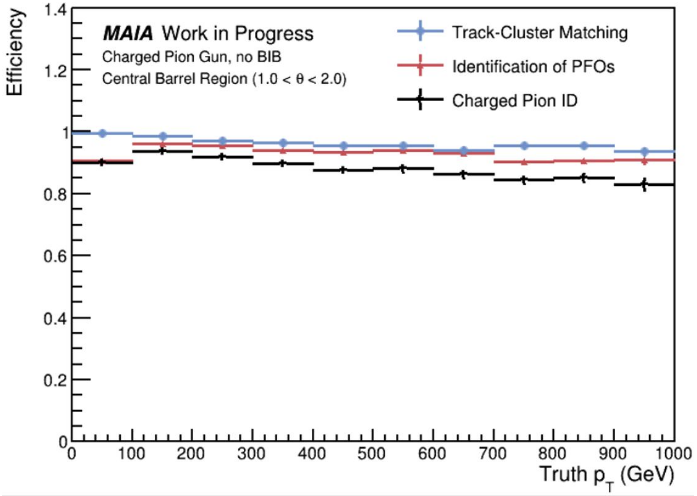
Set of basic ID algorithms

Pursuing two main approaches

MUSIC




MAIA



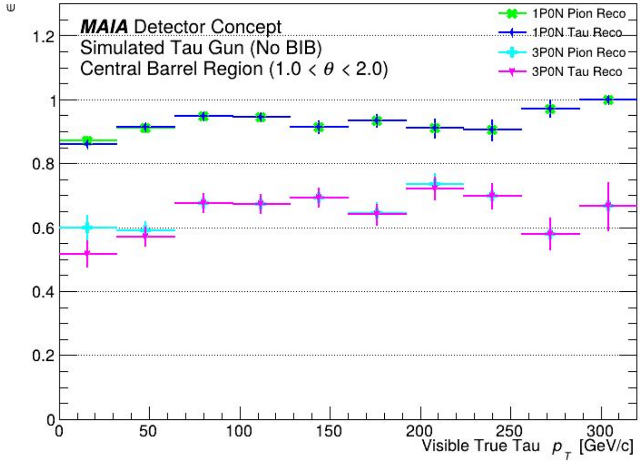
# High-energy jets and flavor tagging

Rapid progress in starting to investigate more complex objects

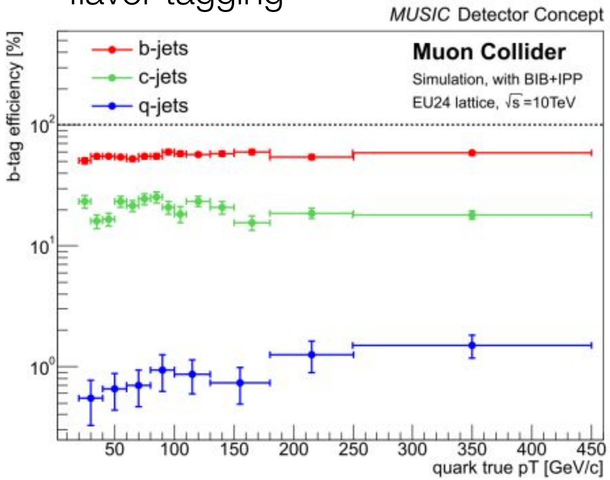
- light, b/c-jets tagging, towards more advanced taggers
- tau reconstruction and ID
- jet substructure

Great area for more people to be involved!

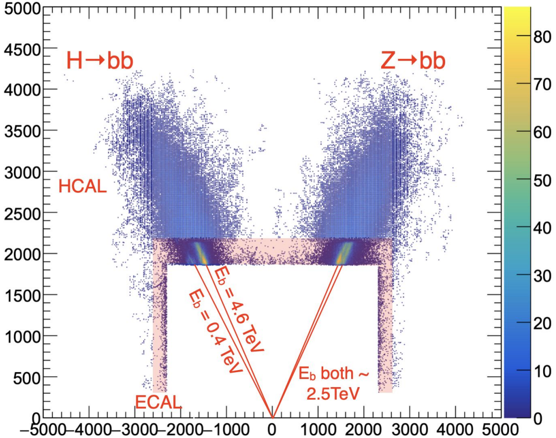
tau reconstruction




flavor tagging




very collimated jets



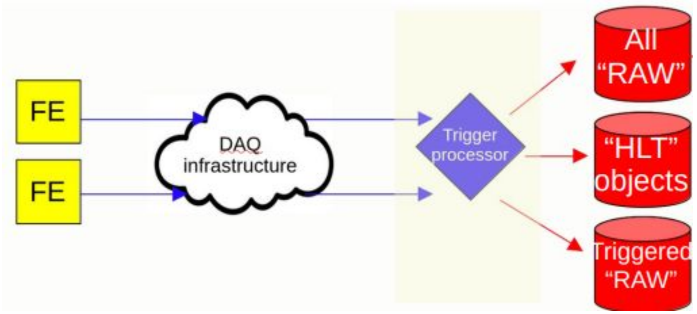
# DAQ and Offline processing

Angira's talk
Kevin's talk

A huge rate of data produced due to BIB

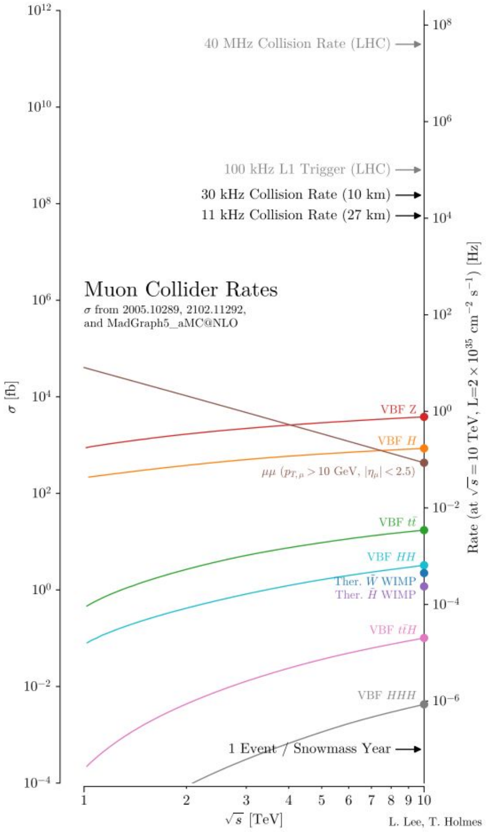
- where should data be reduced?
- what requirements on front-end electronics, DAQ and offline processing and storage?

Initial discussion and first quantitative estimates!




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



# 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
    - many more details not covered here: PID, (fwd) muons, luminosity, quantum detectors and much more!

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

# BACKUP

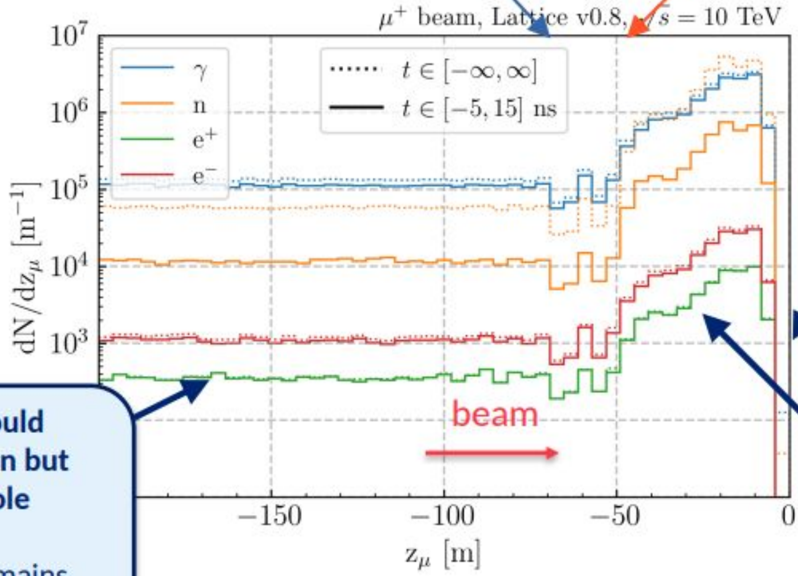
# BIB and Lattice design

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

*Latest 10 TeV lattice version (v0.8)*

**Dipole chicane**

**Pure quads**

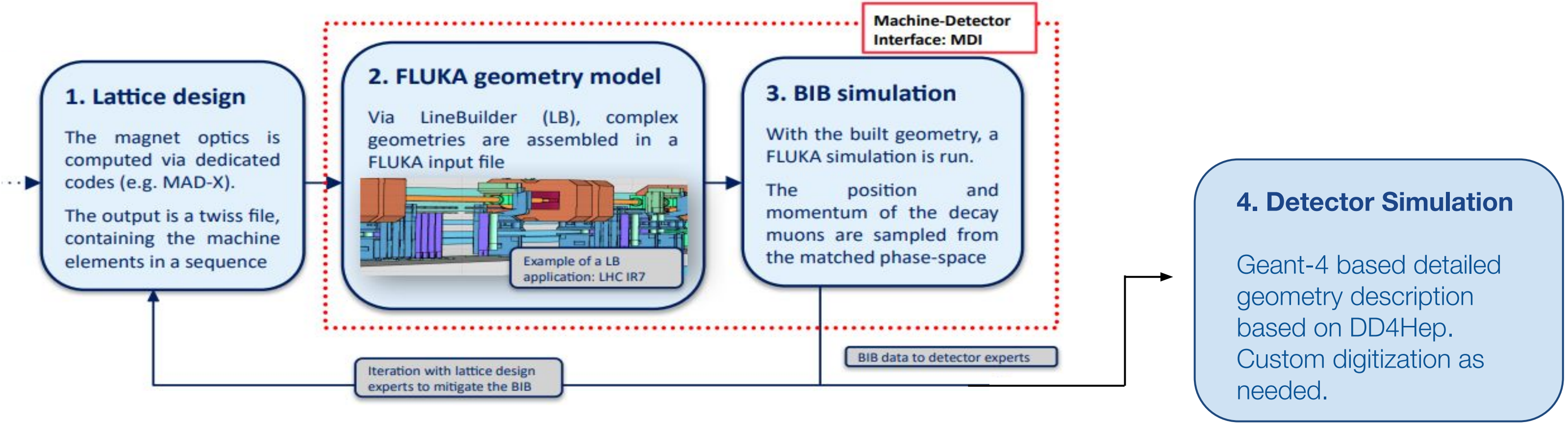



**Decays inside nozzle (between IP and L*) contribute very little to the background**
But: increasing L* from 6 m to 10 m yields only small improvement – O(few 10%) – at the expense of a more complex lattice design

**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



# Requirements / Specifications

| Requirement | Baseline | | Aspirational |
|---|---|---|---|
| | $\sqrt{s} = 3$ **TeV** | $\sqrt{s} = 10$ **TeV** | |
| Angular acceptance | $\|\eta\| < 2.5$ | $\|\eta\| < 2.5$ | $\|\eta\| < 4$ |
| Minimum tracking distance [cm] | $\sim 3$ | $\sim 3$ | $< 3$ |
| Forward muons ($\eta > 5$) | – | tag | $\sigma_p/p \sim 10\%$ |
| Track $\sigma_{p_T}/p_T^2$ [GeV$^{-1}$] | $4 \times 10^{-5}$ | $4 \times 10^{-5}$ | $1 \times 10^{-5}$ |
| Photon energy resolution | $0.2/\sqrt{E}$ | $0.2/\sqrt{E}$ | $0.1/\sqrt{E}$ |
| Neutral hadron energy resolution | $0.5/\sqrt{E}$ | $0.4/\sqrt{E}$ | $0.2/\sqrt{E}$ |
| Timing resolution (tracker) [ps] | $\sim 30 - 60$ | $\sim 30 - 60$ | $\sim 10 - 30$ |
| Timing resolution (calorimeters) [ps] | 100 | 100 | 10 |
| Timing resolution (muon system) [ps] | $\sim 50$ for $\|\eta\| > 2.5$ | $\sim 50$ for $\|\eta\| > 2.5$ | $< 50$ for $\|\eta\| > 2.5$ |
| Flavour tagging | $b$ vs $c$ | $b$ vs $c$ | $b$ vs $c$, $s$-tagging |
| Boosted hadronic resonance ID | $h$ vs $W/Z$ | $h$ vs $W/Z$ | $W$ vs $Z$ |

Baseline: mostly based on current design/ideas and physics benchmark studies
Aspirational: motivated by significantly better physics results achievable
Requirements guide the technology we develop, not all are the same

- strict: when they're absolutely necessary or physics would suffer too much
- soft: when meeting or exceeding them has impact on the accuracy achievable but is far from a black&white picture

# 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

- small collaborations to tackles problems
- horizontal coordination across R&D groups and performance
- a small contribution can go a long way!

more on Nadia's talk!

# … 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?

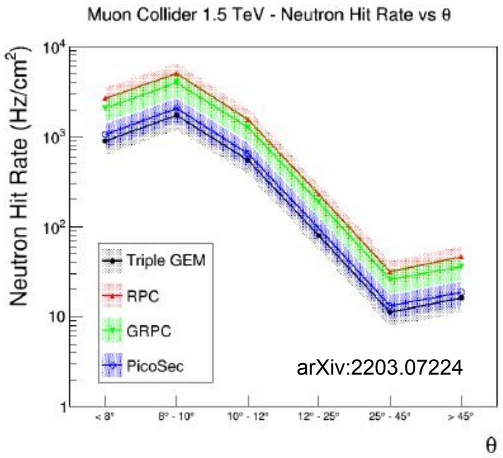
Luminosity monitoring

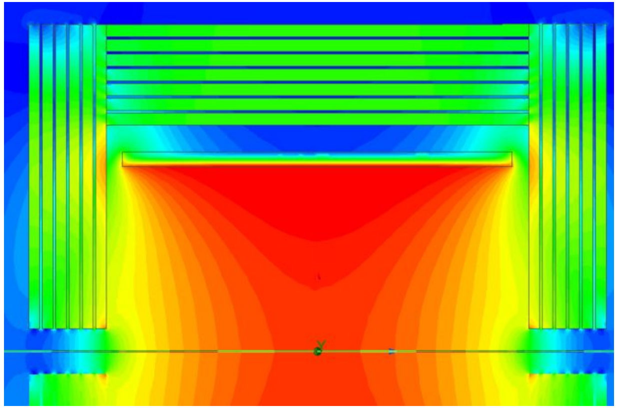
- online and offline measurements

Towards a more realistic solenoid description

Quantum detectors?! Neutrinos “detector”?

Add your own idea here…

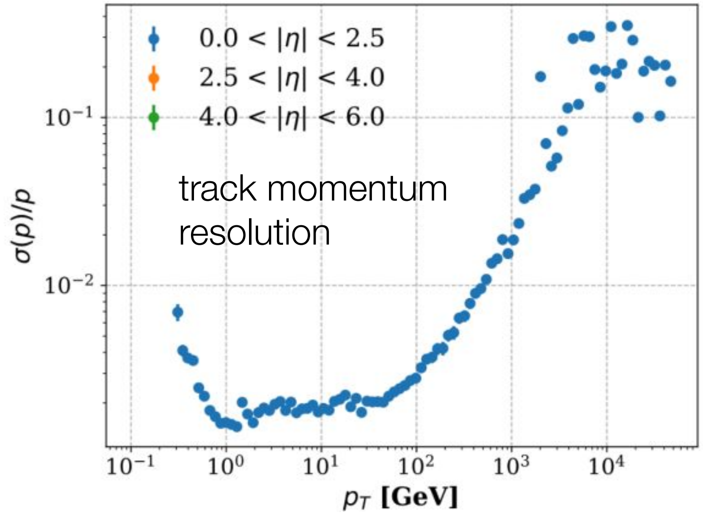


# Full vs Fast simulation

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