BIB simulation: workflow and bottlenecks

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Decaying **muons**

What is a muon to do? μ

1 ***Survive*** *→ hard scatter → physics!*

2 ***Decay*** μ → e ν ν along lattice, launching **TeV-scale electrons** into infrastructure → **beam-induced background (BIB)**

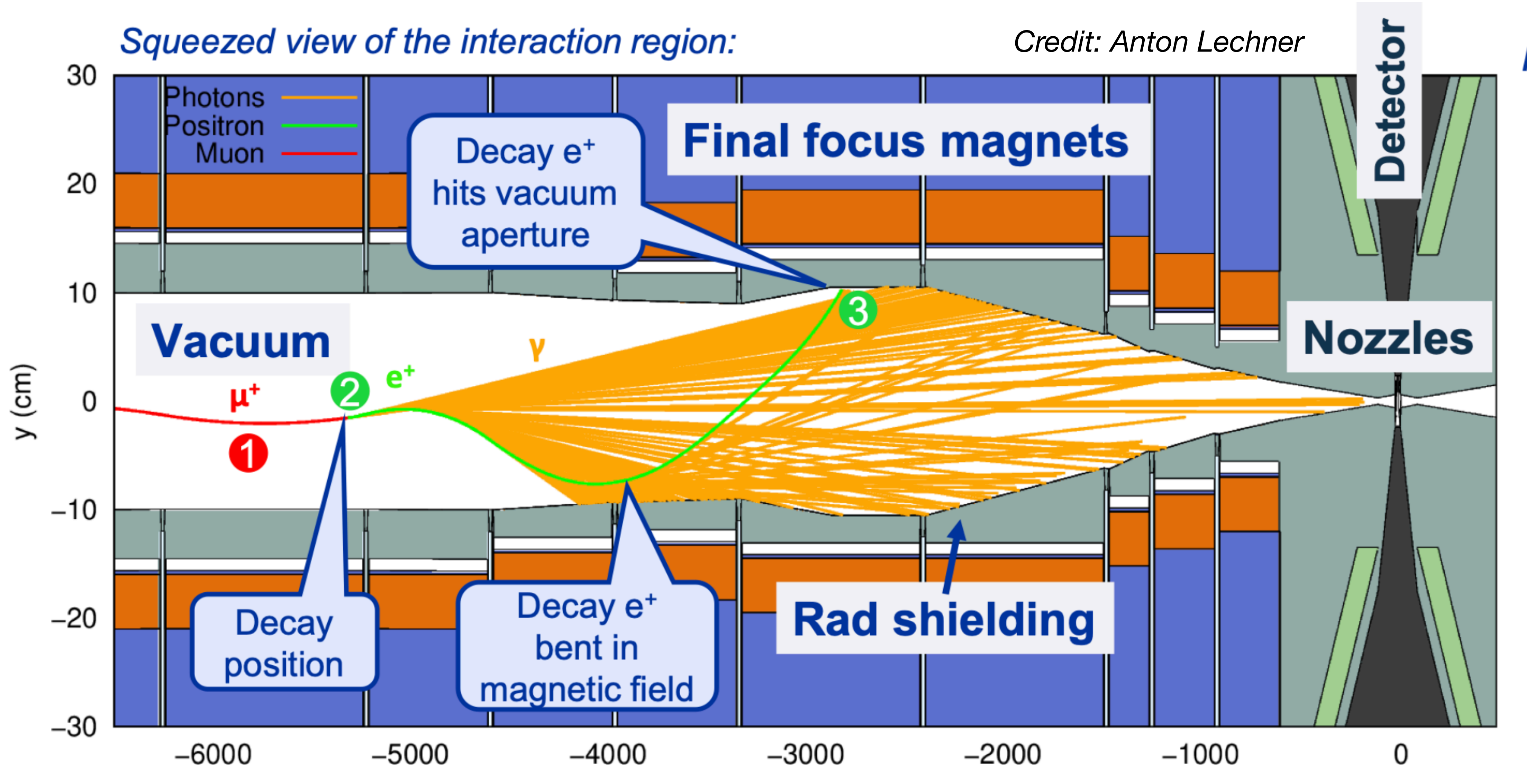
- Electrons radiate bremsstrahlung + synchrotron **photons**
- Photonuclear cascades → **neutrons** + light **hadrons**
- Bethe-Heitler process → secondary **muons**
- (Incoherent **electron** pair production)

What enters the detector volume?

- 10^8 photons, 10^7 neutrons, and 10^6 electrons/positrons*
- These particles are largely out of time, forward, and don't originate at the interaction point

Can't reject them if we don't know how they behave
→ need full-scale, faithful BIB simulation

Squeezed view of the interaction region: *Credit: Anton Lechner*

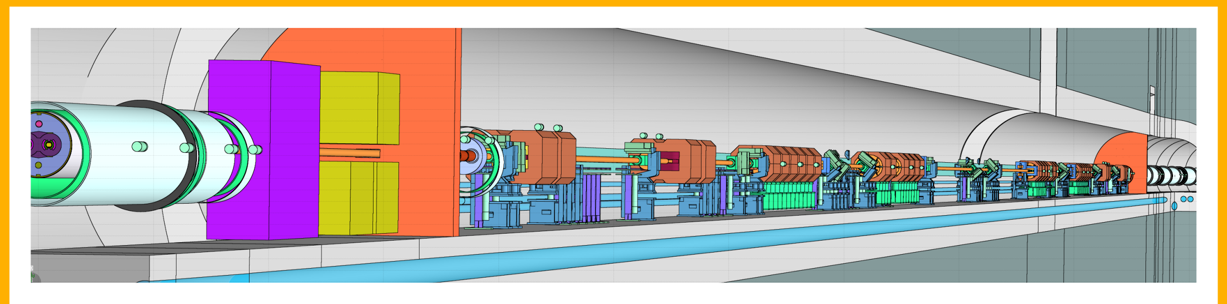


Neutrinos are not shown *Real event from a Monte Carlo simulation*

** > 100 keV for γ, e±; ≥ thermal for n*

The BIB simulation pipeline

Stage I: LineBuilder + FLUKA



Stage II: Geant4

0. MAD-X

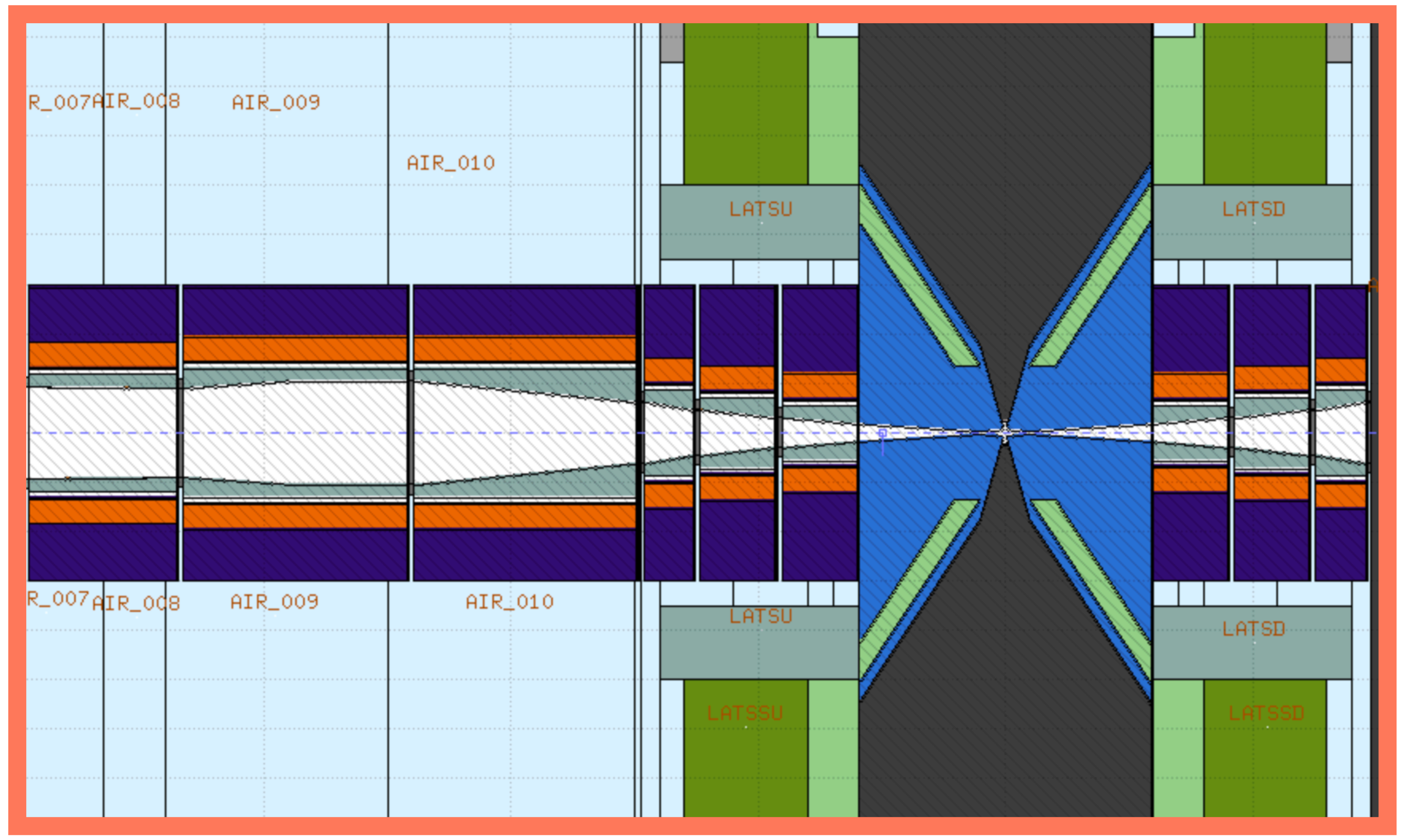
- MAD-X used to design the magnet lattice → generates a twiss file describing length, field strength, aperture
- Beam optics only, no particle tracking

1. LineBuilder

- Takes twiss file and constructs 3D geometry in FLUKA input format
- Draws all magnets, vacuum pipes, shielding elements, etc

2. FLUKA

- Samples muon decay from matched beam phase space
- Propagates decay e± through all beamline magnets (tracks bending, synchrotron radiation emission, etc)
- Handles full EM and hadronic cascade for secondaries: bremsstrahlung, photonuclear reactions, pair production, neutron transport to thermal energies
- Biasing used to enhance muon decay probability
- Writes flat list of table particles (γ, n, e±, μ) at detector boundary



Partial FLUKA/Flair display of v0.8 lattice

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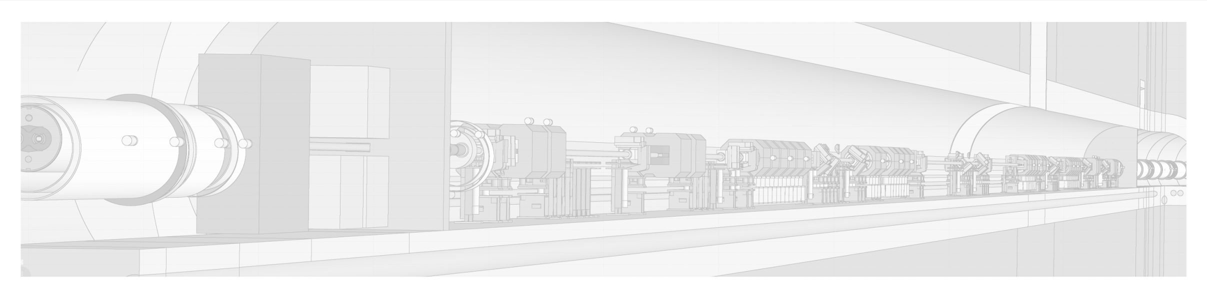

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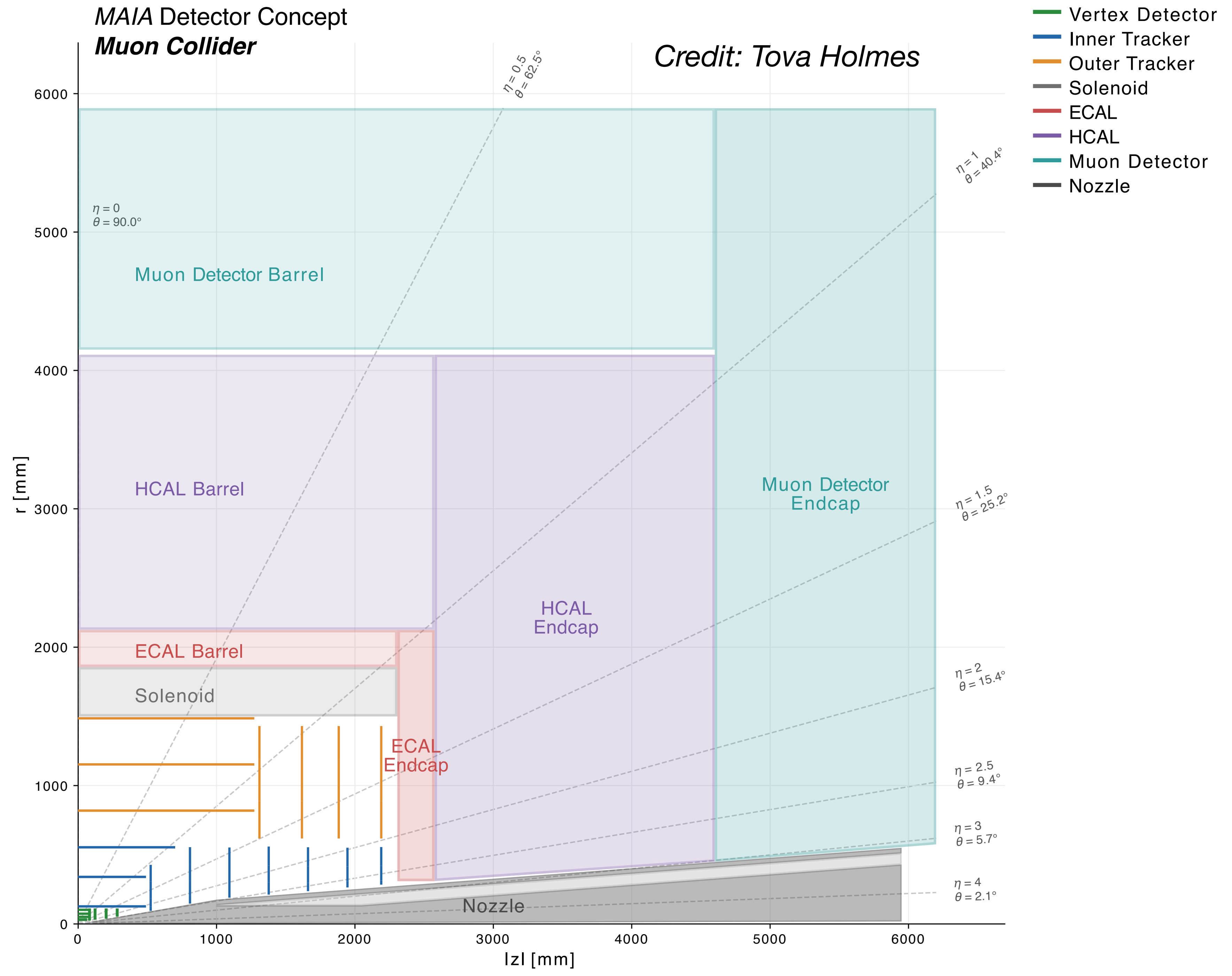


3. Geant4

- Detector geometry (e.g. MAIA) implemented via DD4hep, interfaced to Geant4
- BIB particle list propagated through Geant4 → energy deposits in detector material (simhits)
- Signal events simulated independently through the same detector geometry → simhits merged with BIB at overlay stage

The *ideal* BIB simulation

(Scenario 1: *We Are Timeless Gods with Unlimited Resources*)

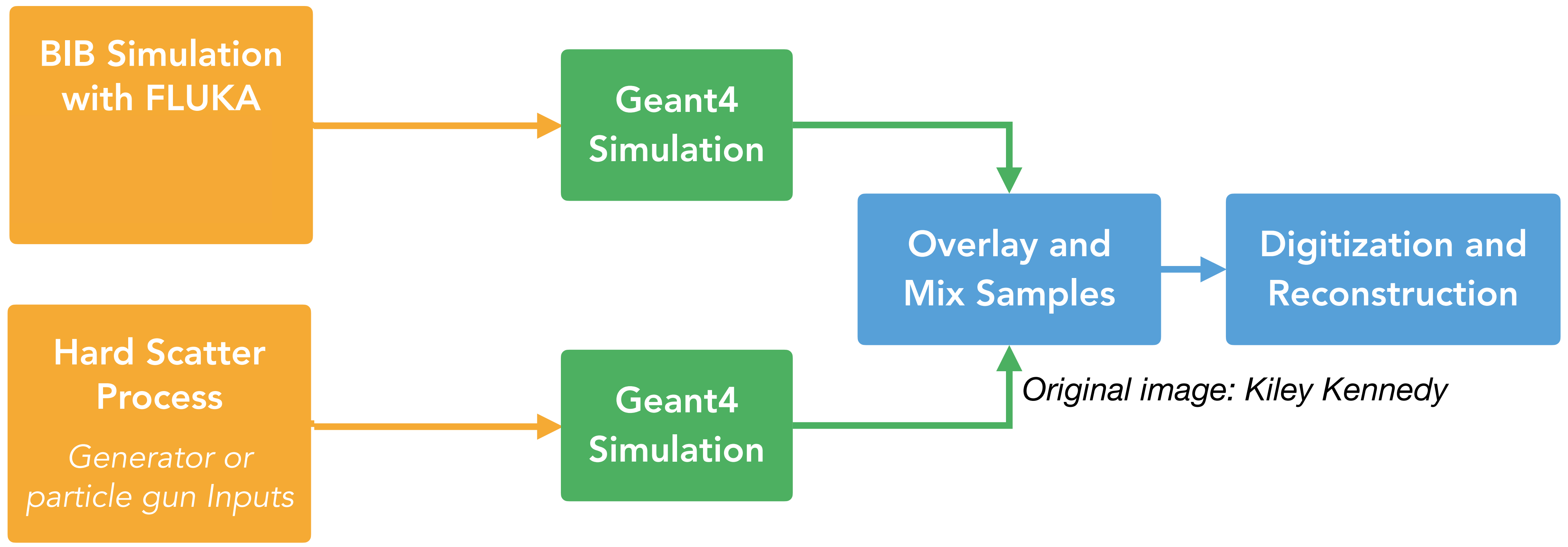
What do we want?

- One fresh, independent FLUKA draw per each bunch crossing
- Full particle correlations, azimuthal asymmetries, and multiplicity fluctuations preserved by construction
- Pipeline always reflects current lattice and nozzle geometry

What would it take?

- Propagating $O(10^8)$ γ, $O(10^7)$ n, $O(10^6)$ $e^\pm$ through ~200m of beamline geometry per event
- Several weeks of CPU time and ~50 GB of disk usage per bunch crossing

> "*Tracing of all the background particles entering the detector region in a single bunch crossing is out of reach for any realistic computing facility….*"



Original image: Kiley Kennedy

Computing and Software for Big Science (2021) 5:21
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ORIGINAL ARTICLE

Full Detector Simulation with Unprecedented Background Occupancy at a Muon Collider

Nazar Bartosik[2] · Paolo Andreetto[1] · Laura Buonincontri[3] · Massimo Casarsa[4] · Alessio Gianelle[1] · Simone Pagan Griso[5] · Sergo Jindariani[6] · Donatella Lucchesi[3] · Federico Meloni[7] · Nadia Pastrone[2] · Lorenzo Sestini[1]

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Abstract
In recent years, a Muon collider has attracted a lot of interest in the high-energy physics community, thanks to its ability of achieving clean interaction signatures at multi-TeV collision energies in the most cost-effective way. Estimation of the physics potential of such an experiment must take into account the impact of beam-induced background on the detector performance, which has to be carefully evaluated using full detector simulation. Tracing of all the background particles entering the detector region in a single bunch crossing is out of reach for any realistic computing facility due to the unprecedented number of such particles. To make it feasible a number of optimisations have been applied to the detector simulation workflow. This contribution presents an overview of the main characteristics of the beam-induced background at a Muon collider, the detector technologies considered for the experiment and how they are taken into account to strongly reduce the number of irrelevant computations performed during the detector simulation. Special attention is dedicated to the optimisation of track reconstruction with the conformal tracking algorithm in this high-occupancy environment, which is the most computationally demanding part of event reconstruction.

Keywords Muon collider · High energy physics · Detector simulation · Scientific computing · Event reconstruction

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What do we do instead?

> *“Tracing of all the background particles entering the detector region in a single bunch crossing is out of reach for any realistic computing facility….”*


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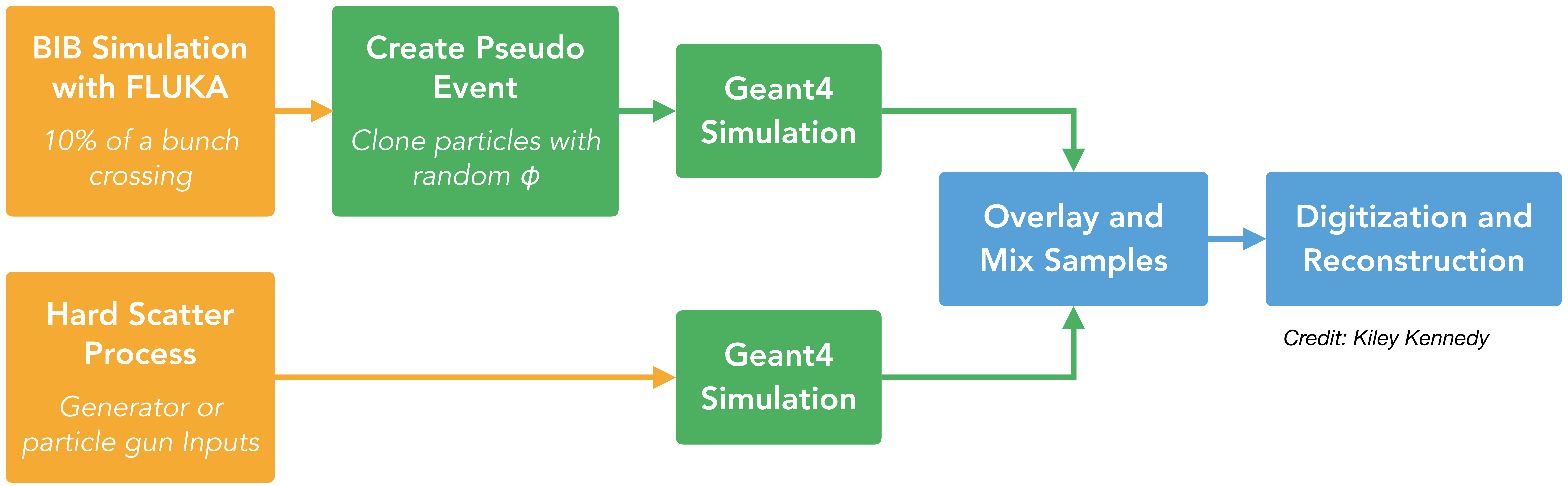
The current realistic alternative

(Scenario 2: *We Are Mortal Physicists with Deadlines*)

USMCC

What do we actually do?

- A single FLUKA sample of 6.7k files (~400k unique parent muons) covers ~10% of a single bunch crossing, shared across all users
- To build full events, particles are grouped into batches by parent muon, replicated 42× with randomized ϕ (azimuthal) rotations, then random combinations of batches are overlaid per physics event
- Result: A dataset equivalent to ~4 bunch crossings, with each parent appearing ~10× in a typical overlaid event



Credit: Kiley Kennedy

The approximation holds… sort of

- Events are statistically independent to reasonable approximation
- But azimuthal symmetry is imposed by construction → nonphysical
- Rare processes with too few parent muons can't simply be recovered by cloning…

Bottlenecks: statistics, rarity, and iteration

Statistical structure problems

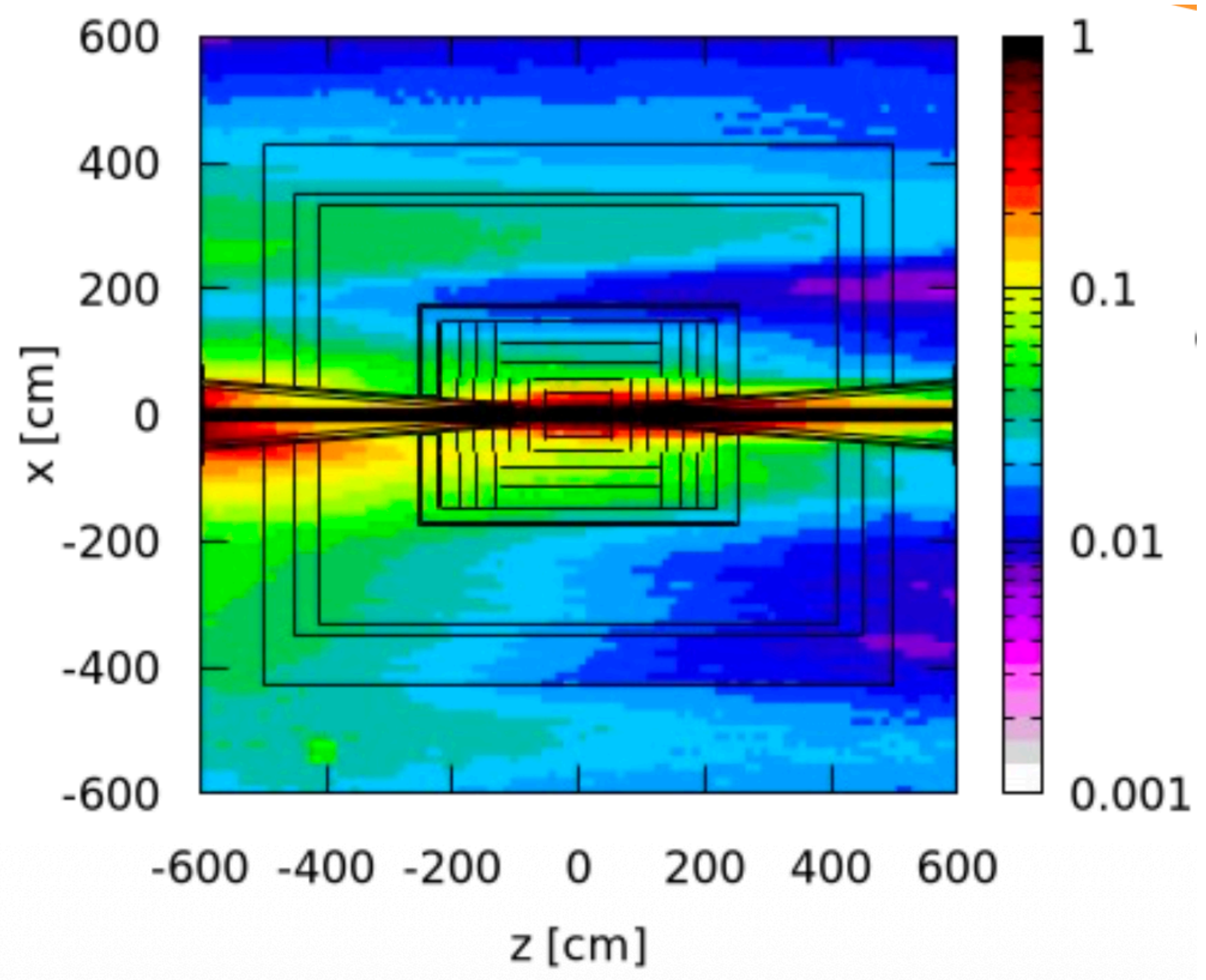
- Cloning scheme breaks correlations
  - Particles from a single parent are rotated by a random ϕ to manufacture stats, but real BIB has azimuthal asymmetries
- A finite, reused sample means structural artifacts propagate into every overlaid event
  - Physical → decay hotspots near lattice elements (e.g. chicane dipoles)
  - Nonphysical → sampling density bugs

Rare events: Bethe-Heitler muons

- BH muons come from high-energy photons in EM cascades from high-energy electron decays → tails of tails of tails
- Considerably understudied: impact in sensitive regions not fully characterized
- Fluence is highly asymmetric and only resolves at high stats, but cloning can't manufacture rare process stats that aren't there in the sample to begin with
- Need a smarter way to get dedicated, targeted samples

Lattice/MDI coupling

- Every modification to machine-detector interface and lattice renders sample obsolete
- Would require weeks of compute to rerun and re-derive all of the above!



X-Z fluence map from BH muons in MUSIC detector volume. Credit: Daniele Calzolari

Lots of room for improvement!

Summary: where are we now?

- BIB simulation is an **essential**, **irreducible** problem: we can't remove what we can't characterize, but full-scale simulation is **computationally out of reach**
- We achieve a **reasonable compromise** in the current FLUKA + cloning pipeline, but it imposes **nonphysical structure** and can't produce the needed stats for **rare**, **impactful processes** (e.g. BH muons)
- Every lattice/MDI change **resets the process** → weeks of compute time needed to update to a usable BIB sample
- More clever approaches to **slicing** + **AI-based improvements** could help build a more reliable, complete, and computationally tractable picture of BIB for future detector studies

Thank you for your attention!