# MUON COLLIDERS: THE PATH TO 10 TEV

## DETECTOR AND MACHINE-DETECTOR INTERFACE CHALLENGES

TOVA HOLMES, U. OF TENNESSEE
15 MAY 2024
DPF-PHENO 2024

RESEARCH CORPORATION for SCIENCE ADVANCEMENT
U.S. DEPARTMENT OF ENERGY | Office of Science

# The driving detector challenge at a muon collider

# The driving detector challenge at a muon collider

how big is this problem?

# How much BIB? – from first principles

muons have a lifetime of 2.2 μs
(but time dilation can help)

$$\tau'_\mu = 21 \text{ ms} \times \left( \frac{E}{1 \text{ TeV}} \right)$$

# How much BIB? – from first principles

muons have a lifetime of 2.2 μs
(but time dilation can help)

$$\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$$

what fraction decay within 20m
of an interaction point per pass?

$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

# How much BIB? – from first principles

muons have a lifetime of 2.2 μs
(but time dilation can help)

$$\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$$

what fraction decay within 20m
of an interaction point per pass?

$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

how much energy do those decay
products have?

$$E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$$

# How much BIB? – from first principles

muons have a lifetime of 2.2 μs
(but time dilation can help)

$$\tau'_\mu = 21\ \text{ms} \times \left( \frac{E}{1\ \text{TeV}} \right)$$

what fraction decay within 20m
of an interaction point per pass?

$$f \approx 6.4 \times 10^{-6} \times \left( \frac{1\ \text{TeV}}{E} \right)$$

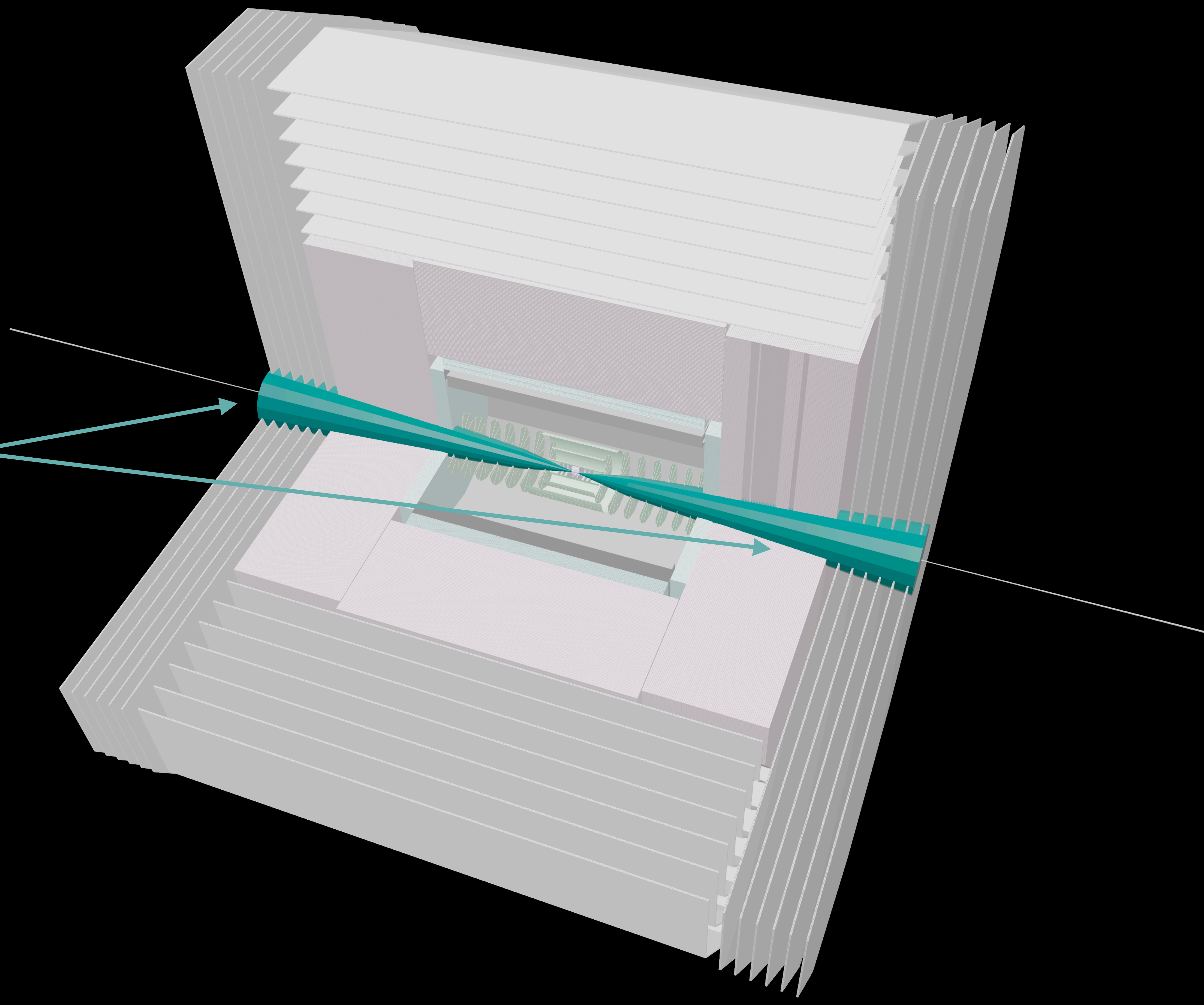
how much energy do those decay
products have?

$$E_{\text{decay}} = 13\ \text{EeV} \times \left( \frac{n_\mu/\text{bunch}}{2 \times 10^{12}} \right)$$

huge backgrounds, huge radiation, huge mess

# How can we deal with this?

need to block BIB from reaching the detector
without interfering with signal

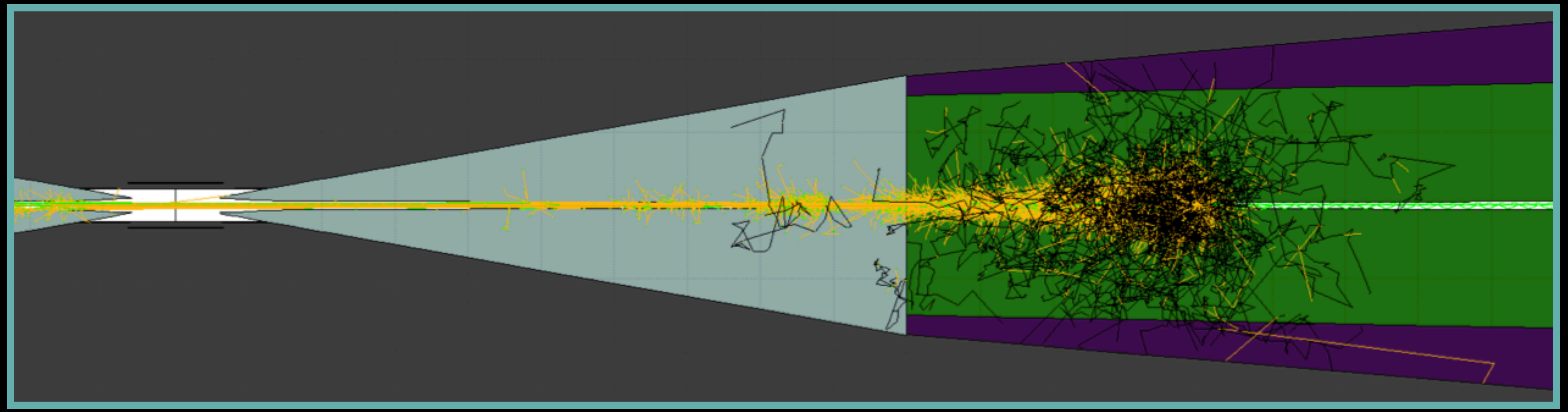


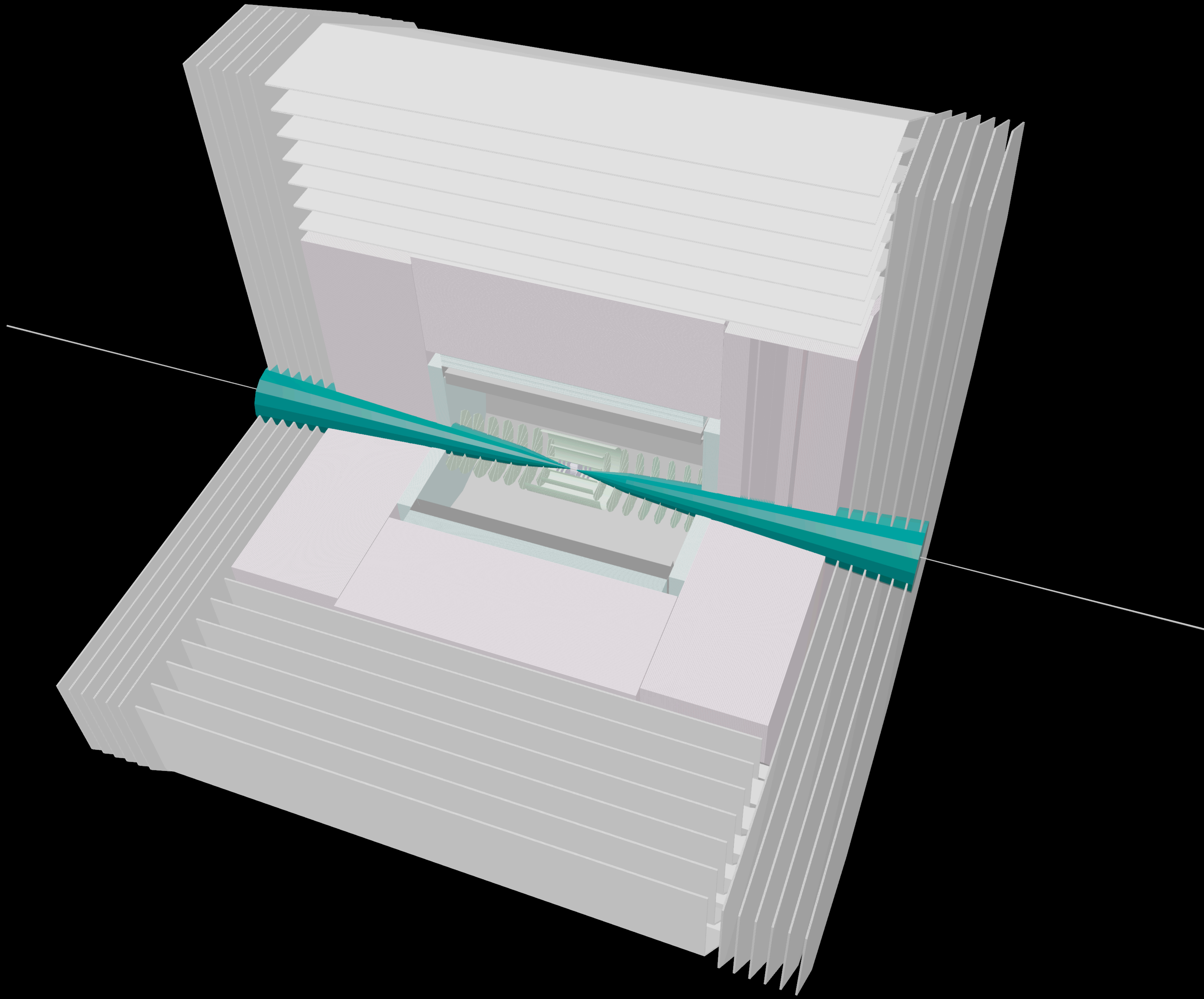
introduce tungsten nozzles
around the beam pipe

# How can we deal with this?

need to block BIB from reaching the detector
without interfering with signal

incoming particles shower in the nozzle;
most energy contained

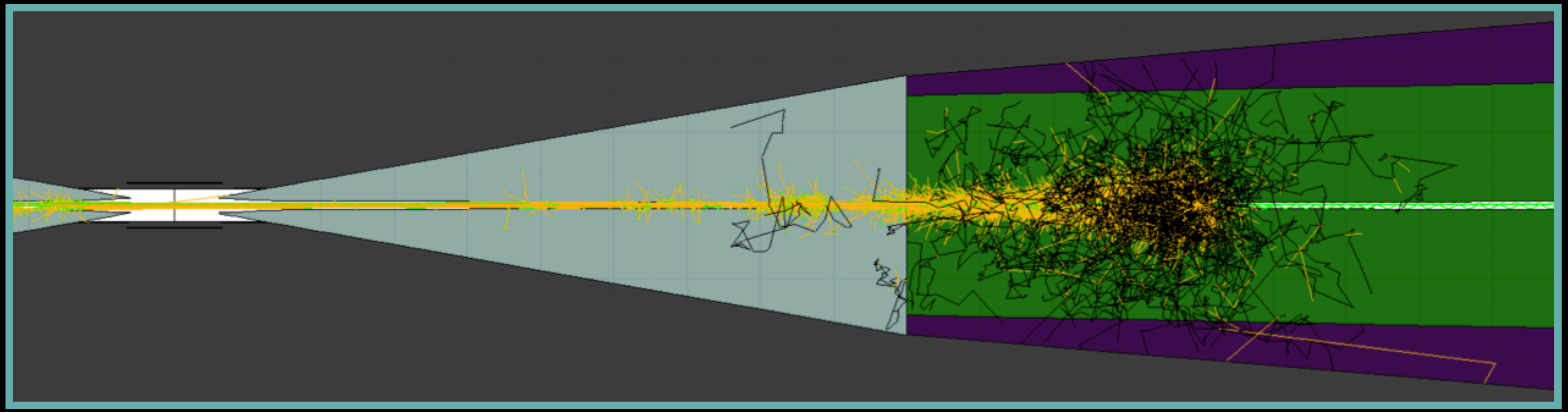




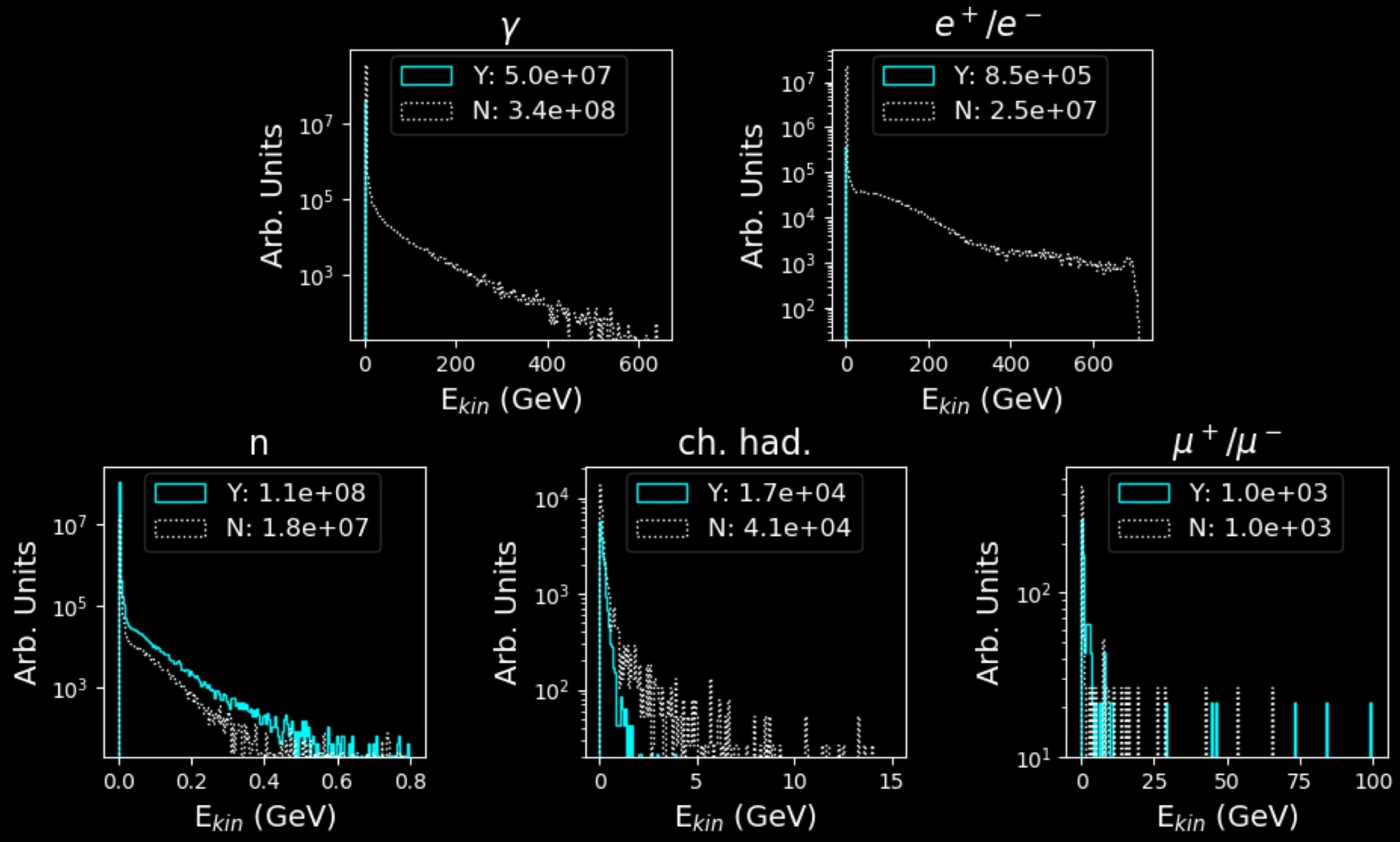
# How can we deal with this?

need to block BIB from reaching the detector
without interfering with signal

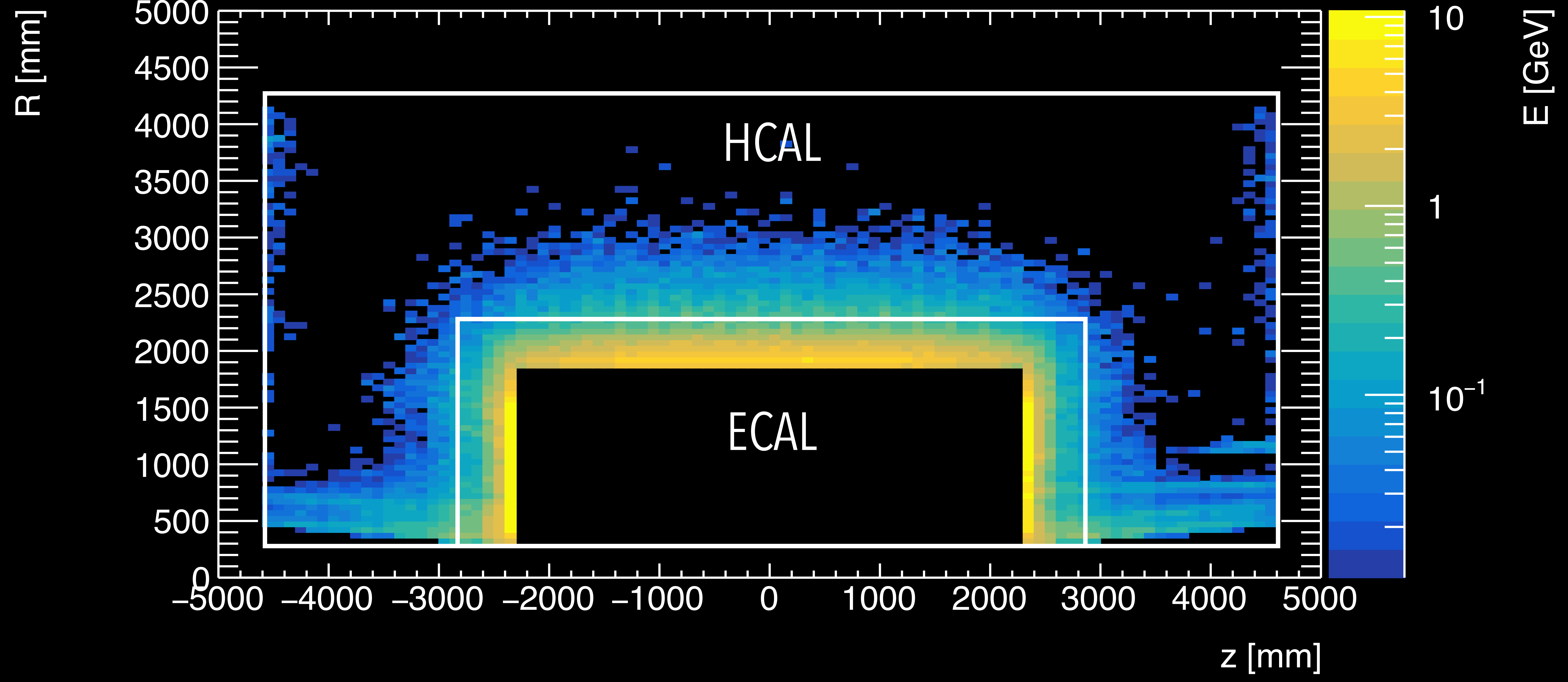
incoming particles shower in the nozzle;
most energy contained



what's left over?



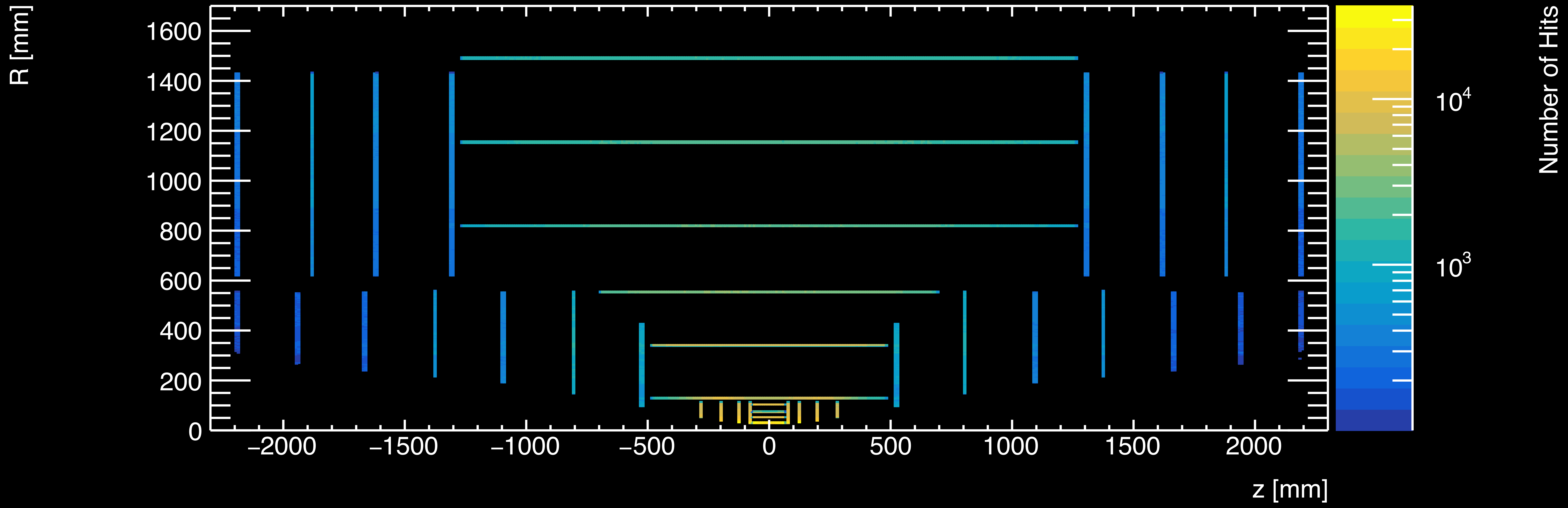
# What's left over?




works very well for the calorimetry - decreases and smears out energy

total energy deposited in the calorimeter: ~1.5 TeV

# What's left over?

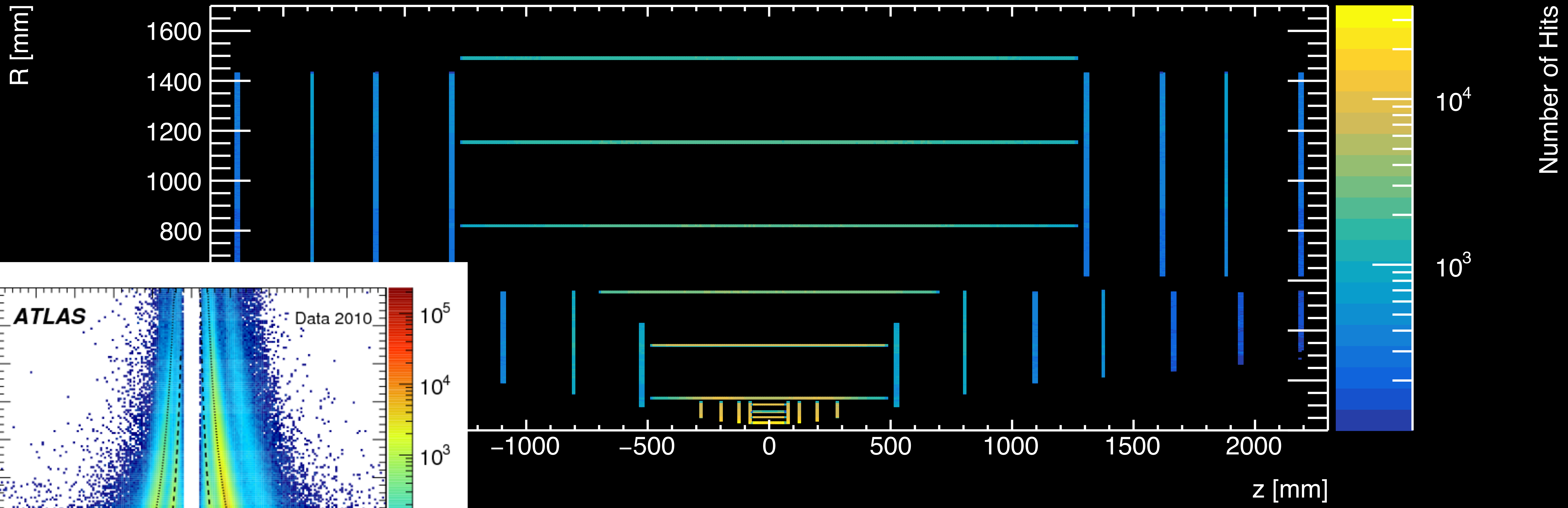


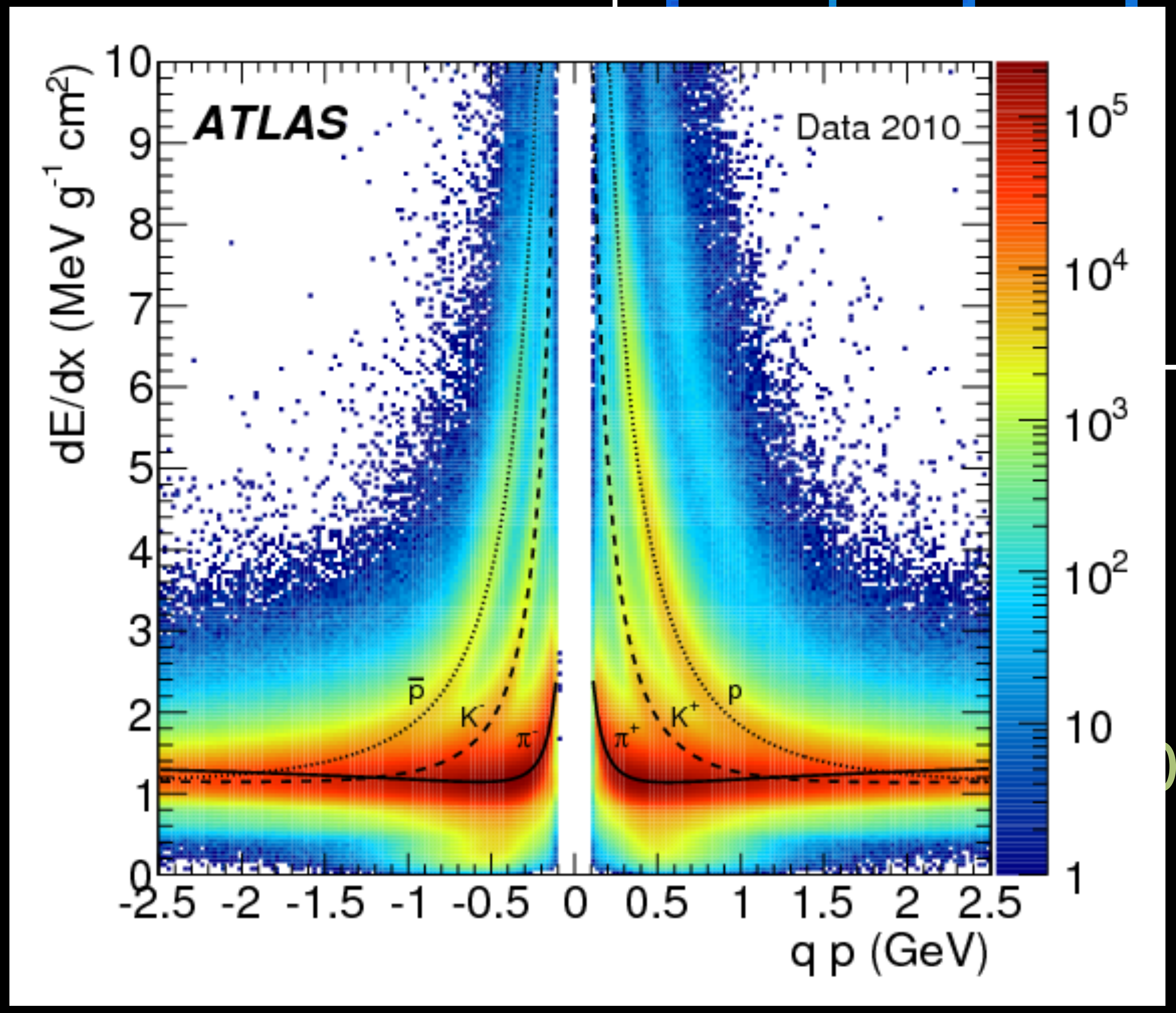

much more challenging in the tracker:

many low energy particles much more challenging than

a few higher energy ones

# What's left over?



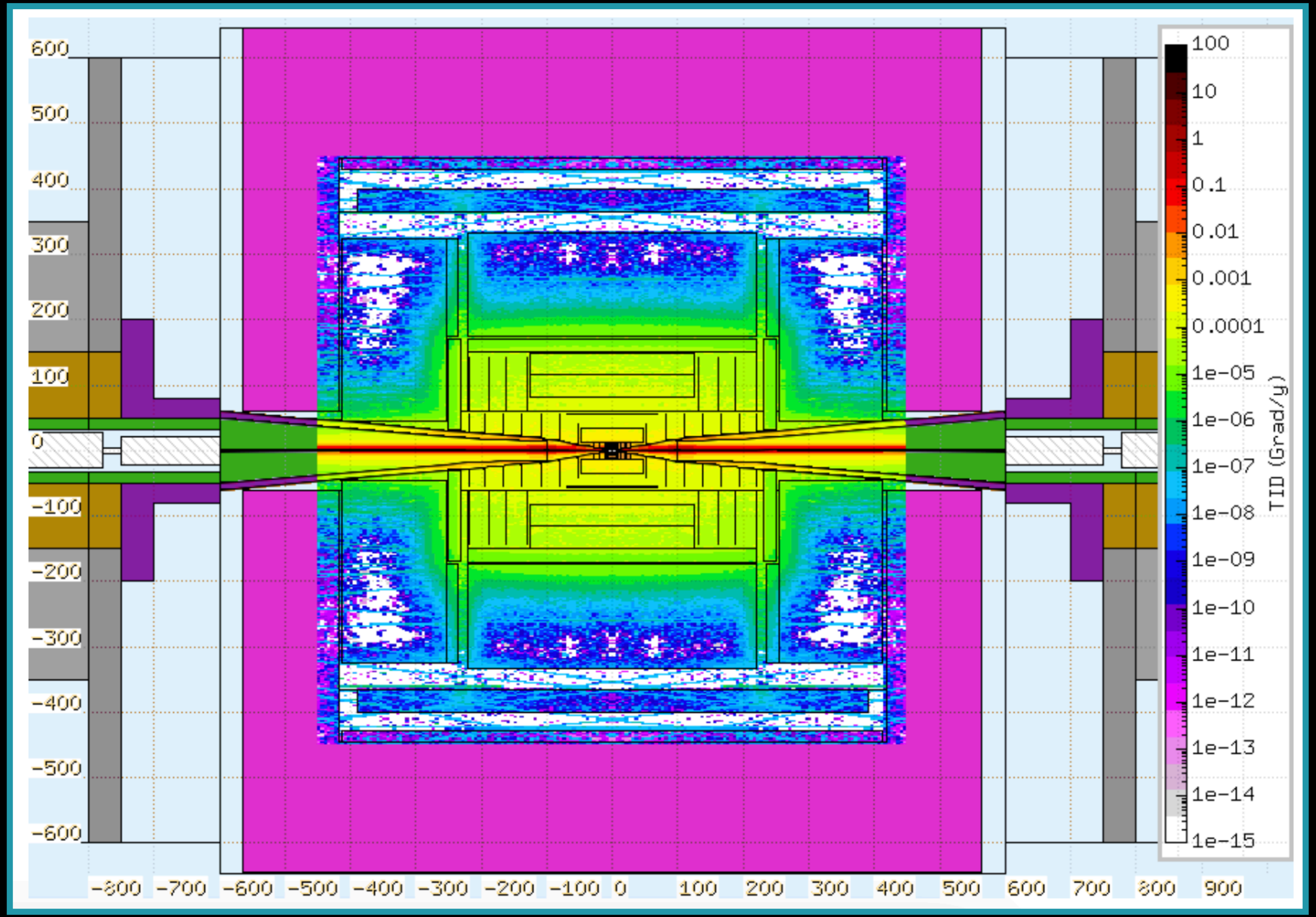




much more challenging in the tracker:

ow energy particles much more challenging than

a few higher energy ones

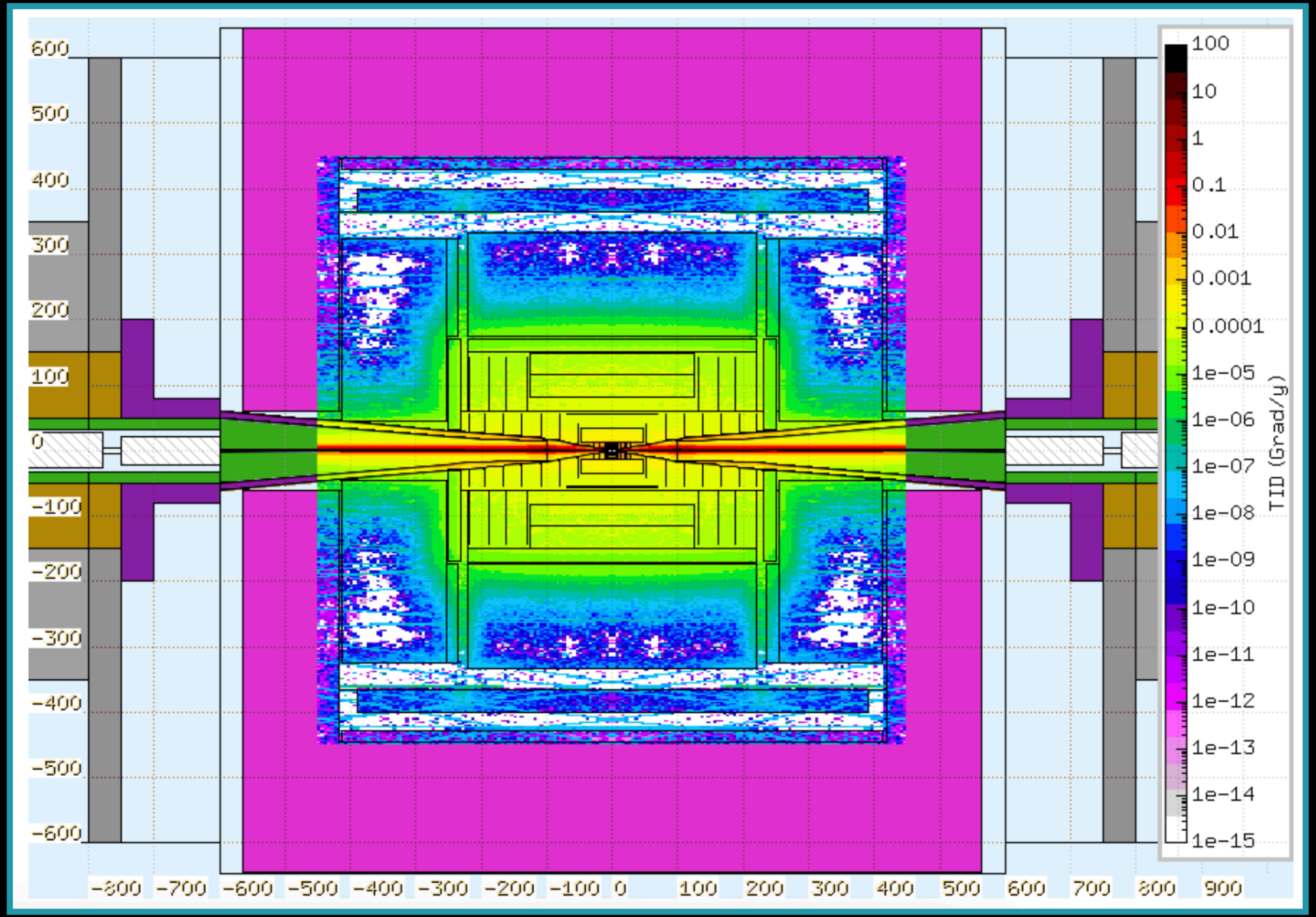
# What's left over?




despite large amount of BIB,
fluence/doses are comparable to the HL-LHC

| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

# What's left over?




| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

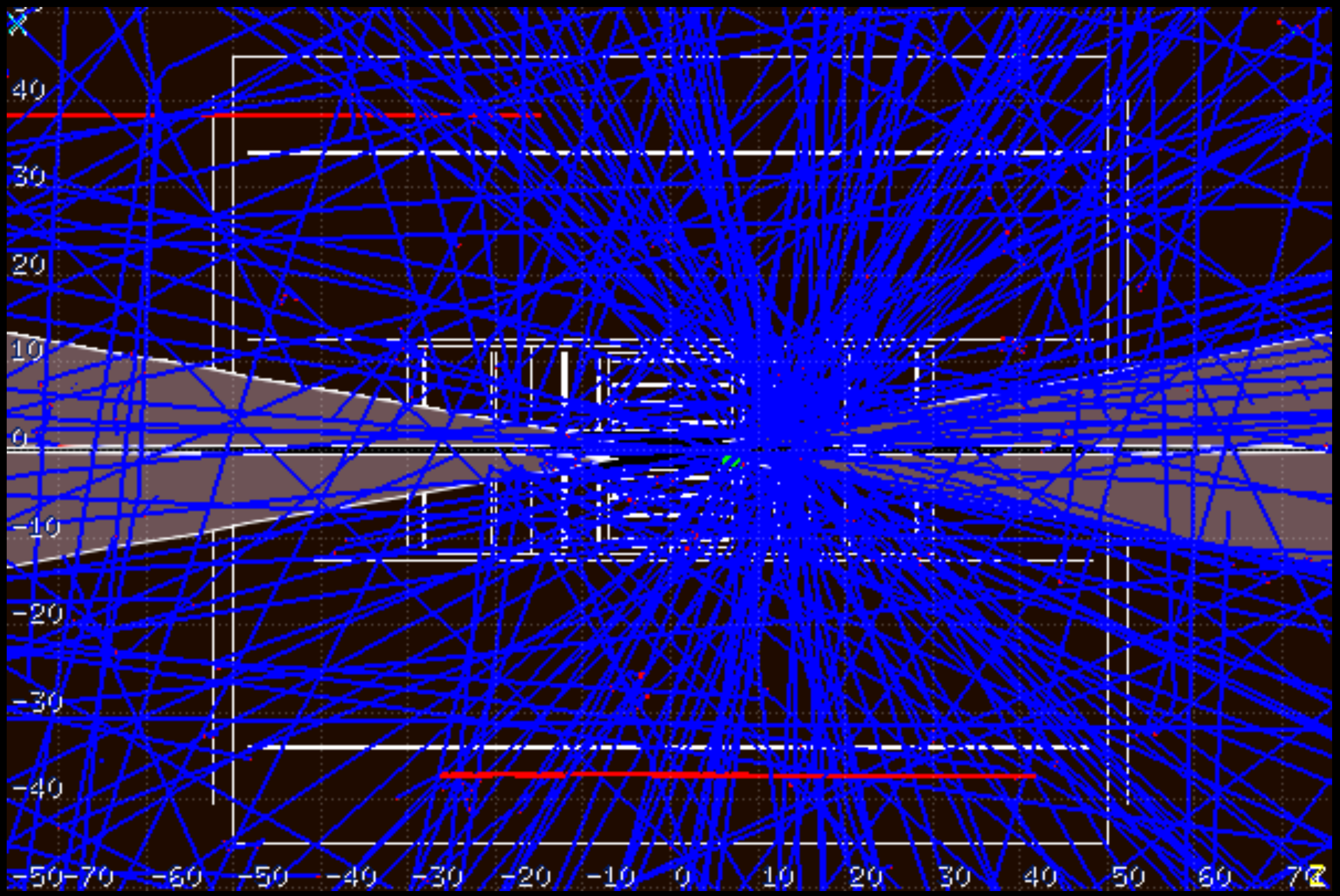
despite large amount of BIB,
fluence/doses are comparable to the HL-LHC

this is because muon collider circulate only two bunches, so collisions are far less frequent

$$t = 33\ \mu s \times \left(\frac{L}{10\ \mathrm{km}}\right)$$

# What's left over?

another plus: BIB looks nothing like signal



photons, electrons, neutrons

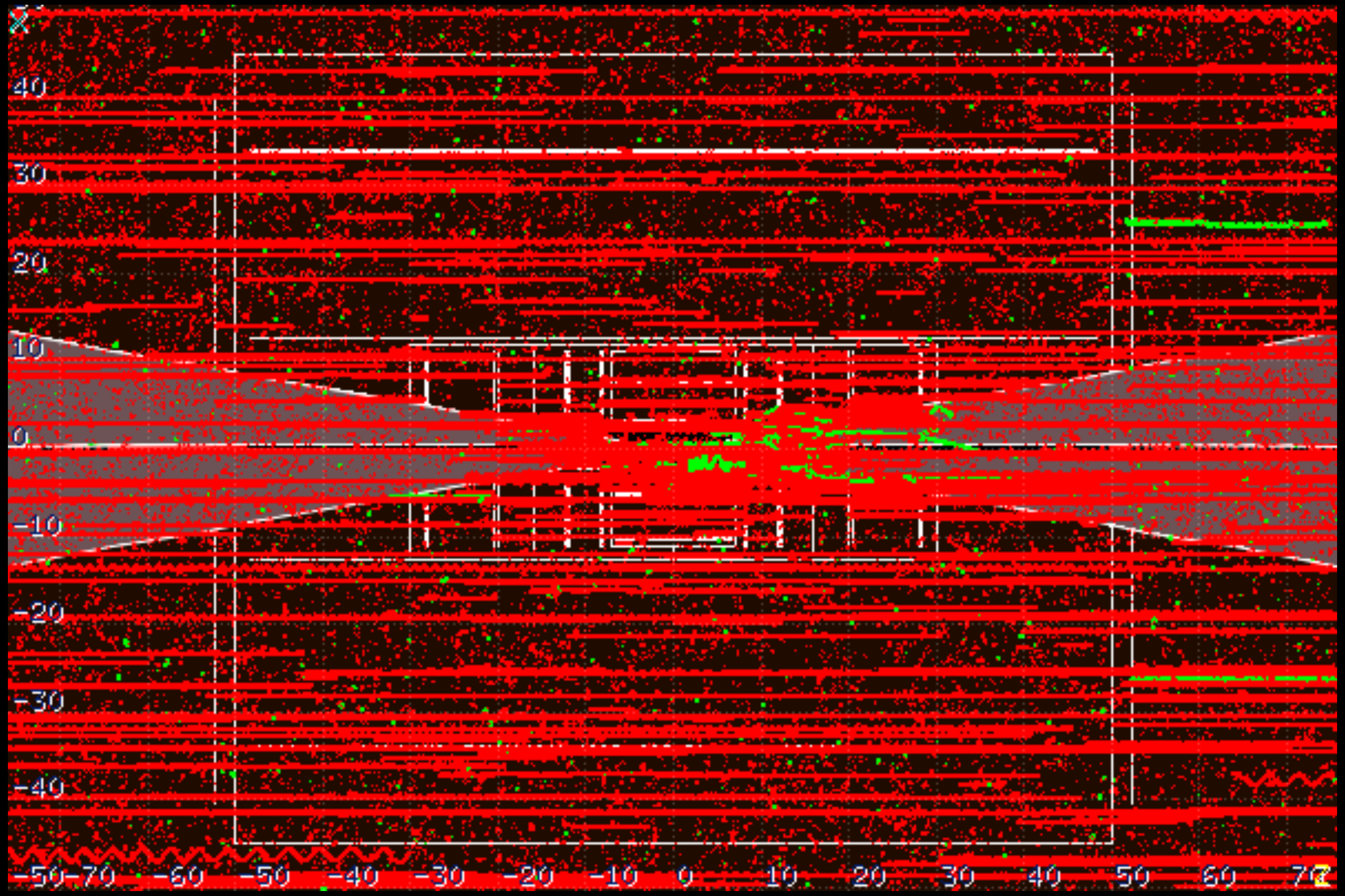
(0.003% of a BIB event)

BIB properties:
arrives largely out-of-time
extremely low energy
emerges from nozzles

once reconstruction has been performed,
easy to differentiate from signal

# What's left over?

another plus: BIB looks nothing like signal




(removing photons), electrons, neutrons

(0.03% of a BIB event)

BIB properties:

arrives largely out-of-time

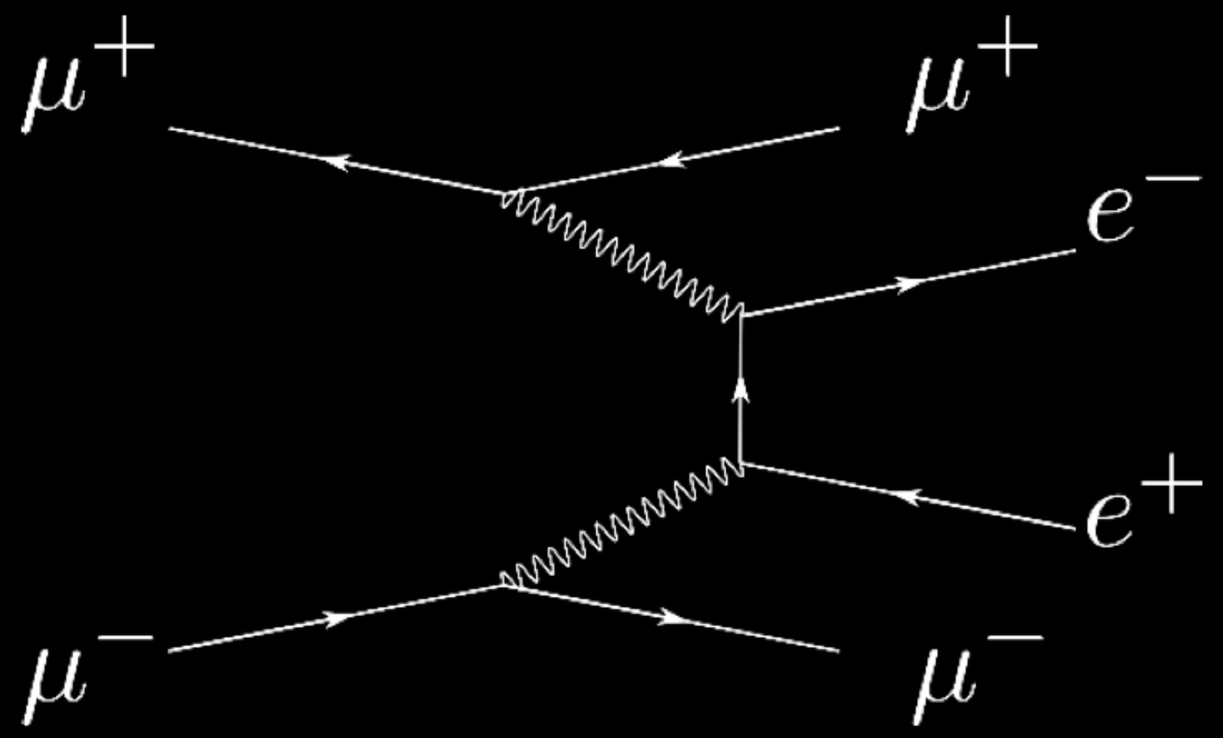
extremely low energy

emerges from nozzles

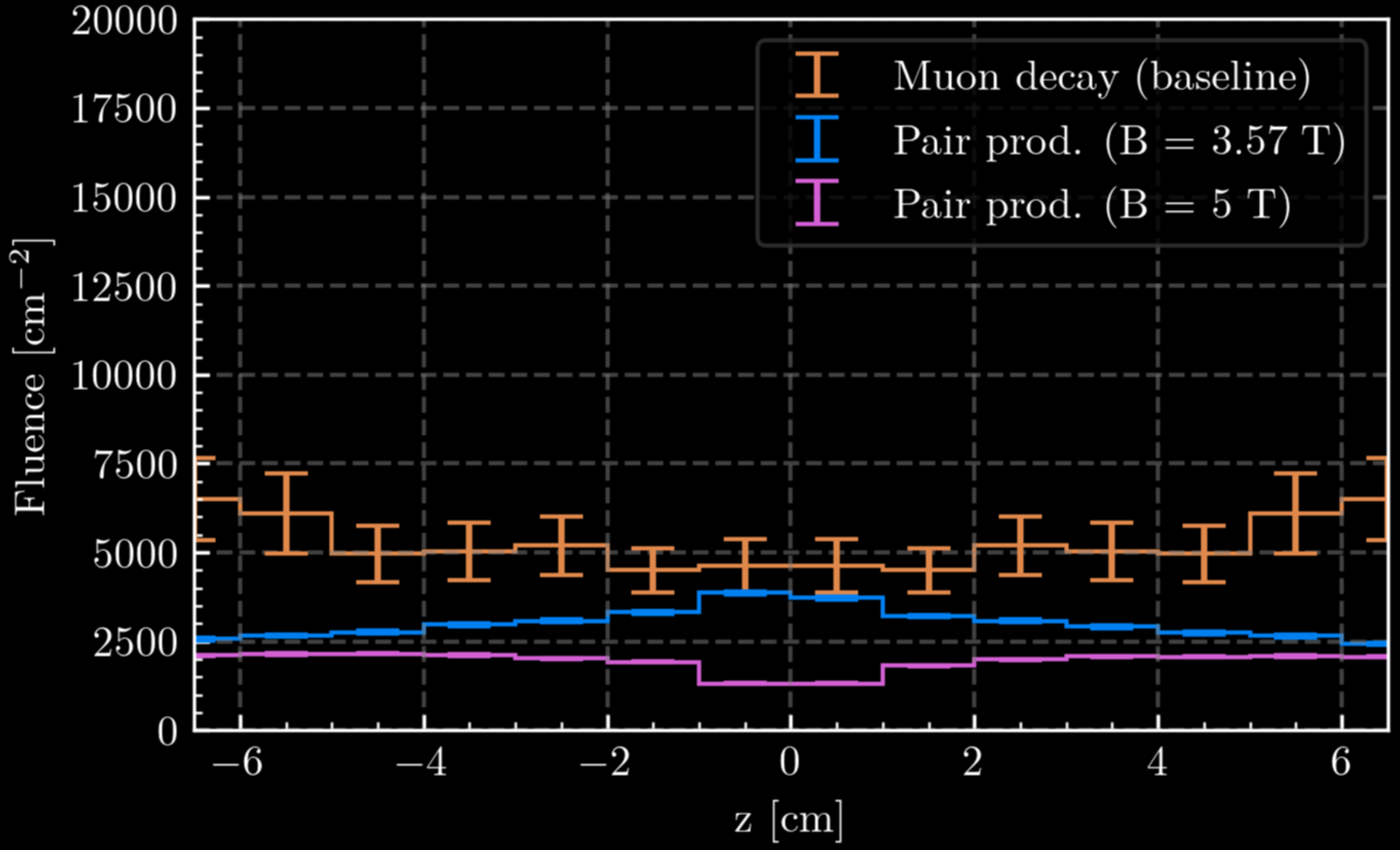
once reconstruction has been performed, easy to differentiate from signal

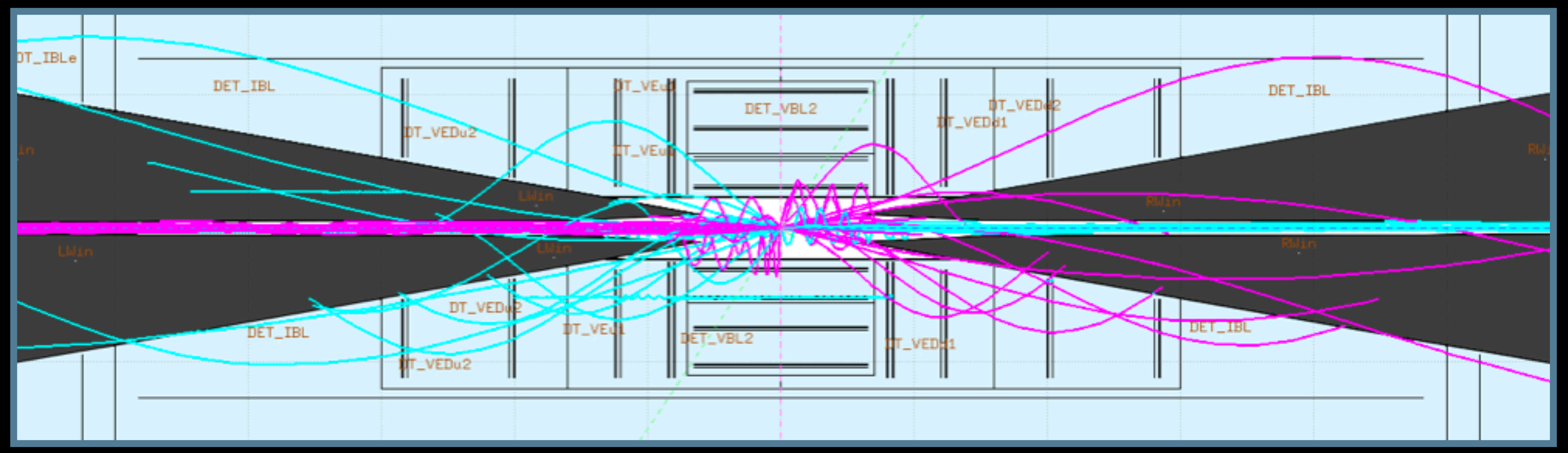
# Another key background

incoherent e+e- scattering




fluence in first pixel layer



these particles are low energy and come from the IP

a strong magnetic field can prevent many from interacting with the detector

# Can we do better?

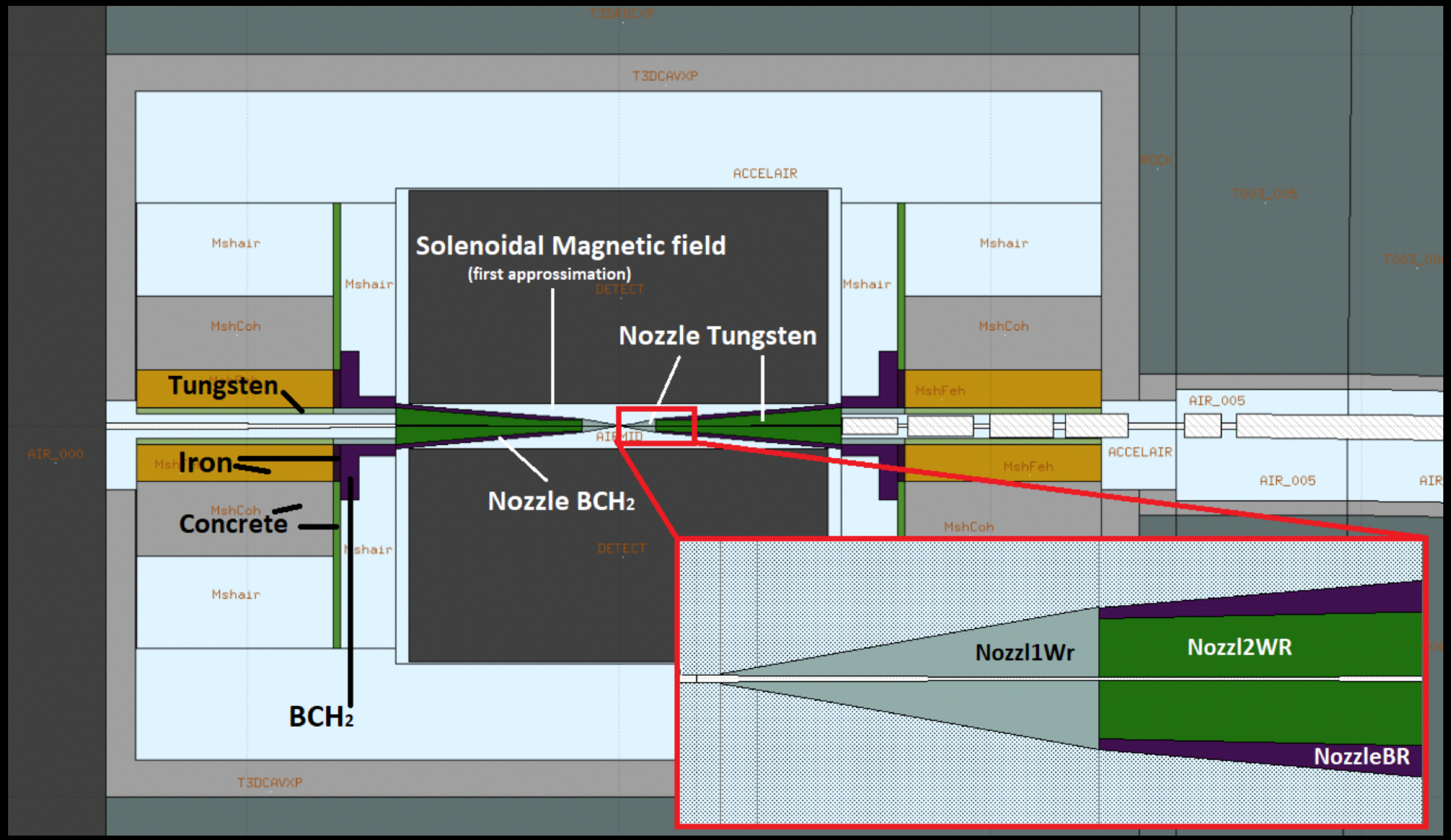
original detector design taken from CLIC (optimized for 3 TeV)

the MAP program optimized nozzles using MARS BIB simulation (at 1.5 TeV)

many efforts to optimize design in recent years, including focus on 10 TeV

tungsten: showers charged particles

borated polyethylene: moderates neutrals



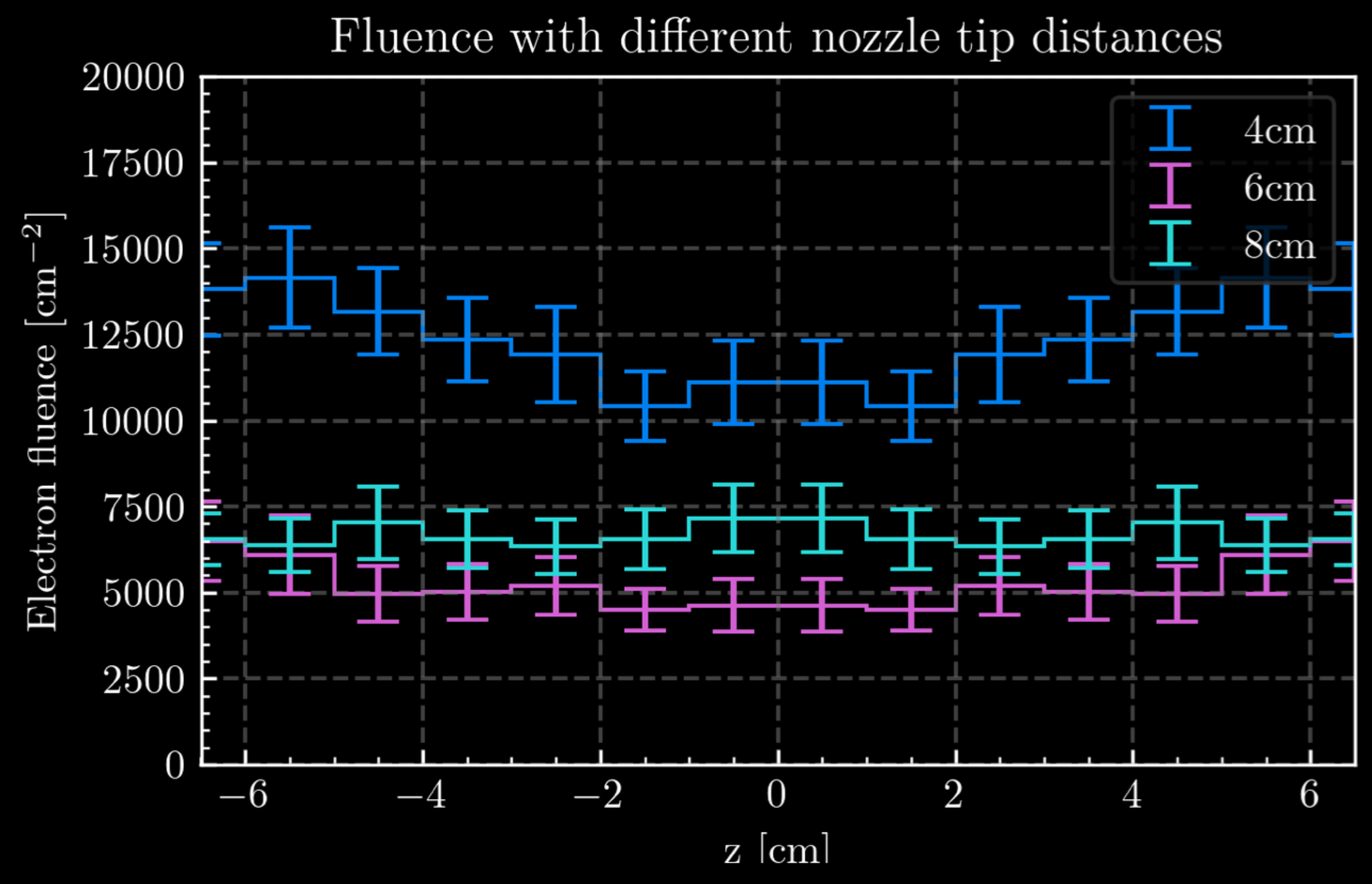

Work in progress: a technical nozzle design including structural support

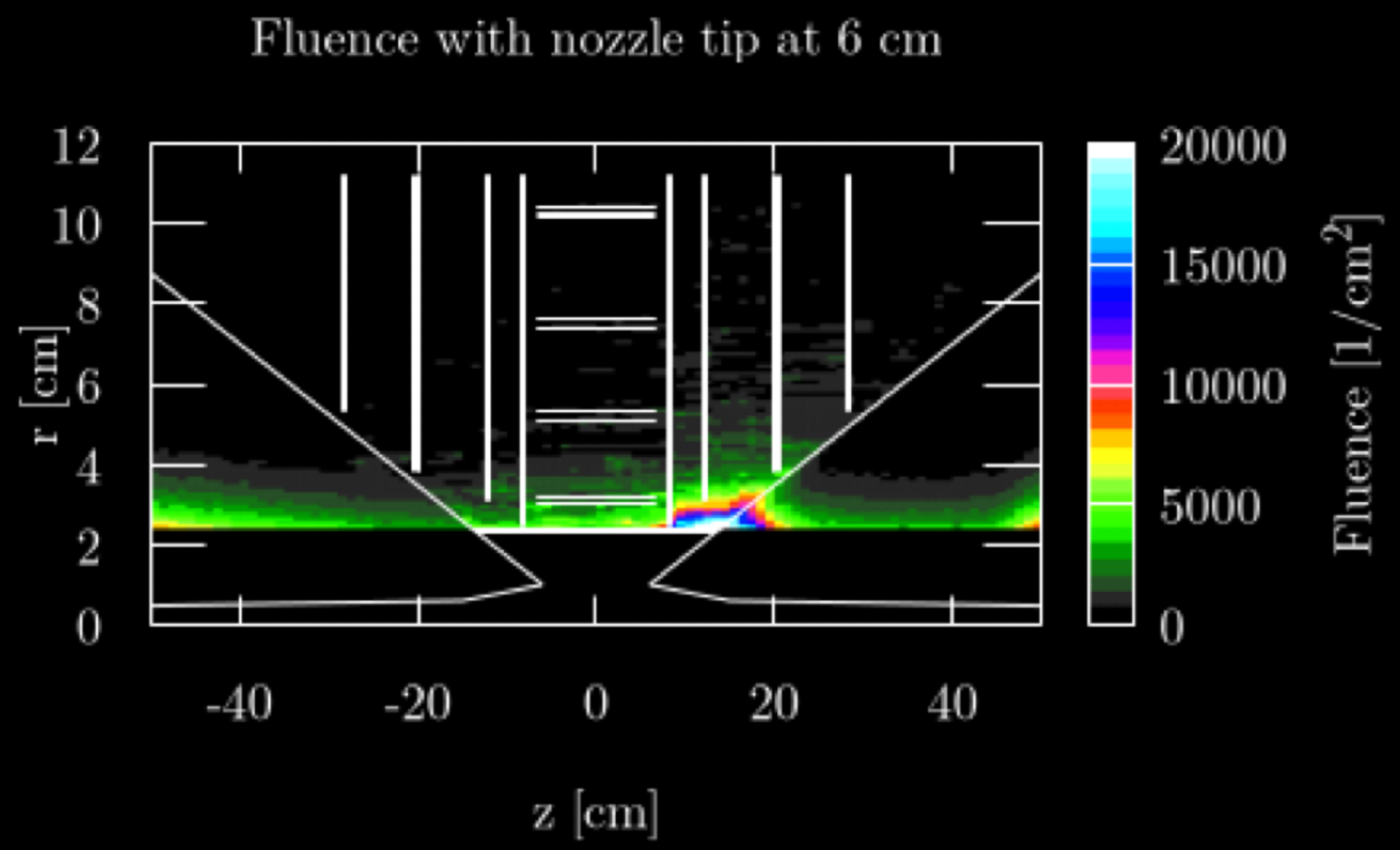
# Can we do better?

Studied tweaks to the position of the innermost nozzle tip

Nozzle details have a strong impact on radiation in pixel detectors

Constrained by physics acceptance: currently at $\theta = 10°$ (i.e. $\eta = 2.44$)



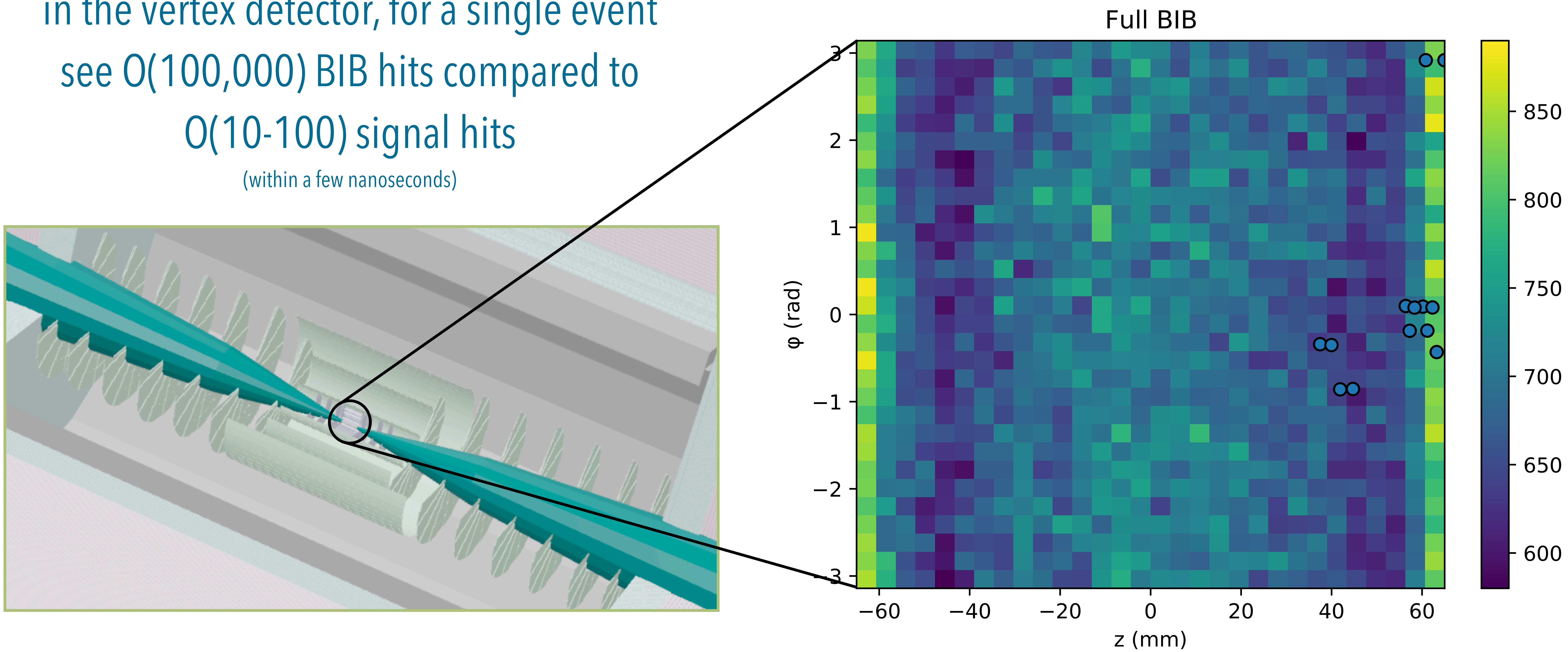
# these backgrounds are the drivers for detector design

## how can we approach them?

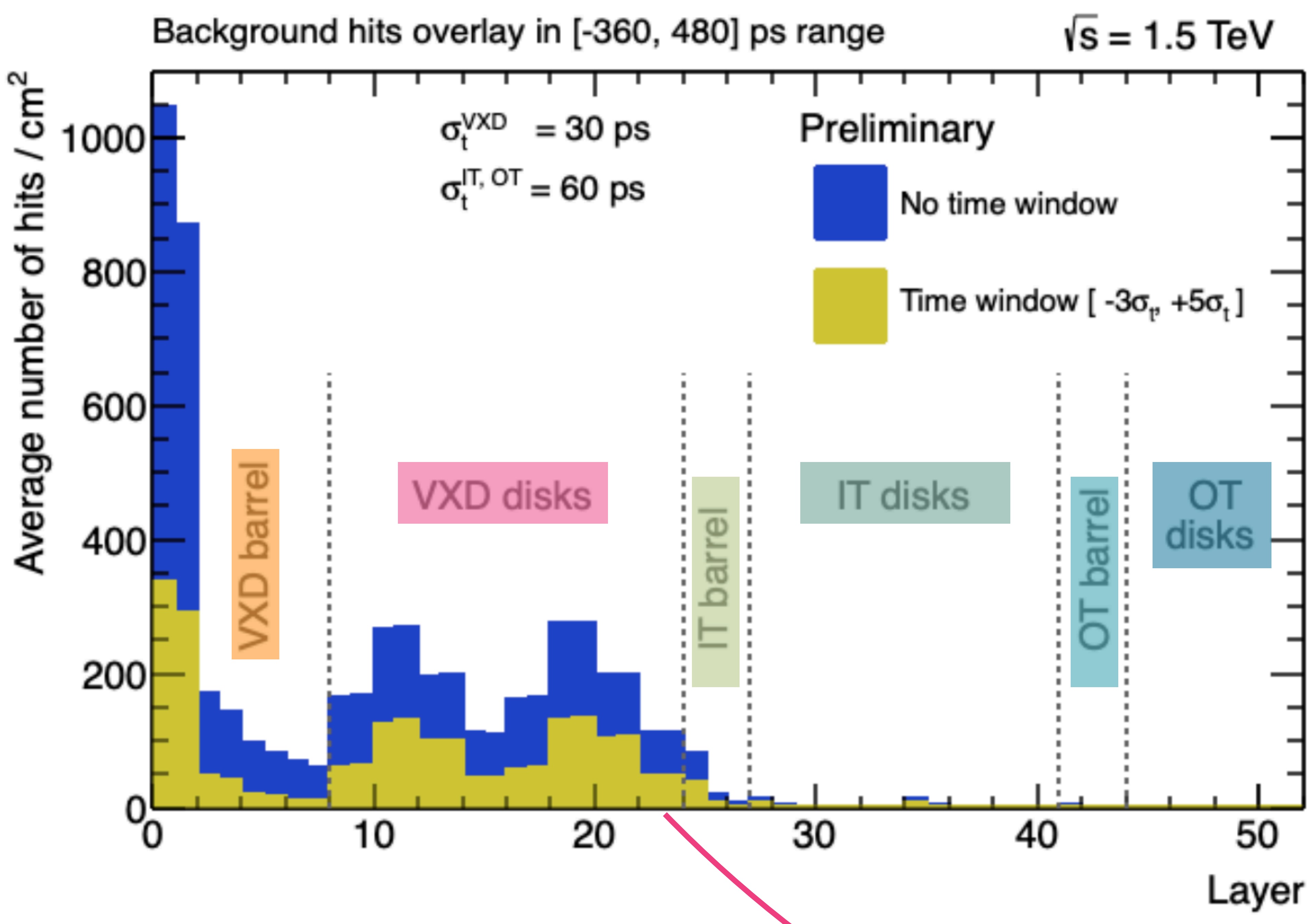
# In the tracker…

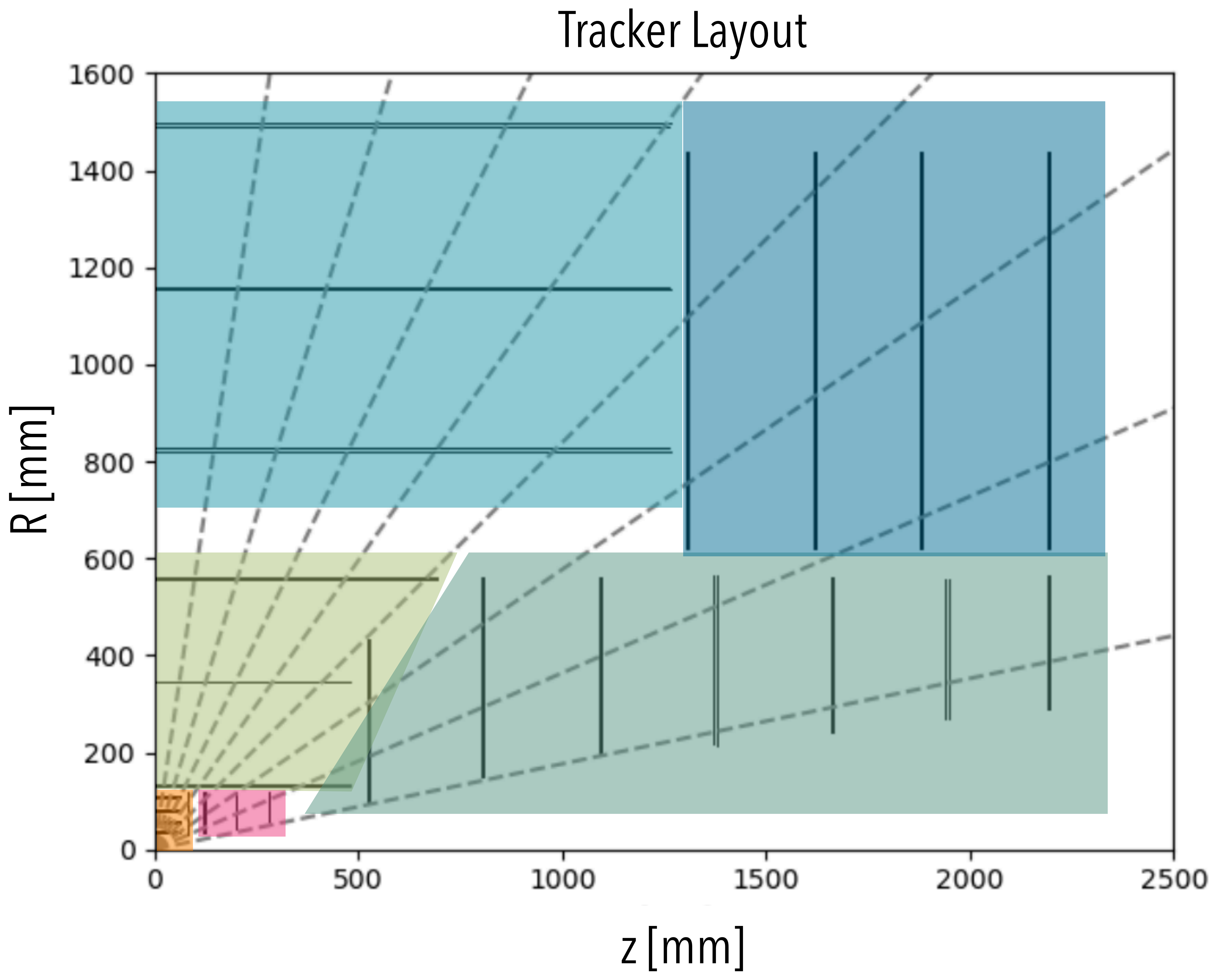
**occupancy** is the challenge:
in the vertex detector, for a single event see O(100,000) BIB hits compared to O(10-100) signal hits

(within a few nanoseconds)



# In the tracker…



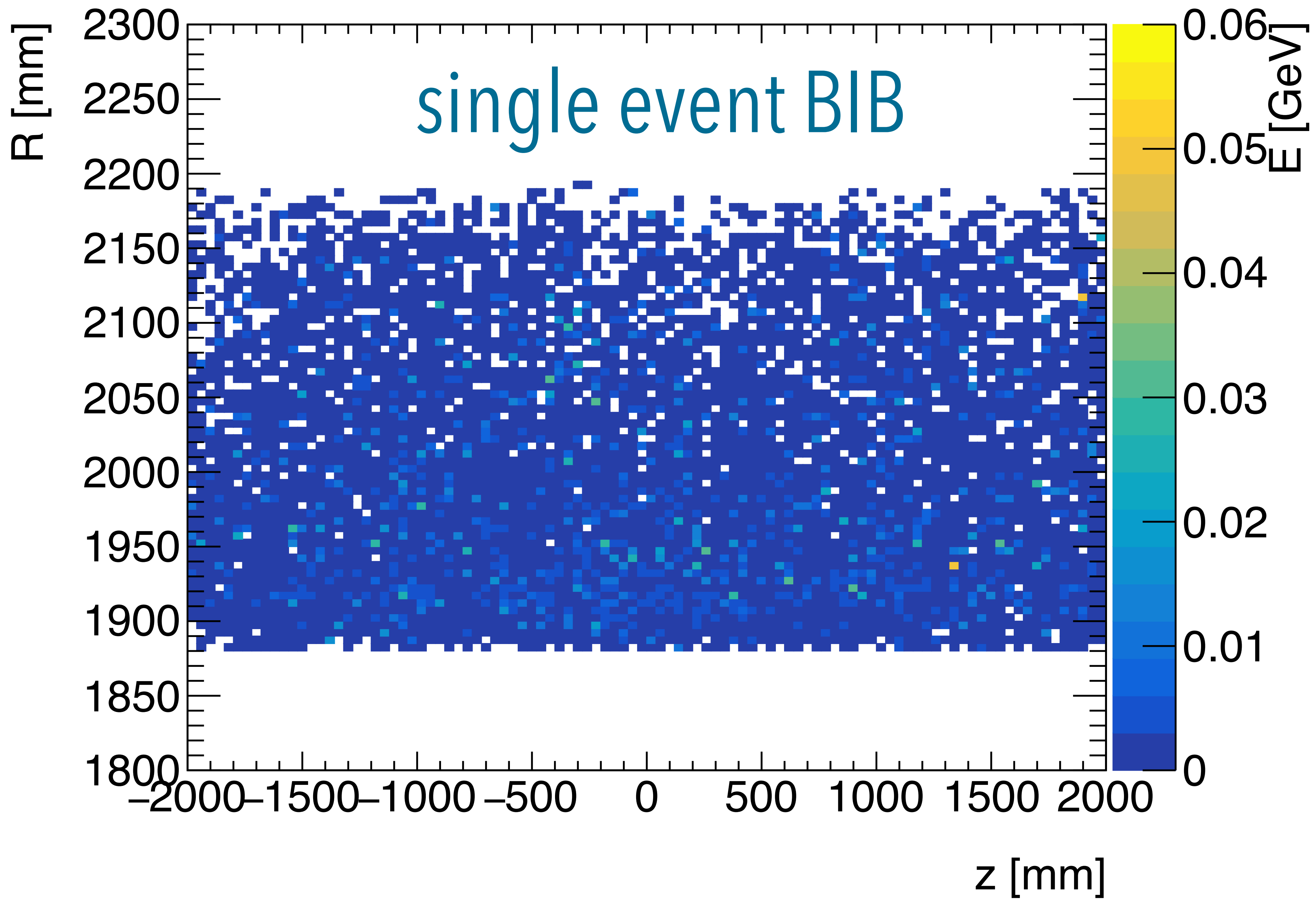



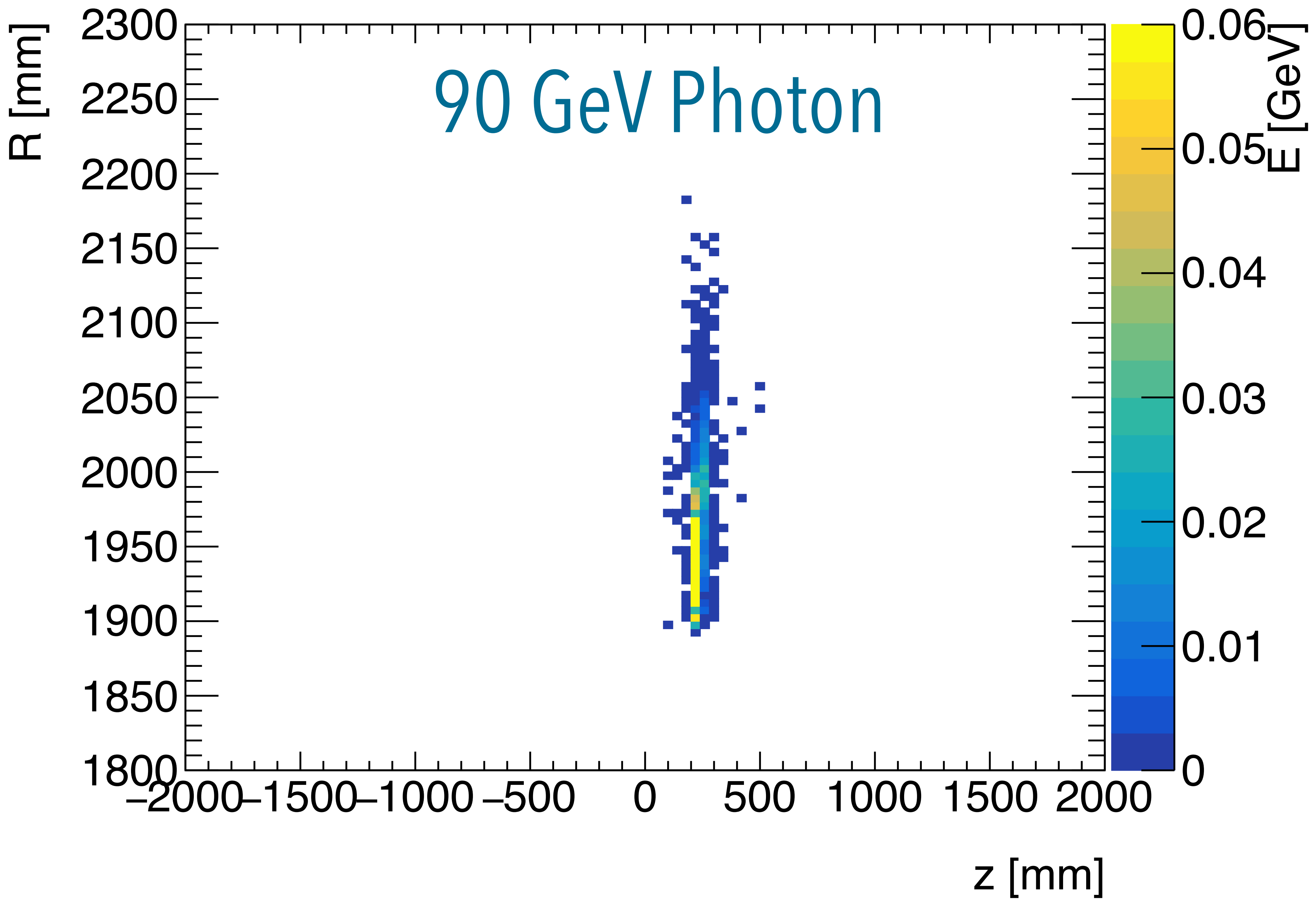

occupancy per layer translates directly into **feature size** and **timing resolution** requirements (targeting ~1%)

(could play with feature size vs. timing emphasis)

| | Vertex Detector | Inner Tracker | Outer Tracker |
|---|---|---|---|
| Cell type | pixels | macropixels | microstrips |
| Cell Size | 25 µm × 25 µm | 50 µm × 1 mm | 50 µm × 10 mm |
| Sensor Thickness | 50 µm | 100 µm | 100 µm |
| Time Resolution | 30 ps | 60 ps | 60 ps |
| Spatial Resolution | 5 µm × 5 µm | 7 µm × 90 µm | 7 µm × 90 µm |

# In the EM calorimeter…



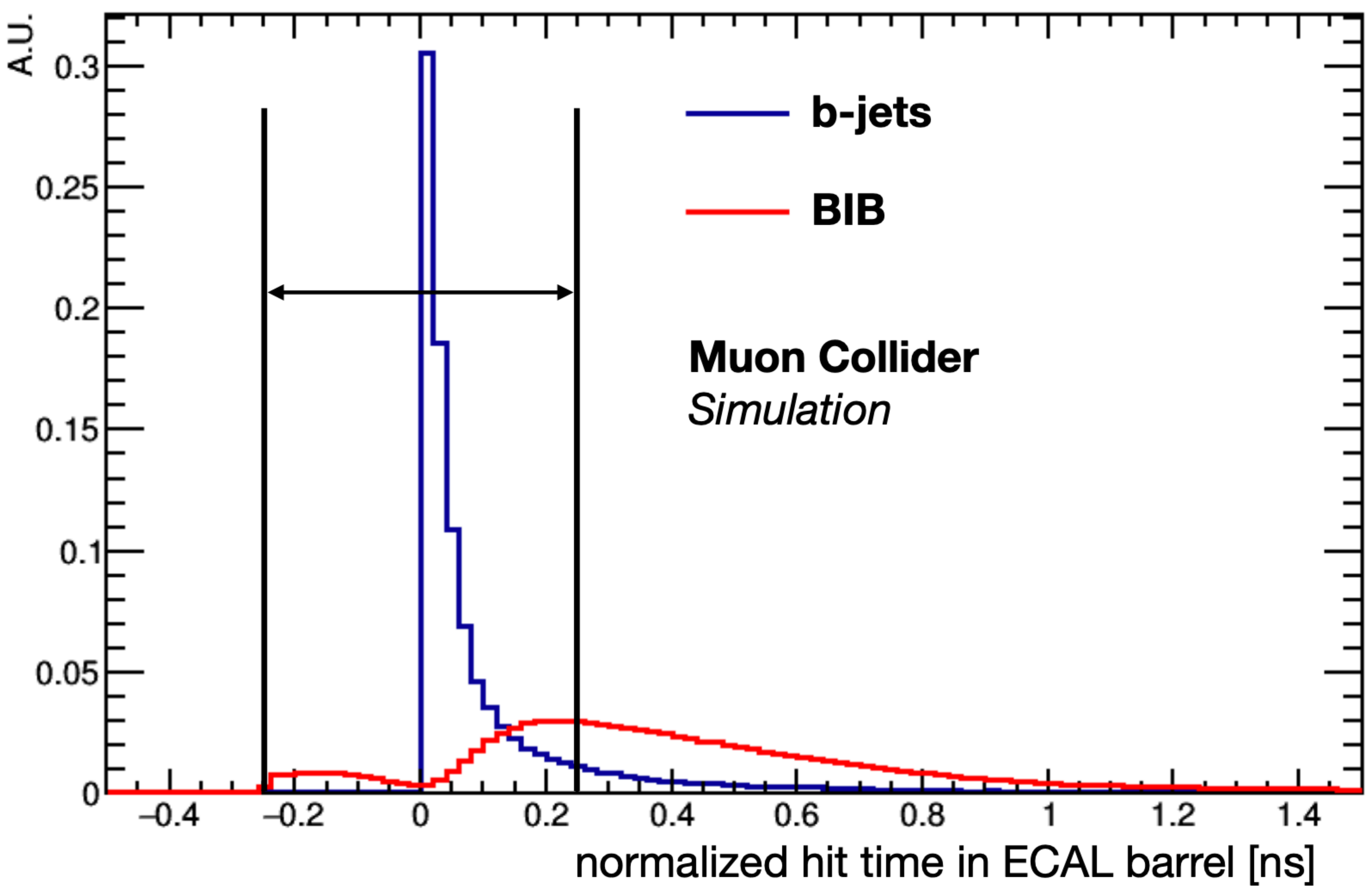




BIB is extremely diffuse, reduced drastically by the end of the ECAL

High-energy signals easy to pick out from BIB

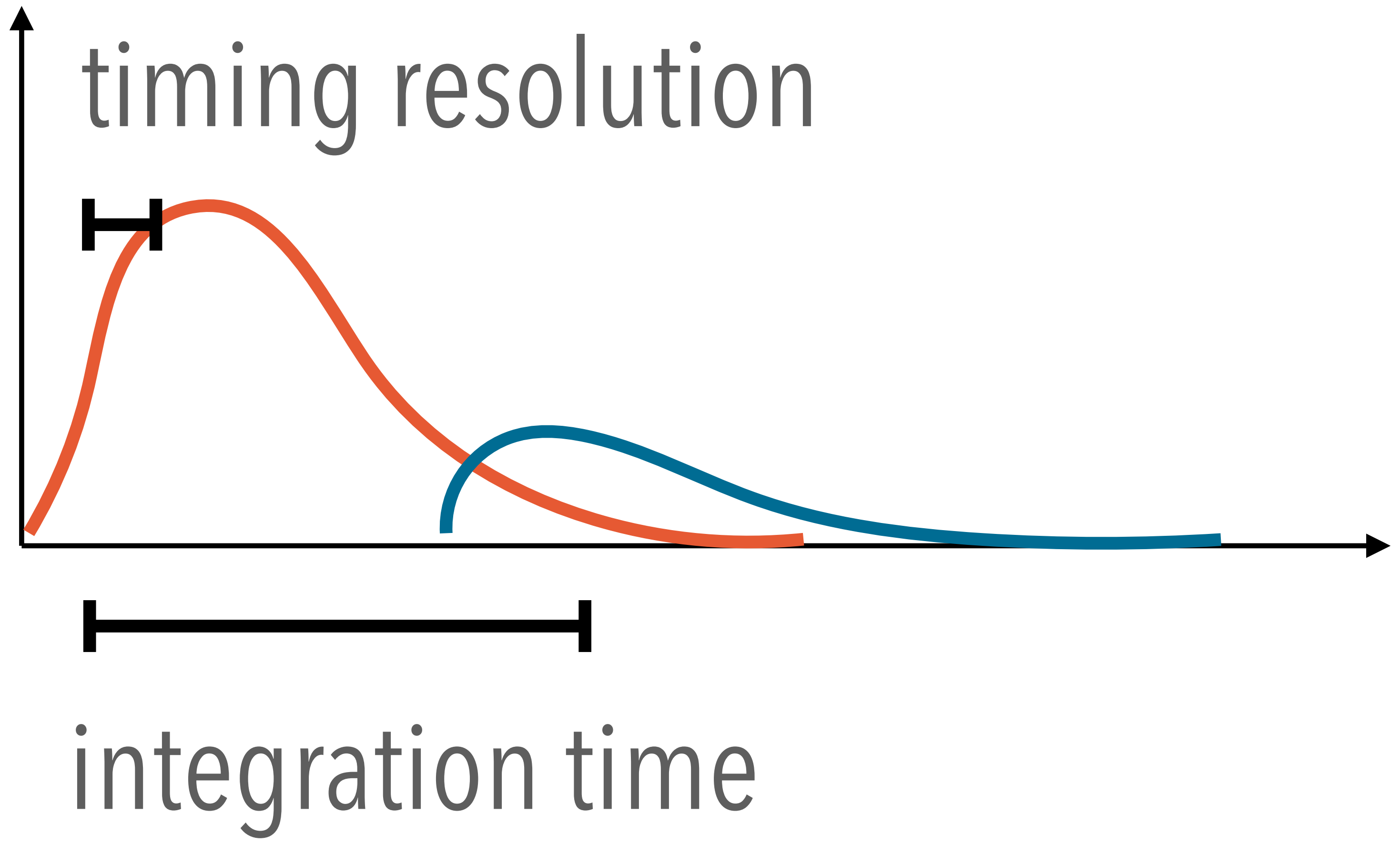
(both made in a phi slice of 0.1, -1 to 10 ns)

# In the EM calorimeter…



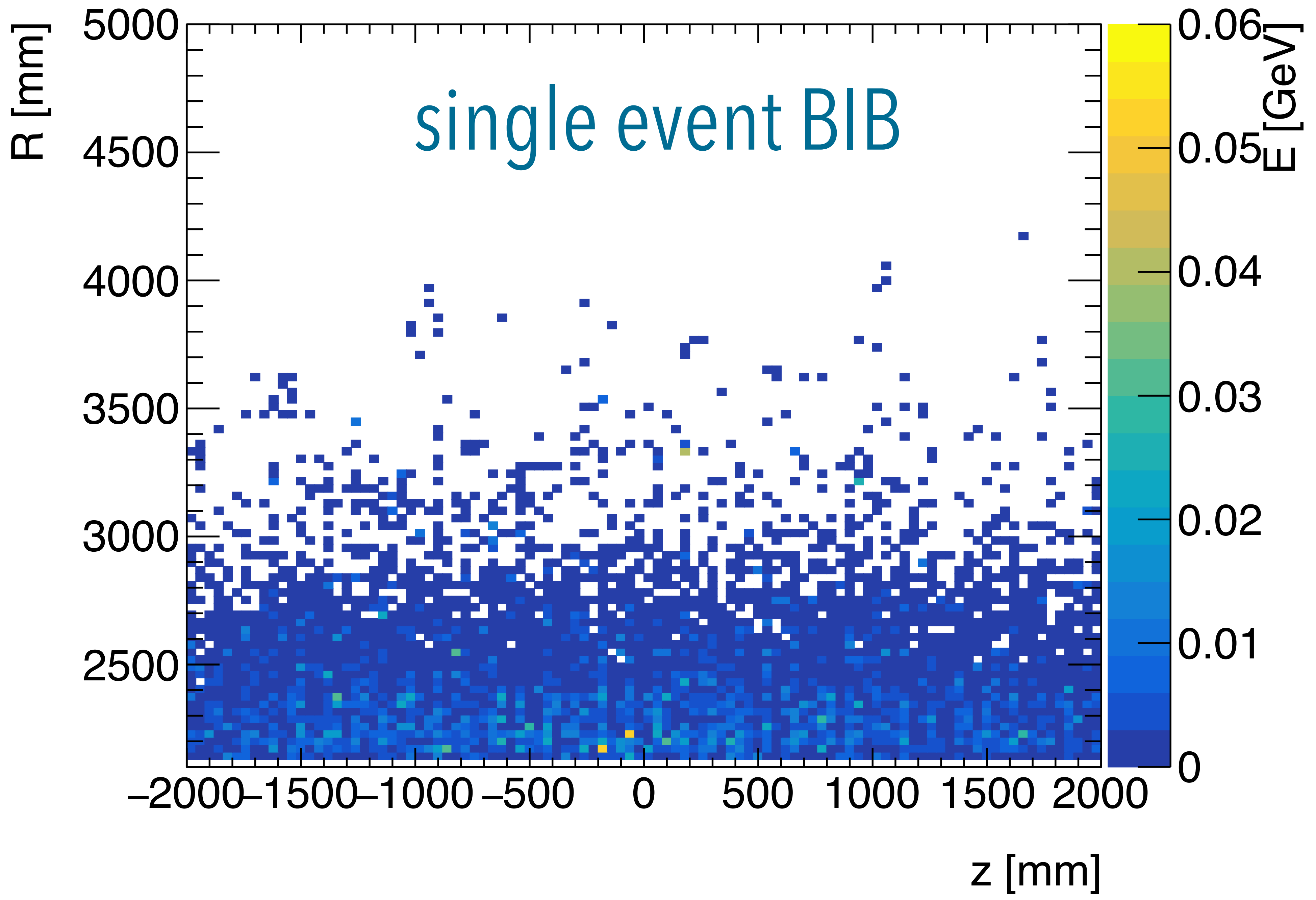

Baseline ECAL is W+Si, 5x5 mm cell size
but also investigating crystal calorimetry (CRILIN)

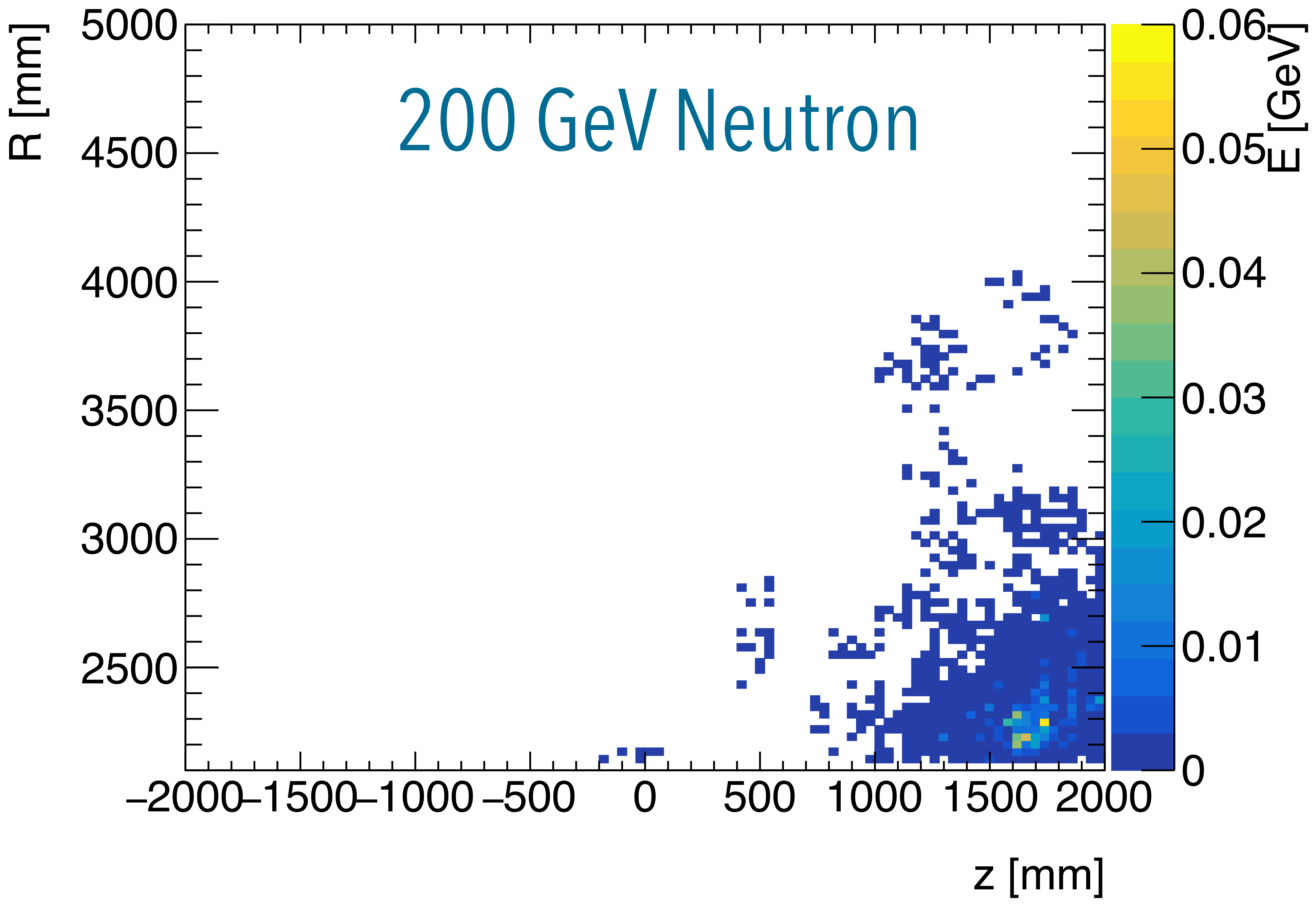
sub-ns timing resolution can further reduce BIB contamination




integration time equally important

# In the hadronic calorimeter…



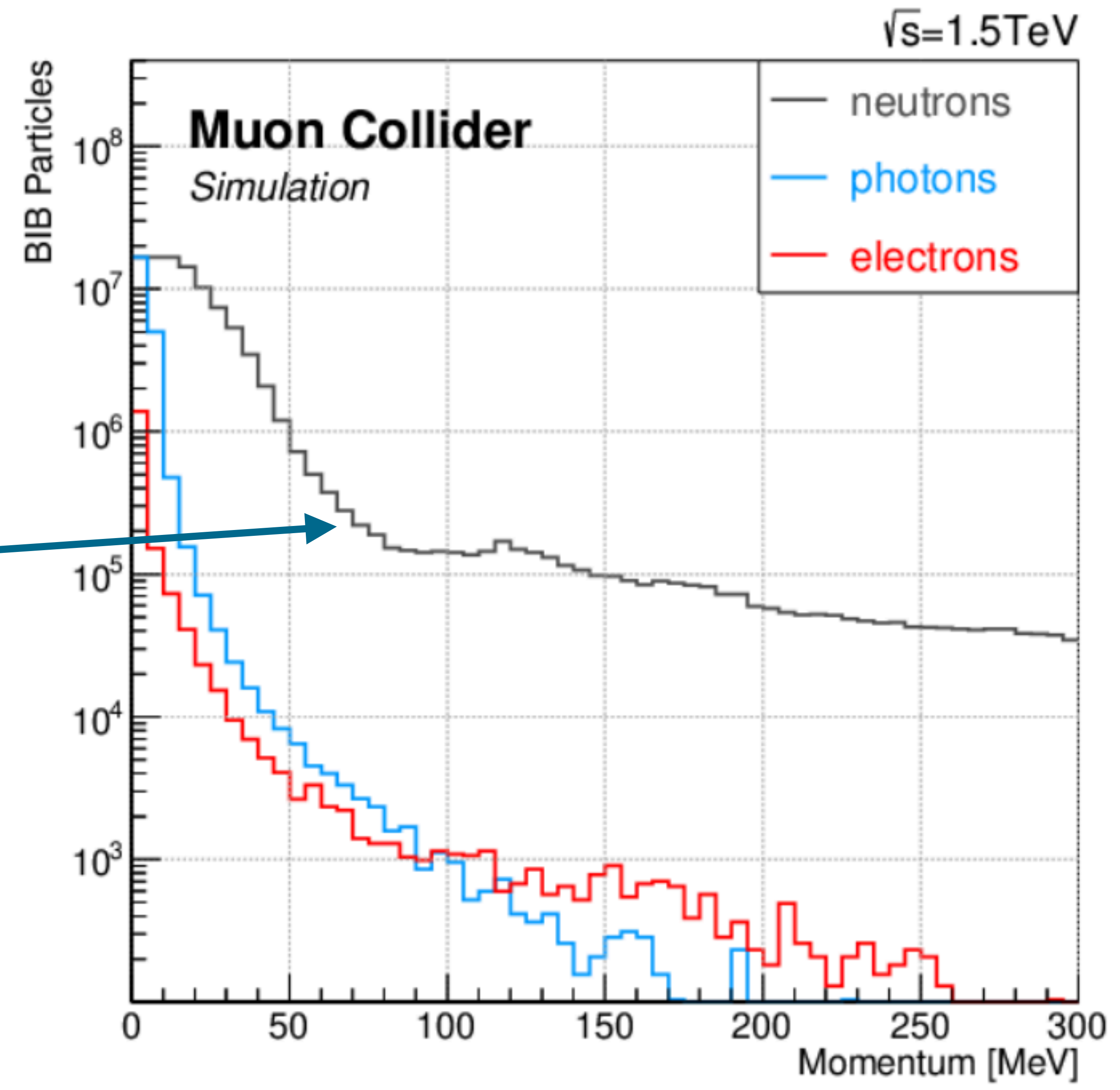

BIB reduced by ECAL, still very diffuse, mostly neutrons remain

Signal still distinct, but stands out less over backgrounds

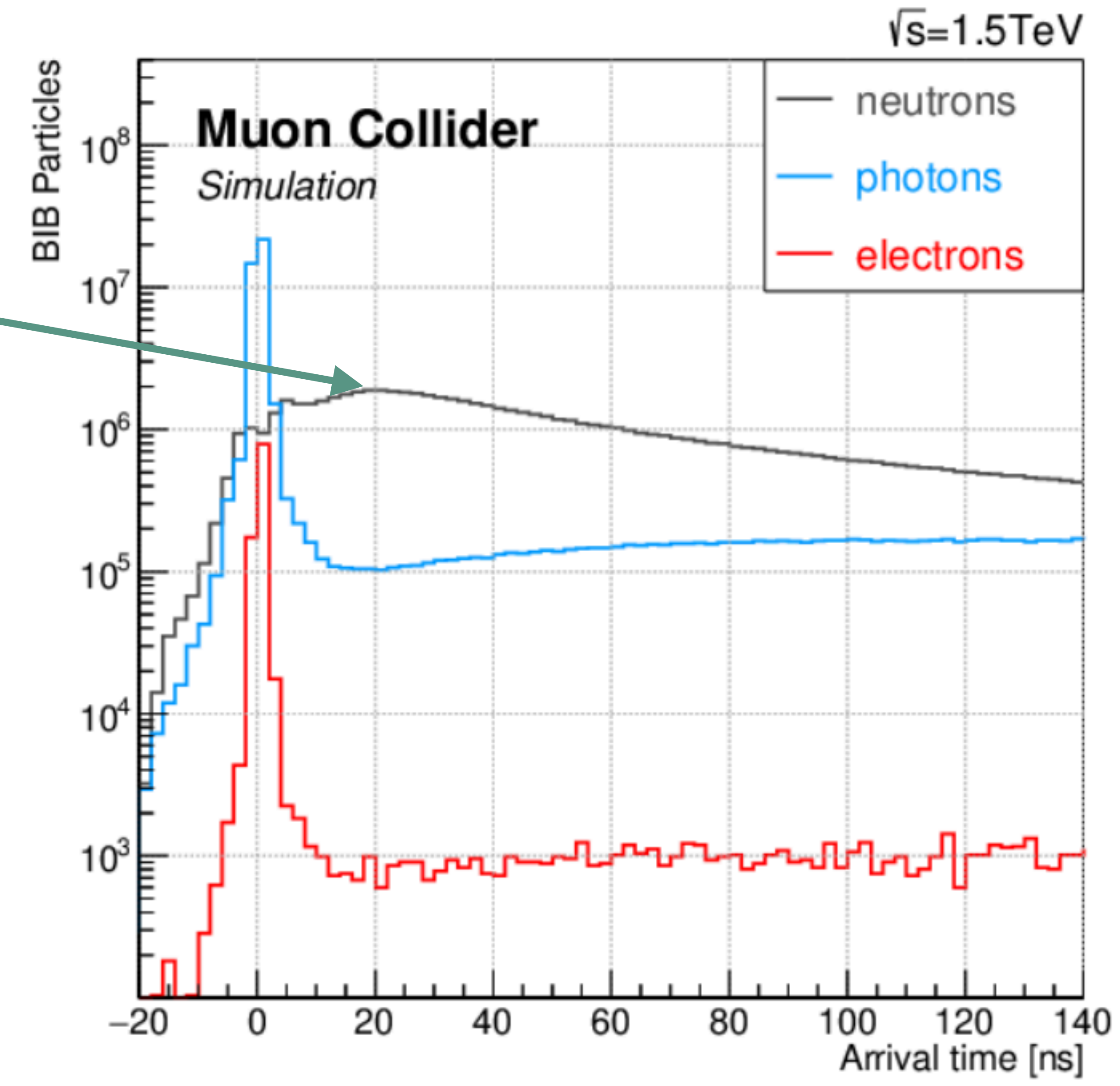
(both made in a phi slice of 0.4, -1 to 10 ns)

# In the hadronic calorimeter…

Not surprising:
there are many high-energy
neutrons in BIB




These high-energy neutrons are
extremely out-of-time – even
ns precision can help a lot here



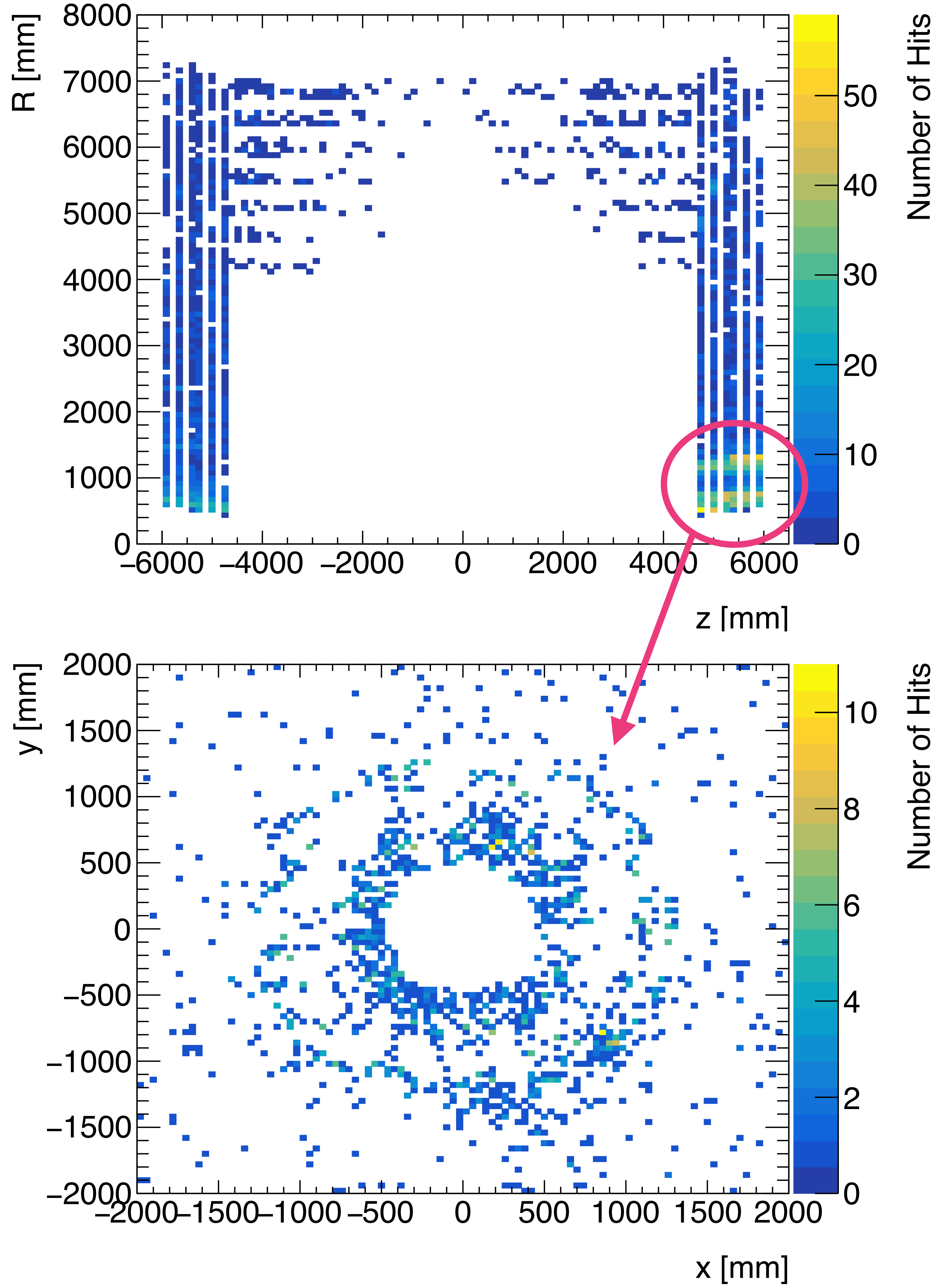

Baseline is 30x30 mm$^2$ scintillating tiles
alternating with steel absorbers

# In the forward region…

very little BIB makes it through the calorimeter
so most of the muon system is straightforward

backgrounds are concentrated in the forward region,
near the beam – will need to handle high rate

also impacts forward luminosity monitoring
(BIB not correlated with luminosity)



# Reading out the detector…

plenty of time to process a given event

much slower event rate than what we're accustomed to

$$t = 33\ \mu s \times \left(\frac{L}{10\ \mathrm{km}}\right)$$

but reading out all BIB hits requires increased cabling, cooling

pushes the challenge from trigger to on-detector processing

| | Readout Window | E Threshold | Hit Size | Total Rate |
|---|---|---|---|---|
| **Tracker** | 1 ns | n/a | 32 bits | ~30 Tb/s |
| **ECAL** | 15 ns | 0.2 MeV | 20 bits | ~30 Tb/s |
| **HCAL** | 15 ns | 0.2 MeV | 20 bits | ~3 Tb/s |
| **Total** | | | | 60 Tb/s |

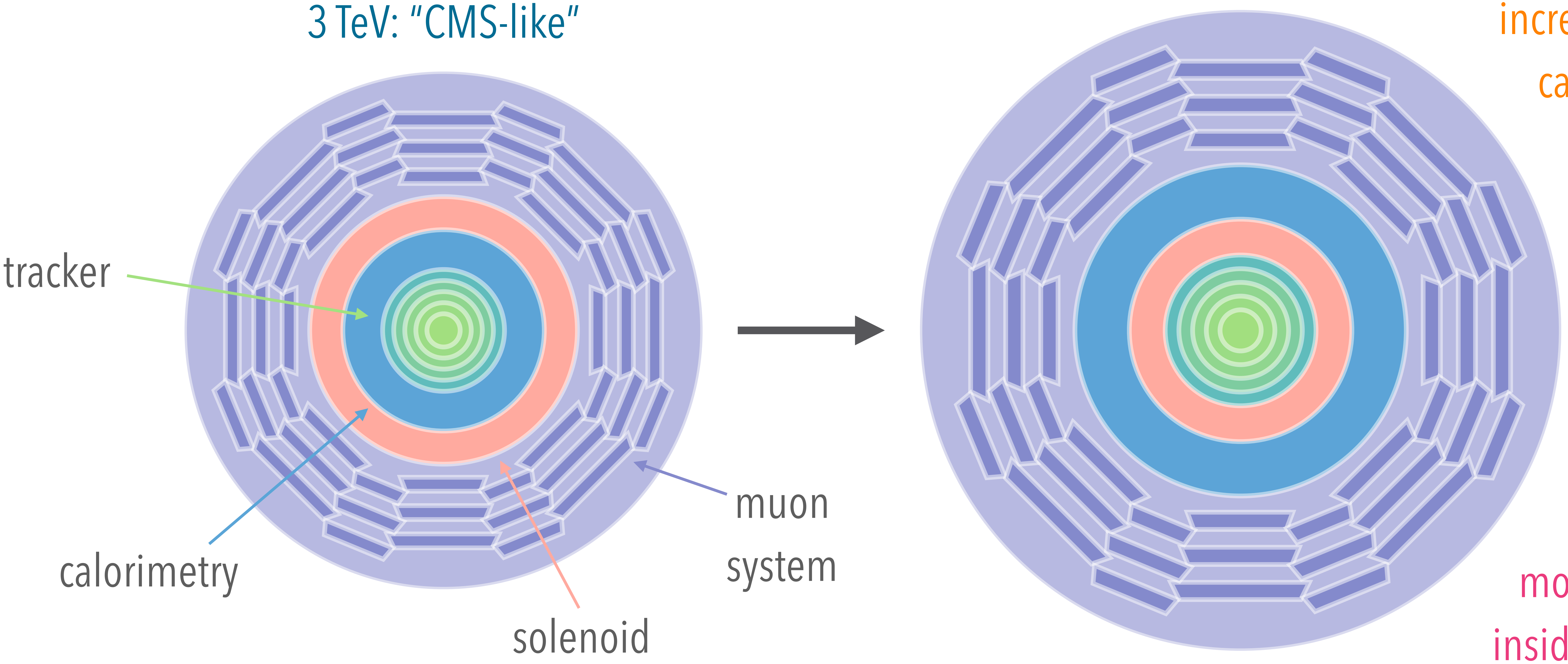
→ same as the CMS HL-LHC max HLT input rate

# Thinking about higher energies…

10 TeV: "ATLAS-like"

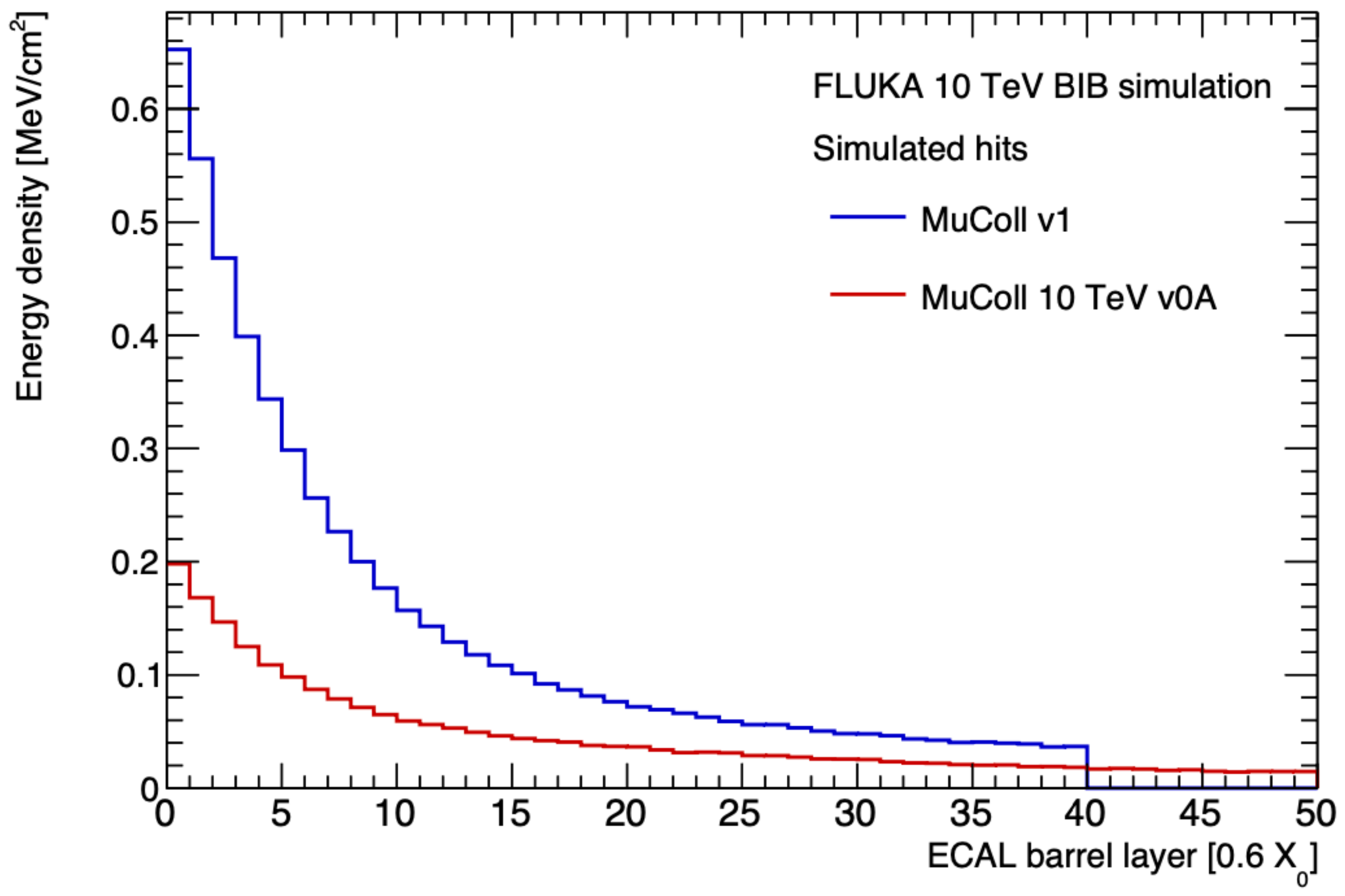
3 TeV: "CMS-like"

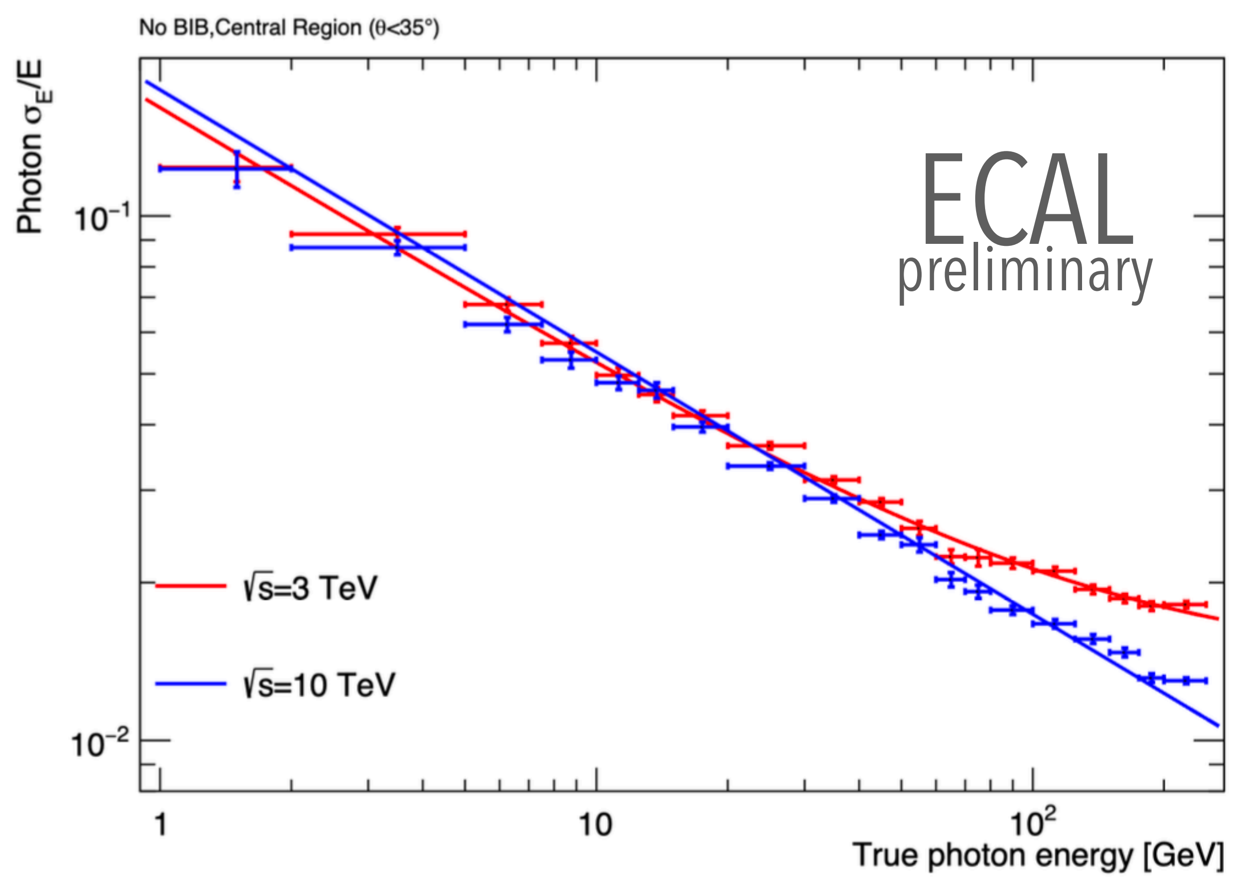
increase depth of calorimeters

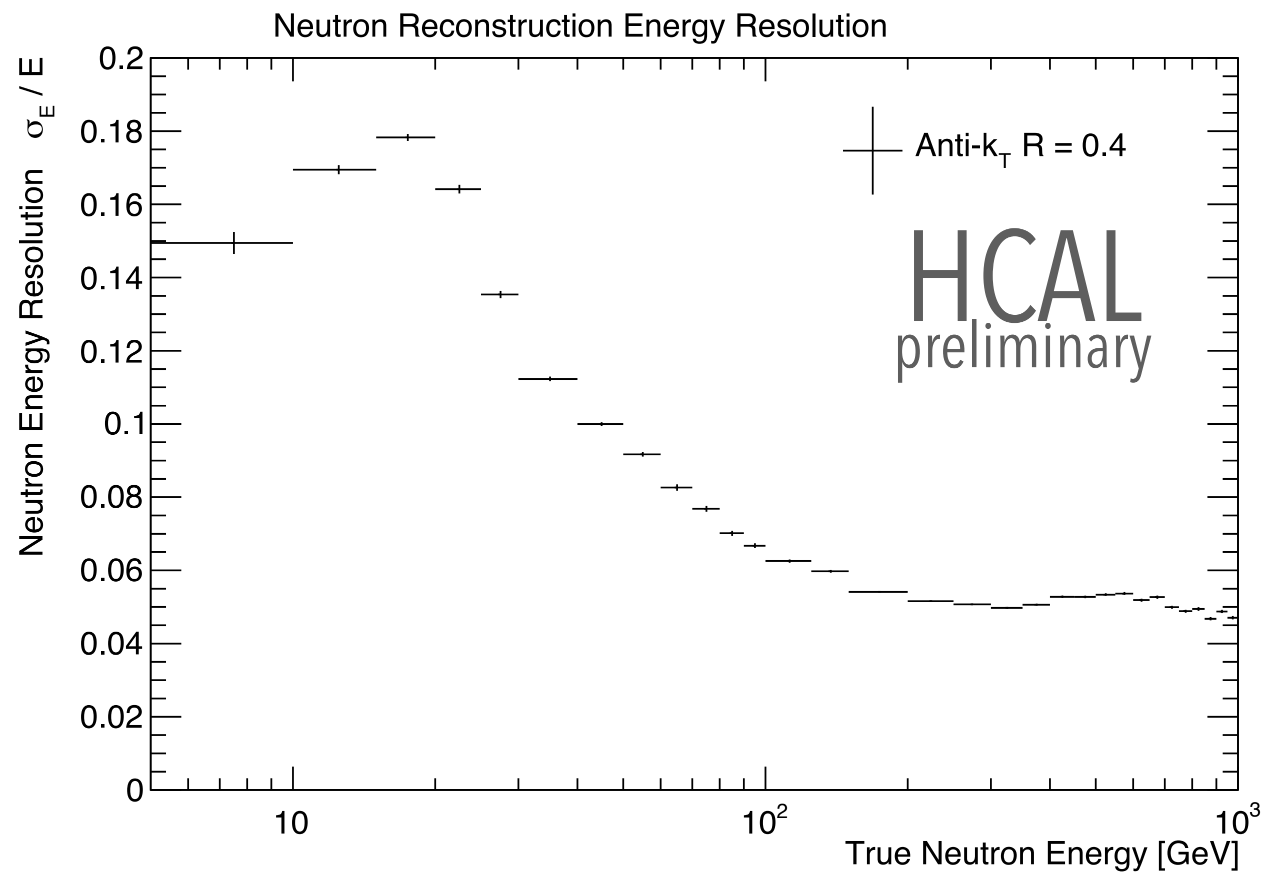



move solenoid inside calorimeter

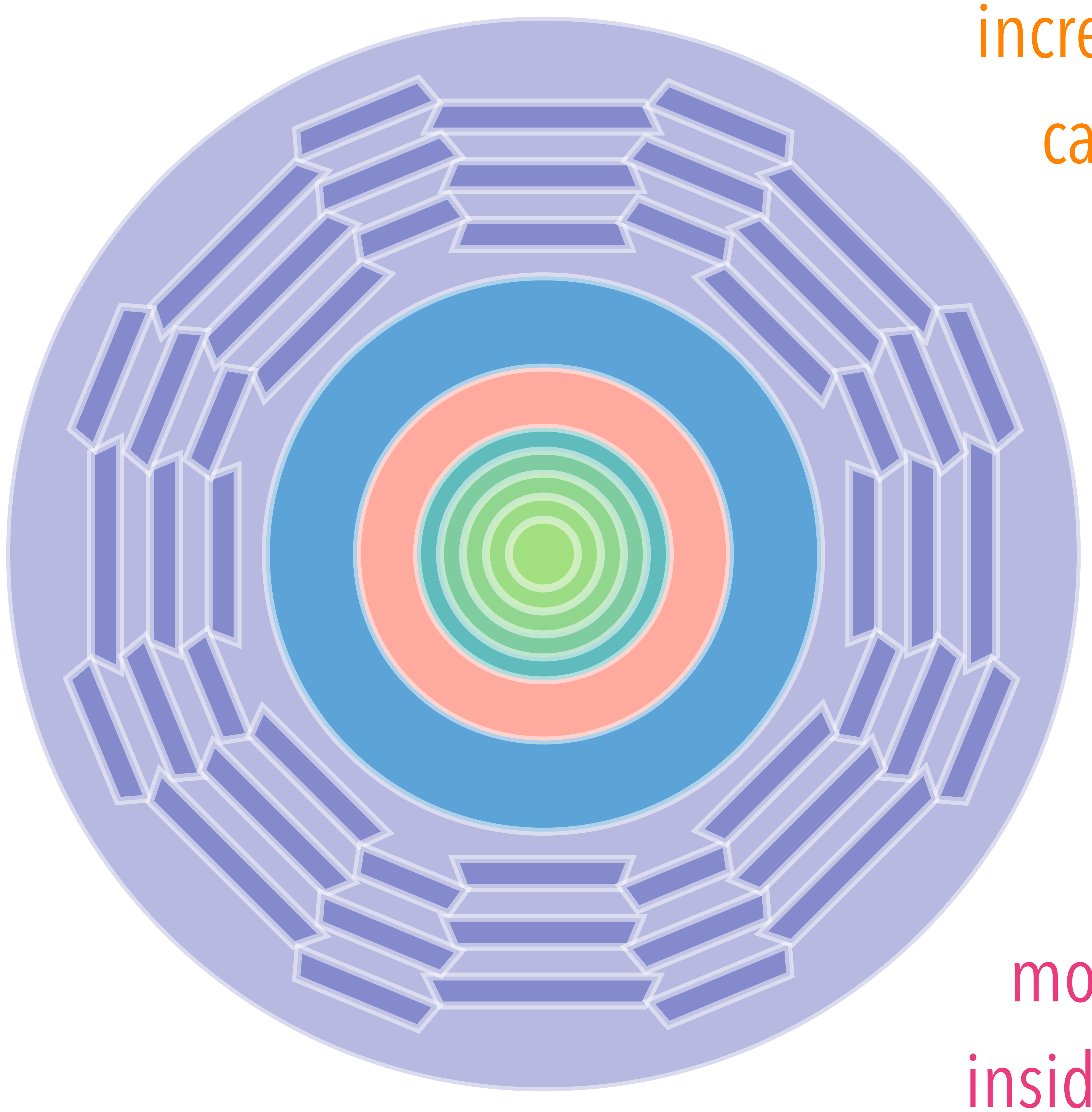
# Thinking about higher energies…




10 TeV: "ATLAS-like"

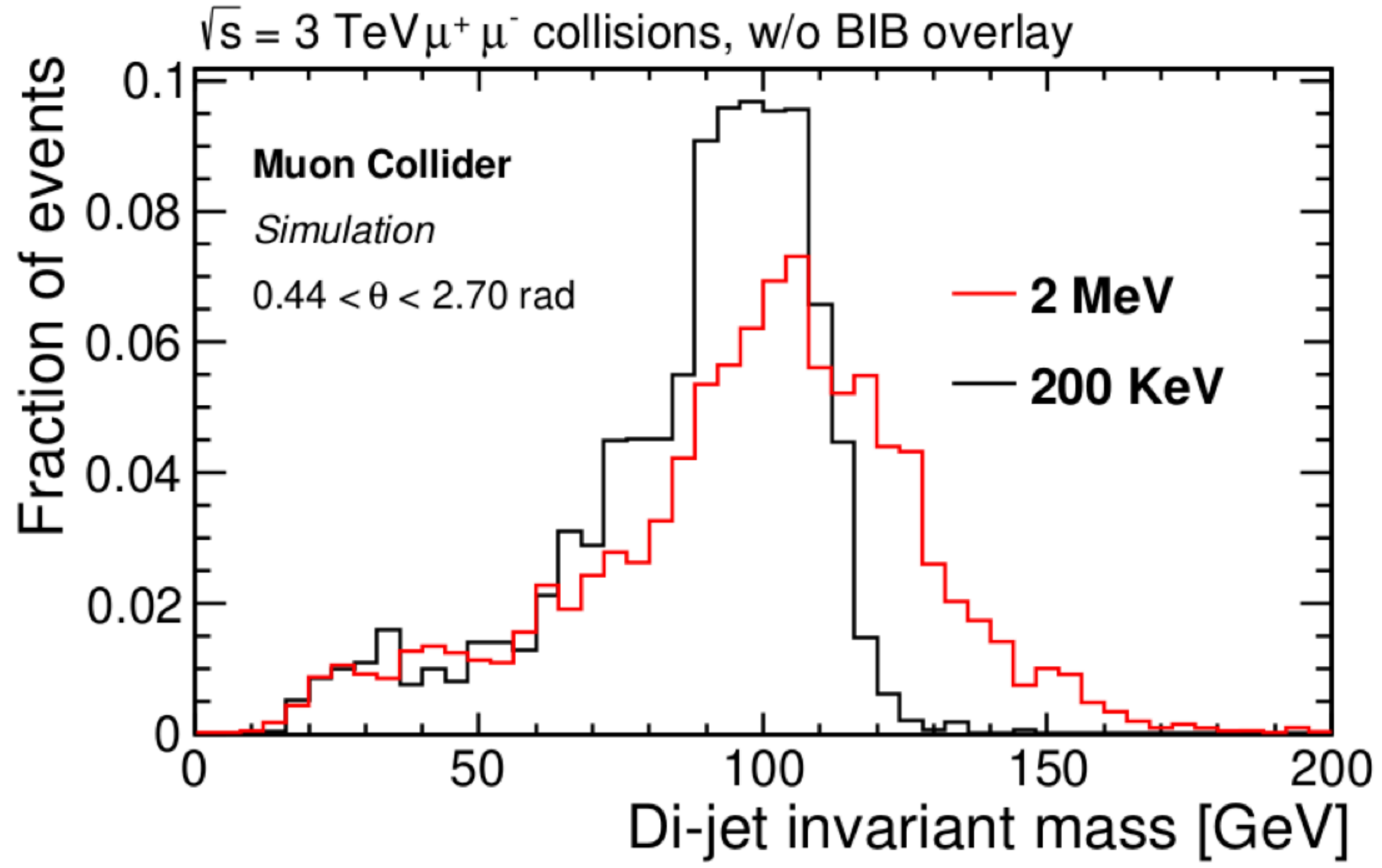


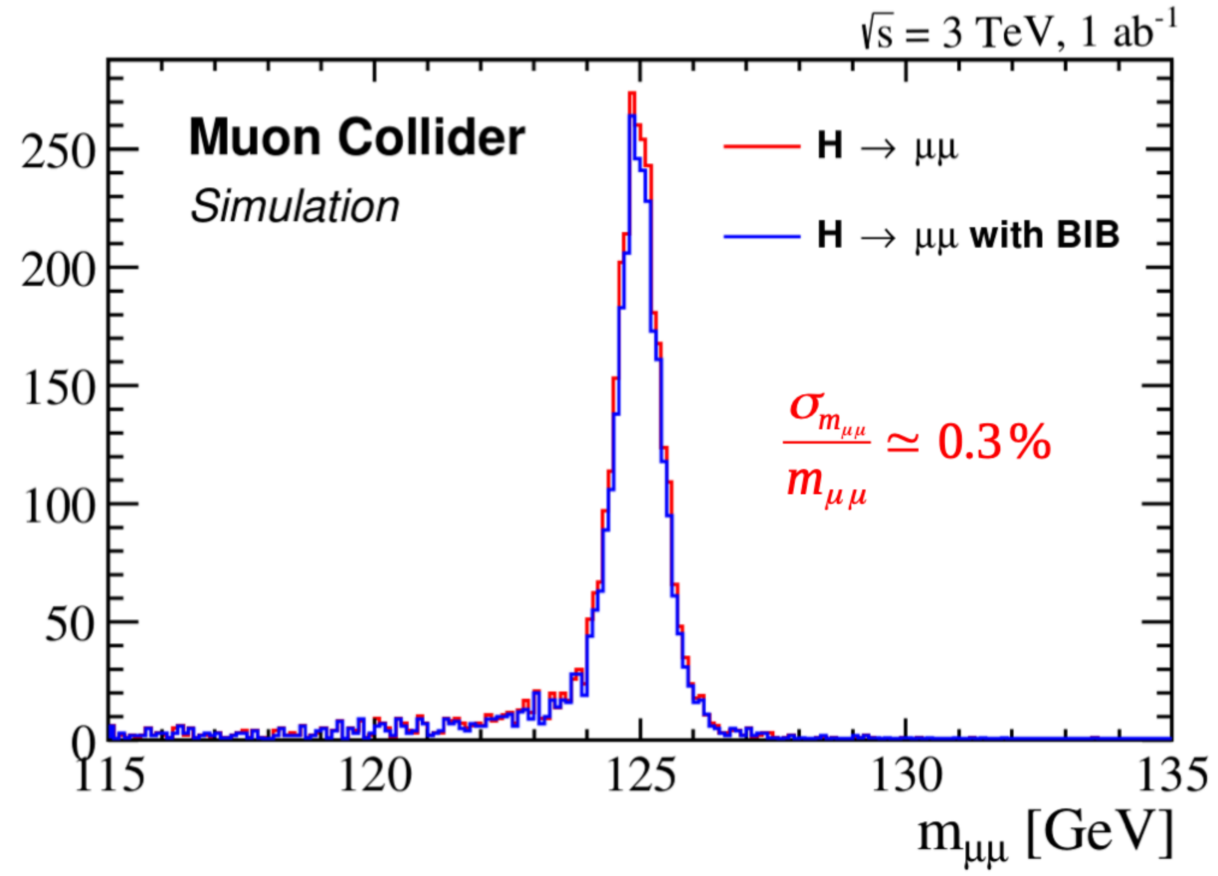
increase depth of calorimeters

move solenoid inside calorimeter

Federico Meloni, Rose Powers, Elise Sledge

# Can we do physics?

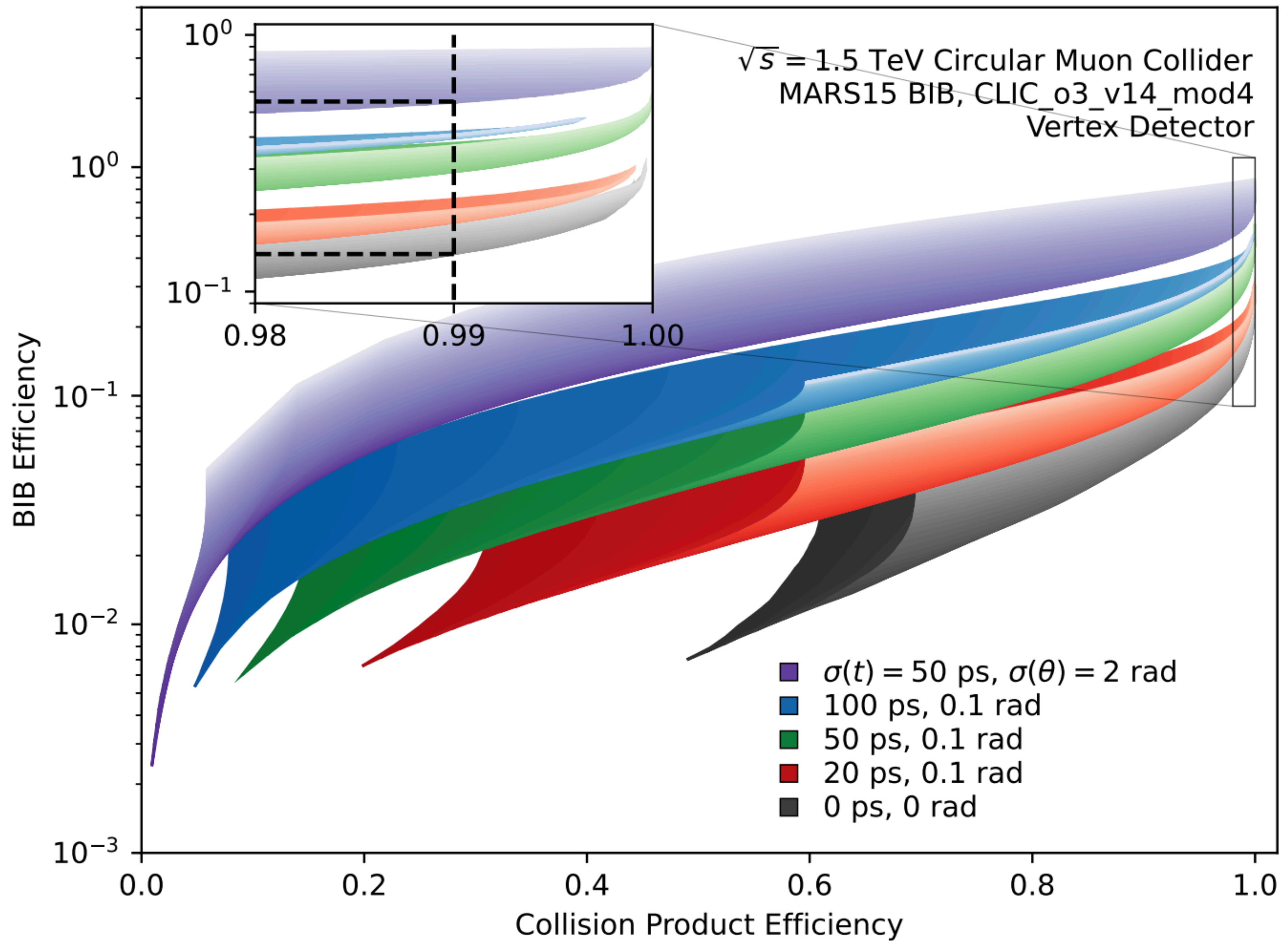


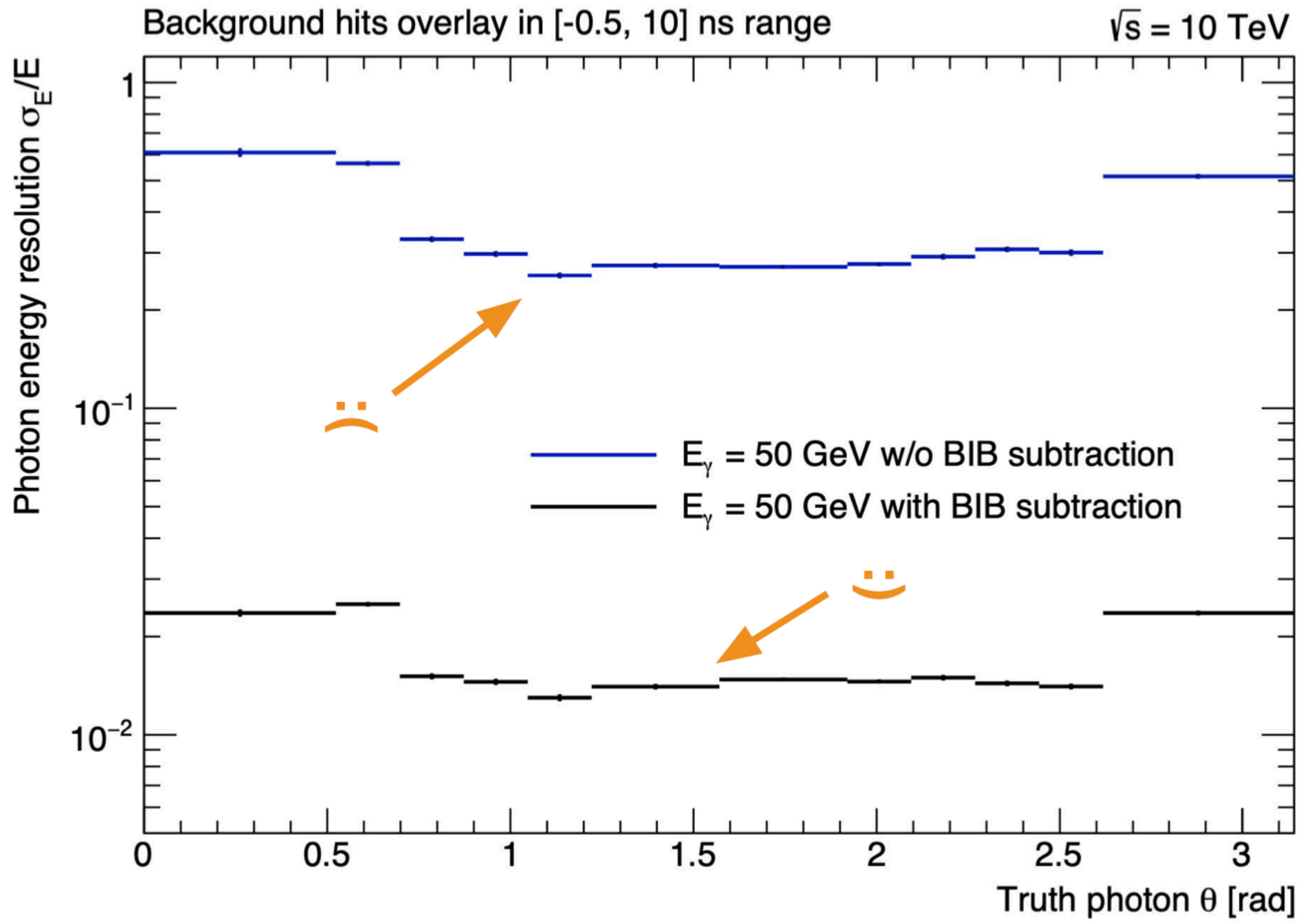



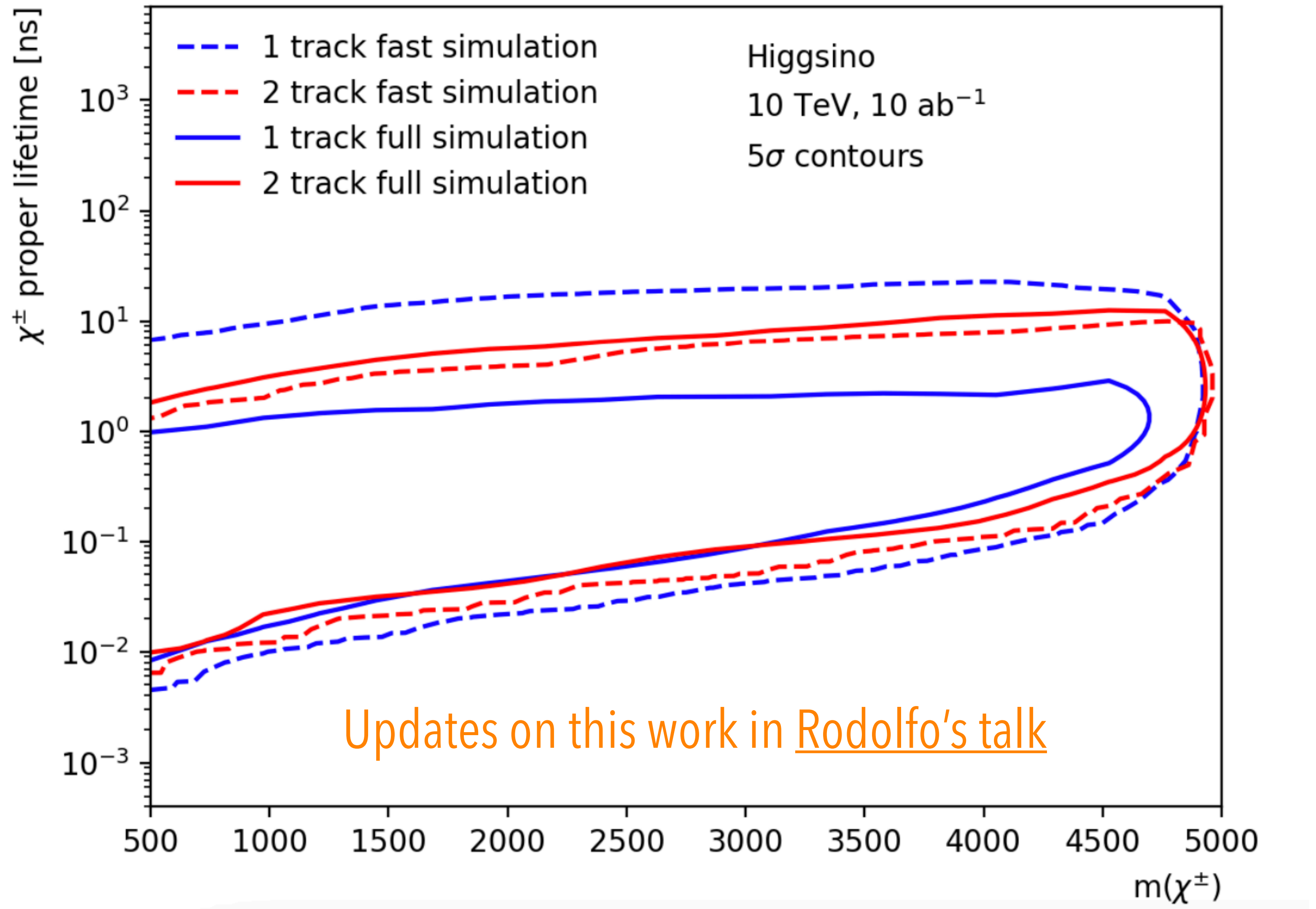

actively exploring algorithms for reducing impact of BIB

big progress – even have sensitivity to unconventional signatures

See Leo's talk tomorrow!




Muon Collider Forum Report, F. Meloni, D. Ally et al., M. Carsarsa

# In conclusion…

big progress in recent years in building a detailed understanding of muon collider detector needs

with the HL-LHC upgrades, we're close to having the technical expertise to build this detector

still lots to be done:

further MDI optimization

detector design including support and services

more sophisticated reconstruction and BIB rejection

and of course:

all of the detector R&D to help get us the timing and on-chip intelligence we need

# Thank you!