# $C^3$ and μC: Motivations for Detector Requirements

*$C^3$ Collaboration Meeting*

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TRIUMF

# Why Have This Discussion?

- $C^3$ and μC are quite different machines, and potentially require quite different detectors

- Our communities are united by a **common interest in future colliders**

- Detectors for these machines may have to be quite different, **BUT** we may be able to find **shared detector interests**

    - Especially as we propose projects for detector R&D, knowing where technologies can serve both detectors can be very useful

- This talk: motivate the physics requirements of each detector

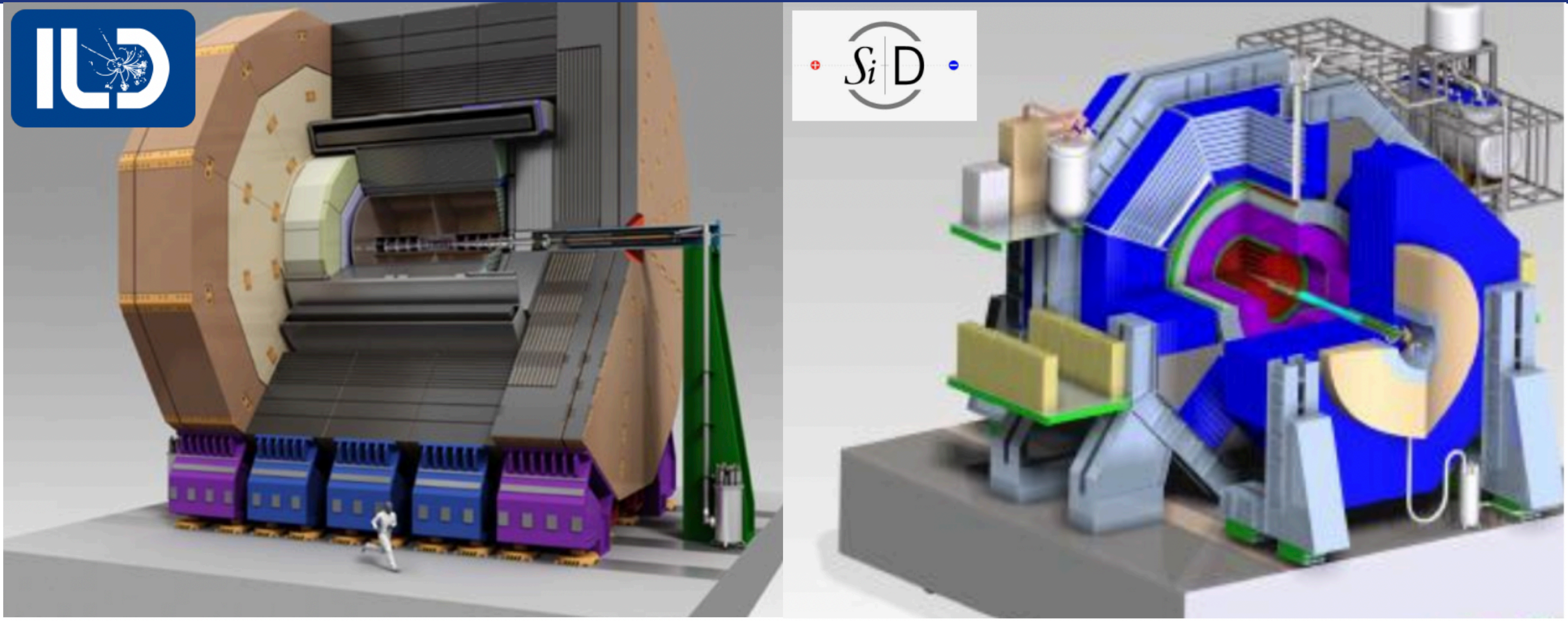
- Discussion session: discuss possible common ground, identify areas of overlap

# $C^3$ Detector Requirements

# Physics Goals: Precision

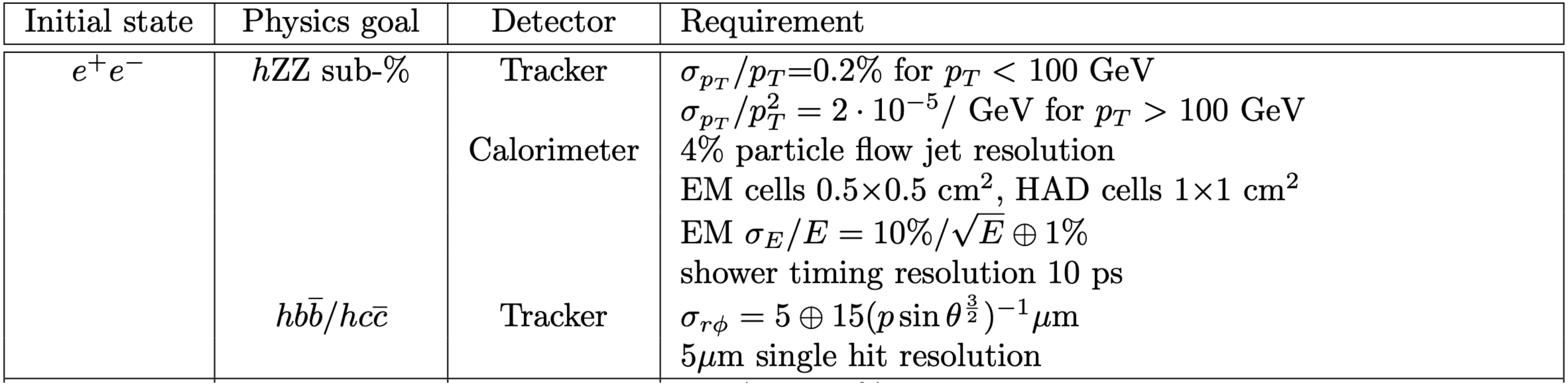
- Many existing resources on ILD/SiD design and motivation: I won't be able to summarize all this great work!
  - ILD talk from Graham, SiD from Jan and Andy
- Main motivation: aim for **precision for Higgs measurements**
- How to achieve precision? **Minimize resolution, especially for jets**
  - Best possible tracking: high magnetic field, minimal material
  - Best possible calorimetry: high granularity (to maximize PFlow), or dual readout (to minimize intrinsic resolution)
  - Maximize acceptance: full measurement of "hadronic recoil" of Higgs will allow for Higgs-decay independent measurements

# Precision Detectors



- ILD and SiD have similar goals, but utilize different technologies
  - SiD: maximize B-field, all-silicon tracking
  - ILD: minimize material with TPC tracking (+ silicon vertex detector)
- Both extremely hermetic to enable recoil measurements

# Requirements for $C^3$



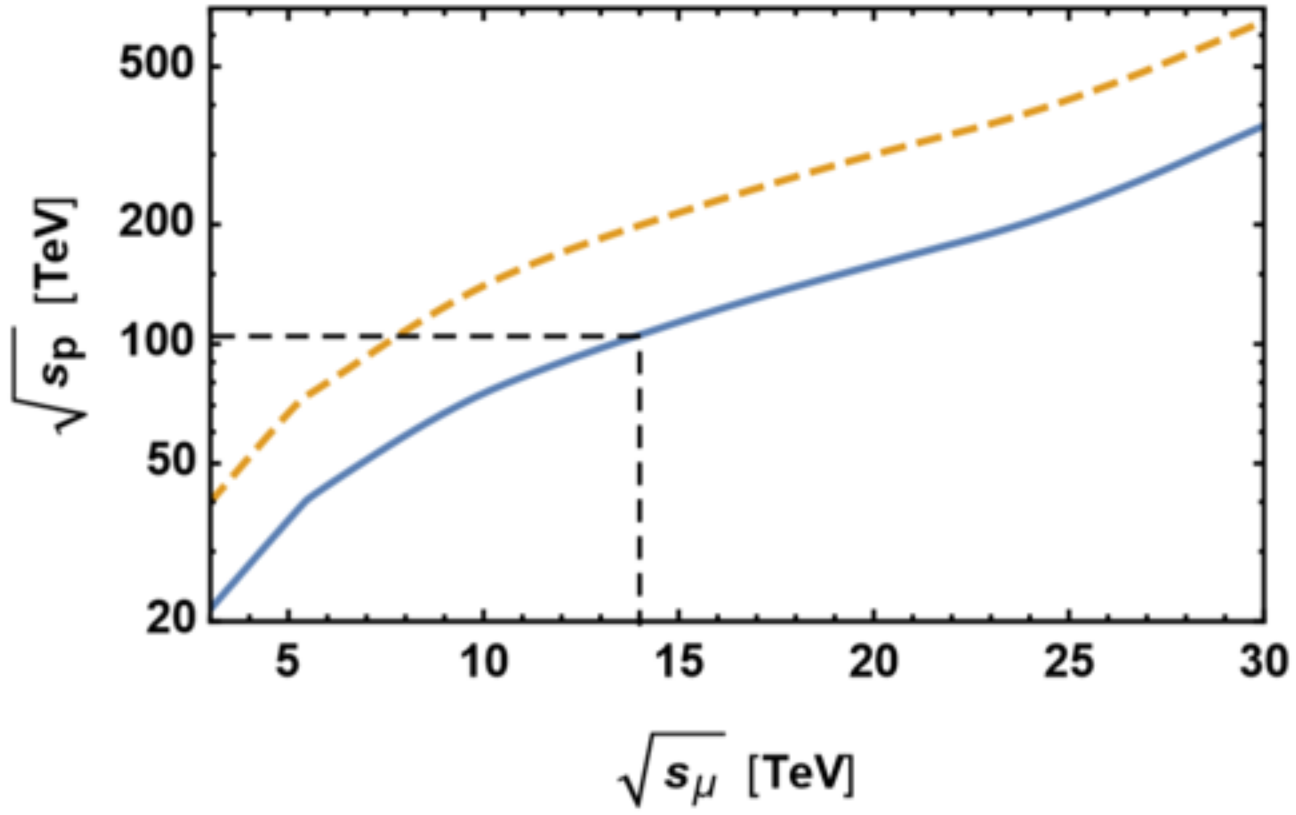
| Initial state | Physics goal | Detector | Requirement |
|---|---|---|---|
| $e^+e^-$ | $hZZ$ sub-% | Tracker | $\sigma_{p_T}/p_T$=0.2% for $p_T < 100$ GeV<br>$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}$/ GeV for $p_T > 100$ GeV |
| | | Calorimeter | 4% particle flow jet resolution<br>EM cells 0.5×0.5 $\text{cm}^2$, HAD cells 1×1 $\text{cm}^2$<br>EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$<br>shower timing resolution 10 ps |
| | $hb\bar{b}/hc\bar{c}$ | Tracker | $\sigma_{r\phi} = 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}\mu\text{m}$<br>5$\mu$m single hit resolution |

- Snowmass report summarizes the detector requirements for Higgs physics
- Many different detector technologies possible to fulfil these goals
  - Improvements still possible beyond these!
  - Alternatives also possible, e.g. dual-readout calorimetry

# μC Detector Requirements

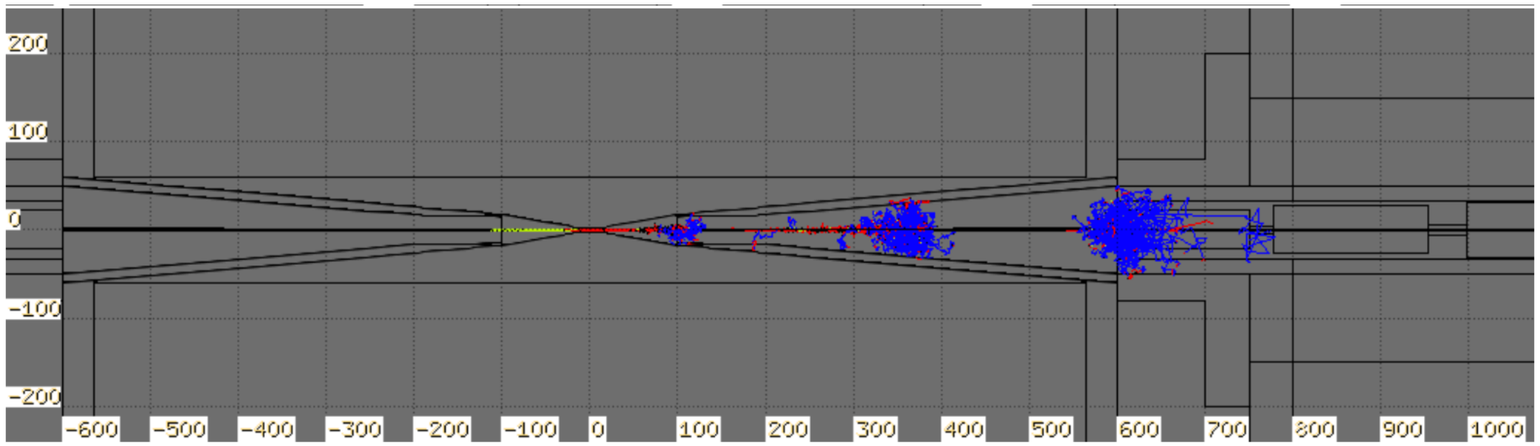
# Physics Goals: Discovery

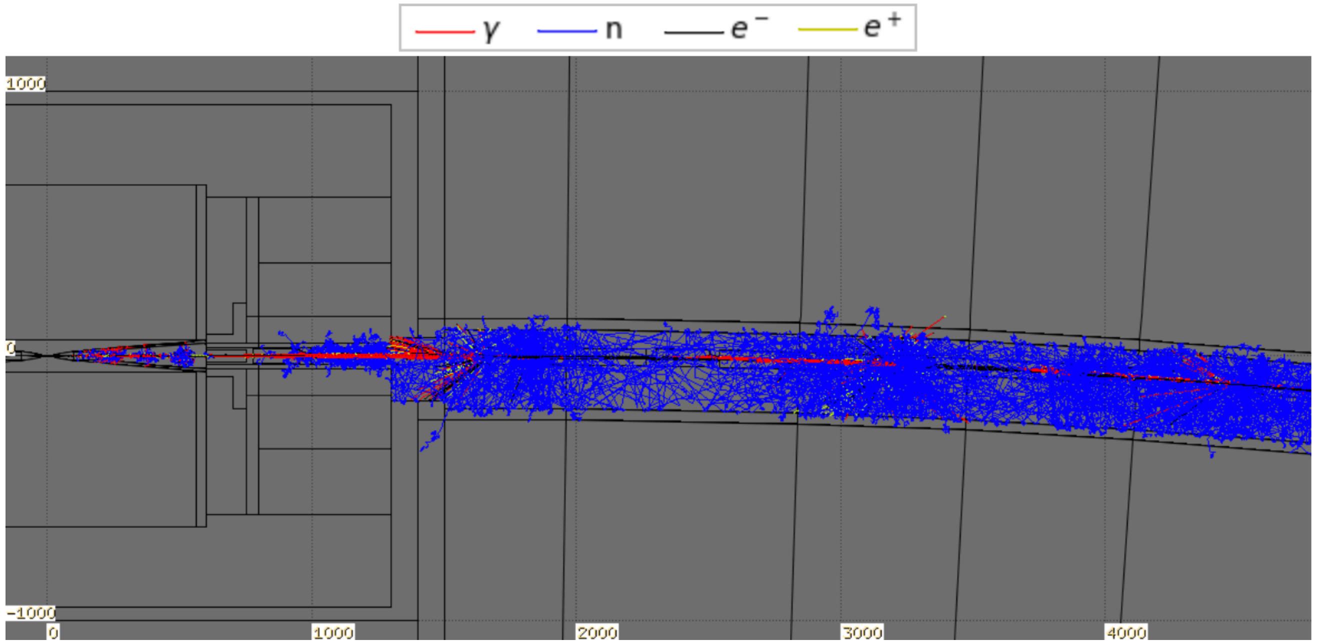
- As Isabel explained, the primary motivation of the muon collider is **discovery physics**
  - It will be able to measure properties of the Higgs and SM as well— but think of it more like FCC-hh
  - A 14 TeV μC has the mass reach of a 100 TeV pp machine!



# The Challenge of BIB

*Decay of one muon near the IP*



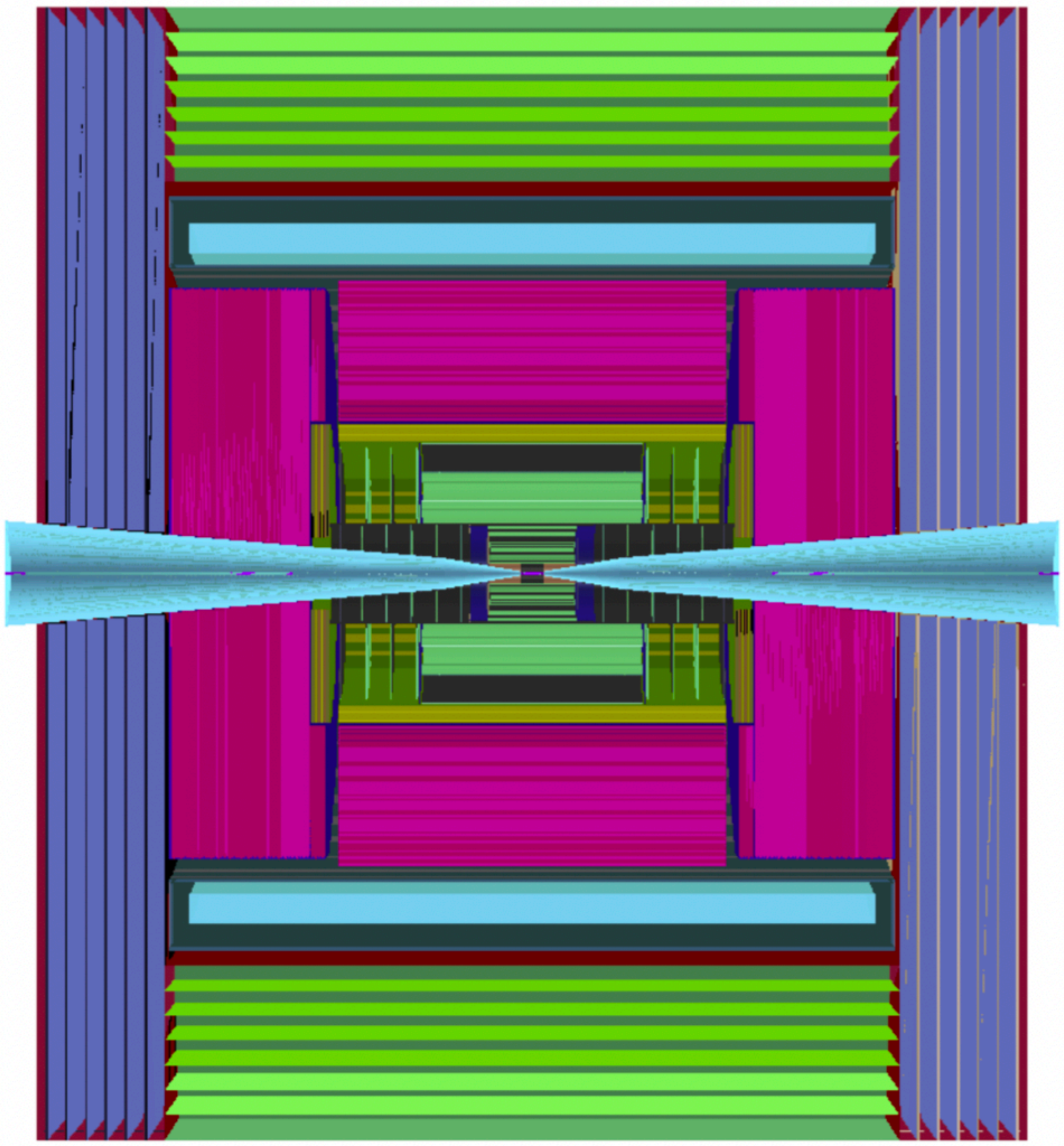


*All decays of one beam near the IP*

- μ are of course not stable: will decay in flight
  - Electrons from decay strike shielding, and produce showers that (unfortunately) penetrate to the detector
- Beams of μ will be continuously decaying: constant stream of background into the detector
  - Mitigating "**Beam Induced Background**" is the main detector design challenge

# Shielding

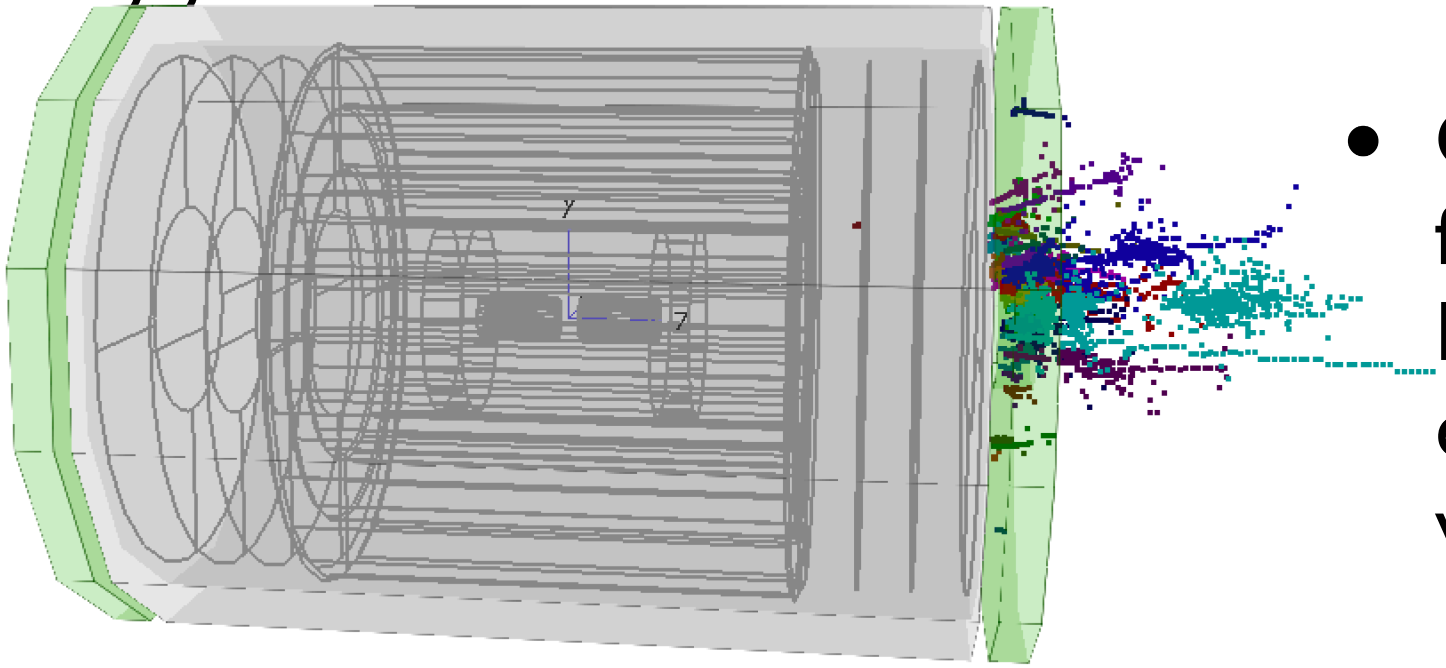
Detector Performance Report

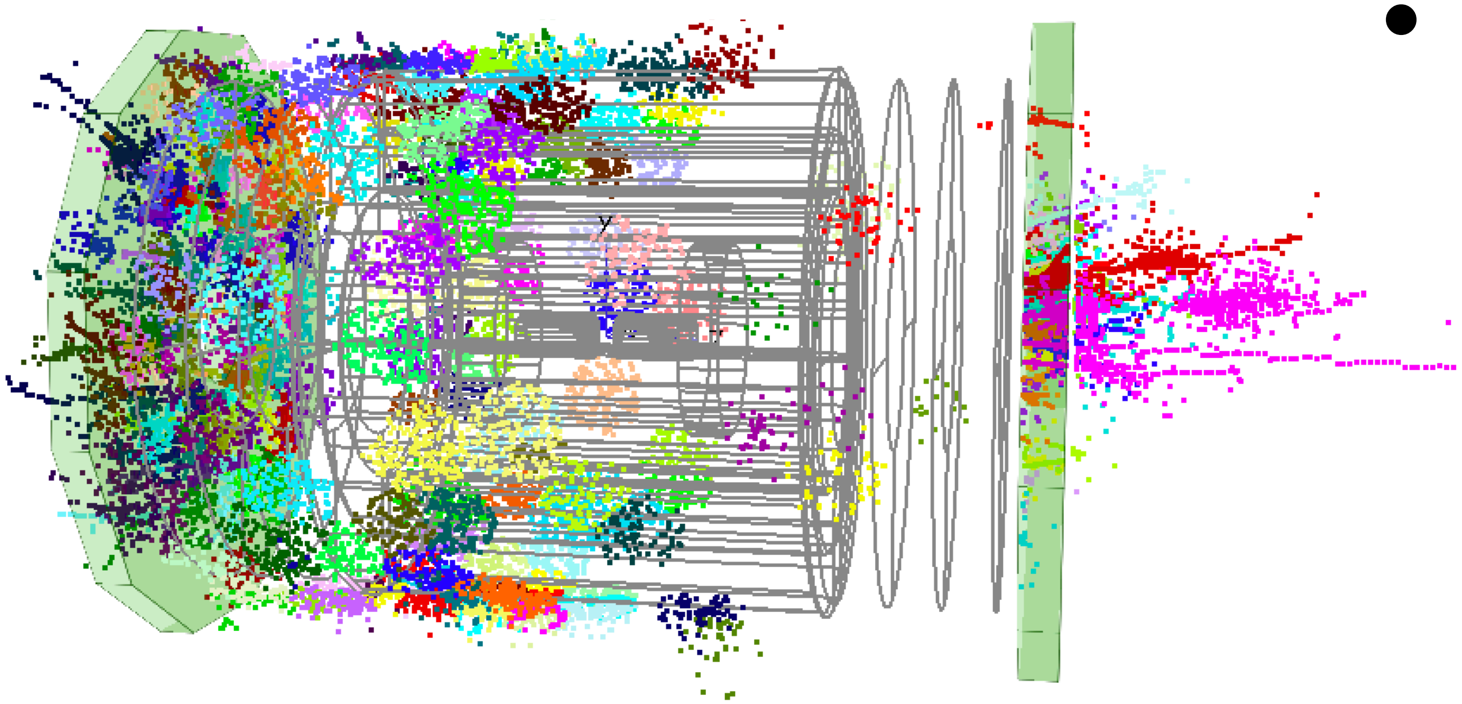


- **Shielding** (in cyan) is the first line of defence against BIB
  - Tungsten nozzles coated in borated polyethylne
  - Reduces background reaching the detector substantially
  - Currently optimized for 1.5 TeV collider: probably substantial room for improvement
- Large implications for detector design!
  - Limited forward coverage
    - Challenges for hadronic recoil, measurements with missing momentum, etc.

# BIB In The Detector

$\mu\mu \rightarrow H\nu\nu \rightarrow bb\nu\nu$





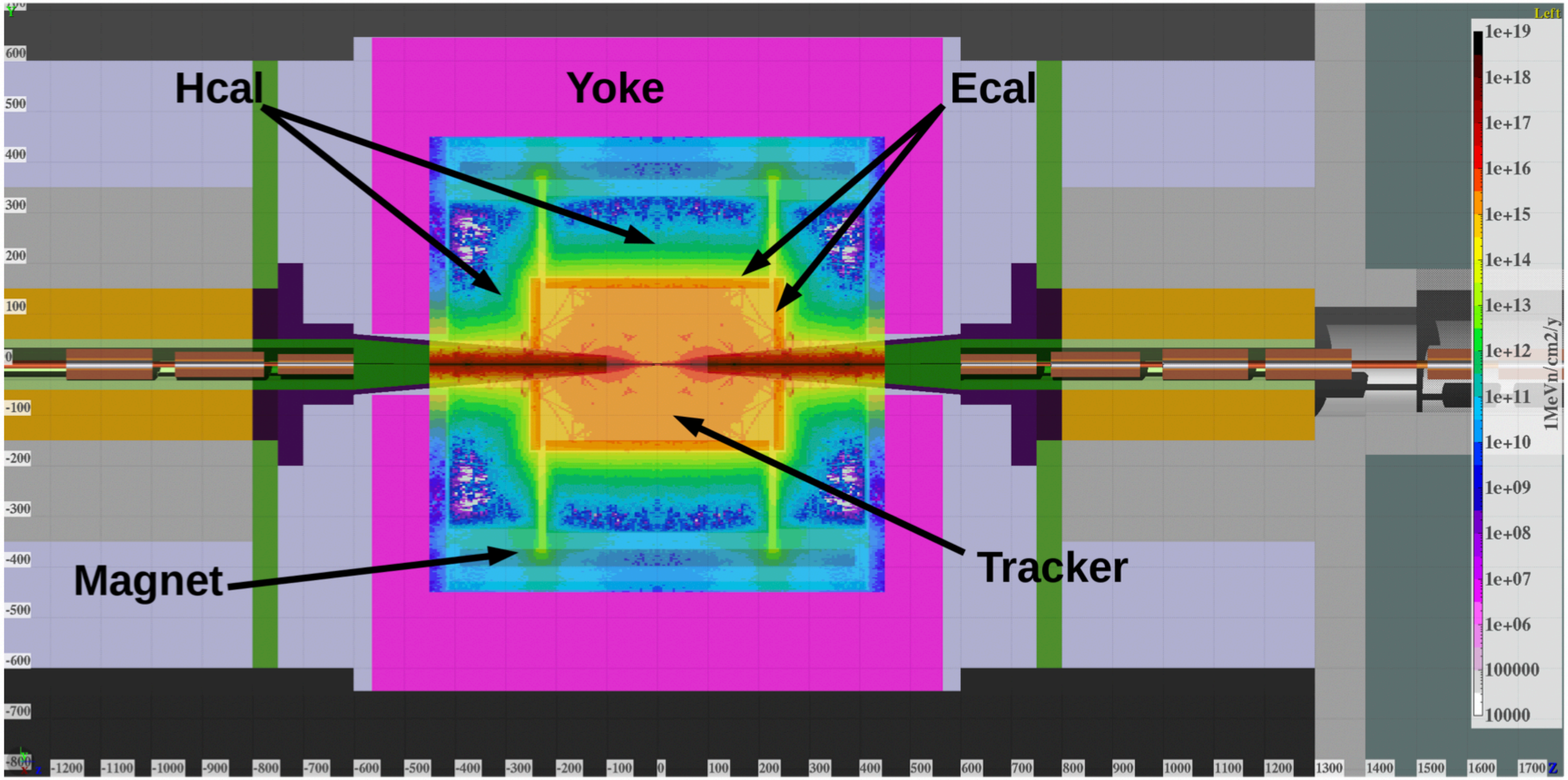
$\mu\mu \rightarrow H\nu\nu \rightarrow bb\nu\nu$ + 0.03% BIB

- Quite a different challenge from pileup at the LHC or FCC-hh: total BIB is greater in energy than the collision, but very soft/diffuse

- Here, even with 0.03% of BIB, the event looks dramatically different from the clean collision!
  - Informs detector design and R&D considerations

# Radiation

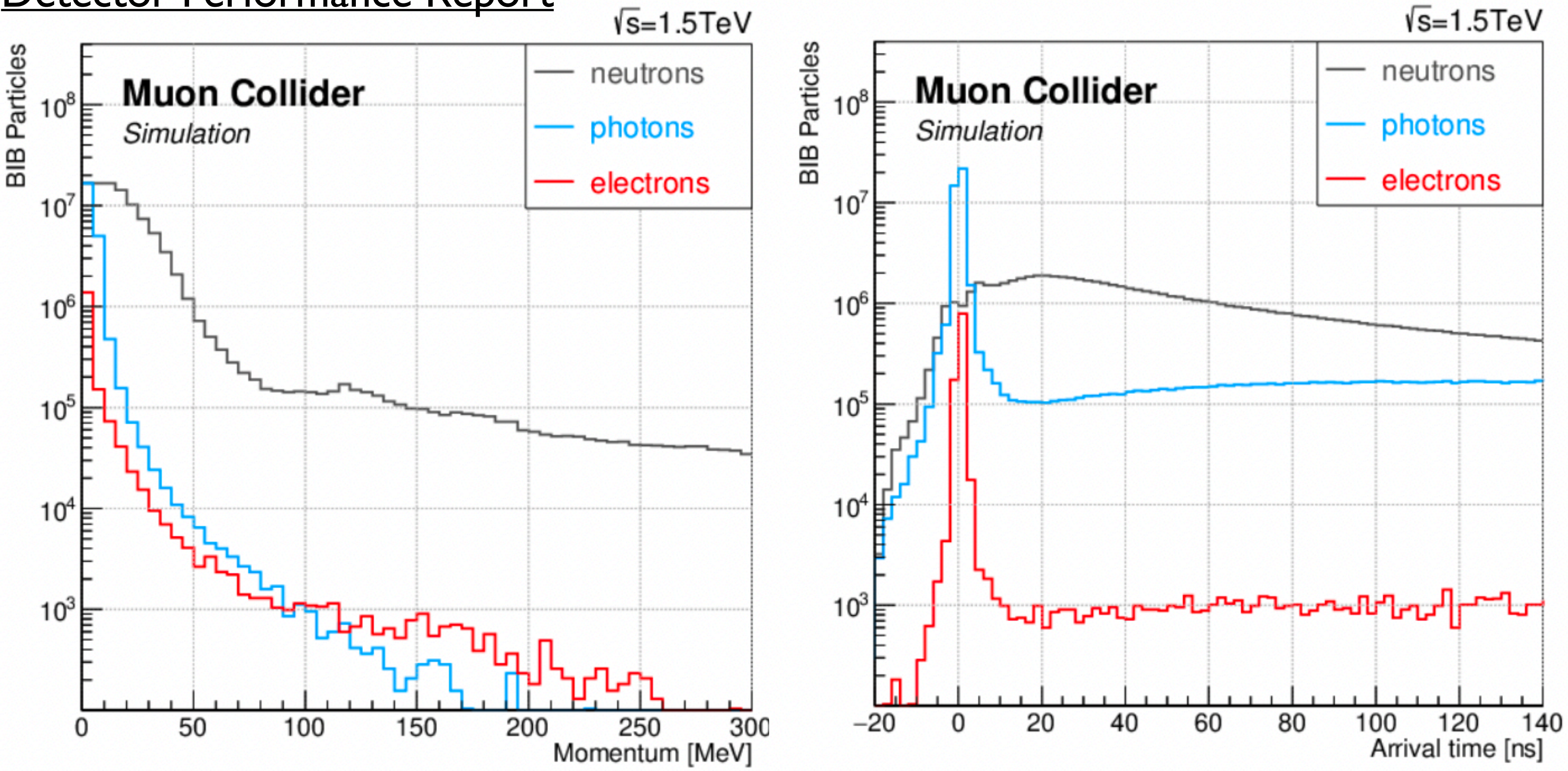
arXiv:2105.09116



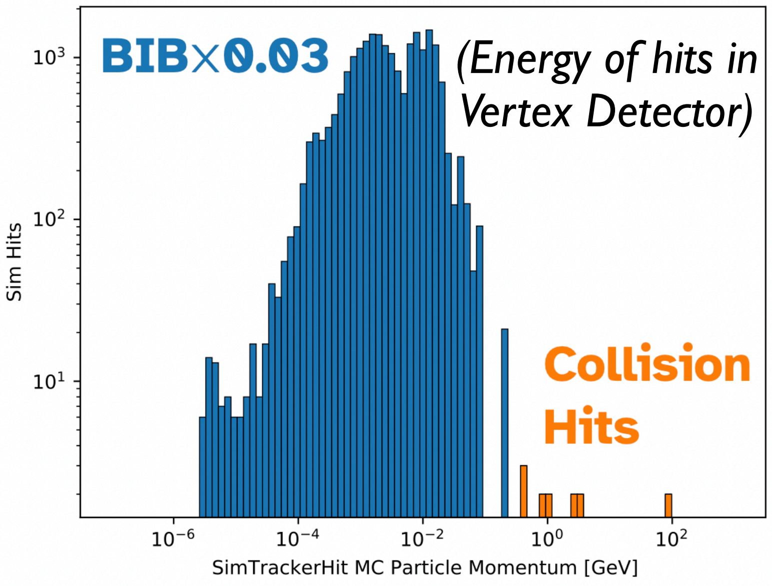
- BIB also causes a significant radiation challenge, especially for vertex detector
  - Expected radiation at the $10^{15}$ $n_{eq}$ / yr: roughly similar to HL-LHC (but very different from $C^3$ requirements!)

# BIB Characteristics

Detector Performance Report



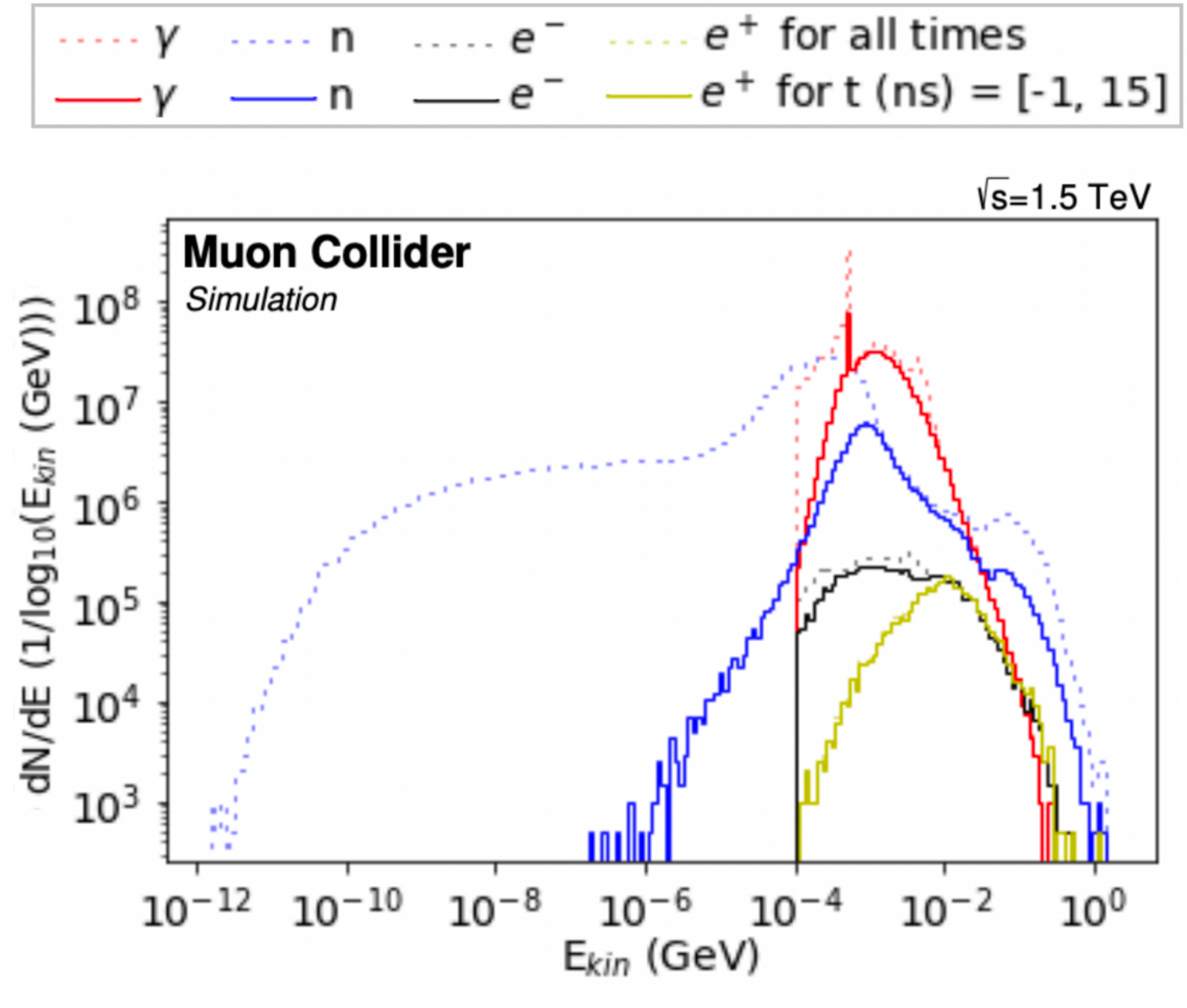
Larry Lee et al



- Huge number of BIB particles: originate from interactions of electrons with shielding, etc.
  - E.g. in vertex detector, HITS are dominated by BIB
- Energy distribution is peaked very low
- Timing is also very dispersed: widely varying arrival times (usually late) for BIB particles

# Timing with BIB

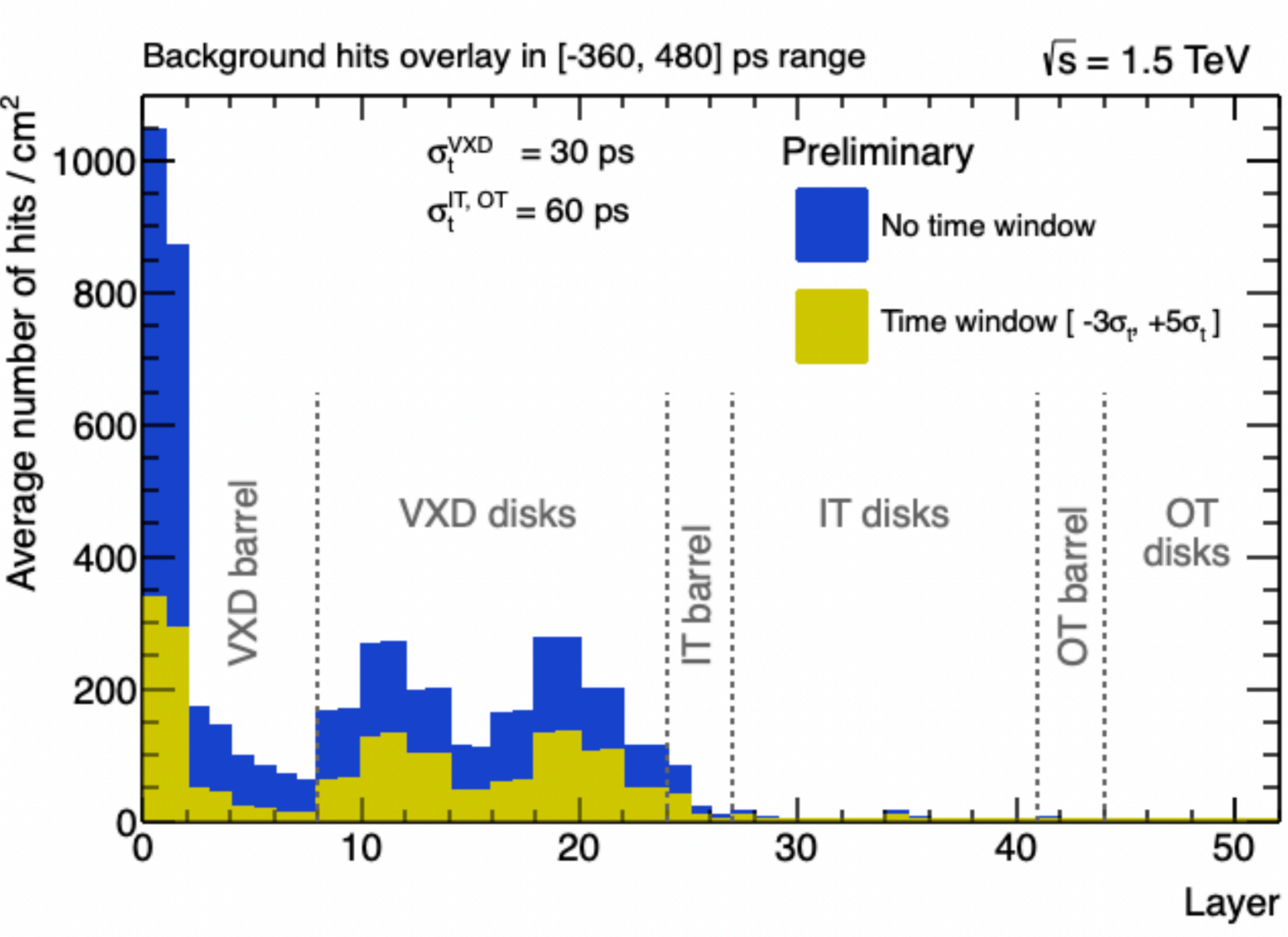
Detector Performance Report

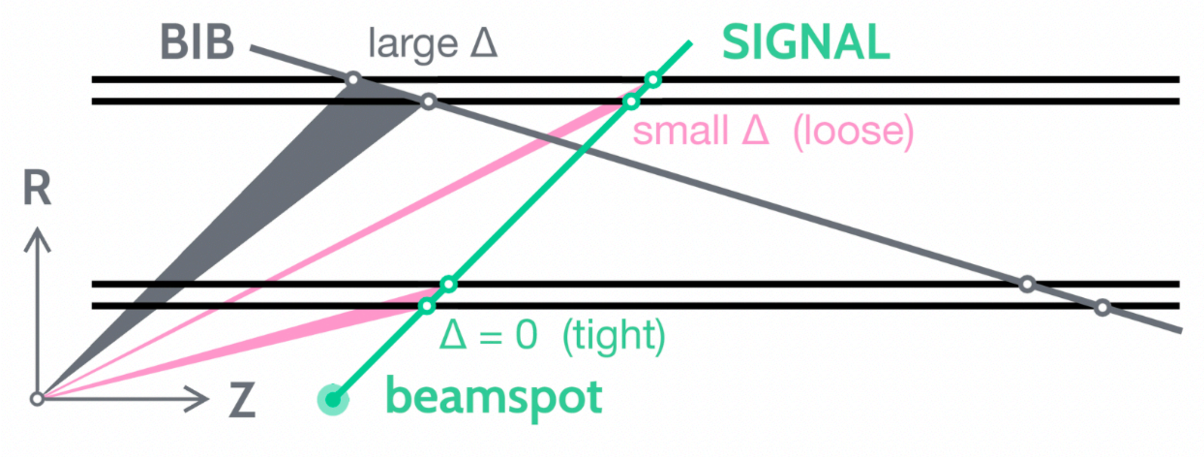


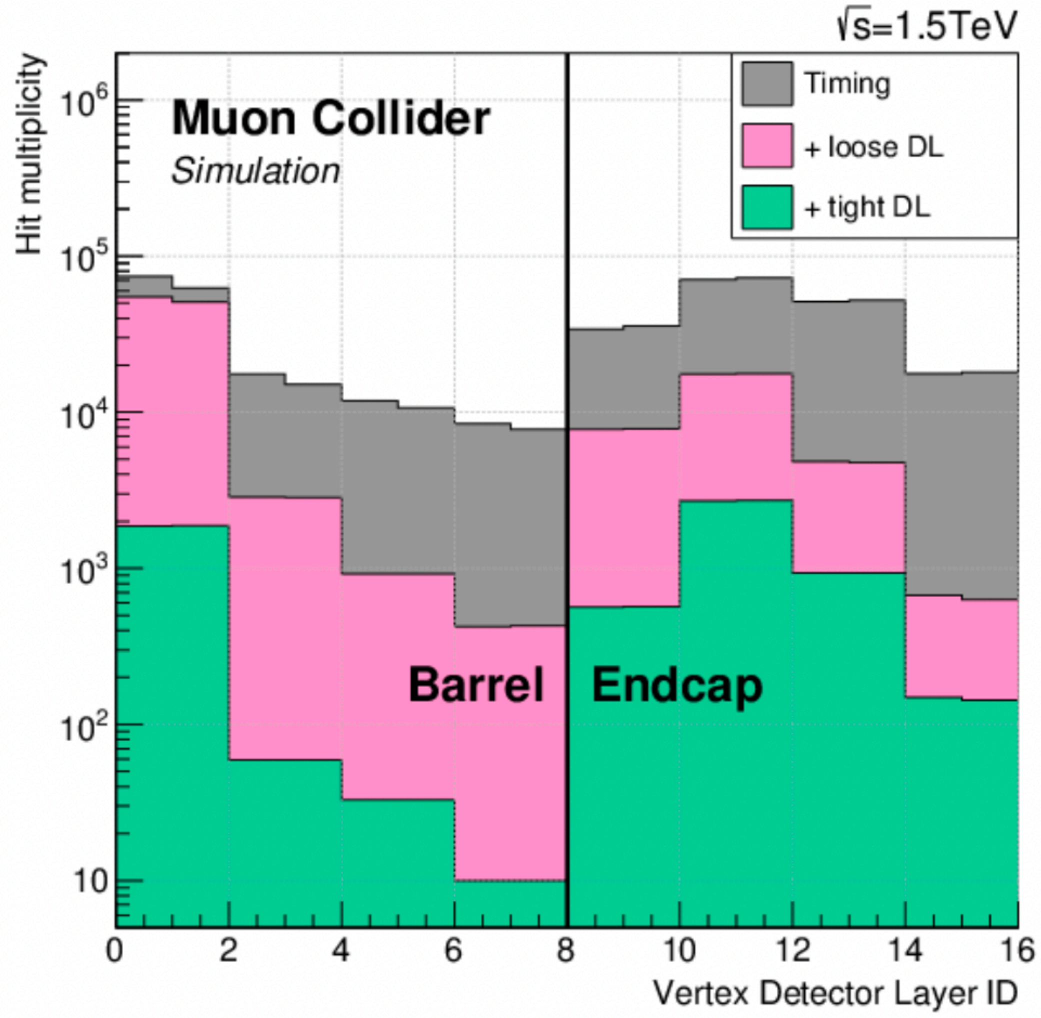
- Timing cuts (even fairly loose!) can substantially reduce impact of BIB
- But large contributions will remain
  - Tighter timing windows and other methods still required to reduce contamination

# Tracking with BIB

Detector Performance Report

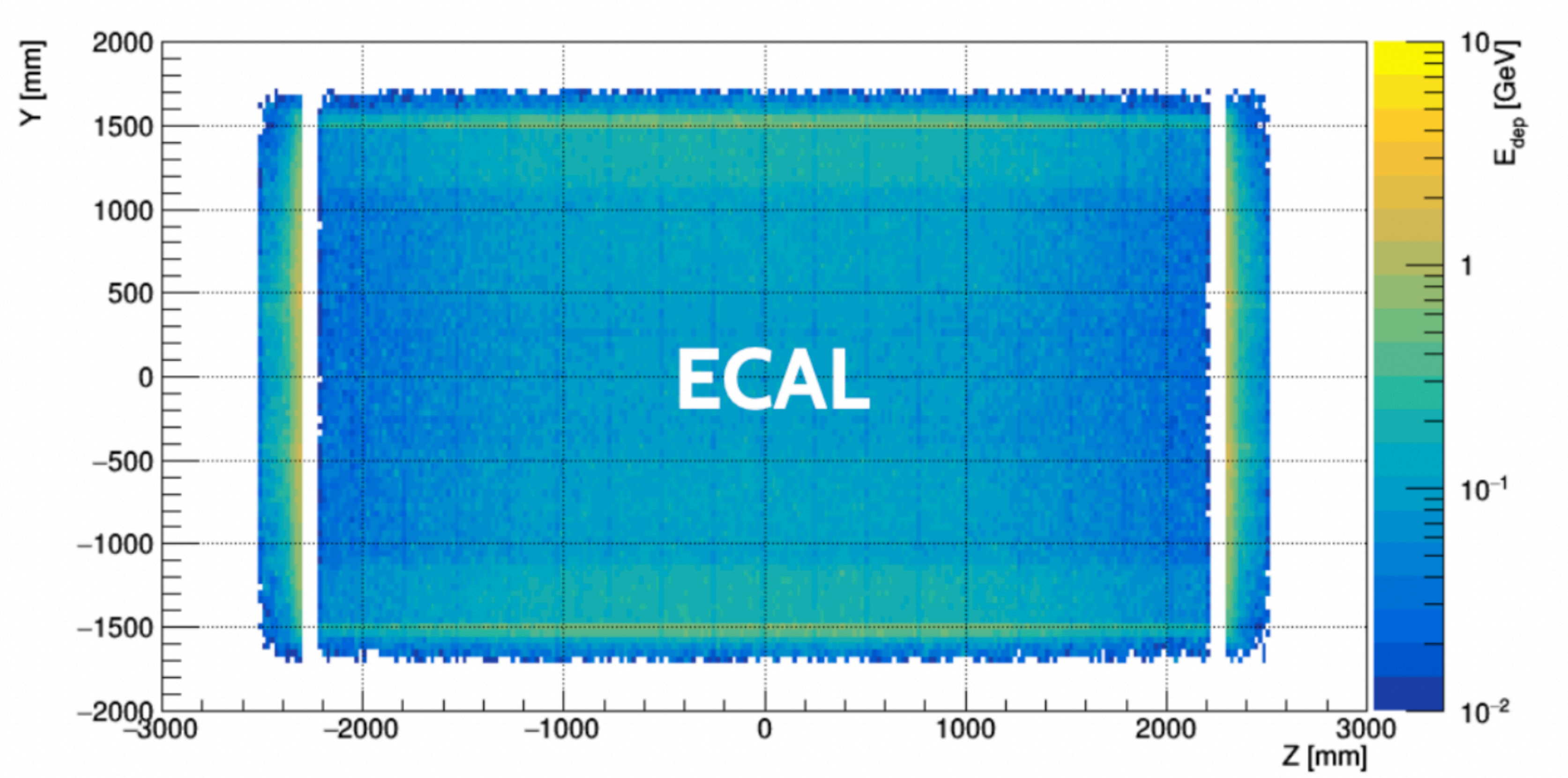


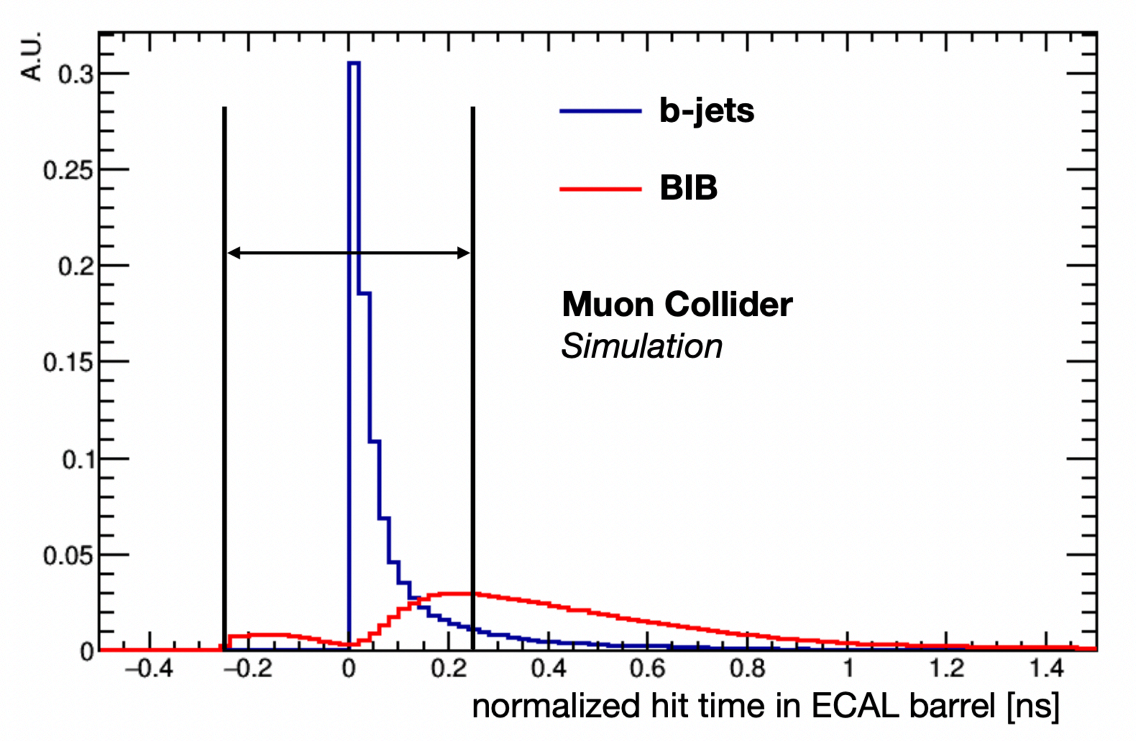




- 30-60 ps timing can reduce hit occupancy even further
- "Double layer" tracking (and beamspot requirement) can reduce occupancy even further
- These are examples of detector development required to operate in the µC BIB environment

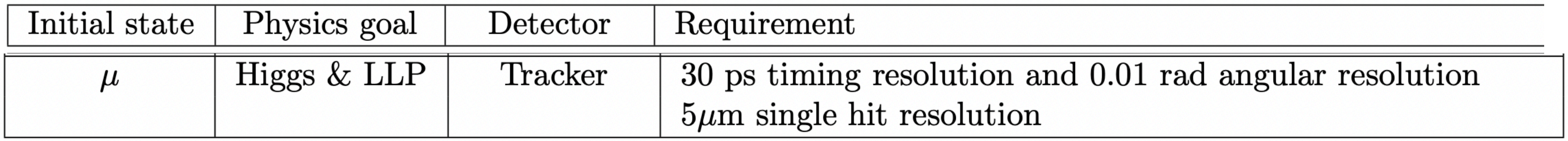
# Calorimetry with BIB





- BIB presents enormous soft, diffuse background to collisions at the μC
    - Integrated energy from BIB substantially greater than scattering!
- Timing can substantially reduce backgrounds
- Exploiting granularity also seems to be key: suppress BIB with energy cuts per cell. Requires high-granularity calorimetry (e.g. CALICE)
- Both cuts substantially deteriorate resolution, but necessary to remove BIB
- Future analysis and detector developments key to improving jet resolution

# Requirements for µC



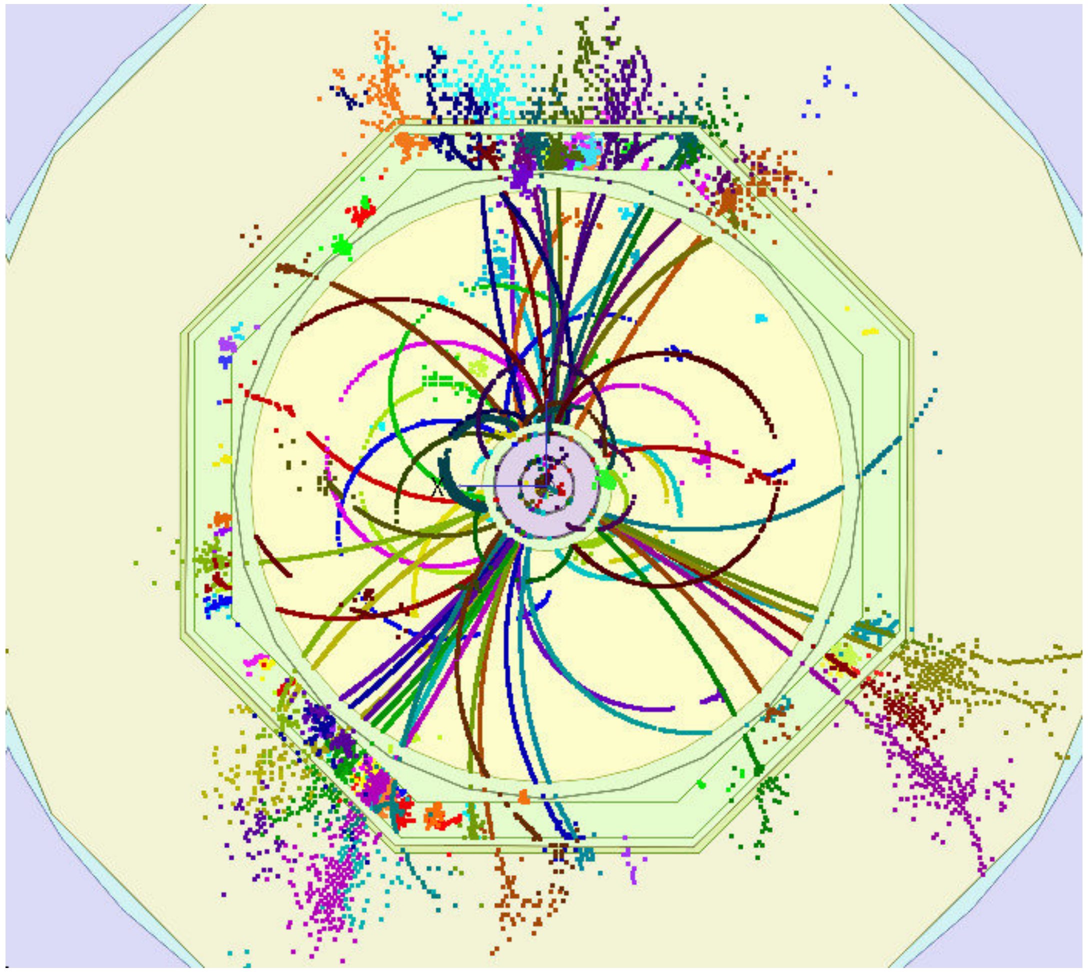
| Initial state | Physics goal | Detector | Requirement |
|---|---|---|---|
| $\mu$ | Higgs & LLP | Tracker | 30 ps timing resolution and 0.01 rad angular resolution<br>$5\mu$m single hit resolution |

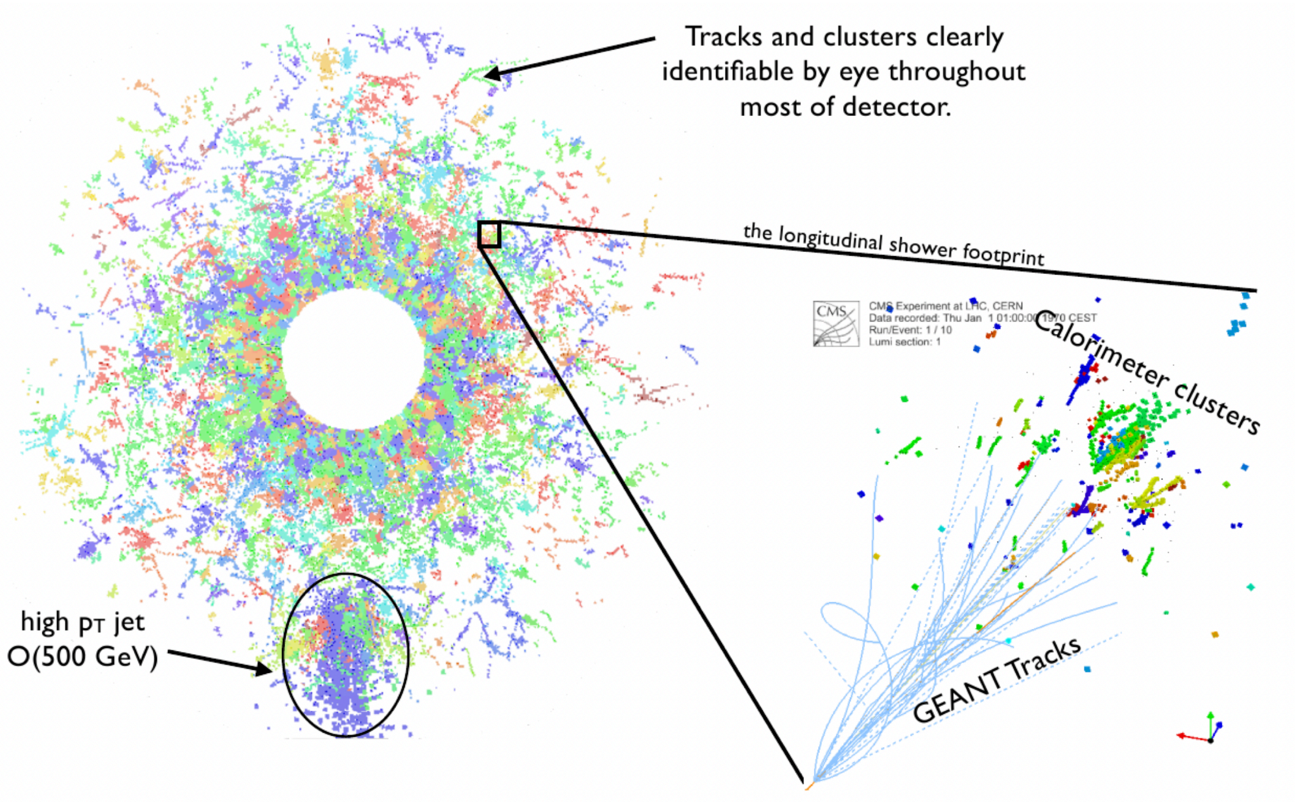
- µC requirements less well defined in Snowmass report, but I hope the previous few slides have given you an impression of what is needed
    - Picosecond timing for tracking, high radiation tolerance, potential double layer for background suppression
    - High granularity for calorimetry for BIB suppression
    - Much less focus on precision (material, etc.): instead, focus on background suppression to enable discovery

# An Example of Complementarity

# HGCal Calorimetry

<u>ILD Calorimetry </u>optimized for PFlow resolution





<u>CMS Calorimetry </u>optimized for pileup (and PFlow resolution)

- CALICE-style high granularity calorimetry was designed for ILD/SiD to obtain best jet resolution for Higgs measurements
- Turns out to be extremely useful for pileup suppression at the HL-LHC: completely different environment and challenges, but same technology becomes applicable!
- **Can we identify overlap like this for two different sets of requirements? Maximize our $$ investments?**

# Conclusions

# Conclusions

- The μC and $C^3$ environments have very different challenges
- Both require ongoing detector R&D and optimization
- In many cases the detector needs require extreme focus, but in others the needs may be able to be addressed by common technologies
- As we build the case for detector R&D funding and new technologies, options that address the needs of both programs may be more attractive
    - But this is open for discussion, and should be physics and $ driven!