Fast Timing

for Muon Colliders

Lawrence Lee

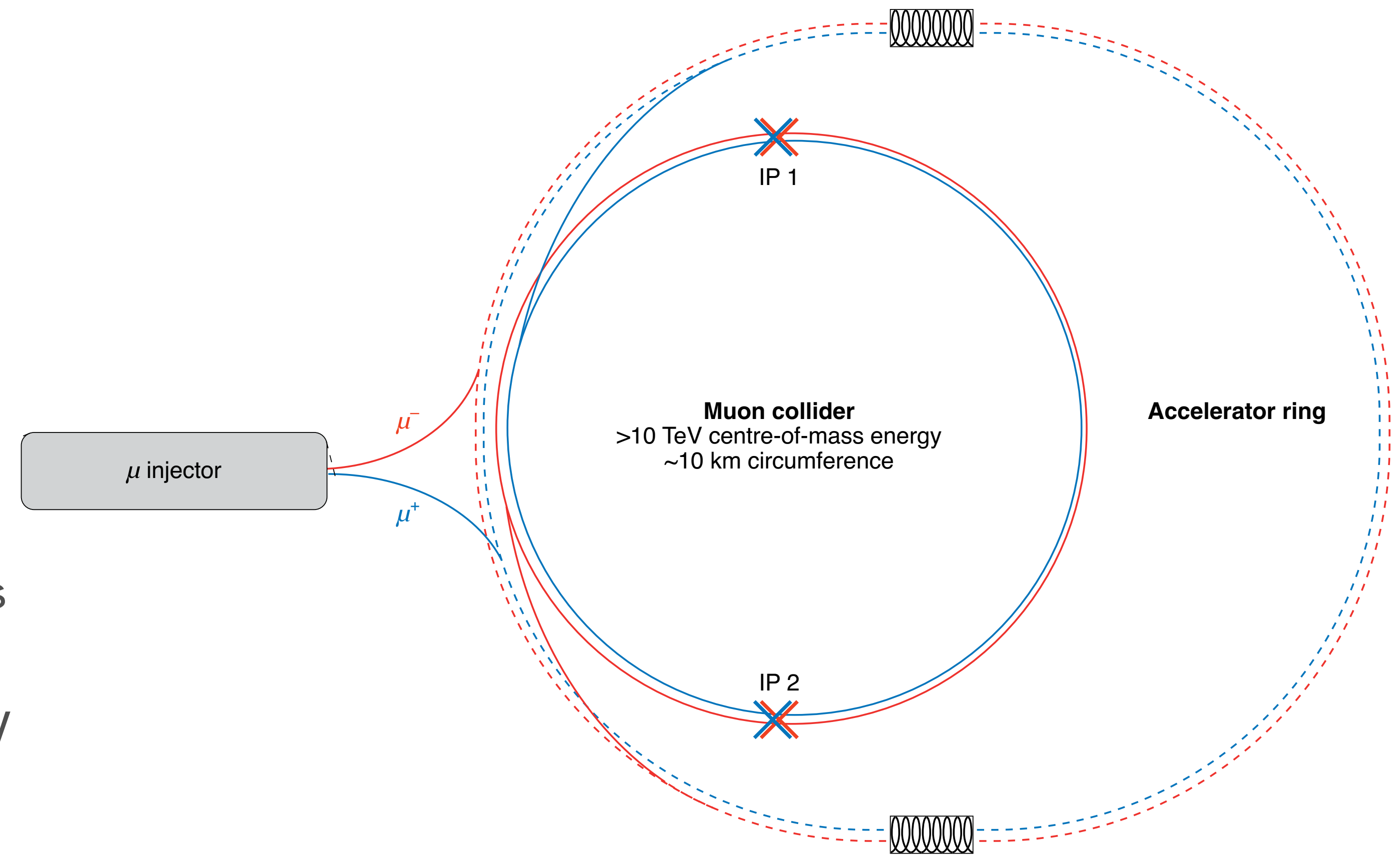
Based on the work of many

Significant input from Simone Pagan Griso, Lorenzo Sestini, Donatella Lucchesi, Chiara Aimè, and others

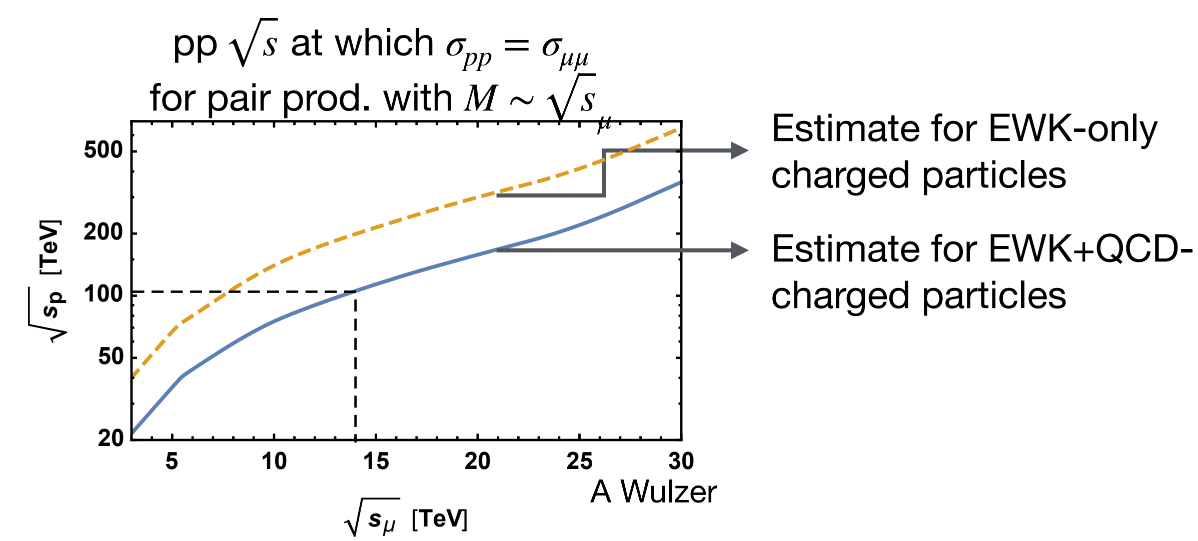
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Discovery Muon Colliders

Nature Physics

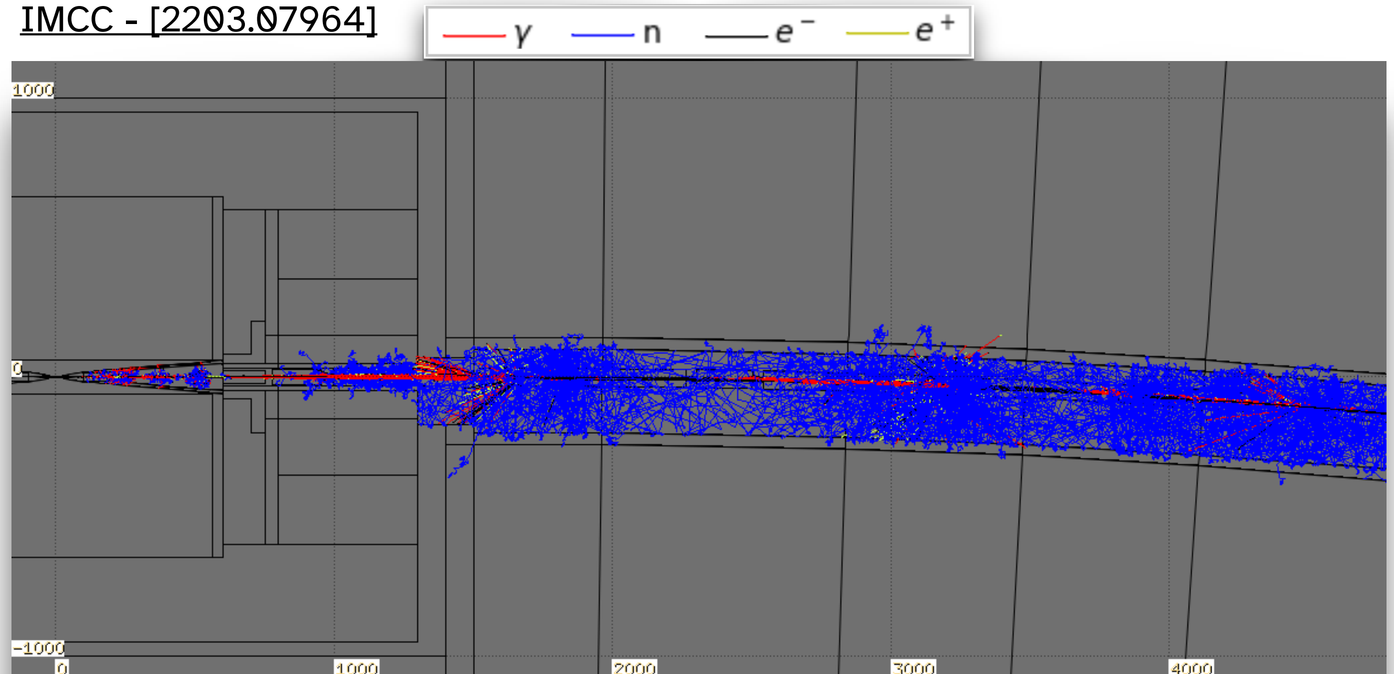


- As discussed throughout this meeting, **Muon Colliders are uniquely great way to push the energy frontier**
  - **Precision** of a lepton collider
  - **Discovery** potential of a hadron collider
    - Hard scatter scale spread from VBF processes
    - Multi-TeV energy reach, some heavy particle production XS rivaling and surpassing 100 TeV pp machines
- Challenges on accelerator side have promising paths forward
- Major EF/AF focus: **Understanding (and reducing) immense Beam Induced Backgrounds (BIB)** largely from metastability of muons
- This talk: Focus on √s=1.5 TeV, but challenges broadly similar for Higgs factory and multi-TeV configurations



Beam Induced Backgrounds

IMCC - [2203.07964]



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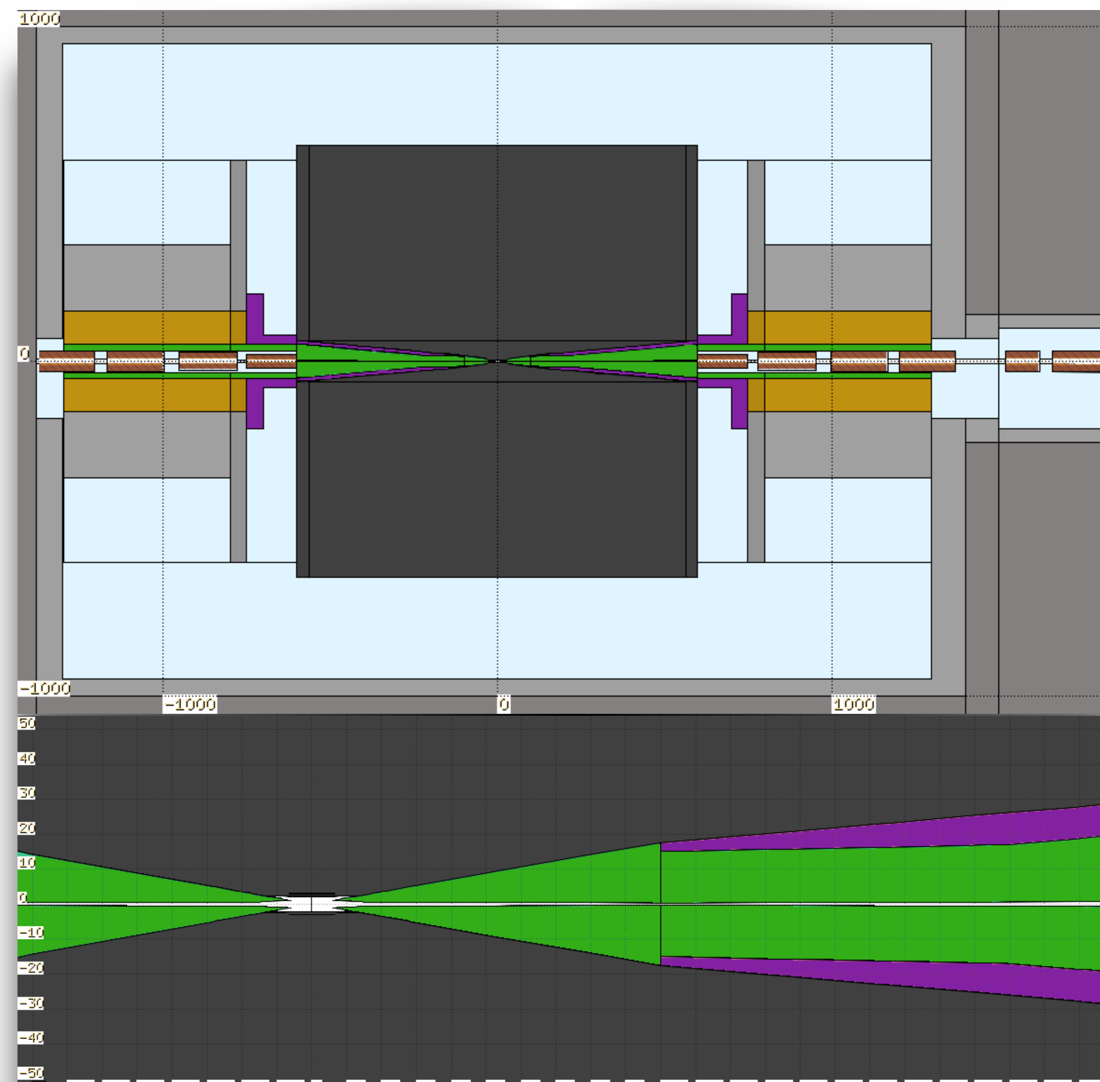
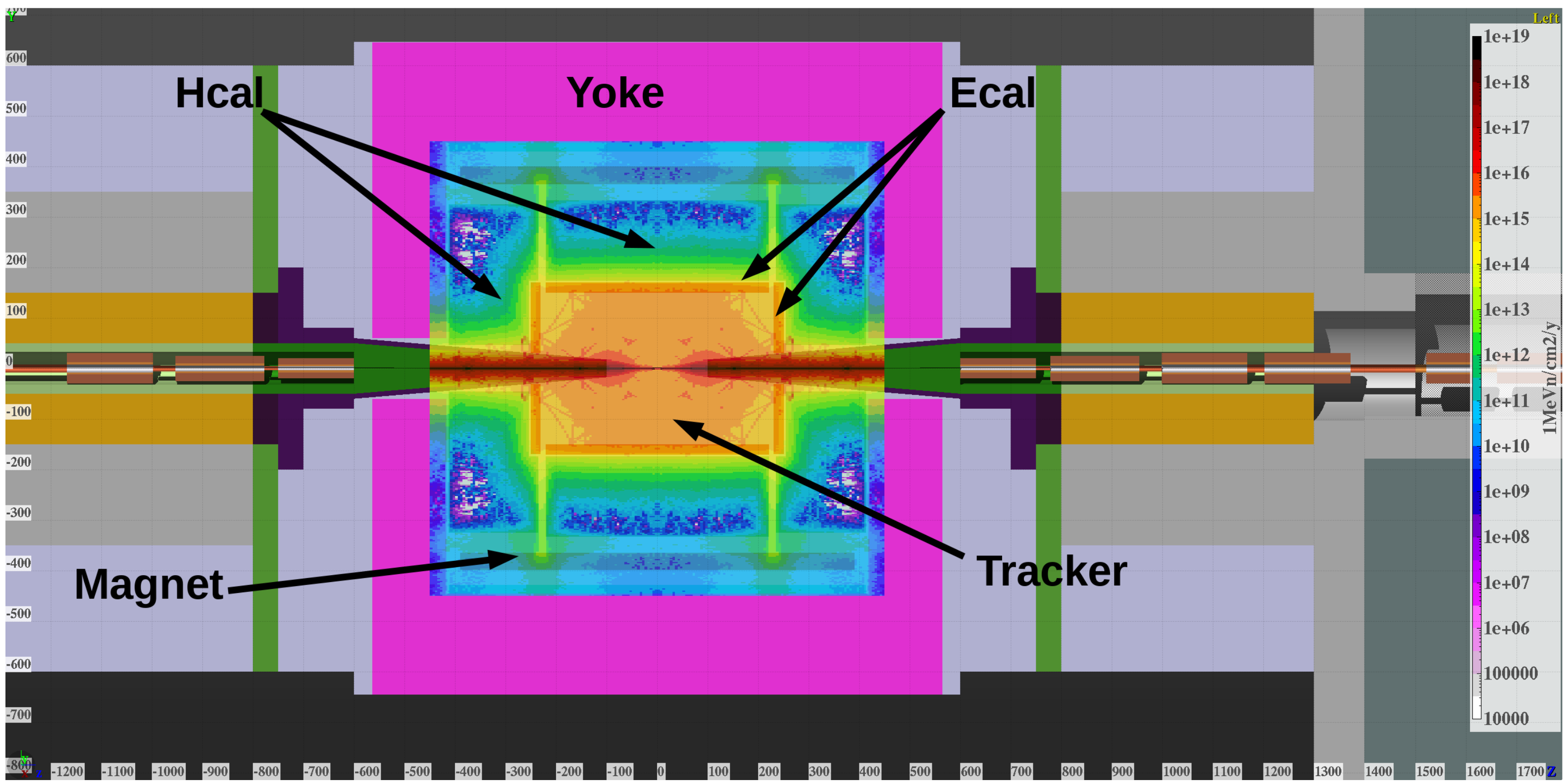


- **Enormous number of particles in detector region** from decaying muons and their byproducts
- As in MAP, forward region covered by coated tungsten conical **nozzles** to shield from BIB
    - Reduces BIB in detector by **many orders of magnitude**
- Most recent studies have assumed modified CLIC detector
- BIB simulations used here: MARS15+FLUKA

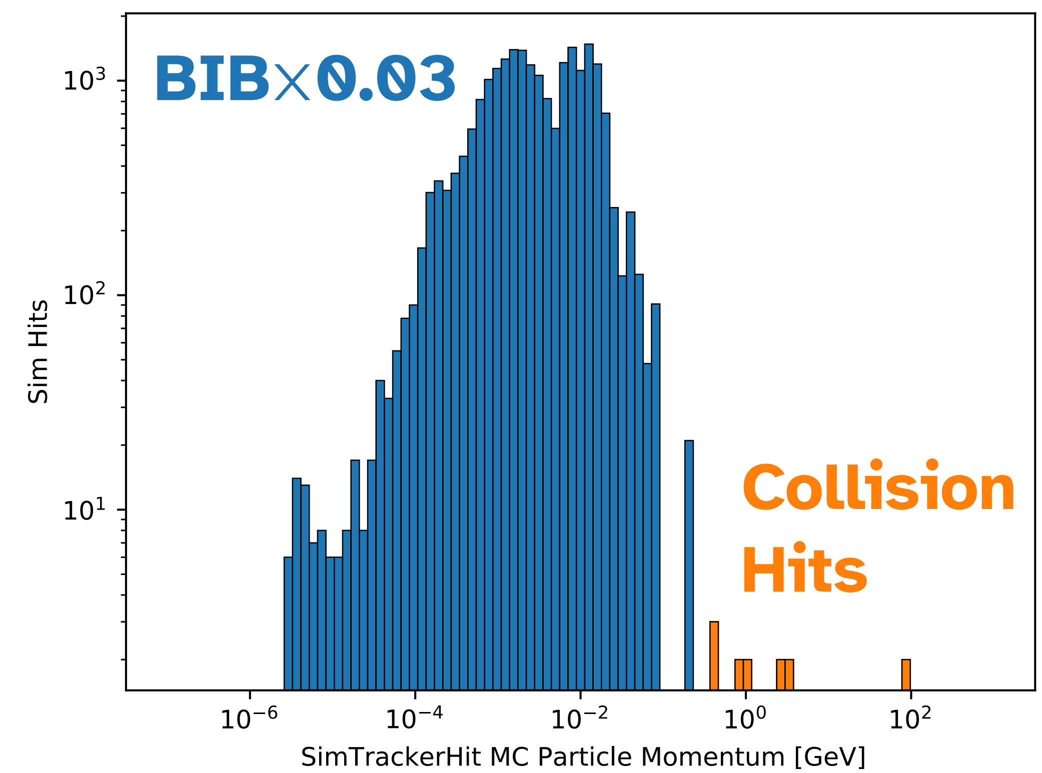
Beam Induced Backgrounds

200-day 1-MeV-neq Fluence



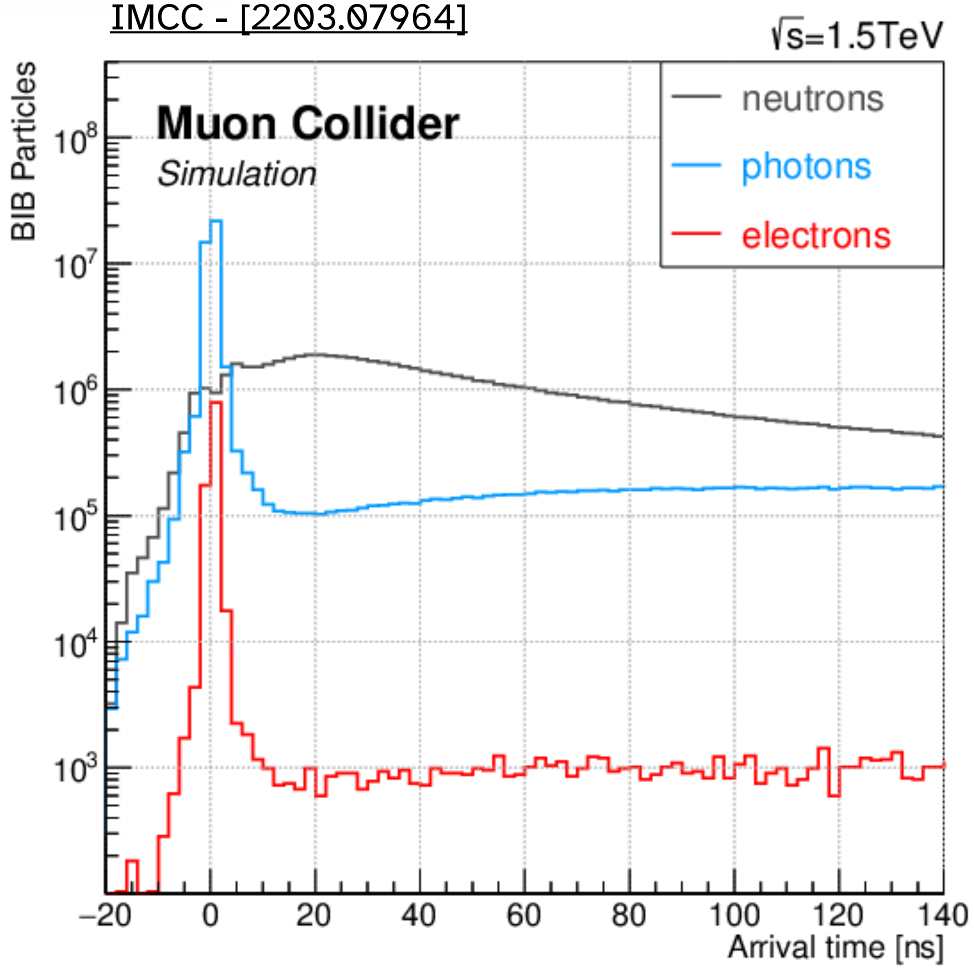
FC, CC, DL, AM, NM, MP, PS - [2105.09116]

GEANT Hits in Vertex Detector

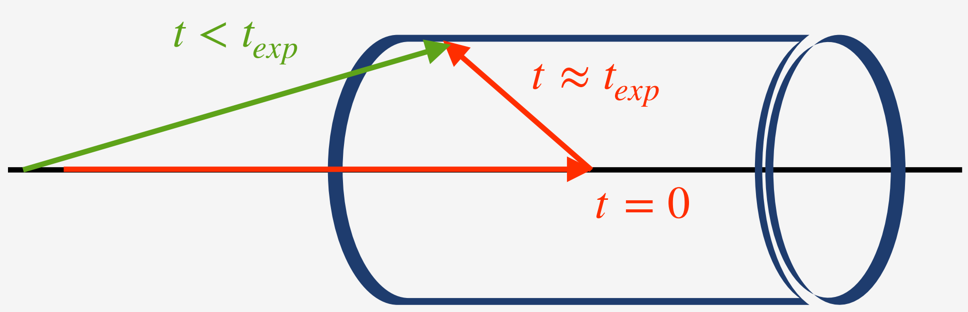


- **Very large fluence** especially near beam line and nozzles
- e.g. in Vertex Detector, hits from collision byproducts **hugely overshadowed by low energy BIB depositions**

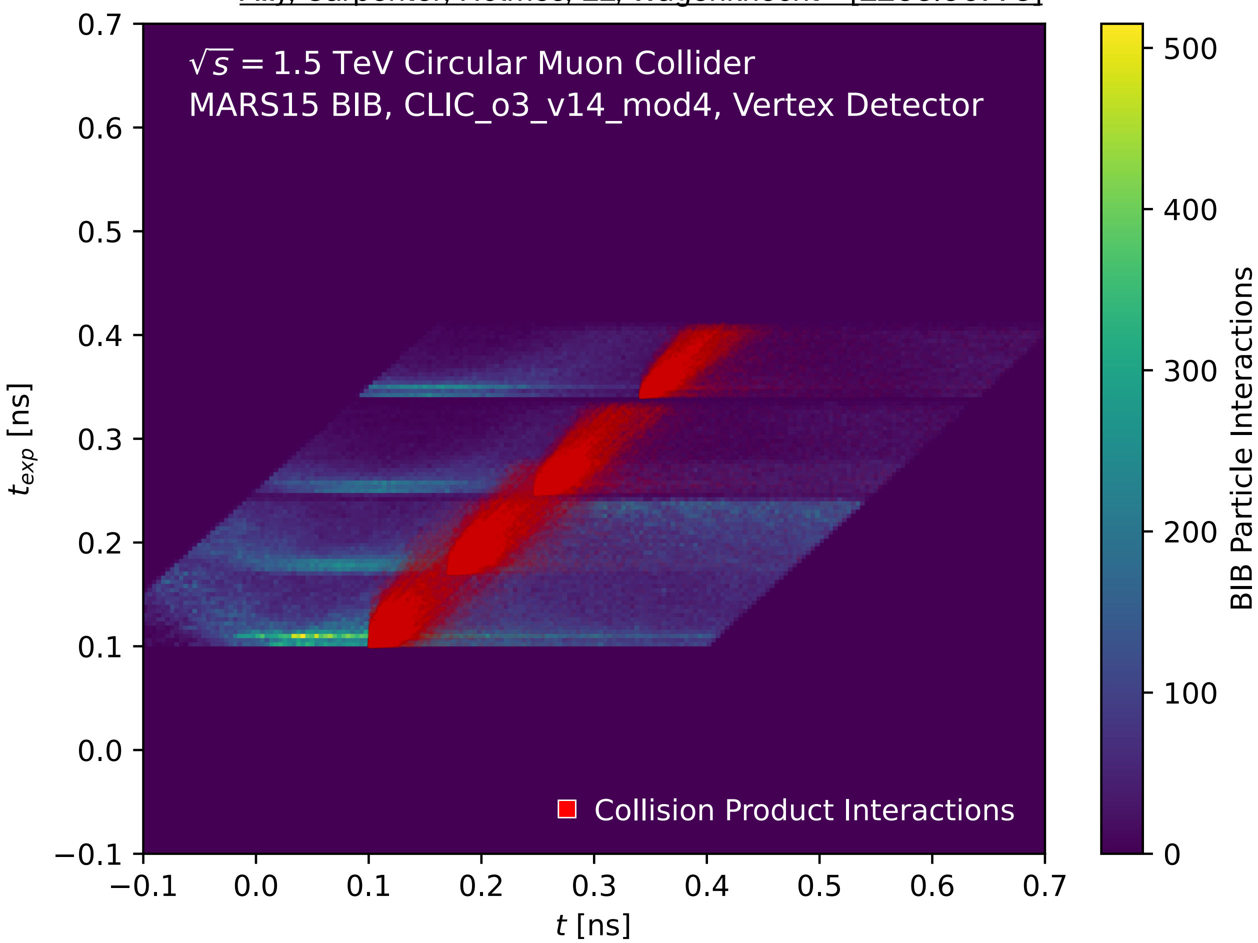
IMCC - [2203.07964]



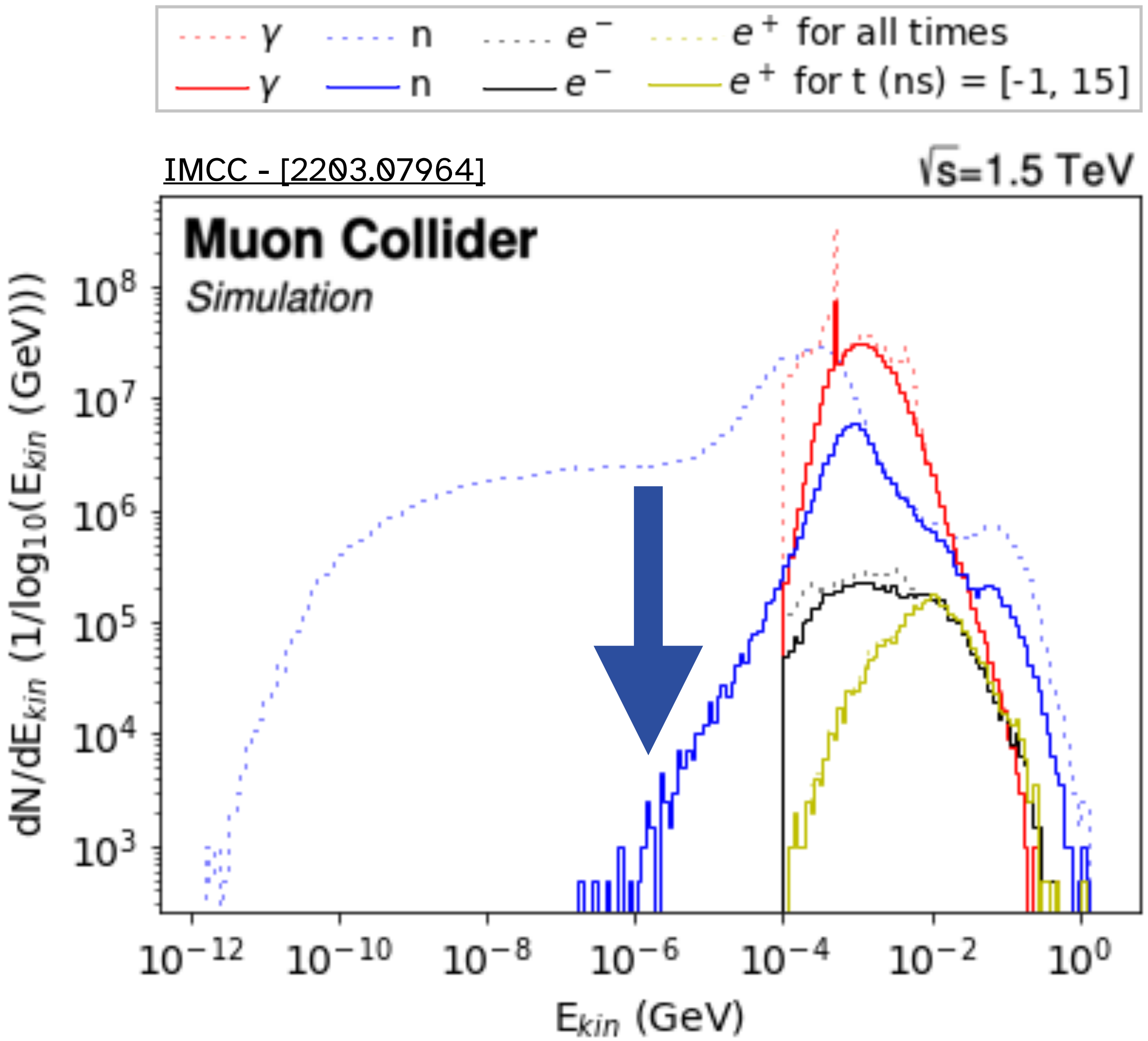
- **BIB particles** enter detector in time w/ BX but also with **very late arrival times**
- Shorter path length means in-time **BIB component arrives earlier than particles** originating from origin
- **High precision timing measurements necessary** to get physics out of a muon collider



Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]



Timing To Reject BIB

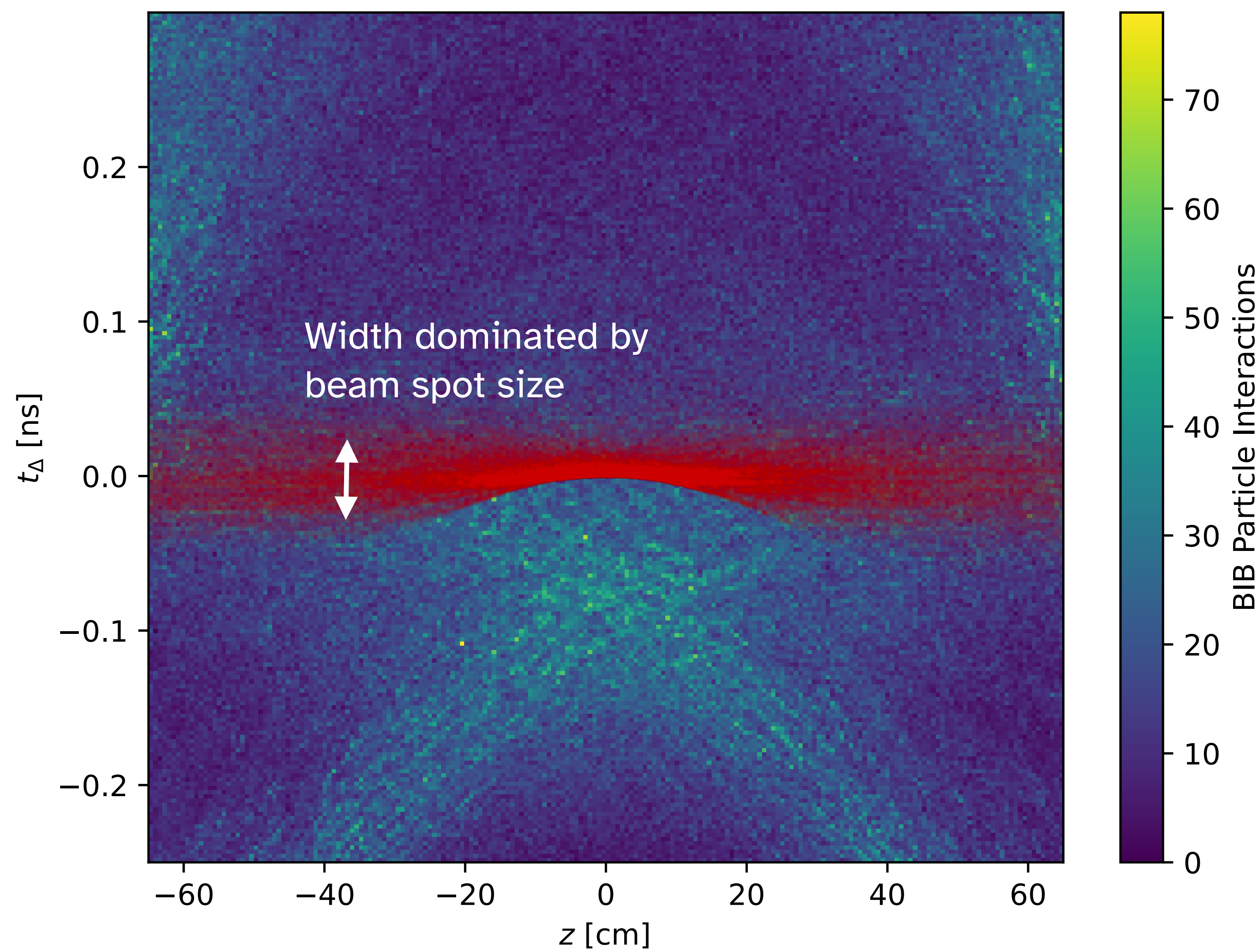


- Broad timing cuts @ **[-1, 15] ns**
  - Greatly reduces BIB effects by orders of magnitude
  - Especially low energy, diffuse contributions
- **But large contributions remain!**

Timing To Reject BIB @O(100) ps

- Below 1 ns, structure to exploit!
- Correct for the time of flight and find the classic **BIB-"fish"** shape
- Detector must resolve time-of-flight to reduce BIB contributions
  - **Position-dependent readout+selection**
- Glancing at plot, **looking towards O(10) ps** resolutions
  - (But studies suggest discrim. power degrades with collider energy)
- Studies performed to start to understand timing needs and promising technologies
  - IMCC - [2203.07964]
  - IMCC - [2203.07224]
  - Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]
  - Lots of studies from previous Snowmass process, MAP, IMCC

$$t_\Delta = t - t_{exp}(\beta = 1)$$



Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]

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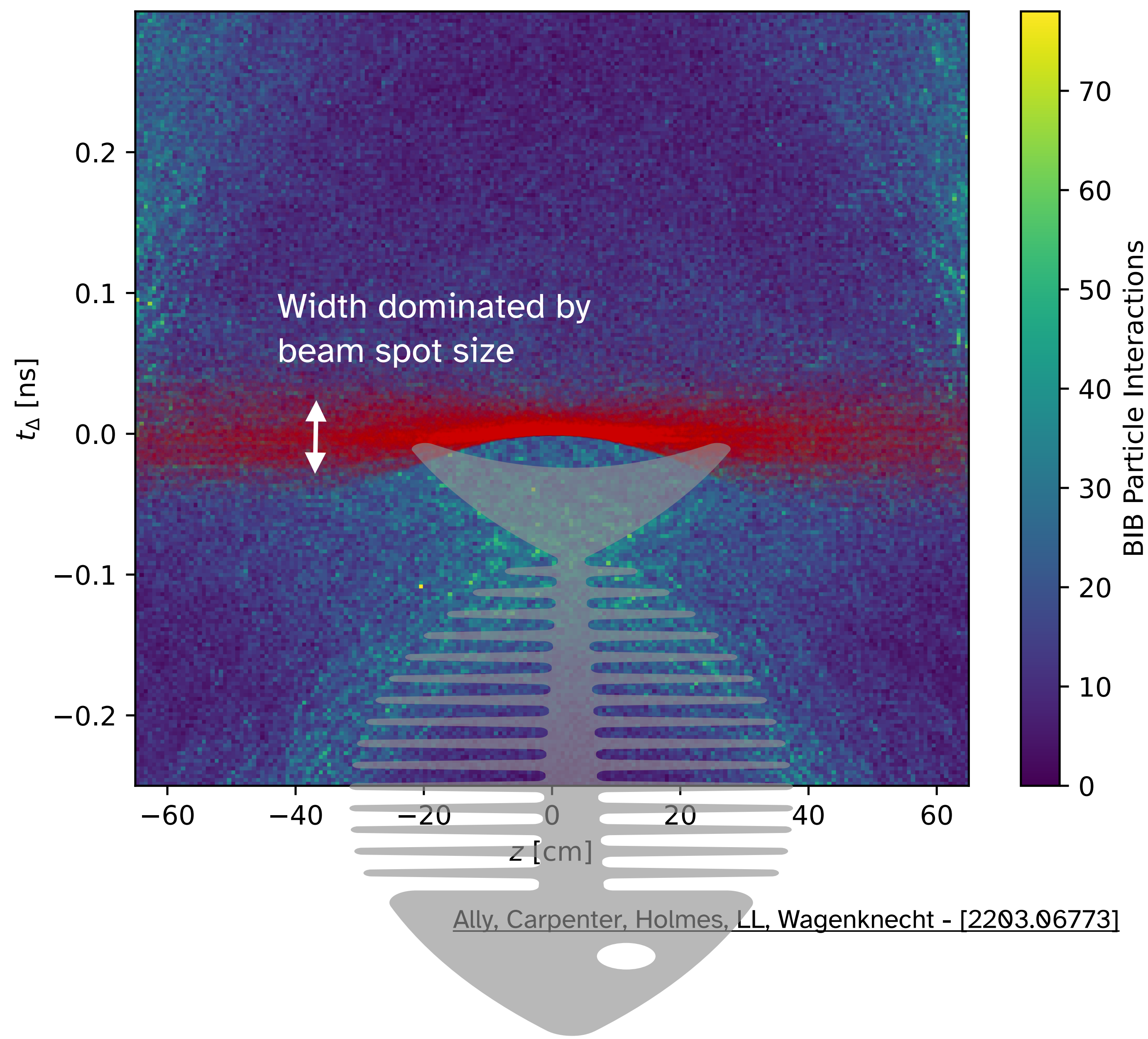

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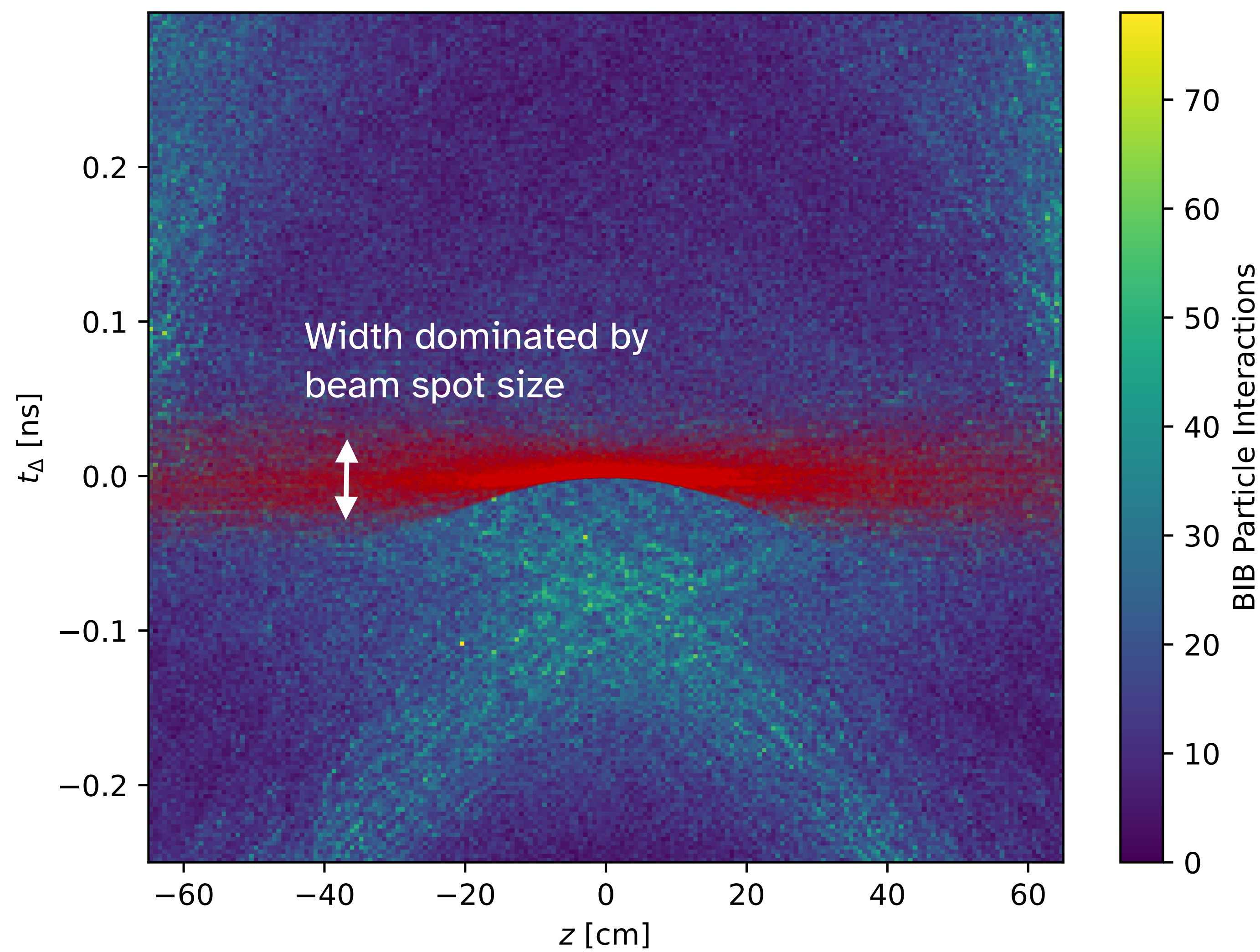


Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]

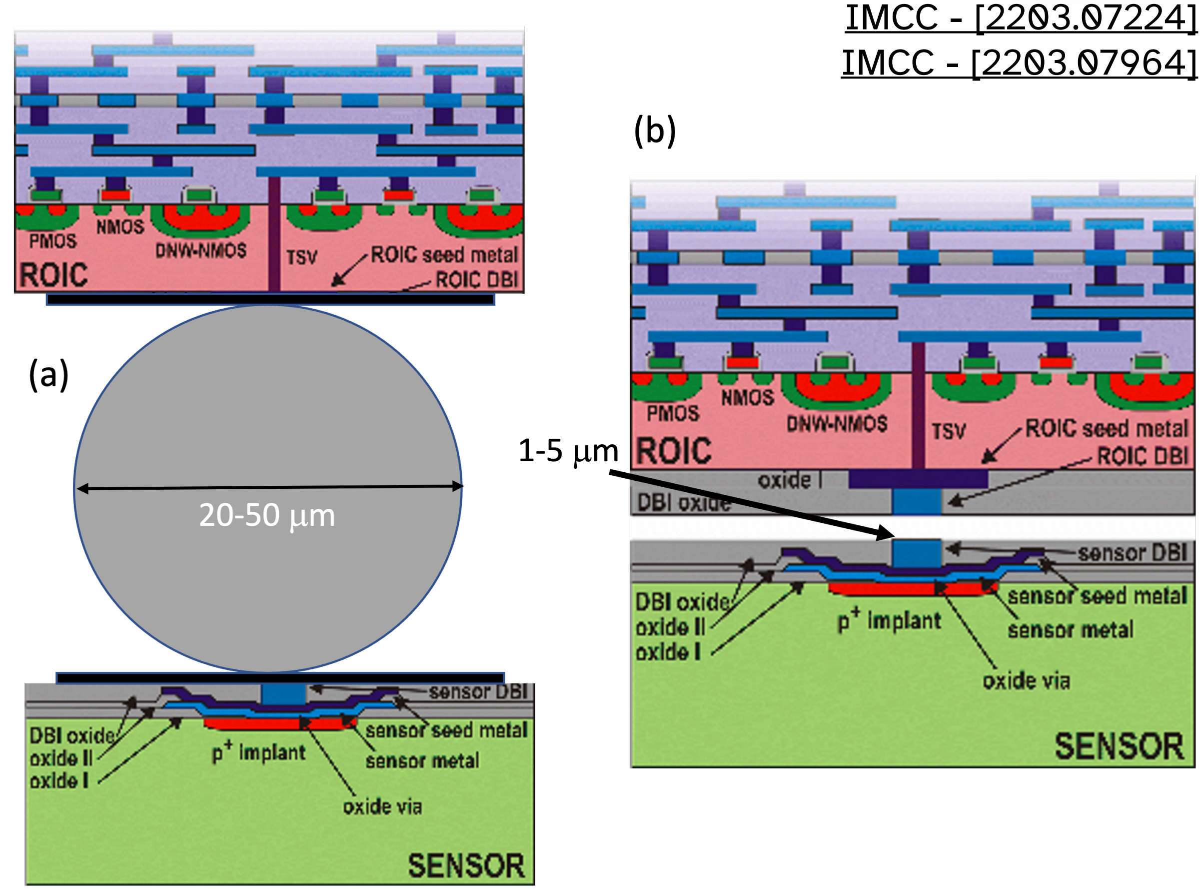
4D TRACKERS

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

Time Resolution | 30ps | 60ps | 60ps

- Tracker should have low occupancy to allow readout and effective tracking algorithms - **Requires BIB reduction**
- Resolution table — Designed to achieve < 1% occupancy
- **R&D efforts crucial**, but ∃ promising tech, e.g.
  - Advanced hybrid bonding tech [3D integration] can give <5 µm pitch and low input capacitance → **20-30 ps resolution**
    - Potential to surpass assumed resolutions!
  - On-detector pulse shape and/or cluster discrimination can help

IMCC - [2203.07224]
IMCC - [2203.07964]



Traditional Bump Bonding
O(10) µm

Stacked bonding
O(1) µm

IMCC - [2203.07964]

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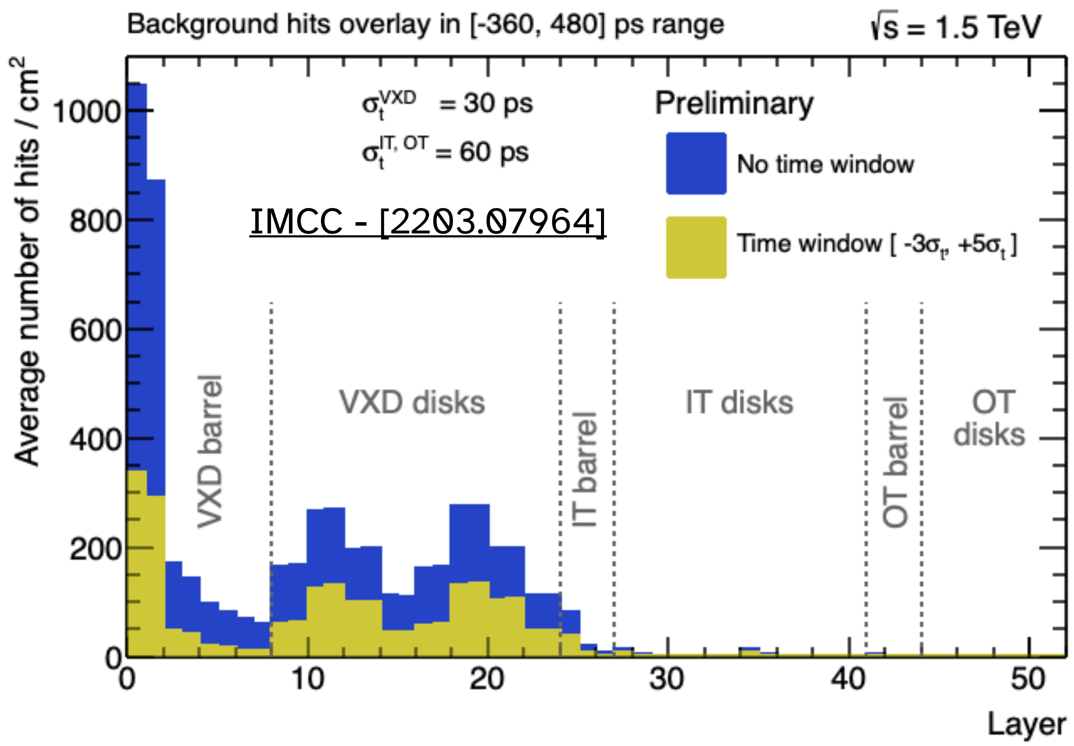

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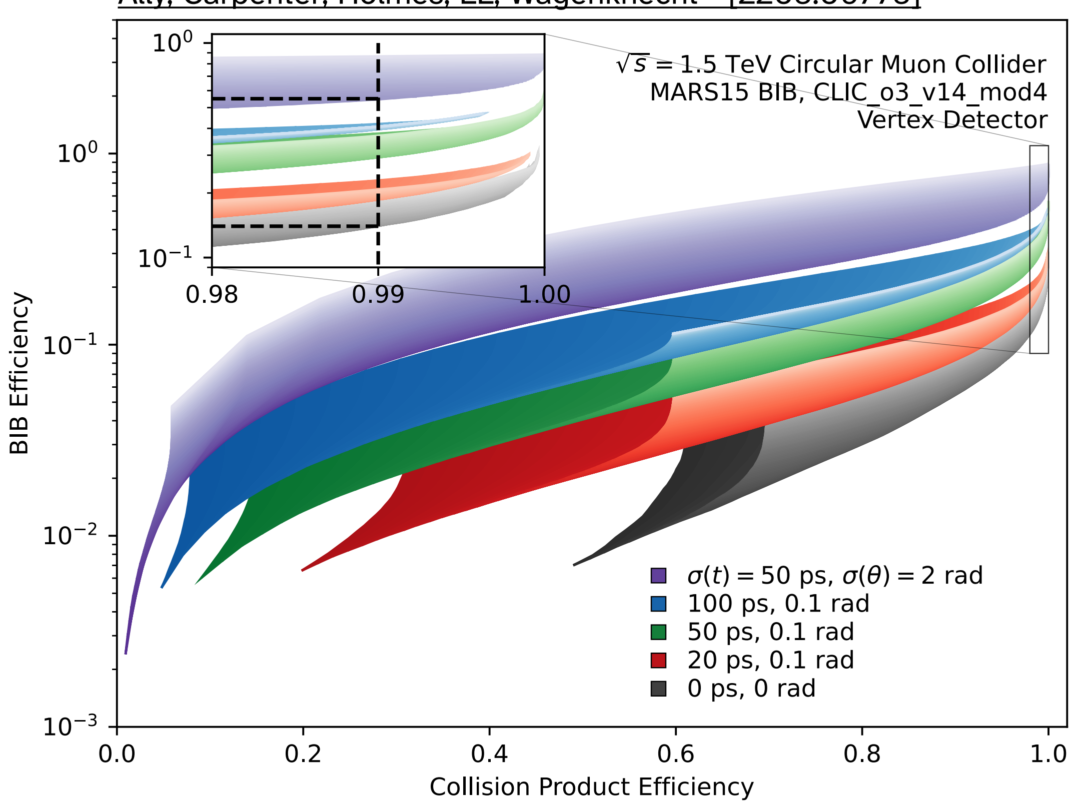

- w/ 20ps res, vertex detector could **reduce hit rate by ~50-70%** (after already selecting [-360,480] ps range)
    - Worst-case hit density ~300 hits/cm² → ~OK for pixel detectors!
- Adding angular info, reduce hit density by 50-80% across vertex detector with only **O(1%) signal loss**
- Rest of tracker: sufficiently low channel occupancy

IMCC - [2203.07964]

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w/ Time Window [-3σ,+5σ]

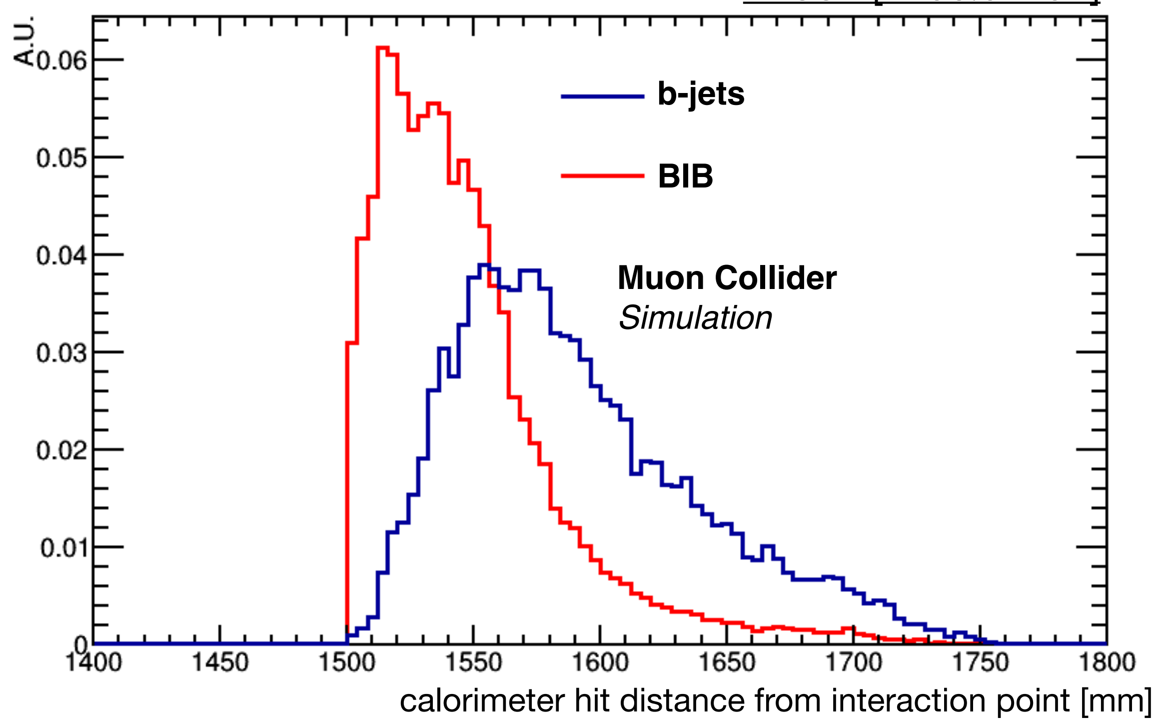
ATLAS ITk Layer	ITk Hit Density [mm^2]	MCD Equiv. Hit Density [mm^2]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.022	0.51
Strips Layer 1	0.003	0.03

- Compare to hit densities expected for ATLAS ITk for HL-LHC
  - **Order of magnitude larger hit densities**
  - Corresponds to channel occupancy of **1% (Muon Collider Detector)** vs **1/1000 (ITk)** [ATL-ITK-PUB-2022-001]
- Even with on-detector time-based BIB rejection, **need significant readout advances**
  - n.b. ATLAS ITk **would not** be able to handle 10x extra rate in its links
    - (HL-LHC rates use up to 60% of 5 Gbps capacity)

Calorimeters

- Lower granularity and larger integration times make calorimeters sensitive to BIB
  - Radial profile shows BIB problem **largest at inner radii**
- Studies assuming time resolutions **80-100 ps**
  - Reject BIB depositions outside a +/-250 ps window
- **Integration times** must be larger (≲100 ns), but these studies assume late BIB tail is diffuse and flat enough to be subtracted
  - **More detailed studies of this assumption ongoing**

IMCC - [2203.07964]



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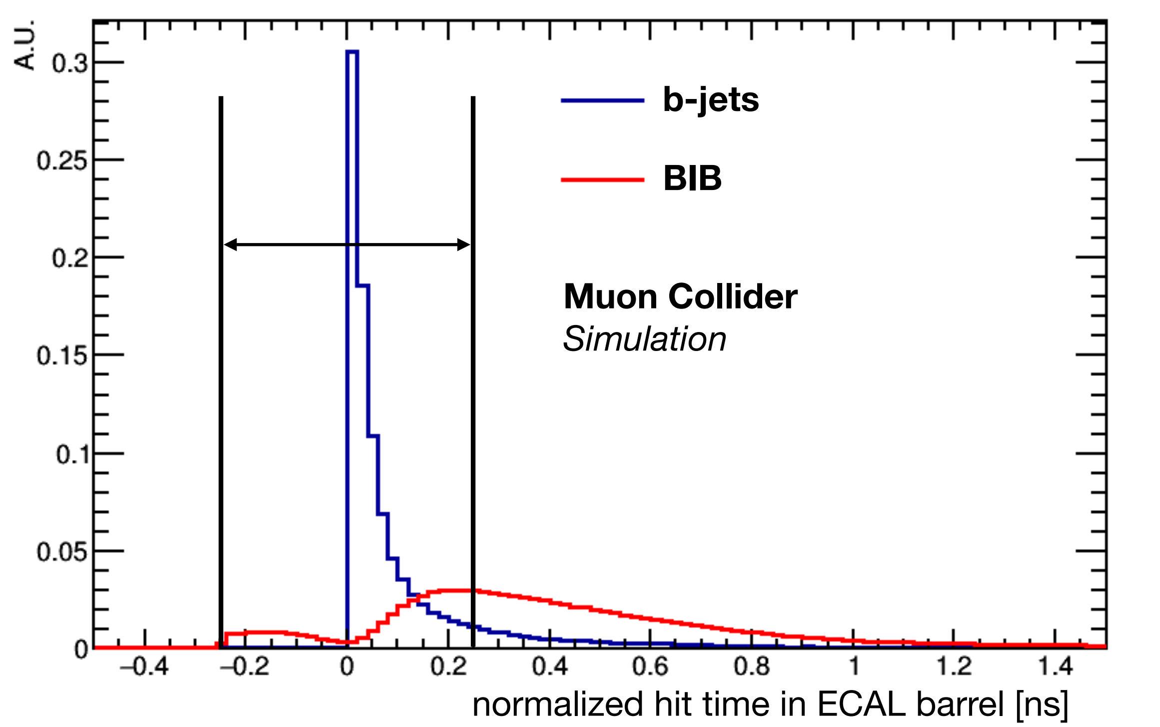

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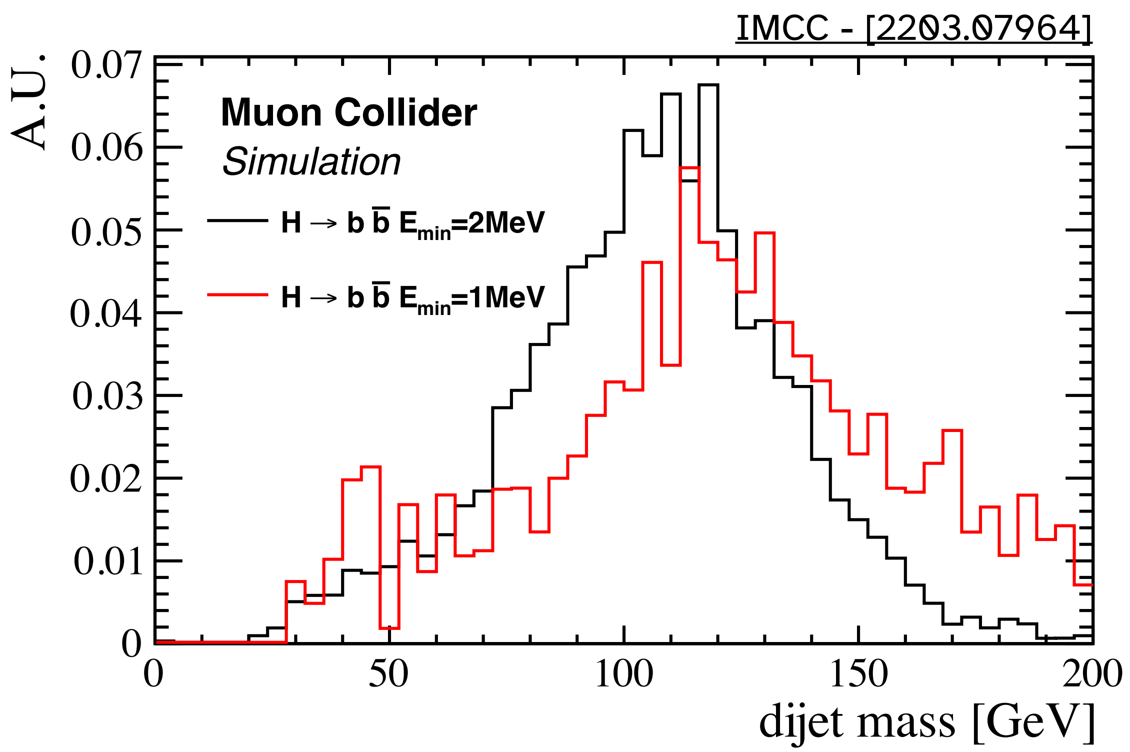
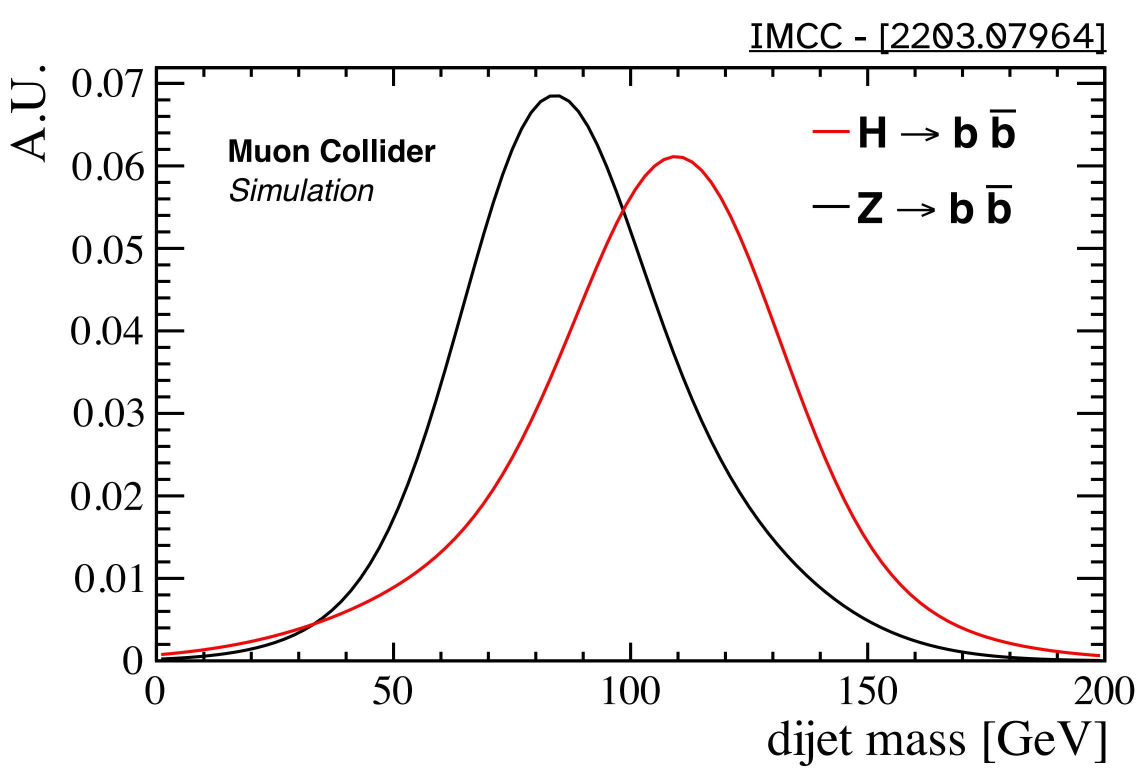


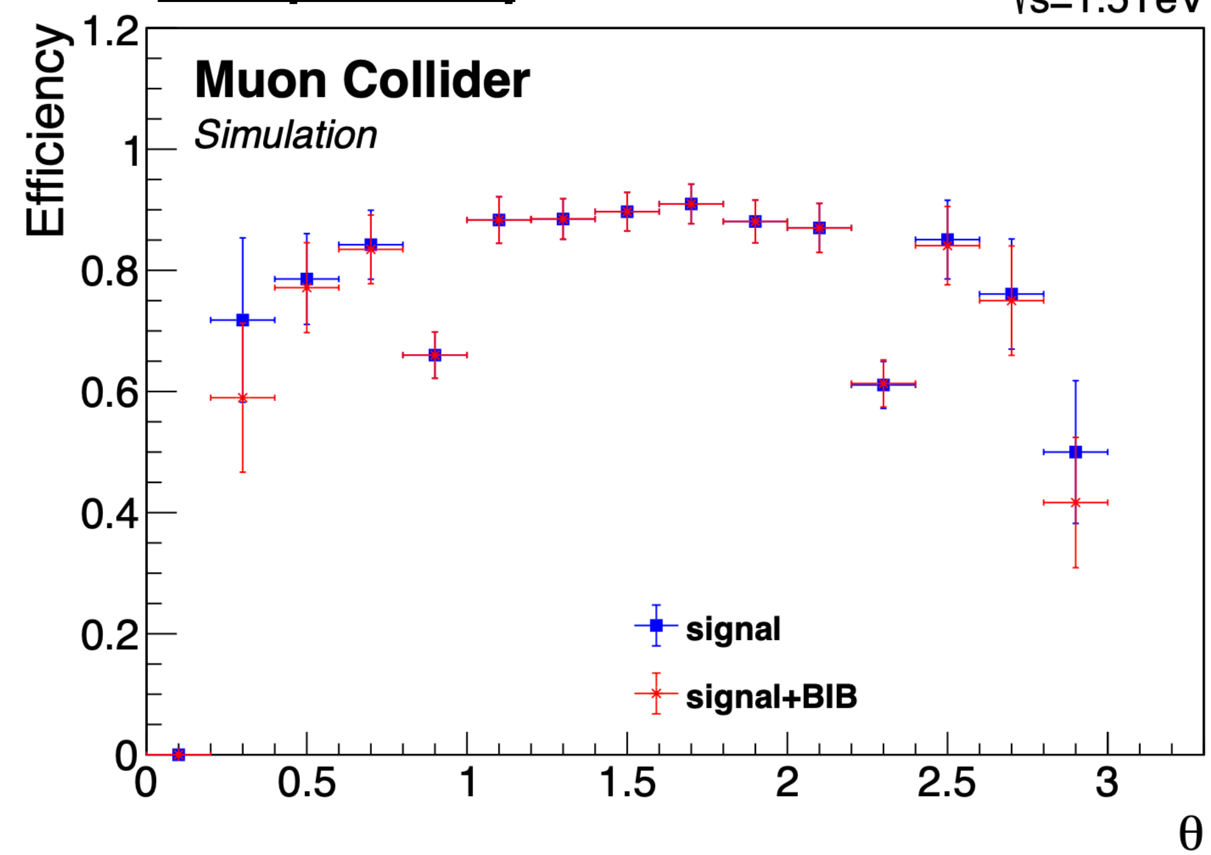


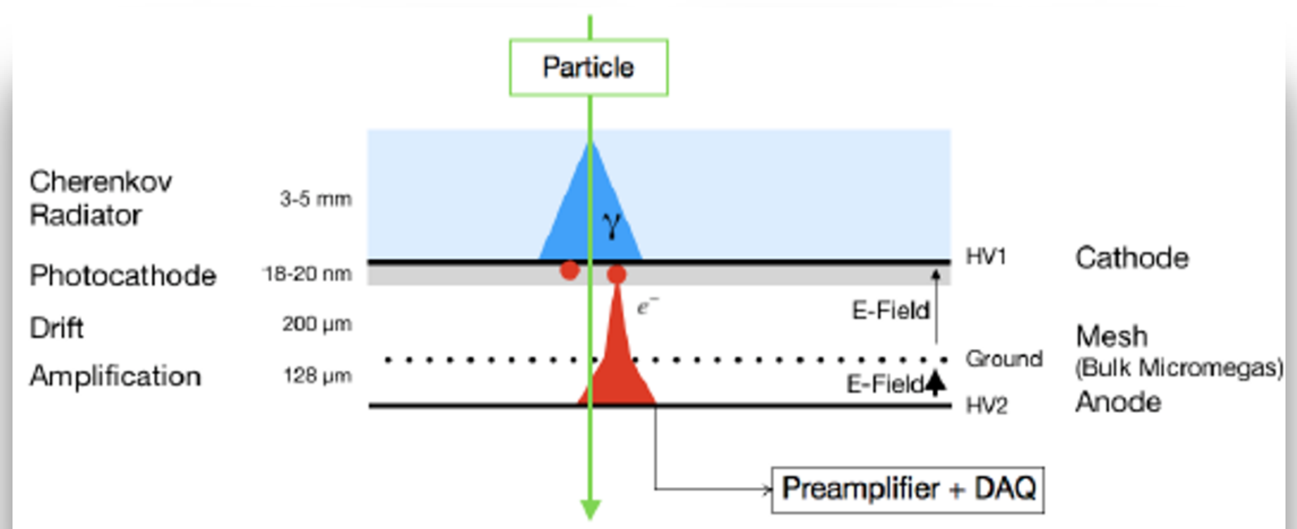
- BIB will have large effect on jet measurements
  - Dijet mass resolution **very dependent on small energy depositions**
- Nonetheless, with assumed resolutions **80-100 ps:**
  - **Enough handles to separate H→bb and Z→bb**

Muon Detectors

- Neutrons and photons dominate BIB effects in muon systems
- Studies have assumed time resolution lower than 1 ns, **but flexibility being studied**
  - **Not** currently defined by occupancy benchmarks like the tracker
- Multigap RPC detectors are able to achieve (very) sub-100 ps timing resolution at high rate, with low resistivity layers
  - But **current gases not viable** for future detectors due to use of freons
  - Environmentally safe MRPC R&D necessary before consideration
- Current gaseous detectors can't achieve this → **R&D needed!**
  - Hybrid Micromegas+Cherenkov reach **25 ps** (∃ active projects exploring this for MCD) PicoSec - [1901.03355]
  - Fast Timing Micropattern (FTM) use multiple drift and amplification gaps to hopefully achieve **< 1 ns** Oliveira, Maggi, Sharma - [1503.05330]

IMCC - [2203.07964]





PicoSec

Summary

- Physics reach of a **multi-TeV muon collider** relies on (among other things) successful mitigation of Beam Induced Backgrounds
- **Timing** is one of the most powerful handles to combat BIB to enable physics
- Roughly playing with/looking towards **(not quite ready to call these "req's")**:
  - **≤30 ps** resolutions for pixel detectors, **≤60 ps** resolutions for further layers
  - **≤100 ps** EM calorimeter resolution, as short as possible integration times
  - Hoping for **ns-scale**, position-precise muon detectors
- Needed for offline BIB discrimination, but also crucial to make **readout** possible
- ∃ promising tech, but **advances in instrumentation R&D crucial (IF experts next!)**

Thanks for your attention!

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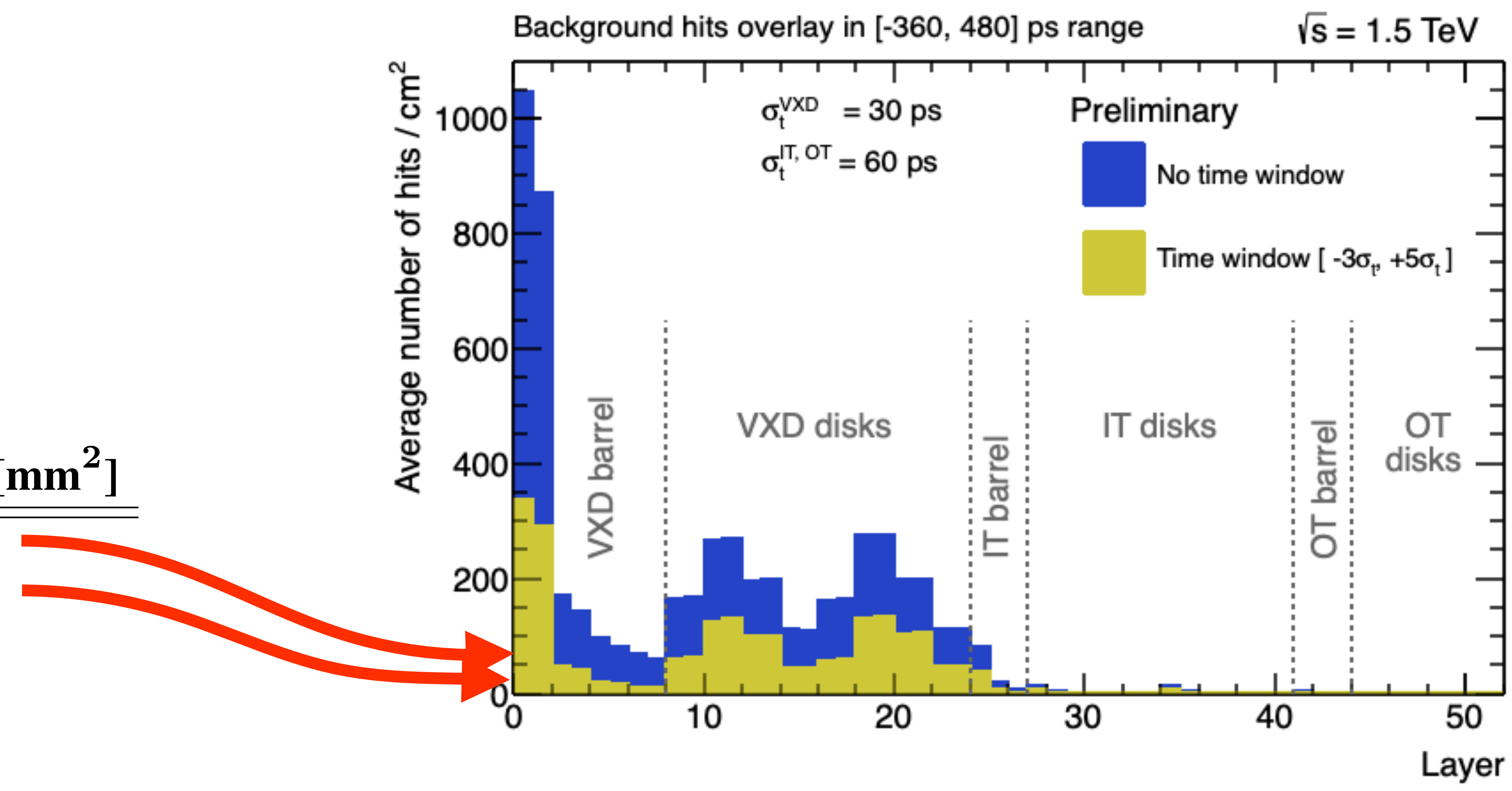


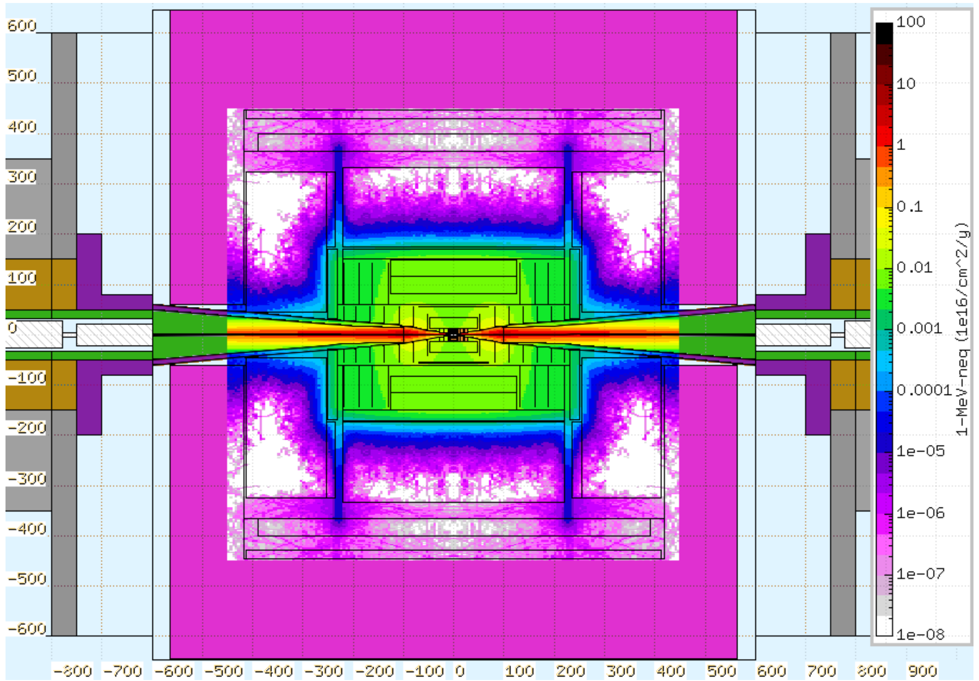


Fig. 3: Map of the 1-MeV-neq fluence in the detector region for a muon collider operating at $\sqrt{s}$ = 1.5 TeV with the parameters reported in Table 1, shown as a function of the position along the beam axis and the radius. The map is normalised to one year of operation (200 days/year) for a 2.5 km circumference ring with 5 Hz injection frequency.

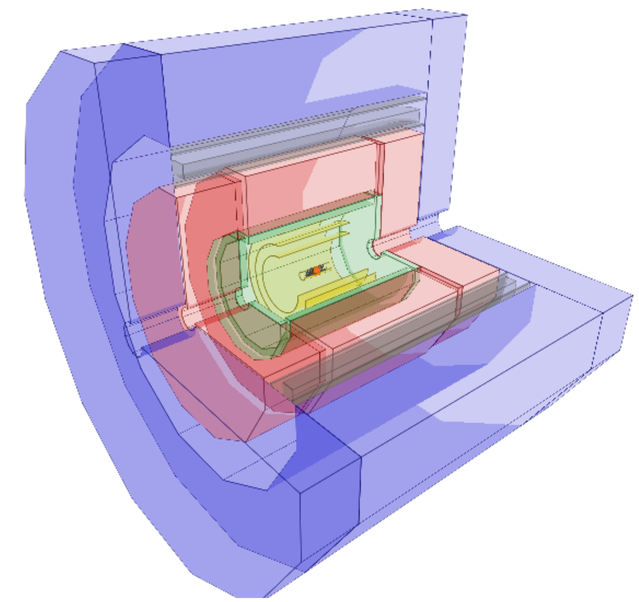


Fig. 2: Illustration of the full detector, from the GEANT 4 model. Different colours represent different sub-detector systems: the innermost region, highlighted in the yellow shade, represents the tracking detectors. The green and red elements represent the calorimeter system, while the blue outermost shell represents the magnet return yoke instrumented with muon chambers. The space between the calorimeters and the return yoke is occupied by a 3.57 T solenoid magnet.

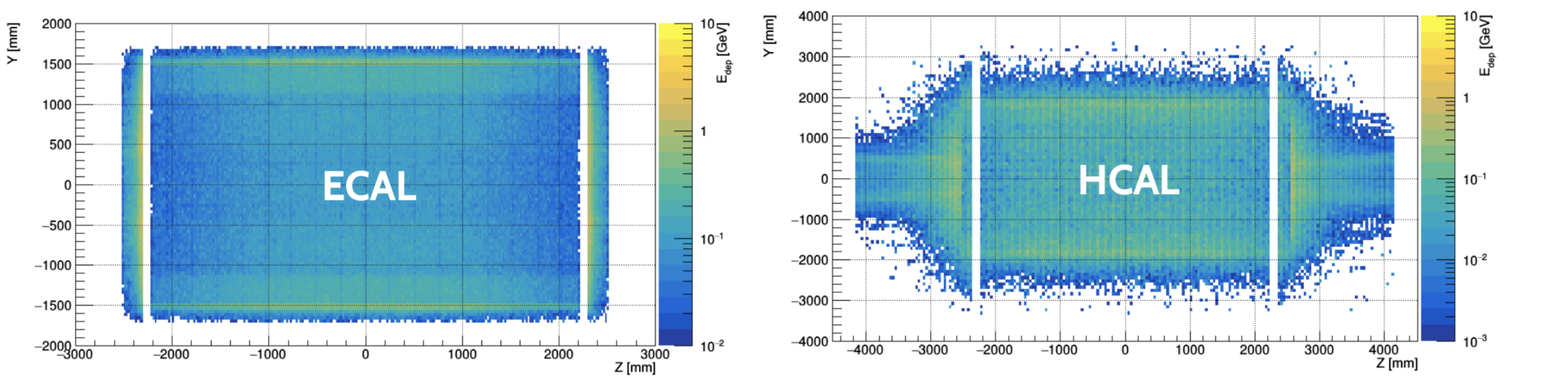
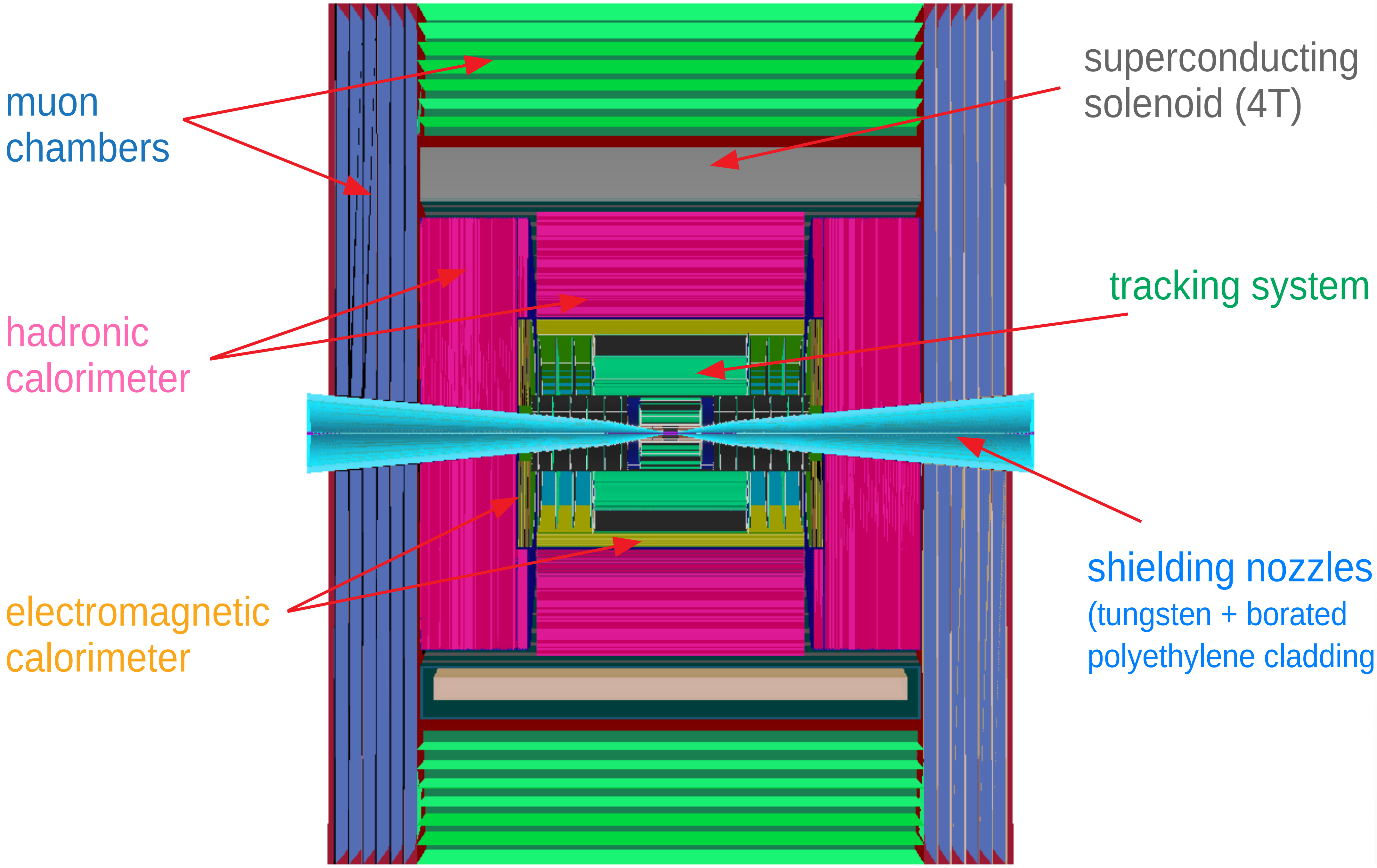
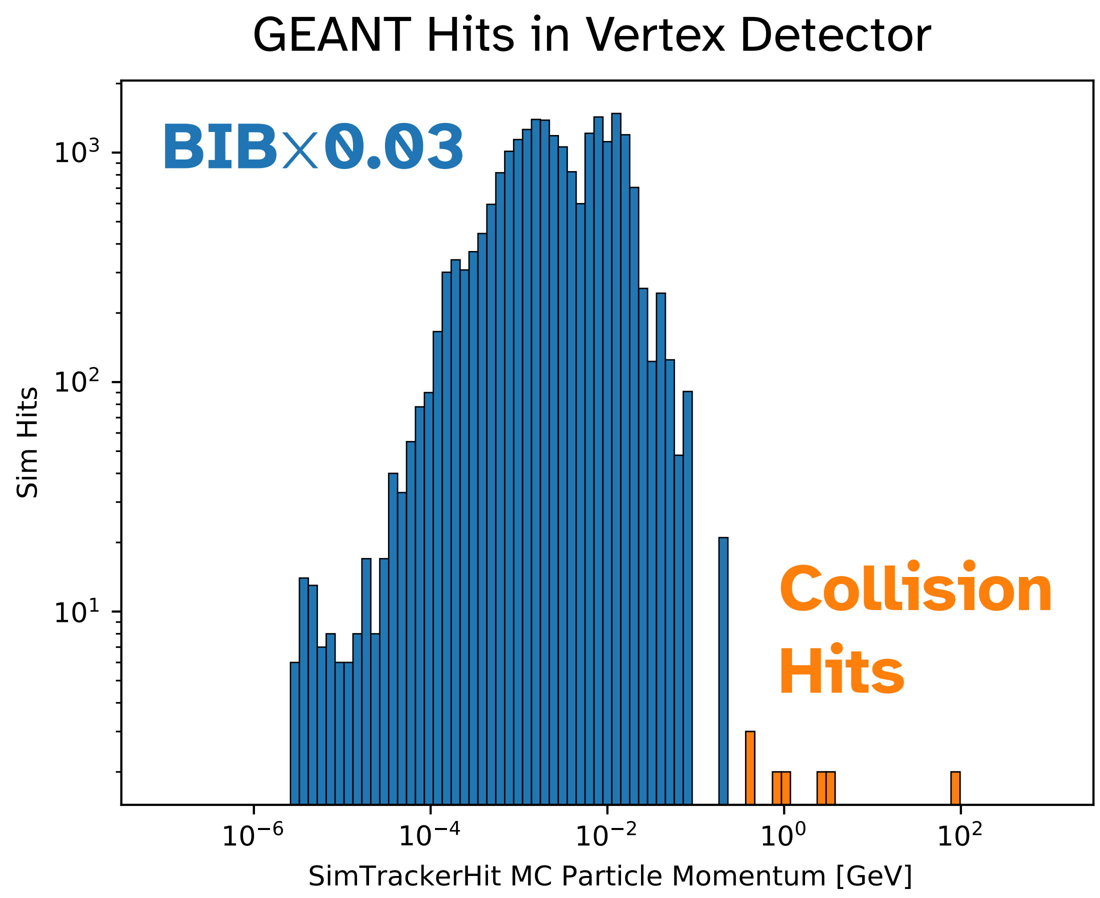


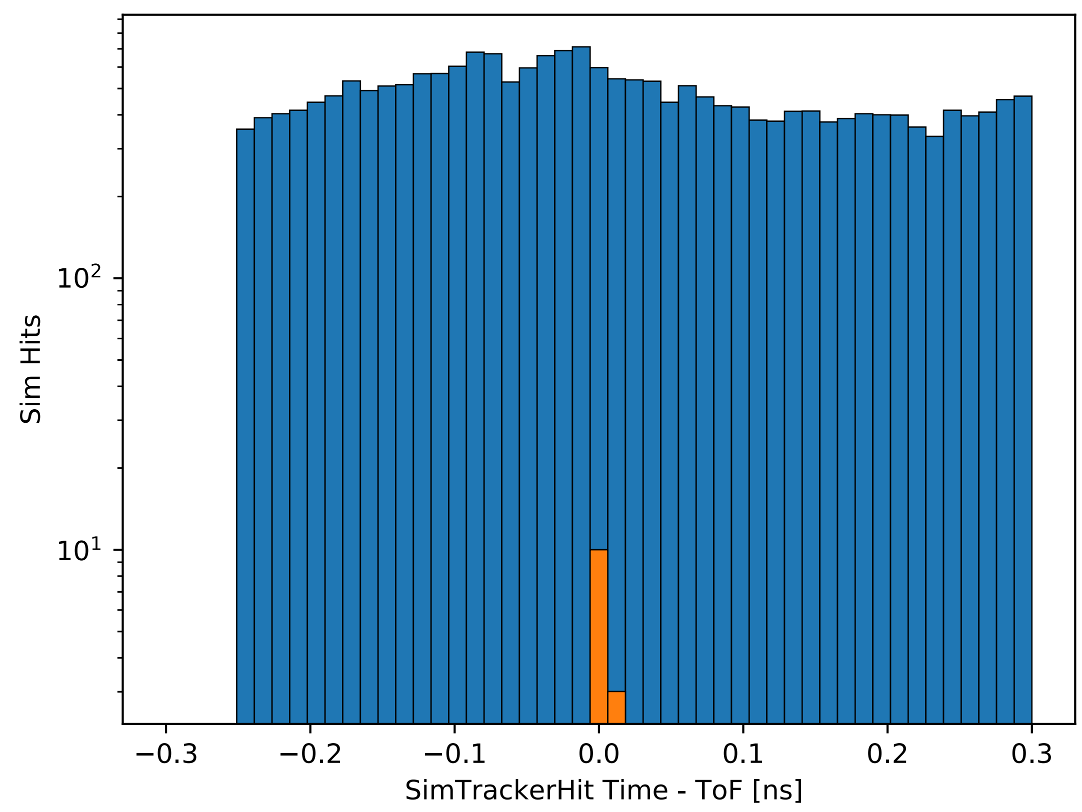
Fig. 9: Energy deposited by the BIB in a single bunch-crossing at $\sqrt{s}$ = 1.5 TeV, in ECAL (left) and in HCAL (right).

Subsystem	Region	R dimensions [cm]	$\|Z\|$ dimensions [cm]	Material
Vertex Detector	Barrel	$3.0 - 10.4$	65.0	Si
	Endcap	$2.5 - 11.2$	$8.0 - 28.2$	Si
Inner Tracker	Barrel	$12.7 - 55.4$	$48.2 - 69.2$	Si
	Endcap	$40.5 - 55.5$	$52.4 - 219.0$	Si
Outer Tracker	Barrel	$81.9 - 148.6$	124.9	Si
	Endcap	$61.8 - 143.0$	$131.0 - 219.0$	Si
ECAL	Barrel	$150.0 - 170.2$	221.0	W + Si
	Endcap	$31.0 - 170.0$	$230.7 - 250.9$	W + Si
HCAL	Barrel	$174.0 - 333.0$	221.0	Fe + PS
	Endcap	$307.0 - 324.6$	$235.4 - 412.9$	Fe + PS
Solenoid	Barrel	$348.3 - 429.0$	412.9	Al
Muon Detector	Barrel	$446.1 - 645.0$	417.9	Fe + RPC
	Endcap	$57.5 - 645.0$	$417.9 - 563.8$	Fe + RPC



Lifted from Donatella Lucchesi


GEANT Hits in Vertex Detector
BIB×0.03
Collision
Hits
Sim Hits
10³
10²
10¹
10⁻⁶
10⁻⁴
10⁻²
10⁰
10²
SimTrackerHit MC Particle Momentum [GeV]


Sim Hits
10²
10¹
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
SimTrackerHit Time - ToF [ns]