How To Build a Detector at a Muon Collider

Lawrence Lee

w/ input from S Jindariani, F Meloni,
& many more, +references

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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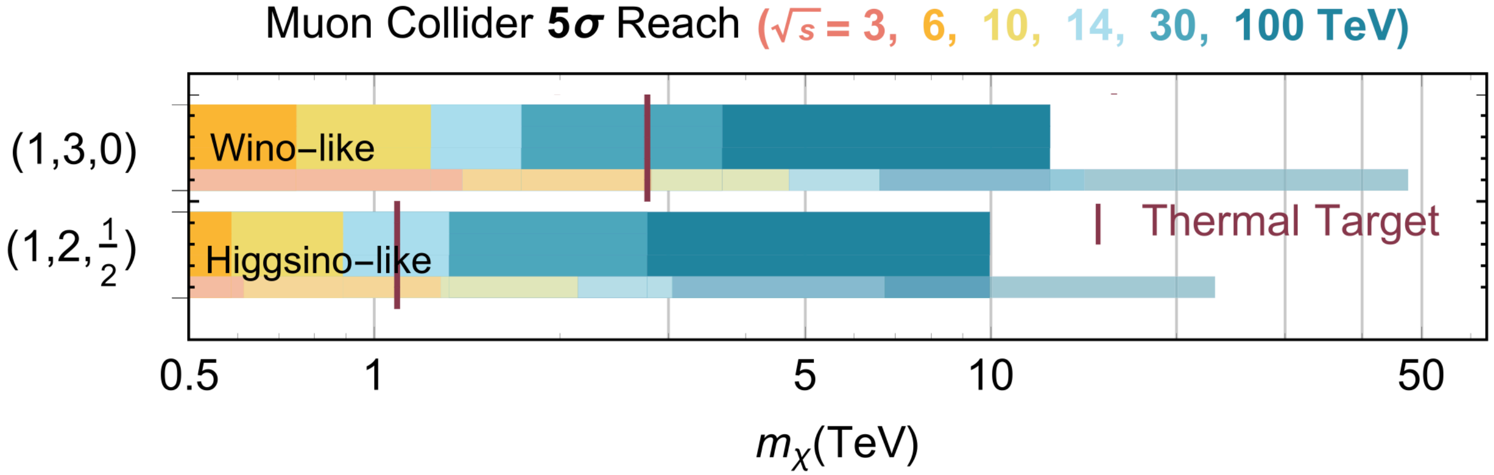
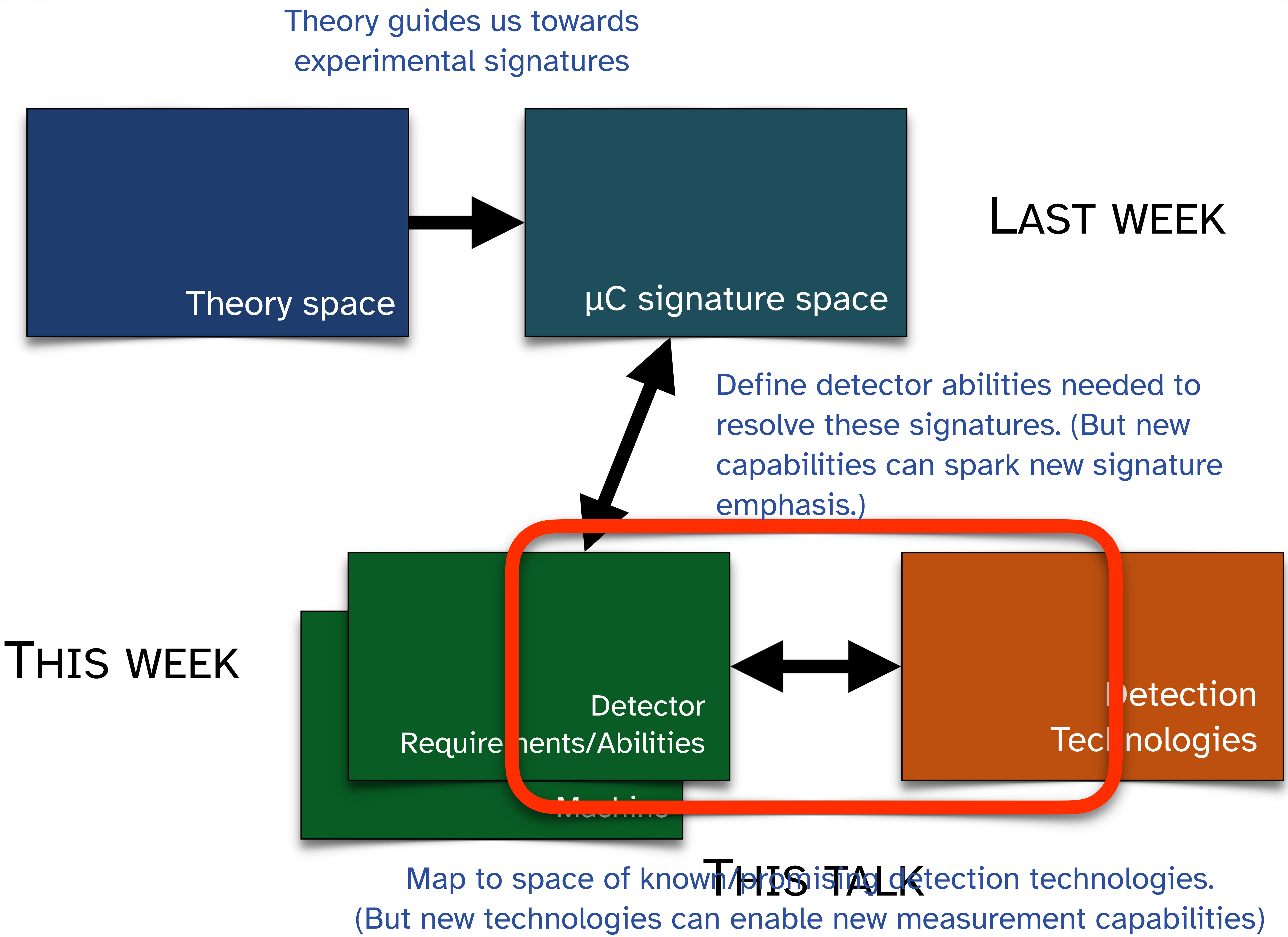
Muon Collider Experiments in Practice

- Message at this workshop:
  - Theory+Experiment+Accelerator: **For long-term success of the energy frontier, multi-TeV μC is a path that is uniquely:**
    - **Powerful** / Sensitive to important physics goals
    - Cost, energy, space **efficient**
- So what needs to happen today to make this happen in the decades to come



You had me at "5σ reach for wino and higgsino thermal targets"

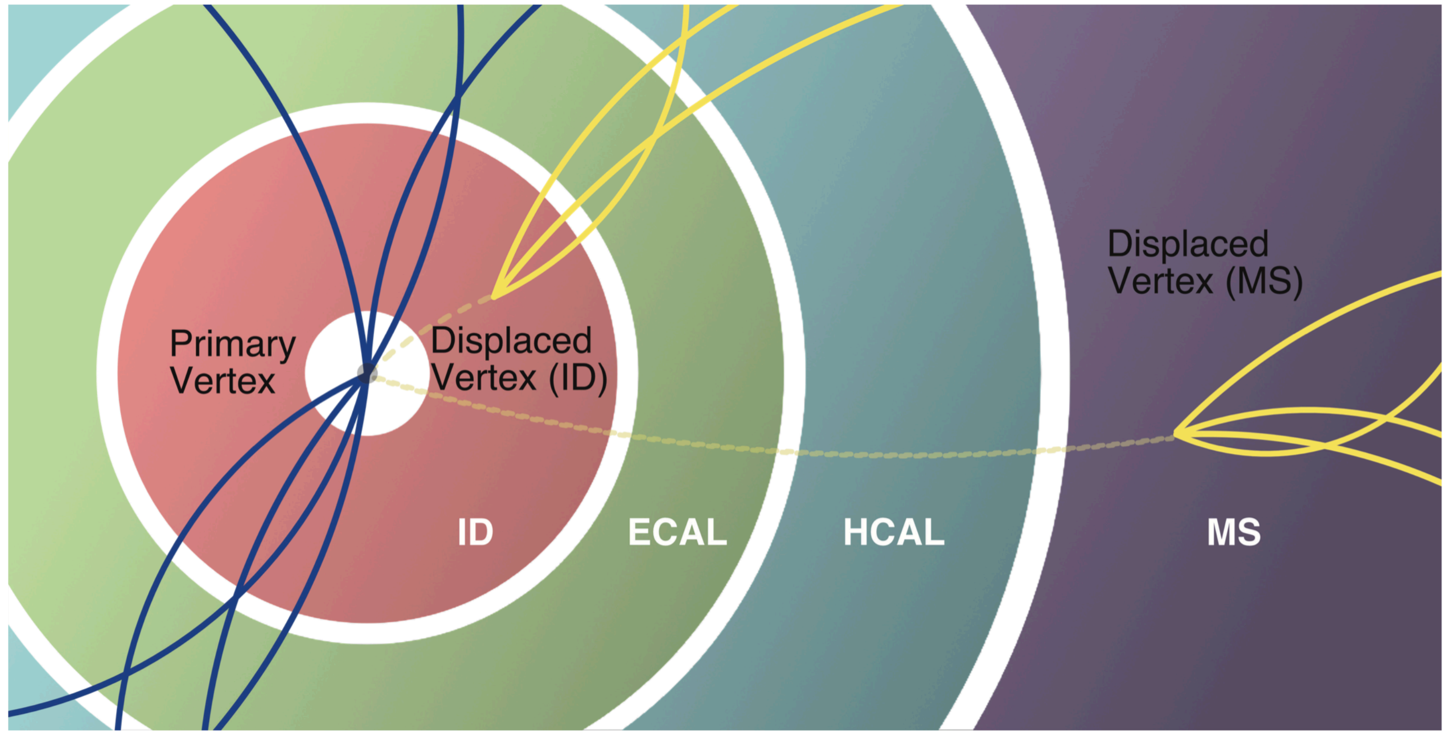
Phys Rev D 103, 075004 (2021)


Theory guides us towards experimental signatures
Theory space
μC signature space
LAST WEEK
Define detector abilities needed to resolve these signatures. (But new capabilities can spark new signature emphasis.)
THIS WEEK
Detector Requirements/Abilities
Machine
Detection Technologies
THIS TALK
Map to space of known/promising detection technologies.
(But new technologies can enable new measurement capabilities)

Quick aside: When defining detector requirements, **be more signature-inclusive.**

E.g. the now-bloomed **LHC Long-Lived Particle program** stretches capability of LHC detectors designed decades ago.

[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu



Over-optimization can hurt future flexibility. In retrospect, would have designed LHC experiments differently…

Be inclusive of more signatures than we can come up with.

What are the major considerations when designing this experiment?

What are the guiding principles and major hurdles?

Major Tent Poles

- **Energy Scale**
  - @ a 10 TeV μC, typical hard scatter at 10 TeV scale!
  - Multi-TeV objects will be the **norm** which will affect how to design the detector

(Similar problems will plague all facilities w/ multi-TeV-scale hard scatters)

Major Tent Poles

- **Energy Scale**
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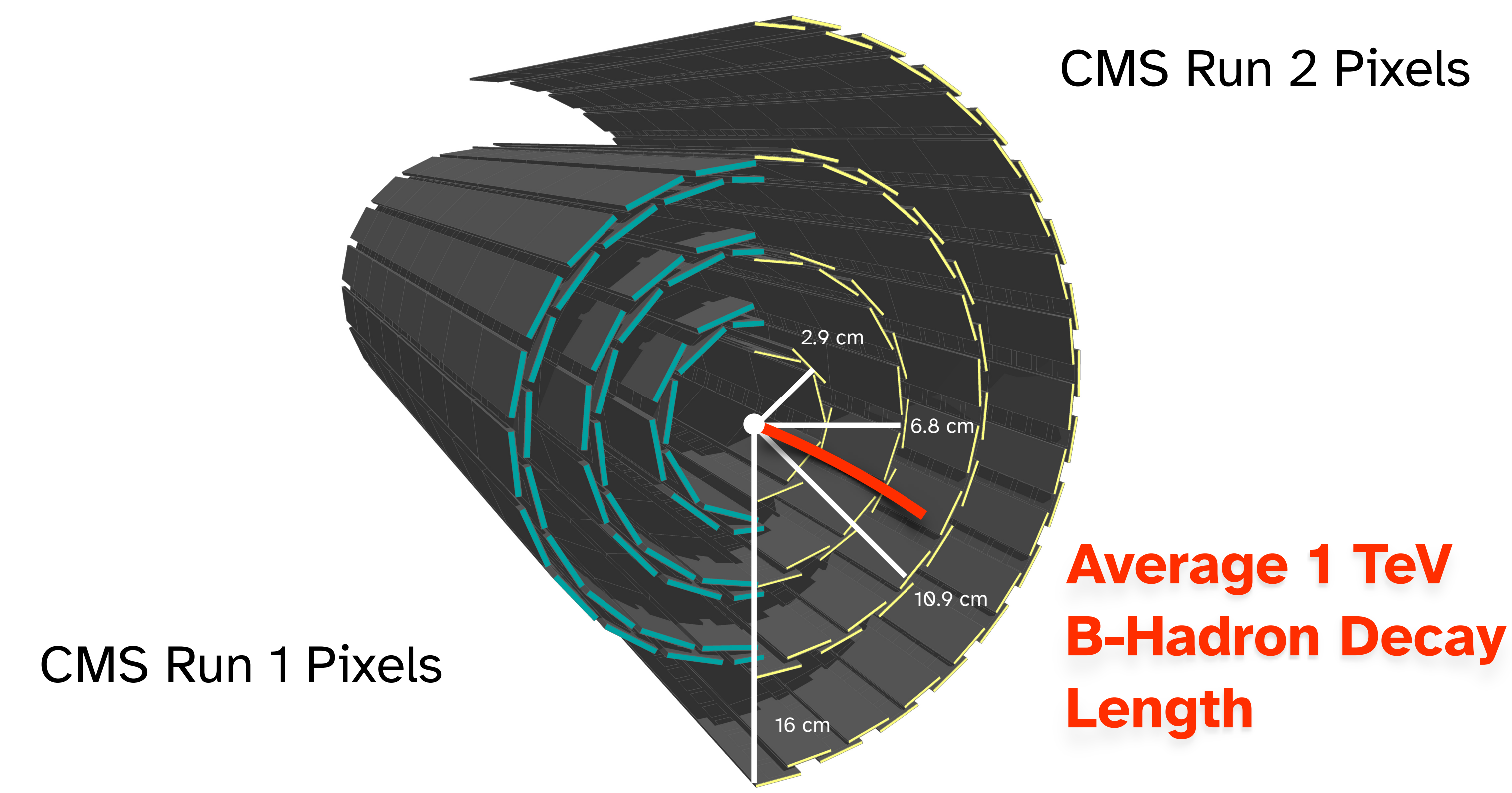
To give a taste: Remember at 1 TeV, a B-hadron travels 10 cm into the detector



Decays happening well into tracker! A lot more precision silicon tracking required.

("B-*layer*" not enough. Need "B-*detectors*"!)

"Exotic" signatures will become Bread and Butter

Major Tent Poles

- **Energy Scale**
  - @ a 10 TeV μC, typical hard scatter at 10 TeV scale!
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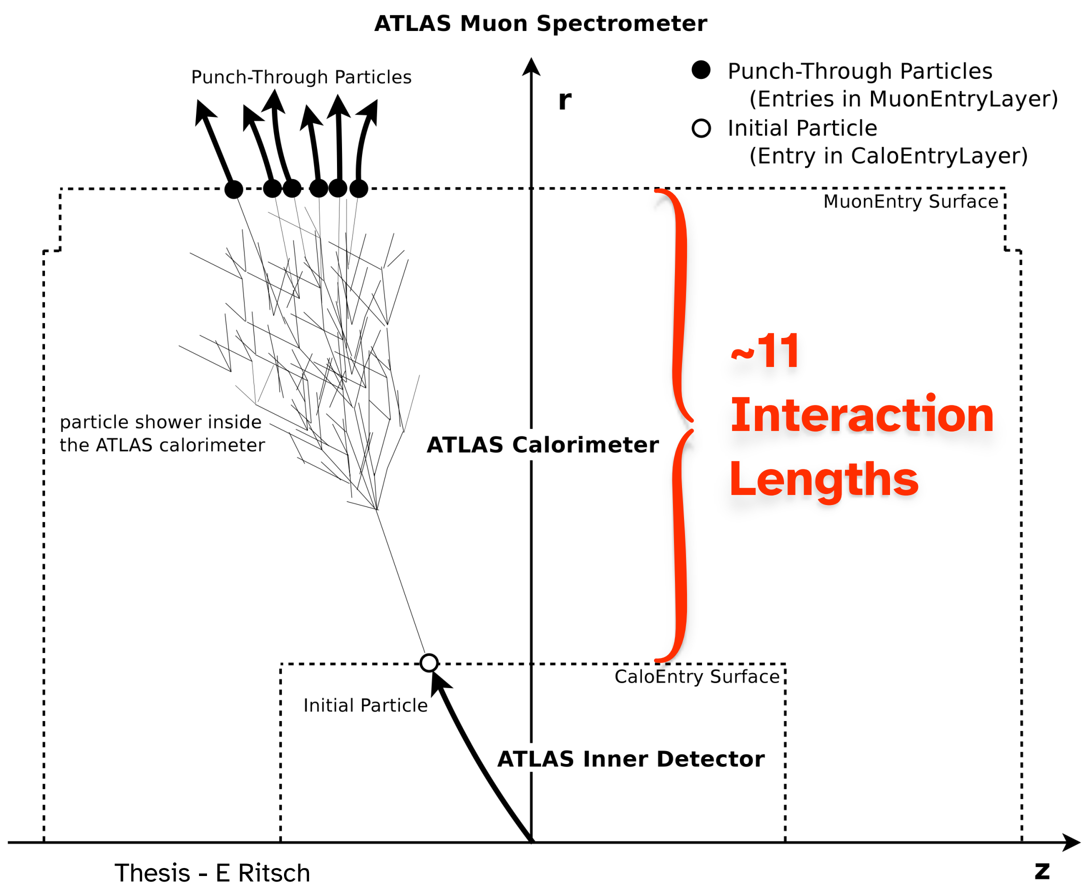
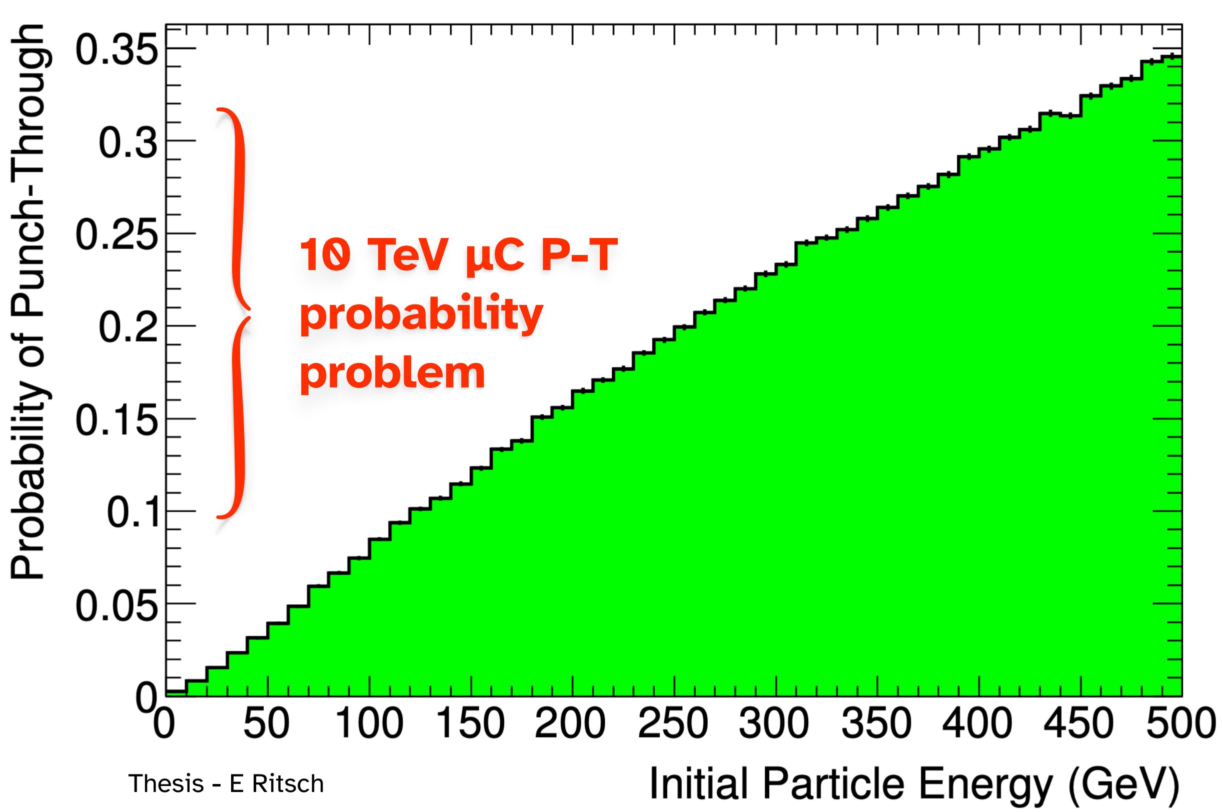
To give a taste: Need more interaction lengths to contain very energetic calorimeter showers





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  - µ's decay → significant energy in detector not produced in the collision
  - Have experience with BIB from LHC, but… this is different…

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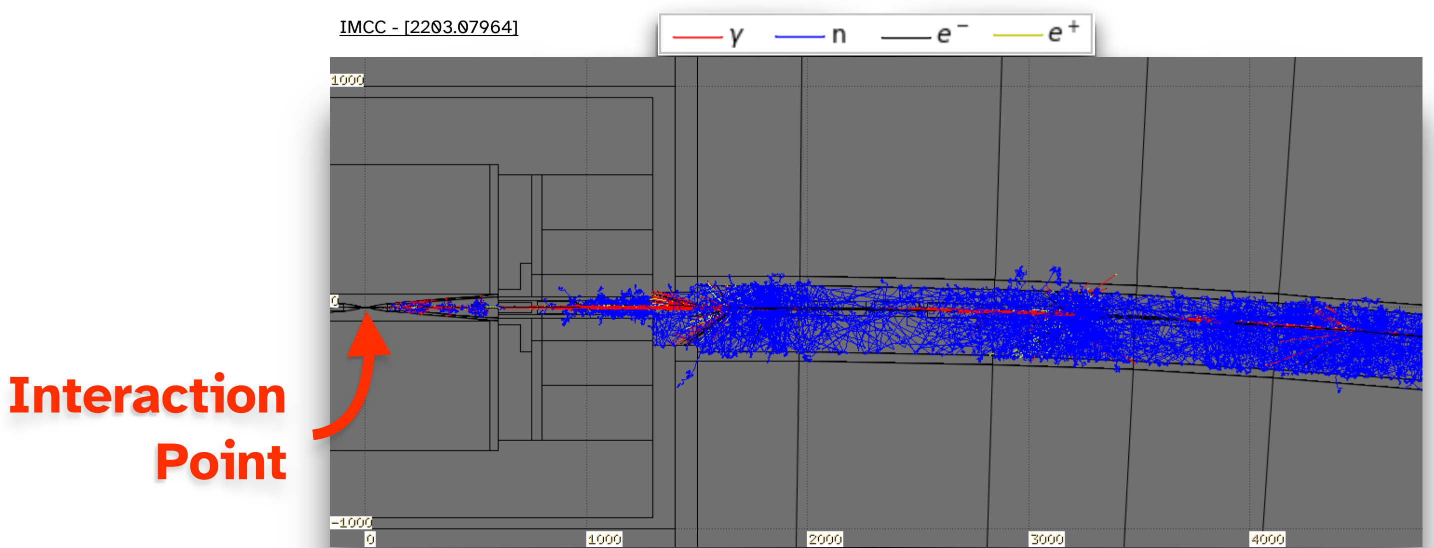


A pretty messy environment at a μC

Detector elements close to the beam face **large** backgrounds!

Identifiable with out-of-time and non-projective nature

• Beam Induced Backgrounds (BIB)

Interesting feature T. Holmes pointed out @ Dec FNAL workshop:

Increased beam energy dilates decay time
→ # of muon decays **suppressed** by 1/ɣ

But more beam energy
→ Muon decay products **more energetic** by ɣ

To leading order (and not by accident!),
Incident BIB energy per unit luminosity doesn't depend on beam energy

Monte Carlo simulator	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	750	1500	5000
μ decay length [m]	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

[IMCC, Submitted to EPJC]

No dramatic change!

Full FLUKA studies support this! BIB levels have weak dependence on beam energy because of competing effects.

But at higher energies, BIB more *localized* — More on this later…

Rising to the Challenge(s)

- **Attacking these problems**
  - **… with overall detector design**
  - … with new detection technologies
  - … with electronics / DAQ design

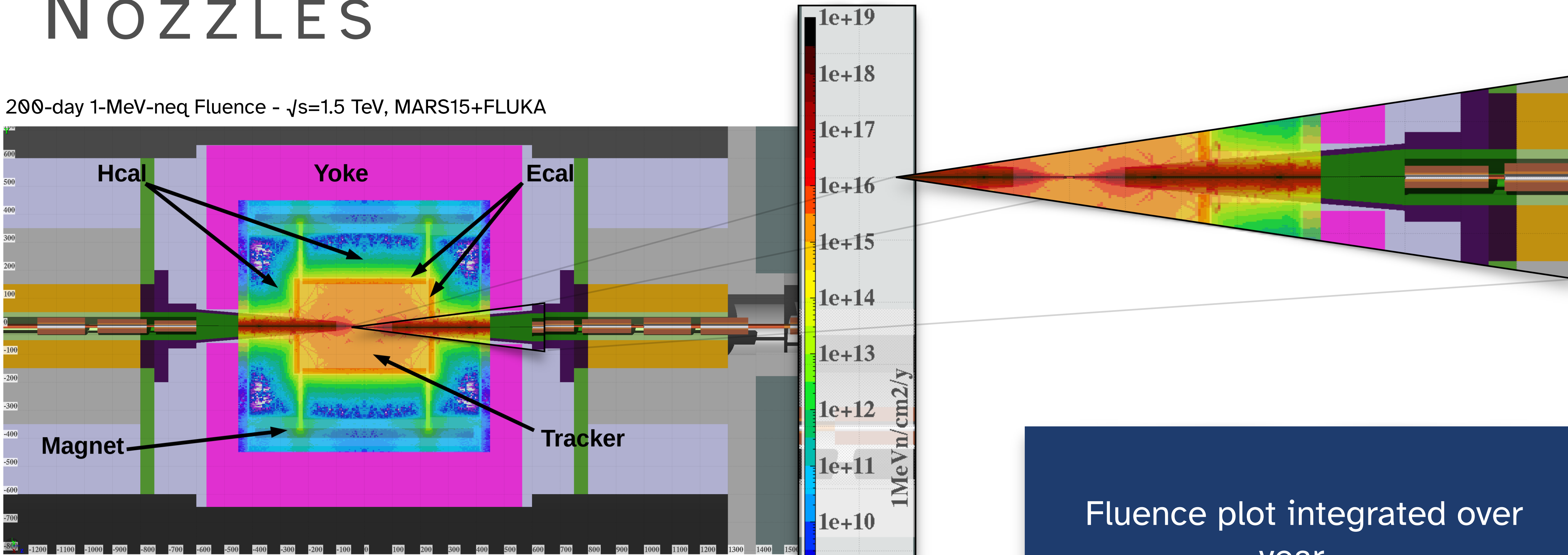
Whole-detector Effects

- **Energy Scale**
  - To leading order, detector sizes need to grow as energy does
    - (Can try to be smarter, but this will be the dominant effect)
  - Need bigger calorimeters / bigger trackers with high precision in more places
  - Common to all possible futures of the energy frontier

- **Beam Induced Backgrounds (BIB)**
  - Very sensitive to MDI design. Need holistic design!
  - To leading order, primary answer is **shield your detector**
  - Uniquely difficult for μC!

Nozzles

200-day 1-MeV-neq Fluence - √s=1.5 TeV, MARS15+FLUKA



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

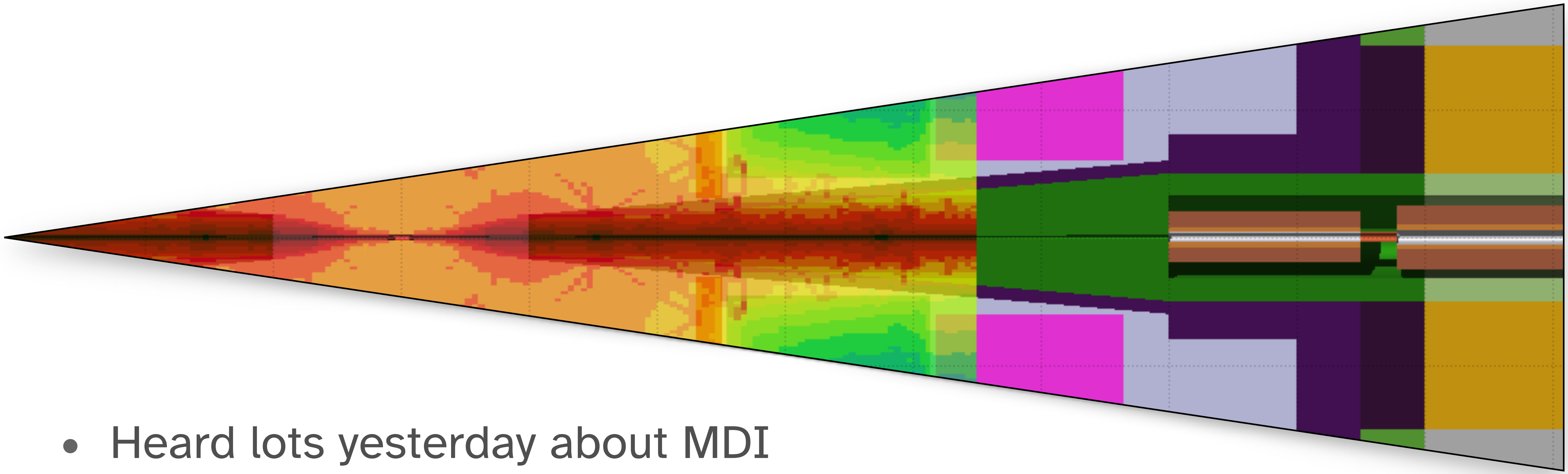
- **Enormous number of particles in detector region** from decaying muons and their byproducts
- Forward region covered by coated tungsten conical **nozzles** to shield
  - Several iterations on materials/shapes/size
  - Reduces BIB in detector by **many orders of magnitude**
- Interactions with nozzle → Bleed secondary energy into the detector.
  - **Nozzle turns highly localized incident energy into *diffuse* detector energy**

Fluence plot integrated over year…

But fluence is still diffuse per **event** *because of the nozzles*

*Nozzles change **character** of BIB s.t. it can be rejected through measurement*

Nozzles



- Heard lots yesterday about MDI
- Nozzle design shown here made for sub-TeV beams
- For 5 TeV beams (which we're starting to eye), need **reoptimization/improvements!**
  - More collimated BIB → Smaller nozzle angle? → Increased detector acceptance?
- New approaches needed for the **22nd century's PeV μC?**

BEAM INDUCED BACKGROUNDS

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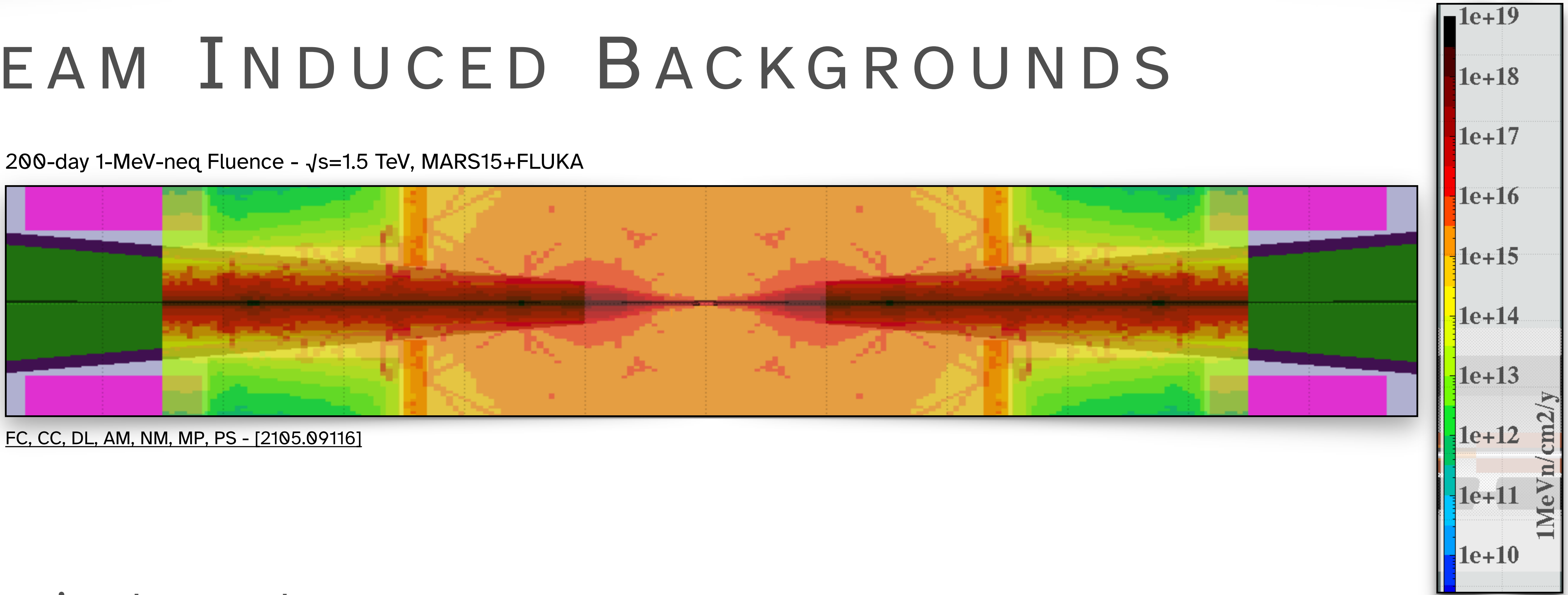
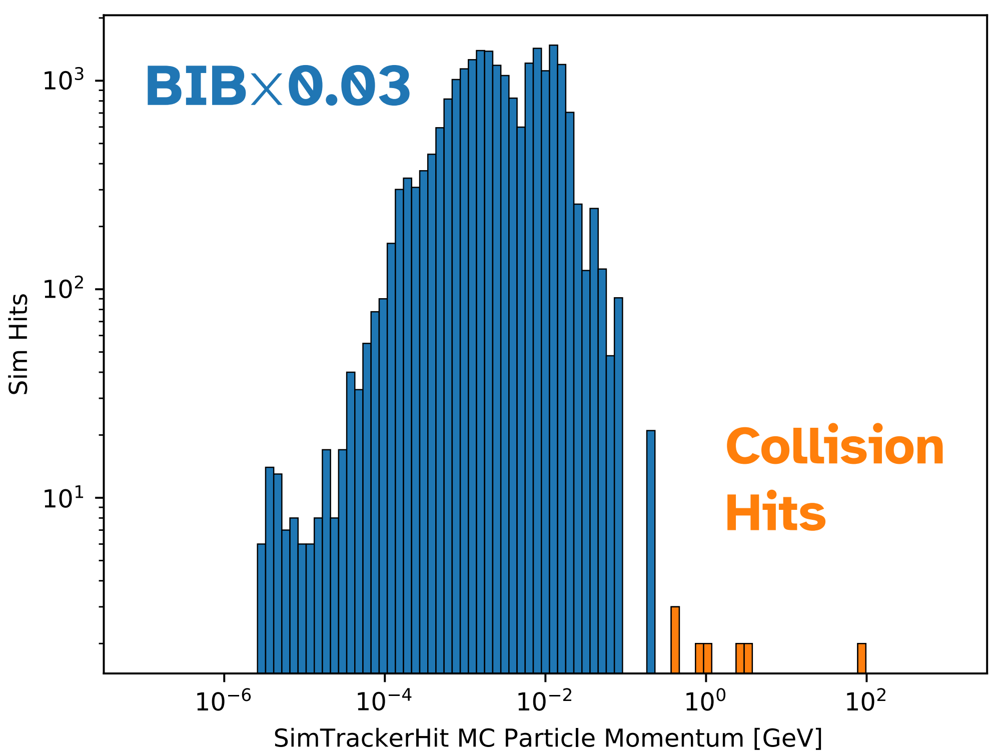


FC, CC, DL, AM, NM, MP, PS - [2105.09116]

- Despite the nozzles…
  - BIB makes the physics more difficult!
  - Sensors near the beam get filled with energy depositions
- **Need to build detectors that are sensitive enough to tell the difference between post-nozzle BIB and signal**

GEANT Hits in Vertex Detector



Rising to the Challenge(s)

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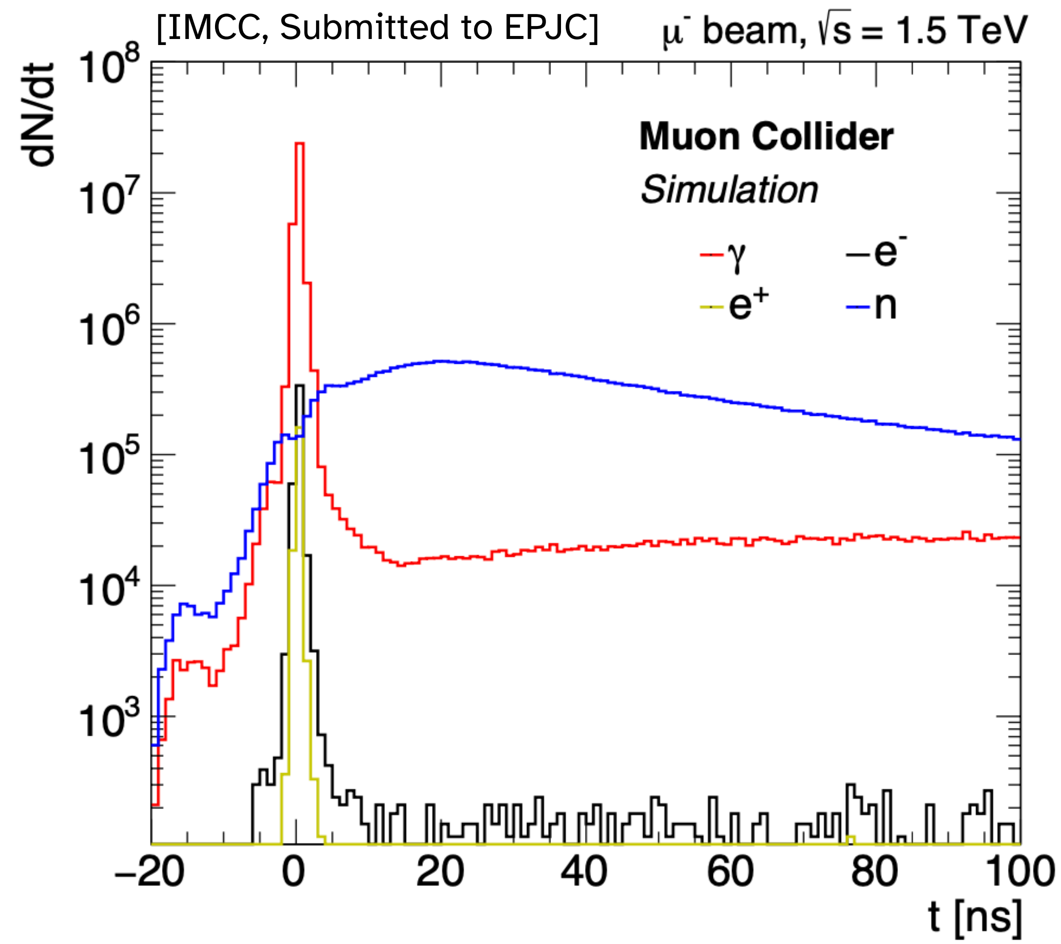
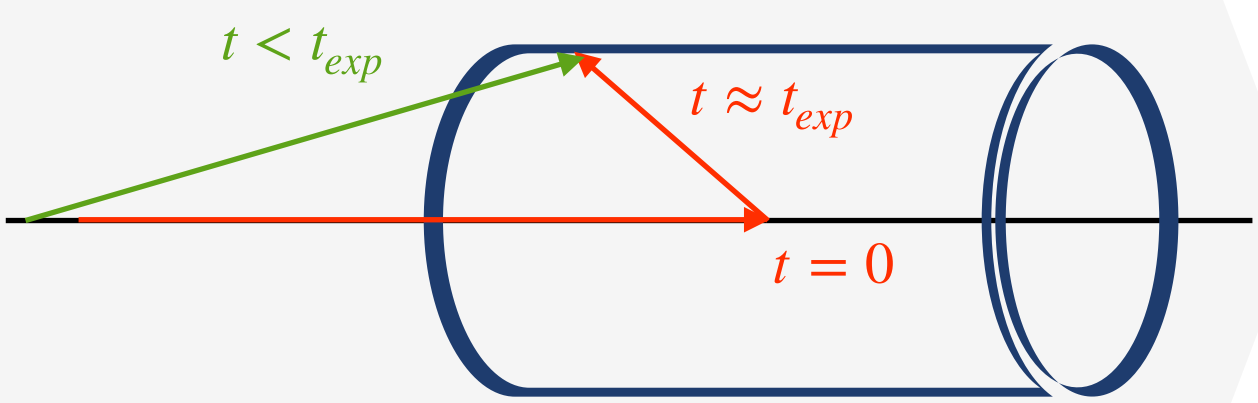
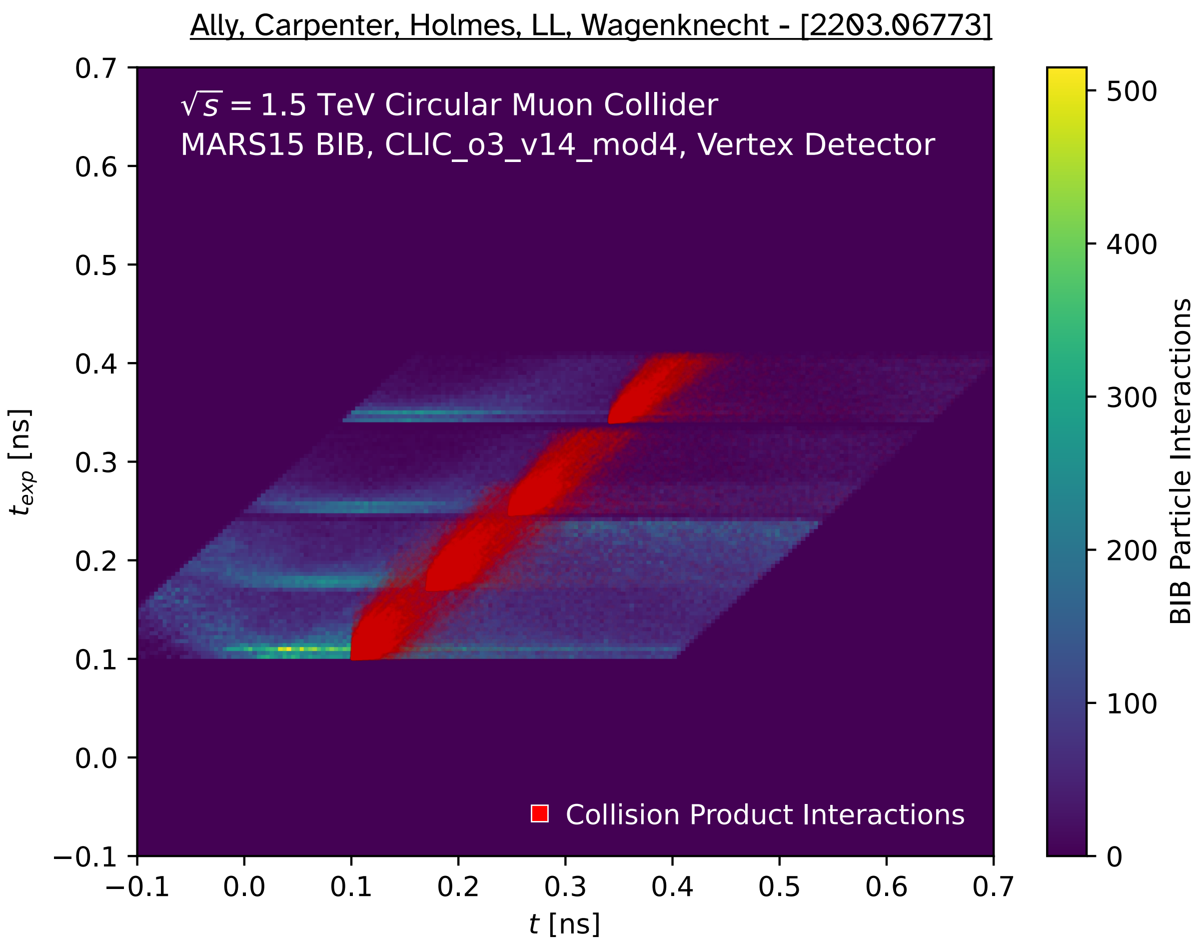
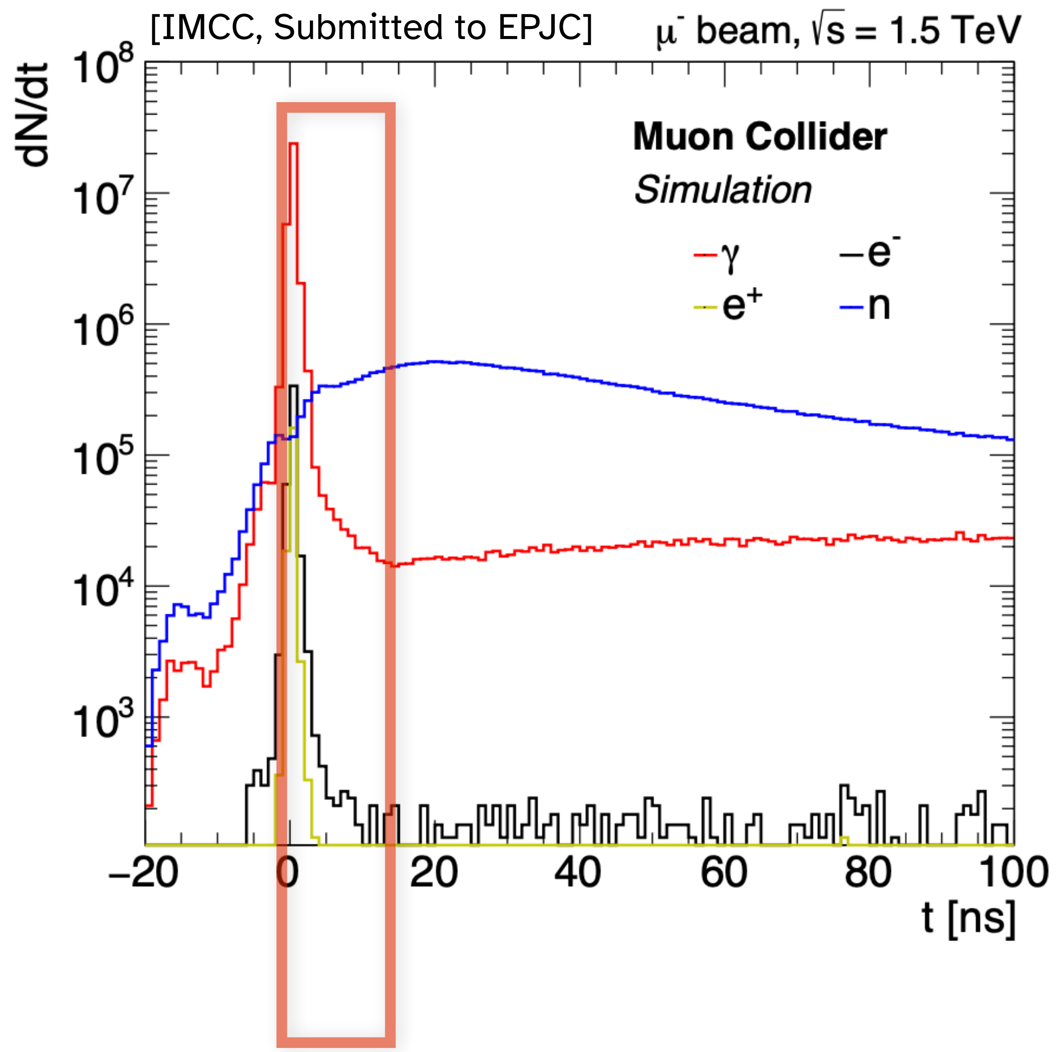


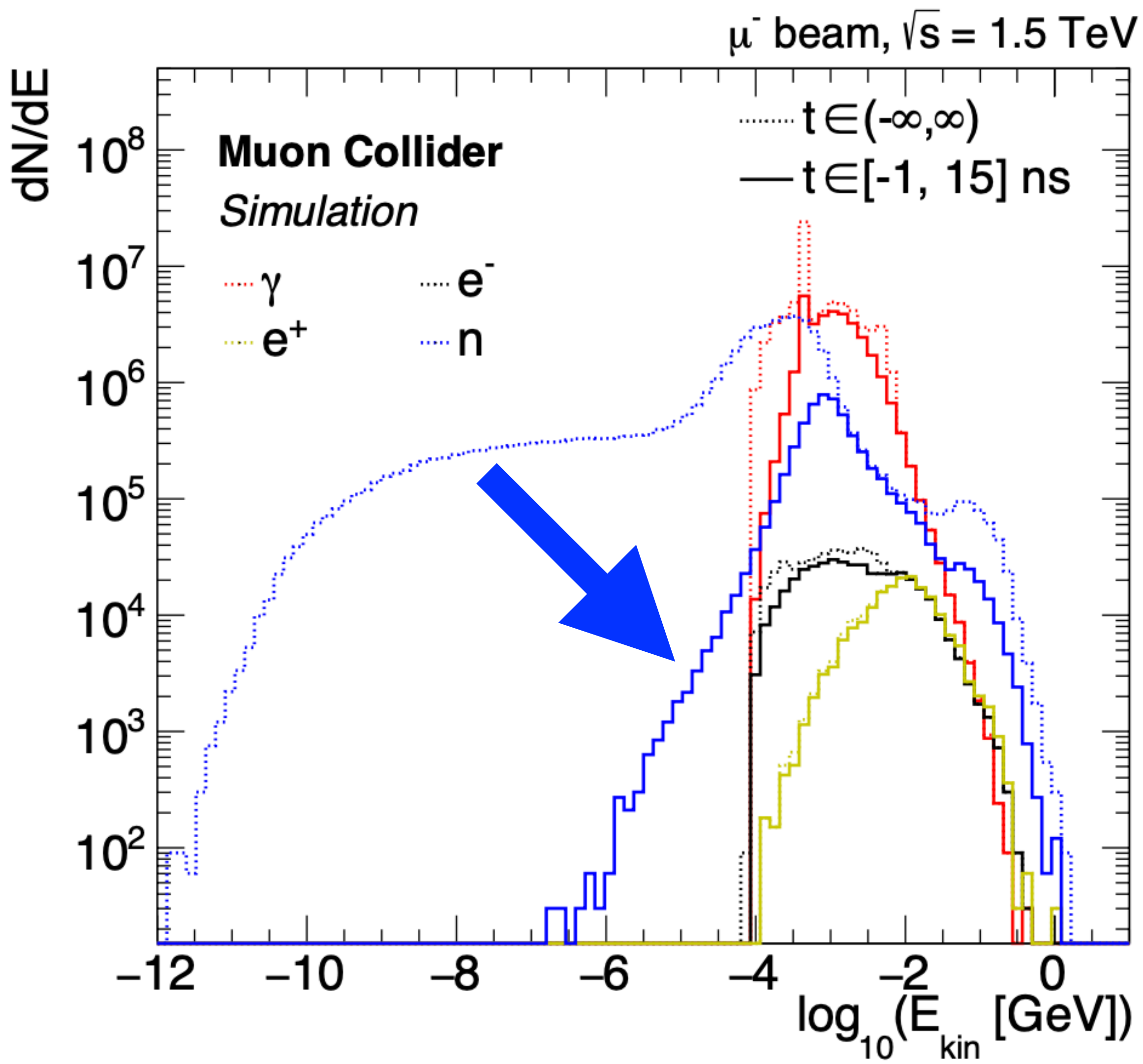
- **BIB ~in time *and* long tails**
- Shorter path length → in-time BIB arrives **earlier** than collision particles
- **High precision timing measurements necessary** to get physics out of a muon collider







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

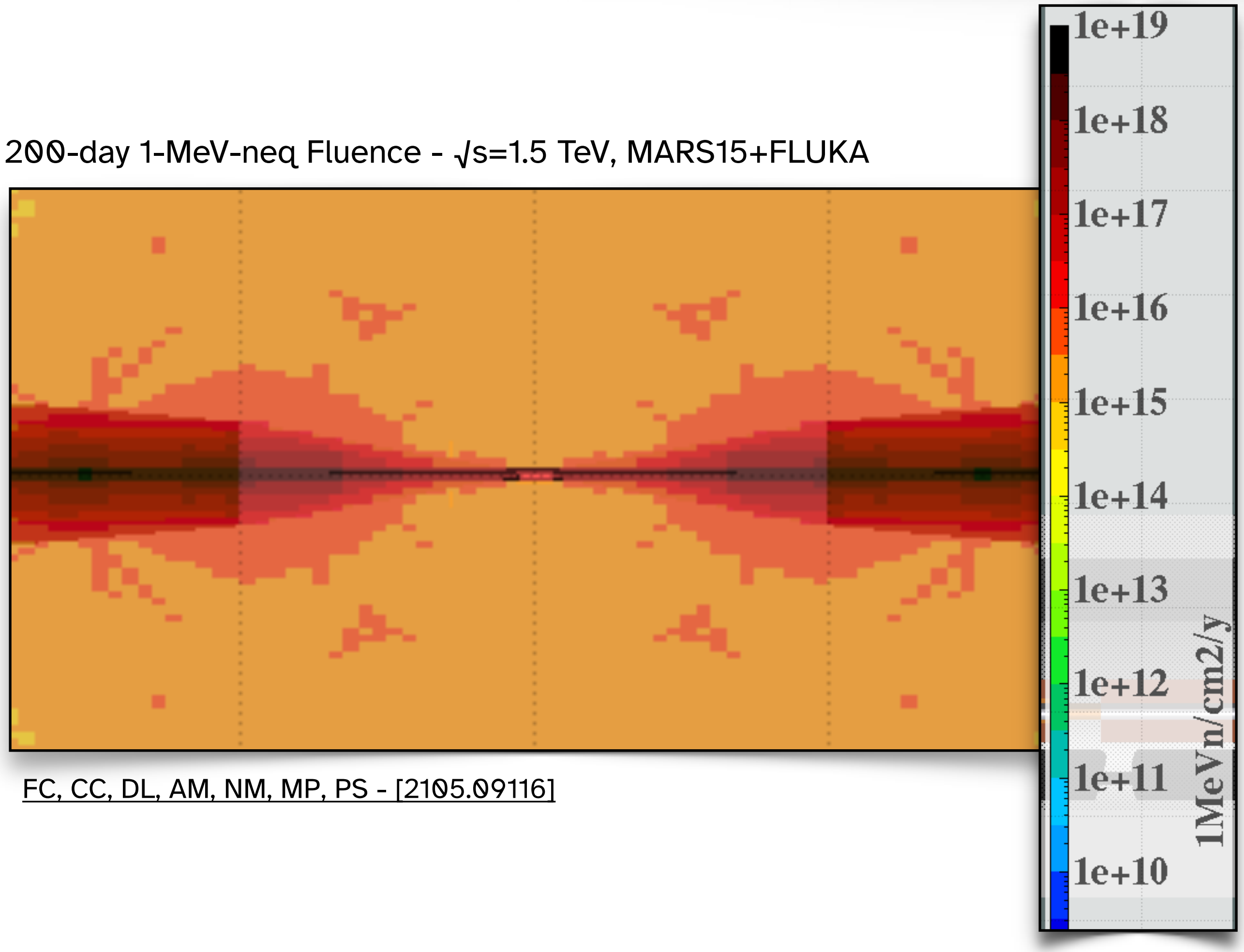


Coarse timing info helps a lot, but not enough

E.G. TRACKER

- Closest to the beam — most affected by BIB
- BIB hits plague readout and offline tracking algorithms
- Build trackers with more information to reject BIB hits on-/off-detector
- Instead of a point in 3-space:
    - **Space-time** point with precision timing
    - Or point in **phase space** with modest pointing/momentum information

200-day 1-MeV-neq Fluence - √s=1.5 TeV, MARS15+FLUKA



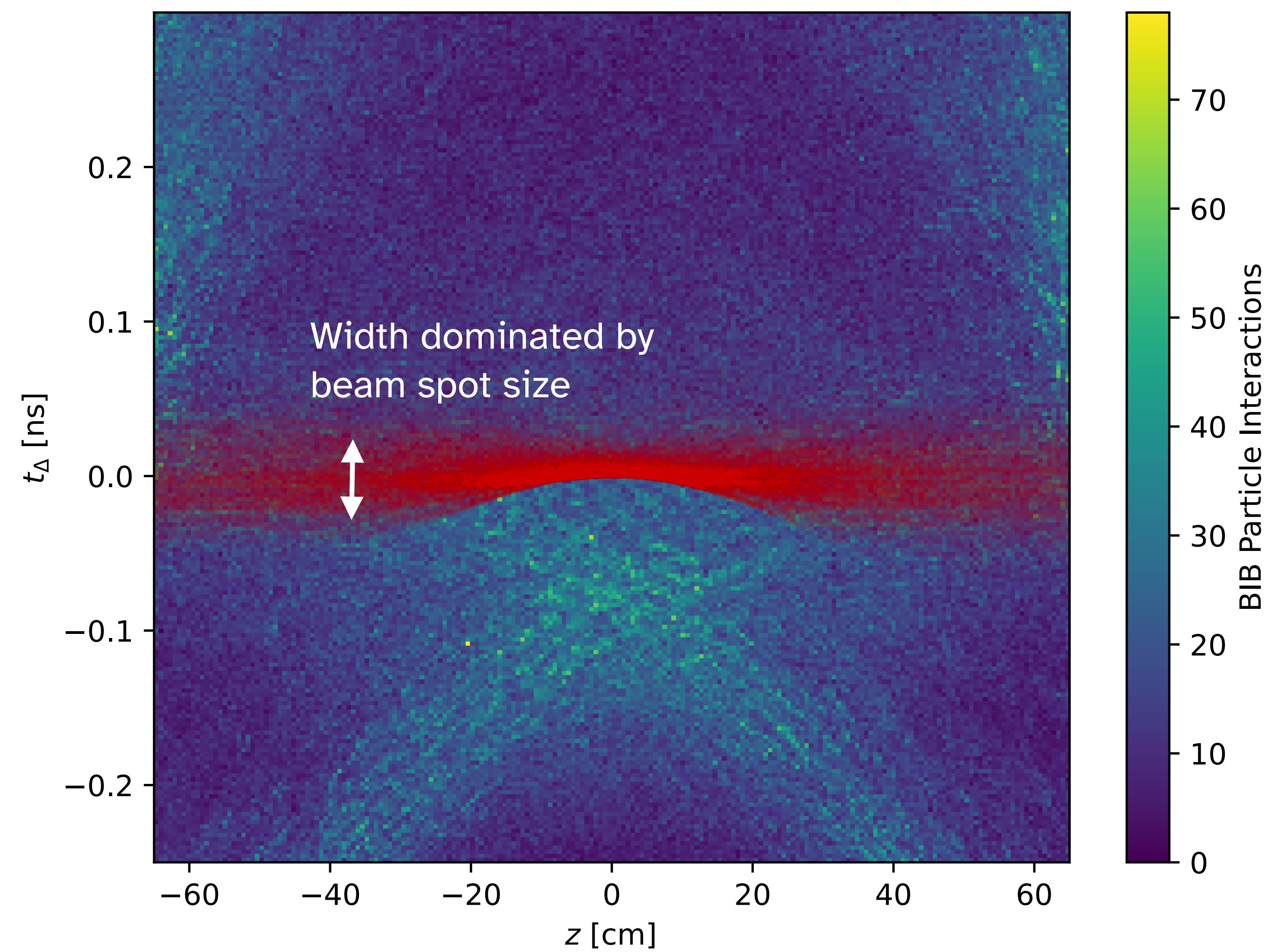
FC, CC, DL, AM, NM, MP, PS - [2105.09116]

Need to build a detector that can do this in an affordable and sustainable way

Tracker BIB Sub-ns Structure

- Below 1 ns, ∃ structure to exploit!
- Classic **BIB-"fish"** shape
- Detector must resolve time-of-flight to reduce BIB contributions
- Beam spread sets best-case timing **resolution scale of O(10) ps**

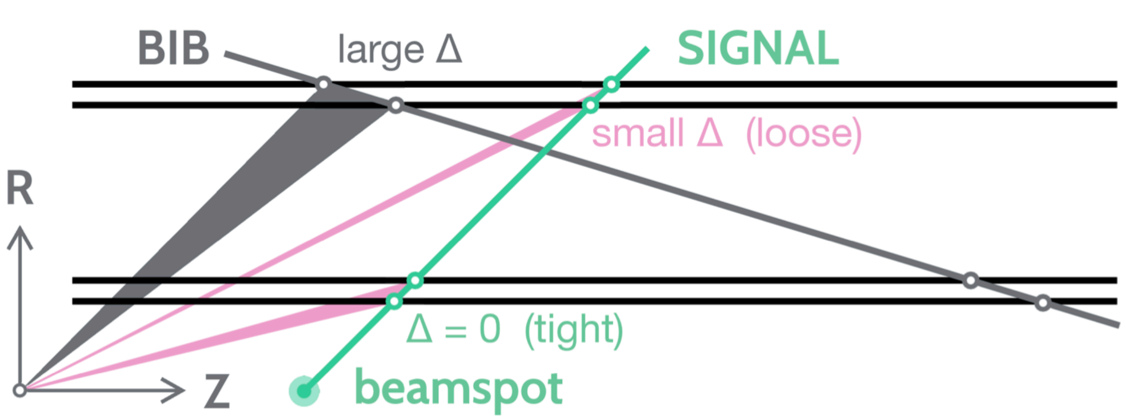
$$t_\Delta = t - t_{exp}(\beta = 1)$$



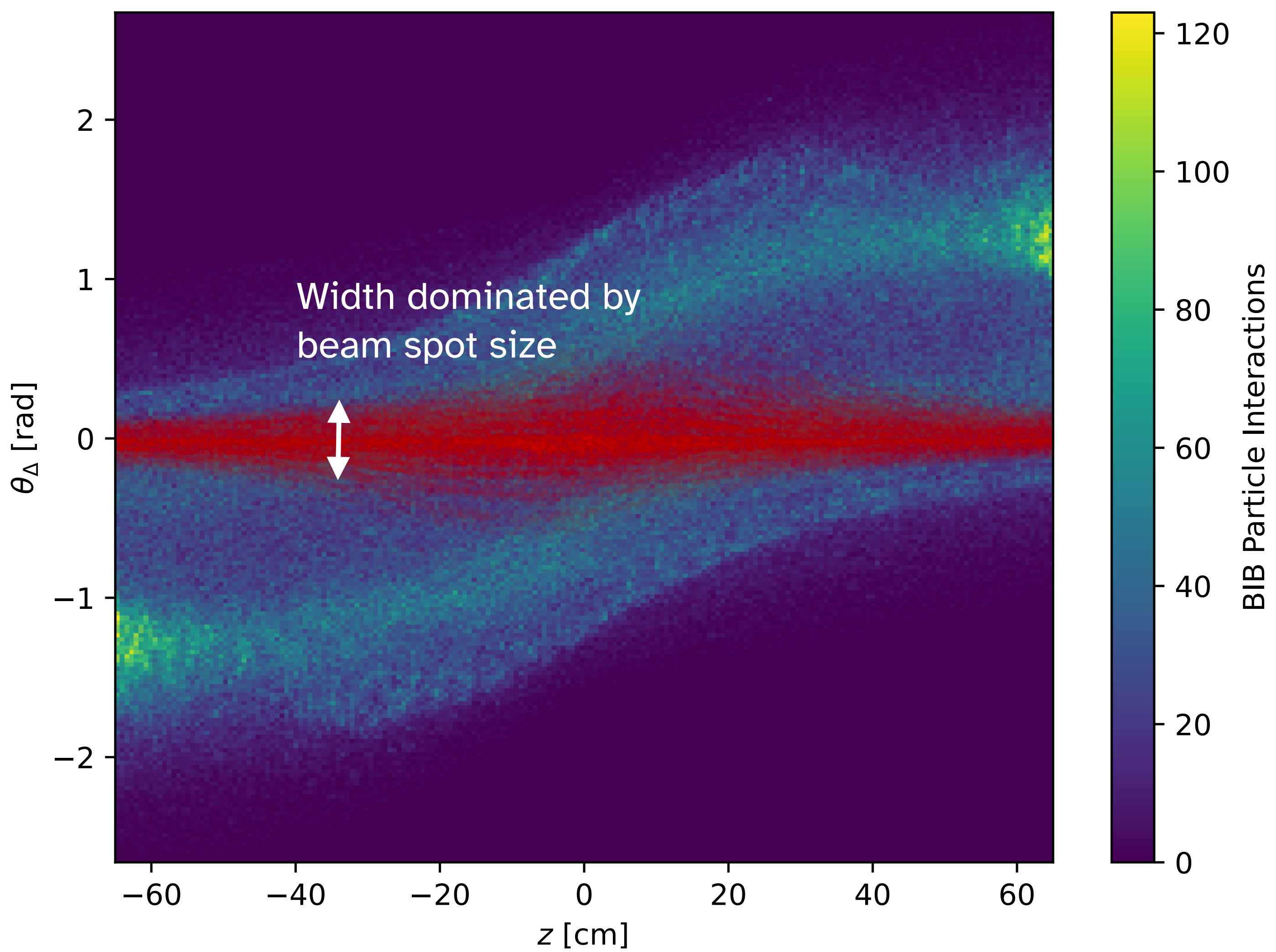
Ally, Carpenter, Holmes, LL, Wagenknecht - [2203.06773]

Angular Information

- BIB is also **non-projective**
- **Per-layer pointing** information can be helpful in rejecting BIB
- Spread (and LLPs) prevent cutting too hard at hit level, but can benefit from more resolution post-vertexing

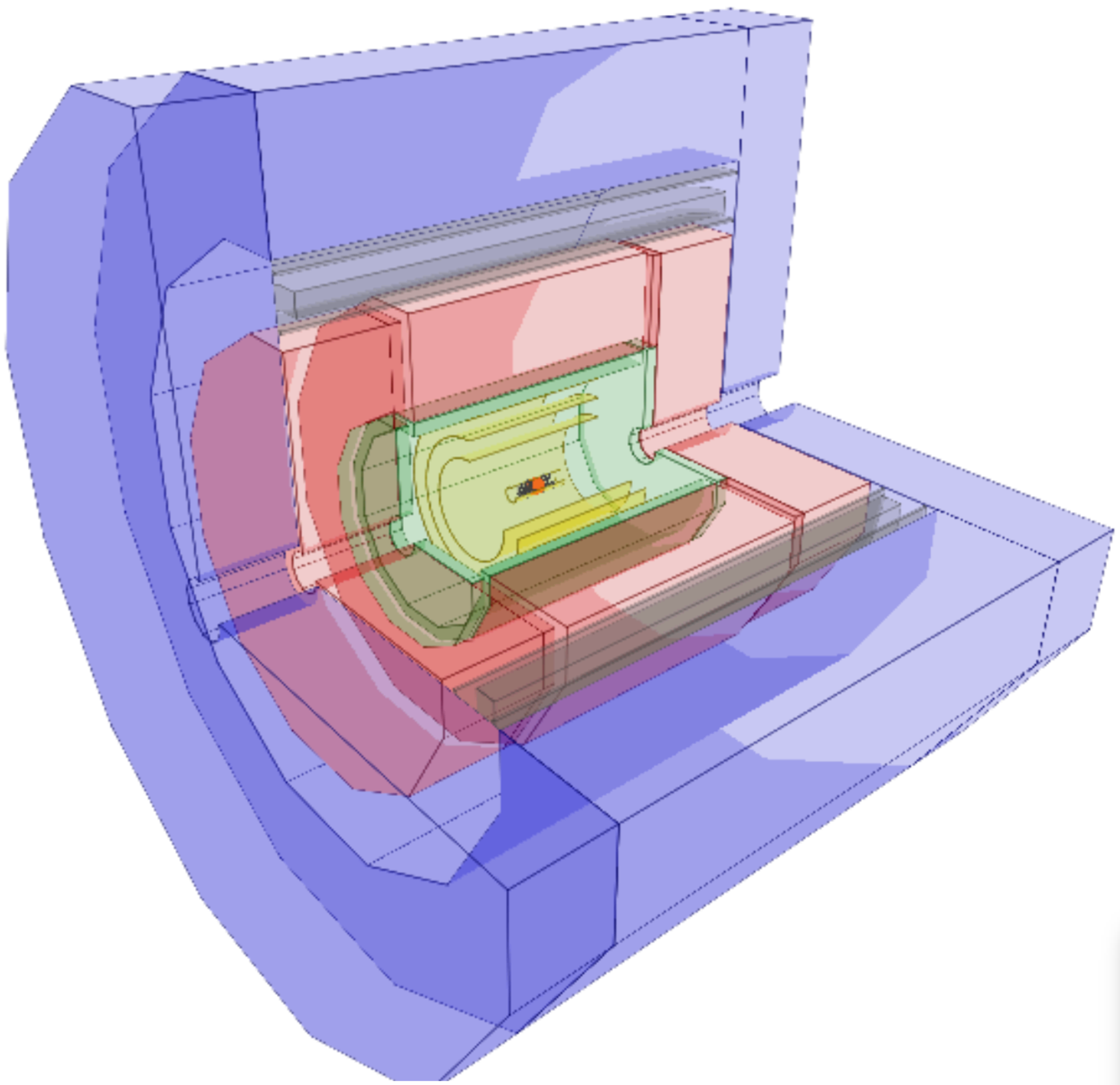


$\theta_{\Delta} = \theta - \theta_{exp}$(From IP)



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

Assumed Detector



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

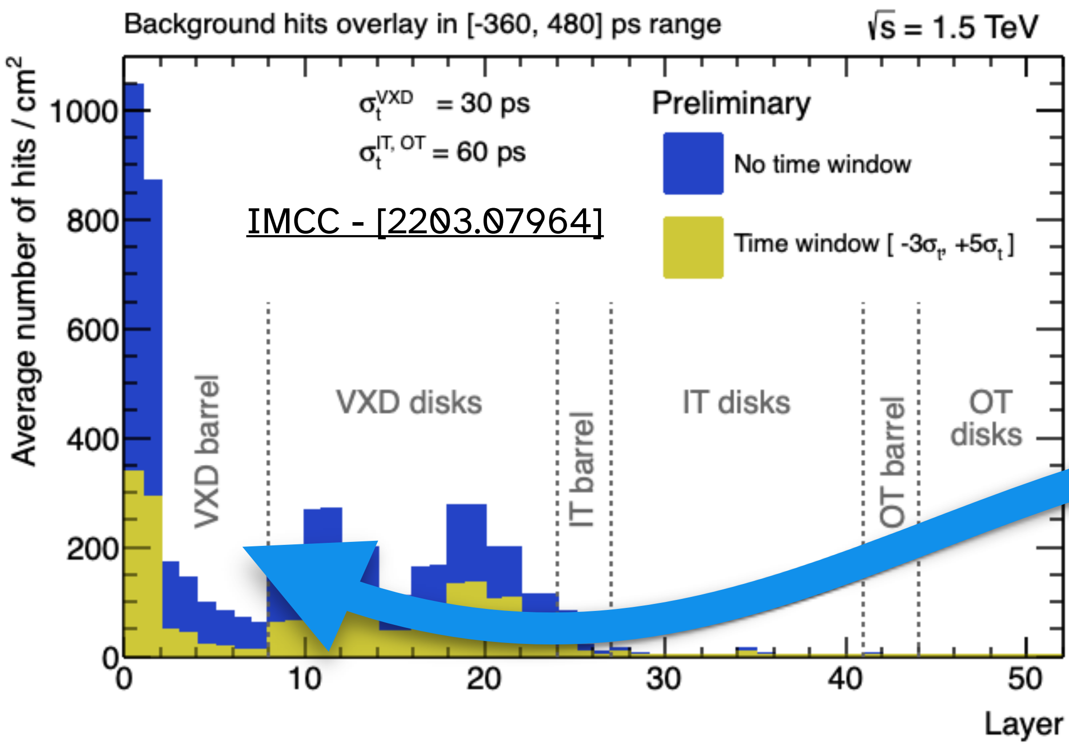
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu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

		Barrel				Endcap			
	Layer IDs	0,1	2,3	4,5	6,7	0,1	2,3	4,5	6,7
Loose DL selections	Max. $\Delta\phi$ (mrad)	2.8	2.0	1.7	1.5	2.1	1.7	1.6	1.5
	Max. $\Delta\theta$ (mrad)	35	18	10	6.5	3.5	1.5	0.7	0.5
	Hit surival fraction	55%				18%			
Tight DL selections	Max. $\Delta\phi$ (mrad)	3.0	2.0	1.6	1.5	2.2	1.8	1.7	1.6
	Max. $\Delta\theta$ (mrad)	0.5	0.4	0.3	0.25	0.2	0.18	0.12	0.1
	Hit survival fraction	2%				2%			

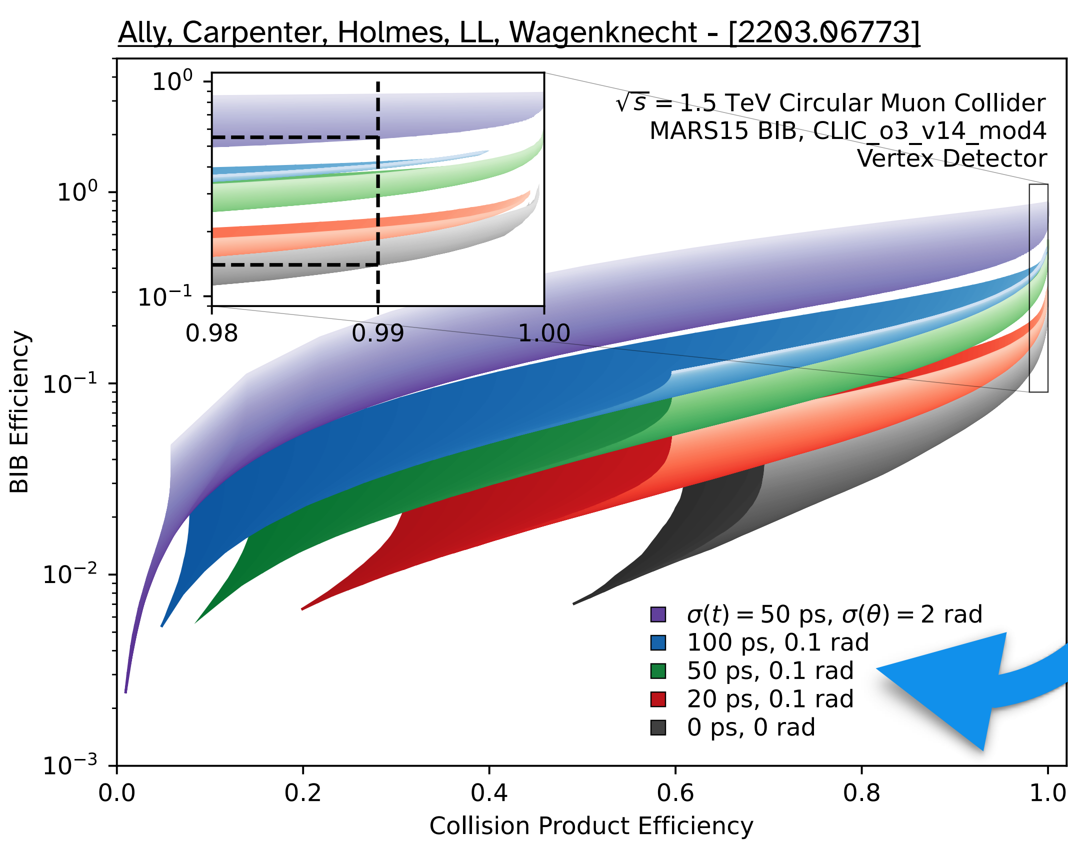
Based on a CLIC detector design + nozzles

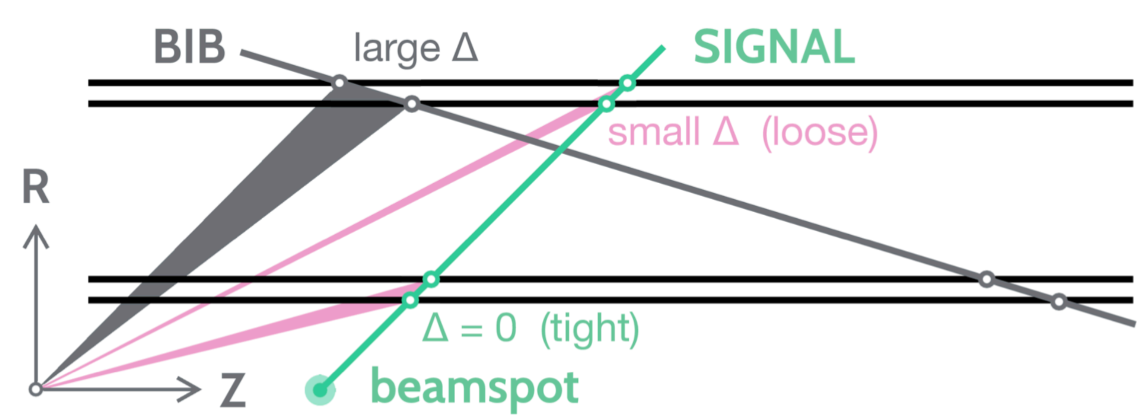
Ultimately needs reoptimization for unique μC environment

For actual information, see [IMCC 2203.07964]

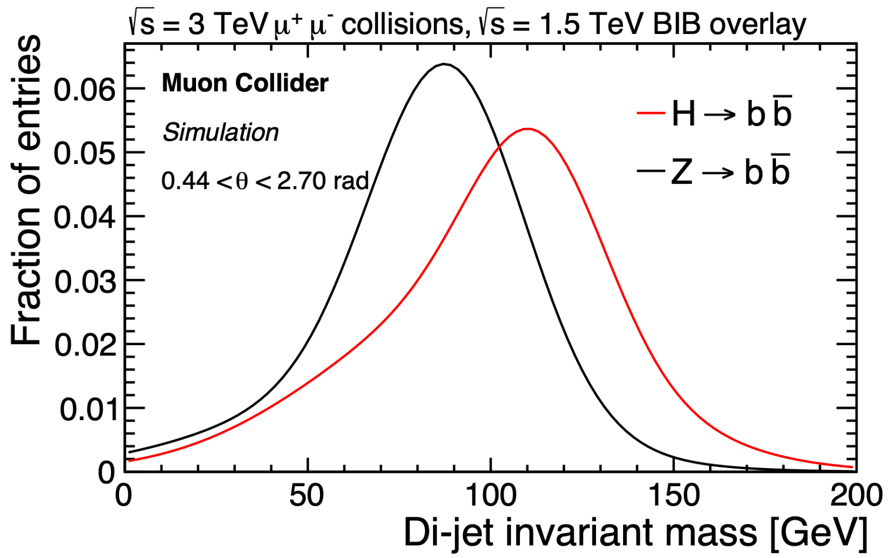


- w/ 30ps res, vertex detector **further reduces hit rate by add'l ~50-70%**
  - Worst-case hit density ~300 hits/cm² → ~OK for pixel detectors!
- **Adding angular info**, reduce hit density even more
  - CMS's double-layer HL-LHC tracker will provide pointing information

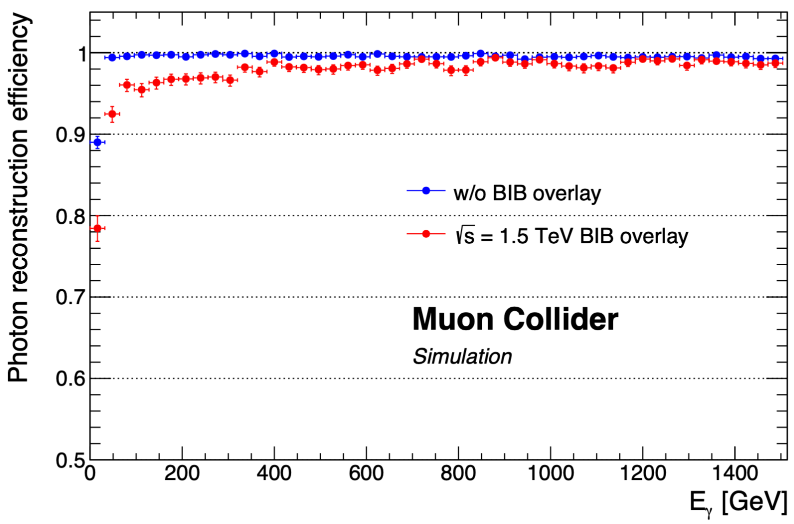




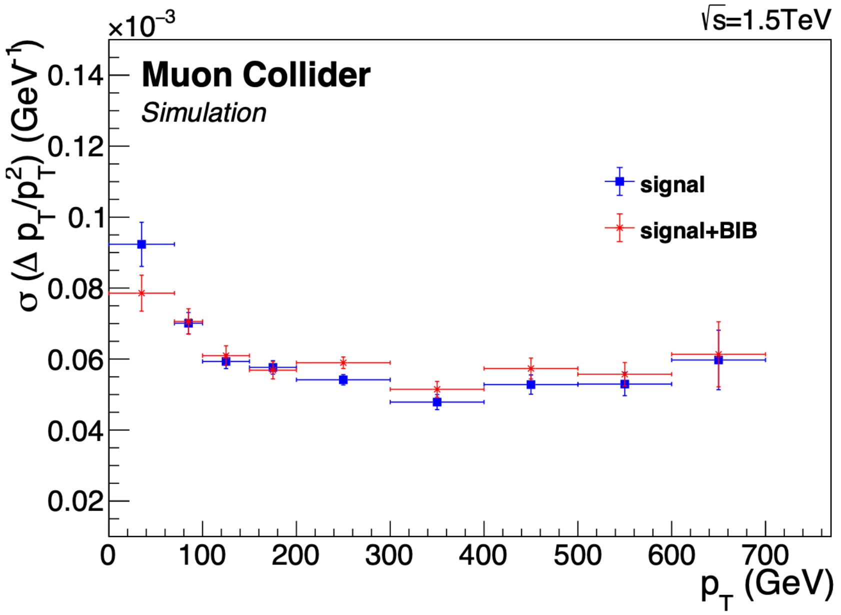
Physics Performance



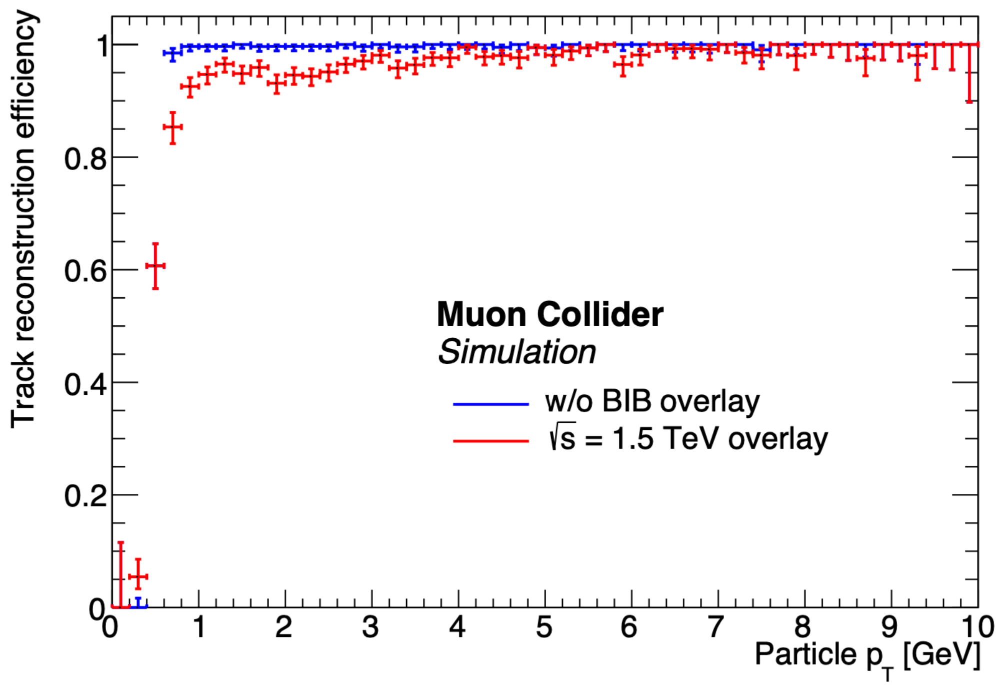
Jet resolutions to distinguish H and Z peaks



Photon efficiencies survive BIB contamination



Very respectable muon measurements



Despite being full of BIB, this tracker can still measure tracks

Appears that we could do physics in this environment!

But IFF we can reach detector performance targets!

∃ promising R&D that suggests this assumed detector is feasible

(Not to scale)

Need precise position, pointing, and timing

Promising R&D Paths

4D TRACKERS

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
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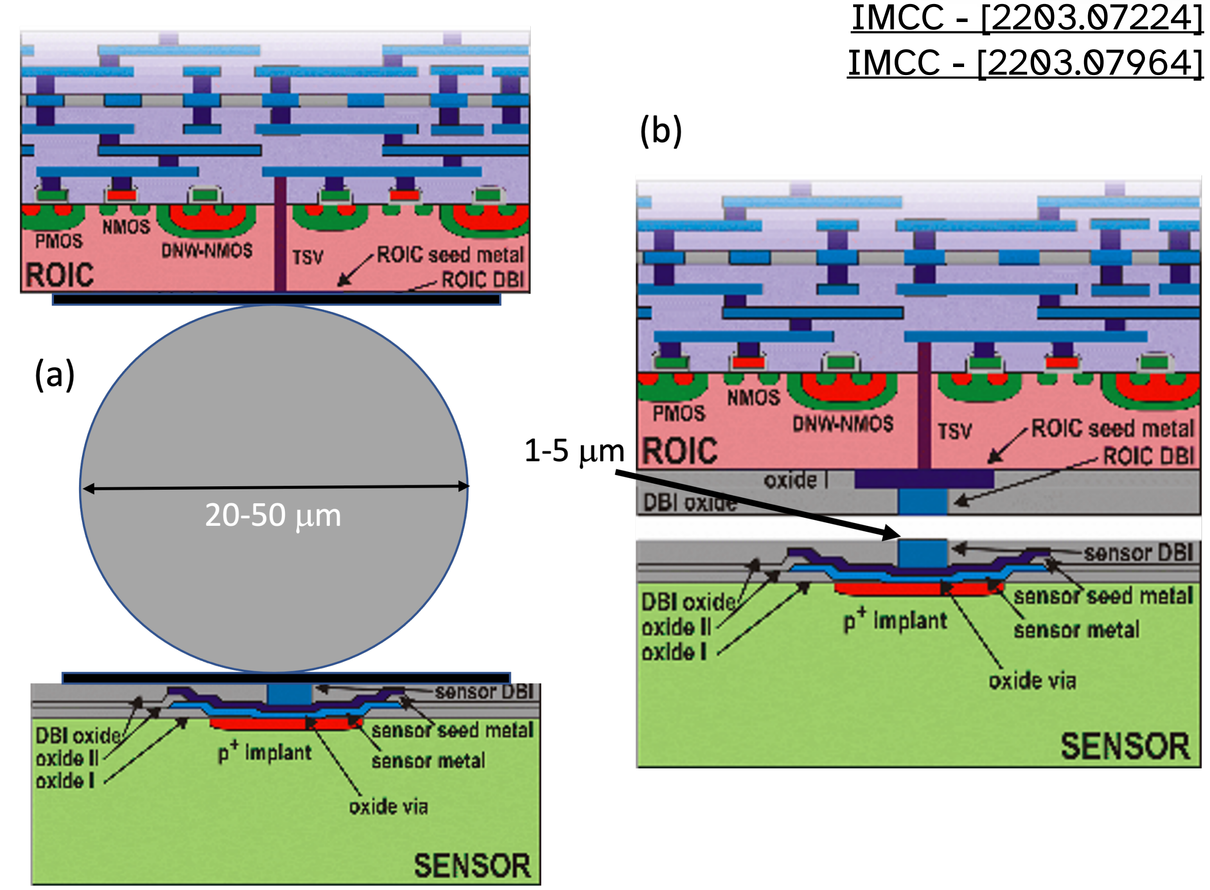
Time Resolution	30ps	60ps	60ps

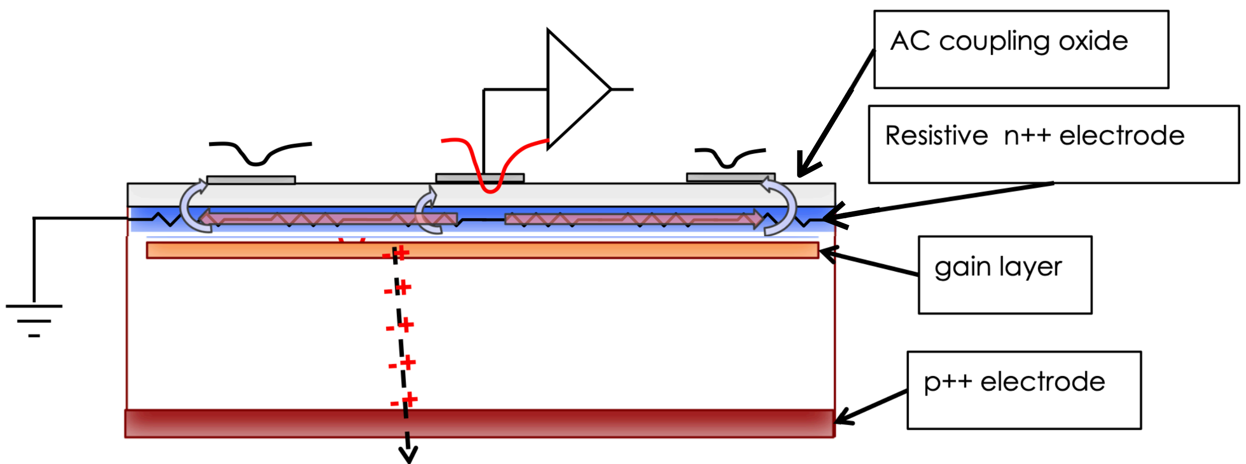
IMCC - [2203.07224]
IMCC - [2203.07964]

- **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**

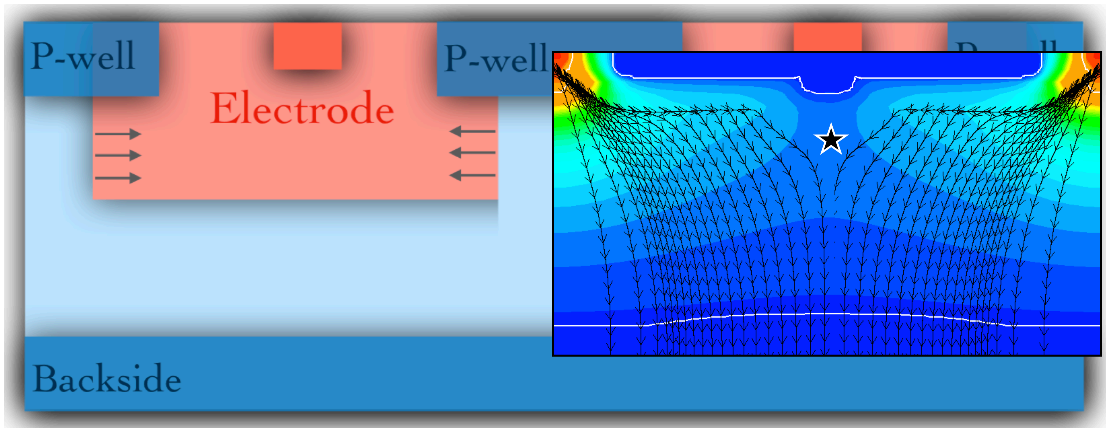


Traditional Bump Bonding
O(10) μm

Stacked bonding
O(1) μm



From talk by N Cartiglia



From talk by M Munker

- **Resistive Silicon Detectors (RSD) / AC-LGADs**
- Multi-pad signals allow for **triangulation of precise position and time**
  - O(1) micron resolution w/ O(100) micron pitch
  - 20 ps resolution w/ 25 micron thickness

- **Monolithic Active Pixel Sensors (MAPS)**
  - On-CMOS charge collection
- More recent advances in fabrication tech → Improved charge collection
- Fast, cheap, more radiation tolerant, low mass
- Quickly developing for current and future facilities

All of these technologies also viable for other facilities

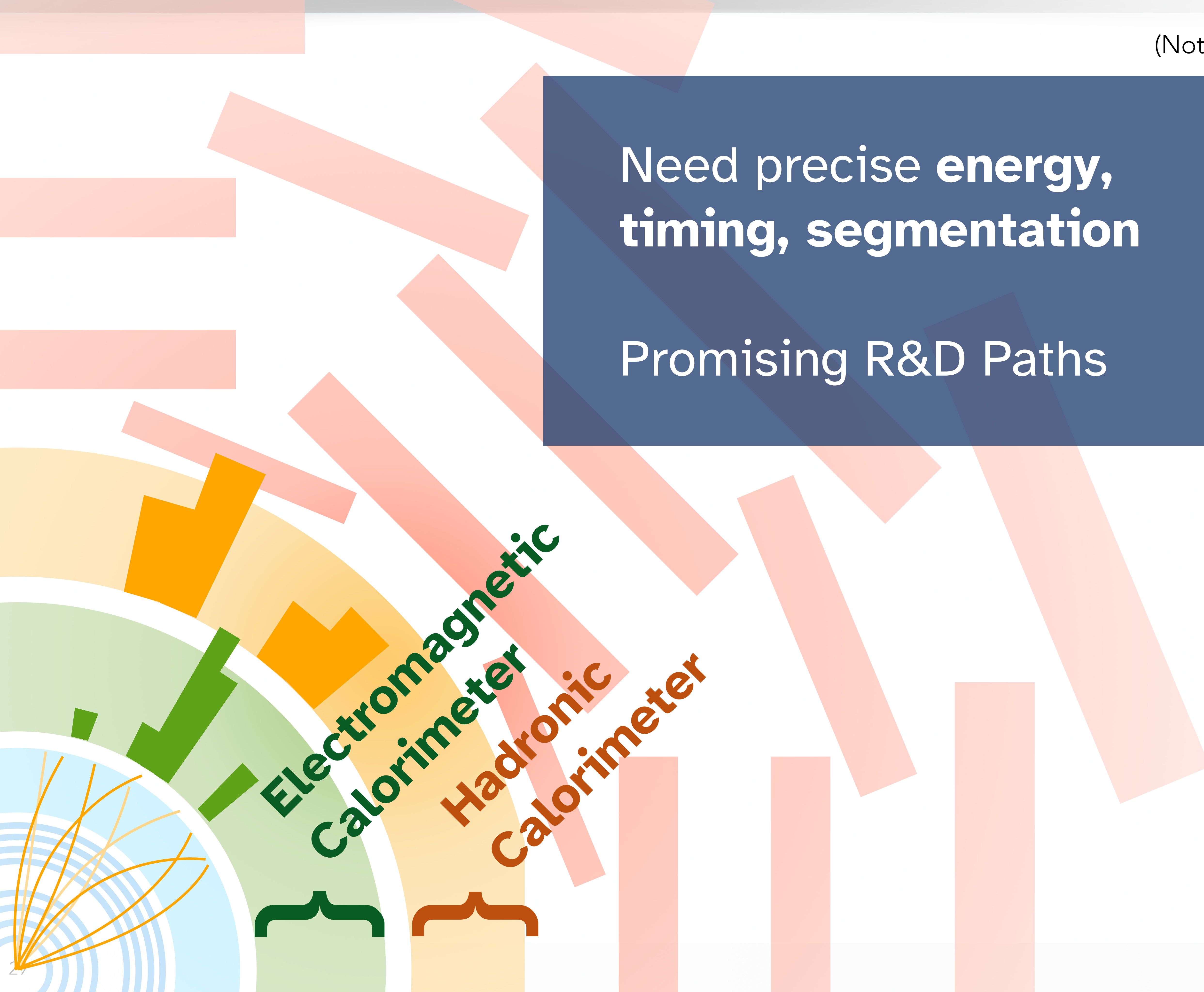
(But emphases [e.g. timing] may differ for μC environment)

[Ref 1, Ref 2, Ref 3]

(Not to scale)

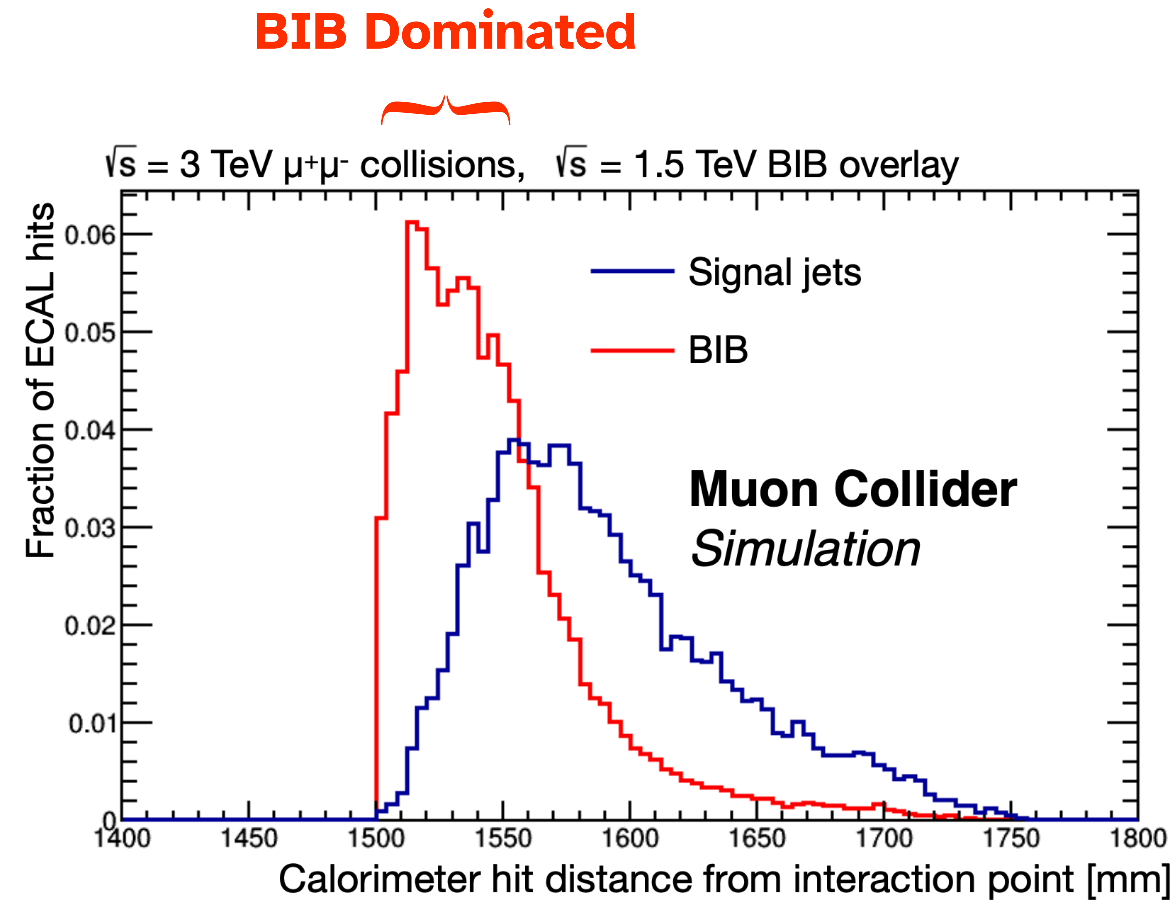
Need precise **energy, timing, segmentation**

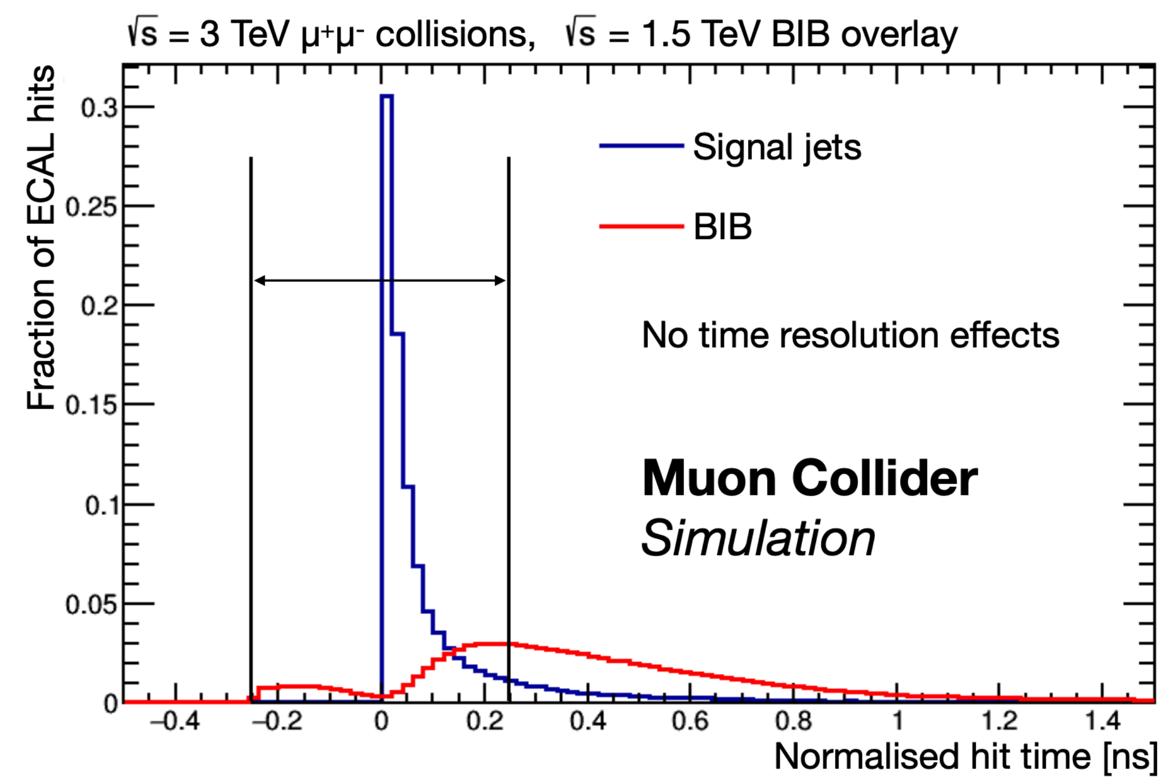
Promising R&D Paths



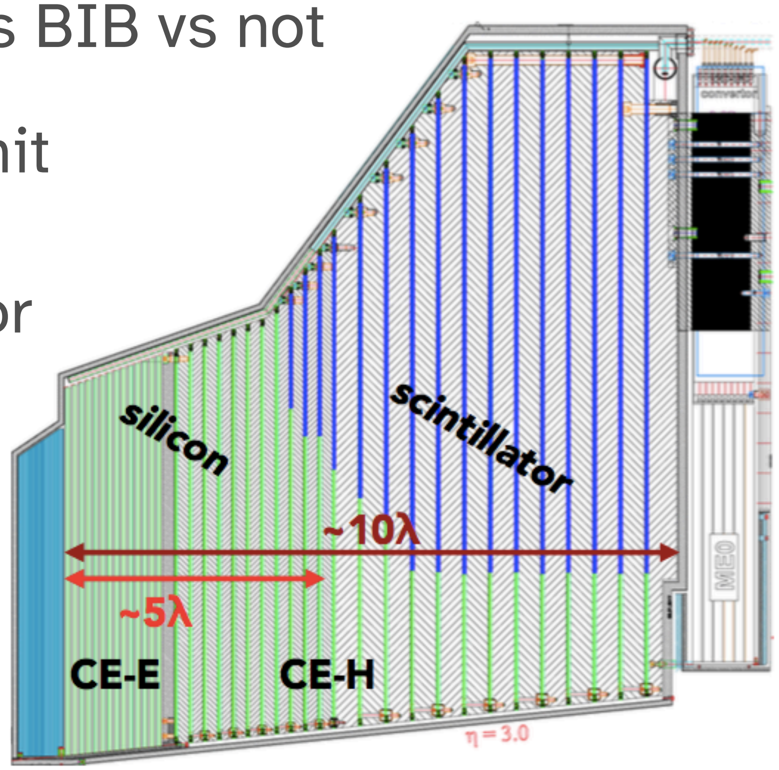
CALORIMETERS

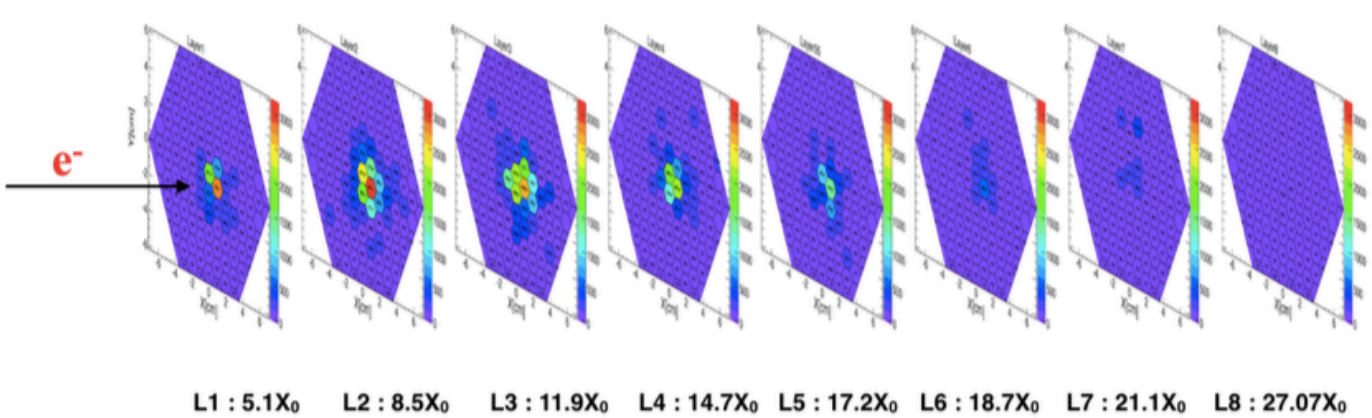
- Lower granularity and larger integration times make calorimeters sensitive to BIB
- Radial profile shows BIB problem **at inner radii** (first 50 mm of depth)
  - Need **longitudinal granularity**
- Long tail in hit time from late BIB neutrons/ photons
  - Timing resolutions **80-100 ps** very useful
- BIB sensitivity from long **integration times**, but assuming it's diffuse and flat enough to be subtracted
  - **More detailed studies of this assumption ongoing**

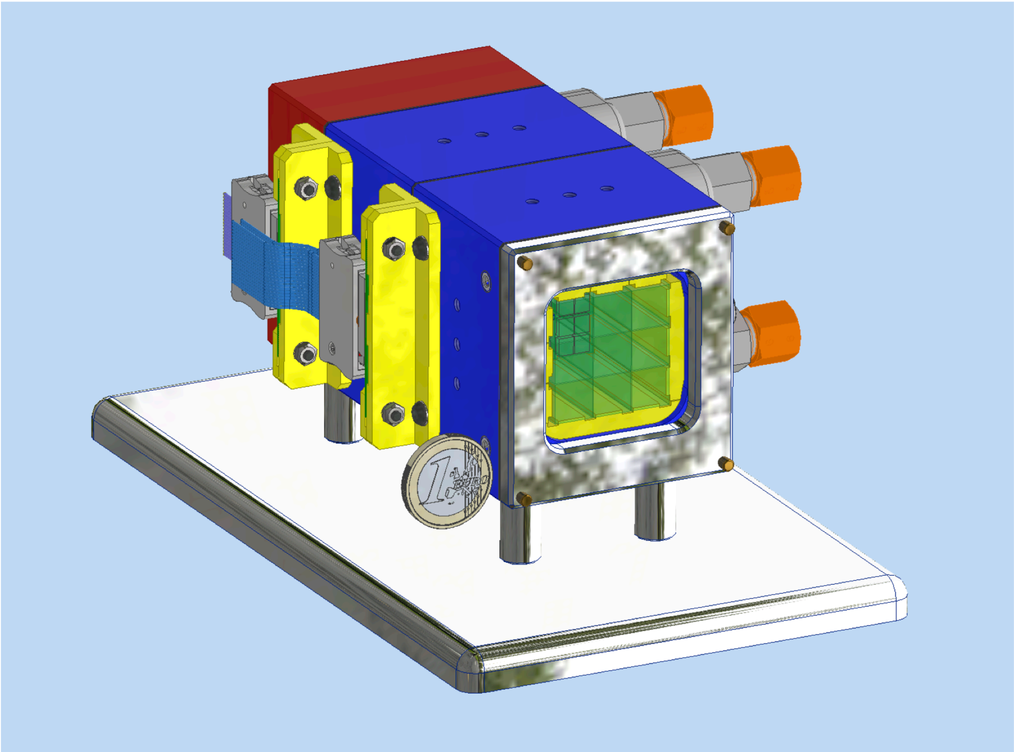




- **CMS HGCal**
  - Precise measurements of shower evolution across 6.5M channels
  - This approach can give detailed view of what's BIB vs not
  - Can already hit O(10) ps resolutions for multi-MIP signals



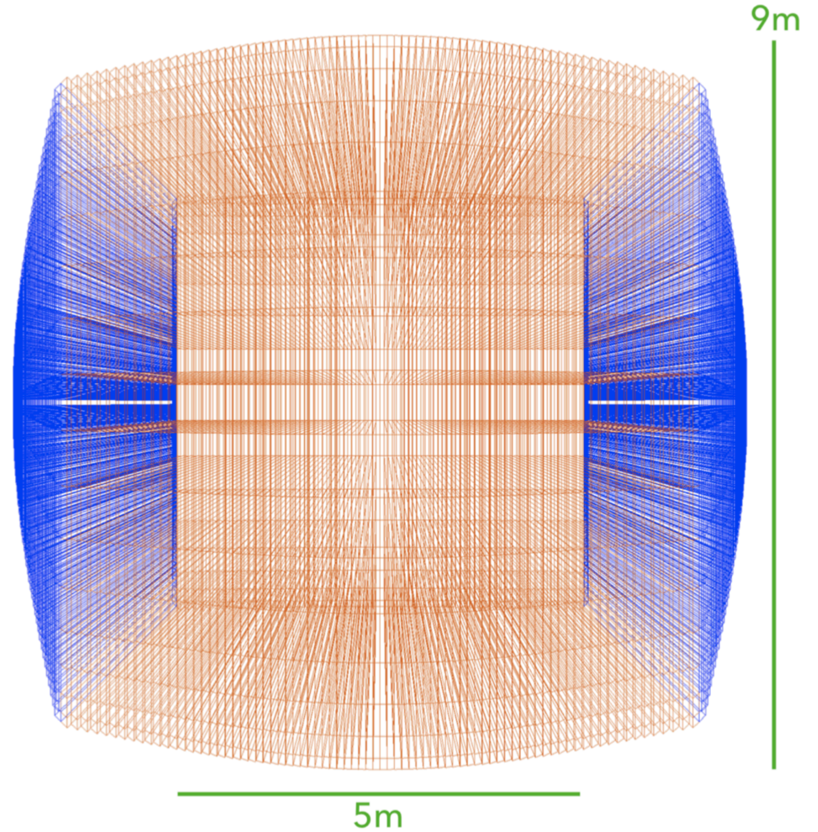


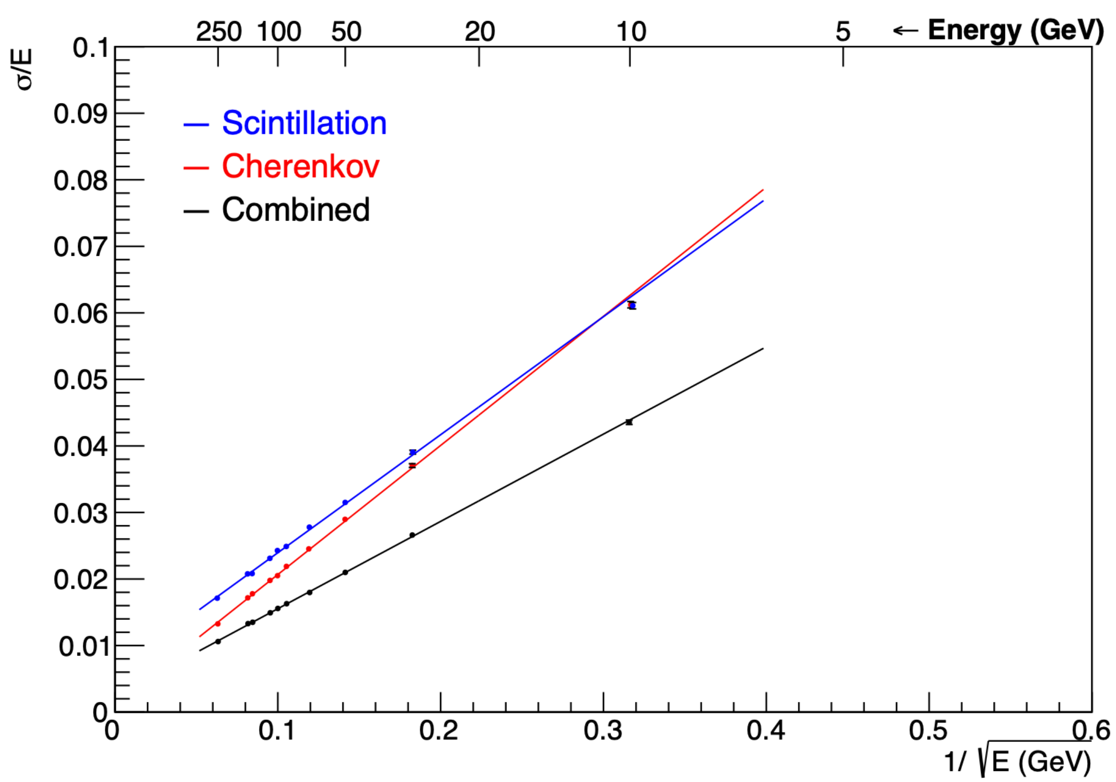


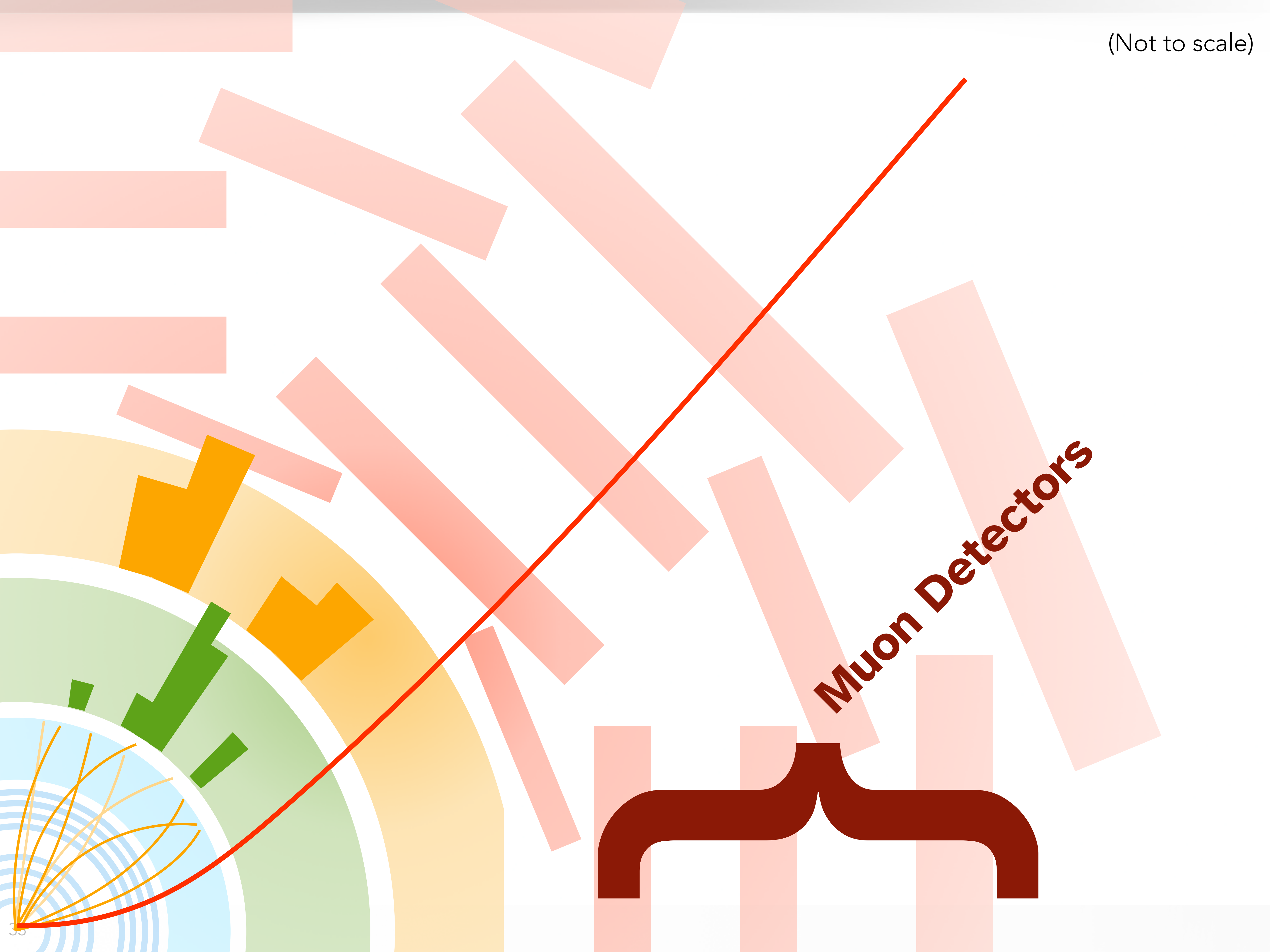
[2206.05838, I. Sarra Talk at IMCC]

- **CRILIN: CRYstal calorimeter with Longitudinal InformatioN**
  - EM calo of lead fluoride crystals
  - Lots of longitudinal information
  - Help separating out BIB with information in first few layers
  - Time resolution down to 15 ps
  - Prototype testing well underway with testbed studies

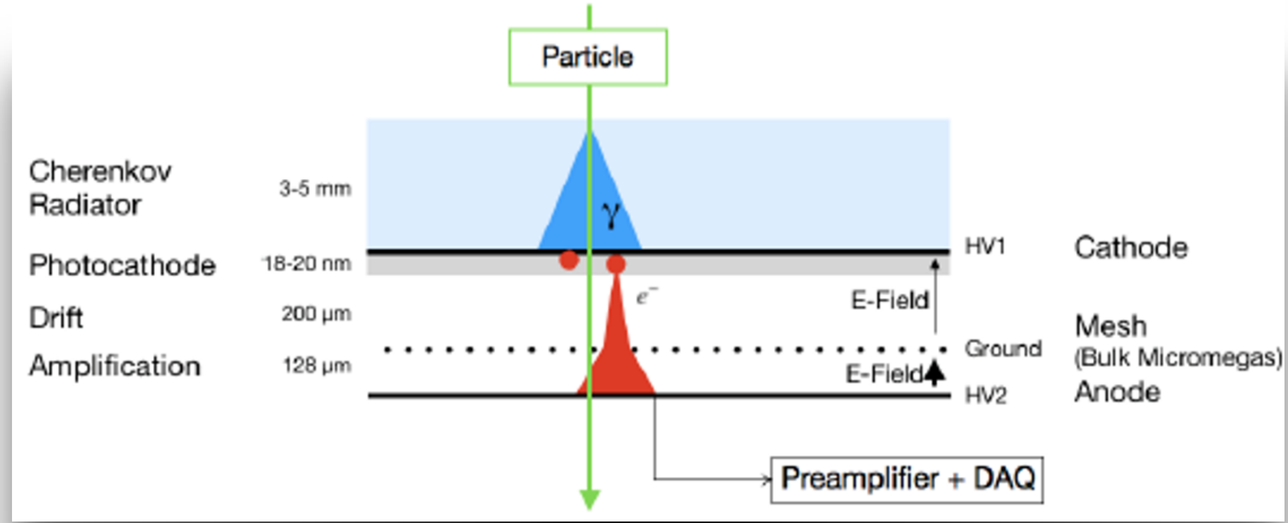
- **CalVision / IDEA / Dual Readout**
  - Improve resolution with combination of scintillation and Cherenkov light
  - Very useful since jet EM components further complicated by BIB injection
  - At high energies, Cherenkov component helps achieve 1% resolutions
  - Timing can potentially give longitudinal resolutions of ~2 cm to help identify BIB component
- Lots to learn from the **CALICE** collaboration for high granularity, PFlow-centric detection






(Not to scale)
Muon Detectors

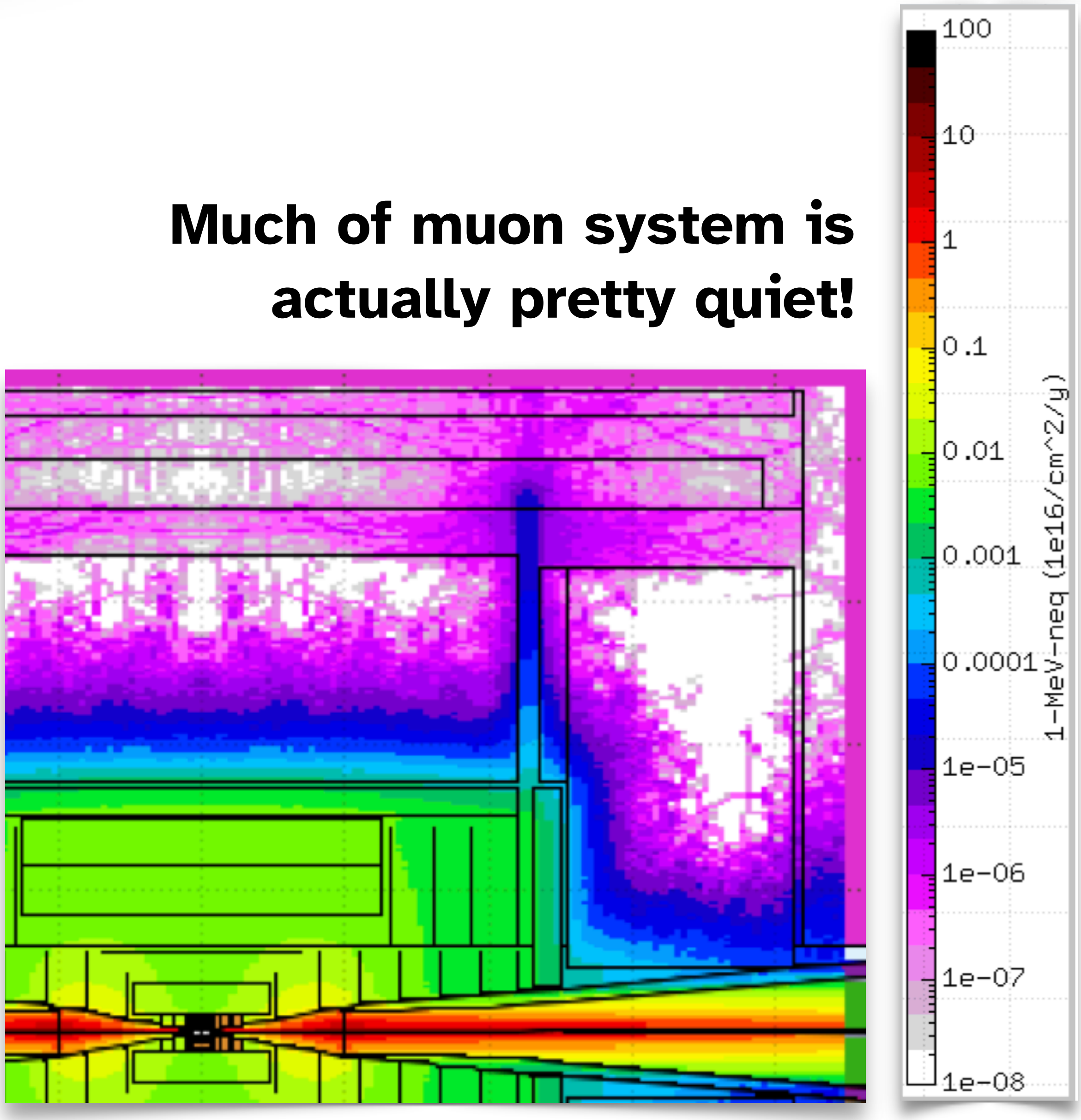
Muon Detectors



PicoSec

- Lots of emerging detector tech for muon detection
- Current gaseous detectors can't achieve <1 ns resolution (without excessive carbon emission) → **R&D needed!**
  - **Hybrid Micromegas+Cherenkov** reach 25 ps PicoSec - [1901.03355]
  - **Fast Timing Micropattern (FTM)** use multiple drift and amplification gaps to hopefully achieve < 1 ns Oliveira, Maggi, Sharma - [1503.05330]
- If occupancy low enough:
  - Traditional **micromegas** could work?
    - Large-scale micromegas being put to the test by ATLAS now
  - **Scintillating fibers/bars** could work?

Much of muon system is actually pretty quiet!



Rising to the Challenge(s)

- **Attacking these problems**
  - … with overall detector design
  - … with new detection technologies
  - **… with electronics / DAQ design**

READOUT

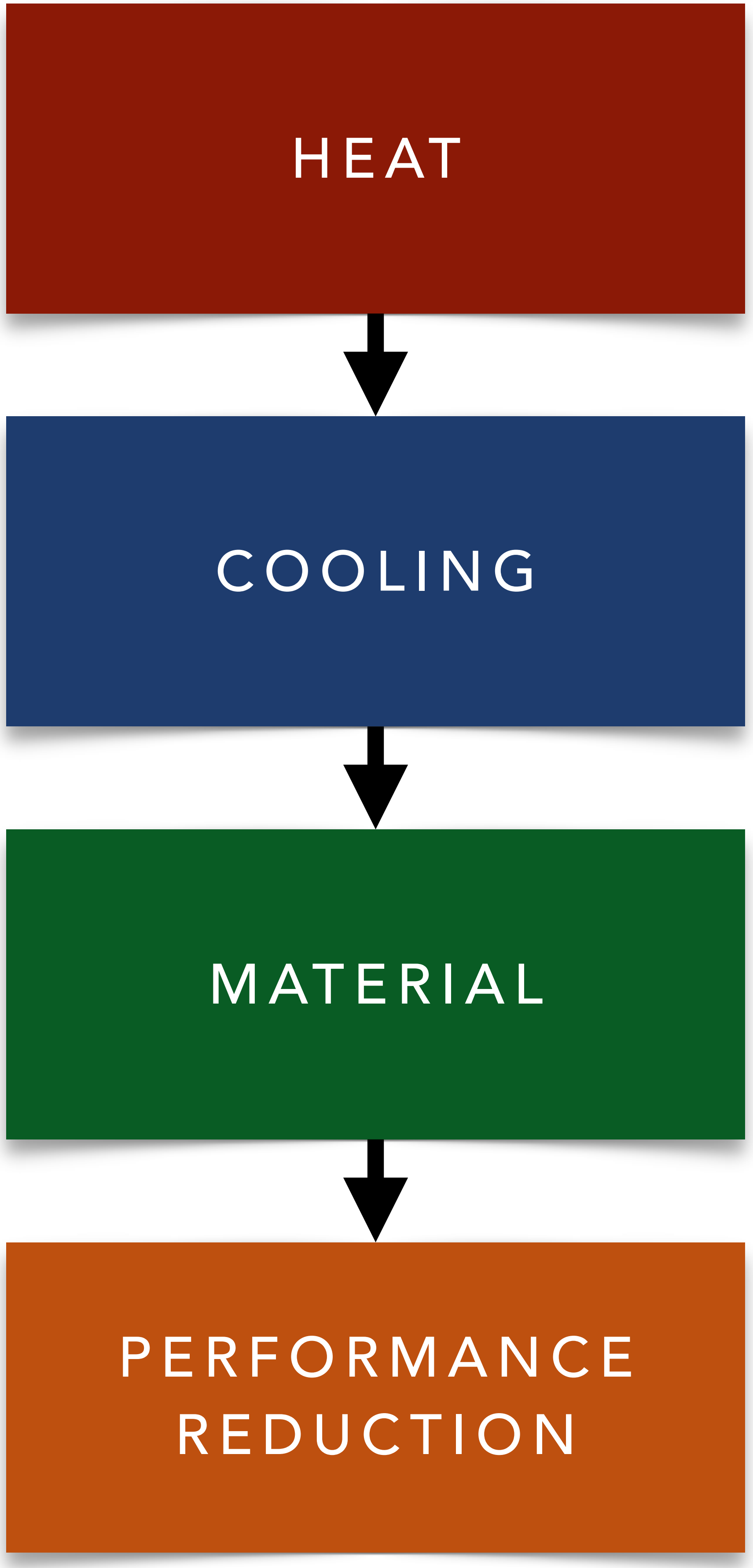
- Need to consider readout throughputs, especially in face of BIB
  - Occupancy is naturally high at μC
  - Can we read it all out? Or do we need in-situ filtering?
    - **Throwing away @ detector level is dangerous**, but it might be necessary…
  - Or do we figure out how to read everything out and try to reject BIB fully offline?

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

Order of mag larger hit density than ATLAS ITK
HL-LHC will use up to 60% of ITK's 5 Gbps links
→ Would need faster Tx lines at μC

- Projected link technology can handle this but…
- Larger links require **more power**
  - With power comes ***heat***
- In high radiation environment, **material budget might be more critical**
  - *BIB-induced* activity compounds problem in **μC-specific way…**



Power Consumption

- Estimates from S Jindariani for vertex detector give power consumption of ~200 mW/cm^2
    - Assumes precision timing info for 100-channel groups
    - With 2x safety factor, **look for *low-mass* cooling solutions to remove ~400 mW/cm^2**

	Upper timing cut (ns)	Module size (cm^2)	Maximum hits/cm^2	Reduction using cluster shapes	Data payload per module (Gbps)	Transmission power per module (W)	Total Transmission Power (W)
VXD barrel L1/L2	15	10	4600	x2	70	0.7	38
VXD barrel L1/L2	1	10	1600	x2	25	0.25	14

	Technology	Pixel size (mm^2)	Detector Capacitance (pF)	Preamp power per channel (mW)	Total preamp power (kW)	TDC Power per channel (mW)	Total TDC Power (kW)
CMS ETL	LGAD	1.3x1.3	3.5	2	16	0.1	0.8 kW
VXD	?	0.025x0.025	0.040	0.02	0.2	0.1 (?)	1.5 kW

2x [160 (FE) + 30 (Tx)] mW/cm^2

≈ 400 mW/cm^2

CO_2 Systems

✅ Thermal Performance
❌ Too much material needed...

Air Cooling

❌ ILC: Handles up to 100 mW/cm^2
✅ Great for material budget

Need 400 mW/cm^2 cooling with minimal material

[2301.13813]

Gaseous Helium Systems

Bathe detectors in He gas flow

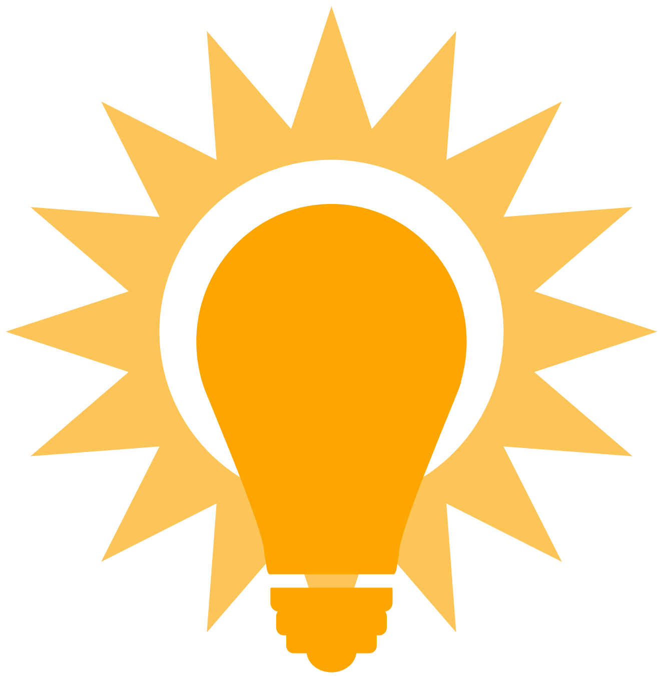
✅ Performance up to 400 mW/cm^2
✅ No cooling pipes!

Promising avenue forward!

Or **another cooling solution** yet to be developed

Or new **lower-power front-ends/transceivers**

Same epilogue question for **all** of these topics:
Is there a not-yet developed R&D breakthrough on the horizon?



Not a solved problem! The **physics reach** of a μC gives *excellent* motivation for detector and electronics communities to push the limit of our capabilities.

Take-away:

- Physics reach of a **multi-TeV muon collider** relies on (among other things) **successful detector R&D program today**
- Numerous challenges in shielding, detector design, detection tech, electronics, services
- **∃ promising tech and *lots* of preliminary work (US and abroad)**, but only scratch surface.

Take-away:

Thanks for your attention!

- Next few years needs everything from
  - Small feasibility studies
  - To inventing *new* technologies
- Will require serious effort and *creativity*
  - **Many synergies** with future ee and hh programs, and also **many μC-specific needs**
  - Strong connection with CERN's IMCC
- **Challenges not insurmountable, but require new instrumentation R&D efforts today**

LL is supported by the Department of Energy, Office of Science, under Grant No. DE-SC0023321.

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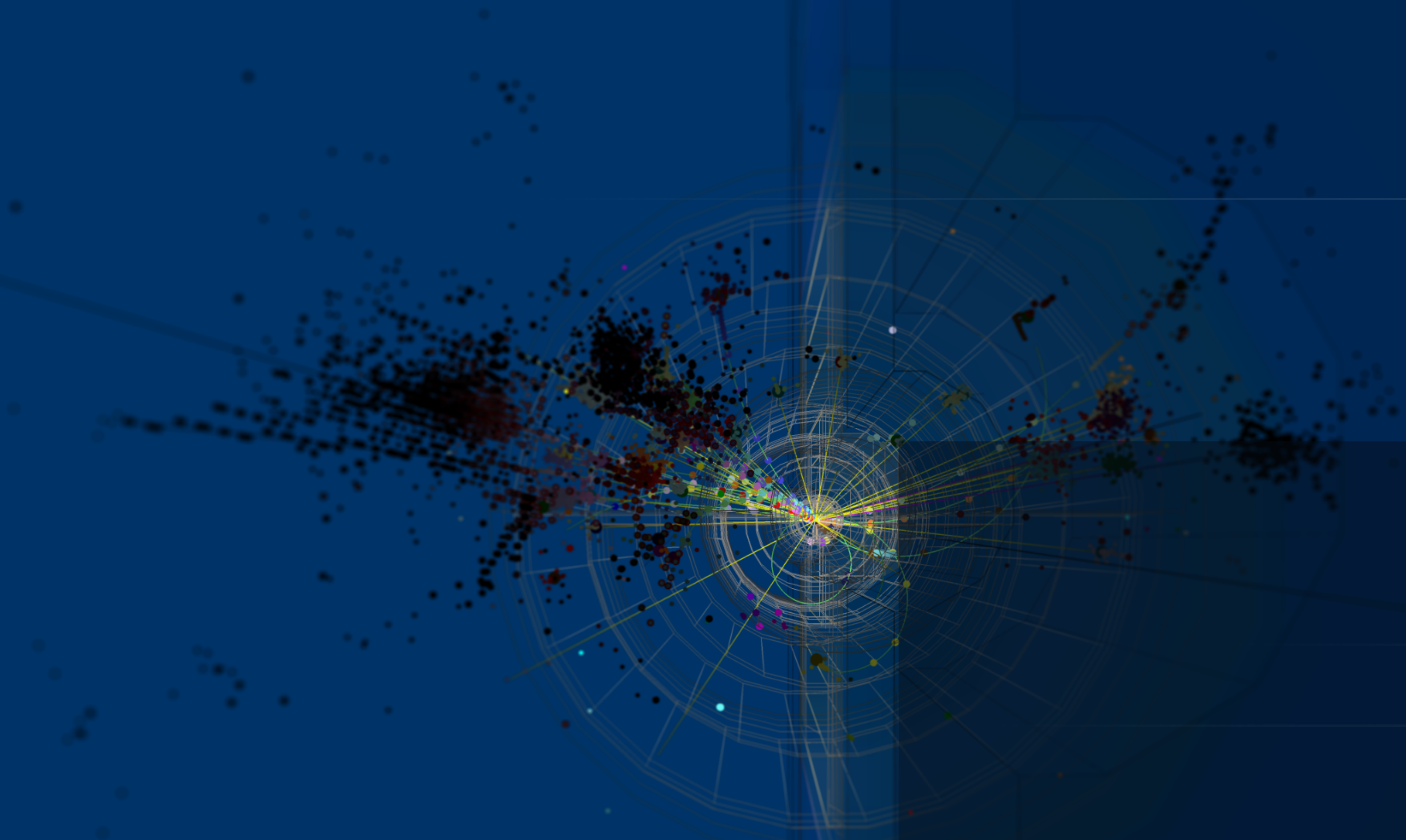

Backup

ATLAS ITk Layer	ITk Hit Density [mm^2]	MCD Equiv. Hit Density [mm^2]
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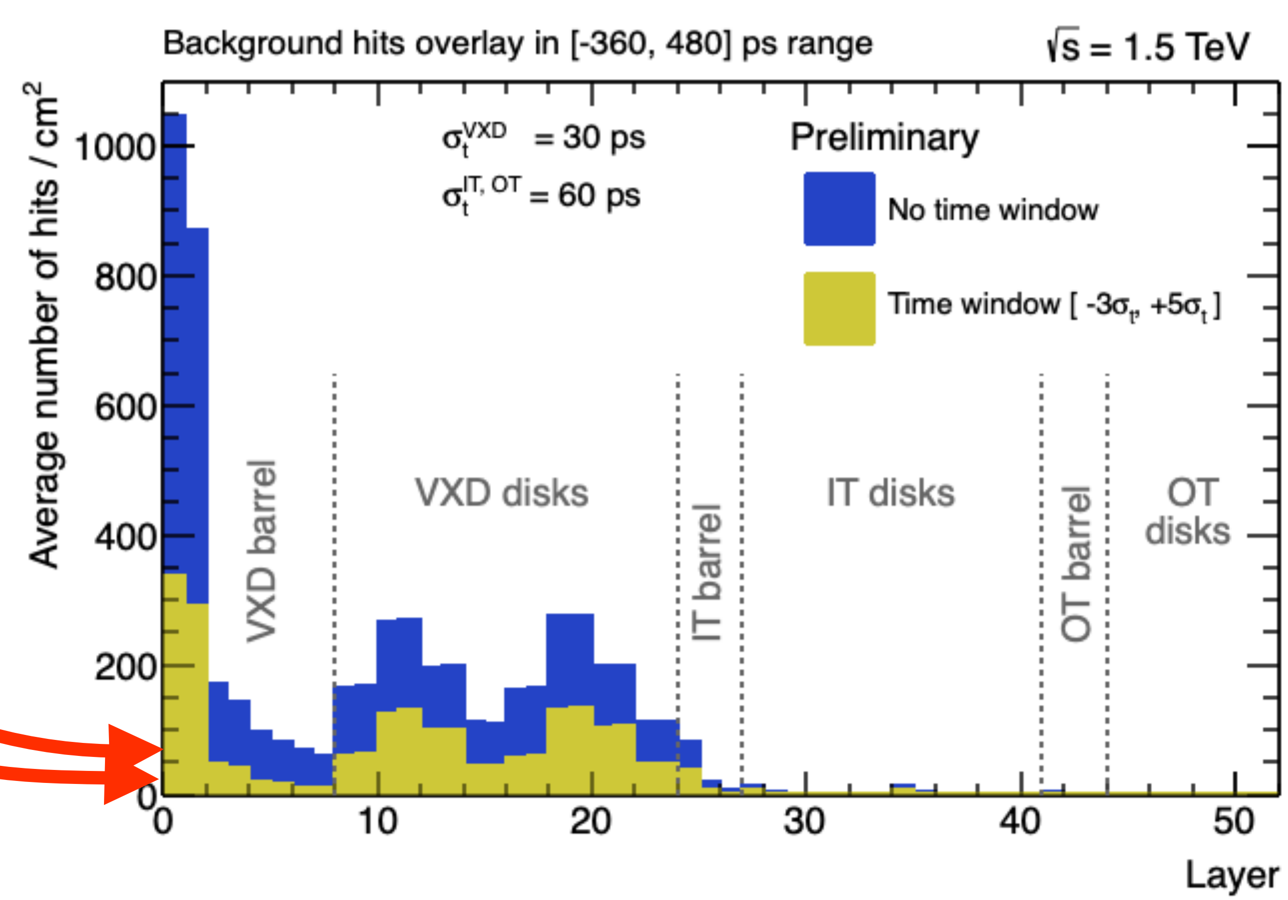


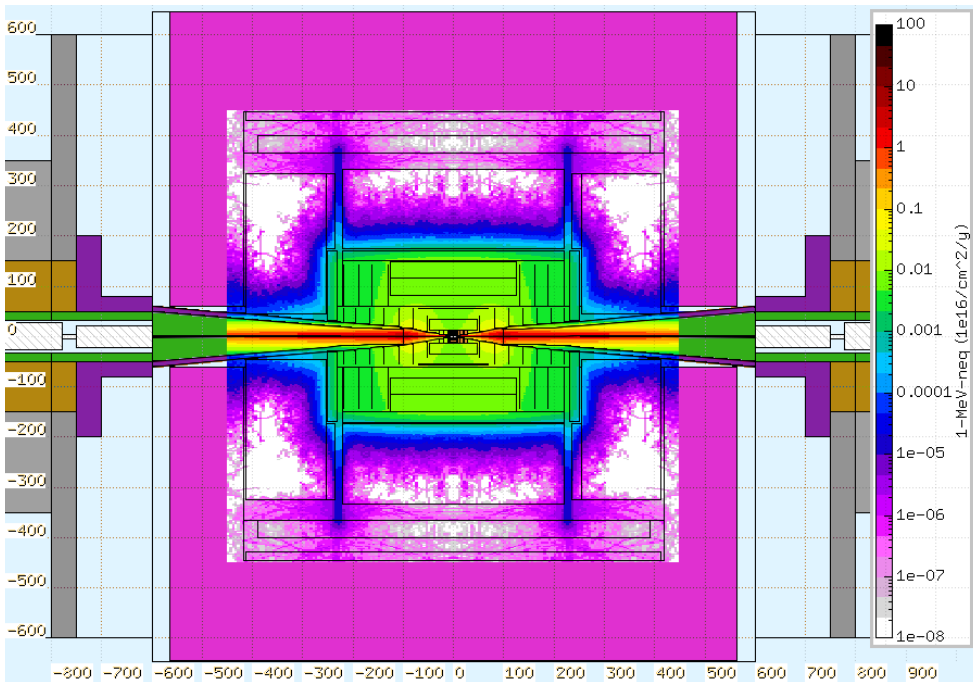


Fig. 3: Map of the 1-MeV-neq fluence in the detector region for a muon collider operating at $\sqrt{s}$ = 1.5 TeV with the parameters reported in Table 1, shown as a function of the position along the beam axis and the radius. The map is normalised to one year of operation (200 days/year) for a 2.5 km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

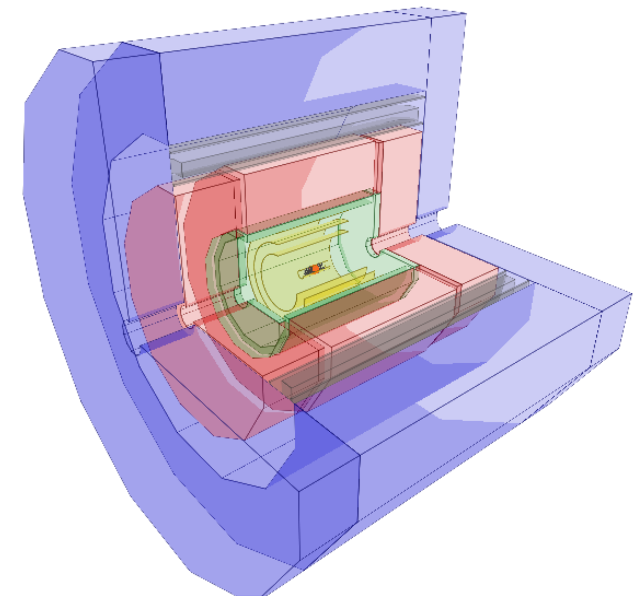


Fig. 2: Illustration of the full detector, from the GEANT 4 model. Different colours represent different sub-detector systems: the innermost region, highlighted in the yellow shade, represents the tracking detectors. The green and red elements represent the calorimeter system, while the blue outermost 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.

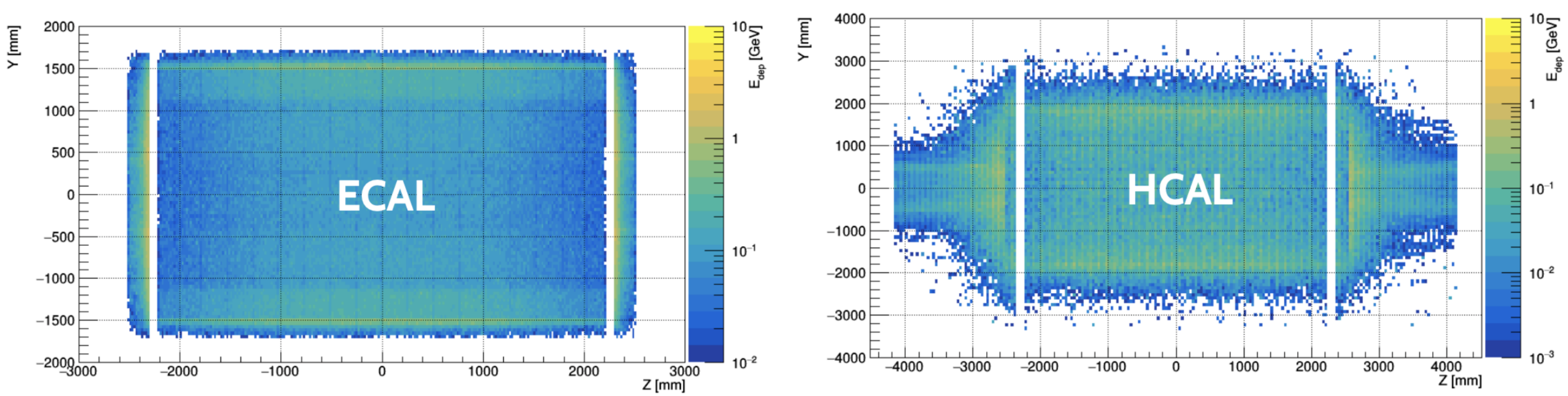
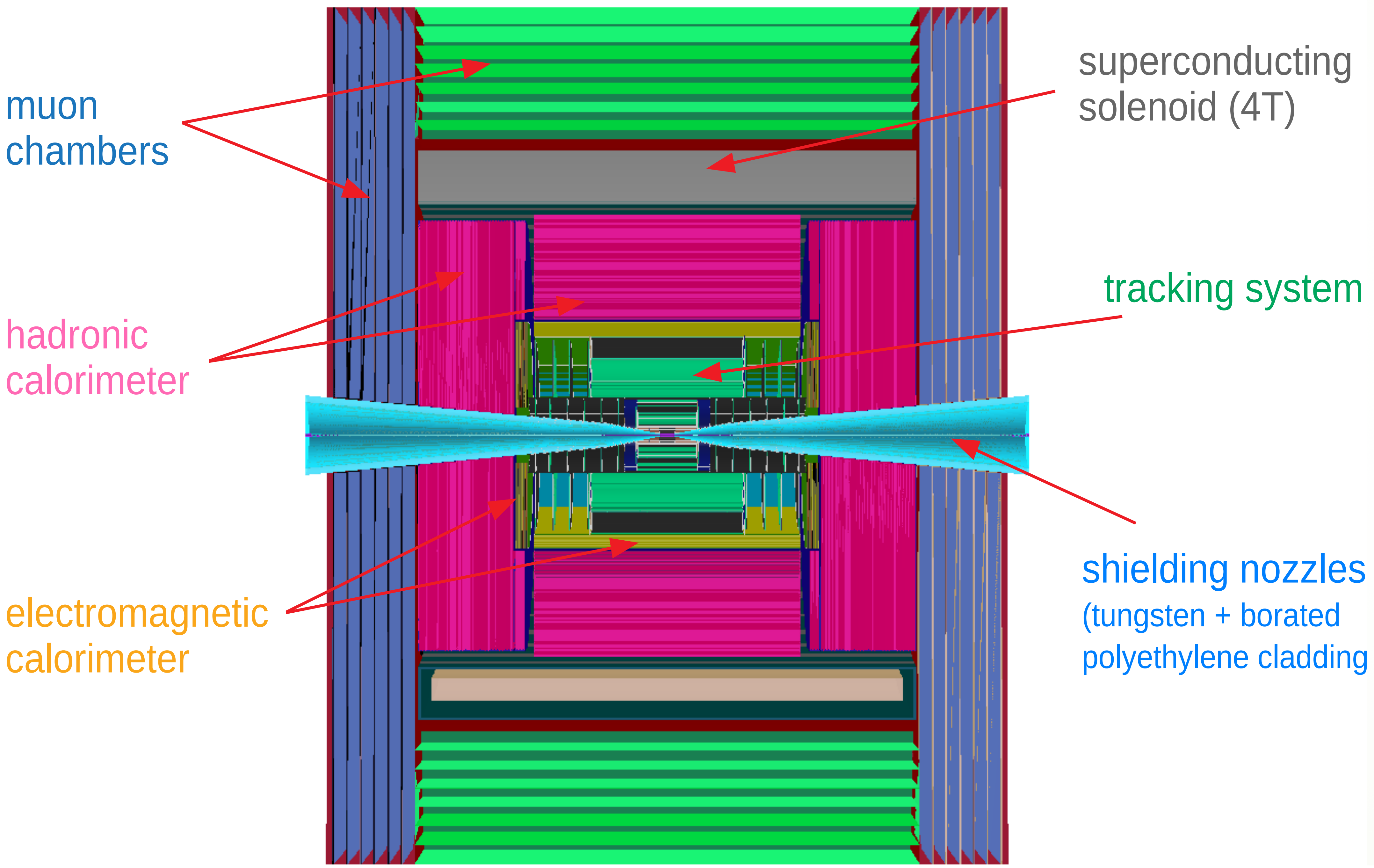


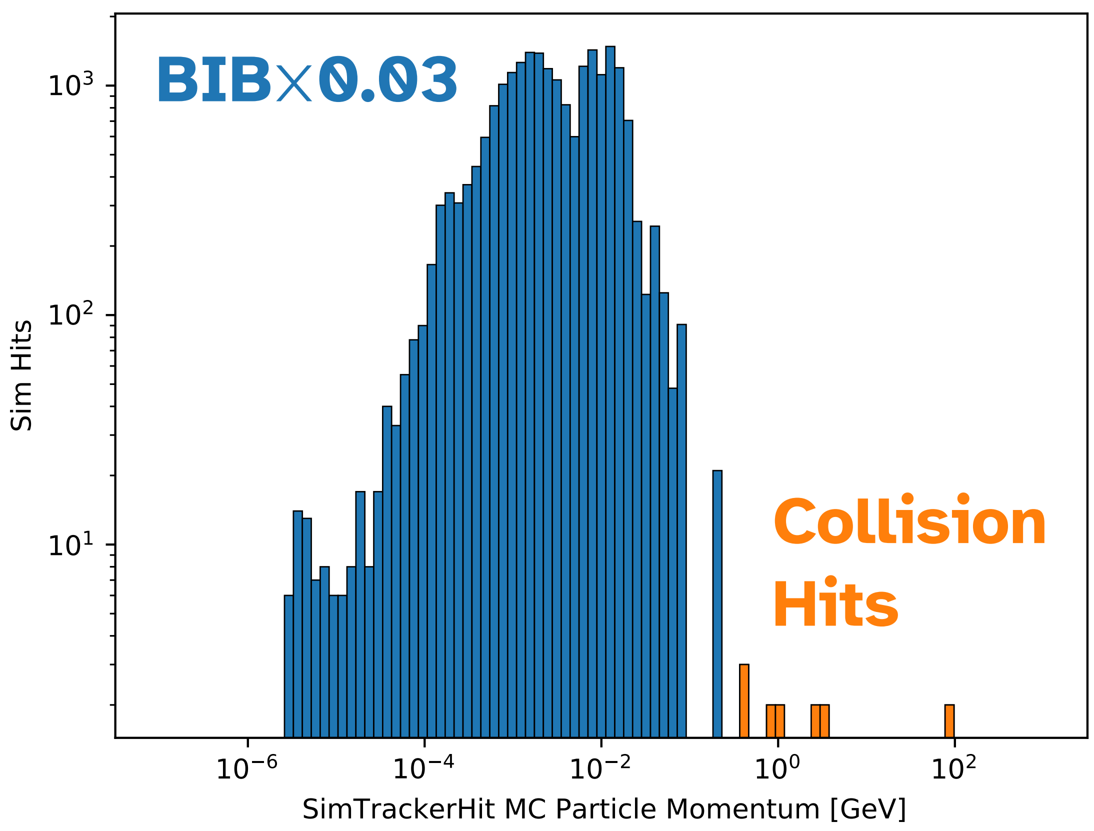
Fig. 9: Energy deposited by the BIB in a single bunch-crossing at $\sqrt{s} = 1.5$ TeV, in ECAL (left) and in HCAL (right).

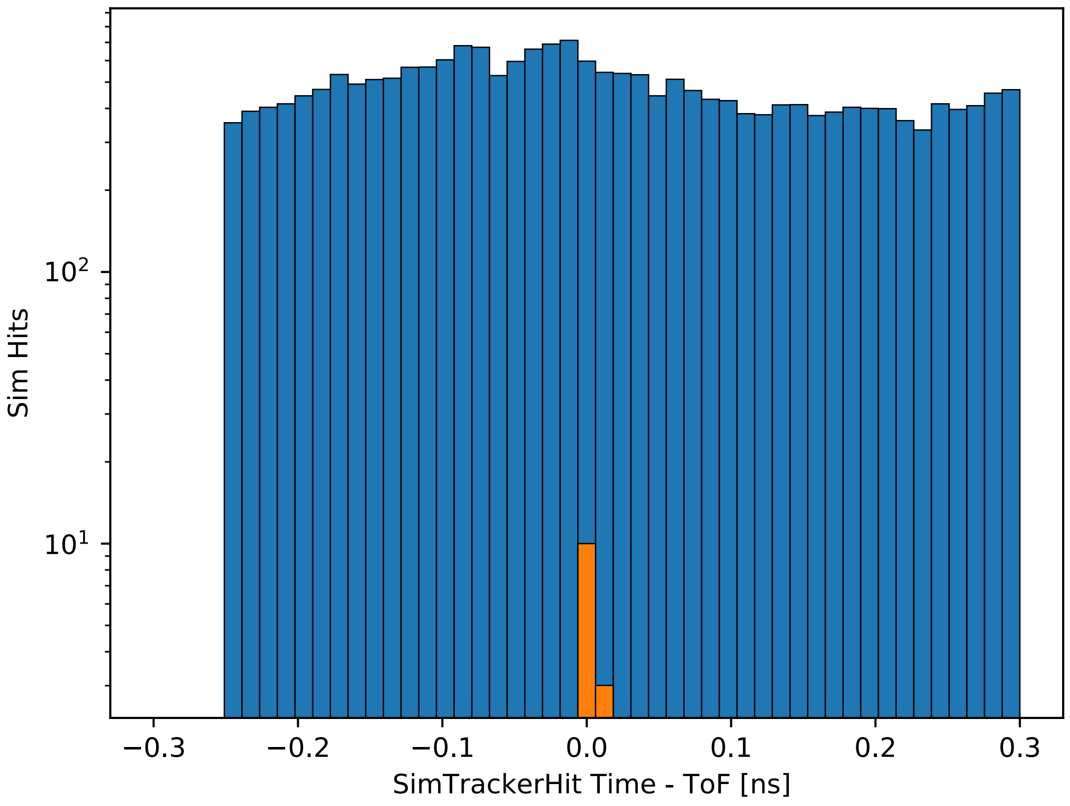
Subsystem	Region	R dimensions [cm]	$\|Z\|$ dimensions [cm]	Material
Vertex Detector	Barrel	$3.0 - 10.4$	65.0	Si
	Endcap	$2.5 - 11.2$	$8.0 - 28.2$	Si
Inner Tracker	Barrel	$12.7 - 55.4$	$48.2 - 69.2$	Si
	Endcap	$40.5 - 55.5$	$52.4 - 219.0$	Si
Outer Tracker	Barrel	$81.9 - 148.6$	124.9	Si
	Endcap	$61.8 - 143.0$	$131.0 - 219.0$	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



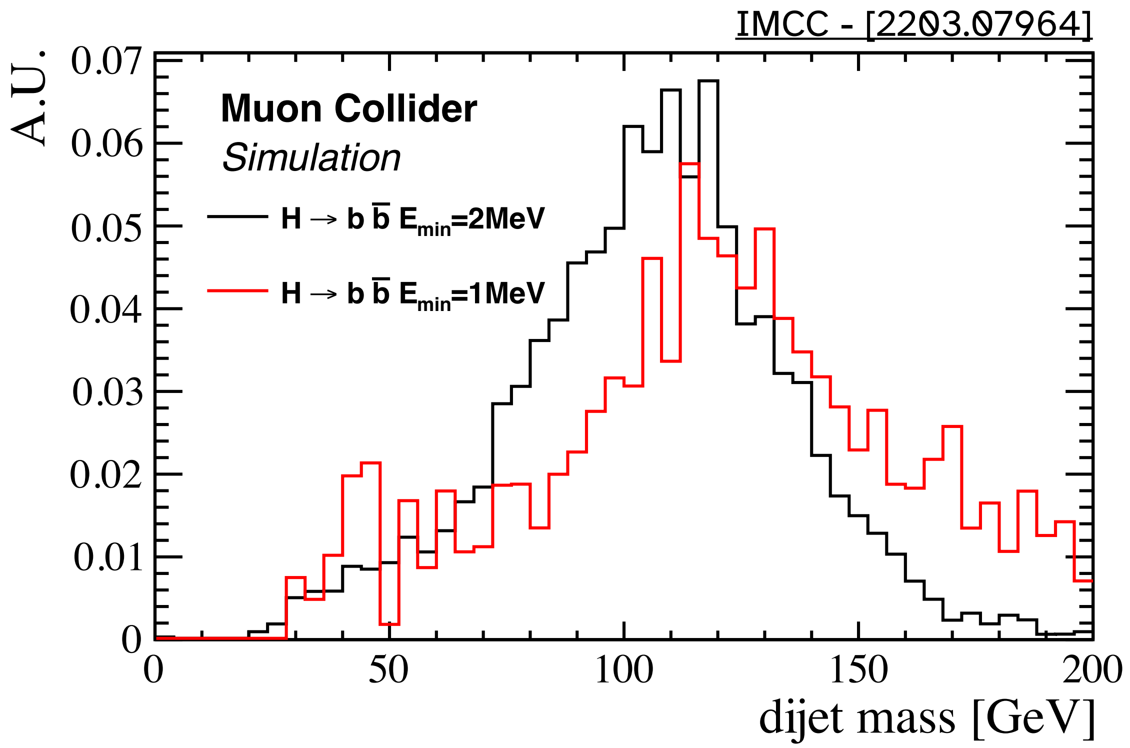
Lifted from Donatella Lucchesi

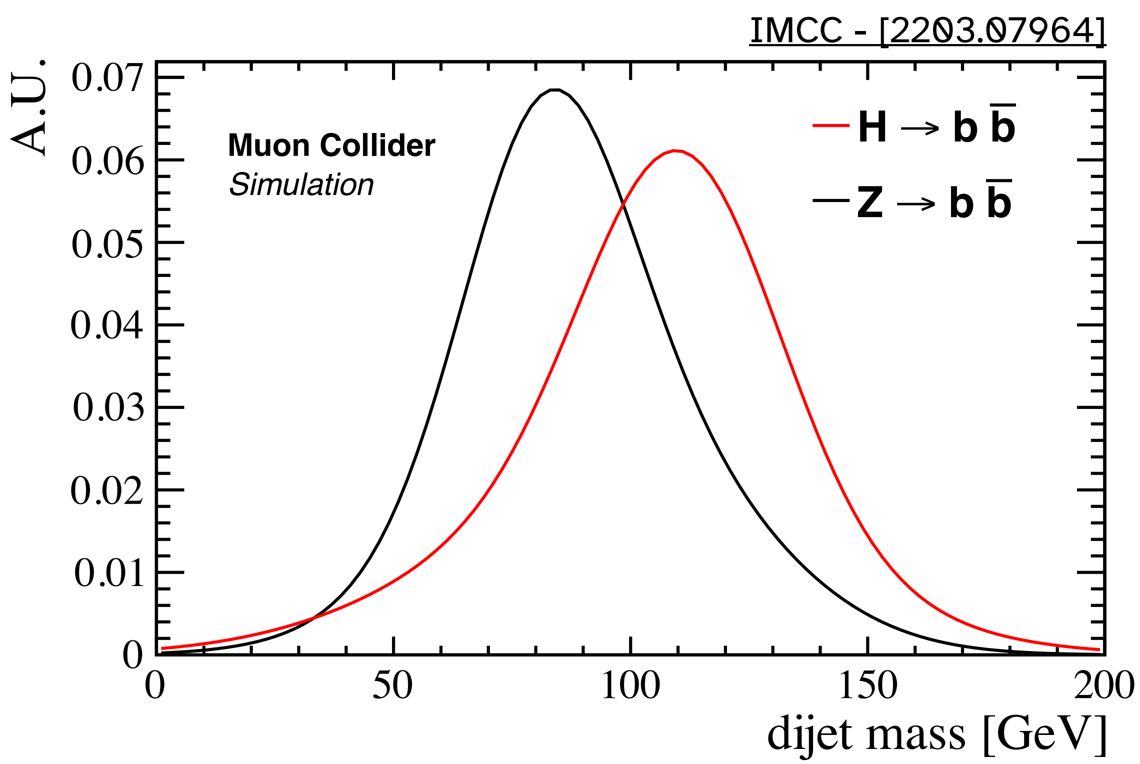
GEANT Hits in Vertex Detector





CALORIMETERS





- 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**

IMCC - [2203.07964]

READOUT LINKS

	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	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

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
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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)

Gaseous Helium Cooling

Bathe detector in Helium gas
Already explored with Mu3e pixels

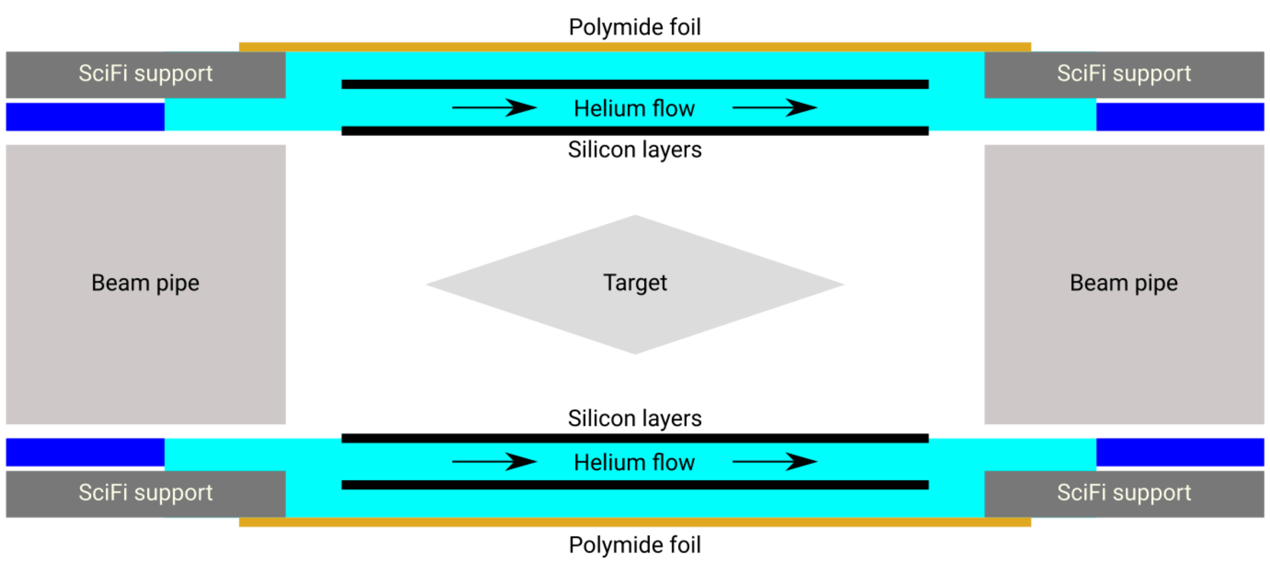
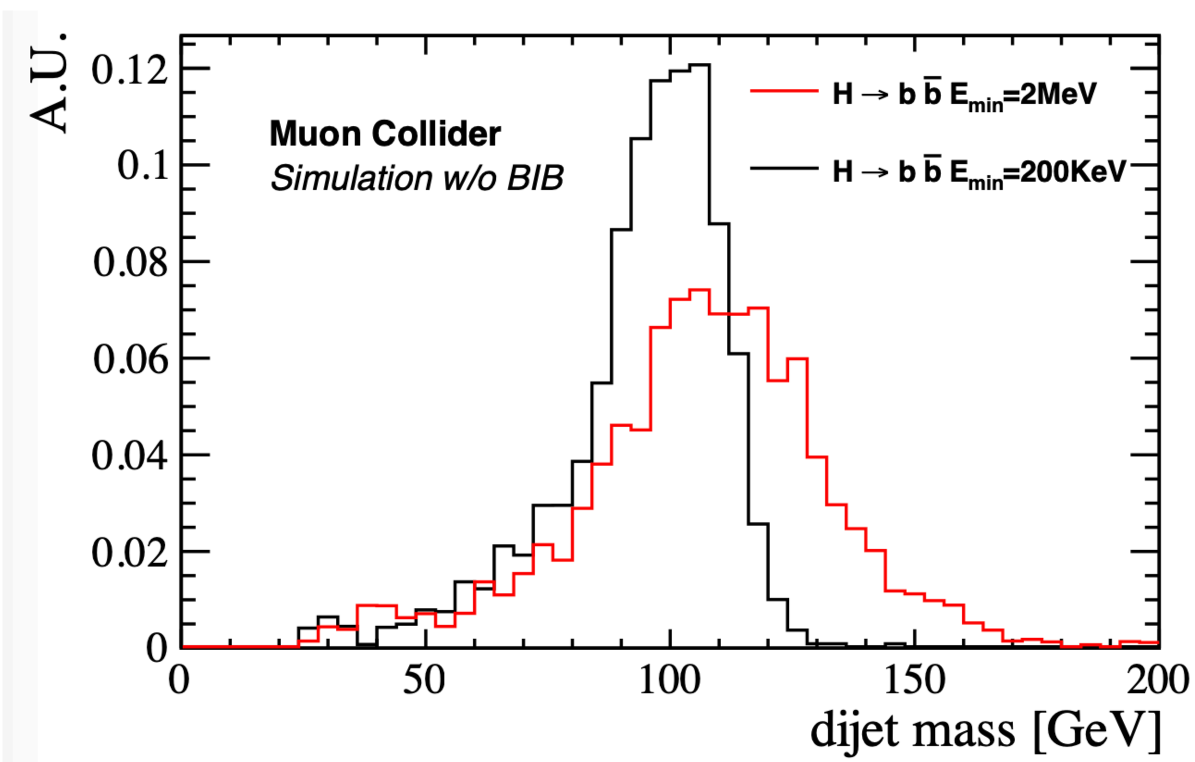
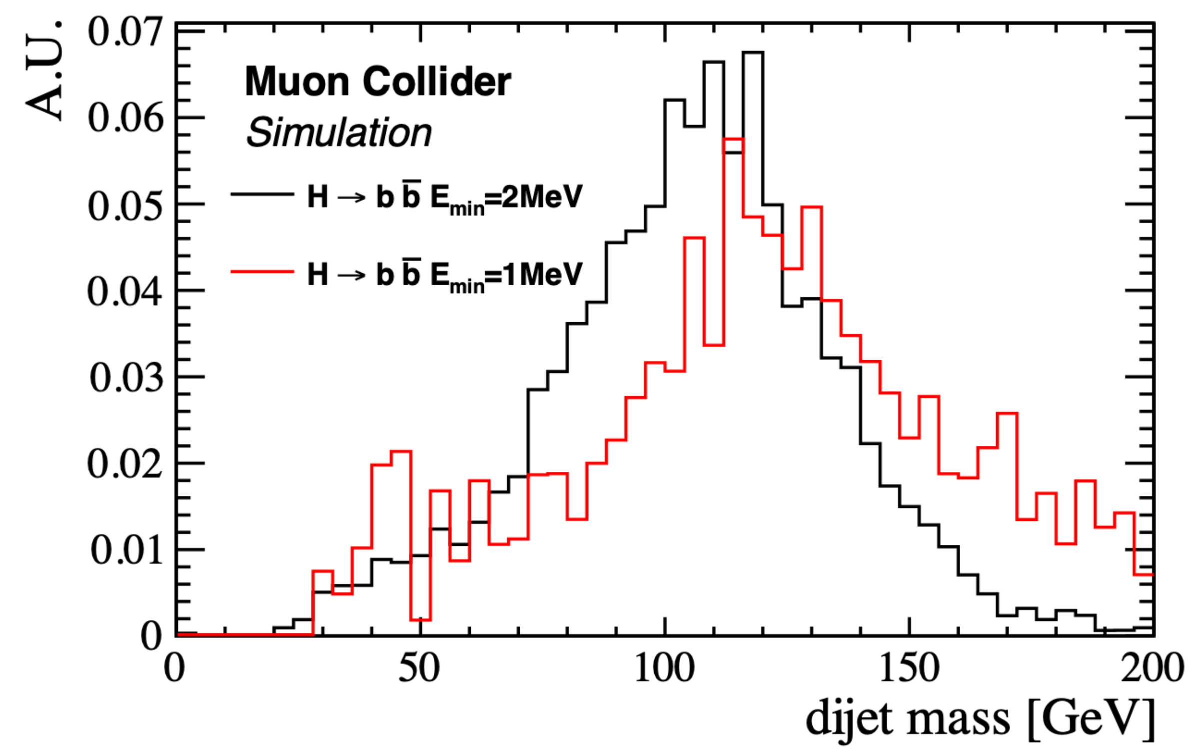


Table 1: Overview of cooling parameters of various pixel barrel detectors. In cases where the pixel detector also has forward disks, values are scaled by area. See Appendix A for details about the values used for calculating the instrumented areas and the total power.

Experiment		Coolant	Phase	Target Temp. °C	Heat density mW/cm^2	Instr. area m^2	Total power W	Ref
CMS	LHC Run 1	C_6F_{18}	liq	-10	333	0.78	2600	[1]
	Phase 1 upgrade	CO_2	liq/vap	-20	500	1.20	6000	[8]
ATLAS	LHC Run 1	C_3F_8	liq/vap	-7	444	2.25	10000	[2]
ALICE	LHC Run 1	C_4F_{10}	liq/vap	+25	643	0.21	1350	[3]
	Upgrade IB	H_2O	liq	+25	300	0.19	570	[9]
	Upgrade OB	H_2O	liq	+25	100	10.7	10700	ibid.
STAR		air	gaseous	+25	170	0.16	272	[6, 7]
Belle II	PXD	$N_2 + CO_2$	gaseous + liq/vap	+25	182	0.033	60	[10, 11]
Mu3e	Vertex	He	gaseous	0	250	0.052	130	[5]
	Outer layers	He	gaseous	0	250	1.31	3276	ibid.

[2301.13813]





- Details of the on-detector BIB mitigation / thresholds matter!