Tracker R&D Directions

Needs in the next 3-5 years

Princeton Muon Collider Workshop - 02/23/24

Timon Heim - LBNL

Questions to "Answer"

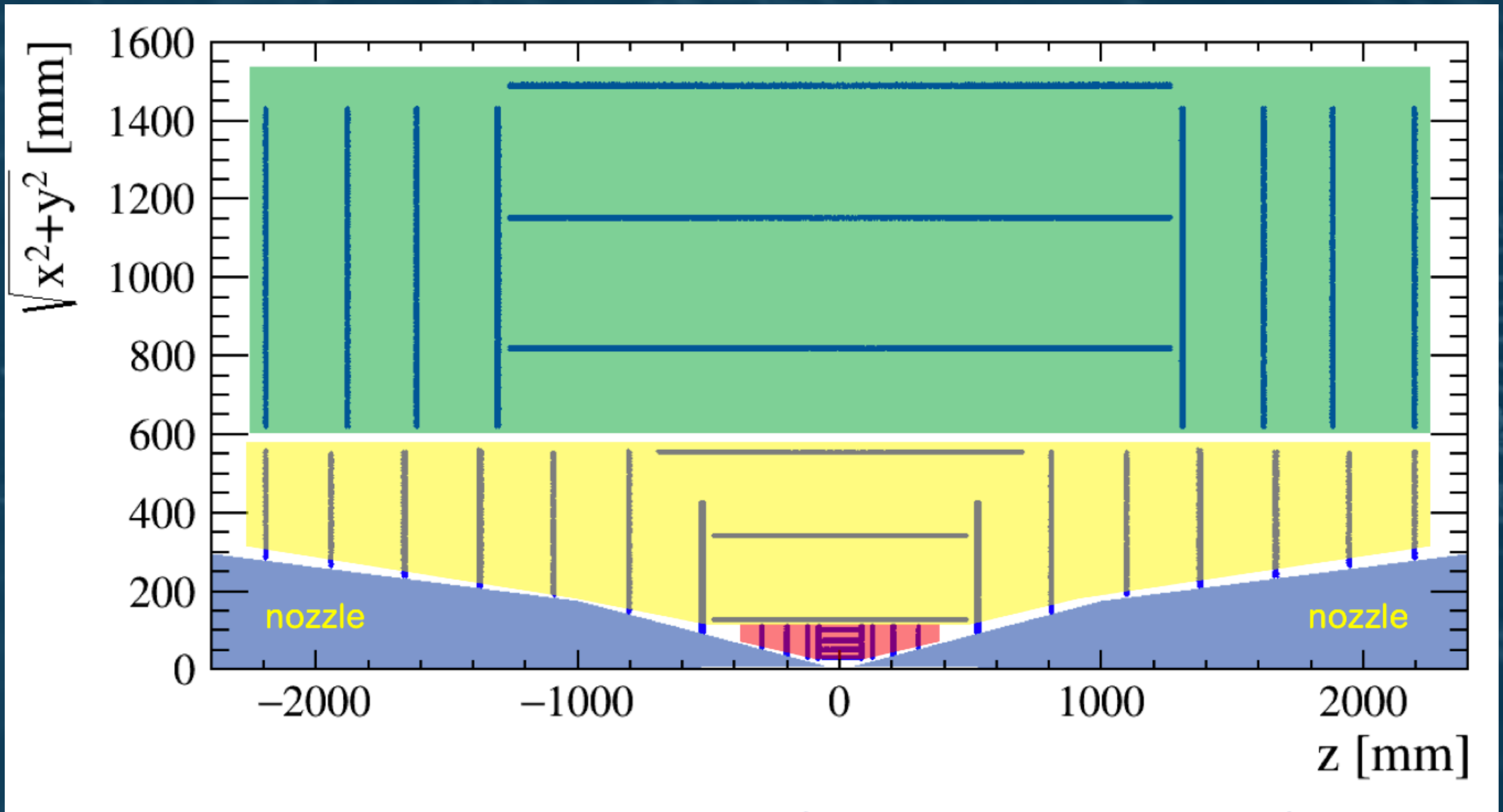
- What are the requirements for Trackers at a muon collider, how do they compare to current day Trackers?
    - What is really special for Trackers at a muon collider?
- Where is current Tracker R&D standing and where is it headed?
    - Does the current R&D direction meet the needs of a muon collider or does it need new efforts/redirection? (Piggyback on other 10 TeV pCM or Higgs Factory needs?)
    - Is there a need to establish new R&D efforts to specifically meet muon collider requirements?
- How to organize R&D and collaboration on R&D?

Requirements

	muC Tracker			ATLAS ITk	
	Vertex Detector	Inner Tracker	Outer Tracker	Pixel	Strips
Resolution [um x um]	25x25	50x1,000	50x10,000	50x50	75x2500
Channels	1200M	290M	170M	5000M	60M
Area [m^2]	0.75	14.5	85	13	165
Double Layer Spacing [mm]	2mm			N/A	5
Total Ionizing Dose [Mrad]*	200	10		1,000	75
Fluence [1MeV neq/cm^2]*	$3x10^{15}$	$1x10^{16}$	$<1x10^{15}$	$2x10^{16}$	$2x10^{15}$
Time resolution	30ps	60ps		25ns (1.5ns)	25ns
Hit density [mm-2]	3.7**	0.5**	0.03**	0.6	0.003
Collision rate	100kHz			40MHz	
Readout percentage	100% (trigger-less)			2.5% (triggered)	
Data Bandwidth	~30Tbps**			13.5Tbps	

*assume 10 year run-time **after ns timing cuts

MuD Tracker



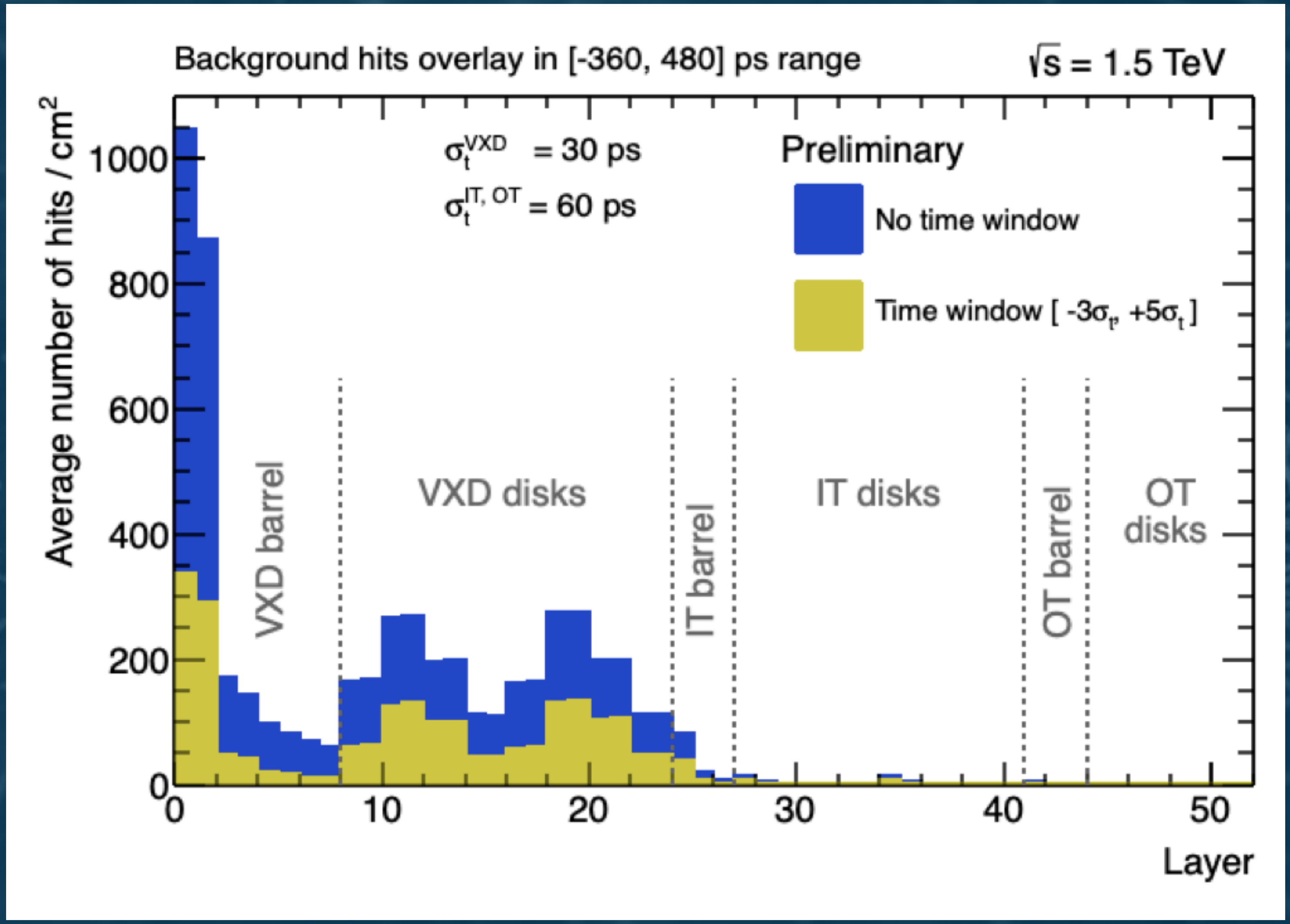
Outer Tracker (OT)
- barrel: 3 cylindrical layers
  endcaps: 4 + 4 disks
- Si sensors:
  50 µm x 10 mm micro-strips
  $\sigma_{r\text{-}\phi}$ = 7 µm, σ_z = 90 µm
  σ_T = 60 ps

Inner Tracker (IT)
- barrel: 3 cylindrical layers
  endcaps: 7 + 7 disks
- Si sensors:
  50 µm x 1 mm macro-pixels
  $\sigma_{r\text{-}\phi}$ = 7 µm, σ_z = 90 µm
  σ_T = 60 ps

Vertex detector (VXD)
- barrel: 4 cylindrical layers
  endcaps: 4 + 4 disks
- double-layer Si sensors:
  25x25 µm^2 pixels
  $\sigma_{r\text{-}\phi}$ = 5 µm, σ_z = 5 µm
  σ_T = 30 ps

M. Casarsa

Hit Multiplicity



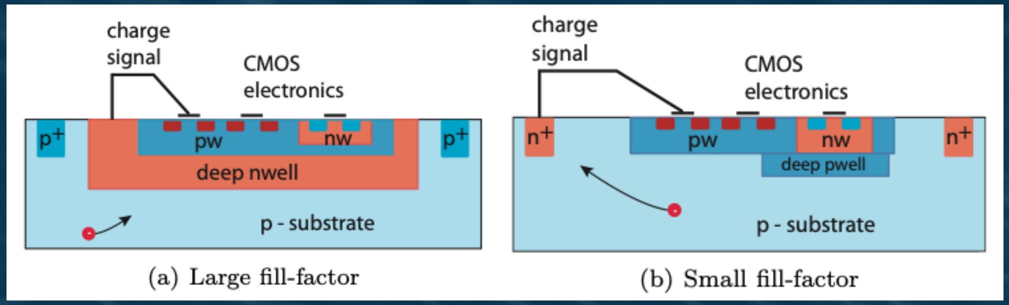
- Beam induced Background (BIB) impacts mostly Vertex Detector
- Timing information vital to reduce hit multiplicity
- Stub finding in double layering or cluster shape can further help

MuD Tracker needs in a nut-shell

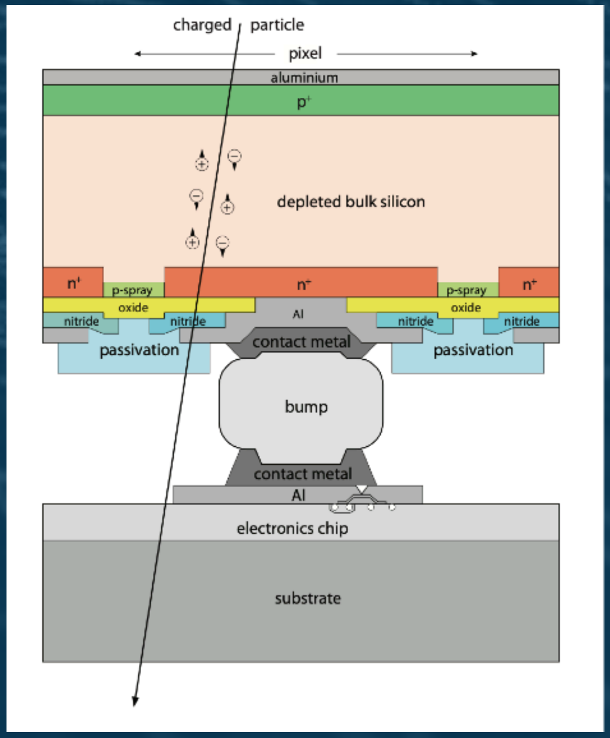
- MuD tracker comparable in many regards to HL-LHC Phase 2 Tracker Upgrades of ATLAS and CMS (Granularity, radiation tolerance, area,
  - More than 10 years of R&D was necessary to arrive where we are now
- But add 30/60ps timing information everywhere!
- Neutron radiation from nozzle adds interesting challenge for Inner Tracker
- General Tracker needs: low mass
  - Reduce power -> reduces mass through cooling and power services
  - On-chip data processing -> reduce output data bandwidth -> reduce data services (majority of non-sensor mass in ATLAS ITk)
- Needs to be mass-produceable!

State-of-the-art Silicon Detectors

- Silicon detector technology separated in two types: monolithic active pixel sensors (MAPS) and hybrid technology
- MAPS:
  - Combination of sensor and readout circuit in the same device
  - Typically based on medium scale fabs with HV/HR-CMOS process
- Hybrid Technology:
  - Sensors:
    - Planar and 3D Si sensor technology basis of ATLAS/CMS trackers
    - Newcomer: low gain avalanche detectors (LGAD)
    - Usage of specialized or boutique fabs to produce rad hard sensors
  - Readout chip:
    - Based on ubiquitous CMOS process produced by large scale fabs
  - Hybridization:
    - Pixel detector rely on costly and complicated bump bond based flip chip process -> active R&D to avoid (thin film, 3D stacking, …) not covered in here

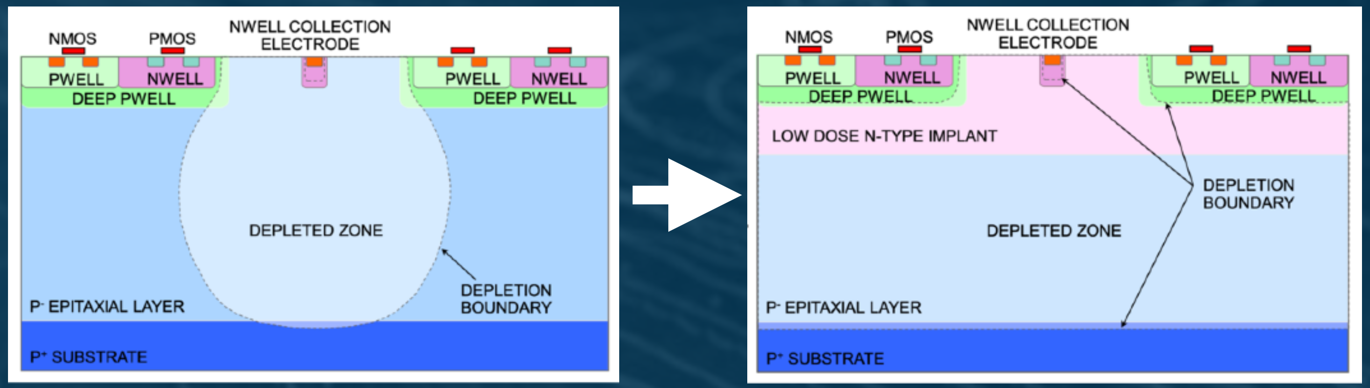


(a) Large fill-factor (b) Small fill-factor



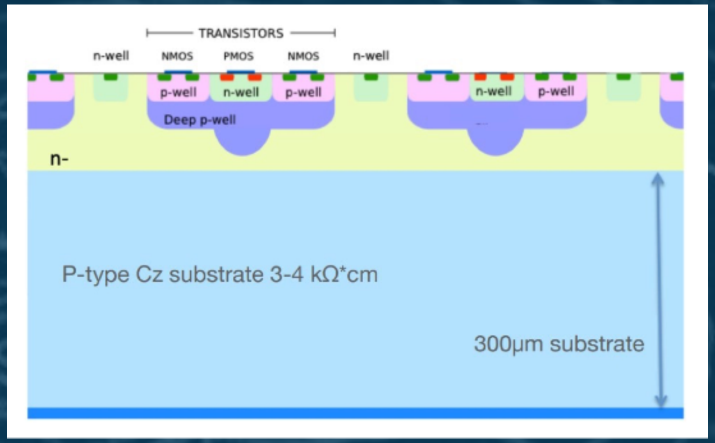
MAPS

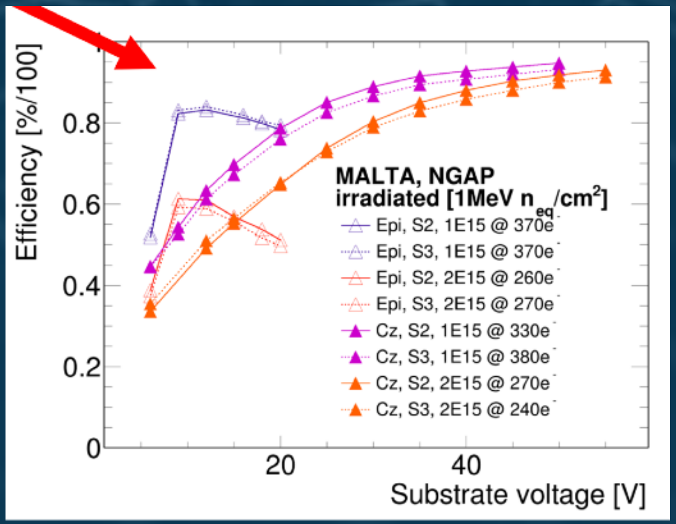
- Monolithic technology has many inherent advantages
  - Production scaling, Mass
  - Widely used in ion collision detector for low pt tracking
- Typical HV-CMOS processes needs to balance fill-factor with noise
- Modified Tower process overcomes this issues via an additional implant under the CMOS wells
  - Not transferable to other vendors?
- Cz substrate showed higher radiation hardness compared to Epi
  - But looses extreme low mass advantage
- So far not possible to achieve both timing precision and even medium radiation hardness



Modified 180nm Tower

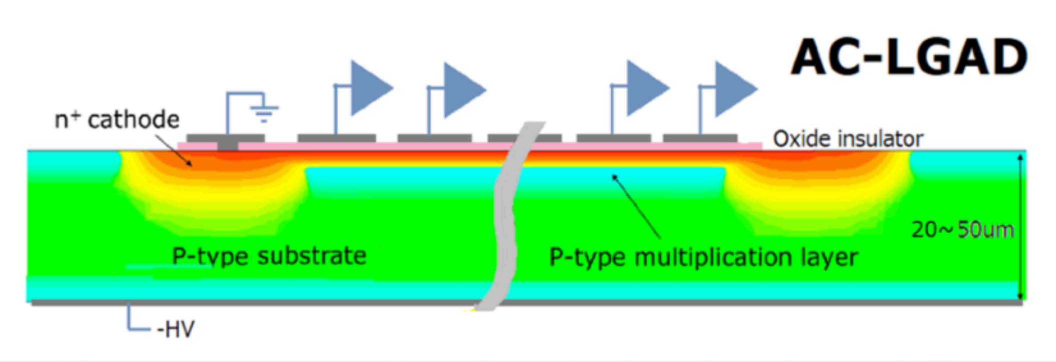
M. Gazi

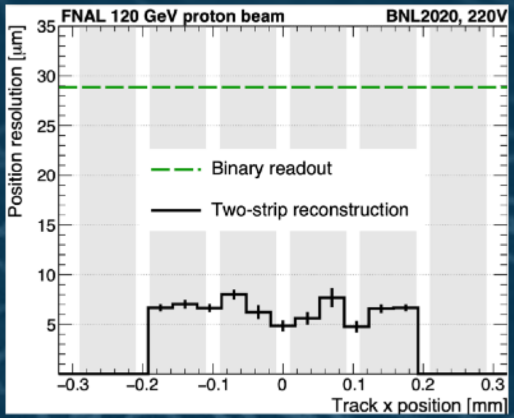


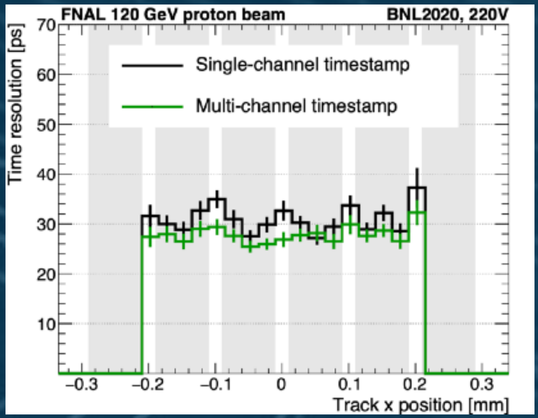


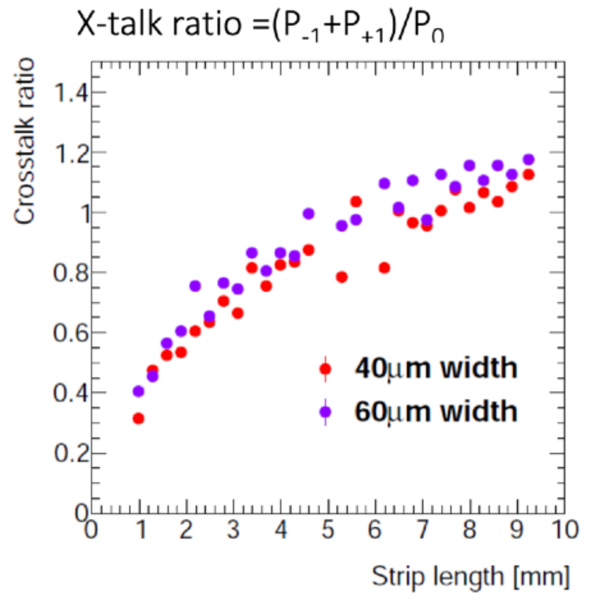
LGAD

- Intrinsic gain layer adds in-sensor amplification
- Gain layer termination requires space -> AC-LGAD
- Though missing isolation increases crosstalk (especially for long strips)
  - Can use crosstalk to further improve pointing resolution
  - But at the price of reduced signal height and added occupancy
- Demonstrated down to 50um by 50um pixel size
- Need to improve radiation hardness (maintain gain against acceptor removal)
- Need to demonstrate production at scale







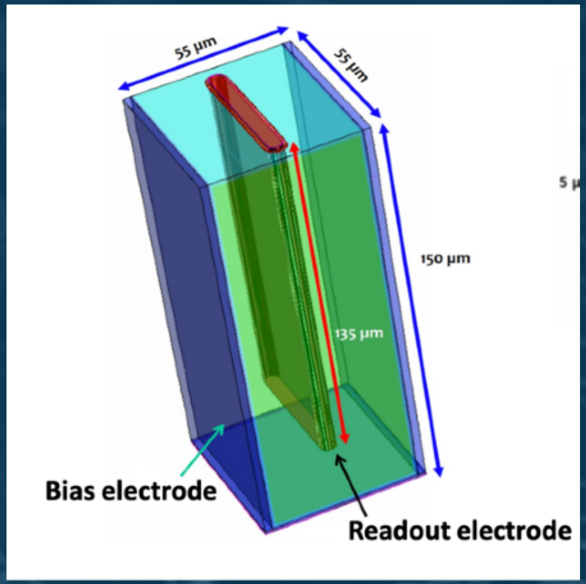


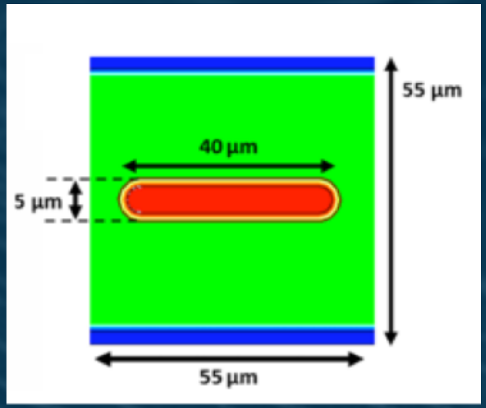
C. Madrid

K. Hara

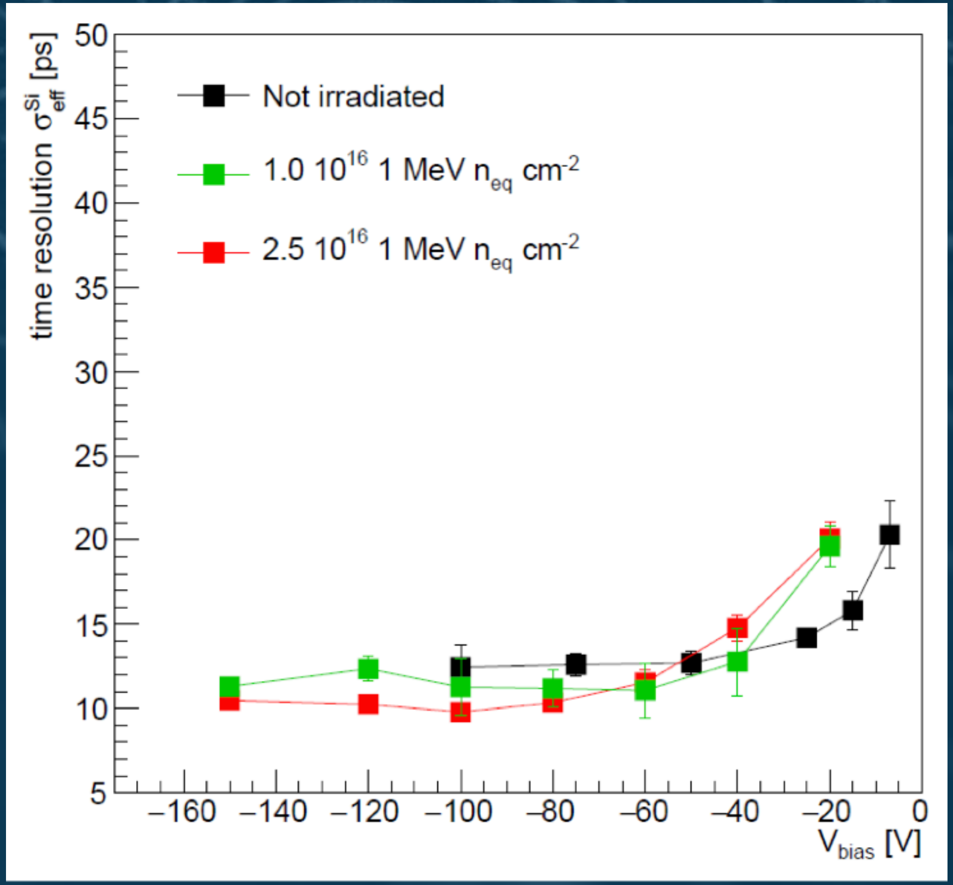
3D Sensors

- 3D sensors great candidate for hybrid technology with high time resolution
- Shown here 3D trench technology (Timespot sensor) further optimized specifically for time resolution
- Measured as little as 10ps resolution even for highly irradiated devices!
- Further miniaturization possible?
- Production at scale?



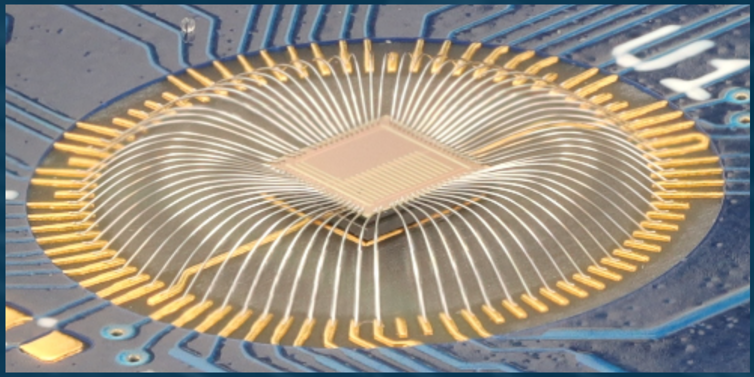


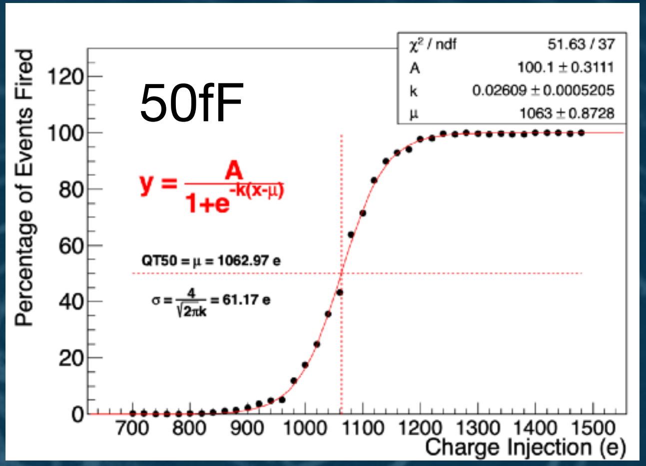
M. Garau

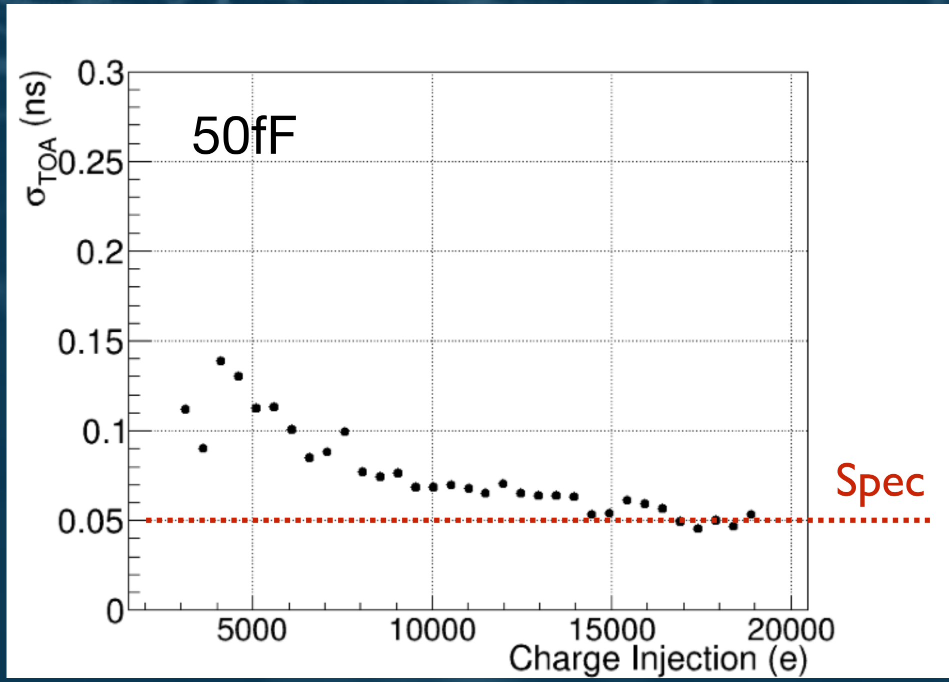


Readout ASIC

- Active R&D in 28nm CMOS
  - Last CMOS technology with intensive radiation hardness?
- First 50um by 50um suitable analog front-end designed and tested (Big Rock AFE) with O(50ps) timing resolution [T. Heim]
  - <4uW per pixel, <1000e threshold, 50fF Cin, 10x30um2
- Can achieve target 50ps jitter spec, but only at higher charge
- Also need low power and small size TDC
  - <1uW per pixel, 10x10um2 - time stretcher based designed and awaiting testing
- 25um by 25um (non-timing) pixels being prototyped in 28nm for CMS “Phase 3” upgrade [B. Parpillion]

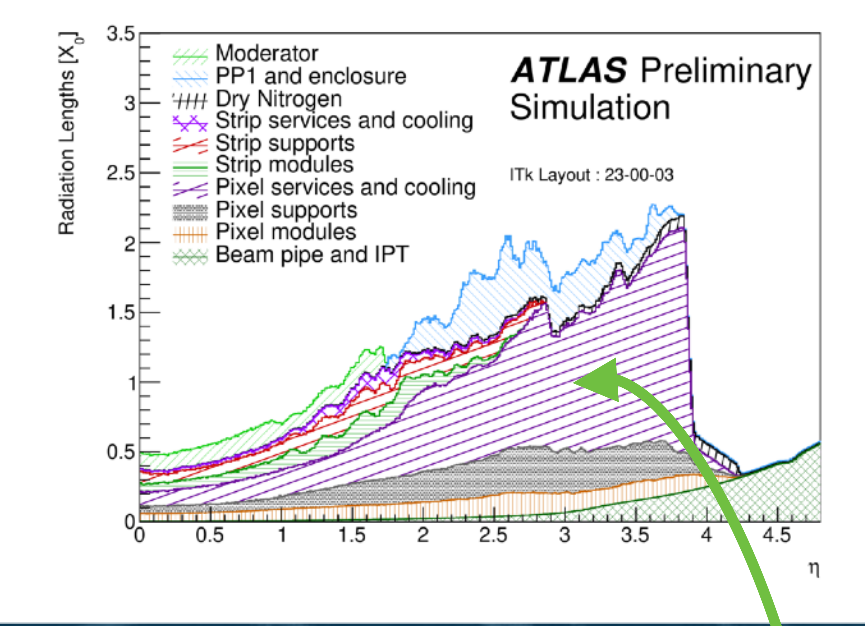




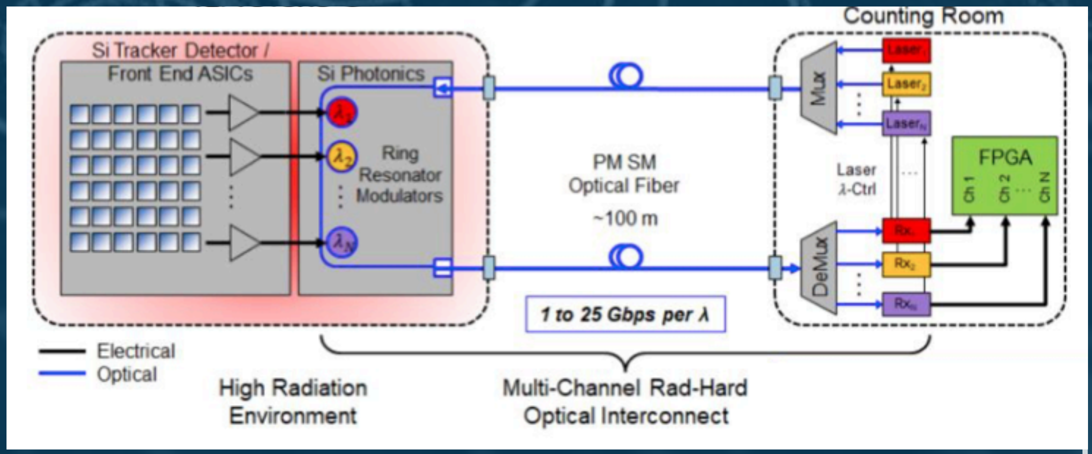


Data Transmission

- Hit multiplicity or addition of timing information will make the data bandwidth explode
- How can we cope without making our detector 99% copper cables?
- Optical data transmission could be the solution!
  - Not new, why not done in the past?
  - Optical components, specifically lasers/diodes are sensitive to radiation
- Solution: move lasers outside of detector volume and use Si photonics ring modulators
  - Inherent wave length multiplexing possible
  - Effectively no bandwidth limit
- First radiation test results look promising, intrinsic strong doping of Si photonics well suited to withstand radiation damage (E. Chansky, UCSD)



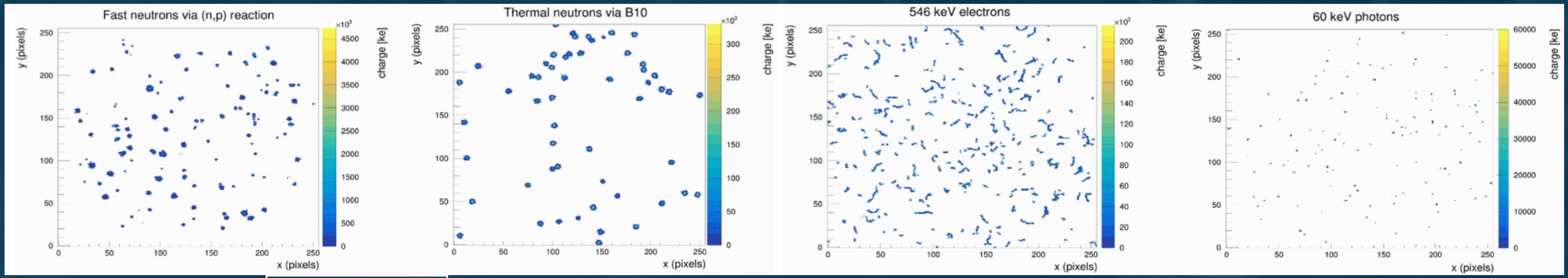
Data Cables!



E. Chansky

On-chip Data Processing

- On-chip data processing in effort to reduce data bandwidth actively being researched [J. Yoo]
- Various approaches: compression (lossy, lossless), ROI readout, stub building, PID, …
    - Most likely topic for AI/ML to contribute -> Edge computing
- Strong interplay with detector simulation, need the right inputs to get the right outcome!
    - On-chip discrimination of BIB and actual events?
- Dangerous area to make mistakes as they might get “locked” into silicon



M. Benoit

Right Heading?

- Generally timing seems to be the key for the muD tracker
- Synergy with other 10TeV pCM (FCC-hh) R&D as it also requires high time resolution and some alignment with Higgs Factory R&D
    - FCC-hh tracker more of an evolution of a muD tracker (also longer timescale)
    - Higgs Factory tracker lacks radiation hardness requirement and multiplicity, while having a heavy emphasis on low pt tracking -> somewhat orthogonal
- 4D tracking identified by community as enabling technology (DOE BRN, Snowmass) and R&D in that direction is actively being pursuit
- But
    - Timing in many/all tracking layers sets stringent requirements on system, not just single components/technologies
    - As muC community should actively engage in discussion with CPAD RDCs to make sure muD tracker R&D is covered holistically -> P5 encouraged this!
    - For instance could drive effort towards building prototype system tests with novel technology to understand system requirements -> important interplay with detector simulation (not covered by CPAD RDC)!
    - Higgs factory tracker needs have been driving community effort to engage in MAPS R&D (something the US is currently not strongly engaged in), does this also cover muC needs?

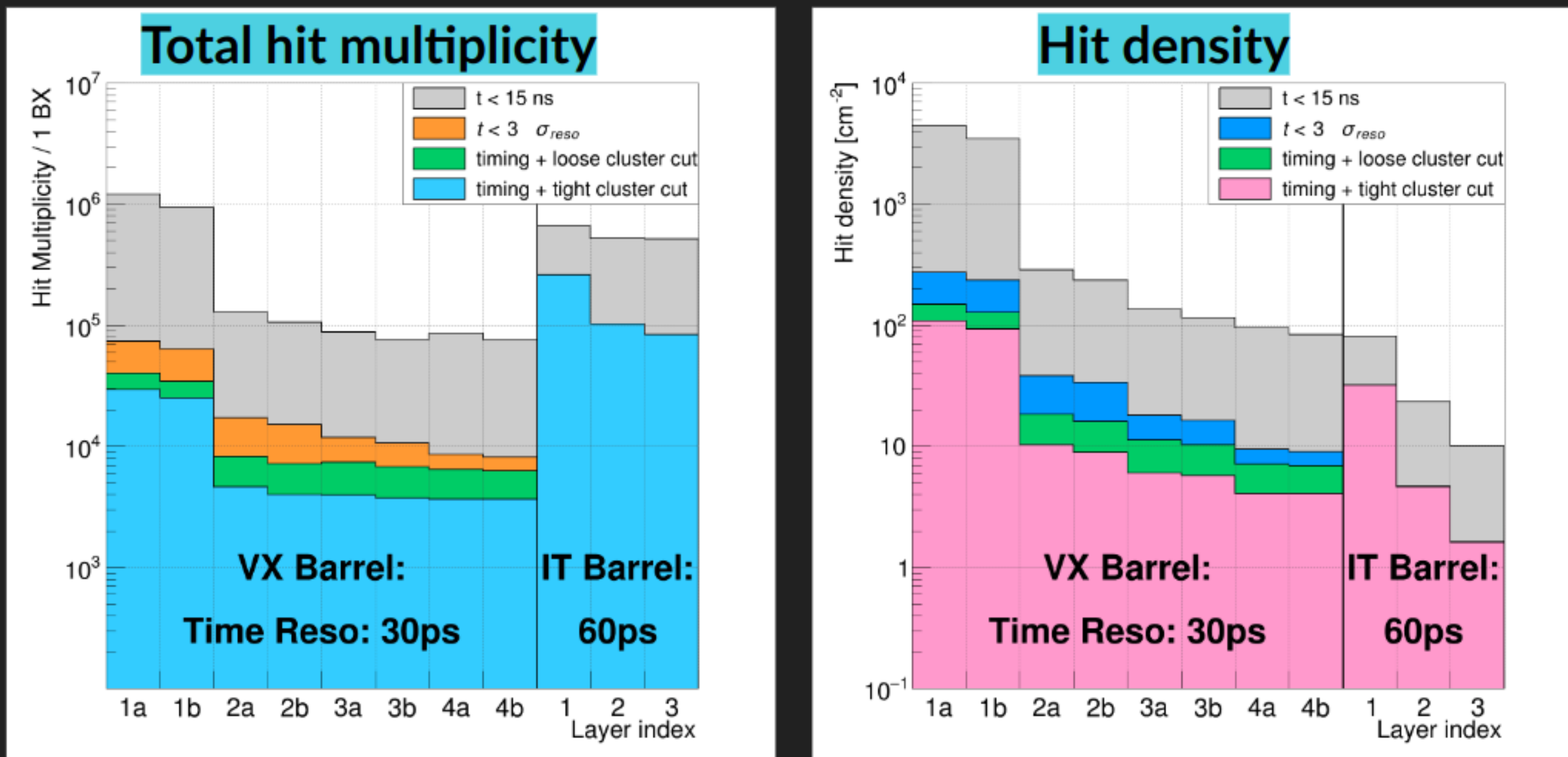
Uncovered R&D?

- muC sets unique requirements due to BIB
  - Currently fully reliant on exploration via simulation
  - Environment “untestable” in classic test beam facilities? How do we know what we do is right and works?
- Could we establish a test beam facility at an existing muon production site that produces an environment that mimics some aspects of the muC?
  - Could this synergize with Dune or muC demo project?
- E.g. have issues with SEE in RD53 readout chips because there is no environment that is similar in SEE rate and particle multiplicity to HL-LHC, can only test one at a time. These blind spots are risky!
- OT needs large size, large production scale, high precision timing detectors -> not directly covered by existing R&D, can hope that we can bank on LGAD or MAPS -> making detectors be producible at scale is a technology challenge!

Backup

Hit Multiplicity Cuts

New occupancy plot with cluster shape



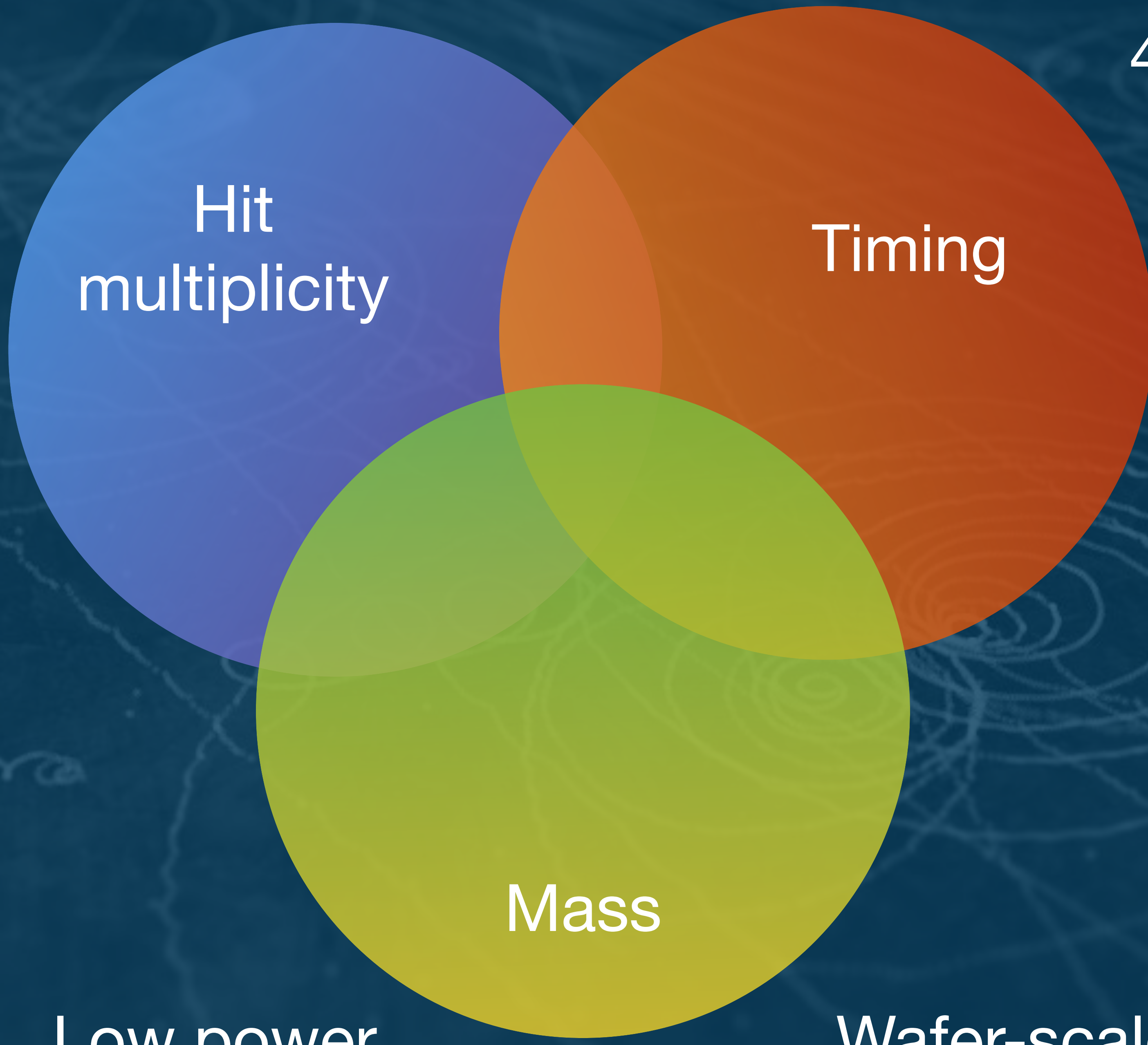
Hit occupancy by layer plot, updated with the real digitizers for the VXB and ITB

Silicon Tracker Landscape

Radiation tolerance

High Granularity

Triggered readout



4D tracking

Particle ID

Background reduction

Low power

Wafer-scale

Low pt