Instrumentation for Colliding Beam Physics - INSTR17

Budker Institute of Nuclear Physics

High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system

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ON BEHALF OF THE ATLAS LAr – HGTD GROUP

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•Overview

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  - Pileup efficiency
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- Sensors
  - Technologies, LGADs
  - Design and testing
  - Test Beam Results
  - Radiation Hardness
- Electronics
- Conclusions and Outlook

•HL-HLC Conditions

HL-LHC Conditions

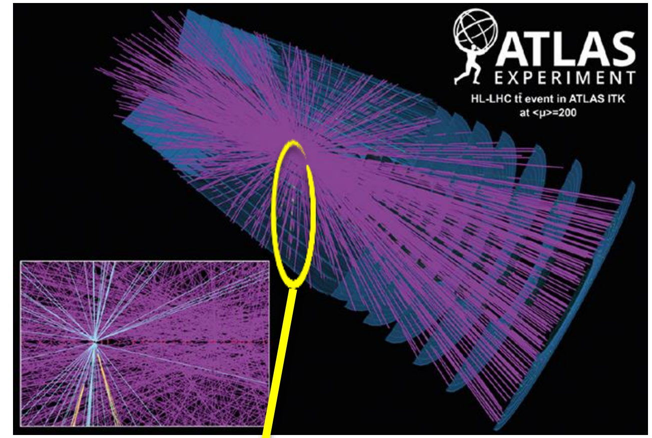
Luminosity

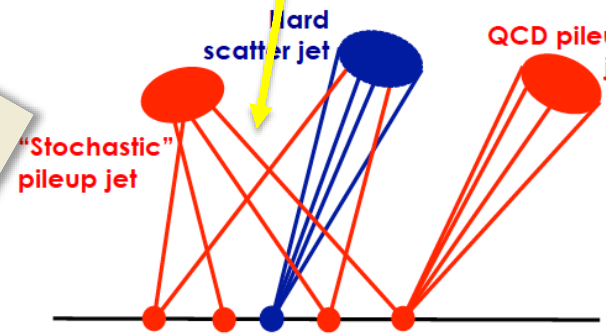
- ✓ Phase I: < 2.2×10^{34} $cm^{-2}s^{-1}$ ($300\ fb^{-1}$)
- ✓ Phase-II : 5 - 7.5×10^{34} $cm^{-2}s^{-1}$ ($3000\ fb^{-1}$)

Conditions

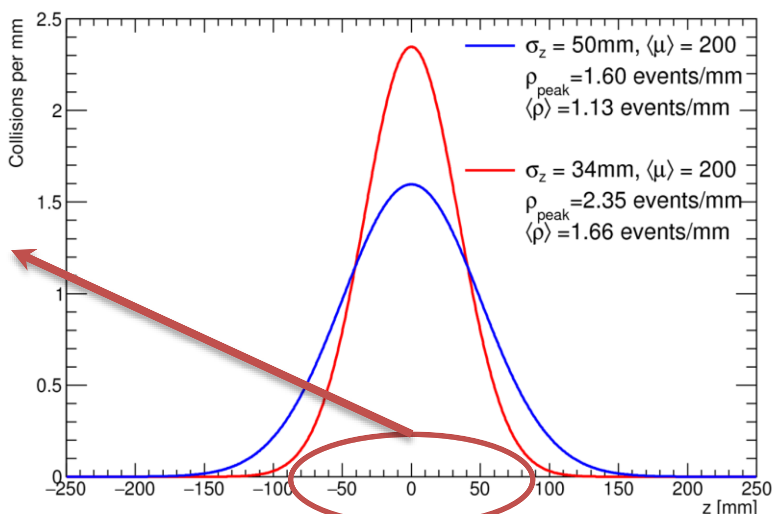
- ✓ 14 TeV beam
- ✓ 6000 primary tracks per event
- ✓ No. of collisions per crossing from 23 to 200 at 150 ps in 50 mm space
- ✓ Extended tracking up to $|\eta| < 4.0$

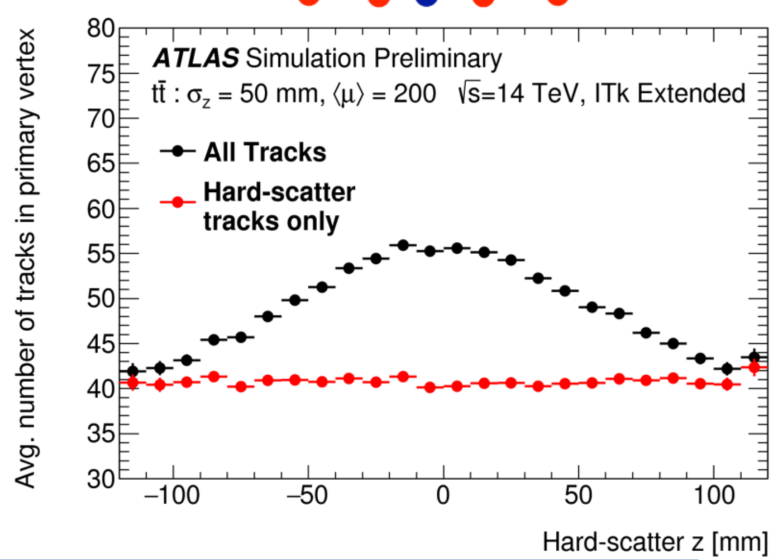
Major Challenge: Pileup





Luminus Region

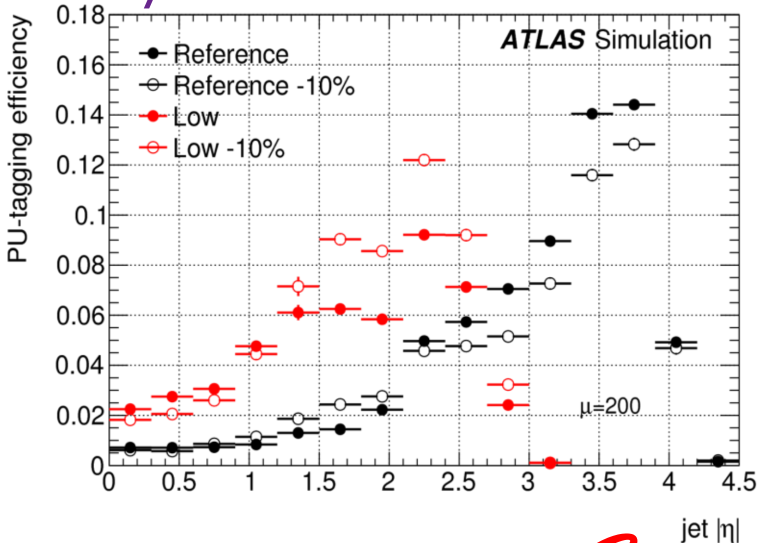




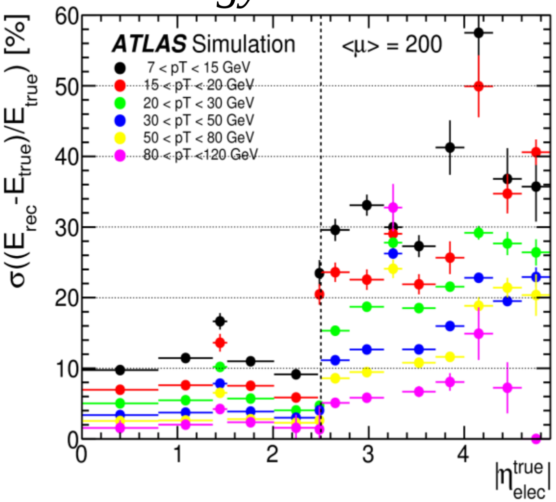
•HL-HLC Conditions

Calorimeter and Pileup efficiency

- ✓ EM calorimeter noise increases by an order of magnitude
- ✓ Pileup rejection is impacted at high η
- ✓ Energy resolution in the EM calorimeter heavily degrades for the low P_T (> 20GeV) regions towards the end caps
- ✓ Up to 20% reduction on the energy resolution for the interesting 20 – 50 GeV P_T region

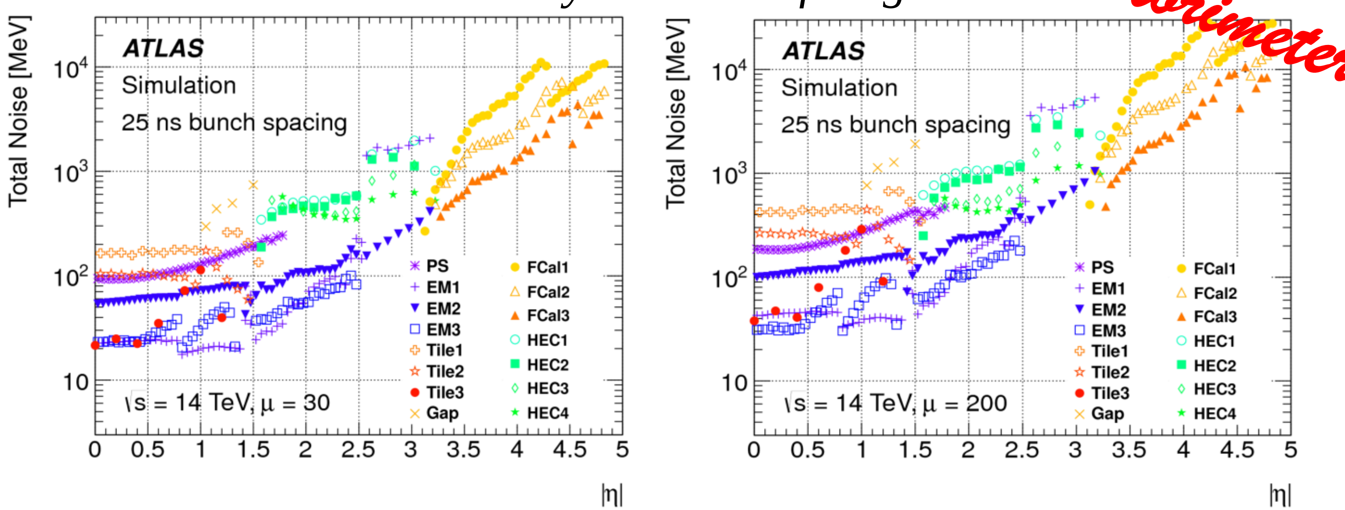


Energy Resolution



Cell noise increase by an order of magnitude

Calorimeter

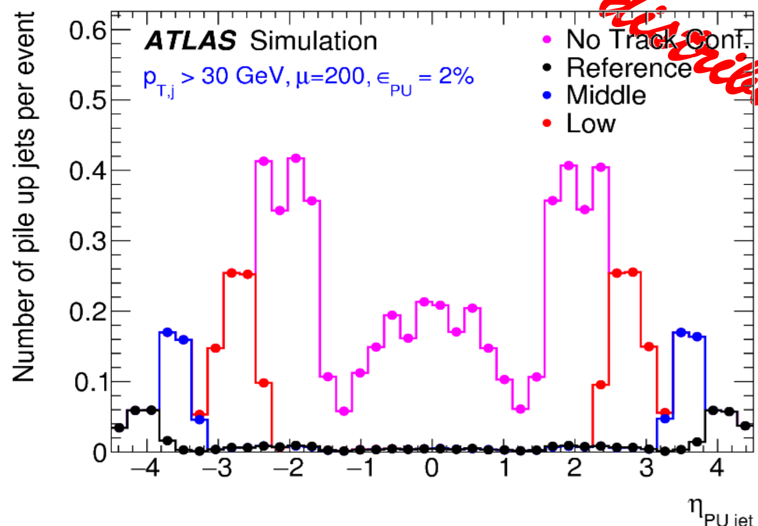


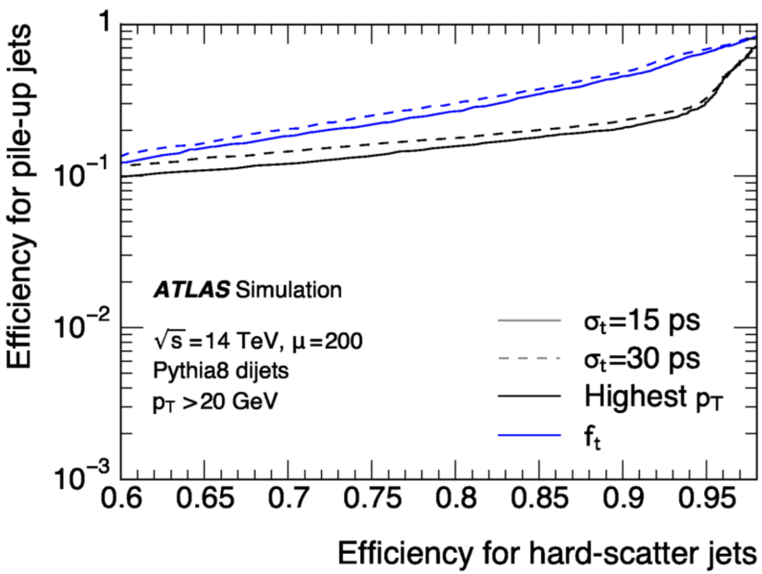
•HGTD Motivation

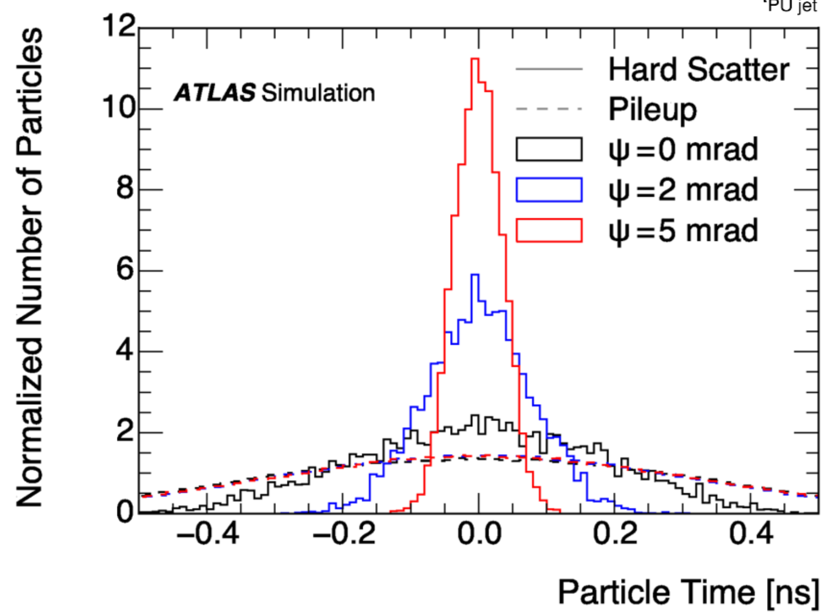
Time – Pileup Rejection

Pileup jet distribution

- ✓ High probability of vertices in close proximity
- ✓ Time information helps pileup rejection
- ✓ Pileup distribution extremely peaked at forward $1.8 < |\eta| < 3.2$ were tracker not completely implemented
- ✓ Track confirmation rejection at 2% for central region but degrades towards end caps







•HGTD Motivation

Important EW channels

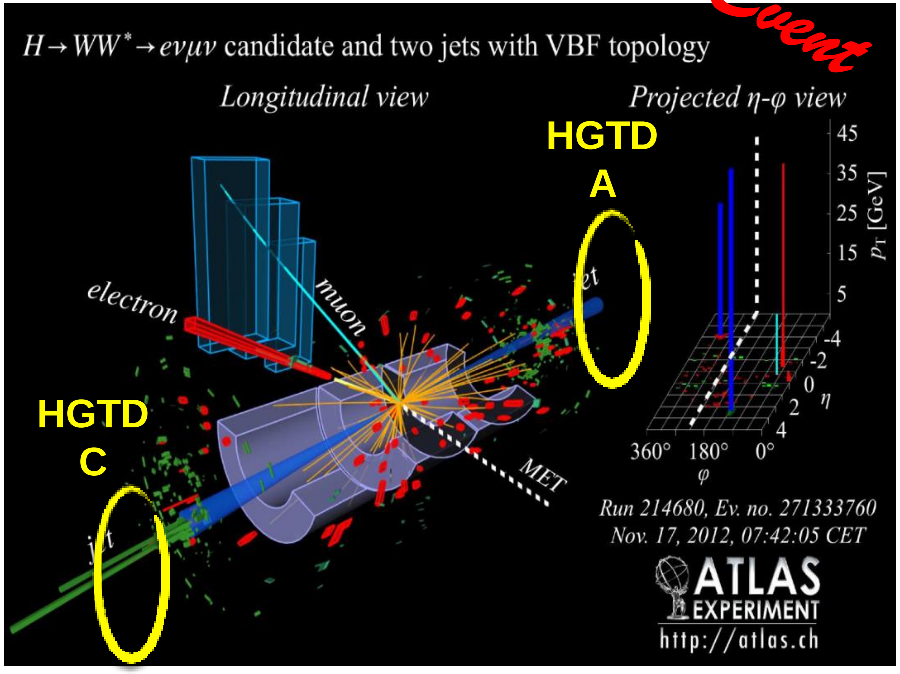
- ✓ Potential of HGTD as a L (40MHz) Time trigger for the VBF 0channel
- ✓ Lower jet P_T thresholds and extend accessible phase space
- ✓ Largest potential in hadronic final state VBF channels (also offline), preferentially forward peaked:

  $H \rightarrow bb,\ H \rightarrow Inv.,\ HH \rightarrow bbbb$

- Pre-shower option :
  - ➢ Improve forward electron /photon reconstruction
  - ➢ Interesting for search in

    $H \rightarrow aa \rightarrow \gamma\gamma jj$

WW Event

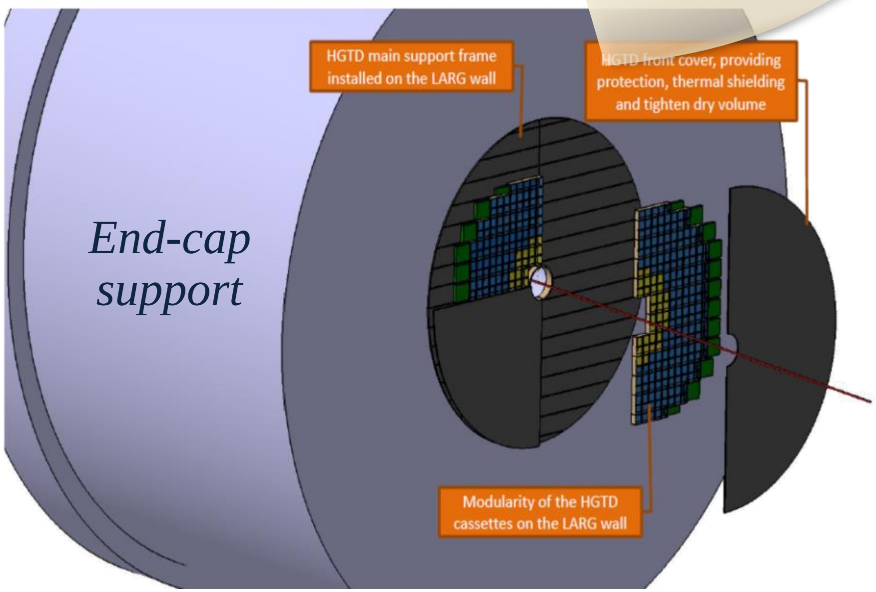


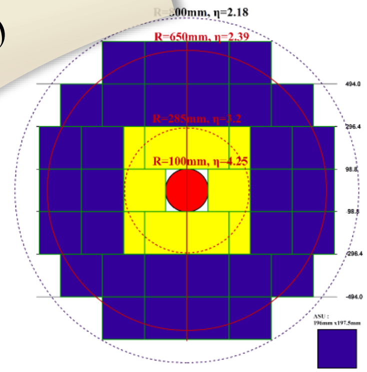
Trigger	SD value	physics
di-γ	25-25 GeV	di-photon
di-τ	40-30 GeV	H→ττ
4-jet	75 GeV	H→bb, HH→4b
E_T^{miss}	200 GeV	H→Inv.

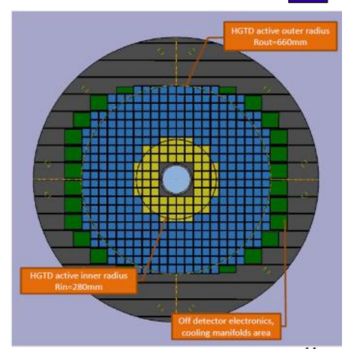
•HGTD System

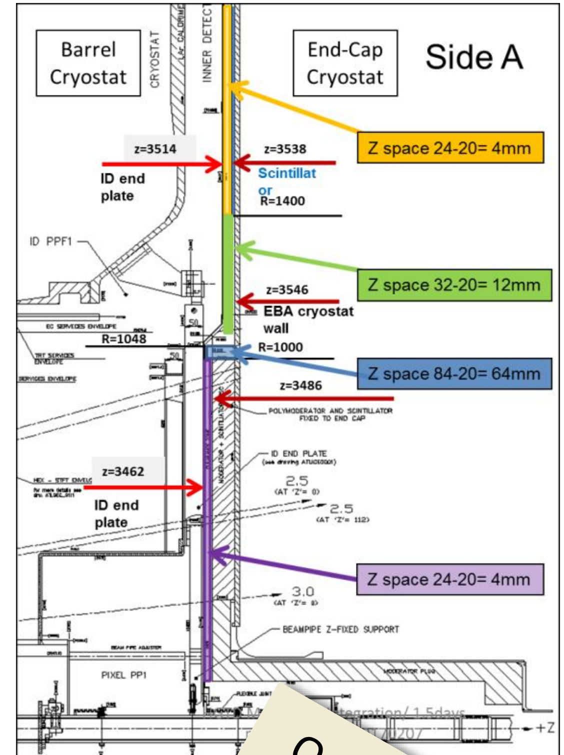
Geometry

- HGTD-Si: 4 si layers
- HGTD-SiW: 4 si layers + $3X_0$ W $2.4 < \eta < 3.2$ (R_{min}=285mm)



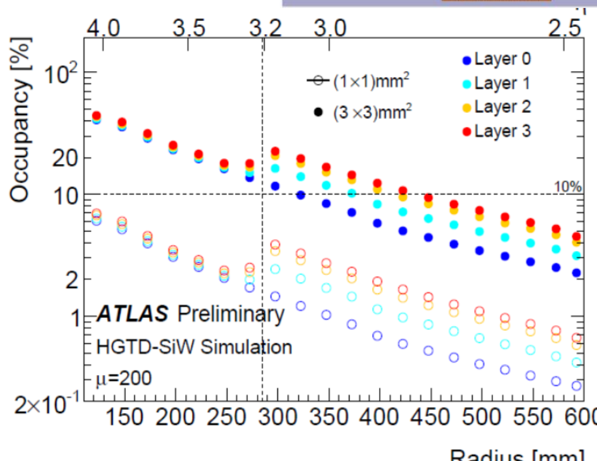


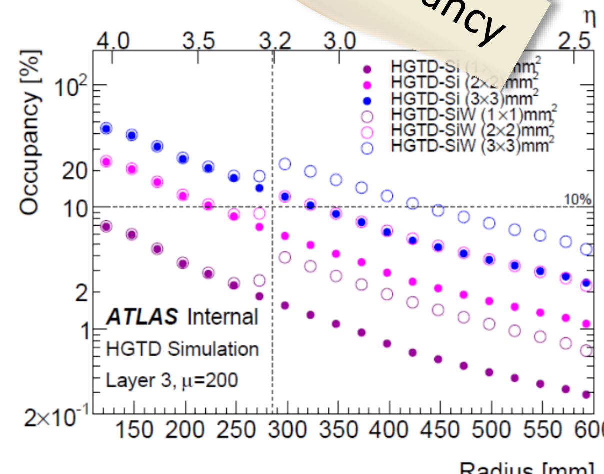




Occupancy

Specifications for 2023	
Coverage	*$2.4 < \eta < 4.2$*
R_{min}	*11 cm*
R_{max}	*65 cm*
Δz	*~ 6 cm*
Δt	*< 50 ps*
Cell Size	*1 mm²*



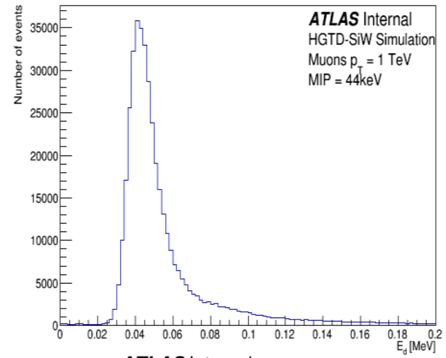


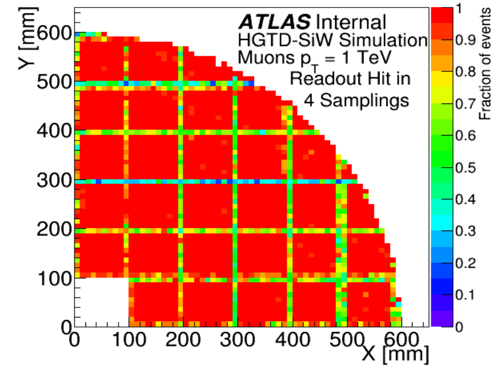
•HGTD System

Performance

Muons

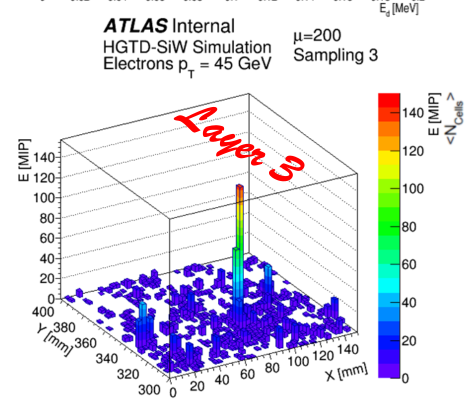
- ✓ 1TeV muons simulation
- ✓ 98.88% efficiency for 4 layers
- ✓ 0.044 MeV/muon at 150 μm
- ✓ 50% of inefficiency from zones

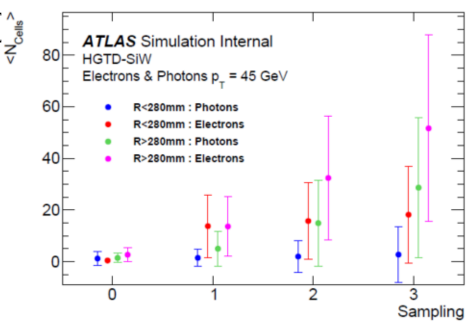




Electrons

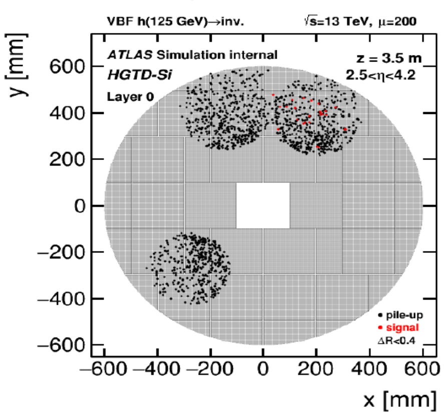
- ✓ Z → ee sample at μ = 200
- ✓ 45 GeV P_T e and γ
- ✓ 6mm radius EM clusters
- ✓ 70 HGTD cells per cluster
- ✓ Dynamic range of 50psec/MIP

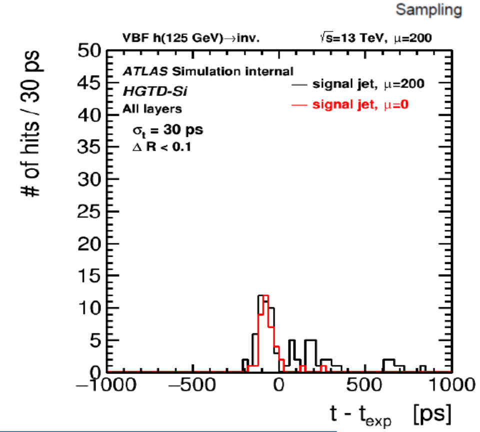




Jets

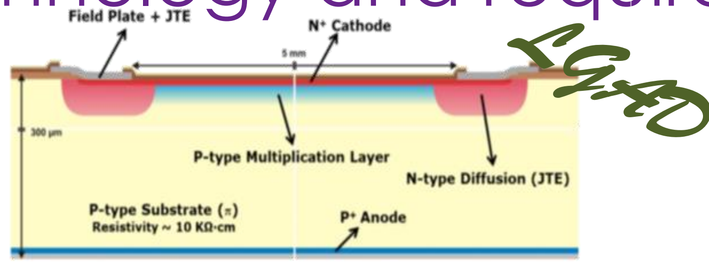
- ✓ H(125GeV) → Inv. sample with jet P_T=72GeV
- ✓ Expected peak in time distribution
- ✓ ~90% signal purity at ΔR < 0.1





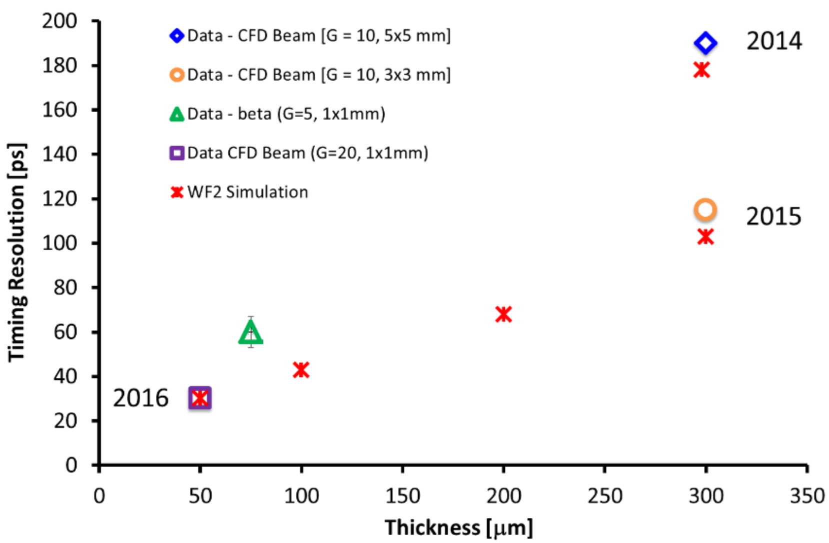
• Sensors

Technology and requirements



Low Gain Avalanche Diodes (LGAD)

- ✓ Most promising technology
- ✓ Secondary implant introducing moderate gain
- ✓ HPK, CNM, FBK produced sensors



Time Resolution

$$\sigma_{tot}^2 = \sigma_{elec.}^2 + \sigma_{Landau}^2$$

$$\sigma_{elec}^2 = \underbrace{\left(\frac{t_{rise}}{S/N}\right)^2}_{\textit{Jitter}} + \underbrace{\left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2}_{\textit{Timewalk}} + \underbrace{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2}_{\textit{Conversion time}}$$

$$\left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N}{dV/dt}\right]_{RMS}$$

$$\frac{t_{rise}}{S/N} \approx \frac{N}{dV/dt}$$

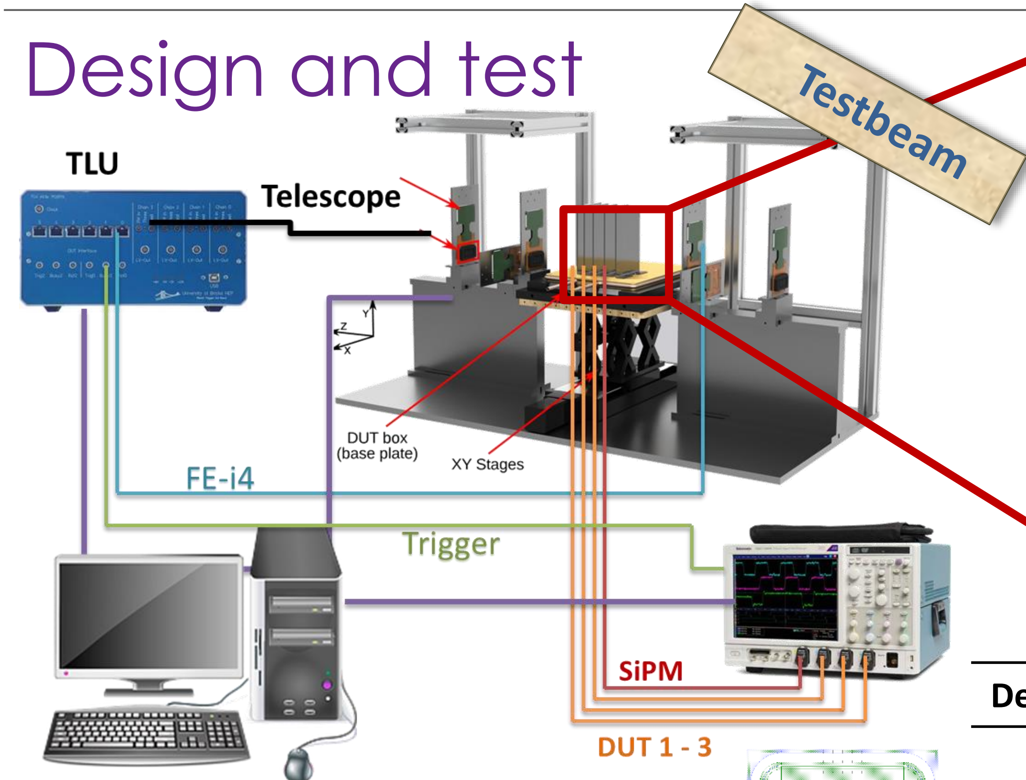
Where: S signal
N noise
$\boldsymbol{V_{th}}$ CFD threshold
t_{rise} *rise time*

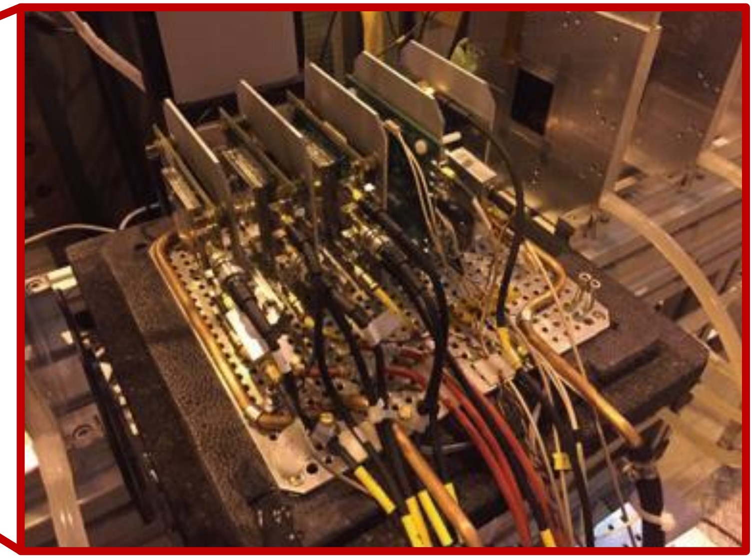
Fast time resolution:

- ✓ Maximize slope (large fast signals)
- ✓ Correct time walk with CFD
- ✓ Minimize noise
- ✓ Thin sensors with integral gain

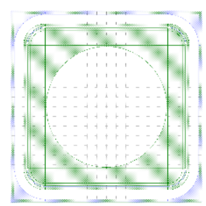
• Sensors

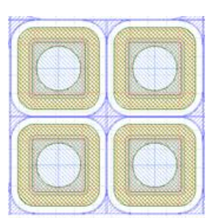
Design and test





- CNM SoI wafers on 300µm handle wafer
- High resistivity sensor region
- Varied amplification implants
- Single diodes and 2x2 arrays



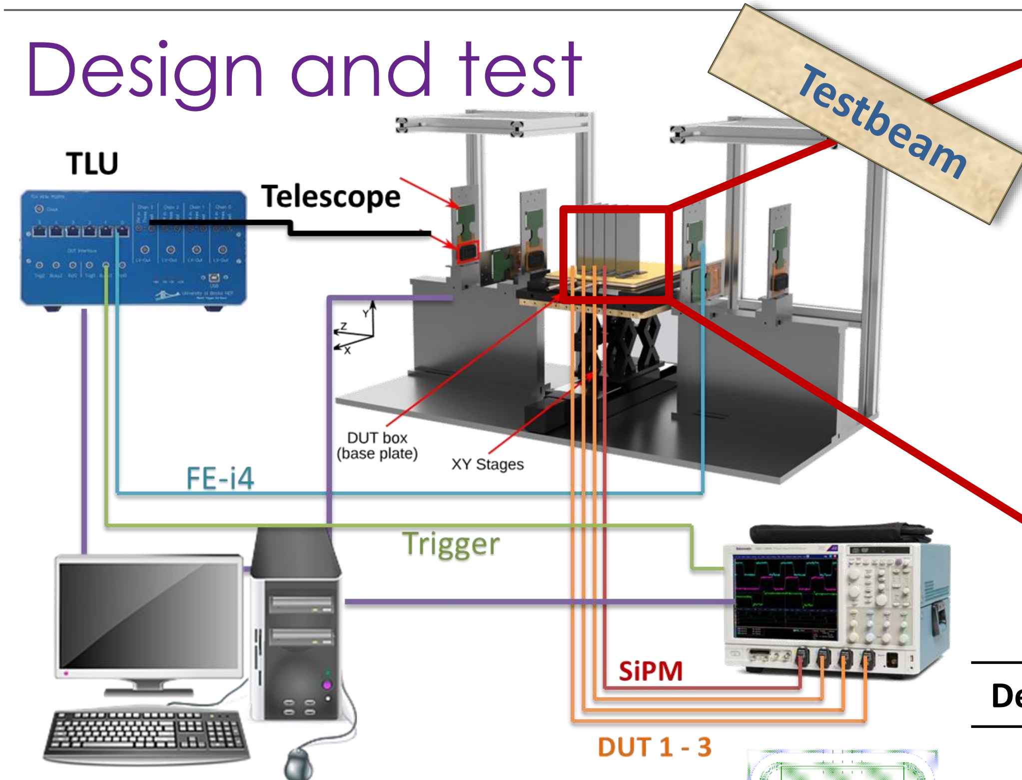


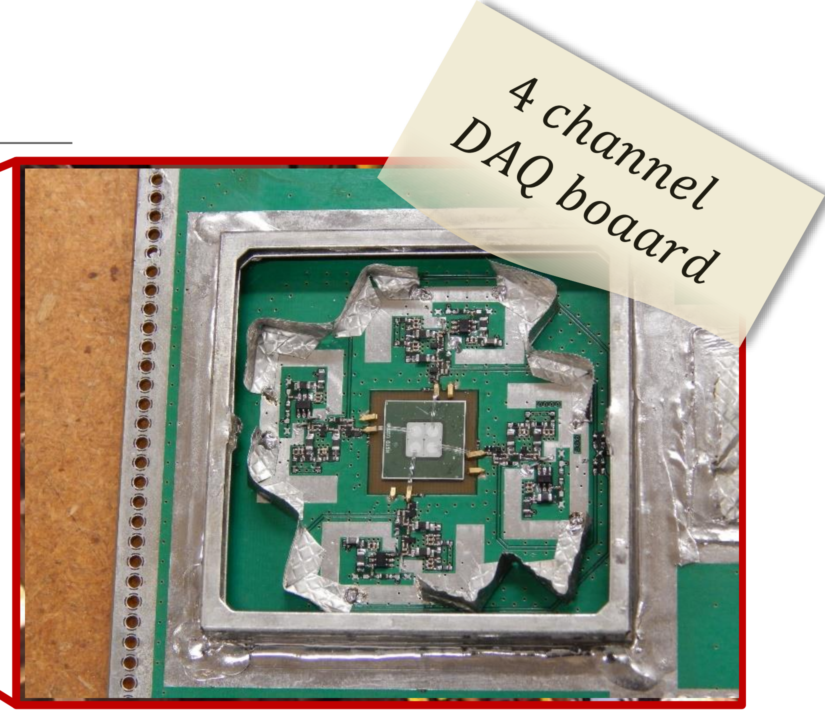
Tested Devices

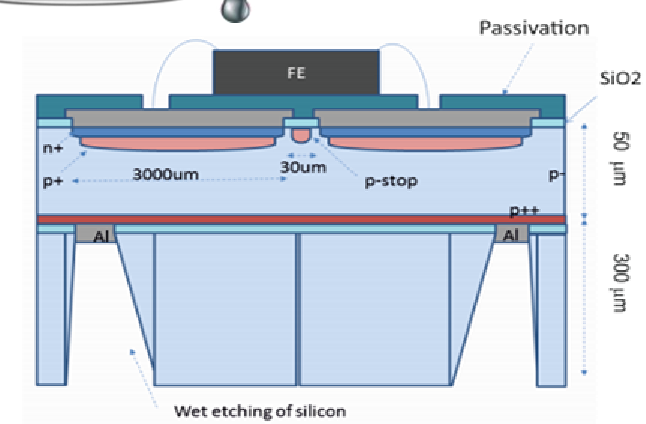
Detector	Size (mm)	Dose	Thickness	C_p (pF)
Single pad	1.2 x 1.2	$1.9 \bullet 10^{13}$	45 µm	3.5 pF
		$1.9 \bullet 10^{13}$	45 µm	3.5 pF
		$2.0 \bullet 10^{13}$	45 µm	3.5 pF
2 x 2 Arrays	2 x 2	$1.8 \bullet 10^{13}$	45 µm	11 pf
		$1.9 \bullet 10^{13}$	45 µm	11 pF
	3 x 3	$1.9 \bullet 10^{13}$	45 µm	23 pF
		$2.0 \bullet 10^{13}$	45 µm	23 pF

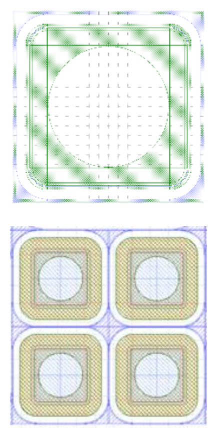
• Sensors

Design and test









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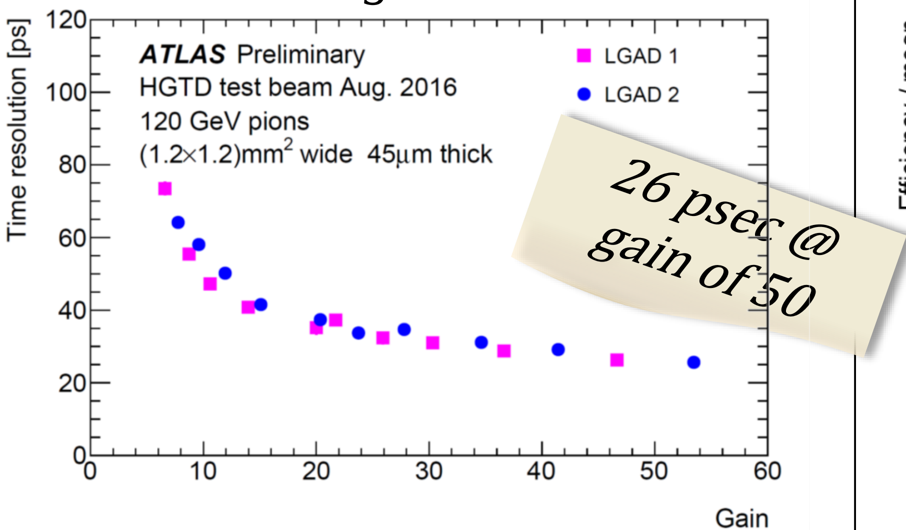
	3 x 3	$1.9 \bullet 10^{13}$	45 µm	23 pF
		$2.0 \bullet 10^{13}$	45 µm	23 pF

• Sensors

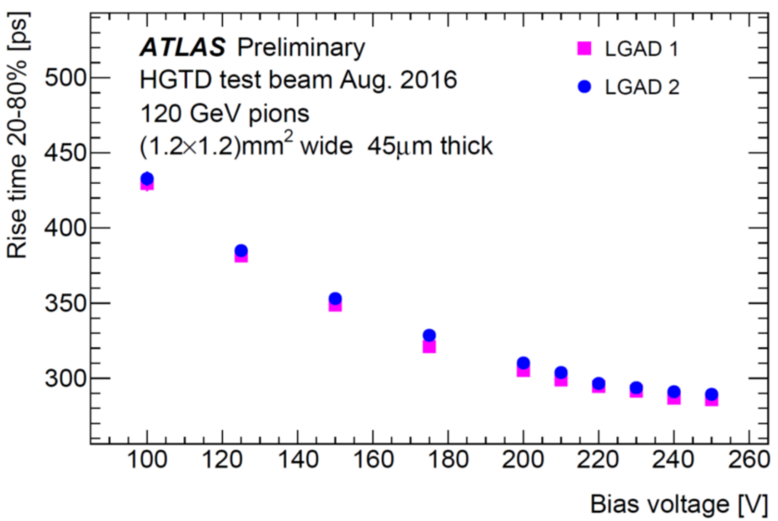
Testbeam Results

Single Diodes

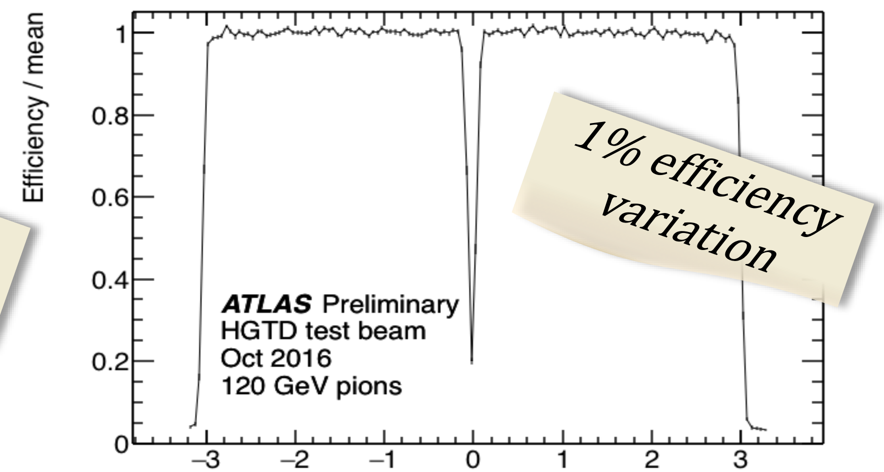
Time Resolution

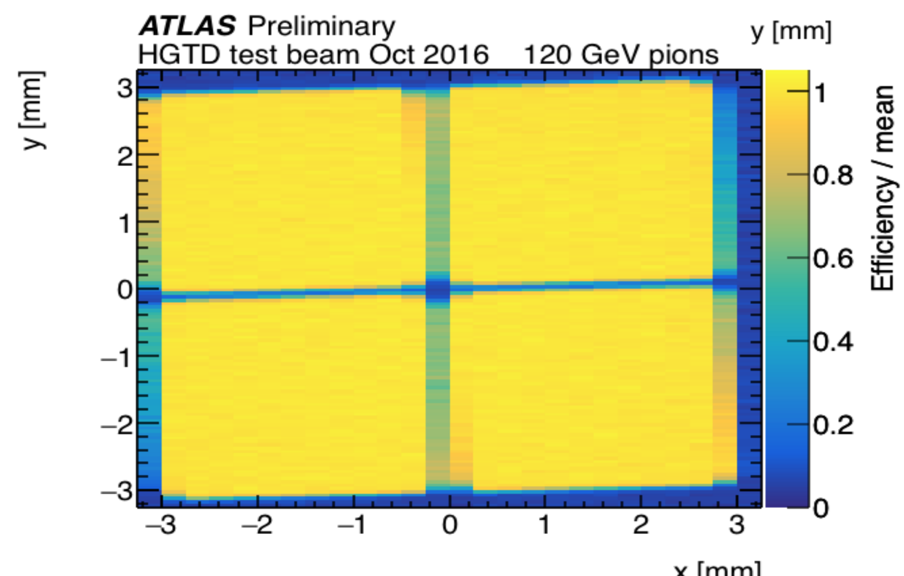


Signal Slope



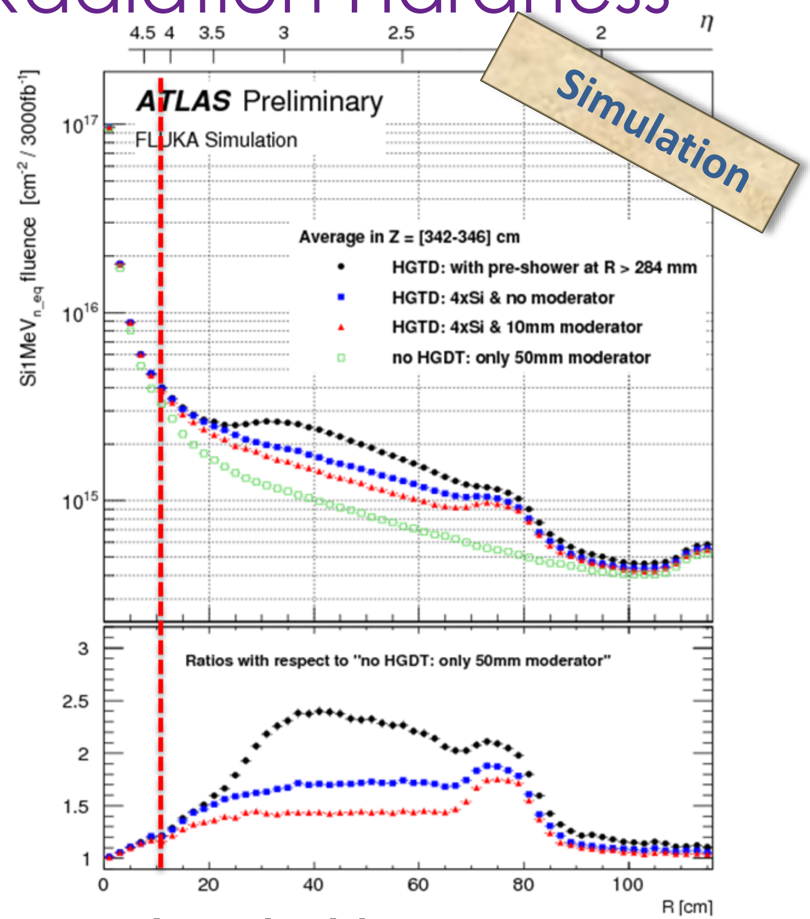
2x2 Arrays (3 x 3 mm)



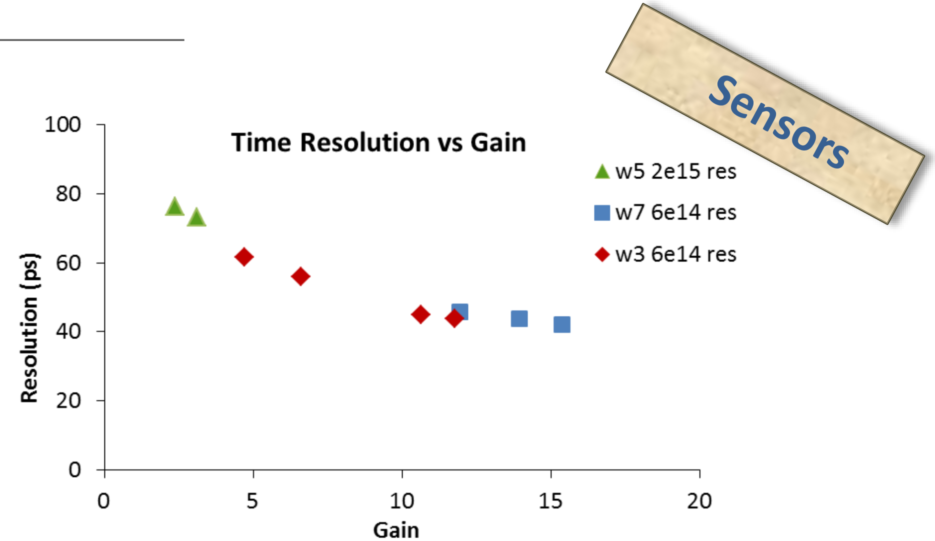


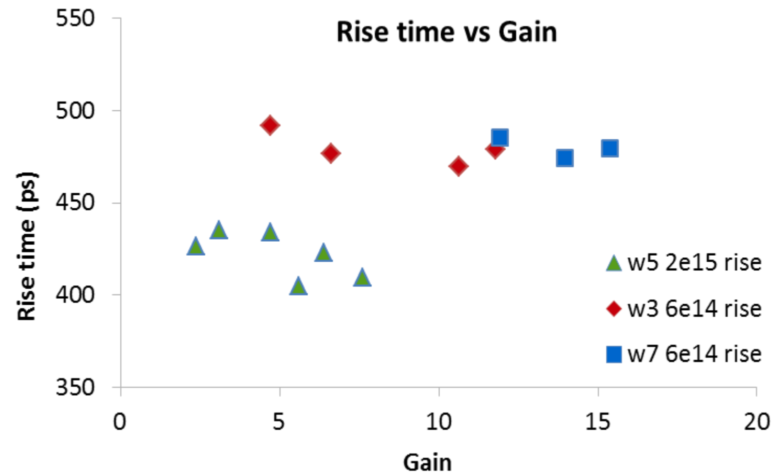
• Sensors

Radiation Hardness



- Similar results Fluka - GCALOR
- Max. (η = 4 .2) after 3000 fb^{-1} ~ 4x10^{15} n/cm^2
- W increases the dose by a factor 3 for R > 30cm in HGTD, possible mitigation by 5mm moderator

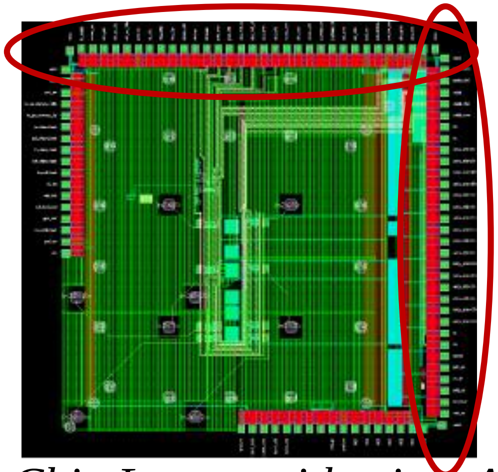




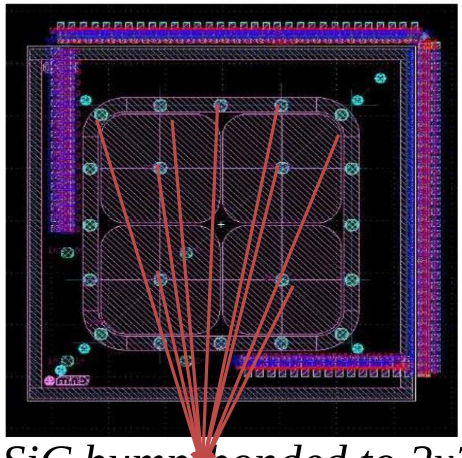
- Thermal neutron irradiation single pad diodes
- Rise time within 10% between fluences
- Time resolution in the order of 40 ps for gain of 10 - 15

•Electronics

ASIC prototype



Chip Layout with wire bonds in the periphery



ASiC bump-bonded to 2x2 array in multiple points

	Detector	1 mm pad	3 mm pad
	Power con.	800 μA	3.2 mA
	V_{in} (Q_{in}/C_d)	2.5 mV	0.625 mV
	Sim. V_{out}	21 mV	17.7 mV
	Noise	0.44 mV	0.66 mV
	S/N	48	27
Inner Layers	Jitter (at G = 10)	23 ps	40 ps
Large Radius	Jitter (at G = 20)	11.5 ps	20 ps

ATLAS LGAD Timing Integrated ReadOut Chip (ALTiRoC)

- TSMC 130nm CMOS Technology
- 3.4 x 3.4 mm total area
- 300μm substrate thickness
- Directly bonds to 2 x 2 arrays
- Four readout channels dedicated for 2 pf/channel, 10 pf/channel and 20 pf/channel sensors
- Channel area 200 x 100 μm
- Integrated Preamplifiers, ToT and CFD
- Under fabrication, expected in April

•Conclusions and Outlook

Sensors, ASIC, Integration and Radiation Hardness

So far….

Physics

- ✓ Very promising results for pileup rejection in the high η region where VBF and exotics will benefit
- ✓ High jet single purity for invisible searches, L0 trigger for VBF channel at 40MHz

Sensors

- ✓ 26 ps time resolution for single $1mm^2$ diodes
- ✓ 95% uniformity with low inefficiencies in the inter-pad regions
- ✓ Operations up to 2e15 at moderate gains with degradation of time resolution due to breakdown

Integration

- ✓ Fixed and simulated geometry and vital space
- ✓ Flex and mechanics designs considered
- ✓ Tests with different detector sizes and electronics
- ✓ First ASIC prototype deigned and submitted

•Conclusions and Outlook

Sensors, ASIC, Integration and Radiation Hardness

To do…

Physics

- ✓ Investigate performance improvements in individual analysis channels at the context of HL-LHC
- ✓ Integrate and produce fully simulated samples with final geometry

Sensors

- ✓ Scale from single pads and 2 x 2 arrays to 2cm x 2cm matrices
- ✓ Improve radiation hardness for neutron irradiated, do proton- pion irradiation
- ✓ Key players with design optimization (HPK, CNM, FBK) to improve inefficiencies

Integration

- ✓ Final geometry and segmentation decisions with respect to occupancy and readout
- ✓ ASIC Test in upcoming test beams, optimization and scaling to full size matrices
- ✓ Services and flex design and simulation, final decisions about integration

•Acknowledgements

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