IFAE Pizza Seminar

Institut de Fisica d'Altes Energies

A High Granularity Timing Detector for the Phase II Upgrade of the ATLAS experiment

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•Overview

Introduction

Motivation

HGTD System

Sensor Development

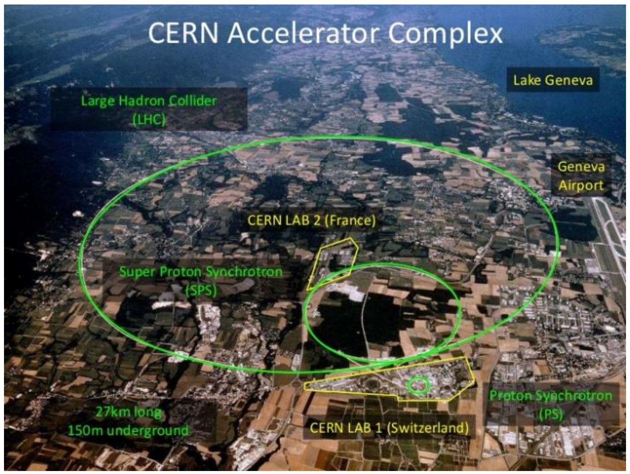
ASICs

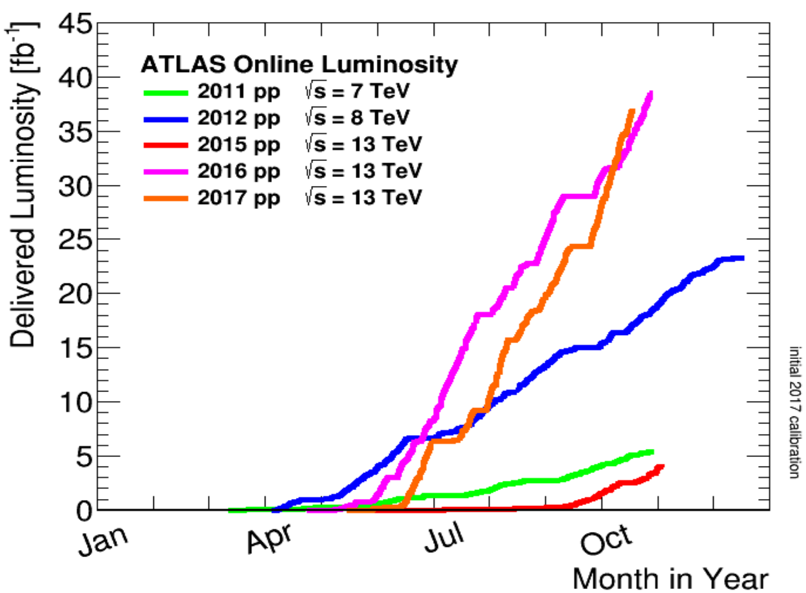
Conclusions

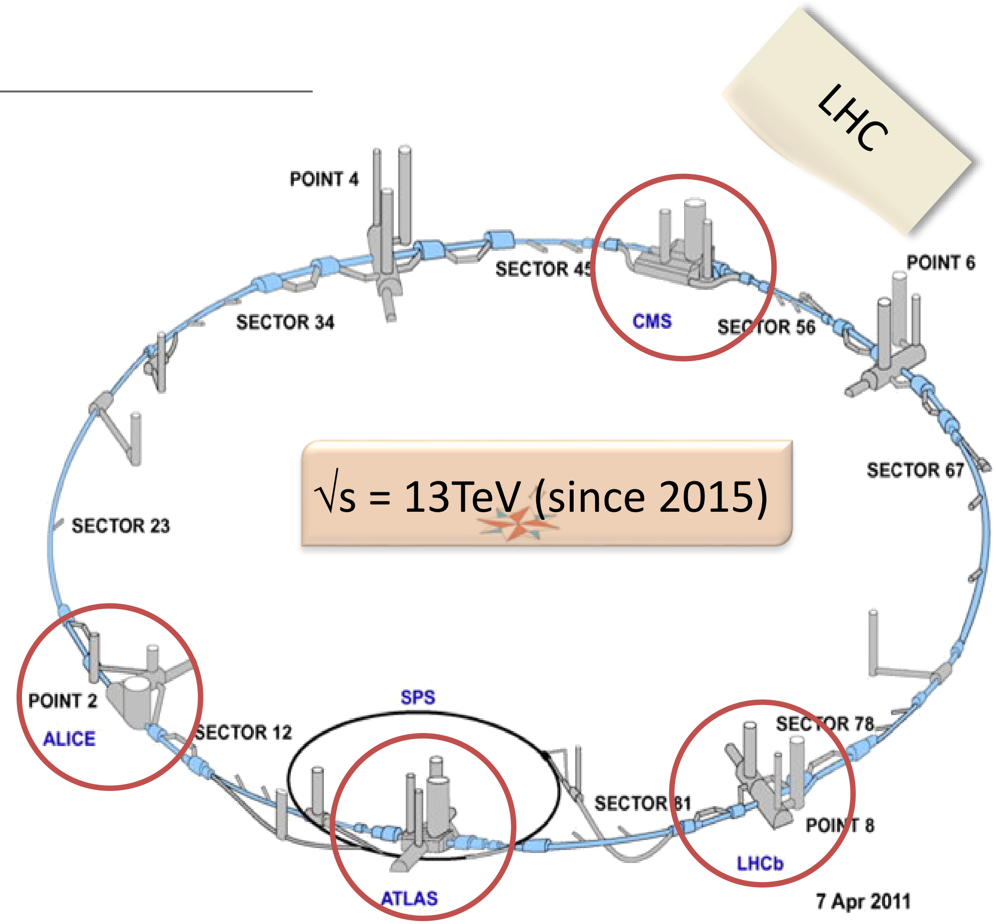
- Introduction and HL-HLC
  - CERN, experiments and timeline
  - μ = 200 pileup conditions
  - Pileup efficiency
- HGTD Motivation
  - Time-Pileup rejection
  - Important EW channels
- The Detector design
  - Geometry
- Sensors
  - Technology - LGADs
  - Design and testing
  - Test Beam Results
  - Radiation Hardness
- Electronics and assembly
- Conclusions and Outlook

•Introduction

CERN and LHC





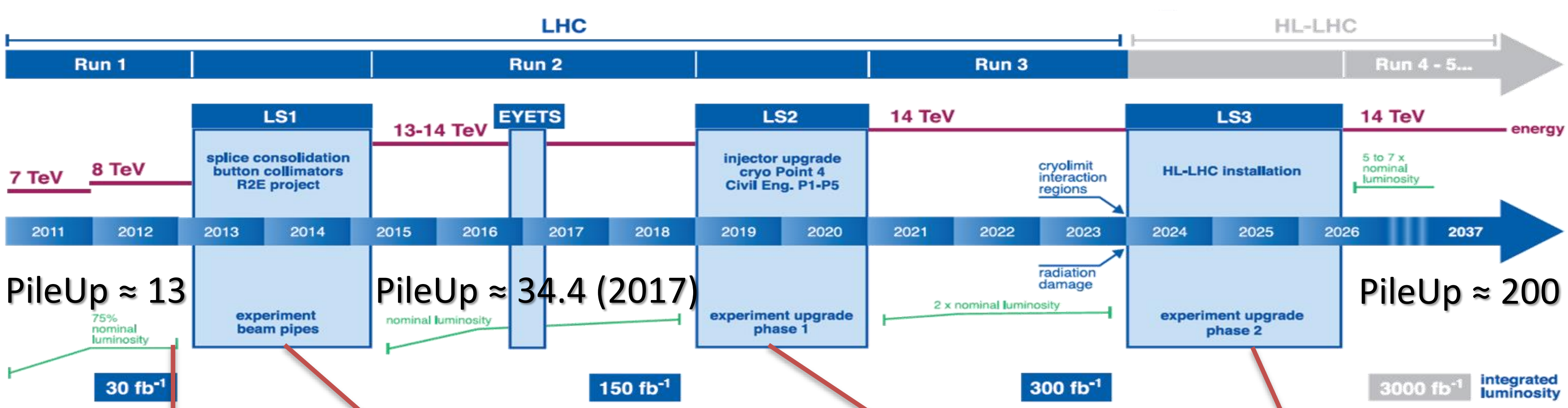


- 8.3 T superconductive magnets
- 26.7 km circumference
- 25 ns bunch spacing (50 ns Run 1)
- 4 main experiments (ATLAS, CMS, ALICE, LHCb)

• Phase 2 Upgrade, towards HL-LHC

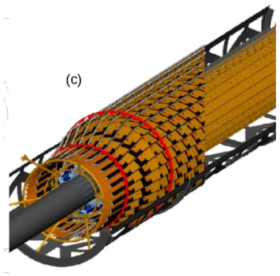
Planning and timeline

LHC / HL-LHC Plan



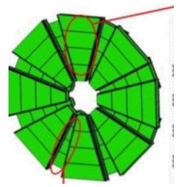
Higgs Discovery

Phase 0 upgrades

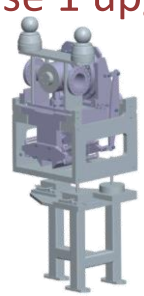


IBL

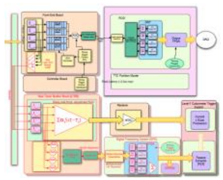
Phase 1 upgrades



New Muon Small Wheel

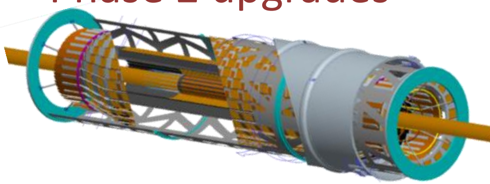


AFP



L1 LAr Trigger

Phase 2 upgrades



Complete Inner Detector Replacement

•HL-HLC Conditions

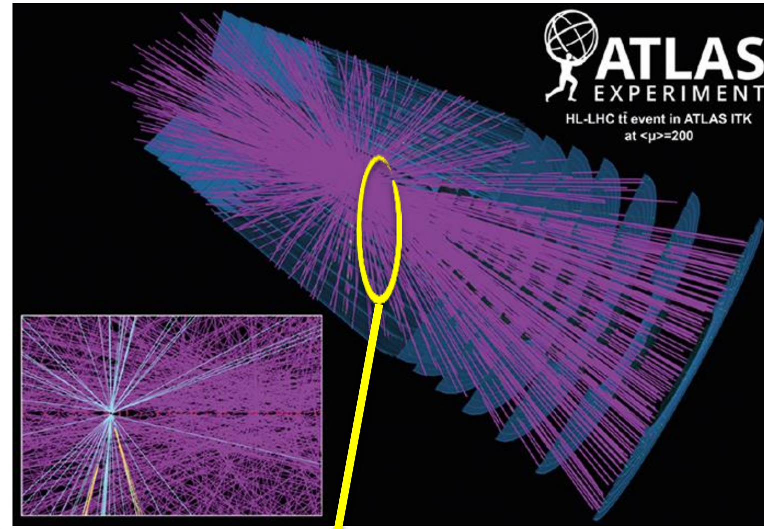
HL-LHC Conditions

Luminosity

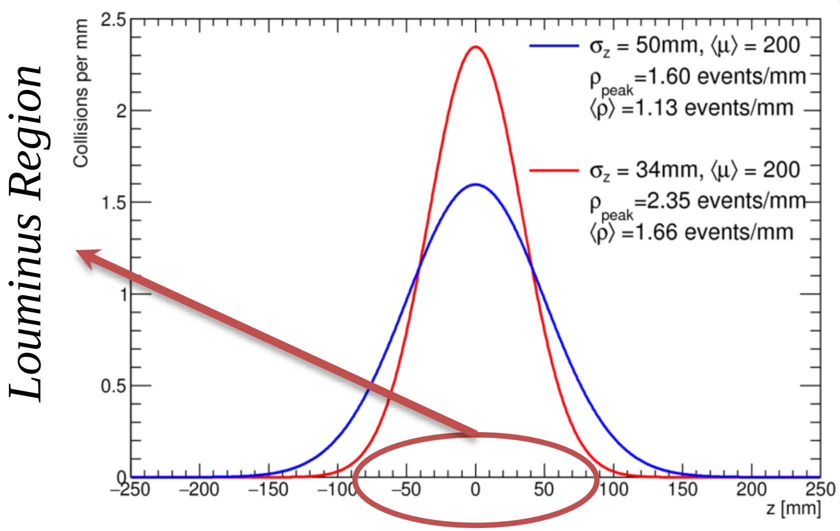
- ✓ Phase I: < 2.2×10^{34} $cm^{-2}s^{-1}$ (300 fb^{-1})
- ✓ Phase-II : 5 - 7.5×10^{34} $cm^{-2}s^{-1}$ (4000 fb^{-1})

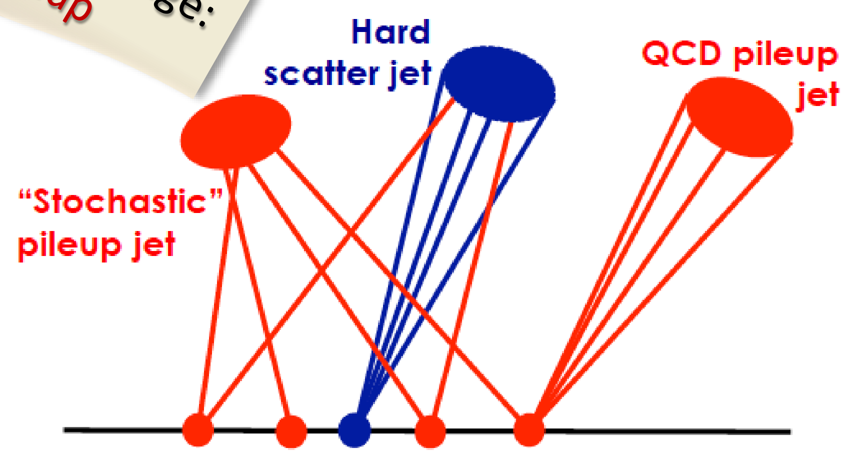
Conditions

- ✓ 14 TeV beam - 6000 primary tracks per event
- ✓ No. of collisions per crossing from 34 to 200 at 150 ps in 50 mm space
- ✓ Extended tracking up to $|\eta| < 4.0$



Major Challenge:
Pileup





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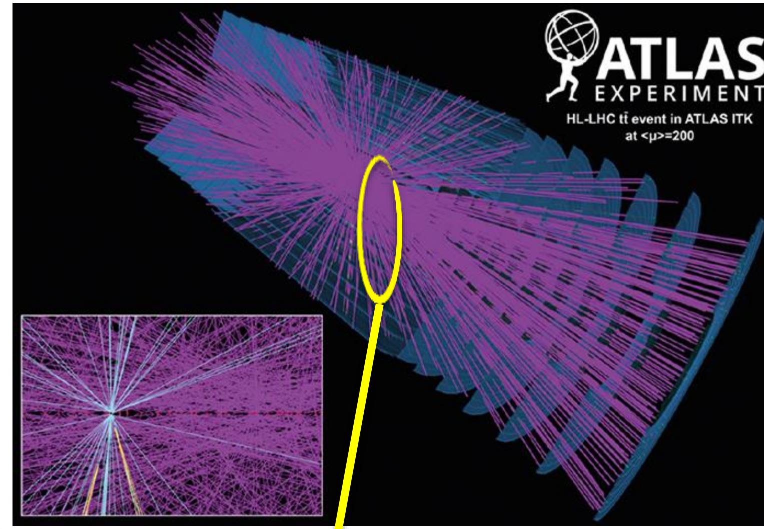

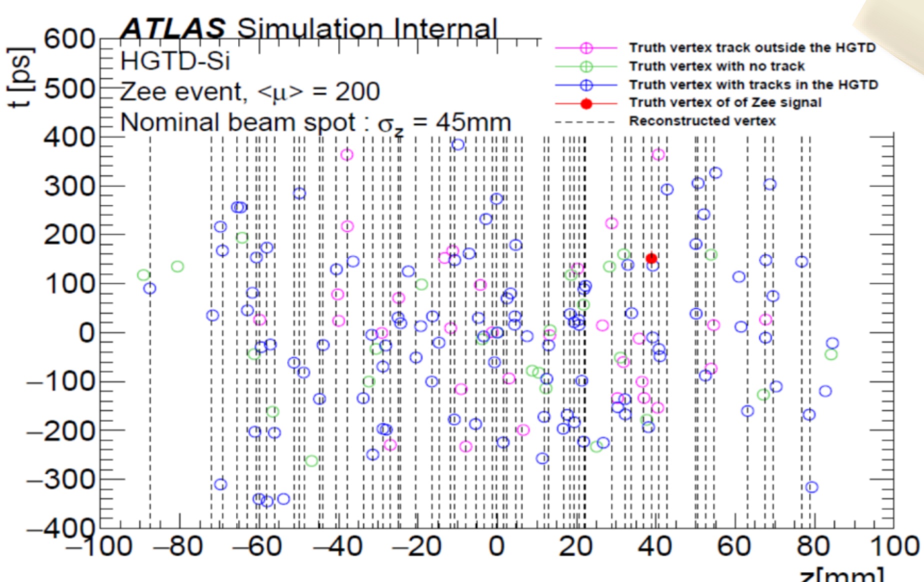

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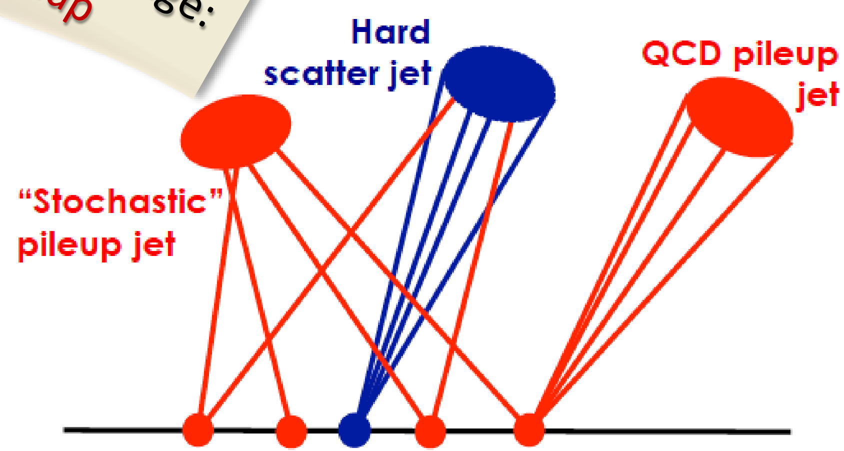
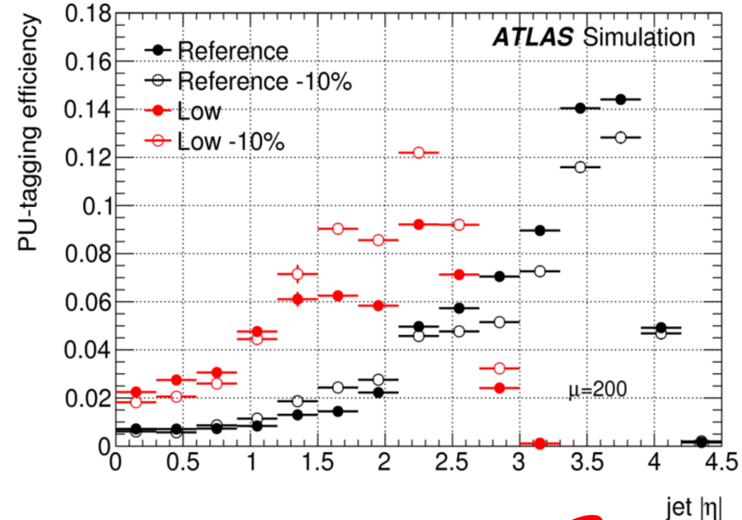


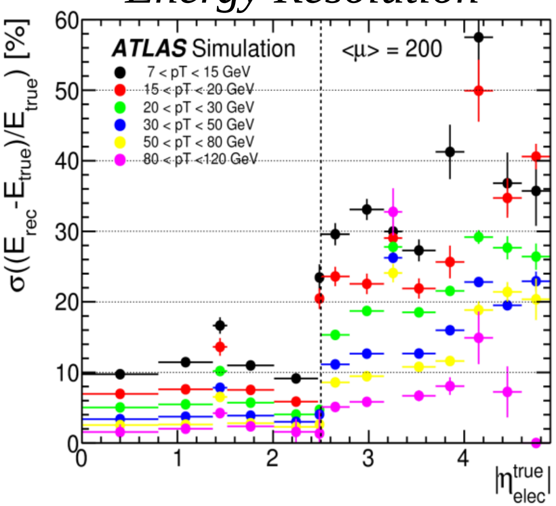
•HL-HLC Conditions

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

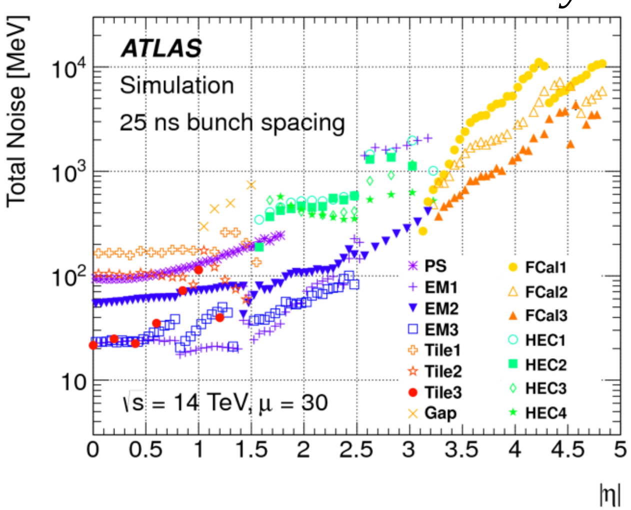


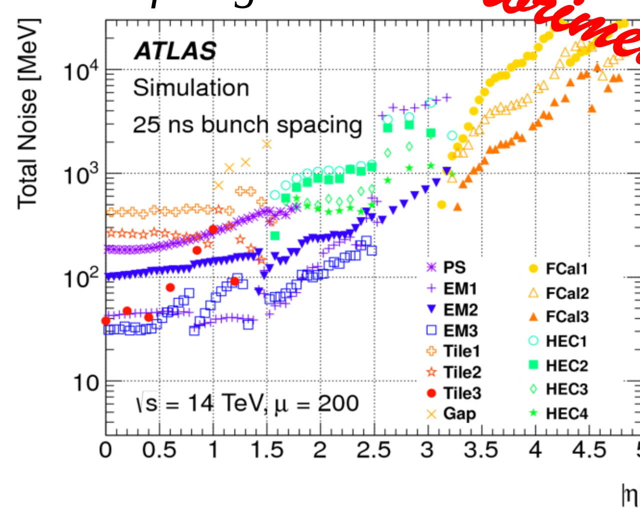
Energy Resolution



Cell noise increase by an order of magnitude

Calorimeter



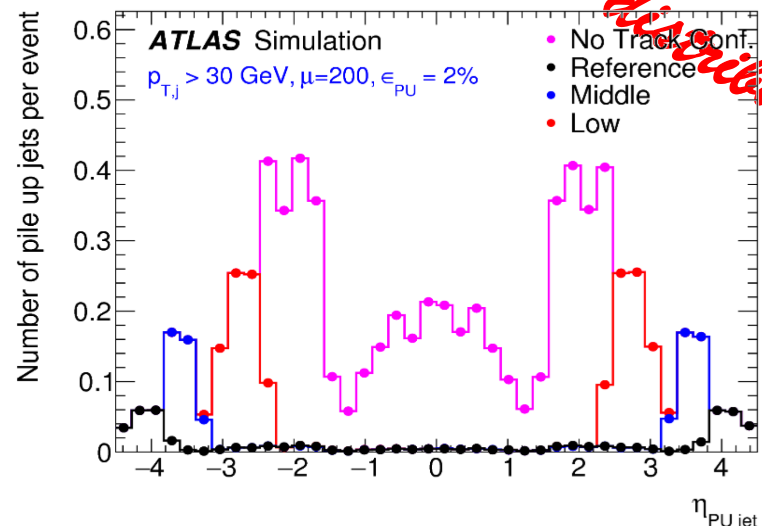


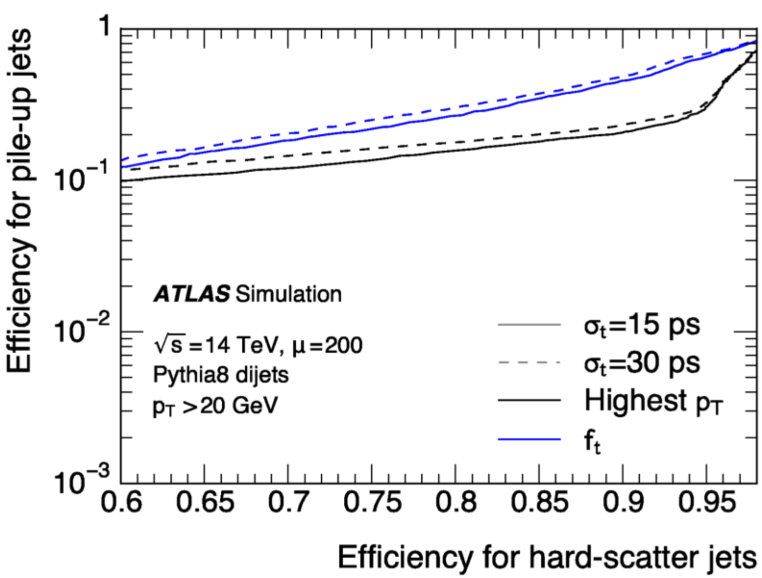
•Timing Motivation

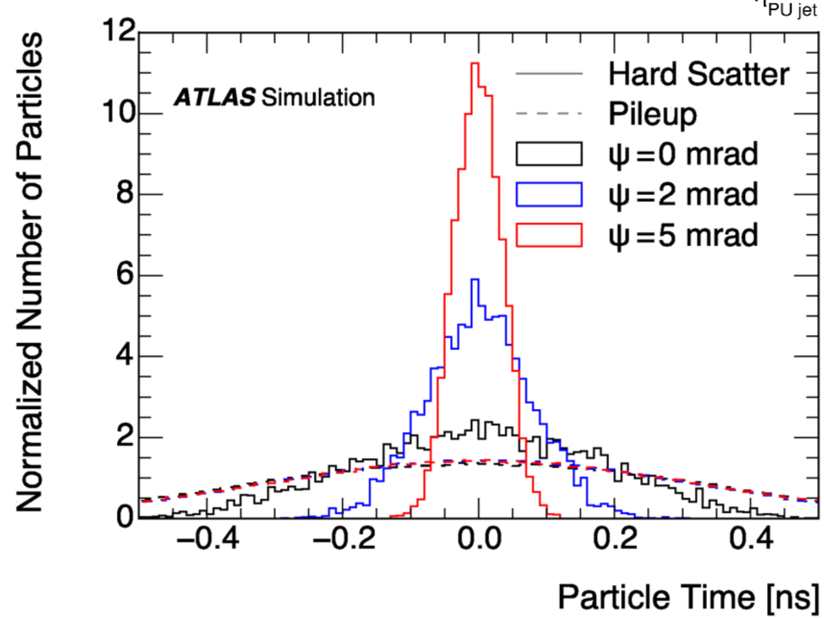
Pileup Rejection

- ✓ High probability of vertices in close proximity
- ✓ Time information ~30psec helps pileup rejection
- ✓ Pileup distribution extremely peaked at forward $1.8 < |\eta| < 3.2$ where tracker not completely implemented
- ✓ Track confirmation rejection at 2% for central region but degrades towards end caps

Pileup jet distribution







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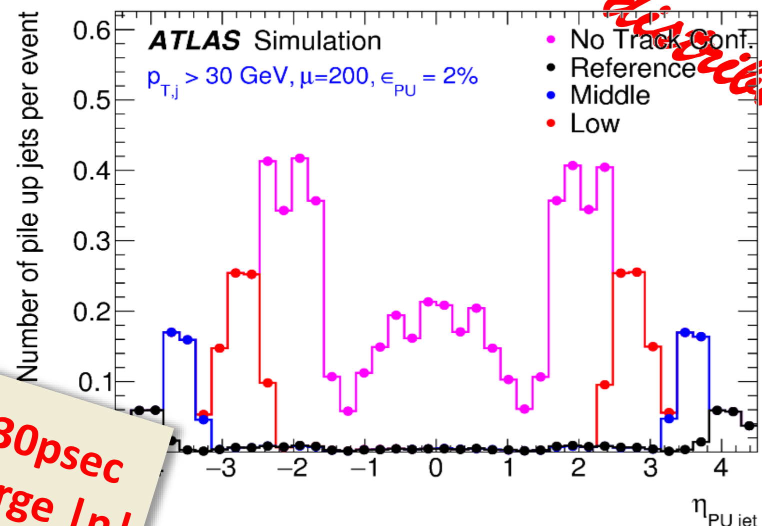
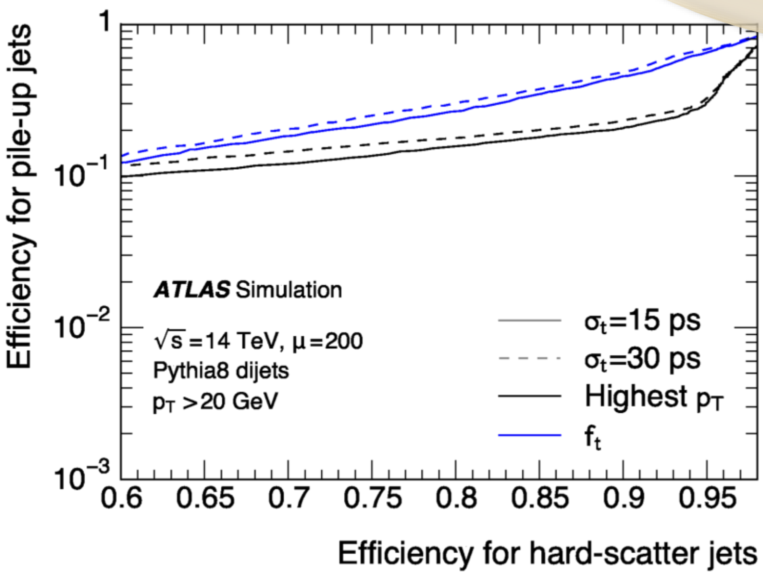
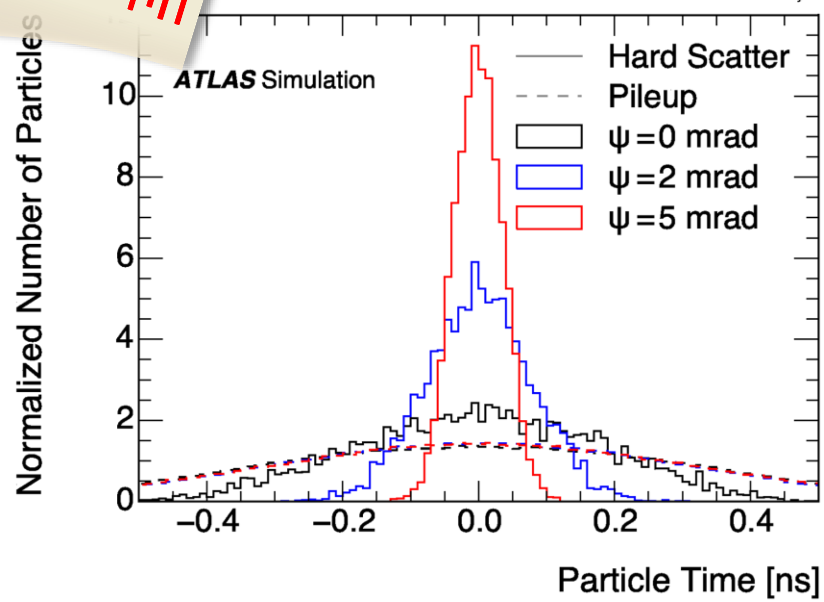


Include a ~30psec detector at large |η|





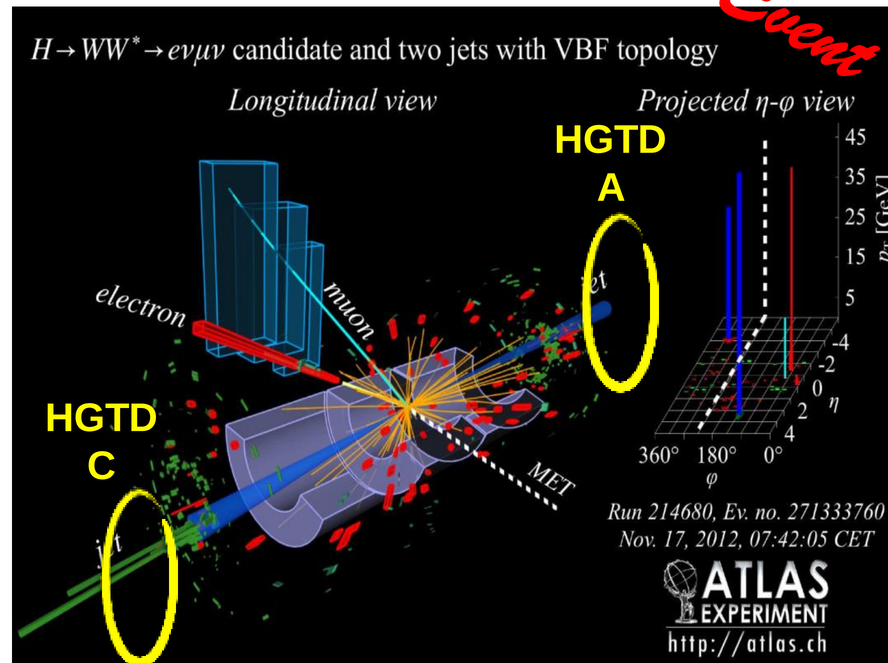
•Physics Motivation

WW Event

Important EW channels

- ✓ Better pileup rejection permits lowering jet P_T thresholds (30 GeV for Endcap)
- ✓ Lowering P_T thresholds allows estending accessible phase space
- ✓ Largest potential in hadronic final state VBF channels (also offline), preferentially forward peaked:

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



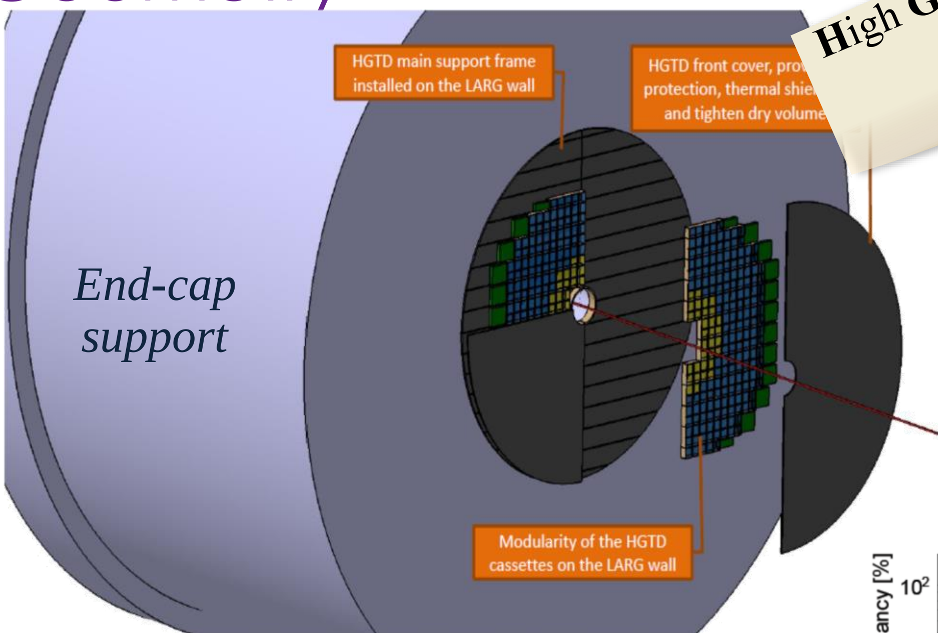
- Physics searches
  - ➢ Higgs to ττ channel (Pilar Casado)
  - ➢ Coupling probing:

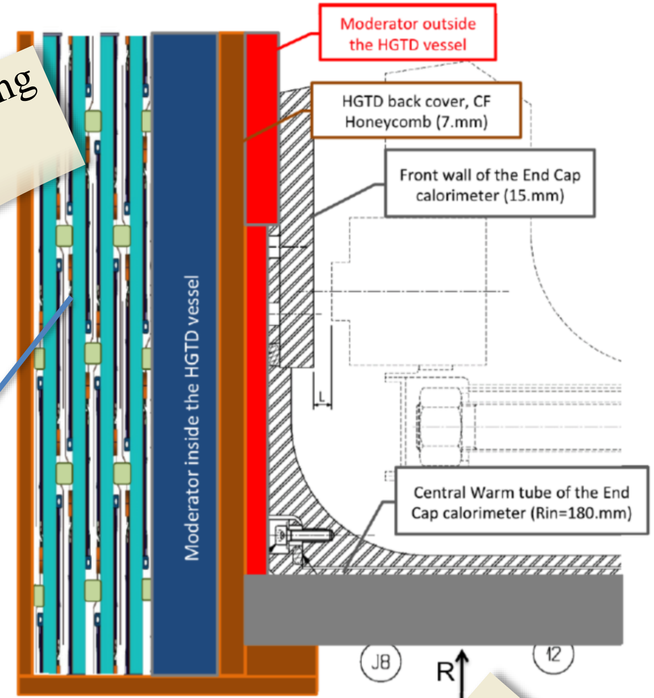
    $H \rightarrow aa \rightarrow \gamma\gamma jj$, $bbH(\rightarrow \gamma\gamma)$

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

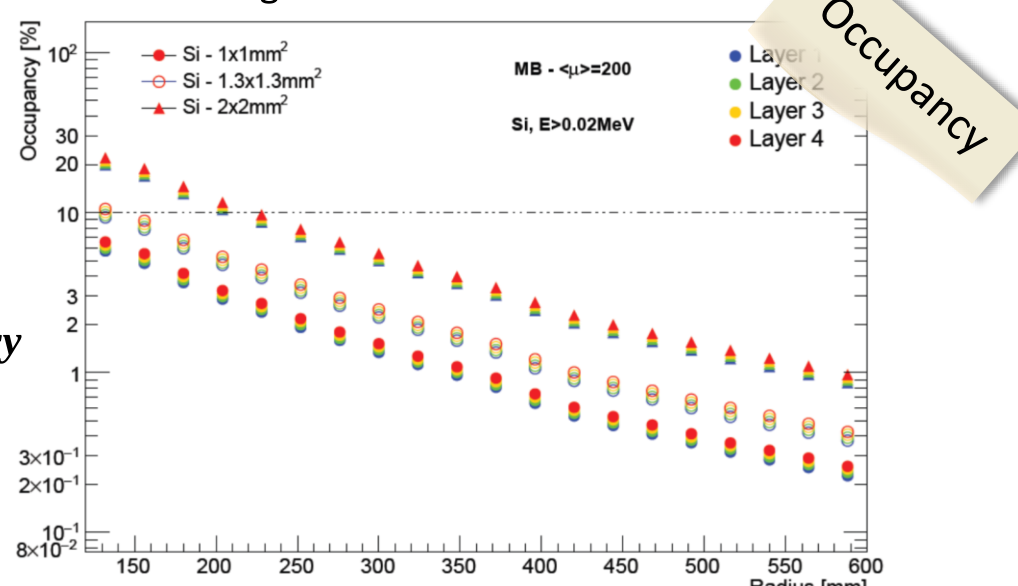




Double sided sensor layers with CO_2 cooling

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

Pad size of ~ 1.3 mm x 1.3 mm defined by occupancy requirement < 10%



• Timing Principles

Concepts and notions

Time Resolution

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

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

Jitter — *Time walk* — *Conversion time*

Where: S signal

N noise

$\boldsymbol{V_{th}}$ CFD threshold

t_{rise} *rise time*

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

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

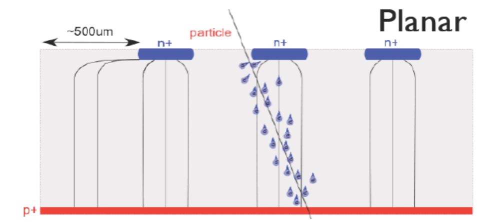
Fast time resolution:

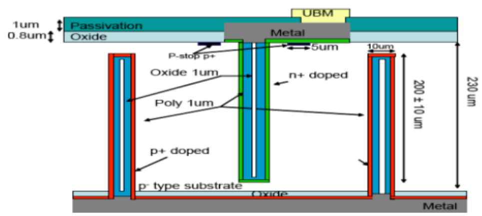
- ✓ Maximize slope (large fast signals)
- ✓ Correct time walk with Constant fraction discriminator
- ✓ Minimize noise to minimize jitter
- ✓ Thin silicon sensors with internal gain

• Sensors

Silicon Technologies

No charge amplification





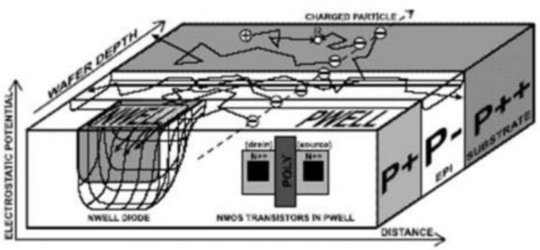
Planar Pixels

- ✓ Standard Lithography
- ✓ Limitations on pitch size
- ✓ High Power dissipation

3D pixels

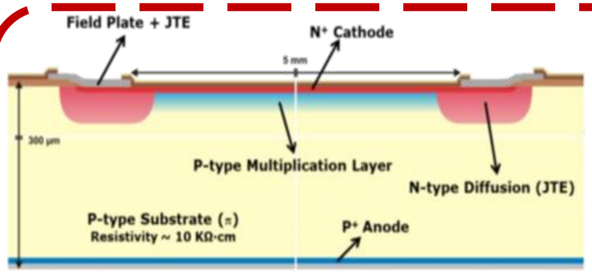
- ✓ Thinner drift volume
- ✓ Radiation Hardness
- ✓ Complicated fabrication

Charge amplification



CMOS Sensors

- ✓ Integrated electronics
- ✓ Commercial process



Low Gain Avalanche Diodes (LGAD)

- ✓ Signal amplification
- ✓ Invented at CNM, initially considered for tracking by IFAE
- ✓ Proposed fro timing by UCSC

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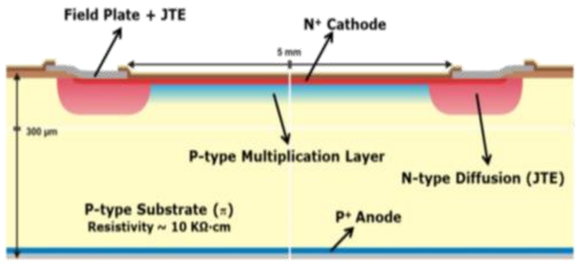
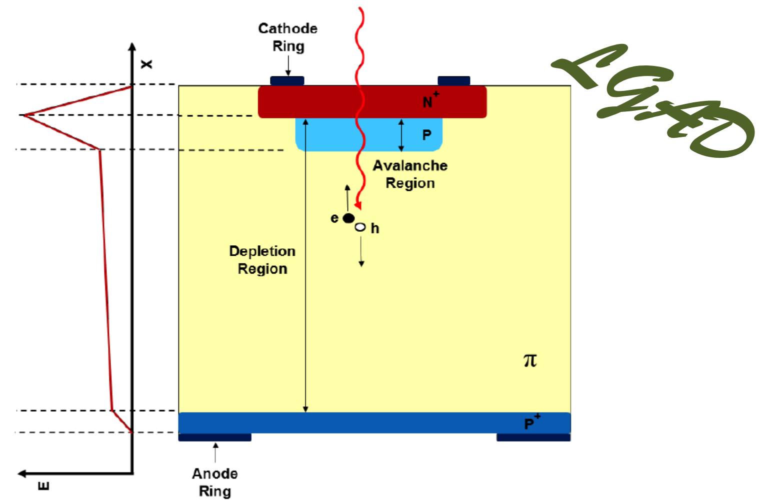
• Sensors

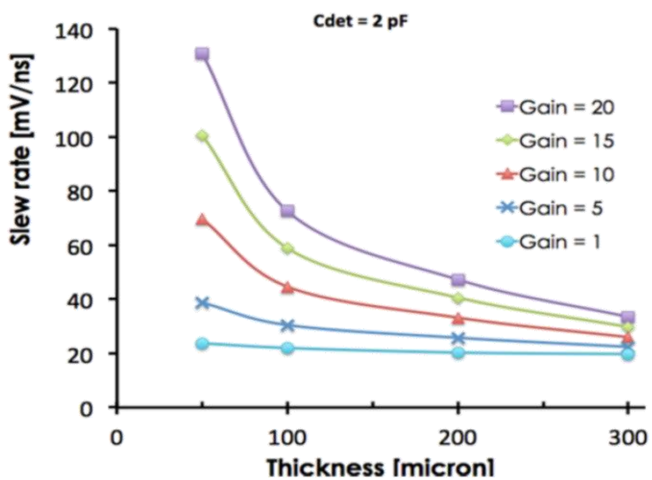
LGADs

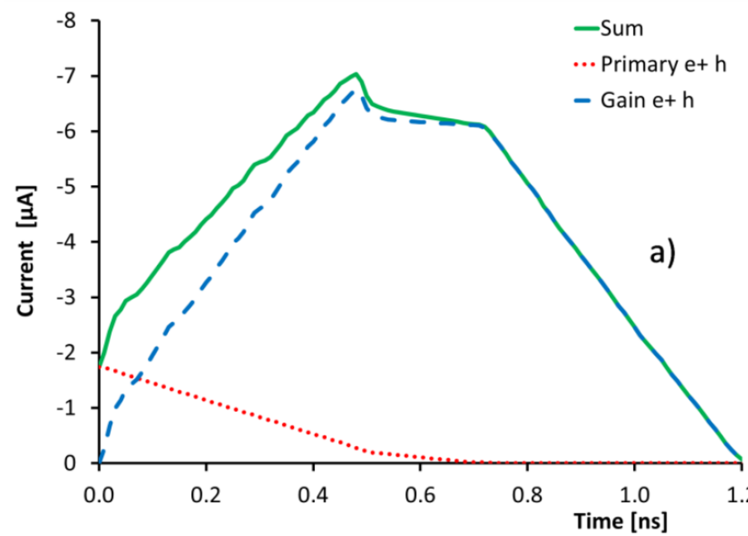




Low Gain Avalanche Diodes (LGAD)

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



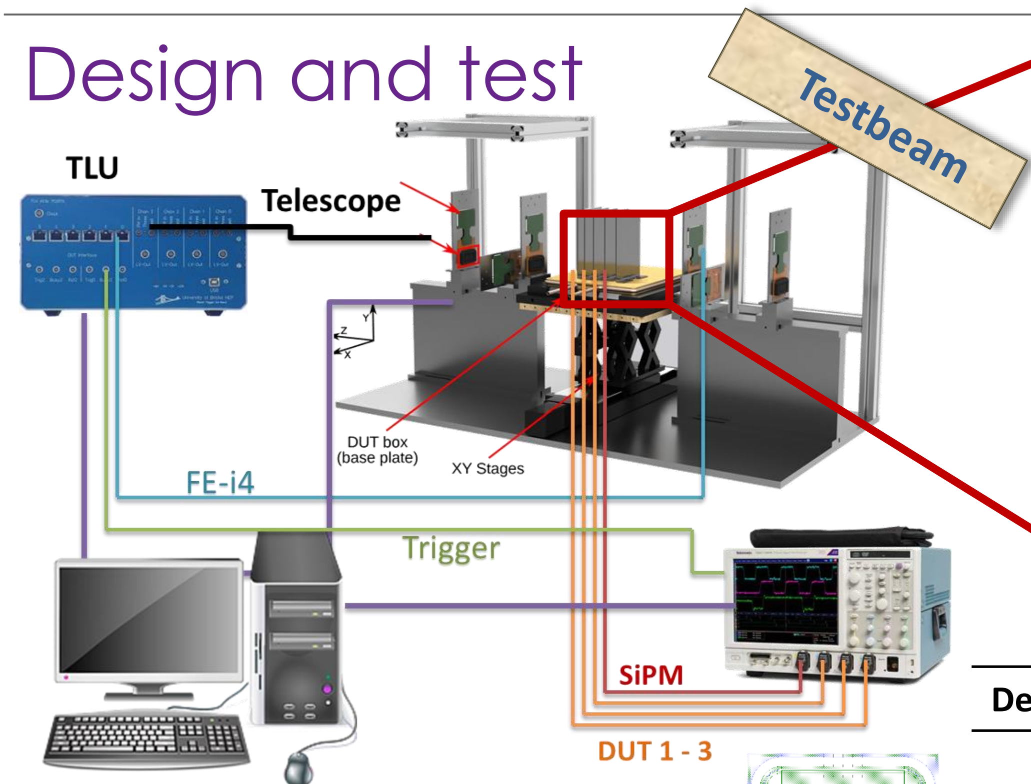


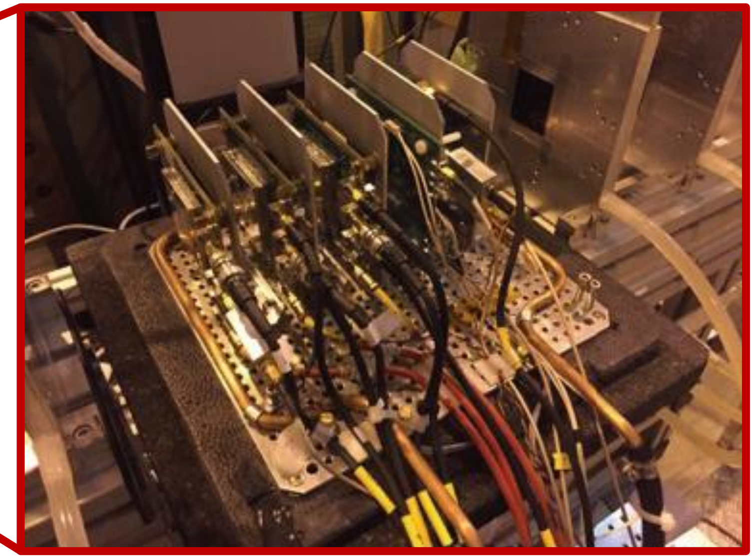
H.-W. Sadrozinski, A. Seiden and N. Cartiglia, 2817 4-Dimensional Tracking with Ultra-Fast Silicon Detectors, arXiv: 1704.08666.

F. Cenna et al., Weightfield2: A fast simulator for silicon and diamond solid state detector, 2822 Nucl. Instrum. Meth. A796 (2015) 149.

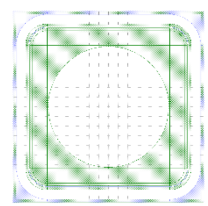
• Sensors

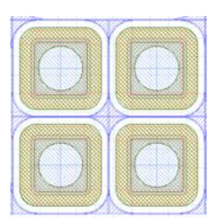
Design and test





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



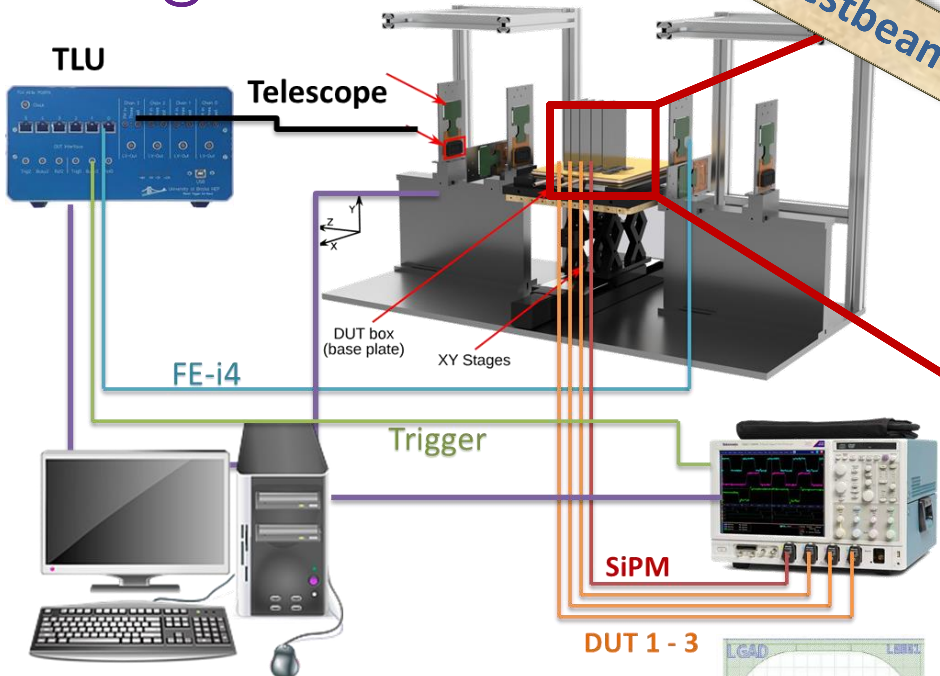


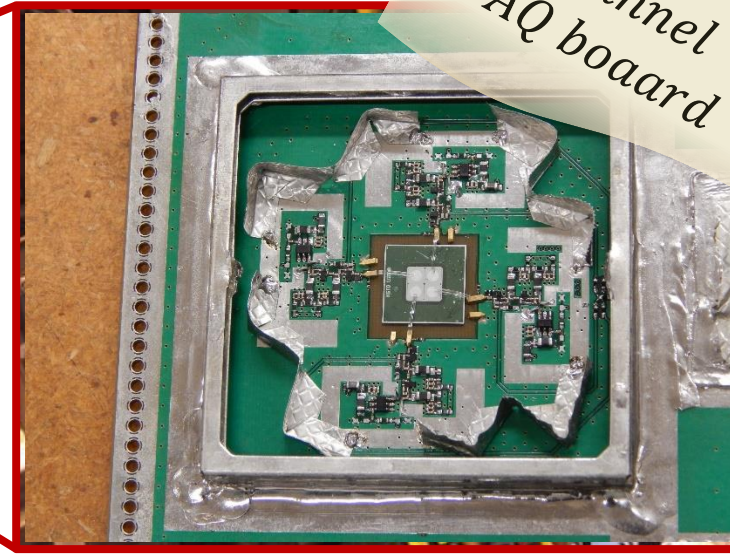
Tested Devices

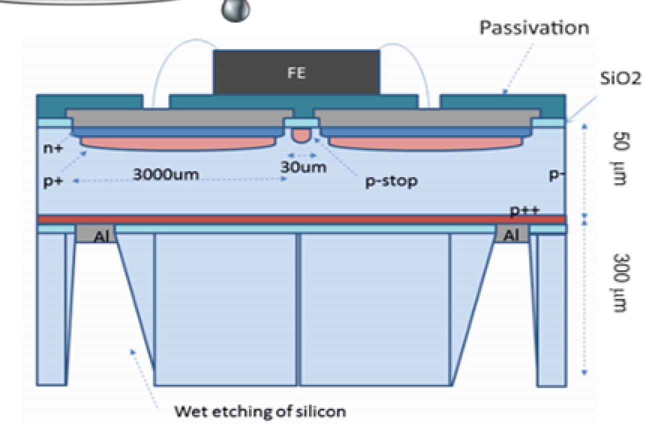
Detector	Size (mm)	Dose	Thickness	C_p (pF)
Single pad	1.2 x 1.2	$1.9 \bullet 10^{13}$	45 µm	3.5 pF
		$1.9 \bullet 10^{13}$	45 µm	3.5 pF
		$2.0 \bullet 10^{13}$	45 µm	3.5 pF
2 x 2 Arrays	2 x 2	$1.8 \bullet 10^{13}$	45 µm	11 pf
		$1.9 \bullet 10^{13}$	45 µm	11 pF
	3 x 3	$1.9 \bullet 10^{13}$	45 µm	23 pF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

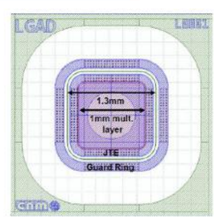
• Sensors

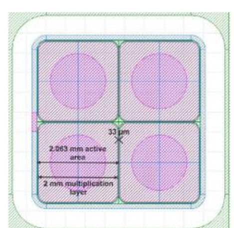
Design and test











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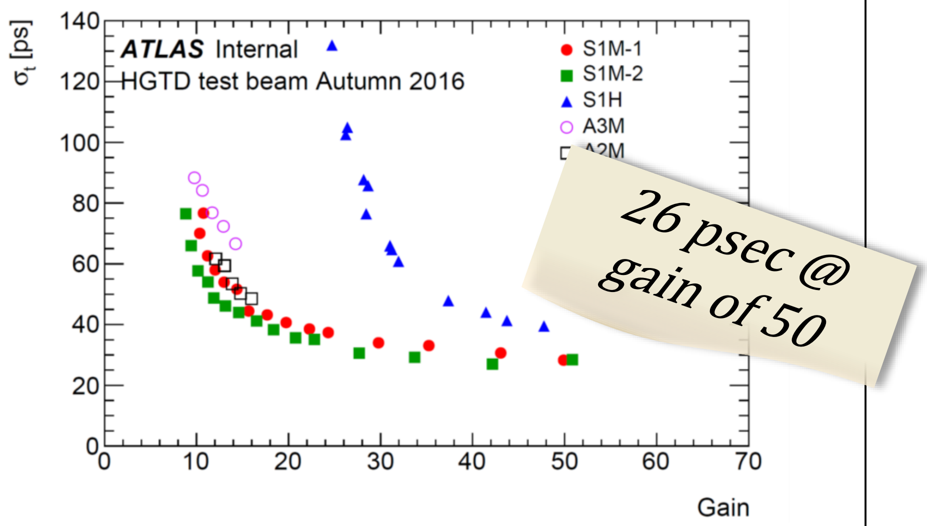
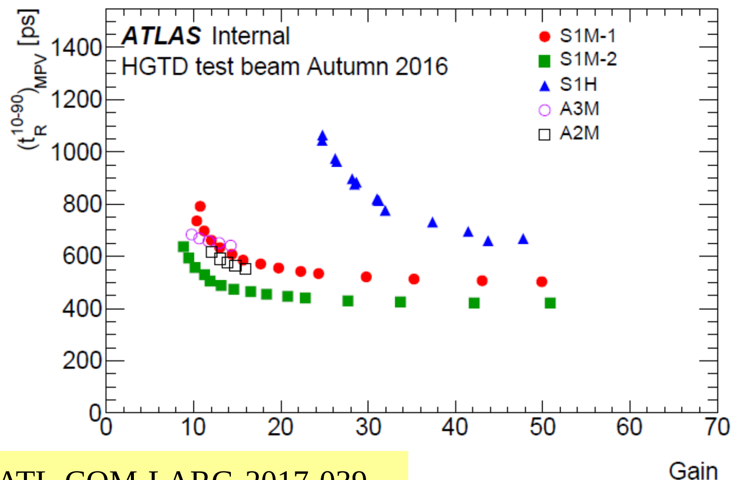
• Sensors

Testbeam Results

Time resolution





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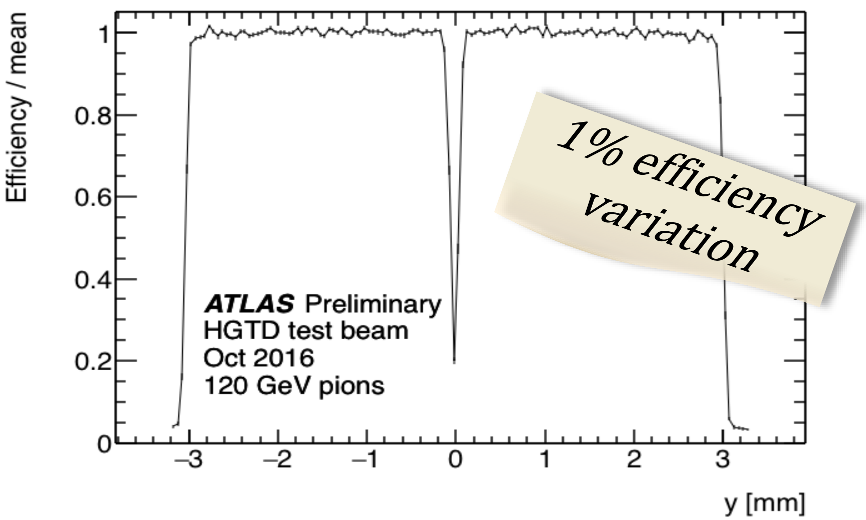
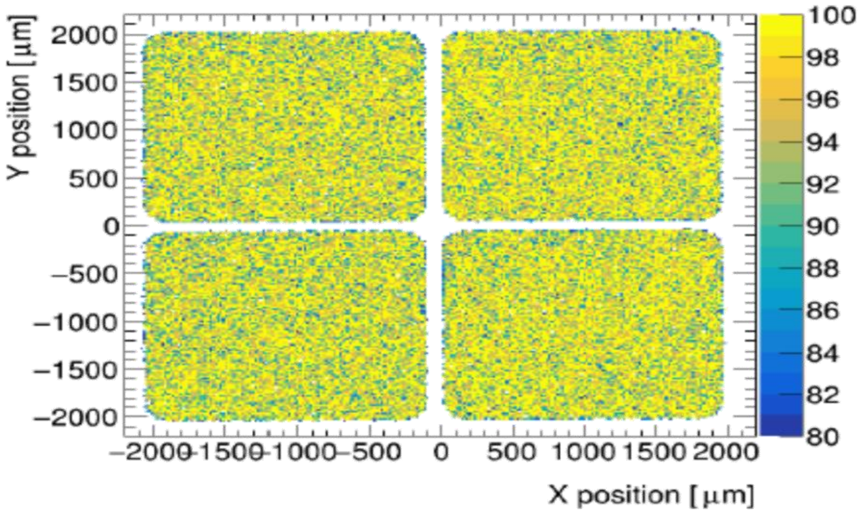
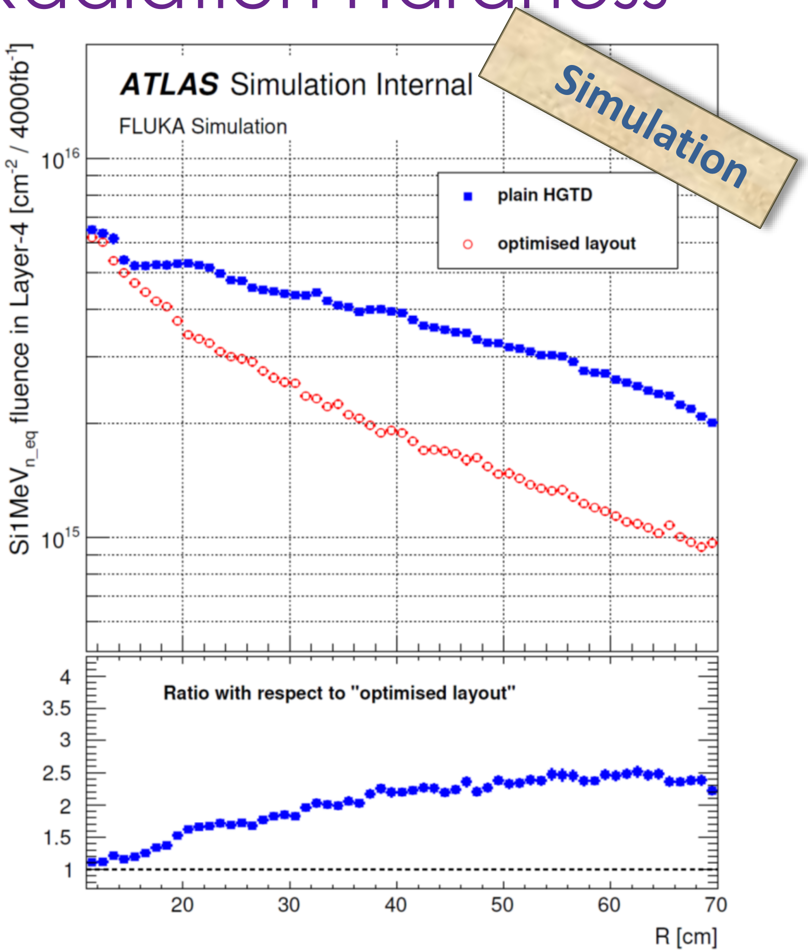
Efficiency maps



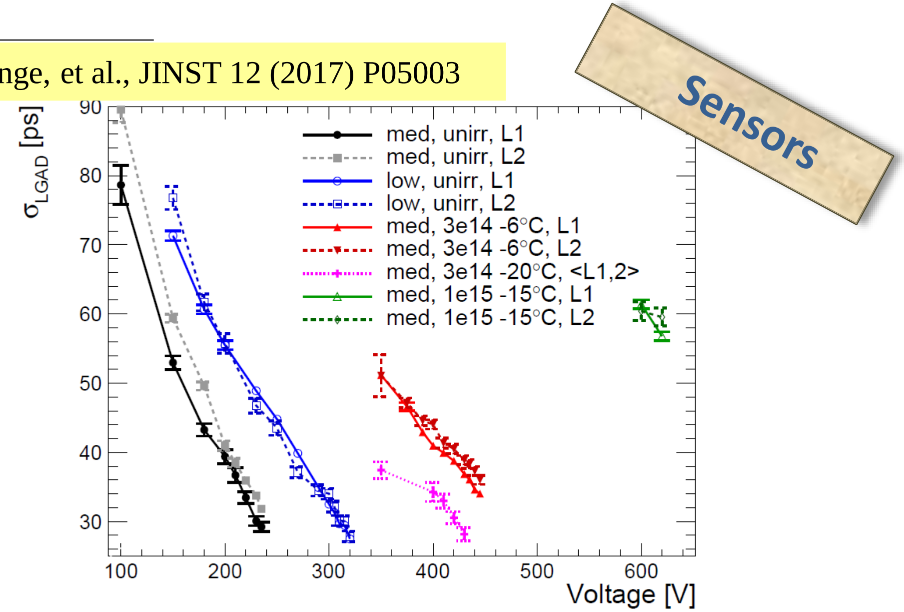


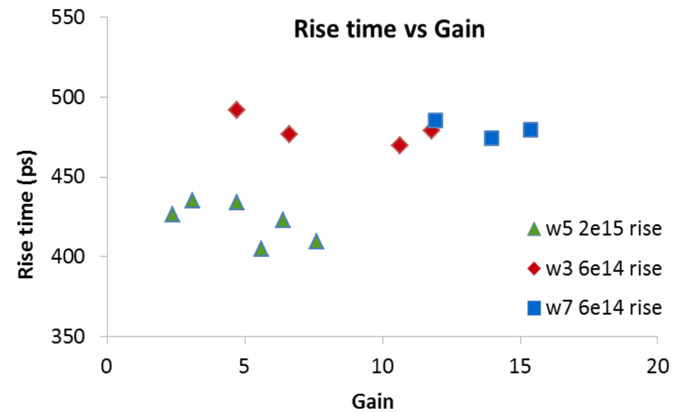
• Sensors

Radiation Hardness



J. Lange, et al., JINST 12 (2017) P05003



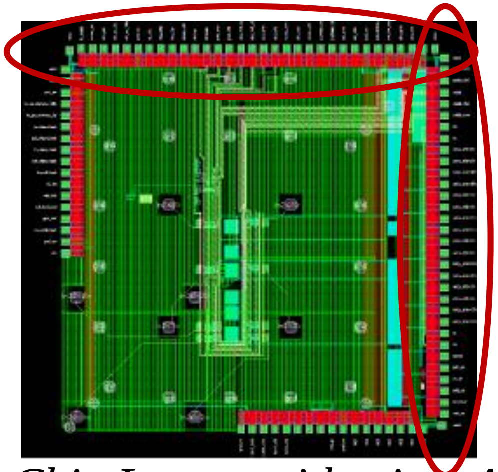


- Similar results Fluka - GCALOR
- Max. (η = 4 .2) after 2000 fb^{-1} ~ 4.5x10^{15} n$_{eq}$/cm^2 (mid cycle replacement)

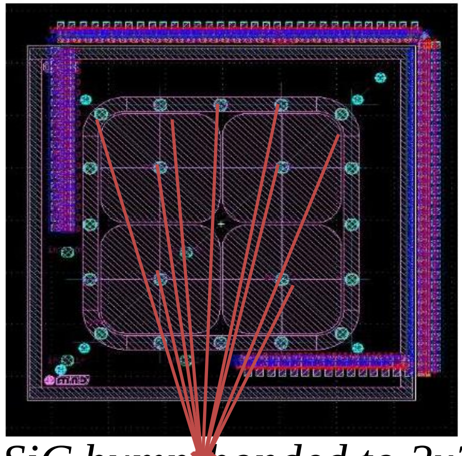
- Thermal neutron irradiation single pad diodes
- Time resolution in the order of 40 ps for gain of 10 - 15

•Electronics

ASIC prototype



Chip Layout with wire bonds in the periphery



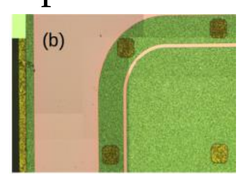
ASiC bump-bonded to 2x2 array in multiple points

	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

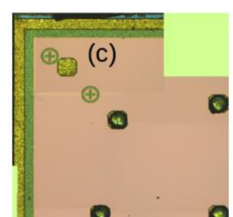
ATLAS ***L***GAD ***T***iming ***I***ntegrated ***R***ead***O***ut ***C***hip (***ALTiRoC***)

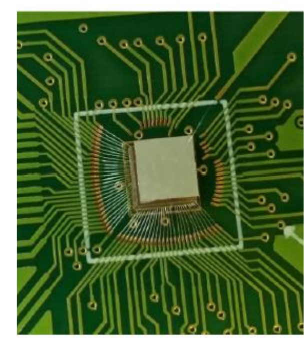
- TSMC 130nm CMOS Technology
- 3.4 x 3.4 mm total area
- 300μm substrate thickness
- Directly bonds to 2 x 2 arrays
- Four readout channels dedicated for 2 pf/channel, 10 pf/channel and 20 pf/channel sensors
- Channel area 200 x 100 μm
- Integrated Preamplifiers, ToT and CFD
- Bonding and bump deposition successfully performed at IFAE

Sensor



ASIC





Assembly

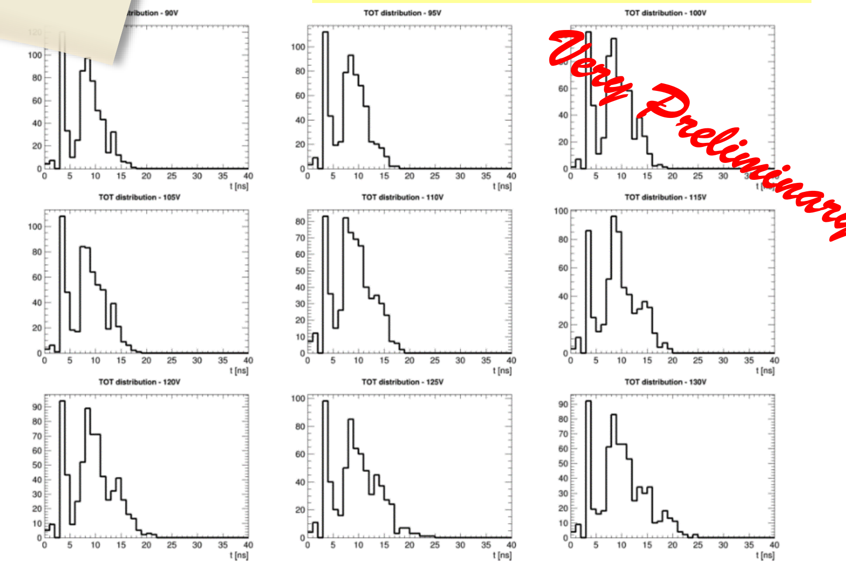
•Electronics

ASIC prototype

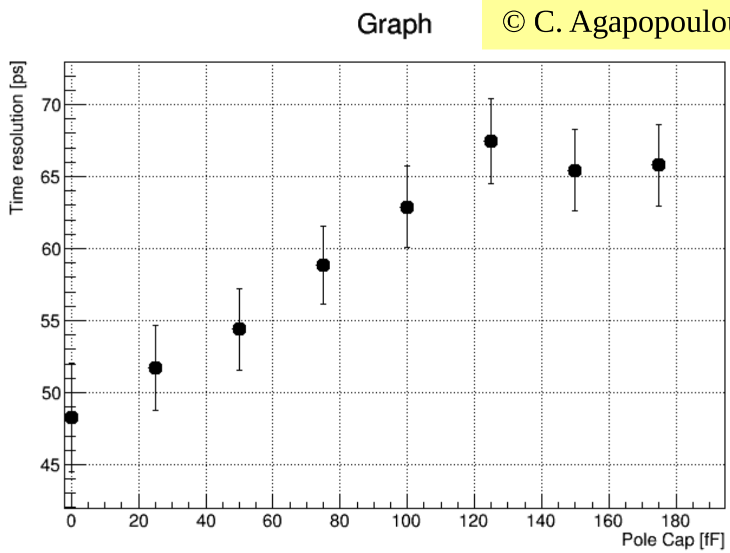
Testing of prototype assembles

IFAE ^{90}Sr

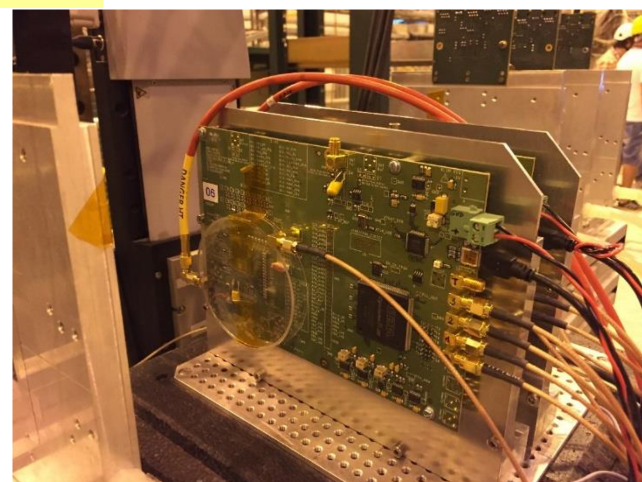
© E. Cavallaro, S. Grinstein (IFAE)



CERN Testbeam



© C. Agapopoulou N. Makovec (LAL)



•Implications

Important mid-points

Pixel Group Responsibilities

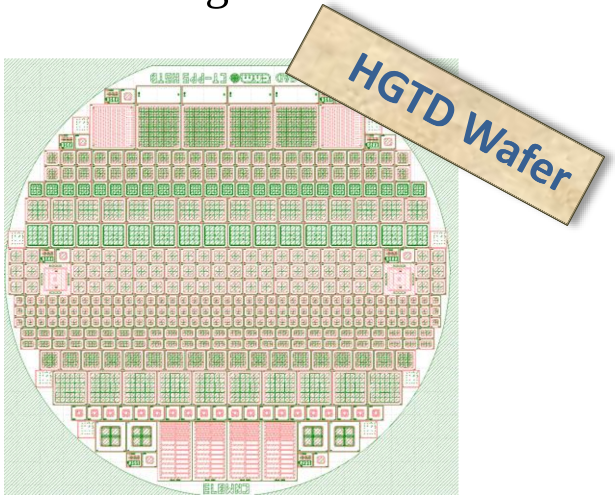
HGTD Module Assembly
Bump bonding and UBM deposition

Group member roles

Gkougkousis Vagelis	HGTD Test Beam coordinator
Joern Lange	HGTD Sensor co-coordinator
	IDR Editor
Raimon Casanova Mohr	Member of the ALTiRoC design team

Sensor RnD and Candidate for production

- **Multi-pad sensor arrays**
- **Gallium and Carbon doped wafers for improved radiation hardness**
- **Fill factor variations to improve geometrical efficiency**
- **Edge implantation variations (JTE)**



•Schedule

Important mid-points

September 2017:	Released IDR on ATLAS review with positive feedback https://cds.cern.ch/record/2276098/files/ATL-COM-LARG-2017-029.pdf
December 2017:	LHC committee review
February 2018:	Official LHCC approval
March – April 2019:	End of Sensor, ASIC, electronics and services RnD
February 2020:	End of Mechanics and assembly RnD
March - April 2021:	Sensor, ASIC and mechanics preproduction and prototype assembly
March 21- January 24:	Modules production, loading and testing
January – April 2024:	Services installation
August – September 24:	Installation HGTD-A
December – January 25:	Installation HGTD-C
January – March 2025:	Commissioning

IFAE is playing a leading role in the R&D ativiites of HGTD and, if approved aims to contribute to HGTD with sensors (from CNM), module assembly and testing

•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

Sensors

- ✓ 26 ps time resolution for single 1mm^2 diodes
- ✓ 95% uniformity with low inefficiencies in the inter-pad regions
- ✓ Operations up to 2e15 n_{eq}/cm^2, meeting the radiation hardness requirements
- ✓ Any timing degradation due to early breakdown

Integration

- ✓ First ASIC prototypes successfully assembled at IFAE and tested in HGTD September CERN testbeam

•Backup

•HGTD System

Performance

Muons

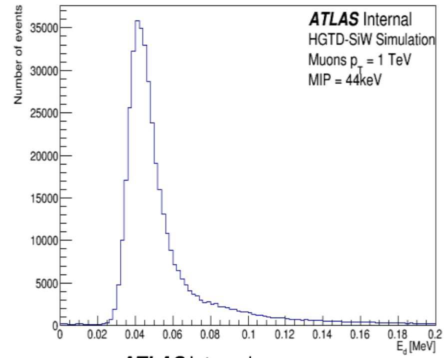
- ✓ 1TeV muons simulation
- ✓ 98.88% efficiency for 4 layers
- ✓ 0.044 MeV/muon at 150 μm
- ✓ 50% of inefficiency from zones

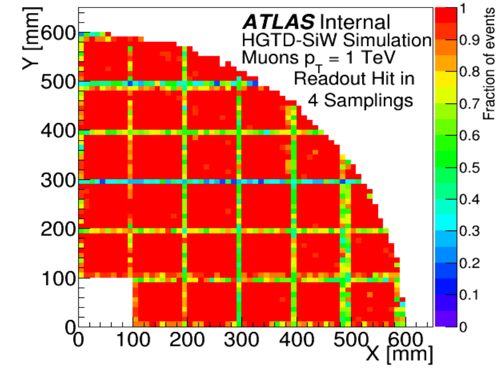
Electrons

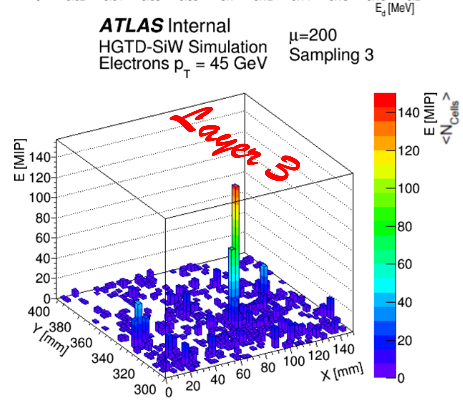
- ✓ Z → ee sample at μ = 200
- ✓ 45 GeV P_T e and γ
- ✓ 6mm radius EM clusters
- ✓ 70 HGTD cells per cluster
- ✓ Dynamic range of 50psec/MIP

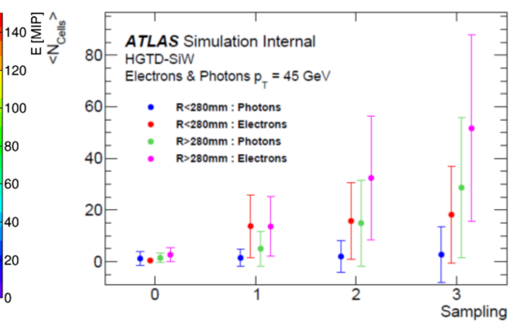
Jets

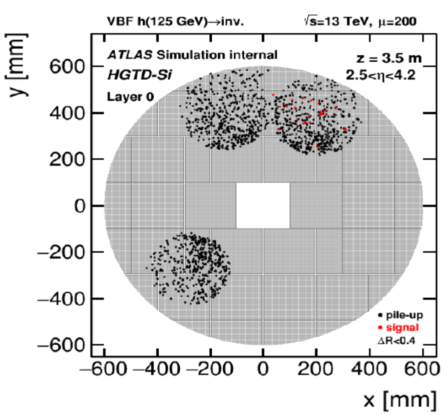
- ✓ H(125GeV) → Inv. sample with jet P_T =72GeV
- ✓ Expected peak in time distribution
- ✓ ~90% signal purity at ΔR < 0.1

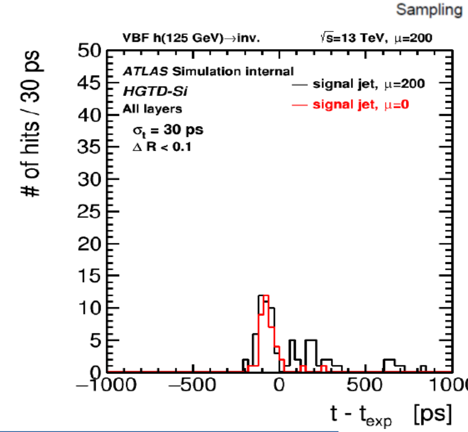












• Physics motivation

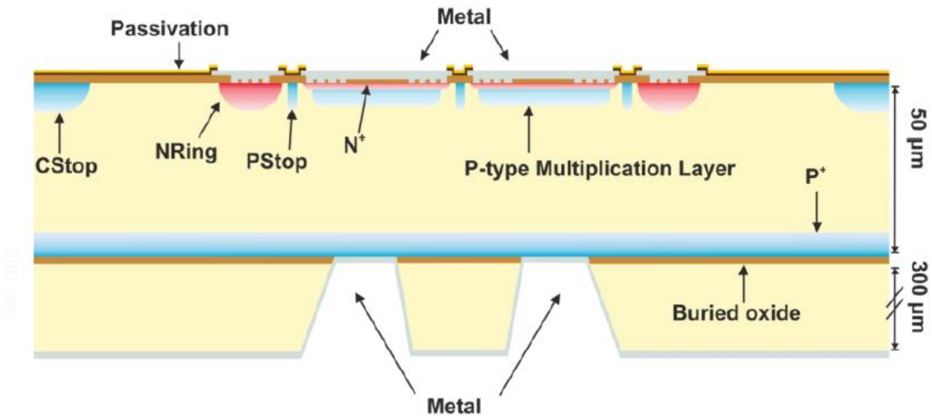
Large eta studies – truth level

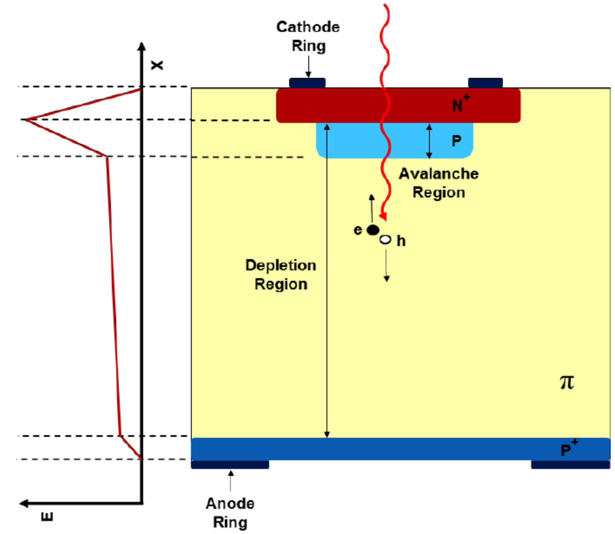
- Truth level fractions for various samples
- Signal presents an increase of 18% in the high eta region
- Background also presents an increase but with less significance than the bbH signal

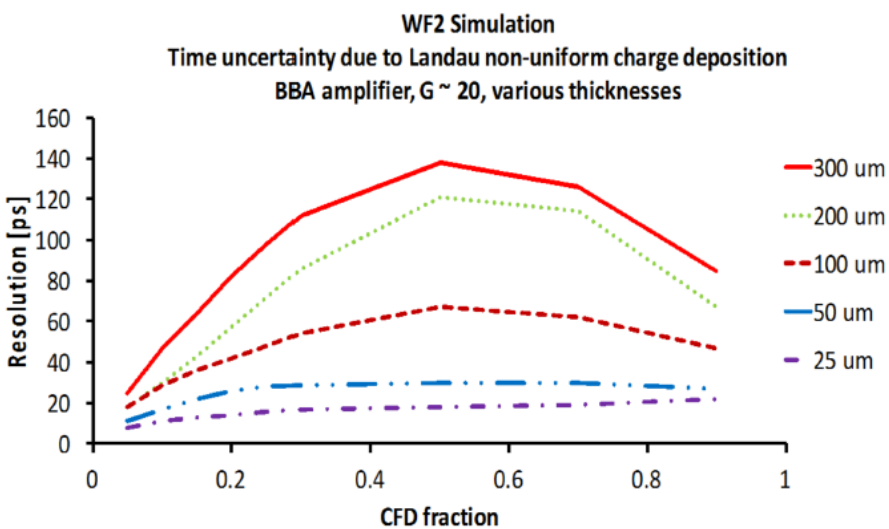
	Leading B	Subleading B	Both b
Pt> 10 GeV bbH	16.6%	20.3%	5.2%
Pt > 20 GeV bbH	14.3%	16.9%	4.2%
Pt>10 GeV bbγγ	10%	14%	3.0%
Pt>10GeV ZH	17.1%	19.8%	5.3%
Pt>10 GeV HH	4.2%	7.6%	1%
Pt>10GeV bbjj	11.9%	18.1%	2.2%

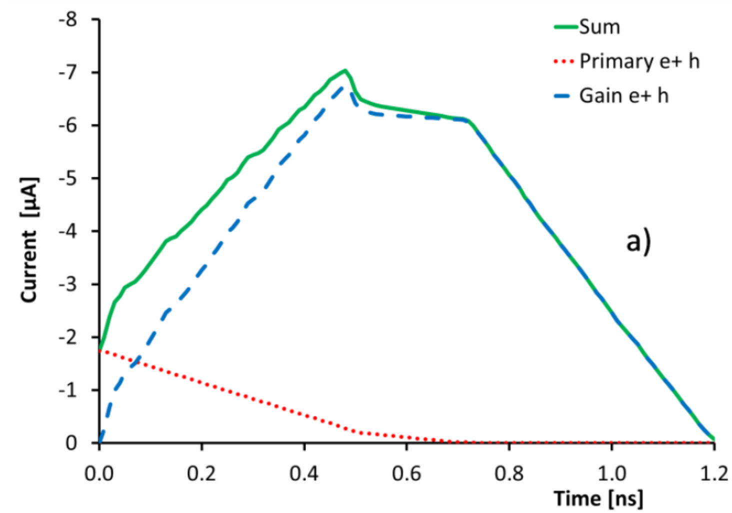
• Low Gain Avalanche Diodes

Field and Landau





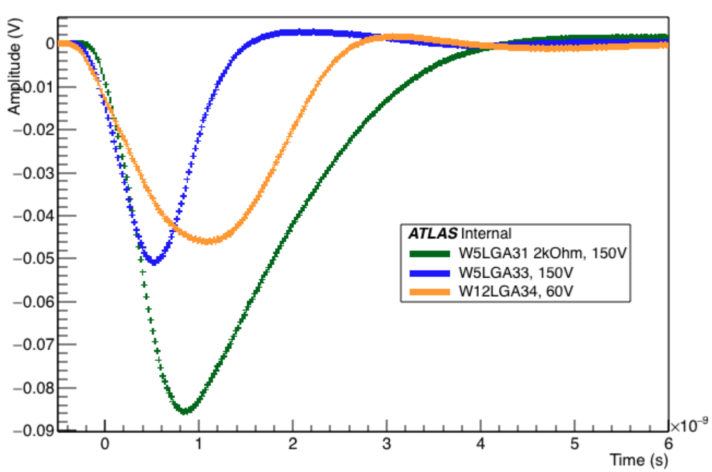


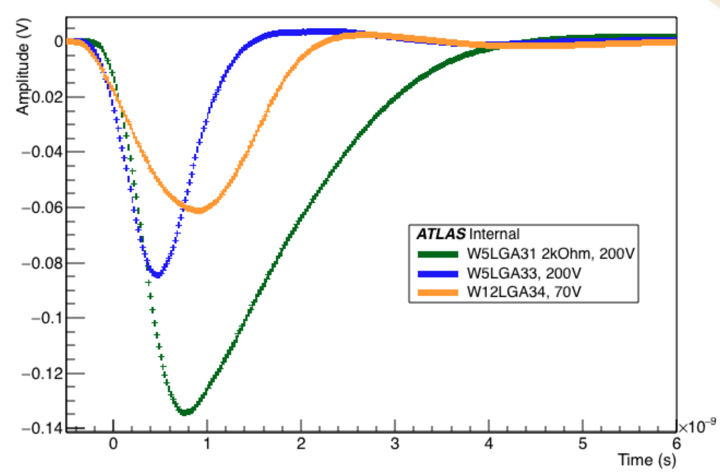


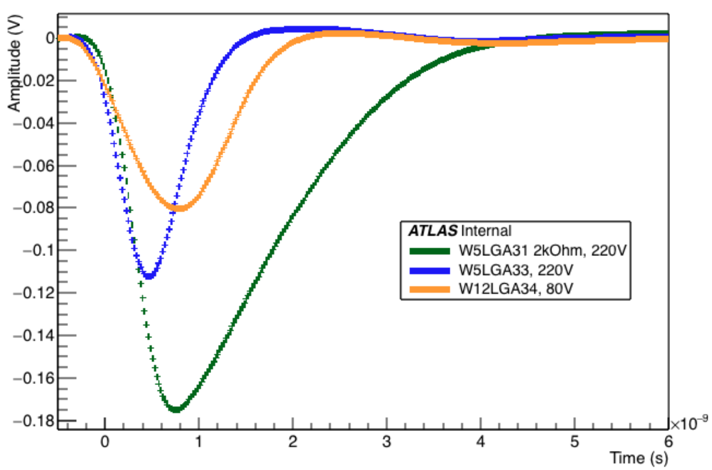
•Single pad sensors

Pulses and timing analysis

Average Pulse Shapes



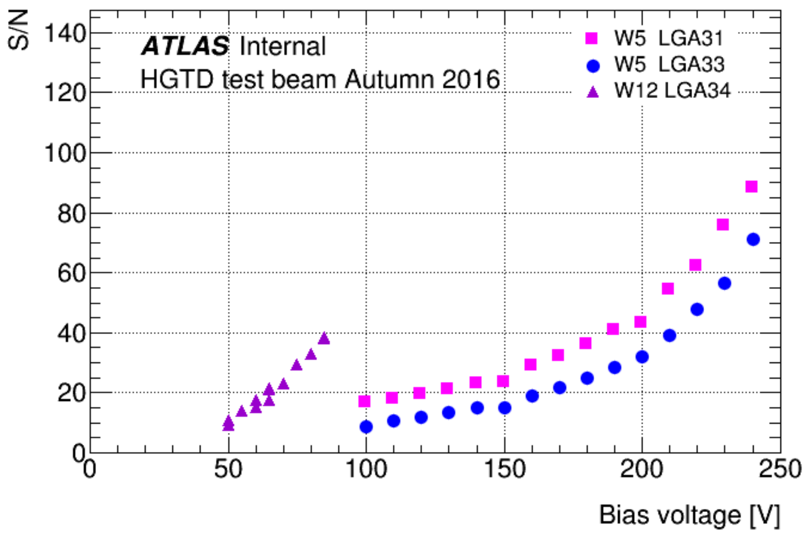


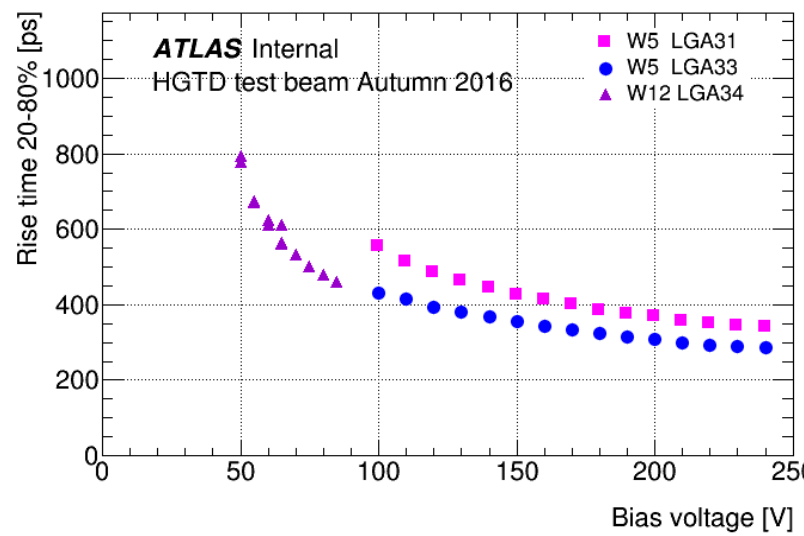


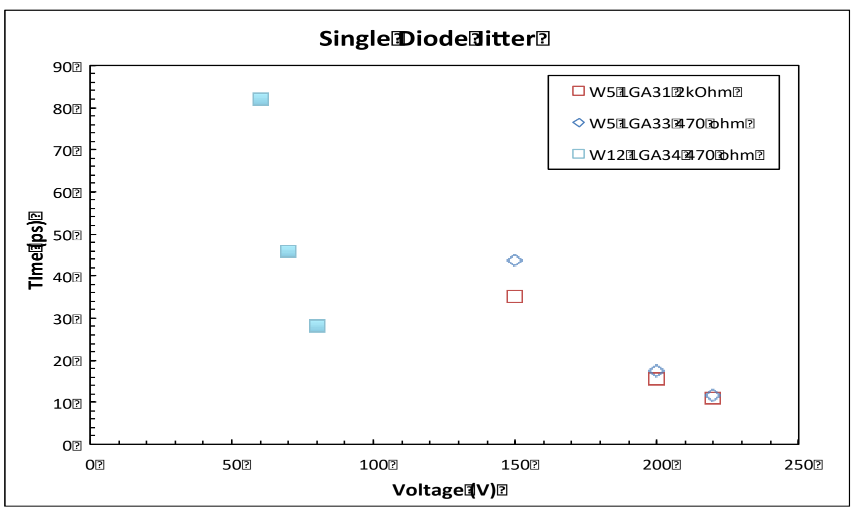
- Pulses corrected at 20% of SiPM pulse height, P_{max}>30mV
- Two W5 sensors at same bias, W12 sensor lower voltage
- 2kOhm (W5LGA31) sensor higher gain but slower raise time
- Higher doping sensor (W12) slower pulses due to lower electron drift velocity, lower gain

•Single pad sensors

Pulses and timing analysis



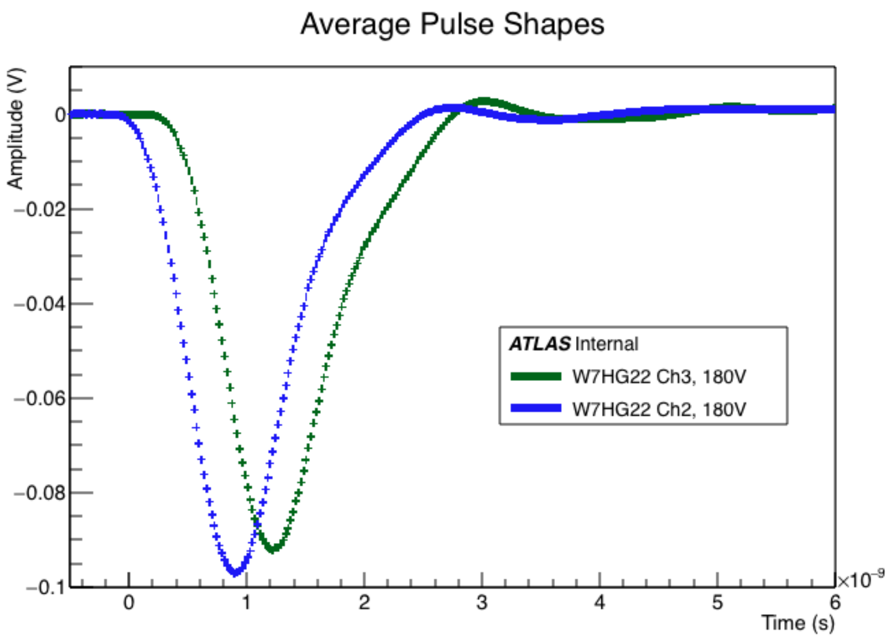


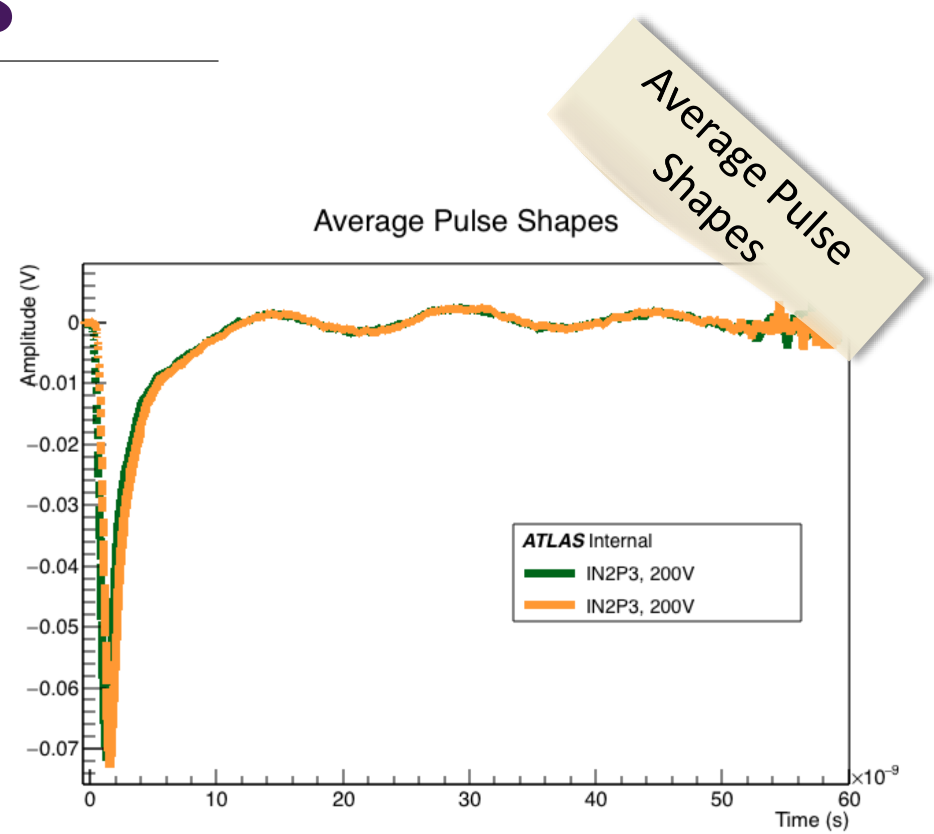


- Rise time defined as 20-80%
- Noise estimated from Gaussian fit at sidebands (20% of preceding points)
- Signal defined as Landau fit of pulse maxima
- Jitter = τ/(S/N), where τ is rise time, SNR signal to noise
- For 2k, jitter close to 470k since has faster rise time but lower SNR

•Four Chanel Boards

Setup and runs





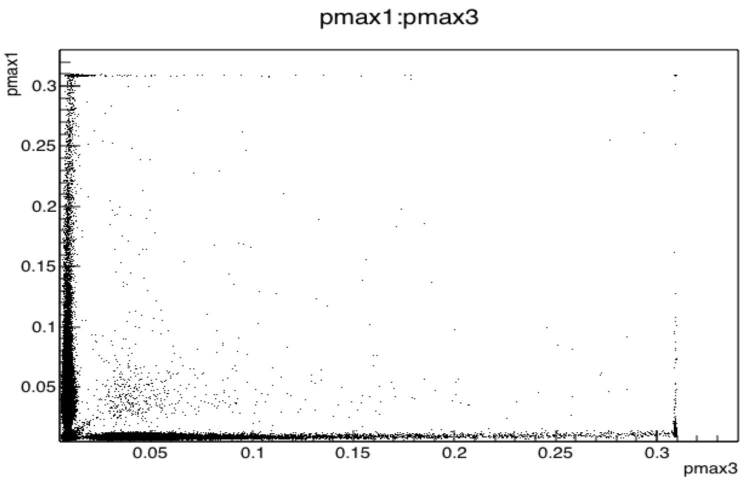
- Pulses corrected at 20% of SiPM pulse height, 300 mV > P_{max}> 40mV, t_{max} cuts
- Ch2 appears to have greater maximum, though timing and jitter only show modest differences due to higher noise
- Ch2 pad was better aligned with beam and SiPM

•Four Chanel Boards

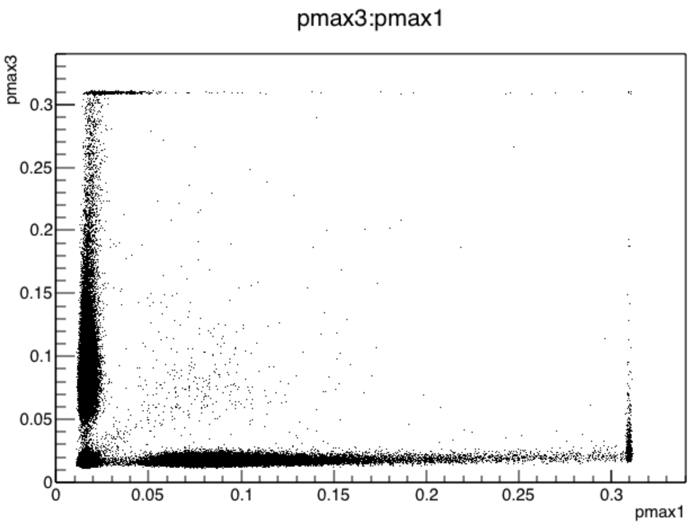
Cross-talks

- Small percentage of coincidence events between neighboring channels.
- Use P_{max} >30mV to define a "hit"
- %Xtalk events= $(n_{13})/(n_1 + n_3 - n_{13})$ where n_i is the number of hits in i^{th} channel, n_{13} is number of coincidences

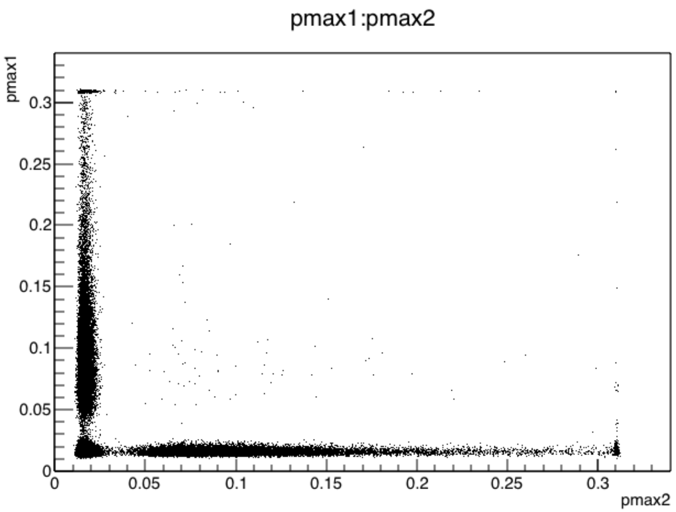
IN2P3 – Xtalk in 0.6% of events



W11HG11 – Xtalk in 1% of events

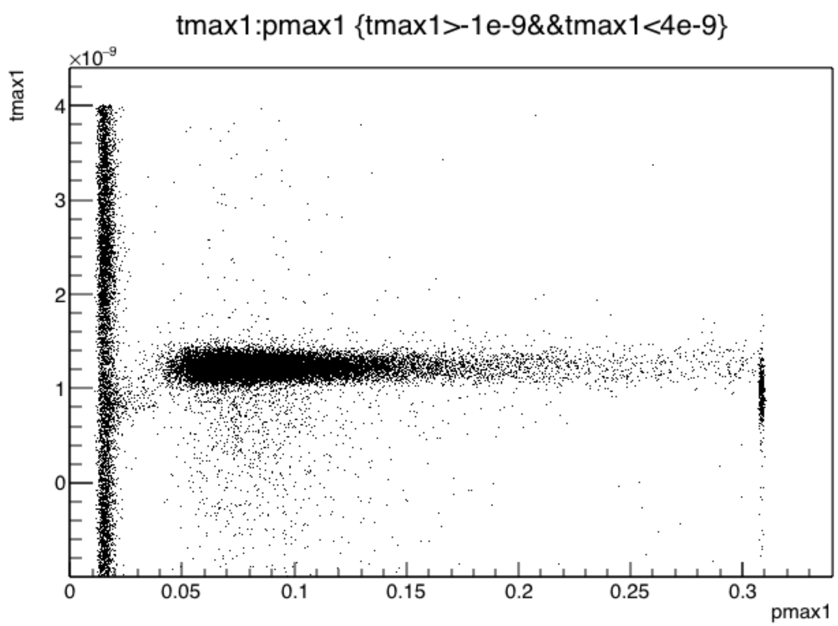


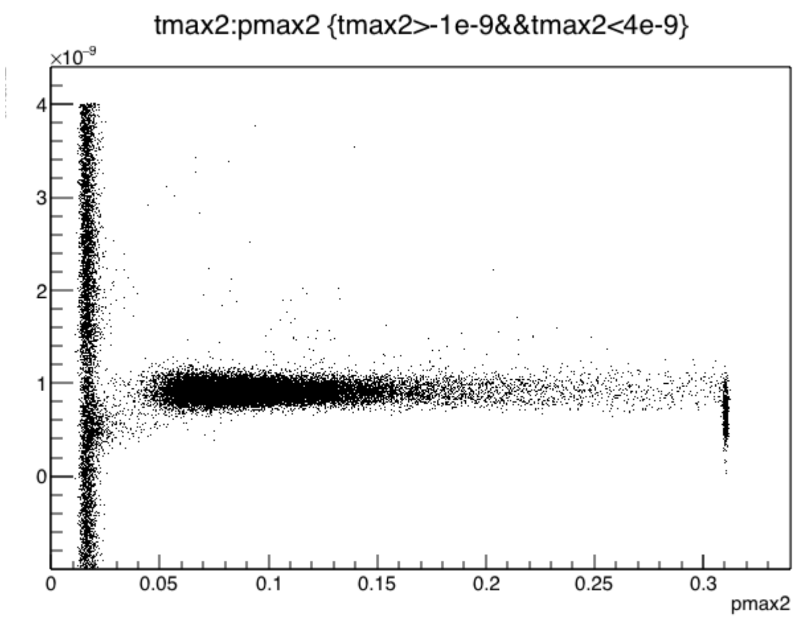
W7HG22 - Xtalk in 0.2% of events



•Four Chanel Boards

Timing Analysis

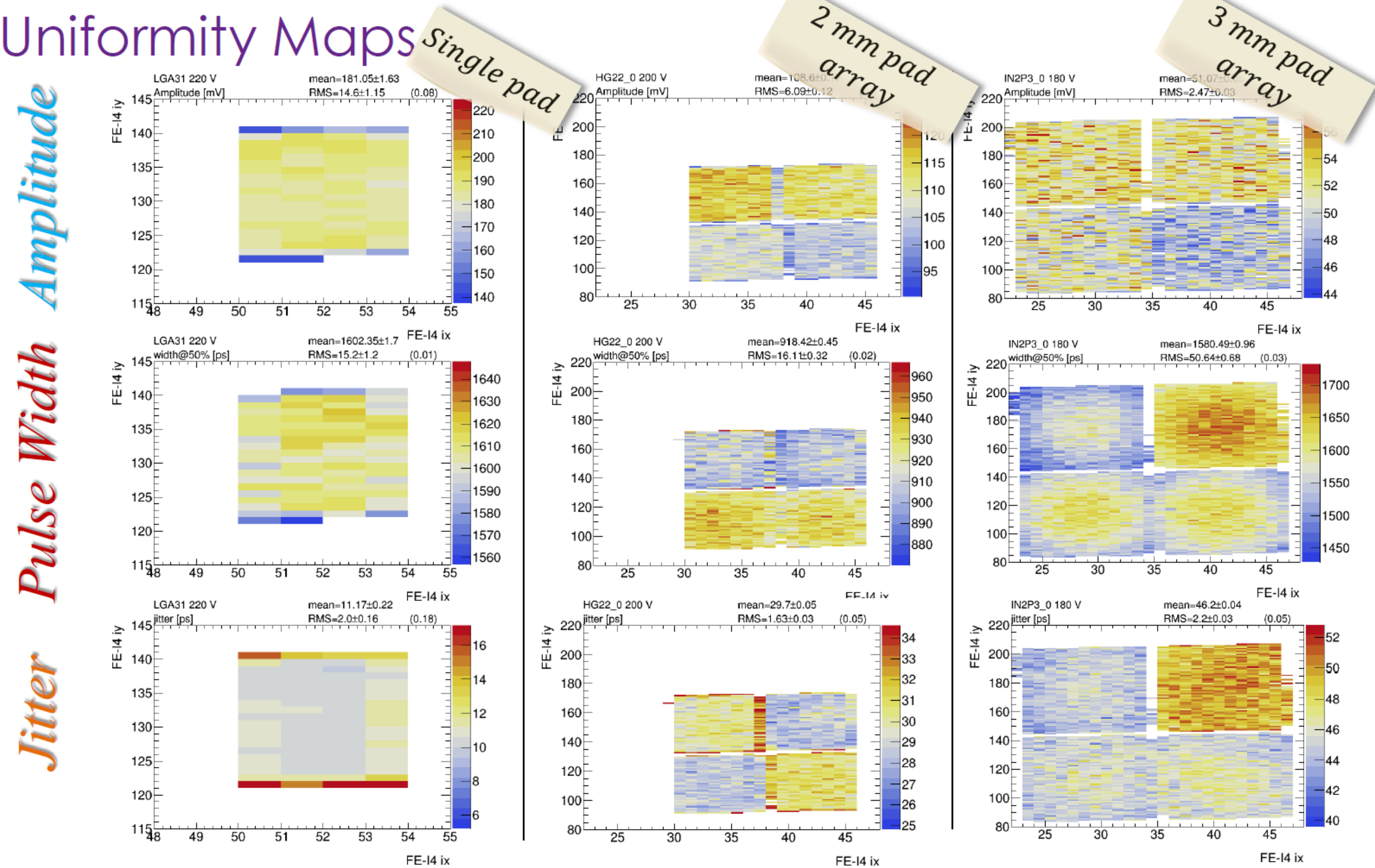




- Time resolution calculated by Gaussian fit to distribution of time differences at 20% of max pulse height on LGAD and SiPM.
- Cut at 40mV, 300mV on DUT
- Cut at 40mV, 600mV on SiPM
- Cuts on t_{max}, time of maximum on DUT

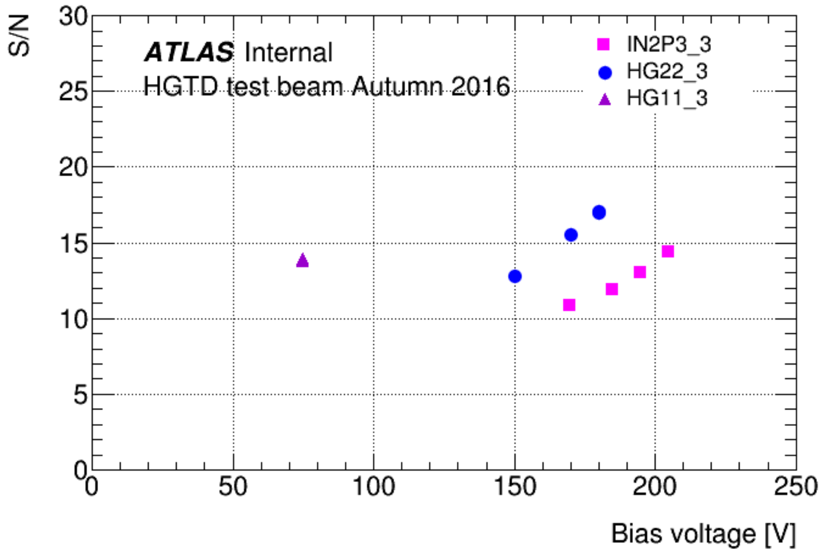
• Sensors

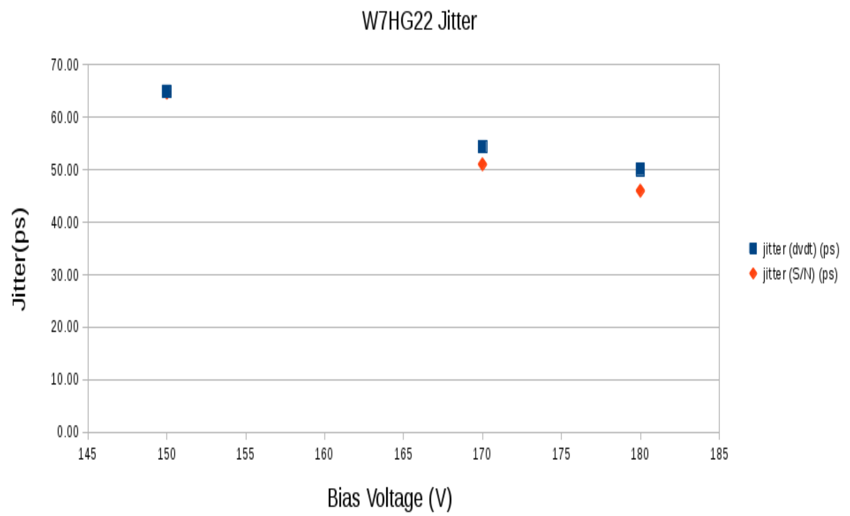
Uniformity Maps

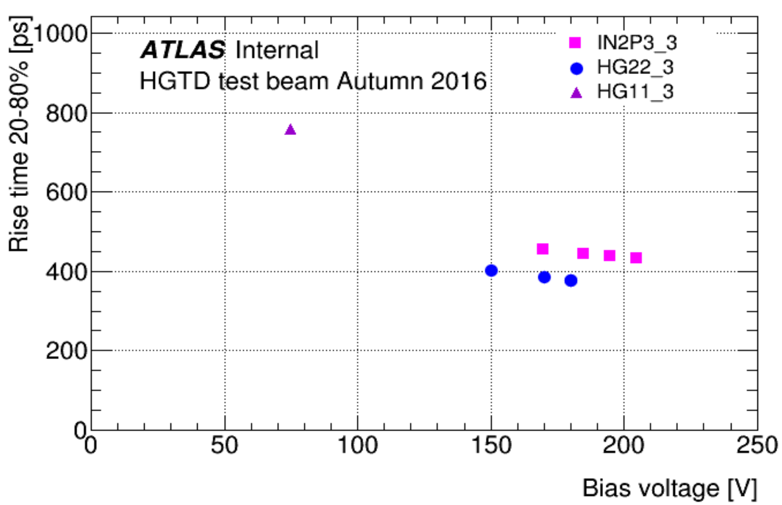


•Four Chanel Boards

Timing Analysis



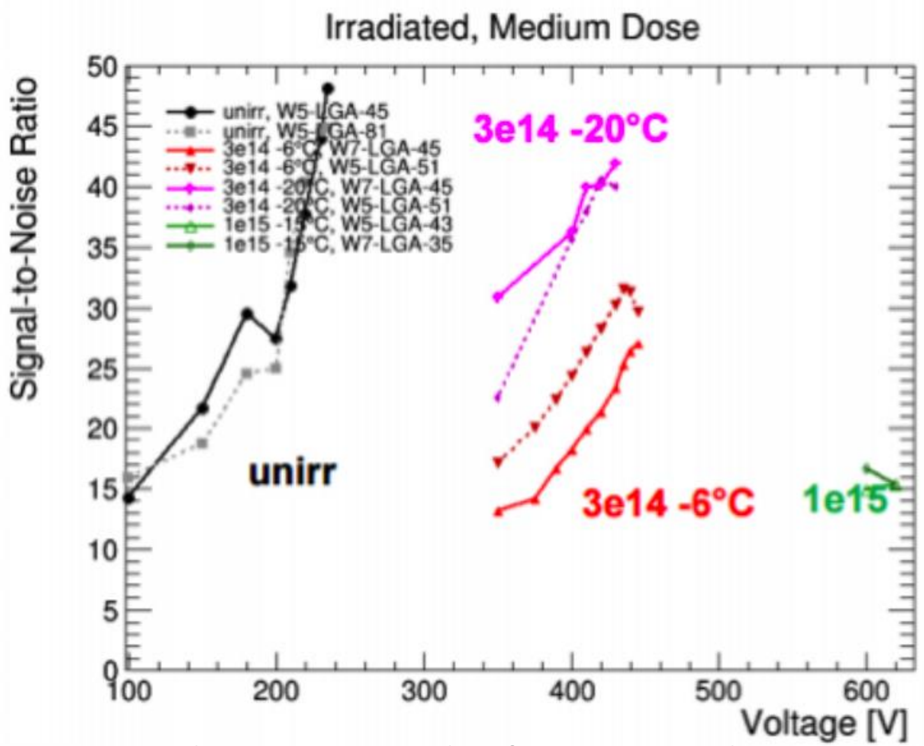


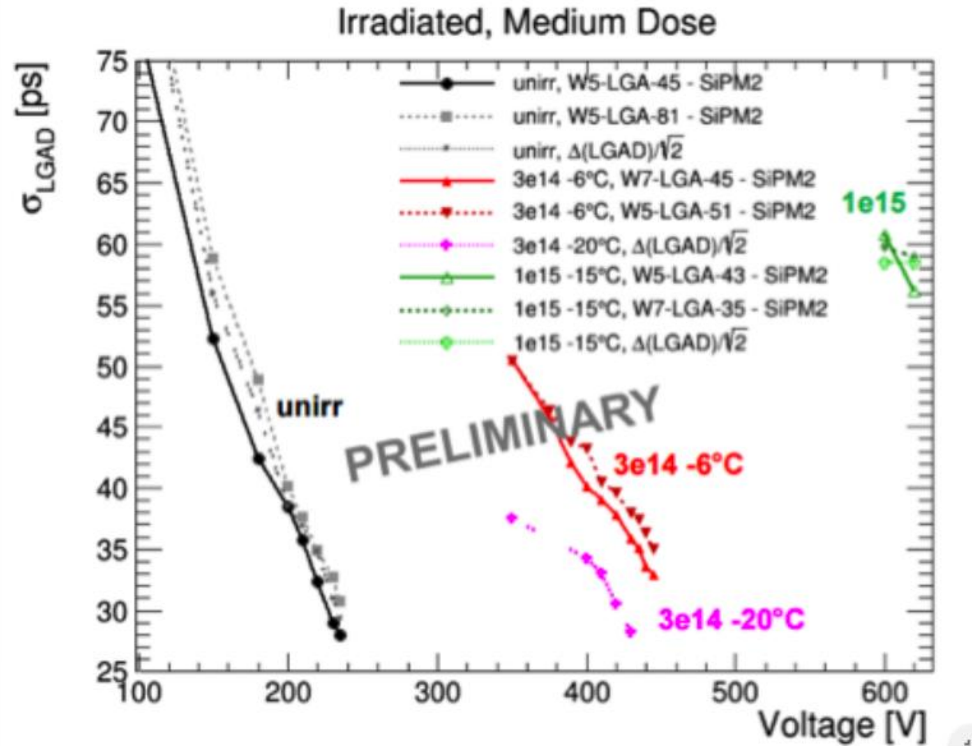


- Rise time defined as 20-80%
- Noise estimated from Gaussian fit at the sidebands (20%)
- Signal defined as Landau fit of pulse maxima
- Jitter = τ/(S/N), where τ is rise time, SNR signal to noise
- HG22 is higher doping and has subsequently lower biasing and gain

•Additional Results

Radiation hardness



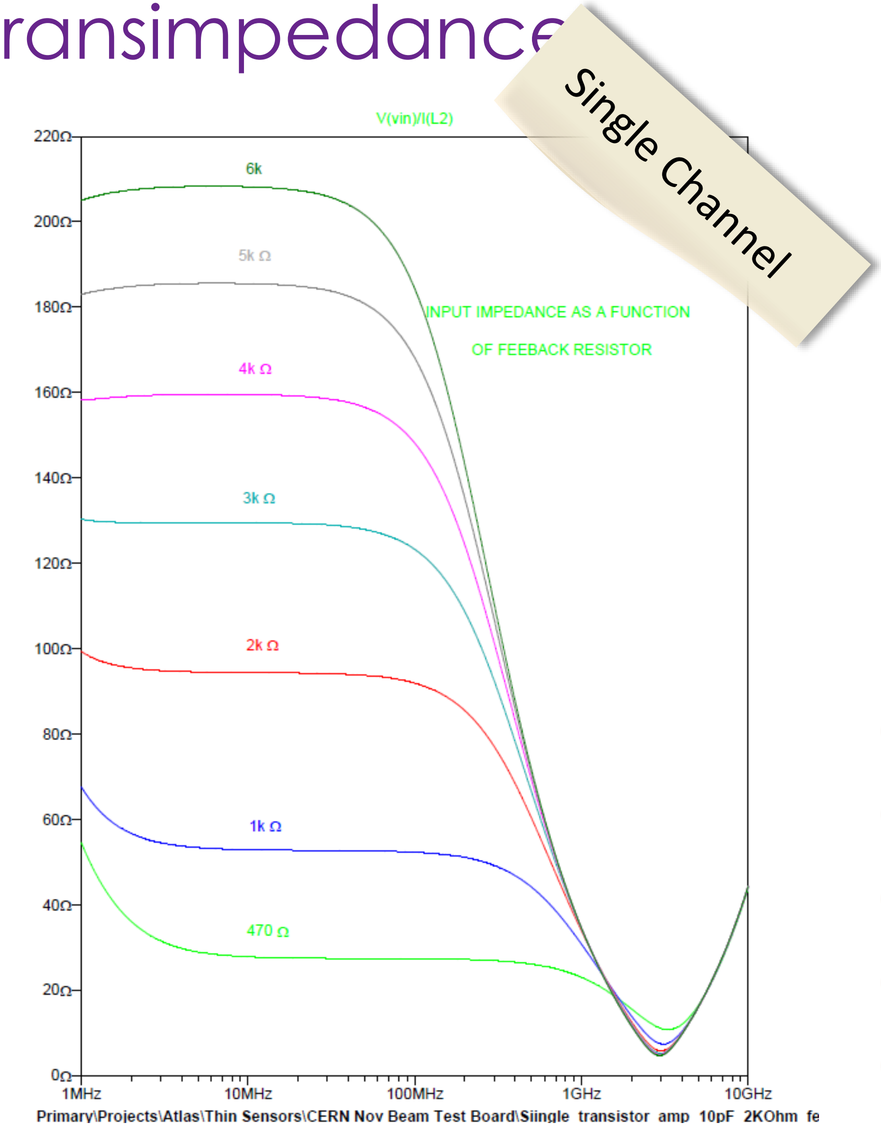


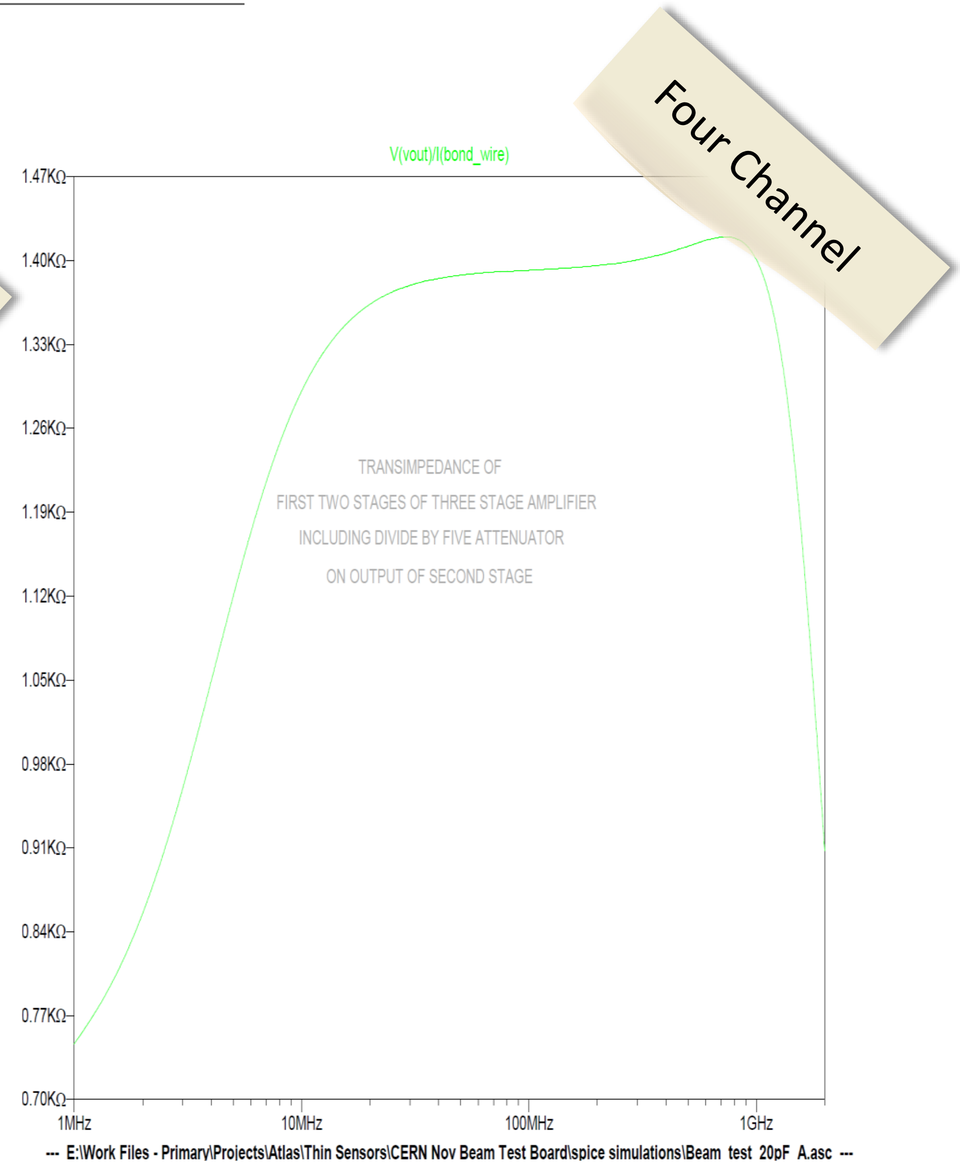
- Preliminary results for AFP testbeam
- Irradiated fluence of 3e14/cm^2 at -20^{0}C presents comparable time resolution with uneradicated sensors
- 1e15/cm^2 breaks down before reaching the same field values as uneradicated one

More details at Joern's presentation:
https://indico.cern.ch/event/580875/contributions/2374877/attachments/1375420/2088359/Lange_LGADtimingResults_RD50_November2016.pdf

• Amplifiers

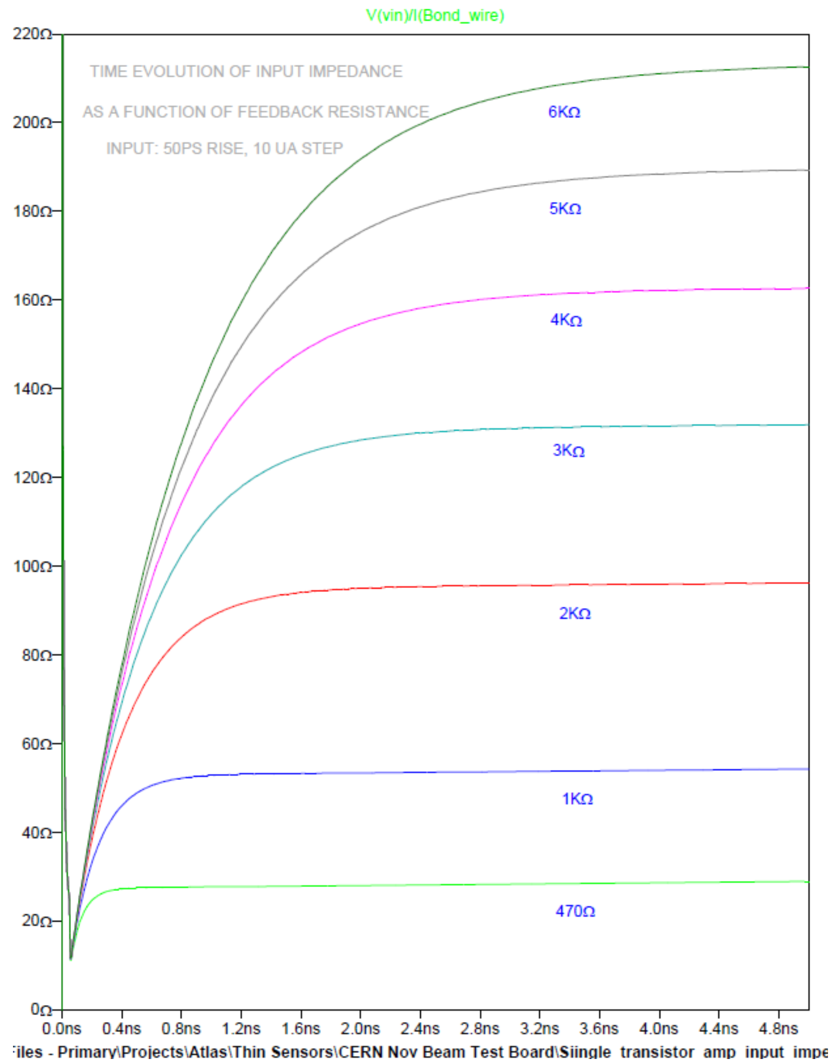
Transimpedance





• Amplifiers

Impedance vs time



Four Channel

• LHC Luminosity

Interactions per crossing for run 2