3rd Workshop on LHCb Upgrade II

LAPP, 22 – 23 March 2017

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

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On behalf of the ATLAS HGTD community

Institut de Física d'Altes Energies

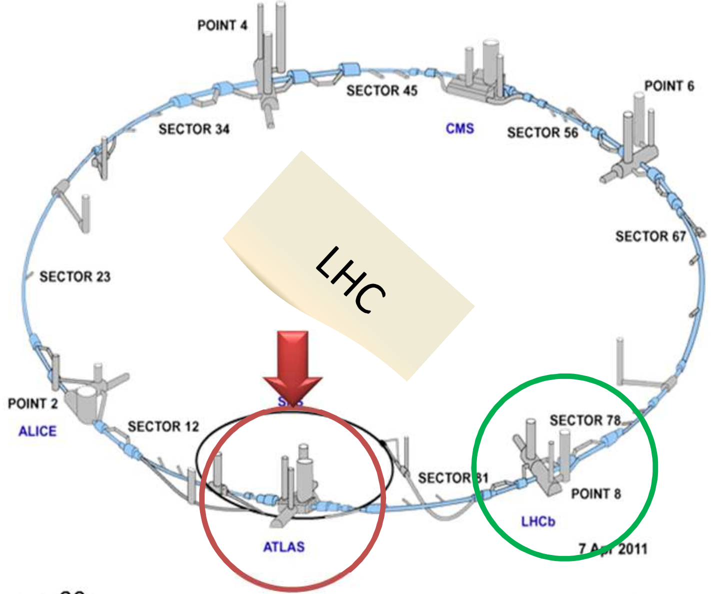
Annecy – March 22nd, 2018

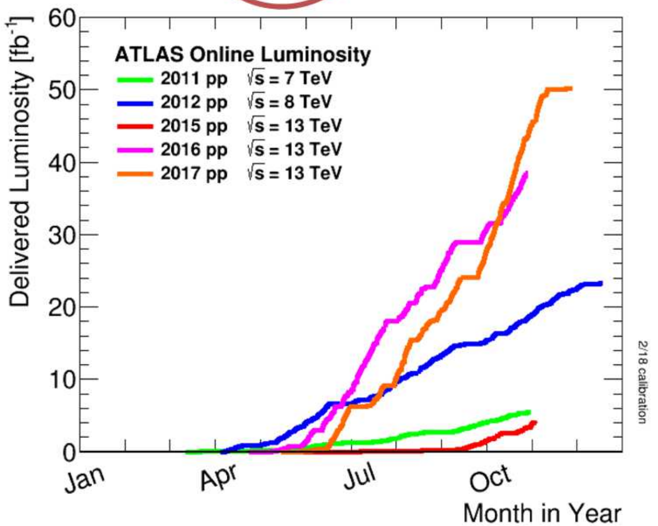
•Overview

- ATLAS and HL-HLC
- Geometry and design
- Low Gain Avalanche Diodes
- Electronics and services
- Physics and Performance
- Online and off-line luminosity estimation
- Timeline and resources
- Conclusions and Outlook

•Introduction

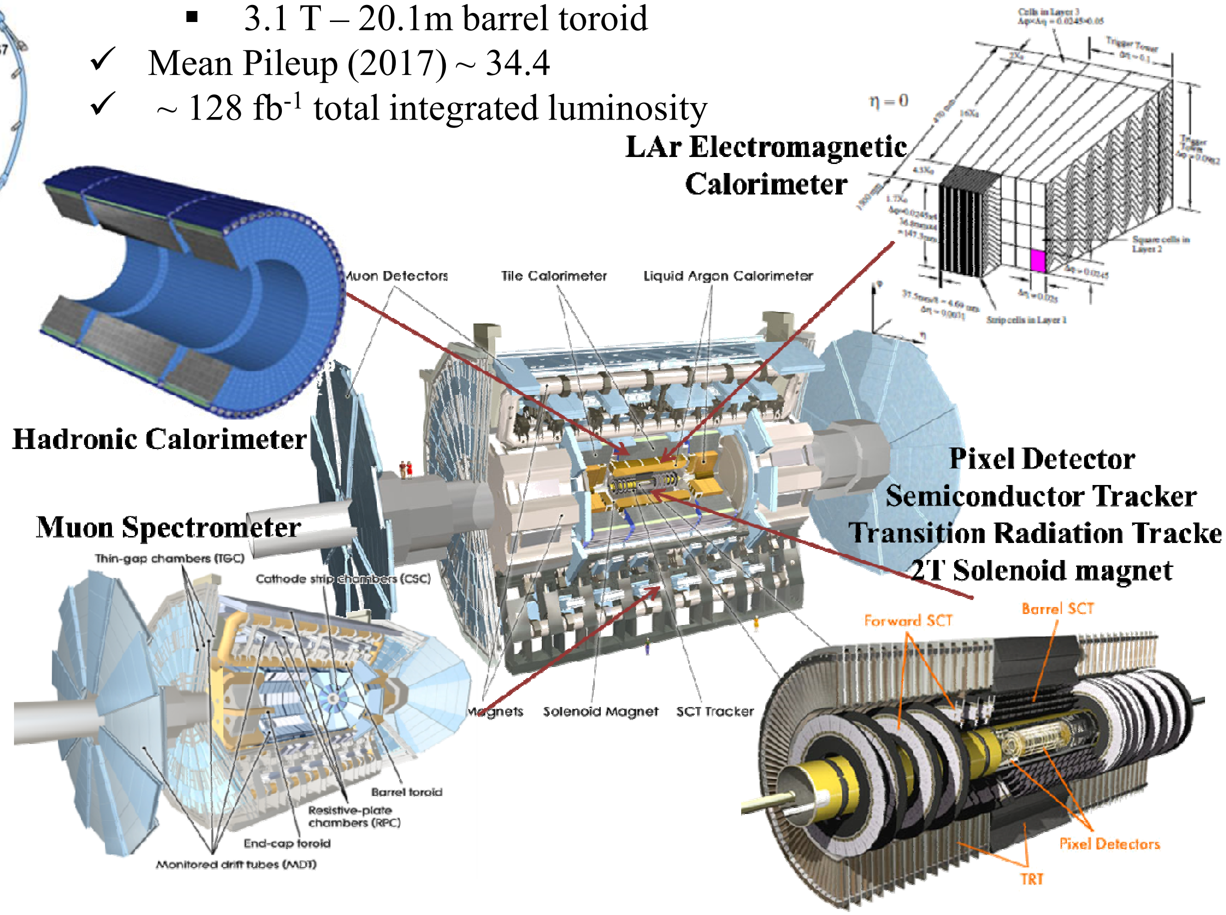
ATLAS and LHC





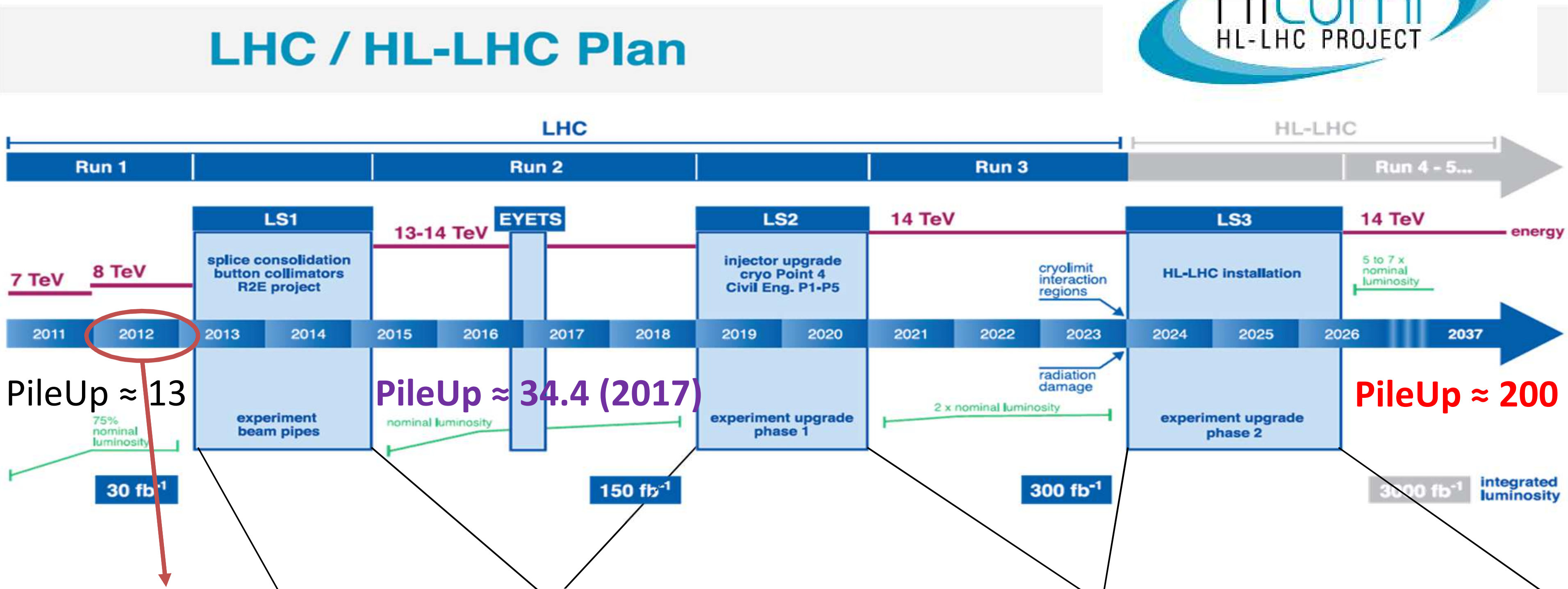
A Toroidal LHC Apparatus

- ✓ Biggest LHC experiment with several sub-detectors
- ✓ 46 x 22 m cylinder, weight of 2000 t, Point 1 of LHC
- ✓ Two superconductive magnets:
  - 2.6 T – 5.3 m long Central solenoid
  - 3.1 T – 20.1m barrel toroid
- ✓ Mean Pileup (2017) ~ 34.4
- ✓ ~ 128 fb^{-1} total integrated luminosity



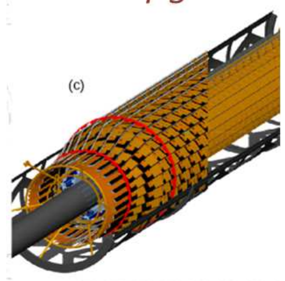
• ATLAS Phase II Upgrade

Timeline



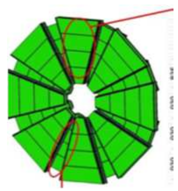
Higgs Discovery September 2012

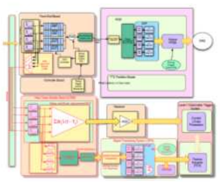
Phase 0 upgrades



IBL

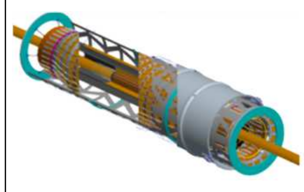
Phase 1 upgrades





New Muon Small Wheel **AFP** **L1 LAr Trigger**

Phase 2 upgrades



Inner Detector Replacement **HGTD**

•HL-LHC Conditions

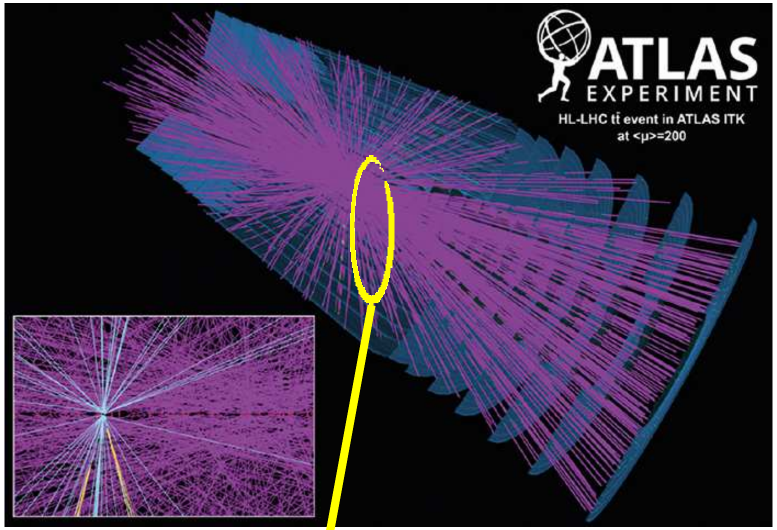
Pileup density

Luminosity

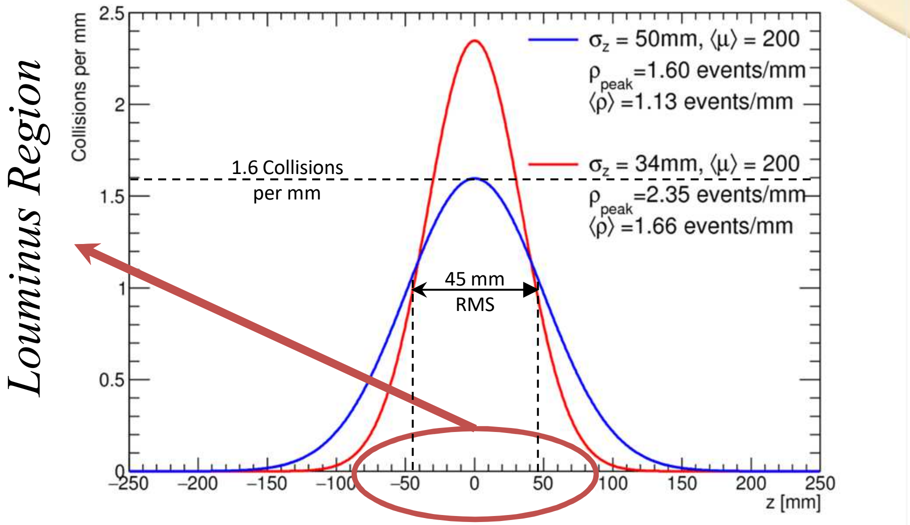
- ✓ Phase I: < 2.2×10^{34} $cm^{-2}s^{-1}$ (300 fb^{-1})
- ✓ Phase-II : 7.5×10^{34} $cm^{-2}s^{-1}$ (4000 fb^{-1})

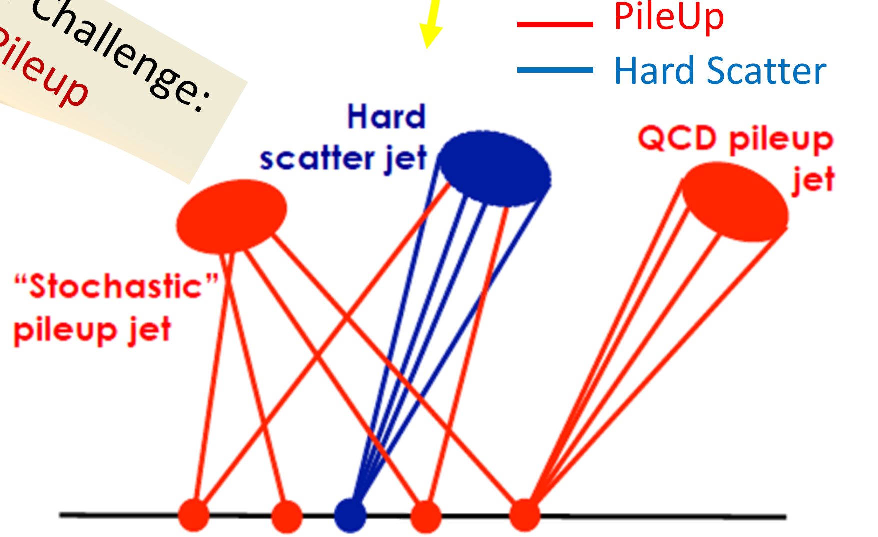
Conditions

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



Major Challenge:
Pileup

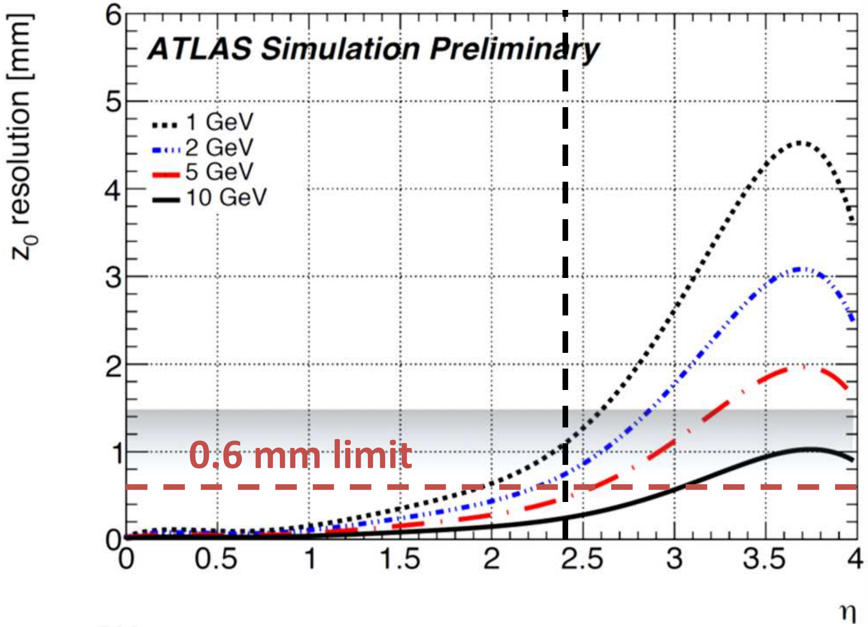




•HL-LHC Conditions

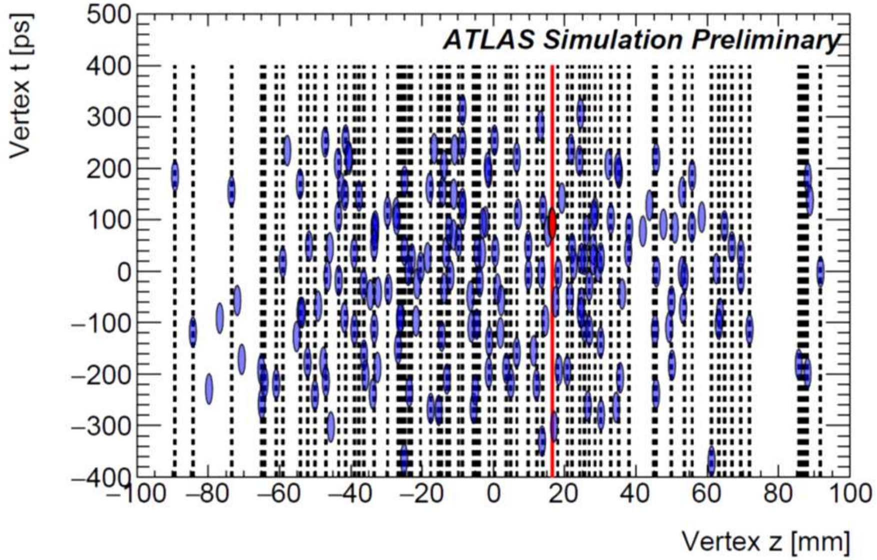
Vertex Resolution

- ✓ Need z_0 resolution < 0.6 mm
- ✓ Tracker much better for central region but reaches the limit ~ $|\eta| = 3$



Time distribution

- ✓ HS present a time peaked distribution with respect to PileUp that are flatter
- ✓ Exploit time spread within pp collisions for vertex separation
- ✓ 30 ps/track transfers μ=200 to μ=30 conditions



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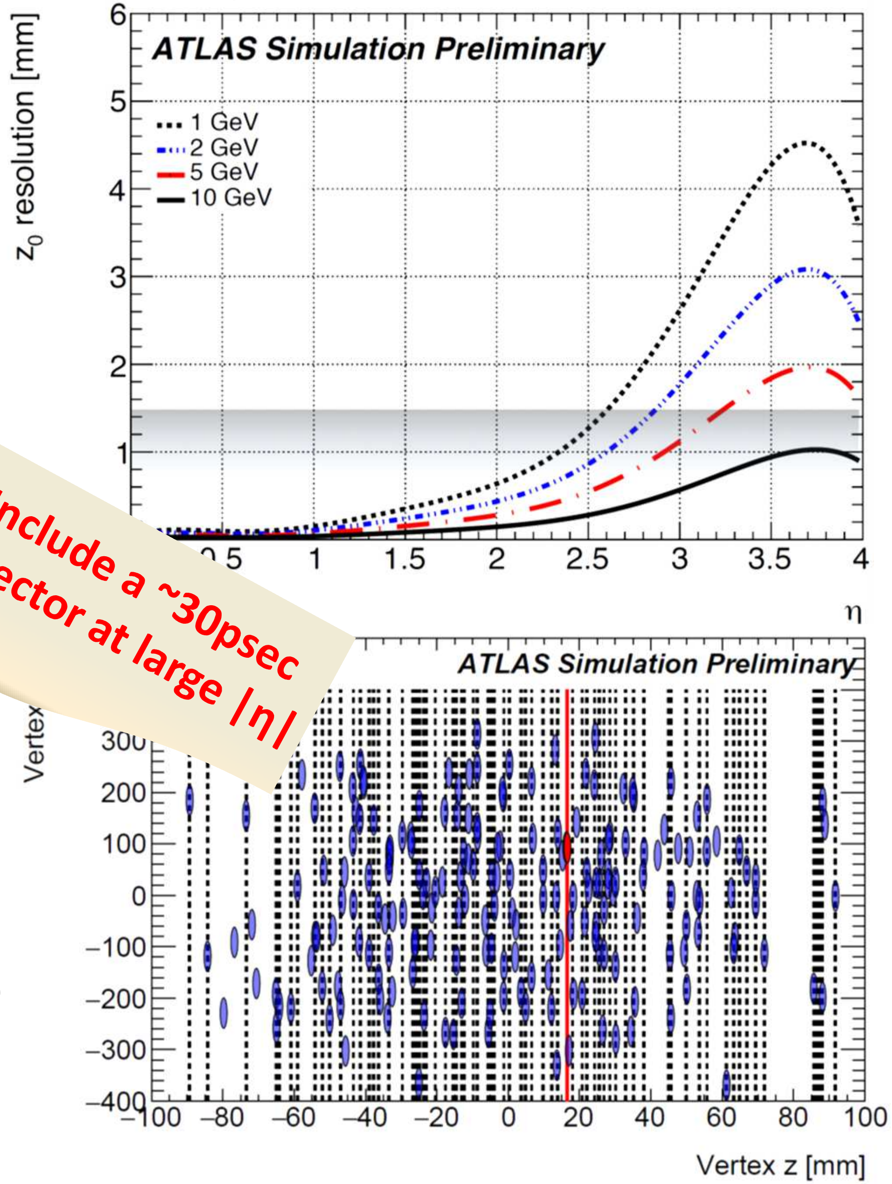
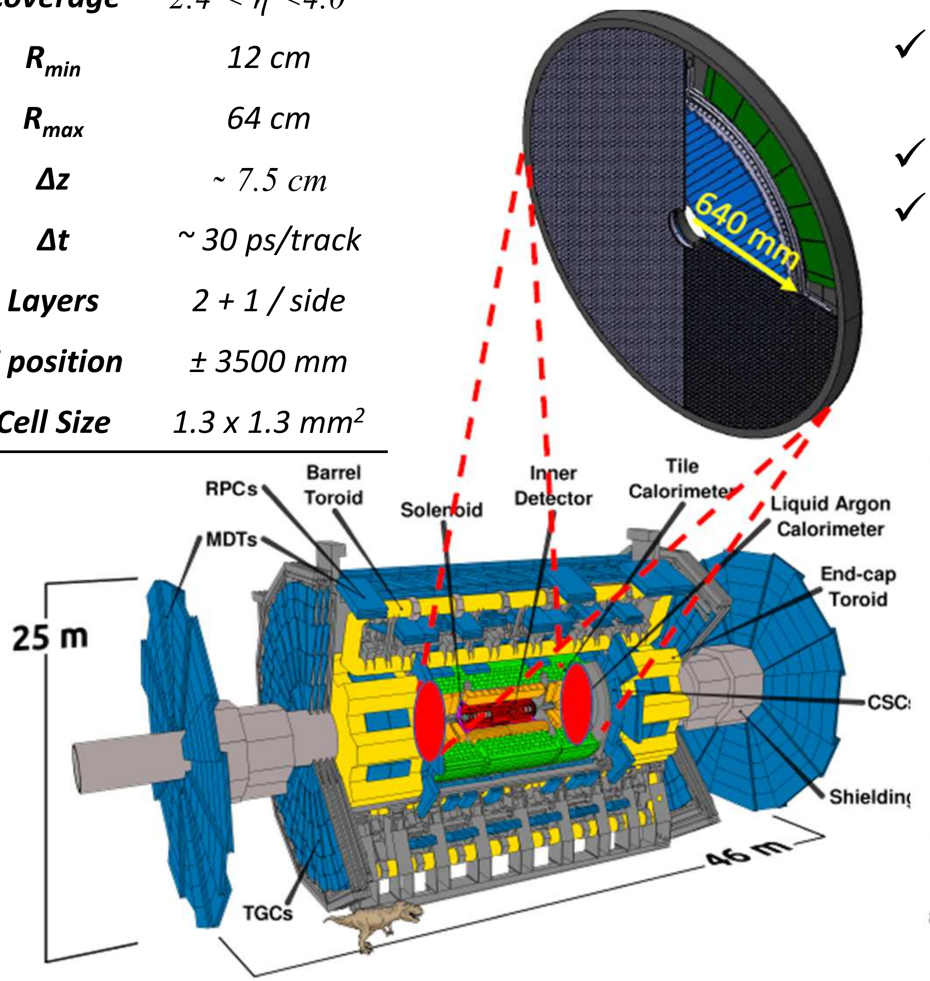


•HGTD System

Position and geometry

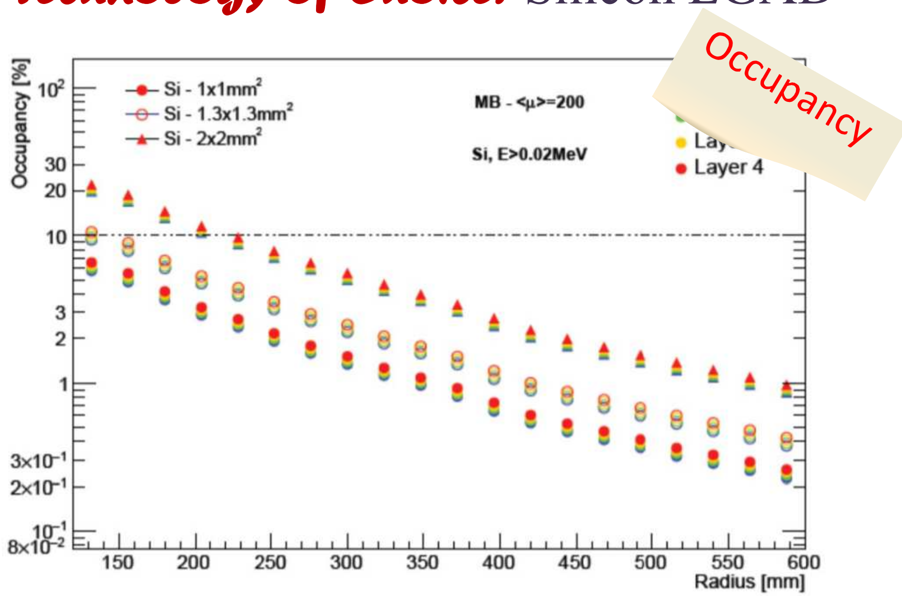
Specifications for 2023	
Coverage	$2.4 < \eta < 4.0$
R_{min}	12 cm
R_{max}	64 cm
Δz	~ 7.5 cm
Δt	~ 30 ps/track
Layers	2 + 1 / side
Z position	± 3500 mm
Cell Size	1.3 x 1.3 mm^2



High Granularity Timing Detector

- ✓ Excellent Time resolution (< 30 ps per track)
- ✓ Radiation Hardness (up to 4.5 x 10^{15} n_{eq}/cm^2 including mid cycle replacement and safe SF)
- ✓ Low volume modular design (7.5 cm total thickness)
- ✓ Low cost optimised layout
- ✓ Occupancy < 10% pad with increased granularity

Technology of Choice: Silicon LGAD



• Sensors

Timing Concepts

Time Resolution

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

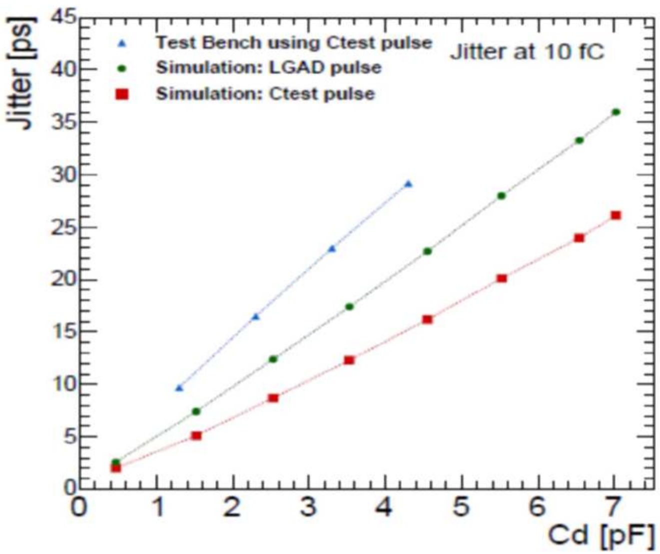
$$\sigma_{elec}^2 = \underbrace{\left(\frac{t_{rise}}{S/N}\right)^2}_{Jitter} + \underbrace{\left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2}_{Time\ walk} + \underbrace{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2}_{Conversion\ time}$$

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

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

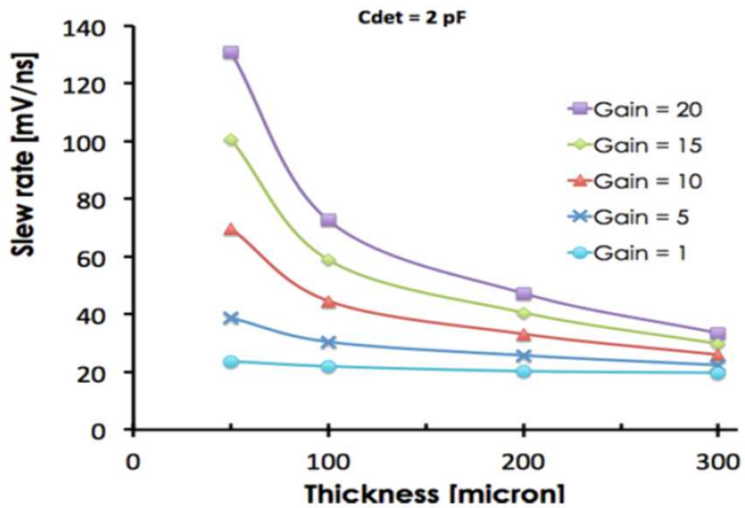
$$\frac{t_{rise}}{S/N} \approx \frac{N}{dV/dt}$$

Dependence on Capacitance



Fast time resolution:

- ✓ Maximize slope (large fast signals)
- ✓ Correct time walk with Constant fraction discriminator
- ✓ Minimize noise to minimize jitter
- ✓ Estimated clock jitter ~ 5 ps
- ✓ Thin silicon sensors with internal gain

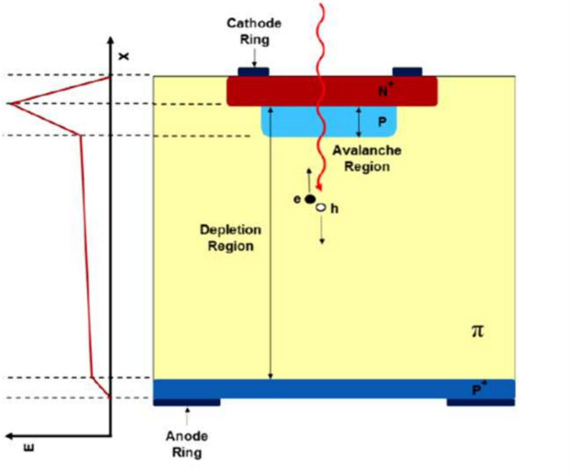


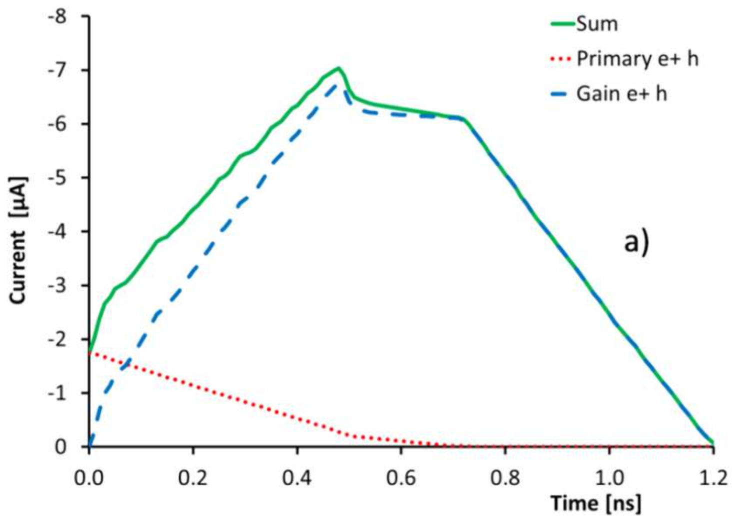
H.-W. Sadrozinski, A. Seiden and N. Cartiglia, 2817 4-Dimensional Tracking with Ultra-Fast Silicon Detectors, arXiv: 1704.08666.

• Sensors

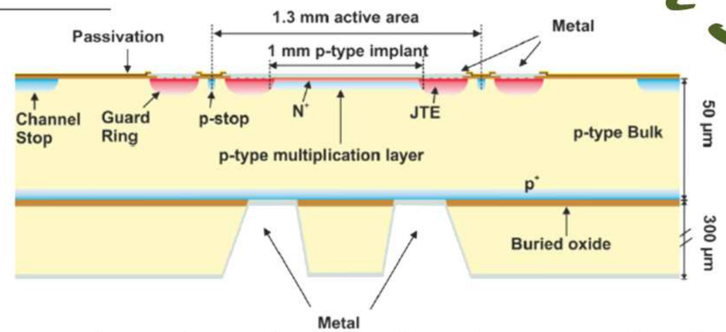
LGADs

CNM SoI



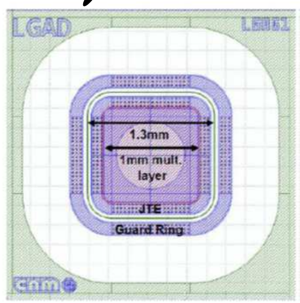


F. Cenna et al., Weightfield2: A fast simulator for silicon and diamond solid state detector, 2822 Nucl. Instrum. Meth. A796 (2015) 149.

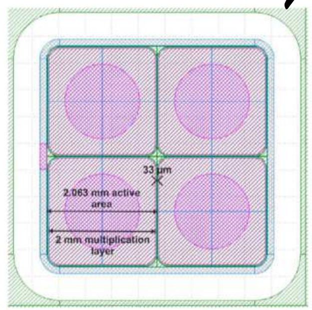


- ✓ Developed and initial R&D productions at CNM (Barcelona)
- ✓ Secondary p implant introducing moderate gain HPK, CNM, FBK produced sensors
- ✓ 50 µm thickness on 250 µm support wafer
- ✓ Different implantation doses including Gallium and Carbon
- ✓ Various structures including:
  - ✓ Pad diodes of 1.3 x 1.3 mm^2
  - ✓ 2 x 2 arrays of 1 x 1 mm^2 pad

Single Diode



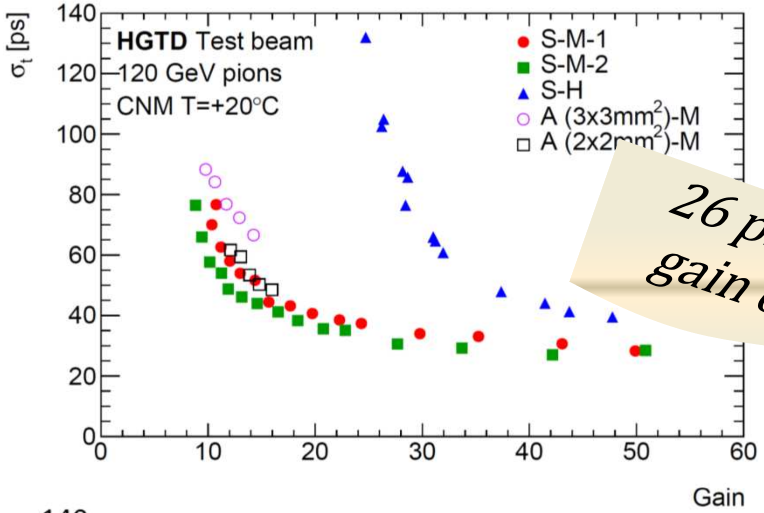
2x2 array



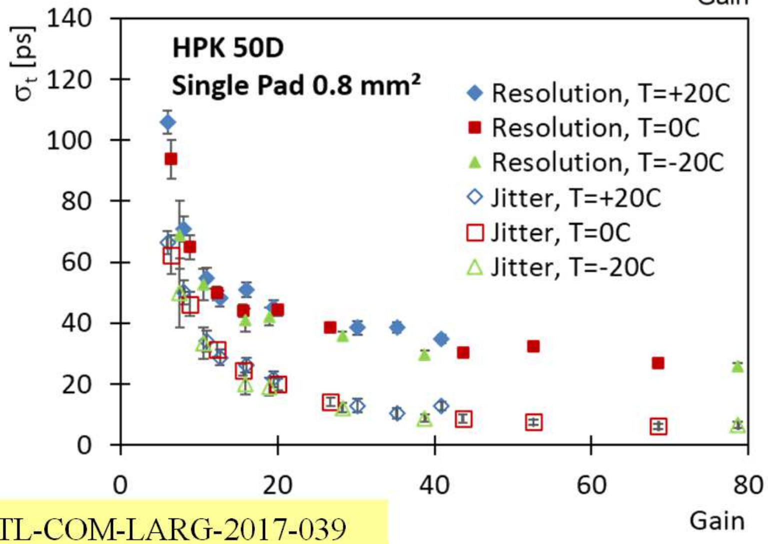
• Sensors

Testbeam Results

Time resolution



26 psec @ gain of 50



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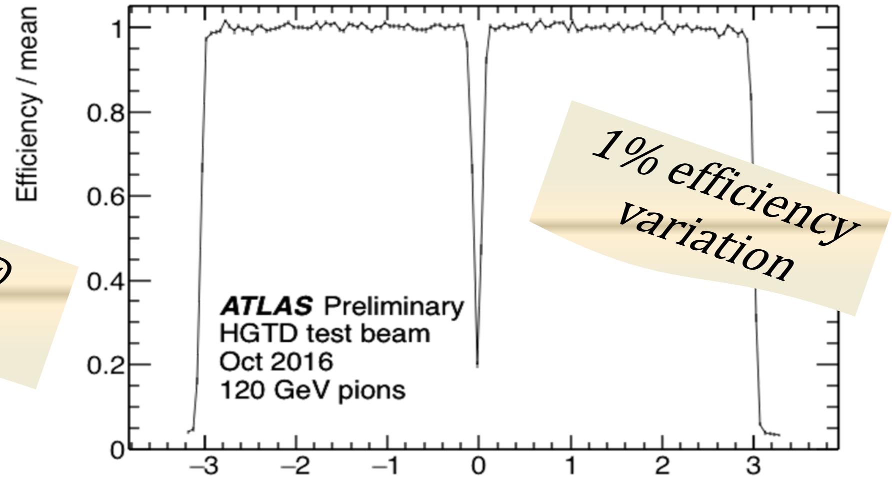
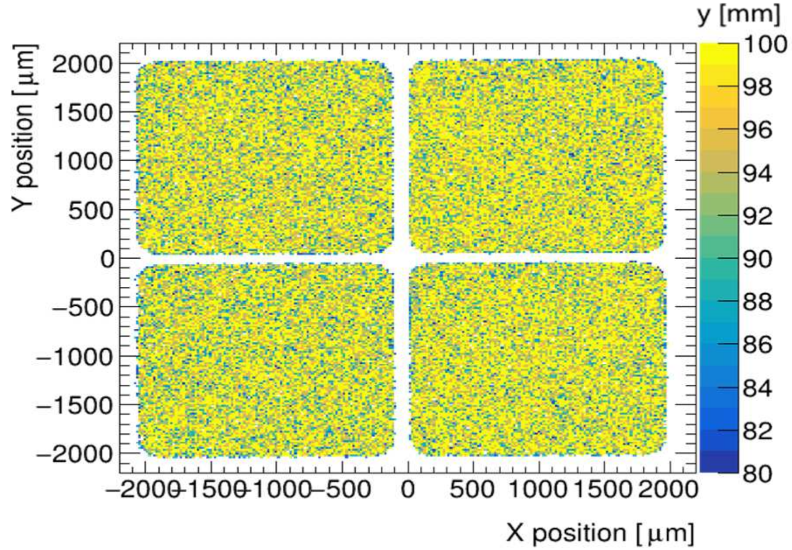
Efficiency maps

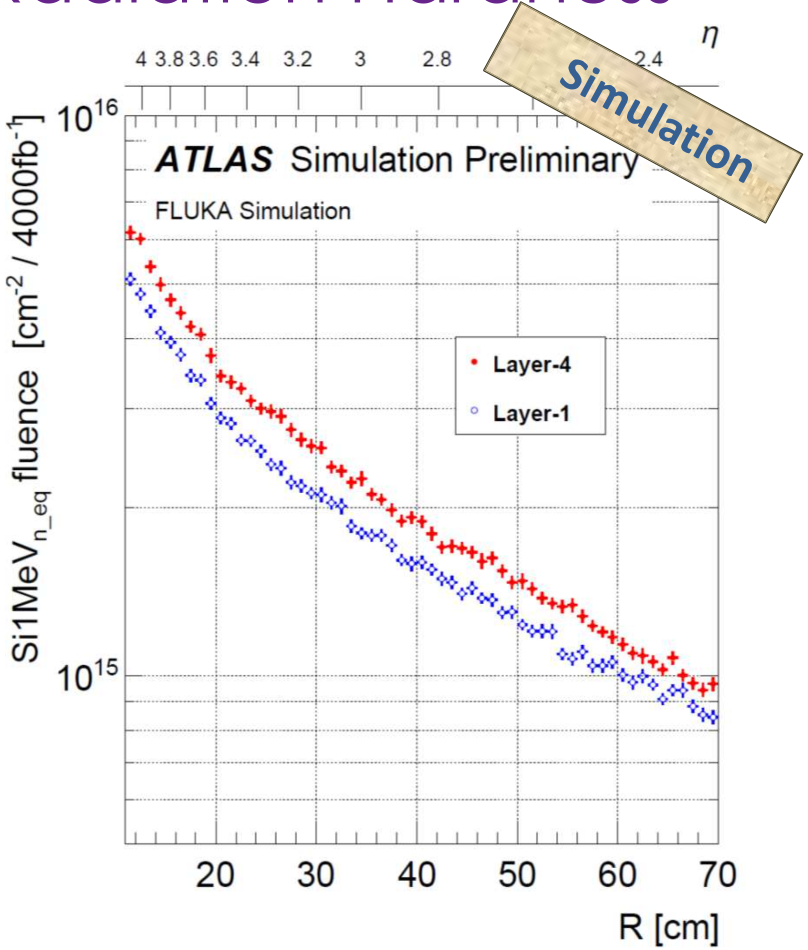


1% efficiency variation



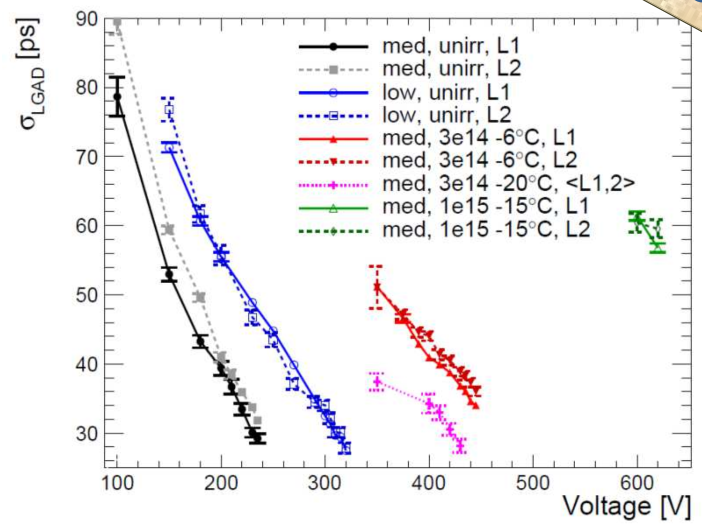
• Sensors

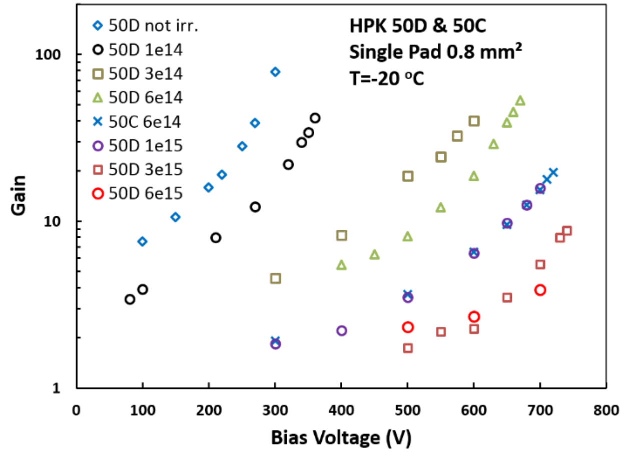
Radiation Hardness



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

Sensors



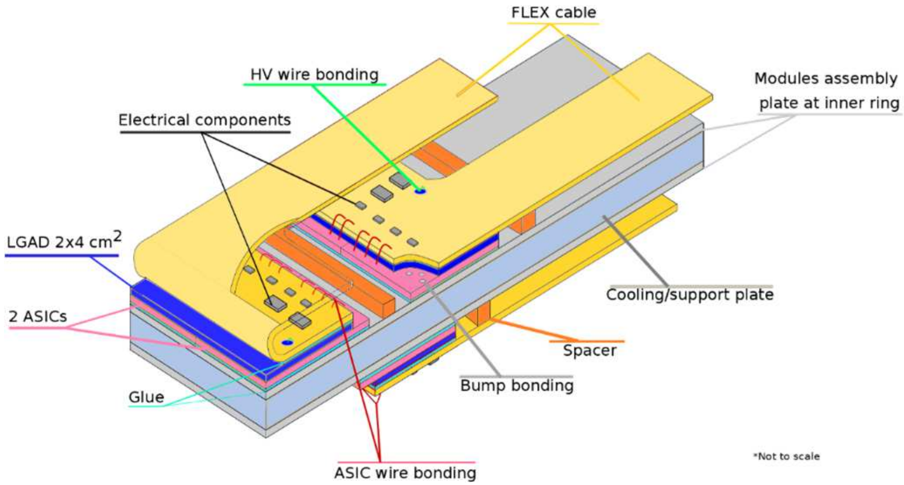


- Similar results Fluka - GCALOR
- Max. (η = 4.0) after 4000 fb^{-1} ~ 4.5 x 10^{15} n_{eq}/cm^2 (mid cycle replacement at 2 x 10^{15})

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

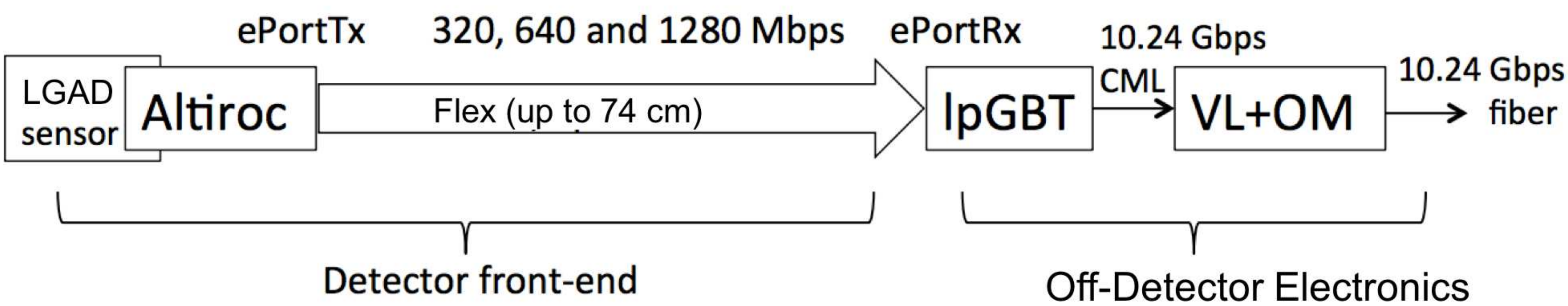
•Integration

ASIC and Signal extraction

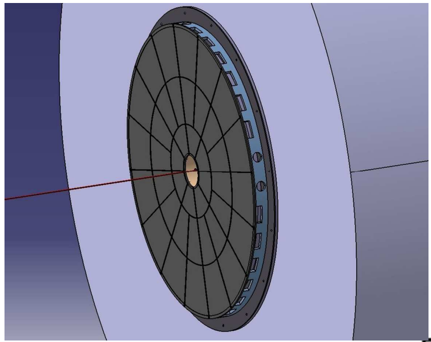


ATLAS LGAD Timing Integrated ReadOut Chip (ALTiRoC)

- 2 x 2 cm die, TSMC 130µm technology
- Bump-bonded to 2 x 4 cm^2 sensors
- Single pixel readout, 225 channels/ASIC
- Readout Rate:
  - 1 MHz detailed hit info after L1
  - 40 MHz number of hits on outer radii for luminosity estimation
- 25 ps estimated time resolution
- Wire-bonded to capton flex

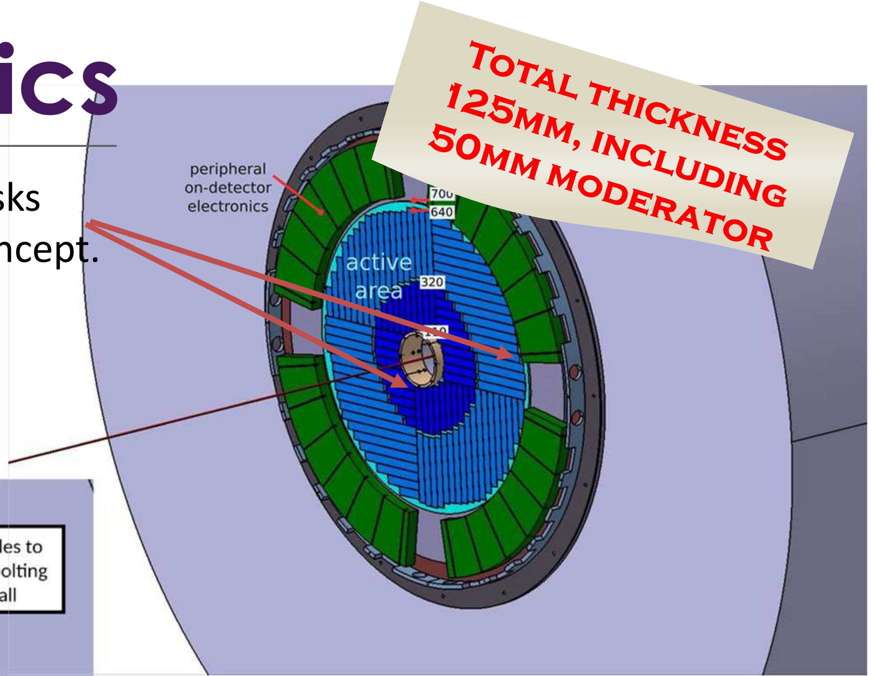


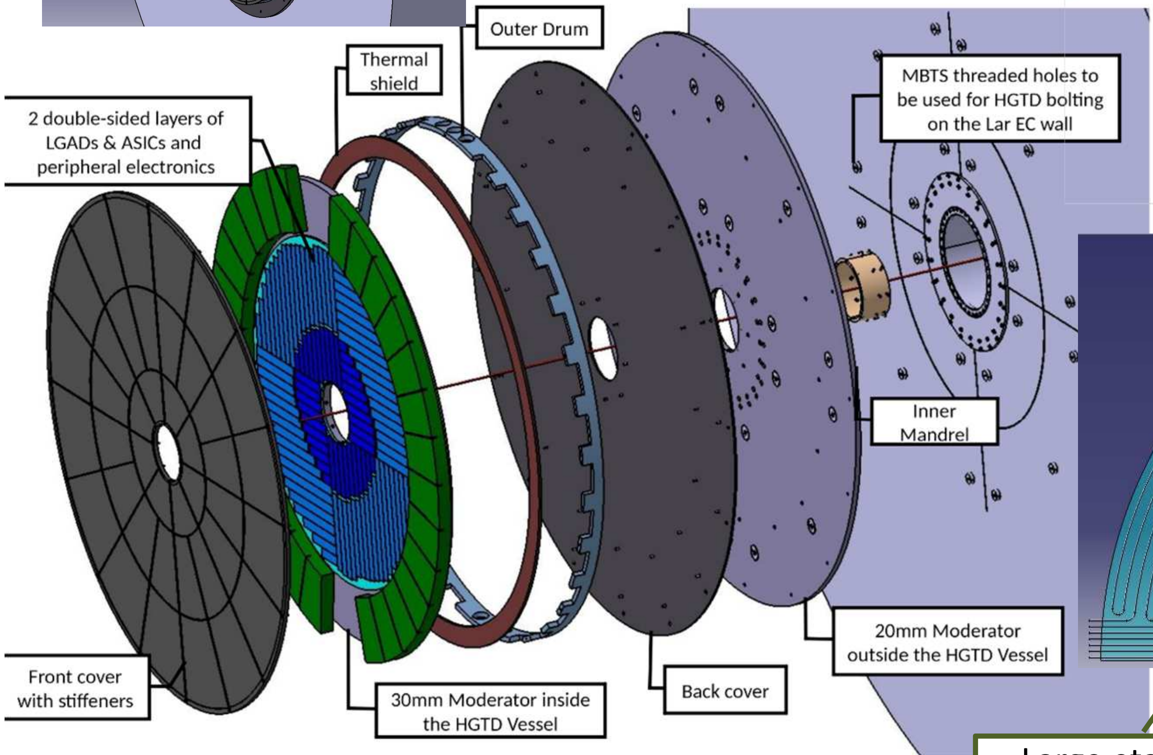
•Integration - Mechanics

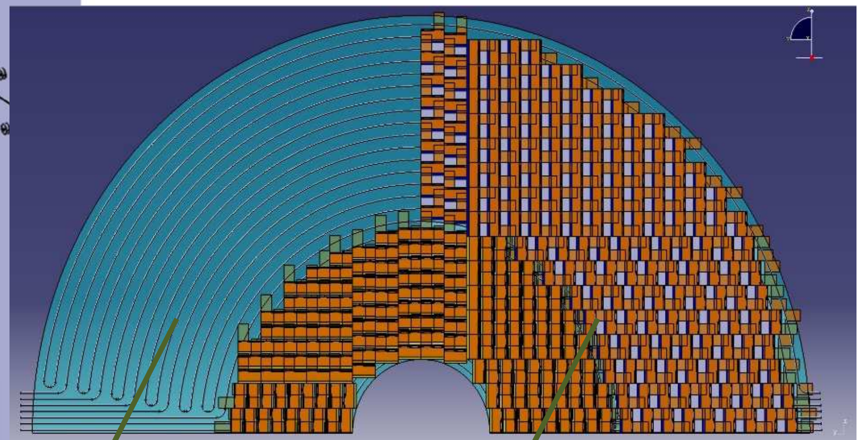


Forward & backward detector disks with central half rings & stave concept.

- ✓ Total 6 m^2 LGAD sensors
- ✓ ~ 800 modules in total
- ✓ 2 x 4 cm^2 per module





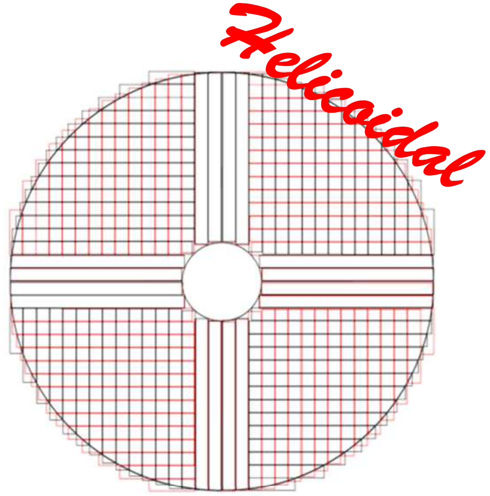


•Integration

Layout Optimization

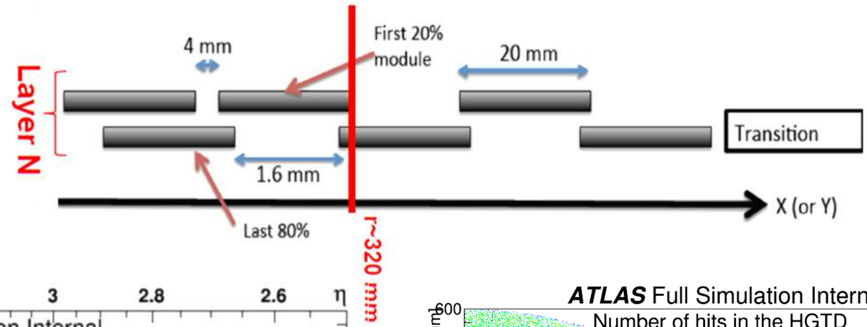
Stave layout

Efficiency		Geometry	
Events with 0 hits	0.7 %	Longest Stave	546 mm
Fraction of events at x or y = 0	52 %	Coverage	91.8 %
		18 staves per quadrant	



Sensor Overlap

- Resolution degrades with irradiation
- Inner region more affected
- Increase number of hits to recover



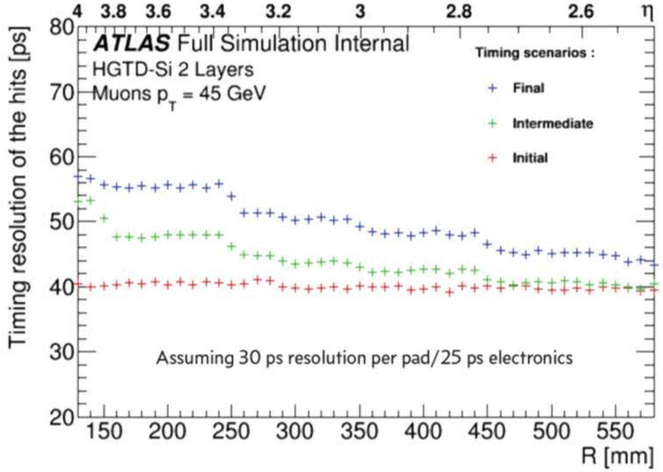
Fill Factor

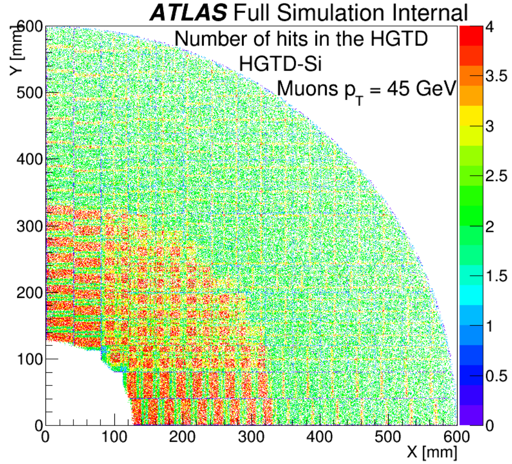
Inter-pad Region

30 μm → 94 %

50 μm → 90 %

100 μm → 82 %

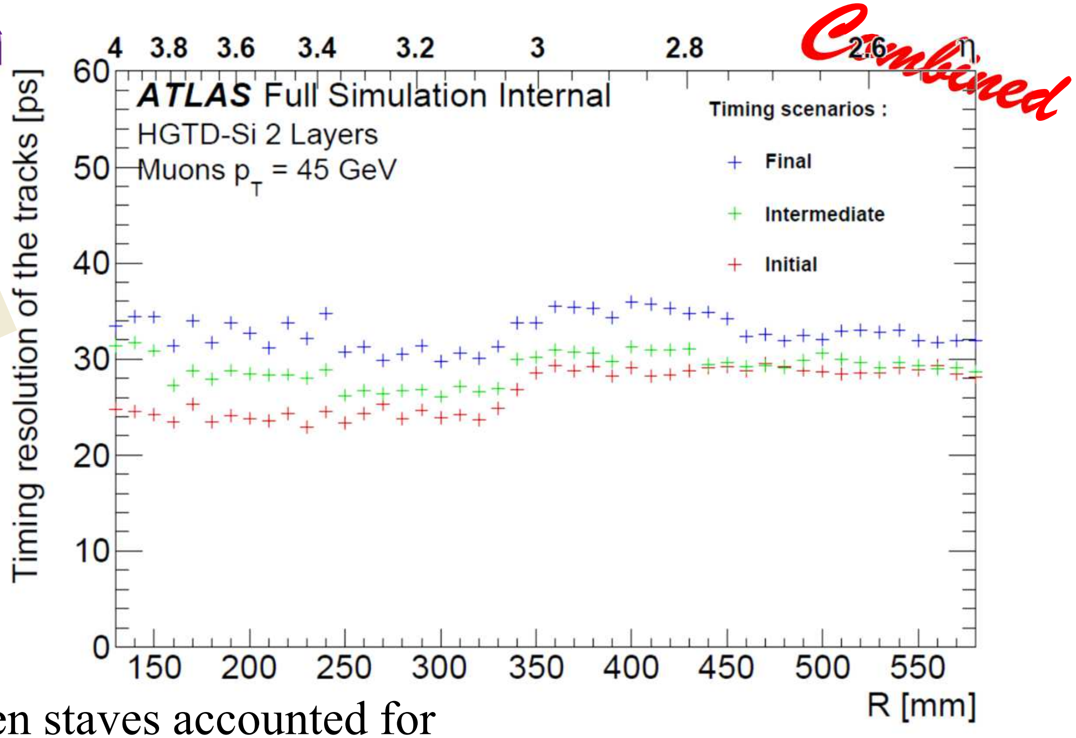




•Physics and Performance

Track resolution

✓ ~2 hits at large radius (R>320 mm), overlap 20 %
✓ ~3 hits at low radius (R<320), overlap 80 %

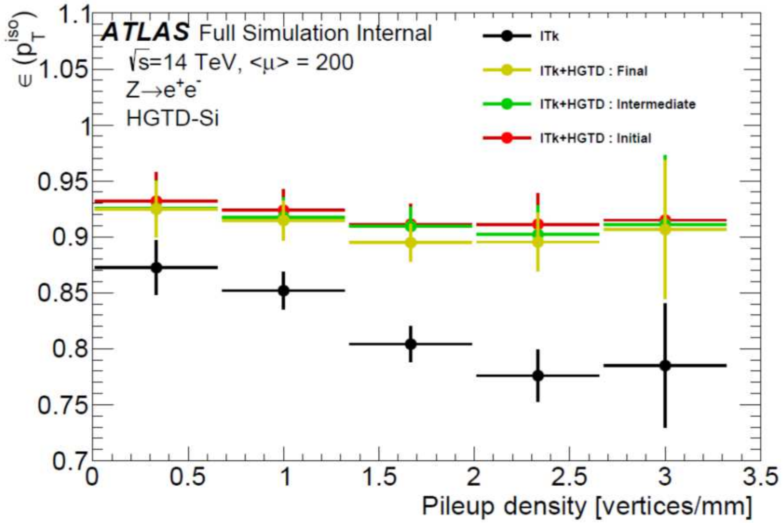


- ✓ Dead regions between staves accounted for
  - 4 mm for 80 % overlap
  - 16 mm for 20 % overlap
- ✓ Track resolution always < 40 psec
- ✓ 3 different timing scenarii
  - ➢ *Initial :* 30 psec per pad and 25 psec for electronic
  - ➢ *Intermediate :* timing resolution after 2000 fb^{-1} (with inner layer replacement)
  - ➢ *Final :* timing resolution after 4000 fb^{-1}

•Physics and Performance

Performance

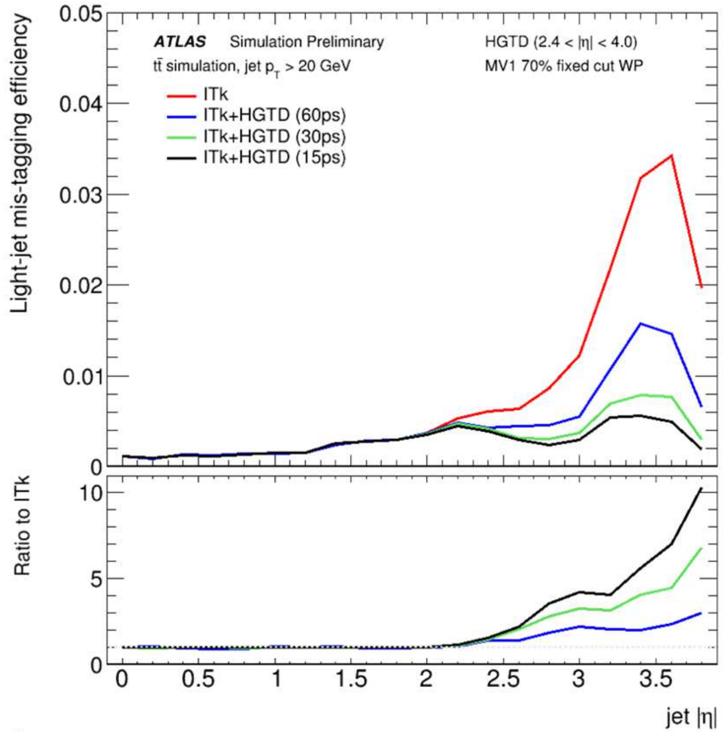
Electron Isolation



- ✓ *2 layers/side with overlap*
- ✓ *Average efficiency ~93% at all cases*
- ✓ *ITk only average efficiency ~83%*

Performance plots currently been updated for new geometry

B-tagging performance



- ✓ *100% Efficient does not use η parametrization nor fill factor*
- ✓ *Initial assumes 30psec across the whole detector*
- ✓ *Slight degradation between initial and final, though larger loss from hit efficiency*

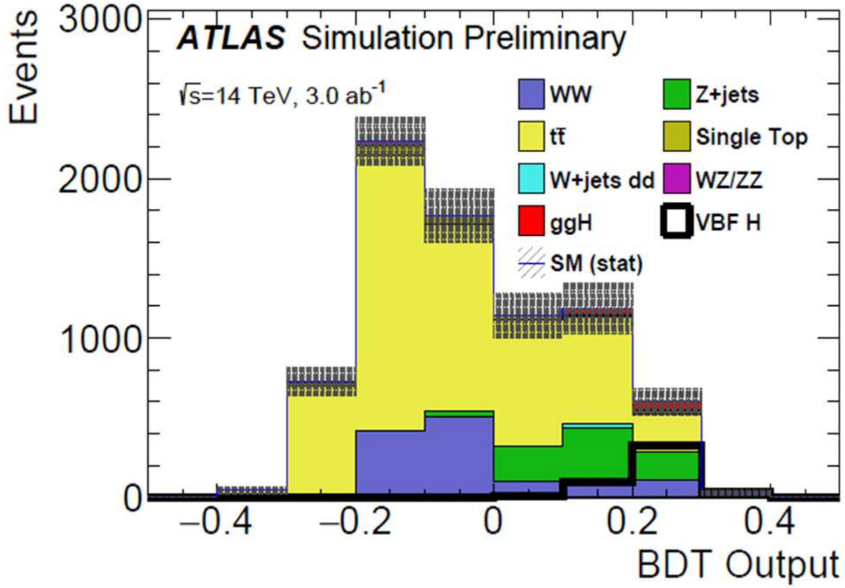
•Physics and Performance

Some EW channels

$qqH \to qqWW^* \to qq + e\nu_e \mu\nu_\mu$

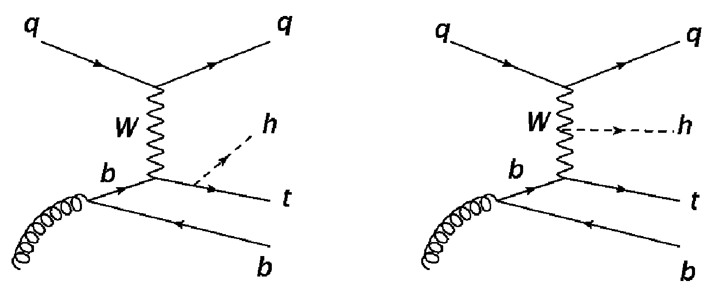
- **8% relative improvement**
  - ➢ 43% background rejection
  - ➢ 3% PU efficiency
  - ➢ BDT analysis
  - ➢ *Top dominated background due to forward b-tagging*

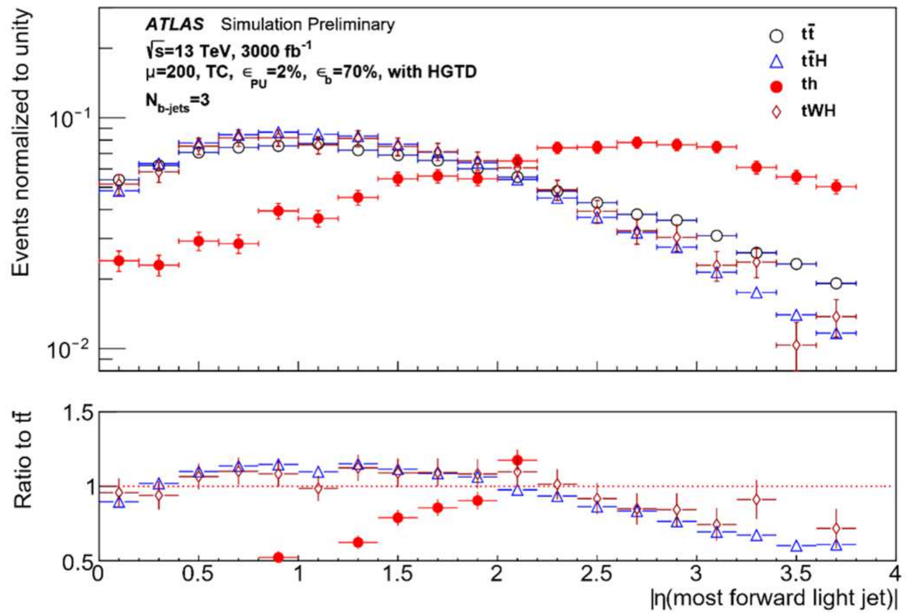
VBF processes under investigation



$tH(\to bb)$

- **11% relative improvement**



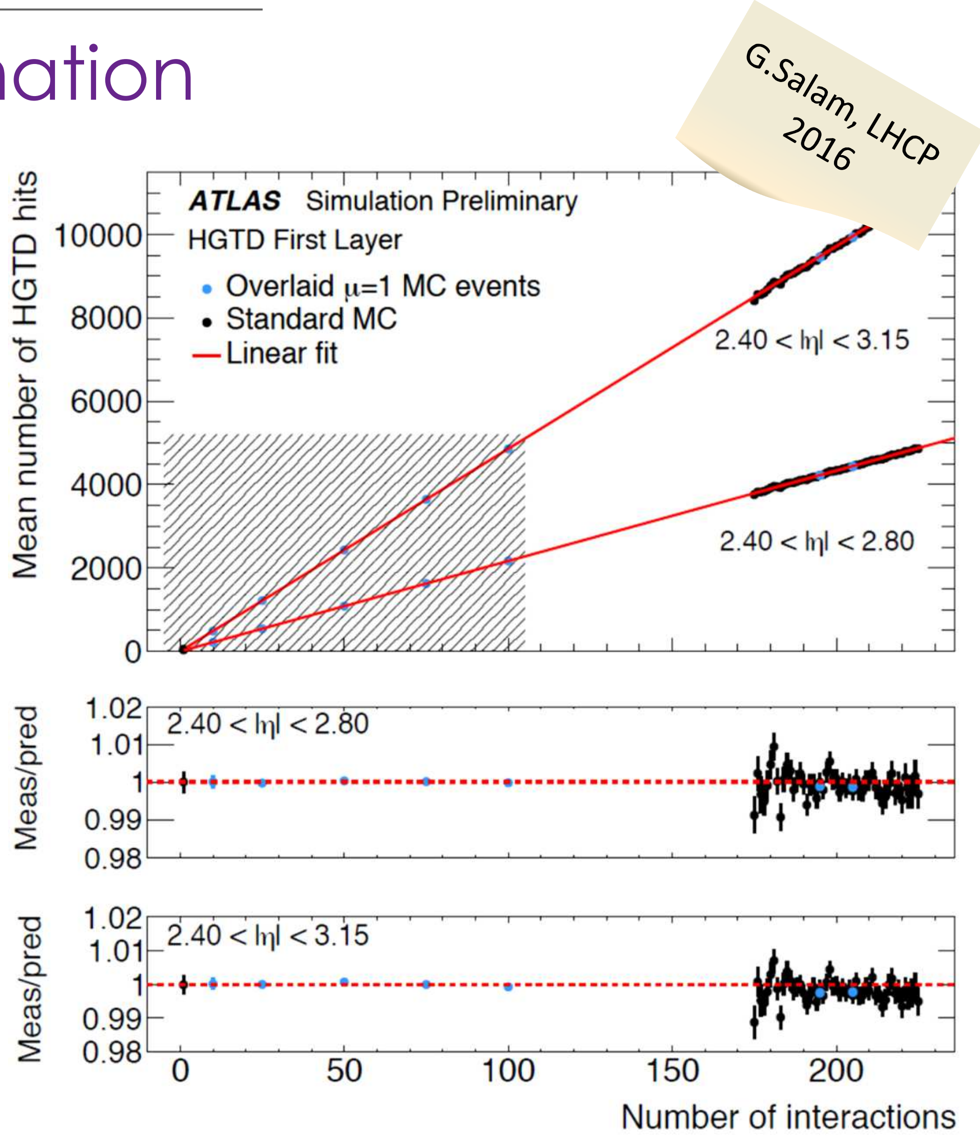


•HGTD as Luminometer

On line and off-line estimation

- **linear dependence of number of hits on number of interactions**
  - ➢ Count hits in the region of 320 mm < R < 640 mm
  - ➢ 0.1% expected statistical uncertainty for 1 sec integration time
  - ➢ Low systematics
    - ➢ Out of time sideband subtraction
  - ➢ Hit count per ASIC and BCID

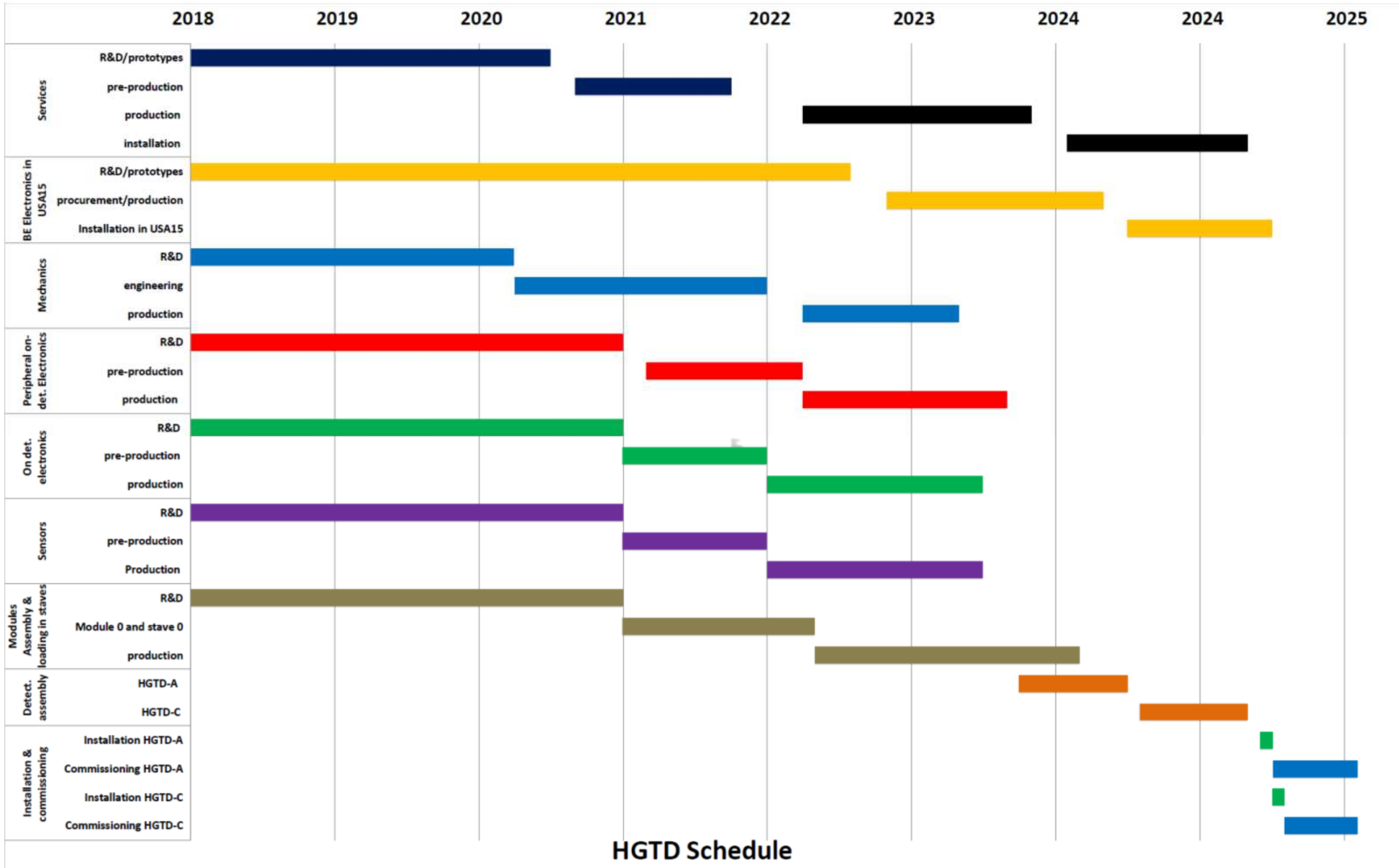
- **On-line Estimation**
  - ➢ 40MHz readout for real time estimation
  - ➢ Provide per BCID interactive estimate
  - ➢ Total latency of 440 ns (100 ASIC+ 340 ns fiber)



•Schedule

Important mile-stones

- 2018 - 2020: Sensor, ASIC, electronics and services RnD
- 2021 - 2024: Fabrication and module assembly
- 2025 - 2026: Installation and Commissioning



•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 un-irradiated 1.3mm^2 diodes
- ✓ 99% uniformity with low inefficiencies in the inter-pad regions
- ✓ Operations up to 6e15 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
- ✓ Validate full ASIC design and expect first prototype at the last quarter of 2018