A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS detector

- detector concept, description and R&D and beam test results

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For ATLAS HGTD Project

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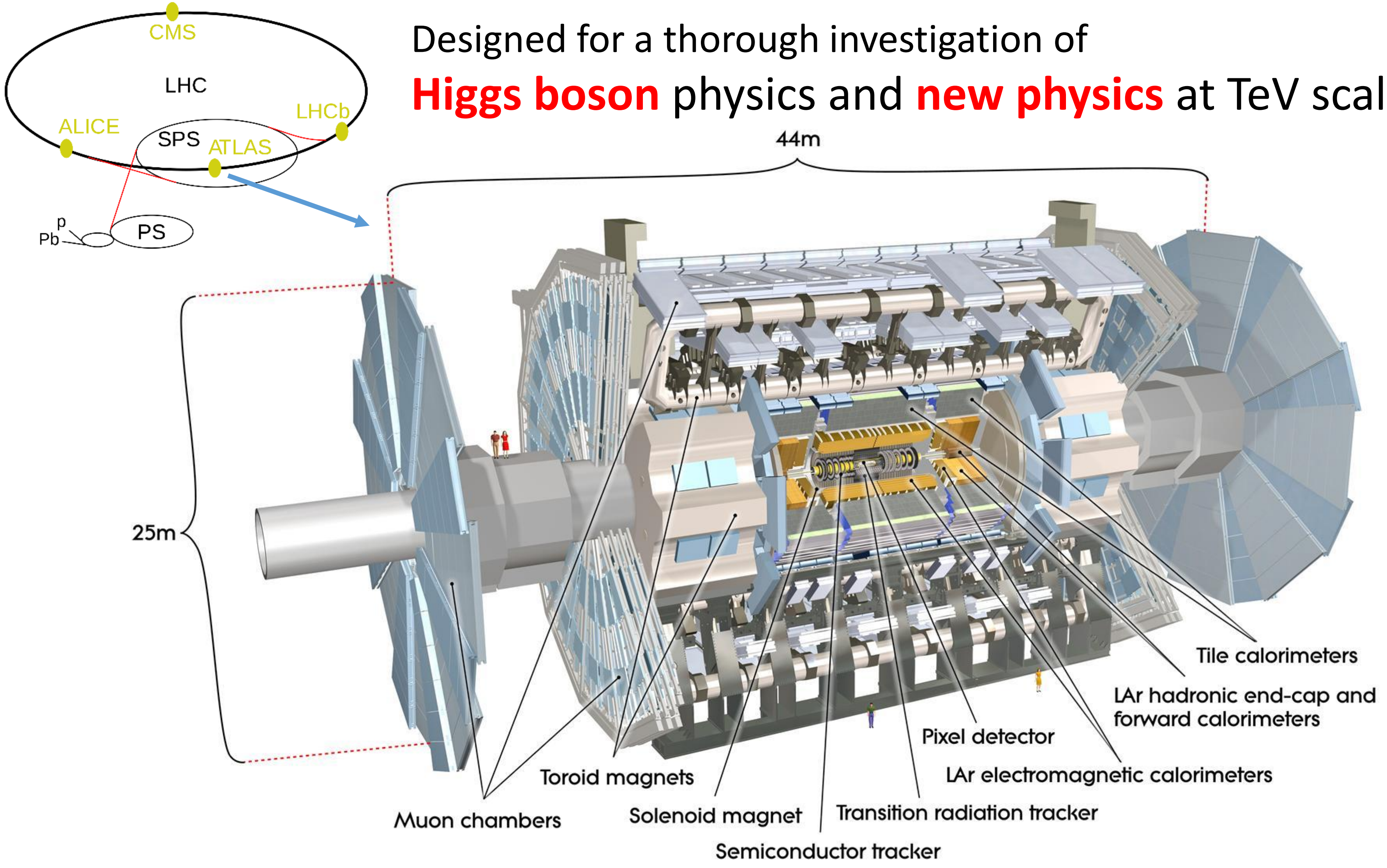
ATLAS Detector

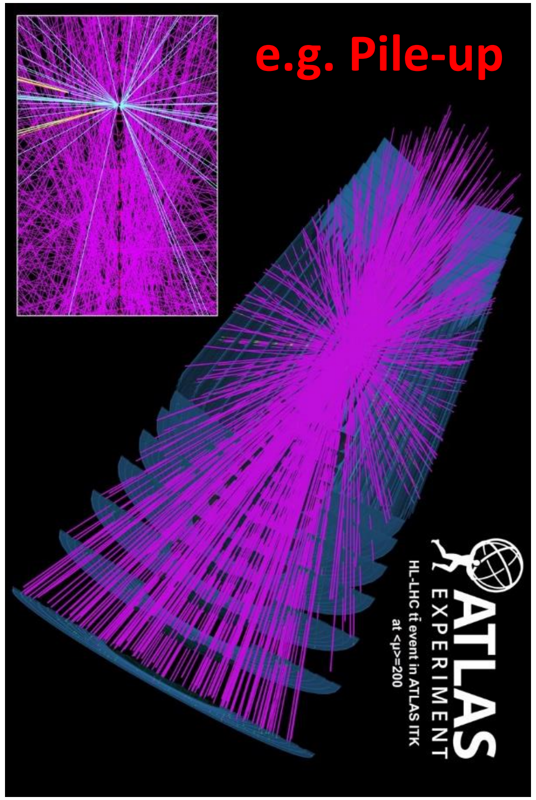
Designed for a thorough investigation of

Higgs boson physics and **new physics** at TeV scale



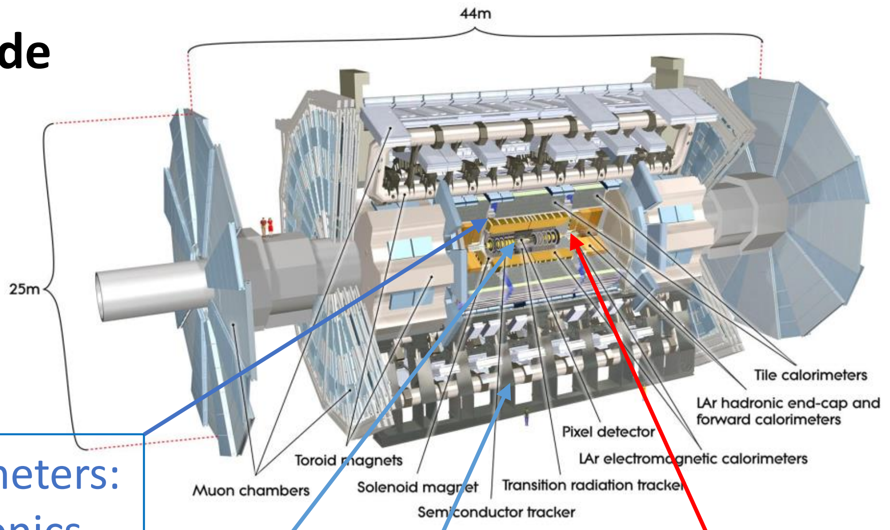
Future: HL-LHC up to 3ab^{-1} 14 TeV pp collisions

Unprecedented opportunities,
Unprecedented challenges



Phase-II Upgrade (2025 – 2027)

Sustainability
Improvement
Novelty



LAr, Tile Calorimeters: Readout electronics

New Inner Detector (ITk): Full silicon detectors

TDAQ System: Trigger and DAQ Upgrade

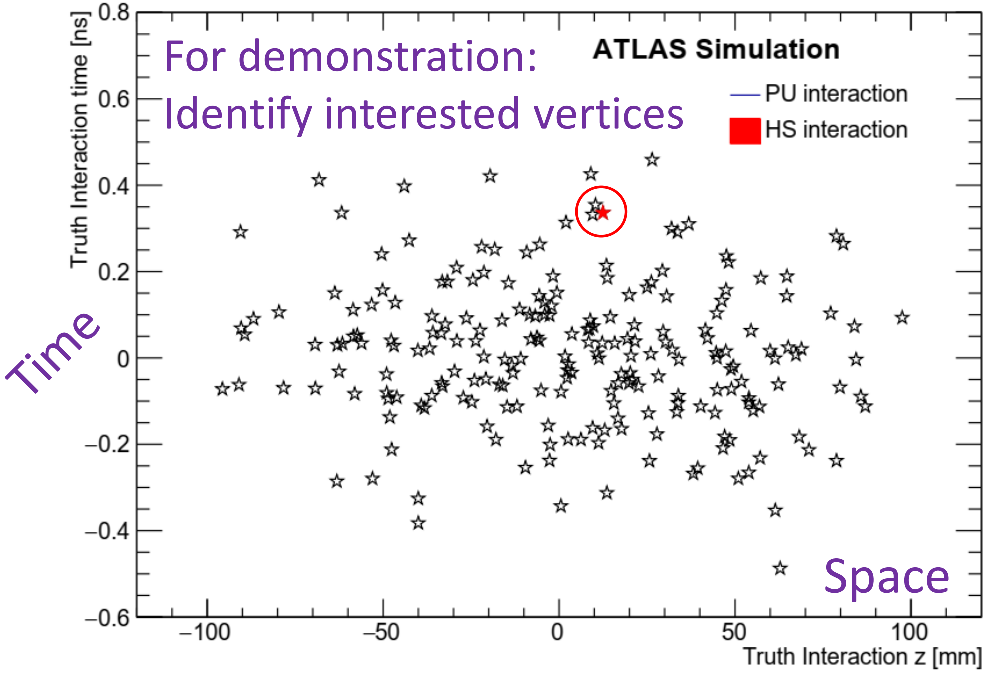
Muon system: Readout electronics; partial upgrade of precision and trigger chambers

High Granularity Timing Detector (HGTD): Track timing in forward region (ATLAS-TDR-031)

More info.

Motivation for HGTD

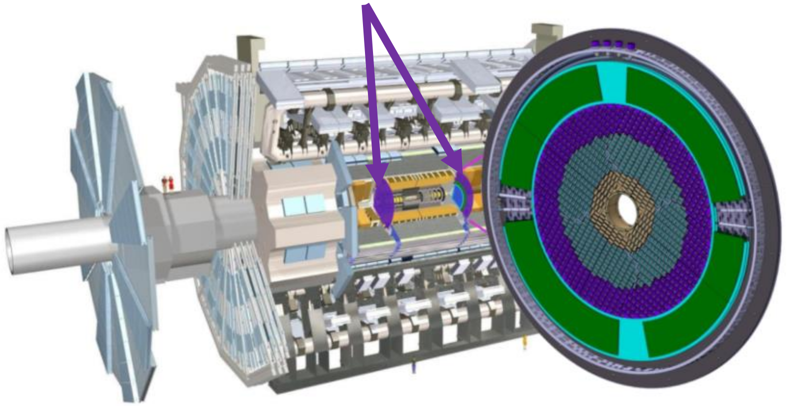
Precise timing O(10) ps will introduce a new dimension for physics at ATLAS



- Improve on the pileup suppression
- Would enhance lifetime/pID measurement

See also relevant discussion in CMS Timing Detector

Minimum-bias scintillator ending service then → **Opportunity to install a novel detector**



- Forward region only (no plans nor resources for a full coverage)
- Tight spatial constraints
- Radiation hardness and O(10) ps timing requires → advanced detector technologies
- Also a luminosity detector

HGTD in a nutshell

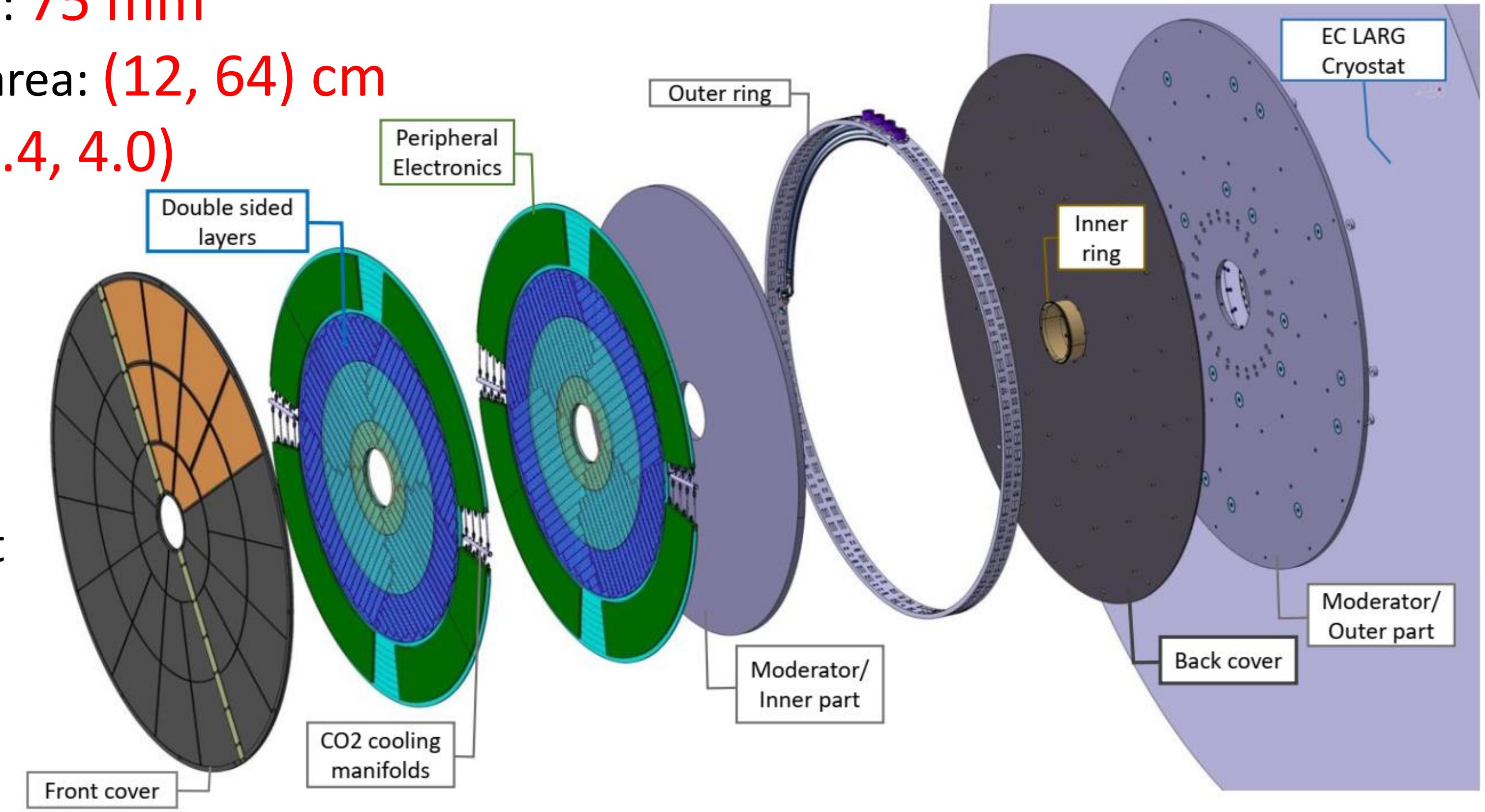
Overall thickness: 75 mm

Radial sensitive area: (12, 64) cm

|η| coverage: (2.4, 4.0)

2 double-sided layers,

4 measurement planes



> 3600000 Low Gain Avalanche Detector (LGAD) units, each 1.3 mm x 1.3 mm x 50 μm (active), grouping into > 8000 modules, containing > 16000 ASIC FEBs ……

Time resolution:

per-hit **35 – 70 ps**

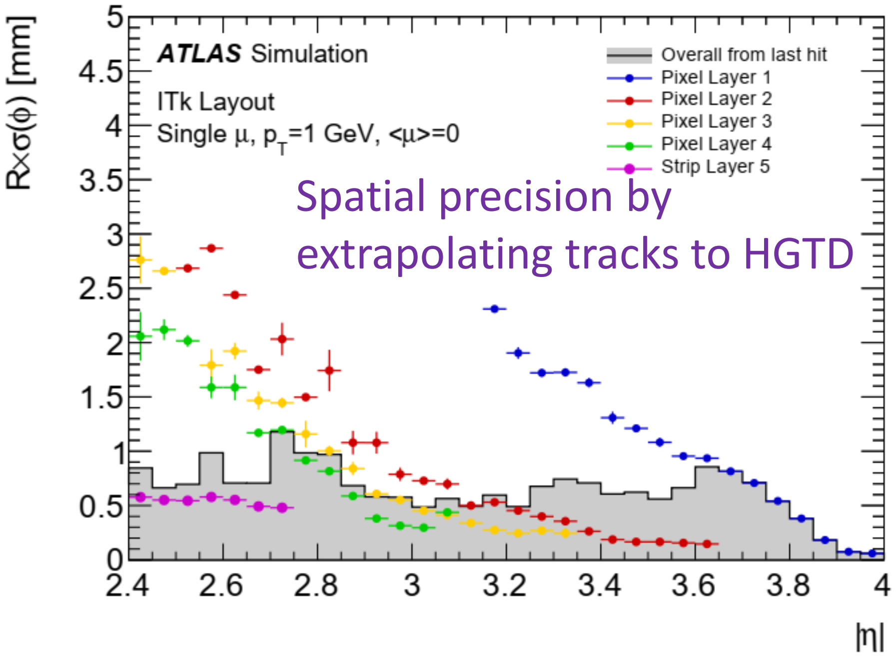
per-track **30 – 50 ps**

Radiation-level dependent

About O(1) mm and O(10) ps

1.3 mm – unit sensor size

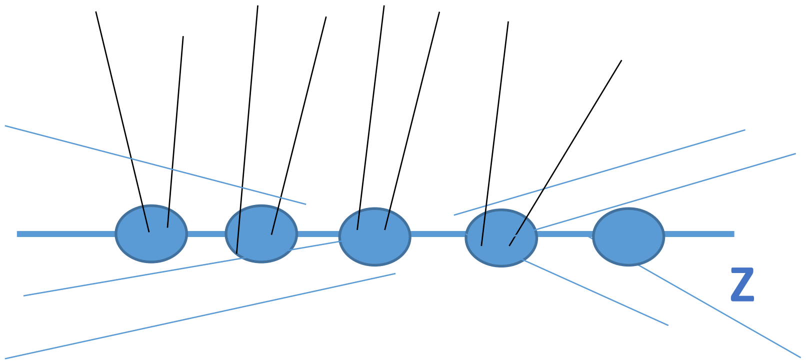
- About the spatial precision of track extrapolation from silicon trackers
- Balanced also between occupancy, double hits, dead areas, capacitance, and increasing channel numbers



35-70 ps per hit

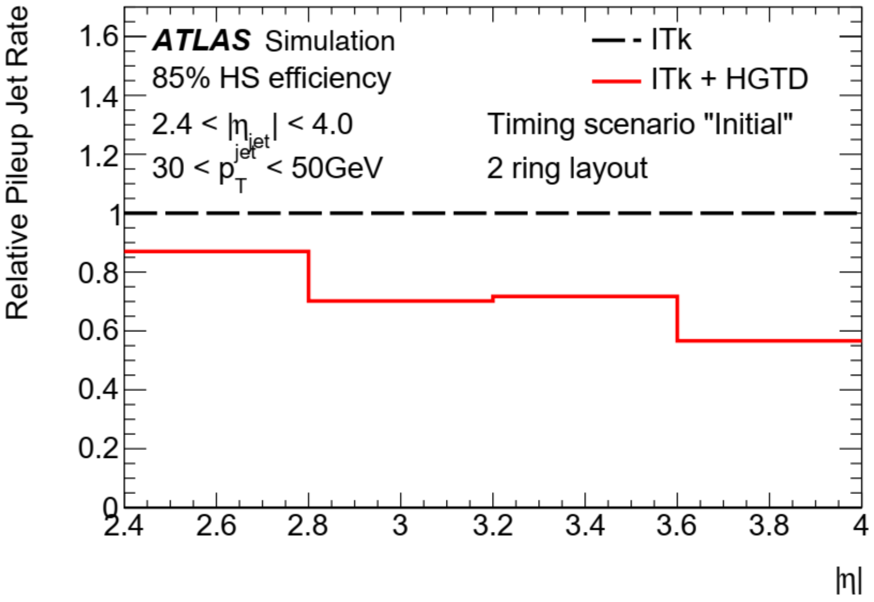
- Already cutting-edge specification
- bottom line: per-hit time resolution ≲ 100 ps to guarantee effectiveness in physics case

Complexity of tracks v.s. vertices, especially in forward region, worsen z_0 resolution

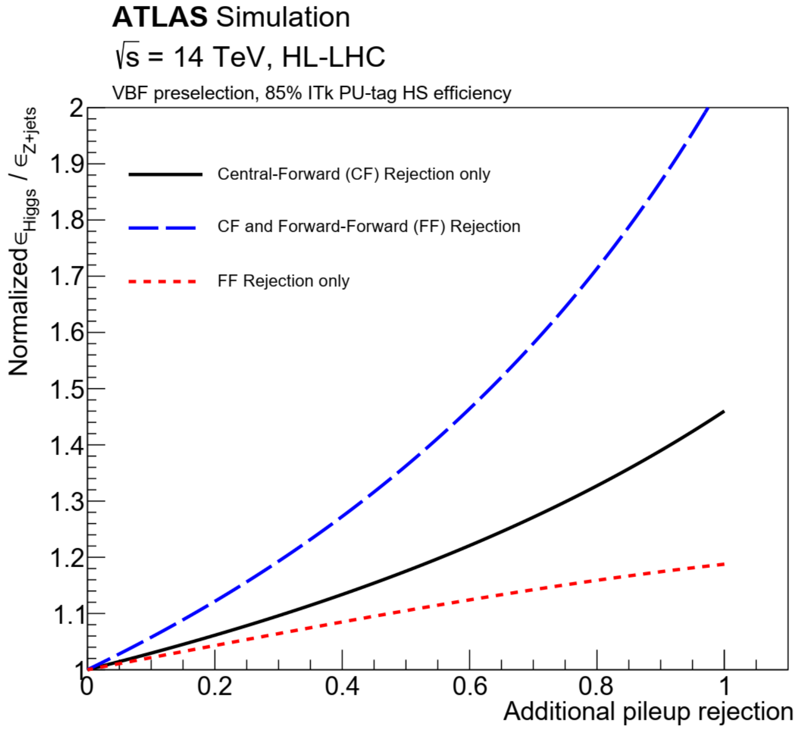


Timing the tracks (blue) can help to solve the mystery

Demonstration of Physics Potentials



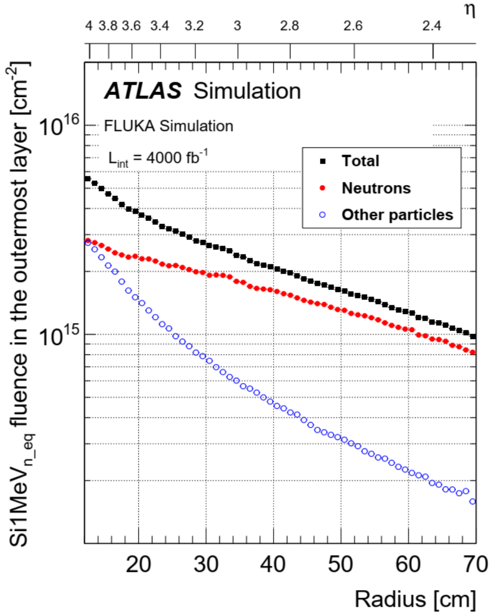
Up to 2 x more power to further suppress pileup contributions in the forward region, on top of the planned full silicon detector

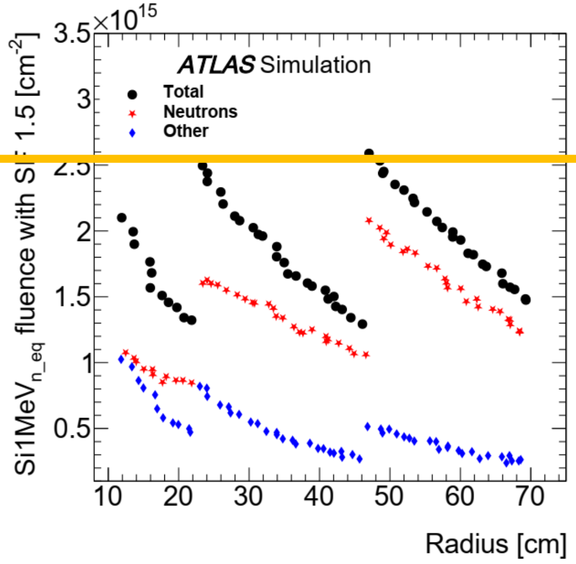


For analyses subject to pileup backgrounds (e.g. VBF H → invisible), sizable improvement of S/N with help of HGTD

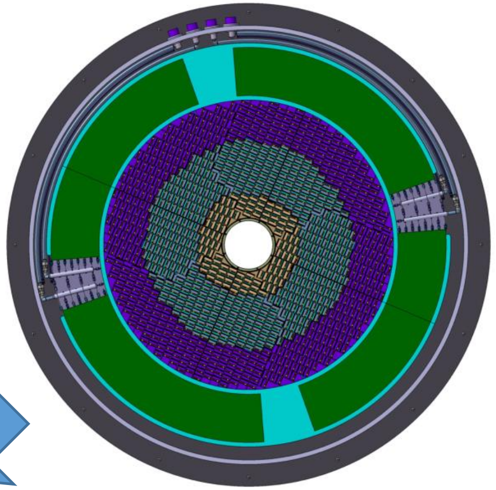
Three-ring and Replacement

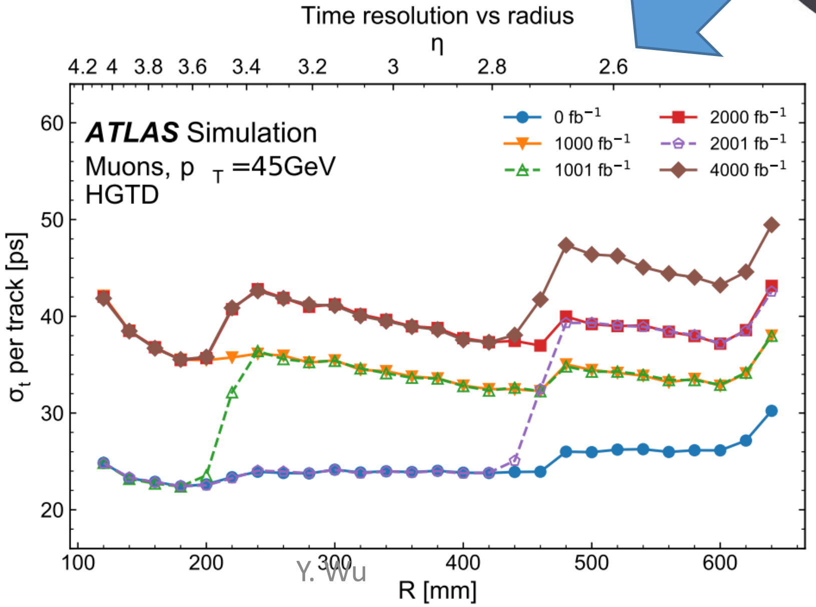
Suffers from high radiation (forward) => worsen performance





Replace inner and middle rings along data taking to keep total dose within safety



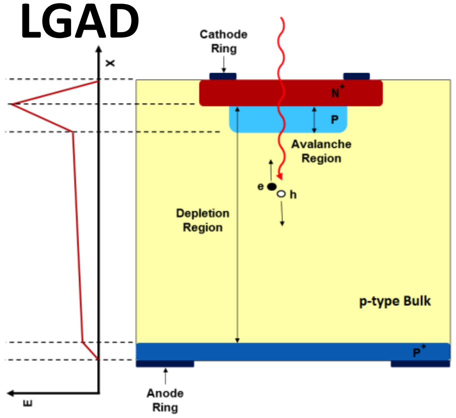


Expected stabilized performance (shown for track σ_t)

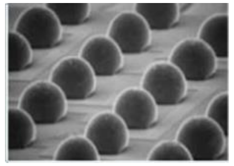
Timing Measurement

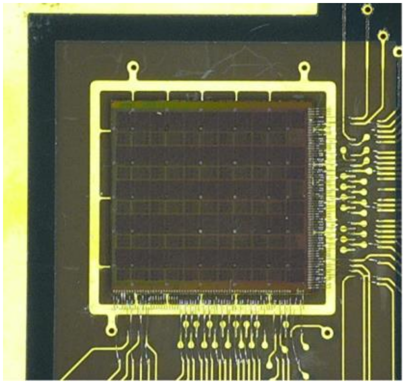
* unirradiated case
** with timewalk correction expected

LGAD



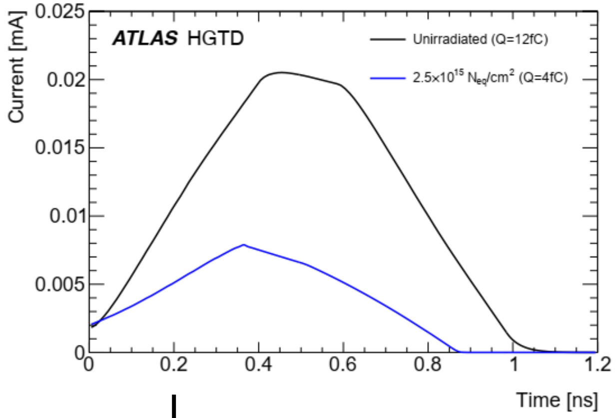
Bump-bonding



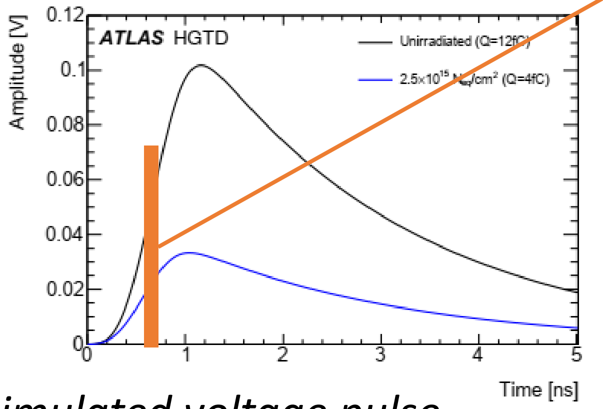


Customized ASIC (ALTIROC)

Simulated current pulse



After preamplification



Simulated voltage pulse

Time of arrival
→ time measurement

Resolution factors:

Sensor:
Landau effects ≲ 25 ps* → non-uniform e-h generation pattern

$$\sigma_{total}^2 = \sigma_L^2 + \sigma_{elec}^2 + \sigma_{clock}^2$$

Electronics / DAQ:
electronic noise (**jitter**), and amplitude variation (**timewalk****) **≲ 25 ps**;
clock distribution **≲ 15 ps**

LGAD Design

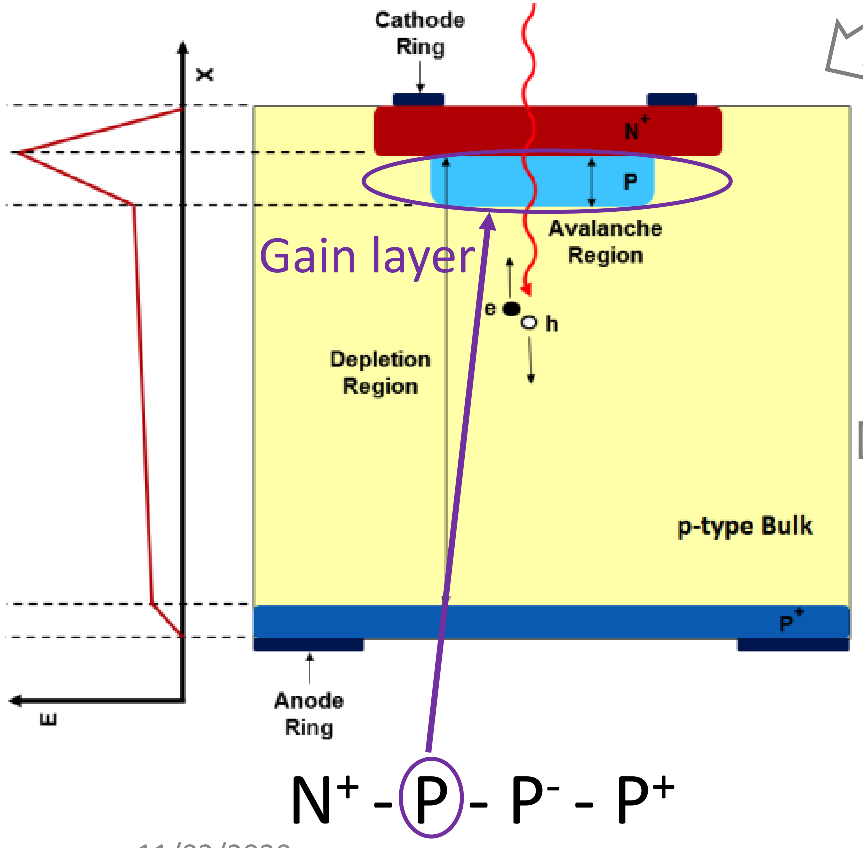
** Pioneered by CNM, Barcelona; further developed with CERN RD50 collaboration*

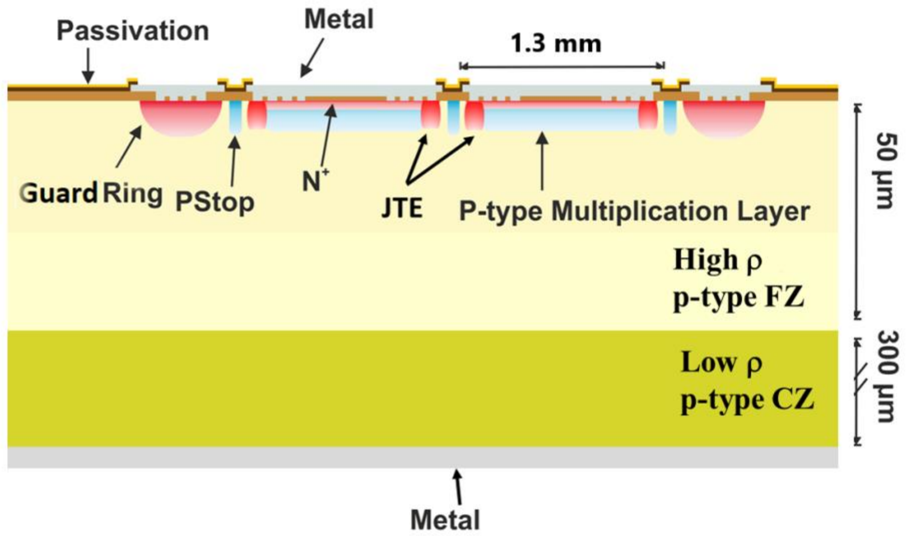
Silicon detector has good virtues for this application (radiation-hard, granularity, mature tech., …)

Keys* to achieve desired resolution

Thin: 50 μm
Gain: x20 (→10 fC)

⇨ Larger dV/dt
Larger S/N
Less Landau non-uniformity





Careful R&D (with JTE, PStop, GR, interpad gap, etc.) to guarantee quality of E-field

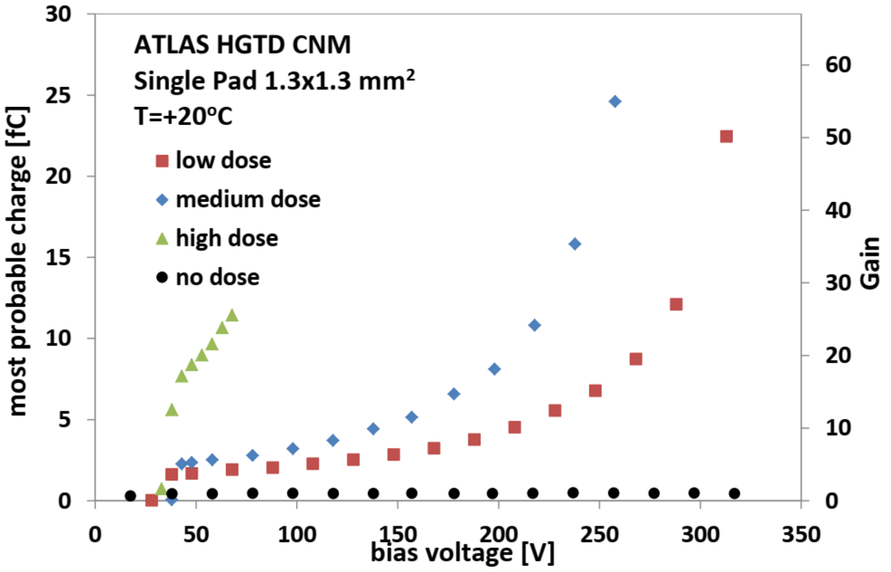
Sensor Performance

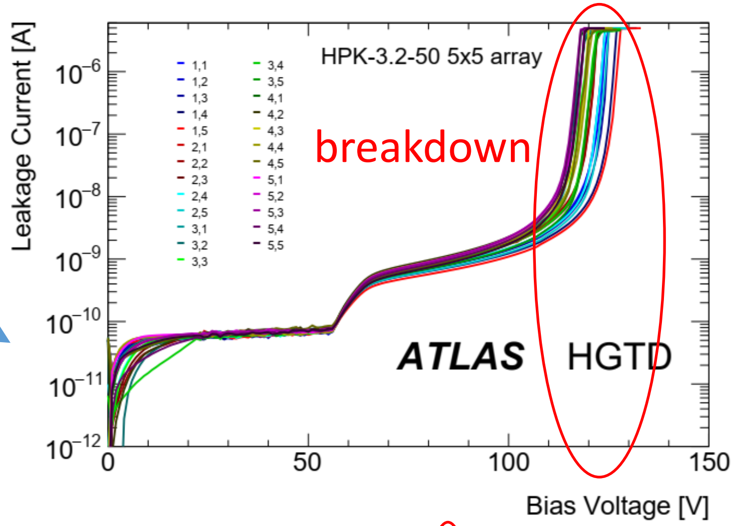
Sensor R&D involves multiple manufacturers (varying gain doping etc.)

Electrical measurement (I-V, C-V)
Laser or radioactive source, Test beam

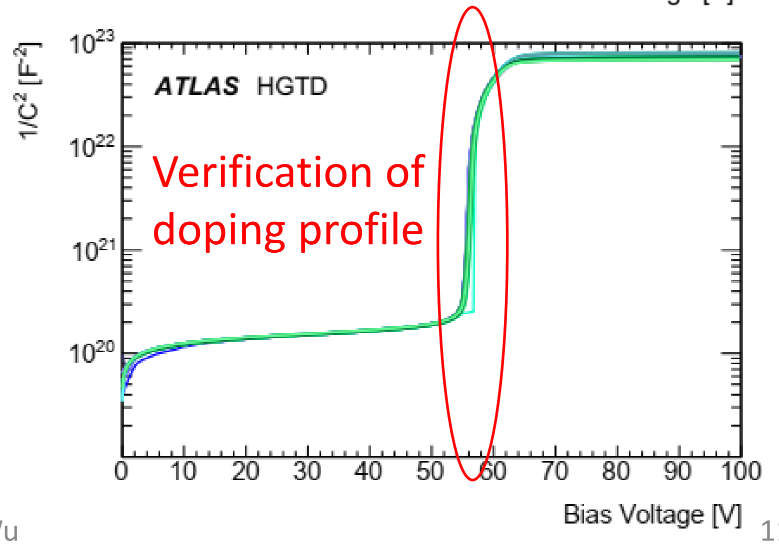
Promising performance shown (unirradiated sensors)

Effectiveness of doping gain layer





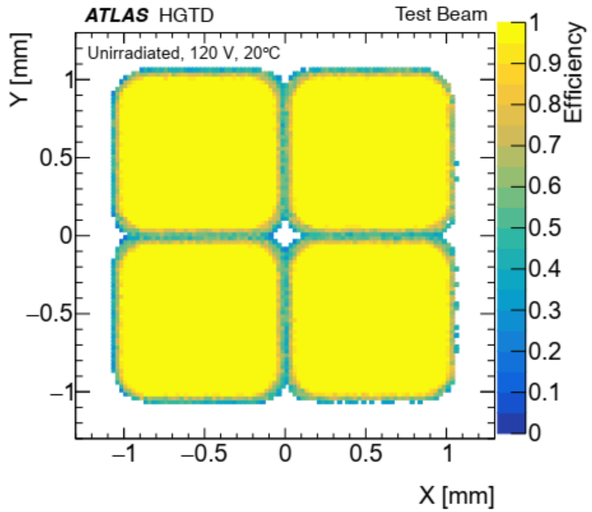
I-V



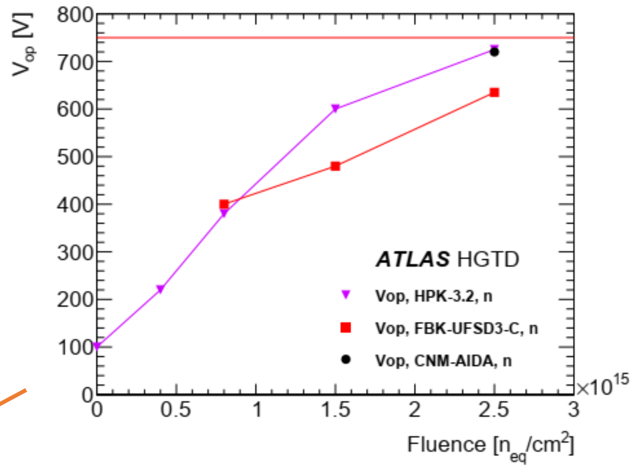
C-V

Sensor Performance

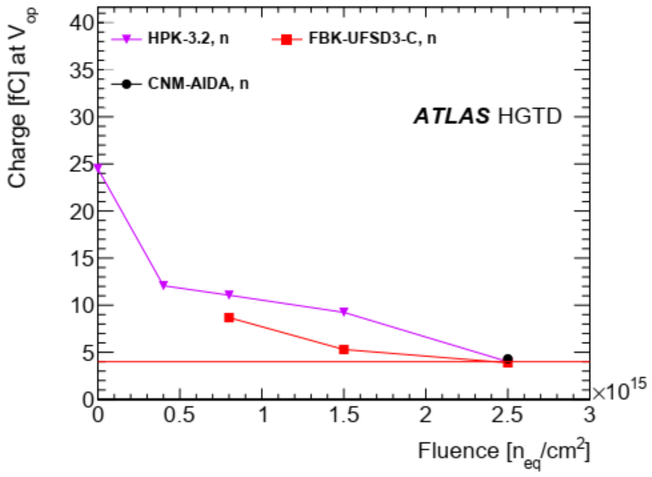
Test beam verified high hit efficiency

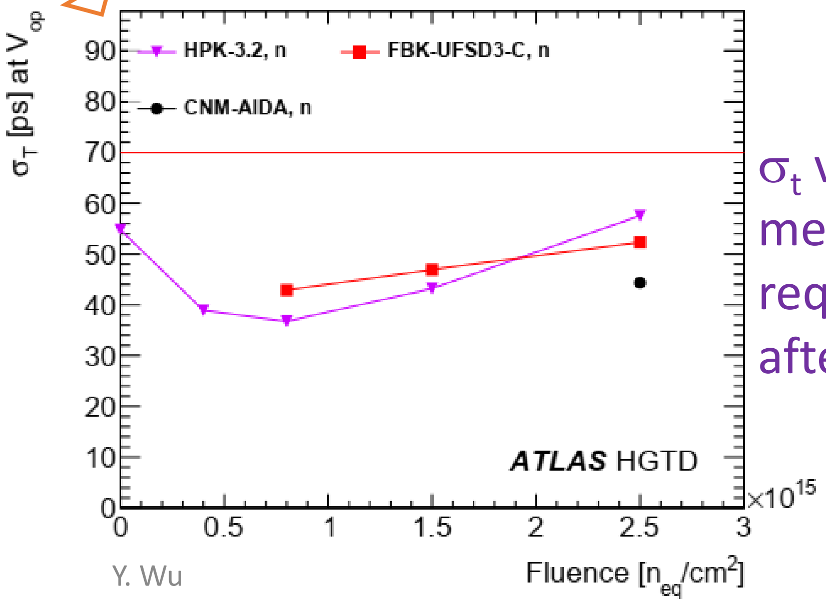


Operation voltage v.s. fluence: 100→ 700 V



Charge collection v.s. fluence

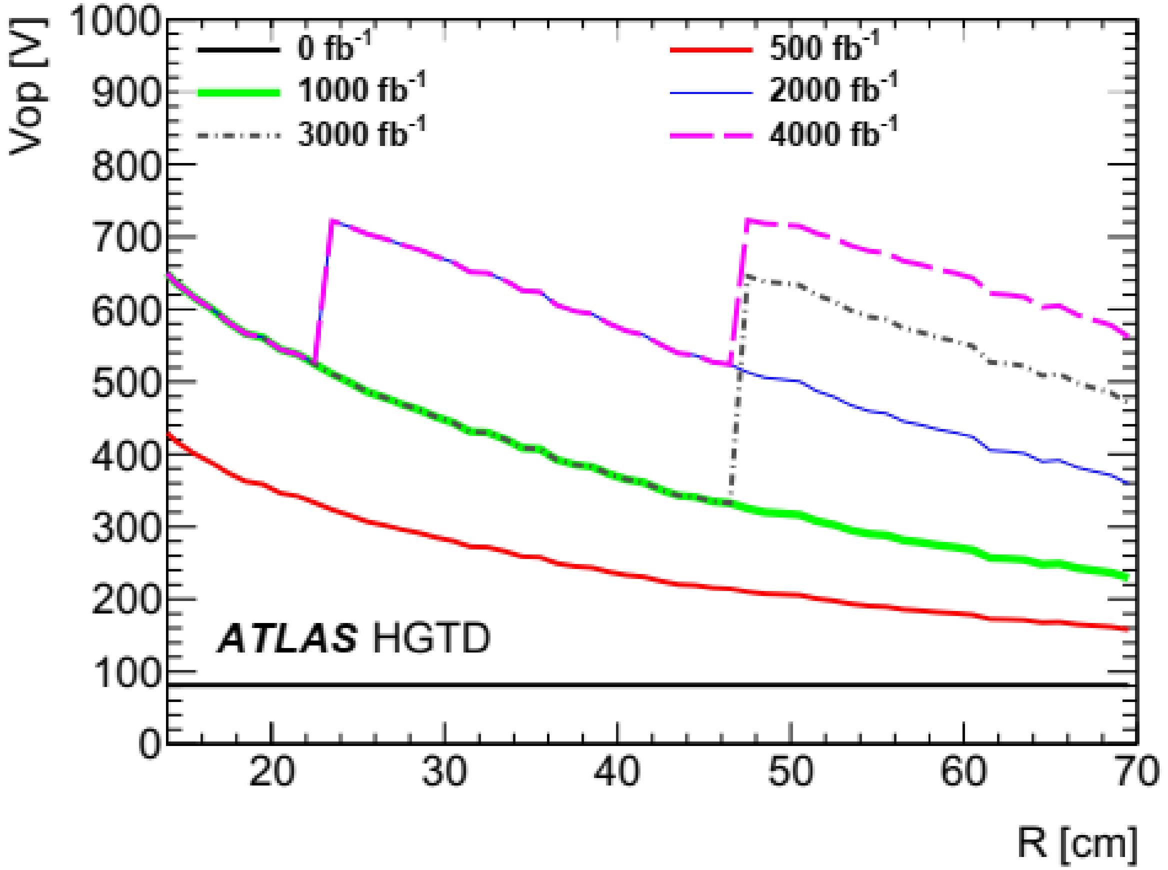




σ_t v.s. fluence: meet the requirement after irradiation

Operation and Plan

Planned operation voltage for LGAD v.s. lumi / R



LGAD manufacturing shown to meet detector specification

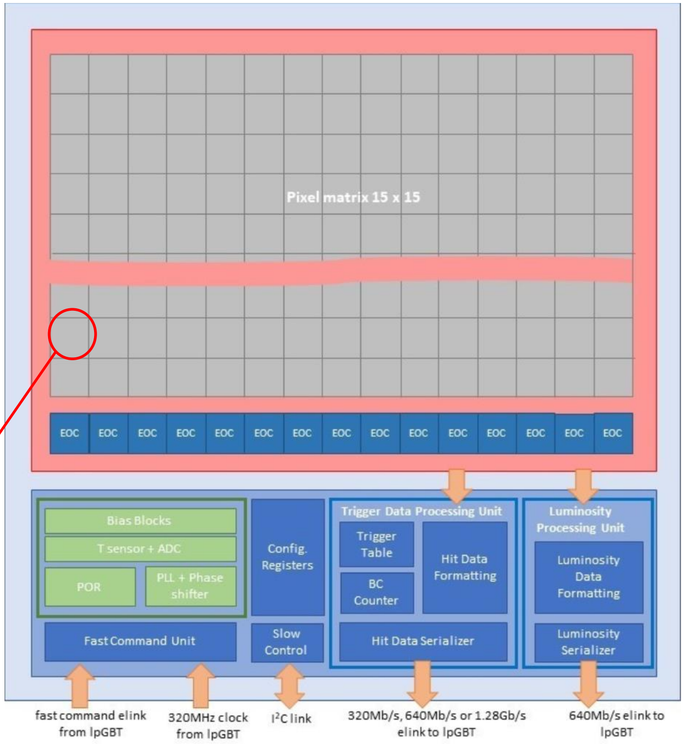
Further optimization ongoing …

Frond-end Electronics

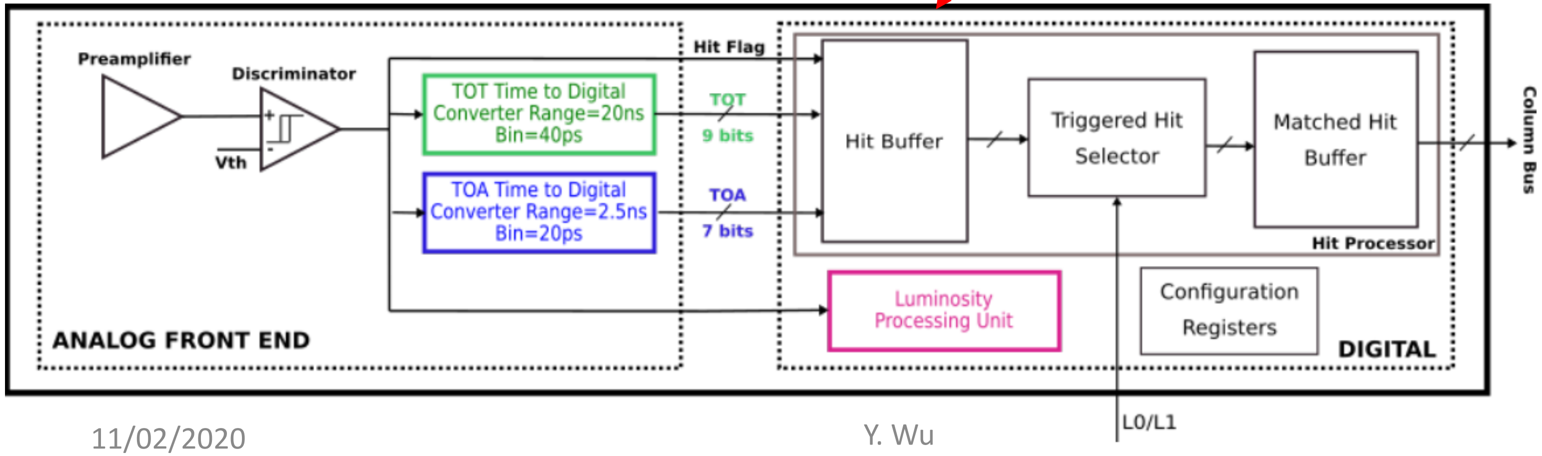
ALTIROC Key characteristics:

- Radiation hardness
- Noise <= 0.5 fC
- Dynamic range: 4-50 fC
- Low min-threshold: 2 fC
- Cross-talk < 5%
- Jitter, time-walk, TDC O(10) ps
- e-link driver bandwidth up to 1.28 Gbit/s

ASIC chip schematic

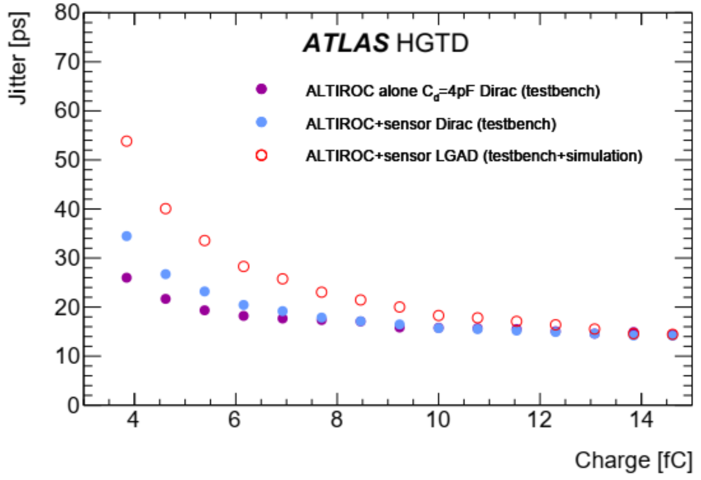


Single channel schematic

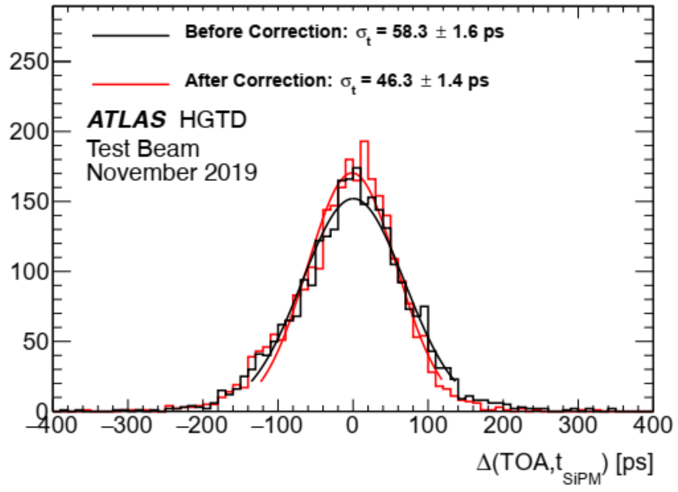


FEE performance

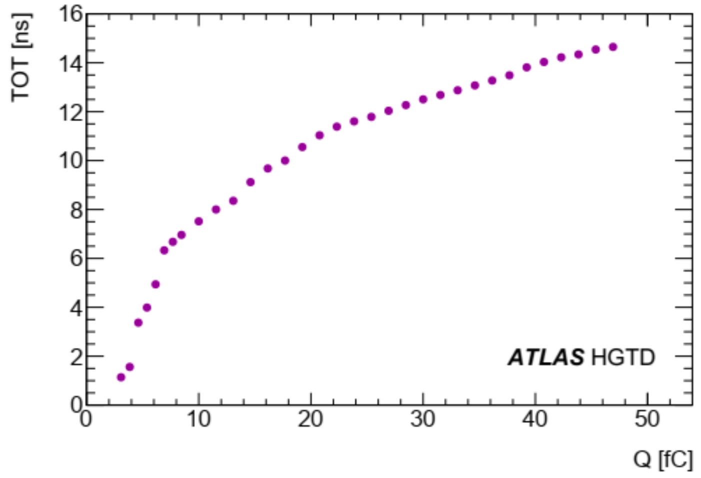
Jitter Estimation: meet the goal



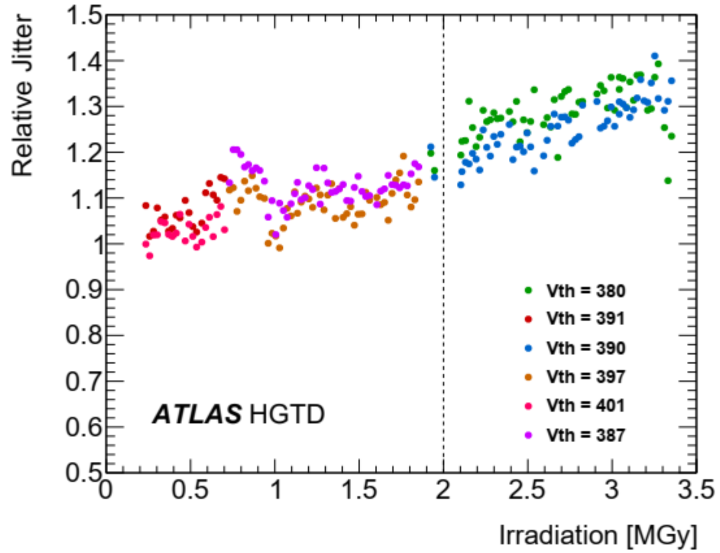
Test-beam LGAD+ALTIROC time resolution



TOT vs Q: used for time-walk correction



Stability of jitter v.s. irradiation

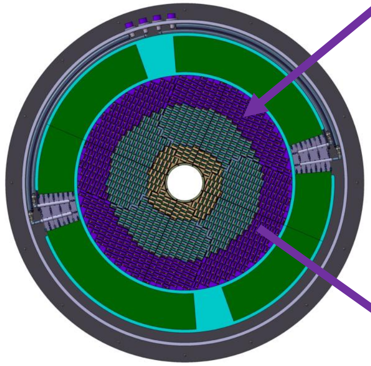


Iteration and completion of ALTIROC ongoing…

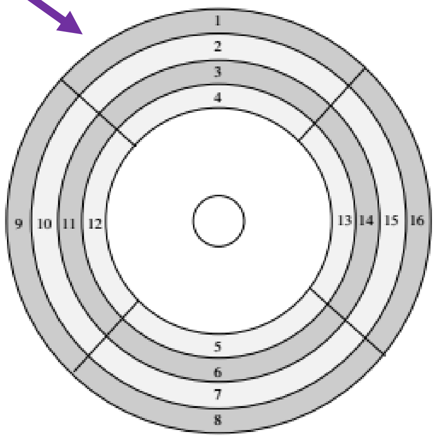
Luminosity Measurement

Precise knowledge of luminosity is a key to many physics studies

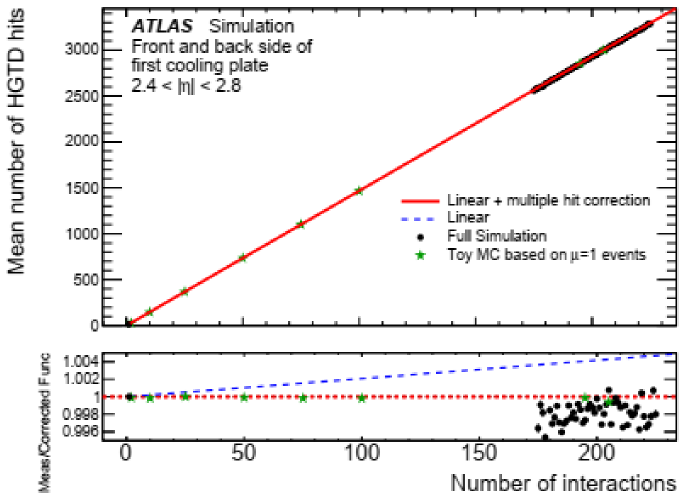
HGTD provides precise bunch-by-bunch luminosity measurement in its outmost ring



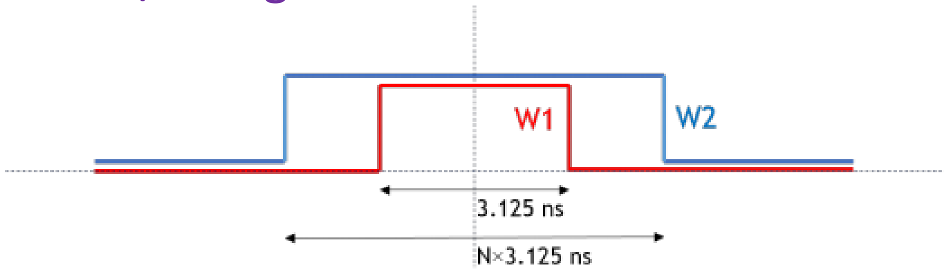
Planned for 16 partitions with independent measurements



High granularity → great linearity between measurements and luminosity

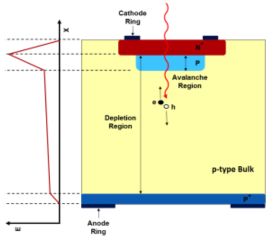


Unique two timing window scheme at ASIC level give in-situ measurement of noise/afterglow

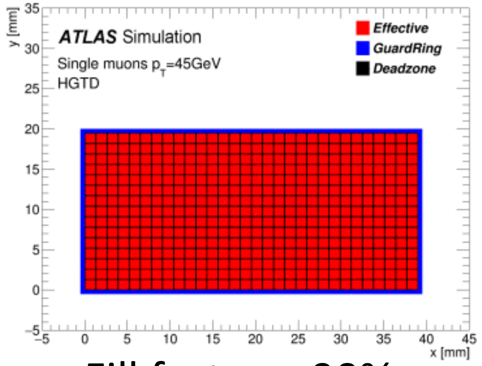


The Flow

Single LGAD Pad

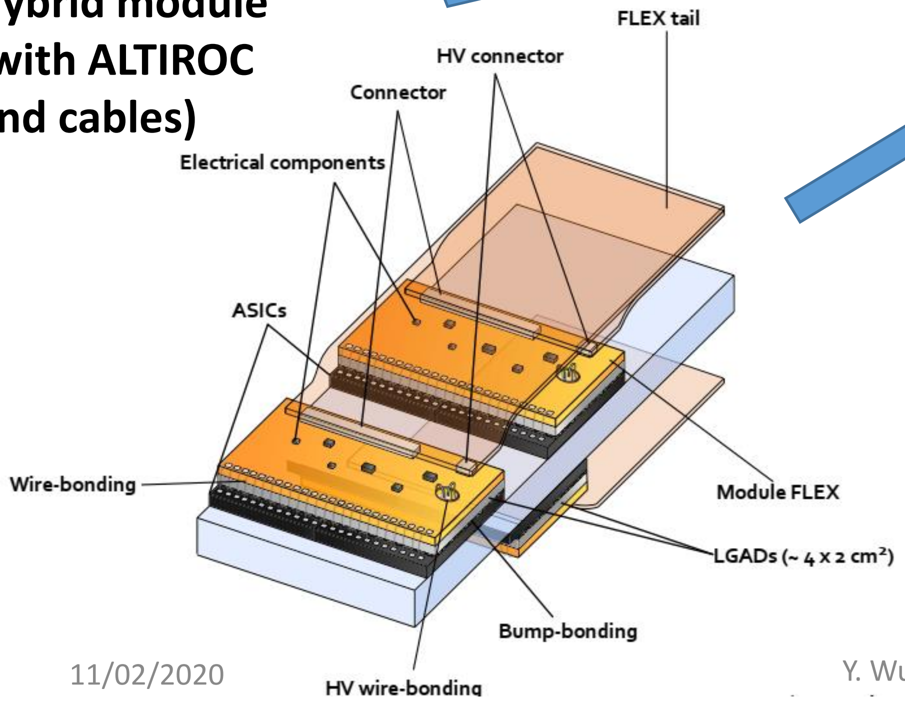


15 x 30 LGAD module



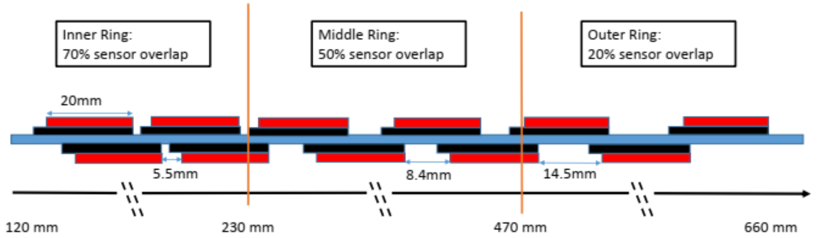
Fill factor ~ 90%

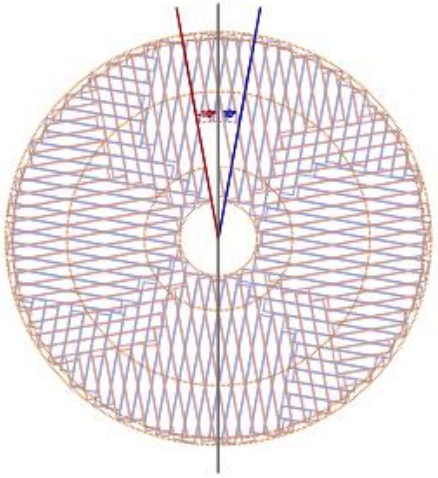
Hybrid module (with ALTIROC and cables)



Position modules on support structure

Front/Back Overlay per layer





Layer 1 and 2: small inclination angle

Summary

HGTD will be a novel subdetector in ATLAS for HL-LHC, providing precise timing measurement capabilities and unique luminosity measurement, to host in a very narrow space

Adapt **novel detector technologies** (LGAD) and require **high-standard ASIC**, both been carefully R&D-ed and found promising

Technical Design Report (ATLAS-TDR-031) recently approved by CERN, R&D / prototyping / production continues in next years, to be install in 2026-2027

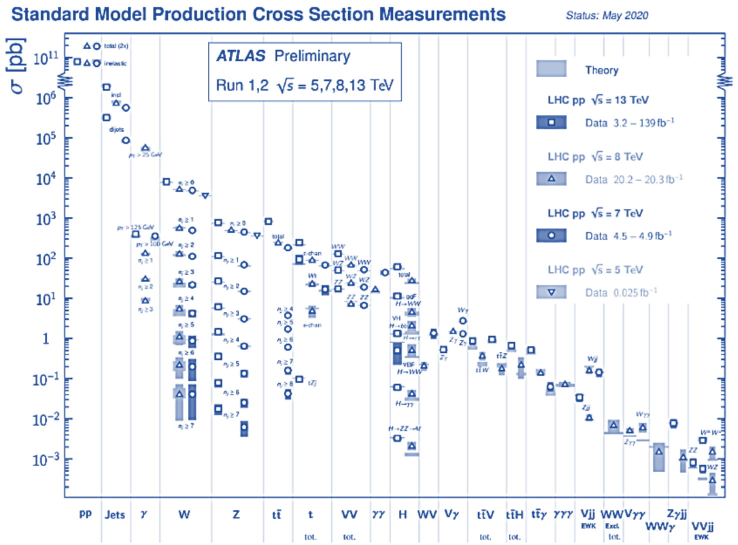
Although forward only, potential of physics capabilities shall not be underestimated and is being pursued

Thank you for your attention!

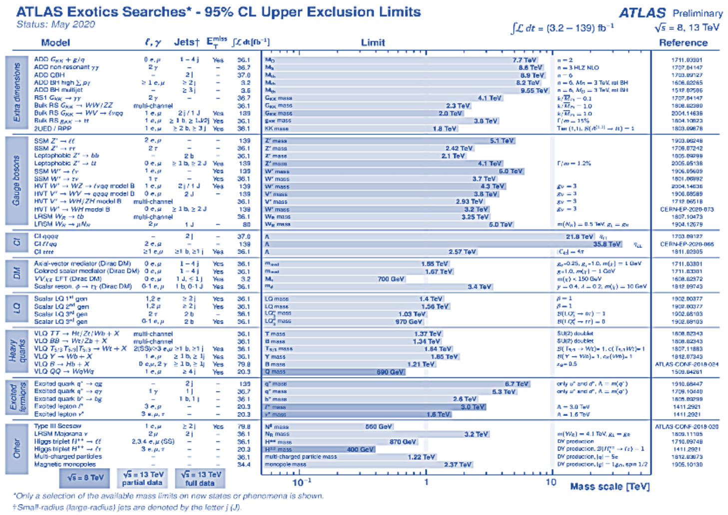
Backup

Now: 140 fb^{-1} 13 TeV pp collisions

Measurements



Searches

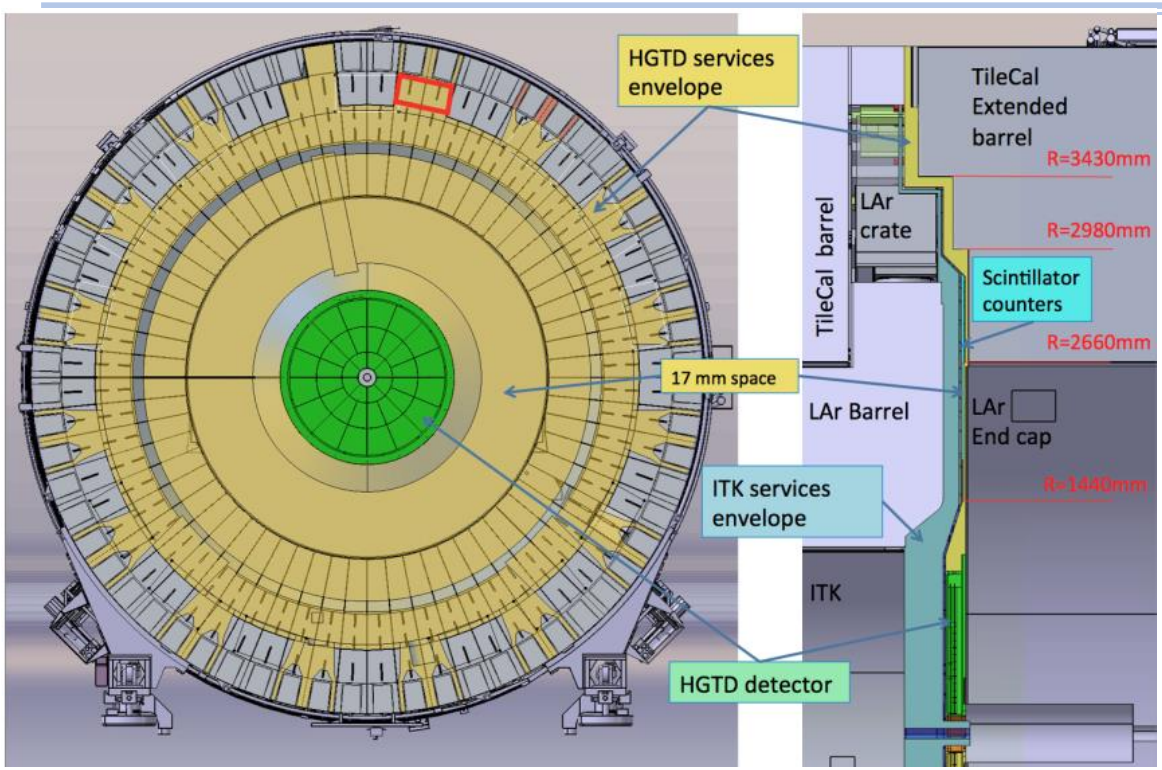


1000+ phase spaces or channels investigated

Standard Model more precisely **verified**, yet **no new physics** found

Ultimate sensitivity to help reveal the nature of Higgs boson and existence of new physics at **High-luminosity LHC,** with about **3 ab^{-1}** 14 TeV pp collisions

More



Cooling and services with a very tight space budget

=> Careful R&D has been conducted