Fast timing detectors for HL-LHC in ATLAS and CMS

LHCP2018: Sixth Annual Conference on Large Hadron Collider Physics,
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Christian Ohm (KTH Stockholm & Oskar Klein Centre),
on behalf of the **ATLAS** and **CMS** collaborations

Outline

1. The challenge: pileup at the HL-LHC
2. The MIP timing detectors in ATLAS and CMS
3. Impact on performance for physics objects
4. Impact on physics program
5. Additional usage for the timing detectors
6. Summary

Outline

Related talks at LHCP:

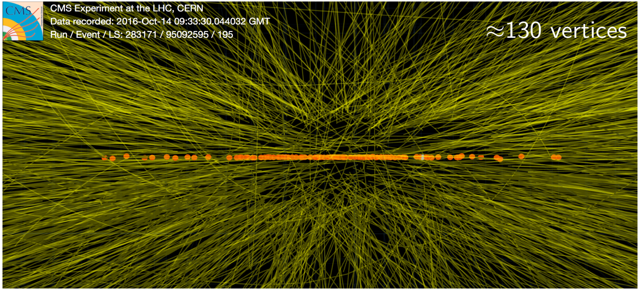
- Later this session: Ed Scott, “Calorimetry at very forward rapidity”
- Plenary on Sat: Jean-Baptiste Sauvan, “Status of ATLAS and CMS upgrades on calorimetry and timing and future prospects”

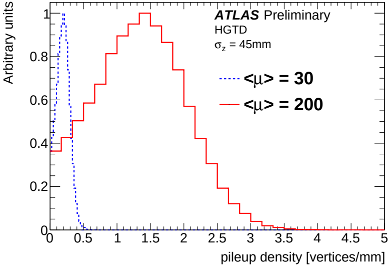
More information:

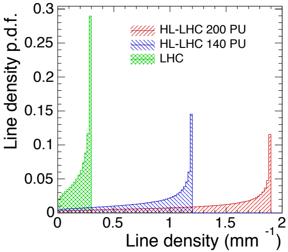
- CMS Technical Proposal
- ATLAS Technical Proposal - soon public!
- Recent CERN Detector Seminars:
  - Josh Bendavid (CMS), May 4, 2018
  - Laurent Serin (ATLAS), June 1, 2018

The challenge: pileup

Motivation: pileup at the HL-LHC ($\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2}s^{-1})







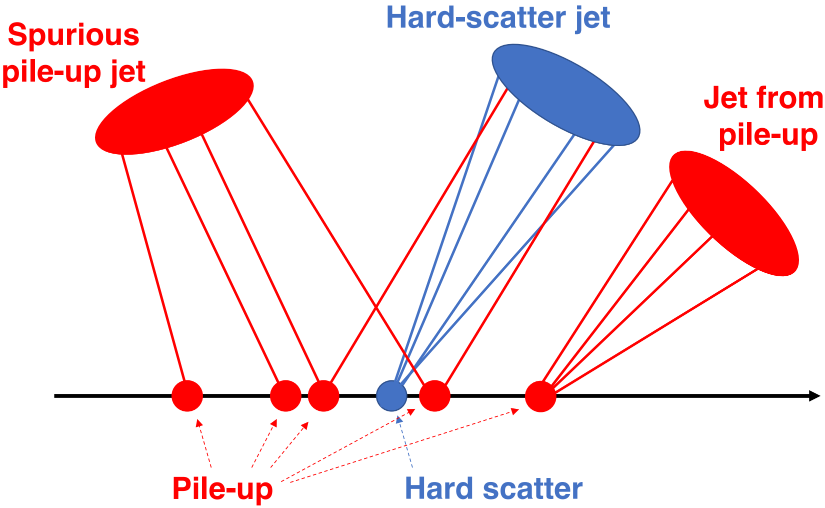
- Beam spot RMS 45 mm
- Pileup up to $\langle \mu \rangle = 200$

  $\Rightarrow$ 1.6 vertices/mm on average

Track-to-vertex association ambiguous when

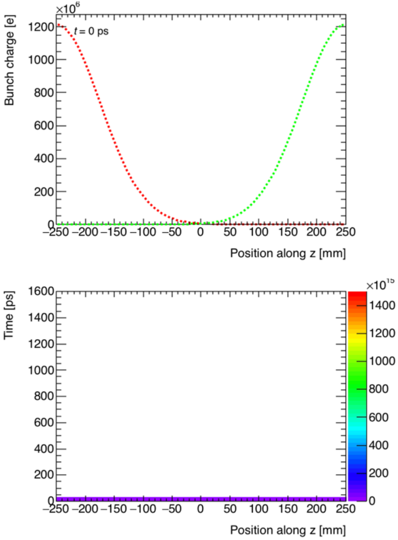
$$\sigma(z_0) \gtrsim 1/\rho(\mathrm{vtx})$$

Motivation: effects of pileup



Need to associate: tracks to vertices, tracks to objects ⇒ objects to vertices

The solution: Exploit the *time dimension* of the beam spot



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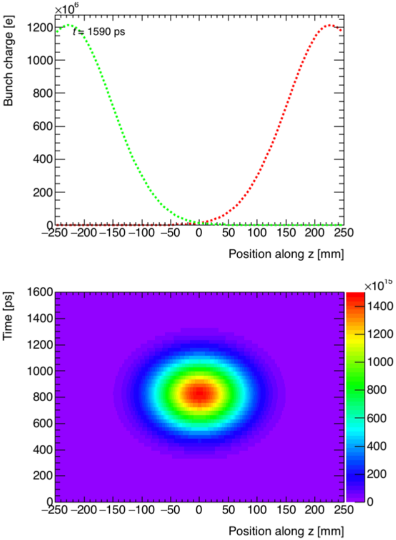
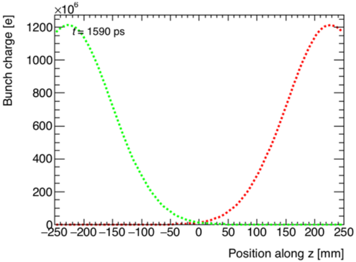
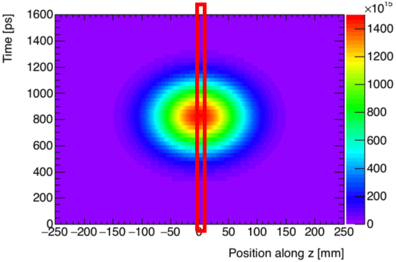


The solution: Exploit the *time dimension* of the beam spot

- Tracks coming from z region look like they're from one vertex
- Expect up to $\sim$10 vertices in region $\sim z_0$ resolution





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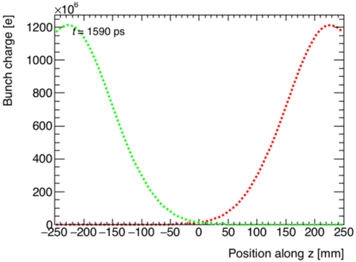

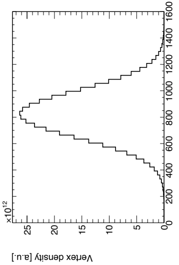

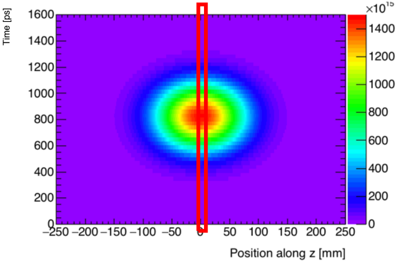

- With time info, the vertices can be resolved!
- Time projection (left) has bin size of 30 ps

(No crossing angle here, AU for z-scale, animation for illustration only!)

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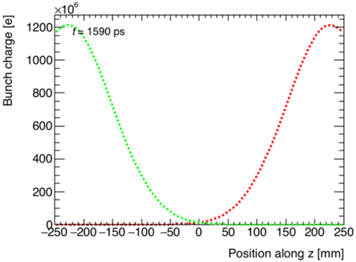
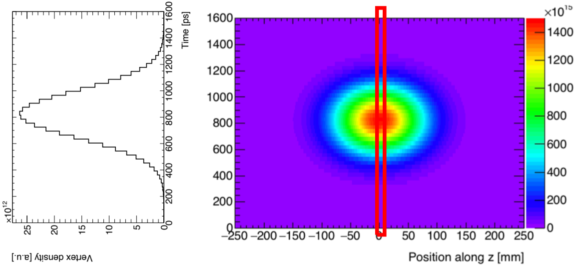




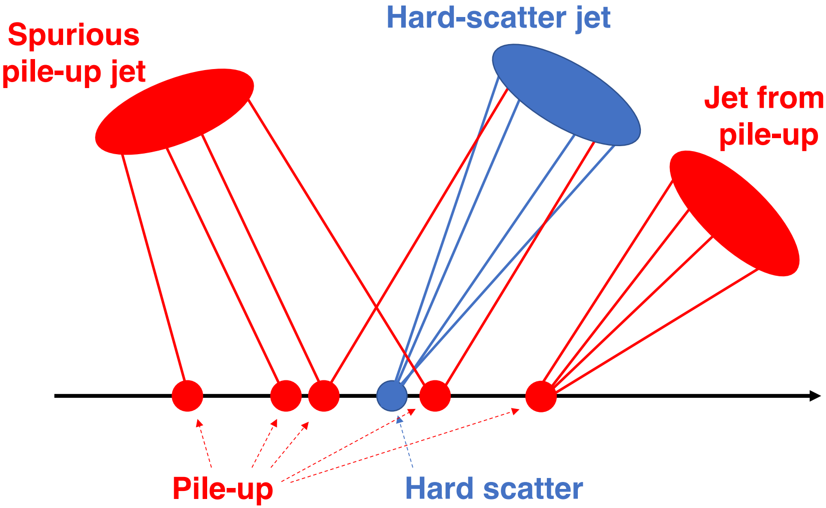
- With time info, the vertices can be resolved!
- Time projection (left) has bin size of 30 ps

(No crossing angle here, AU for z-scale, animation for illustration only!)

(NB! At $v = c$, 1 mm corresponds to 3 ps
$\Rightarrow$ Primary gain is *not* improved position from time-of-flight, but from knowing *times of vertices*

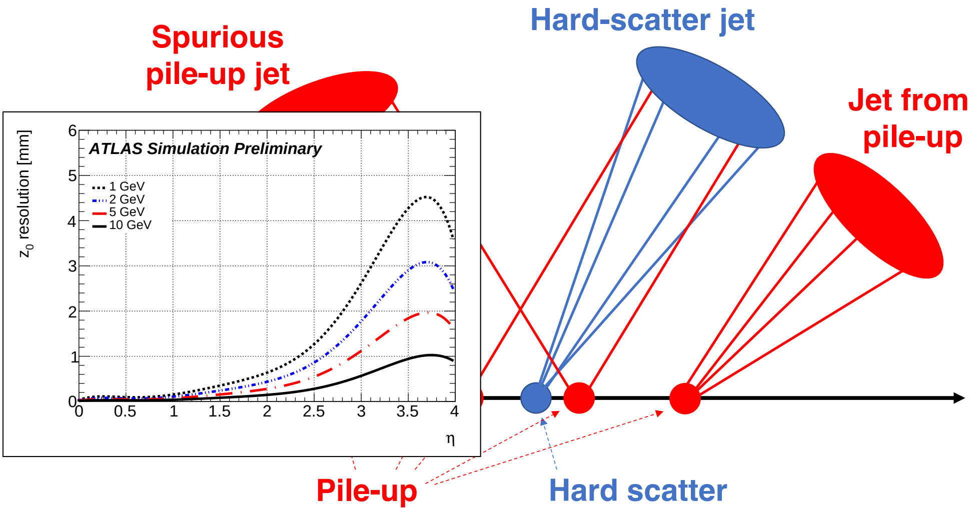
The detectors

Forward region most challenging



Measure time of tracks and thereby vertices ⇒ improve track-to-vertex association!

Forward region most challenging



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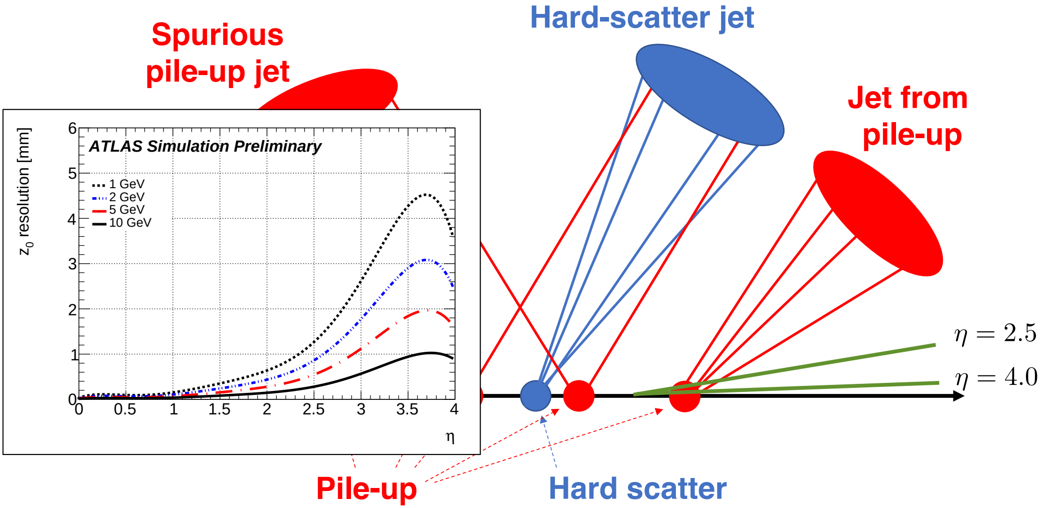
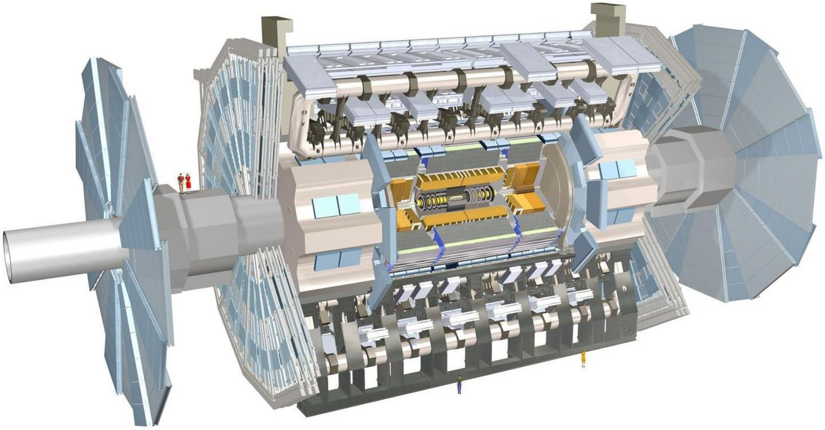


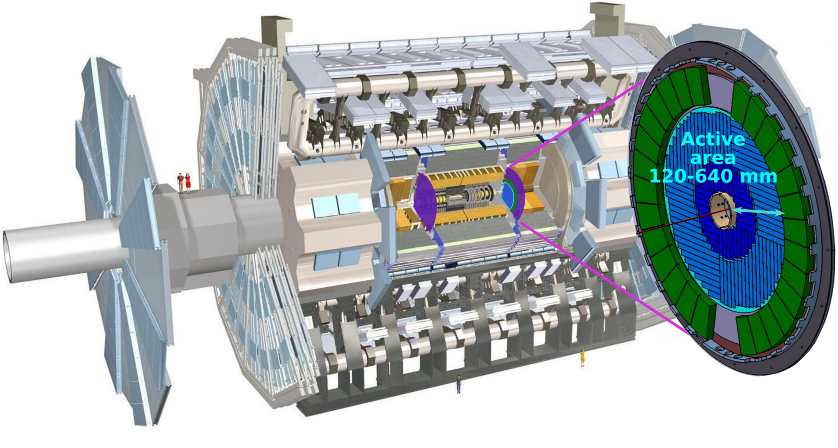
Measure time of tracks and thereby vertices ⇒ improve track-to-vertex association!

ATLAS: High-Granularity Timing Detector (HGTD)



The ATLAS detector

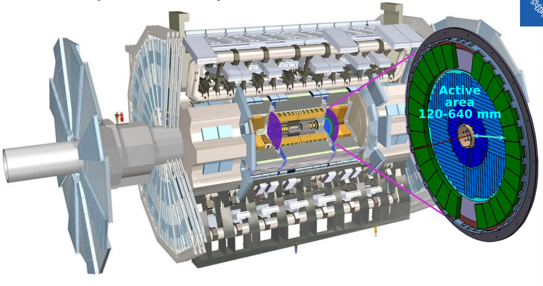
ATLAS: High-Granularity Timing Detector (HGTD)

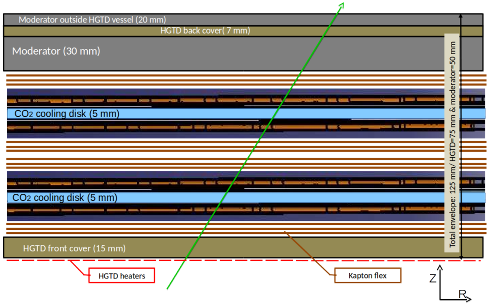


HGTD will provide timing measurements for charged particles in $2.4 < \eta < 4.0$.

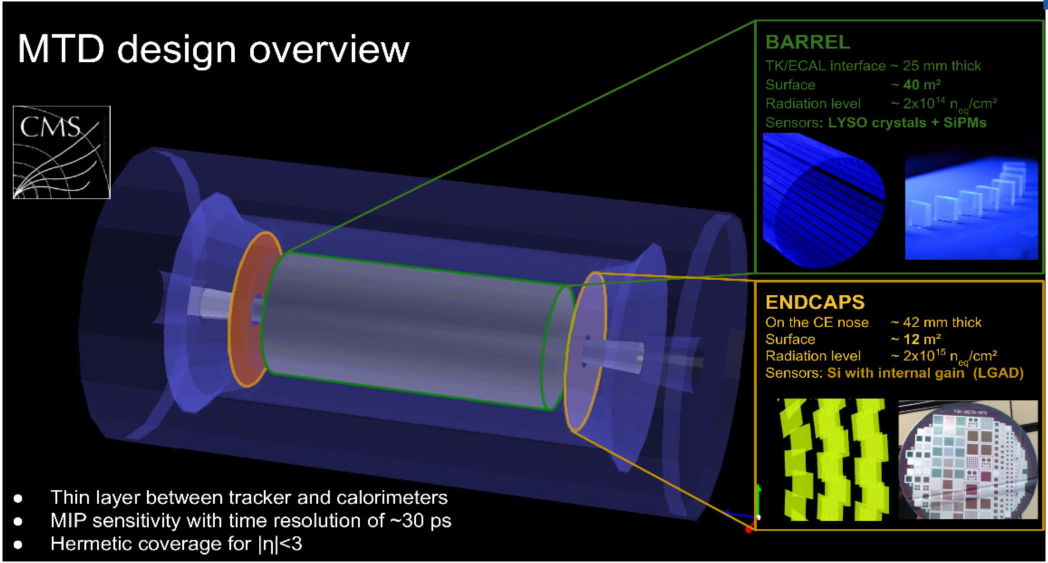
ATLAS: High-Granularity Timing Detector (HGTD)

- Two endcap disks at $z = \pm 3.5$ m (where Minimum-Bias Trigger Scintillators are now)
- 6.3 m^2 active area: $120 \text{ mm} < R < 640 \text{ mm}$
  $\Rightarrow 2.4 < |\eta| < 4.0$
- Radiation: 3.7×10^{15} $\text{n}_{\text{eq}}/\text{cm}^2$ fluence, 4.1 MGy TID (incl. safety of 1.5 resp 2.25)
- Si-based Low Gain Avalanche Diode technology $\Rightarrow \sigma_t = 30$ ps/track
- Sensors on both sides of two cooling plates with varying overlap $\Rightarrow$
  - $\langle n_{\text{hits}} \rangle = 3$ for $R < 320$ mm
  - $\langle n_{\text{hits}} \rangle = 2$ for $R > 320$ mm
- Requirement of occupancy $< 10\%$
  $\Rightarrow 1.3 \text{ mm} \times 1.3 \text{ mm}$ pixels





CMS: MIP Timing Detector (MTD)



CMS: MIP Timing Detector (MTD)

Barrel:

- LYSO crystal + silicon photo-multiplier
- Timing layer built into barrel tracker support tube (between tracker and ECal Barrel)
- Less radiation in barrel region
- Stringent installation schedule requirements $\Rightarrow$ use mature, production-ready technology

Endcap:

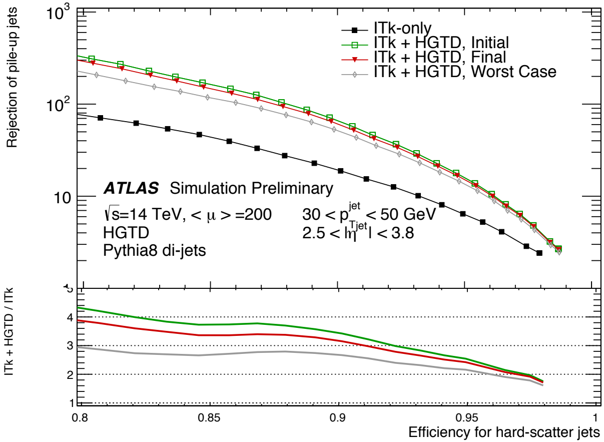
- Low Gain Avalanche Detector technology (like ATLAS)
- Single layer between tracker and calorimeter (on HGCal "nose")
- Higher radiation dose
- Later installation date $\Rightarrow$ time for more R&D

	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\lvert\eta\rvert < 1.5$	$1.5 < \lvert\eta\rvert < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\lesssim$ 2e14 neq/cm^2	$\lesssim$ 2e15 neq/cm^2
Installation Date	2022	2024

(LYSO = Lutetium-yttrium oxyorthosilicate)

Impact on performance of physics object reconstruction

Pileup-jet rejection: ATLAS

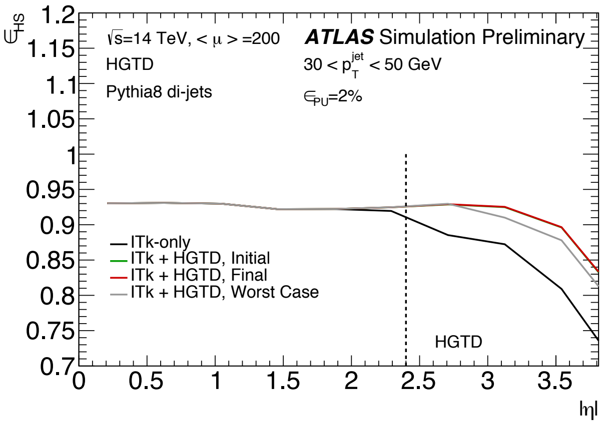


- Pileup-jet rejection as a function of hard-scatter jet efficiency in forward region
- No HGTD (black) and HGTD with different $\sigma(t)$

(Corresponding plots for CMS MTD in backups)

With initial and final timing resolution ($\sigma(\mathrm{t}) = 30$ ps), rejection improved by factor of 1.6-4

Pileup-jet rejection: ATLAS

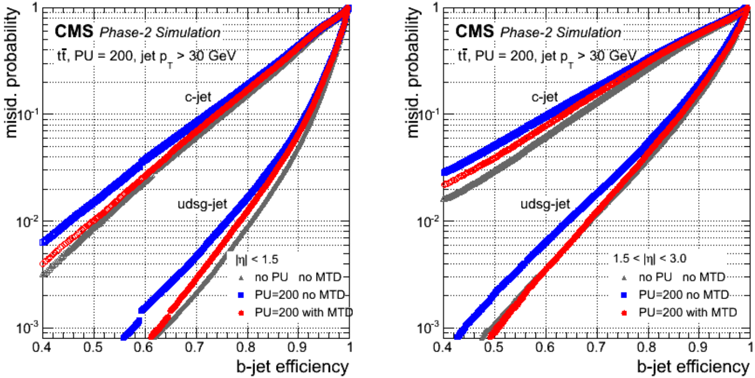


Fixed pileup-jet eff of 2%, HS eff vs η

- Pileup-jet rejection as a function of hard-scatter jet efficiency in forward region
- No HGTD (black) and HGTD with different $\sigma(t)$

(Corresponding plots for CMS MTD in backups)

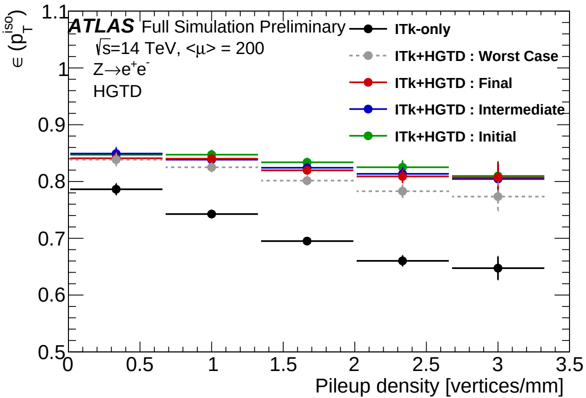
Tagging of heavy-flavor jets: CMS



- Heavy-flavor tagging improved significantly in CMS in both barrel (left) and endcap (right)
- In endcap $udsg$-jet rejection similar to with no pileup and no MTD
  $\Rightarrow$ MTD $\sim$ removes effect of pileup

(Corresponding plots for ATLAS HGTD in backups)

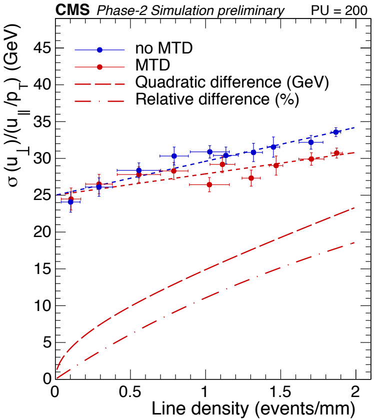
Improvements for lepton isolation: ATLAS



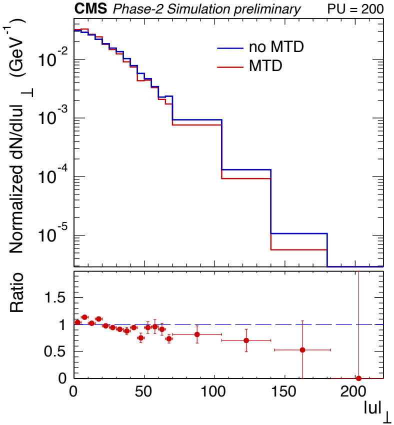
- Efficiency for **electron isolation** selection as a function of pileup vertex density
- No HGTD (black) and HGTD with different $\sigma(t)$ scenarios
- HGTD removes the majority of the effects of pileup, recovers 15% for average HL-LHC vertex density
- $\sigma(t) < 30$ ps does not help much

(Plots for *muon* isolation for CMS MTD in backups)

Improvements in $E_{\mathrm{T}}^{\mathrm{miss}}$: CMS



(a) MET Resolution



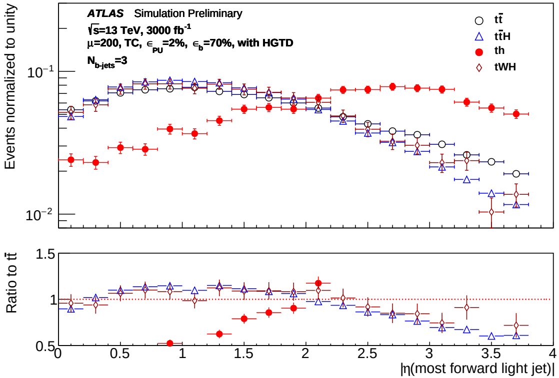
(b) MET Tails

15% resolution improvement (left), $> 30\%$ reduction of tails (right)

$\Rightarrow$ big help for $E_{\mathrm{T}}^{\mathrm{miss}}$-based BSM searches! (ATLAS working on $E_{\mathrm{T}}^{\mathrm{miss}}$ results towards TDR)

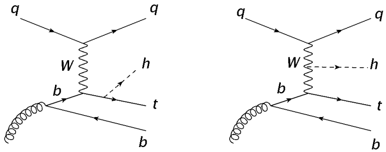
Impact on physics program:
Examples of studies done so far

ATLAS: Impact on tH (final state with ≥ 2 b-tagged jets)



$|\eta|$ for most forward light-jet shown in the $3b$ region for tH followed by $H \to b\bar{b}$ and the backgrounds from $t\bar{t}$ and $t\bar{t}H$ production

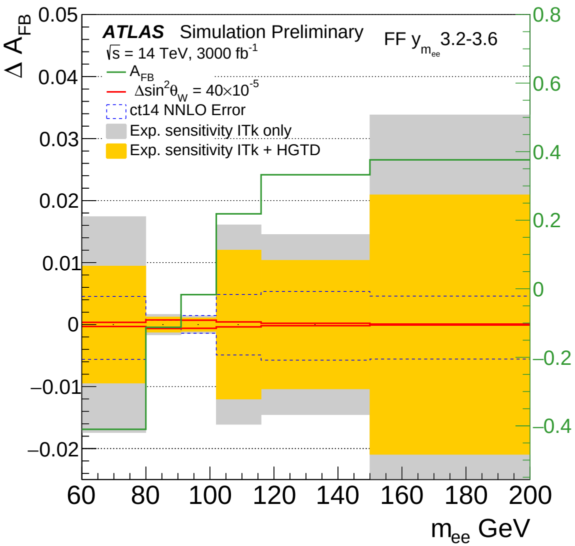
- Probes sign of top-Yukawa coupling directly (left, if negative $\Rightarrow \sigma(tH)$ x10), complementary to $t\bar{t}H$



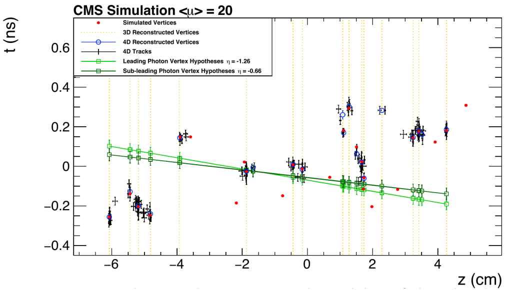
- Sensitivity to tH increased by 11% using HGTD
- Primarily due to improved b-tagging

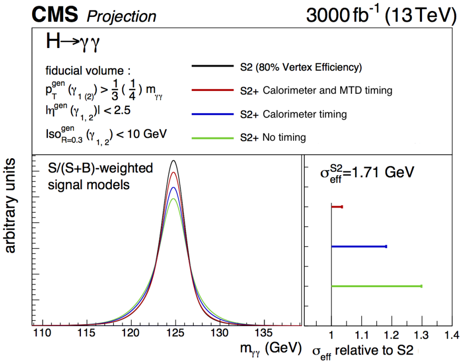
ATLAS: Measurement of weak mixing angle

- Precision SM: Measurement of weak mixing angle, $\sin^2\theta_W$
- In $Z \to ee$ channel, forward electrons provide sensitivity, HGTD gives gain
- Plot shows sensitivity improvement when both electrons in HGTD acceptance
- Inclusively, HGTD gives 11% reduction of total experimental uncertainty



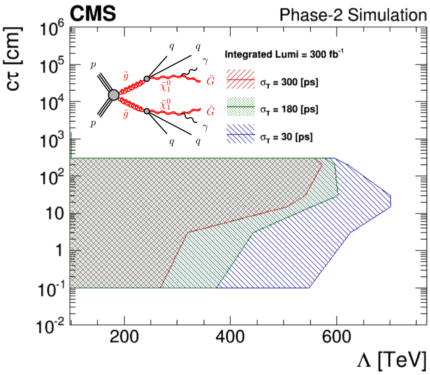
CMS: Vertex selection for $H \to \gamma\gamma$

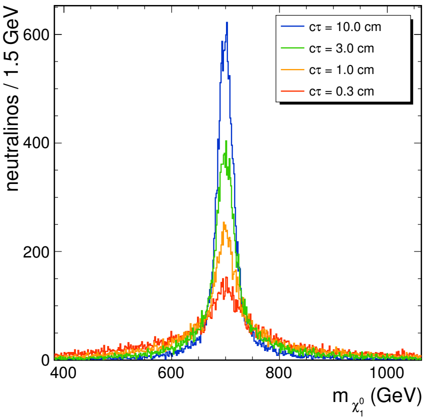




- Timing for vertices allows efficient photon-to-vertex association, triangulation in t-z space
- Restores vertex selection eff. to Run-2 level (80%), corresponding to ∼30% effect on $m_{\gamma\gamma}$
- Significant increase in stats-limited diff. xsec measurements

CMS: Examples for long-lived beyond-SM particles

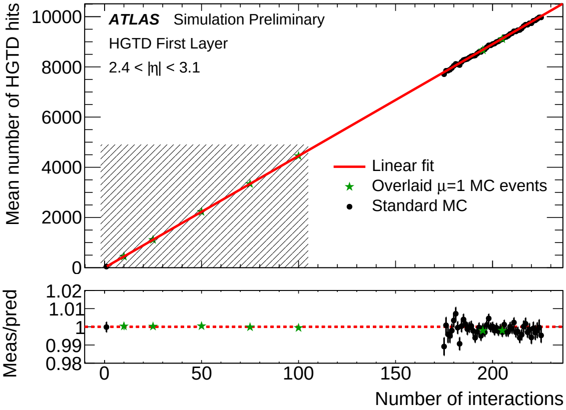




Long-lived neutralino (i.e. gauge-mediated SUSY breaking) decaying to $\tilde{G}$ and

- Late/displaced γ (left), increased mass reach in $m^0_{\tilde{\chi}}$
- Late/displaced Z (right) - allows LLP mass measurement (if discovered)

HGTD as a luminometer (ATLAS)



- Traditional luminometers relying on zero counting will struggle at HL-LHC (too high occupancy)
- HGTD will provide powerful luminosity capabilities:
  - High granularity ⇒ low occupancy
  - Can provide bunch-by-bunch luminosity estimates at 40 MHz
  - Fast, short detector signal ⇒ handle on "afterglow"
- Excellent n_{hits} vs. μ linearity!

Usage of timing detectors in the trigger

Quite simple: provide a Level-0 minimum-bias trigger (ATLAS)

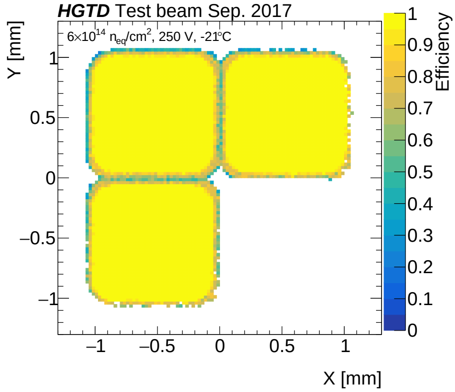
- Concrete plan to provide minimum-bias trigger (soft-QCD measurements, heavy-ions, van der Meer scans) - it *is* replacing the MBTS

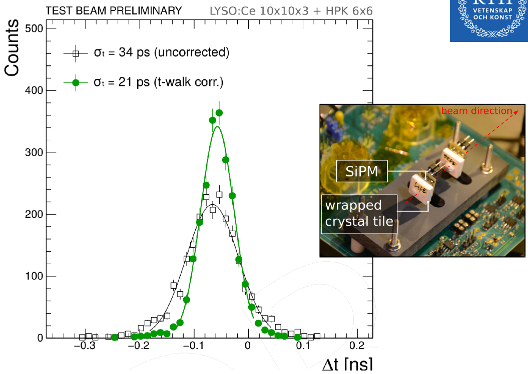
More use-cases being investigated:

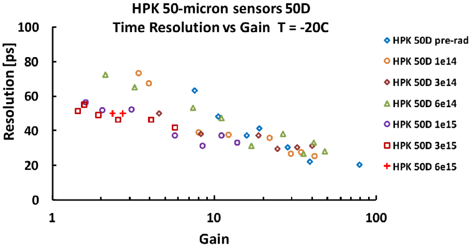
- Generally: could object-level improvements be implemented in high-level trigger?
  - Improve trigger-object performance?
  - Save CPU with event and object cleaning
- Could timing detectors provide info to the hardware trigger?
  - CMS: vertex timing info particularly powerful in combination with track trigger
  - ATLAS: investigating how online luminosity (μ) measurement can be used in trigger

Results from test beam measurements

- Comprehensive tests by ATLAS and CMS teams, benefiting very much from RD50 work!
- HGTD test beam paper (1804.00622)







Summary: ATLAS and CMS timing detectors

- Increased vertex density at HL-LHC $\Rightarrow$ ambiguous track-to-vertex association
- Spatially overlapping vertices can be resolved in the time dimension with accurate MIP ($\rightarrow$ vertex!) timing measurements
- ATLAS: HGTD
  - Two endcap disks, $2.4 < |\eta| < 4.0$
  - $\sigma_t = 30$ ps/MIP and high rad. $\Rightarrow$ LGADs
- CMS: MTD
  - Full barrel and endcap coverage ($|\eta| < 3.0$)!
  - LYSO+SiPM (barrel) and LGADs (endcap)
- Both projects added to respective Phase-II upgrade plan and moving towards TDRs

Significant object-level improvements:

- Pileup-jet tagging
- Lepton isolation
- Flavor tagging
- $E_{\mathrm{T}}^{\mathrm{miss}}$

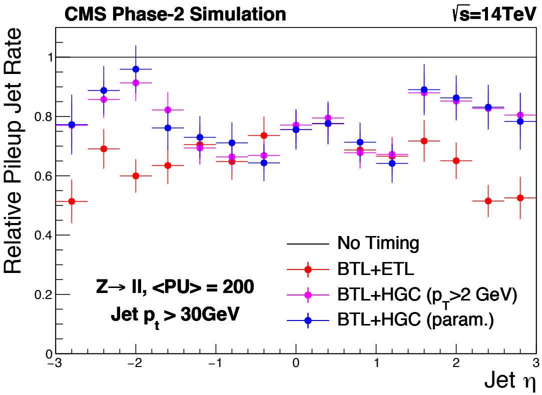
$\Rightarrow$ Physics sensitivity gains, e.g.

- Measurements of $\sin^2\theta_W$ and tH
- $H \rightarrow \gamma\gamma$, LLP searches
- Luminosity measurements (ATLAS)

Currently working on R&D, design, prototyping and studies for TDRs!

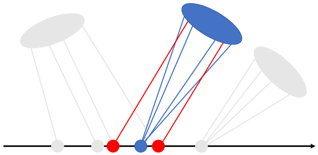
Back-up

Pileup-jet rejection: CMS



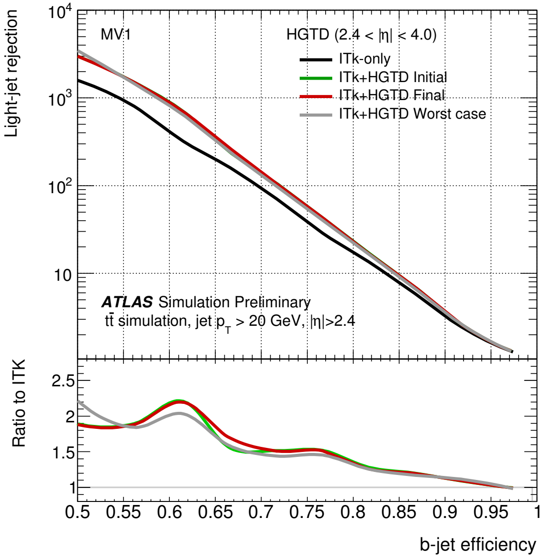
- Pileup-jet rejection as a function η
- Gains also seen in barrel region
- Reference uses no new timing info, clear additional gain from Endcap Timing Layer (ETL) also when comparing to scenario with High-Granularity Calorimeter (HGC)
- (Small difference between HGC timing resolution model used)

Tagging of heavy-flavor jets: ATLAS



- Light-jet rejection versus b-jet efficiency within the HGTD acceptance $\rightarrow$
- At 70% WP, light-jet rejection improved by a factor of $\sim$1.6

Particularly useful for physics with reducible bg from mis-tagged light jets!



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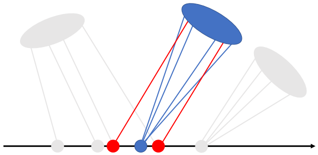
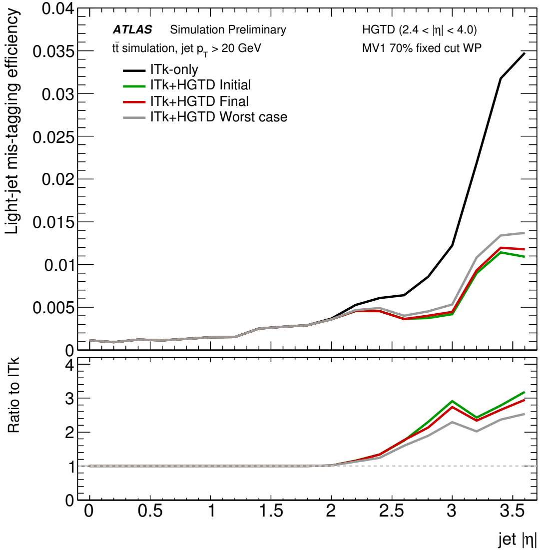
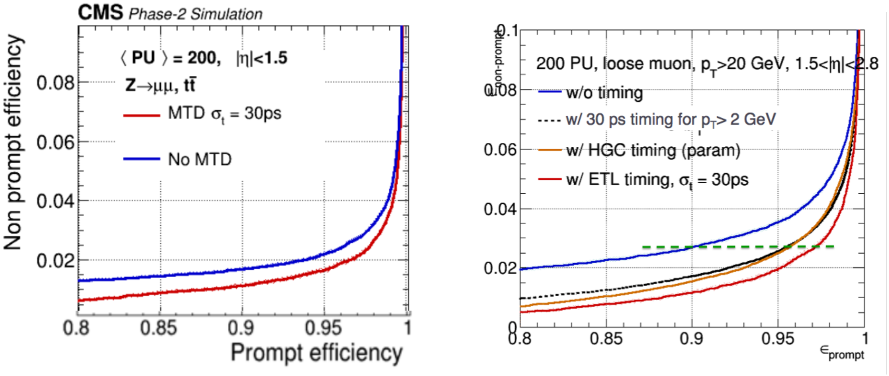


- Light-jet rejection versus b-jet efficiency within the HGTD acceptance $\rightarrow$
- At 70% WP, light-jet rejection improved by a factor of $\sim$1.6
- At high η rej. improved by factor $\sim$3

Particularly useful for physics with reducible bg from mis-tagged light jets!



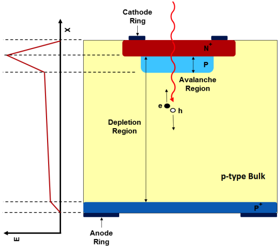
Improvements for lepton isolation: CMS

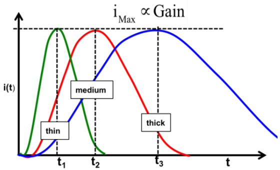


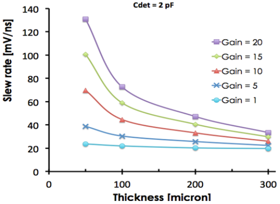
- Muon isolation improved also in CMS in barrel (left) and more significantly in endcap (right)

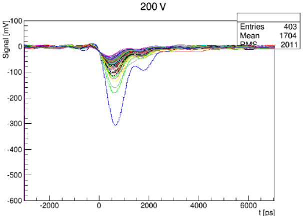
Low Gain Avalanche Diode

- n-on-p planar silicon detectors
- Low internal gain (lower noise amplification)
- Good radiation hardness
- Excellent timing resolution



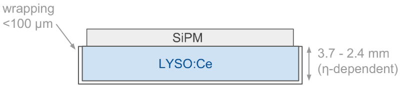




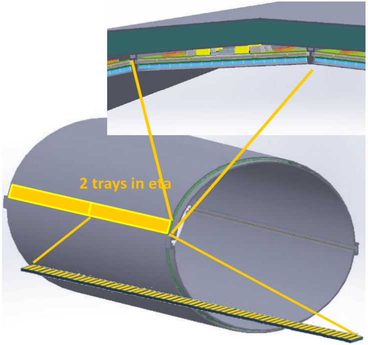


- Gain is independent of the thickness
- Thinner pads/larger gain give smaller rise times
- 50 µm is baseline and 35 µm under study
- Radiation damage can be mitigated by cooling ($-30\,^{\circ}$C)

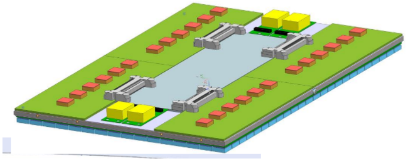
Details about CMS barrel layer design (borrowed from J. Bendavid)

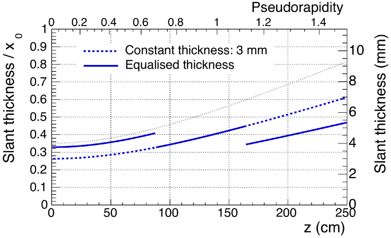


11x11 mm tile, 4x4 mm SiPM active area, ∼ 250k channels



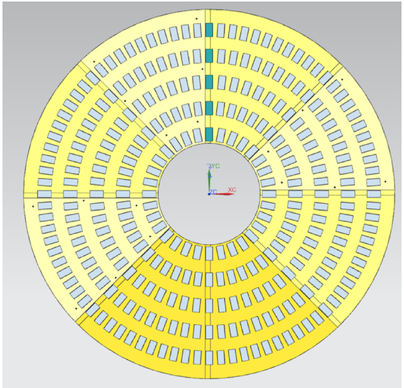
25 mm of available space within tracker support tube





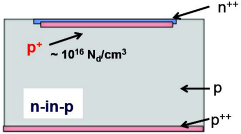
Variable thickness to maintain more uniform material budget and signal-to-noise

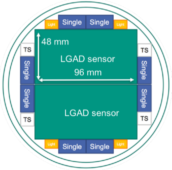
Details about CMS endcap layer design (borrowed from J. Bendavid)

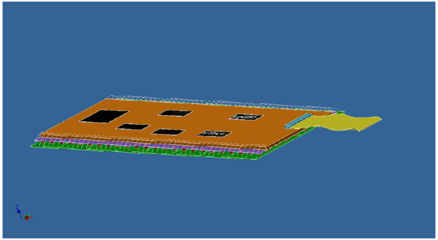


Overlapping disk structure for hermetic coverage with single LGAD layer

$\sim$ 95% coverage, limited by dead area between pixels

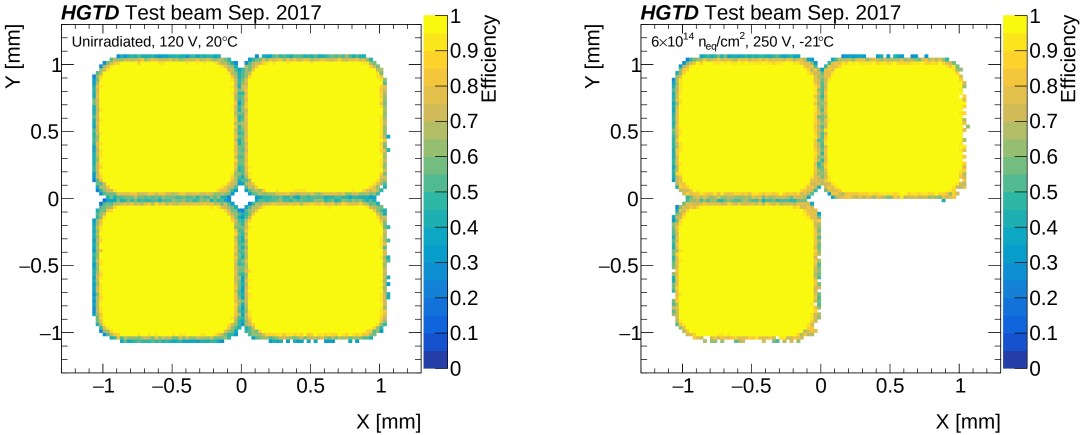






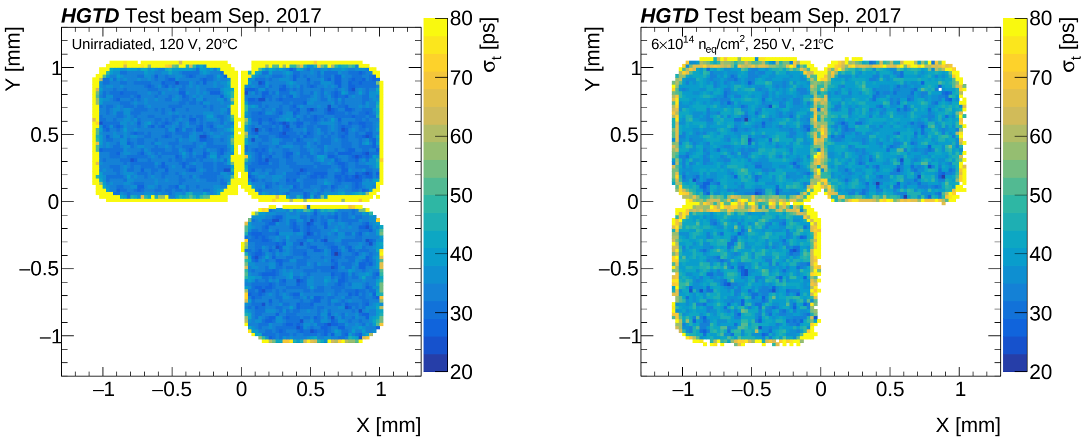
1x3 mm LGAD channels, read out in groups of 3 for $|\eta| < 2.1$ where occupancy allows, 1.8 M channels at readout level

Effect of irradiation in test beam (ATLAS, Sep 2017 measurements)



Efficiency kept high by increased bias voltage and lower operating temperature

Effect of irradiation in test beam (ATLAS, Sep 2017 measurements)



Timing resolution before and after irradiation
(Lower right: dead readout channel)

ATLAS HGTD: details about read-out electronics

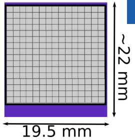
(Largely borrowed from Sabrina Sacerdoti's talk at

11th Workshop on Picosecond Timing Detectors for

Physics and Medical Applications, Torino, May 17th)

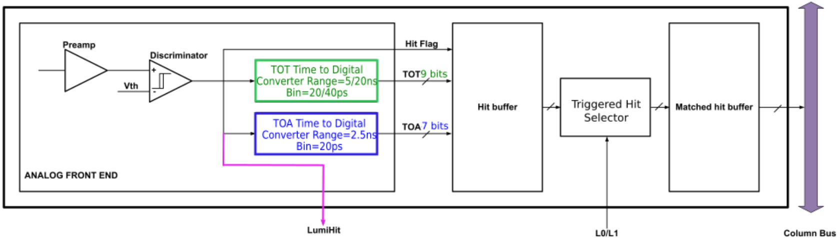
(For CMS MTD details, see their public TP document)

HGTD: ALTIROC ASIC



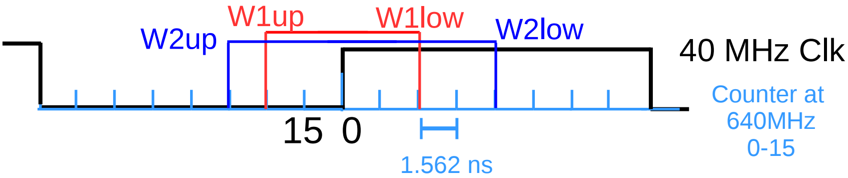
Sensors of 225 pixels $(1.3 \times 1.3\,\mathrm{mm}^2)$ read out by an ASIC bump-bonded to the sensor with the following requirements:

- Should keep the excellent time resolution of the LGADs, $\sigma_{el} < 25$ ps
- Power consumption constrained by cooling power (sensors at $-30\,^{\circ}$C)
- Current status:
  - ALTIROC0_v1: analog single-pixel chip, ALTIROC0_v2: test bench studies are starting
  - Single-channel readout layout finished, post-layout simulations ongoing
  - Off-pixel design ongoing (e.g. phase-shifter and lumi data formatting unit)
  - 5×5 pixel version (ALTIROC1) to be submitted in June



Electronics - Luminosity

- Luminosity is linearly proportional to n_{hits}
- Non-linearities arise from:
  - pixels hit by multiple particles
  - non-collision backgrounds (e.g. *afterglow*) $\Rightarrow$ measure n_{hits} in a smaller and wider time window around the BC



- Two time windows, W2>W1
- Rising and falling edges of both windows are tunable
- Transmit the sum of hits per ASIC for each BC
- Only for ASICs at $R > 320$ mm
- The sum over ASICs is computed in 64 regions and saved

Time resolution

Contributions to the resolution of the time measurement:

$$\sigma_t^2 = \sigma_L^2 + \sigma_{\text{timewalk}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{clock}}^2$$

- σ_L Landau fluctuations in the deposited charge in the sensors
- $\sigma_{\text{timewalk}}^2 = [\frac{V_{th}}{S/t_{\text{rise}}}]_{\text{RMS}} \propto [\frac{N}{dV/dt}]_{\text{RMS}}$
- $\sigma_{\text{jitter}}^2 = \frac{N}{dV/dt} \sim \frac{t_{\text{rise}}}{S/N}$
- σ_{clock}^2 contribution from the clock distribution < 10 ps

Additional contributions from TDC and t_0 calibration are expected to be negligible.