Expected performance of the upgrade ATLAS experiment for HL-LHC

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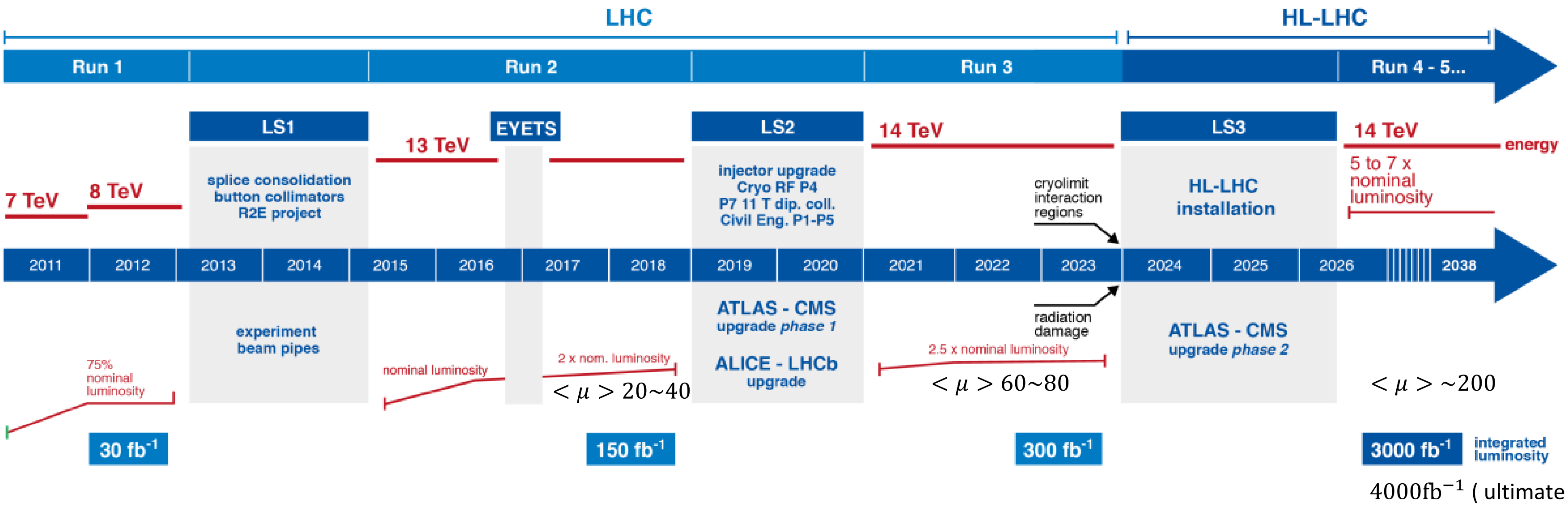
Outline

- **Physics programs and challenges at HL-LHC**
- **The upgrades of ATLAS detector for HL-LHC**
- **Expected performance**
  - Trigger and reconstruction of physics objects
  - Physics sensitivity
- **Summary**

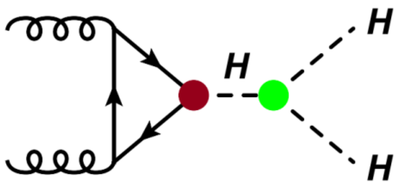
Roadmap to High Luminosity LHC



- The high-luminosity LHC (HL-LHC) is intended to provide $300\ \text{fb}^{-1}$ of data each year during an operating period of roughly 10 years.
  - An instantaneous luminosity of $\mathcal{L}\sim7.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - An average of 200 inelastic proton-proton interactions per bunch crossing (pile-up, $<\mu>=200$)

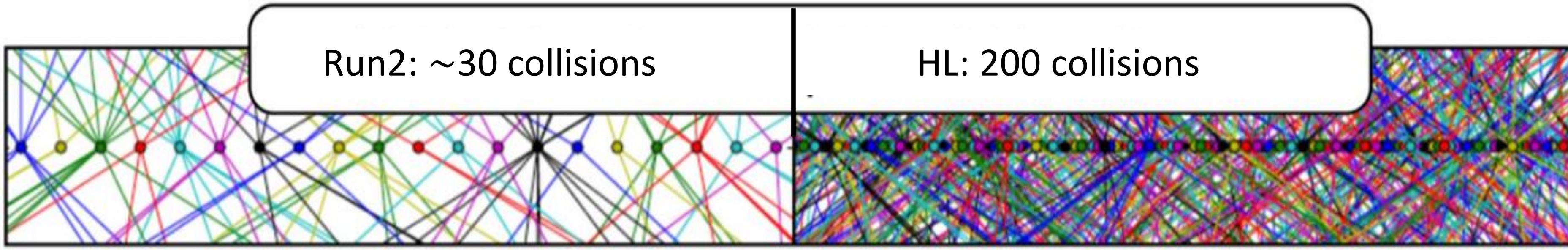
Physics programs at HL-LHC

- Precision measurements of **Higgs boson couplings**
  - As many Higgs production and decay channels as possible
  - Providing constraints **on potential non-Standard Model**
- Exploration of **Higgs potential** by study of Higgs-boson pair production
  - Higgs trilinear self-coupling, λ_{HHH}, related to the form of the Higgs potential
  - A direct test of the spontaneous symmetry breaking in SM
  - **Promising channels:** $HH \rightarrow b\bar{b} + b\bar{b},\quad b\bar{b} + \gamma\gamma,\quad b\bar{b} + \tau^+\tau^-$
  - ➢ **High efficiency b-tagging is critical**



- Sensitivity to **new particles or rare decays** involving new physics
  - Taking the BSM predicted Z' boson (mass~TeV) in the TopColour mode which primarily decays to $t\bar{t}$ as an illustration
  - A $t\bar{t}$ resonance search is a benchmark to evaluate **BSM physics prospects at HL-LHC**
  - ➢ **Dense tracking environment inside the high p_{T} jets**
    - Highly boosted top quarks due to the high mass of Z'

HL-LHC environment



- **High pile-up density at HL-LHC**
  - Current detector could not stand such harsh radiation environment
- **Challenging for track-to-vertex association**

➢ **Detector need to be upgraded**

  - **High-granularity** robust against the high occupancy
  - **Radiation-hard** withstanding the high particle fluence
  - **Extended coverage** of tracking with improved performance

- **Essential to mitigate effects from pile-up**
  - **Good objects reconstruction** (leptons, jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, b-tagging)

The Trigger and DAQ Upgrade

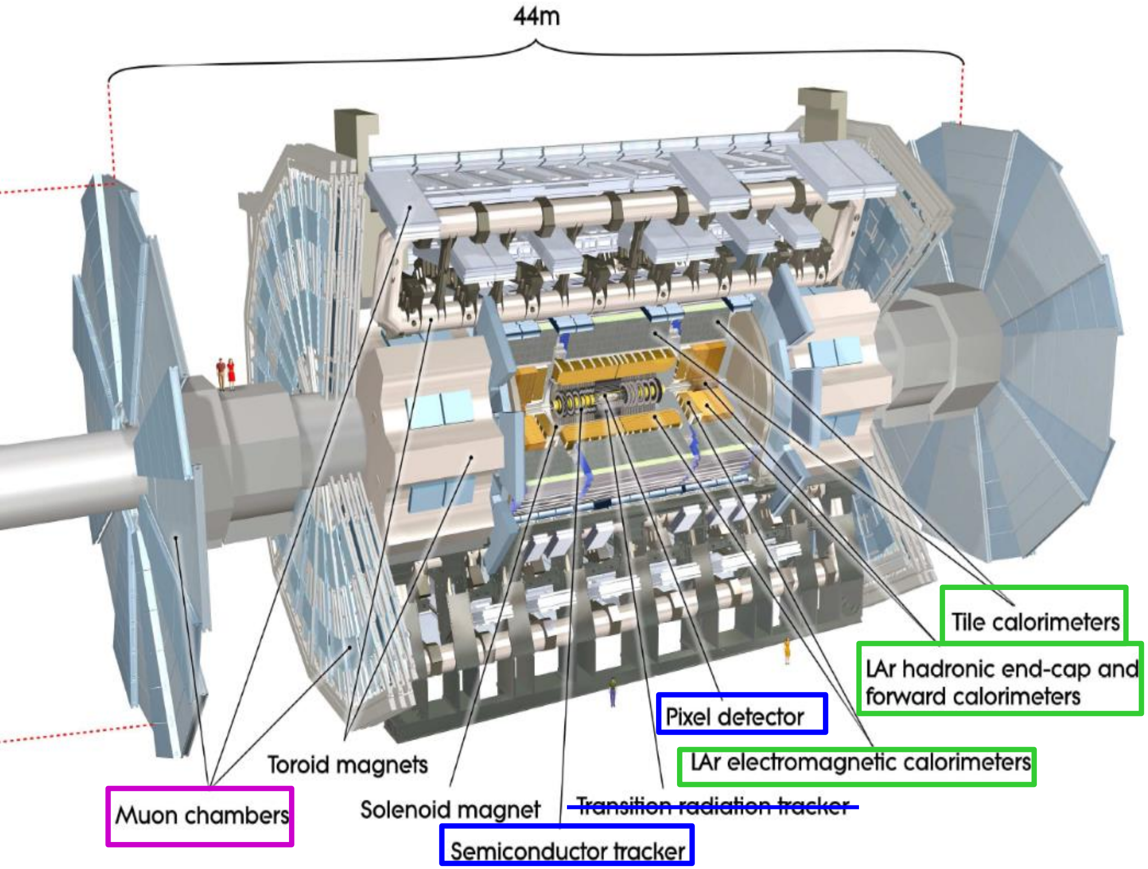
- **High instantaneous luminosity means higher data rates**

- **New designed trigger/DAQ system**
  - To cope with high rates while keeping **low trigger thresholds**
  - The baseline architecture: **a single-level hardware trigger + event filter**
  - **1 MHz trigger rate** instead of 100 kHz
    - A big challenge for the detector readout
  - **10 kHz output data rate** instead of 1 kHz

- **New readout electronics for all systems**
  - To cope with the increased occupancies and data rates

The Upgrades of ATLAS Detector for HL-LHC

- To maintain or improve ATLAS performance
- To cope with the increased occupancies and data rates



All-silicon new Inner Tracker (ITk)

New inner Muon barrel trigger chambers

Calorimeters (only TDAQ)

New readout electronics for all systems

New High-Granularity Timing Detector

Possible High-η muon tagger

TDRs for the ATLAS phase-II upgrades

- **6 Technical Design Reports**

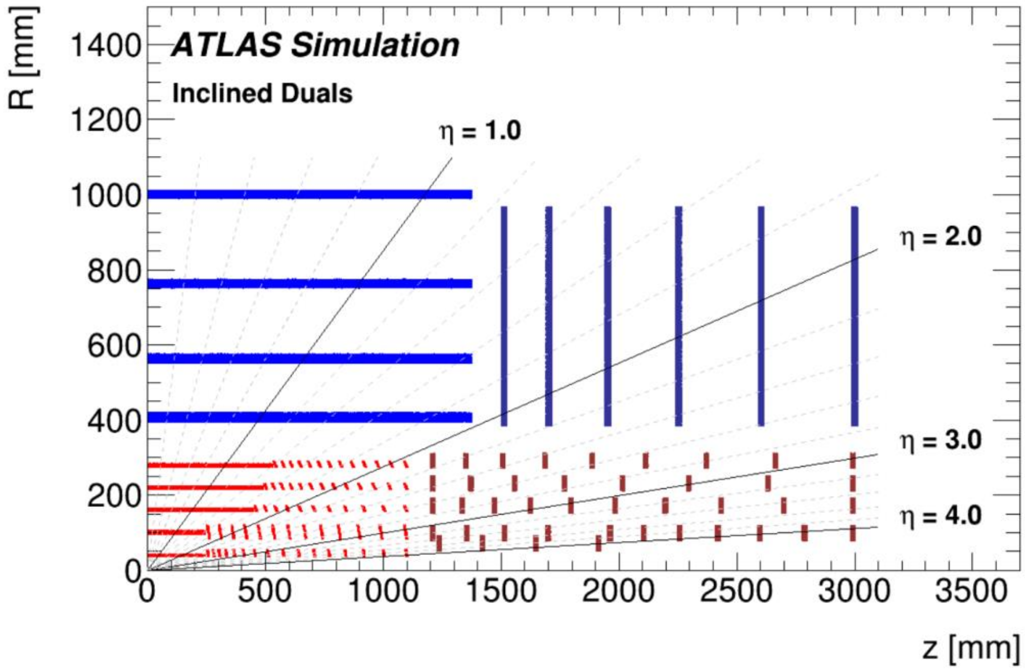
Tracker Strip TDR	CERN-LHCC-2017-005	**Public**
Muon TDR	CERN-LHCC-2017-017	
Tracker Pixel TDR		**Approved, will be public soon**
LAr TDR		
Tile TDR		
TDAQ TDR		

- **1 Technical Proposal**

HGTD TP — **Under review**

TDR is planned for early 2019

ATLAS Inner Tracker (ITk)



- **High-granularity**
- **Radiation-hard**
- **Extended coverage to η of 4** ($|\eta| < 2.5$ for Run 2)

- **200m^2 of silicon** with 5G pixels and 80M strips

The Pixel detector : 5 layers with inclined sensors in barrel

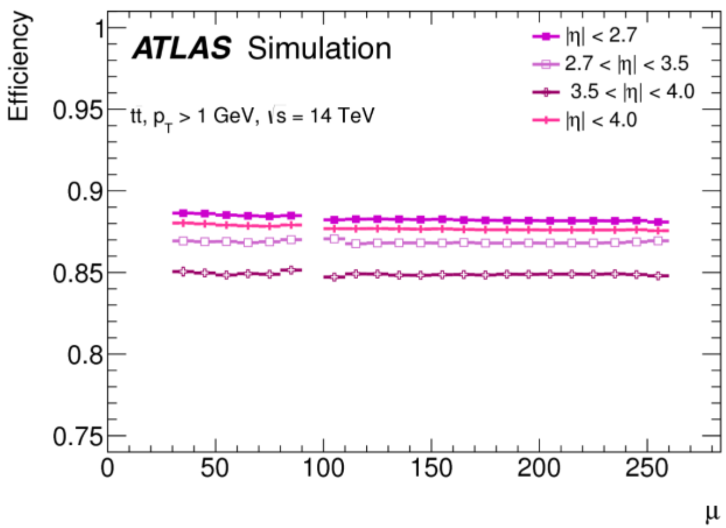
- **Inclined sensors** reduce the amount of silicon needed due to the large angular coverage
- **End-cap rings** (replacing traditional disks) are individually placed to optimize the coverage

The Strip detector : 4 barrel layers and 6 end-cap disks on each side

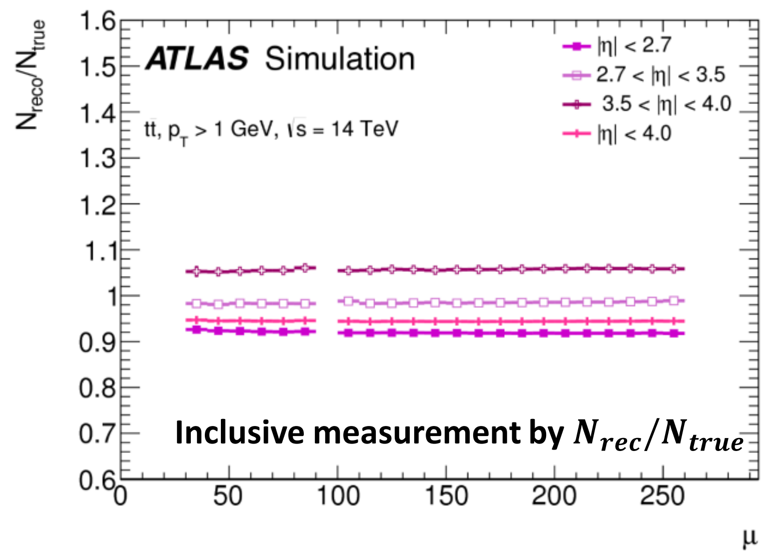
- **Double modules with a small stereo angle** to provide 2D measurements

Phase-II Tracking Performance (1)

- **Tracking efficiency**
  - Fraction of high quality tracks matched to a truth primary particle



- **Fake or mis-reconstructed tracks**
  - Secondary tracks
  - Mis-measured low-p_T tracks due to the limited σ_{p_T} in the forward region



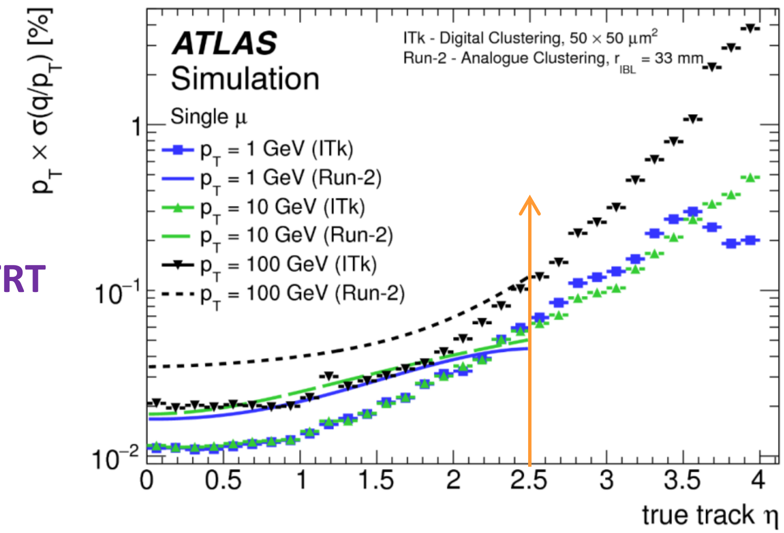
- **Tracking efficiency and fake rates are stable over the full range of pile-up for all intervals of η**
- **Good performance even at high pile-up**

Phase-II Tracking Performance (2)

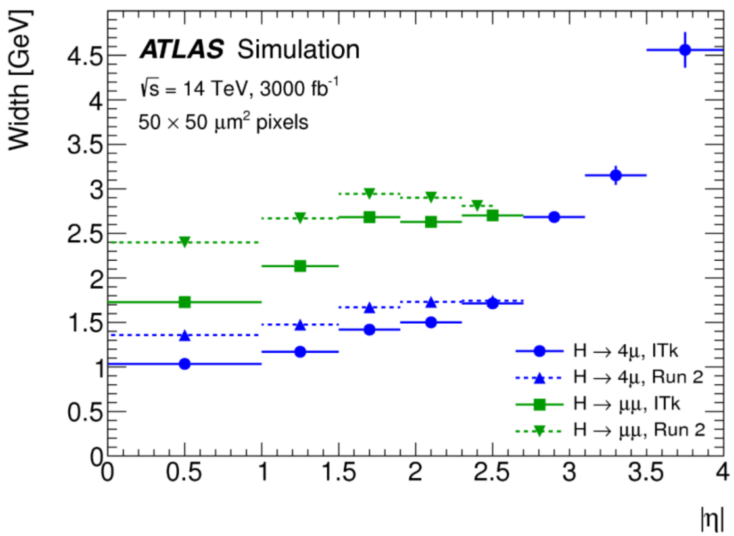
- **Better track parameter resolution**
  - **Smaller pixels**

  Better momentum resolution example
  - **Higher precision of strip tracker compared to TRT**
  - **Reduced material**

  Better momentum resolution → better mass resolution



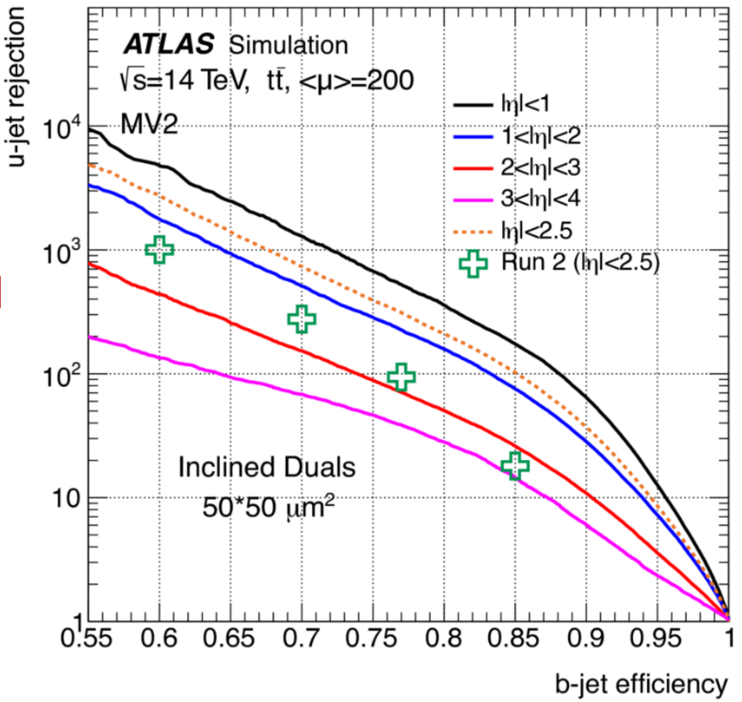
- **Comparable resolution of transverse impact parameter** with Run 2
- **Better resolution of longitudinal impact parameter** (smaller pixel pitch in beam direction)



- **Track parameter resolutions** directly determine the b-tagging capability and lepton or jet reconstruction

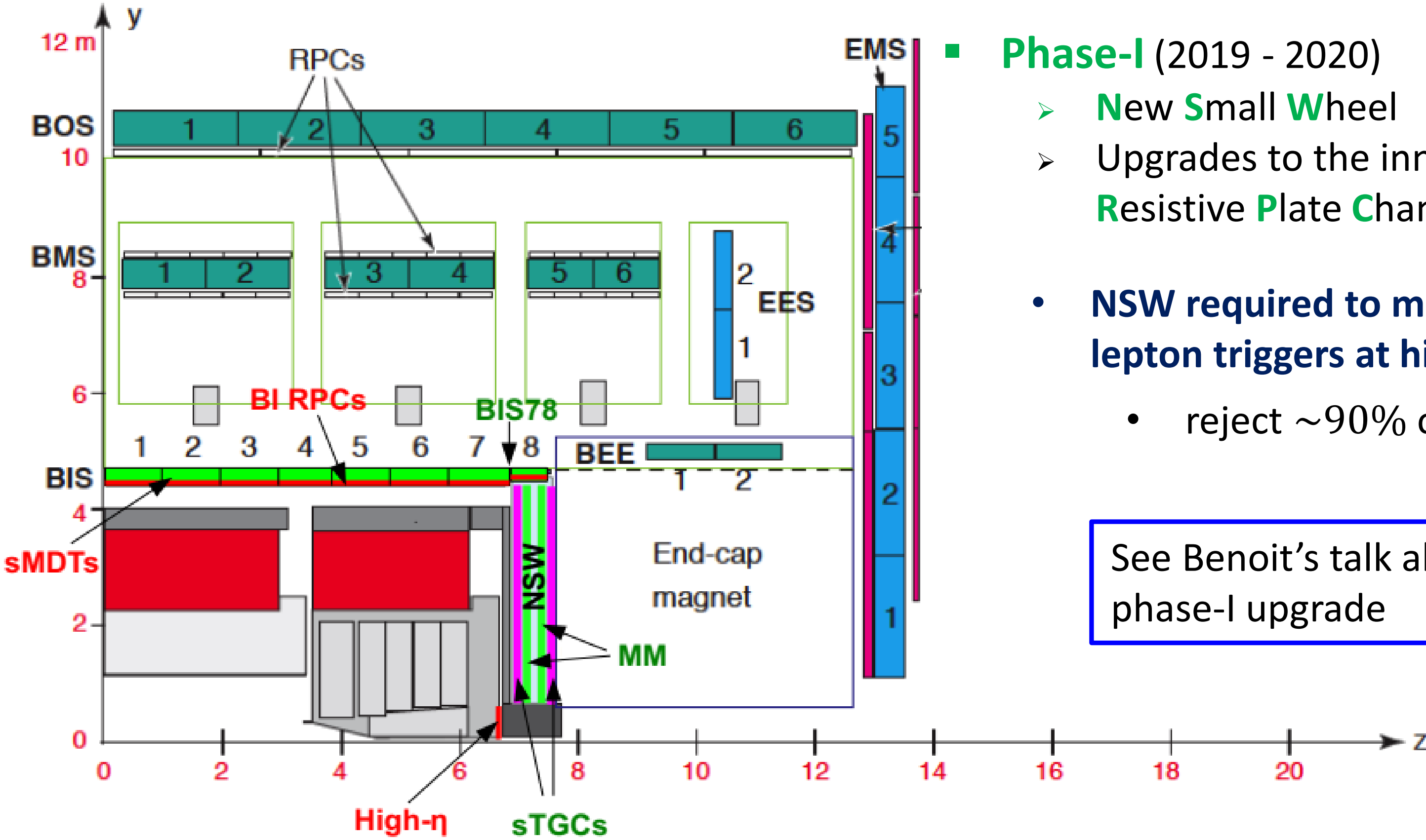
b-tagging Performance

- **Multivariate techniques** based on
  - Impact parameters of associated tracks
  - Properties of reconstructed secondary vertex
- ***b*-tagging algorithms have been fully re-optimized for the new layout**
  - **Better rejection capability of ITk even at high pile-up levels**
  - **The extended coverage of ITk enables the *b*-tagging in the forward region.**



- *b*-tagging is sensitive to the contamination of pile-up tracks
  - It considers **tracks with large impact parameters**
  - **Essential to mitigate effects from pile-up**

Muon Spectrometer



- **Phase-I** (2019 - 2020)
  - **N**ew **S**mall **W**heel
  - Upgrades to the inner barrel **R**esistive **P**late **C**hambers

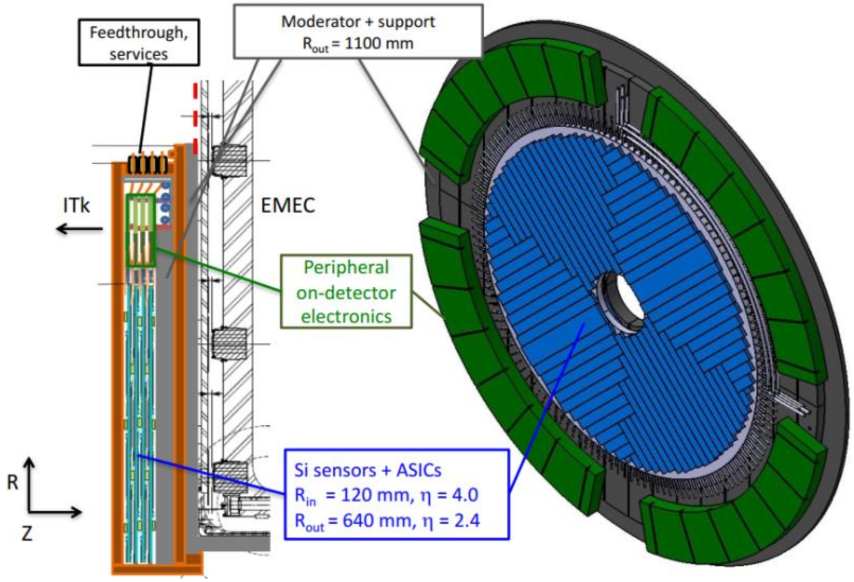
- **NSW required to maintain low-p_T lepton triggers at high rates**
  - reject ~90% of fake triggers

See Benoit's talk about Muon phase-I upgrade

- **Phase-II** (2024 – 2026, mainly about trigger for Muon spectrometer)
  - New inner RPC stations
  - Monitored Drift Tubes information to be added at the hardware trigger
  - Investigating the addition of a high-η tagger

High-Granularity Timing Detector

- Precise assignment of tracks to Hard-Scatter (HS) vertex → to mitigate the pileup effects
  - **Space separation** of vertices in the beam direction (z)
    - High pile-up density at HL-LHC
    - σ_{z_0} is not good in the forward region
  - **Time separation of vertices**



HGTD

- Designed to distinguish between **collisions occurring very close in space but well separated in time**
- Located just outside of ITk covering the forward region $\mathbf{2.4 < |\eta| < 4.0}$
- Consisting of 4 silicon layers
  - 10% occupancy in $1.3 \times 1.3\ \mathrm{mm}^2$ pixels
- Expected **timing resolution of 30 ps** will greatly improve the track-to-vertex association in the forward region
  - Compared to 180 ps RMS spread of collisions

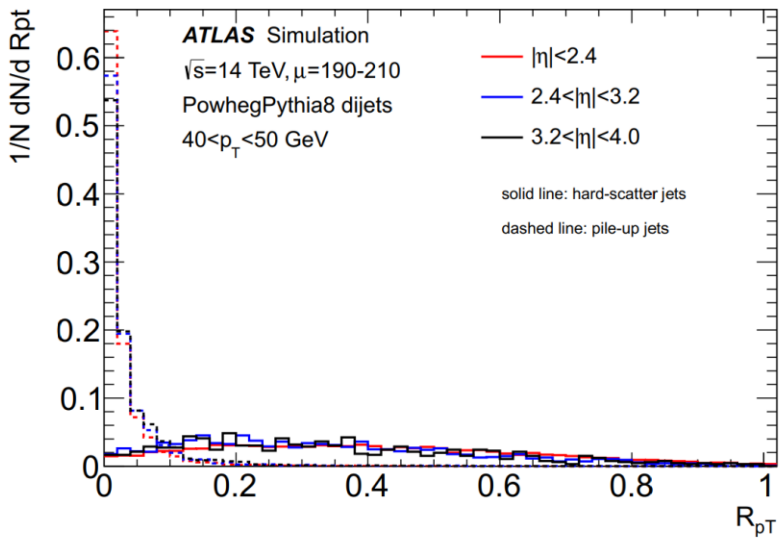
Pile-up Jets Suppression

- **Pile-up jet tagging** with the discriminant

$$R_{p_{\mathrm{T}}} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

  – Defined as the scalar sum of the p_{T} of all tracks within a jet associated with the HS vertex, divided by the jet p_{T}

  – **Small value of $R_{p_{\mathrm{T}}}$ for pile-up jets**

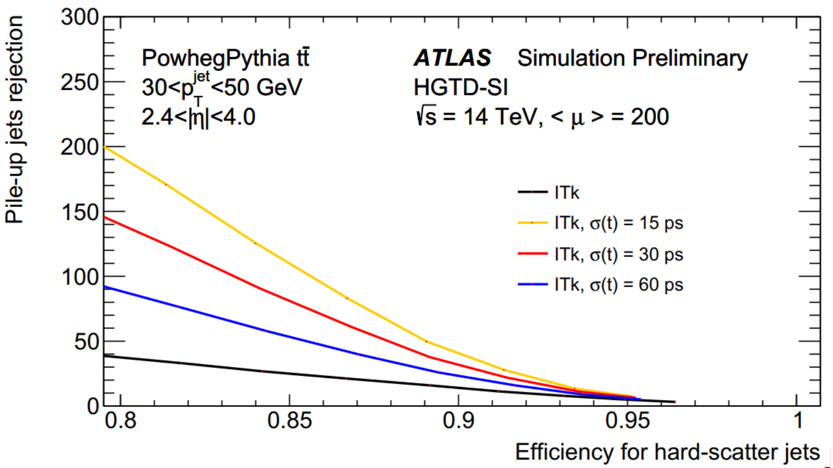


- Rejection vs efficiency as a scan over the $R_{p_{\mathrm{T}}}$ requirement

➢ **Significant improvement of pile-up jet rejection in the forward region**

  - **Extended coverage of ITk**
    - **Track-based pile-up suppression**
  - **HGTD**
    - **Timing information**

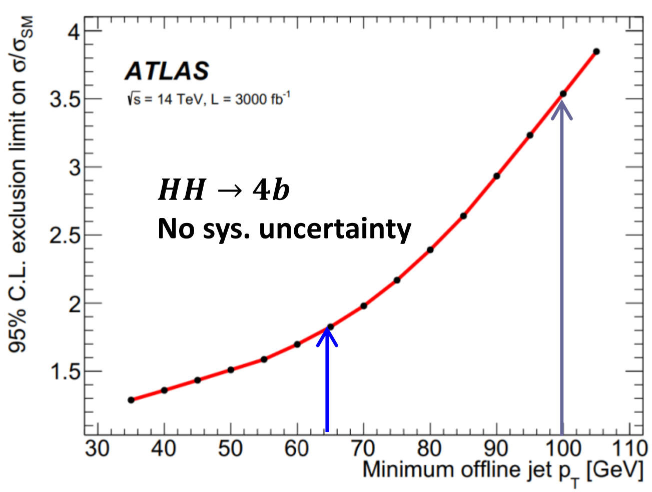
Rejection = 1/ mis-tag-efficiency

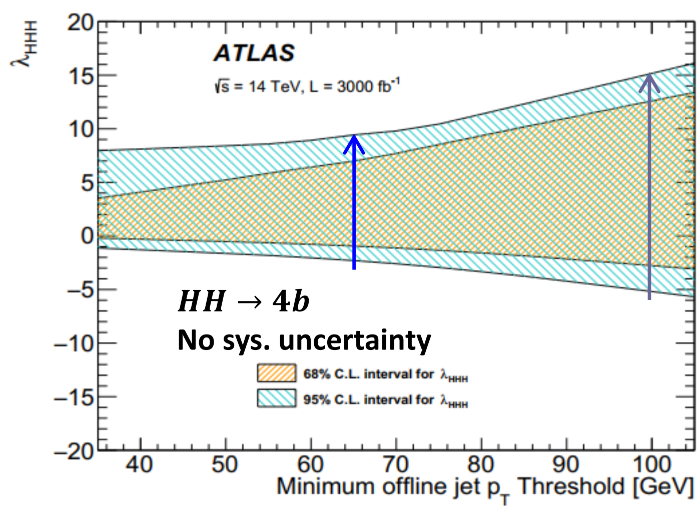


The Expected Sensitivity to $HH \to 4b$

- **The effects of upgraded ATLAS detector are taken into account** by
  - applying energy smearing, object efficiencies and fake rates to truth level quantities
  - following parameterizations based on detector performance studies with full simulation and HL-LHC conditions

- $HH \to 4b$ High sensitivity to b-jet trigger threshold → Trigger system upgrade is critical
  - Substantial degradation with increased minimum jet p_T requirement
  - 100 GeV → 65 GeV (w/o → w/ upgrade) ~ × 2 sensitivity



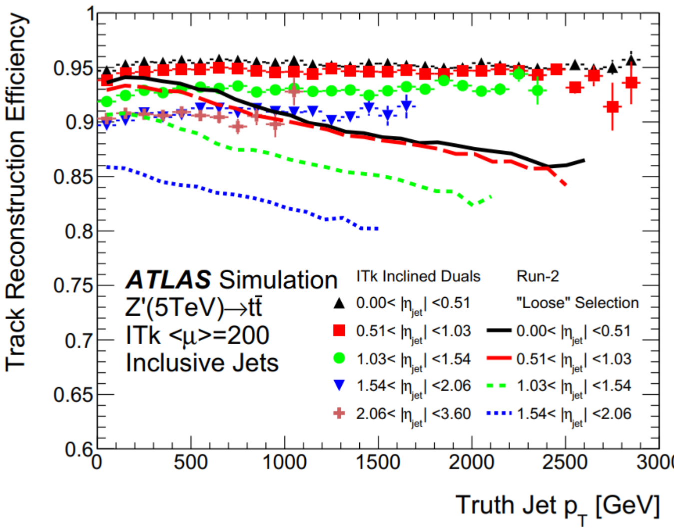


- **More channels combined to get enough statistics**
  - $b\bar{b} + \gamma\gamma$
  - $b\bar{b} + \tau^+\tau^-$

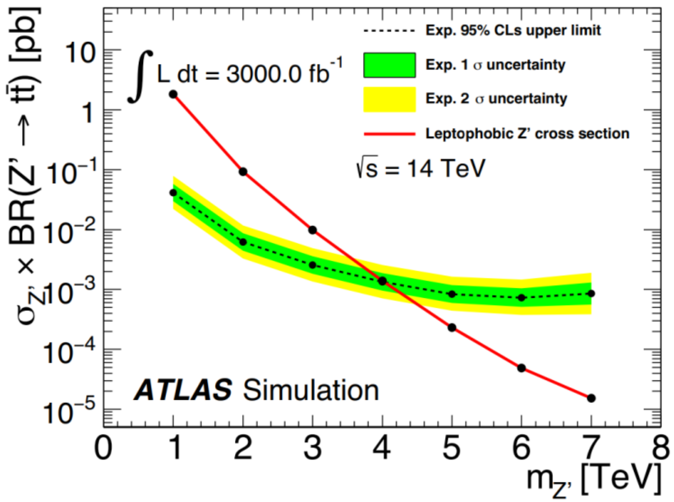
  ……

The Expected Sensitivity to $Z' \rightarrow t\bar{t}$

- Single lepton + jets channel ($t\bar{t} \rightarrow WbWb \rightarrow l\nu bqq'b$)
- **Stable tracking efficiency inside jets with increasing p_T**
  - Top quarks tend to produce b-jets with $p_{\mathrm{T}} > 600\mathrm{GeV}$
  - **Robust against the high-density tracking environment**



- If no signals observed, expect to exclude this resonance for $m_{Z'} < 4$ TeV after HL-LHC (ATL-PHYS-PUB-2017-002)
  - Topcolour model of spin-1 Z' assuming $\Gamma = 1.2\%$
  - LO×1.3 to account for NLO effects
  - The most recent ATLAS search using 36.1 fb^{-1} of data taken at $\sqrt{s} = 13$ TeV excludes $m_{Z'} < 3.2$ TeV (Talk by Siyuan Sun)



Conclusions

- **Challenging to maintain or improve the performance in very dense environment with pileup up to 200**

- **Significant upgrades planned for the ATLAS detector for HL-LHC**
  - All-silicon ITk with extended coverage to improve the tracking performance
  - HGTD to mitigate pile-up effects
  - Trigger system upgrade to keep lower trigger threshold

- **The performance of the physics objects reconstruction is expected to be better than the current detector.**

Backup

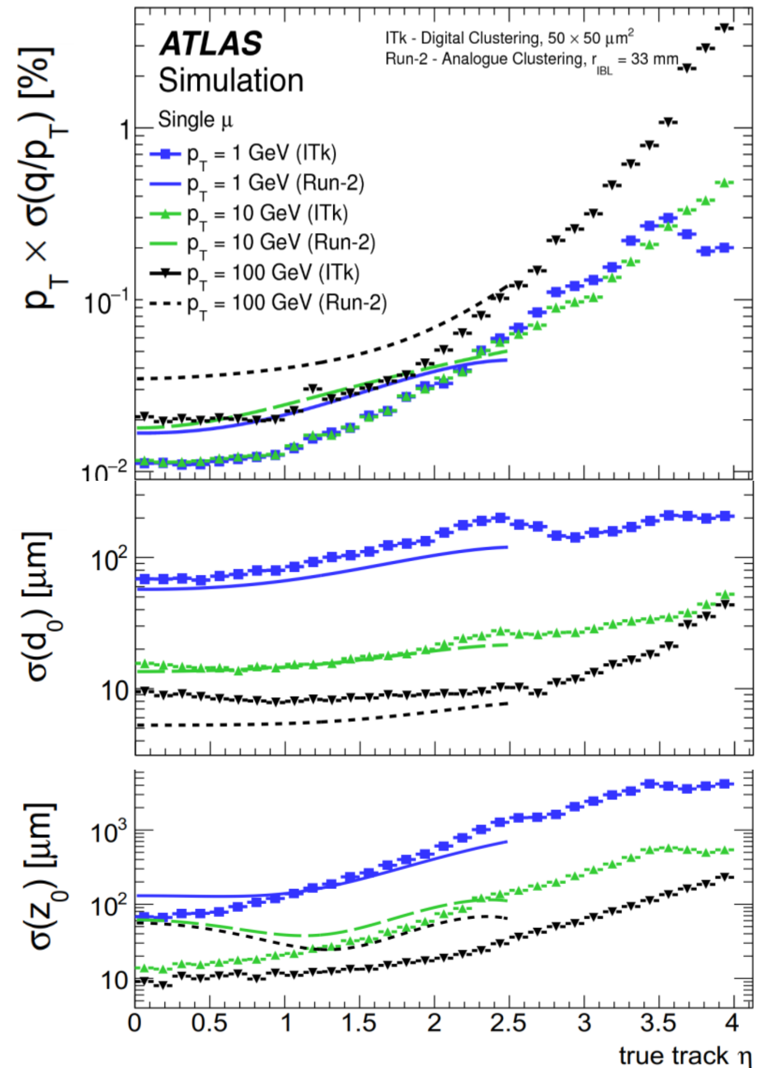
Phase-II Tracking Performance

- **Track parameter resolutions** directly determine the b-tagging capability and lepton or jet reconstruction

- **Better resolution of transverse momentum (p_{T})**
  - **Higher precision of strip tracker compared to TRT**
  - **Reduced material**

- **Expected comparable resolution of transverse impact parameter (d_0)**
  - **Larger radius of ITk**
  - Analog clustering would help

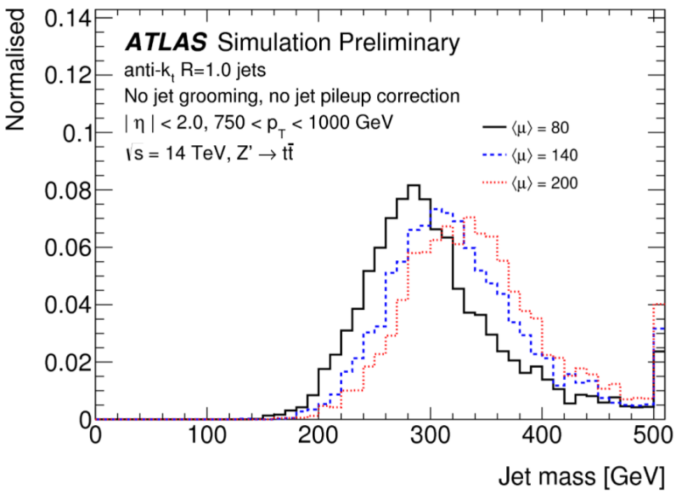
- **Better resolution of longitudinal impact parameter (z_0)**
  - **Decreased pixel pitch in the *z* direction**

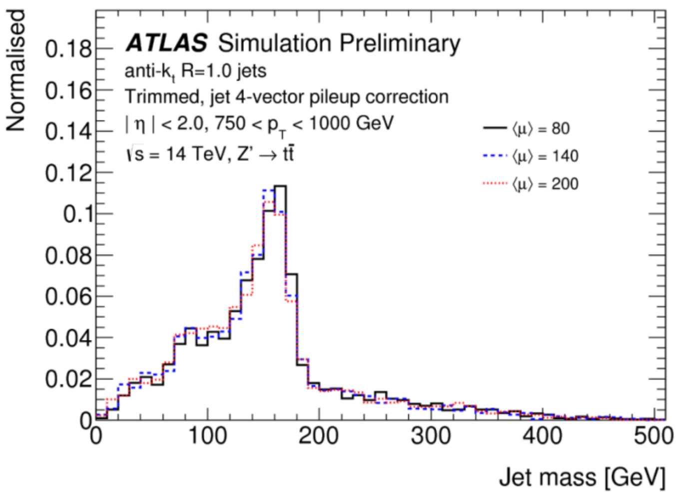


Jet reconstruction

- Pileup is one of the main challenges for jets
  - Soft particles from nearby pileups are likely to contaminate the jets from HS.
  - This is especially true for boosted objects the products of which are very collimated.

- Typical boosted signature with jet radius R = 1.0 for $Z' \longrightarrow t\bar{t}$
  - Grooming algorithms significantly reduce the sensitivity to pileup (reduced jet area) https://cds.cern.ch/record/1459530
  - After grooming and applying pileup corrections, the leading jet mass resolution is significantly improved and the pileup dependency is removed.



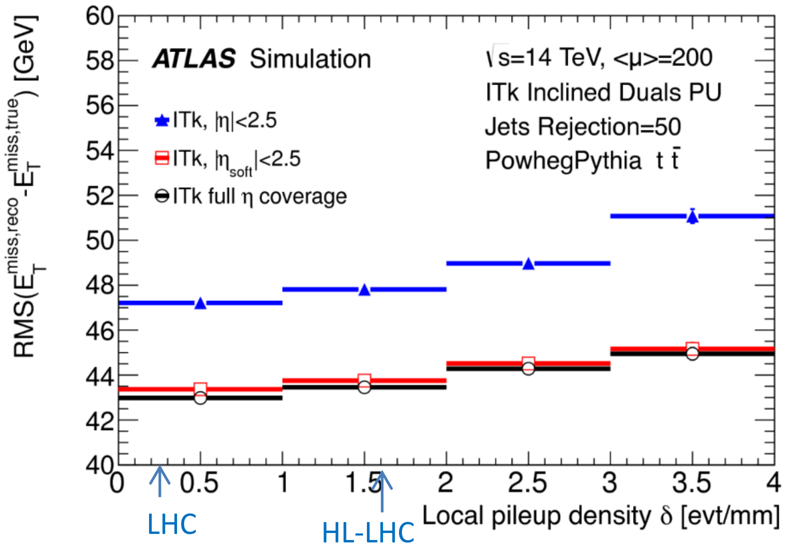


Missing Transverse Energy

- **An important variable in searches for exotic signatures.**
  - In SM, $E_{\mathrm{T}}^{\mathrm{miss}}$ arises from neutrinos.
  - There are also prospects for such particles in BSM theories.

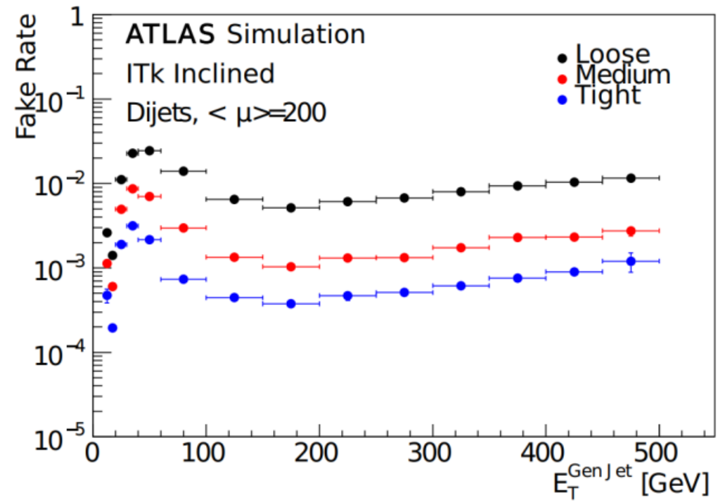
- $E_{\mathrm{T}}^{\mathrm{miss}}$ is computed as the vector momentum sum of high p_{T} physics objects, plus the soft-term from low p_{T} particles associated to the HS vertex.

- **Better E_{T}^{miss} resolution** in the high pile-up conditions
  - ✓ Benefitting from the strong **pile-up jet rejection of ITk** in the forward region
  - ✓ The gain in the soft term using tracks in the forward region is small

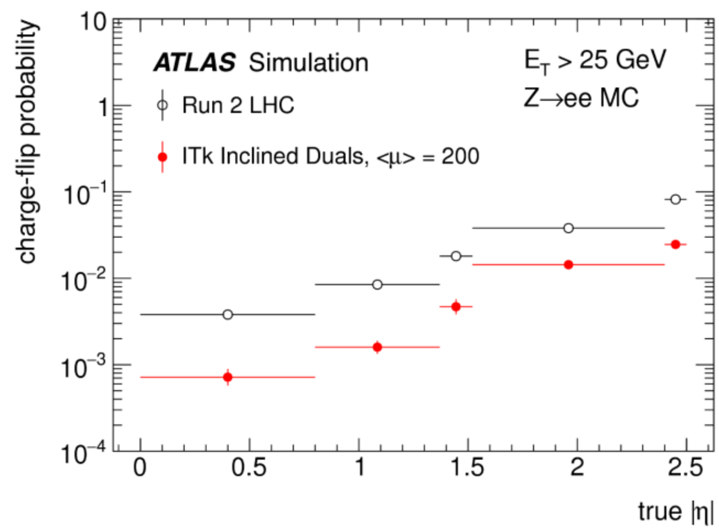


Performance of electron reconstruction

- **Similar performance with Run2 is expected**
  - Likelihood based electron identification, combing calorimeter and track variables
  - It improves about a factor of 2-5 in rejection of jets.
  - This would also be carried out for ITk.

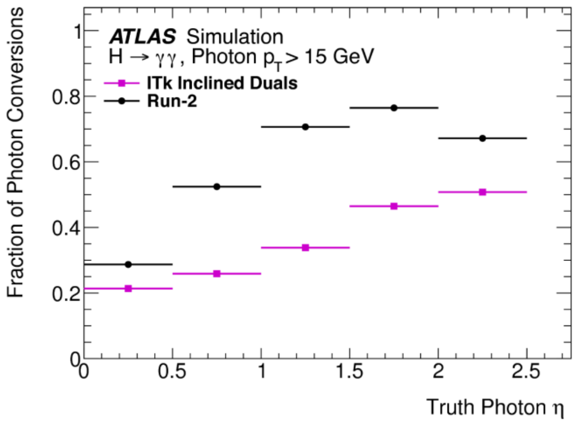


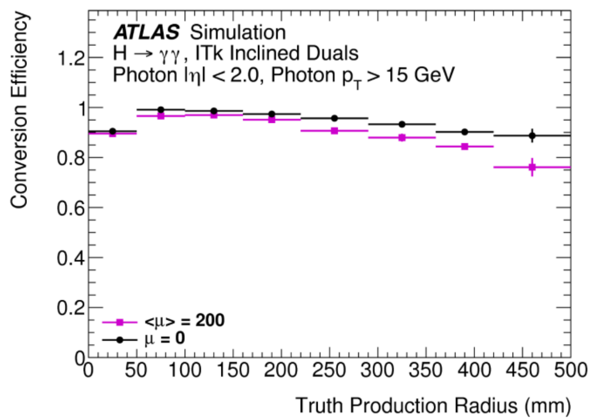
- **Charge mis-identification** is caused predominantly by Bremsstrahlung .
  - The EM cluster corresponding to the initial **matched** to the wrong-charge from the conversion leptons
  - The electron track may fail the tracking recovery for Bremsstrahlung, leading to a **poorly measured short track**.
  - **Reduced material of ITk significantly decreases the mis-identification probability.**



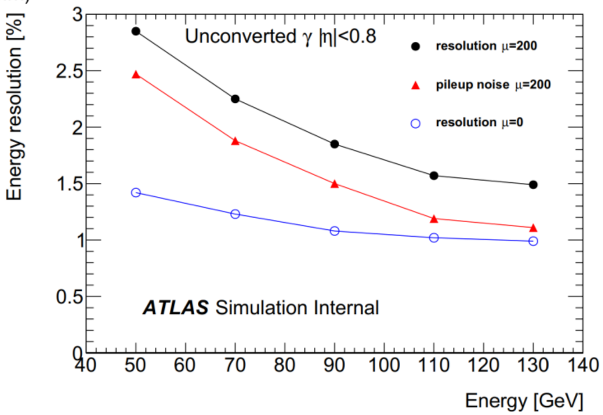
Performance of photon reconstruction

- Photon conversion → affects the reconstruction efficiency and the energy calibration
  - Much-reduced material budget of the ITk significantly decreases the probability of photon conversion.
  - A conversion track-finding algorithm has been developed for the ITk based on the Run 1 and Run 2 experience
  - The conversion reconstruction efficiency is slightly lower in high pile-up condition



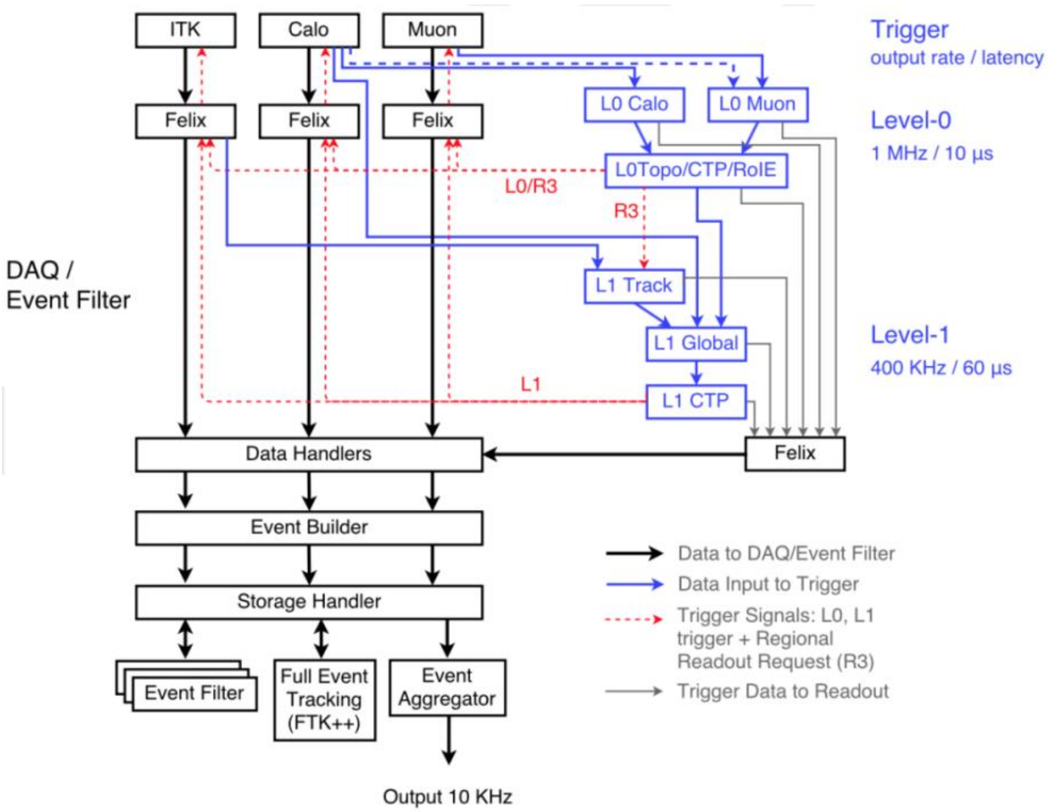


- The energy resolution of photons under $<\mu> = 200$ is worse than $<\mu> = 0$ (studied in very central region)
  - Pileup-only contribution = $\sqrt{\sigma^2_{\mu=200} - \sigma^2_{\mu=0}}$
  - The pileup noise dominates the energy resolution for photons with energy up to 130 GeV, and has an increasing impact for lower E_T



Two-level hardware-based TDAQ Upgrade

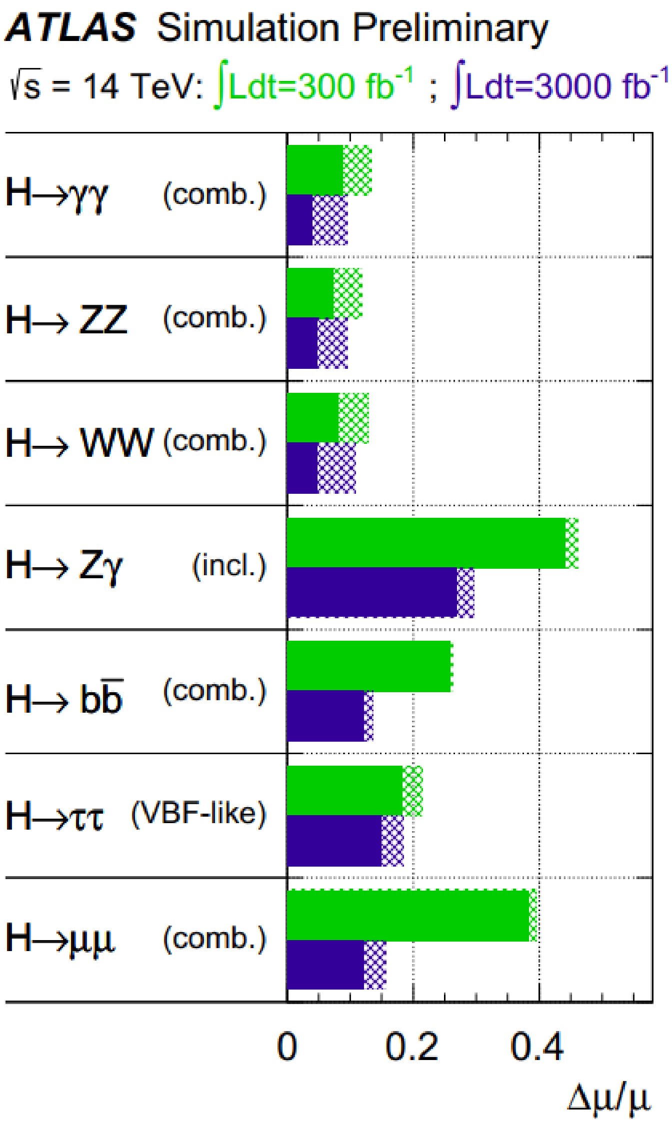
- A two Level hardware-based trigger system
  - The **L0** trigger accepts inputs from the Calorimeter and Muon trigger systems.
  - Hardware-based track reconstruction is implemented in the **L1** trigger system
  - The track segments are matched with calorimeter and muon features in the Global Trigger, after which the Central Trigger Processor forms the **L1** decision.



- **The L1 trigger provides the necessary rejection** using precision pattern recognition and by building topological triggers that match data across detector systems.
- The **readout capacity** is increased from 100kHz to **1 MHz** and the **output data** are increased from 1 kHz to **10 kHz**

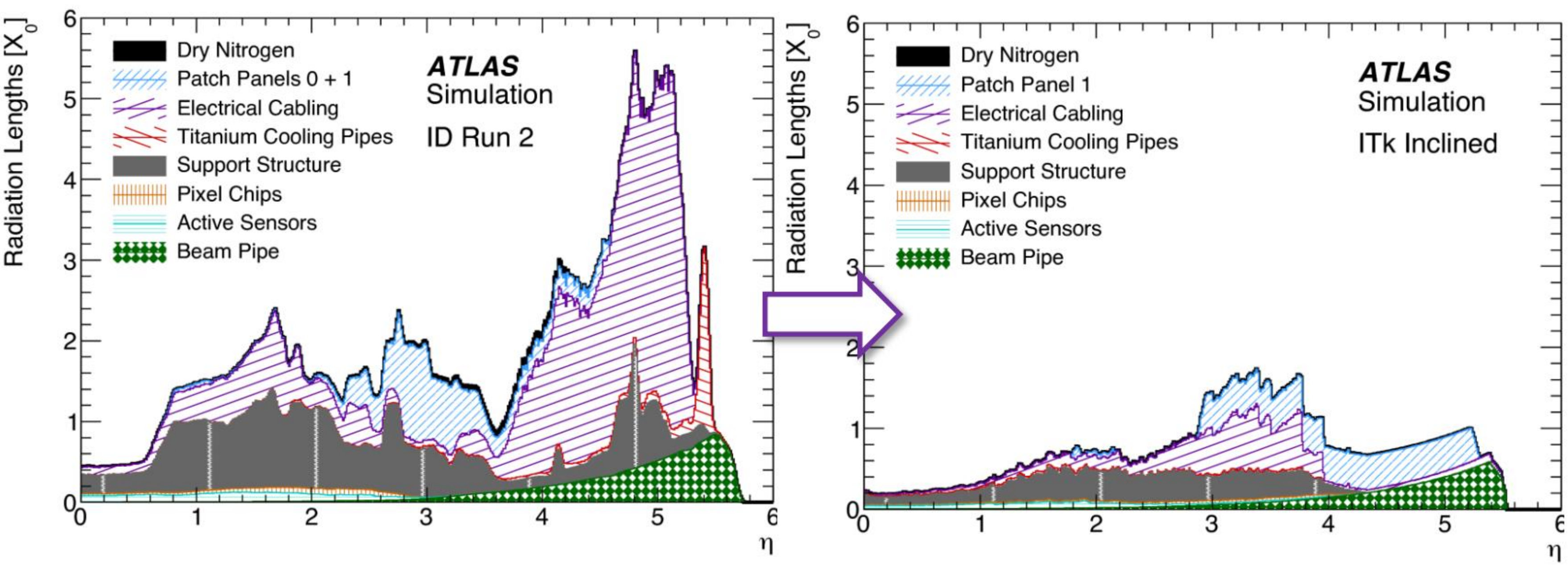
Higgs Signal Strength at HL-LHC

- Assuming a SM Higgs boson
  - A mass of 125 GeV
- Not including improved analyses techniques
  - **Run 1 analysis strategy with expected performance at $< \mu > = 140$**
  - New estimations are going on.
- **Statistical uncertainty reduced** relative to 300 fb^{-1} data which would be accumulated before Phase-II
  - **4-5% for main channels, 10-20% on rare modes**
  - Theoretical uncertainty (hashed area) not negligible for several channels→ expected to be improved



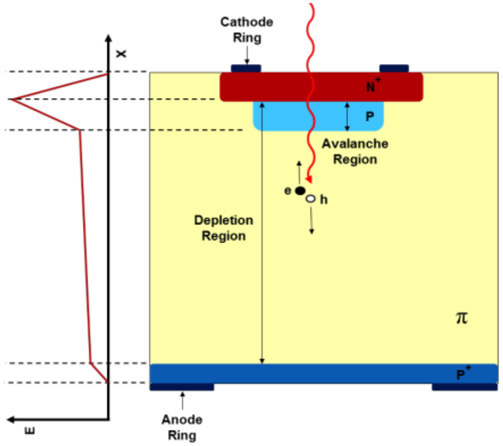
Material Budget of ITk

- A reduction of multiple scattering of all particles→ improves the tracking efficiency and resolution
- Reduced conversion probability of photons
- Less energy of particles lost before the calorimeters

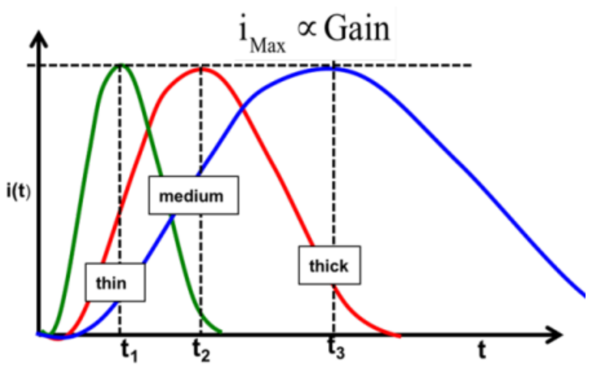


HGTD

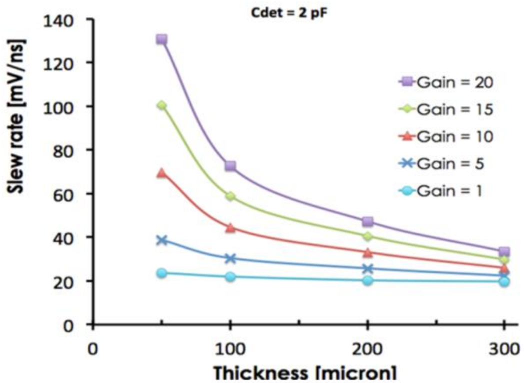
- The technology chosen for the HGTD sensors is Low Gain Avalanche Detectors (LGAD)
  - n-on-p silicon detectors containing a extra highly-doped p-layer below the n-p junction to create a high field which causes internal gain
  - an initial current is created from the drift of the electrons and holes in the silicon
  - When the electrons reach the amplification region, new electron/hole pairs are created and the holes drift towards the p^+ region and generate a large current



Cross section of an LGAD diode



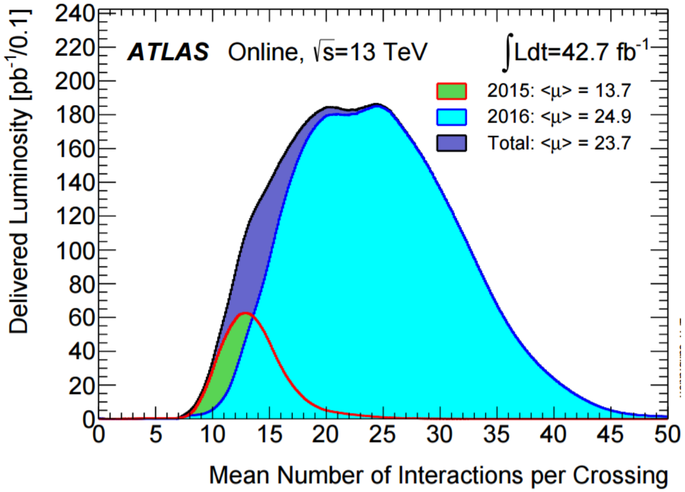
Current signals for different thicknesses

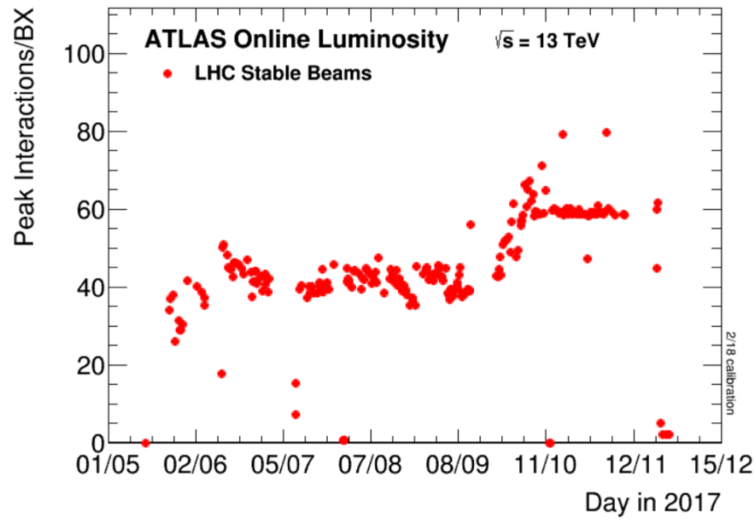


Signal slope as function of thickness.

An LGAD thickness of 50 microns has been adopted.

pileup





$$\frac{\mu}{\sqrt{2\pi}\sigma_z} e^{-\frac{(z-z_0)^2}{2\sigma_z^2}}$$