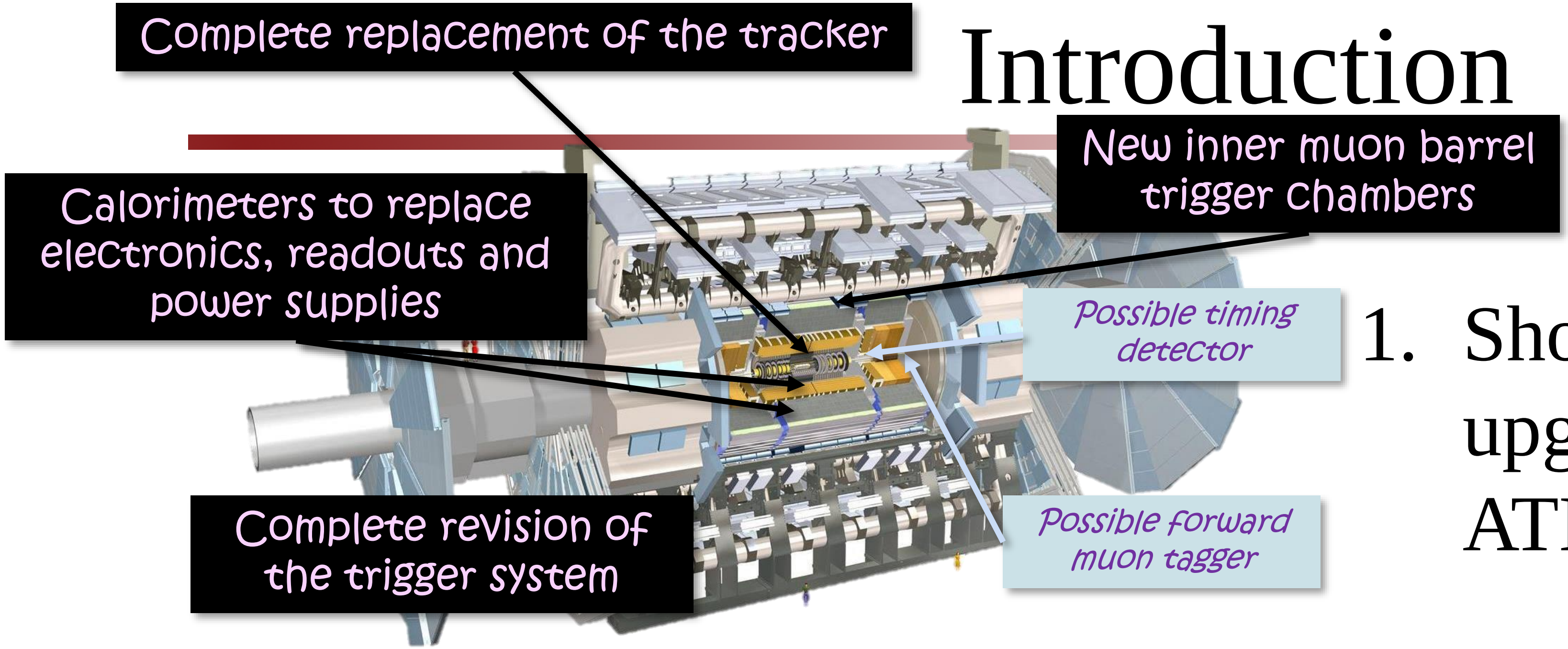
ATLAS Expected Performance at HL-LHC

-Workshop on the physics of HL-LHC, and perspectives at HE-LHC-

Nora Pettersson

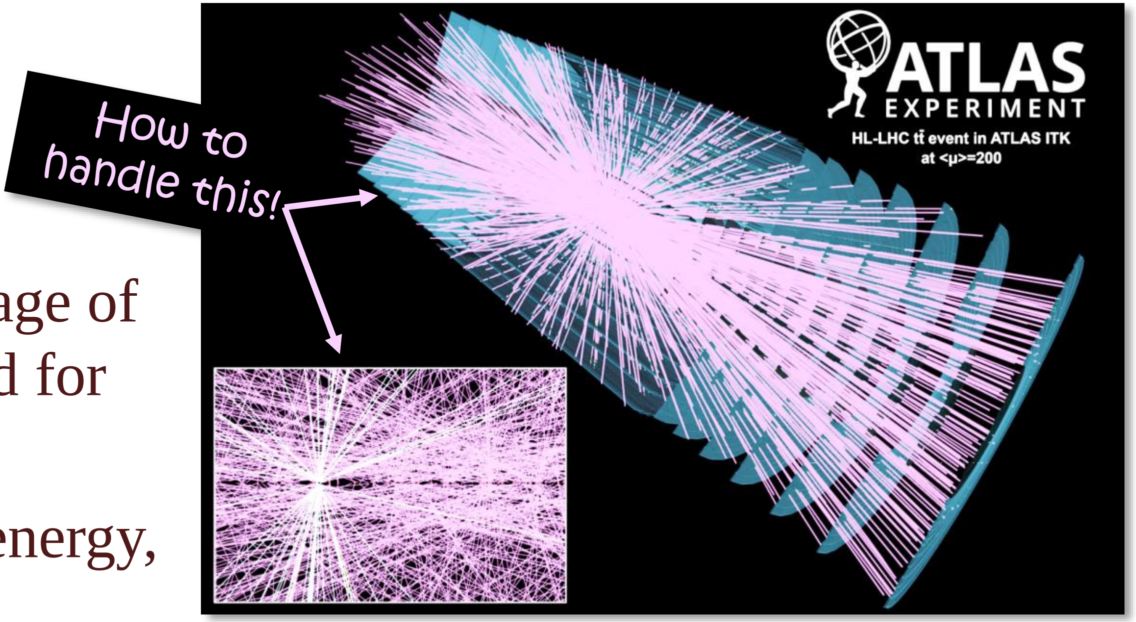
on behalf of the ATLAS Collaboration

Introduction



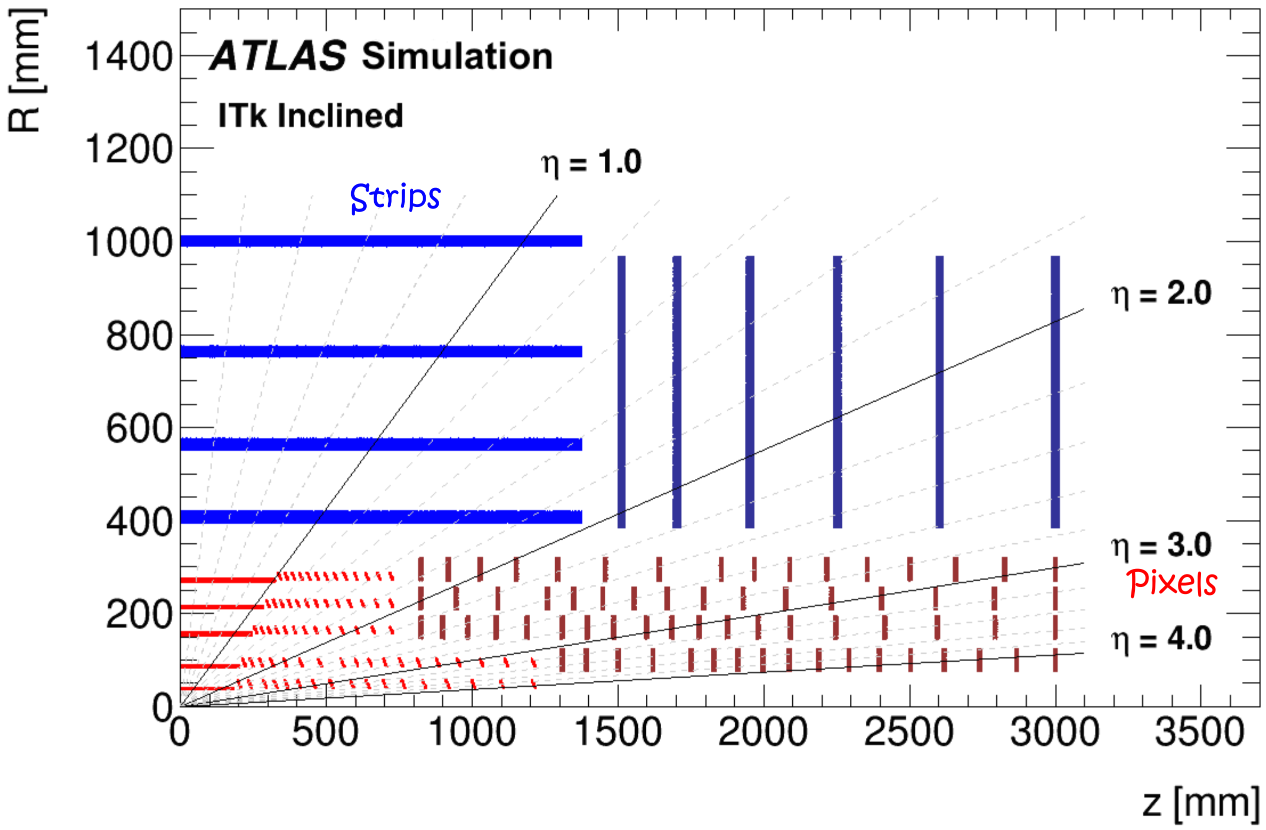
1. Short summary of the planned upgrade for Phase-I/II for the ATLAS detector

2. Expected performance of the upgraded Phase-II ATLAS detector
   - How to face the challenge of going up to an average of 200 interactions per bunch crossing as is expected for luminosities of $7.5 \times 10^{34}\ cm^{-2}s^{-1}$
   - Tracking, vertexing, pile-up mitigation, missing energy, jets, electrons, photons, muons, b-tagging,…

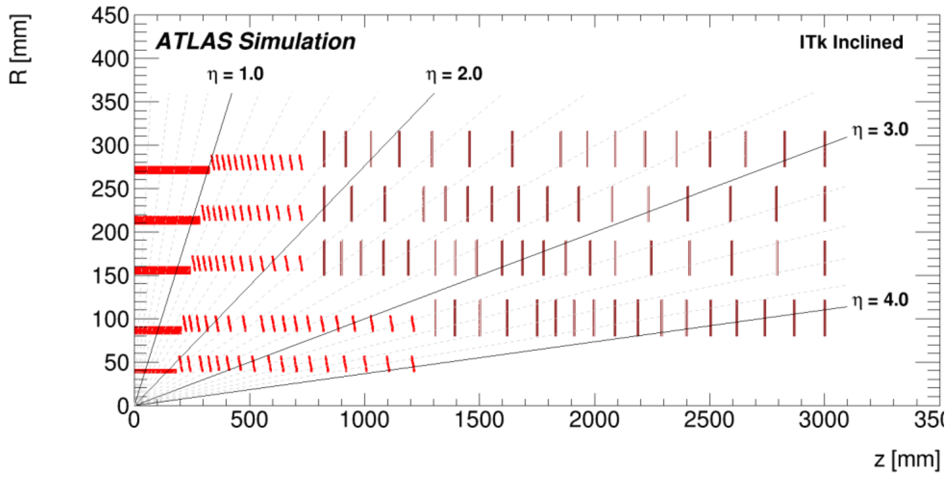


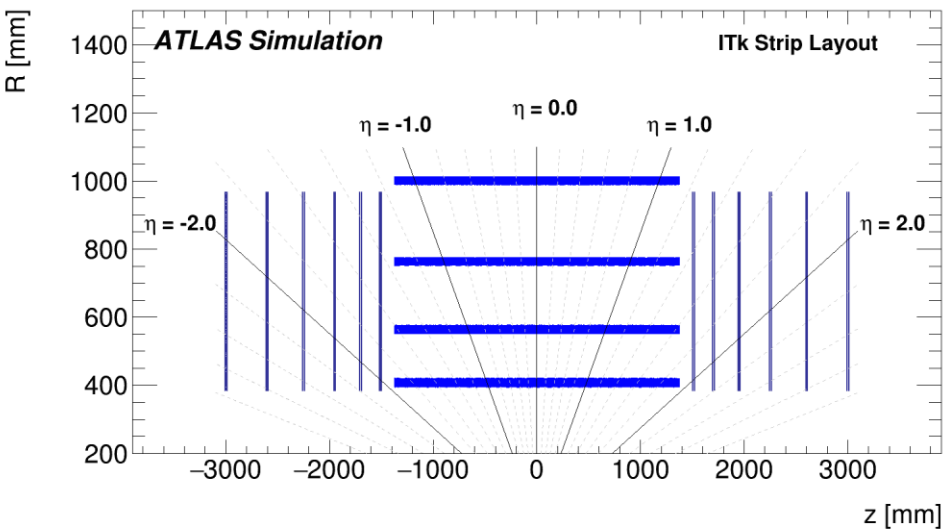
Phase-II Inner Tracker Upgrade

- The current Inner Detector (ID) will need to be replaced to keep the excellent tracking performance at HL-LHC environment
  - Radiation dosage severe for the inner most layers – approaching end of life during Run-3
- HL-LHC environment demands
  - Increased radiation hardness
  - Higher granularity of pixel detector to reduce the occupancy and to handle the high pile-up environment
  - Reduction of material to benefit tracking and calorimeter performance
  - Extended coverage of the tracking volume up to $|\eta| < 4.0$ mainly to identify pile-up jets and mitigate their effect



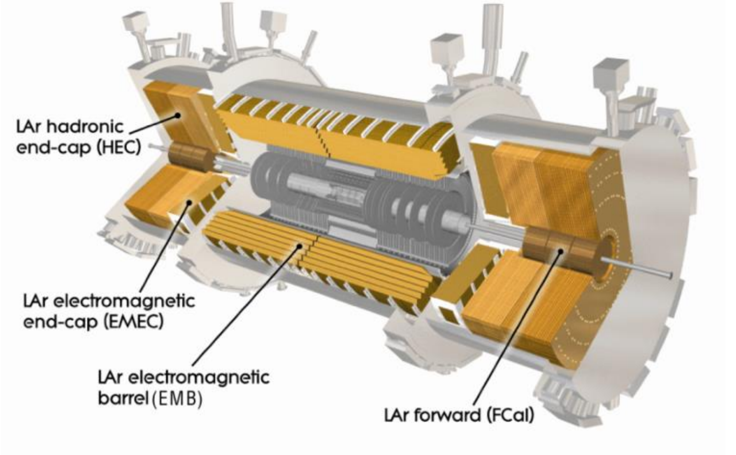
Phase-II Inner Tracker Upgrade



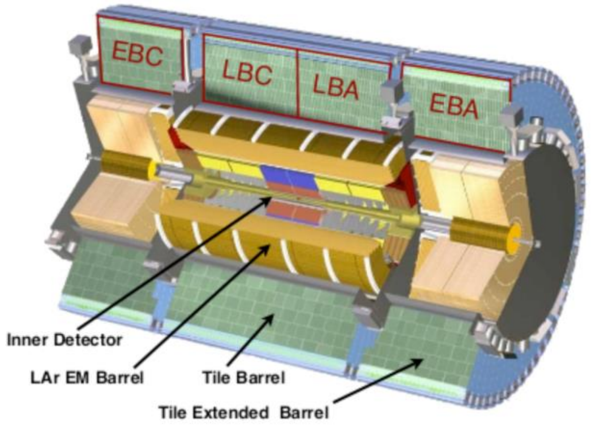


- The Pixel detector consists of five barrel layers with inclined sensors starting from |η| > 1.0
  - Reduces the material traverse by particles and improves tracking performance (and energy measurements of the calorimeter)
  - Less silicon surface than a traditional barrel needed to cover the same detector volume
  - Endcap rings replacing traditional disks to improve the coverage and at cost of less silicon surface
  - Two pixel pitches still under consideration $50x50$ or $25x100\ \mu m^2$ - current ID using $50x250$ (400) μm^2
    - All results presented are using $50x50\ \mu m^2$
- The Strip detector consist of four strip barrel layers with and six endcap disks on each side of the barrel
  - Covering up to |η| < 2.6
  - Modules at a stereo angle of 52(40) mrad for barrel (disks) to provide two dimensional measurements

Phase-II Liquid Argon Upgrade



- ATLAS Liquid Argon (LAr) Calorimeters
  - EM calorimeter $|\eta| < 3.2$
  - Hadronic calorimeter for $1.5 < |\eta| < 4.9$
- Calorimeters expected to fully operational at HL-LHC
- *For HL-LHC* a total replacement of the electronic readouts and low voltage powering is planned
- Main motivations for the upgrade
  - Required by restricted radiation tolerance of current front-ends
  - Present readout system will be incompatible with the planned upgrade of the ATLAS trigger system
  - Necessary to avoid degradation of performance in high pile-up environment
  - Allows for partial suppression of out-of-time pile-up effects
- New readout architecture more acquiescent
  - Will allow for higher resolution information of the calorimeters to be available at the lowest level of the trigger system
- This yields enhanced capabilities to develop trigger algorithms to benefit *physics!*

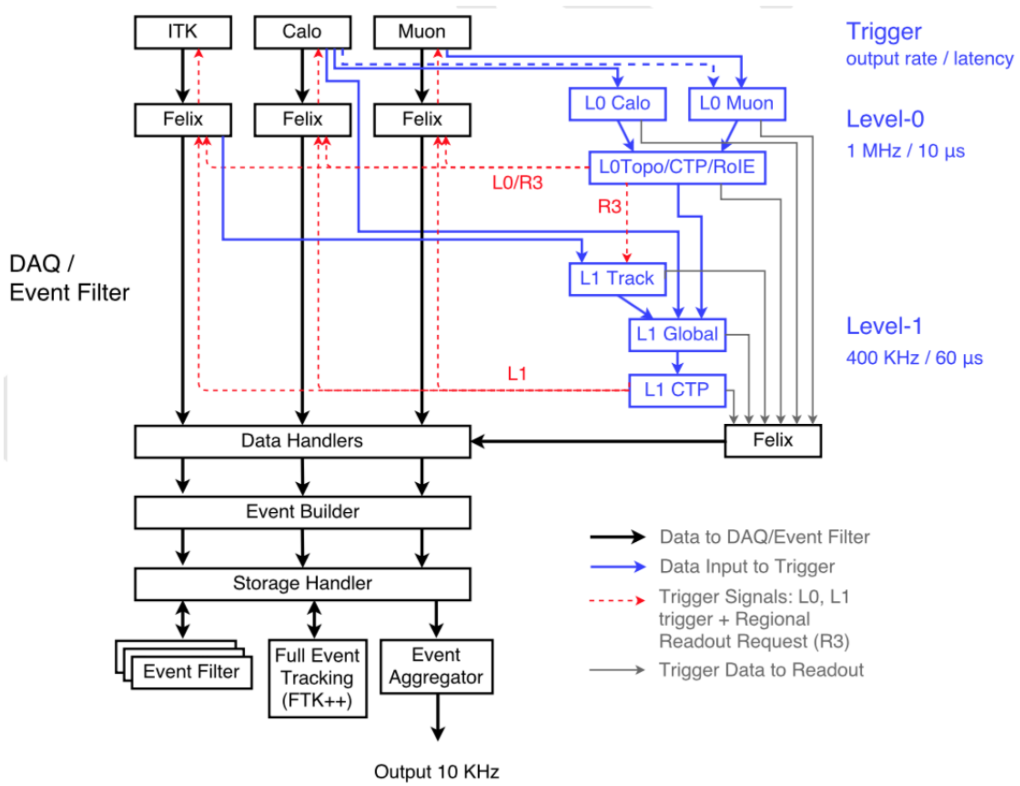


Phase-II Tile Calorimeter Upgrade

- The Tile Calorimeter (TileCal)
  - The hadronic calorimeter that captures about 30% of the jet energy
  - Total coverage for $|\eta| < 1.6$
- Calorimeters and optics expected to operate without problems at HL-LHC
- *Phase-II upgrade* to replace all front-end and back-end electronics and the power supplies
  - Outdated readout electronics and on-detector components to suffer from increased radiation dosage
    - HL-LHC dosage an order of magnitude larger than design values for the current components
- Yield significant improvements of the readouts
  - Full information from TileCal available for the trigger system at 40MHz

Phase-II Trigger and Acquisition Upgrade

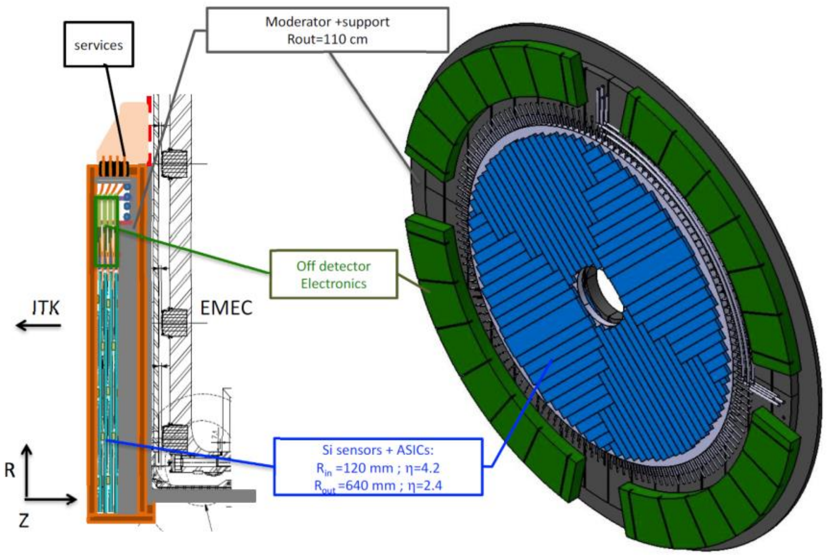
- A complete upgrade of the Trigger and Acquisition (TDAQ) is required to cope with the conditions at HL-LHC
- Phase-I:
  - Calorimeter information available at higher granularity at hardware level
  - Hardware tracking - Fast Tracker (FTK)
    - Including tracking information at trigger level-1
  - Increased coverage of the muon triggers



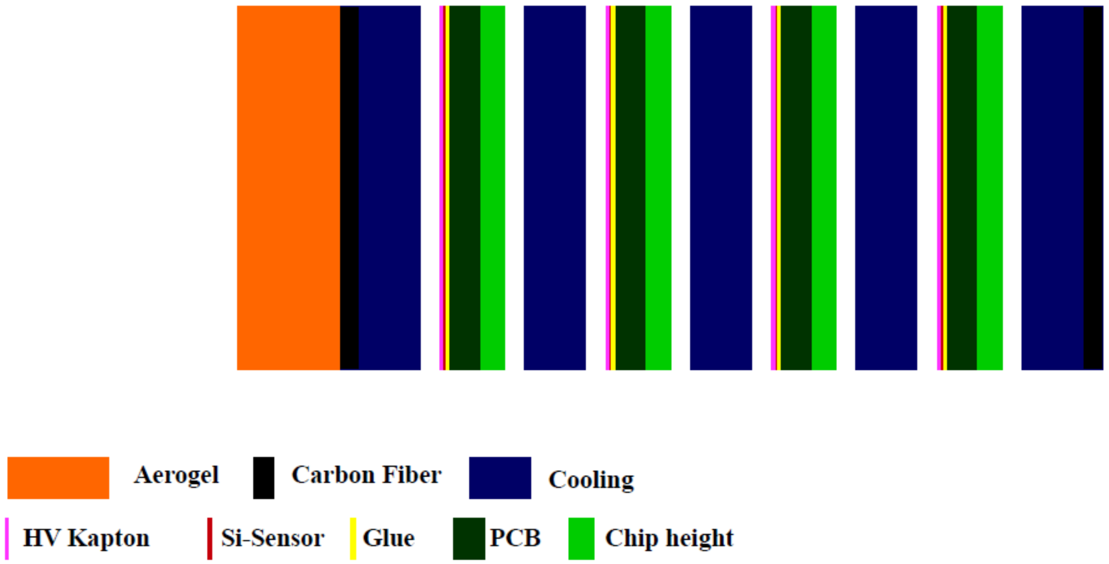
- Phase-II:
  - The readout capacity is increased from 100kHz to 1 MHz and the output data are increased from 1 kHz to 10 kHz
  - Tracking information to be made available earlier in the trigger architecture
  - Full Calorimeter granularity at the hardware trigger level

High-Granularity Timing Detector

- *Under consideration:* Forward timing detector
- Located at just outside of the ITk envelop at z ~ 3500 mm and spans 120 to 640 mm in r
  - Cover the forward region $2.4 < |\eta| < 4.2$

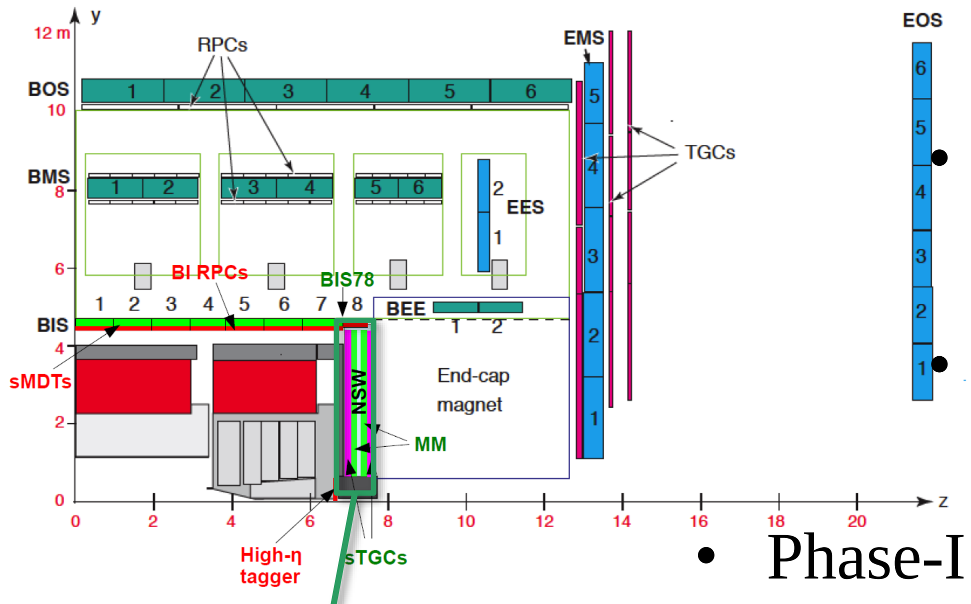


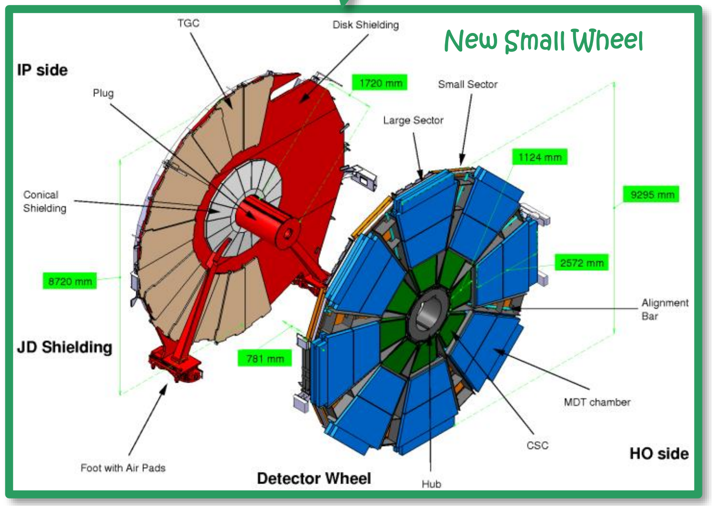
- Consists of four silicon layers
  - $1.3 \times 1.3\ mm^2$ silicon pads



- Expected 180 ps spread of collisions at HL-LHC
  - A time resolution of 30 ps helps assign a collision vertex to every charged particle
- Additional information to help with resolving low momentum particles from pile-up interactions
  - Especially, in the very forward region where ITk impact parameter resolution is of $\mathcal{O}(mm)$
- Improves general performance due to pile-up suppression
- Capabilities for luminosity monitoring

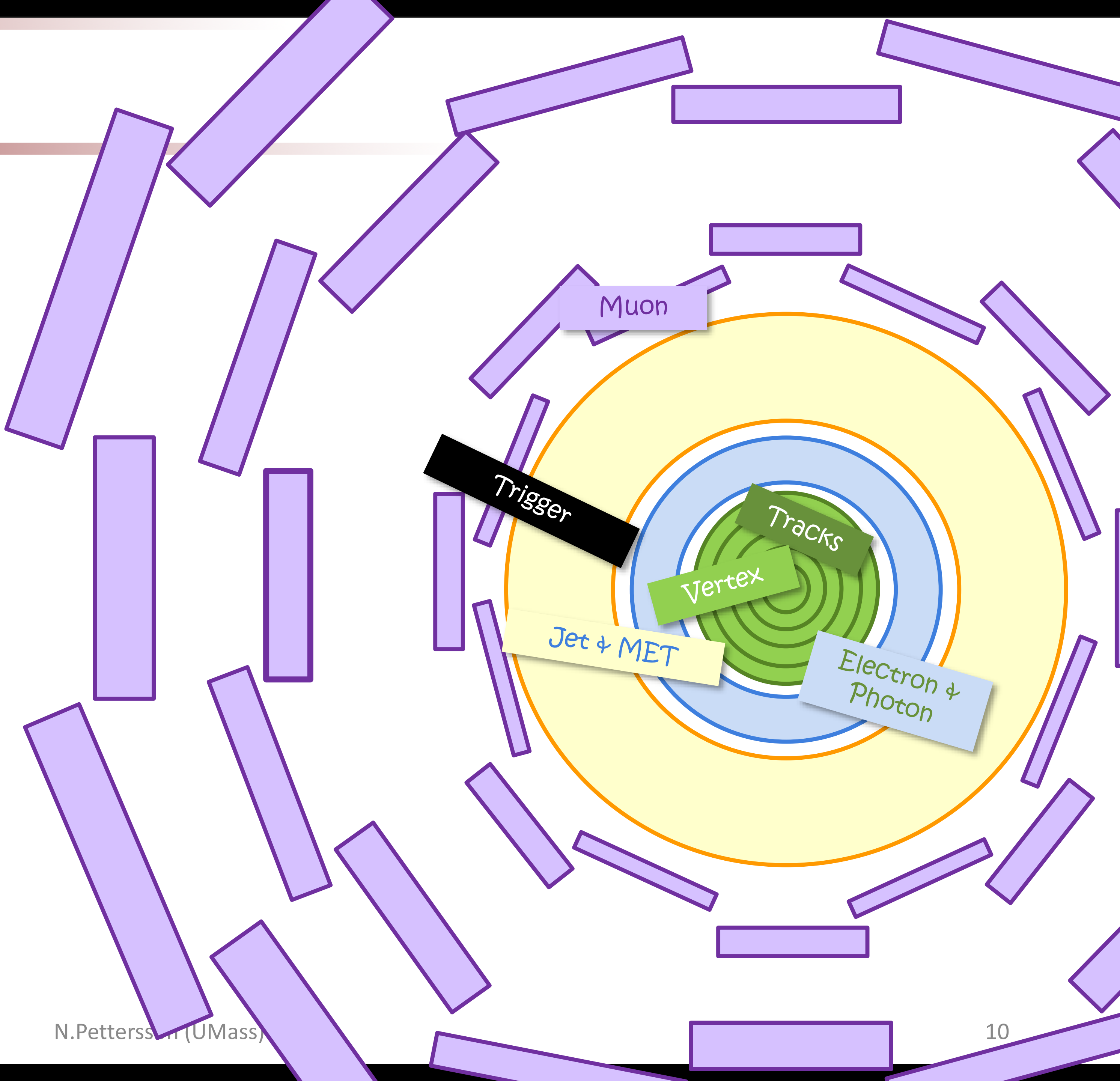
Phase-I/II Muon Upgrade





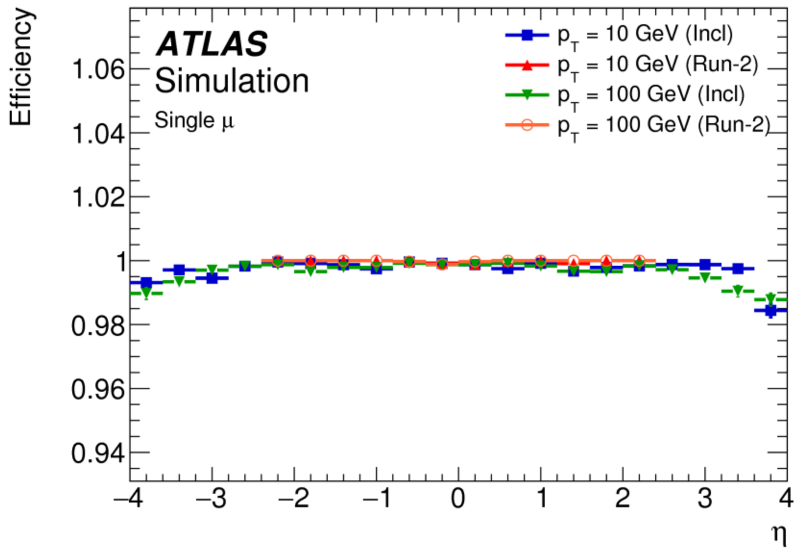
- Upgrades needed to the whole Muon Spectrometer (MS)
  - Motivated by the need to meet demands on the trigger and partial detector replacements to maintain performance
- Upgrades to the trigger and readout electronics
  - Partial upgrades to front-ends and power systems
- Phase-I:
  - Installation of the New Small Wheel (NSW) with Micromegas (MM) and small-strips Thin Gap Chambers (sTGC)
  - Upgrades to the inner barrel resistive plate chambers (RPC)
- Phase-II:
  - Major upgrades to the barrel to increase acceptance and robustness
    - New inner RPC stations to allow for down to 2 out of 4 layer coincidence
    - To make place for the RPCs, some of the old Monitored Drift Tubes (MDTs) are to be removed
  - MDTs information to be added at the hardware trigger to improve the turn-on
  - Investigating the addition of a high-η tagger

Expected Performance of the Phase-II ATLAS

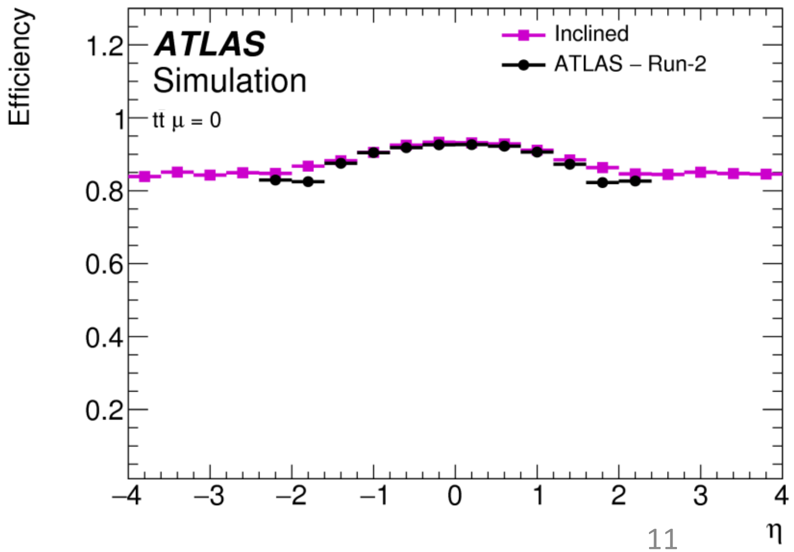


Phase-II Tracking Performance

- High tracking efficiency over the full acceptance for single muons
  - For momentum $p_T > 10$ GeV the efficiency is greater than 99% for the central region
    - Slight degradation in the very forward region due to not yet fully optimised reconstruction and layout

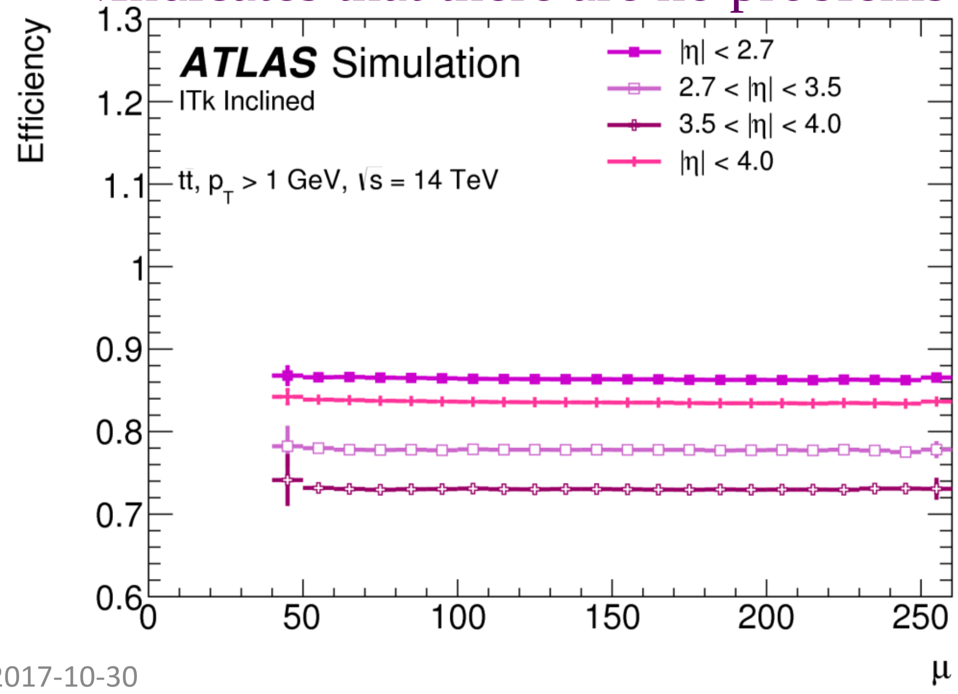


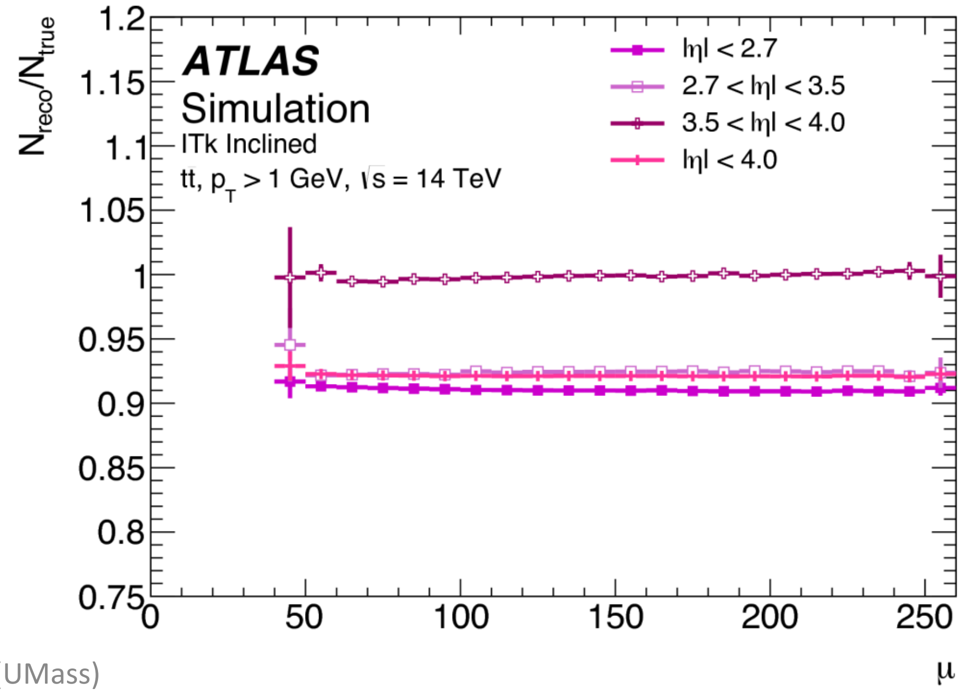
- Great performance for single events such as $t\bar{t}$
  - Efficiency from 95% to 85% for $\mu = 0$
  - Similar or higher than the current ATLAS ID for the full η-range



Phase-II Tracking Performance

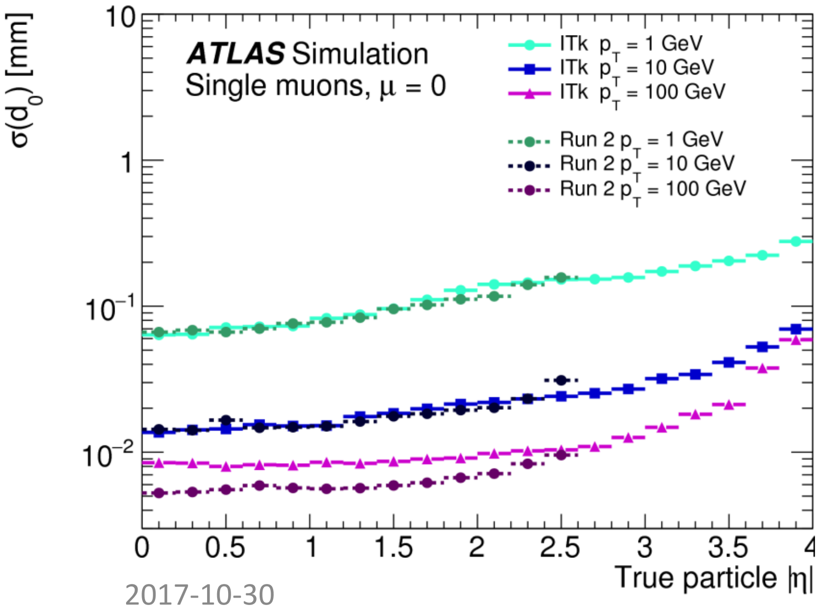
- The future tracker must be able to cope with the environments at HL-LHC
  - Track reconstruction efficiency versus μ extremely stable for all intervals of η
- Inclusive rate of the reconstructed tracks over the generated particles
  - Likewise the efficiency, these rates are independent of pile-up for the inclined layout
    - Indicates that there are no problems with increased number of fakes

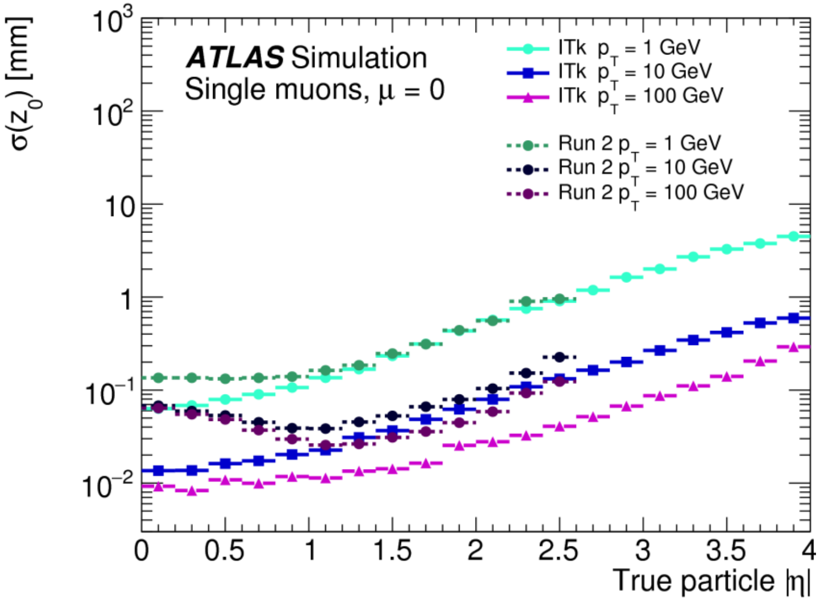


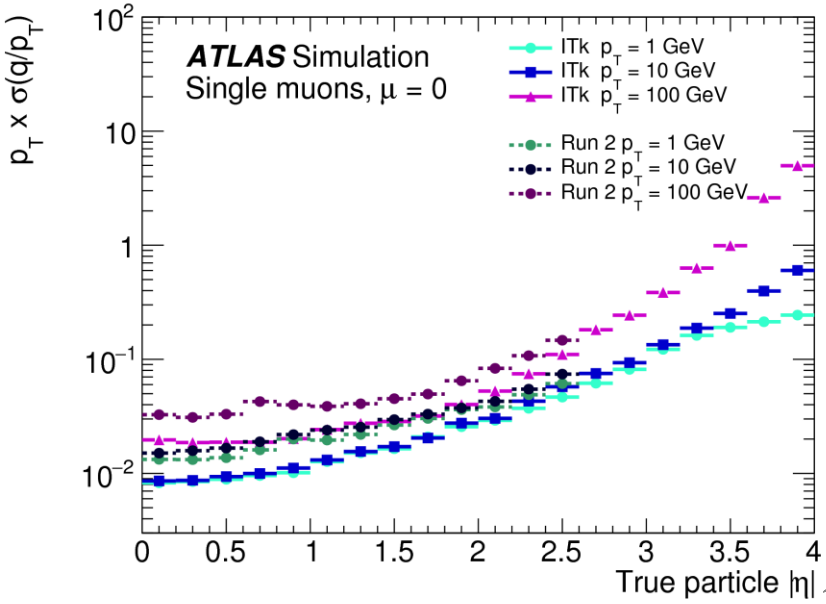


Phase-II Tracking Performance

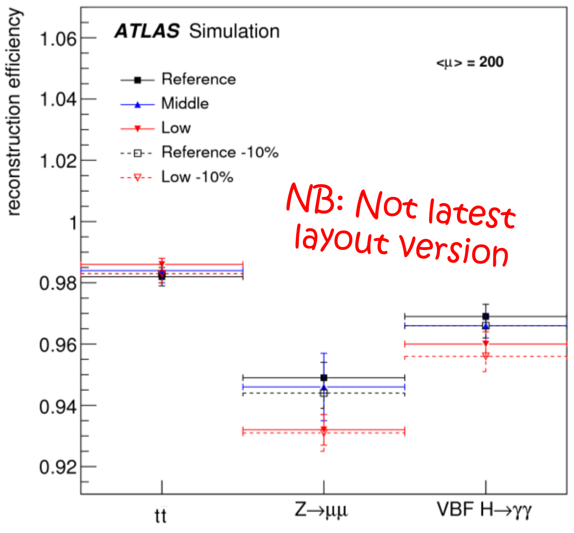
- Excellent capability to resolve the position and momentum
- Transverse impact parameter (IP) resolution d_0 similar to current ID
    - Run-2 performance better at very high momentum due to analogue clustering calibration while such calibrations are not yet ready for the ITk
        - ITk with analogue clustering expected to provide similar resolutions as for the current ID
- Significant improvements in the longitudinal IP resolution z_0
    - Reduction of pixel pitches from 250 and 400 μm to 50 μm for ITk
- Momentum resolution substantially improved by high precision measurements along the full track length provided by the full silicon tracker

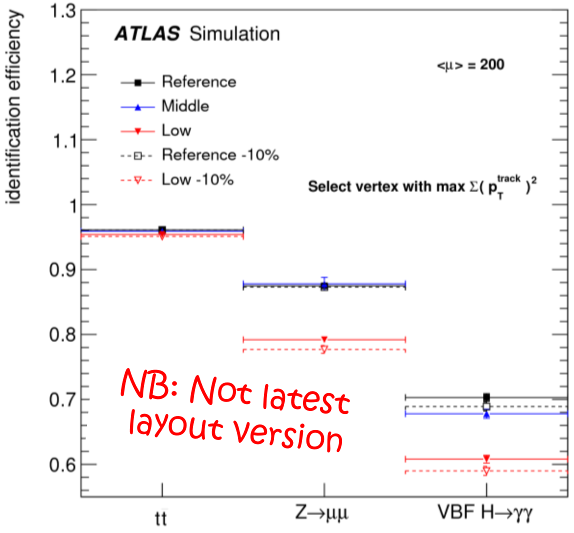






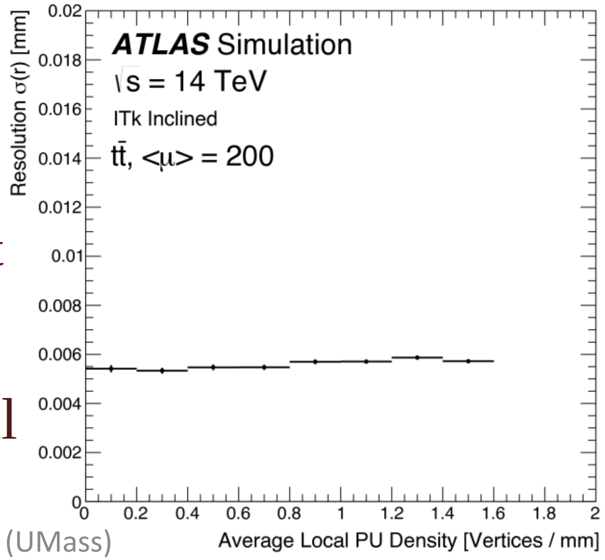
Phase-II Vertexing Performance

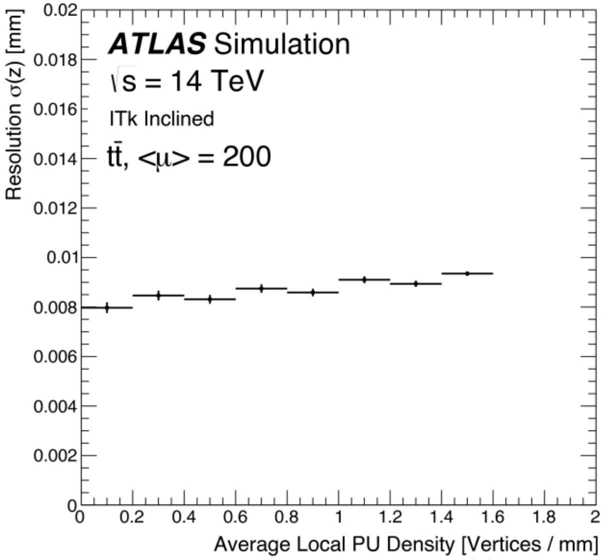




- The new tracker presents high vertex reconstruction efficiency
  - Close to 99% for $t\bar{t}$ at $\mu = 200$
- Good efficiency for identifying the Hard-Scatter (HS) interaction
- Demonstration of significant improvements for $Z \rightarrow \mu\mu$ and $VBF\ H \rightarrow \gamma\gamma$ gain by forward tracking
  - Low (|η| < 2.7) versus Reference (|η| < 3.6)

- Maintaining excellent vertex position resolutions in the transverse and longitudinal directions
  - Slight pile-up dependency on the resolution
    - Picking up more and more pile-up tracks that might impact the vertex fit negatively
  - However, only minor degradation of 1 μm for r and 2 μm for z when going to high average local pile-up densities for $t\bar{t}$





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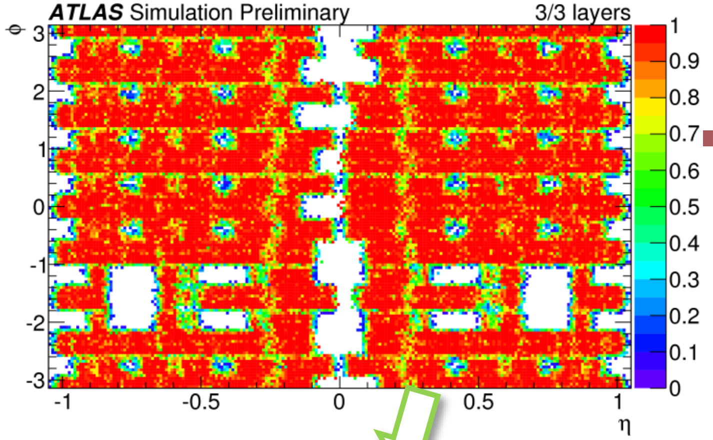
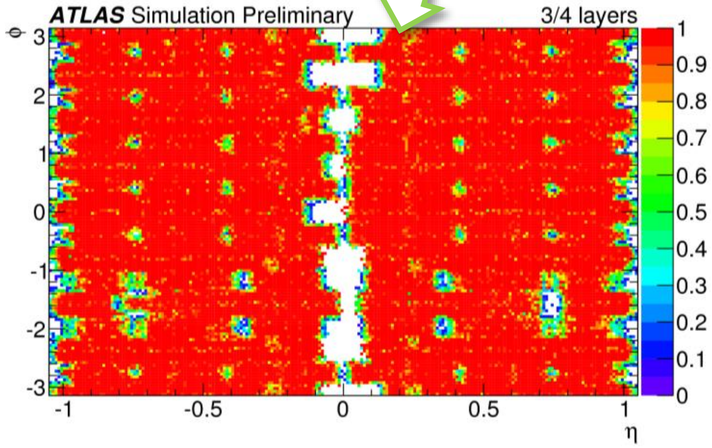
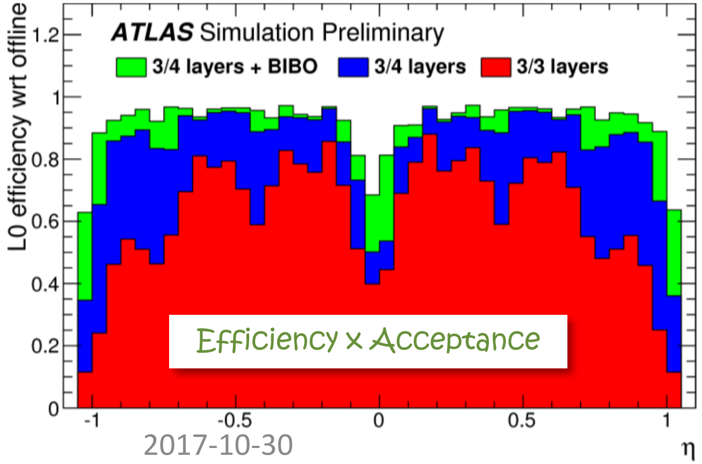
Phase-II Muon Trigger Performance



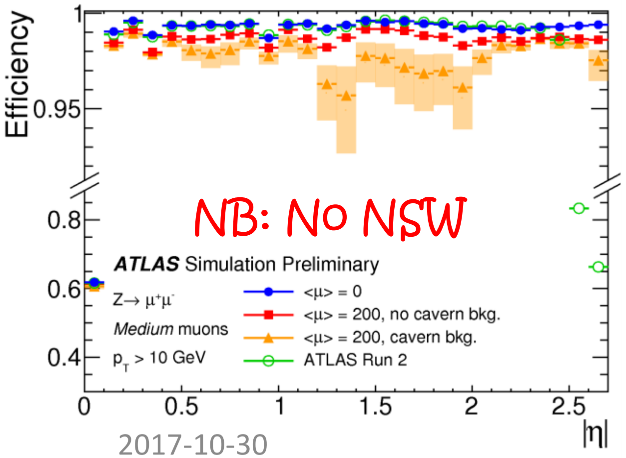


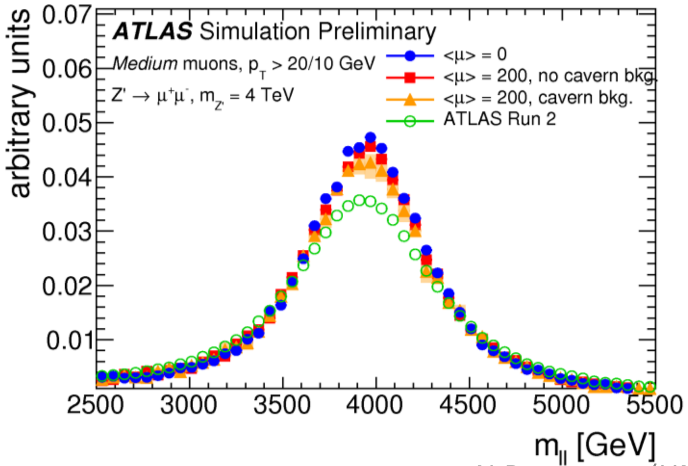


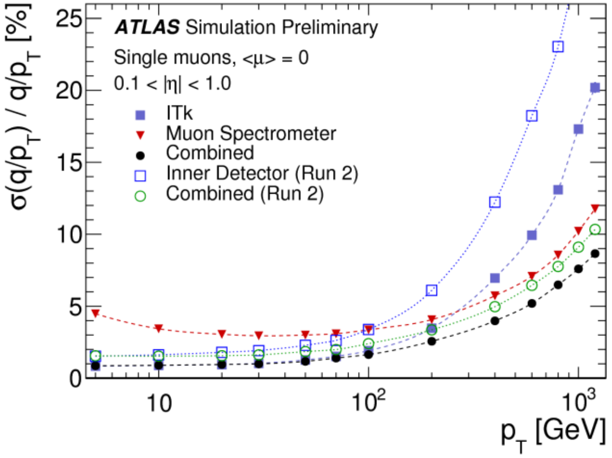
- The current barrel trigger requires three layer coincidence 3/3 in the RPC
  - Holes in coverage caused by magnet supports limit trigger acceptance
- Upgrades to barrel will allow for 3/4 instead
  - Increasing acceptance of the barrel trigger from 82% to 90%
- Excellent trigger efficiency even in the worst case scenario for HL-LHC run conditions
  - HV reduced to maintain the chamber currents
    - Considering a safety limit of a factor of two

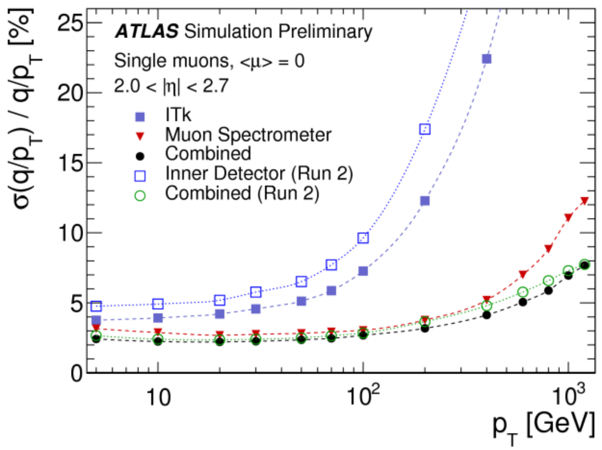
Phase-II Muon Reconstruction

- Expected to keep the same high muon reconstruction efficiency
  - Same performance as the current ATLAS with a degradation of ~1.5% with $\mu = 200$
  - Cavern background yields further efficiency losses which are expected to be improved by the NSW
- Minor impact on the mass resolution for $Z \to \mu\mu$ going from $\mu = 0$ to $\mu = 200$
  - Further optimisations of the selection are expect to improve measurement $\mu = 200$









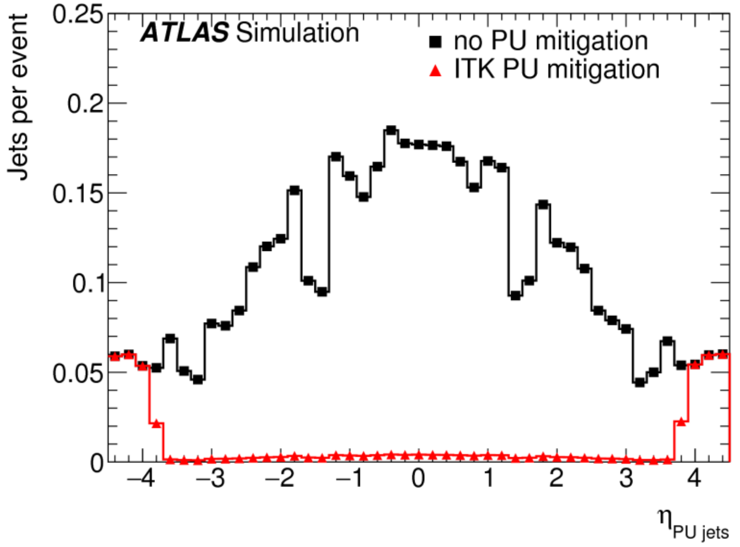
- Main change of the $\sigma(p_T)$ comes from ITk
  - p_T range where the resolution is dominated by the tracker increased from around 100 GeV to 250 GeV for |η| = 0.1 from the current ID to the ITk
  - $\sigma(p_T) = 1 - 2\%$ for |η| < 1.0 versus 1.5-3% for current ATLAS for the low p_T-range

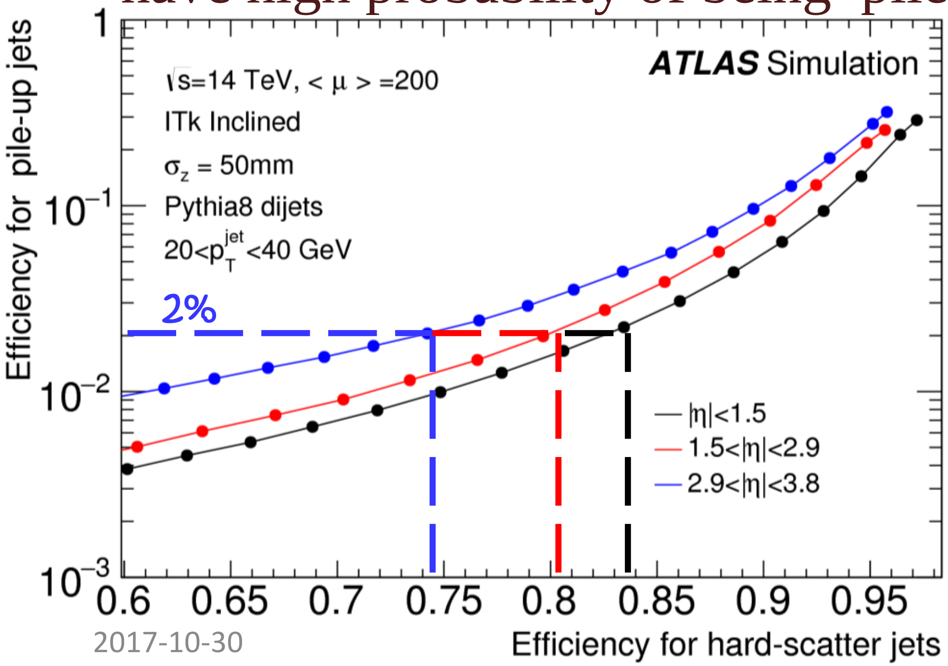
Significant improvements in the barrel region for the high momentum range

  - Minimal improvements are seen in the forward regions compared to the current detector are expected since resolution in the forward region is dominated by the MS measurements

Phase-II Pile-up Mitigation

- Utilise tracking and vertexing information to aid jet and MET reconstruction via pile-up suppression
  - Extended coverage of the tracker improves the capabilities to identify pile-up jets
- R_{p_T} defined as the scalar sum of p_T of tracks within the jet-cone and associated to the HS vertex divided by the jet p_T
  - Small values correspond to a low fraction of tracks from the HS and have high probability of being pile-up jets

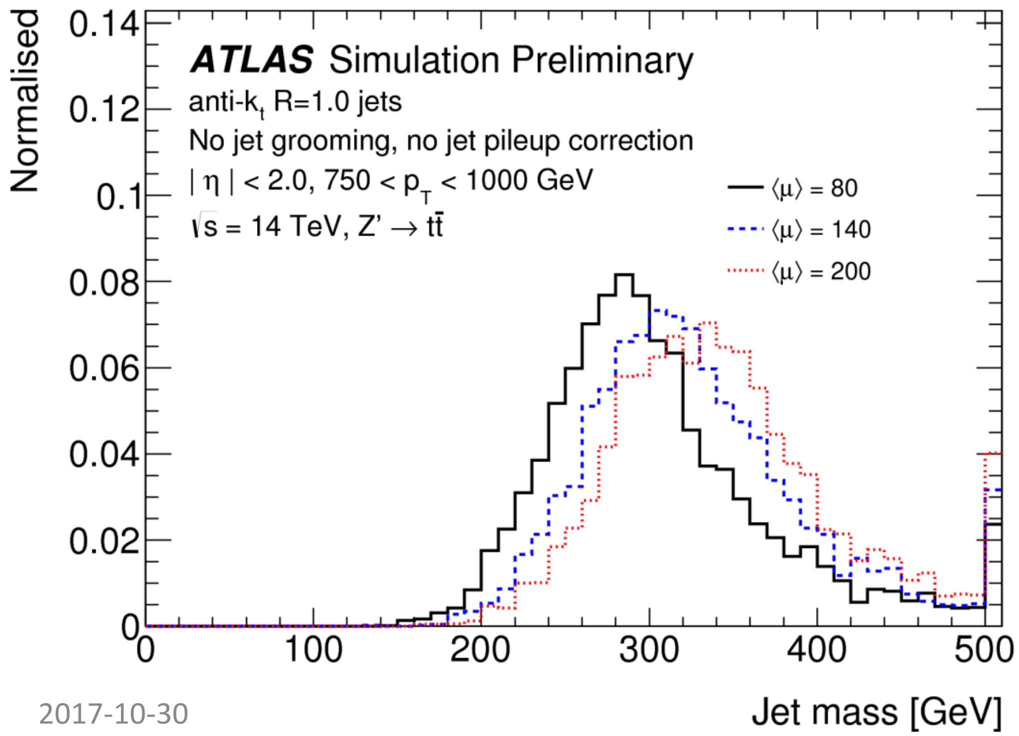


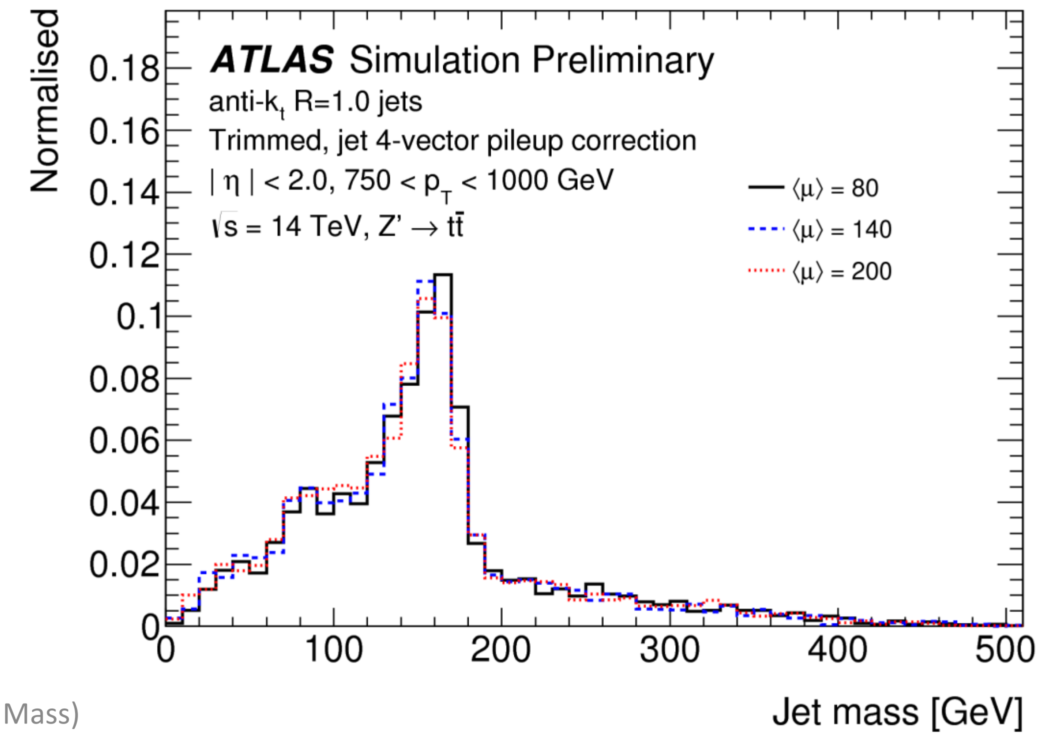


- ITk helps reduce the pile-up jets by a factor of 50
  - Translates into 2% efficiency for pile-up jet
  - Studies here and in the following slides use *no timing information*
- Assuming a factor 50 pile-up rejections yields
  - 84%, 80% and 75% efficiency for HS jets for $|\eta| < 1.5$, $1.5 < |\eta| < 2.9$ and $2.9 < |\eta| < 3.8$ respectively

Phase-II Jet Reconstruction

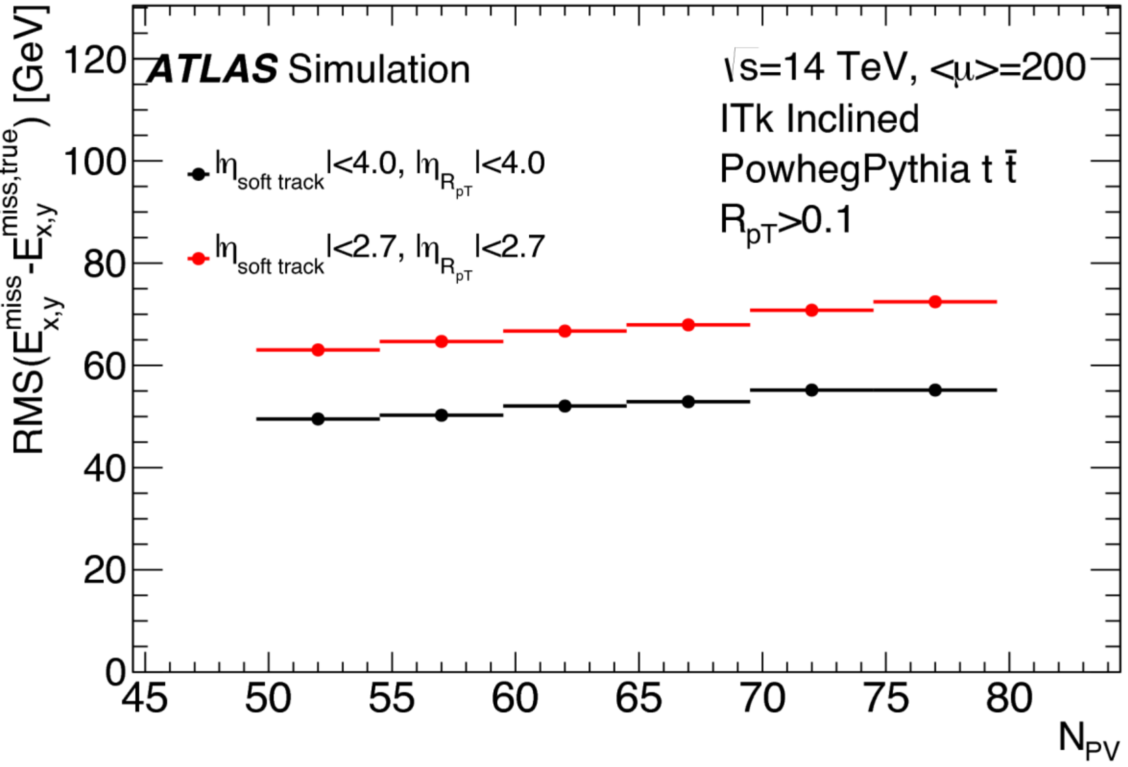
- Pile-up mitigation top priority for jet reconstruction
  - Leading jet mass increasing with pile-up
- Typical boosted signature with jet radius R = 1.0 for $Z' \rightarrow t\bar{t}$
  - Leading jet mass shown for before and after grooming and applying pile-up corrections
    - Reducing pile-up dependency and regaining jet mass resolution





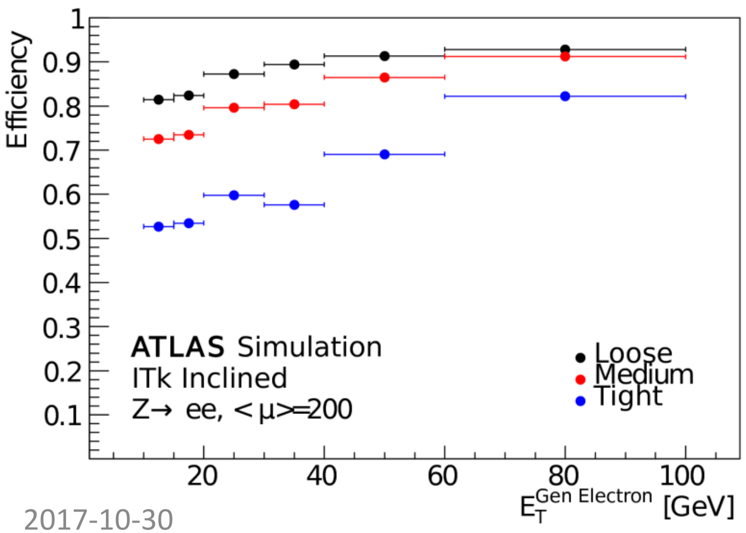
Phase-II MET Resolution

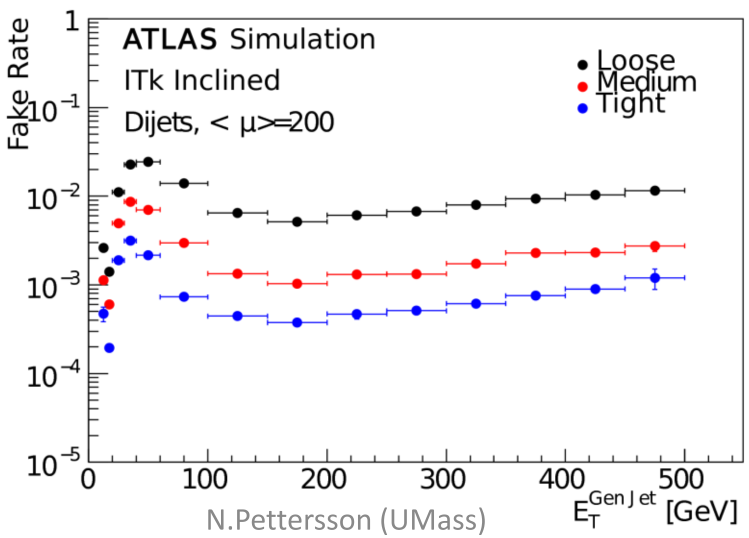
- E_T^{miss} computed as the vector sum of high momentum objects and soft term from low momentum particles
  - Soft-term calculated from tracks associated to the HS vertex
- Good capabilities to identify pile-up tracks are critical E_T^{miss} calculation
  - Extended tracker coverage from the ITk from |η| < 2.7 to |η| < 4.0 demonstrates 30% improvements on the $E_{x,y}^{miss}$ resolution
    - Mainly owning to pile-up suppression
    - But also small gain via the soft-term

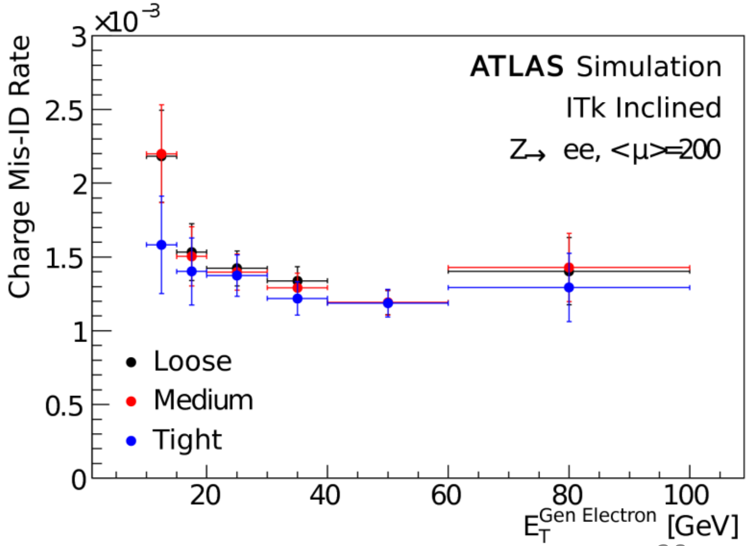


Phase-II Electron Reconstruction Performance

- Using same reconstruction and selection as for current ATLAS
  - Efficiency and fake rates similar to ATLAS performance in *Run-I*
- Run-II introduced optimised identification in form of MVA
  - Utilising tracking and calorimeter variables
- Improvements are expected with ITk optimised identification
  - Will re-gain at least same the performance of Run-II







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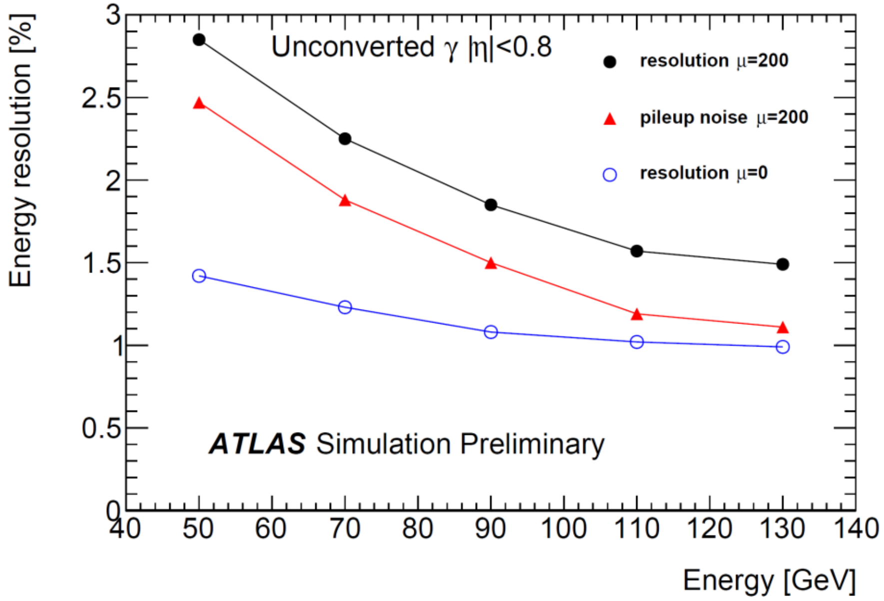
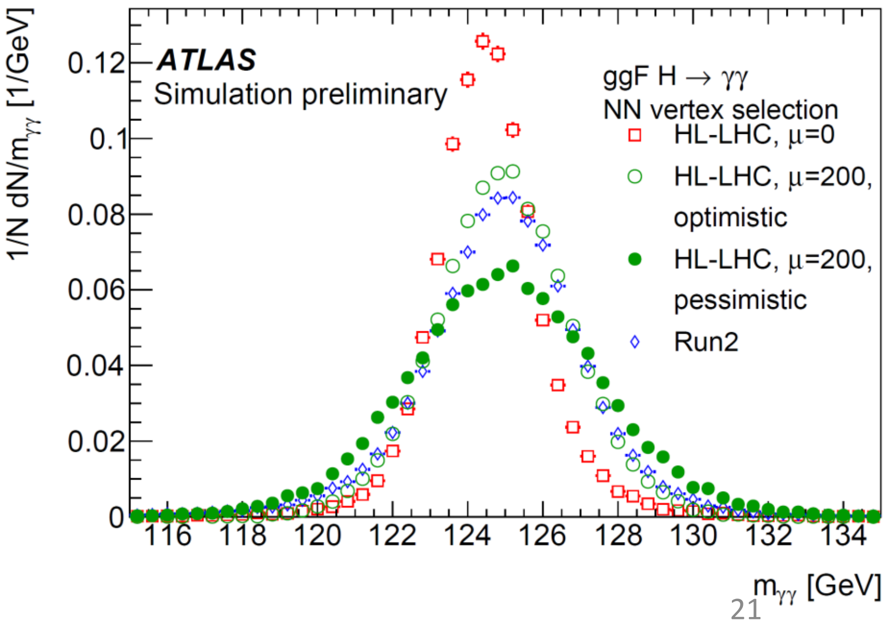
Phase-II Photon Reconstruction Performance

- Energy resolution for unconverted photons
  - Using the same reconstruction as for the current ATLAS and applying noise estimated from the current electronics
    - Shown for the very central η-region
  - Comparing the reoslution for $\mu = 0$ to $\mu = 200$
  - Dominant factor comes from of pile-up
    - Increasing impact for lower energies

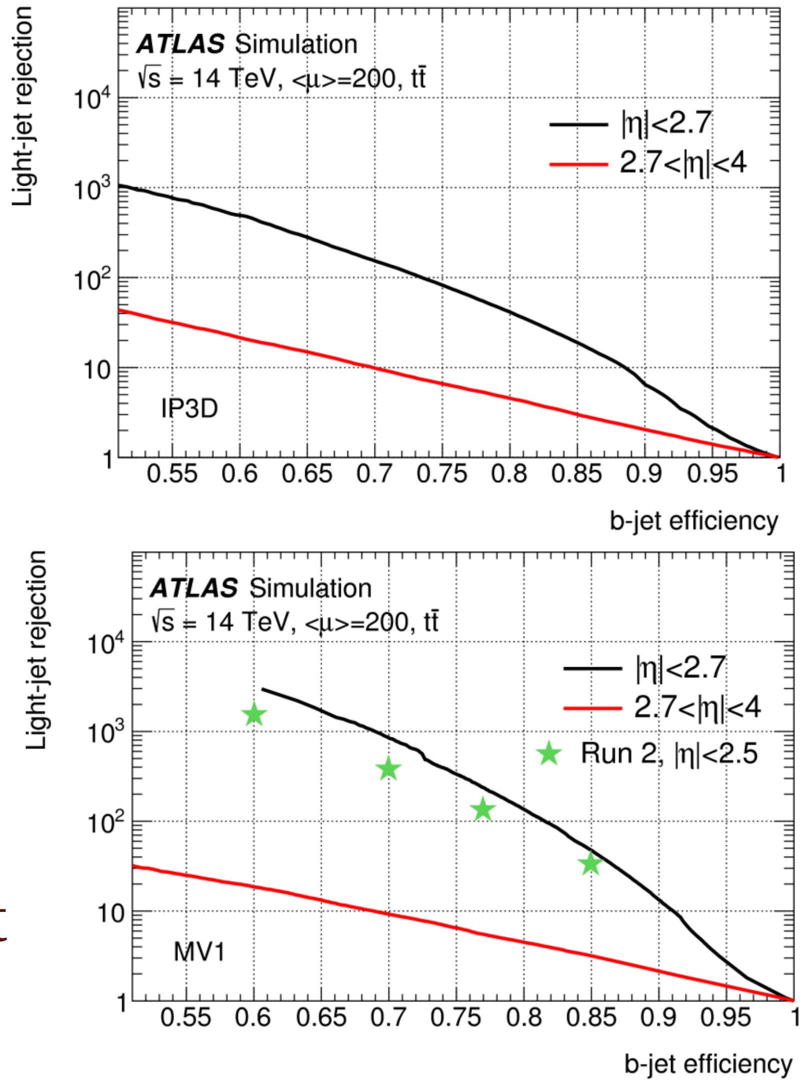


- Diphoton invariant mass for $ggH \rightarrow \gamma\gamma$ shows that degradations to be expected for the high pile-up scenario of $\mu = 200$ w.r.t $\mu = 0$, but still *similar or slightly better* than Run-2!
  - Performance differences are due to improvements expected to the photon reconstruction and offline corrections
  - Reduced material in the ITk gives fewer converted photons
- No impact of pile-up on the photon direction determination observed

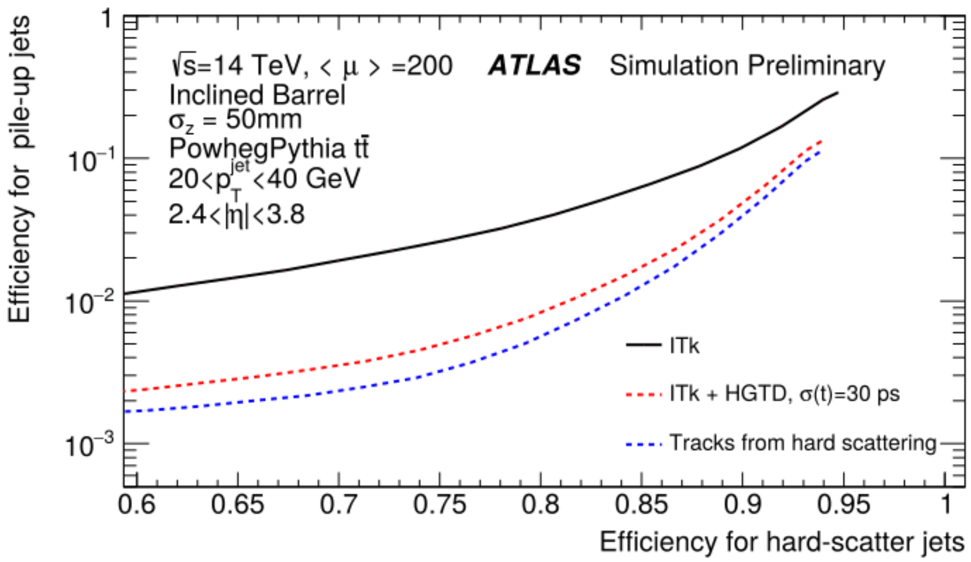


Phase-II B-Tagging Performance

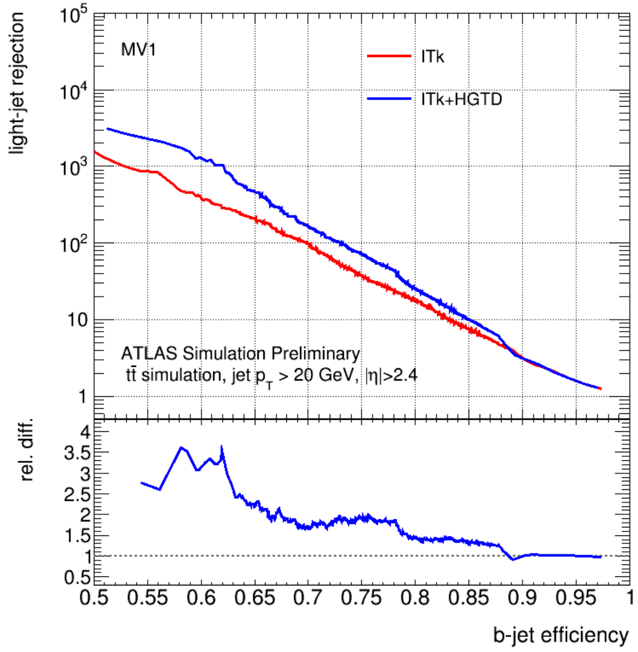
- Identifications of jets containing a b-hadron using multivariate techniques
  - Relying on three algorithms based on the current ID
    - Track selection, likelihood parameterisations for low-level (IP3D), high-level multivariate approaches (MV1)
    - Calibration and training need to be updated to ITk especially in the forward region
- Non-optimal training for MV1 already yields good b-jet efficiency
  - At 70% efficiency a rejection of 1000 (10) is seen for the central (forward) region
  - IP3D slightly worse performance as it relies on a subset of the information available to MV1



High Granularity Timing Detector



- Timing information adds discriminatory power
  - Possibility to identify particles from pile-up interactions and minimises pile-up dependency
  - Assign each charged particle to their production vertex using the time information



- Huge improvement of the pile-up rejection efficiency with the addition of the HGTD
- Available timing information and the improved pile-up rejection benefits several areas
  - Reduces pile-up contamination in the primary vertex, vertex reconstruction efficiency and identification, lepton isolation efficiency, MET resolution, etc…
- Significant improvements of b-tagging performance due to rejections of tracks from pile-up interactions

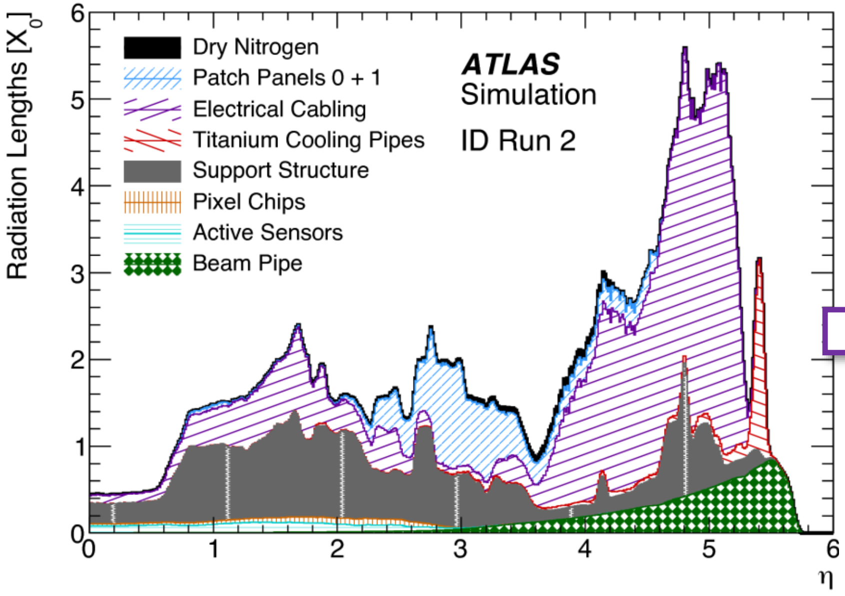
Conclusions

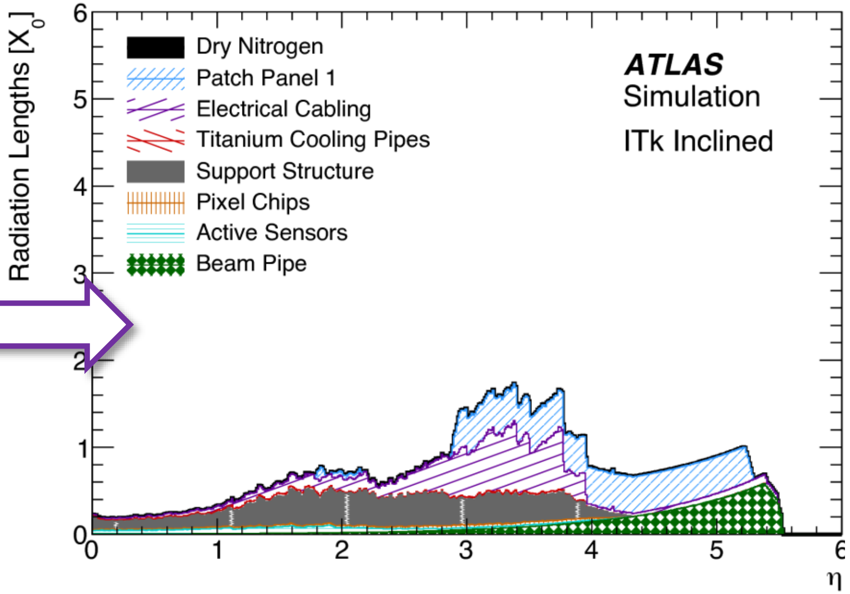
- Significant upgrades planned to for the ATLAS detector for phase-I/-II
  - Complete replacement of the Inner Detector
    - Improved tracking performance and extended coverage!
  - Upgrades to the Liquid Argon and Tile calorimeters readouts and electronics to provide more information to be available at L0 trigger
  - New barrel trigger chambers to be installed in the Muon Spectrometer to improve trigger acceptance and to maintain current efficiency for HL-LHC
- Maintaining similar performance as the current ATLAS in very dense pile-up environments of up to $\mu \sim 200$ is a tough challenge
- Doing very well so far for physics objects reconstruction
  - Expected performance for ***most areas*** is on par or better for than the current detector
    - Excellent tracking and vertexing performance, high capabilities of pile-up mitigation, good energy and momentum resolutions, low fake rates, excellent b-tagging, etc...
- The future looks bright for physics!

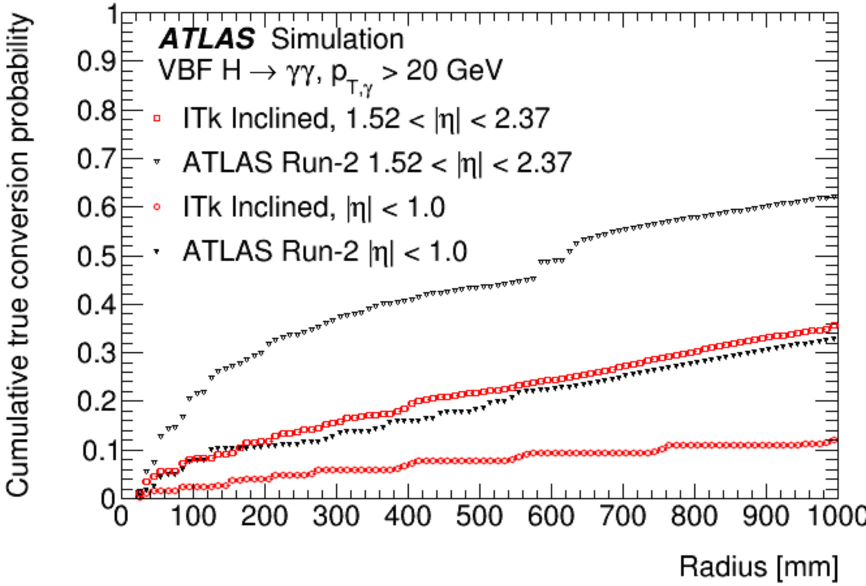
BACKUP

Material Budget of the Phase-II Tracker

- Significantly reduction of the material inside the tracking volume
  - Leads to a reduction of multiple scattering of all particles
  - Reduced conversion probability of photons
- Improves the tracking efficiency and resolutions
- Particles lose less energy before the calorimeters



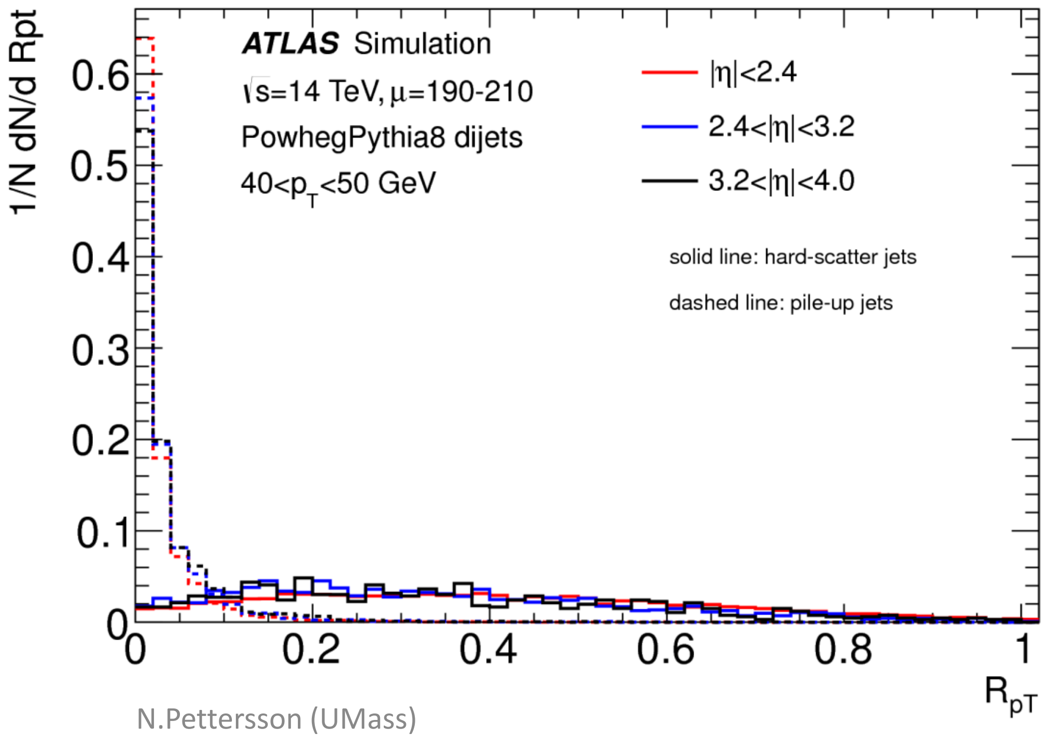




Pile-up Jet Suppression

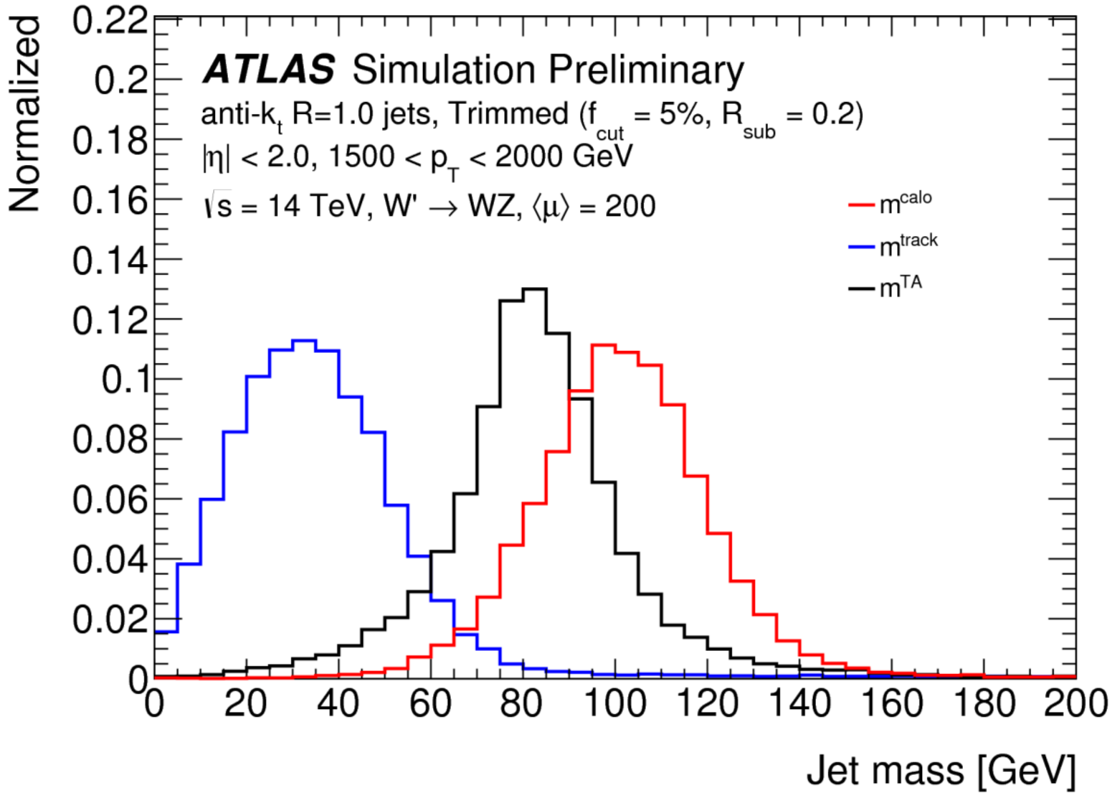
- R_{p_T} defined as the scalar sum of p_T of tracks within the jet-cone and associated to the HS vertex divided by the jet p_T
  - Small values indicating few tracks associated to the HS vertex
    - High probability for being a pile-up jet

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



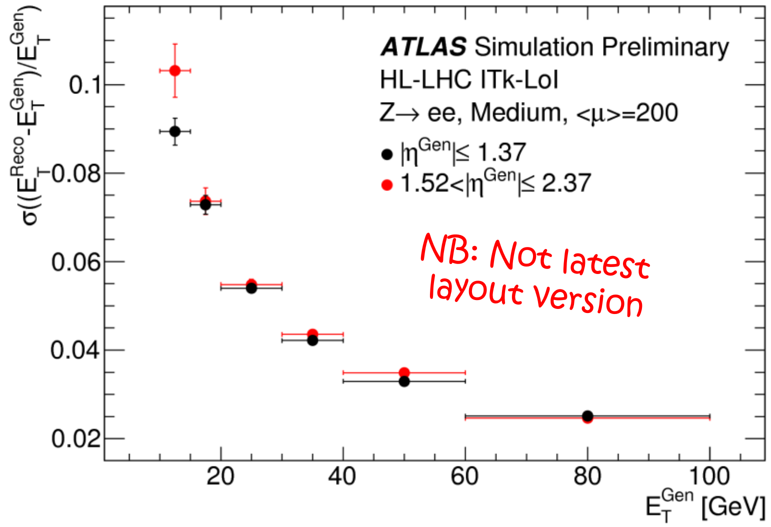
Phase-II Jet Reconstruction

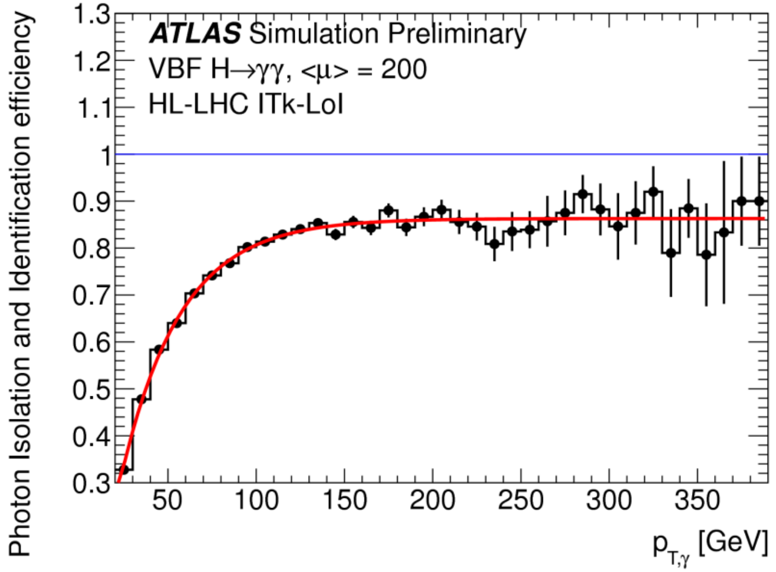
- Jet mass reconstructed for $W' \rightarrow WZ$ at $\mu = 200$
  - Shown using different techniques relying on calorimeter-based m^{calo} and mass from associated tracks m^{track}



- Track-assisted mass m^{TA} closest to the real mass of the W
  - Takes into accounts for the neutral particles contribution
  - Scales m^{track} using calorimeter information with p_T^{calo}/p_T^{track}

Electron and Photon Reconstruction

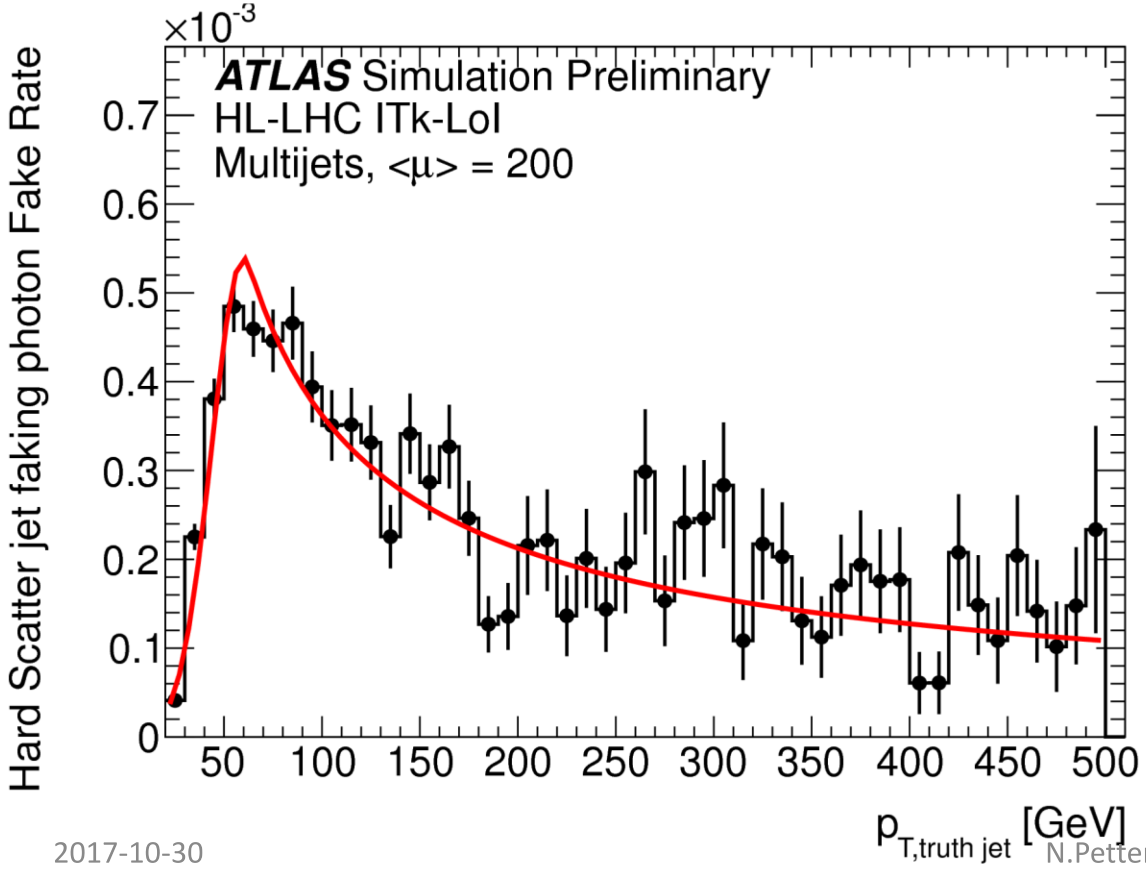


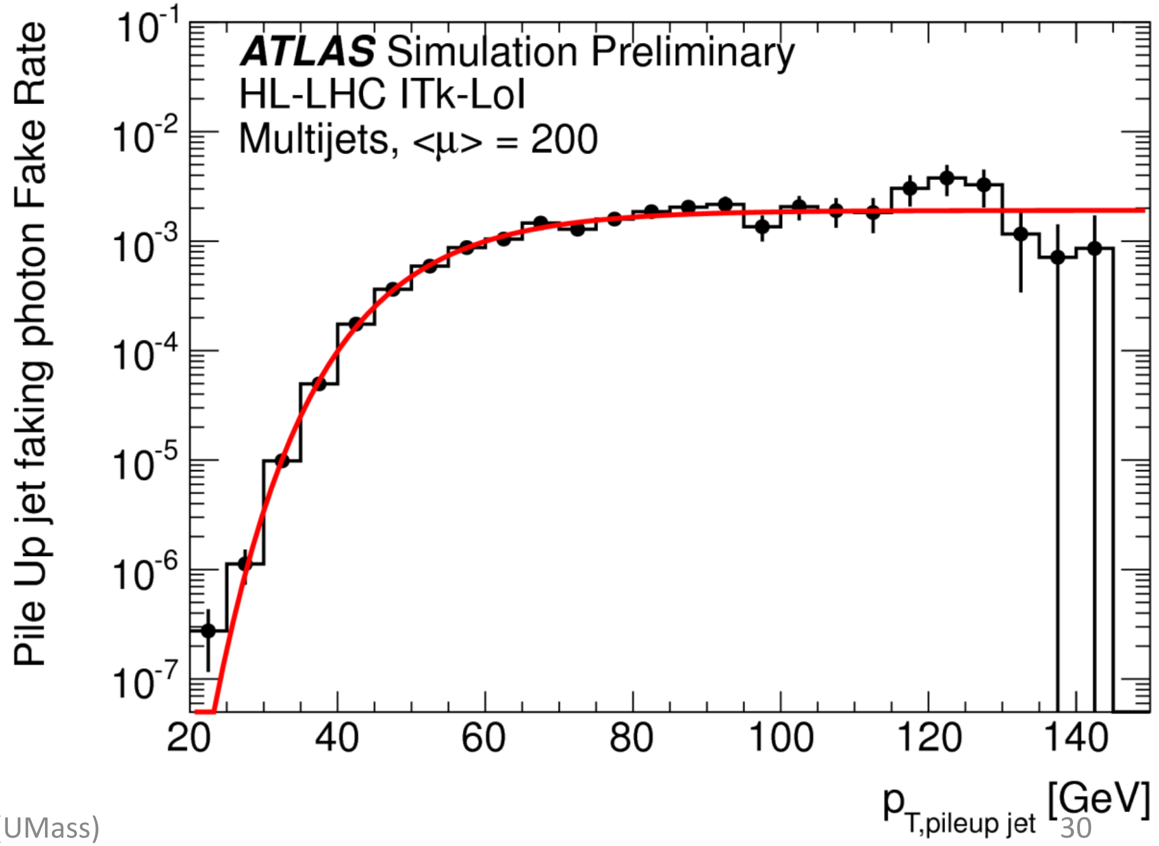


- Electron reconstruction efficiency is computed taking into account several sub-steps
  - The electromagnetic cluster reconstruction, the track reconstruction, the cluster-track matching, and the selection efficiency to pass the track-quality requirements
- Electron energy resolutions nearly independent of pile-up
  - Almost the same resolution sampling term and the constant term as for current ATLAS
  - Pile-up only affects and increases noise terms
    - Shows an effect on the energy resolution at low momentum
- Average combined photon signal efficiency 70% similar to current performance
  - Fake rates from HS jets $\sim 2.4 \cdot 10^{-4}$
  - And $\sim 7.0 \cdot 10^{-5}$ for pile-up jets

Photon Identification and Isolation

- Rate of which a jet from the hard scatter or a fully calibrated pile-up jet is identified as a photon and passing the isolation criteria





Photon Direction Determination

- "Selected Vertex" using calorimeter and tracking information to determine the vertex position minimal impact compared to selecting the true vertex
  - Diphoton invariant mass resolution is dominated by the photon energy resolution and the vertex resolution plays a minimal role even at $\mu = 200$