ATLAS Detector Upgrade Prospects

M. Dobre on behalf of the ATLAS Collaboration

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Outline

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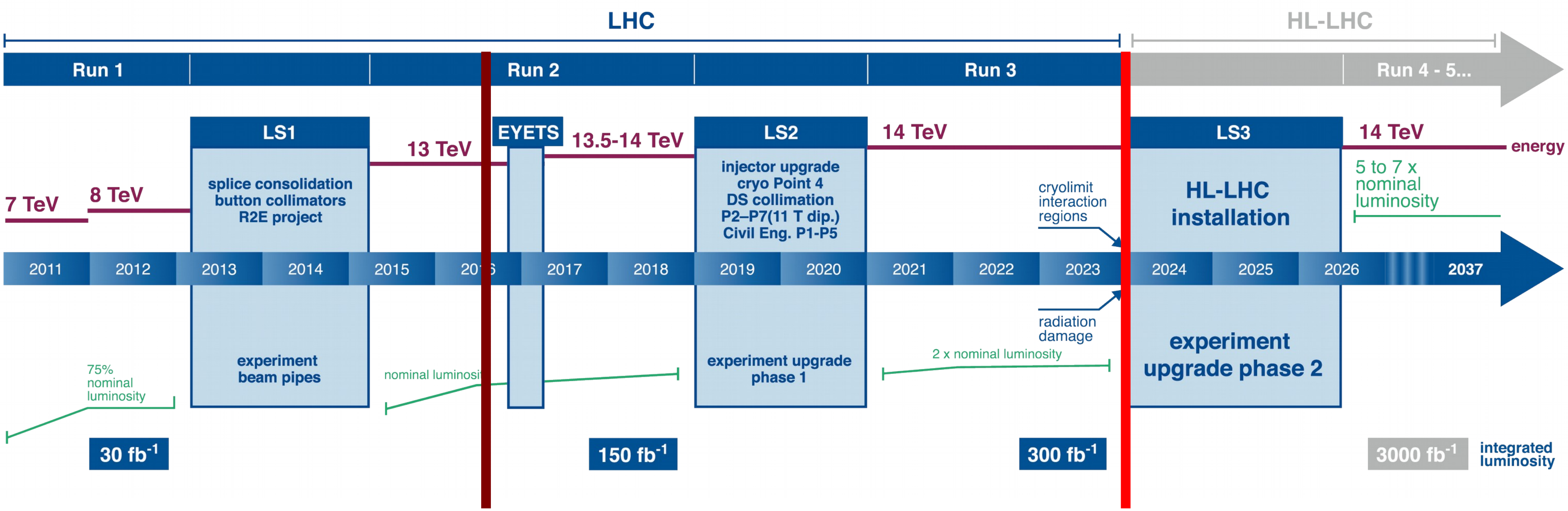
- Detector upgrades
  - Trigger and data acquisition system
  - Muon detector
  - Tracking
  - Calorimeter
- Physics prospects
  - Physics performance of physics objects
  - Higgs measurements
  - Standard Model studies
  - Beyond Standard Model searches
- Conclusions and Outlook

LHC / HL-LHC Plan



- LHC has had a successful Run2 so far, with good operation and many physics results published with the newly recorded data by all experiments (ATLAS results in particular were presented by S. Smirnov in the previous talk).

- In order to maximize the physics output of this unique facility, major upgrades of the machine and of the detectors are planned to start after Run2 to increase the nominal luminosity by up to a factor of 7.5, aiming to deliver 3000 fb^{-1}.

- The aim of the detector upgrades is to achieve a similar or better performance than with the current design, even in the presence of high pileup rates.

- During LS2, the upgrade of several detector systems is foreseen and it will function as a foundation for the HL-LHC upgrades: the upgrades of the *calorimeter trigger system* and of the *associated LAr trigger electronics*, the *New Small Wheel* (**NSW**) and the *Fast TracKer trigger* (**FTK**).

- Many studies and possible detector designs were published for the HL-LHC upgrade, the most recent being the Scoping Document (LHCC-G-166) and the notes for this year's workshop of the **E**uropean **C**ommittee for **F**uture **A**ccelerators (**ECFA**)

- The proposals for each subdetector's design are analysed and the impact on the physics potential is assessed through detailed studies using parametrizations of the expected detector performance.

- The main changes foreseen for the detector upgrade are: new all-silicon tracker, new muon trigger chambers, complete upgrade of readout electronics, higher trigger rate and readout capabilities

- The upgraded detector should be able to give a similar or better performance to the one of the current detector setup, in conditions of very high pileup rates (from ~24 in Run 2 to ~200 in HL-LHC)

Trigger and Data Acquisition System

- The current ATLAS detector electronics was designed to buffer data for a maximal latency of **2.5 μs** and cope with Level-1 trigger rates up to **100 kHz**.

- For Phase-II Upgrade, **Level-0 trigger** will be introduced to accommodate latencies less than **6 μs** and rates up to **1 MHz**, with the L1 rates going up to **400 kHz**.

Detector electronics (ITk, Tile, LAr, MS) → **L0** (6/10 μs) (1 MHz) → **L1** (30/60 μs) (400 kHz) → **L1 Accept/ Region of Interest**

- **L0 trigger** will have two components: L0 Muon Triggers and L0 Calorimeter Triggers.

- **L0 Muon Triggers** will have an efficiency in the barrel region of 92%-96% and the local polar angle β can be used to reduce the trigger rate by up to 50% with minimal losses in efficiency.

- **L0 calorimeter triggers** will reuse the system installed as part of the Phase-I ATLAS upgrade and will be adapted for the Phase-II ATLAS upgrade

- **L0 calorimeter triggers** will be based on feature extractor processors with very fine granularity covering the areas $|\eta| < 2.5$ for electrons, photons and taus, $|\eta| < 4.9$ for jets and allowing an entire event to be processed in a single module.

Trigger and Data Acquisition System

- **L1Track** will use hits from ITk strips and pixels to find tracks within Regions of Interest (RoI) which are seeded by L0 triggers – p_T of the tracks used for the templates will be restricted to **p_T > 4 GeV**.

- **L1Track** has the largest impact on electron identification and on pileup rejection for multi-object events.

- **L1Global** is a time-multiplexed trigger system receiving input from the LAr and Tile Calorimeters, from L0 and from L1Track, with the calorimeter data being transmitted to it with a latency of 1-2 μs after the L0 decision.

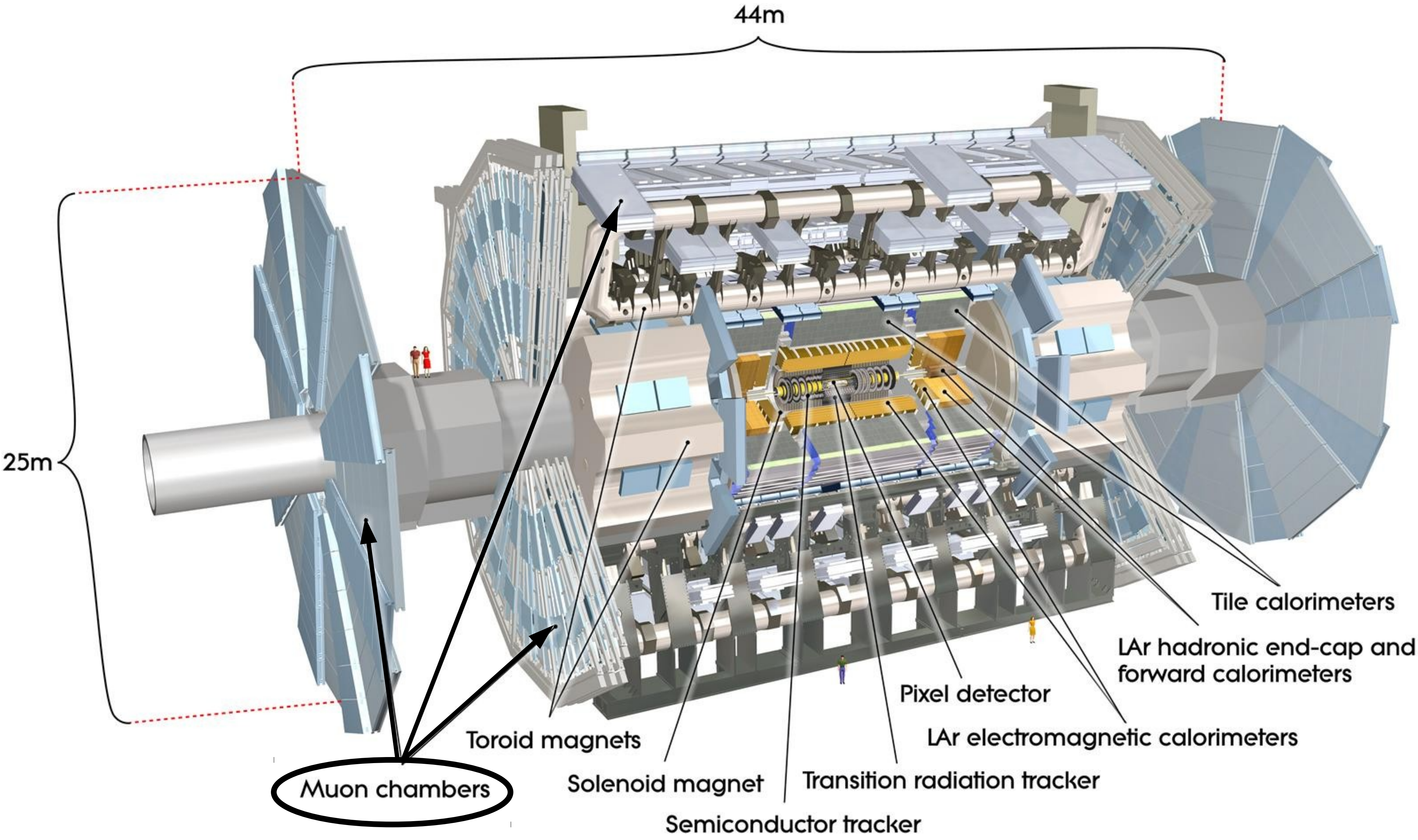
- The central trigger processors (CTP), **L0 CTP** and **L1 CTP**, will ensure that L1Track and L1Global do not overflow.

- The data from the detector will be transferred to the readout system, Front-End Link Interface eXchange (**FELIX**), then to a network which will pass it to the event filter and to the monitoring and calibration processors.

- The ATLAS event size is expected to increase from the **current 1.5 MB** to approximately **5 MB**, leading to a trigger rate a factor of 4 larger than today.

- The expected recording rate will be **5-10 kHz**, leading to output rates of **1-2.2 kHz** each for electrons with p_T > 22 GeV and for muons with p_T > 20 GeV.

Muon Spectrometer (MS)



Muon Spectrometer

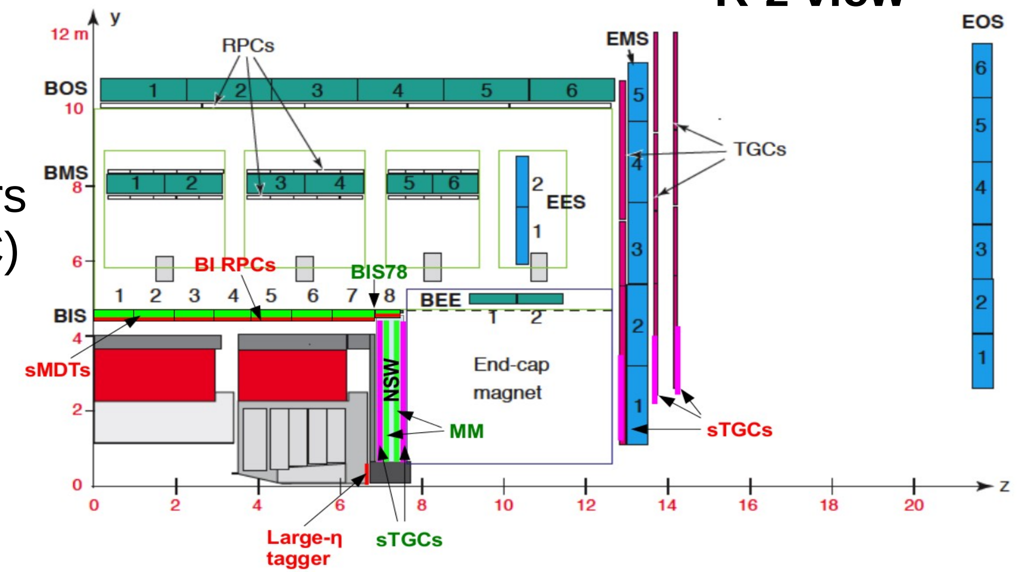
- **Phase-I upgrade**: the detectors of the inner layer in 1.3 < |η| < 2.7 will be replaced by an additional layer of **R**esistive **P**late **C**hambers **(RPC), s**mall-strip **T**hin **G**ap **C**hambers (**sTGC**) and **M**icro**M**egas (MM) detectors

- **Phase-II upgrade**: replacement of the whole readout electronics in order to be able to cope with the larger rates expected

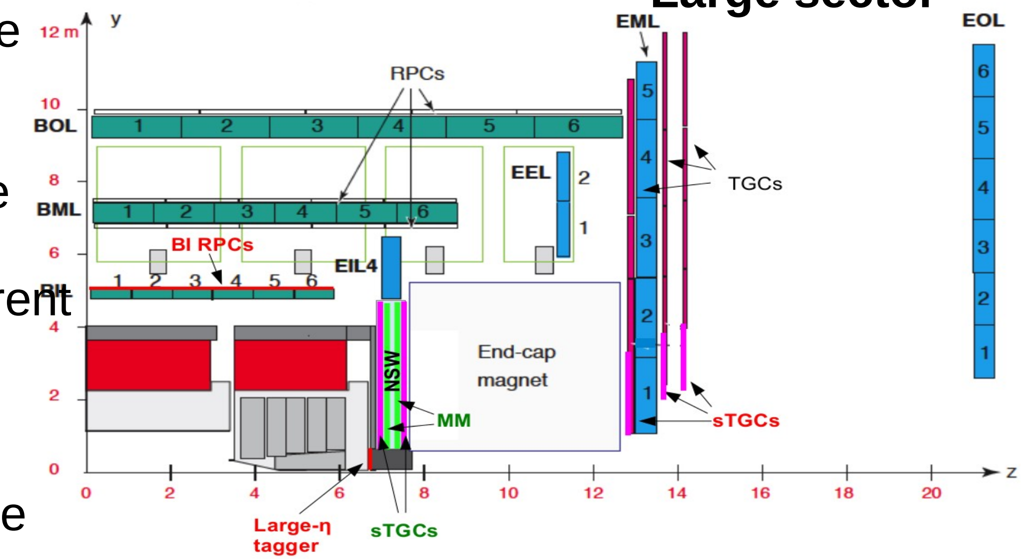
- Current **M**onitored **D**rift **T**ubes (**MDT**) chambers can safely operate in most of the MS during the HL-LHC period
  - *exception*: the higher rates in the **e**nd-cap **i**nner layer (**EI**), which will be addressed by the installation of the **N**ew **S**mall **W**heel (**NSW**)
  - new small MDTs will replace some of the current ones to make space for the additional RPCs

- A new type of TGC will be installed in the EI to improve the accuracy of the muon track θ angle measurement, during Phase-I

R-z view

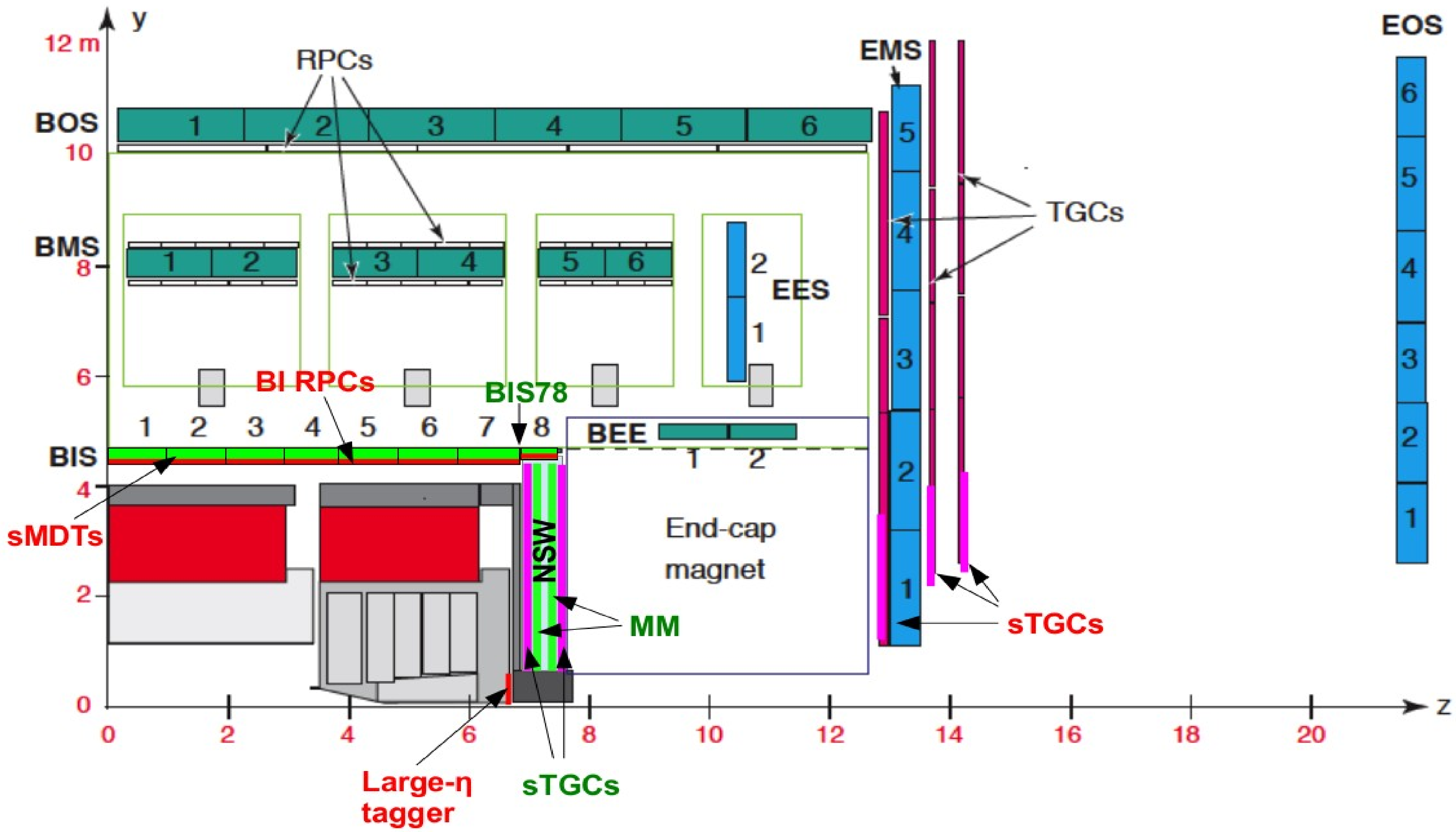


Large sector



Muon Spectrometer

R-z view



Upgrades foreseen for LS2

Upgrades foreseen for LS3

Unchanged

Muon Spectrometer

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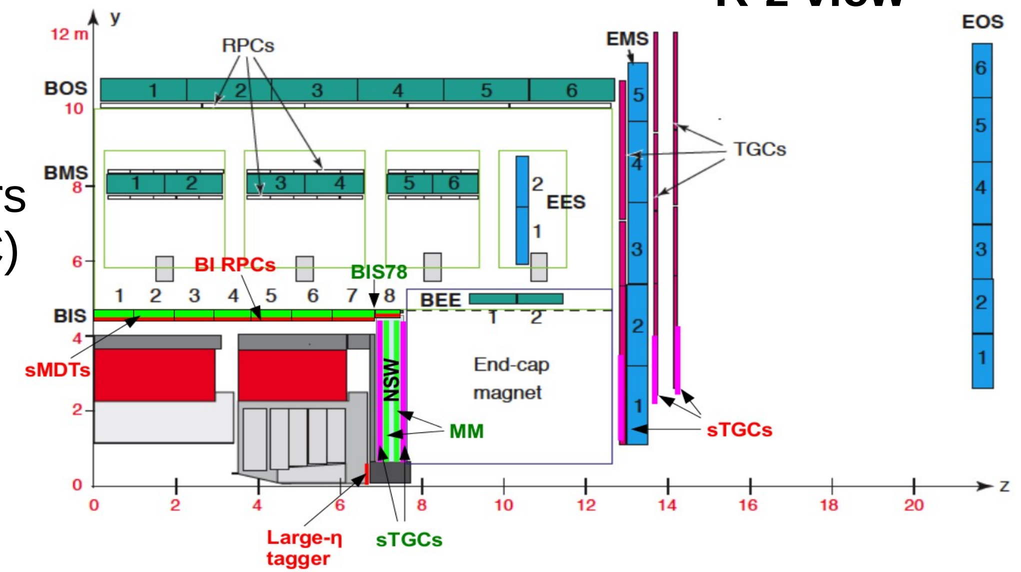
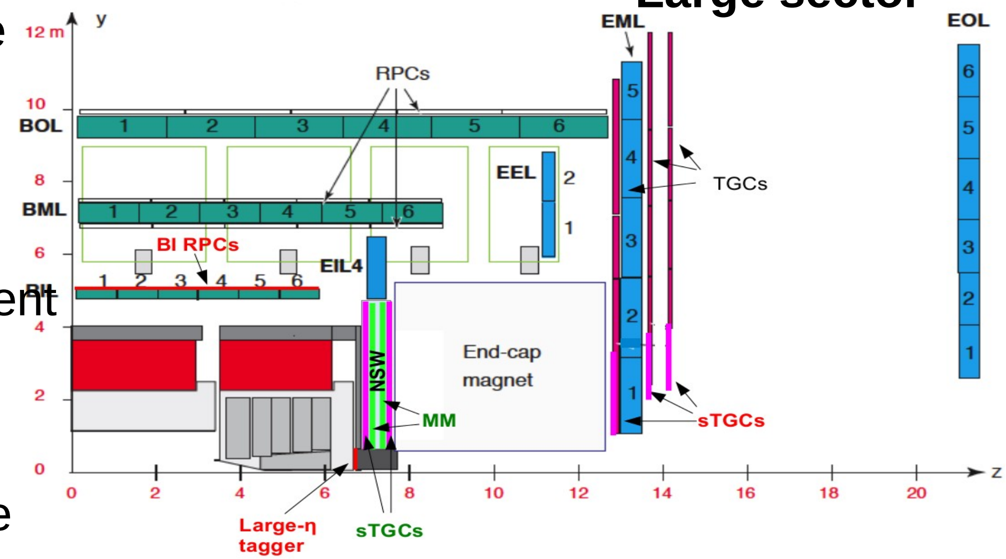
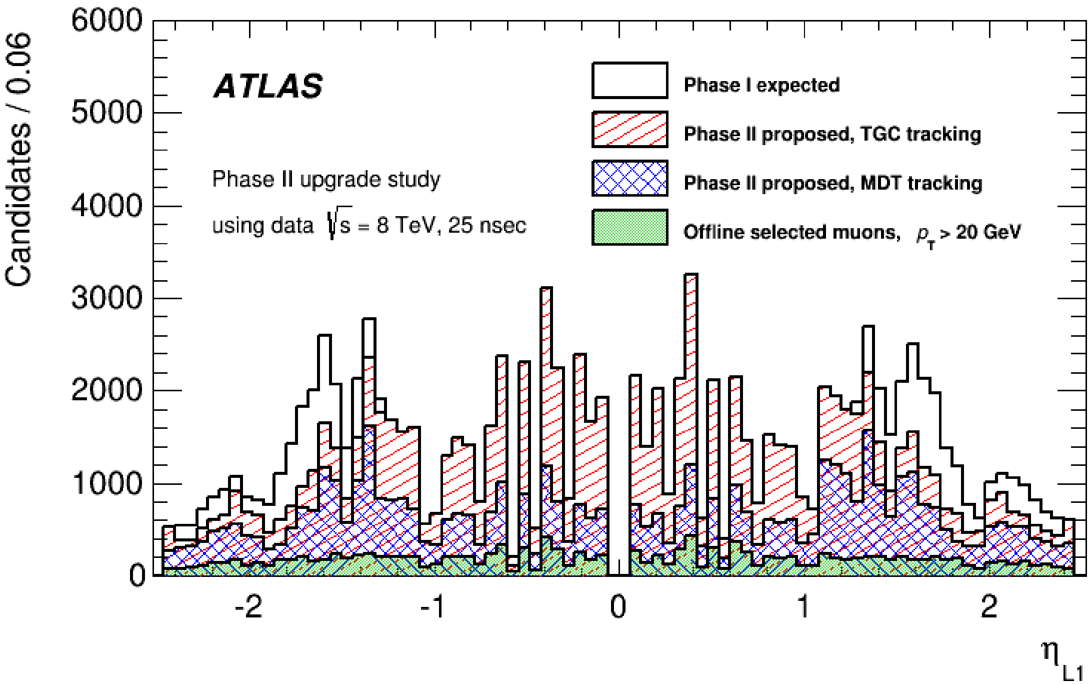


Large sector



Muon Spectrometer

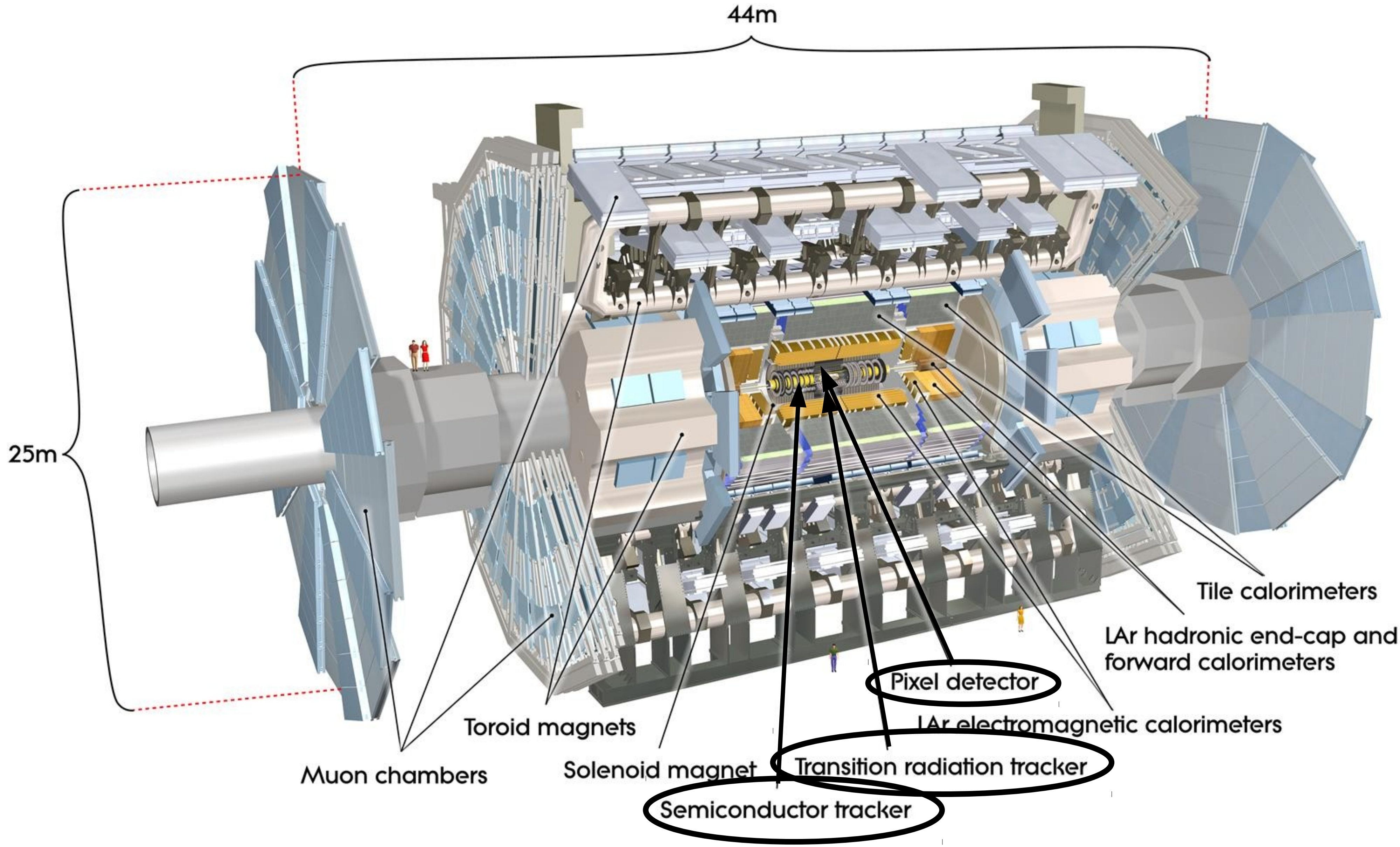
- A new layer of RPC will be added to improve the performance of the inner barrel stations of the MS - the efficiency of the barrel triggers will be ~95%
- A muon tagger for the high η region will be added to extend the inner tracker capabilities
- New paths and methods are studied to reduce the trigger rates and improve the reconstruction of the tracks
- The current power supplies will also be replaced during Phase-II, to cope with the large radiation doses foreseen



LHCC-G-166

Rate study for single muon trigger with 20 GeV threshold based on Run 1 data,
8 TeV, 25 ns bunch spacing

Tracking

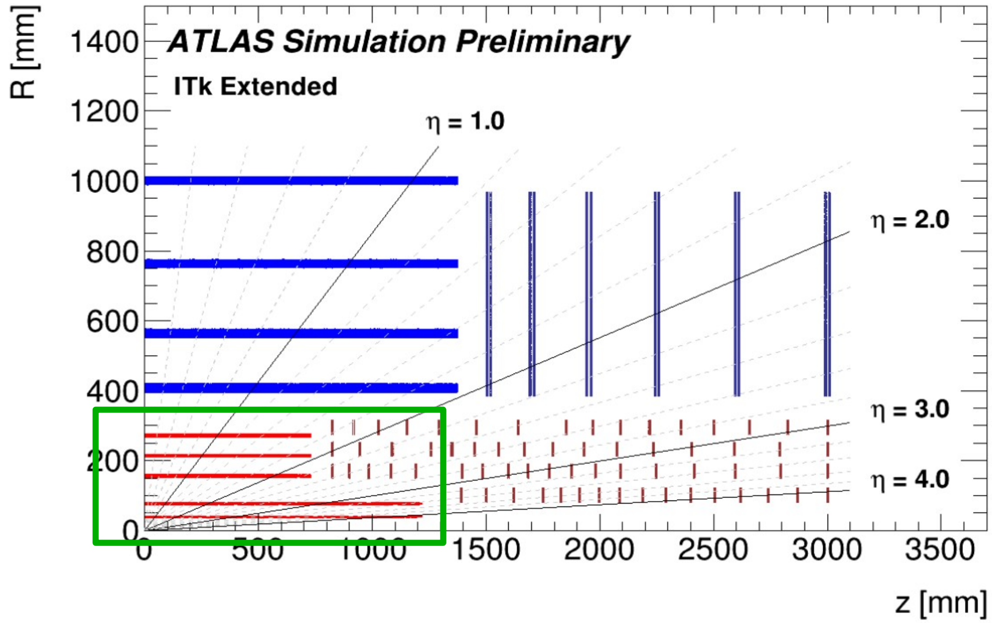

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

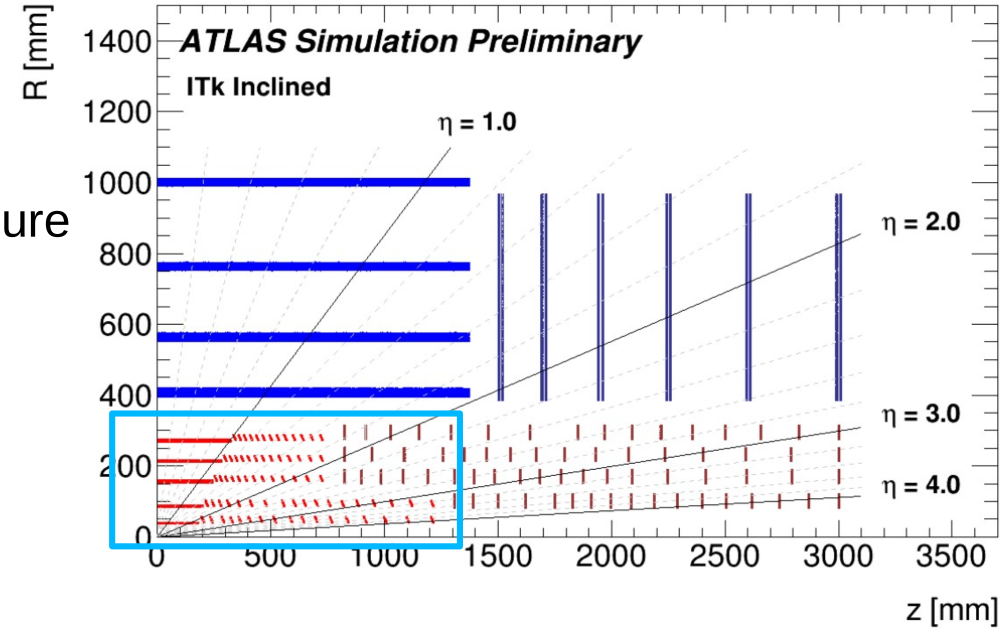
Tracking

ATL-PHYS-PUB-2016-025

- The **I**nternal **Tr**ac**k**er (**ITk**) for the Phase-II Upgrade will be an all-silicon tracker
- The eta coverage up to **|η| = 4.0** is under study
- ITk will have two components: **Pixel** and **Strip**
- Two designs studied for the Pixel detector: **Extended** and **Inclined**
- The **Pixel** barrel design is divided into an insertable 2-layer inner barrel, surrounded by a fixed outer barrel

  - the insertable part is necessary in order to ensure high performance for the entire 3000 fb^{-1}, as it may necessitate replacement due to radiation damage.





Tracking

- The **Strip** detector of the ITk is situated just outside the Pixel detector

- It consists of four double-sided barrels and six strip discs in each of the two forward regions

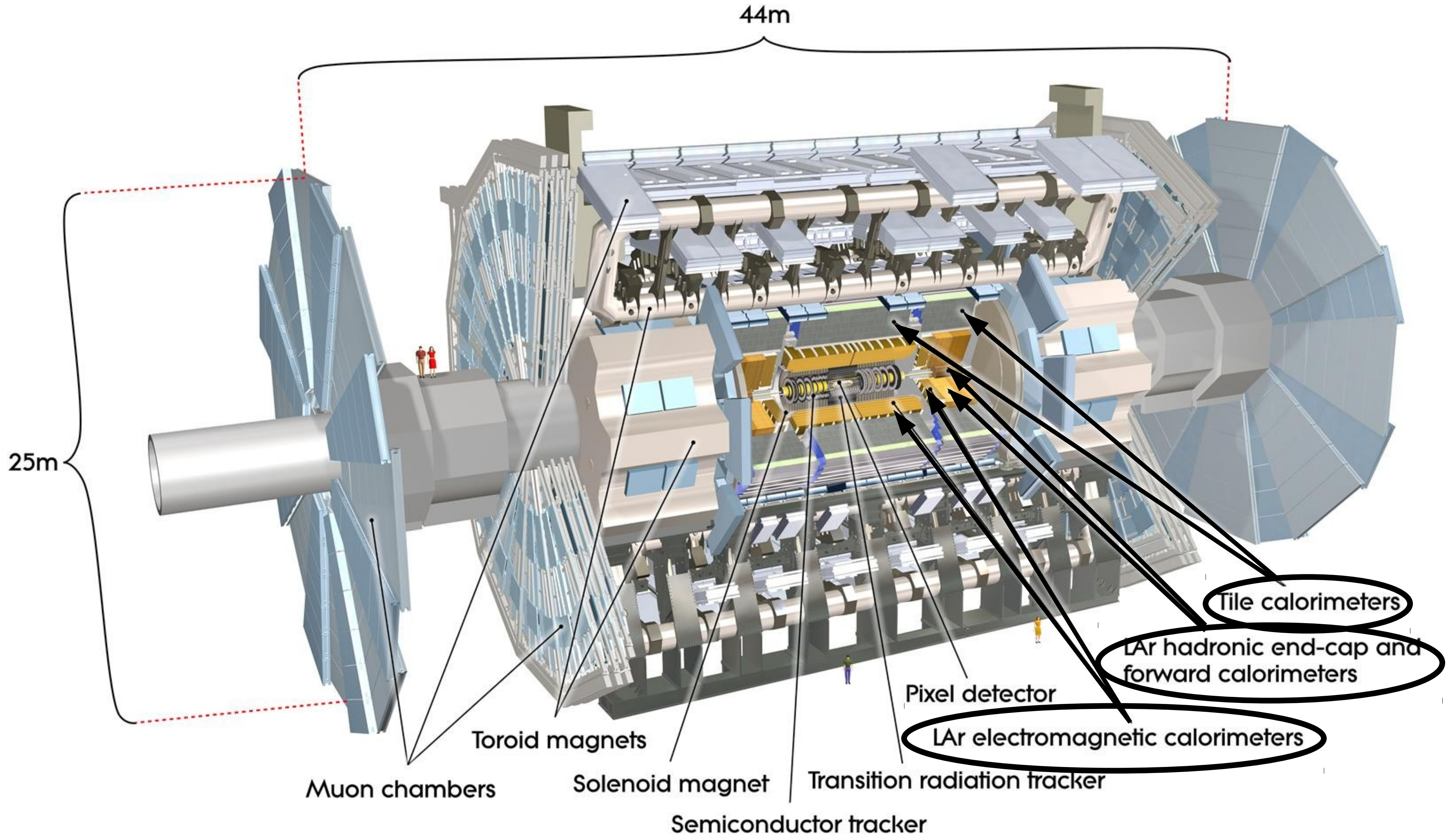
- For a mean pileup of 200 and at the smallest radius of the pixel detector, each of the front-end readout chips will be producing data at a rate of ~5 Gb/s.

  → R&D is in progress for solutions for cables and configurations for such large data transmission volumes and rates

- Due to the large increase in the number of both strip (from 4,088 to 20,000) and pixel modules (from 1,744 to 10,000), the powering scheme needs to be changed with respect to the current Inner Detector's

  → groups of modules will share the same low voltage and high voltage supplies

Calorimeters



Calorimeters

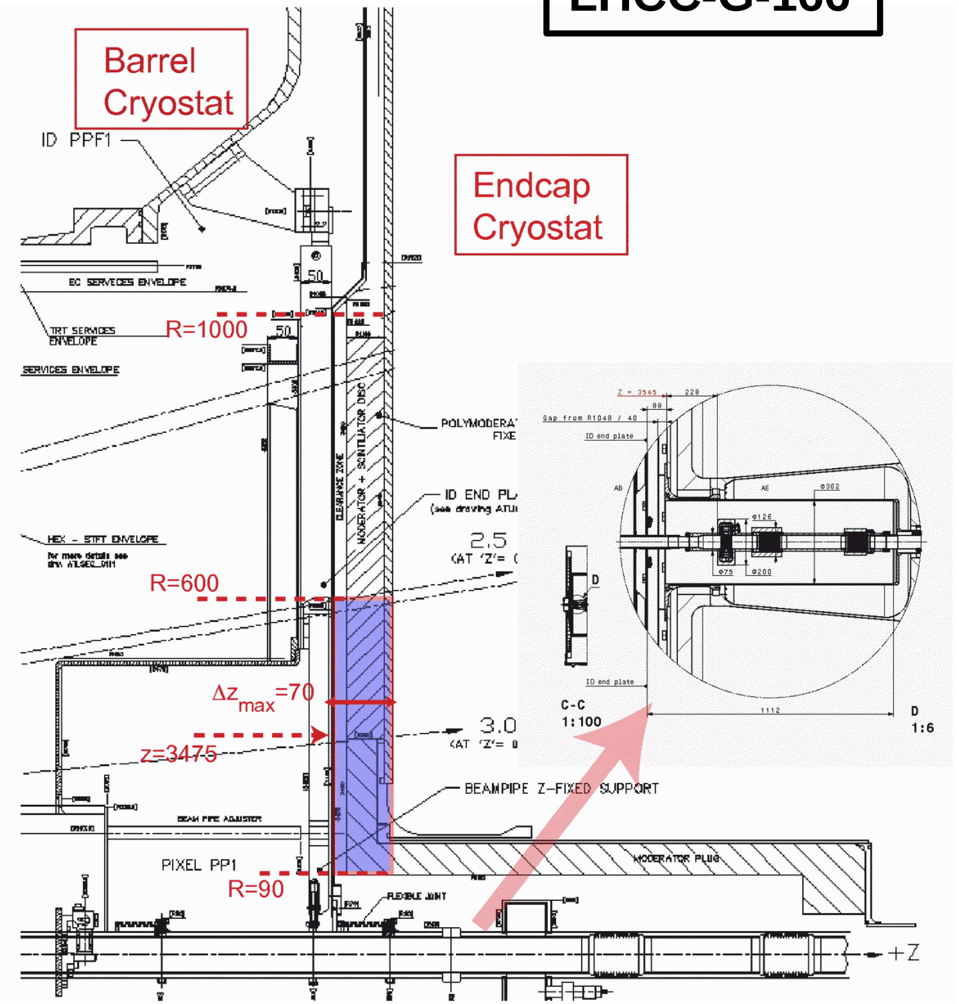
- The **L**iquid **Ar**gon (**LAr**) calorimeter, the Scintillating **Tile** hadronic barrel detectors (**TileCal**) and the **H**adronic **E**nd-cap **C**alorimeter (HEC) maintain their required performance under HL-LHC conditions and will not be replaced.

- A new **H**igh **G**ranularity **T**iming **D**etector (**HGTD**) is an option considered to be added in front of the LAr end-caps to allow a mitigation of pileup effects in the forward and end-cap regions.

- The readout electronics of the LAr and the TileCal need to be exchanged due to limited radiation tolerance and the necessary upgrade in the trigger chain.

- During Phase-I upgrade additional electronics will be installed to ensure finer granularity signals for the L1 calorimeter trigger, and the paths will then be used in the new trigger scheme of Phase-II upgrade.

LHCC-G-166



Physics Objects Performance: Introduction

- The main areas of interest in the physics programme of the HL-LHC are:
  → Higgs boson measurements of its properties, production and decay modes
  → Standard Model precision measurements and the study of rare processes
  → searches for phenomena beyond Standard Model

- The performance of the upgraded detector is assessed using events generated at 14 TeV from several Standard Model processes, including $Z \rightarrow l\,l$, ttbar and vector boson fusion production of the Higgs boson $H \rightarrow \gamma\,\gamma$.

- Minimum-bias pileup events are overlaid on the hard scatter events of interest, this information being used to reconstruct the physics objects

- The response of the detector is simulated by
  → smearing p_T and energy of the reconstructed physics objects using smearing functions
  → applying reconstruction efficiencies for the objects

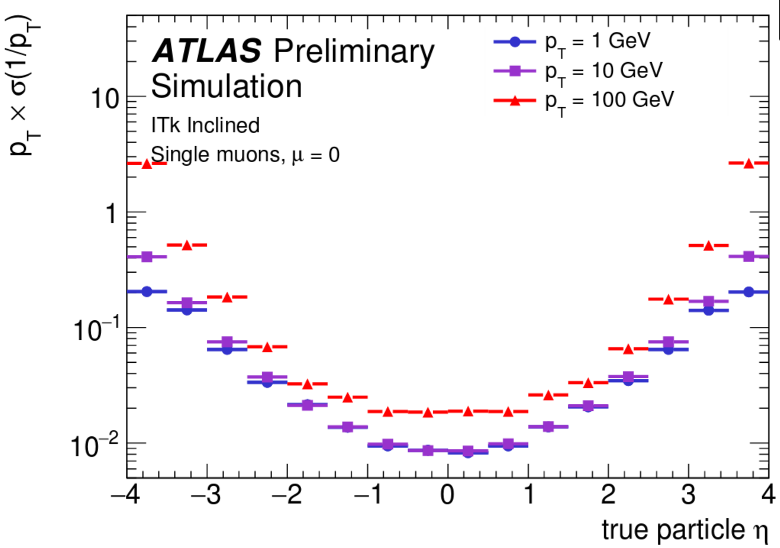
- Trigger response is also emulated by applying trigger efficiency functions

Physics Objects Performance: Tracking

- The large η extension of the tracker has a significant impact on the identification of physics objects and on pileup mitigation.
  → most visible contributions are in the area of jets and missing E_T performance.

- The latest tracking performance study used ttbar and minimum bias samples.
  → very good tracking efficiency across full acceptance
  → non-primary and fake tracks are under control
  → excellent impact parameter resolution
    - d_0: <30 μm in |η|<3.5 and <50 μm in |η|<4 for p_T = 10 GeV muons
    - z_0: <300 μm in |η|<3.5 and <450 μm in |η|<4 for p_T = 10 GeV muons
  → excellent p_T resolution

- Although the performance of the 'Inclined' layout is usually shown as representative, no conclusion was yet reached about the choice of layout



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Extended (Inclined) layout

Requirement	Pseudorapidity interval		
	$\lvert\eta\rvert < 2.7$	$2.7 < \lvert\eta\rvert < 3.4$	$3.4 < \lvert\eta\rvert < 4.0$
Pixel+Strip hits	≥ 9	$\geq 7(9)$	$\geq 6(9)$
Pixel hits	≥ 1	≥ 1	≥ 1
Holes	< 3	< 3	< 3
Pixel holes	< 2	< 2	< 2
Strip holes	< 3	< 3	< 3
p_T [MeV]	> 900	> 400	> 400
$\lvert d_0\rvert$	≤ 2 mm	≤ 10 mm	≤ 10 mm
$\lvert z_0\rvert$	≤ 25cm	≤ 25cm	≤ 25cm

Physics Objects Performance: Tracking

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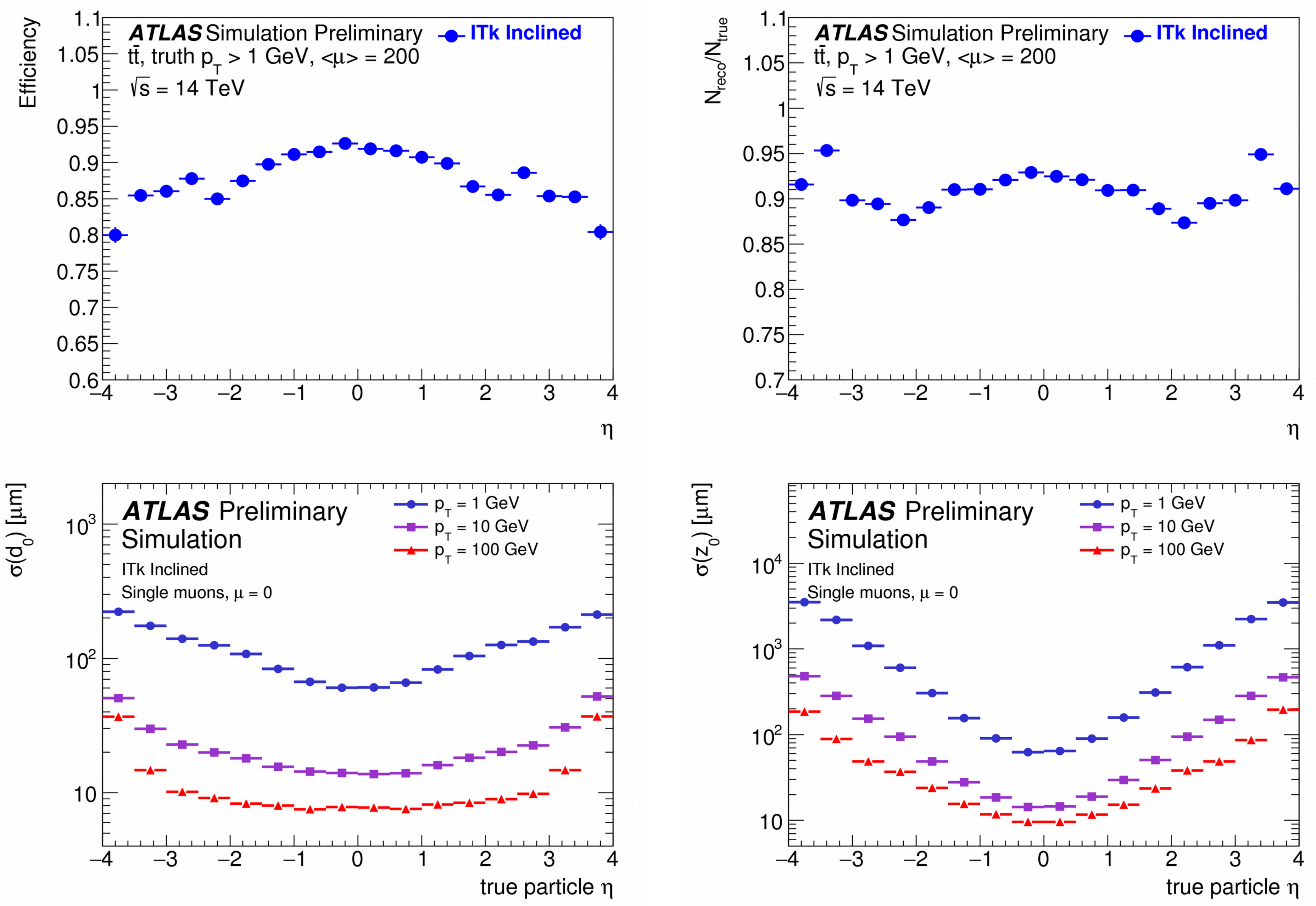
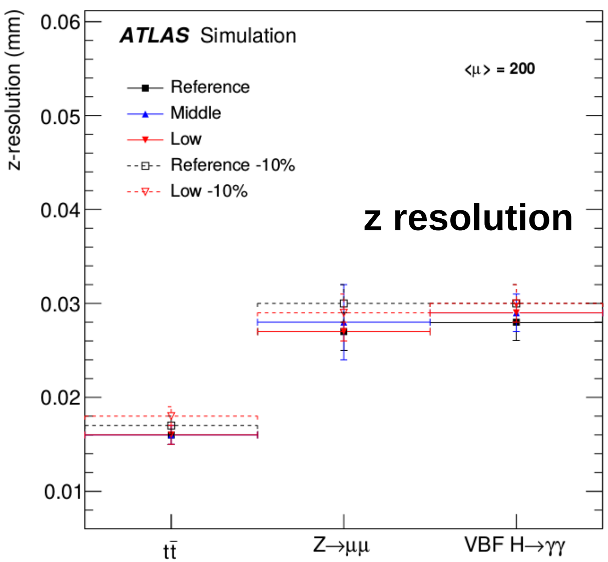
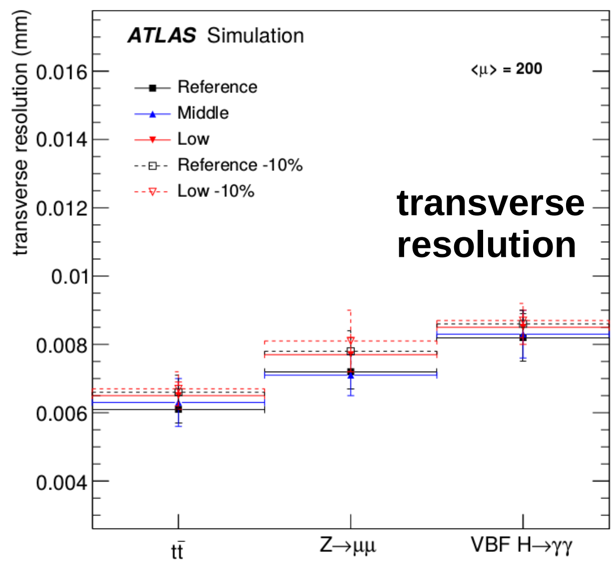
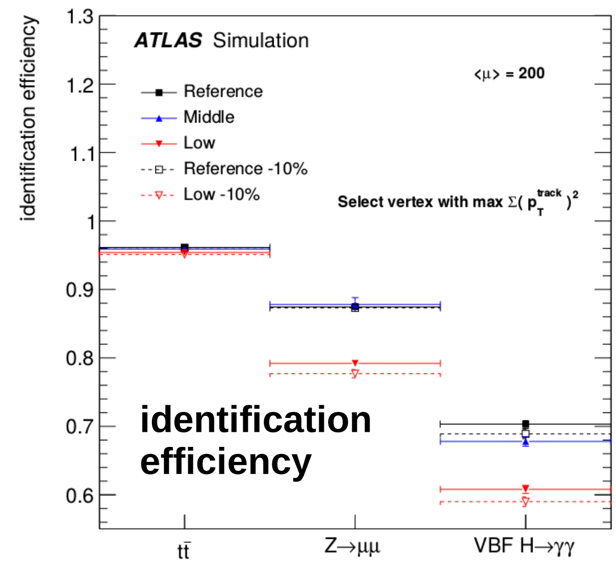


Physics Objects Performance: Primary Vertex

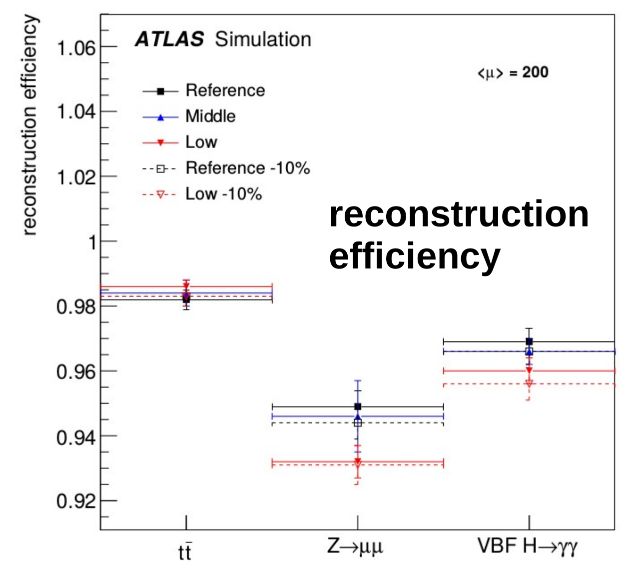
LHCC-G-166





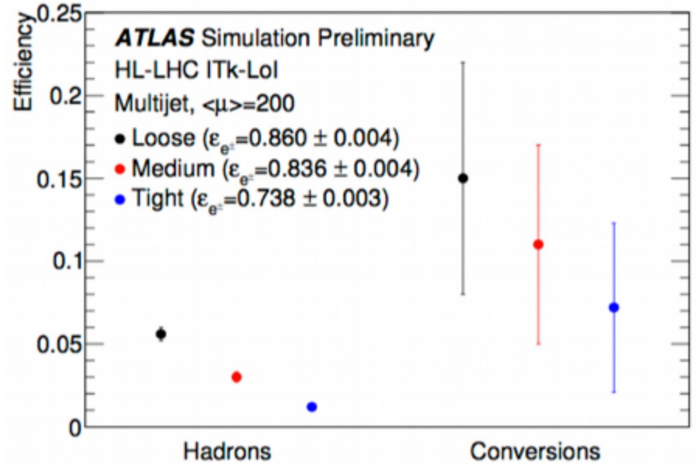


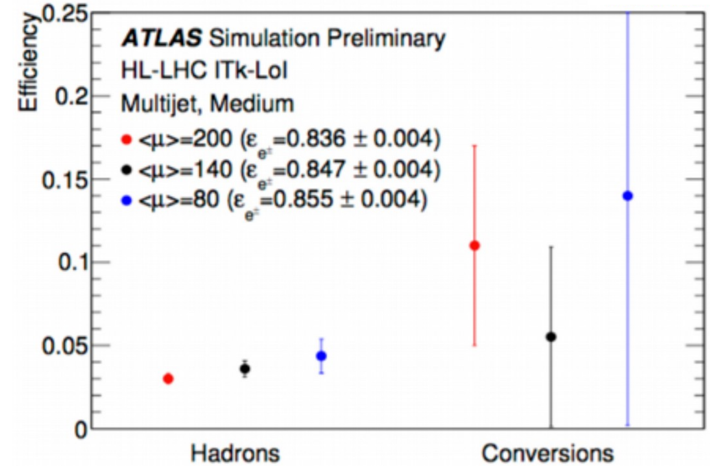
- The performance of primary vertex finding is studied using samples of ttbar, Z → μμ and H → γγ events with μ = 200
- The vertexing performance does not depend strongly on the layout, but on the process
  → exception: the identification efficiency
  → good overall vertexing performance



Physics Objects Performance: Electrons

- Re-optimized electron identification in the context of a different detector configuration
- Main backgrounds: photon conversions and jet-fakes
  - → charge misidentification rate from Z→ee: **(0.026±0.013)%**
  - → identification efficiency is estimated to be around **70%** (compared to **85%** in Run2)





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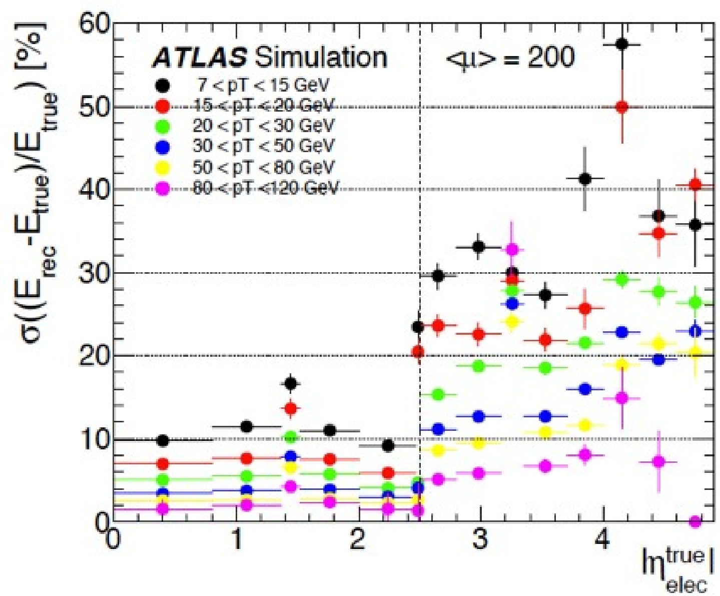
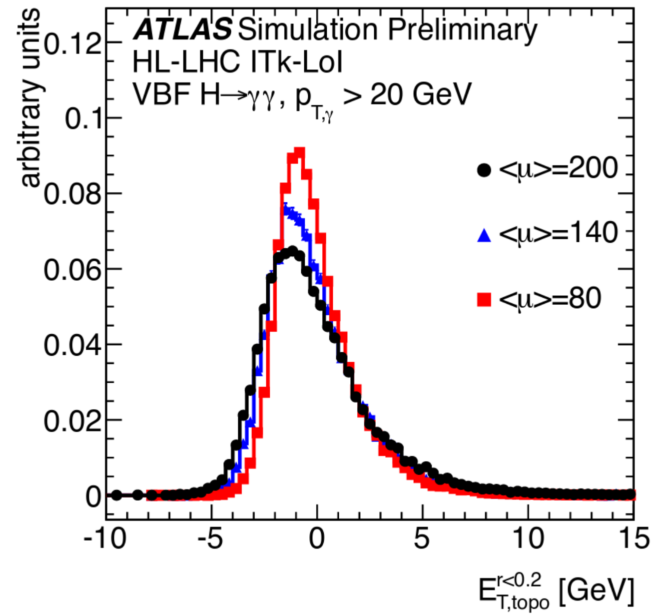
- Pileup affecting only the resolution of low p_T electrons
- The forward electron performance still needs to be optimised for the new detector

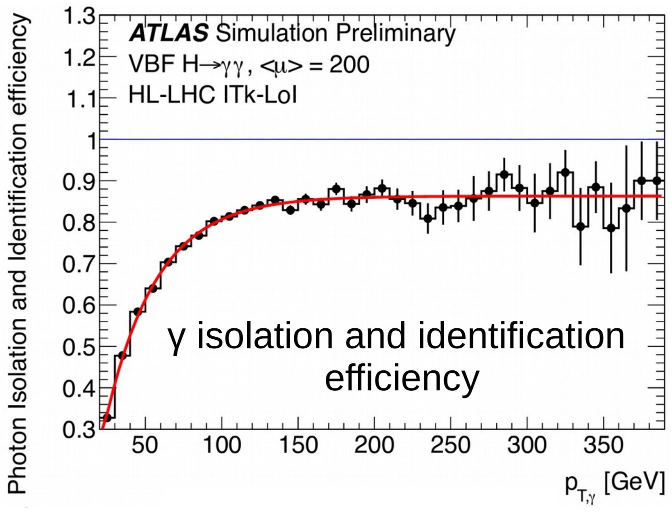


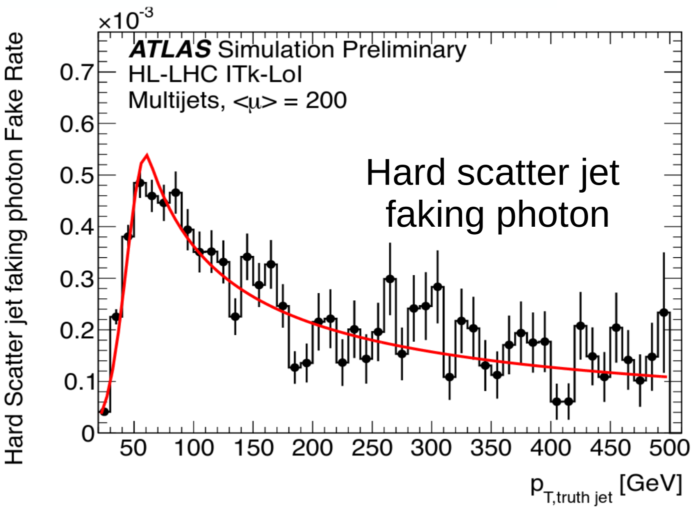
LHCC-G-166

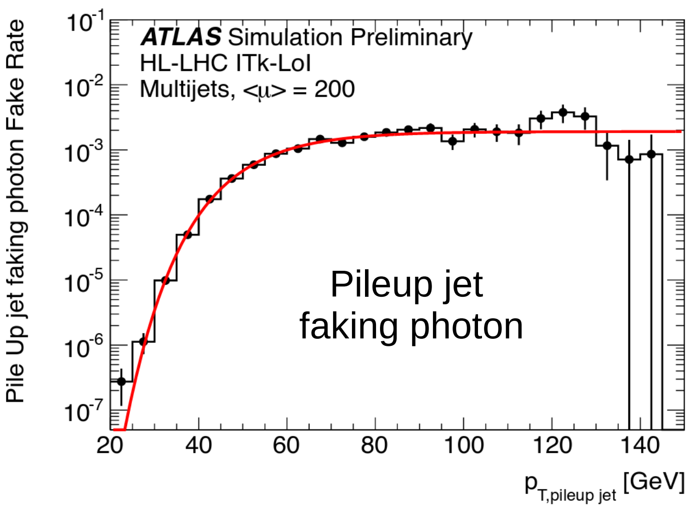
Physics Objects Performance: Photons

- Photon identification studied using calorimeter-based variables only
- Cutting $E_T < 6$ GeV in a radius of 0.2 around the photon leads to a good isolation and to an efficiency of over 95%
- The mean combined efficiency is around 70%
- Average combined fake rates of 7×10^{-5} and 8×10^{-4} for the pileup and hard scatter jets, respectively









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Physics Objects Performance: Muons

- Upgrades of the MS are not expected to change significantly the reconstruction performance but improvements are foreseen in the resolution for combined (ITk+MS) muons and in the large η region

- New studies of the muon performance are available, using the full ITk simulation instead of the parametrised resolution

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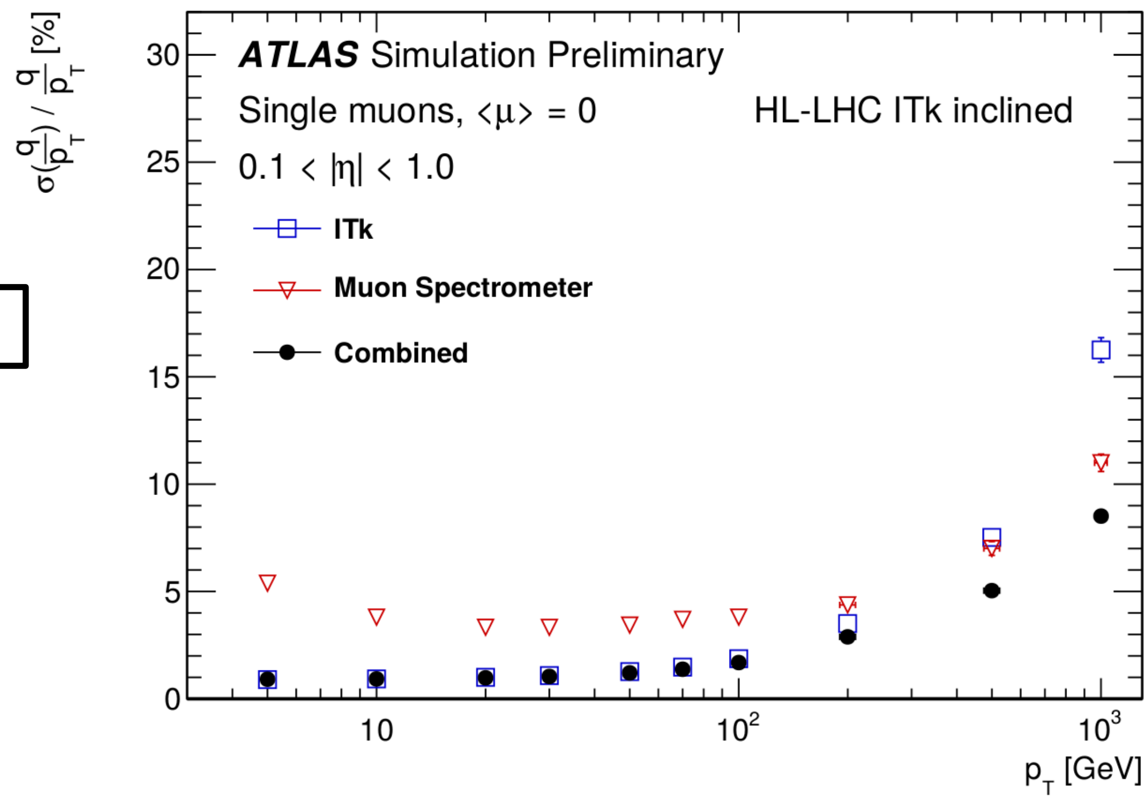
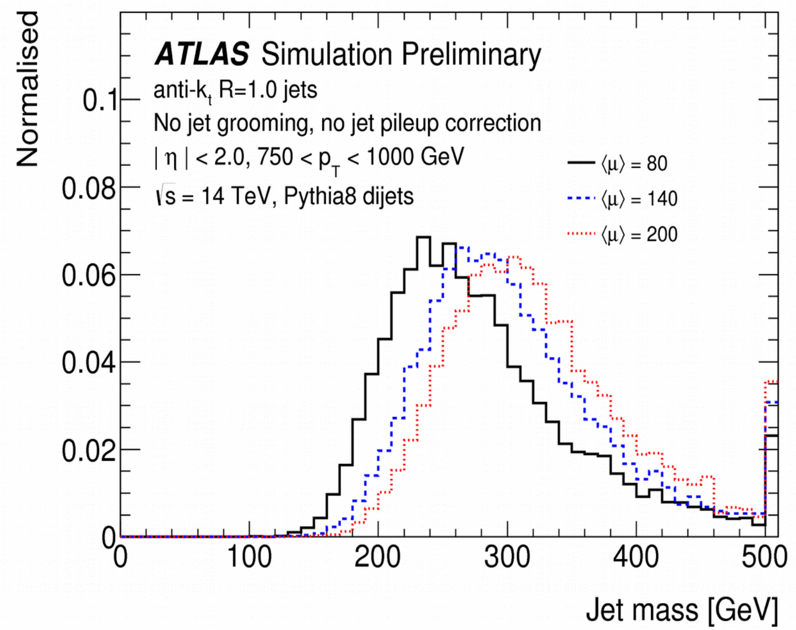


Physics Objects Performance: Jets

- For 2% pile up survival probability we have ~75%, 80% and 85% efficiency for the hard scatter jets, depending on the η region
- Different algorithms investigated for pileup mitigation at cluster level
- Large impact of the pileup on jet reconstruction



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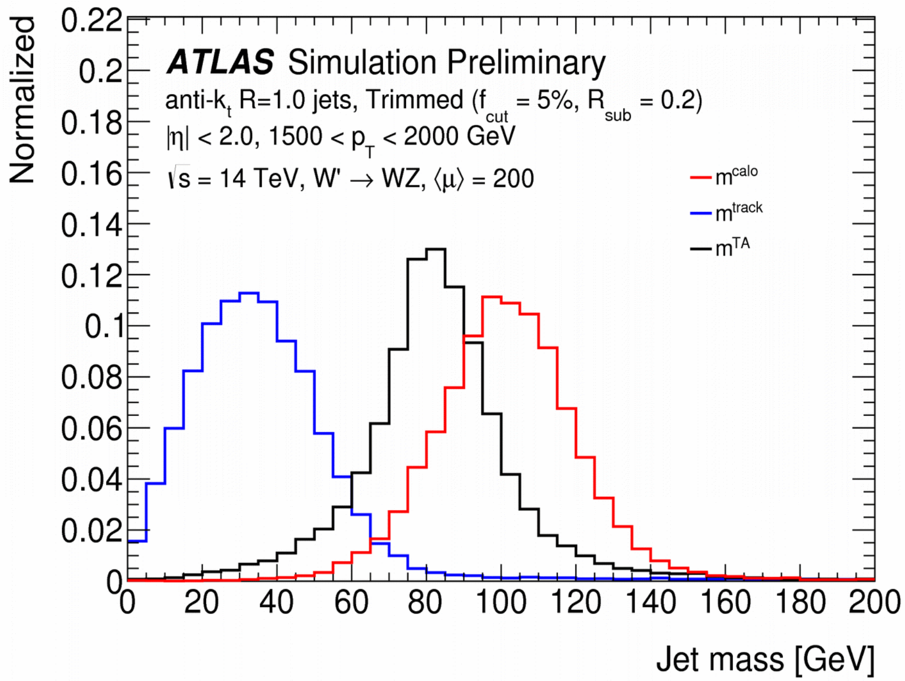
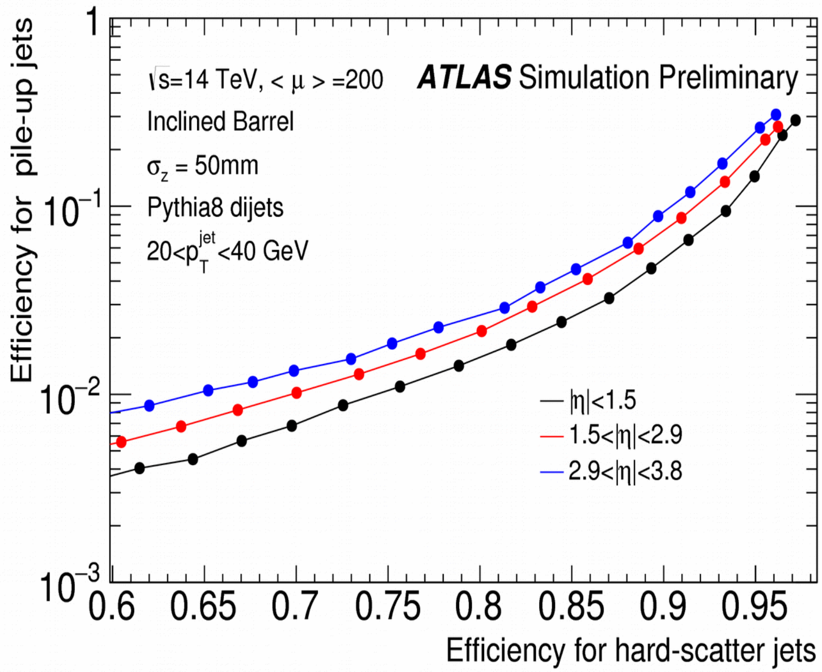


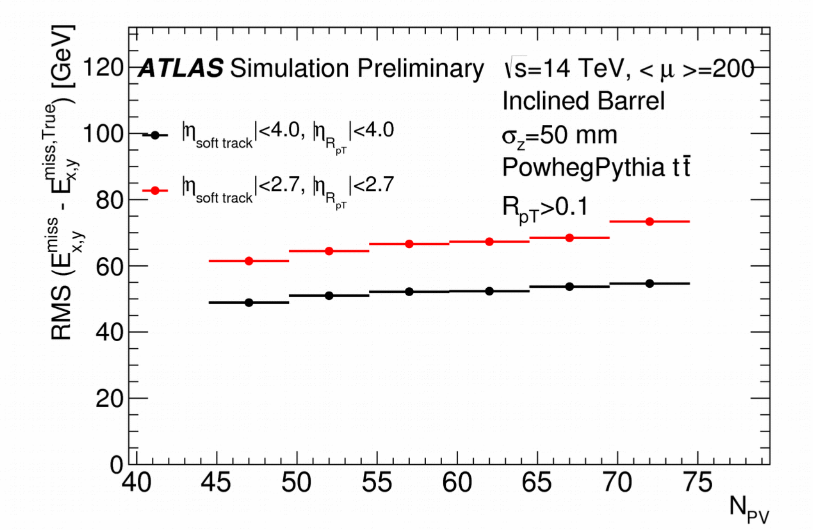


Physics Objects Performance: E_T^{miss}

JETM-2016-012

- Tracking extension improves the E_T^{miss} resolution
  - → Applying R_{pT} > 0.1 to all jets improves the E_T^{miss} resolution significantly

$$R_{pT} = \frac{\sum_{i \in PV0} p_T^{track,i}}{p_T^{jet}}$$



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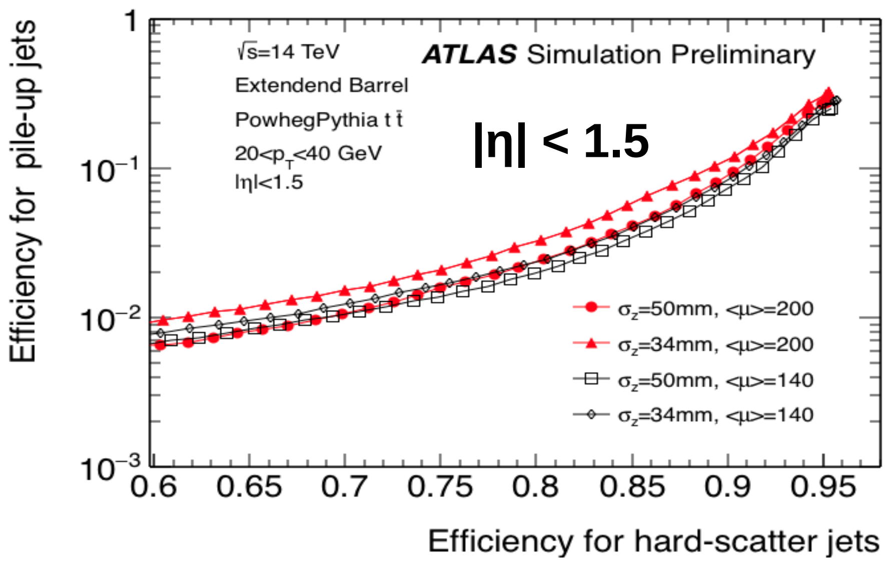
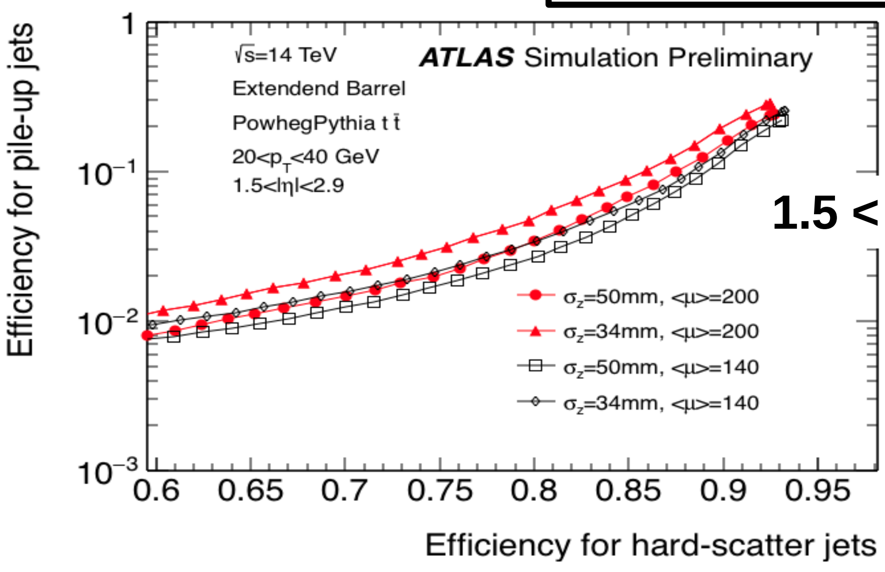


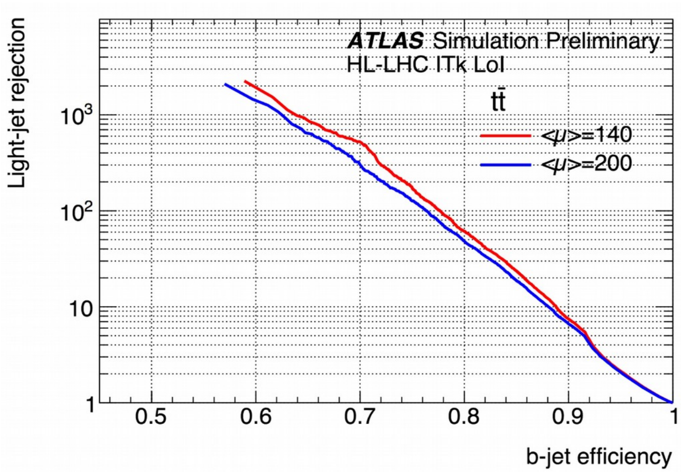


1.5 < |η| < 2

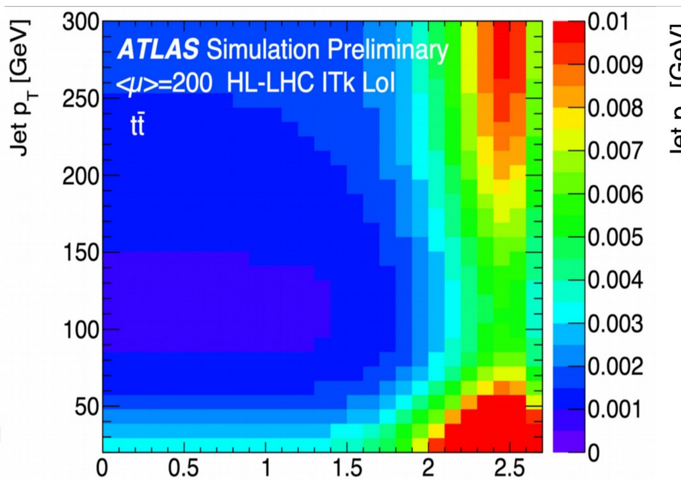
Physics Objects Performance: Flavour Tagging

- b-tagging studied using a ttbar sample with at least one semileptonic top decay
- Jet p_T > 20 GeV, $|\eta|$ < 2.7
- b-jet defined as jets matched to b-quark from top quark decay only (i.e. hard scattered b-quark)
- The performance is estimated to be similar to the one of the Inner Detector in Run2 conditions
- Considering a working point of 70% average b-tagging efficiency, the mistag rate is 0.1-1%, c-jet efficiency 10-25% and b-jet efficiency 40-80%

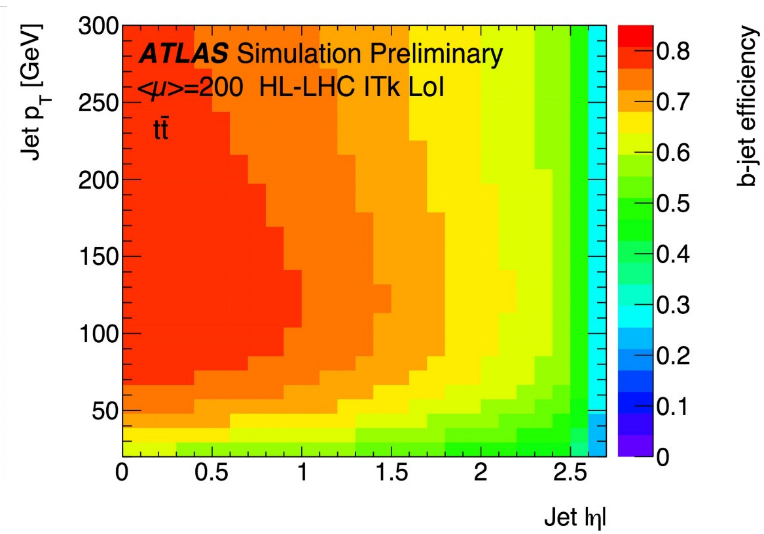
Light flavour jet rejection



Light flavour efficiency



b-jet efficiency



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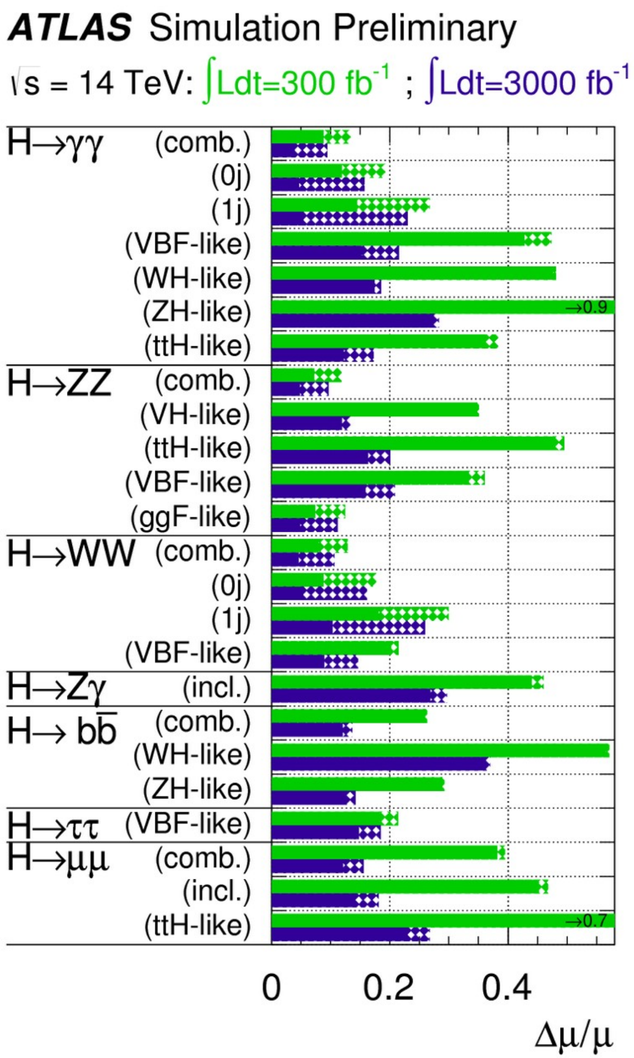
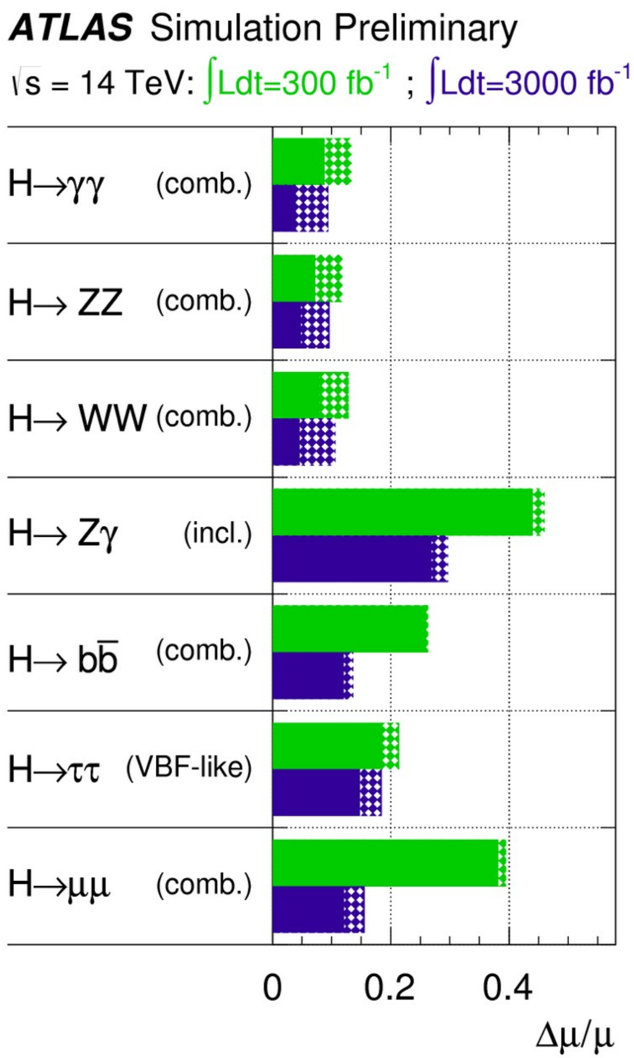
Higgs Production and Rare Processes

- ATLAS presented comprehensive results for Higgs bosons couplings at HL-LHC at the ECFA workshop in 2014
- The subsequent studies concentrated on the impact of various detector designs on the precision Higgs boson measurements and on the study of the rare Higgs boson processes





ATL-PHYS-PUB-2014-016

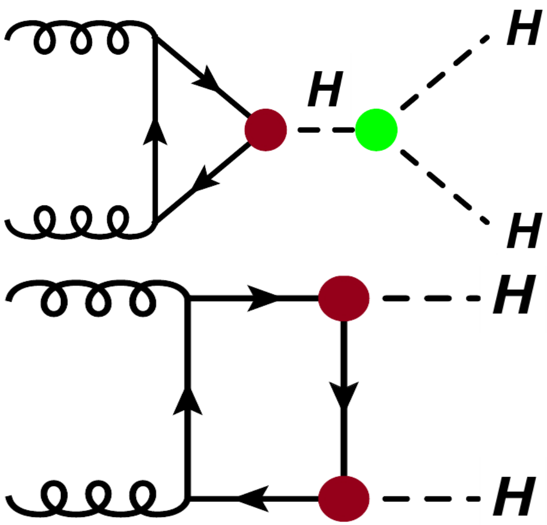
Higgs Production and Rare Processes

Channel	Result	Reference
$H \to J/\Psi\ \gamma$	$BR < 44 \times 10^{-6}$ @95% CL (pileup 140)	ATL-PHYS-PUB-2015-043
off shell $H \to ZZ \to 4l$	$\Delta\mu/\mu \simeq 50\%$ (pileup 140)	ATL-PHYS-PUB-2015-024
VBF $H \to W^+ W^-$	$\Delta\mu/\mu \simeq 14$ to 20% (pileup 140 and 200)	ATL-PHYS-PUB-2016-018
VBF $H \to ZZ \to 4l$	$\Delta\mu/\mu \simeq 15$ to 18% (pileup 140 and 200)	ATL-PHYS-PUB-2016-008
$HH \to b\ b\ \tau\ \tau$	$0.6\ \sigma$ (pileup 140)	ATL-PHYS-PUB-2015-046
$HH \to bbbb$	$0.4\ \sigma$ (pileup 200)	ATL-PHYS-PUB-2016-024
ttHH, $HH \to bbbb$	$0.35\ \sigma$ (pileup 200)	ATL-PHYS-PUB-2016-023

Higgs Production and Rare Processes: HH → bbbb

ATL-PHYS-PUB-2016-024

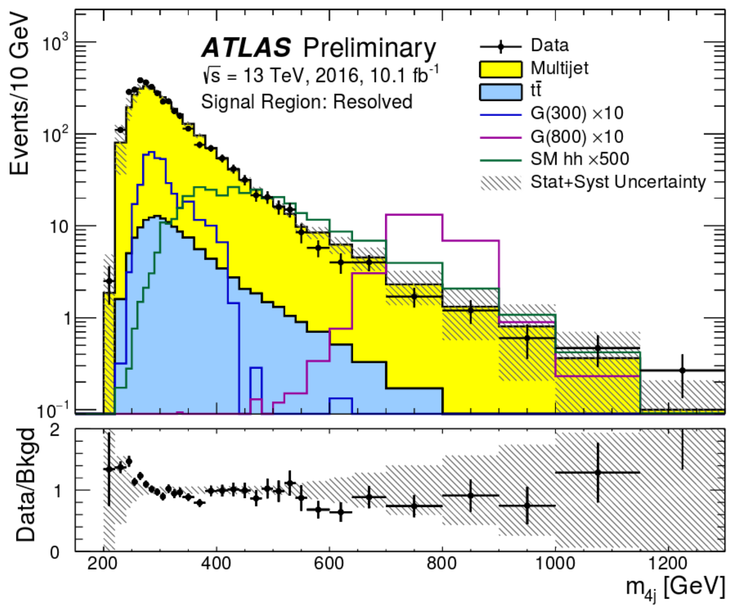
- Estimates of the sensitivity for 3000 fb^{-1} are based on the extrapolation of the results obtained using the 2016 dataset of 10.1 fb^{-1} proton-proton collision events at 13 TeV

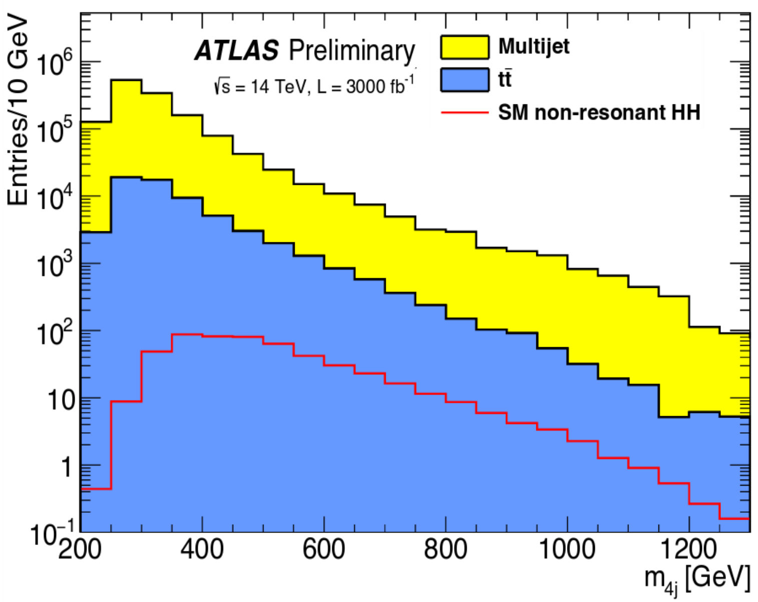


Selection: at least 4 b-tagged jets with p_T > 30 GeV and |η| < 2.5

Reach: In the absence of any signal and without (with) systematics, cross-sections 1.5 times (5.2 times) greater than the SM prediction are excluded at the 95% confidence level

- Higher p_T thresholds investigated – positive impact on the reach





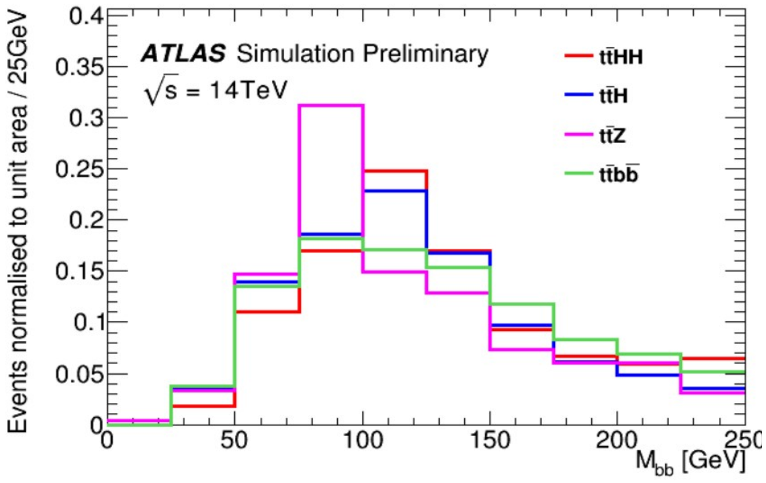
Higgs Production and Rare Processes: ttHH production

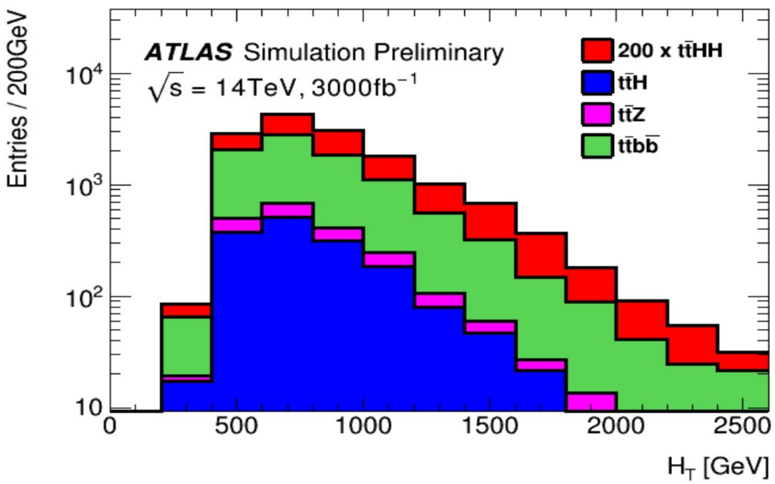
ATL-PHYS-PUB-2016-023

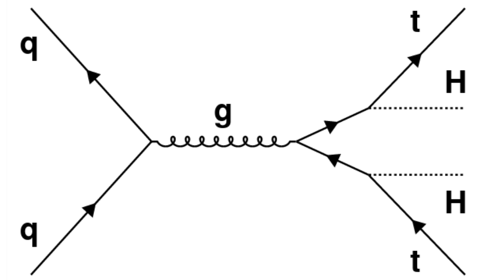
- Study using 14 GeV simulated events, with ttbar decaying semileptonically and HH → bbbb
  - important for measuring the HHH coupling

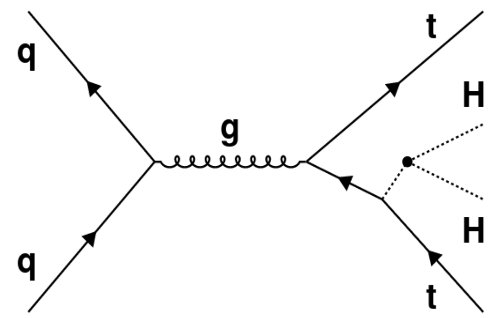
Selection: cut-based, at least 7 jets with $p_T > 30$ GeV and $|\eta| < 4.0$, with at least 5 or 6 b-tagged jets among them, exactly 1 electron or muon

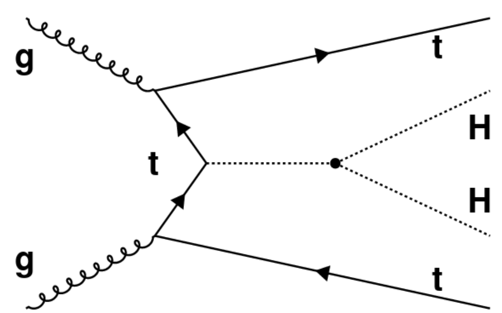
Results: statistical significance of the ttHH production will not exceed 0.35 σ







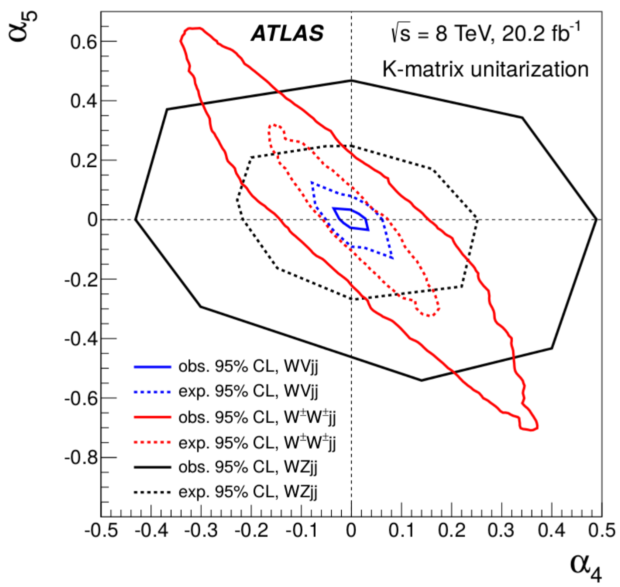




Standard Model Precision Measurements

- SM studies will be able to reach unprecedented precision
- Studies published so far for HL-LHC
  → $W^\pm W^\pm$ and WZ scattering
  → Flavour changing neutral currents (FCNC) analyses

arXiv: 1609.05122

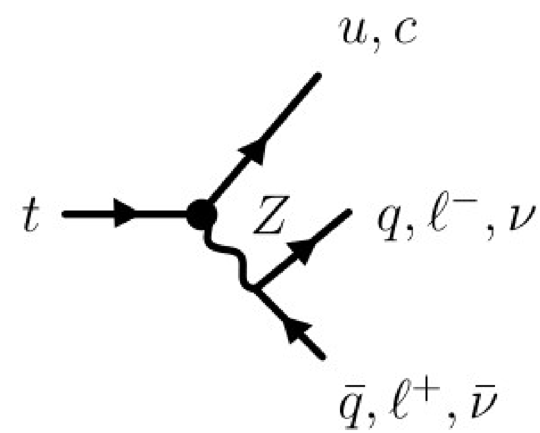


- $W^\pm Vjj \rightarrow l^\pm$ + hadrons + tag jets + E_T^{miss}
- V (W,Z) decaying hadronically and reconstructed as 2 jets or 1 large-R jet
- Interpret as limit on anomalous quartic gauge couplings
- Benefits from the tracker extension in the forward region

Scenario	Z_{σ_B}	$\Delta\sigma/\sigma$
Reference scenario	11.3 ± 0.6	5.9%
Middle scenario	6.06 ± 0.3	11%
Low scenario	5.02 ± 0.2	13%

Standard Model: Top Measurements

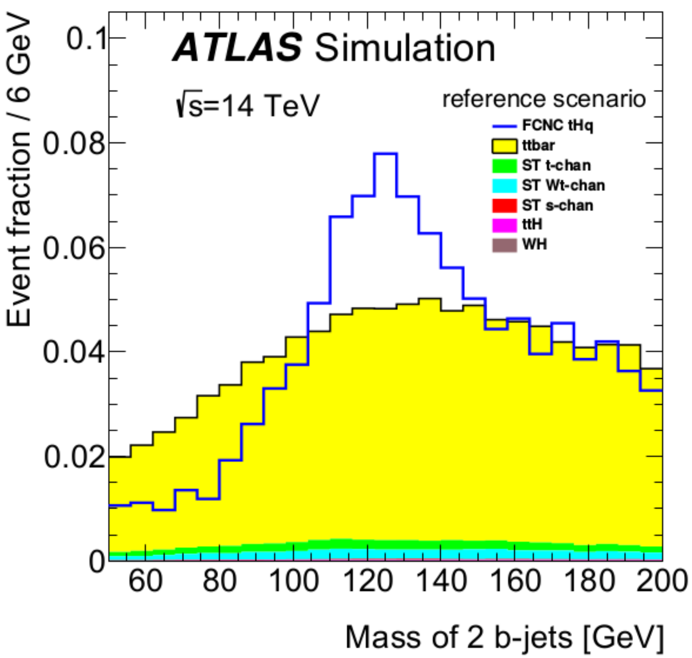
FCNC analyses: top quark → Zq trilepton
top quark → Hq

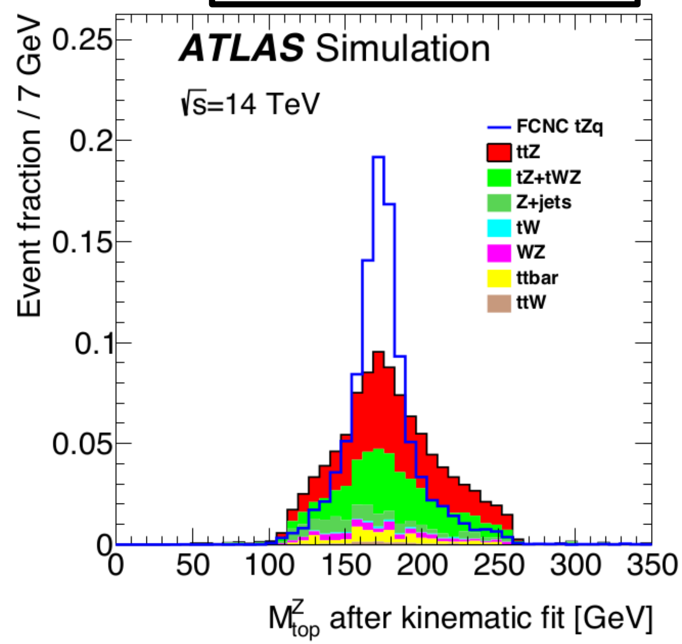


- **Selection (tZq)**: three leptons, one OSSF in Z-mass window
  ≥1 b-jet, ≥ 1 non-b-jet
- Sensitivity increases by a factor of 2 to 6 (depending on channel and scenario)

- **Selection (tHq)**: several topologies with different numbers of b-jets and non-b-jets
- Sensitivity increases by a factor of 20

ATLAS-PUB-2016-019





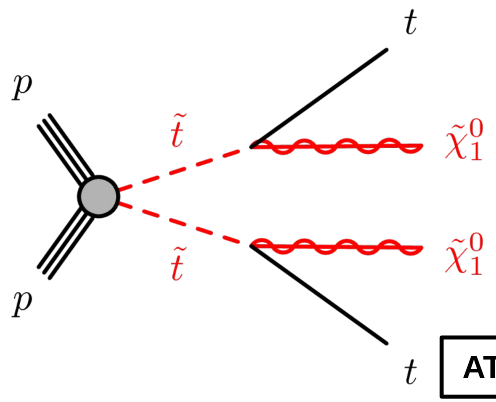
Beyond Standard Model Searches

New result for ECFA 2016: <u>compressed top squark pair production</u> ($\Delta(m_{stop} - m_{N1}) \approx m_{top}$)

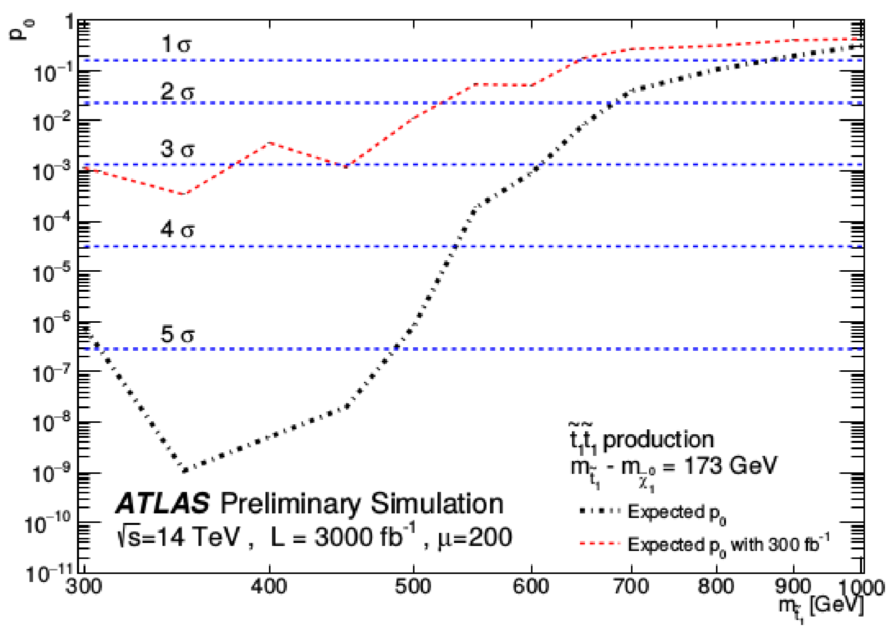
Selection: 2 central leptons (electrons, muons) having p_T > 25 Gev, at least 2 central b-jets with R=0.4 and p_T > 30 GeV

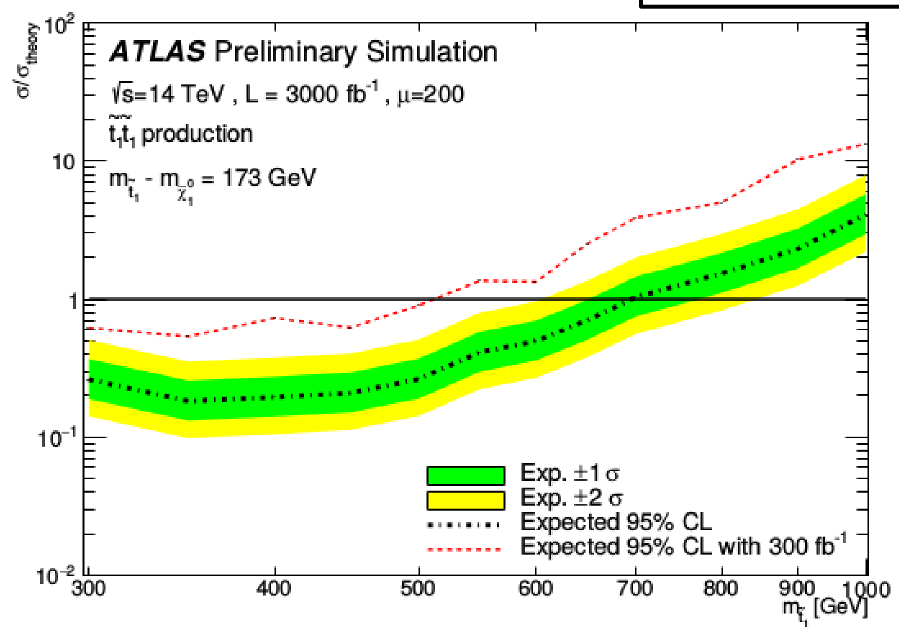
Reach: discovery potential up to top squark masses of 480 GeV and exclusion potential for top squark masses of 700 GeV for 3000 fb^{-1}

	SR
Expected Standard Model	13.8 ± 6.5
$t\bar{t}$	11.4 ± 5.1
$t\bar{t} + Z$	2.4 ± 1.5
Others	$0.0^{+1.8}_{-0.0}$
$\tilde{t}_1\,\tilde{t}_1\; m(\tilde{t}_1, \tilde{\chi}^0_1) = (350, 177)$ GeV	62.7 ± 7.5
$\tilde{t}_1\,\tilde{t}_1\; m(\tilde{t}_1, \tilde{\chi}^0_1) = (700, 527)$ GeV	11.0 ± 2.0



ATL-PHYS-PUB-2016-022



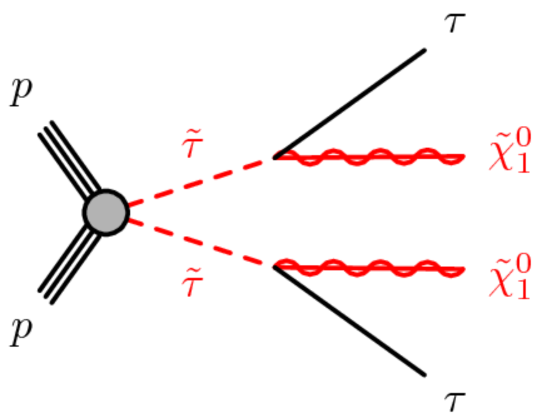


Beyond Standard Model Searches

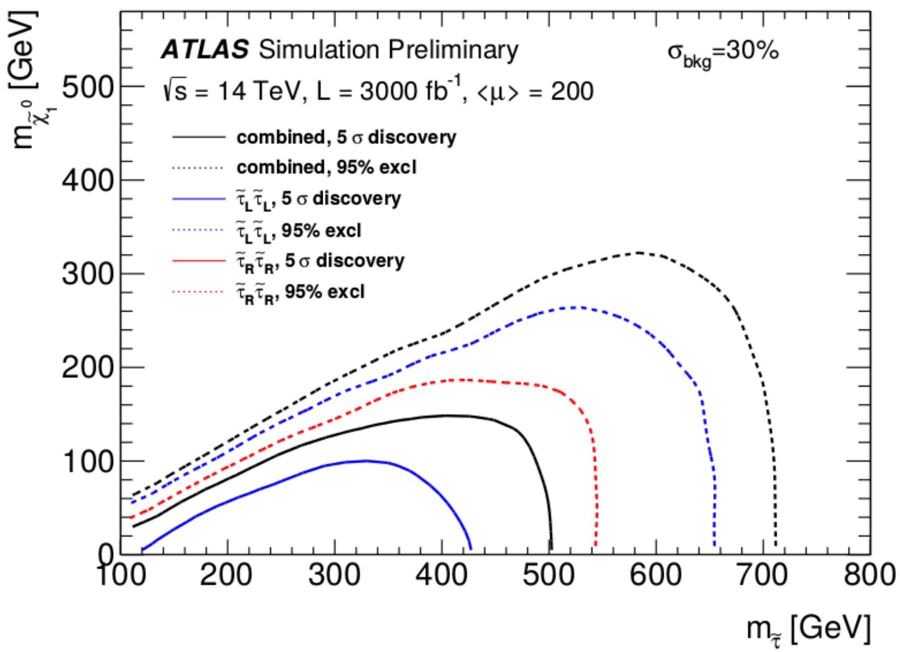
New result for ECFA 2016: search for direct stau production

Selection: 2 hadronically decaying central taus with $p_T > 20$ GeV, centrally produced electrons and muons with $p_T > 10$ GeV, jets with R=0.4 and $p_T > 50$ GeV

Reach: - discovery potential between 100 and 500 GeV stau mass (depending on the model)
- exclusion potential: 540-700 GeV stau mass (depending on the model)



ATL-PHYS-PUB-2016-021



SM process	Event yields
W+jets	1.91 ± 0.19
$t\bar{t}$	0.97 ± 0.23
Z+jets	0.009 ± 0.009
diboson	0.03 ± 0.02
SM total	2.9 ± 0.3
$m(\tilde{\tau})$ = 100 GeV, $m(\tilde{\chi}_1^0)$ = 0 GeV	19.1 ± 0.9
$m(\tilde{\tau})$ = 300 GeV, $m(\tilde{\chi}_1^0)$ = 0 GeV	31.6 ± 0.4
$m(\tilde{\tau})$ = 500 GeV, $m(\tilde{\chi}_1^0)$ = 0 GeV	14.21 ± 0.11

Beyond Standard Model Searches

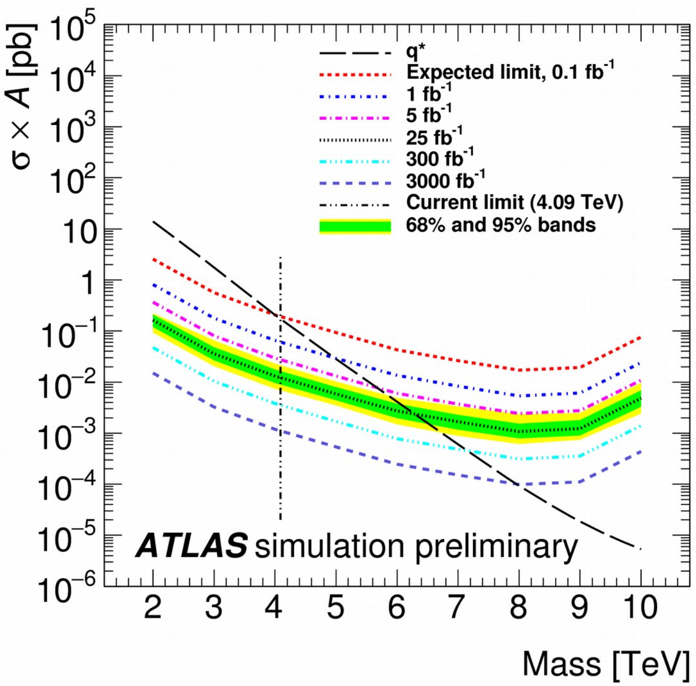
New result for ECFA 2016: dijet resonance searches

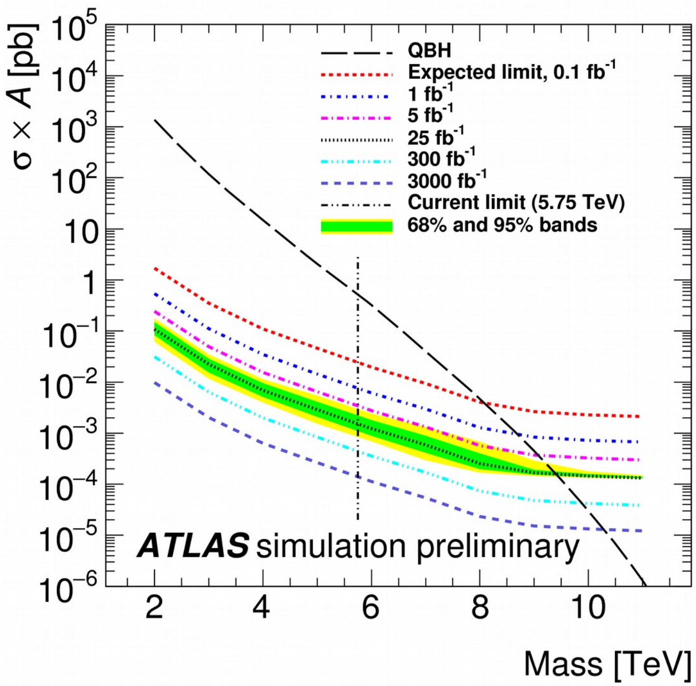
ATL-PHYS-PUB-2015-004

Benchmark models: - excited u and d quarks
- quantum black holes (QBH)

Selection: two leading jets within the rapidity interval $|y| < 2.8$, p_T(next-to-leading jet) > 50 GeV, $0.5*|y_1-y_2| < 0.6$, $m_{jj} \geq 1.5$ TeV

Reach: - exclusion potential: excited quarks with masses up to 8 TeV and QBH with masses up to 10 TeV
- discovery potential: already from the first 100 pb^{-1} of data for excited quarks with masses of 4 TeV and QBH with masses up to 8.2 TeV



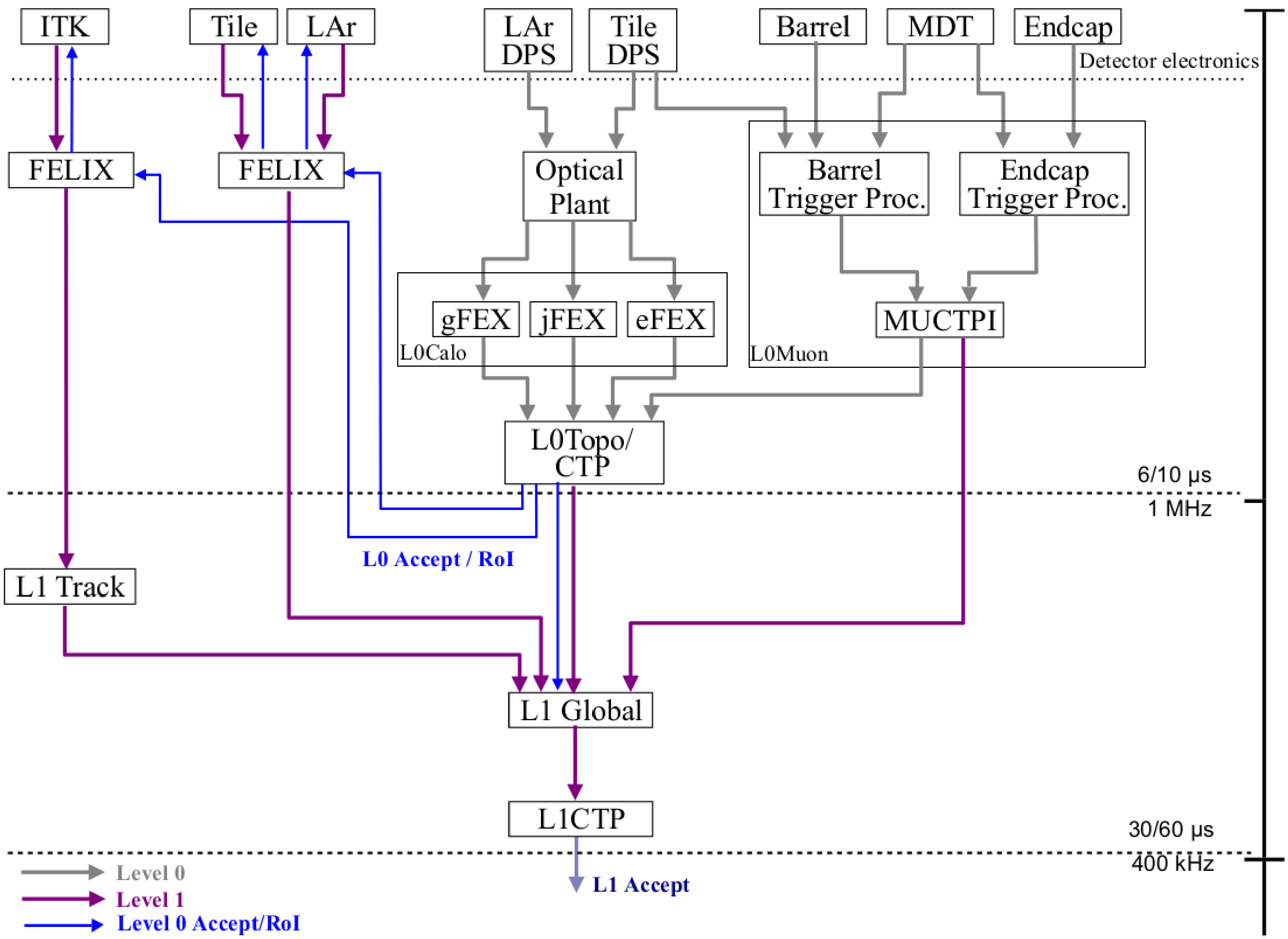


- Updated detector designs and performance studies are published for ECFA 2016
- Technical design reports are expected for most of the detector subsystems in 2016-2017
- Pileup mitigation is one of the largest concerns for HL-LHC runs and many new or alternative strategies and designs are being studied to address it
- The performance of the physics objects is expected to improve due to the extension of the tracker in the large η region, new trigger strategy, new and updated electronics for most of the detector subsystems
- Good progress is recorded in the Higgs physics studies, with many results published since ECFA 2014, concentrating mostly on rare processes
- FCNC studies become more attractive with the higher statistics available
- Beyond Standard Model searches will benefit from the upgrade to extend discovery and exclusion potential

BACKUP

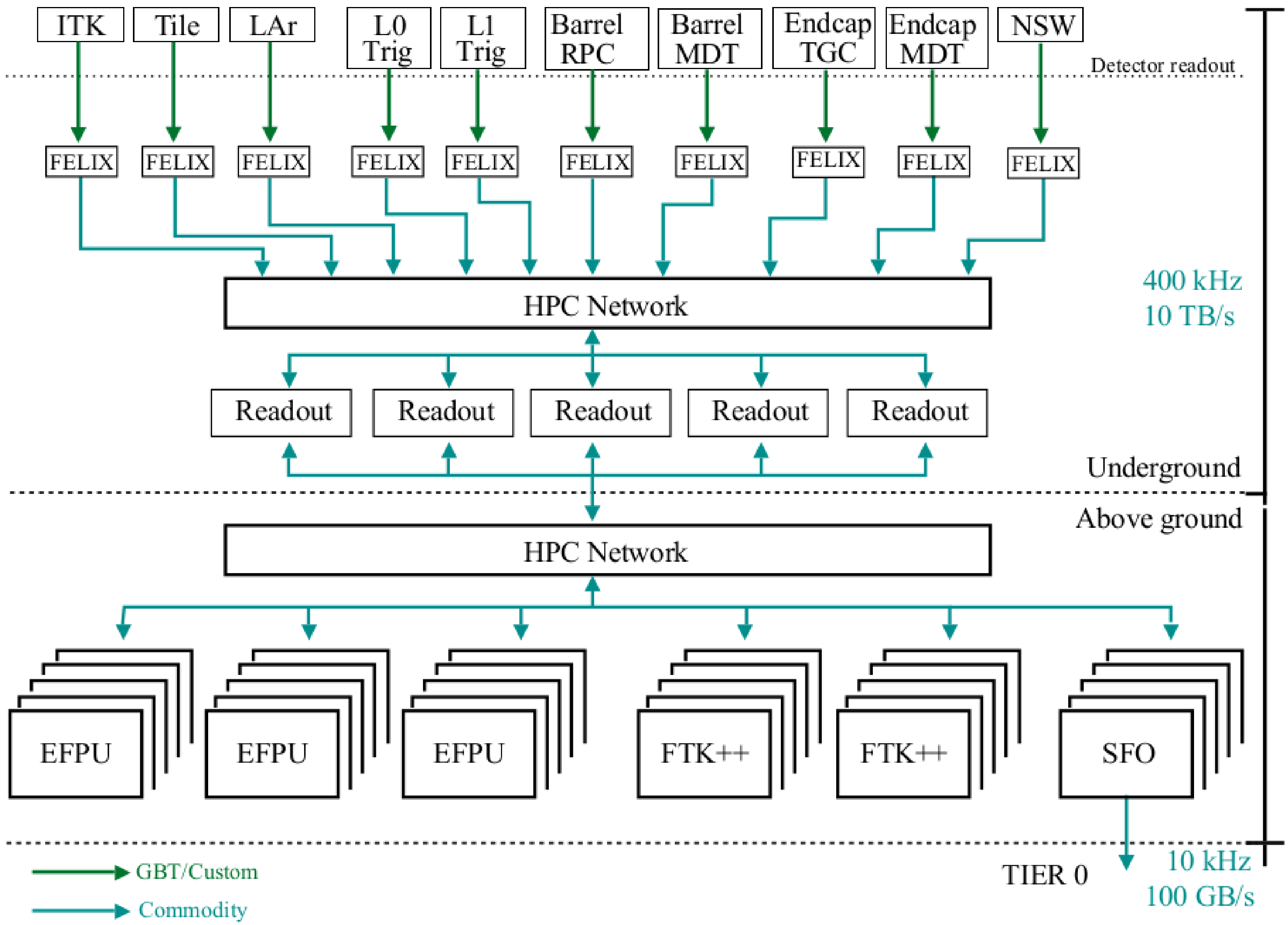
Trigger Layout

LHCC-G-166



Data Acquisition Scheme Layout

LHCC-G-166



Upgrade Scenarios in the Scoping Document

- In the Scoping Document there are three possible detector configurations discussed: Reference, Middle and Low
- Each of them is constrained by a specific budget and are designed such that the physics performance is maximized in conditions of very high pile-up rates
- While the studies made for this year's ECFA workshop assumed a configuration similar to the Reference scenario, no definitive decision is yet reached for the final design of the detector for the HL-LHC runs

System	Reference	Middle	Low
Calorimeter trigger (e/γ)	$\|\eta\| < 4.0$	$\|\eta\| < 3.2$	$\|\eta\| < 2.7$
Pixel detector	$\|\eta\| < 4.0$	$\|\eta\| < 3.2$	$\|\eta\| < 2.7$
Very forward muon tagger	$2.6 < \|\eta\| < 4.0$	-	-