The upgrade of the ATLAS experiment: physics potential and new detector features

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PANIC21

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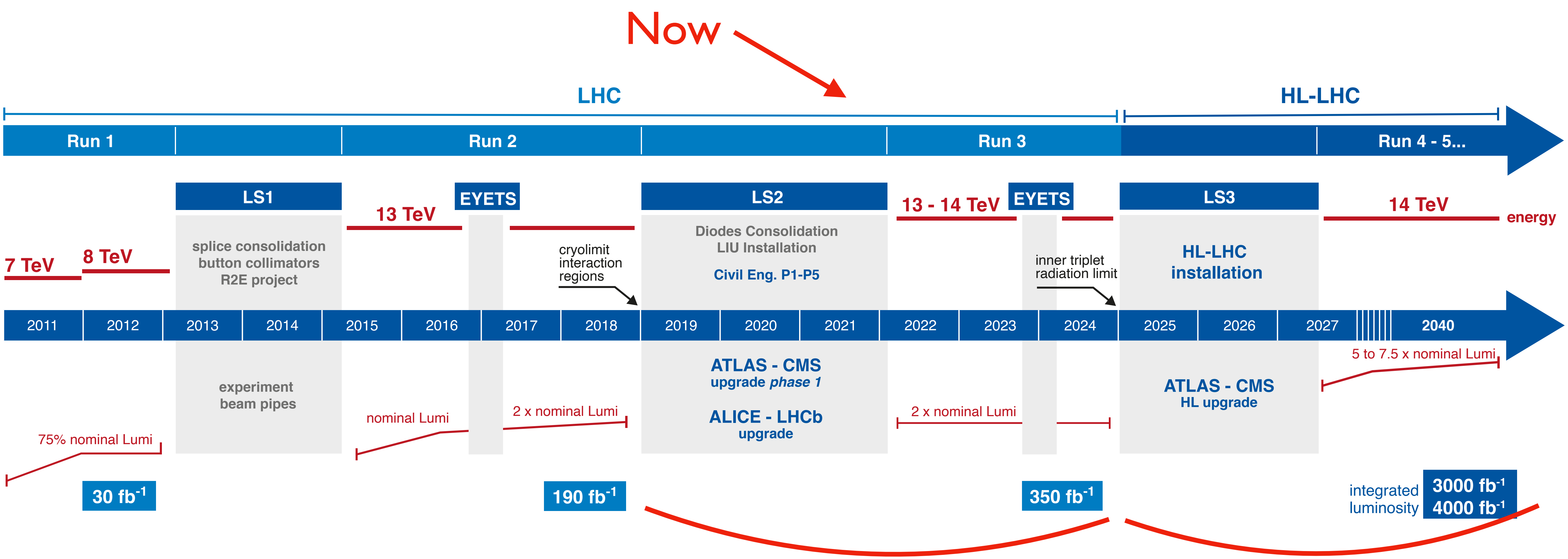
LHC Plan



Two ATLAS upgrades:

Phase 1: currently doing installation and commissioning

~2x more data than current Run 2 data set

~80 collisions/x-ing

Phase 2: currently under construction

~15-20x more data than current Run 2 data set

~200 collisions/x-ing

Outline

Phase-1 : Summary of upgrade

Phase-2 (HL-LHC) :
- Physics Prospects
- Sub-system upgrades:
  - Tracker
  - Trigger+DAQ
  - Calorimeters + Muons
  - New timing detector

This talk focusses on the physics goals and detector performance, the following three talks will give info of the technologies and status

Phase-1

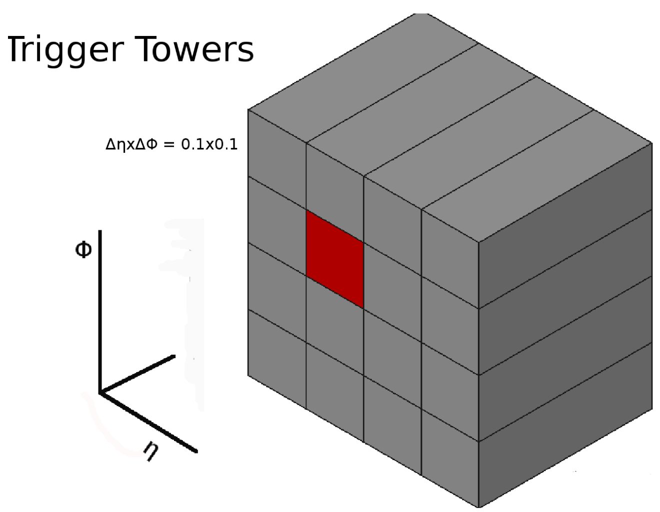
2x nominal LHC luminosity
Main Challenge is trigger rate related
Trigger menu dominated by e and μ lepton triggers

Phase-1 Upgrade

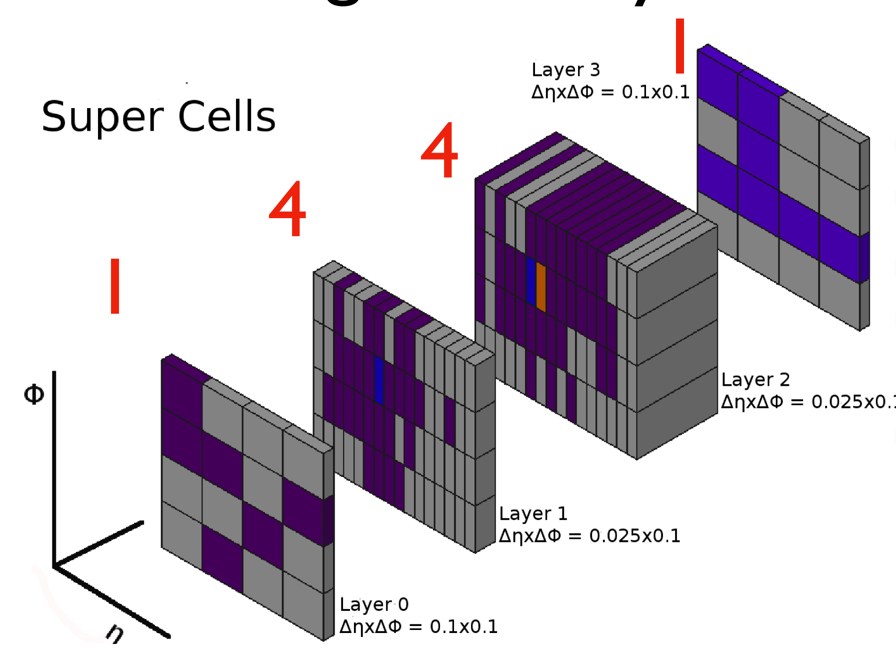
Phase-1 LAr TDR

Electron and photon triggers

New Liquid Argon (LAr) calorimeter trigger path with finer granularity

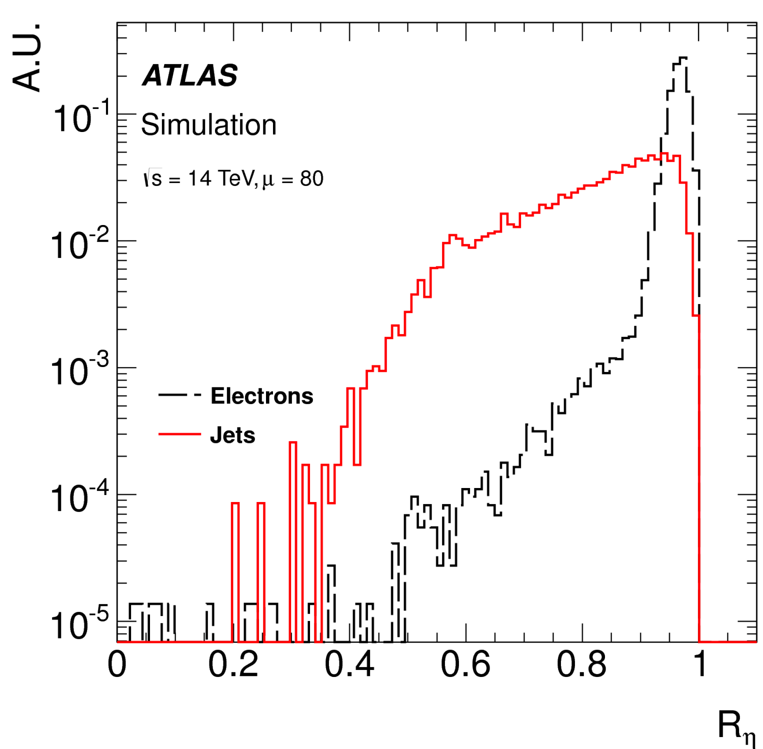


Phase-1:
10 measurements
where we had 1

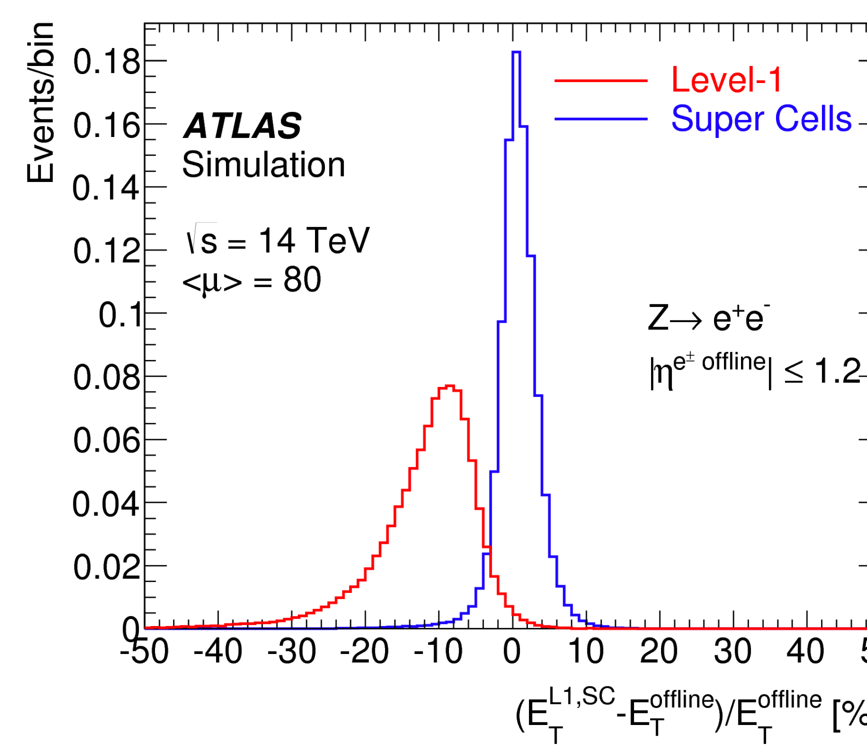


Current used in Run 1 & 2

Ratio of neighboring cell energies gives rejection of jets



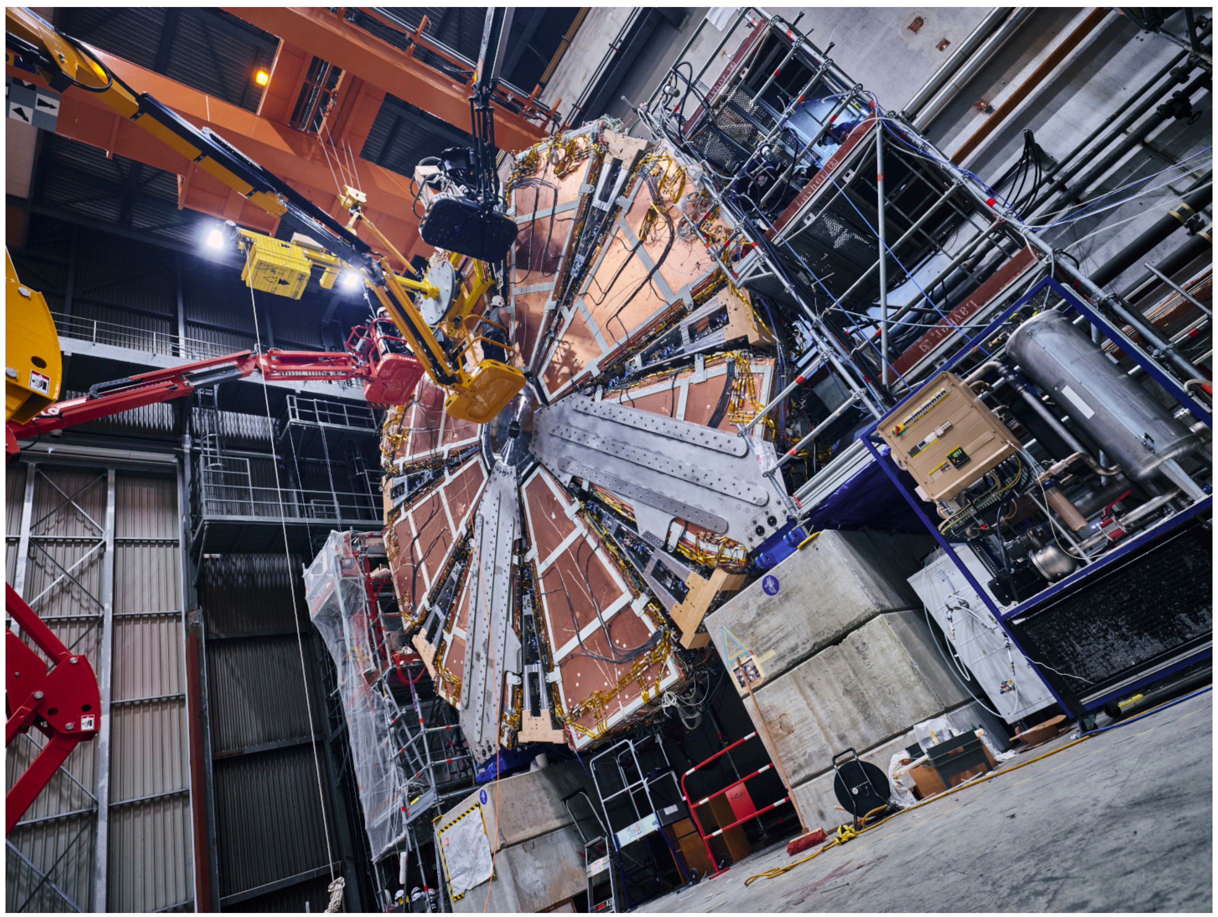
Better energy resolution

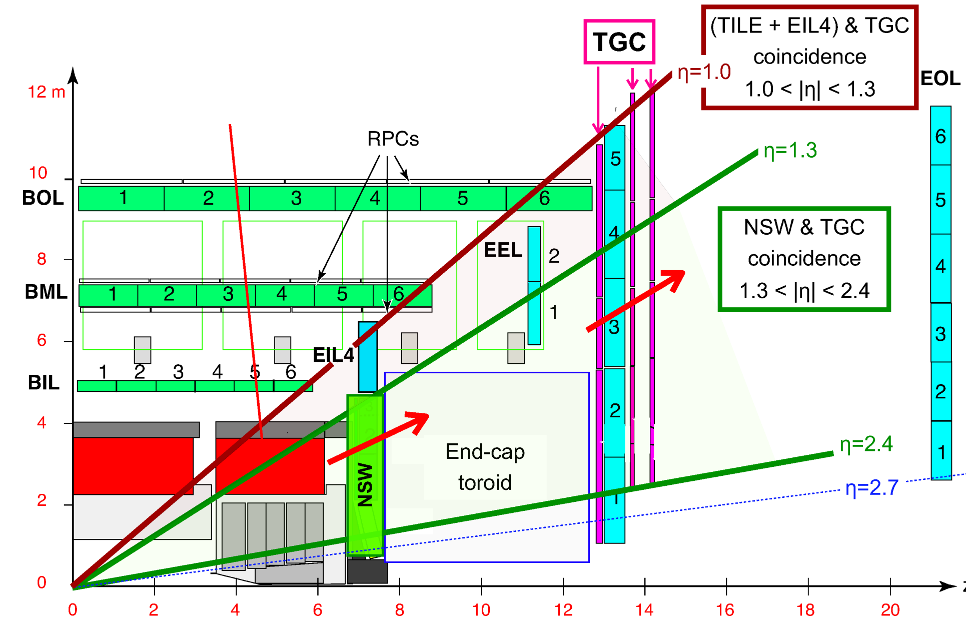


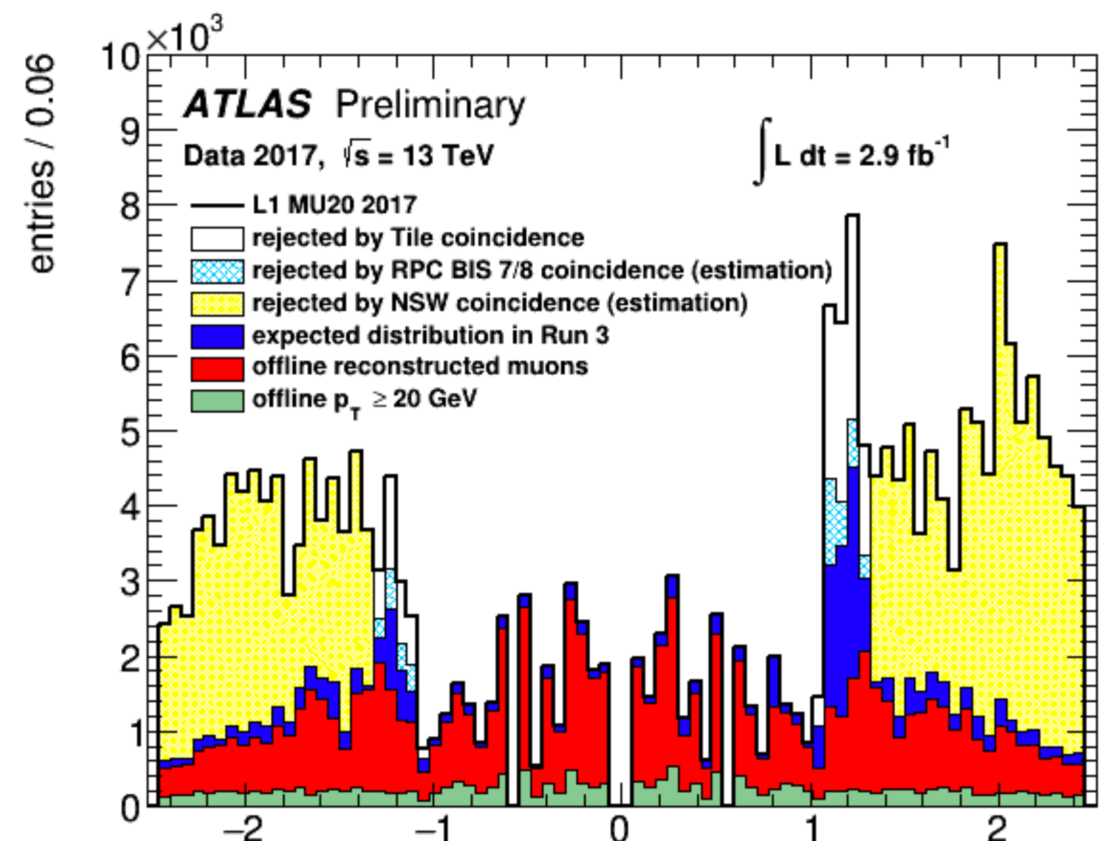
Phase-1 Upgrade

Improving muon triggers requires new chambers

New end-cap muon chambers:
New Small Wheel (NSW)







Two technologies: Phase-1 Muon TDR

- sTGC: timing resolution for triggering
- Micromegas: high resolution (100 μm) for offline momentum resolution

link to plot

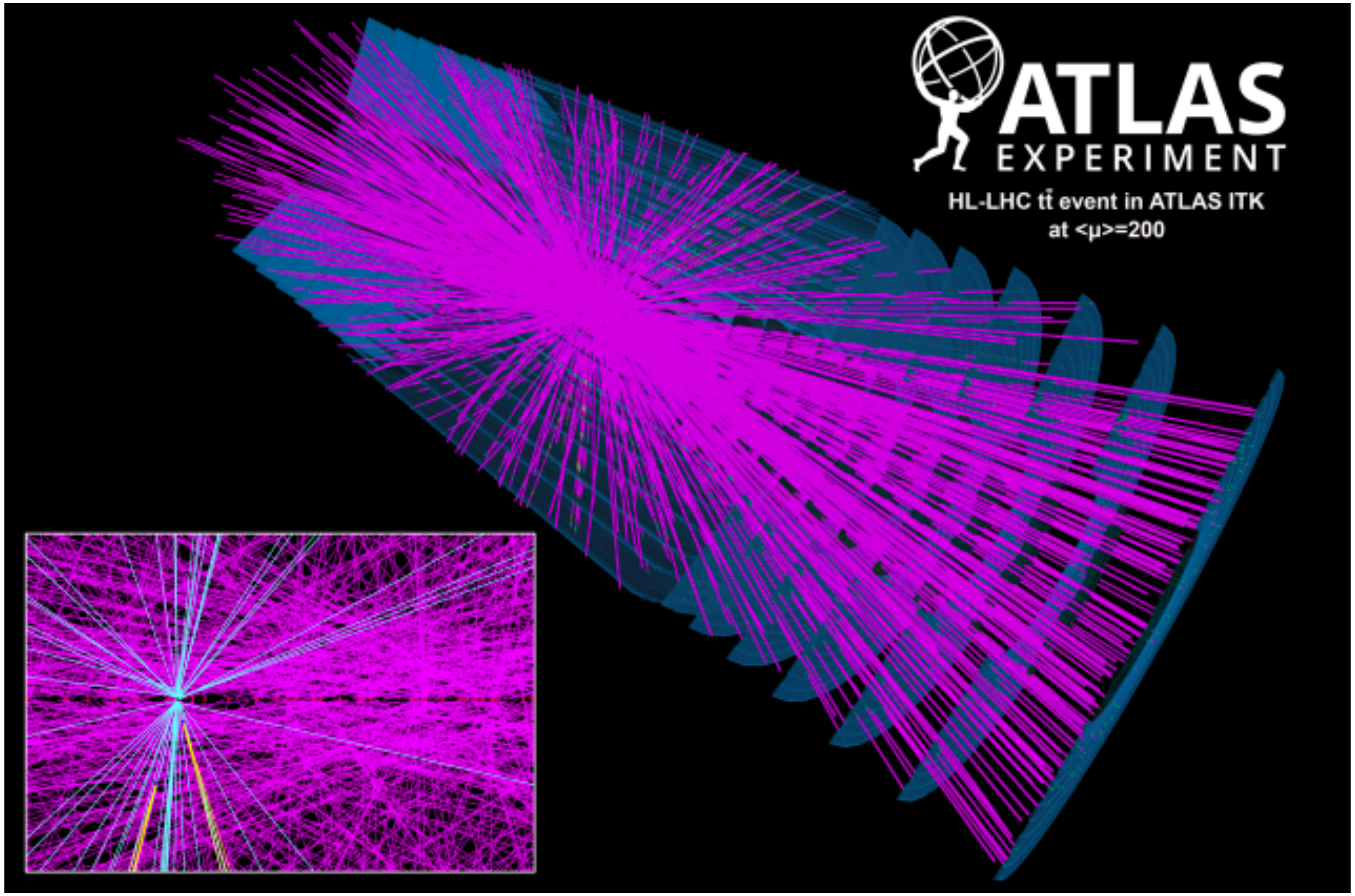
Phase-2

5-7.5x nominal LHC luminosity
20x data (=big reach)
Demanding 200 collisions per crossing (aka pile-up)
High particle fluence challenge for detector radiation tolerance

Physics Prospects

- Many sensitivity studies, but just scratches the surface of what will be done

Detector Upgrades



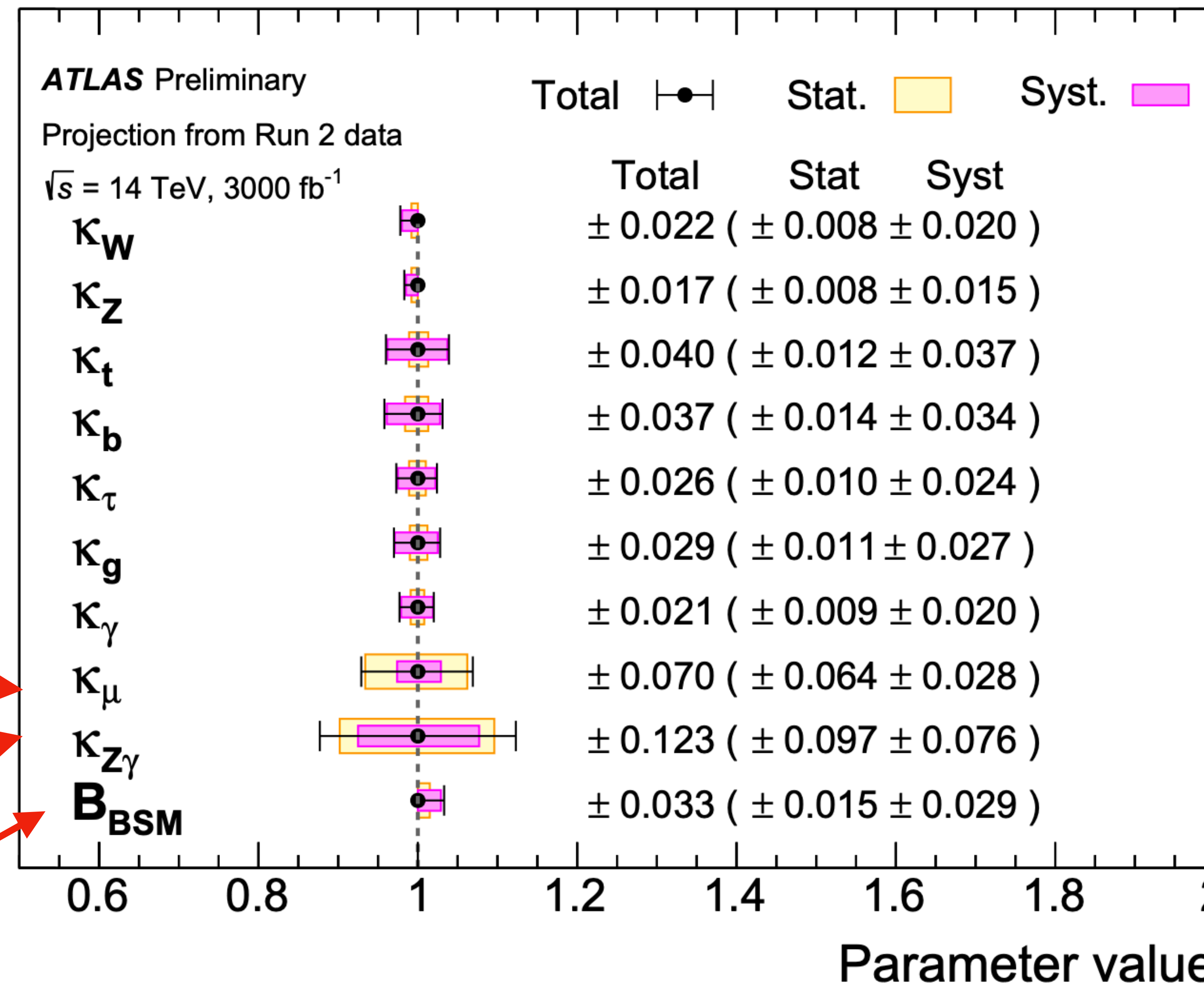
Broad Physics Program

High precision Higgs Coupling

High precision(2-4%) W, Z, top, bottom, τ, gluon, and photon measurements

Precise 2nd generation coupling measurement

Constraints on rare SM Higgs decays



Strong indirect constraints on BSM Higgs decays (without reconstructing the decay!)

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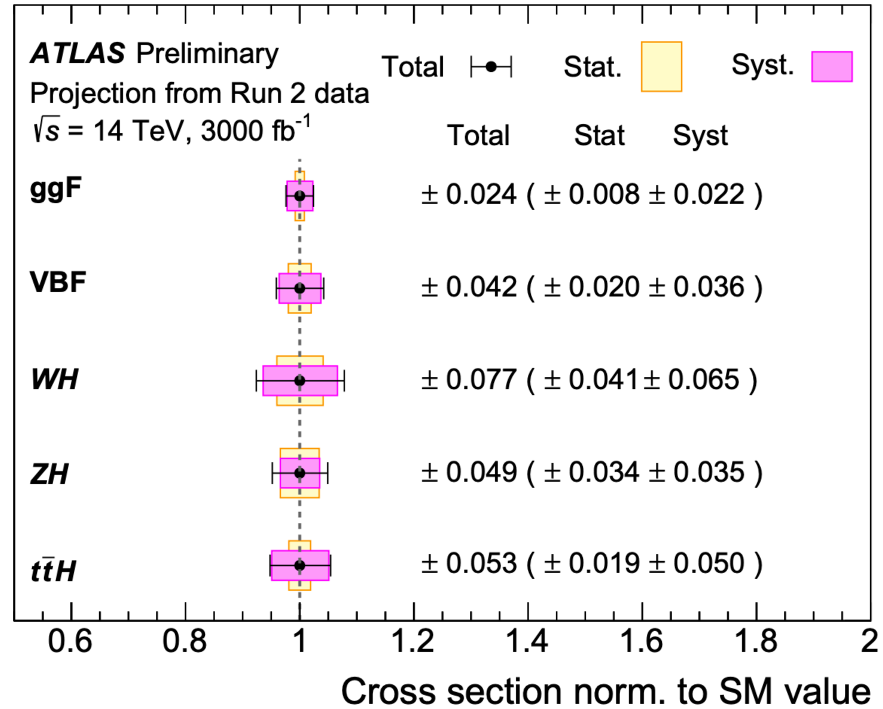
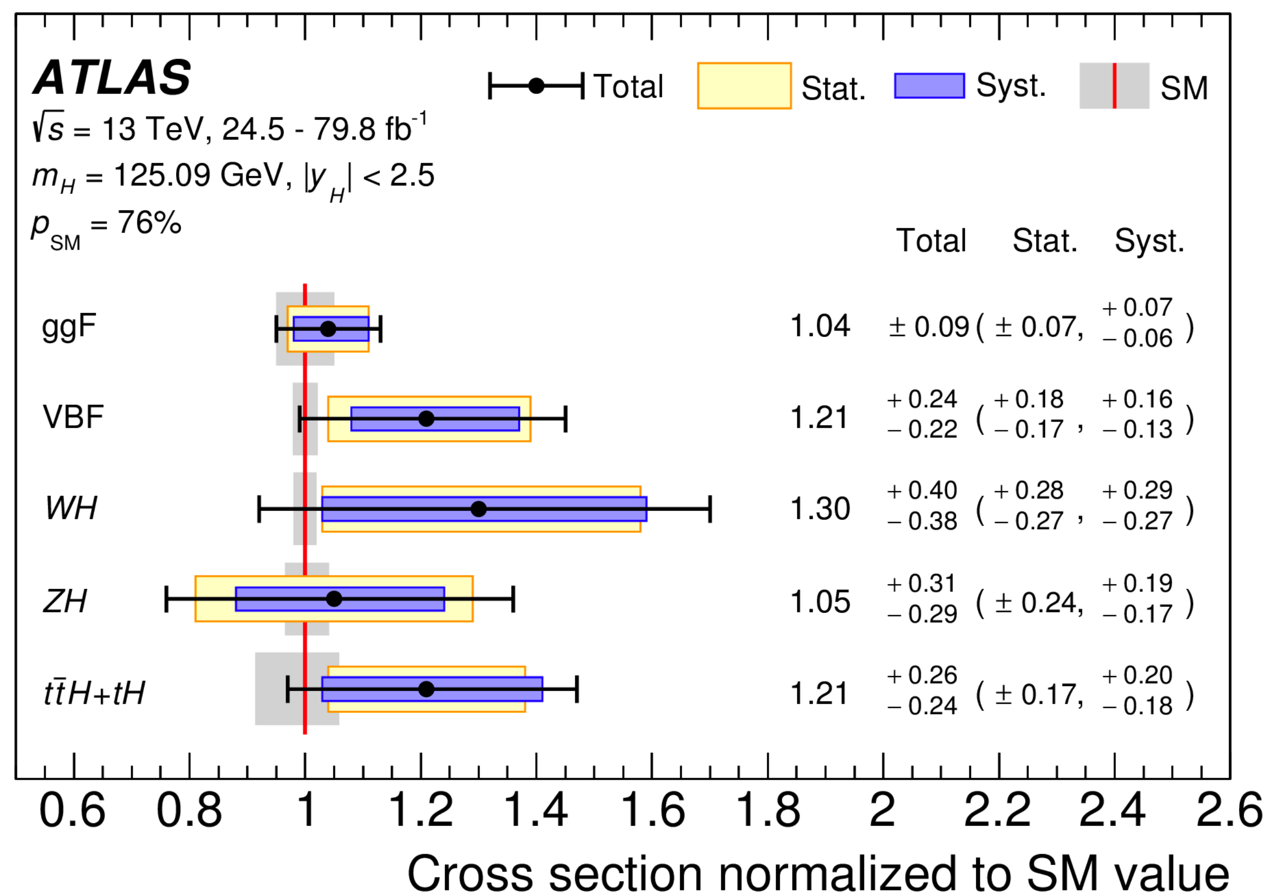
Broad Physics Program

High precision comparing to Run 2

HL-LHC limits by production process



Run 2 limits by production process



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Broad Physics Program

Higgs self-coupling

$$
\begin{aligned}
V(\phi^\dagger\phi) &= \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \\
&\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4
\end{aligned}
$$

Mass term

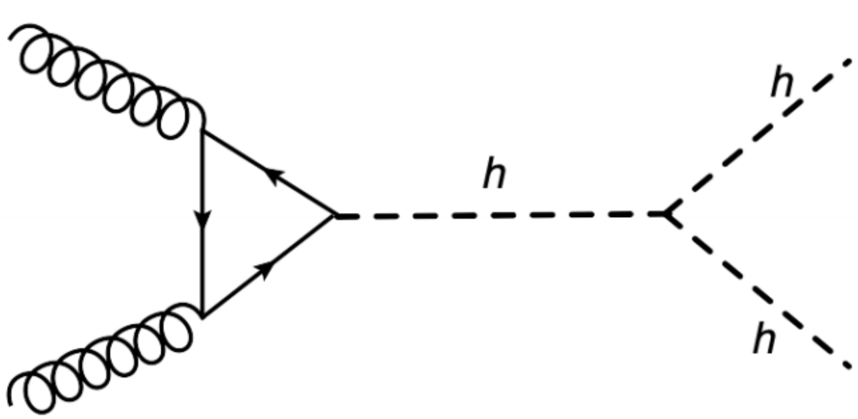
Self-coupling

Higgs self-coupling is an unmeasured parameter of SM

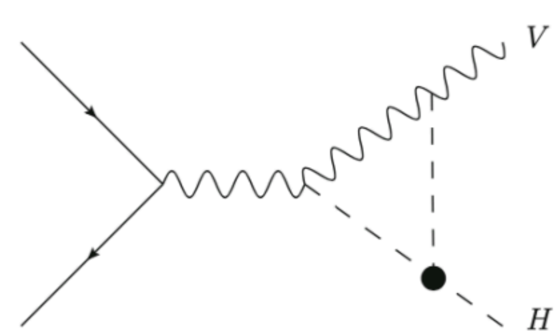
Fully predicted in SM $\lambda_{HHH} = \kappa_{HHHH} = \frac{m_H^2}{2v^2}$.

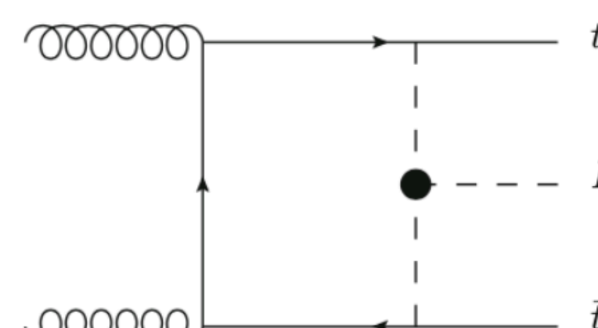
Directly probes shape of Higgs potential

Can be probed through pair production



…or indirectly in single Higgs couplings

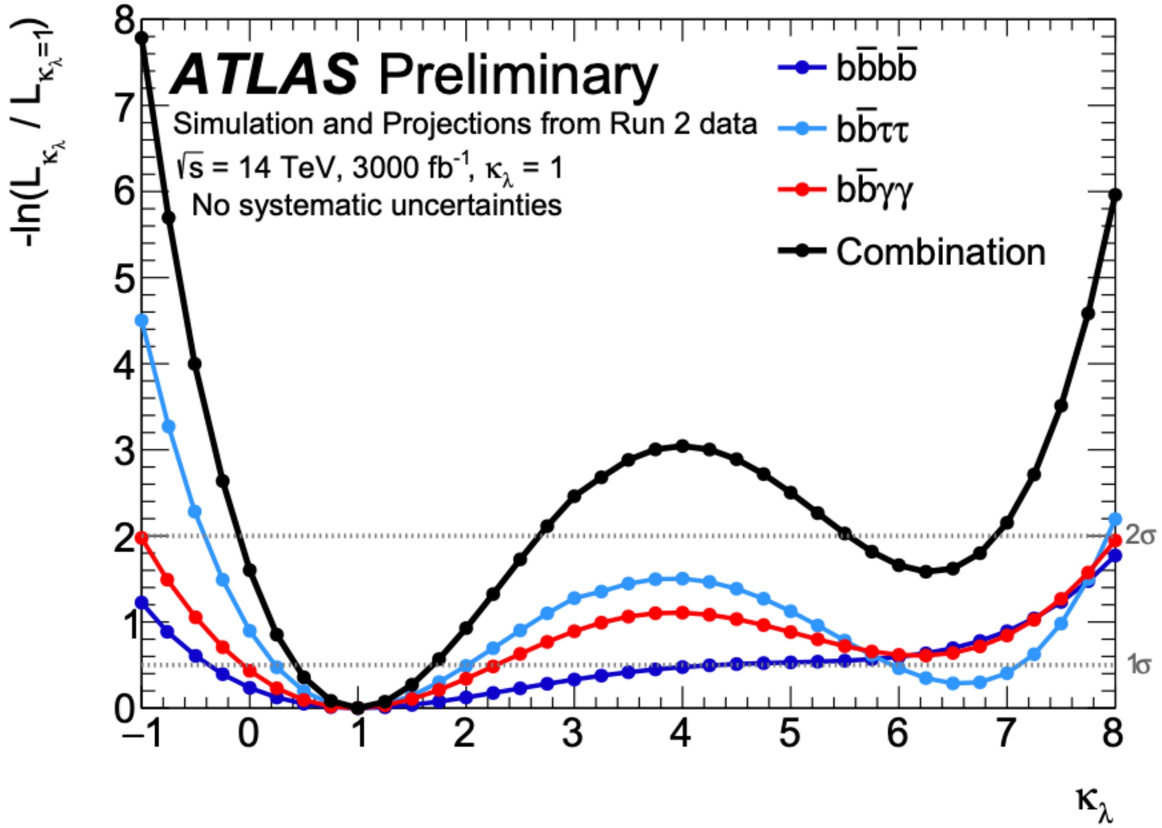




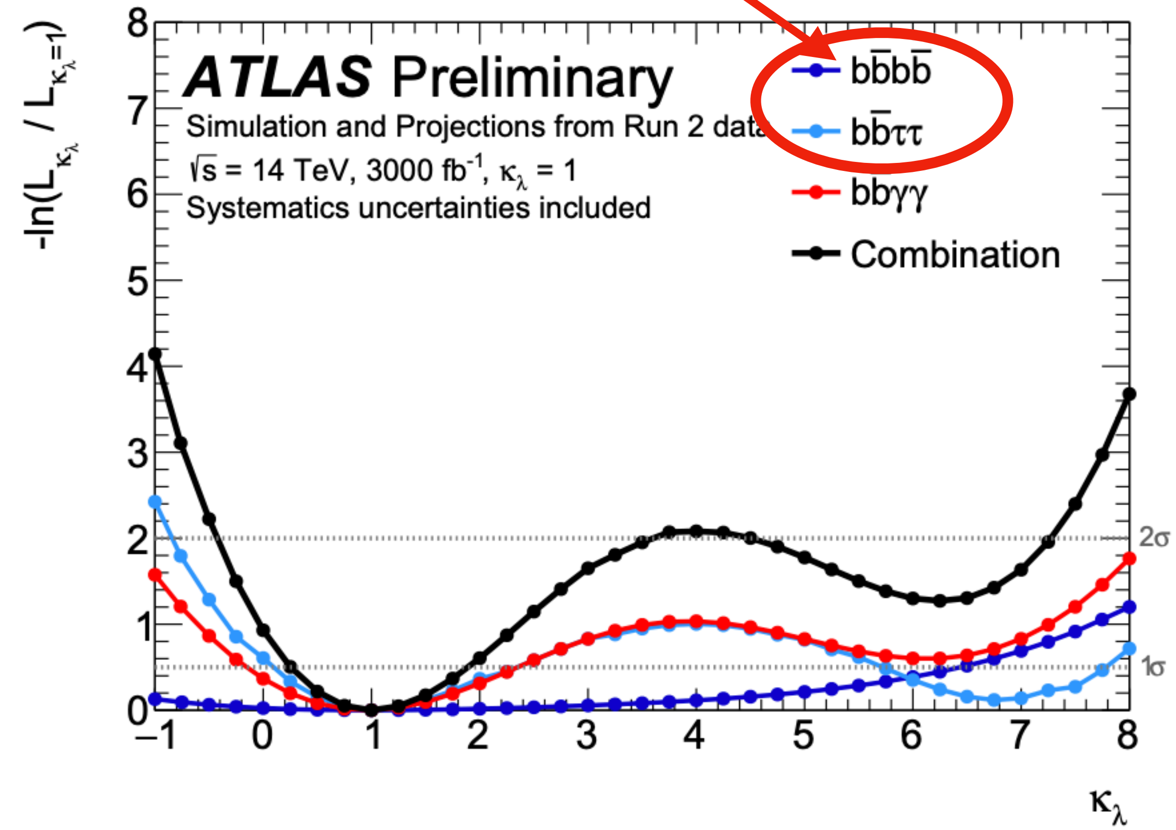
Broad Physics Program

Higgs self-coupling from Higgs Pair Production

4b and bbττ are very hard to trigger on
One of the trigger upgrade design drivers



Without systematics



With systematics

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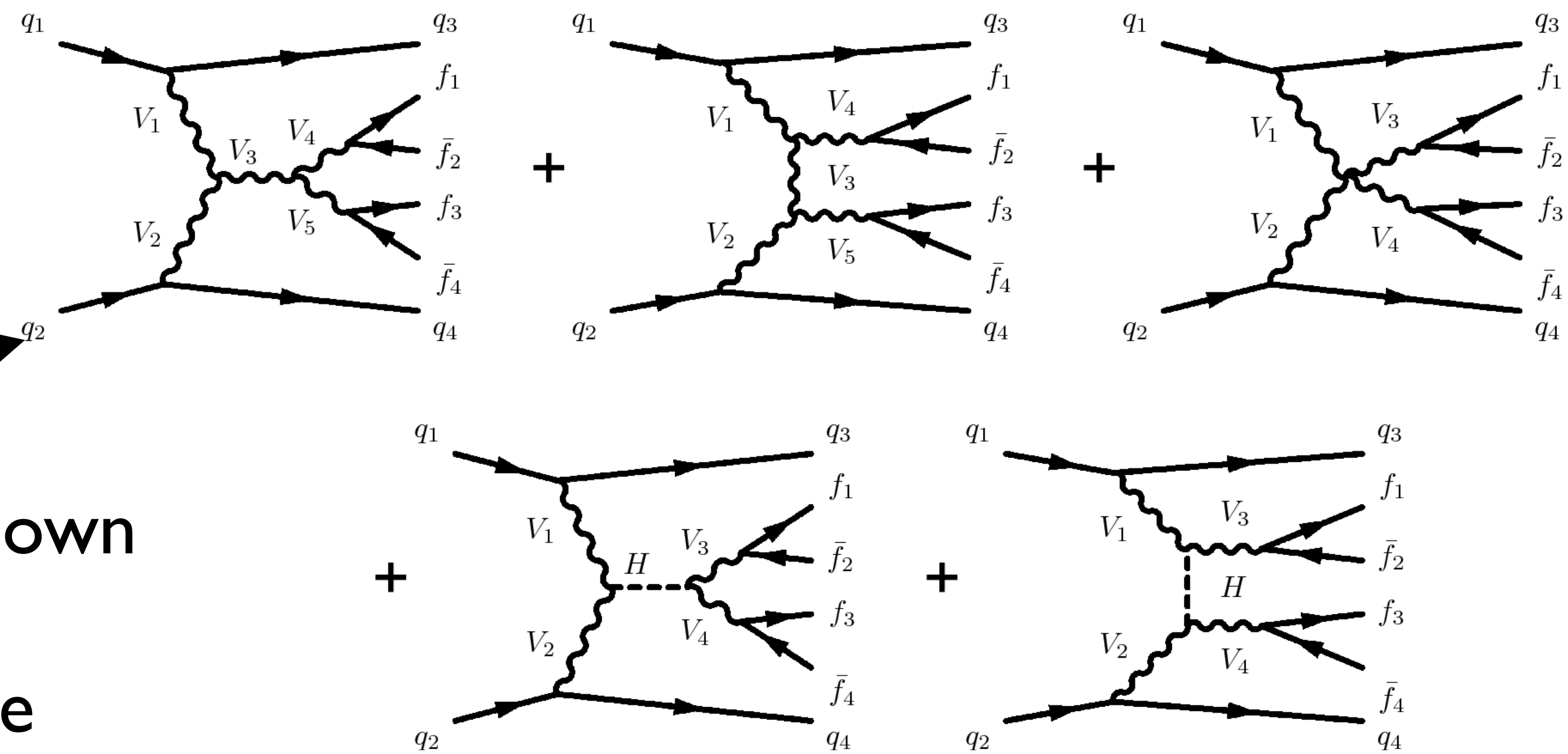
Broad Physics Program

Electroweak Probes

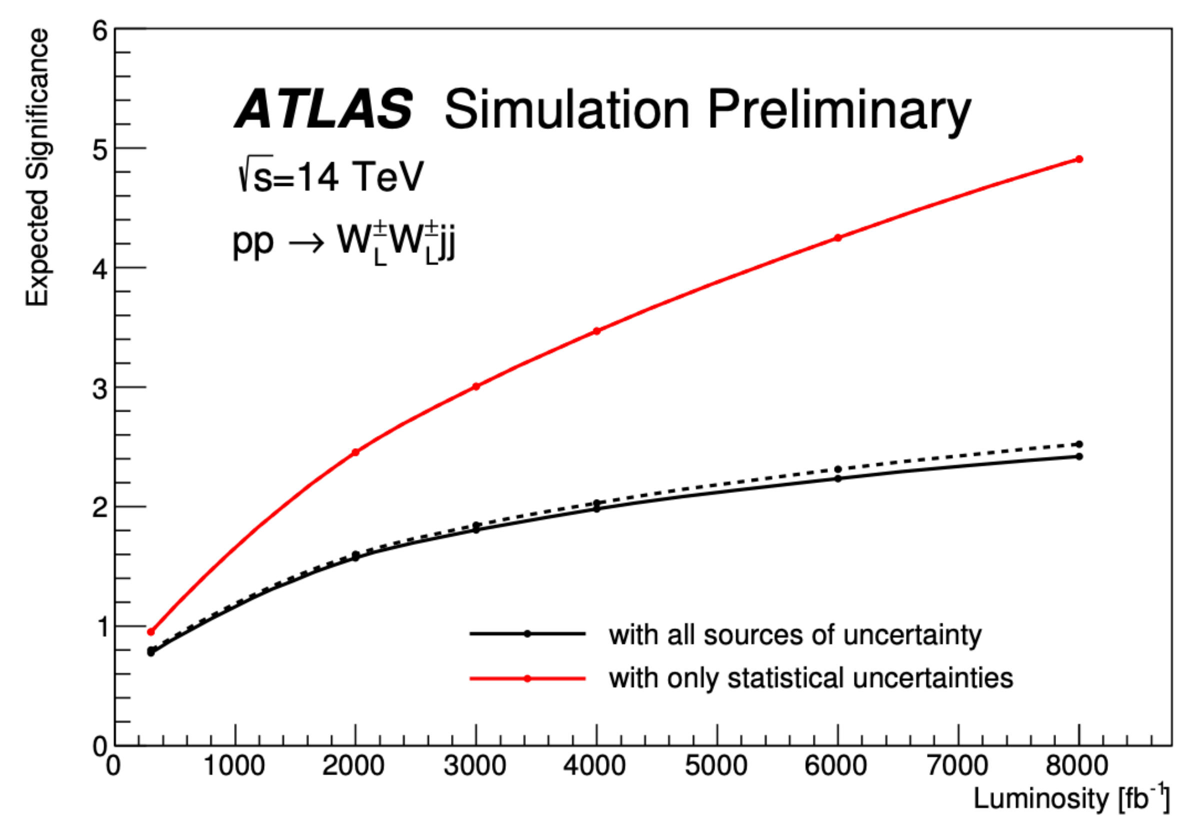
Many SM probes including vector boson scattering (VBS), quartic couplings, sin θ_W, W mass, etc.



E.g. In WW VBS, it is still unknown whether the discovered Higgs boson preserves unitarity of the longitudinal VV scattering amplitude at all energies,

6% measurement of the cross-section

1.8σ significance for $W_L W_L \Rightarrow W_L W_L$ scattering at SM level



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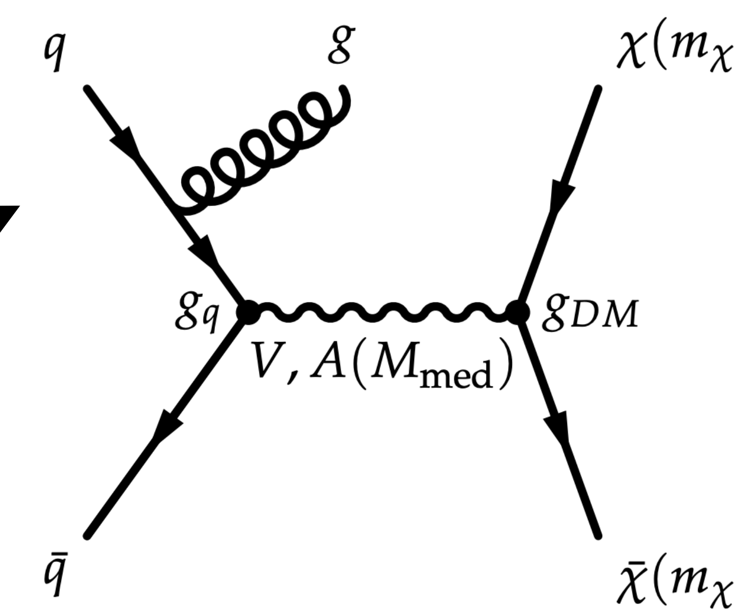
Broad Physics Program

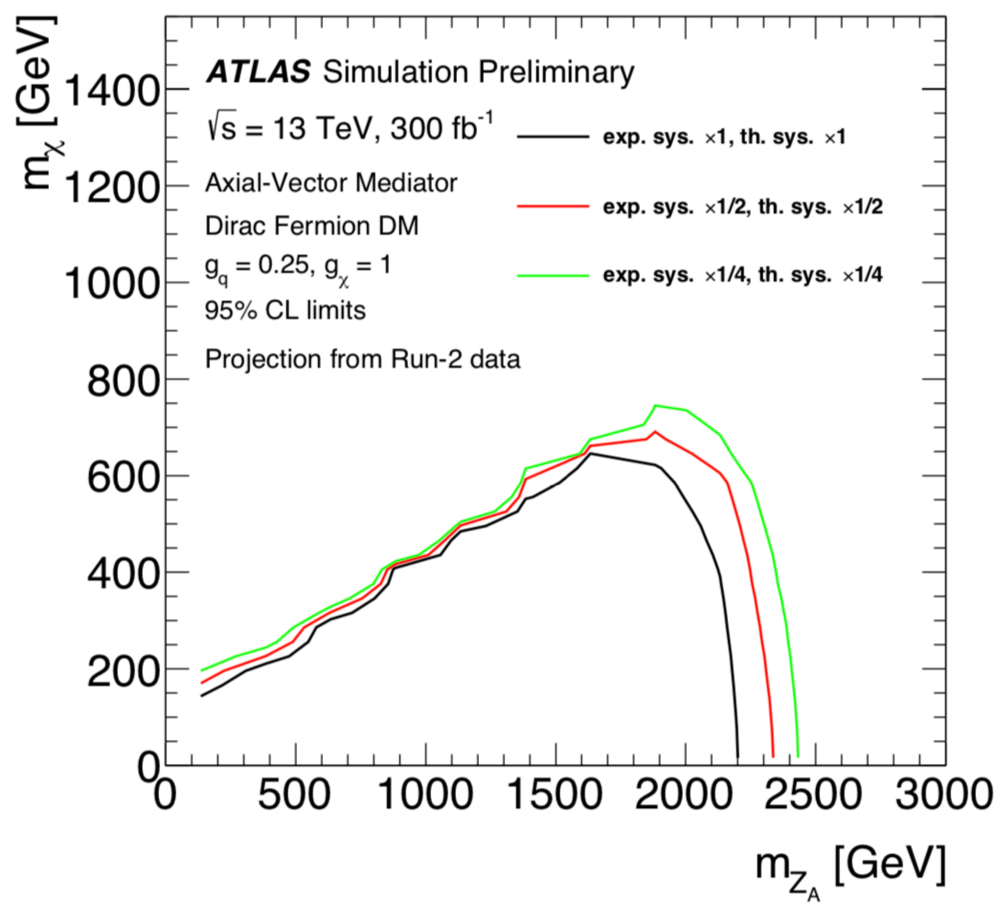
Model independent dark matter searches

Many possible signatures: Mono-jet, Mono-top, Mono-Z, Mono-Higgs, VBF + MET.

Example Mono-jet quantified with simplified models

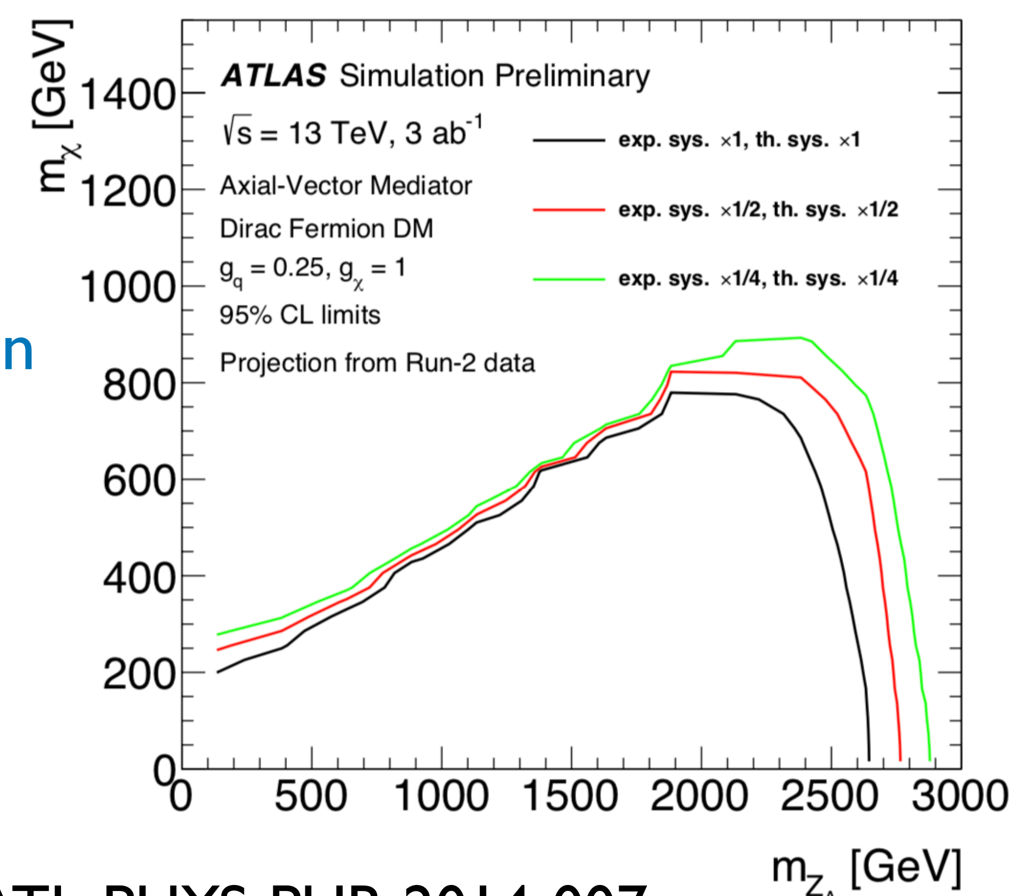


300 fb^{-1}



increase ~400 GeV in mediator and ~200 GeV in DM mass

3000 fb^{-1}



ATL-PHYS-PUB-2014-007

Broad Physics Program

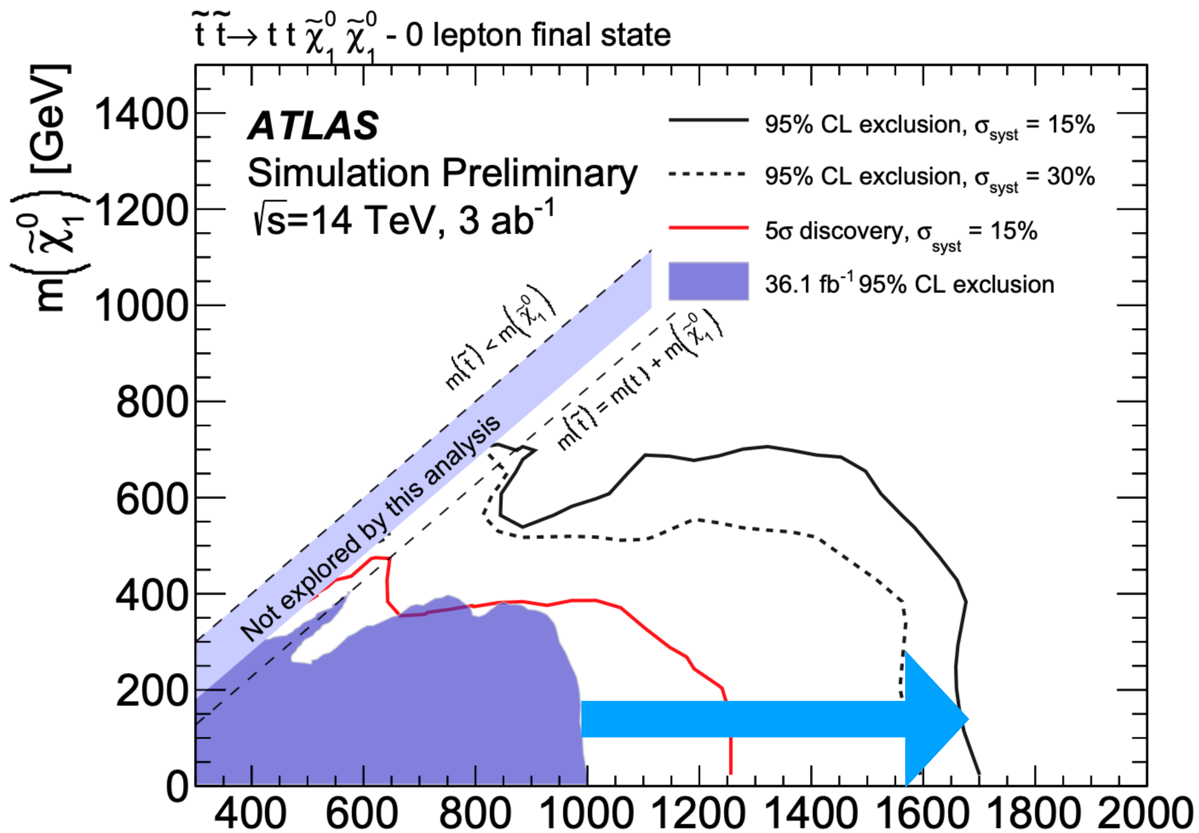
New particle (BSM) Reach

SUSY lives on, also a proxy for other resonant BSM searches

Broad variety of signatures in BSM modes requires flexible detectors

Large increase in reach for classic SUSY signatures

Stop decay to neutralinos



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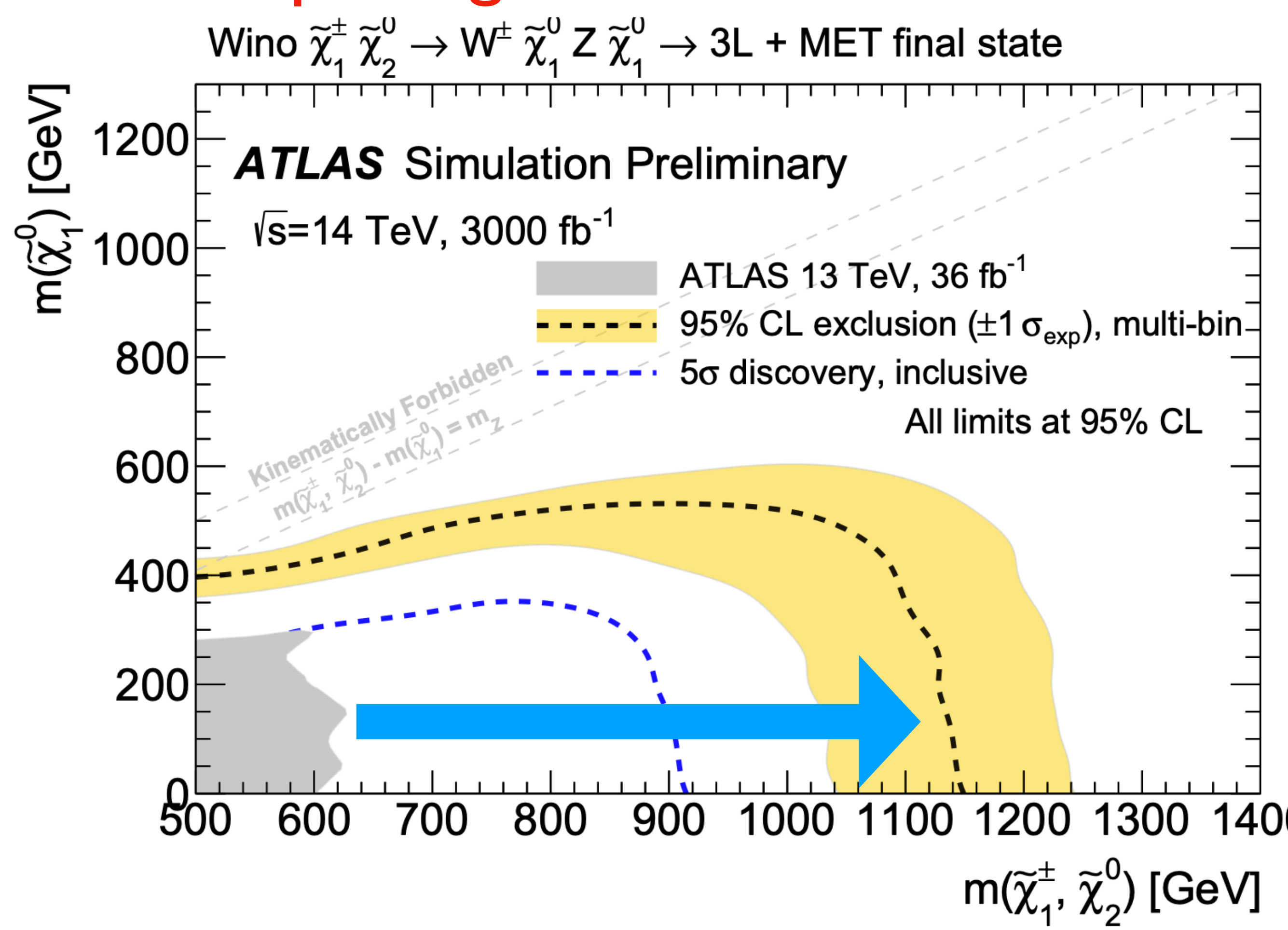
SUSY "trilepton" search for large mass splitting



Broad Physics Program

New particle (BSM) Reach

..and for compressed spectra searches

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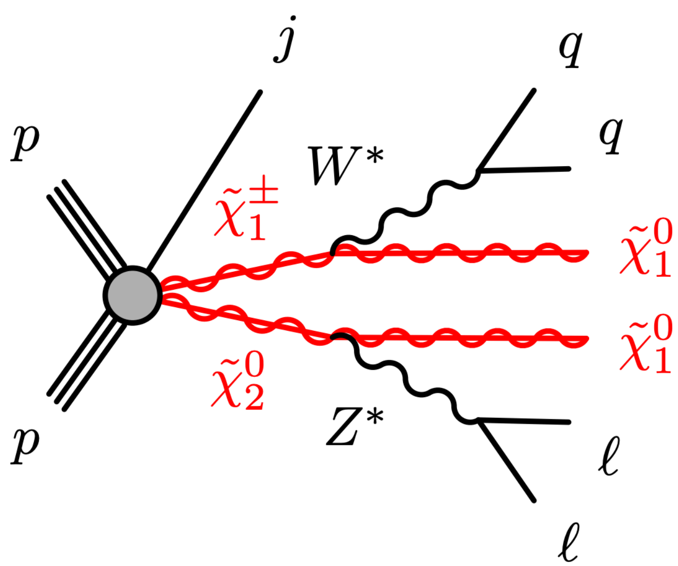
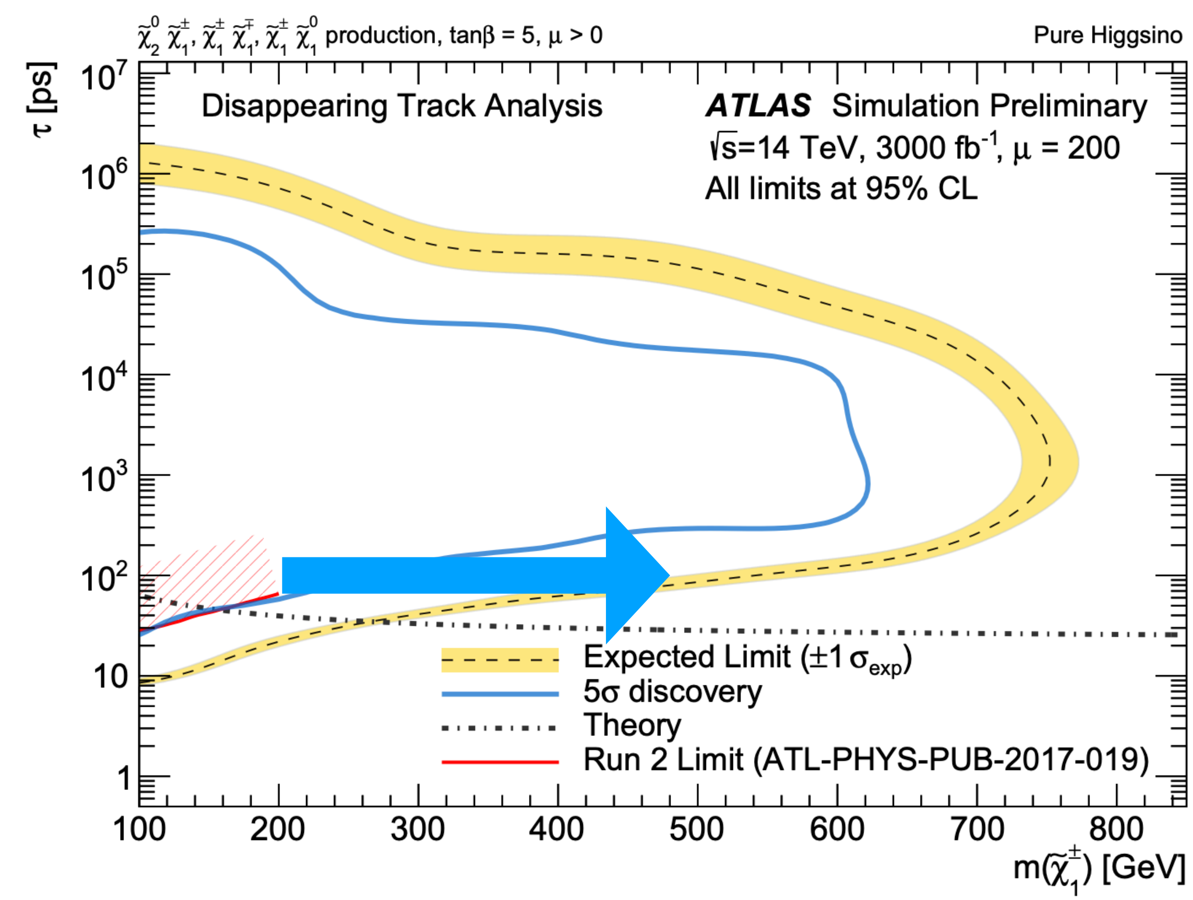
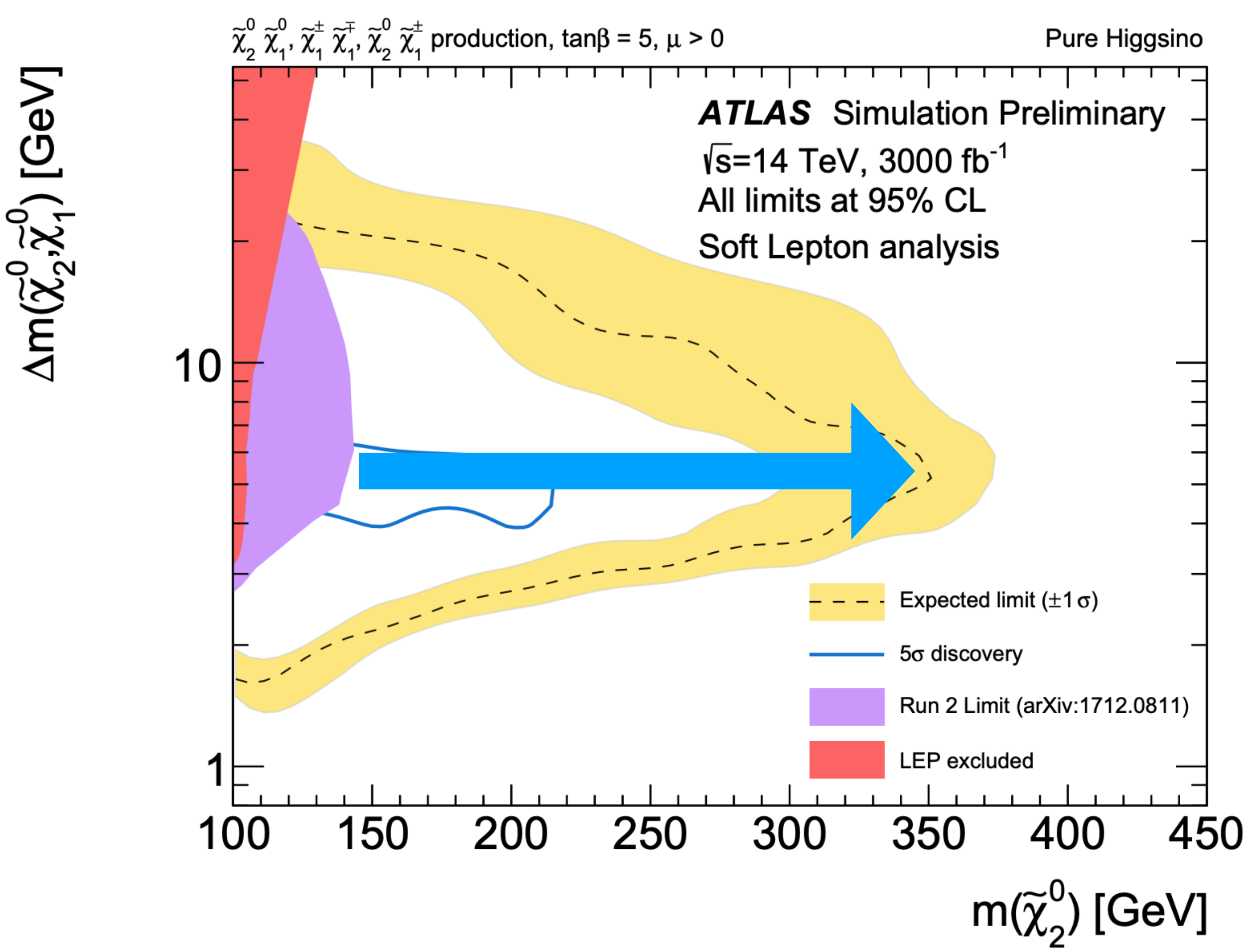
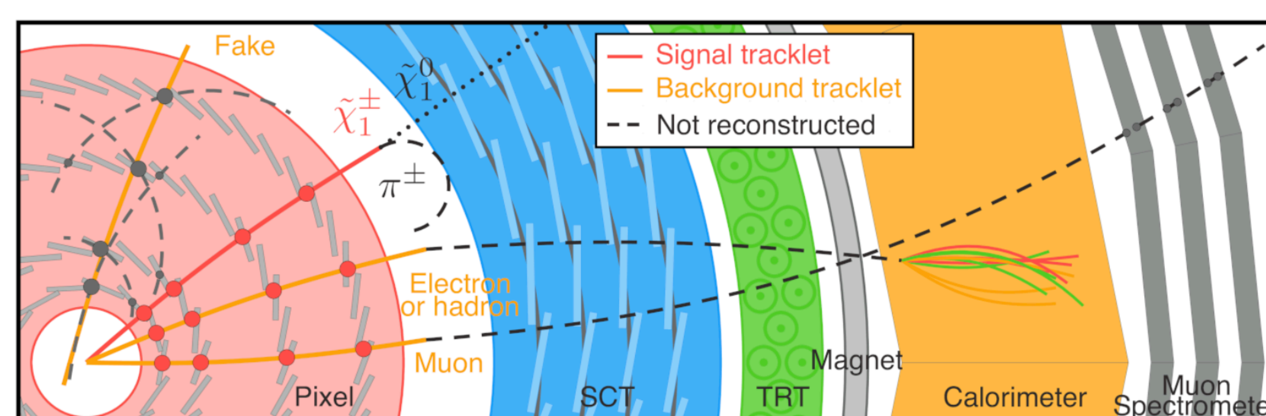




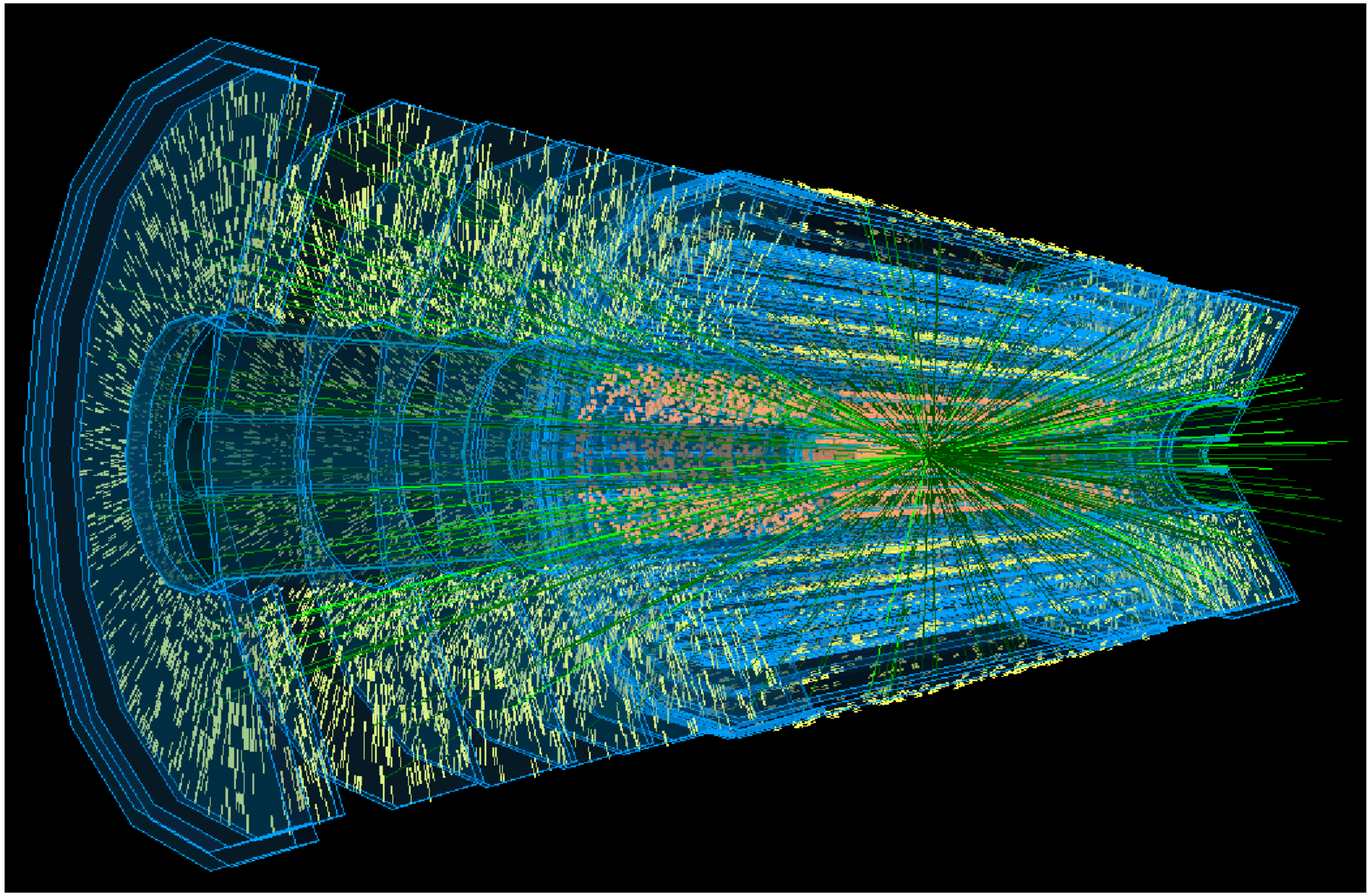




Tracker Upgrade

Intense environment
More performance required

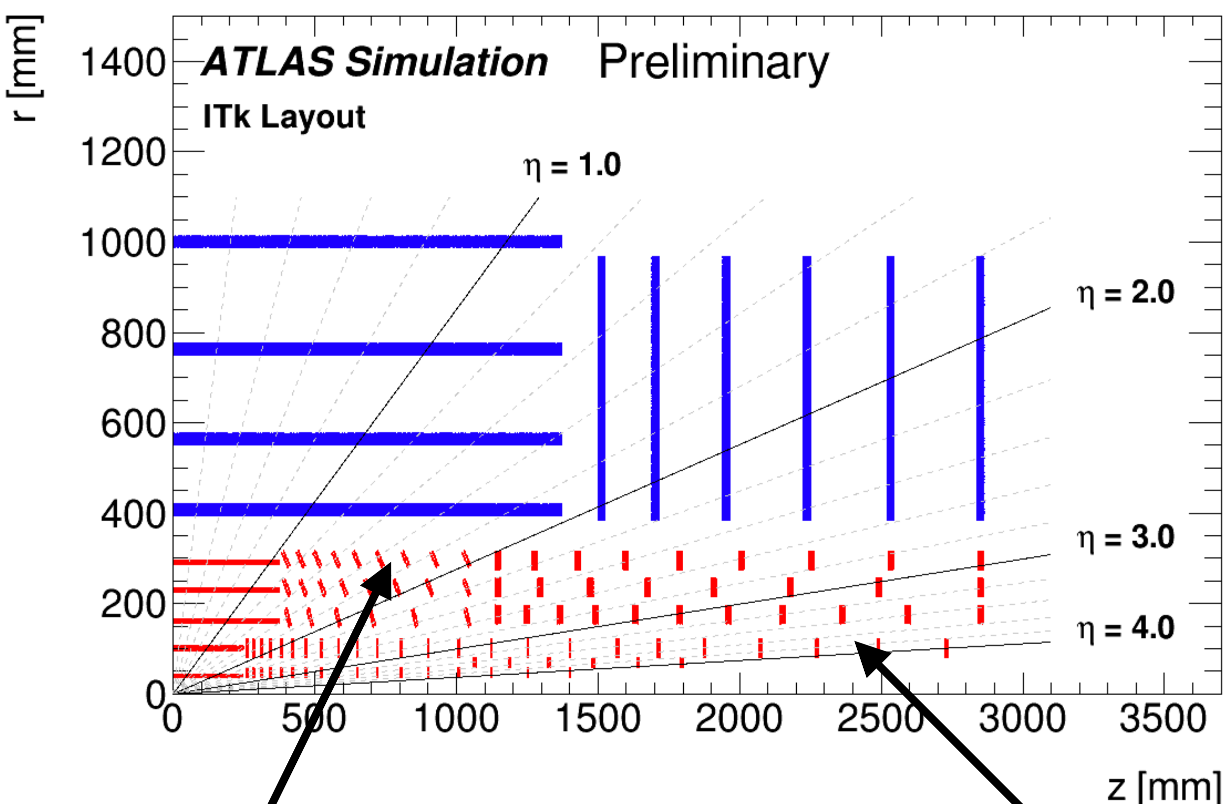
- Radiation Tolerance
  - Sensor, electronics and mechanical must survive to 4000 fb^{-1}
  - Inner pixel layers replaced at 2000 fb^{-1}
- High efficiency with low fake rate in 200 pile-up (~x10 Run 1)
- Higher trigger rate
- Higher η coverage
- Minimize material for track and calorimeter performance



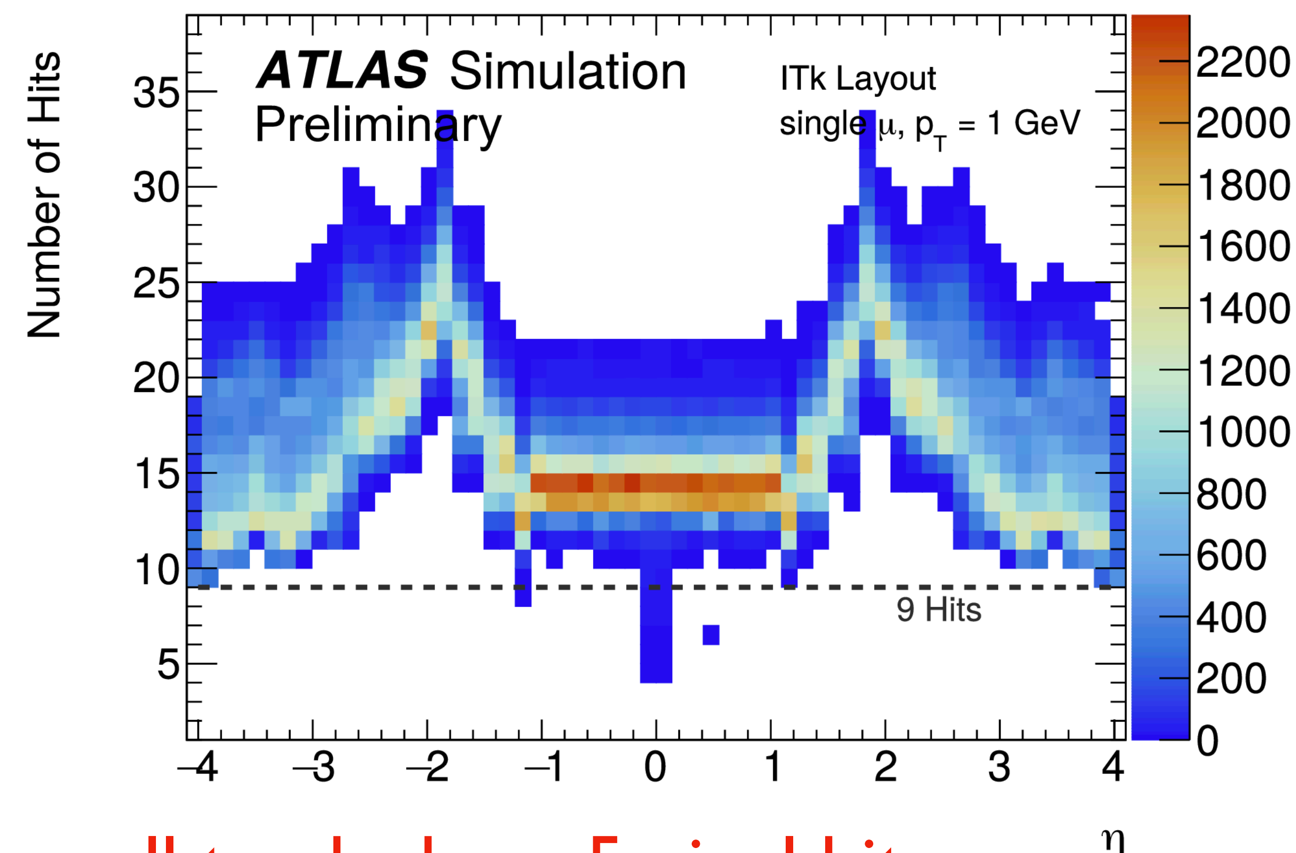
Tracker Upgrade

High efficiency with low fake rate in 200 pile-up (~x10 Run 1)

Coverage to |η| > 4.0



Good coverage across full η range



~all tracks have 5 pixel hits

Inclined sensors provide shorter path length of particles through overlap region sensors

Unique ring design allows tuning of forward sensor placement

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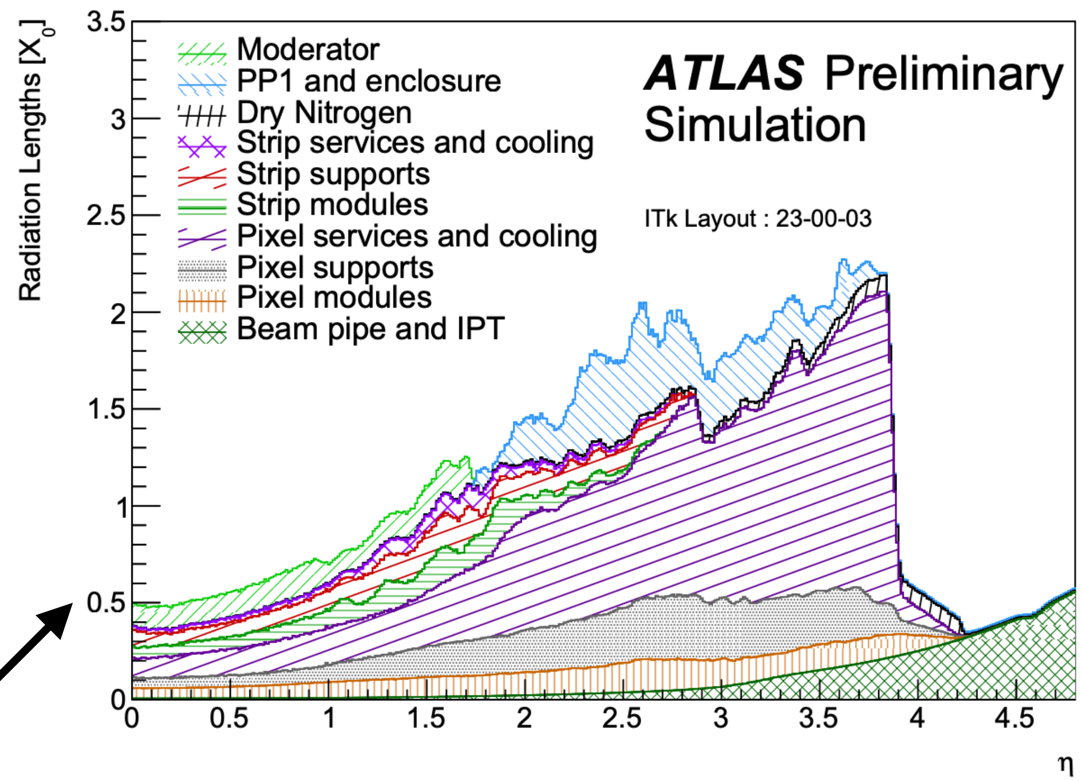
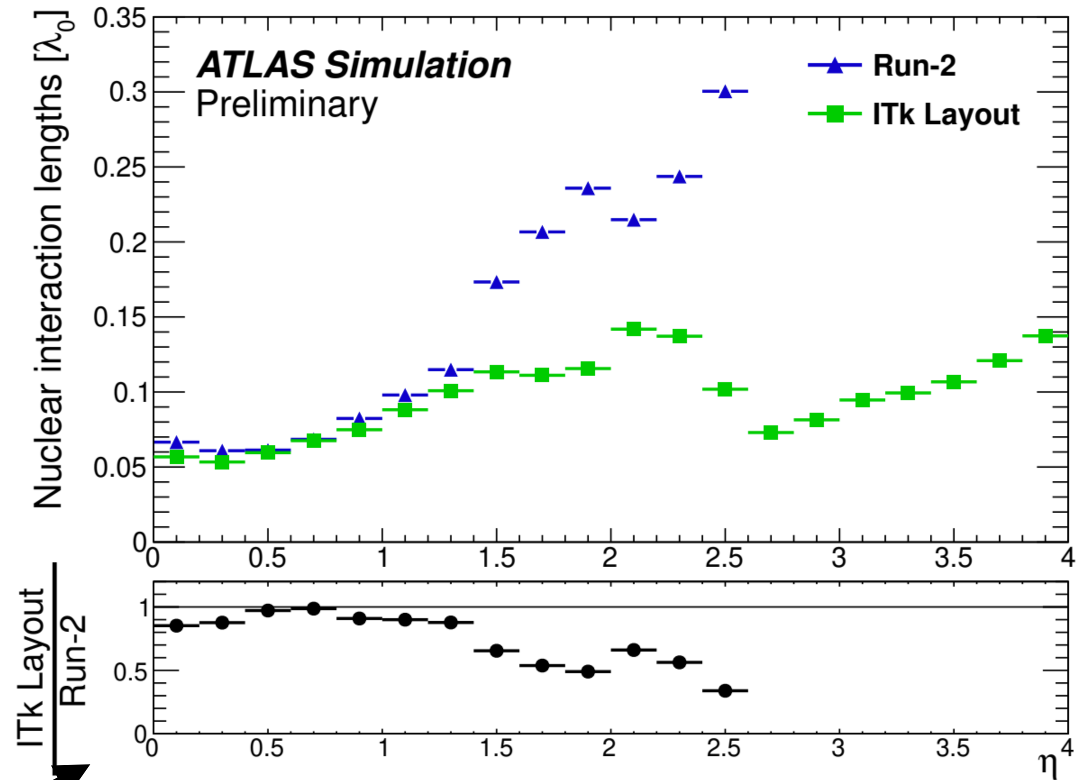
Tracker Upgrade

Material

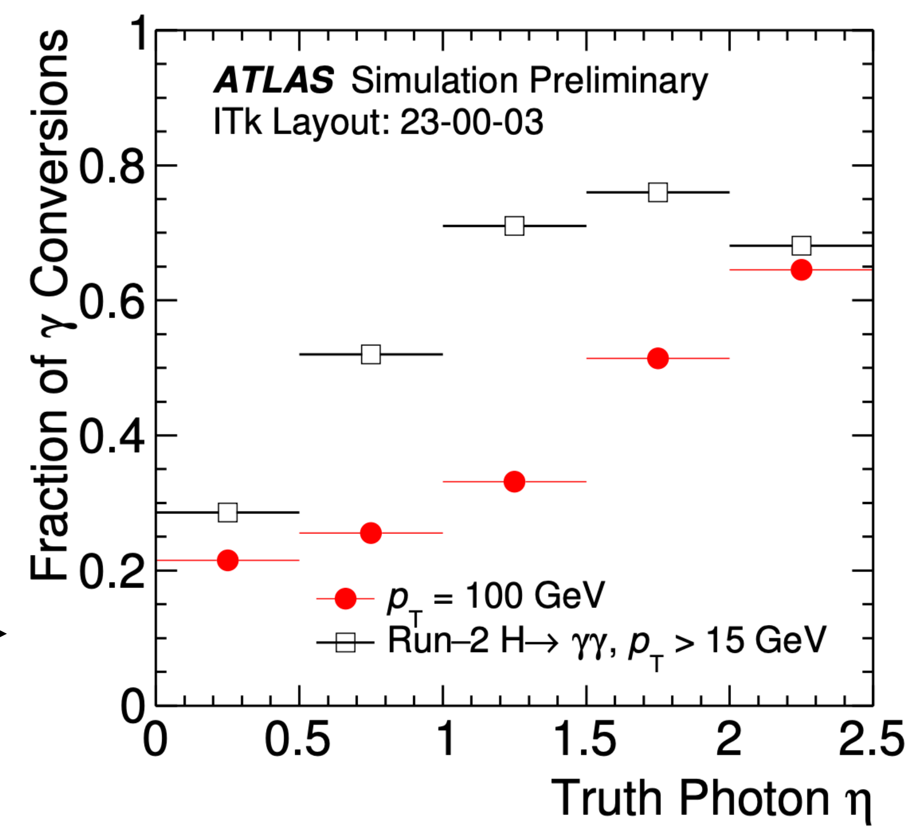




Material is complex sum of contributions for the sensors, supports, services, and cooling

Material similar to Run 2 with improvement in transition region

Example: Impact of improved material



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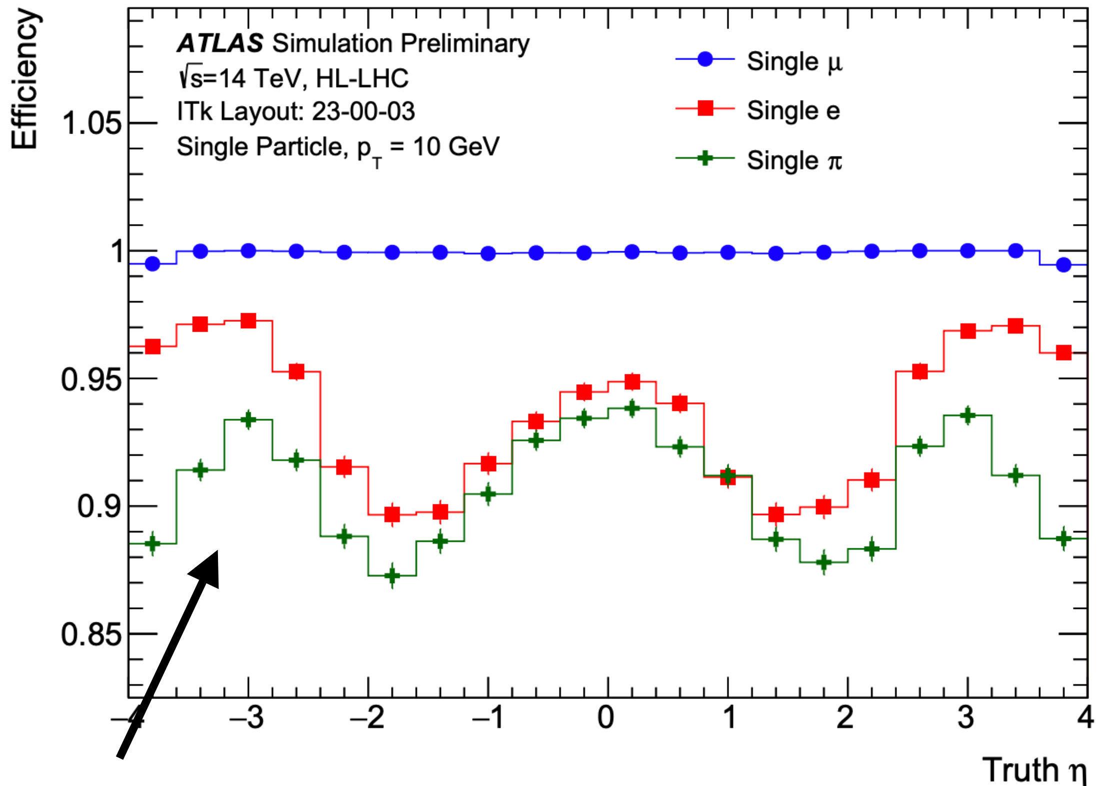
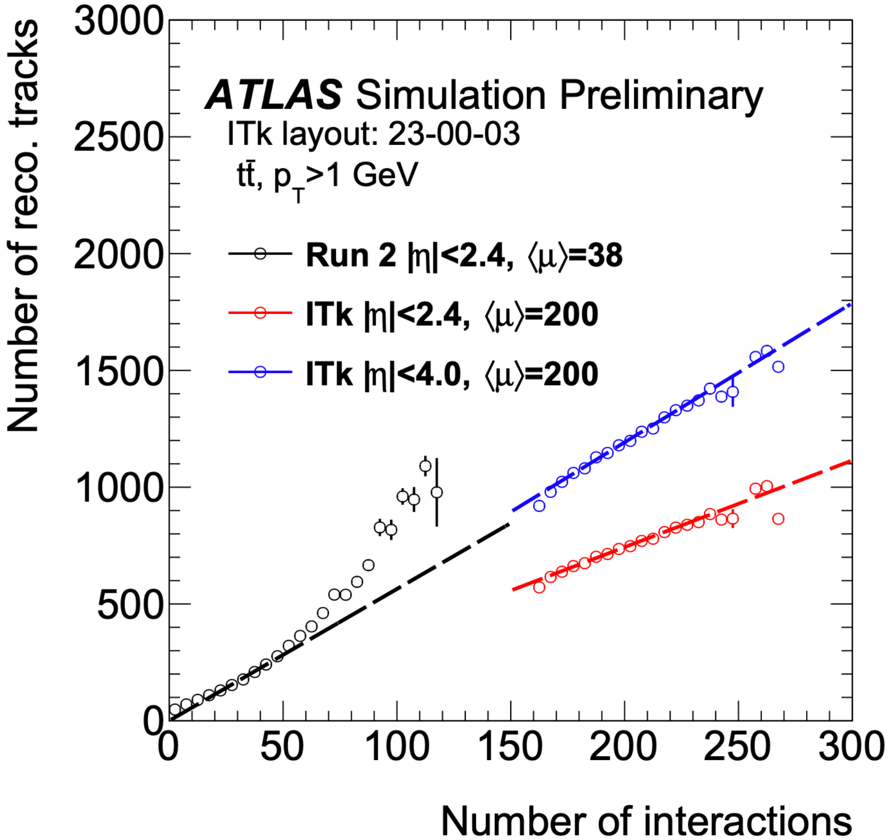
Tracker Upgrade

Tracking Performance



Excellent efficiency across all rapidity for e, μ, π



Low fake rate

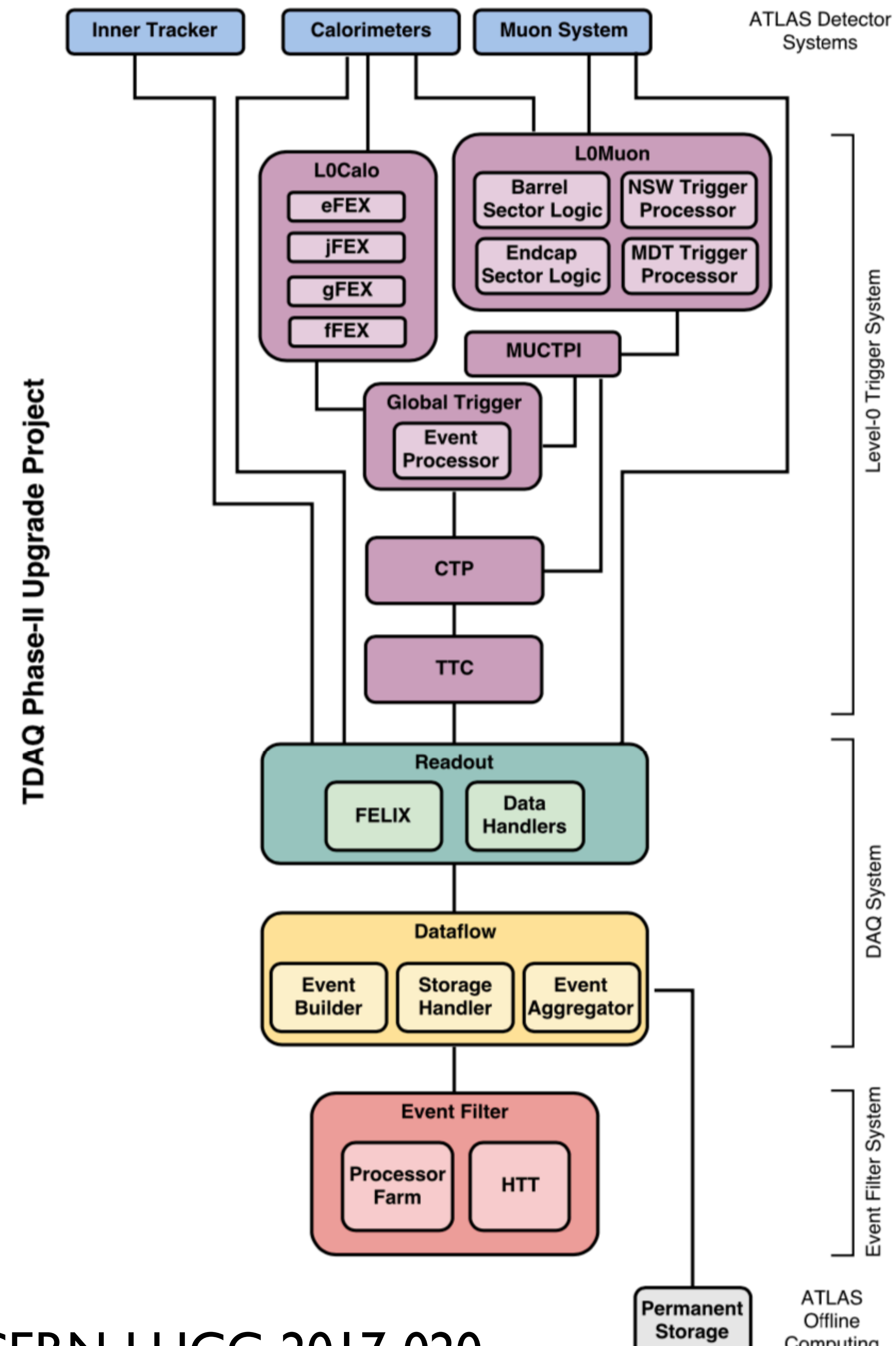
Linearity of number of track candidates with number of interactions indicates low fake rate

good z_0 resolution gives similar pile-up rejection at low η, better rejection in the forward region

b-jet tagging, better or similar to Run 2 + with ITK b-tagging in forward region

ATL-PHYS-PUB-2019-014

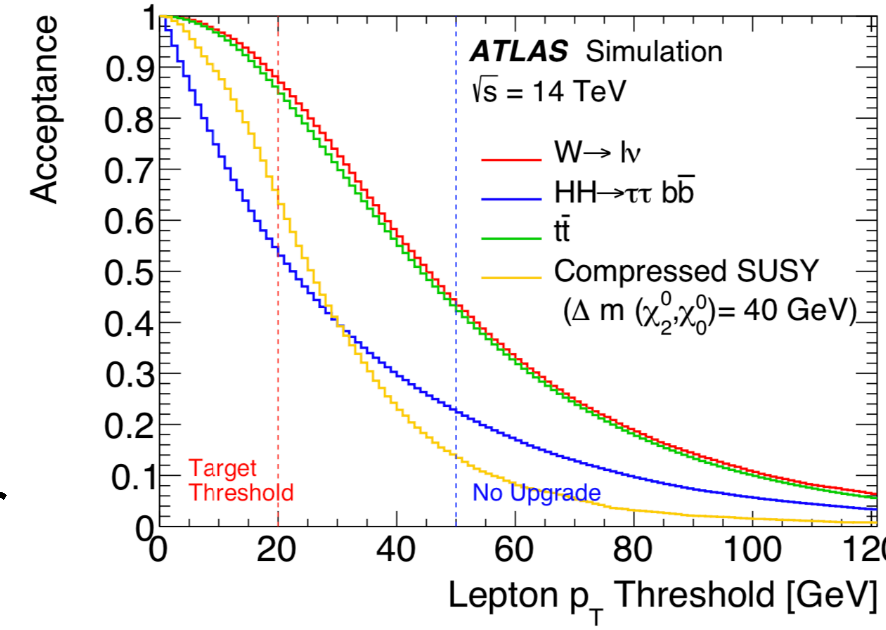
Trigger+DAQ



CERN-LHCC-2017-020

Physics rate increases from Run-2 by roughly ~3.75x, but…

- Would like to return thresholds to ~Run-1 level to expand acceptance and limit related systematics
- Pile-up makes discrimination harder

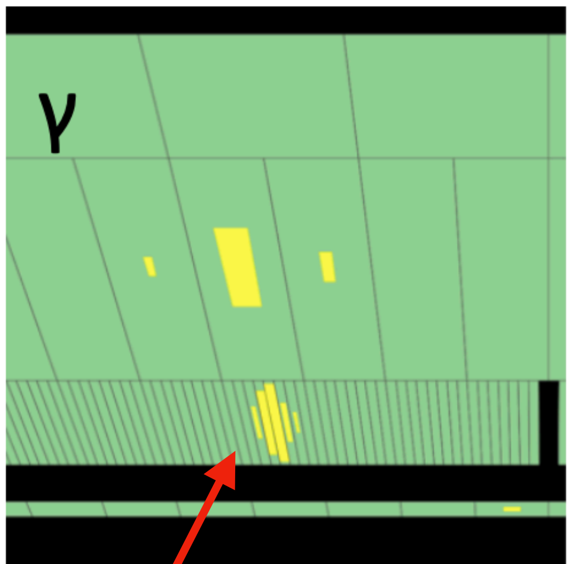


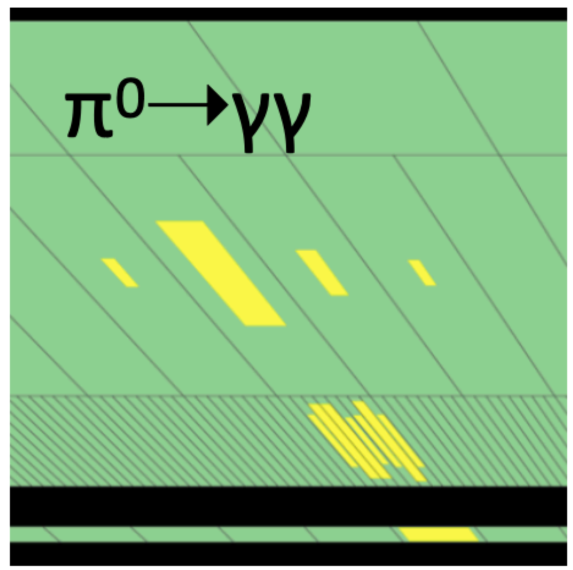
Approach

- Increase total rate limit from 100 kHz in Run-1/2/3 to 1 MHz
- Add even more discrimination compared to Phase-1 upgrade
  - Full granularity calorimeter info with a zero-suppression threshold
  - Use of MDT chambers in L0 Muon system
  - "Global" trigger is a time-multiplexed system that gets full granularity calorimeter + reconstructed muon info into one very large FGPA

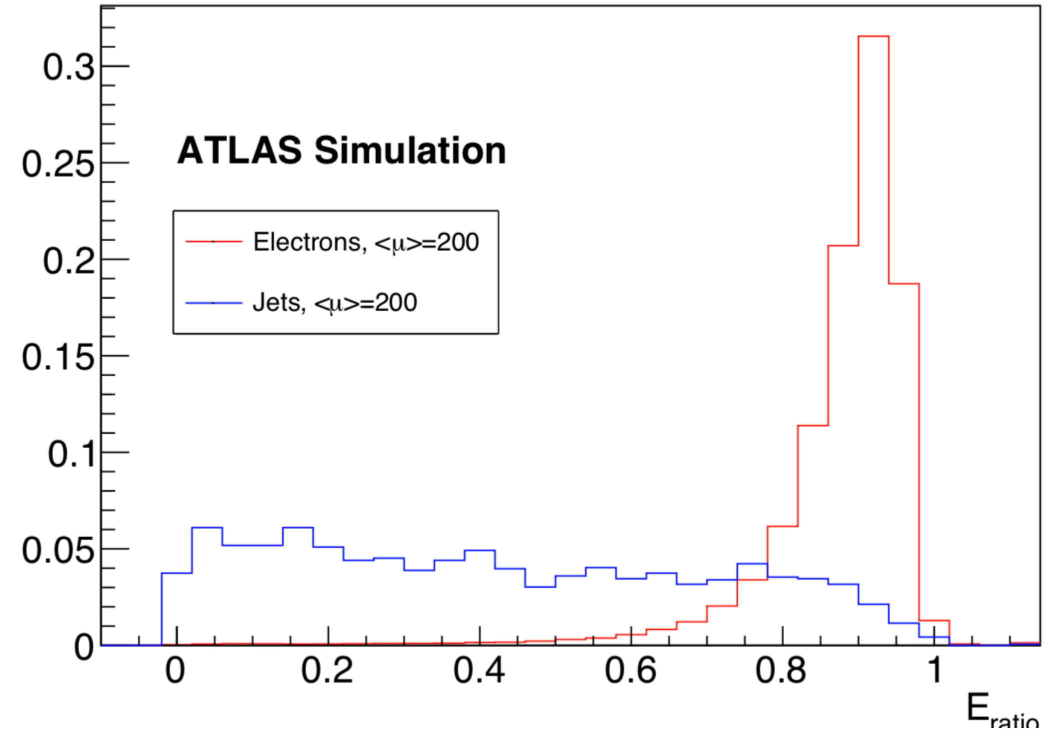
Trigger+DAQ

Full Granularity, full detector effects



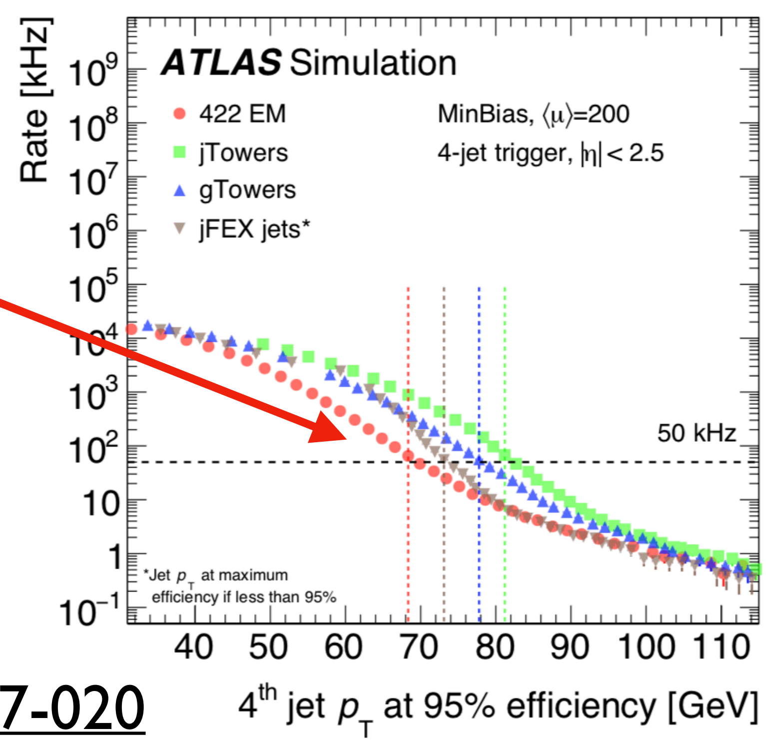


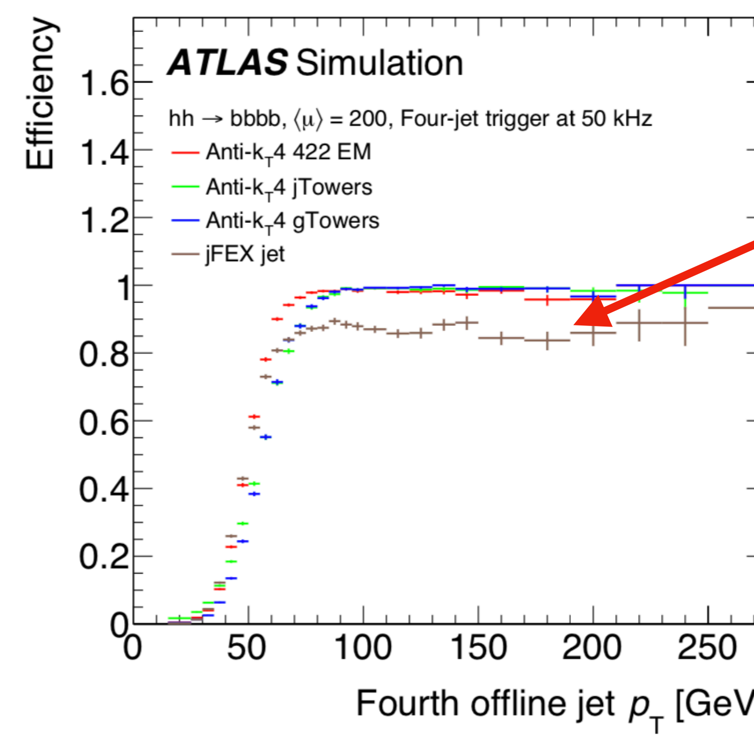
These "η" strips are not use in full granularity in phase I



$$E_{\text{ratio}} = \frac{E_{\text{highest energy cell}} - E_{\text{2nd local maximum energy cell}}}{E_{\text{highest energy cell}} + E_{\text{2nd local maximum energy cell}}}$$

Full granularity clustering improves jet energy resolution





Full detector allows for more anti-k_T like algorithm that improves near by jet efficiency

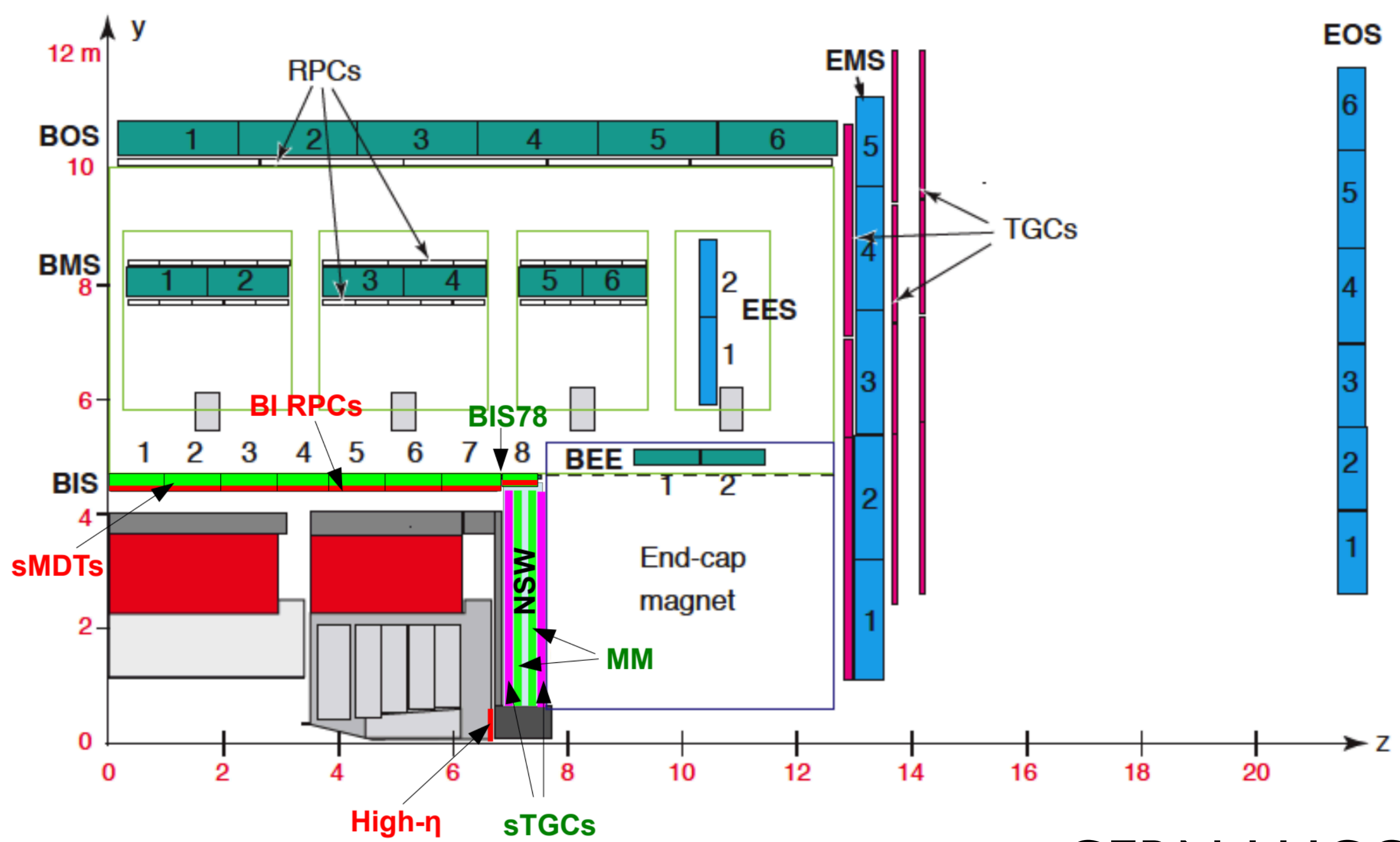
CERN-LHCC-2017-020

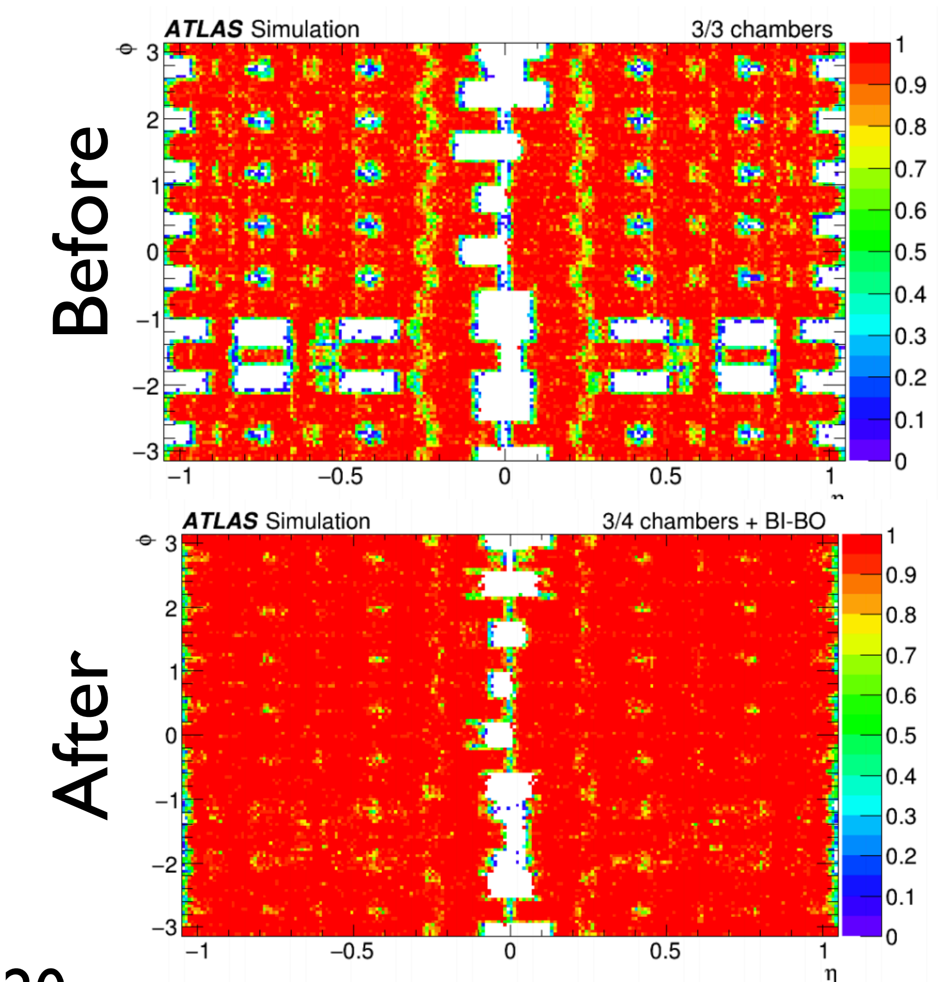
Calorimeters and Muons

Trigger upgrades require 1 MHz readout with 10μs L0 latency support and readout out of back to back bunches

Both the Liquid Argon and Tile Cal are responding to this using full 40 MHz readout with the event boundary defined in off-detector electronics

Muons are also reading out at 40 MHz plus adding new chamber to improve trigger efficiency





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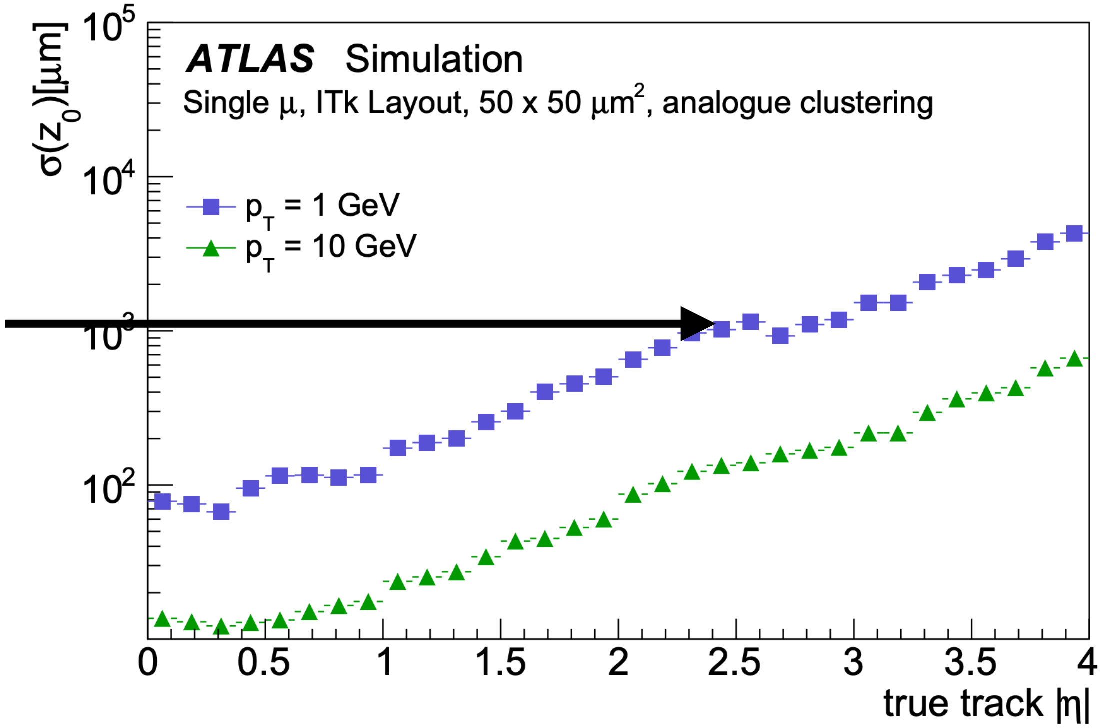
Forward Timing Detector

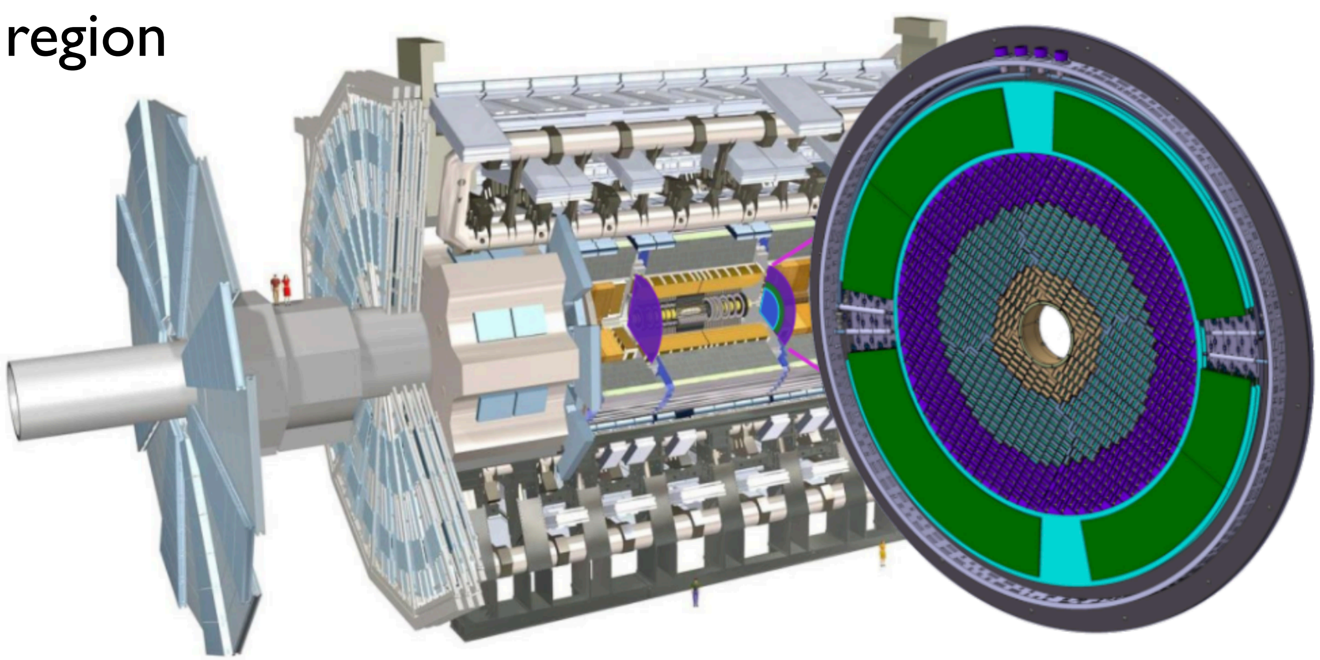
High Granularity Timing Detector

Based on “Low-Gain Avalanche Detector” (LGAD) sensors

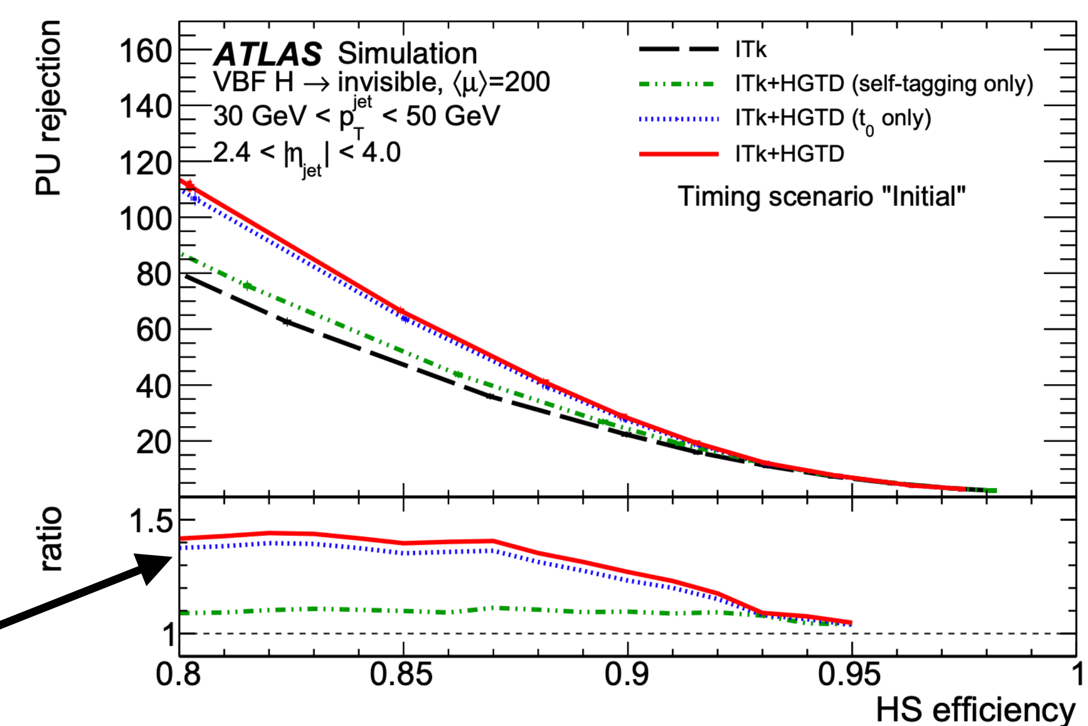
Covers $2.4<|\eta|<4.0$ where tracking resolution is worse (order 1mm, while we expect 1.8 collisions/mm ***on average***)



Located in front of the calorimeters in the forward region



Timing resolution 30 ps (start of run) to 50 ps (end of run)



Improves forward pile-up reject by ~40%

ATLAS-TDR-031

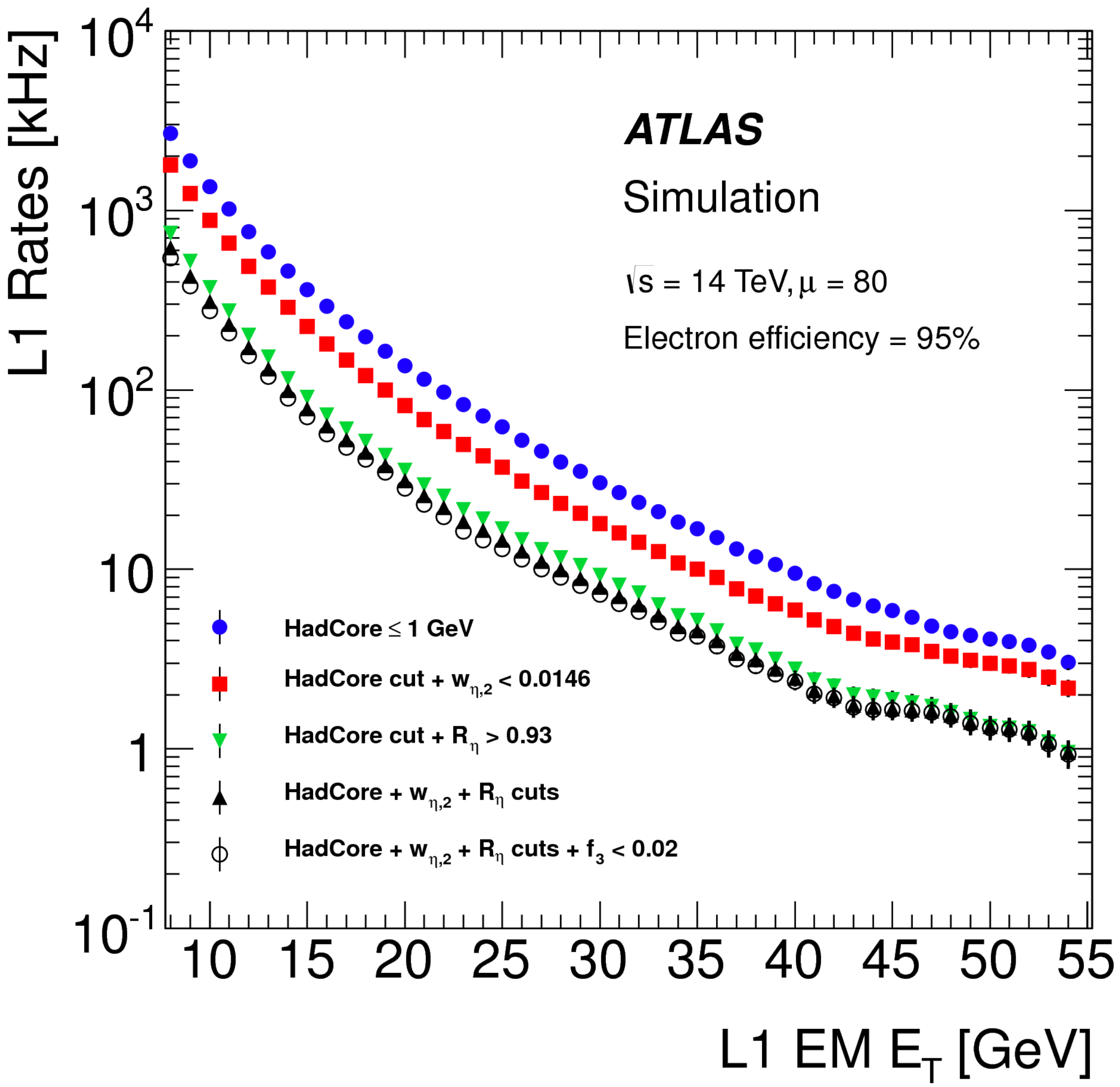
Conclusion

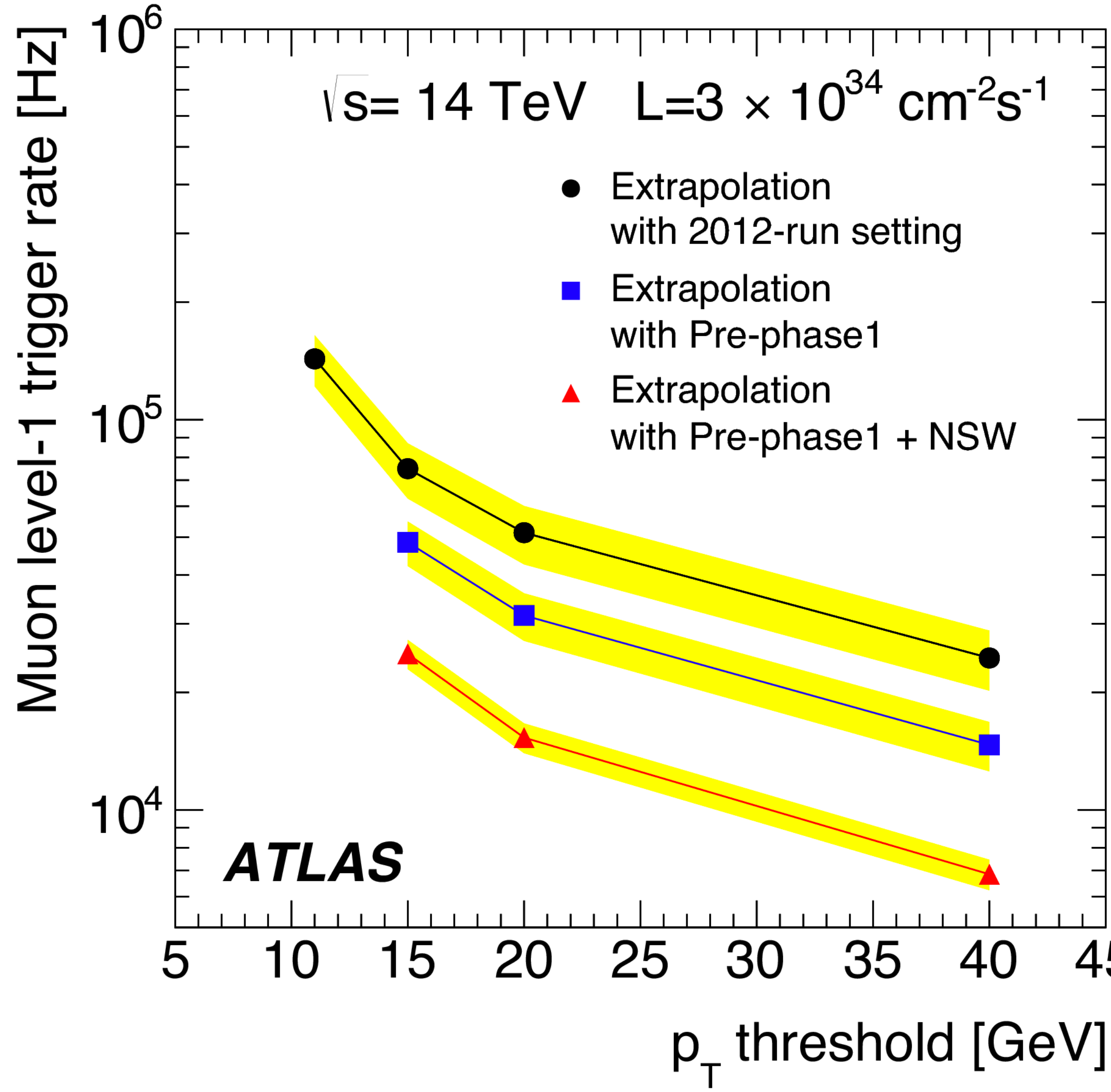
ATLAS is upgrading the detector to maximize physics output from Run 3 and HL-LHC

- Phase-1 for Run 3 is in installation and commissioning focused on triggers
- Phase-2 for HL-LHC is a broad upgrade maximizing tracking performance, trigger acceptance, and robust pile-up rejection
- The following three talks will cover more on the technologies that are designed to achieve these goals and their status.

Backup

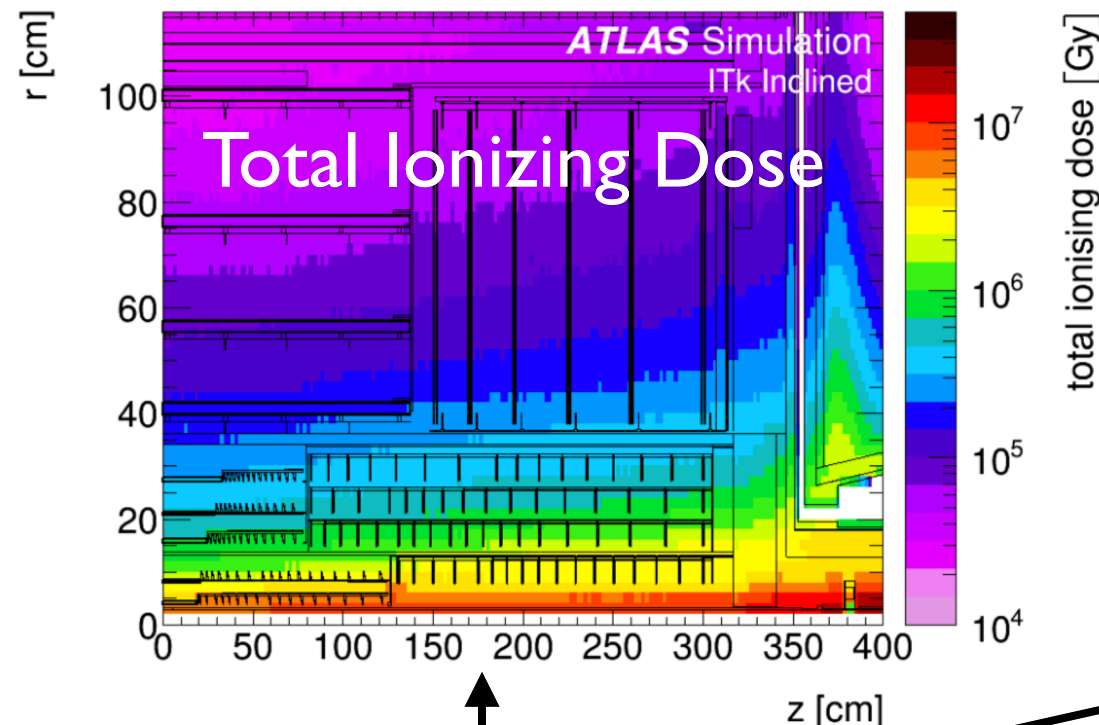
Phase-1 backup: rates

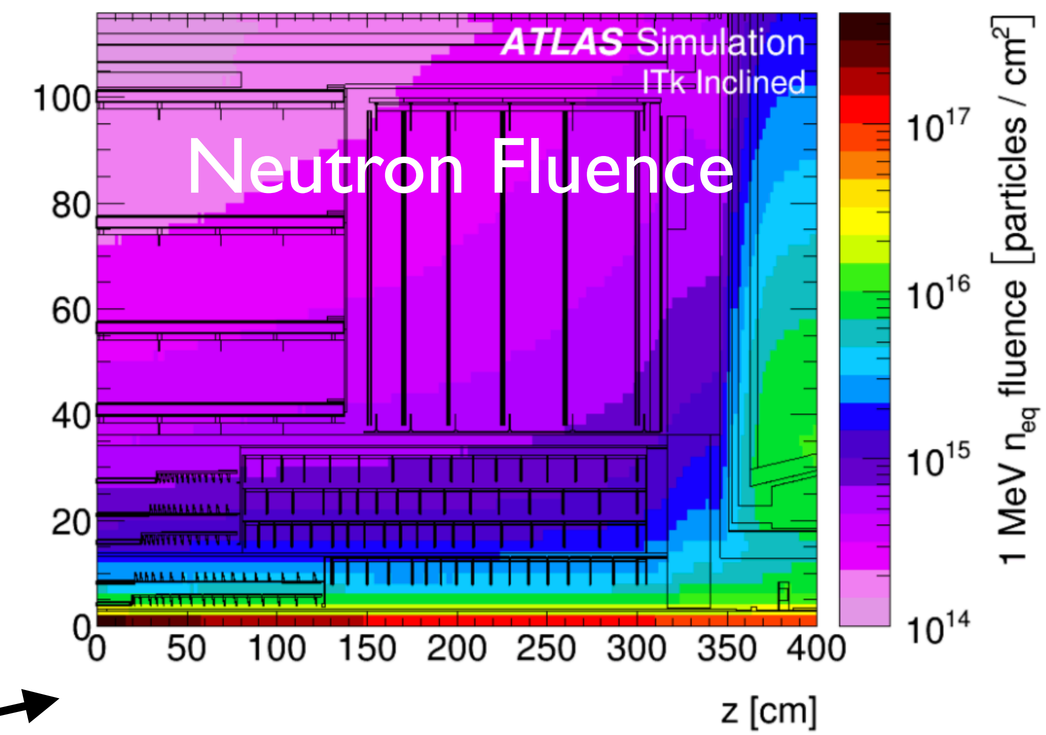




Tracker Upgrade

Radiation Tolerance



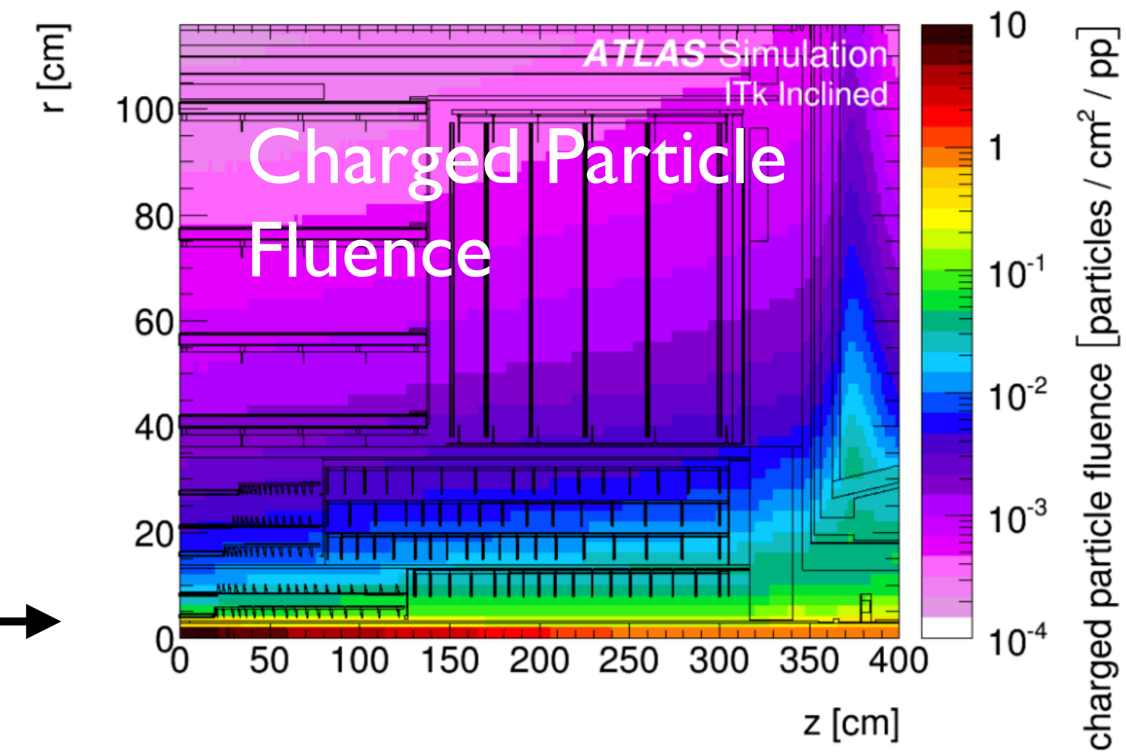


Sensor, electronics and mechanical must survive to 4000 ab^{-1} ~ 10x nominal LHC

Pixels need to survive from 53 to 1300 MRad and 1 to 11×10^{15} neutrons/cm^2 depending on layer

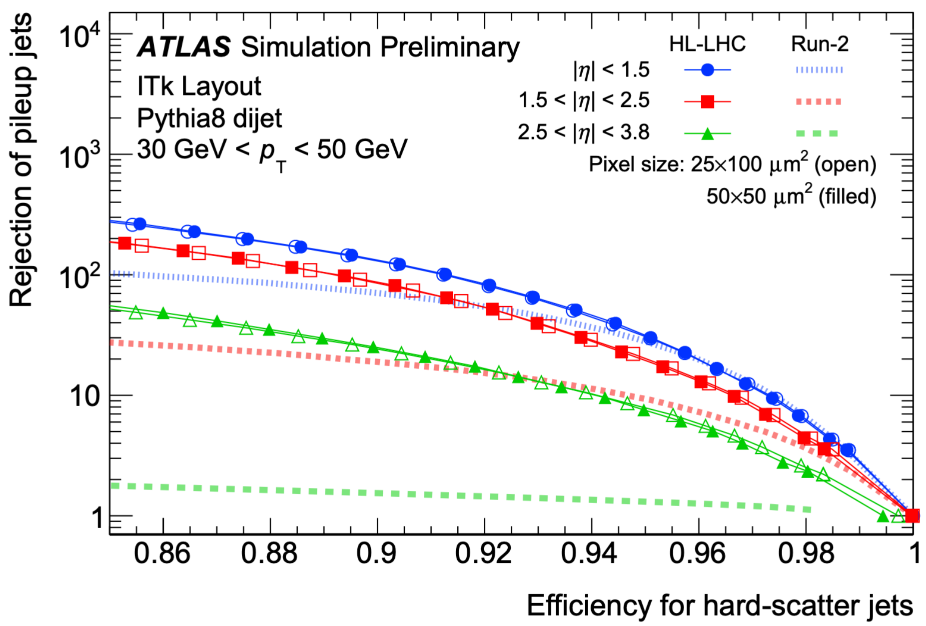
Inner pixels will need to be replaced at 2000 ab^{-1}

Readout rates are also high due to the shear number of charged particles especially for inner pixels



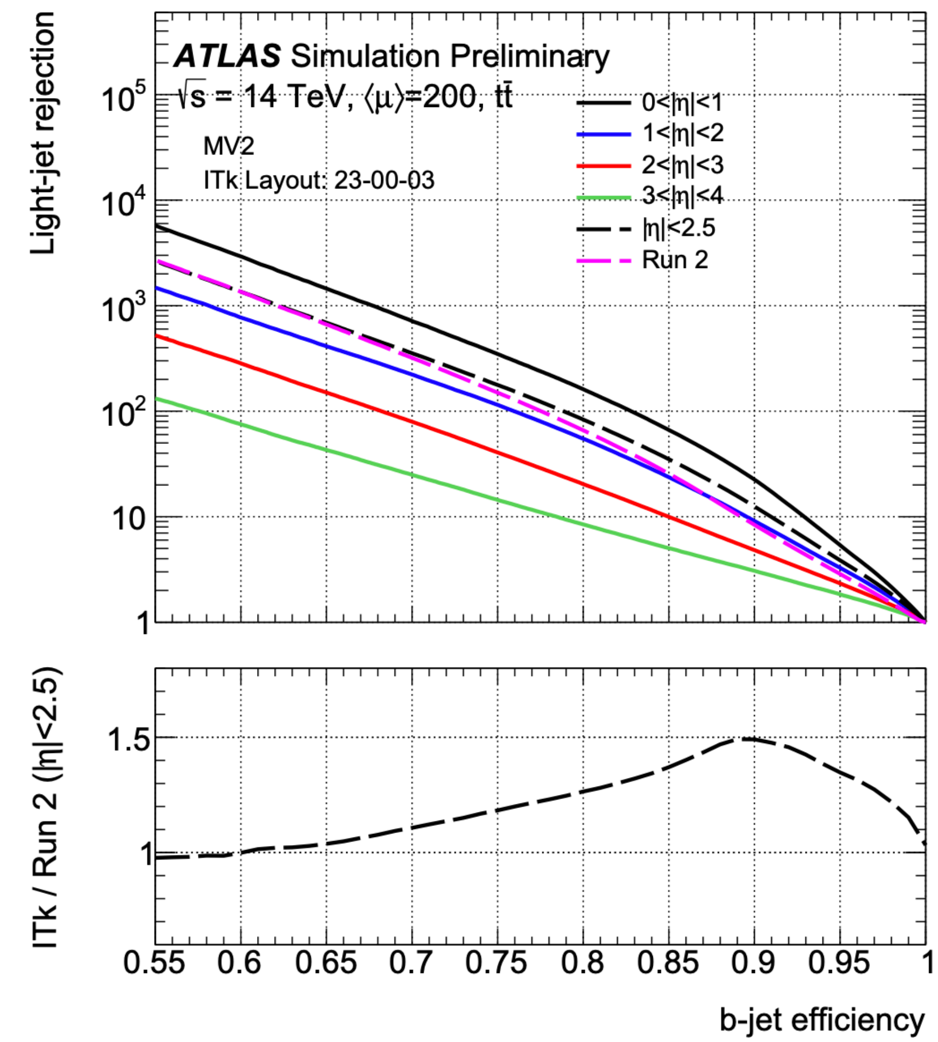
Tracker Upgrade

Tracking Performance

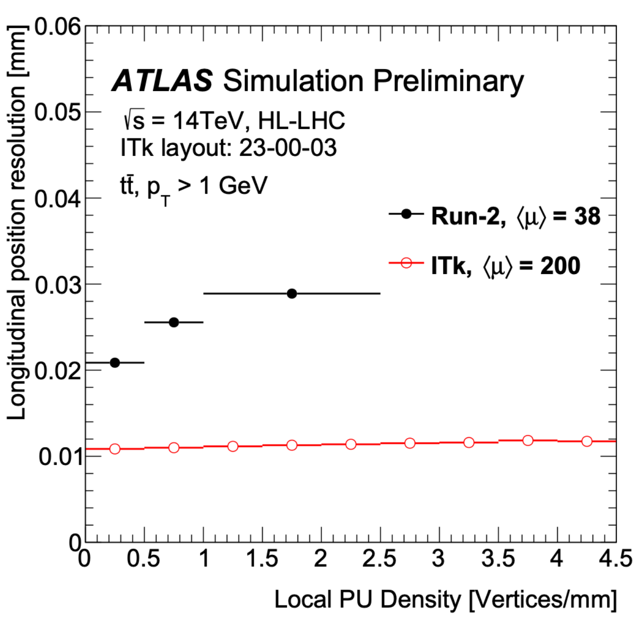


Similar pile-up rejection at low η, better rejection in the forward region

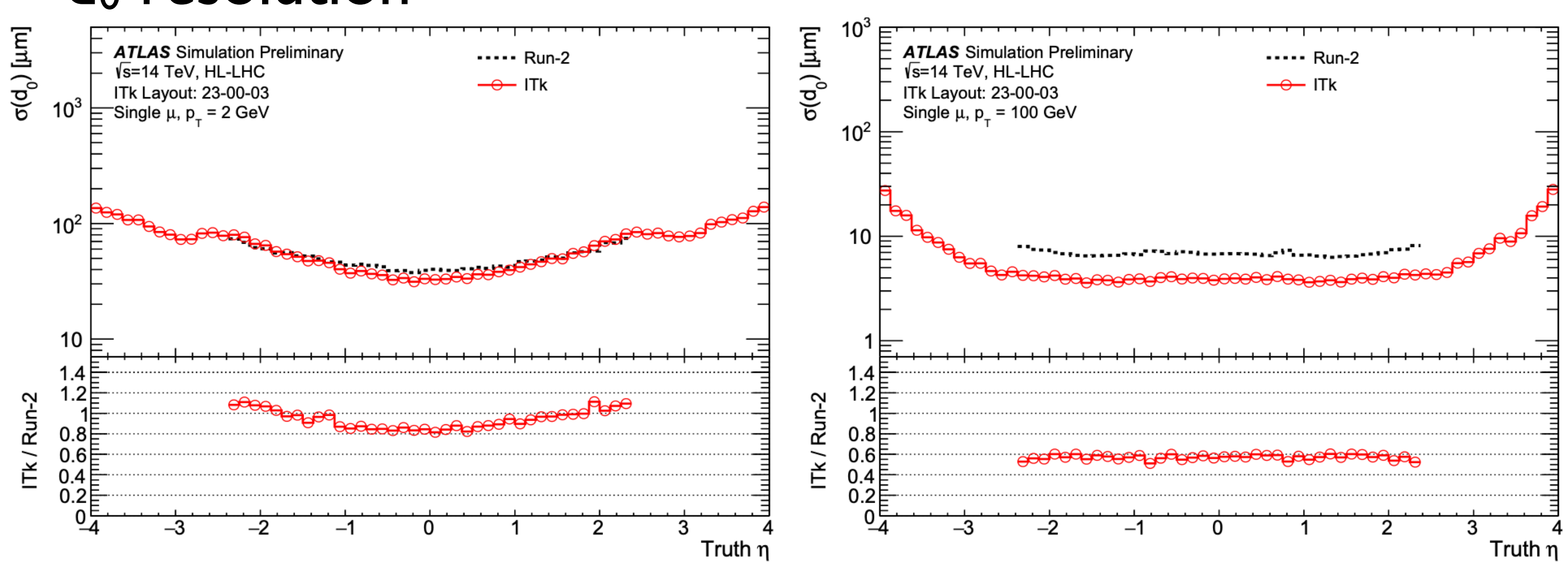
b-jet tagging, better or similar



Improved vertex resolution



d_0 resolution

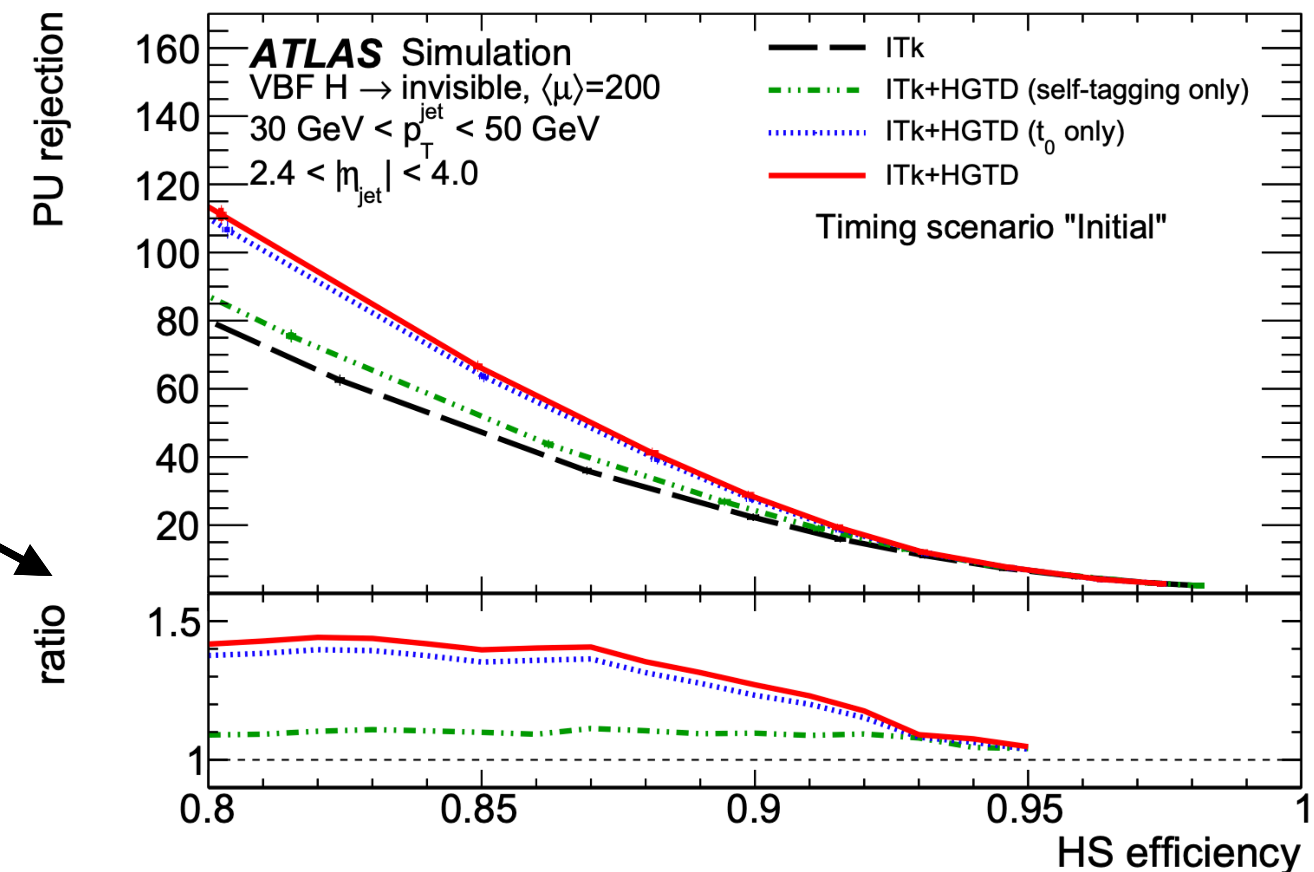


Forward Timing Detector

High Granularity Timing Detector

Timing resolution 30 ps (start of run) to 50 ps (end of run)

Improves forward pile-up reject by ~40%



Improves forward lepton isolation, probable improvements in forward b-tagging, MET, and other possible applications

Example Event