Simulation of Pile-up in the ATLAS Experiment

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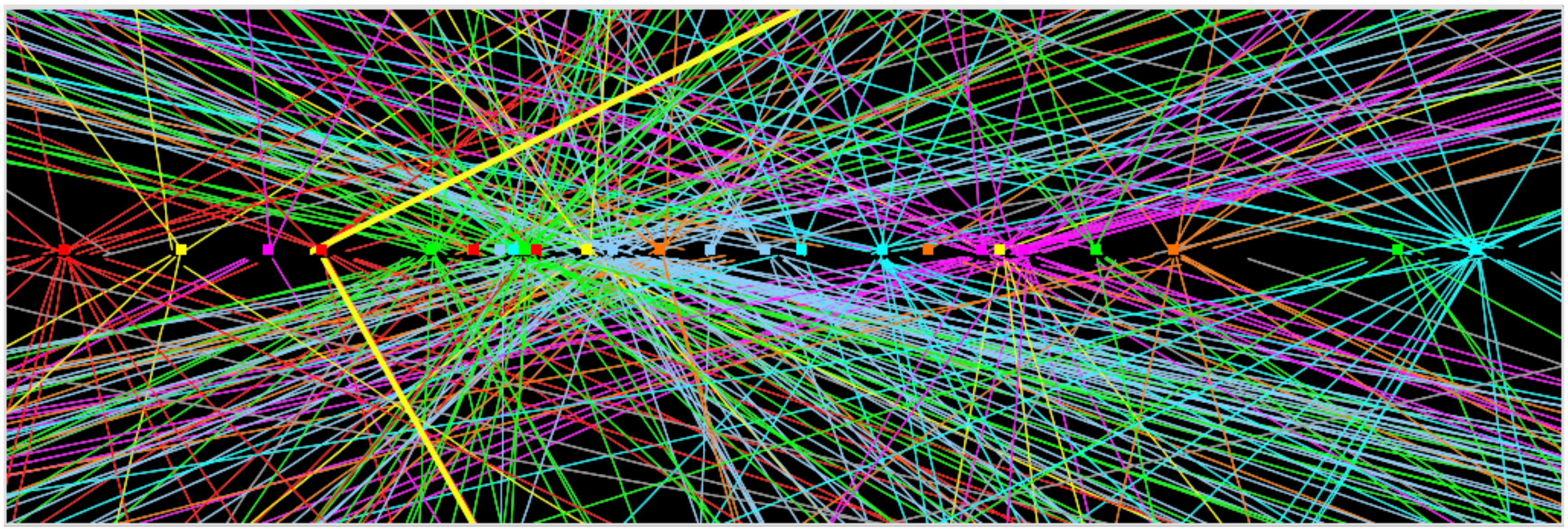
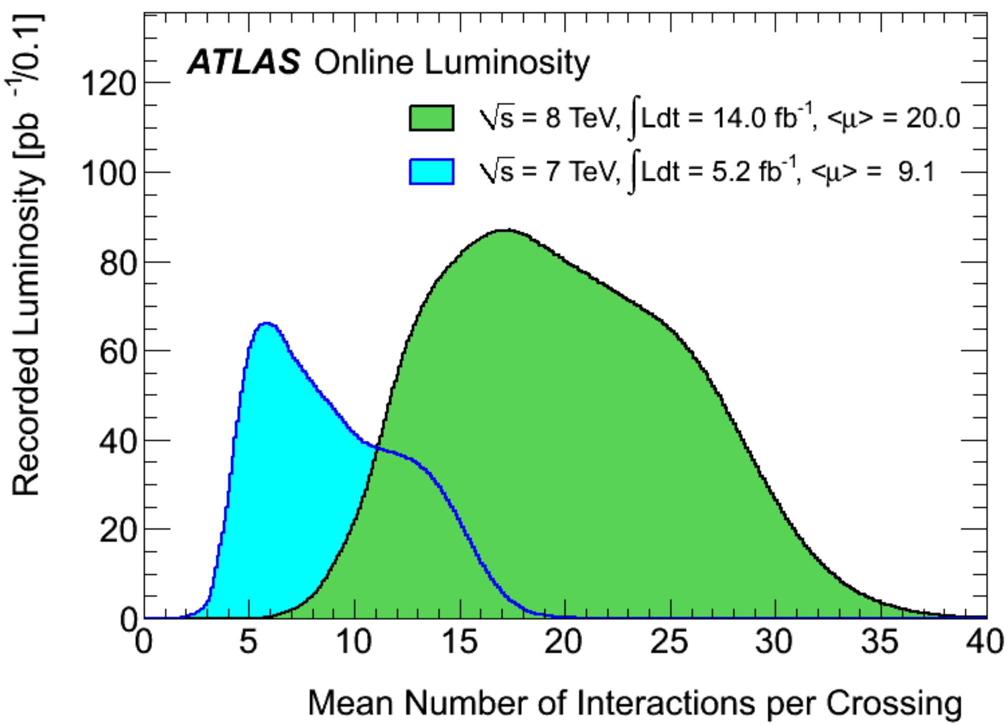
What is Pile-up?

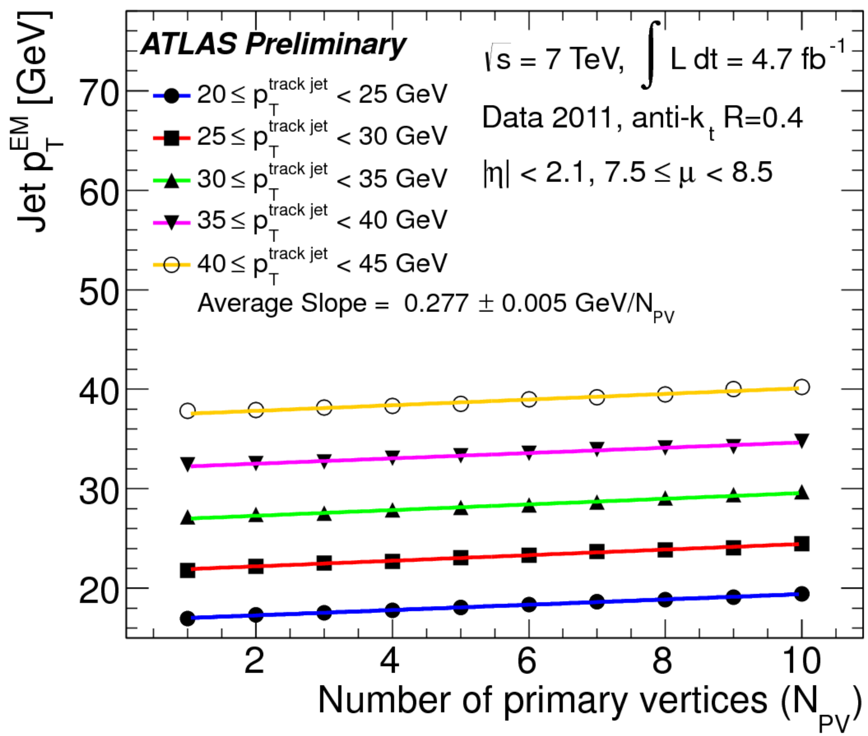
- The LHC luminosity is high enough that we see more than one proton-proton collision every time bunches cross at the detectors.
- These additional proton-proton collisions are what we call *pile-up*.
- There are five components of pile-up that we have to cope with:
  - **In time**, additional proton-proton collisions;
  - **Out of time**, additional proton-proton collisions (our detectors may be sensitive!);
  - **Beam halo** (beam scraping on upstream collimators);
  - **Beam-gas** collisions (interactions with the not-quite-vacuum in the beampipe); and
  - **Cavern background** (neutron and photon gas in the cavern).



How much does it matter?

- During 2011 and 2012 the average number of collisions per bunch crossing (<μ>) increased up to almost 40.
- In the next run we anticipate typical <μ>~40, with peaks up to 80.
- In some upgrade scenarios we could have <μ>~200!
- Every physics object is affected (e.g. jets collect more energy).
  - We *must* be able to model this stuff!





Approaches to Modeling

- In ATLAS we have two approaches:
  - Simulation from first principles, treating each component individually;
  - Modeling using data, aka "Overlay."
- Each has its own advantages and disadvantages…

Simulation

- Can use "future detector" layouts;
- Can extrapolate to very high luminosity;
- Can get some understanding of origins of effects (e.g. what detector regions backgrounds are coming from);
- Relies heavily on MC modeling;
- Lots of work to incorporate changing run and detector conditions in a reasonable way.

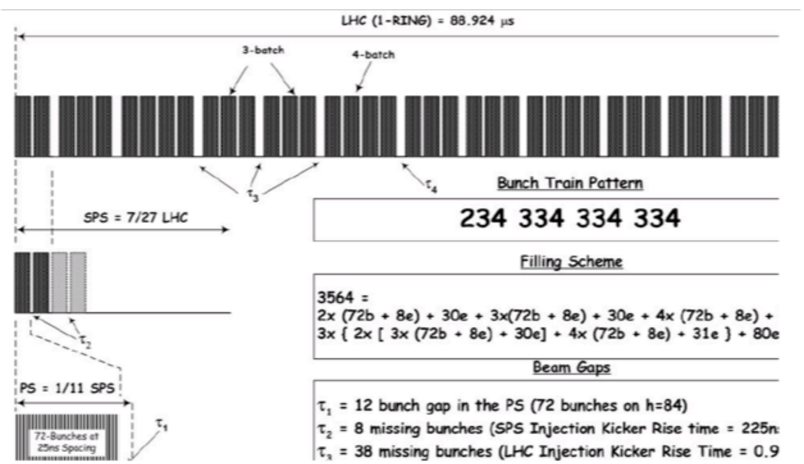
Overlay

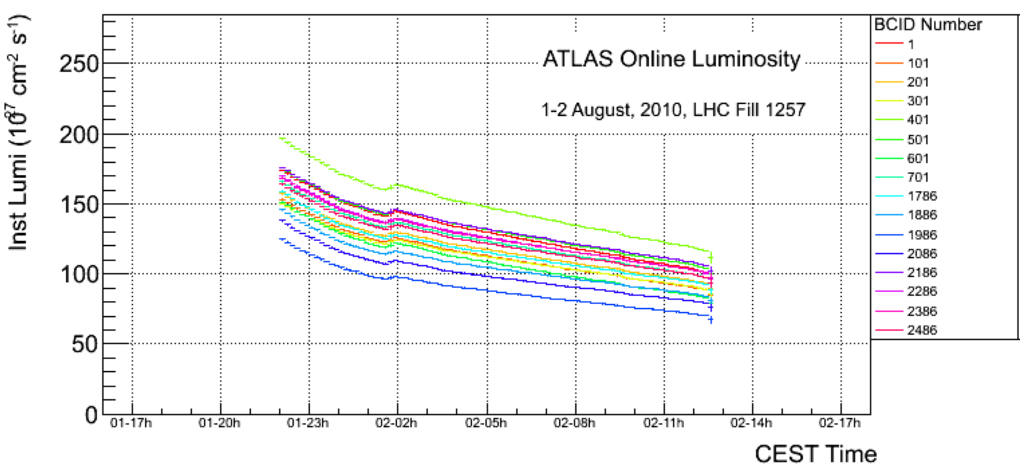
- Perfect modeling of detector, machine, and run conditions;
- No issue with understanding of minbias spectra or the MC modeling of difficult physics;
- Perfect modeling of detector effects
- Need to match data and MC (signal) conditions to get the signal right;
- Can't use future layouts / conditions easily (some exceptions to this).

Right now simulation is the *main line* used by ATLAS, but we keep overlay for certain applications, in particular Heavy Ion MC

In-Time Pileup

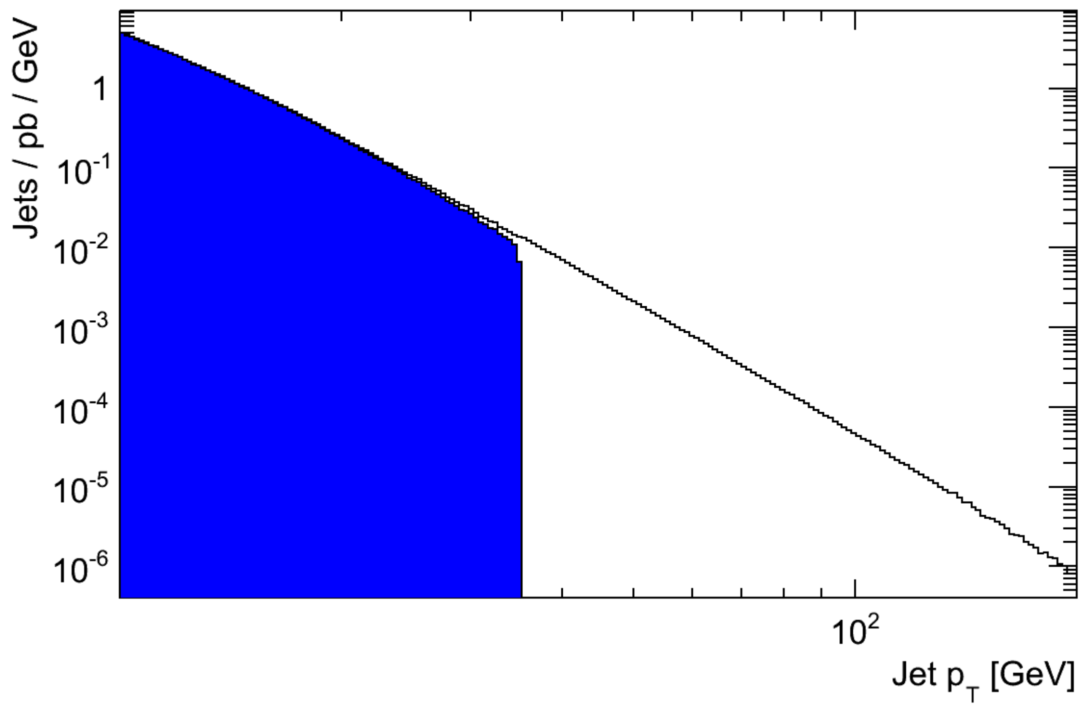
- Minimum bias events generated with Pythia(8)
  - Includes all inelastic possibilities (non-, single-, and double-diffractive)
- Simulated using “regular” setup
  - Some information is trimmed out to save disk space, e.g. true particle history
  - Some extra information is kept to replace the loss, e.g. true particle jets
- Overlaid at a rate to match that recorded on the detector
  - Including variations by data taking period
  - Including bunch structure in the machine (long and short gaps)
- New possibilities for including bunch-by-bunch variation in beam charge
  - In data seen as differences in the leading bunch(es) (right bottom)





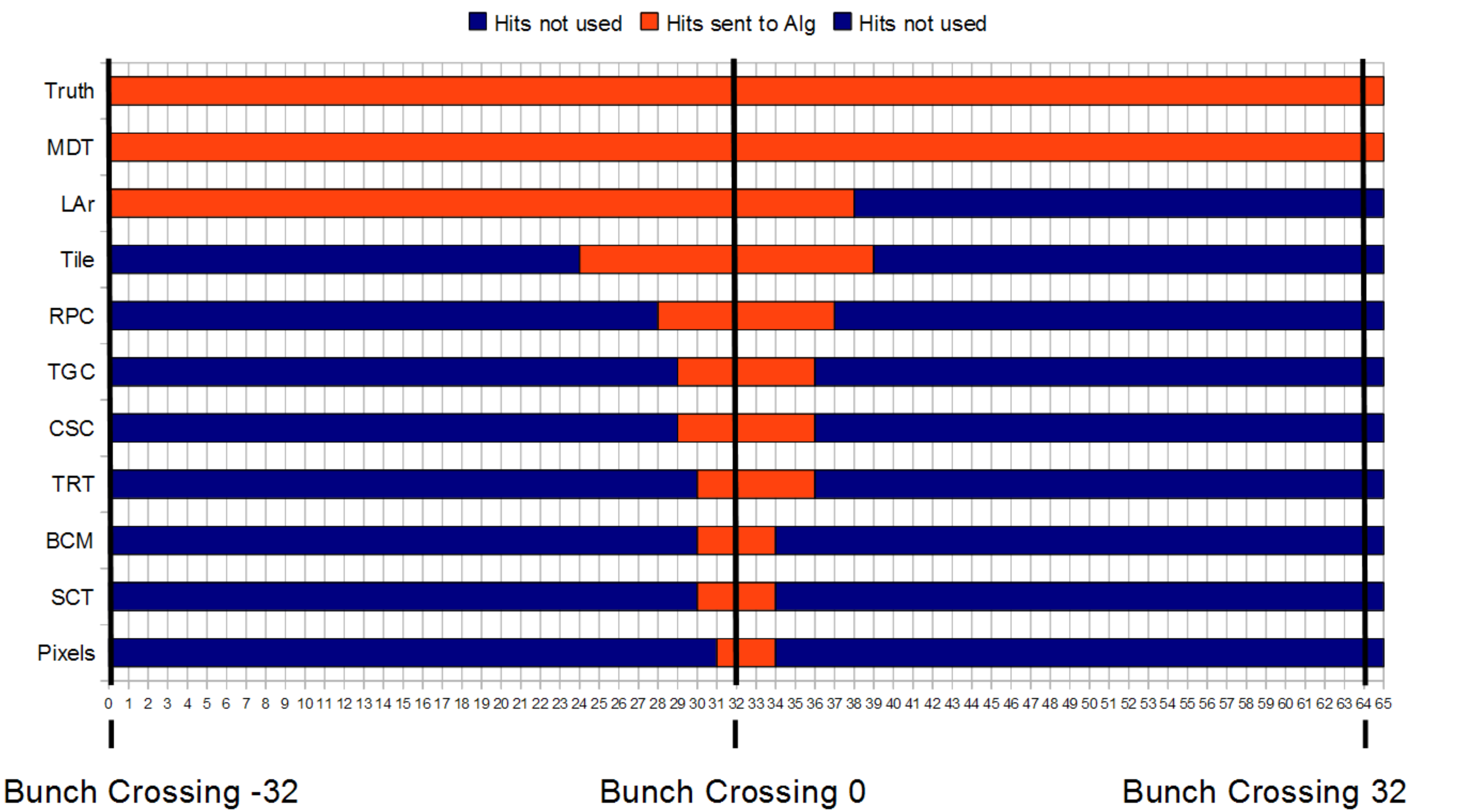
Mitigating Spikes

- Of course, it's almost impossible to simulate unique mininum bias events for each simulated sample
  - 50M event signal sample would need ~64B minimum bias events!!
- Split the sample into events with and without a high-p_T jet (p_T>35 GeV)
- By rule, never put the same event with a high-p_T jet down twice in the same dataset (or try very hard to avoid it)
- Reduces rate of spikes in MC from over-sampling of some high-p_T jets
- Can re-use low-p_T jet sample at will, saving disk space
- Only problem is that the rates vary with beam energy, so at 14 TeV this picture will have to change somewhat…



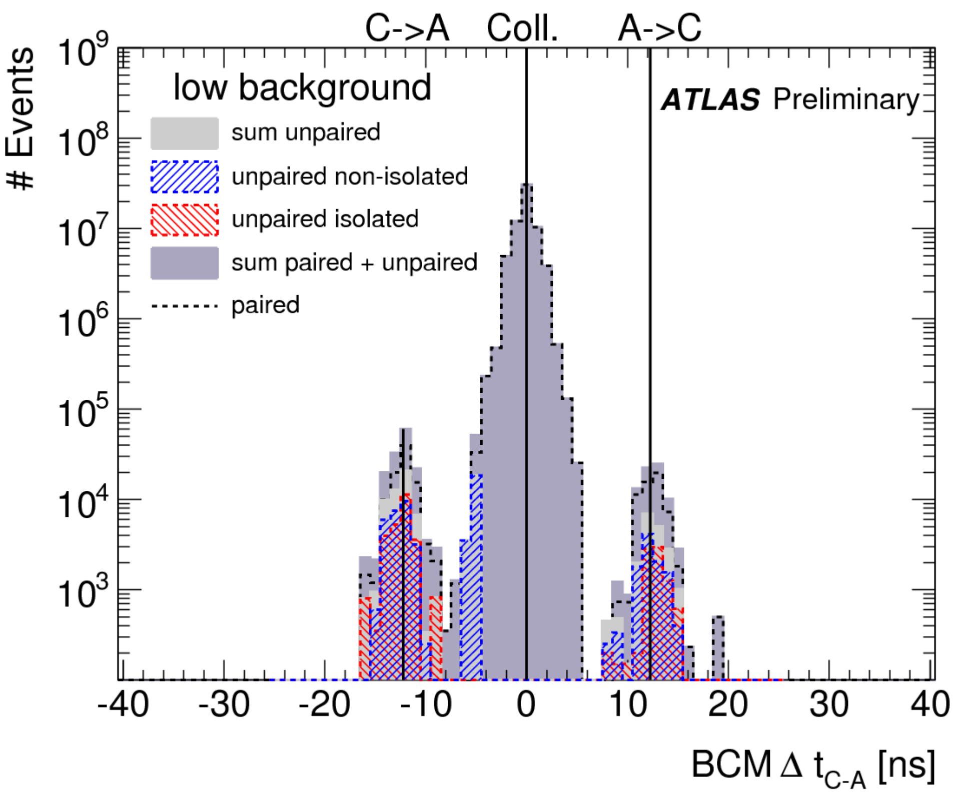
Out of Time Pileup

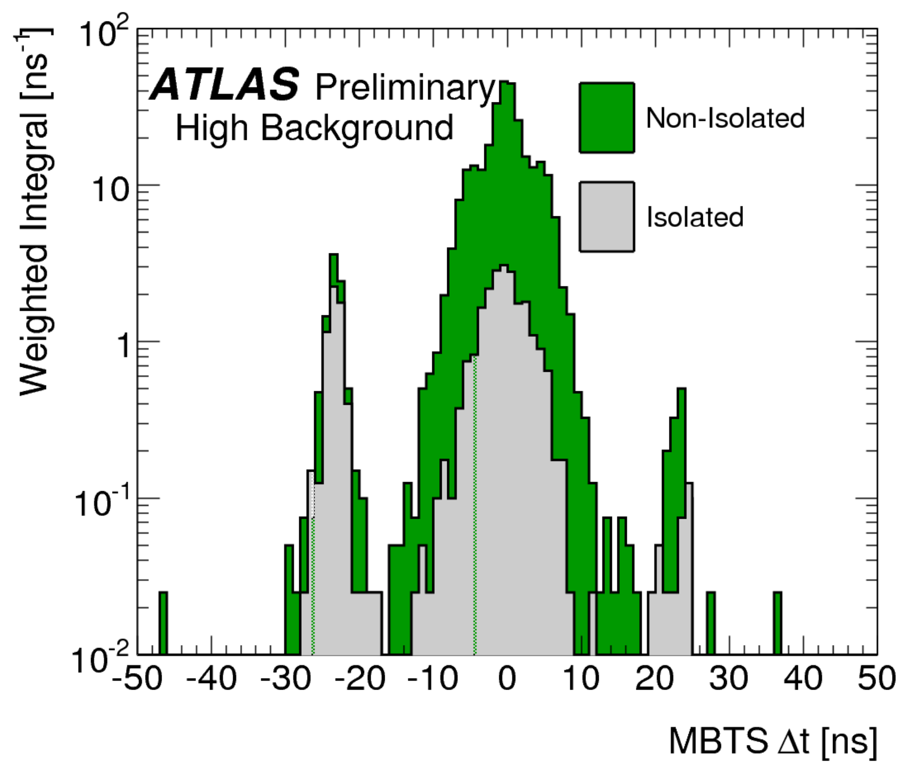
- Different detectors sensitive to different time windows
- Cutting this down in simulation is critical for performance gains!
  - But including it is critical to get shadowing, saturation, and pulse effects right!



Beam Gas

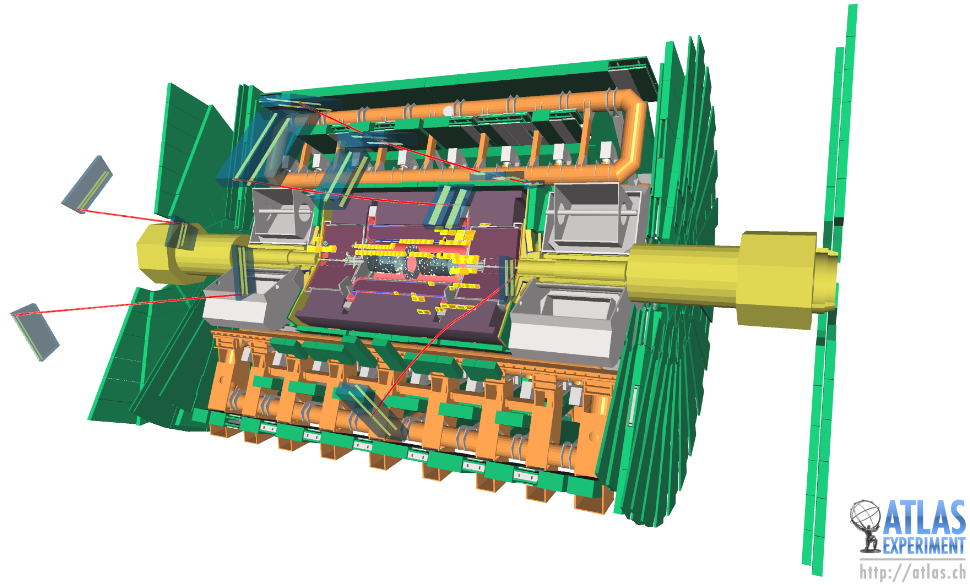
- Occasional proton-C/N/O interactions off-center in the beampipe
- Generally these come out of time and can be removed in analyses
- We have the ability to generate and simulate these, but we do not
  - Asymmetric generation (moving proton on stationary gas) and time offset are a bit tricky, but analyses cut them out and they're usually low rate

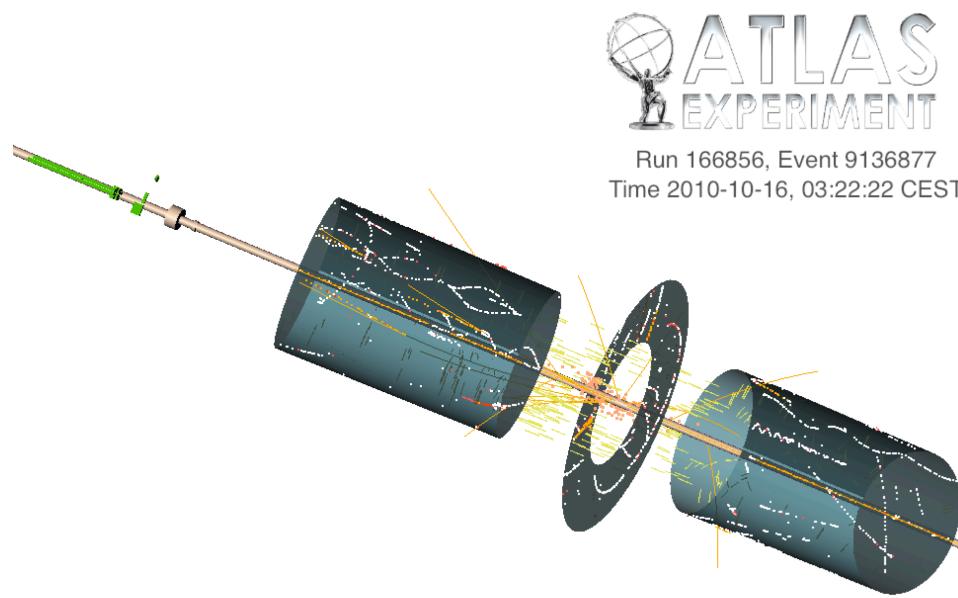




Beam Halo

- Consists of particles from scraping on upstream collimators
- Requires dedicated modeling of upstream region magnets, field, collimators, etc
  - Not really our area in ATLAS!
  - LHC team provides particle four-vectors at interface between ATLAS and machine
- We *can* overlay events like this, but they are "low" rate and are cleaned out of analyses, so we normally *don't*
  - Even worst case, order Hz compared to MHz of collisions

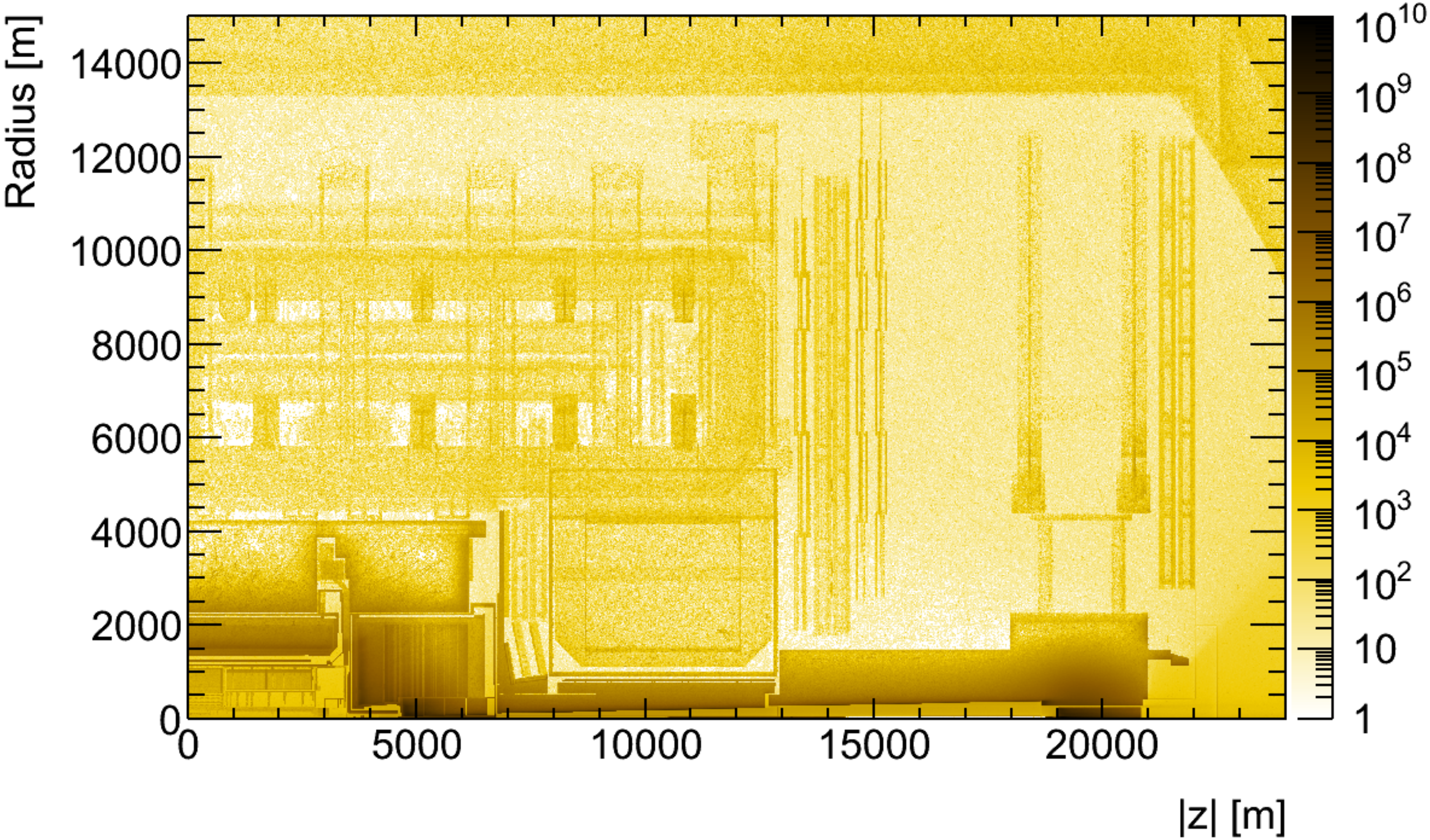




Cavern Background

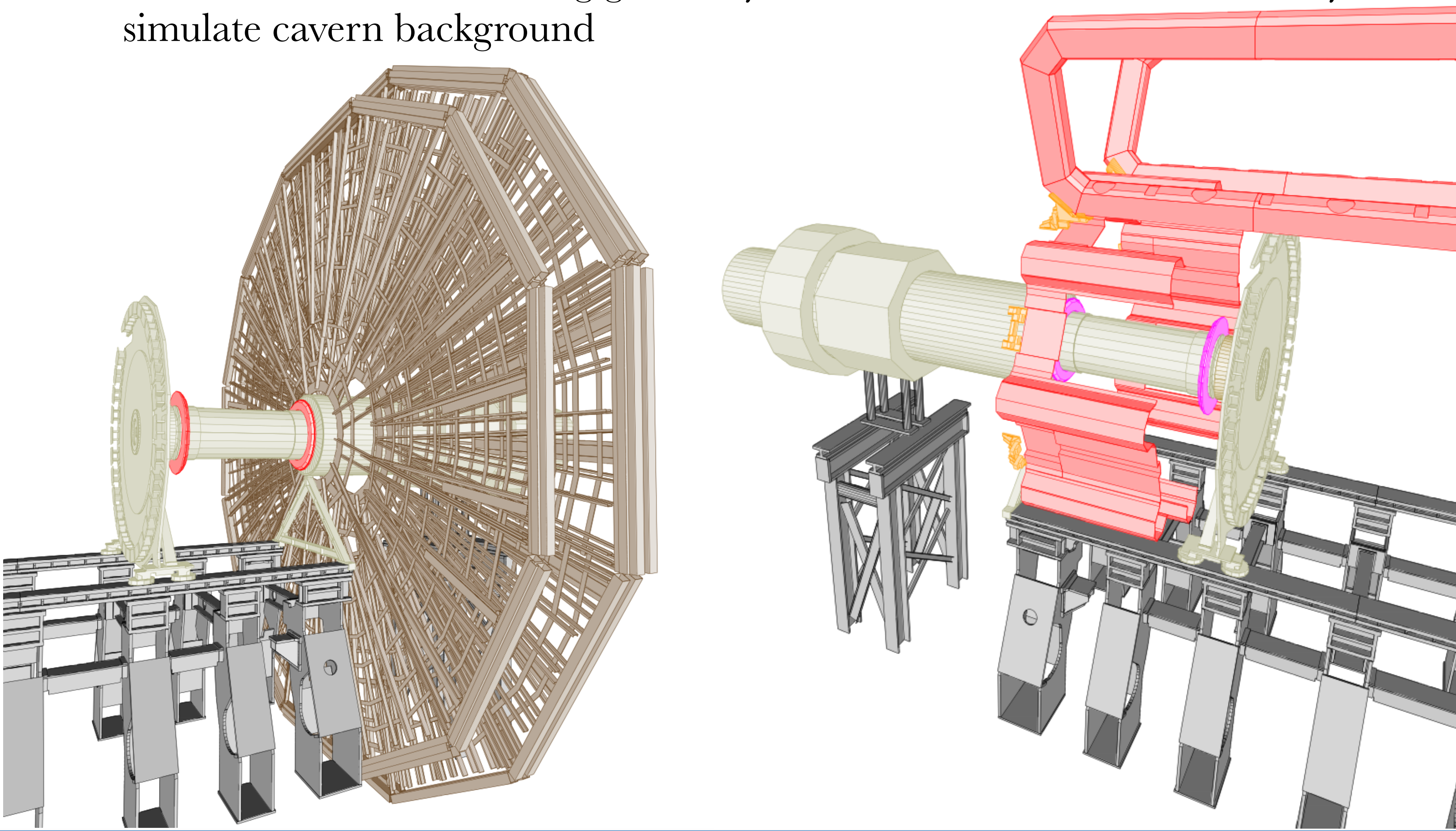
- Two methods for cavern background simulation
- Both start from generated minimum bias interactions
- "Main" detector simulation takes one of two paths
  - Simulation with FLUKA, recording particle fluxes in scoring volumes around the muon system chambers
  - Simulation with Geant4, recording neutrons as "cavern background"
  - Fluxes in quite good agreement!
- A similar second step of simulation is run
  - From the fluxes (for FLUKA) or from the neutrons (Geant4) to energy deposits in the muon system chambers
  - Some "time wrapping" to make the simulation of 2s of flux "easy"
- Standard signal digitization to emulate detector response
  - Requires special tuning, as the digitization is often written assuming signal particles (muons), and background and signal don't look alike
- Requires many features that standard simulation is insensitive to
  - Concrete cavern wall, shielding, cladding of shielding, far forward region
- Many tools along the way for benchmarking and cross-checking

Cavern Background Detector X-Rays



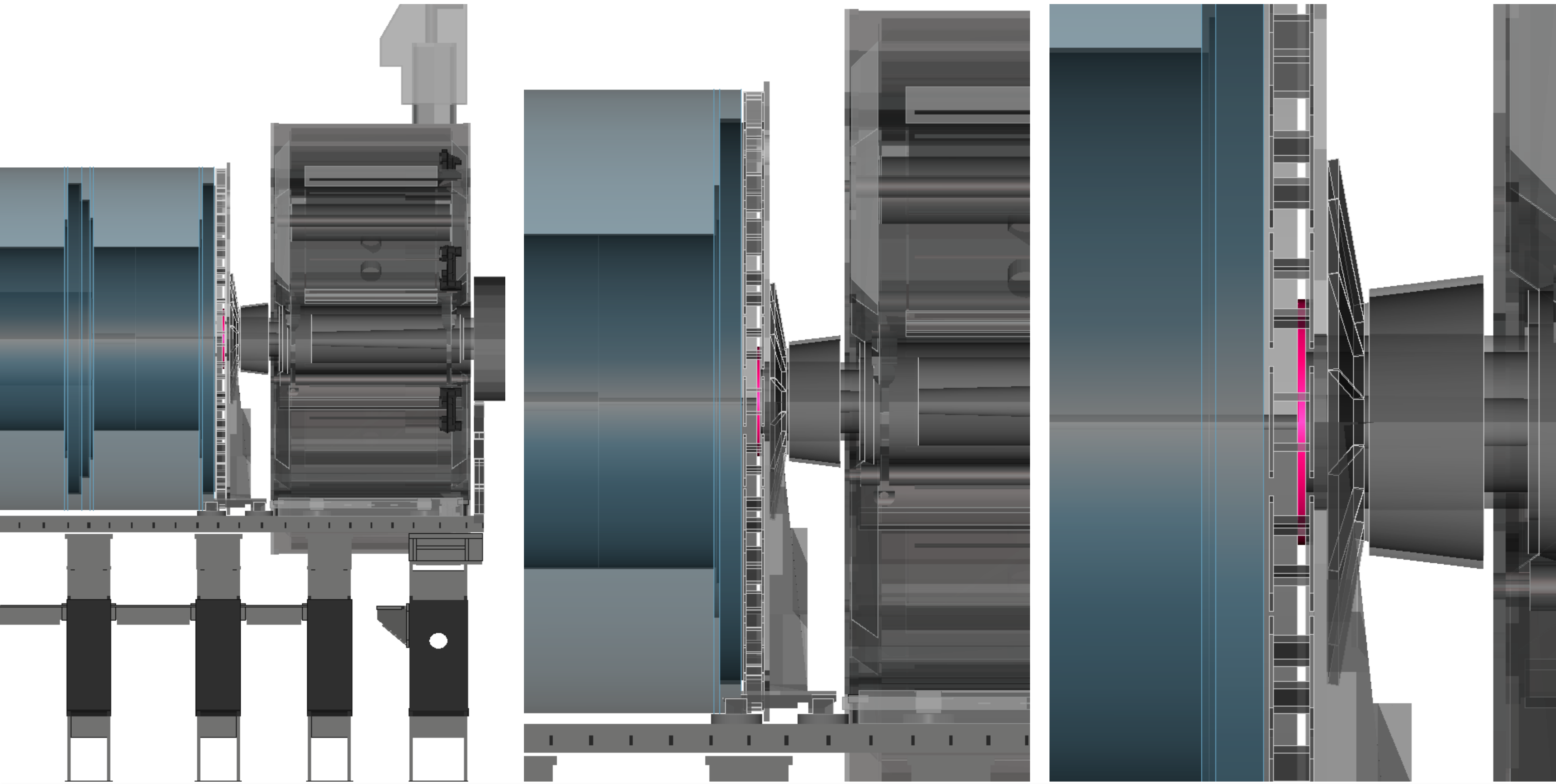
Cavern Background for Shielding

- Cavern simulation detailed enough to feed back to detector design
- Detailed review of shielding geometry and materials in order to correctly simulate cavern background



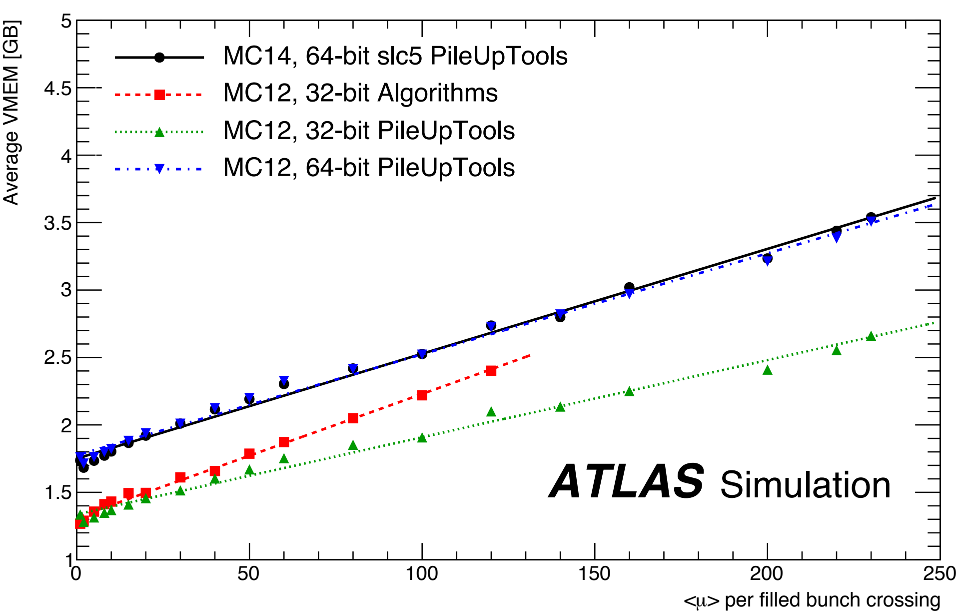
Cavern Background for Shielding

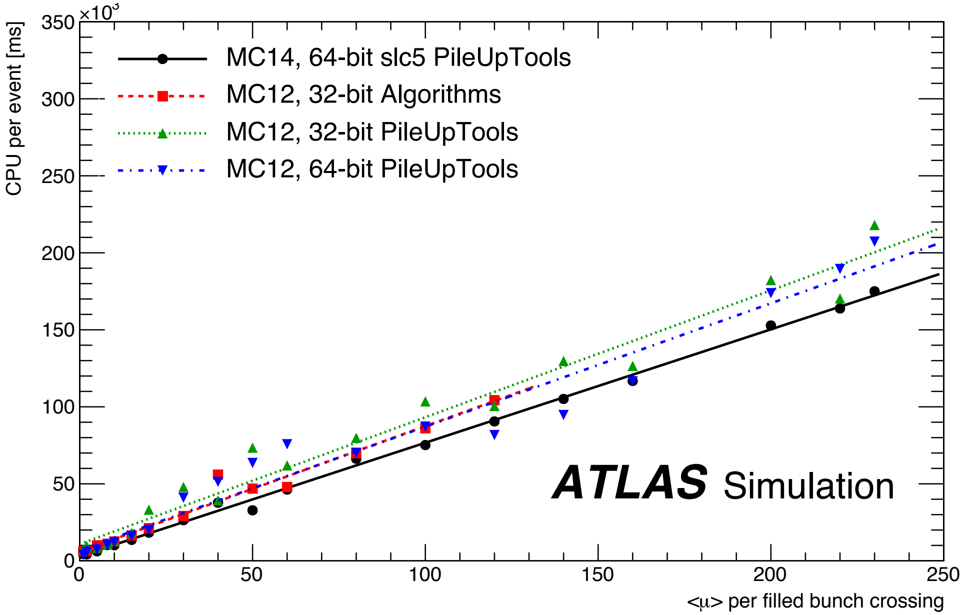
- Cavern simulation detailed enough to feed back to detector design
- New pieces of shielding introduced in 2012 and 2015 largely as a result of studies of cavern background simulation!



Computing Performance

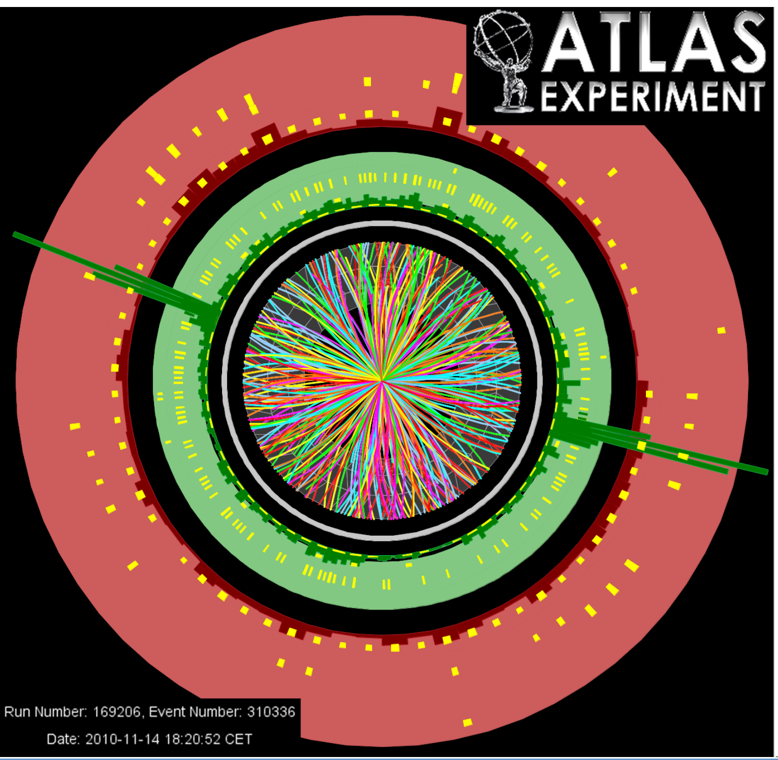
- Obvious trade-off between CPU and memory
  - For high luminosity, we spend the CPU on I/O to avoid serious memory limitations ("Algorithms" → "PileUpTools")
  - For low luminosity it's possible to pay with some memory and save some CPU (32-bit → 64-bit, slc5 → slc6)
  - Memory shows much more regular growth; normal non-linear effects on CPU like changing from active memory to swap

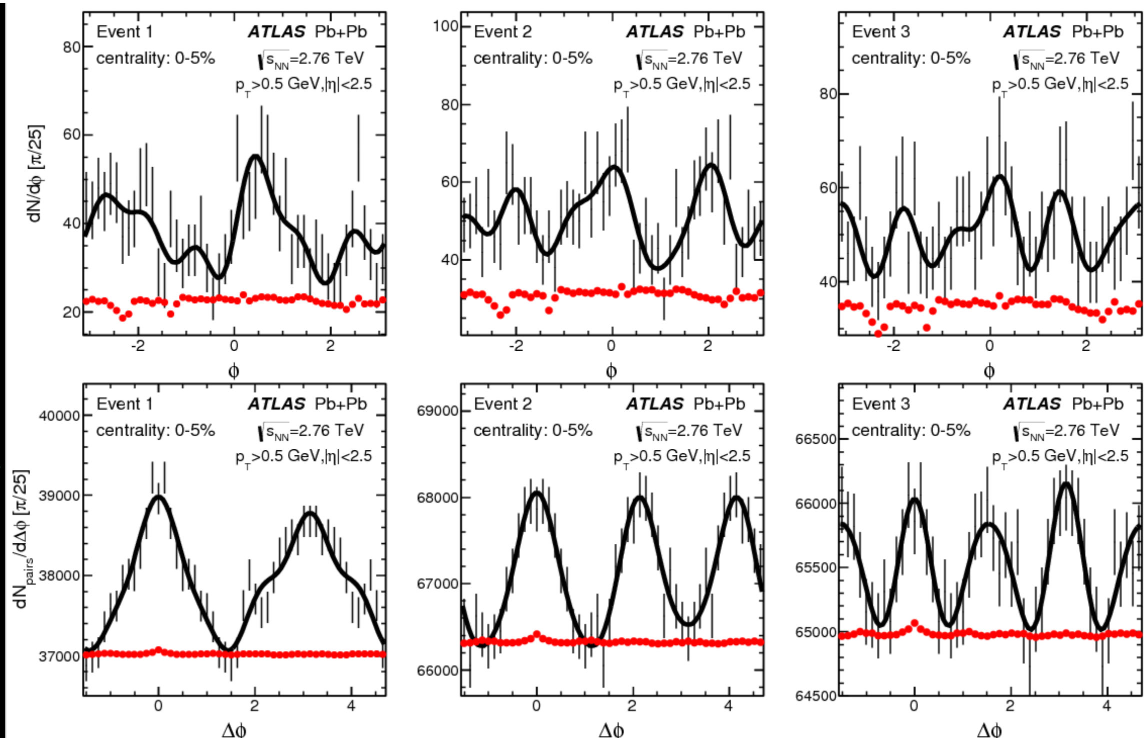




Overlay

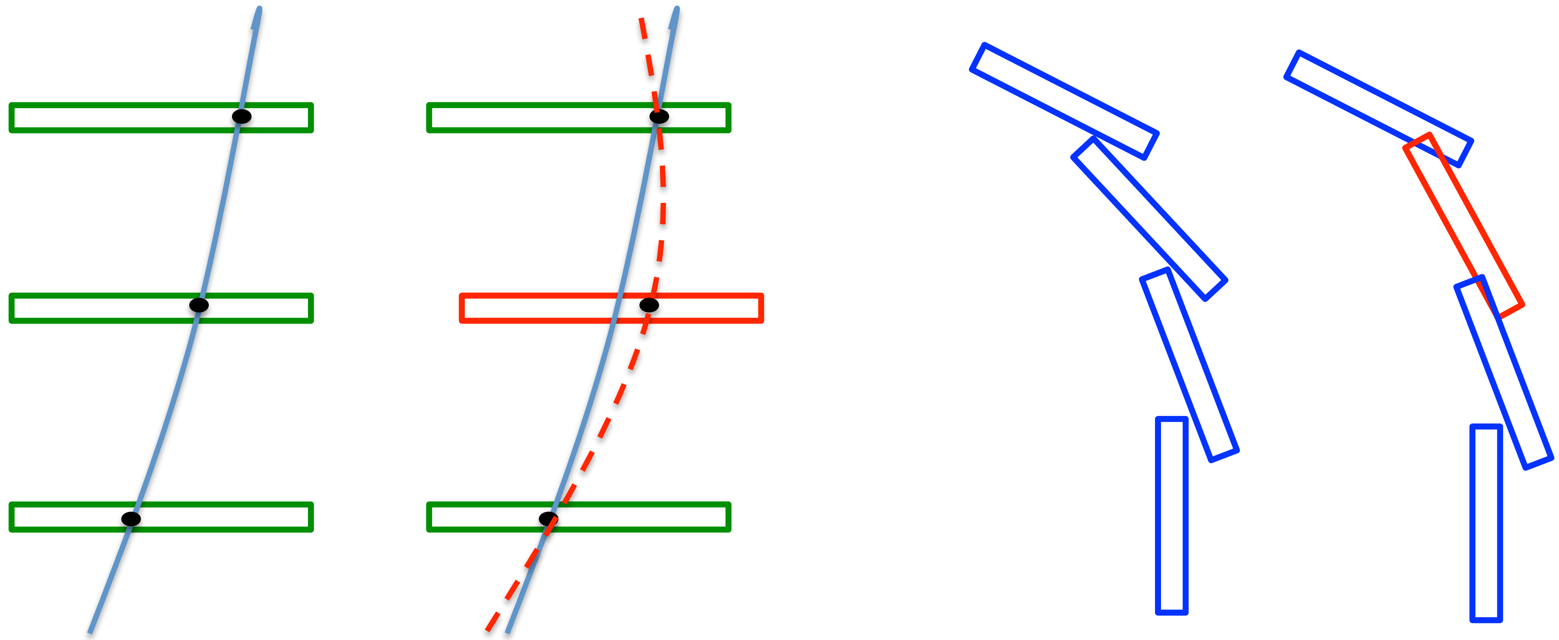
- Data collected via special "zero bias" triggers
- Have to be careful with detector read-out zero suppression!
- Used heavily in heavy ion studies, where the many-charged-particle background and high-rate flows are very difficult to get right
  - Can add a *simulated* Z or di-jet event on top of *data* collision background
  - Quite complicated correlations (right) come for free!





Overlay

- Changing the alignment of either the data or the simulation for the reconstruction (so that they can be reconstructed with the same conditions) can cause major problems in tracking because of changes in track sagitta
- Using the data alignment during simulation can cause overlaps in volumes, creating the potential for crashes, missed hits, or other problems in the simulated events
- Must solve one of these two problems. ATLAS prefers the one on the right.



…And the Future

- ATLAS is now moving to an integrated simulation framework
  - See talk by Chiara Debenedetti
- Very fast simulation needs a new approach to pile-up
  - Generate-and-simulate on-the-fly?
  - Approximate using only in time pile-up?
  - Approximate using some parameterizations?
- At the same time, the LHC is moving to upgrades
  - Into higher pile-up than we've ever dealt with – μ of 200 is not impossible in some of these upgrade scenarios
  - Will need to continue to tweak and improve algorithms in order to maintain the current event rate
  - Parallel approaches might help here by sharing a common background event cache, but many difficult associated issue have to be ironed out
- Of course, Overlay does not have major performance problems with high μ , but it cannot "simulate the future" well

Summary

- ATLAS has developed two methods for simulating the effect of pile-up
- One bottom-up approach (simulation by component)
  - Allows the study of future detector layouts, future machine scenarios, and the detailed origins of backgrounds
- One top-down approach ("overlay")
  - Automatically gets many things right (geometry, alignment, particle distributions and kinematics, data conditions)
- Having both methods ensures that we're fully prepared for the 2015 high-energy run and future upgrade scenarios
- Computing performance will have to continue to develop in order to cope with the evolving machine conditions