ATLAS Pileup and Overlay Simulation

Andy Haas (NYU) on behalf of the ATLAS Collaboration

LHC Detector Simulations, CERN
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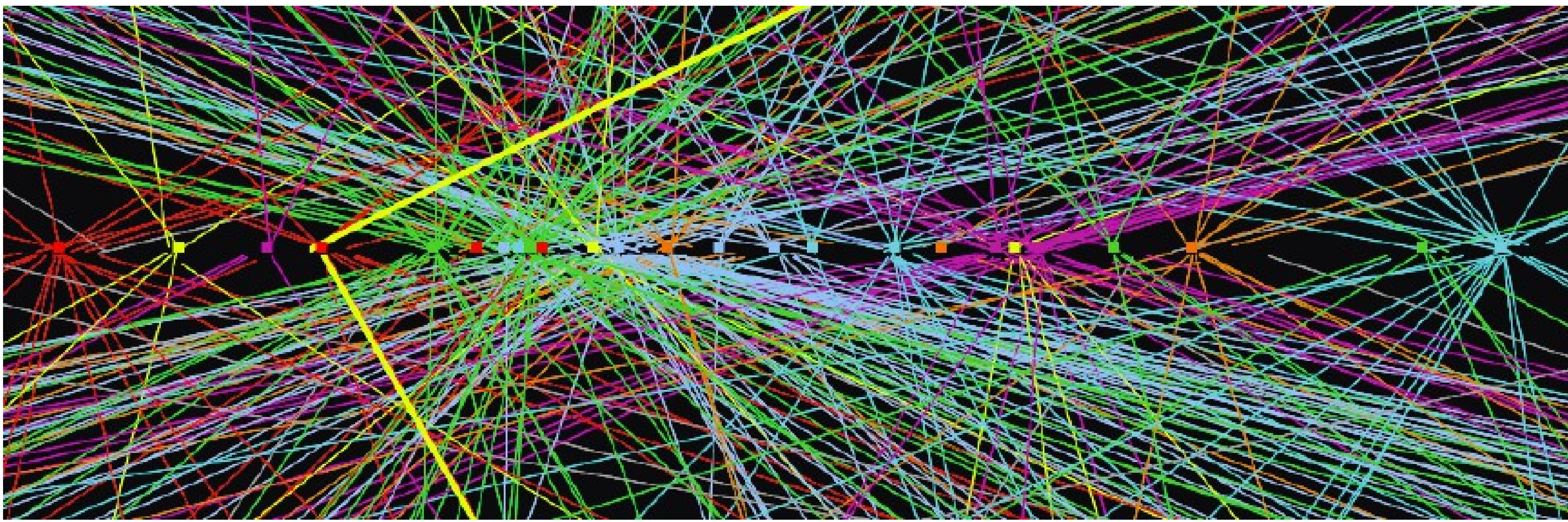

https://indico.cern.ch/event/279530/

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Introduction

- In addition to hard interaction:
  - Pileup from other collisions in current and surrounding bunch crossings
  - Cosmics, Beam-gas, Beam-halo, Cavern background, Detector noise, ...

Option 1: **"Pileup MC" (current default)** **Simulate all processes in MC* and mix together in proper ratios with realistic timing**	**Option 2:** **"Overlay"** **Simulate only hard interaction in MC and overlay a "random" data event to include all backgrounds****

- Overlay method used by BaBar, D0, ...
- Pileup MC method mostly used so far at ATLAS
  - Overlay being used for some studies, specialized analyses, and Heavy-Ion

*Cosmics, beam-gas, beam-halo are small $\rightarrow$ not currently included in pileup MC

**Statistics of rare background events such as beam-halo will be very poor.
Must trigger on a signature of the *signal* MC event to accurately model background rates.

Option 1: Simulating Pileup

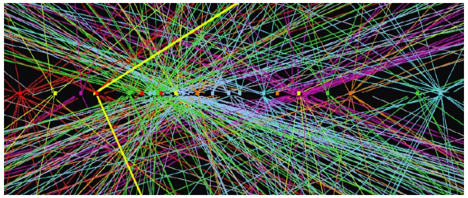
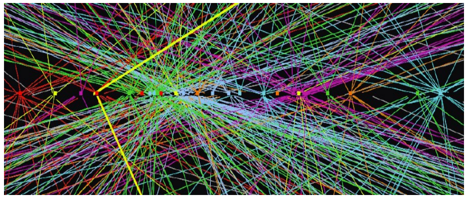
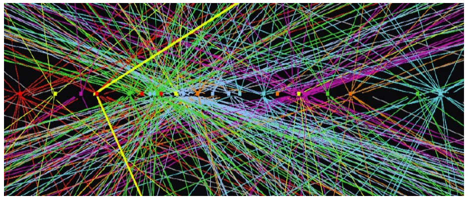
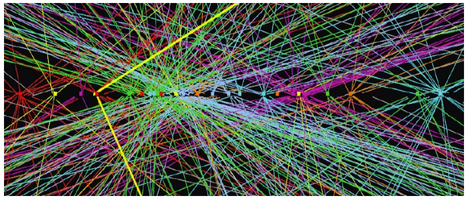
(1) Run the event generation for “minbias” for single pp interactions
→ Pythia8, A2 tune, MSTW2008LO PDFs
→ Inelastic (non-diffractive) and single/double diffractive

(2) Run GEANT4 on each minbias event to simulate detector energy/time “HITS”

(3) Combine multiple (thousands!) of HITS events during digitization
→ Use representative #interactions per bunch crossing, shifted in time, to reproduce in-time and out-of-time pileup
→ Sample bunch spacing/pattern within the sensitive time window of ATLAS detectors [-800,800] ns

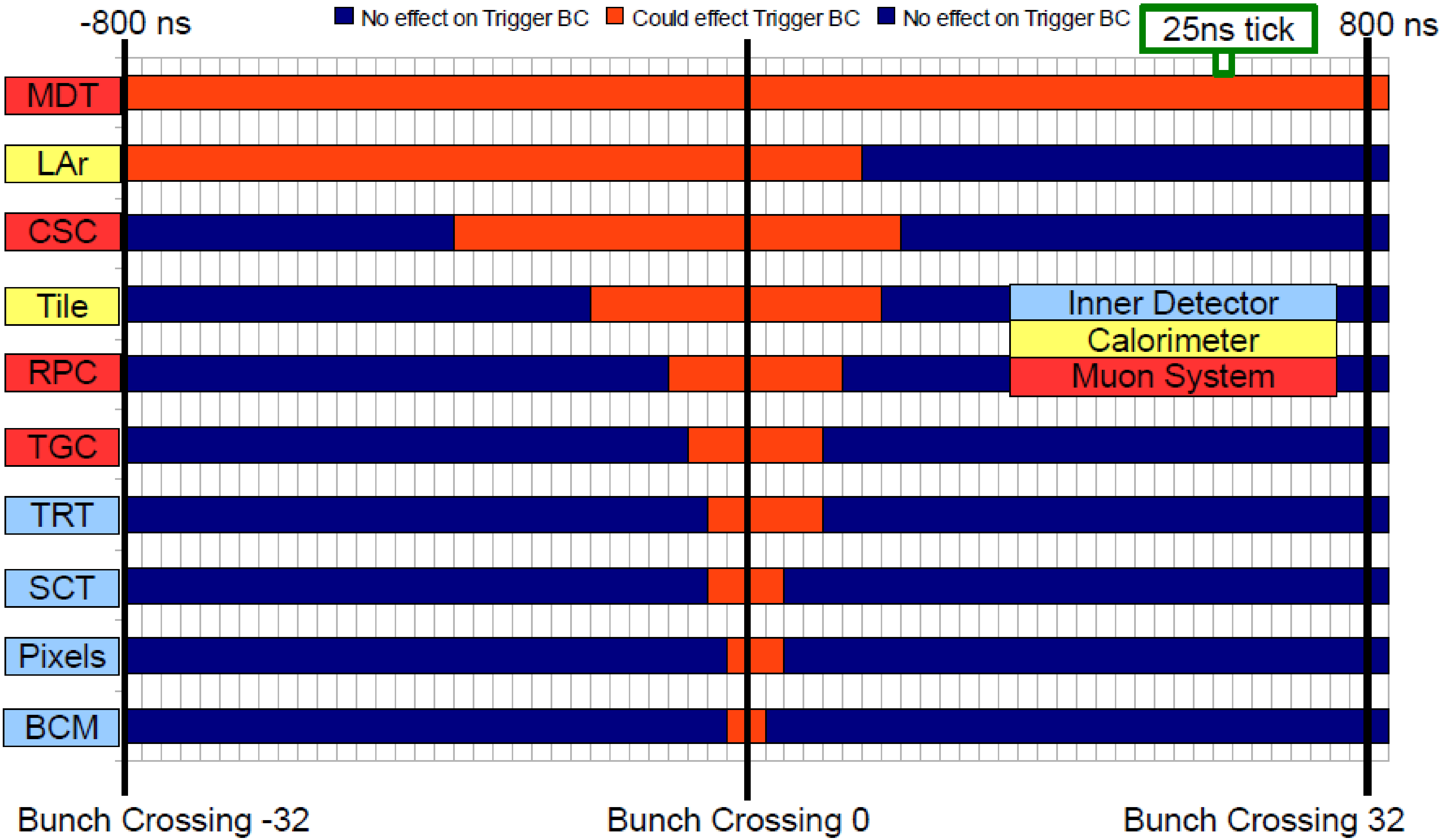
(4) Add model of detector noise separately

(5) Add cavern background separately (see talk by Jochen Meyer)

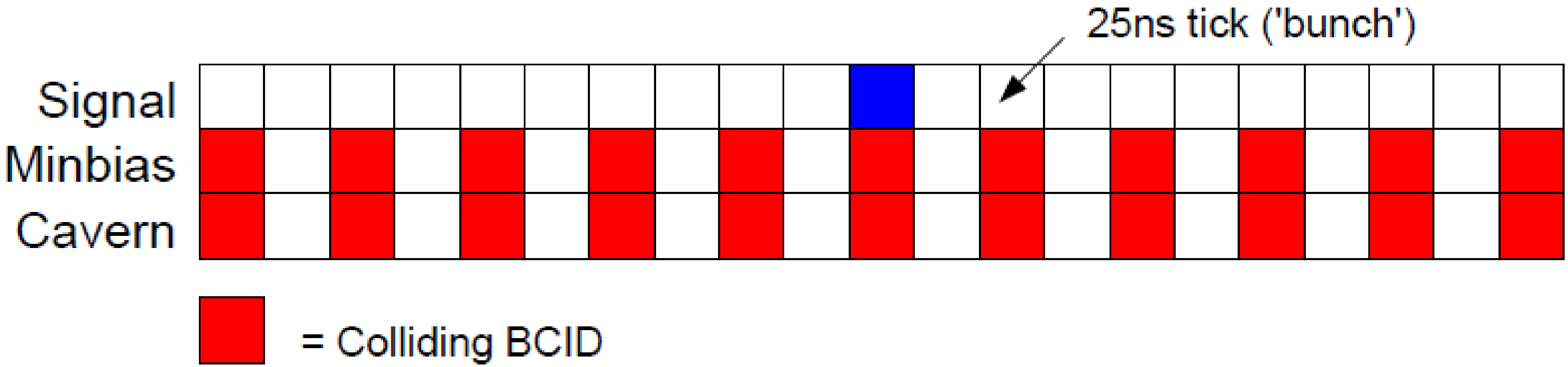
... -100 ns -50 ns **0 ns : In-time** +50 ns ...

ATLAS Sensitive Time Window

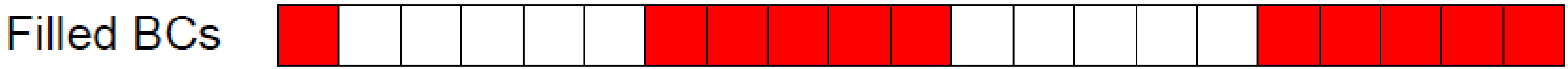


Simulating Pileup: Bunch Structure

Example of a pile-up model with fixed 50ns spacing between colliding BCIDs:



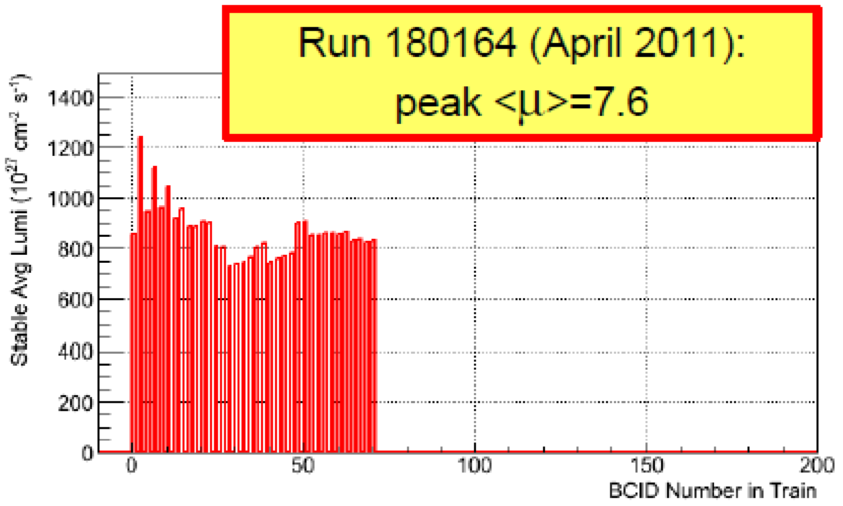
In reality the structure of colliding and non-colliding BCIDs can be more complicated.

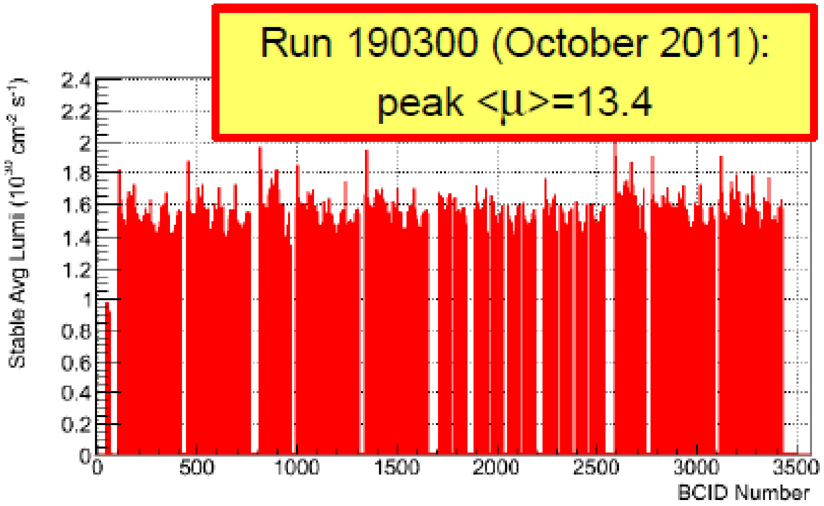


- The pile-up/detector response is affected by the position of the triggering BCID in the bunch train (see later).
- Bunch structure modelling is included in the pile-up simulation.
  - Patterns can be up to 3564 elements in length and wrap-around if required.
  - Each triggering BCID is picked from the colliding BCIDs in the pattern, with a probability proportional to the relative luminosities of each bunch crossing.

Simulating Pileup: Variable (Bunch) Luminosity

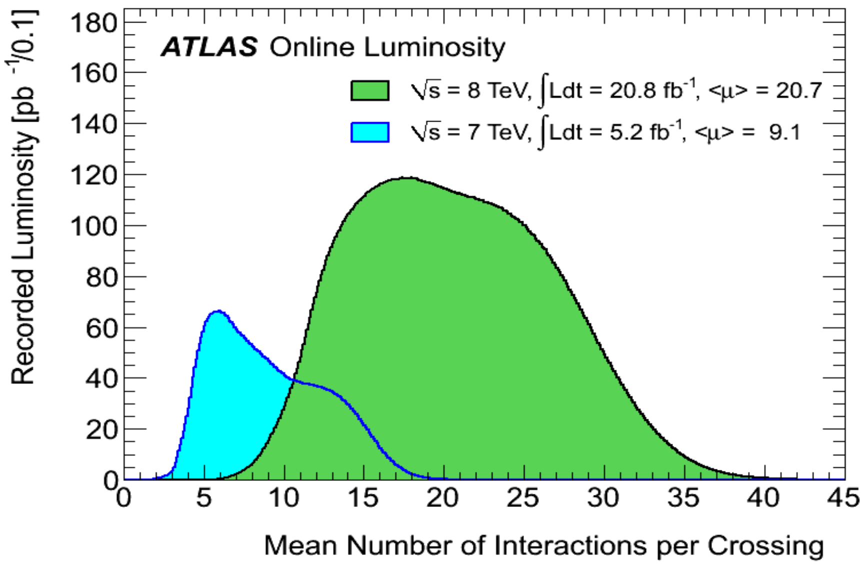
- Well known that <μ> varies over time.

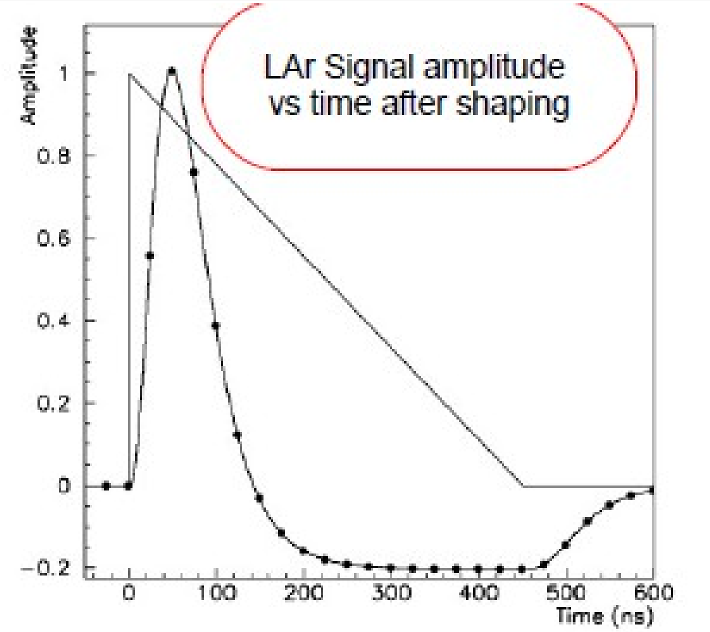


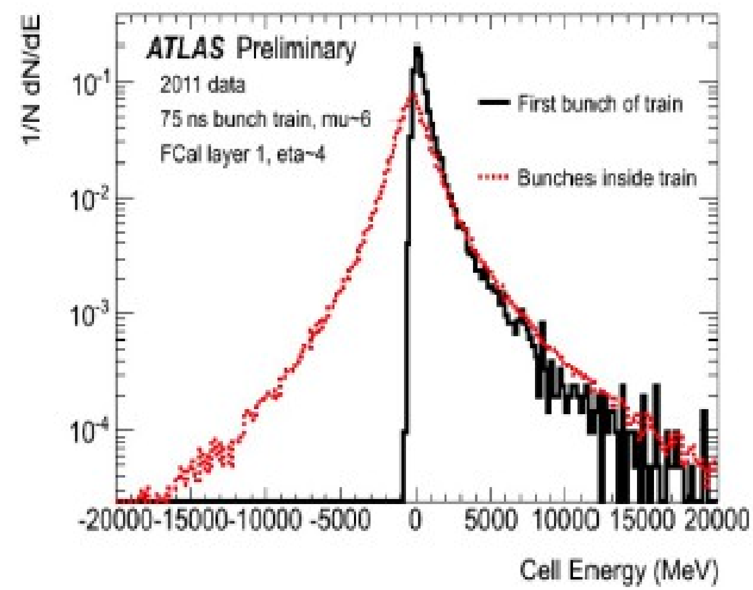


- μ can also vary greatly from BCID to BCID in data, as the plots above show.
- Both in-time and out-of-time pile-up effects are important.
- Problem:
- Simulating samples at a fixed <μ> value makes it difficult to re-weight MC to data...

Impacts of Pileup



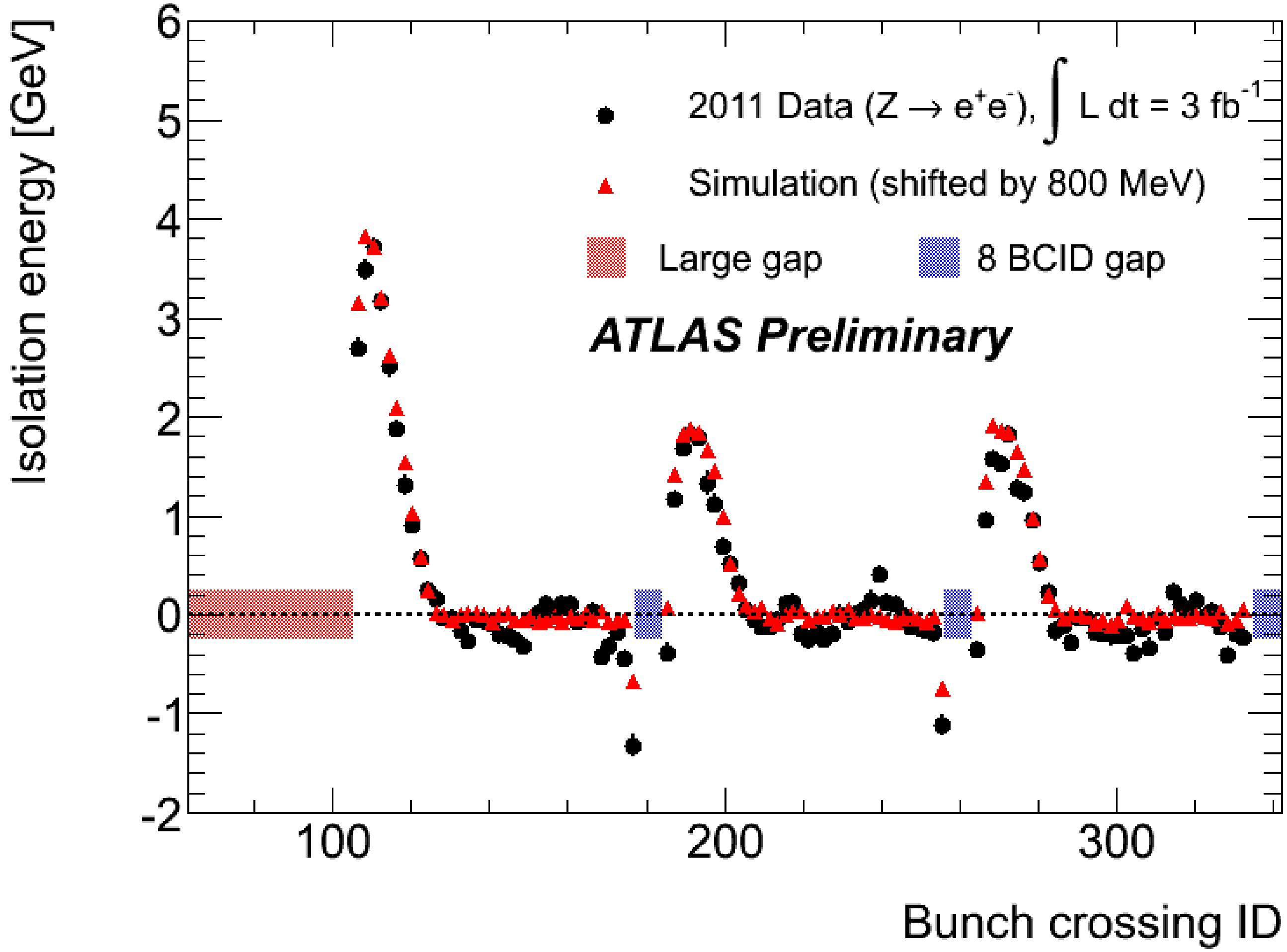




- Do not expect a significant impact on tracking, nor muons, nor even electrons and photons.
- But sizeable impact on jets (+ETmiss) and τ.
- LAr drift-time is ~ 500 ns and out-of-time bunches have impact on measurement.
- Bipolar pulse shaping designed so that <ET> ~ 0 for 25 ns bunch-spacing and uniform intensity per BX.
- Optimal performance will require correction per cell type in η-bins and as a function of luminosity to set average measured ET to ~ 0.
- **Correction was applied for all 2012 data and MC...**

Impacts of Pileup

- Energy in calorimeter in cone around electrons → higher at start of bunch train, before negative tails from out-of-time pileup contribute
- Modeled well by simulation, but also explicitly corrected for at the cell level during reconstruction for 2012 data and MC



Simulating Pileup: Digitization

- For each MC job, create a cache of minbias events in memory
  - Only read in / cache the parts of each event that are needed (e.g. discard HITS in silicon strips outside [-50,50] ns)

- Generating huge samples of minbias background is expensive!
  - 20M minbias events simulated for 2012 (10M "low-pt", 10M "high-pt")
    - "low-pt": no AntiKt6Truth jets with pT>35 GeV
  - ~7 TB storage at each MC production site

- Reuse simulated minbias events across various MC samples
- Also reuse "low-pt" out-of-time minbias events within a MC sample

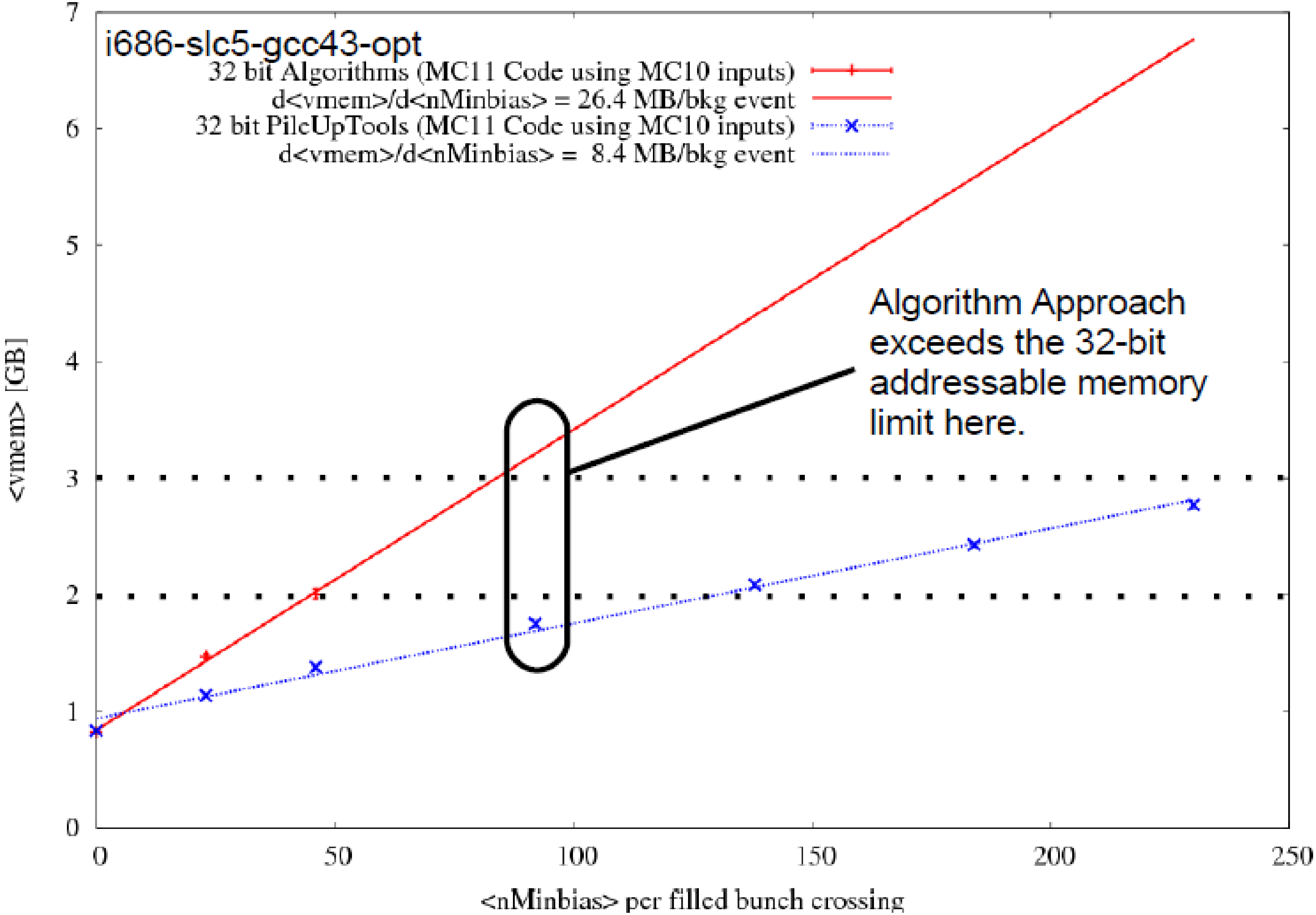
Simulating High Luminosity Pileup

- For High luminosities previous pile-up approach has issues...
- Consider a typical upgrade scenario:
  - 200 pp-collisions per colliding BCID
  - fixed 50ns spacing between colliding BCIDs
  - → ATLAS would be sensitive to 33 colliding BCIDs
    - → 33 x ~200 x 2 = **O(13200)** background events (minimum bias+cavern) required per single signal event!
- Having this many simulated events in memory at once is not feasible, so an alternative must be found...

Simulating High Luminosity Pileup

- The previous pile-up approach (AKA the "Algorithm" approach) :
  - digitizes the information from all required bunch crossings for a given sub-detector before moving on to the next sub-detector.
  - Background event info cached to allow re-use.
- The "PileUpTools" approach:
  - provides one filled bunch crossing at a time to all sensitive sub-detectors.
  - Background events are read as required and discarded from memory after each filled bunch crossing is processed.
    - Sacrifice caching of background to save memory.
    - Resulting increase in I/O Time means an increased wall-clock time.
  - A single pile-up Athena Algorithm calls an Athena AlgTool for each sub-detector. The AlgTools know the time window for which they are sensitive to bunch crossings.
  - Digits/RDOs are produced from intermediate information cached locally by the sub-detector tools, after all filled bunch-crossings have been processed.

PileUpTools Memory Savings (32-bit)



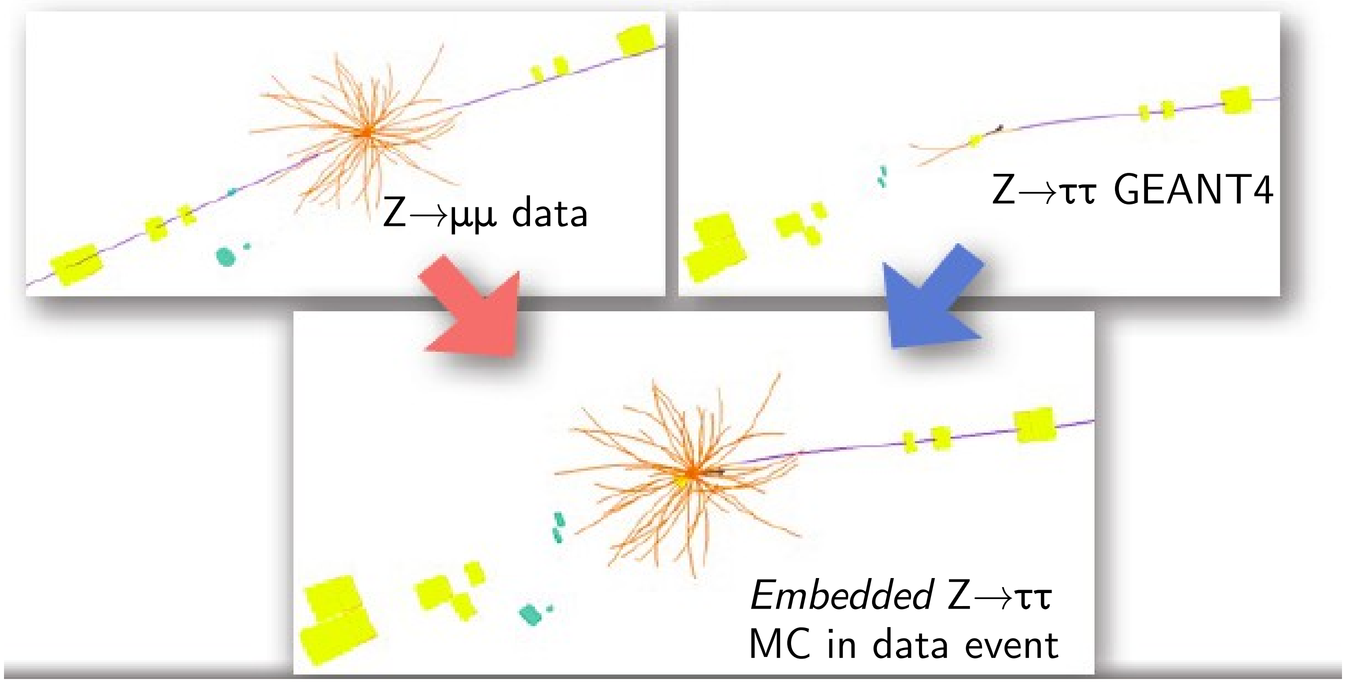
Option 1.5: Simulation Using Embedding

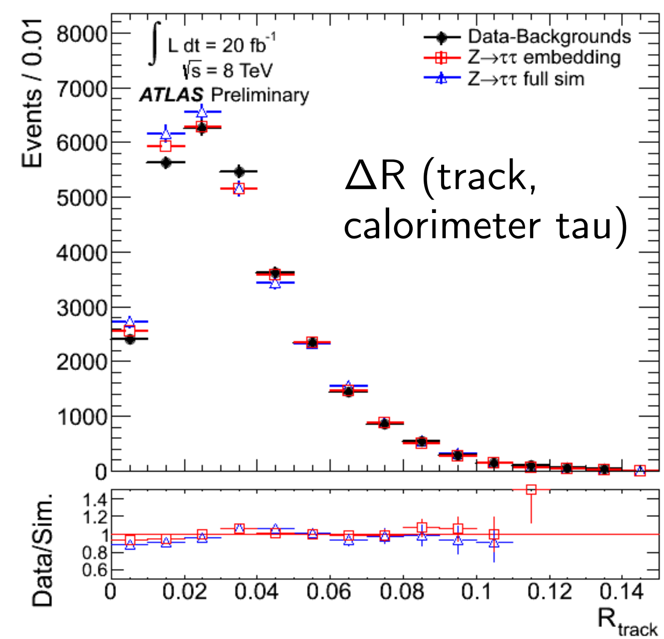
- For specialized studies, such as $Z \to \tau\tau$ simulation, also perform *embedding* at reconstruction (not digitization) level

- remove muon tracks and simulated calorimeter energy from data
- replace by full-sim $Z \to \tau\tau$ decays, generated with Tauola
- re-run full event reconstruction: pile-up, jets and E_T^{miss} from data
- normalization from MC prediction (trigger effect not simulated)
- validation with $\mu \to \mu$ embedding (data to data) and Alpgen MC

Constrain systematics on tau-ID and $Z \to \tau\tau$ kinematics / mass ...

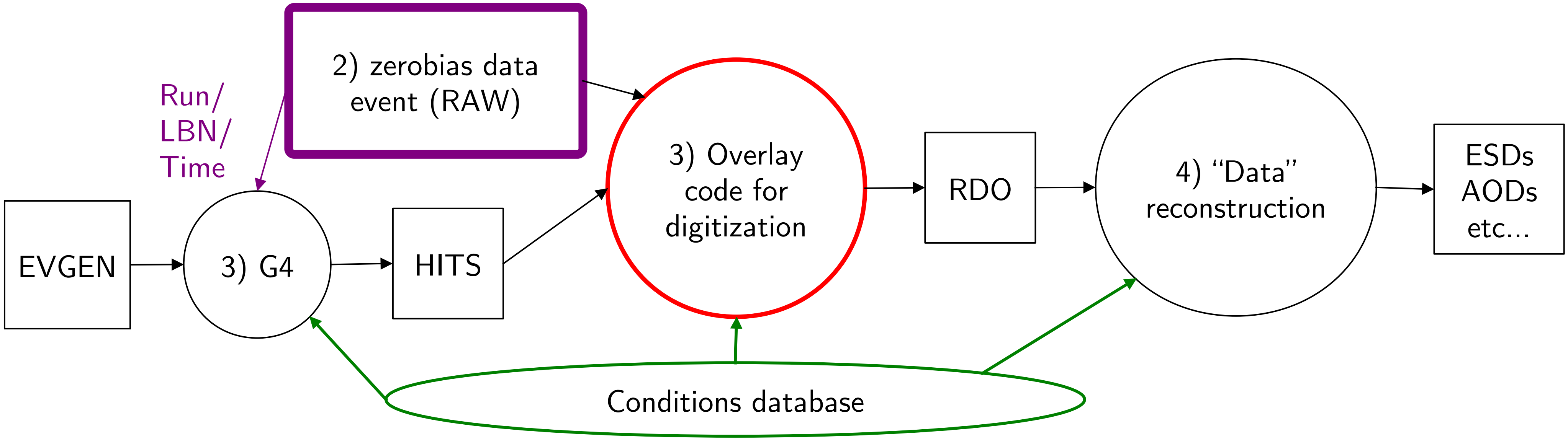
Underlying event and Z pT distribution from data





Option 2: Overlay pileup (and noise) from *data*

1. Define data period to simulate and select "random" (RAW) zerobias data events, proportional to luminosity (details later...)
2. Simulate hard-scatter events (GEANT4) with conditions matching each selected data event (beamspot, alignments, dead modules, etc.)
   $\rightarrow$ Note: running GEANT4 on geometry with *data alignments*
3. Overlay each zerobias data event with matching GEANT4 event at the detector channel level, then digitize combined signals
4. Reconstruct the combined event as data



Zerobias datasets

- Trigger L1_ZB fires 1 turn after EM14 → *proportional to bunch lumi*
  - Prescaled to keep ~1 Hz in 2011, ~10 Hz in 2012 → ~65 M events
  - No zero-suppression: about 3MB/event
- Sample zerobias events from lumiblocks in the desired time-period to reproduce the instantaneous luminosity profile of L1_EM30 (account for changing prescales, etc.)

Zerobias RAW filelist	"map" file		Output file (100 events)
data12_8TeV...lbn00345.0001...RAW	6 wanted		
data12_8TeV...lbn00345.0002...RAW	4 wanted		
data12_8TeV...lbn00346.0001...RAW	1 wanted	→	Zerobias_001.RAW
data12_8TeV...lbn00347.0001...RAW	3 wanted		
. . .	. . .		
about ~60 files			

This is just 1 job for 100 events.
500 jobs needed for a 50k dataset.
1000 50k datasets for 50M events.

Now works in MC production system!

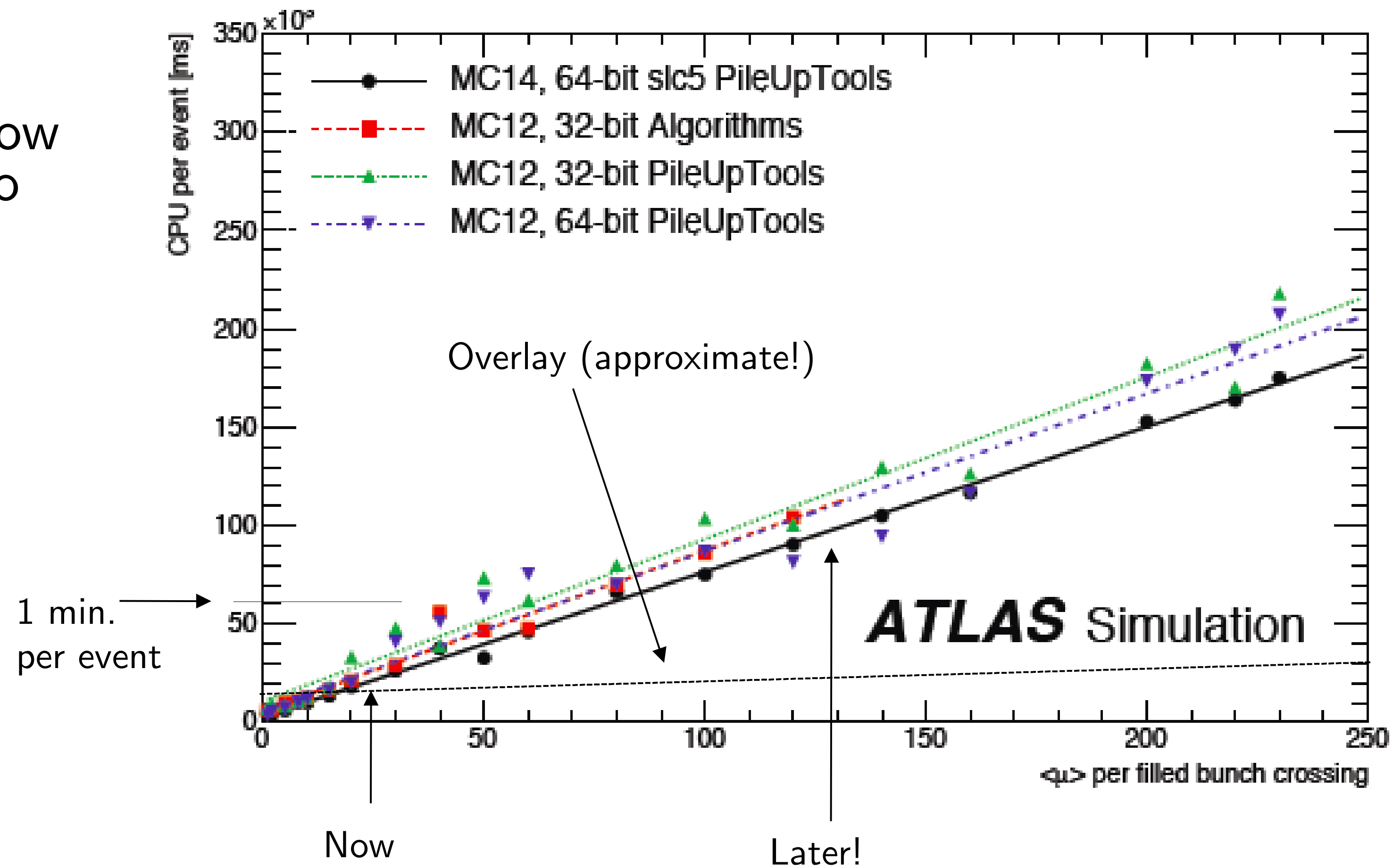
Pileup Simulation vs. Data Overlay

- Drawbacks compared to pileup simulation:
  - Less accurate when combining overlapping background and signal on the same channel for some subdetectors (e.g. silicon)
    - Zerobias data is readout zero-suppressed for some detectors (e.g. pixels)
  - Background reconstructed with MC R-T relations (TRT, MDT), so slight resolution degradation for background tracks and muons
  - Potential GEANT4 geometry overlaps when using data alignments
  - Limited (but large) statistics of background data
  - Can't simulate future detector geometries (for some upgrade studies)
  - Don't have the background truth information – it's data!
- Overlay advantages:
  - Real pileup data events – no generator tuning
  - #vertices and inst. luminosity match data – no event weighting
  - Real mix of BCID variation, in-time/out-of-time pileup, satellite bunches
  - Real detector noise, occupancy – including cavern background
  - Real detector conditions (beamspot, dead channels, etc.)
  - Less CPU and memory need at high luminosity...

Pileup Simulation vs. Data Overlay

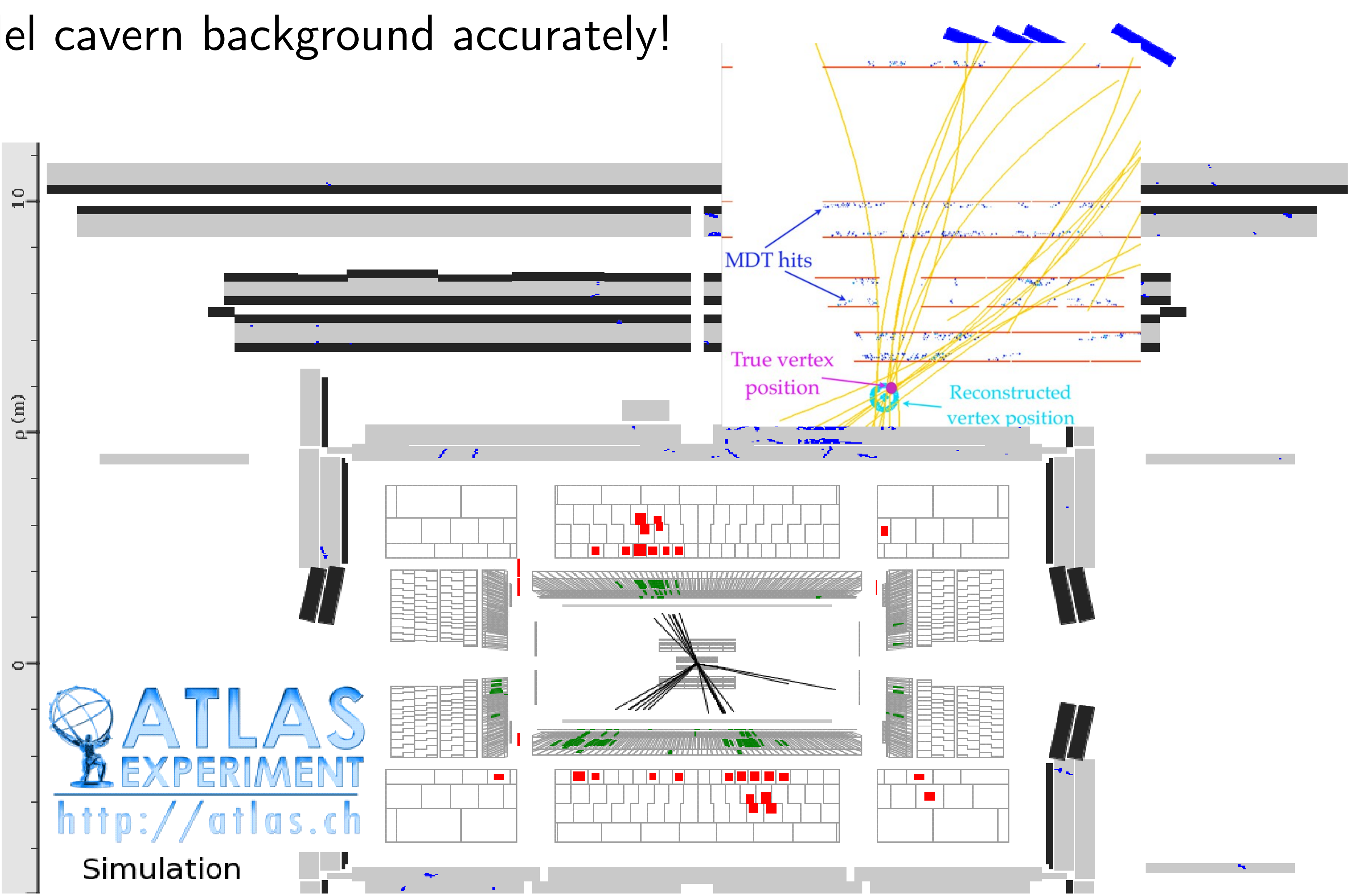
- Digitization of ~thousands of added simulated HITS events grows ~linearly with the number of pileup interactions
- Overlay only has to add *one* data event, independent of luminosity!

- Digitization time now ~small compared to GEANT4 time
- More critical later, especially for fast simulation methods
- Other methods (fast digi) also being explored (see talk by Robert Harrington)



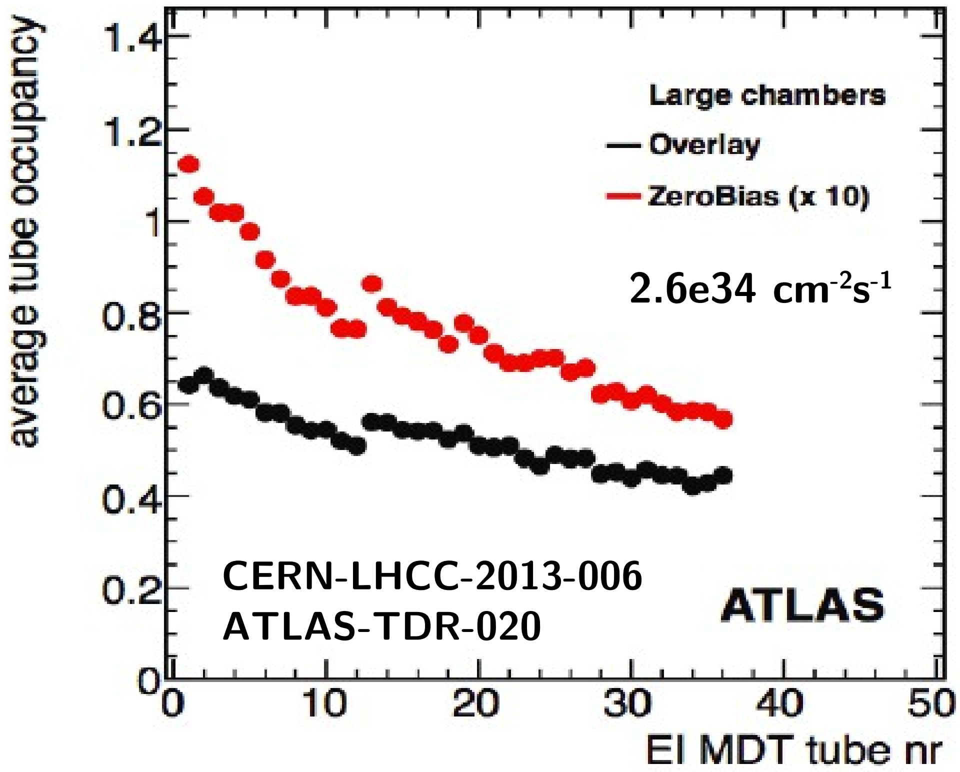
Overlay MC for pp Physics

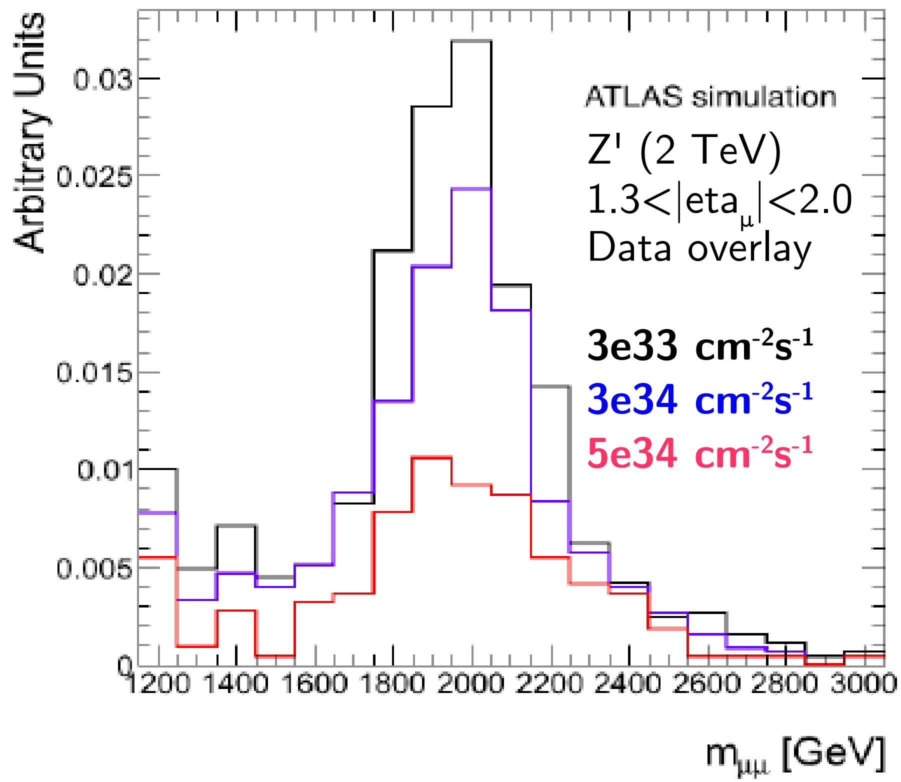
- One example: "Search for Higgs decay to long-lived particles"
  - Reconstruct displaced vertex in muon system
  - Background from punch-through jets and *cavern background hits*
  - Must model cavern background accurately!



ATLAS Upgrade Studies Using Overlay

- Cavern background is nicely modeled in overlay
- Overlay *multiple* zerobias data events to simulate higher luminosity!
  - Noise is double-counted, but negligible in the muon system
  - Validated using 3 low-luminosity events compared to 3x luminosity data
- Saturation of MDT End-cap Inner tubes confirmed
  - Helped to motivate New Small Wheel Upgrade

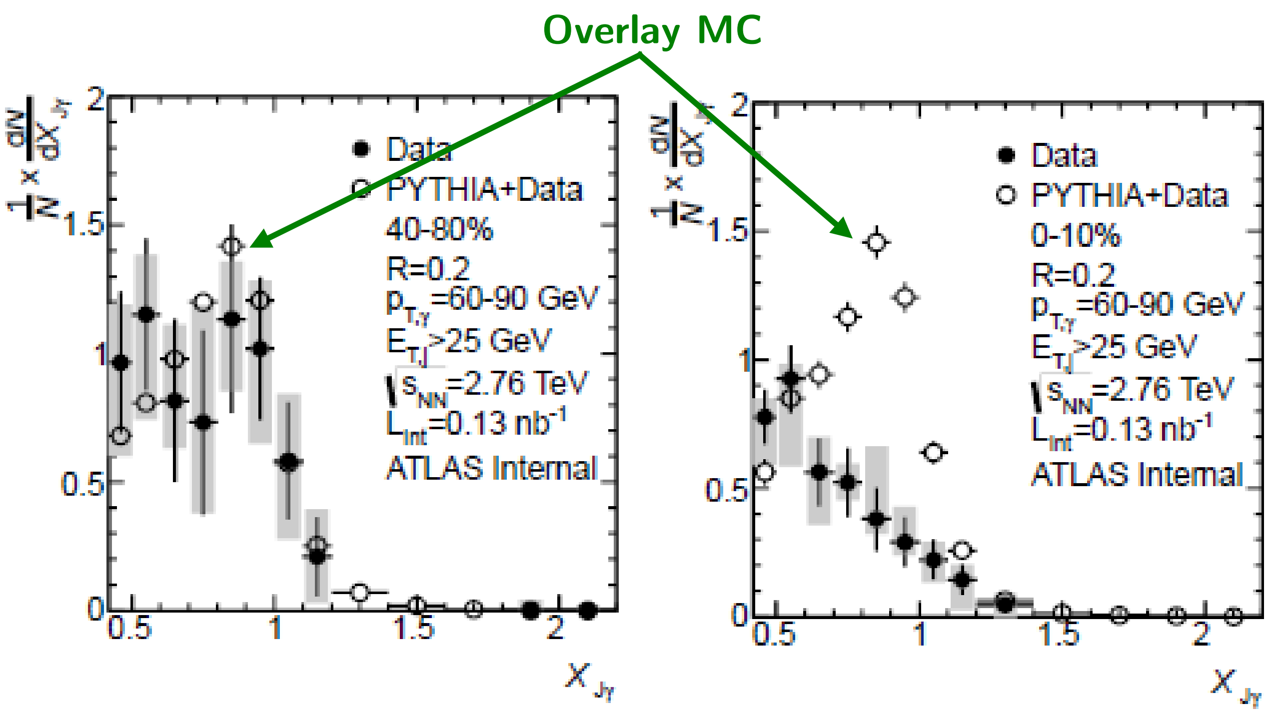


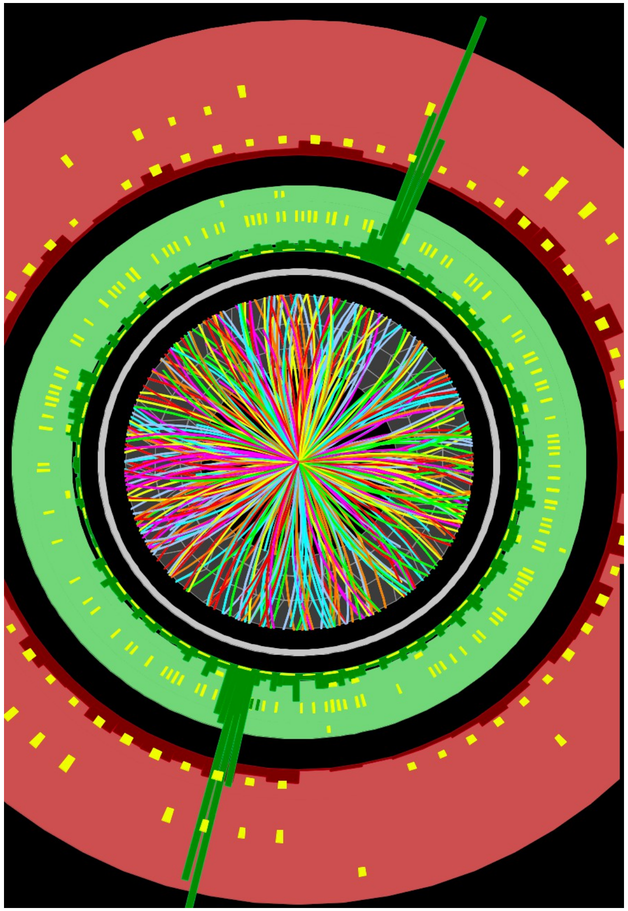


Heavy Ion Simulation Using Overlay

- Almost no pileup in heavy-ion collisions, but..
  - Underlying event is huge, difficult and costly to simulate!
- Use (minbias) HI data, overlay hard parton interaction simulated at the *same event vertex position*
  - ~20M HI overlay MC events produced
  - Used for many HI results successfully …

Measurement of the correlation of jets with high pT isolated prompt photons in lead-lead collisions at sqrt(s)=2.76 TeV

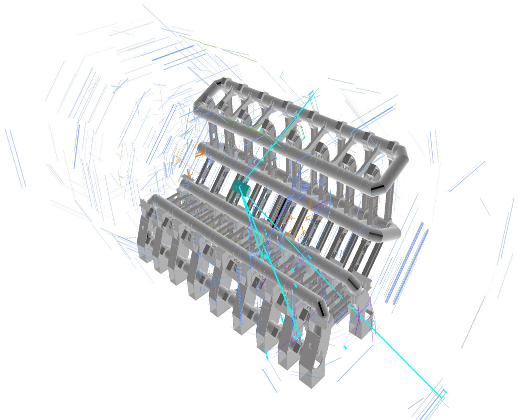




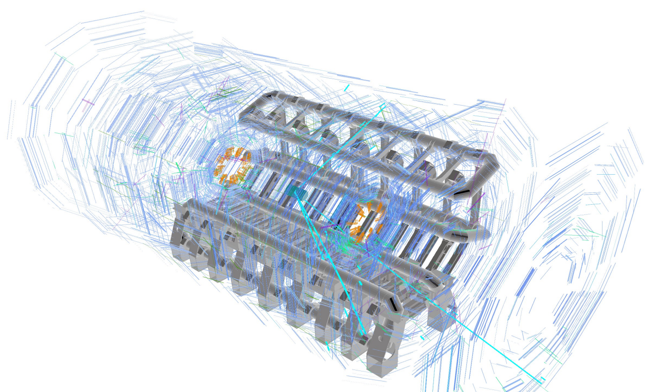
Conclusions

- ATLAS uses several methods for modeling pileup and other detector backgrounds in our simulation
  - Simulated Pythia8 minbias is currently used for most simulations
  - Embedding is used for specialized studies, e.g. for $Z \rightarrow \tau\tau$
  - Overlay is an alternate method, currently used for some performance studies, pp and HI physics analyses, and detector upgrade studies

- Working to improve accuracy and speed of all these methods
- Pileup will become increasingly important with larger inst. luminosity
- We must model pileup efficiently to simulate larger datasets



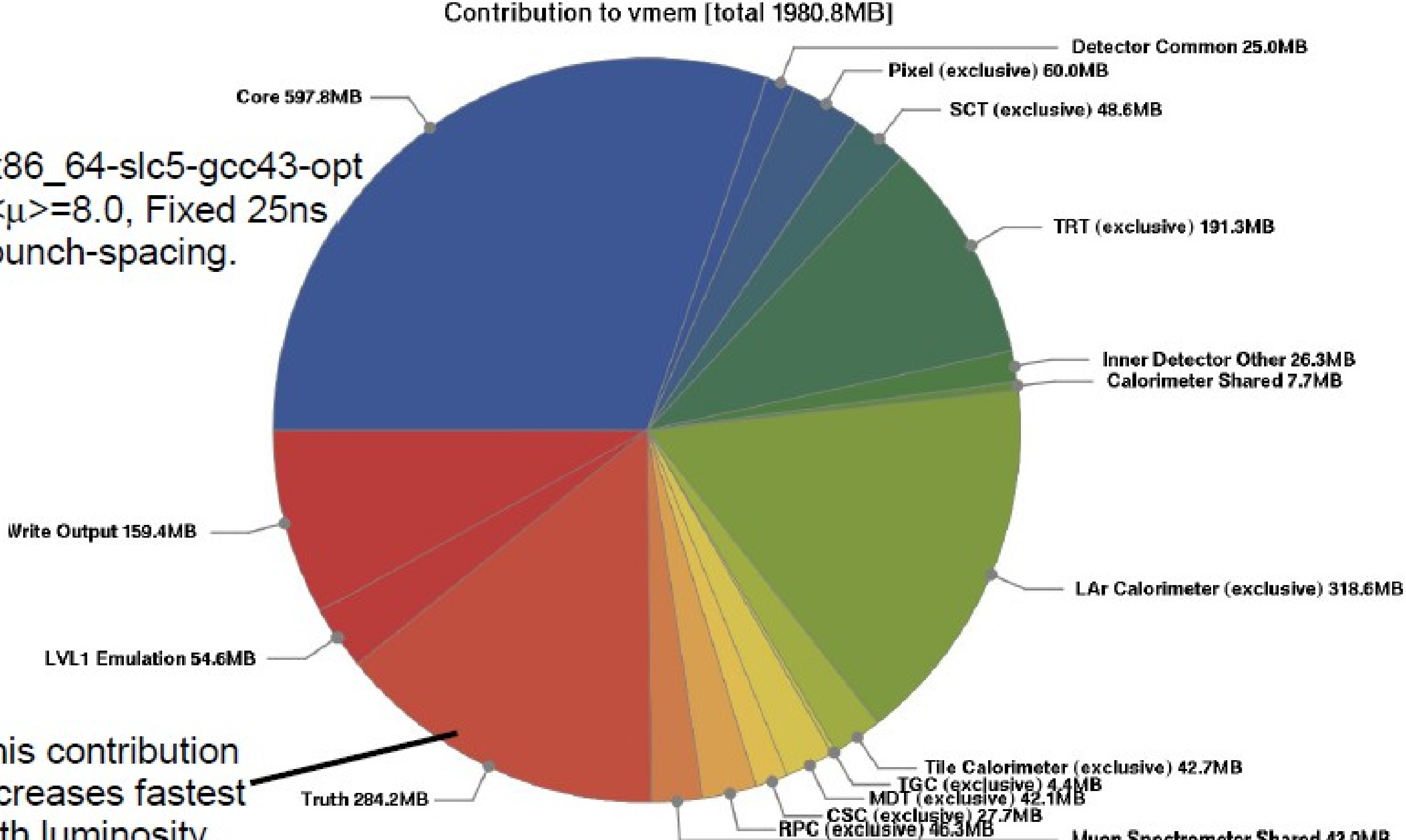
$H \rightarrow ZZ \rightarrow 4\mu$ @ 2.6e33



$H \rightarrow ZZ \rightarrow 4\mu$ @ 2.6e34

Backup

Pile-up Digitization: vmem breakdown

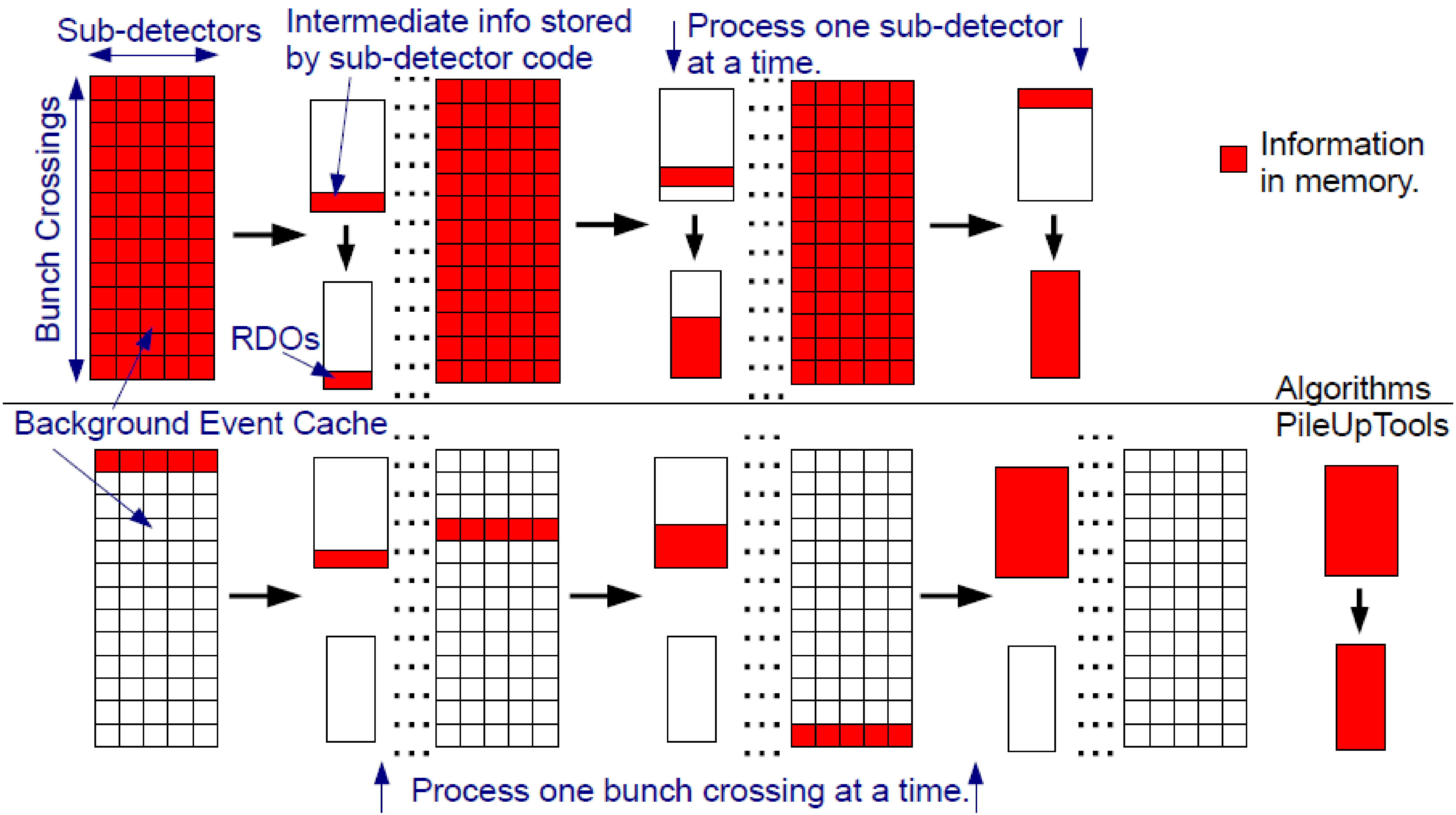


x86_64-slc5-gcc43-opt
<μ>=8.0, Fixed 25ns bunch-spacing.

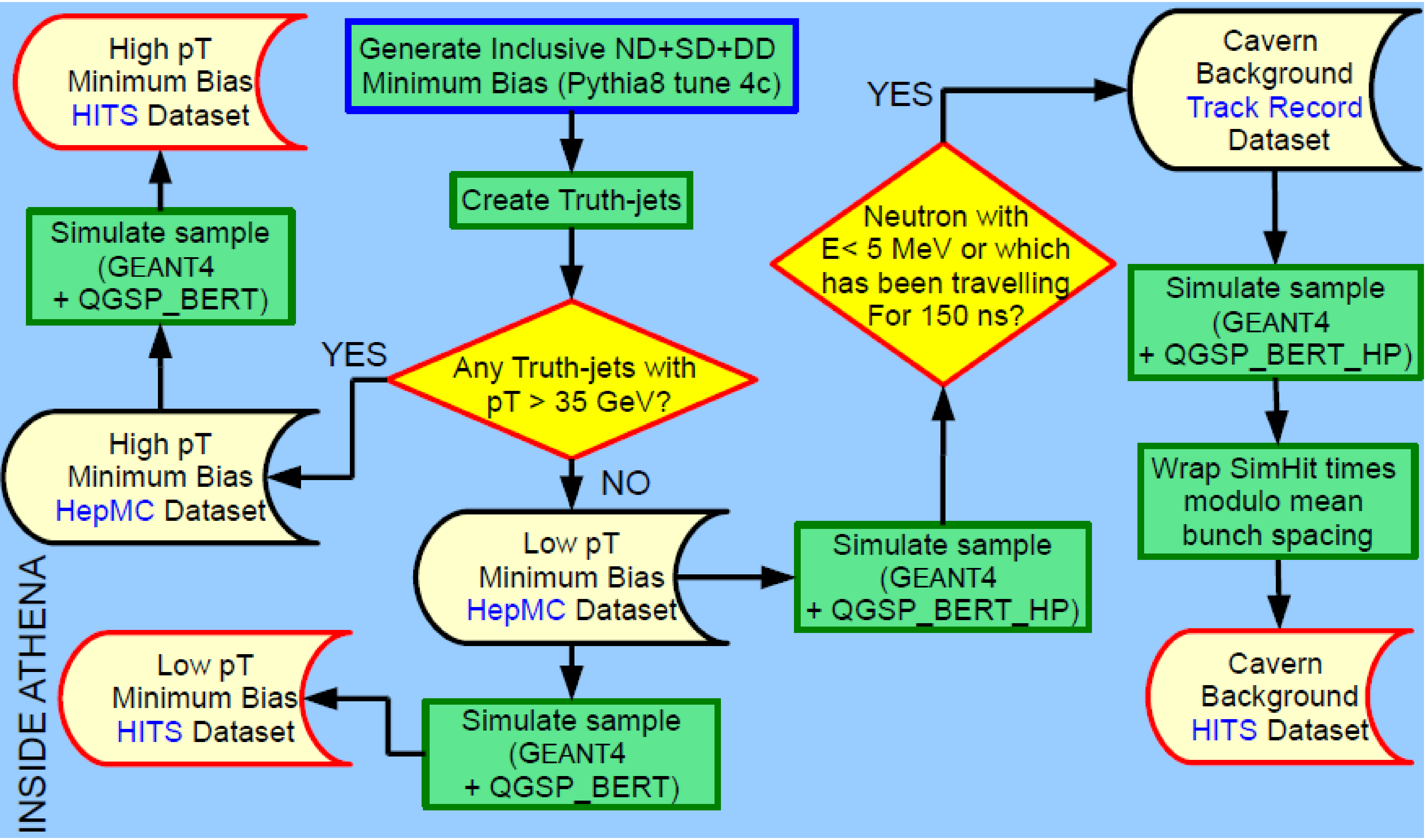
This contribution increases fastest with luminosity.

One approach to save memory under validation is to filter truth info in the background HITS files.

Algorithm and PileUpTools Approaches to Pile-up Digitization



Simulating Pileup: Pythia8+GEANT4



Impacts of Pileup

- Jet offsets from pile-up are modelled to <50%
- Remaining differences from BCID-to-BCID beam current variation were not modelled in **2011 MC**