Challenges of the HL-LHC

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Physics 290E

LHC / HL-LHC Plan

What's Left to Do?

1. Precise **Higgs Boson** Measurements
   - Impact of New Physics on Higgs Couplings
     - $\Delta\kappa/\kappa = 5\%/\Lambda_{NP}^2$ (Λ_{NP} in TeV)
   - Coupling to 2nd generation fermions ($H \rightarrow \mu\mu$)
   - Possibly observe HH production at 3σ
   - BR(H→invisible) < 3% (24% today)
   - Study Vector Boson Scattering at high energies
2. Discover Potential for New Particles
   - Up to ~20-30% larger reach than current LHC

Key Challenges for HL-LHC

- **Luminosity** (Data Rate)
  - HL-LHC plans to reach 5-7.5x the nominal luminosity of previous runs
- **Pileup** (Number of collision in an event)
  - Up to $< \mu > = 400$ collisions for a given event (compare to ~40-60 in Run 2)
  - Resolving these collisions will take much better tracking
- **Tracking**
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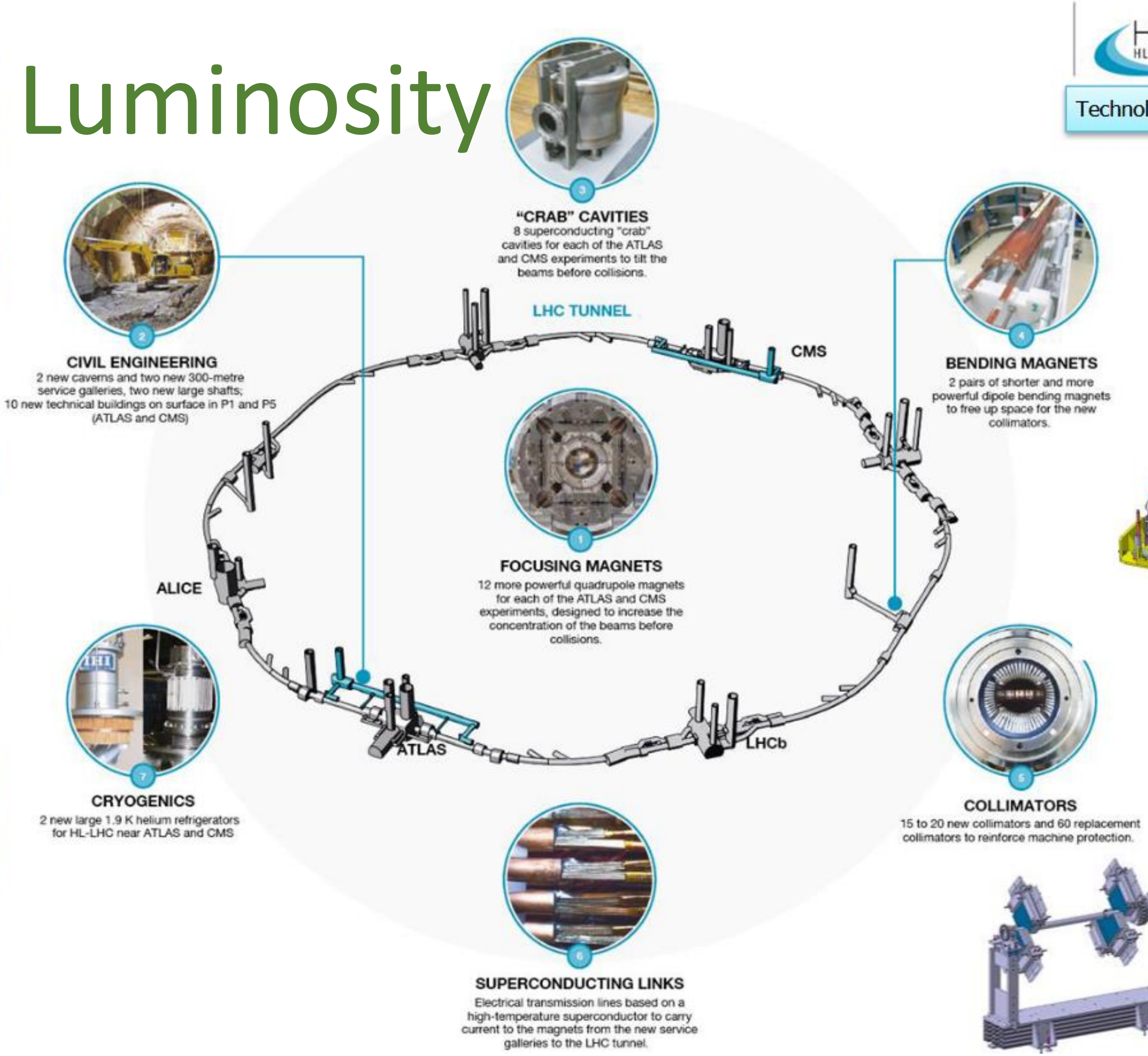
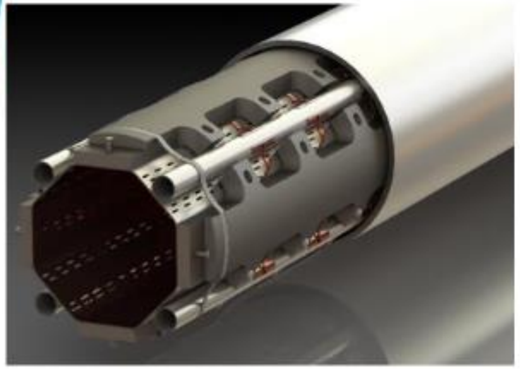
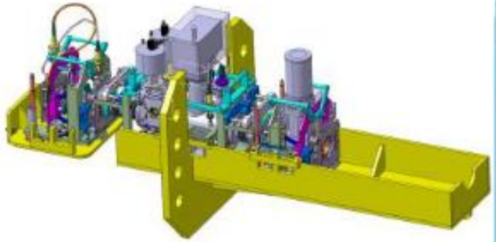
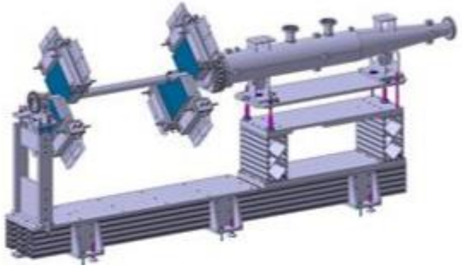
Luminosity









HiLumi
HL-LHC PROJECT

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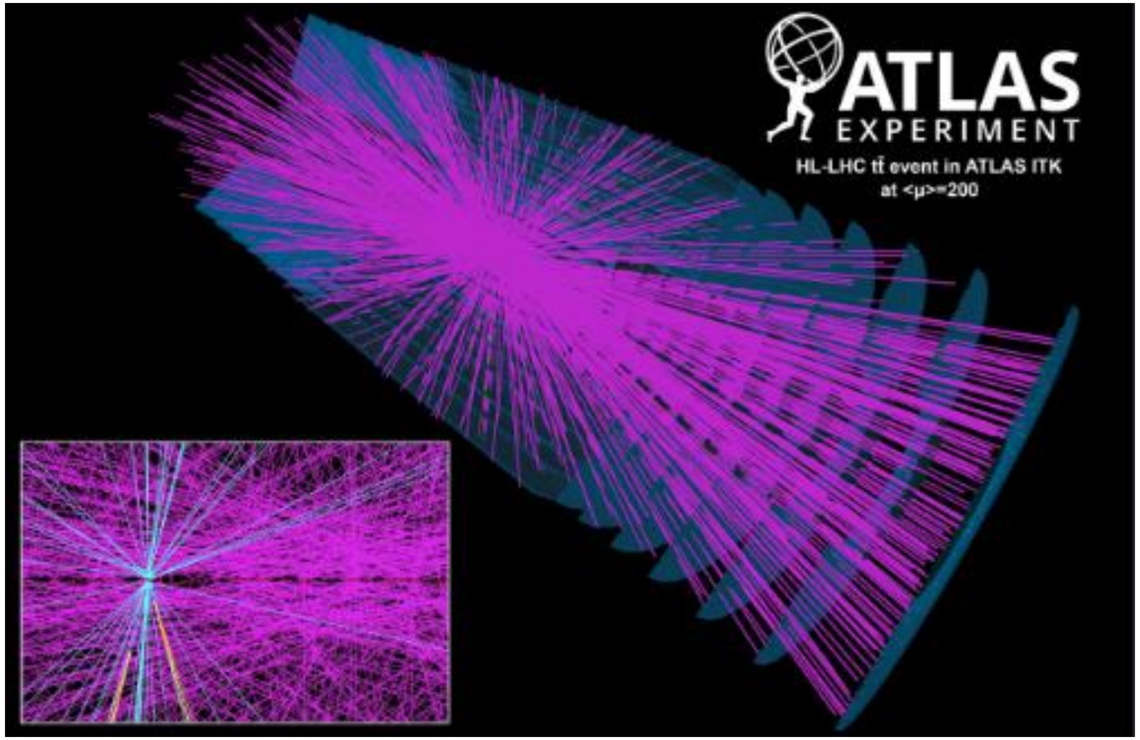
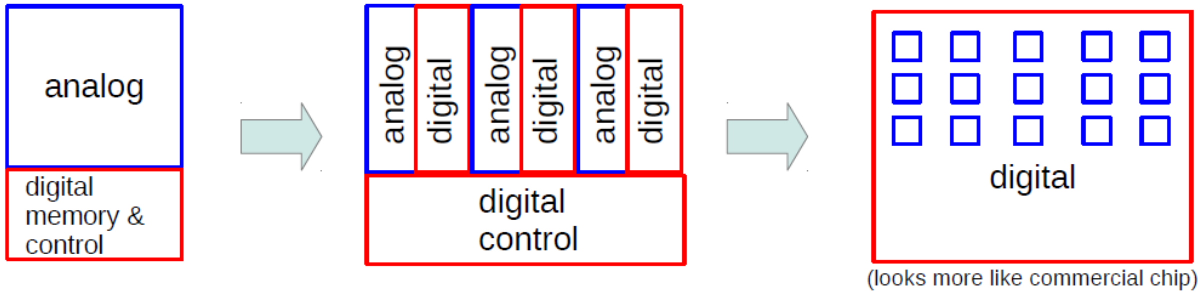
ITk Design Requirements

- Radiation Hardness
  - New Sensor Technologies
  - New ASIC designs
- Granularity
  - Must resolve 200 collisions
  - High PV reconstruction efficiency
- Extended Tracking
  - Must go out to $|\eta| < 4$
- Minimize Detector Material

Pileup Environment much worse in HL-LHC (200 collisions)



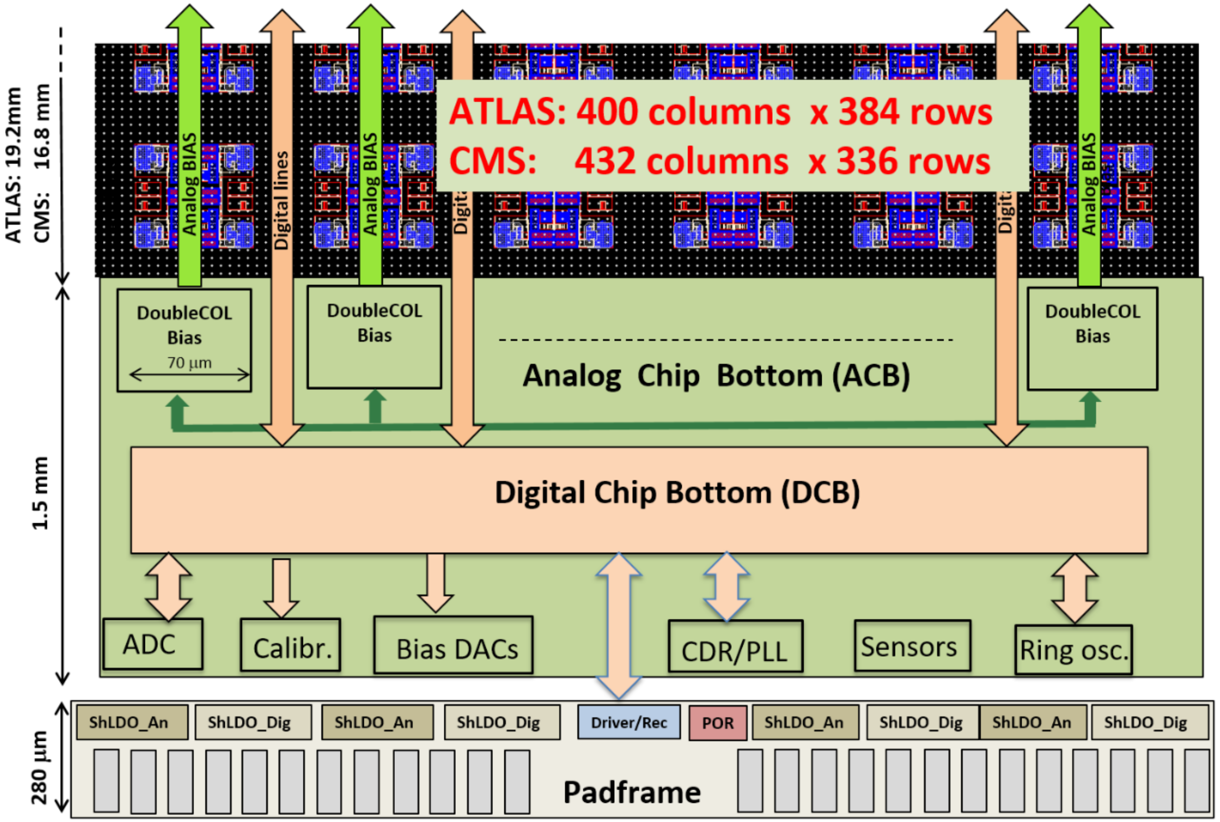
Designing the new Pixel ASIC (ITkPixV1)



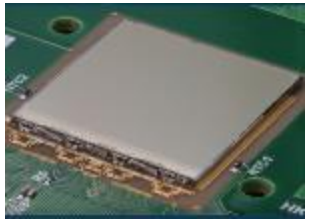
16 yrs ago
Full custom
including logic

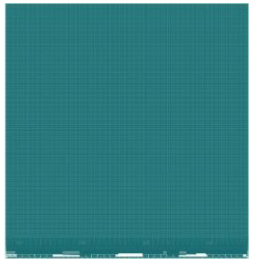
8 yrs ago
Full custom layout
With synthesized logic inserts

Now
Full digital flow
With analog inserts



- Read-Out ASIC for both experiments which communicates with Pixel Matrix and DAQ system
- Analog portion of chip done the standard way.
- Digital part is extremely complicated and makes up most of the design.
- ASIC bump-bonded to sensors (new 3D and planar technologies)





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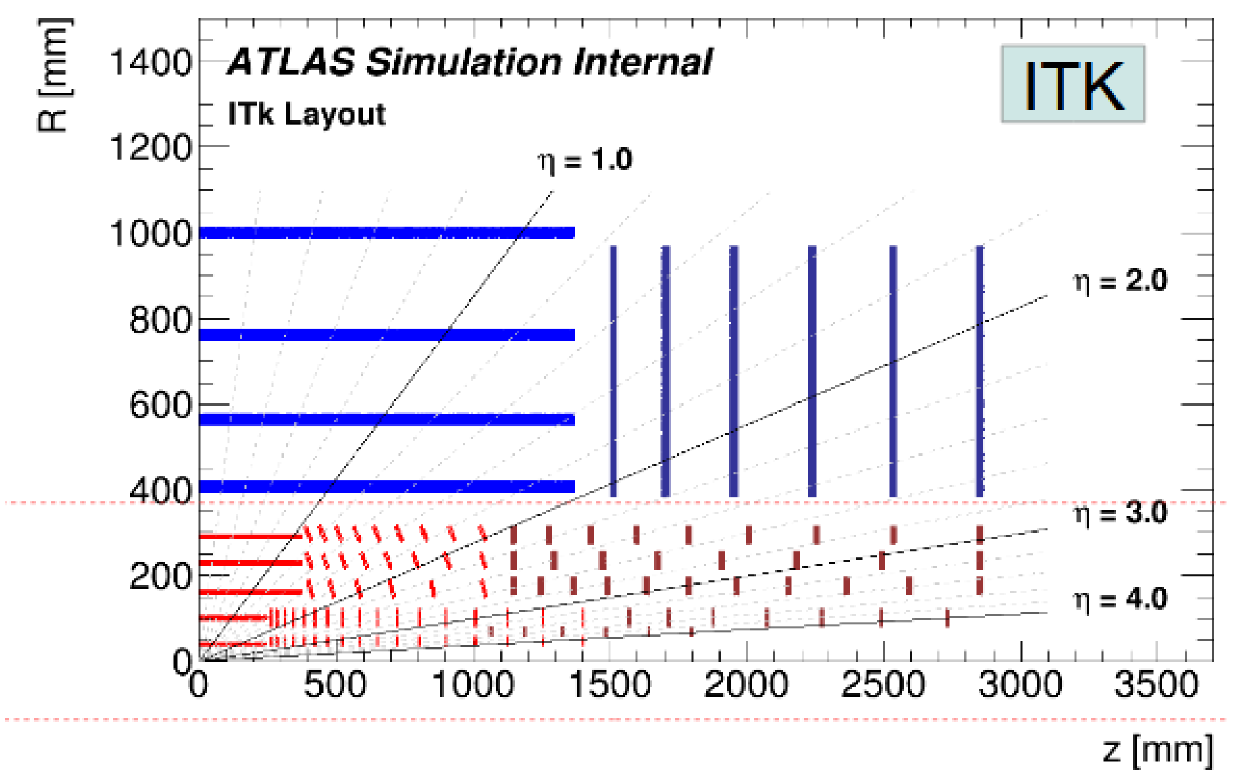
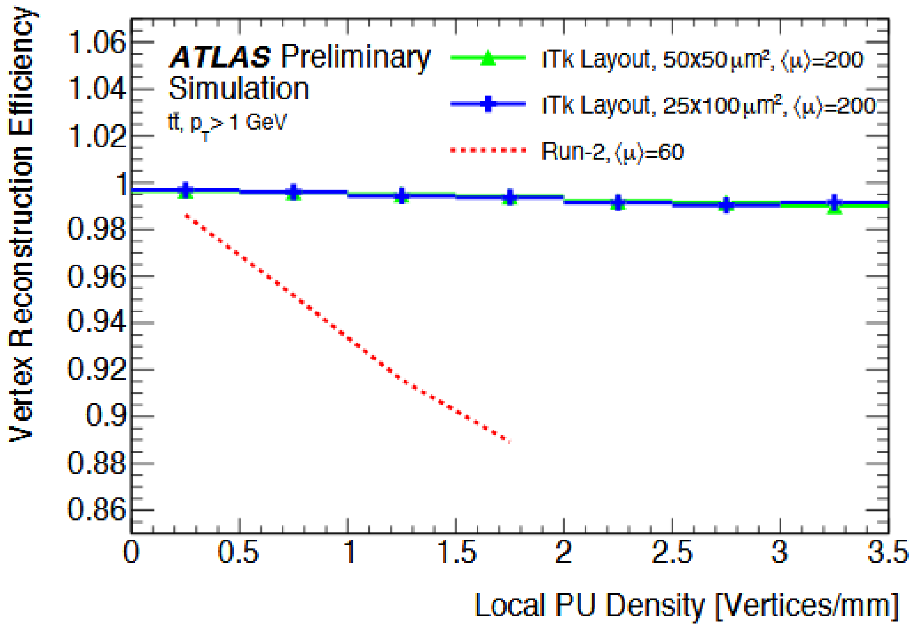
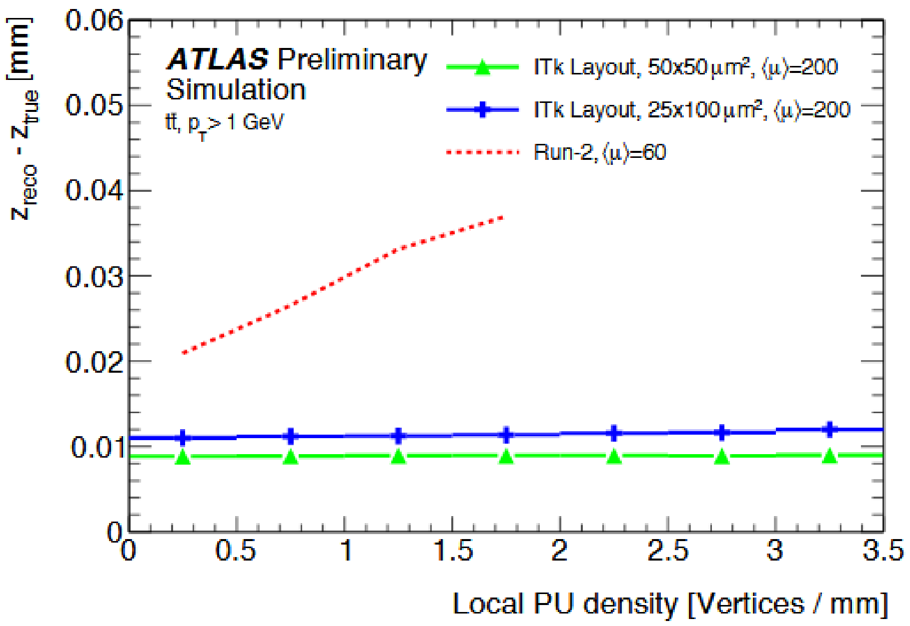
Replacing the Inner Tracker (ITk)

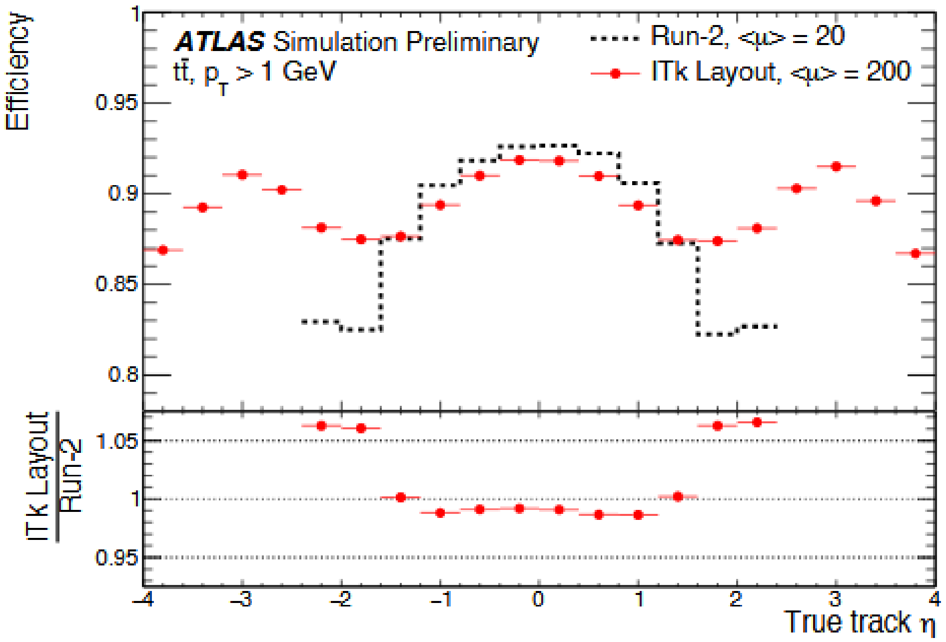
- All silicon tracking!!
- Pixel: 5 layers and mult. ring disks (1.1B channels)
- Strips 4 layers + 12 endcap disks (60M channels)
- Inclined pixel layers to minimize number of modules
- Much higher angular coverage

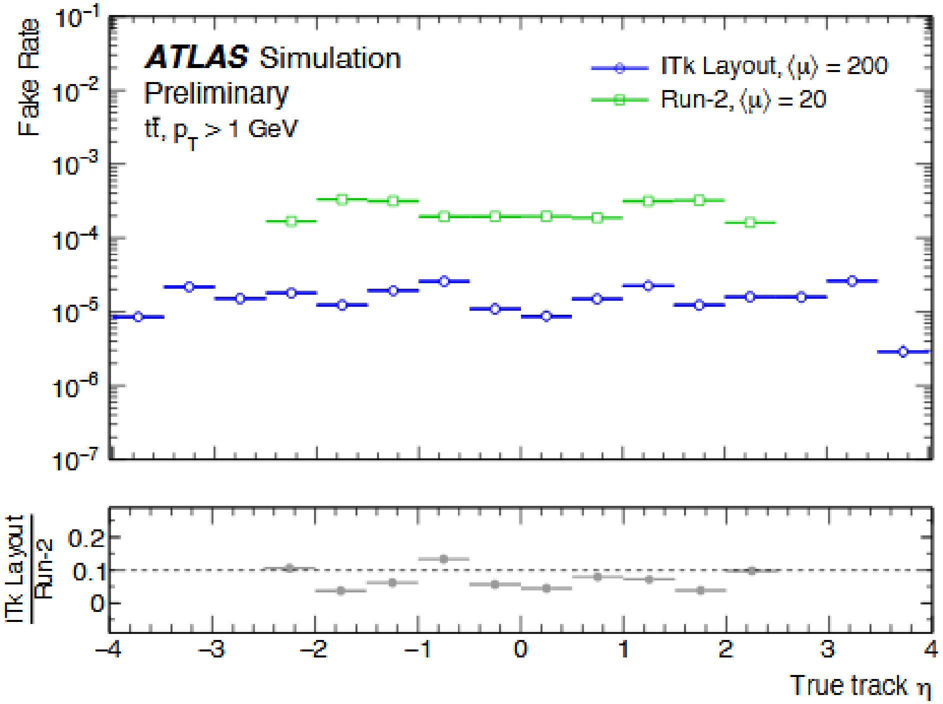


ITk Performance

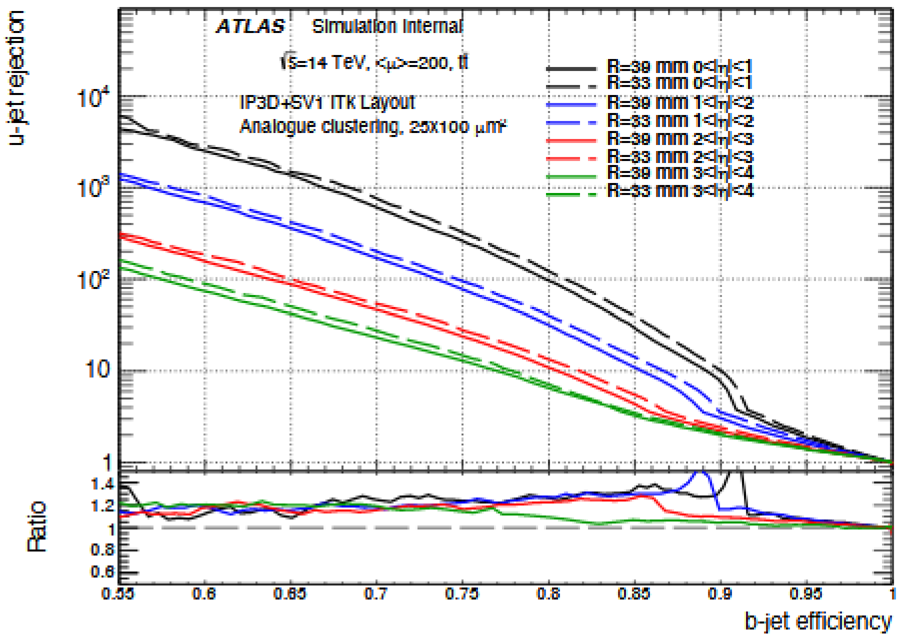


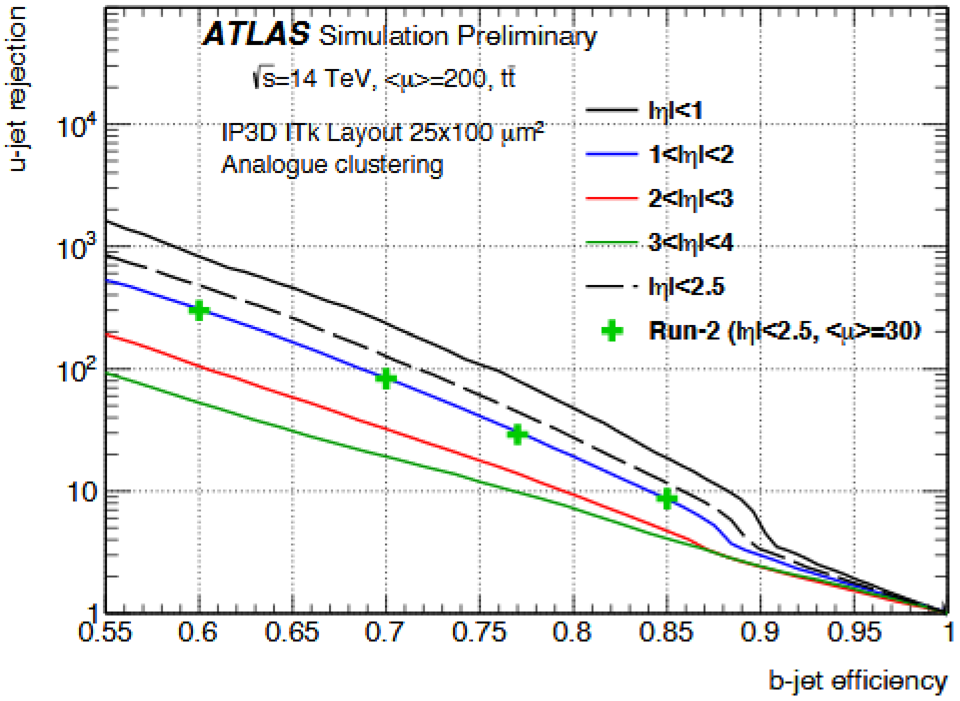






B-tagging Performance





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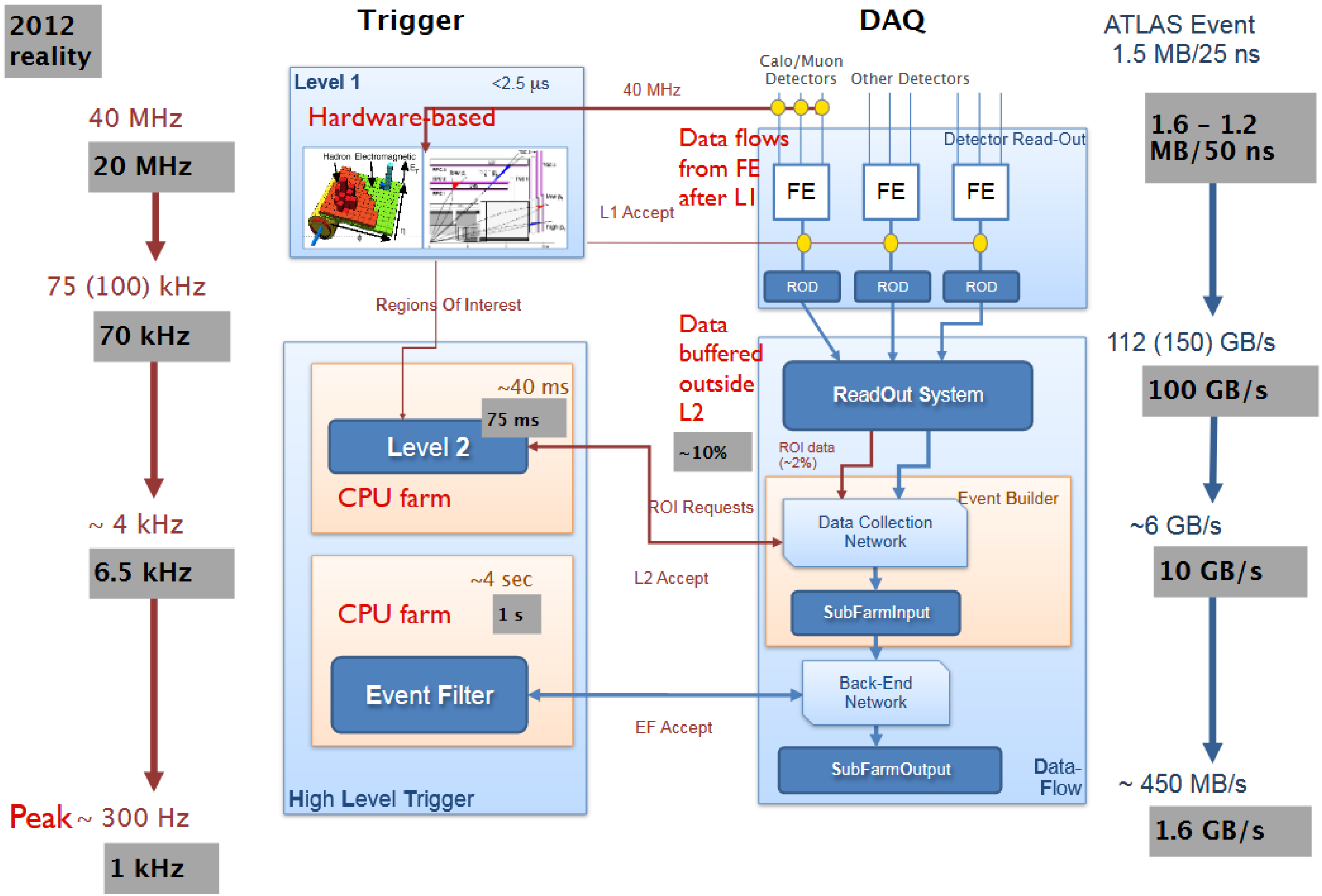
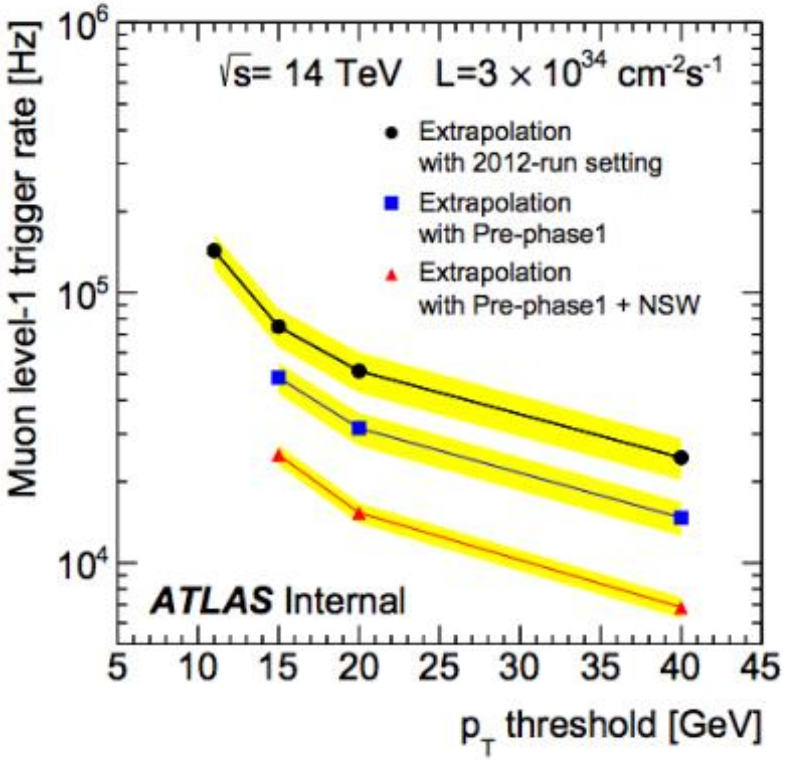
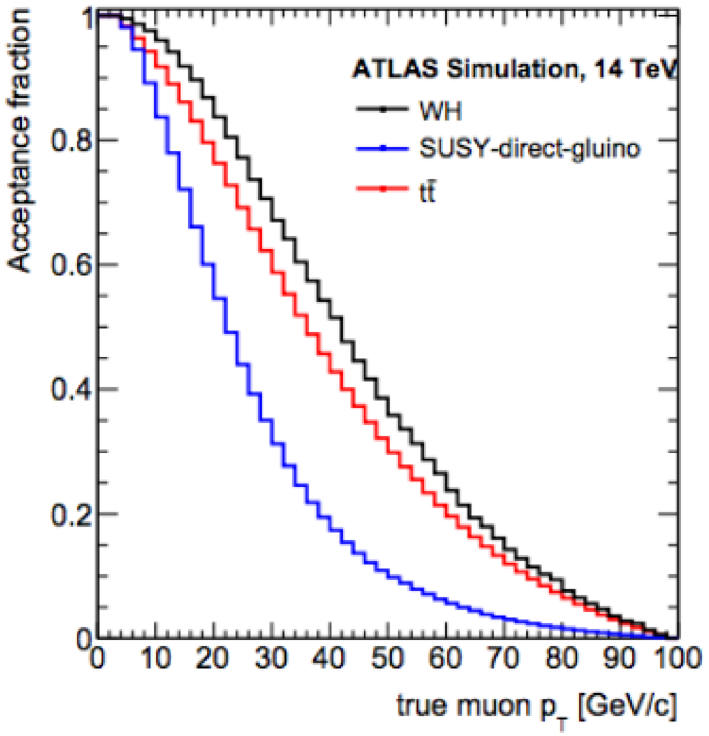
ATLAS trigger system overview



Trigger: Issue of Losing Interesting Physics

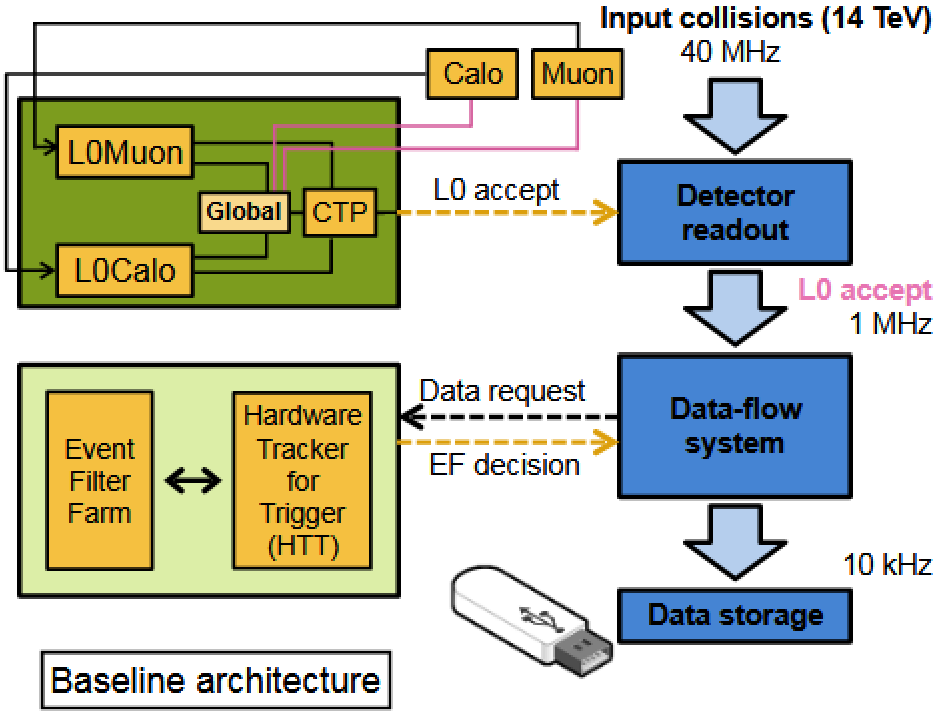
- There exists a battle between trigger p_T threshold and rate
- Rates determined by:
  - Resolution (muons below threshold)
  - Fakes (particles not associated with the underlying event)
- Rate of two overlying objects passing trigger:
  - $Rate = \frac{1}{2}(p\mu)^2 f$
- Rate α $(Pileup)^2$





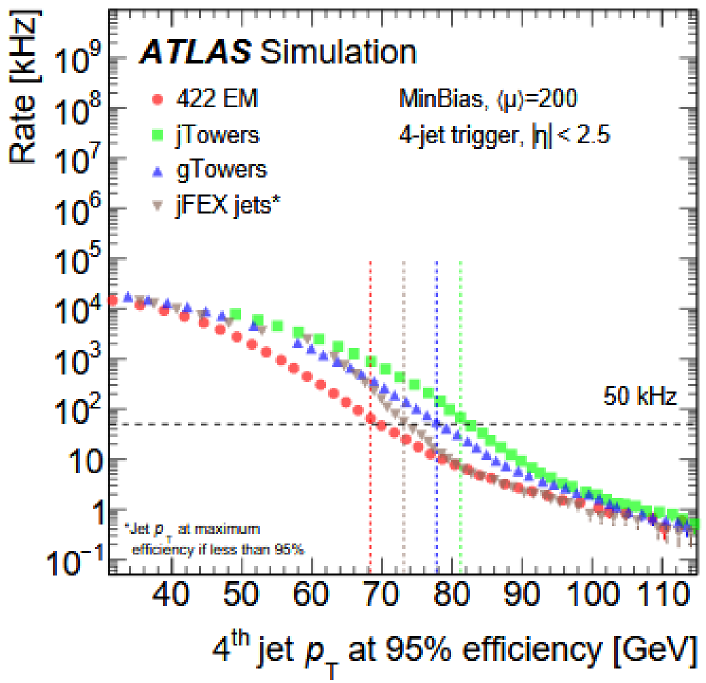
HL-LHC Triggering Scheme

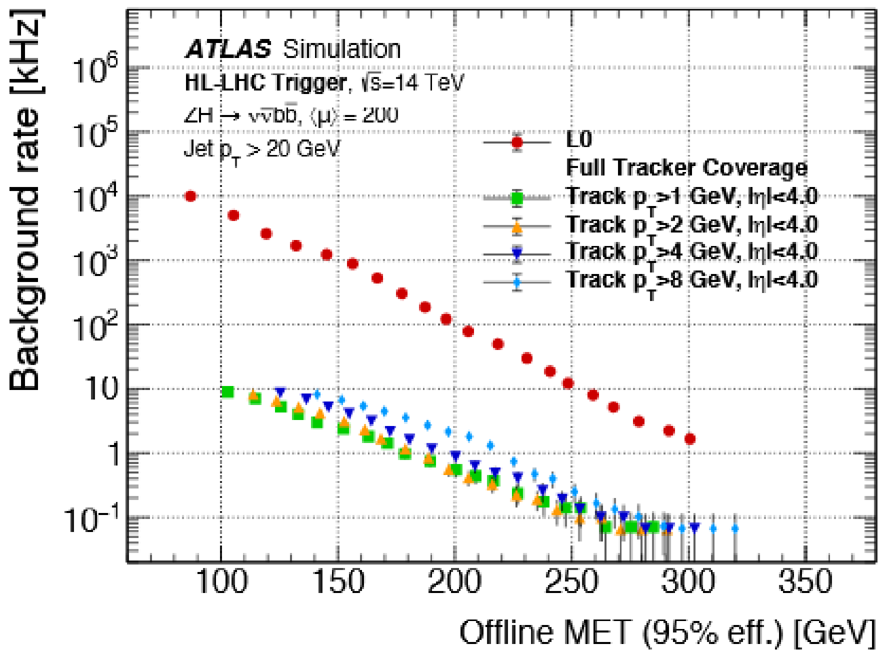
- L0 trigger upgrades:
  - Global Trigger: Implements offline-like algorithms and pre-processing providing full-granularity energy data
  - Topological selections based on p_T and angular requirements
- Event Filter trigger upgrade
  - Regional track reconstruction limited to a Region of Interest (RoI) of the detector
  - Associated memory technique: Accelerated tracking using pre-loaded pattern banks



HL-LHC Trigger Performance

Trigger name	Physics signatures	Threshold [Run 1] (GeV)	Threshold [Run 2] (GeV)	Threshold [HL-LHC] (GeV)
Isolated single e Isolated single μ	$WH, ZH, t\bar{t}$, EW SUSY	25 25	27 27	22 20
Di-γ	$H \to \gamma\gamma, HH \to b\bar{b}\gamma\gamma$	25, 25	25, 25	25, 25
Di-τ	$H \to \tau\bar{\tau}$, EW SUSY	40, 30	40, 30	40, 30
Four-jet w/ b-jets	$HH \to b\bar{b}b\bar{b}$, RPV SUSY	45	45	65
H_T	SUSY	700	700	375
MET	$ZH \to \nu\bar{\nu}b\bar{b}$, Dark Matter	150	200	200





Conclusion

- We found our four main challenges to be **Luminosity**, **Pileup**, **Tracking**, **Triggering**
  - Left out a lot of interesting upgrade technologies and efforts: NSW, HGTD, LGADs, Calo Readout Upgrades, etc.
- Solutions were innovated by creating new technologies, leveraging old, designing new schema, implementing more efficient algorithms
- Fruit of this labor means we can continue to probe interesting physics at similar readout rates and better detector efficiencies
- Still a lot of work to do to produce all the necessary detector material, test and install
- Here's to 2027

Resources

- https://indico.cern.ch/event/742082/contributions/3072114/attachments/1734070/2803878/HL-LHC-FG.pdf
- https://indico.cern.ch/event/742082/contributions/3072115/attachments/1733884/2803534/HL-LHC_Status_Rossi_v1.pdf
- https://indico.cern.ch/event/276587/attachments/502881/694424/HL-LHC-Trigger.pdf
- https://cds.cern.ch/record/2692161/files/ATL-DAQ-PROC-2019-020.pdf