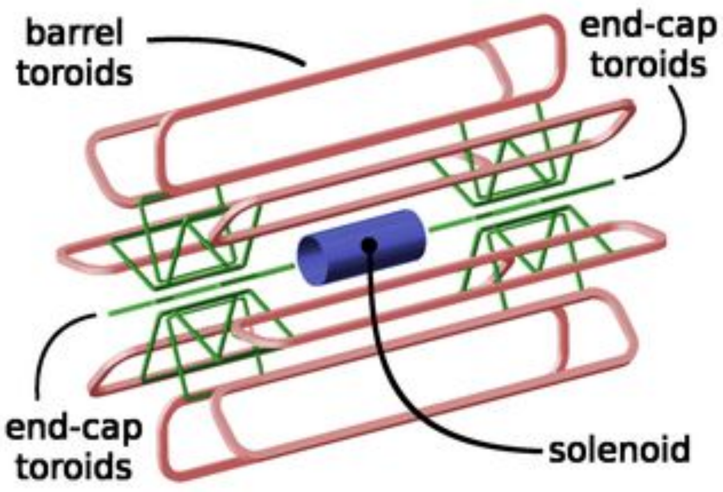
Detecting Particles

Magnets

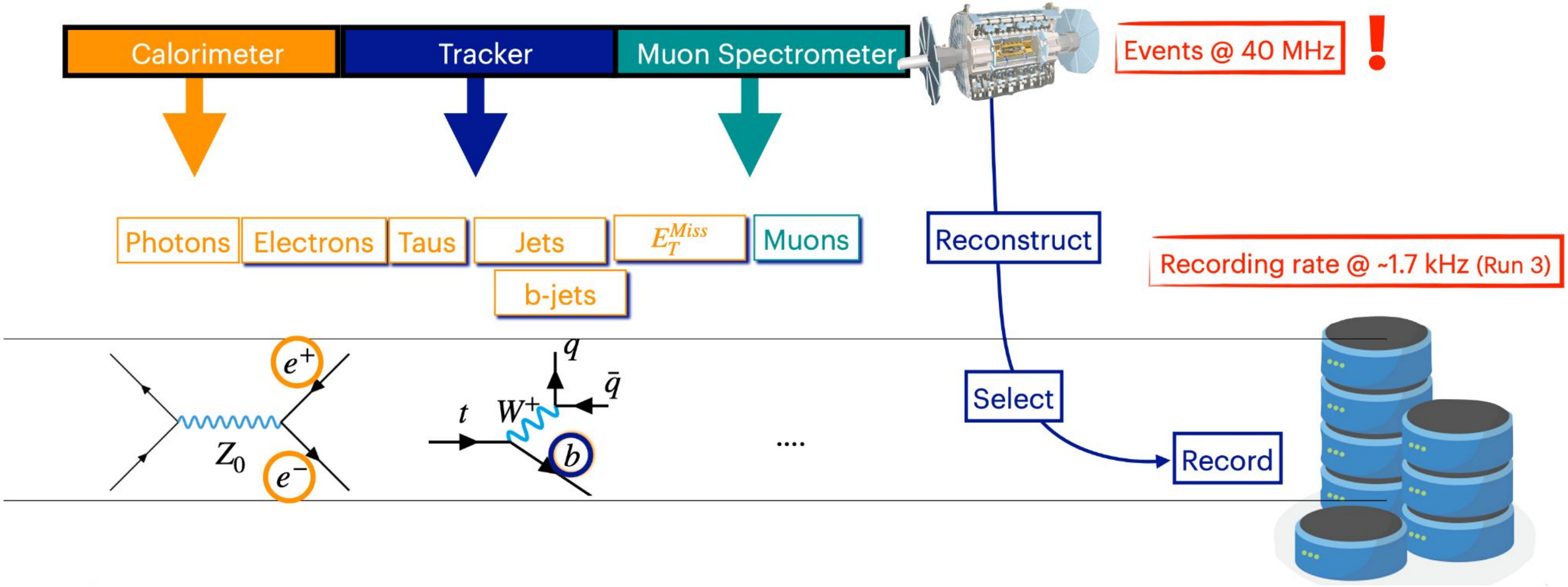
- Magnetic fields used to curve charged particle tracks
  - Allows measurement of charge and momentum
- Solenoid provides field for inner detector
  - 2 T
- Toroids provide field for muon spectrometer
  - ~4 T



Triggers

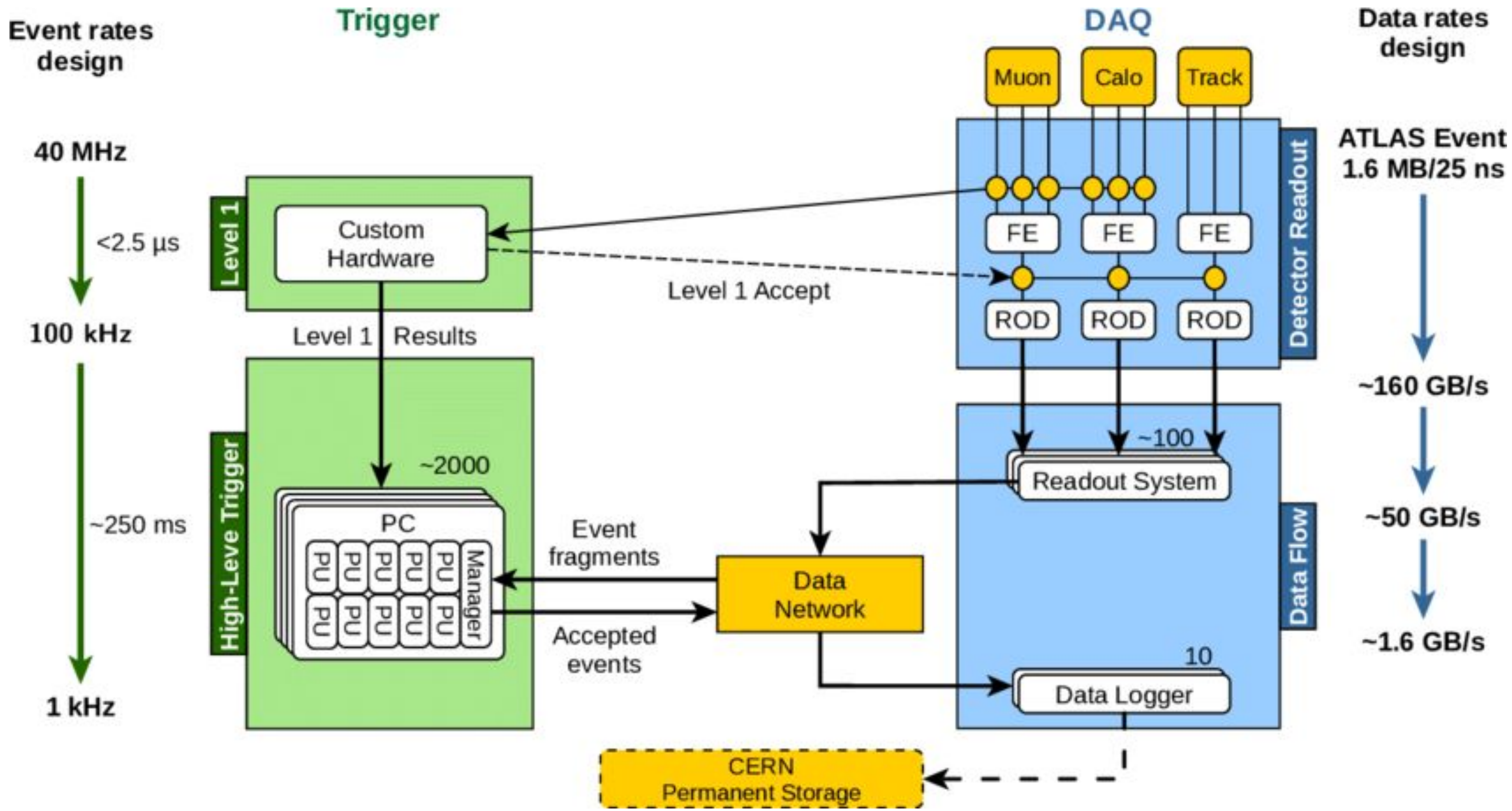
- Most collisions in ATLAS are not interesting
  - Low-angle elastic scattering is much more common than hard scatter events
- Not feasible to read out or store data from every event
  - Data rates are far beyond the capabilities of our readout electronics
  - Would result in petabytes of data daily - cannot be stored
- Trigger used to automatically select events that may be interesting
  - Events with large deposits of energy in the detector are stored for reconstruction and analysis
- Two-level trigger system
- Level 1 (L1) trigger
  - Hardware-based trigger making coarse decisions about energy deposits
  - 40 MHz ⇒ 100 kHz
- High-Level Trigger (HLT)
  - Software-based trigger making sophisticated decisions about precise signatures
  - 100 kHz ⇒ 1.7 kHz

Triggers



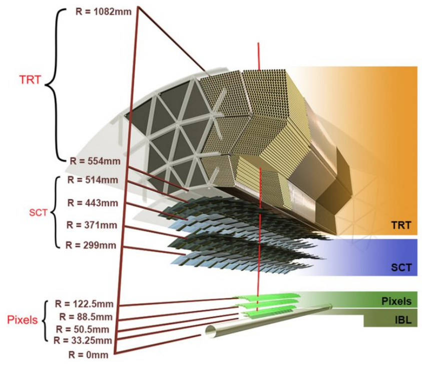
Calorimeter
Tracker
Muon Spectrometer
Events @ 40 MHz
!
Photons
Electrons
Taus
Jets
E_T^{Miss}
Muons
b-jets
Reconstruct
Recording rate @ ~1.7 kHz (Run 3)
e^+
e^-
Z_0
q
$\bar{q}$
t
W^+
b
....
Select
Record

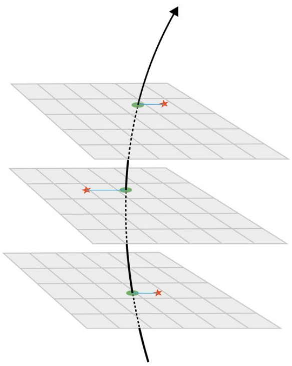
Data acquisition

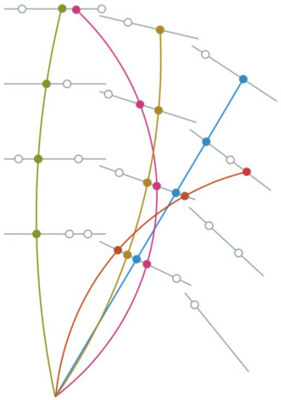


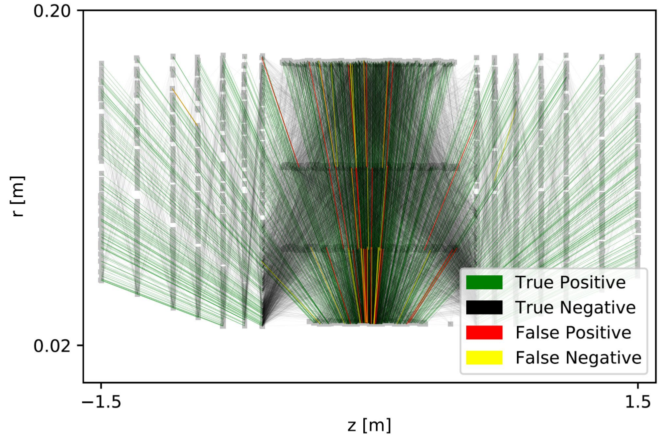
Tracking

- Charged particles interact with trackers and leave space points
  - Interactions with silicon in ID and gas in MS
- Magnetic fields cause trajectories to curve as particle propagates
  - Measure momentum from curvature and sign of charge from direction
- Algorithm used to create track through space points through layers
- Sophisticated machine learning techniques used for very dense environments



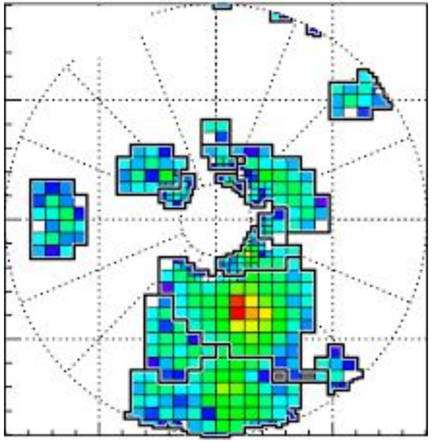


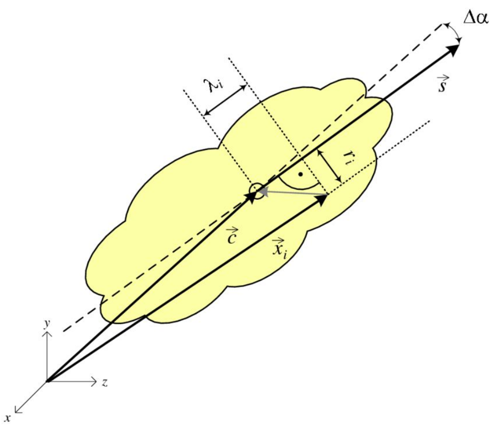


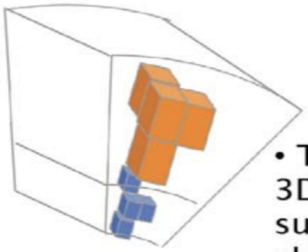


Calorimeter clusters

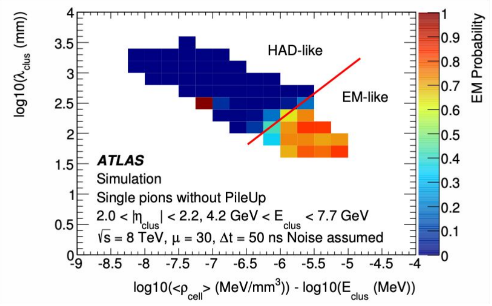
- Energy deposited in calorimeters is measured in individual cells
- Cells are clustered together in 3D based on topological relationships to form TopoClusters
- Clusters can be characterized as HAD-like or EM-like
- Calibrations can be applied to clusters
- Finite size and poor direction accuracy
- Energy resolution improves with increasing energy





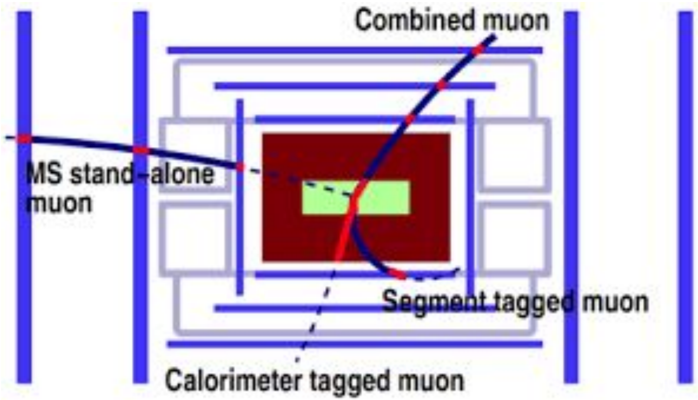


• **TopoClusters**: 3D noise-suppressed clusters of cells



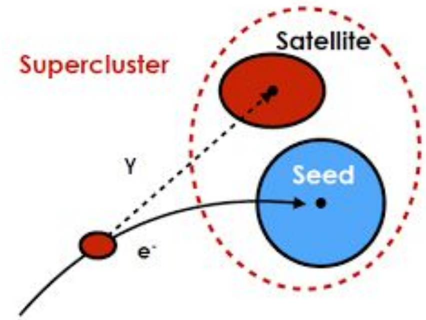
Muon reconstruction

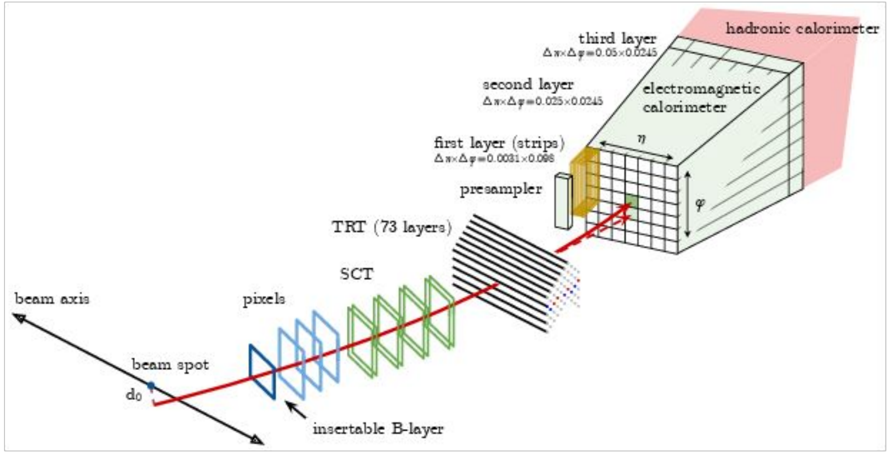
- Muons interact in ID and MS, leaving space points in both systems
  - Minimal interactions in calorimeters, but can be included in reconstruction and calibration
- ID tracks are matched to MS tracks to form muons
- Identification and impact parameter criteria are used to veto muons from heavy hadron decays
- Momentum measured from track curvature



Electron reconstruction

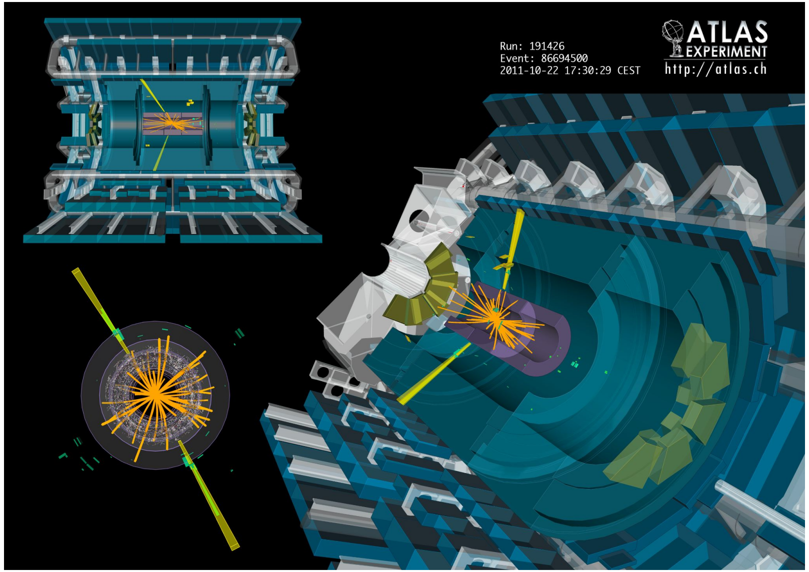
- Electrons leave a track in the ID and a cluster in the calorimeters
- Reconstructed as an EM-like cluster associated to an ID track
  - Nearby photon clusters are added in to account for colinear radiation
- Likelihood-based method used to identify electrons
- Energy measured from cluster due to better resolution at high energy
  - Calibration applied to account for detector effects
- Direction measured from track





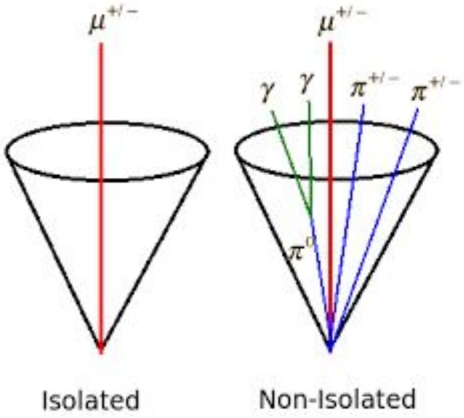
Photon reconstruction

- Photons leave an EM-like calorimeter cluster but no track
- Photons can convert to e^+e^-, resulting in two nearby electrons
  - Opposite-sign electron pair consistent with conversion are used as photon
- Energy measured from calorimeter cluster(s)
  - Calibration applied similar to that of electrons
- Direction taken from cluster or conversion tracks



Isolation

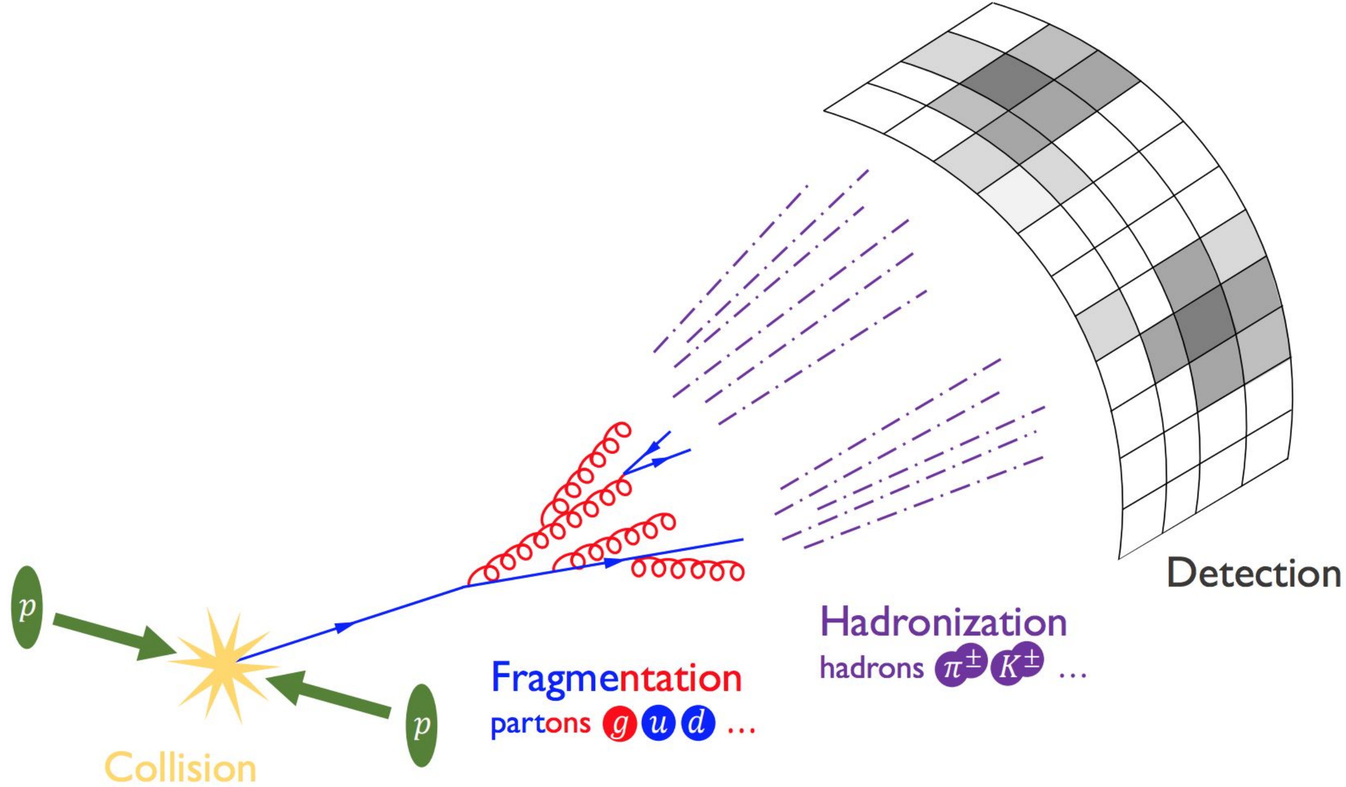
- “Prompt” leptons and photons produced in initial interaction or decays
  - Generally what we want to use
- “Non-prompt” come from hadron decays or collinear radiation
  - Generally not used in event reconstruction
- Isolation criteria can be used to identify prompt leptons and photons



Hadronic jet formation

- Color confinement prevents isolated quarks and gluons
- High energy partons “stretch” gluon link until quark/anti-quark pairs form
  - More energetically favorable than long-distance QCD binding
- Radiated gluons fragment to form additional quark pairs
- Pair formation continues until parton energies are too low to create more
- Partons combine to form hadrons (hadronization)
  - Heavy, unstable hadrons can decay to leptons, photons or lighter hadrons
  - Photons can be radiated from charged hadrons
- Wide “spray” of stable hadrons, leptons and photons enter the detector
- Total energy and direction of this “spray” is related to the originating parton
  - Not entirely correct due to color connectivity and other effects
  - Useful to see it as a proxy for the originating parton

Hadronic jet formation

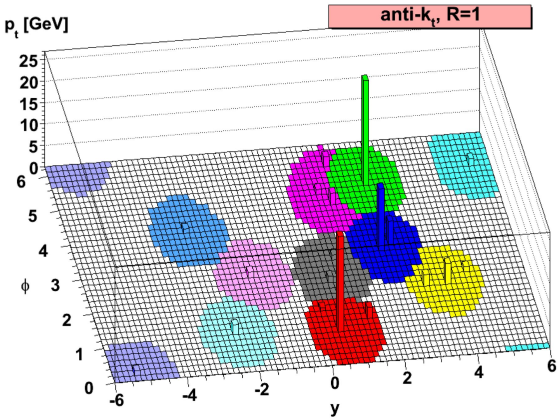


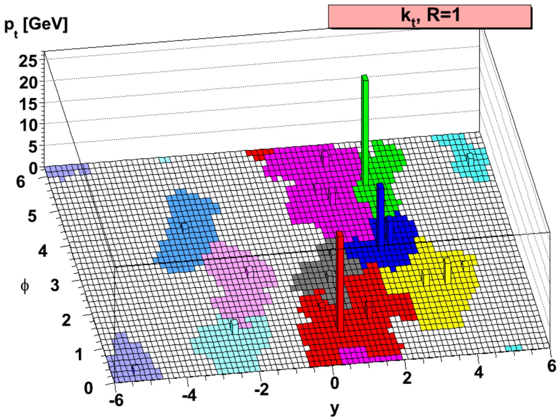
Jet reconstruction

- Hadronic jets are reconstructed to attempt to capture full parton energy
  - Can be thought of as conical due to particles propagating outward from a single point
- Inputs to reconstruction are typically a combination of tracks and clusters
  - Any type of object with a 4-momentum can be used
- Modern algorithms iteratively combine object to form jets
  - Combinations based on energy and angular distances between objects
- ATLAS uses anti-k_t (p = -1) algorithm with R = 0.4 and R = 1.0

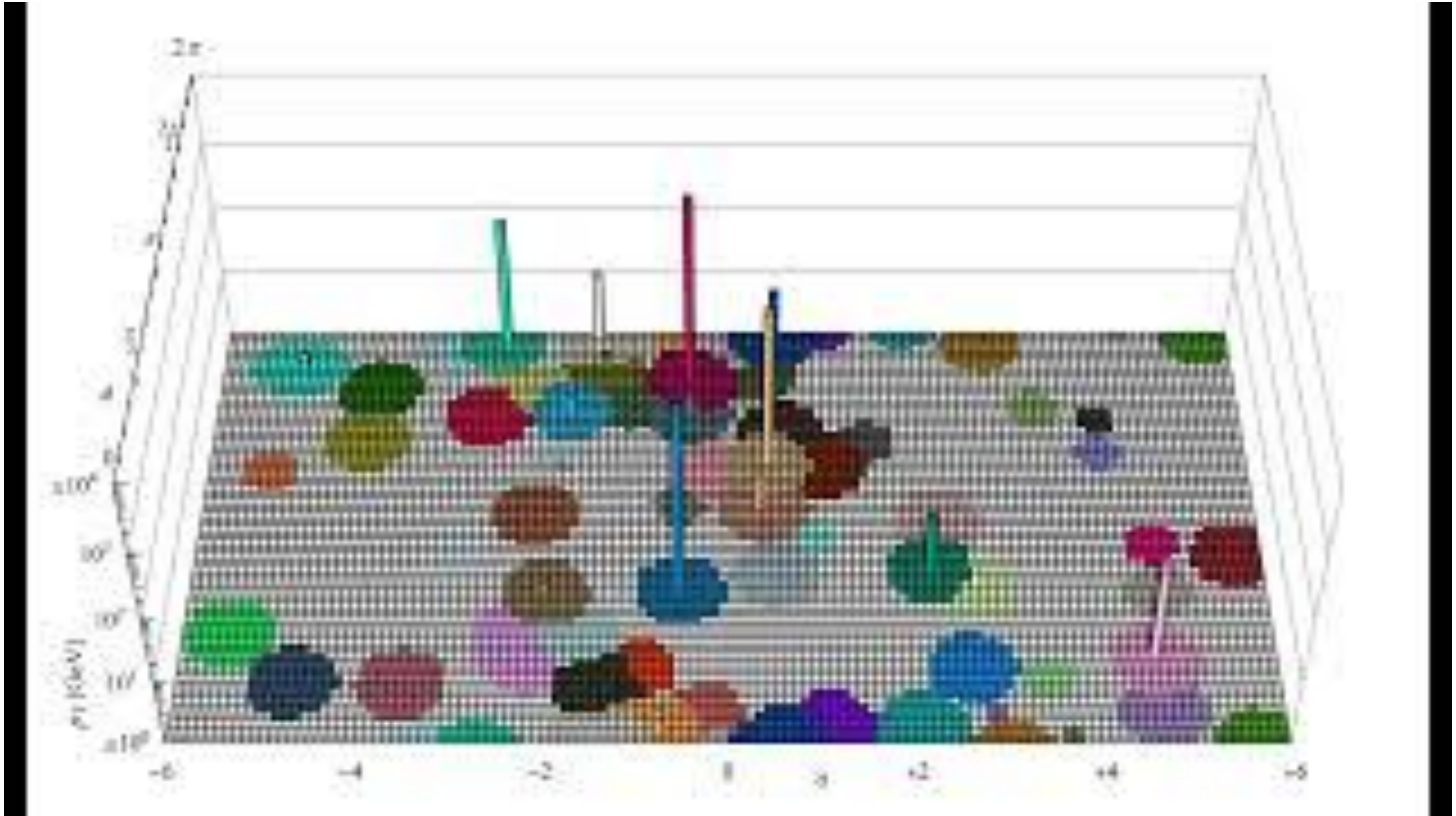
$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = k_{t,i}^{2p}$$





Jet clustering

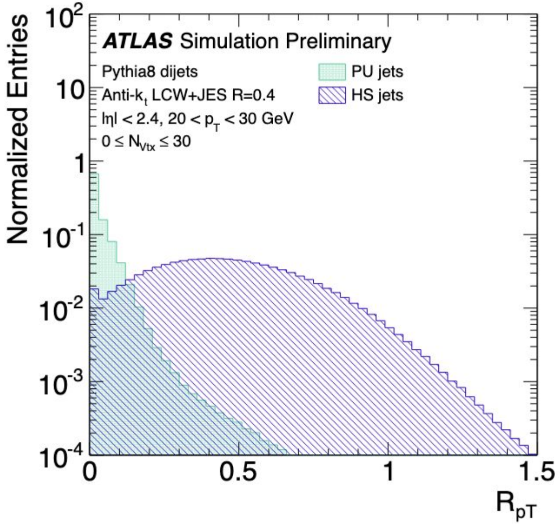


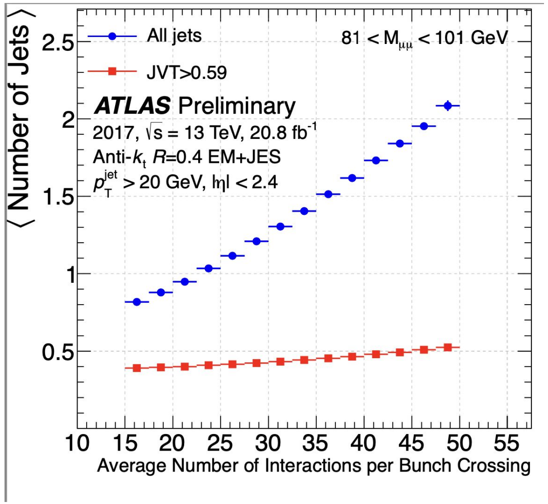
Effect of pileup on jets

- Jets have a significant angular size (other particles do not)
- Hadron collisions have a significant amount of pileup hadronic jets

➢ Highly susceptible to effects of pileup

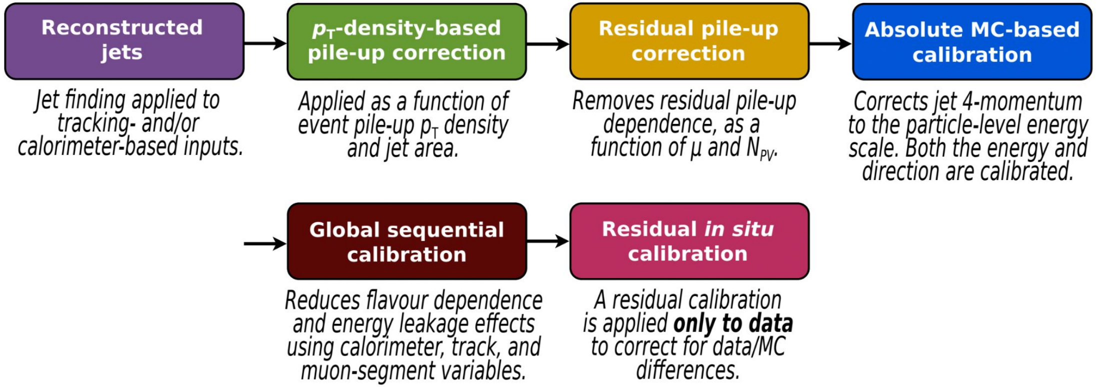
- Jets originating from pileup and pileup energy in hard scatter jets

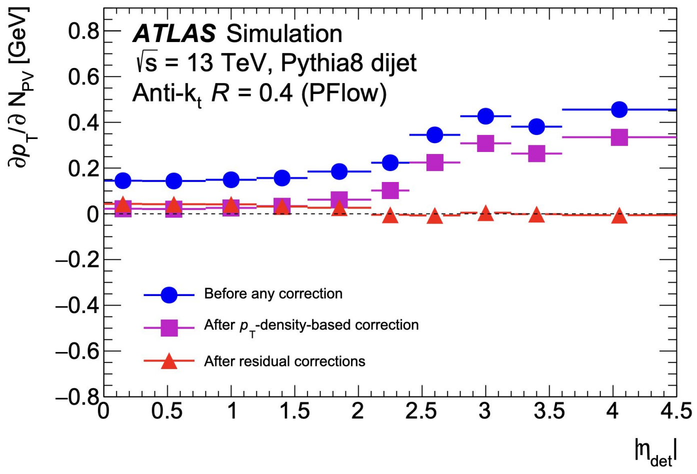




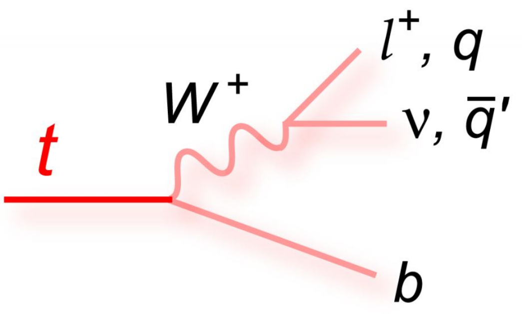
Jet calibration

- Reconstructed jets do not have correct energy
  - Inelastic QCD interactions, energy leakage, decays to neutrinos and muons, pileup, etc.
- Corrections are applied to calibrate jet energy to “correct” value

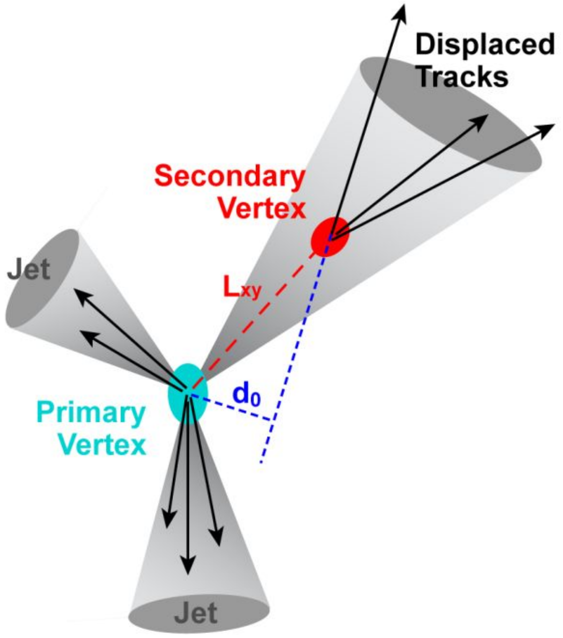




Flavor tagging

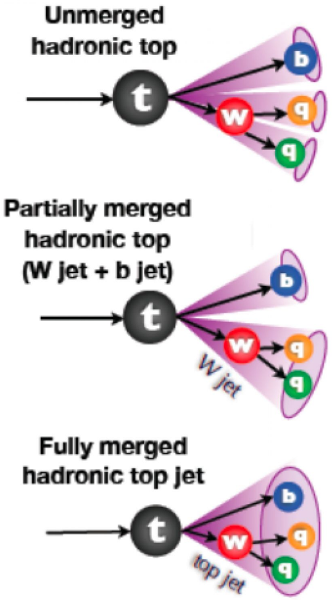


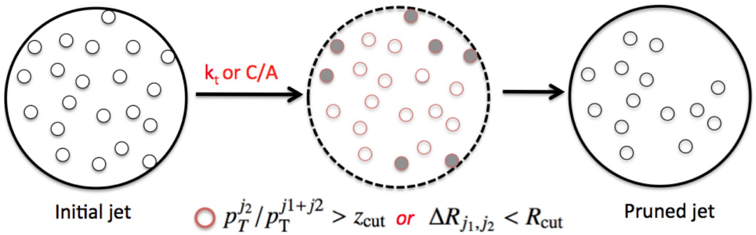
- Jets originating from b quarks are different from light quark or gluon jets
- B-hadrons have a finite lifetime and decay a distance from primary vertex
  - Often decay into muons
- Jets from b quarks have a larger mass
- Useful to tag b-jets when looking to top quarks or H→bb decays
  - Top quarks decay almost exclusively as t→Wb

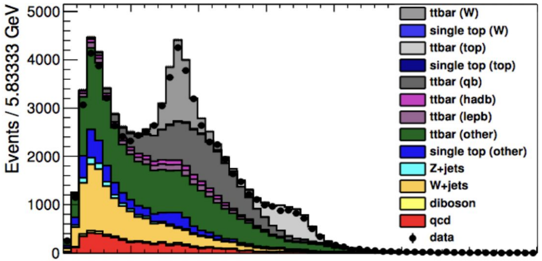


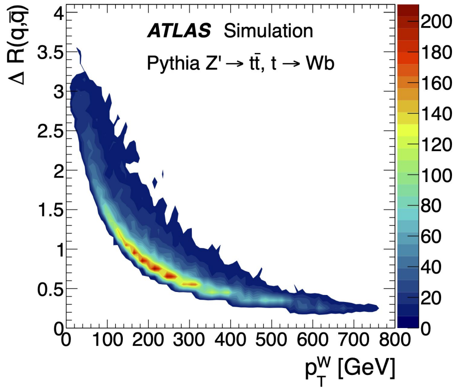
Large-R jets

- Hadronic decay products from high-momentum particles merge
  - Individual products cannot be reconstructed
- Use large-R (R = 1.0) jets for reconstruction
- More susceptible to pileup than R = 0.4 jets
  - Pileup deposits directly removed
- Substructure (distribution of energy within jet) can help identify origin
- Jet mass corresponds to originating particle



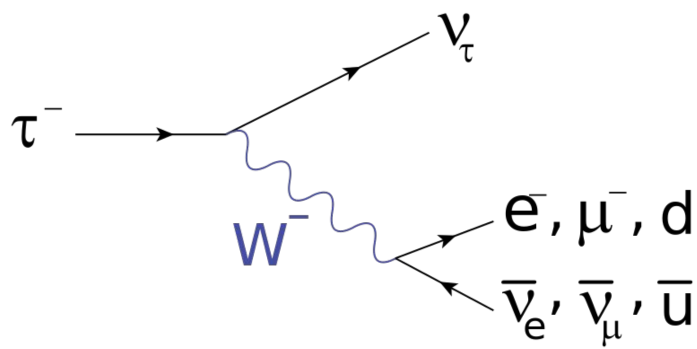


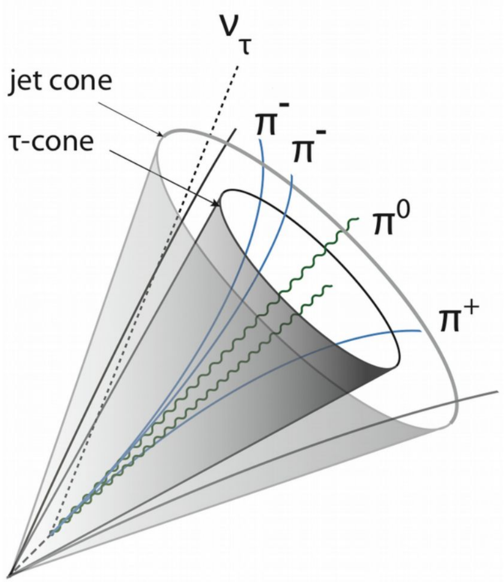




Hadronic τ reconstruction

- τ leptons can decay leptonically (e/μ + 2ν) or hadronically ($(x+1)\pi^{\pm}+y\pi^{0}+\nu$)
    - Leptonic τ leptons seen as an electron or muon
- Hadronic τ lepton reconstruction/identification seeded by a R = 0.4 jet
- Required to have 1 or 3 tracks in inner cone (R = 0.2) with net charge of ±1
- Region of 0.2 < R < 0.4 is used for isolation





Overlap removal

- ATLAS object reconstruction algorithms run independently of one another
  - The same energy deposits can be reconstructed as multiple objects (e.g., jet and electron)
- We want to avoid double counting energy
- Overlapping objects are removed from analysis
- All types of objects are iteratively compared and various overlap conditions are used
- May eventually become obsolete

Missing transverse energy

- Invisible particles cannot be directly detected
  - Neutrinos, DM candidates, SUSY particles, etc.
- Existence inferred from transverse momentum imbalance (MET or EtMiss)
- MET calculated from calibrated objects
- Additional soft track term