Data analysis in high-energy physics

Search for top—anti-top quark resonances in proton-proton collisions with ATLAS data

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In order to do physics in ATLAS we need to reconstruct some physics objects that represent those found in nature.

http://atlas.physicsmasterclasses.org/videos/teilchenidentifikation.swf
Electrons

- Produce Inner Detector (ID) hits from which their trajectories can be reconstructed —> Momentum measurement
- Produce electromagnetic showers in the electromagnetic calorimeter
- Two processes are dominant in EM showers: pair production (photons) and bremsstrahlung (electrons)
- Linear extent of EM shower depends on the calorimeter material (radiation length)

\[ X_0 = \frac{716.4 \cdot A}{Z(Z + 1) \ln \frac{287}{\sqrt{2}}} \text{ g cm}^{-2} \]

- An Inner Detector track and energy deposition in the EM calorimeter are needed for identifying an electrons
Photons

- Photons are neutral = no interaction with Inner Detector
- Produce **electromagnetic showers** in the electromagnetic calorimeter
- Reconstruction techniques for photons are similar to those used for electrons
- Photons can give rise to electron pairs: photon conversion
Muons

- Produce Inner Detector hits from which their trajectories can be reconstructed
- Muons are heavier than electrons and thus lose little energy (~GeV) in the EM and hadronic calorimeters. **Minimum ionizing particles.**
- Produce hits in the Muon Spectrometer (MS)
- Muons can be reconstructed from different combinations of signatures in the ATLAS detector, e.g, Calorimeter+MS, MS only, etc.
- Muons in ATLAS can come from cosmic rays too!
Jets

Basically a spray of particles that can be contained in a given catchment area

Origin

- Initiate from the hadronization process of partons from decaying quarks and gluons

In ATLAS

- Electrically charged hadrons ($\pi^\pm$, $K^\pm$) leave tracks in the ID
- Photons from neutral hadron decays ($\pi^0$) are detected in the EM calorimeter
- All hadrons are start a hadronic shower in the Hadronic calorimeter
- Hadronic showers originate from strong interactions between hadrons and nuclei of the detector material
- Hadronic showers are wider than EM showers
Jets
Reconstructing jets

- Energy deposition in calorimeters is reconstructed as cluster: for example the energy deposited by a single pion.
- Clusters are combined into a single object. Ideally cone-like
- Different recombination algorithms use different metrics for jet reconstruction

Reconstructed jets in ATLAS
- Preferred algorithm is Anti-kT
- Produces conical shapes in ideal cases
- Performs well in case of jet overlap
- It is infrared (soft gluon emission) and collinear (collimated particles) safe
- Jets are usually classified based on a distance parameter \( R \)
  - \( R=0.4 \): most common jets
  - \( R=1.0 \): Large-R jets or fat jets
Tau leptons can decay leptonically or hadronically

Leptonic decays
• Due to their mass, taus decay before reaching the ID
• Electrons and muons from tau decays look as if they came directly from the interaction point

Hadronic decays
• Taus usually decay to one to four pions of which one or three are electrically charged
• Each charged pion has an associated ID track
• Tau identification, in broad terms, looks for narrow jets associated with one or three ID tracks

Taus usually decay to one to four pions
Primary and Secondary Vertices

Primary vertex

- Roughly speaking, a primary vertex is found by associating reconstructed tracks to vertex candidates
- In a given event, only one primary vertex is chosen as the interaction of interest
- Vertex of interest is often chosen as that with the highest sum of the transverse momentum of the tracks associated to it

Secondary vertex

- Mainly used for identification of jets from b-quarks
- Applicable to searches for long-lived particles that decay far from the interaction point
- Extrapolation of tracks associated with secondary vertices show impact parameters of ~mm
• The transverse momentum of colliding partons is negligible

• Ideally the momentum of all objects associated to the primary vertex should balance in the transverse plane

• This is not always the case:
  ‣ Escaping neutrinos
  ‣ Reconstruction inefficiencies
    ‣ New physics!

• The momentum imbalance in the transverse plane is know as Missing Transverse Energy or Missing $E_T$ (MET)
Jets from b-quarks

• Jets from b-quarks contain displaced vertices
• Displaced vertices come from the decay of b-hadrons from the b-quark hadronization
• Insertable b-layer (new) and Pixel detector contribute greatly to the measurement of the displaced tracks’ impact parameter
• The MV1 algorithm used a Neural Network (NN) to classify jets: the NN response is available in the ROOT ntuples

Why is it so important to identify b-jets?
• The LHC is a tt production machine
• Top quarks decay ~100% to Wb
• The Higgs boson decays mostly to b-quark pairs
Selecting Interesting Collision Events

• In an analysis we want to select only the collision events that are of our interest
  ‣ If my signal process contains an electron or a muon, I would like to select events that have an electron or a muon
  ‣ I would not like to select events that contain jets

• Appropriate trigger thresholds have to be selected in order not to lose any signal
  ‣ Often in terms of transverse energy or momentum

• Triggers can be "tricked" by objects they are not designed for
  ‣ Electron and photon triggers can be fired by jets
  ‣ Undesired background processes may enter in the category of selected events

• Triggers select signal events, but also select background events with the same final state
The efficiency of a trigger for selecting events is not ideal
  ‣ The turn-on is not a step function

Trigger efficiency also depends on detector geometry and may have additional requirements

It is desirable to work on the plateau of the trigger efficiency
  ‣ That’s when the trigger efficiency reaches it’s (near) maximum

**Example**

- It is inevitable to lose some signal due to trigger inefficiencies.
- It is important to select the appropriate trigger so that most of the signal is kept
How good is our trigger for our purpose?

…or how do we choose a trigger?

- We want to maximize signal acceptance, i.e., select the lagers number of events possible
- Things that affect the trigger acceptance:
  - Trigger object transverse momentum: $p_T > 40 \text{ GeV}$
  - Trigger Object multiplicity: 2 muons, 4 jets, etc.
  - Kinematic acceptance: $|\eta| < 2$

**Example**

- We have a signal process in which a particle $X$ of mass $m_X$ decays into six jets
- For mass $\leq 1000 \text{ GeV}$, the "multijet trigger" is the best choice
- For higher masses, the fat jet trigger is the best
- A logical OR of all the triggers would be the best (not always possible)
• We have reviewed the ATLAS physics objects. We will go into them in a more detailed way as it becomes necessary.

• We have reviewed some basic concepts on trigger acceptance and efficiency.
Thanks!