Using Jet-shapes in the Search for TeV-Scale Particles at the ATLAS Detector*

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Introduction

- LHC proton-proton collider (CERN) currently operating at record collision energy (√s=7 TeV)
  - Designed to reach peak collision energy of 14 TeV
- ATLAS detector is largest detector of LHC
  - Involved in search for physics beyond Standard Model (SM)
  - SM is successful but incomplete description of particles & their interactions
- ***Many theories beyond SM predict as-yet unobserved particles with mass on the scale of TeV***
  - Supersymmetry, Extra-Dimensions, & others
  - TeV mass-scale much larger than heaviest currently observed particle (top quark, ~173 GeV)
- General feature of neutral TeV-scale particle "X" is primary decay channel through fully hadronic top-pair production...

$$X \rightarrow t\bar{t} \rightarrow (W+b)(W-\bar{b}) \rightarrow (q\bar{q}b)(q\bar{q}\bar{b})$$

- Final state: 6 jets, one from each quark
- In the case of decay from initial TeV-scale particle, light decay-products (jets) highly Lorentz-boosted, collimated.
  - Results in jet-overlap at detector (see **fig. 1**)
  - ***Decay will be detected as a pair of jets rather than six jets***
  - Jets will look like decay due to less exotic QCD hadronization processes
- ***Goal- find a method of separating signal composite jets from background QCD jets.***

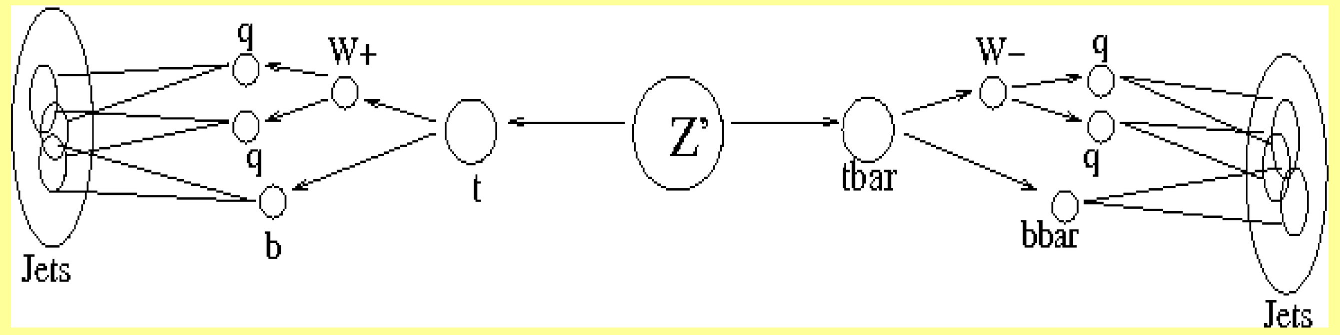

Fig. 1. Schematic of a hypothetical Z' in its rest-frame decaying by a top-pair to 6 jets which appear as 2.

Proposal

We propose a method using ***global jet-shape variables*** as a means of differentiating signal from background & improving signal-to-background ratio (SBR).

- DOES NOT use jet sub-structure
  - NO cluster analysis
  - NO principal-component analysis
- Treat each reconstructed jet as an ***ellipse***
- Define several ***shape-variables*** based on the idea of an ellipse
  - Axis & semi-axis lengths
  - Eccentricities
- Calculate several shape-variables for each jet to determine if it is a QCD mono-jet or a multi-jet of interest

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Shape-Variables Method

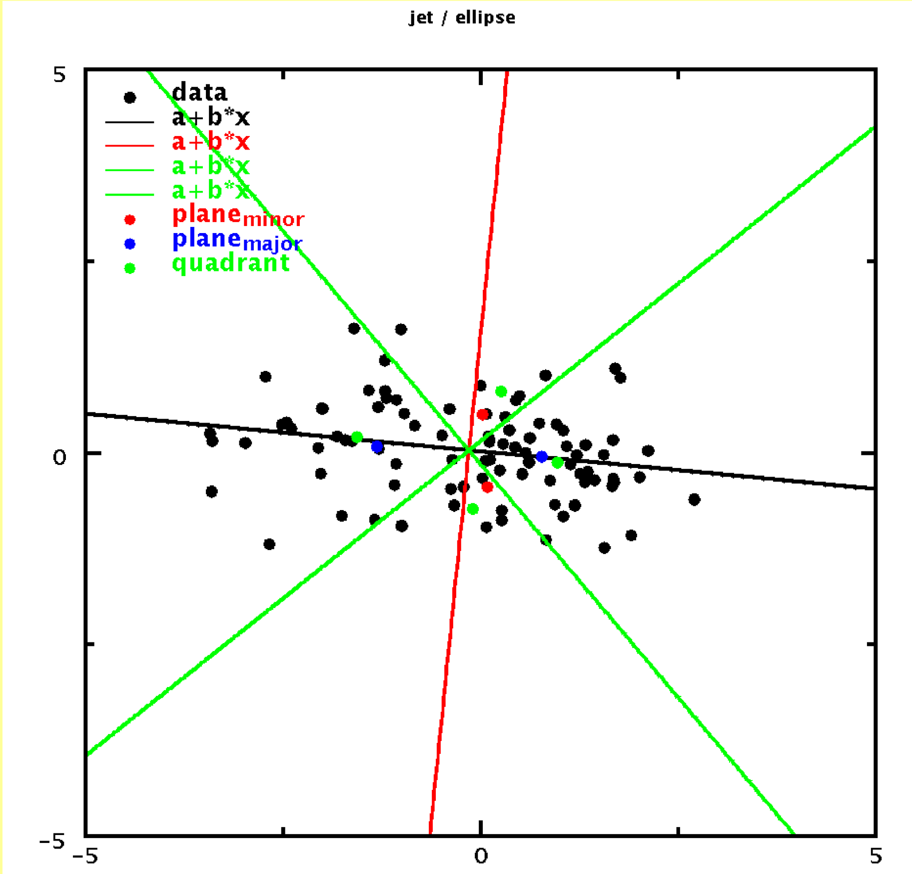

Fig. 2. Idealized jet in arbitrary phase-space. Black/Red lines are major/minor axis-lines. Green lines define quadrants. Blue/Red points are semi-plane centers. Green points are quadrant centers.

- Constituent points (hadrons) of each reconstructed jet are mapped onto eta-phi space...
  - Each point has position in eta (pseudorapidity) and phi (azimuth) as well as a weight (energy)
- Need to define variables of a classical conic-section out of a composite object of discrete points. Several Steps..
  - **1) Find geometric (i.e. unweighted) mean of all points in jet. This is the jet-center.**
  - **2) Perform unweighted linear-regression to find the major axis-line of the ellipse.**
  - **3) Minor axis-line is defined as perpendicular to the major, through the jet-center.**
- With axes defined, need to calculate lengths. 2 main methods of doing this...
  - **Quadrants-**
    - **4) Rotate major/minor axis-lines by 45 degrees to define 4 quadrants, each containing 1 semiaxis.**
    - **5) Find weighted mean of each quadrant (independently of points in other quadrants). This is quadrant center.**
    - **6) Length of semiaxis is distance between jet-center and quadrant center. Length of axis is distance between opposite quadrant centers.**
  - **Semi-planes-**
    - **4) Let axis-lines divide phase-space into 2 sets of 2 semi-planes; each point is above or below the major line & above or below the minor line.**
    - **5) Find weighted mean of each semi-plane (Weighted means above/below the minor axis-line define the endpoints of major semiaxes. Weighted means above/below the major axis-line define endpoints of minor semiaxes.**

The Variables...

- Major length (distance between major semiaxis centers)
- Minor length (distance between minor semiaxis centers)
- Eccentricity = 1 – (major length / minor length)
  - Range [0,1]. 0=perfect circle. 1=infinitely elongated (line)
- Semi-major lengths (distances between each semiaxis center and the global jet-center)
- Major eccentricity = 1 – (semimajor 1 / semimajor 2)
  - Like eccentricity. How 'skewed' ellipse is to one side.
- Minor eccentricity = 1 – (semiminor 1 / semiminor 2)
- Absolute length (distance between most extreme jet constituents after projection onto major axis-line)
- Absolute width (distance between most extreme jet constituents after projection onto minor axis-line)

- Each variable can be described by either ...
  - the semi-plane method or the quadrant method.
  - Proper eta-phi distance or by distance after orthogonal projection of centers onto the axis-lines
- With 4 possible ways of calculating each of the above variables, there are ***over 20*** identified shape-variables

Monte-Carlo Results

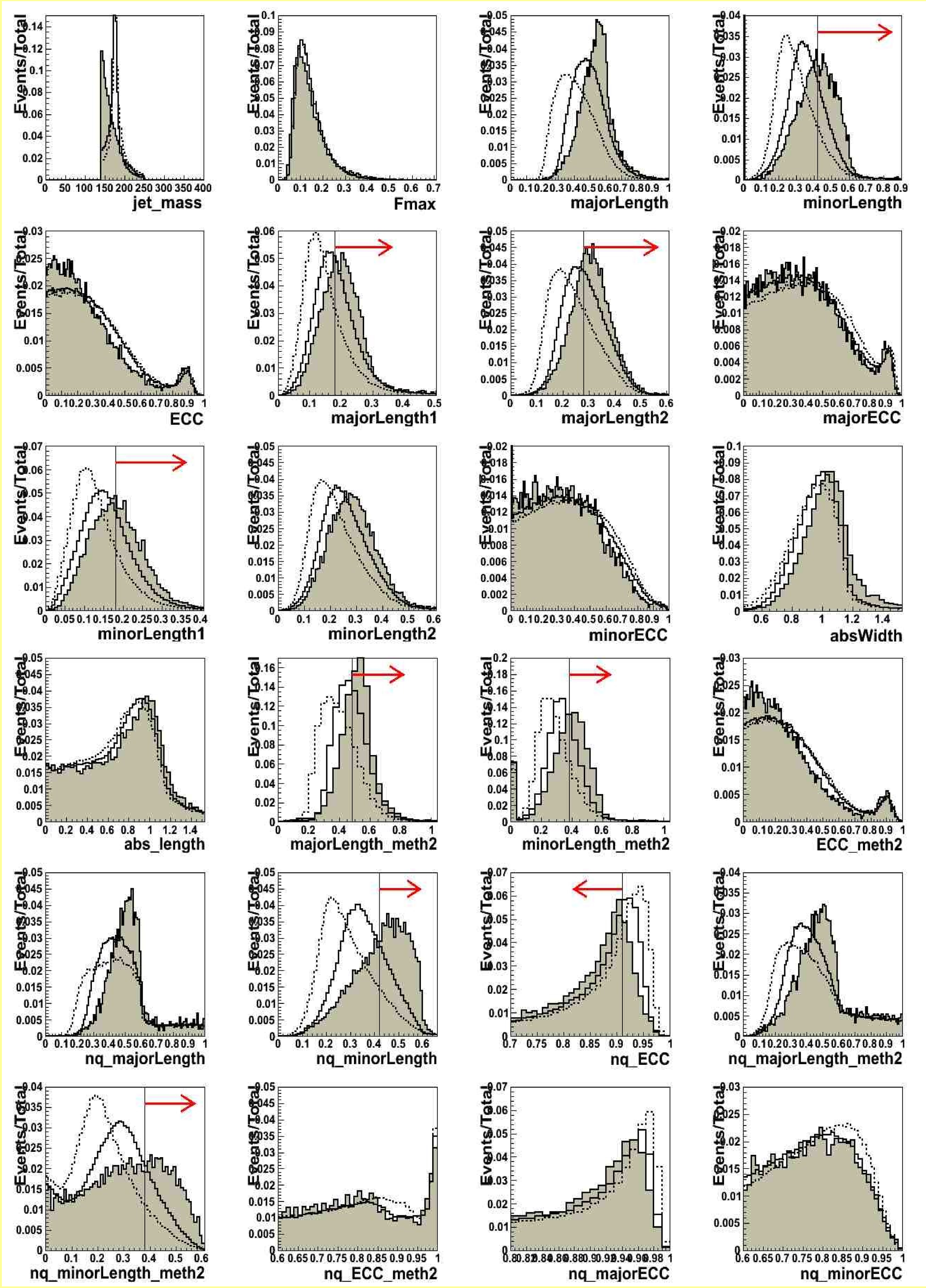

Fig. 3. 24 Variables for the leading-p_T jet after a jet-mass cut at 140 GeV. Filled histogram is QCD background, Solid line is 2 TeV signal, dashed line is 3 TeV signal. Vertical lines & red arrows denote the rejection areas for 9 variables. Length-variable units are in eta-phi distance units. Eccentricity-variables are unitless. Prefix "nq_" signifies semi-plane method, Suffix "_meth2" signifies projection onto axis-lines. Absence of prefix/suffix signifies the other method.

- Monte-Carlo (Pythia) truth studies performed for the hypothetical Z' boson. 500,000 events produced each for...
  - QCD background (including top-quarks)
  - 2 TeV and 3 TeV signal Z' (decaying through fully hadronic top-pairs)
- C++ program calculated shape-variables for 1st and 2nd leading p_T jets from each event
  - Only jets with p_T above 500 GeV accepted
  - Jets reconstructed by anti-k_T algorithm with cone size R=0.6
- QCD jet-mass peaks at ~40 GeV, signal jet-mass peaks at top-quark mass
- First apply a jet-mass cut (only jets with invariant mass above a certain value accepted. Upper bound on mass always 250 GeV)
- Look at resulting distributions (**fig. 3**) to apply shape-variable cuts
- Pick several shape-variables which discriminate signal & background well, apply rejection cuts
- Calculate rejection & relative rejection of cuts, see if improved (**table 1**)
  - Rejection factor is number of total events divided by number of events accepted after cuts
  - Relative rejection factor is background rejection divided by signal rejection

a) Relative Rejection Factors: 2 TeV

Mass Cut	Just Mass	≥ 5 variables	≥ 6 variables	≥ 7 variables
Jet1 150GeV Jet2 130GeV	177.3 / 2.1 =84.4	444.2 / 4.0 =111.1	584.4 / 5.5 =106.3	925.3 / 9.0 =102.8
Jet1 140GeV Jet2 140GeV	185.8 / 2.2 =84.5	545.0 / 4.2 =129.8	746.5 / 6.0 =124.4	1388.0 / 9.9 =140.2

b) Relative Rejection Factors: 3 TeV

Mass Cut	Just Mass	≥ 5 variables	≥ 6 variables	≥ 7 variables
Jet1 150GeV Jet2 130GeV	127.3 / 1.7 =74.9	260.9 / 2.3 =113.4	319.5 / 2.7 =118.3	460.5 / 3.4 =135.4
Jet1 140GeV Jet2 140GeV	133.3 / 1.7 =78.4	292.7 / 2.3 =127.3	372.8 / 2.7 =138.1	602.2 / 3.4 =177.1

Table 1. Rejection & relative rejection factors for different cuts. Number of variables indicates number of shape-variable cuts a jet must pass to be accepted. Numerators are QCD rejection factors, denominators are signal rejection factors. Relative rejection factor is factor of signal-to background improvement due to the cut.

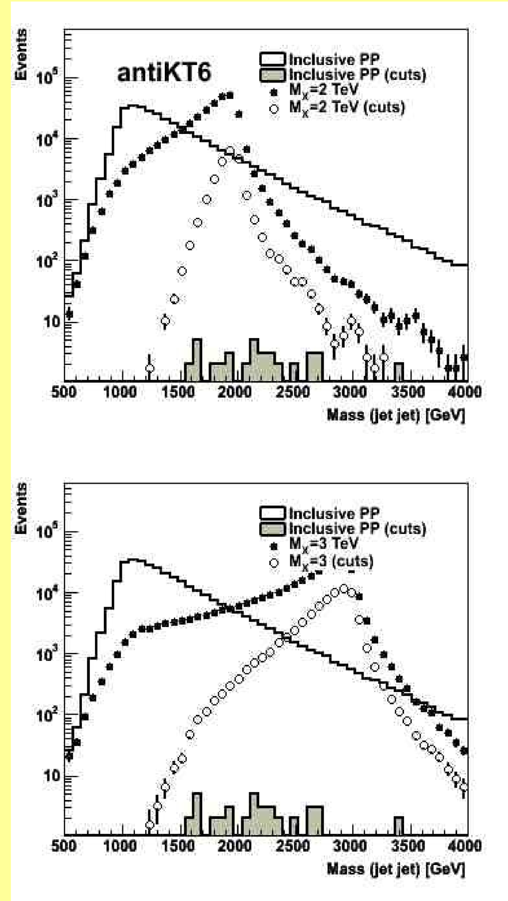

Fig. 4. Jet1-Jet2 invariant mass histograms, before and after cuts. Mass cut at 150 GeV, ≥ 7 shape-variables. "Inclusive PP" is background. "(cuts)" is distribution after cuts. Relative rejection factors for these cuts are **215.9** (2 TeV) and **284.2** (3 TeV). Distributions are normalized by requiring equal numbers of events.

Conclusions

We have outlined a jet-shape-variables method for separating multi-jets from mono-jets. Monte-Carlo studies show that it is possible to use the shape-variables method to achieve Signal-to-background improvement factors of well over 100. Mass cuts coupled with several shape-variable cuts produced the best rejection. Relative rejections of 130 for a 2 TeV Z' and over 175 for a 3 TeV Z' are possible while maintaining low signal rejection. Relative rejection factors of well over 200 are possible with higher signal rejection. We conclude that the shape-variables method may be useful in the search for TeV-scale particles.

Next steps include full-detector simulations for ATLAS. Assuming a positive result, the method may then be applied to data-analysis, as more data becomes available.